FUTURE FACILITIES

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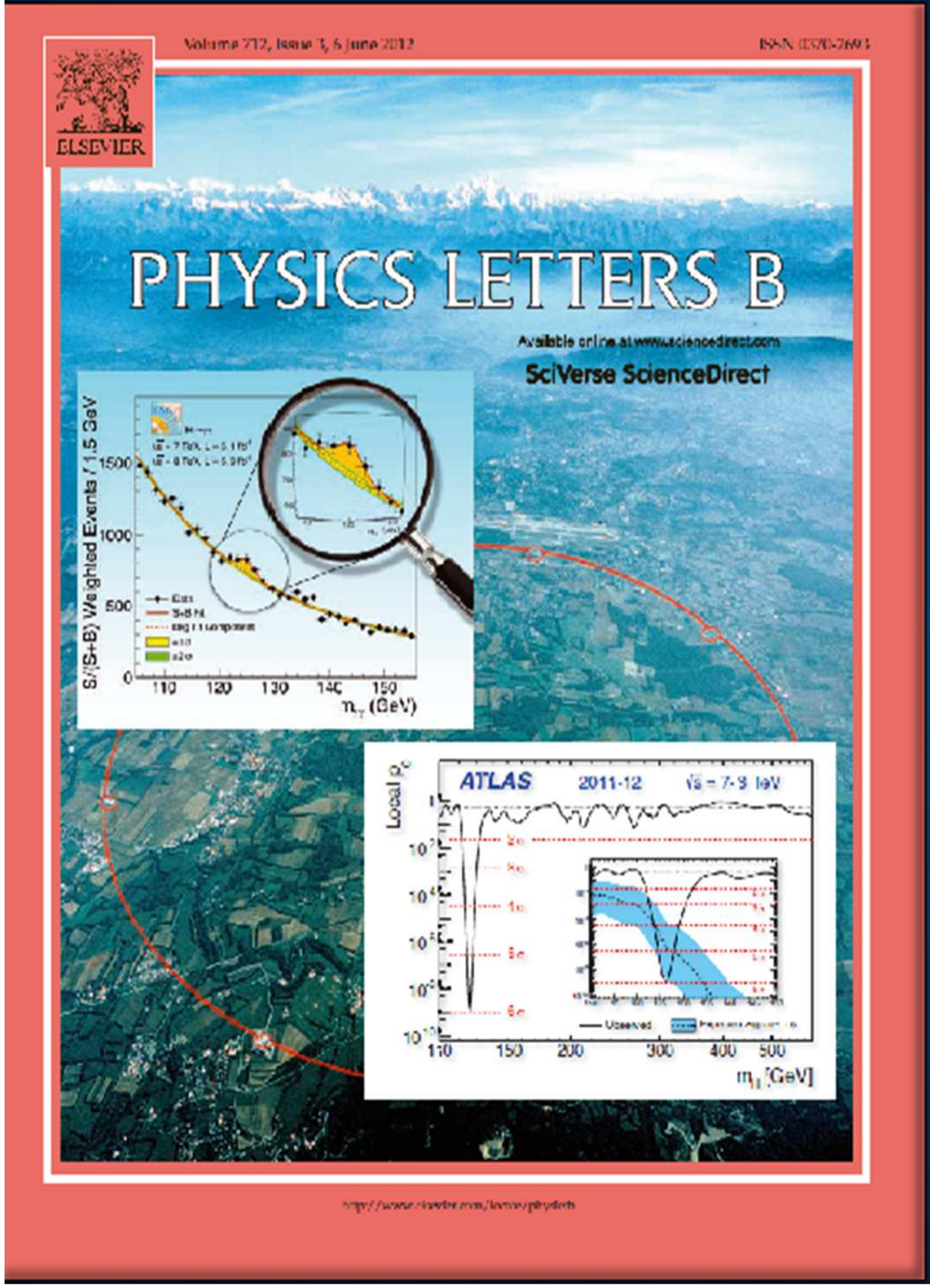
FIVE YEARS AGO ALREADY



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The Economist

JULY 7TH–13TH 2012

Economist.com

In praise of charter schools

Britain's banking scandal spreads

Volkswagen overtakes the rest

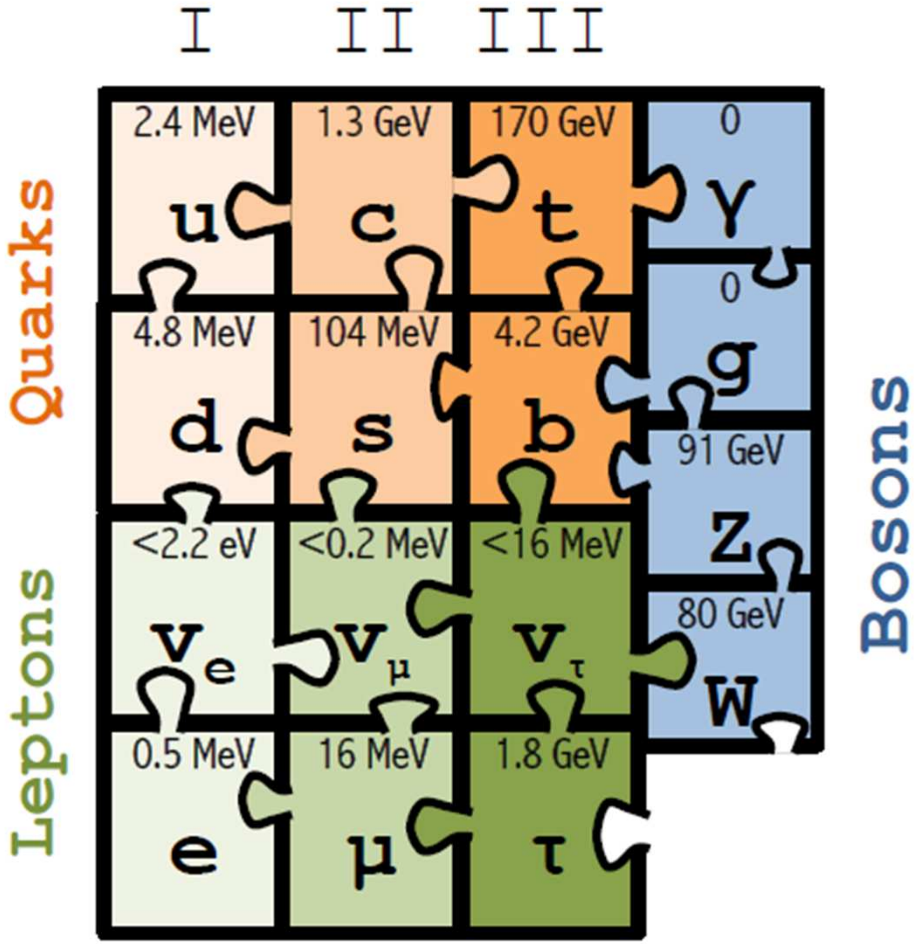
A power struggle at the Vatican

When Lonesome George met Nora

A giant leap for science

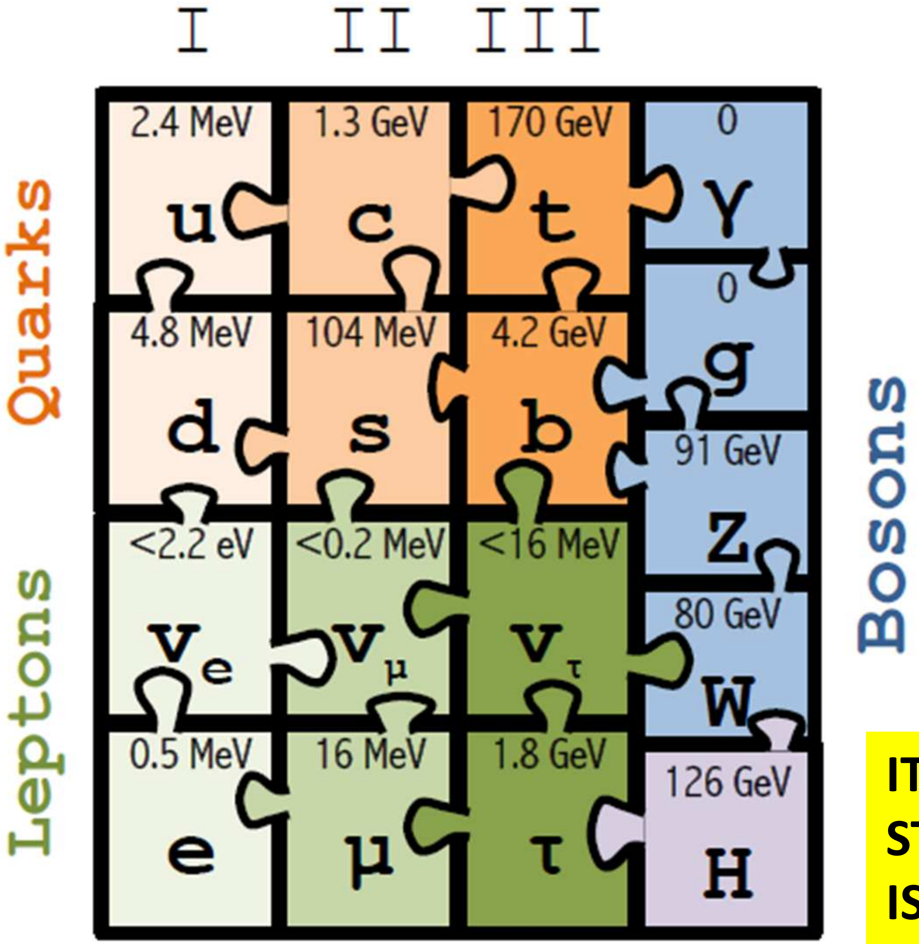
Finding the Higgs boson

1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t’Hooft and Veltman get Nobel Prize



(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)
Higgs Boson discovered (LHC)
Englert and Higgs get Nobel Prize



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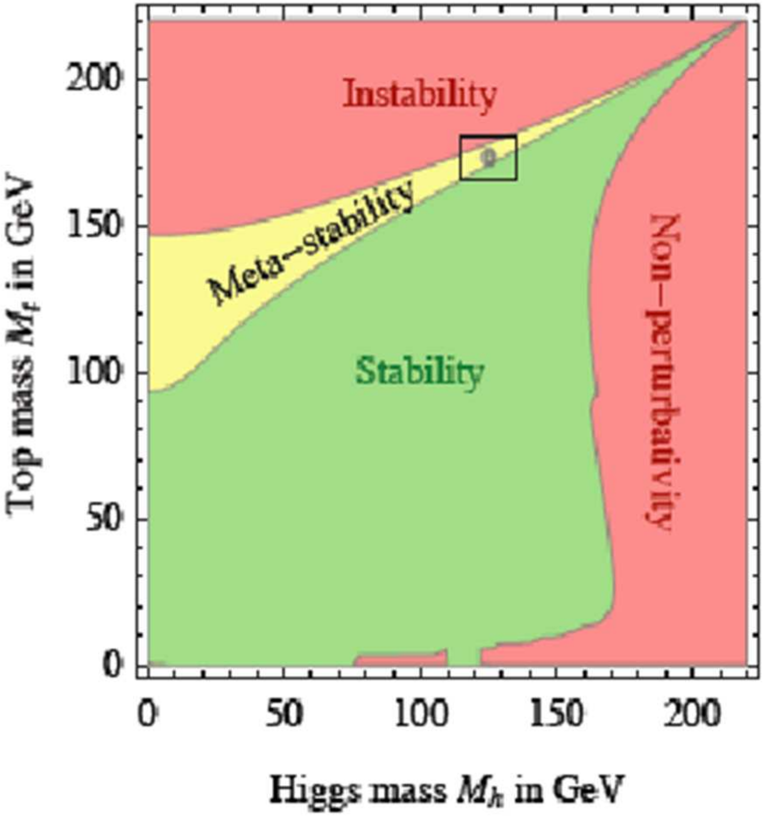
IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

Is it the end?


Instability
Meta–stability
Stability
Non–perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200

Is it the end?

Certainly not!

-- Dark matter
-- Baryon Asymmetry in Universe
-- Neutrino masses

are experimental proofs that there is more to understand.

We must continue our quest

HOW?

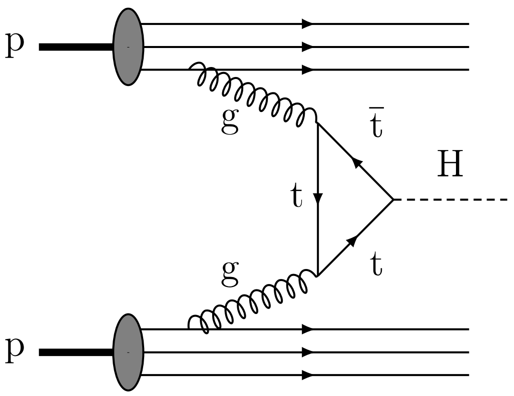
Detection through **Direct observation**

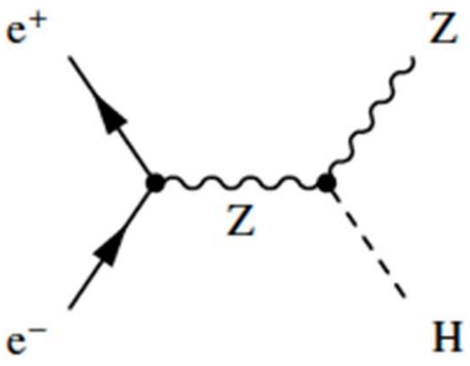
or

deviations from precise predictions (ref. Uranus to Neptune)

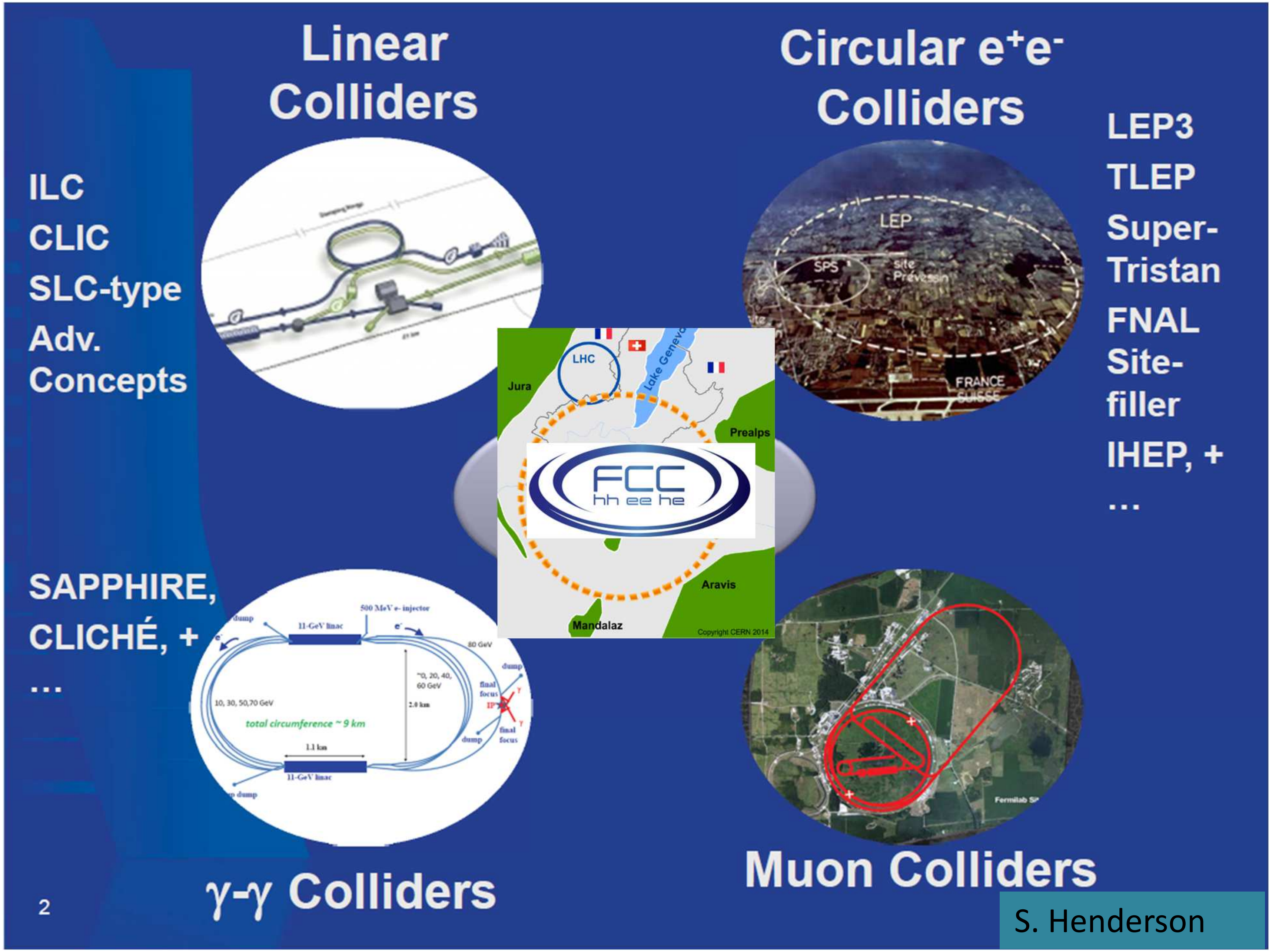
Where is Everybody?

pp collisions / e^+e^- collisions





p-p collisions	**e^+e^- collisions**
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	High energy (>≈380 GeV) e^+e^- requires **linear** collider High precision (<≈380 GeV) best at **circular** collider



Linear Colliders

- ILC
- CLIC
- SLC-type
- Adv. Concepts

Circular e^+e^- Colliders

- LEP3
- TLEP
- Super-Tristan
- FNAL Site-filler
- IHEP, +
- …

- SAPPHIRE,
- CLICHÉ, +
- …

γ-γ Colliders

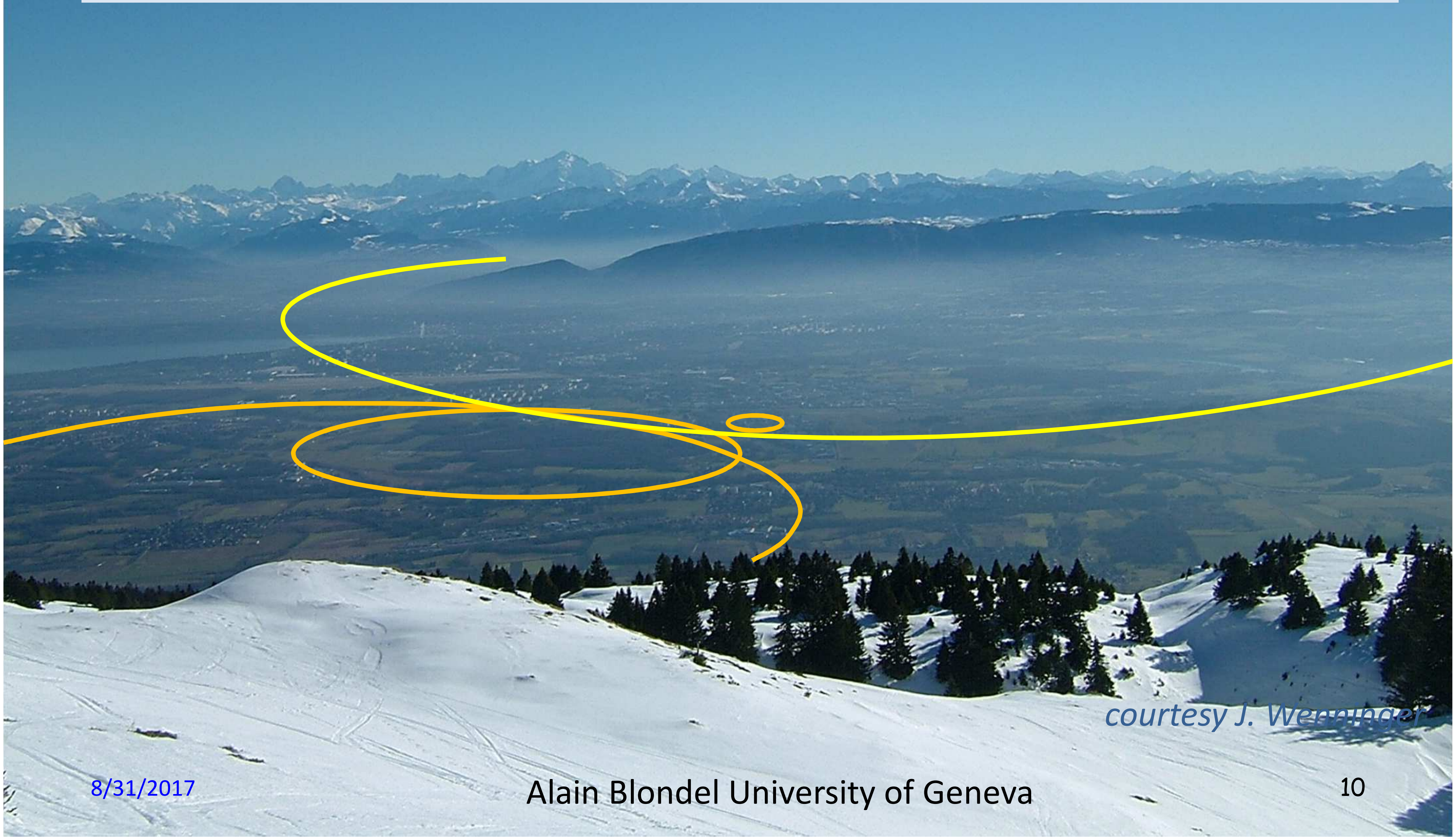
Muon Colliders

2

S. Henderson

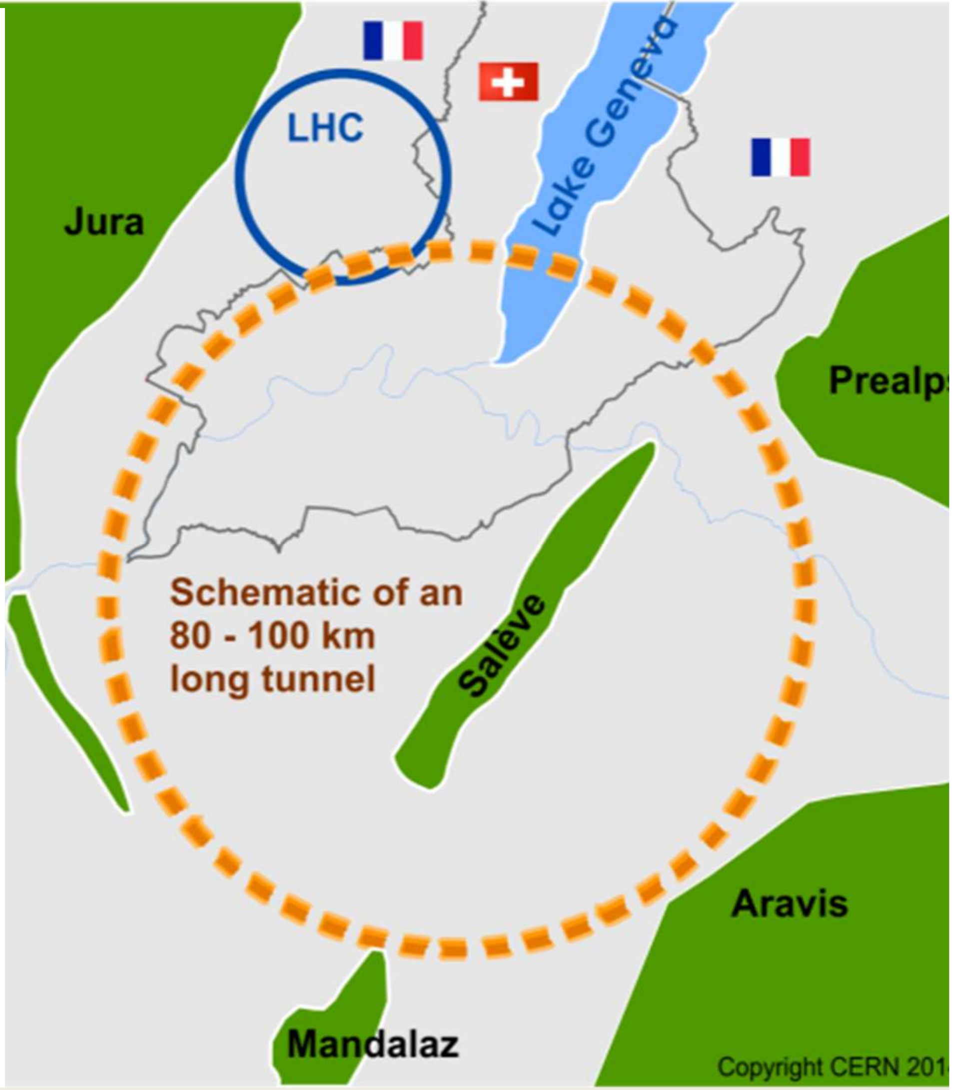
The FCCs

a story of synergy and complementarity



courtesy J. Wenninger

The Future Circular Colliders
CDR and cost review for the next ESU (2018)



International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:***
  ***100 TeV pp*-collider (*FCC-hh*)**

~16 T magnets

→ defining infrastructure requirements

Possible first steps:

- ***e^+e^-* collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV

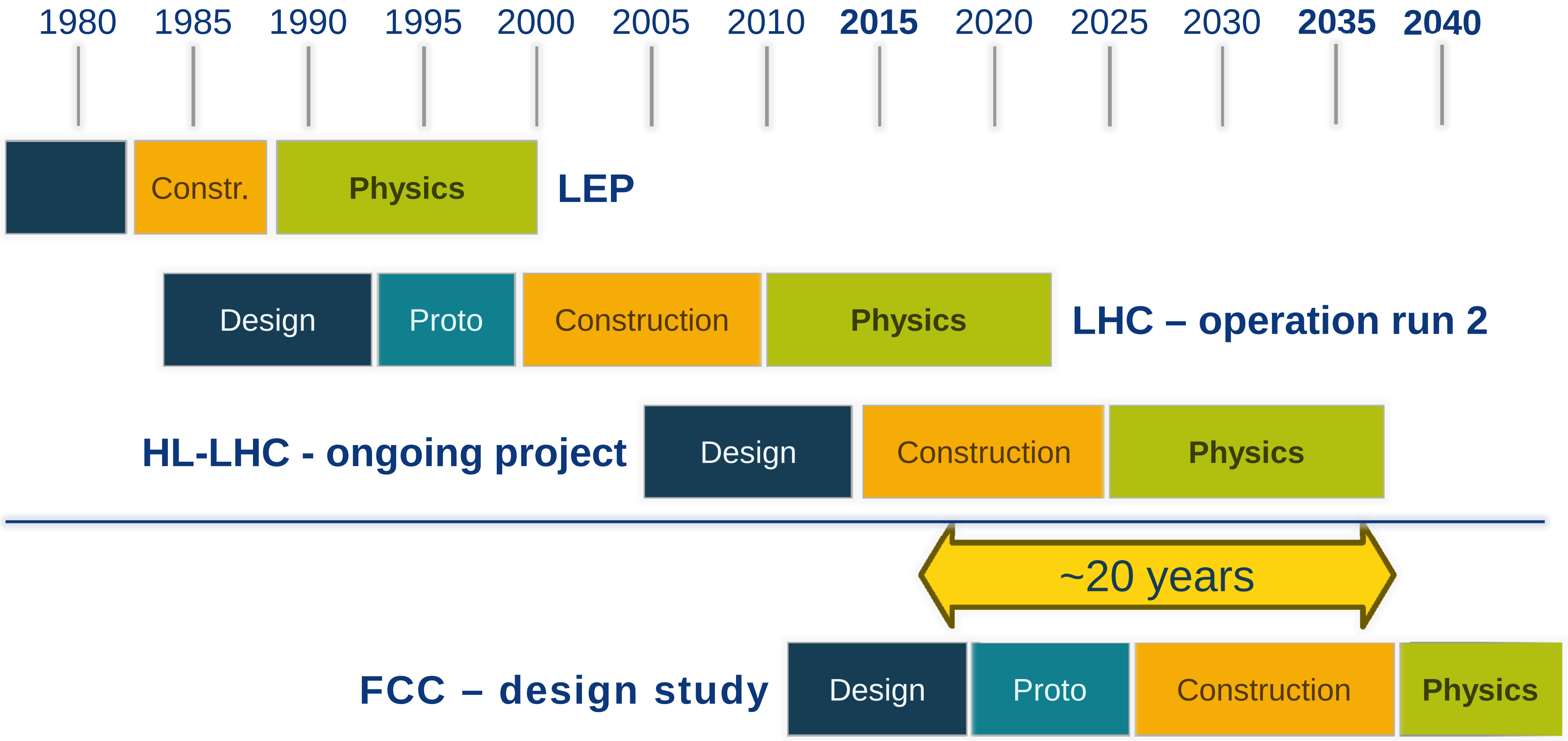
- ***HE-LHC* 16T ⇒ 28 TeV**
  in LEP/LHC tunnel

Possible add-on:

- ***p-e* (*FCC-he*) option**

From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014

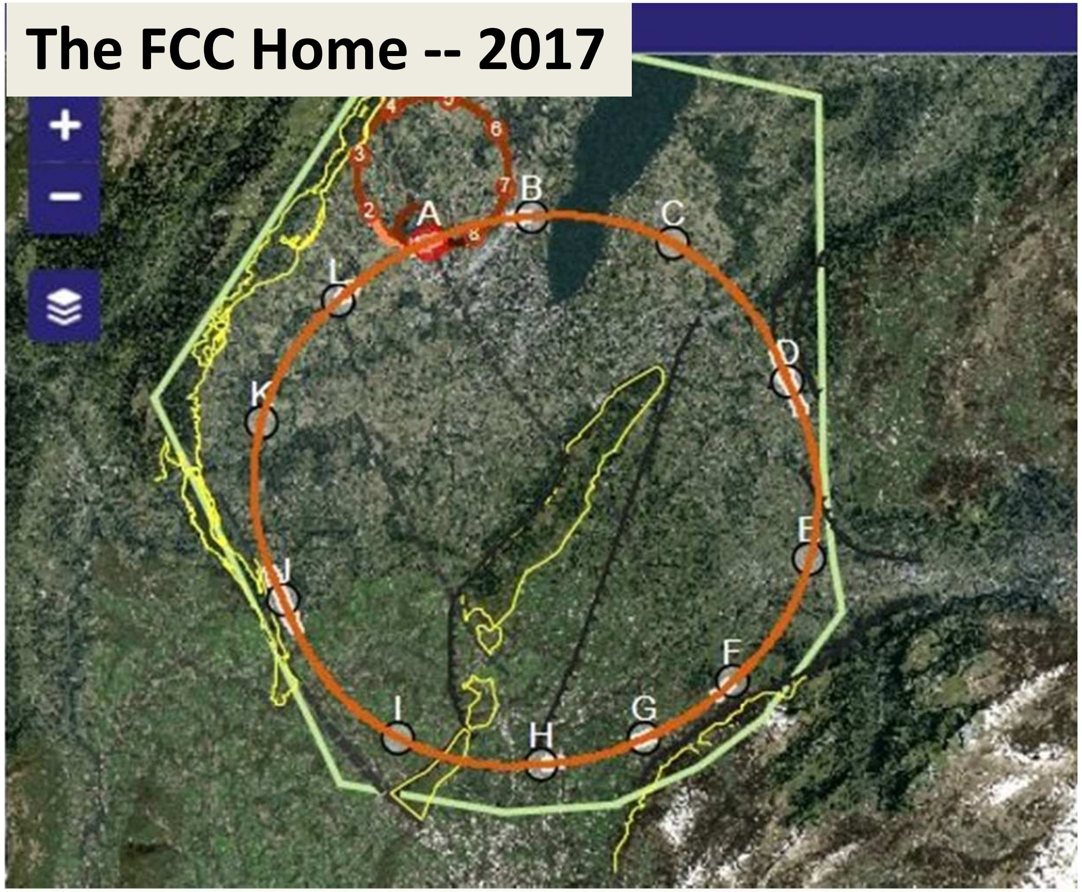
CERN Circular Colliders & FCC



Must advance fast now to be ready for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy

The FCC Home -- 2017



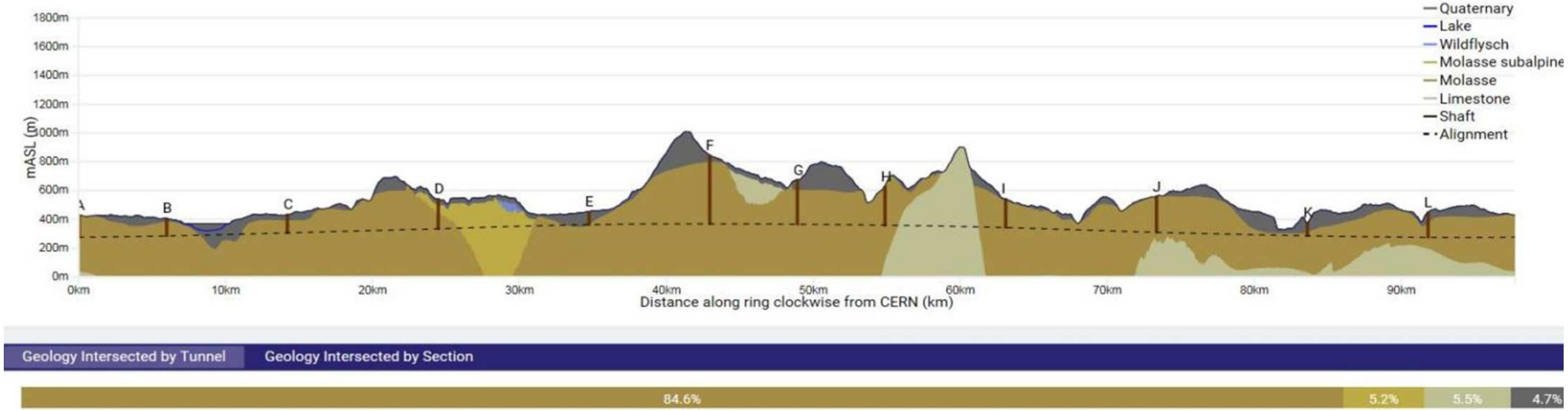
Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc. optimum: **97.5 km**

Tunneling

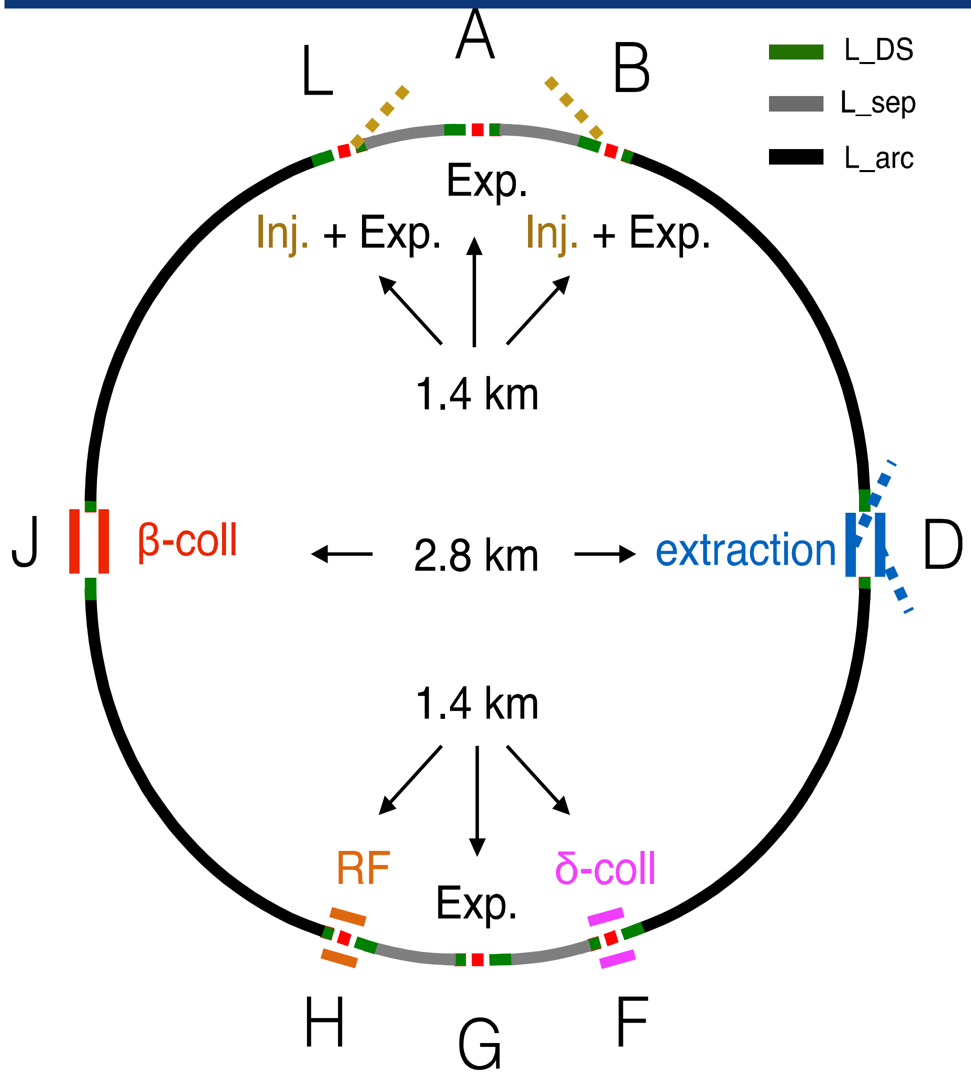
- Molasse 90% (good rock),
- Limestone 5%, Moraines 5% (tough)

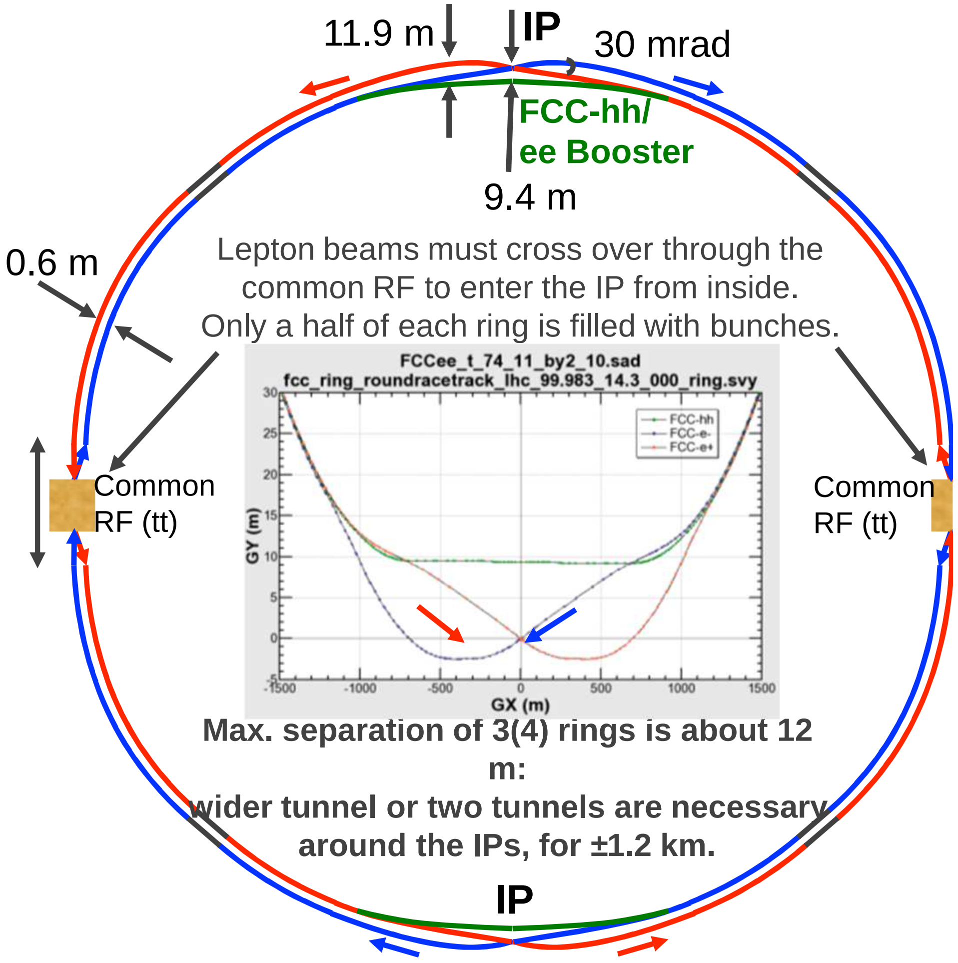
Shallow implementation

- ~ 30 m below Léman lakebed
- Reduction of shaft lengths etc...
- One very deep shaft **F** (476m) (RF or collimation), alternatives being studied, e.g. inclined access



common layouts for hh & ee





Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

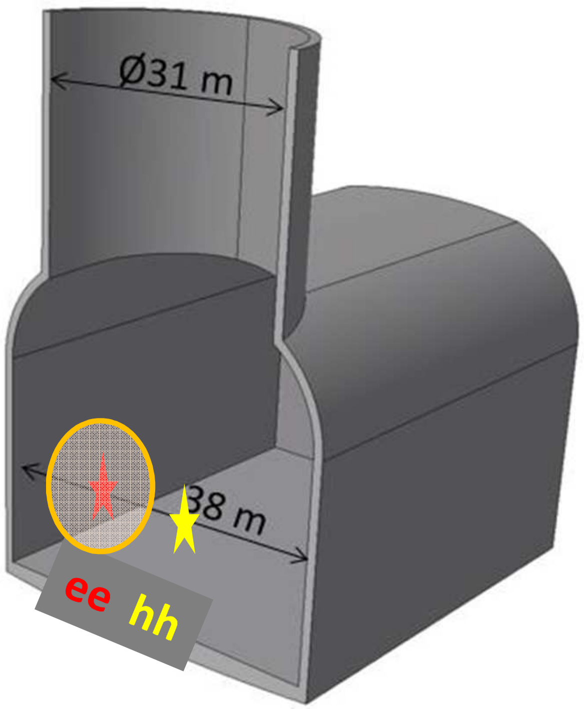
Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

FCC-ee 1, FCC-ee 2,

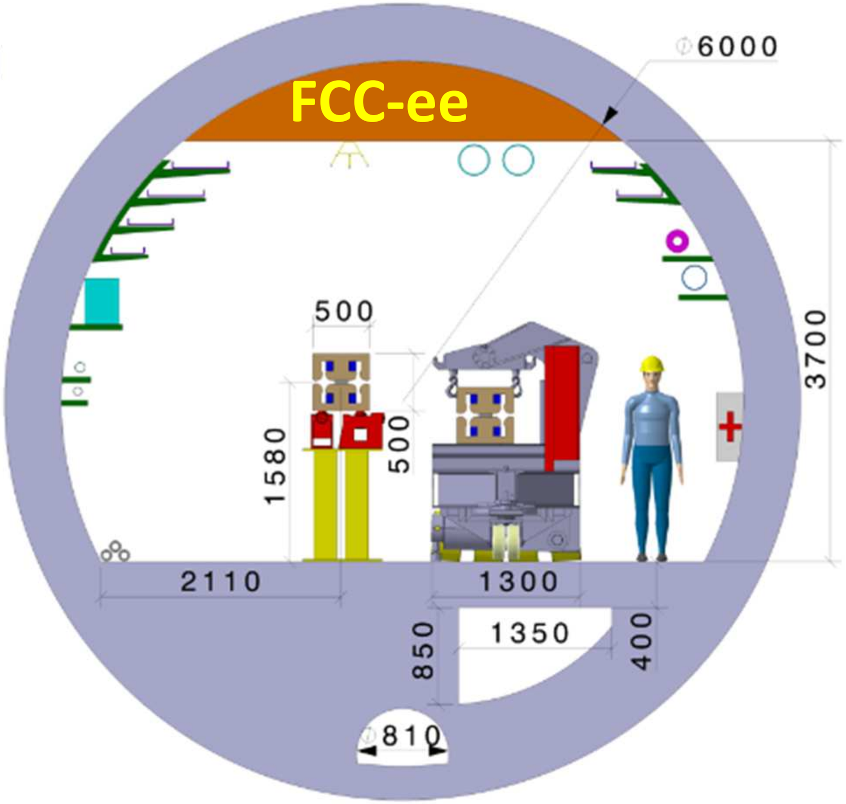
FCC-ee booster (FCC-hh footprint)

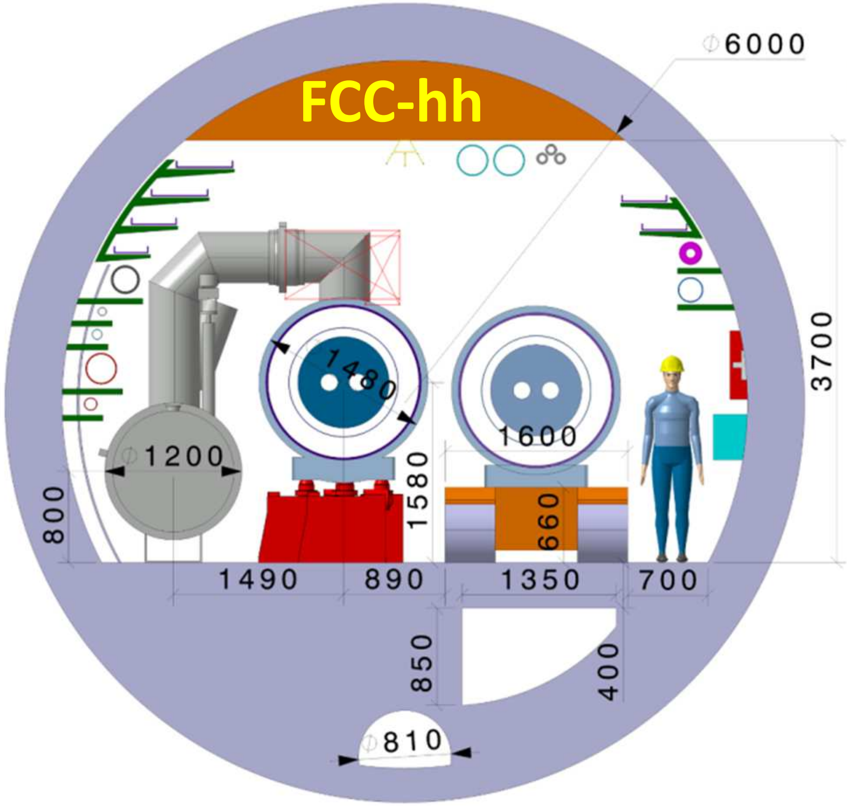
Asymmetric IR for ee, limits SR to expt

2 main IPs in A, G for both machines



Sharing the FCC experimental caverns
(Prelim. layout as of FCC-Rome meeting)

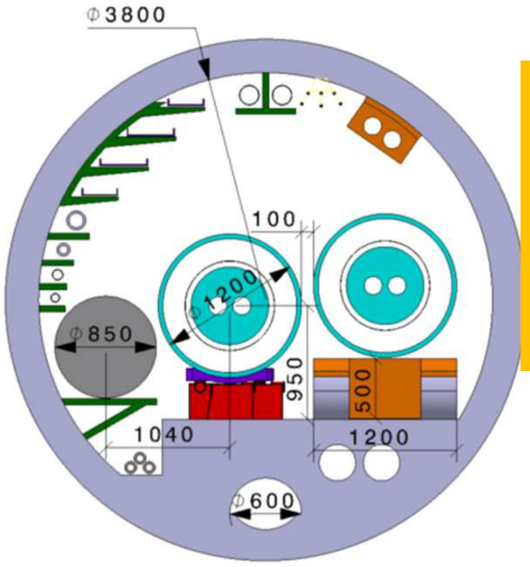




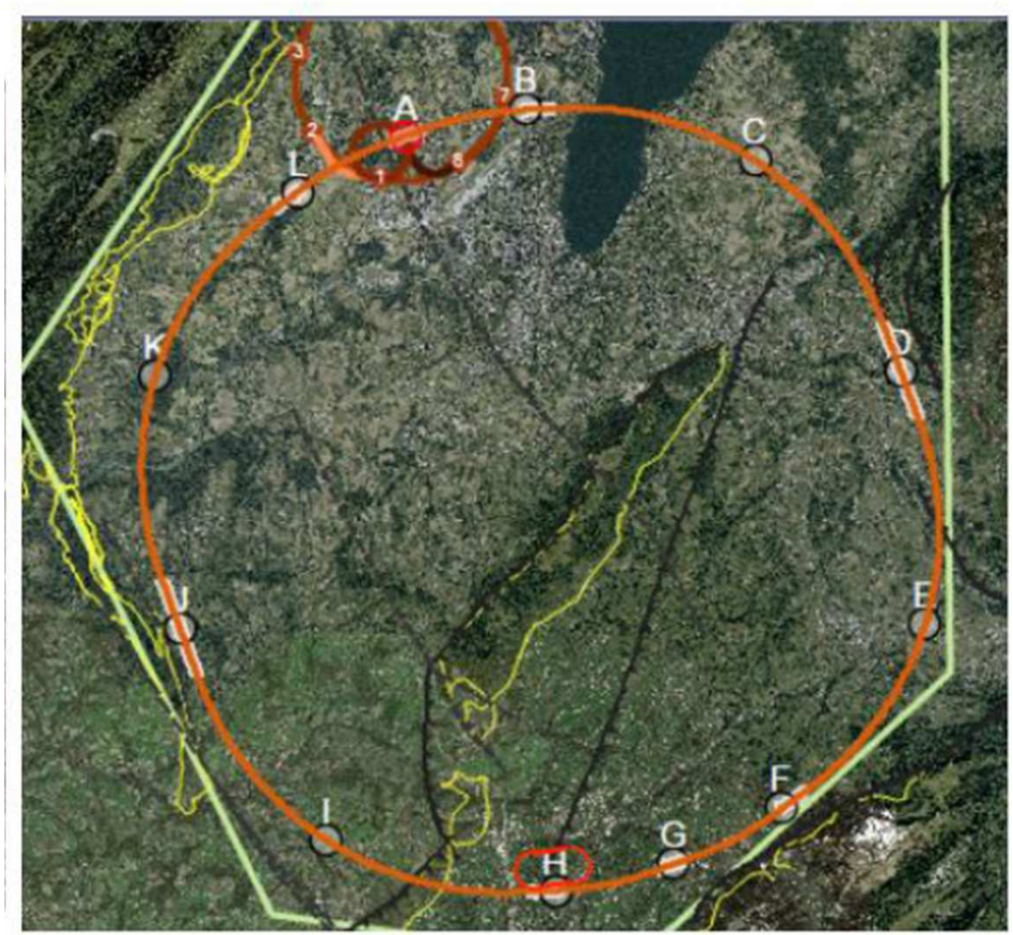
HE-LHC :
constraints:
No civil engineering, same beam height as LHC
→ Magnets OD ca. 1200 m max
QRL (shorter than FCC) OD ca. 850 mm (all included)

Magnet suspended during „handover“
from transport vehicle to installation transfer table

Compliant 16T magnet design ongoing (challenge)
+ still many items to study!



If HE-LHC can work in 3.8m ∅ ... it will feed-back to FCC tunnel design!



FCC-eh

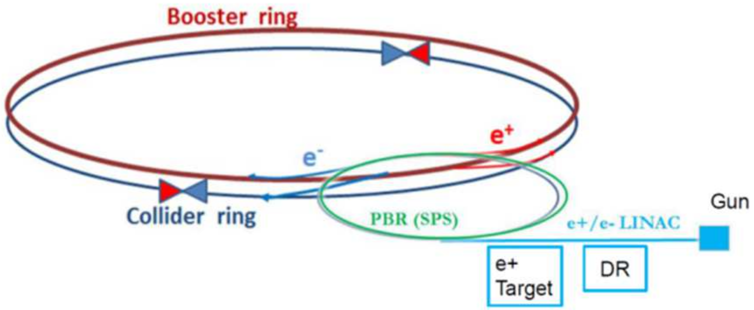
LHeC or FCC-eh function as an add-on to LHC or FCC-hh respectively: additional 10km cicumference Electron Reciculating Linac ERL.

The possibility to collide FCC-ee with FCC-hh is not considered in the framework of the study

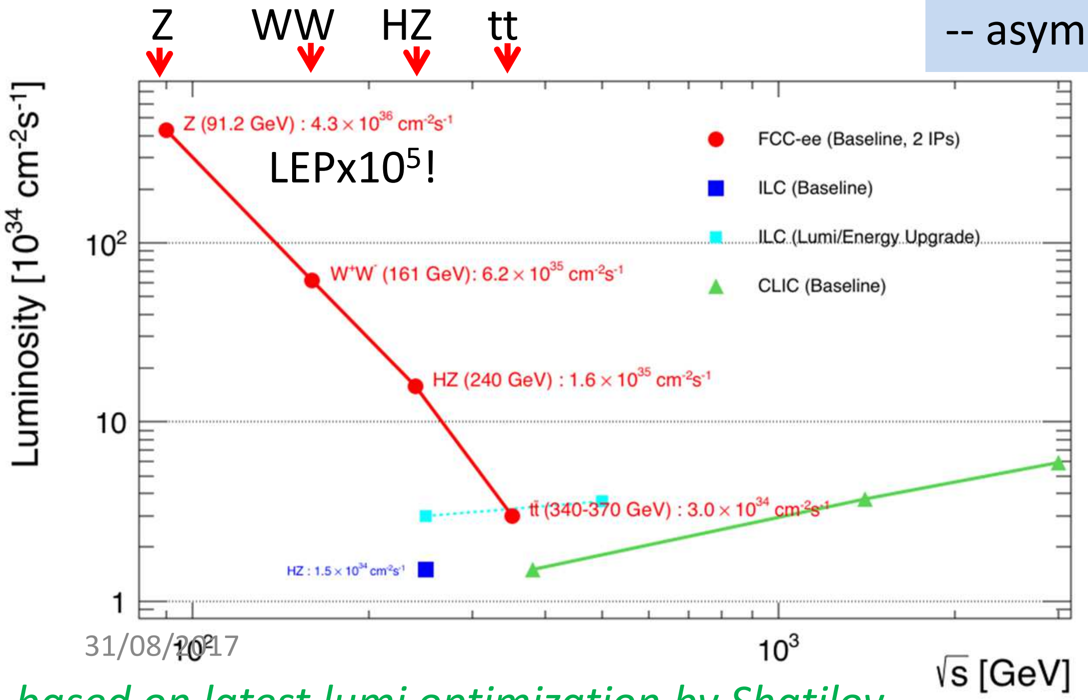
In the case of FCC-eh it could profit from the -- then existing -- FCC-hh,
and, perhaps, from considerable RF of the -- then dismantled -- FCC-ee

FCC-ee

AB, F. Zimmermann 2011 (LEP3@240 GeV)



top-up injection for high duty factor
several schemes possible



based on latest lumi optimization by Shatilov

Q: Why is luminosity so much higher than LEP?

A: inspired by b-factory designs

-- continuous injection (high efficiency)

-- e+ and e- separate (→many bunches)

-- fix 100 MW Synchrotron Radiation at all E

-- low β^*_y , O(1mm)

-- larger ring ($P_{SR} \propto E^4/\rho$)

-- beam cross at angle (30 mrad)

-- crab waist crossing

-- asymmetric IP to avoid SR → LEP levels

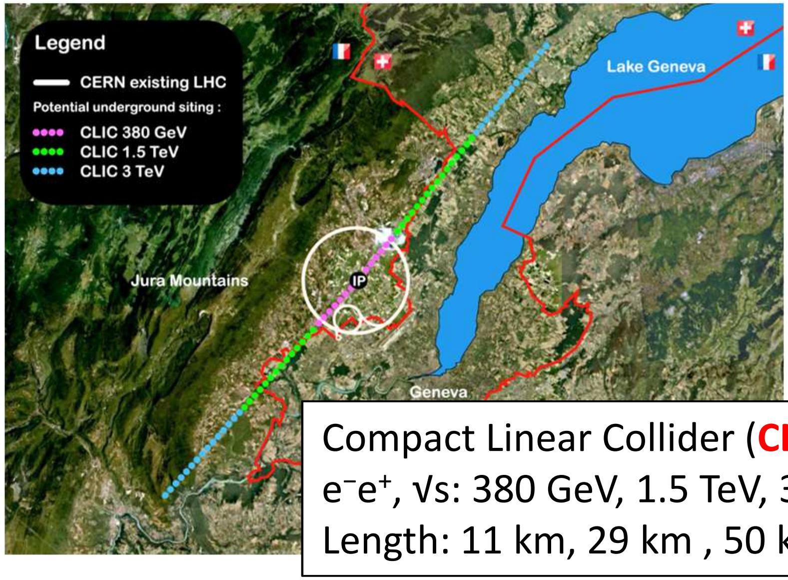
Luminosity performance dominated by

-- at Z, WW, H energies:
beam-beam instabilities
→ simulations

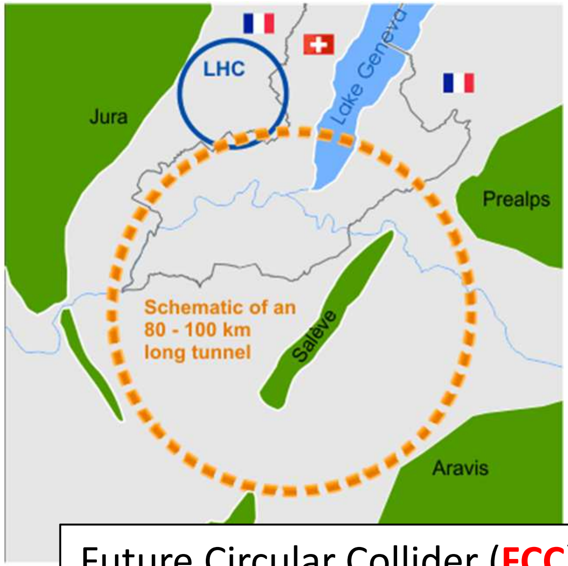
-- at top energy: beamstrahlung depends on value of $\varepsilon_y/\varepsilon_x$
0.2% assumed (0.25%@superKEKB)
0.4% achieved at LEP

-- limit from injector is much higher

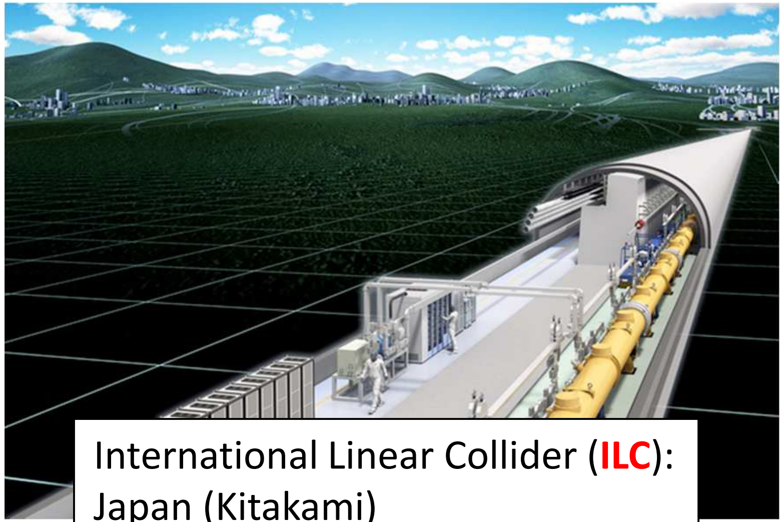
studies of high-energy e^+e^- colliders



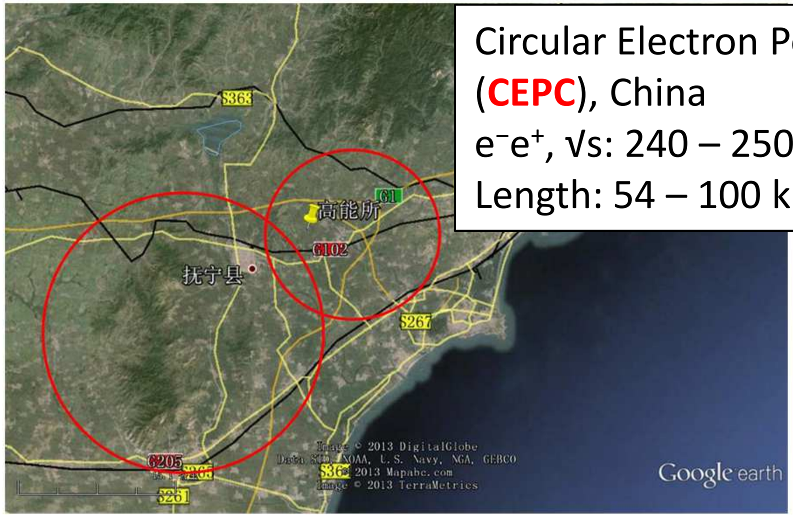
Compact Linear Collider (**CLIC**): CERN
e^-e^+, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC**): CERN
e^-e^+, $\sqrt{s}$: 90 - 350 GeV; pp, $\sqrt{s}$: ~100 TeV
Circumference: 90 - 100 km

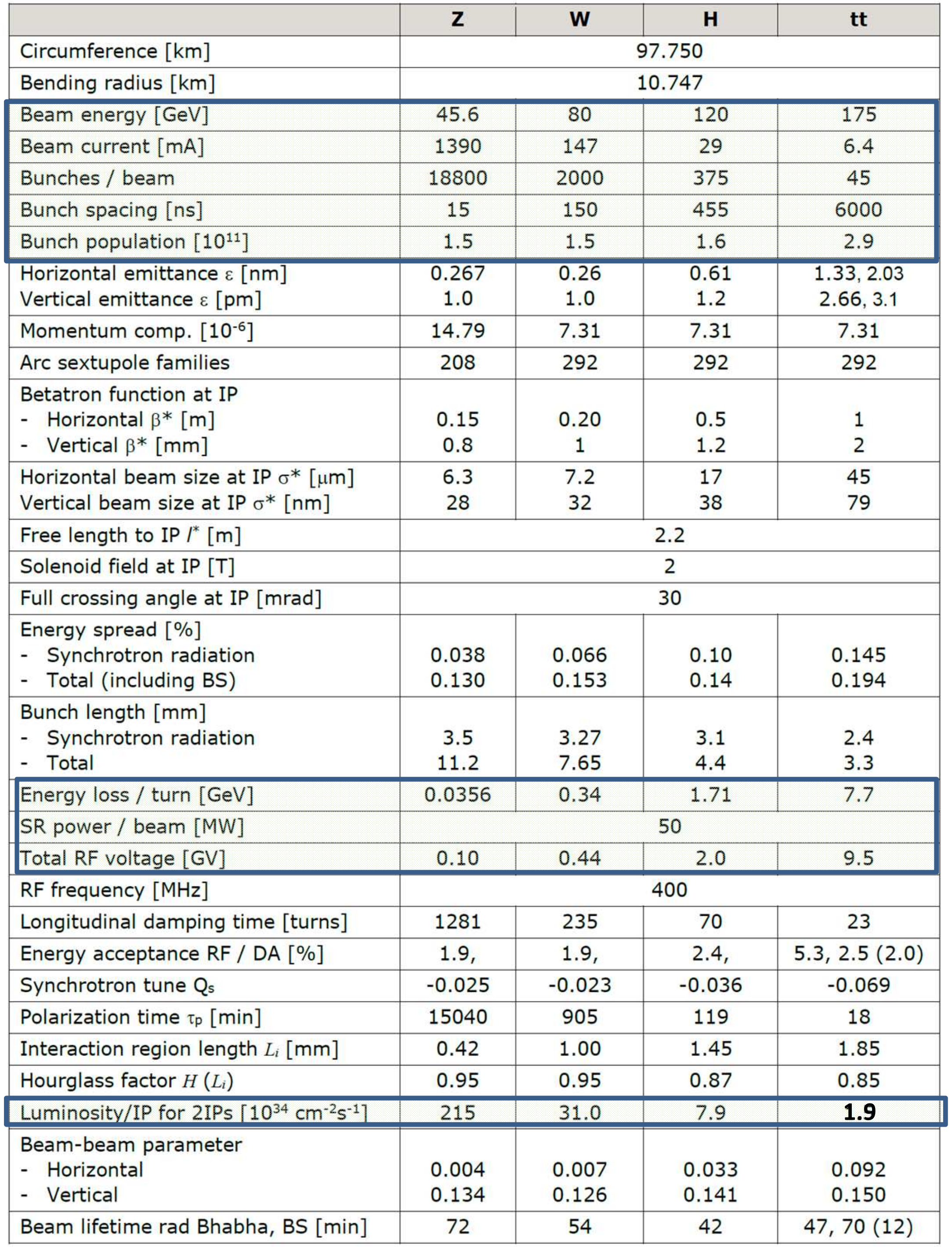


International Linear Collider (**ILC**):
Japan (Kitakami)
e^-e^+, $\sqrt{s}$: 500 GeV (1 TeV)
Length: 31 km (50 km)



Circular Electron Positron Collider (**CEPC**), China
e^-e^+, $\sqrt{s}$: 240 – 250 GeV; SPPC pp,
Length: 54 – 100 km

Recent FCC-ee parameter list

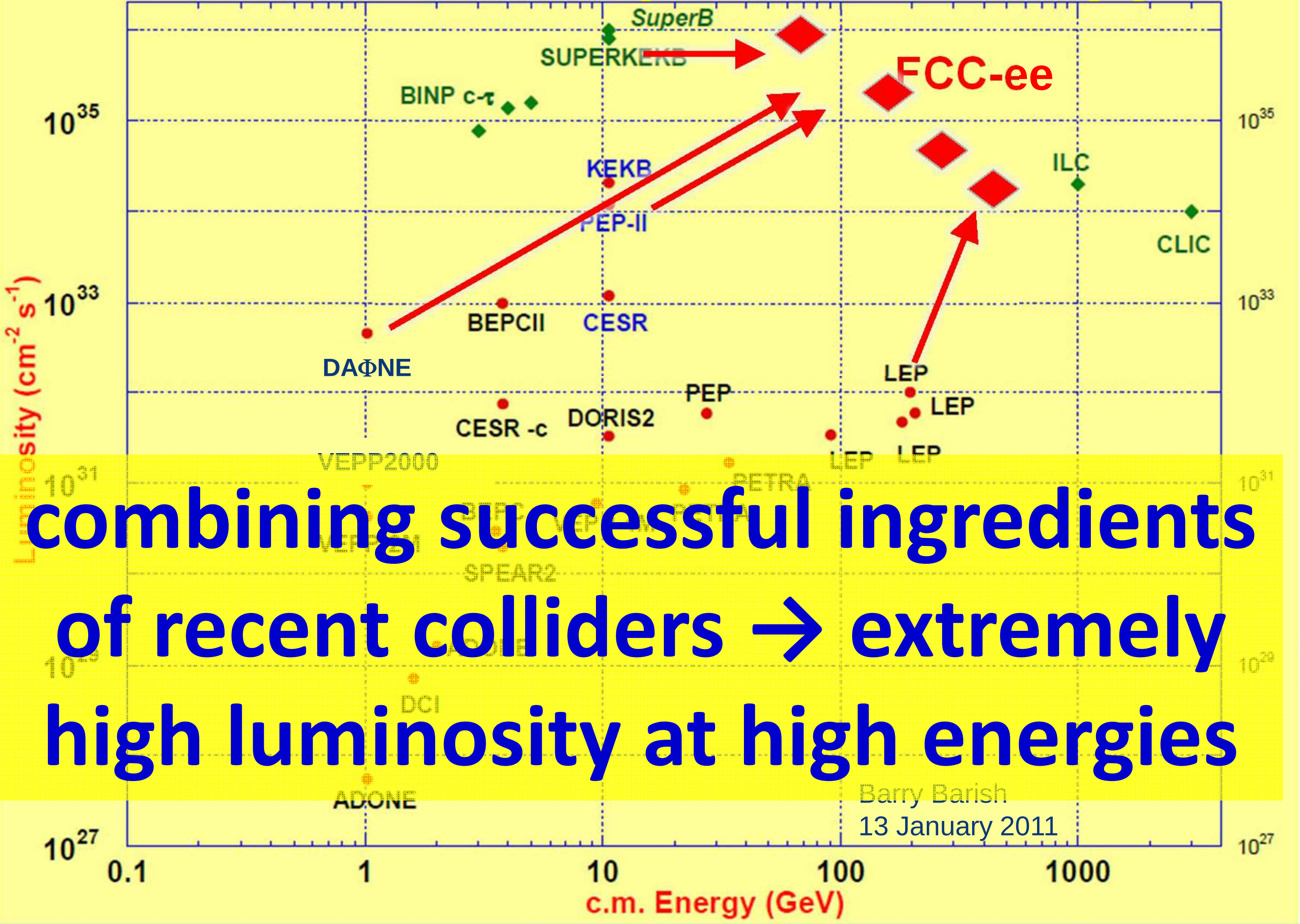


	Z	W	H	tt
Circumference [km]	97.750			
Bending radius [km]	10.747			
Beam energy [GeV]	45.6	80	120	175
Beam current [mA]	1390	147	29	6.4
Bunches / beam	18800	2000	375	45
Bunch spacing [ns]	15	150	455	6000
Bunch population $[10^{11}]$	1.5	1.5	1.6	2.9
Horizontal emittance ε [nm]	0.267	0.26	0.61	1.33, 2.03
Vertical emittance ε [pm]	1.0	1.0	1.2	2.66, 3.1
Momentum comp. $[10^{-6}]$	14.79	7.31	7.31	7.31
Arc sextupole families	208	292	292	292
Betatron function at IP				
- Horizontal β* [m]	0.15	0.20	0.5	1
- Vertical β* [mm]	0.8	1	1.2	2
Horizontal beam size at IP σ* [μm]	6.3	7.2	17	45
Vertical beam size at IP σ* [nm]	28	32	38	79
Free length to IP l^* [m]	2.2			
Solenoid field at IP [T]	2			
Full crossing angle at IP [mrad]	30			
Energy spread [%]				
- Synchrotron radiation	0.038	0.066	0.10	0.145
- Total (including BS)	0.130	0.153	0.14	0.194
Bunch length [mm]				
- Synchrotron radiation	3.5	3.27	3.1	2.4
- Total	11.2	7.65	4.4	3.3
Energy loss / turn [GeV]	0.0356	0.34	1.71	7.7
SR power / beam [MW]	50			
Total RF voltage [GV]	0.10	0.44	2.0	9.5
RF frequency [MHz]	400			
Longitudinal damping time [turns]	1281	235	70	23
Energy acceptance RF / DA [%]	1.9,	1.9,	2.4,	5.3, 2.5 (2.0)
Synchrotron tune Q_s	-0.025	-0.023	-0.036	-0.069
Polarization time τ_p [min]	15040	905	119	18
Interaction region length L_i [mm]	0.42	1.00	1.45	1.85
Hourglass factor H (L_i)	0.95	0.95	0.87	0.85
Luminosity/IP for 2IPs $[10^{34}\ \mathrm{cm^{-2}s^{-1}}]$	215	31.0	7.9	**1.9**
Beam-beam parameter				
- Horizontal	0.004	0.007	0.033	0.092
- Vertical	0.134	0.126	0.141	0.150
Beam lifetime rad Bhabha, BS [min]	72	54	42	47, 70 (12)

D. Shatilov

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	175
arc cell optics	60/60	90/90	90/90	90/90
momentum compaction [10^{-5}]	1.48	0.73	0.73	0.73
horizontal emittance [nm]	0.27	0.28	0.63	1.34
vertical emittance [pm]	1.0	1.0	1.3	2.7
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	1.95
tunes, half-ring (x, y, s)	(0.569, 0.61, 0.0125)	(0.577, 0.61, 0.0115)	(0.565, 0.60, 0.0180)	(0.553, 0.59, 0.0343)
longitudinal damping time [ms]	414	77	23	7.5
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8
total RF voltage [GV]	0.10	0.44	2.0	9.5
RF acceptance [%]	1.9	1.9	2.3	5.0
energy acceptance [%]	1.3	1.3	1.5	2.5
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.147 / 0.192
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.45 / 3.25
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.33
bunch intensity [10^{11}]	1.7	1.5	1.5	2.7
no. of bunches / beam	16640	2000	393	48
beam current [mA]	1390	147	29	6.4
luminosity [10^{34} cm^{-2}s^{-1}]	**230**	**32**	**7.8**	**1.8**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.095 / 0.157
luminosity lifetime [min]	70	50	42	39
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	12
actual lifetime by BS (“weak”) [min]	> 200	20	20	24

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection

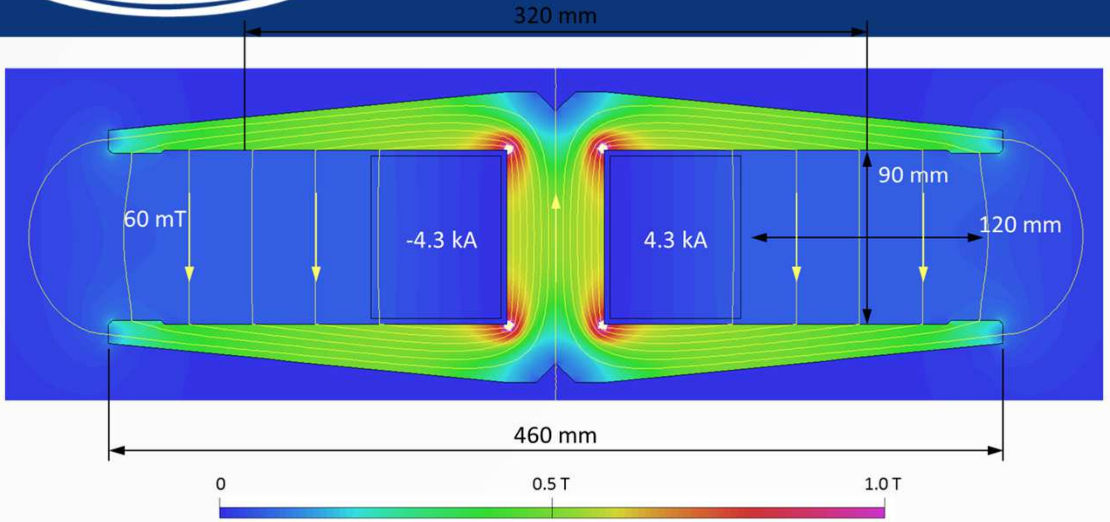
DAFNE: crab waist

Super B-factories
S-KEKB: low β_y*

KEKB: *e*$^+$ source

HERA, LEP, RHIC:
spin gymnastics

efficient 2-in-1 arc magnets



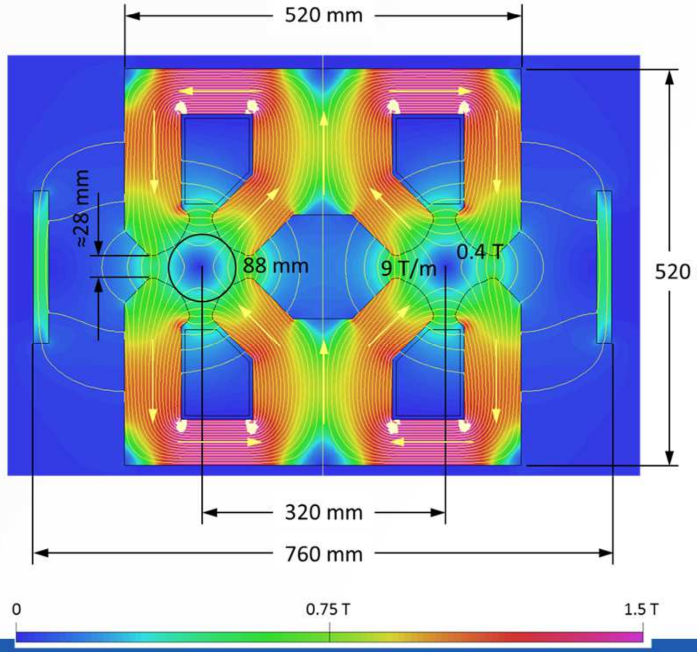
dipole based on
twin aperture yoke
and single busbars as coils

A. Milanese

twin 2-in-1 quadrupole

the novel arrangements of the magnetic circuit allow for considerable savings in Ampere-turns and power consumption, less units to manufacture, transport, install, align, remove,…

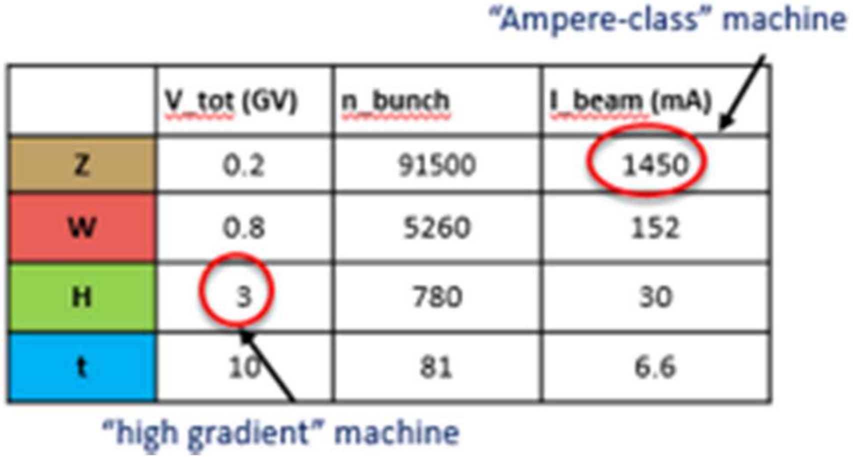
midplane shield
for stray field



FCC-ee physics run

- **FCC-ee physics goals (sum of two IPs):**
  - 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV)
  - 10 ab^{-1} at the WW threshold (~161 GeV with a +/- few GeV scan)
  - 5 ab^{-1} at the HZ maximum (~240 GeV)
  - 1.5 ab^{-1} at and above the ttbar threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the rest at 365-370 GeV)
- **Assumptions:**
  - 200 scheduled physics days per year, i.e. 7 months – 13 days of MD/stops.
  - "Hübner factor" H=0.75 (lower than value achieved with top-up injection at KEKB, ~0.8).
  - Half the design luminosity in the first two years of Z operation, assuming machine starts with Z (similar to LEP-1; LEP-2 start up was much faster)
  - Machine configuration between WPs is changed during winter shutdowns (effective time of about 3 months/year)

IMPLEMENTATION AND RUN PLAN



"Ampere-class" machine

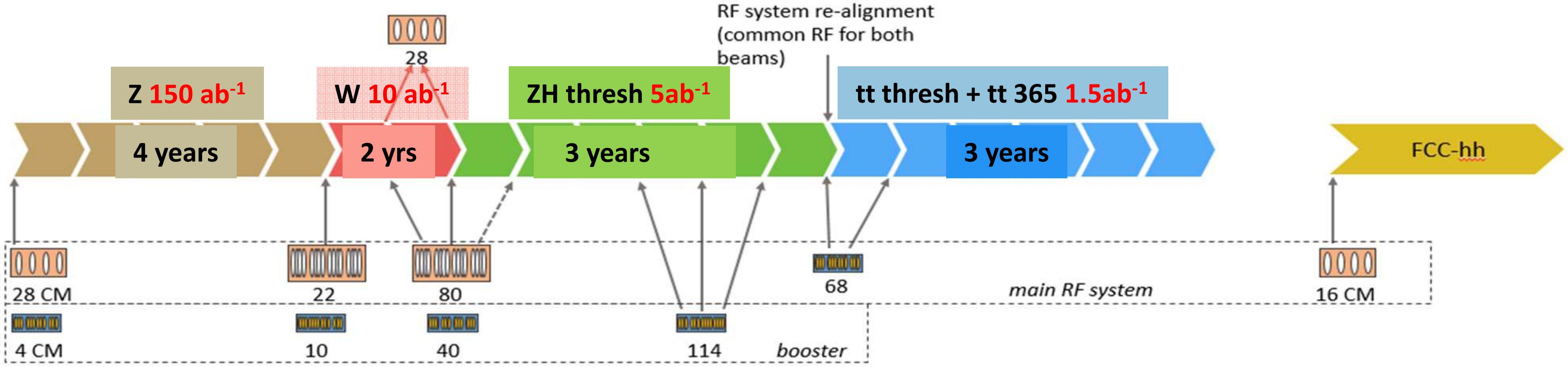
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100MW, 400MHz RF power distribution system**

➔ Spreads the funding profile



indicative: 2(comm) + 2 2 3 5 total ~12 years

highly efficient RF power sources

2014 breakthrough in klystron theory:

–”**congregated bunch**” V.A. Kochetova, 1981] (later electrons faster when entering the output cavity)

- “**bunch core oscillations**” [A. Yu. Baikov, et al.: “Simulation of conditions for the maximal efficiency of decimeter-wave klystrons”, Technical Physics, 2014](controlled periodic velocity modulation)

- “**BAC**” method [I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov, “*A way to increase the efficiency of klystrons*”, IVEC 2013] (Bunch, Align velocities, Collect outsiders)

These three methods together promise a klystron efficiency ~90%

An international collaboration “HEIKA” (CERN, ESS, SLAC, CEA, MFUA, Lancaster U, Thales, L3, CPI, VDBT) is now designing, building and testing prototypes at several places around the world. **Simulations and first hardware tests extremely encouraging.**

For CW operation ... .. work in progress

FCC klystron prototype - initial target parameters

Operating frequency	800 MHz initially
Target RF Output power	1.5 MW (cw)
Voltage	40 kV
N-beams×Current	16×2.6 A $= 42$ A
Target Efficiency	**90%**
Perveance	16×0.33 μK $= 5.25$ μK
Number of cavities	8
Cathode loading	< 2 A mm^{-2}
Length	2.3 m

E. Jensen, I. Syratchev, C. Lingwood

FCC-ee total power

subsystem	Z	W	ZH	$t\bar{t}$	LEP2 (av.2000*)	TLEP$t\bar{t}$ * M. Ross	TLEP$t\bar{t}$ ** 2013
collider total RF power	163	163	145	145	42	217	185
collider cryogenics	2	5	23	39	18	41	34
collider magnets	3	10	23	50	16	14	14
booster RF + cryo	4	4	6	7	-	5	5
booster magnets	0	1	2	5	-	-	-
injector complex	10	10	10	10	<10	?	?
physics detectors (2)	10	10	10	10	9	?	?
cooling & ventilation***	47	49	52	62	16	62	26
general services	36	36	36	36	9	20	20
total	**275**	**288**	**308**	**364**	**120**	**359**	**284**

power roughly ∝ luminosity

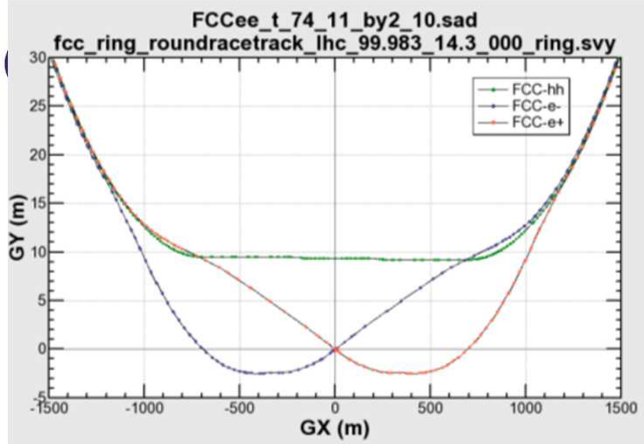
for comparison, total CERN complex in 1998 used up to 237 MW

*M. Ross, ``Wall-Plug (AC) Power Consumption of a Very High Energy e+/e- Storage Ring Collider,'' 3 August 2013, http://arxiv.org/pdf/1308.0735.pdf ; **M. Koratzinos et al., ``TLEP: A High-Performance Circular e+e- Collider to Study the Higgs Boson'', Proc. IPAC2013 Shanghai, 12--17 May 2013, {http://arxiv.org/pdf/1305.6498.pdf 2013,
*** private discussions with M. Nonis

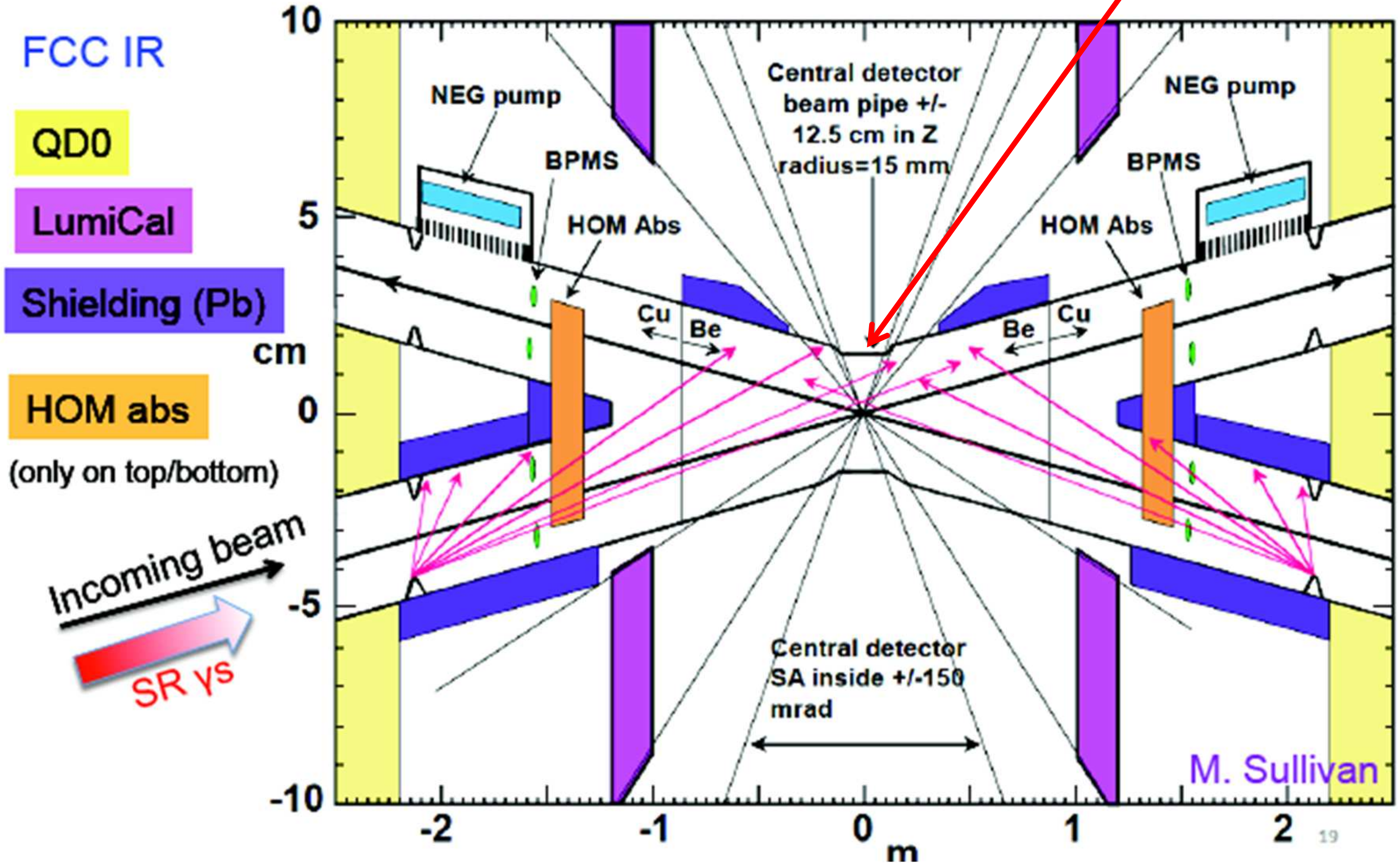
presentation at IPAC'16

*dividing total energy used by 200 days

Detailed layout of the Interaction Region



Beam pipe radius at IP is 15mm ☺



Beam Polarization and Energy calibration

First priority is to achieve transverse polarization for precision energy calibration
in a way that allows continuous beam calibration by resonant depolarization
(energy measurement every ~10 minutes on 'monitoring' single bunches)

- **This is a unique feature of circular e+e- colliders**

- baseline running scheme defined with monitoring bunches, wigglers, polarimeter

- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

➔ target is O(±100keV) at Z and W pair threshold energies (averaged over data taking)

<u>longitudinal polarization?</u>

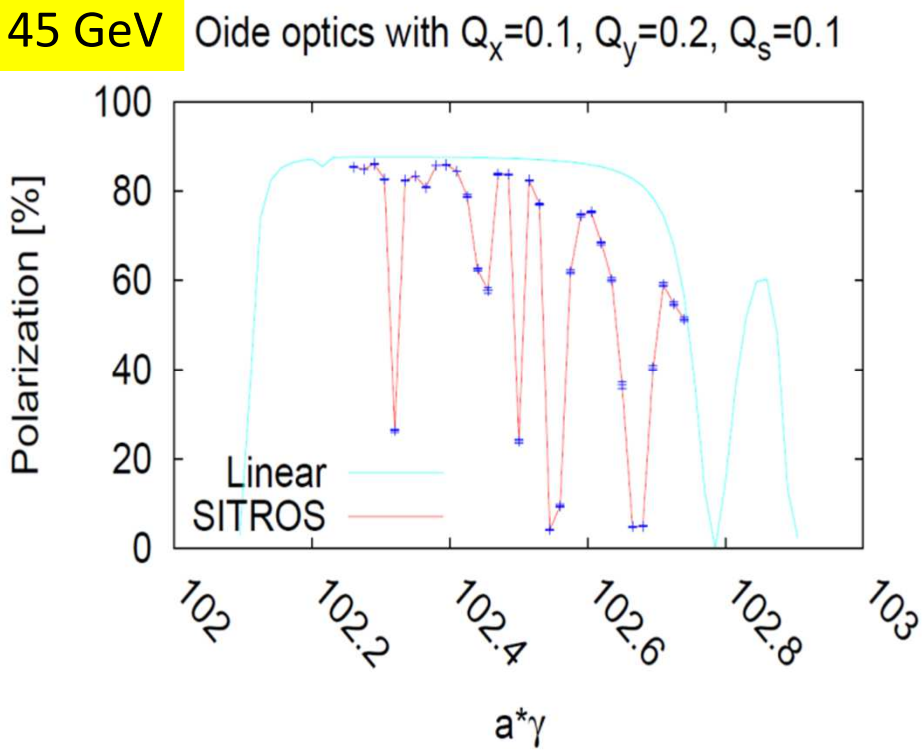
➔ lower priority

at Z, W, top: no information that we cannot obtain otherwise from unpolarized A_{FB} asymmetries or final state polarization (top, tau)

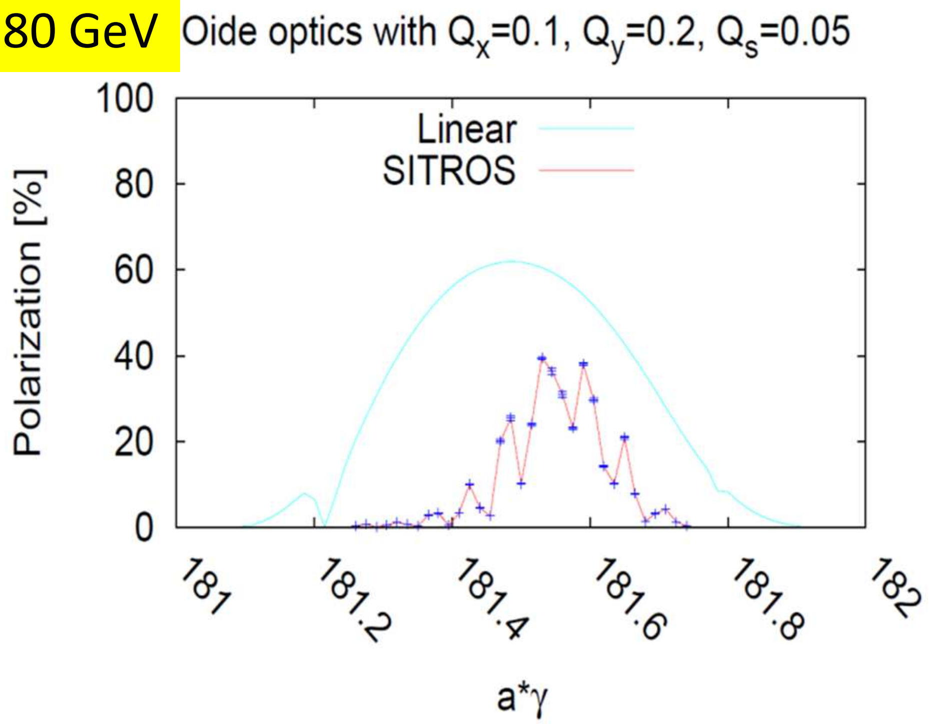
+ too much loss of luminosity in present running scheme to provide gain in precision.

Beam Polarization and Energy calibration

45 GeV



80 GeV



At the Z obtain excellent polarization level
but too slow for polarization in physics
need wigglers for Energy calibration
– OK as long as $\sigma_{Eb} <$ ~55 MeV

$\sigma_{Eb} \propto E_b^2/\rho$

At the W expectation similar to LEP at Z
→ enough for energy calibration

Simulations by Eliana Gianfelice

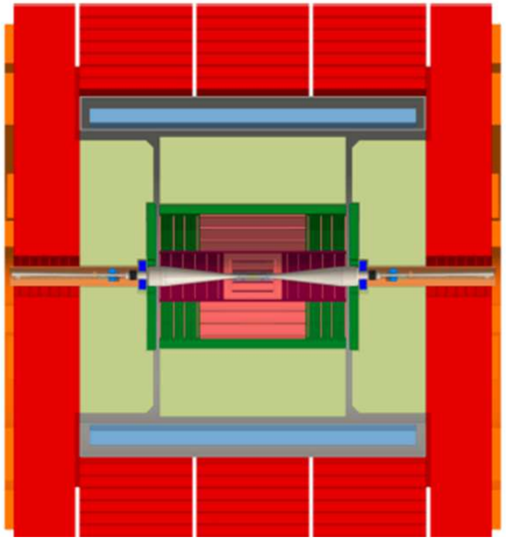
A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s , δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3 ,$\Delta\alpha$ **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3 , ε_2, $\Delta\alpha$ **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<0.5 MeV**	E_cal & Statistics	Backgrounds, QED/EW
m_{top} MeV/c2	**Input**	173340 ± 760	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 50 MeV?

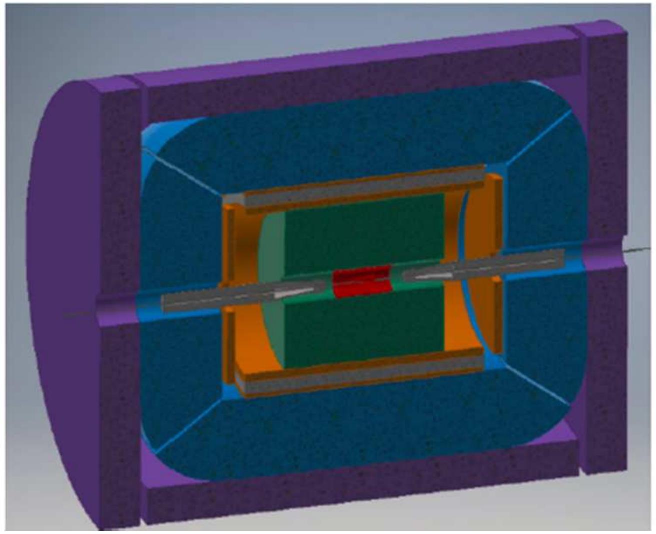
FCC-ee Detectors

Two integration, performance and cost estimates ongoing:
-- Linear Collider Detector group at CERN has undertaken the adaption of CLIC-SID detector for FCC-ee
-- new IDEA, detector specifically designed for FCC-ee (and CEPC)

"CLIC-detector revisited"



"IDEA"



- Vertex detector: ALICE **MAPS**
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)

$m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s $(m_z\ m_W\ m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality

-- ex FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.

+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

DISCOVER dark matter as «invisible decay» of H or Z or in LHC loopholes.

DISCOVER very weakly coupled particle in 5-100 GeV energy scale

such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD etc….

NB the «Z factory» plays an important role in the 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164,

100 TeV

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Performance easier to achieve with 25 ns second spacing… 5ns preferred by expts!

16 T magnets

FCC goal is 16 T operating field

- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

⇒ Strong synergy with HL-LHC

R&D on cables in test stand at CERN

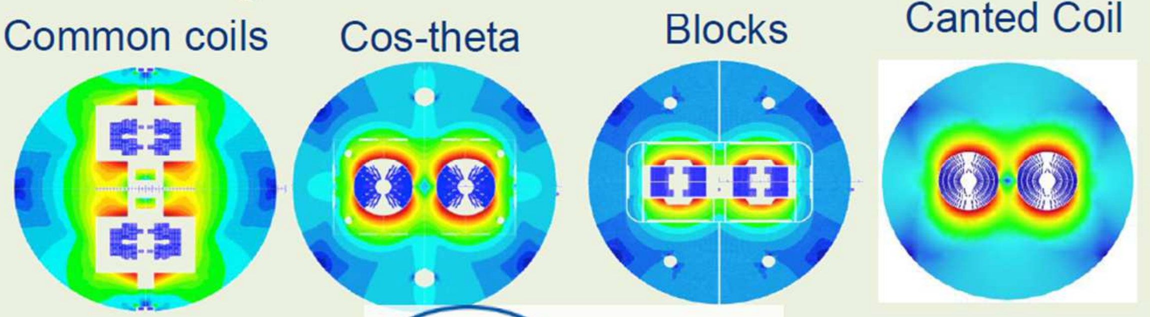
Target: $J_C > 2300$ A/mm^2 at 1.9 K and 16 T (**50% above HL-LHC**)

Industrial fabrication:
Target cost: 3.4Euro/kAm

Key cost driver
16 T demonstrated in coil
Hope for US model test early 2018: 14-15 T
Short magnet models in 2018 – 2023
12 T for HL-LHC

Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.



CIEMAT, CEA, INFN

EuroCirCol
A key to New Physics

Swiss contribution via PSI

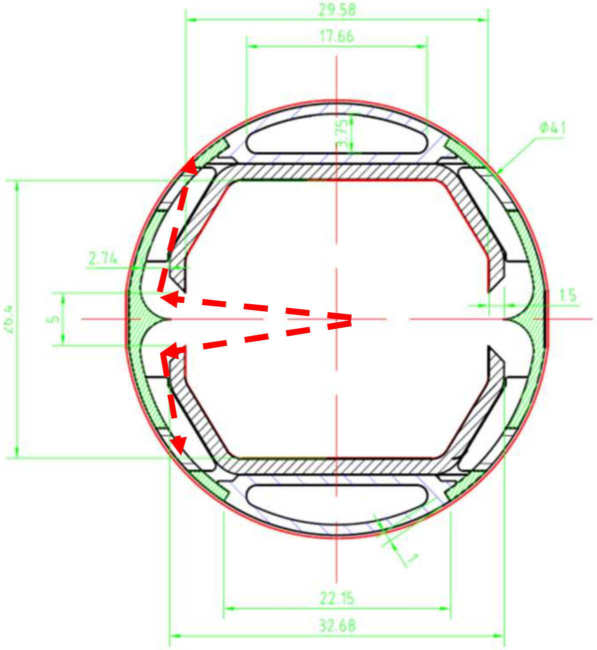
D. Schulte, EPS'17

-- possible shorter term application SCSPS or HE-LHC
-- For longer timescale HTS is also studied → 20T

Cryogenic beam vacuum system

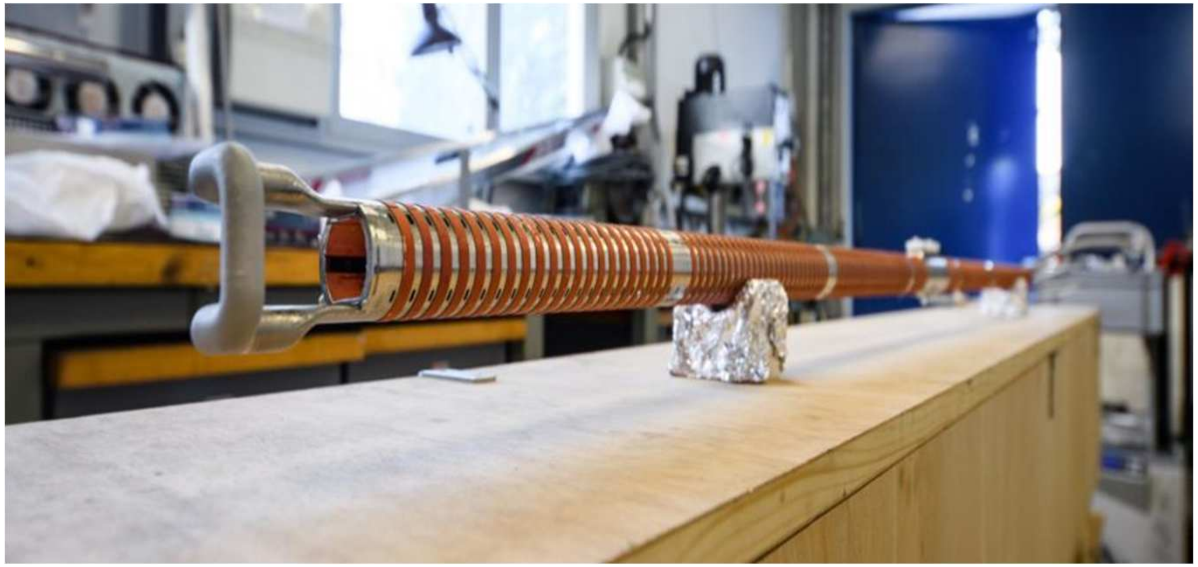
One of the most critical elements for FCC-hh

- Absorption of synchrotron radiation at ~50 K for cryogenic efficiency (5 MW total power)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

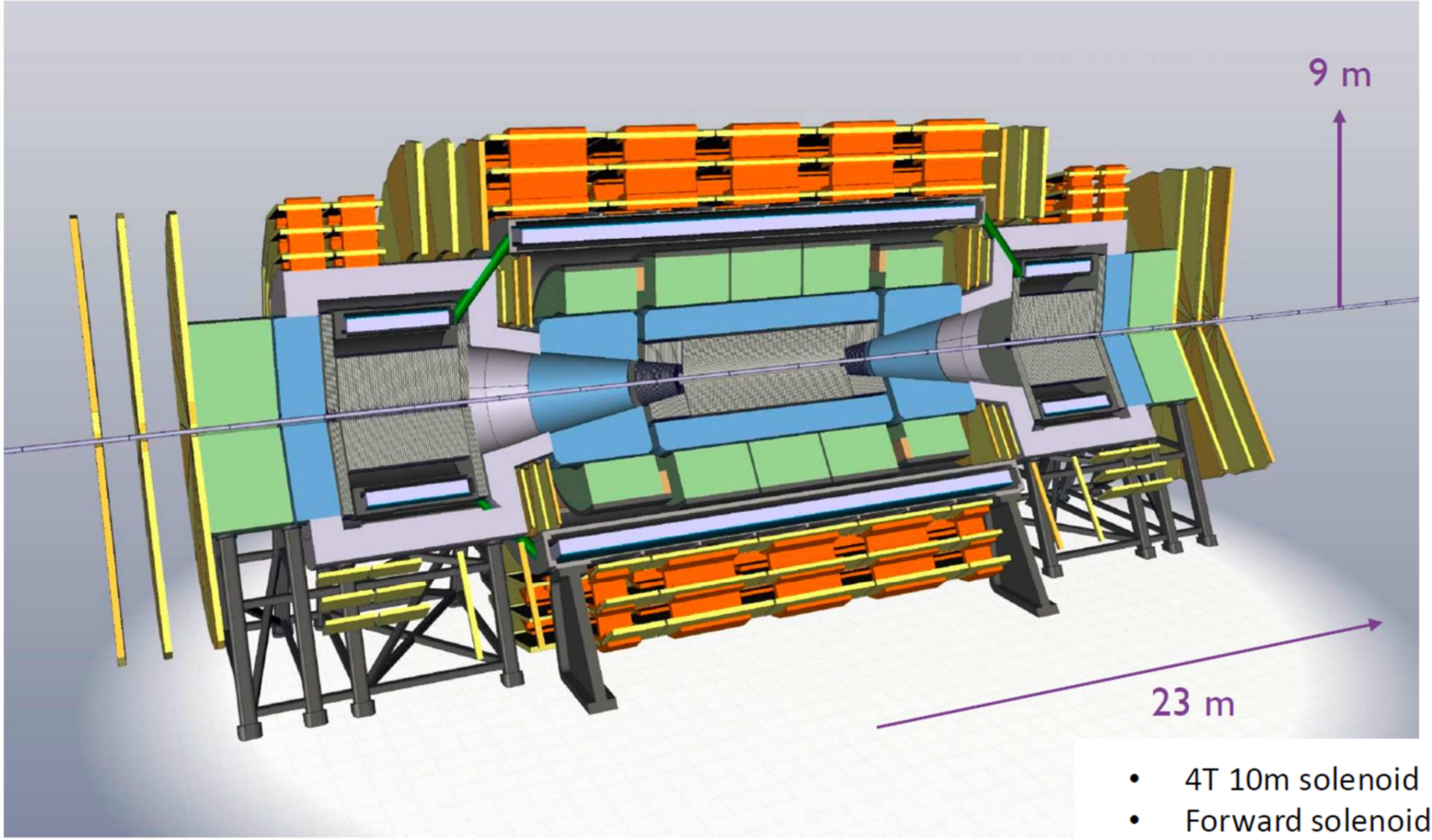


FCC Beamscreen prototype for test at ANKA:

External copper rings for heat transfer to cooling tubes



FCC-hh reference detector



- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL Lar
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

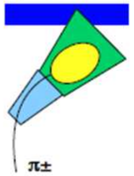
Solenoids in Central *and* forward areas no flux return.

Object reconstruction and performances

✦ Particle Flow Reconstruction

- Using charged hadrons, muons, electrons and calorimeter towers to build particle-flow objects
- Tracks from pile-up are rejected if $|Z_0 - Z_{\mathrm{PV}}| > \sqrt{\sigma^2(Z_0) + \sigma^2(Z_{\mathrm{PV}})}$

✦ Jets

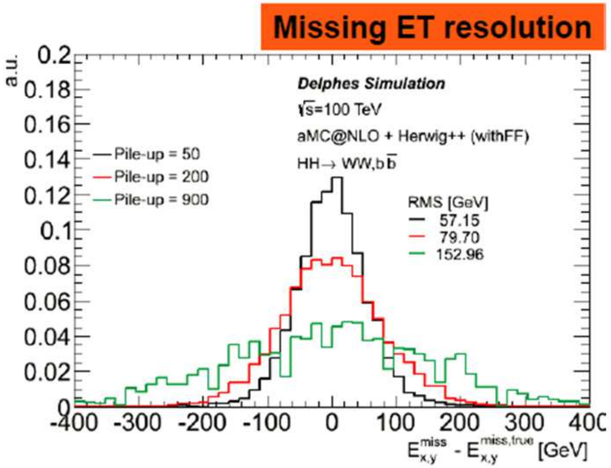


- Anti-Kt (Fast Jet) algorithm
- particle-flow objects as inputs
- R = 0.4
- Jet Area pile-up correction:
- private calibration to particle level $p_T^{\mathrm{corrected}} = p_T^{\mathrm{raw}} - \rho \cdot \mathrm{JetArea}$
- $p_T^{\mathrm{jet}} > 20$ GeV

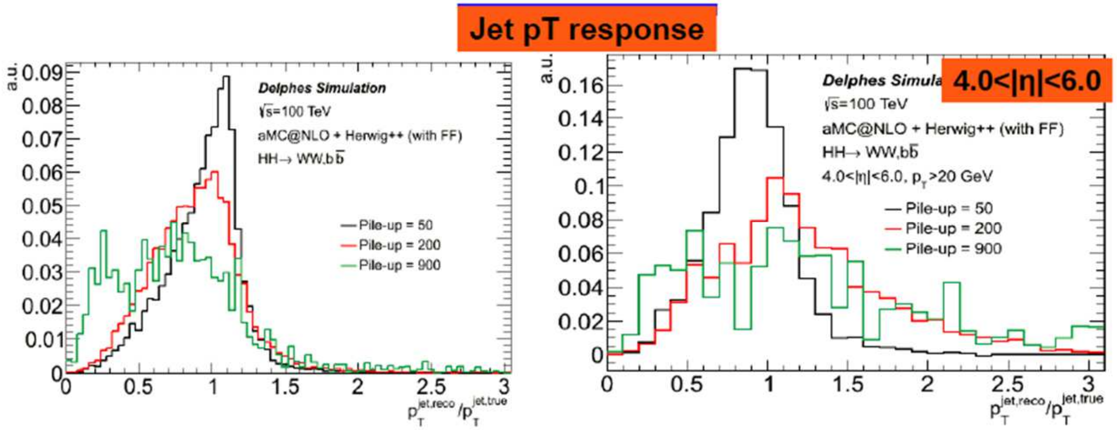
✦ Missing Transverse Energy

- Anti-Kt (Fast Jet) algorithm
- negative vector sum of Jets, after pile-up correction and calibration

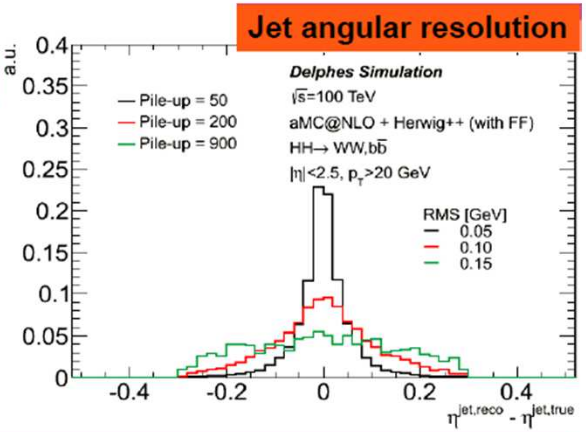
Missing ET resolution



Jet pT response



Jet angular resolution



FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!
ex: strongly coupled new particle up to 50 TeV
Excited quarks, Z’, W’, up to ~tens of TeV
Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks
-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau/ZZ$, ttH/ttZ @% level
-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
-- detection of rare decays $H \to V\gamma$ ($V= \rho,\varphi,J/\psi,\Upsilon,Z\ldots$)
-- search for invisibles (DM searches, RH neutrinos in W decays)
-- renewed interest for long lived (very weakly coupled) particles.
-- rich top and HF physics program

-- Cleaner signals for high Pt physics
-- allows clean signals for channels presently difficult at LHC (e.g. $H \to bb$)

PHYSICS COMPLEMENTARITY

Some examples

Higgs Physics -- ee → ZH fixes Higgs width and HZZ coupling , (and many others)
-- FCC-hh gives huge statistics of HH events for Higgs self-coupling

Search for Heavy Physics
-- ee gives precision measurements (m_Z m_W to < 0.5 MeV, m_{top} 10 MeV, etc…)
sensitive to heavy physics up to … 100 TeV
-- FCC-hh gives access to direct observation at unprecedented energies
Also huge statistics of Z,W and top → rare decays

QCD -- ee gives $\alpha_s \pm 0.0002$ (R_{had})
also H→gg events (gluon fragmentation!)
-- ep provides tructure functions and $\alpha_s \pm 0.0002$
-- all this improves the signal and background predictions
for new physics signals at FCC-hh

Heavy Neutrinos -- ee: very powerful and clean, but flavour-blind
-- hh and eh more difficult, but potentially flavour sensitive
NB this is very much work in progress!!

Physics references

FCC-ee

-- First look at the physics case of TLEP JHEP 1401 (2014) 164 arXiv:1308.6176

-- "Precision Observables and Radiative Corrections", https://indico.cern.ch/event/387296/

-- "Higgs at FCC-ee", https://indico.cern.ch/event/401590/

-- "High-precision α_S measurements: from LHC to FCC-ee", https://indico.cern.ch/event/392530/

serie ongoing: FCC-ee physics Indico: https://indico.cern.ch/category/5259/

Physics at a 100 TeV pp collider: CERN Yellow Report (2017) no.3

1) Standard Model processes: https://arxiv.org/pdf/1607.01831v1.pdf
2) Higgs and EW symmetry breaking studies: https://arxiv.org/pdf/1606.09408v1.pdf
3) Beyond the Standard Model phenomena: https://arxiv.org/abs/1606.00947
4) Heavy ions at the Future Circular Collider: https://arxiv.org/abs/1605.01389

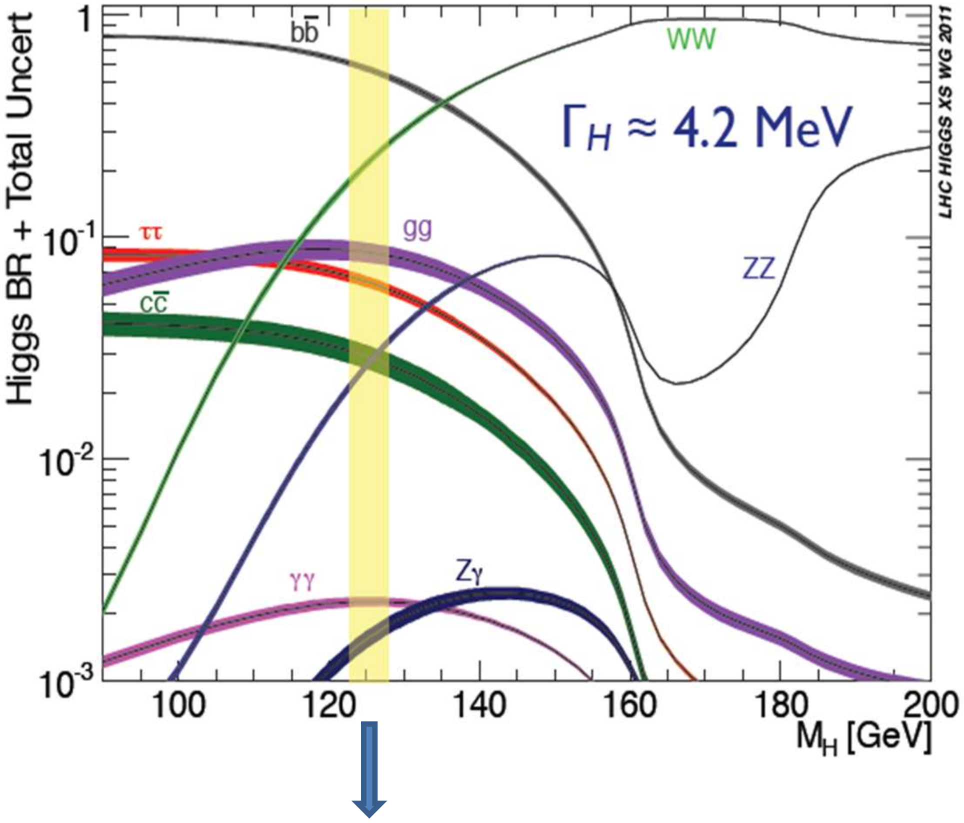
LHeC and FCC-eh

- "A Large Hadron Electron Collider at CERN: Report on the Physics and

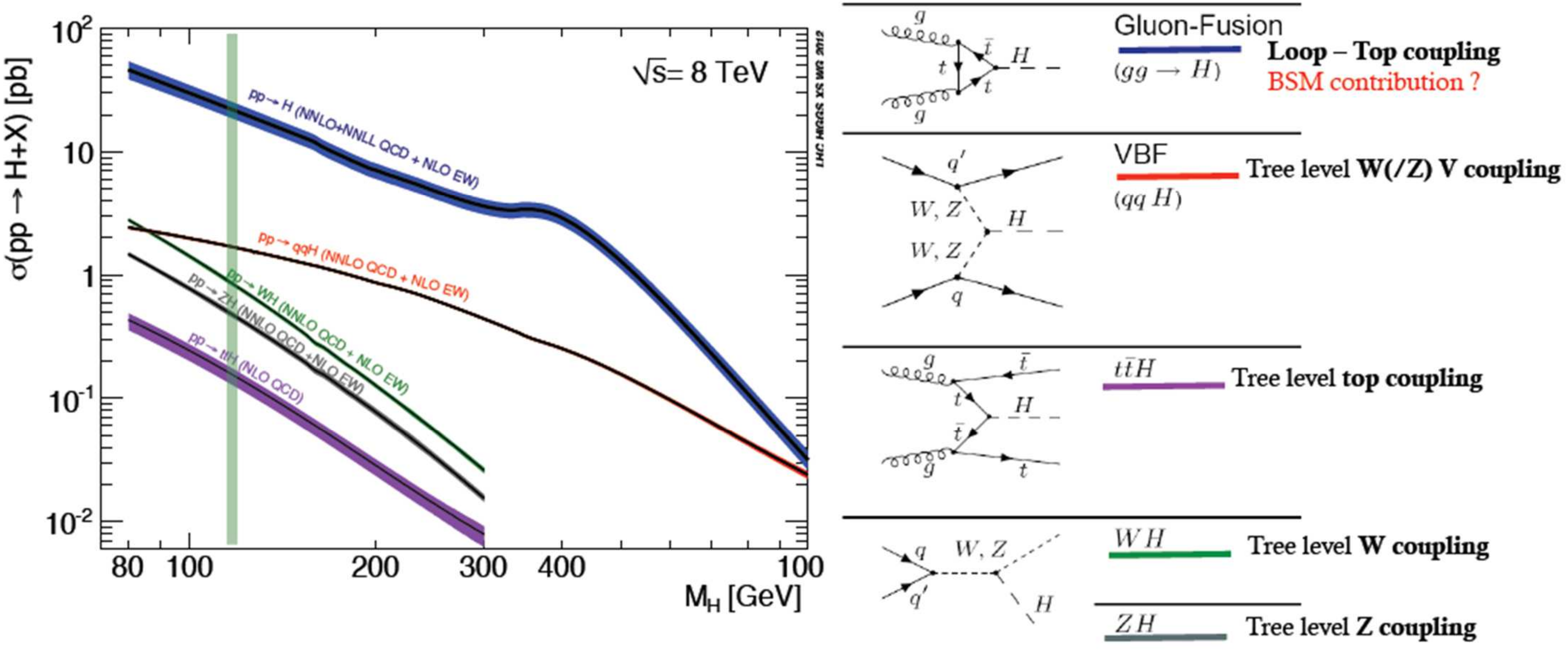
Higgs Physics

The only known spin = 0 elementary particle
We must study it as well and thoroughly as we can

Aram Apyan
Michelangelo Mangano
Biagio Di Micco
Fady Bishara
Ennio Salvioni
Masahiro Tanaka
Gilad Perez



μμ



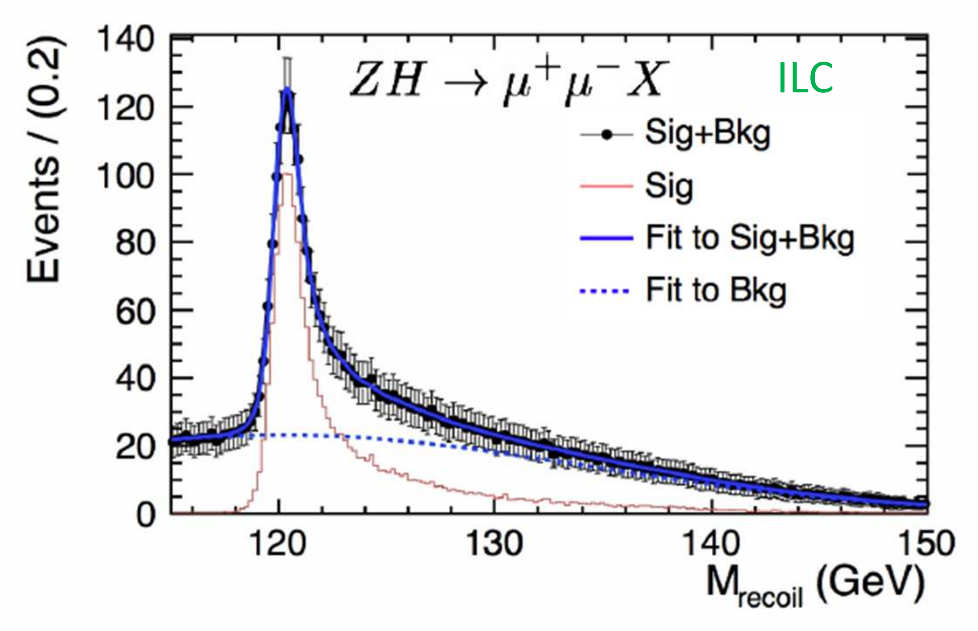
The LHC is a Higgs Factory !

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .
Challenge will be to reduce systematics by measuring related processes.

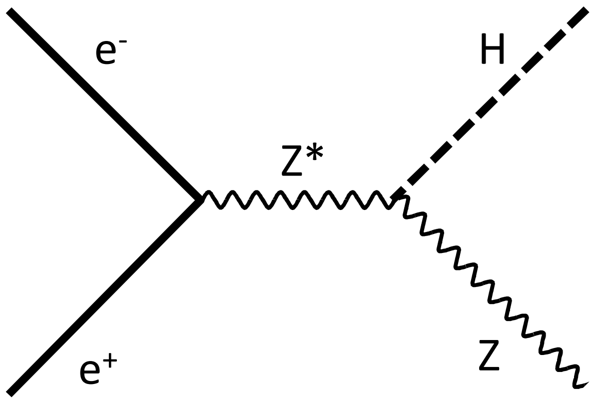
$$\sigma_{i\to f}^{\ observed} \propto \sigma_{prod} \ \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

overall normalization by Γ_H required
this is also true for FCC-hh and FCC-ep

FCC-ee
H signal in missing mass

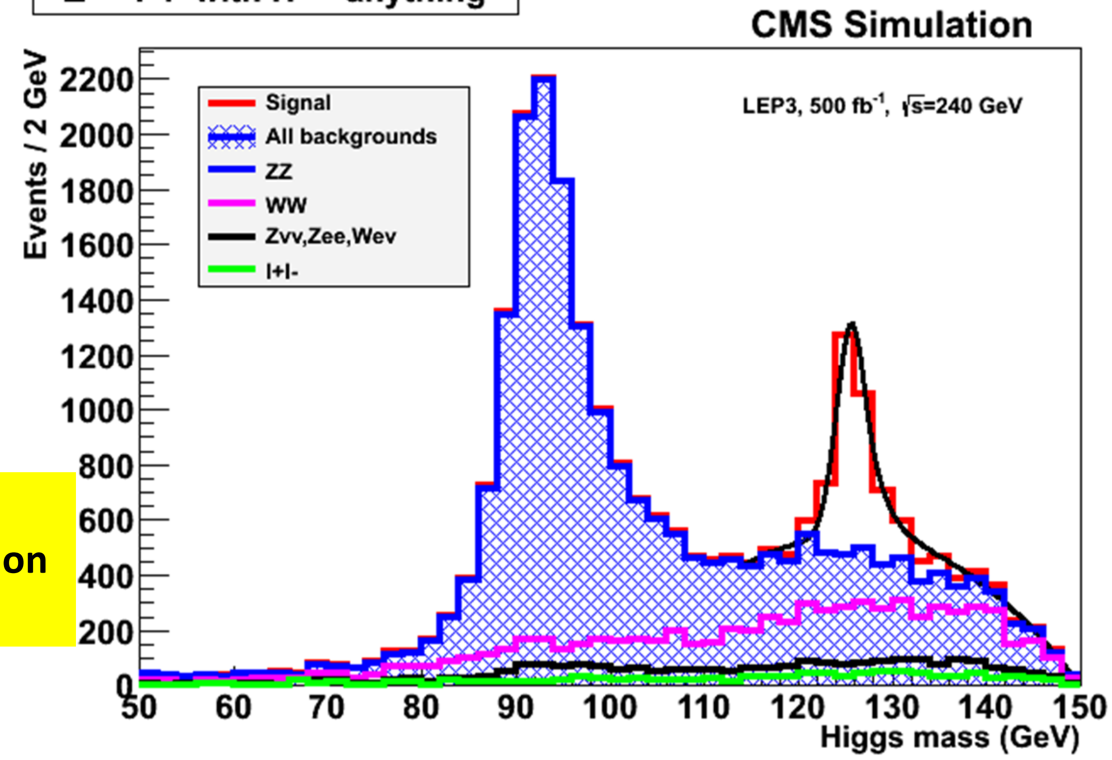


total rate ∝ g_{HZZ}^2
ZZZ final state ∝ g_{HZZ}^4 / Γ_H
➔ measure total width Γ_H and g_{HZZ}
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold

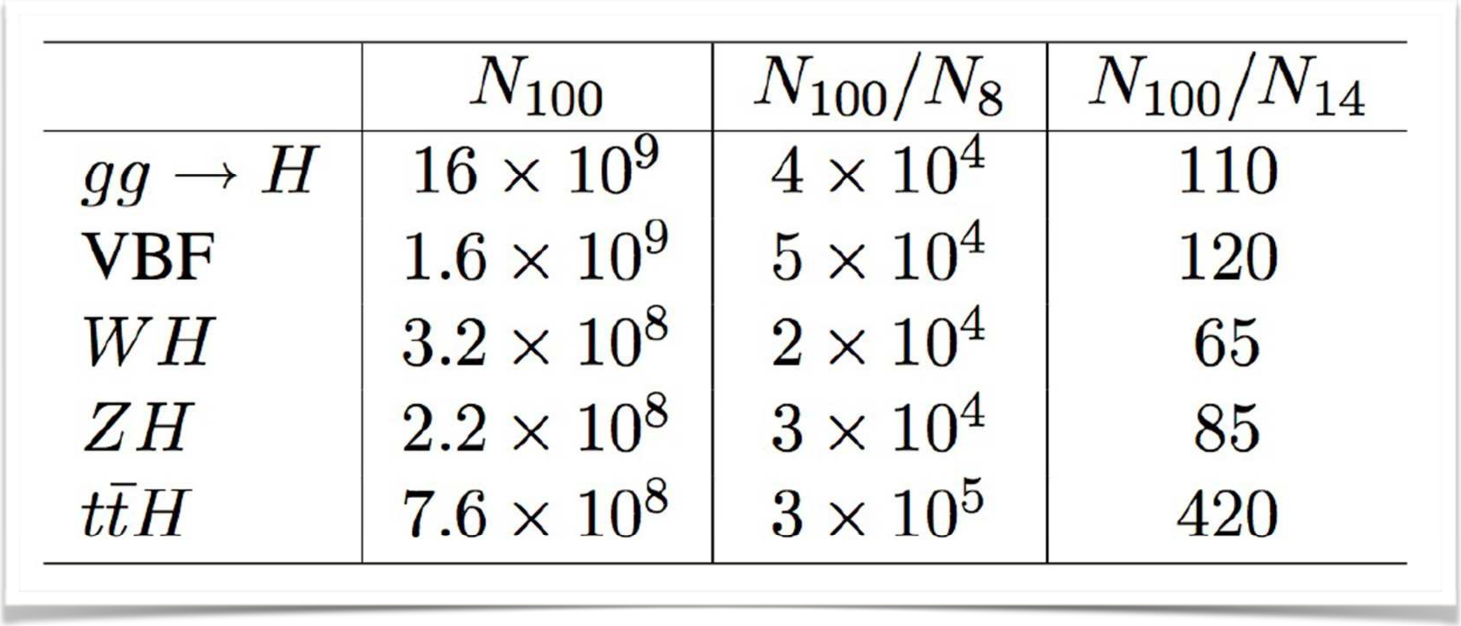


UNIQUE!
The ability to measure the Higgs cross-section without seeing the Higgs is crucial for this.

Z -> l+l- with H -> anything



SM Higgs rates at 100 TeV



	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

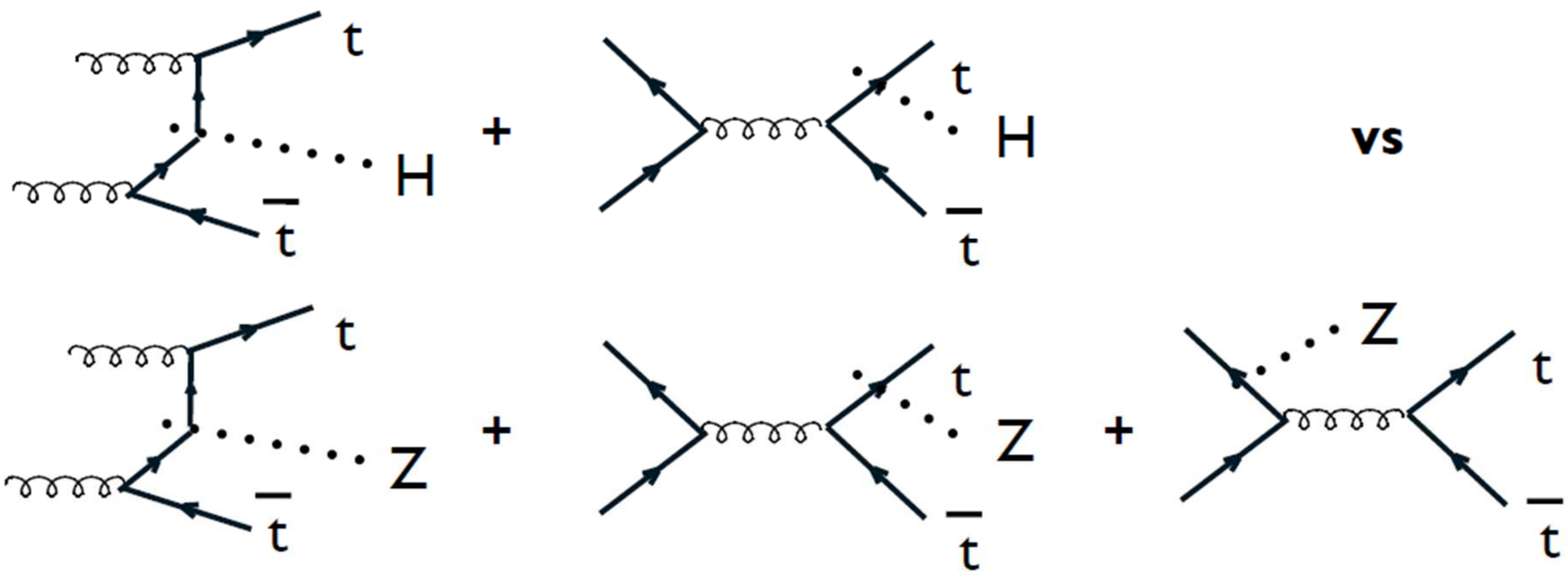
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

Top Yukawa coupling from σ(ttH)/σ(ttZ)



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:
  - o correlated QCD corrections, correlated scale dependence
  - o correlated α_S systematics
- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:
  - o correlated PDF systematics
  - o correlated m_{top} systematics

	$\sigma(t\bar{t}H)[\mathrm{pb}]$	$\sigma(t\bar{t}Z)[\mathrm{pb}]$	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

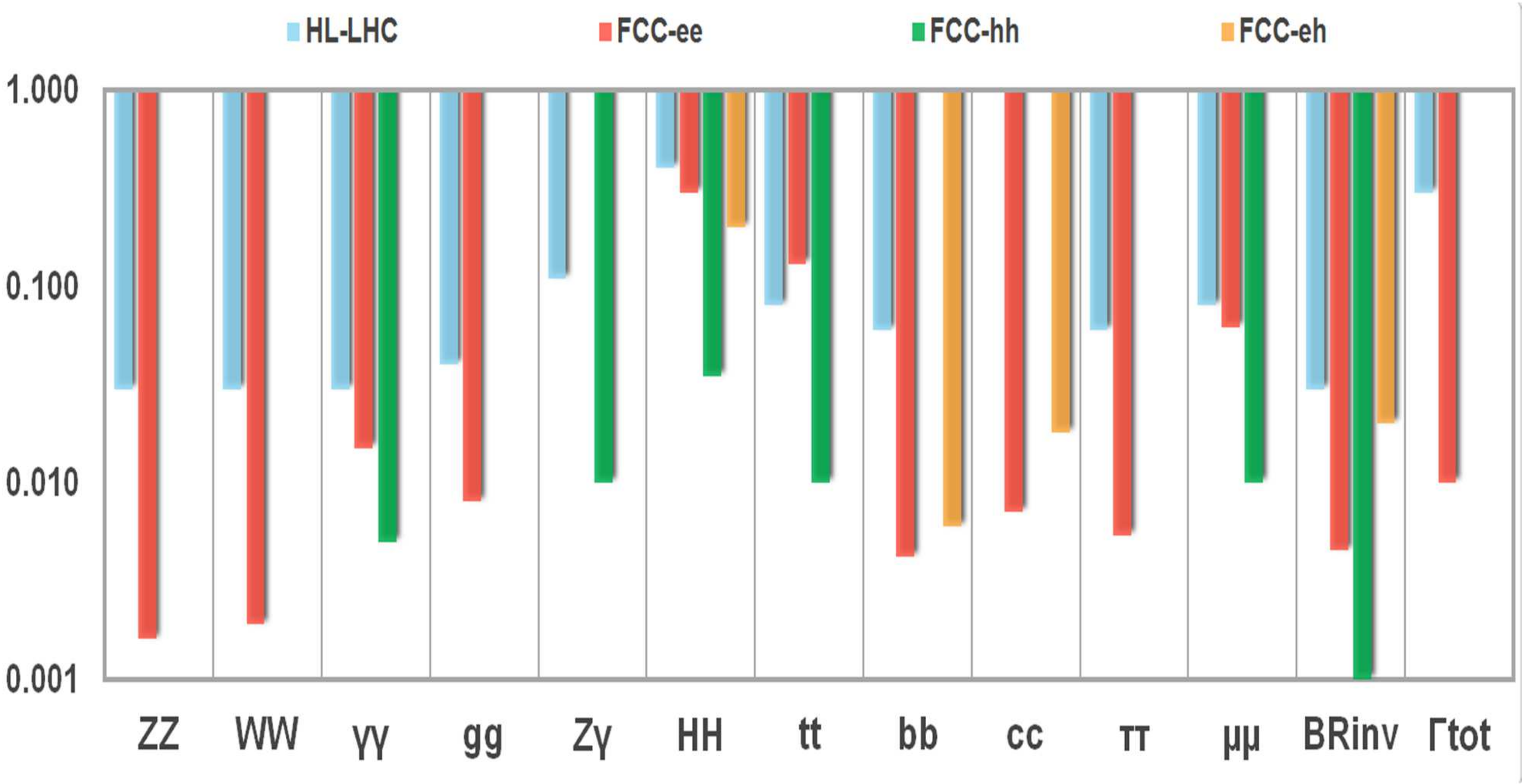
(± scale ± PDF)

HIGGS PHYSICS

Higgs couplings g_{Hxx} precisions

hh, eh precisions assume
SM or ee measurements

g_{Hxx}	FCC-ee	FCC-hh	FCC-eh
ZZ	**0.15 %**		
WW	**0.20%**		
Γ_H	**1%**		
$\gamma\gamma$	1.5%	**<1%**	
$Z\gamma$	--	**1%**	
tt	13%	**1%**	
bb	**0.4%**		0.5%
$\tau\tau$	**0.5%**		
cc	**0.7%**		1.8%
$\mu\mu$	6.2%	**2%**	
uu,dd	$H \rightarrow \rho\gamma$?	$H \rightarrow \rho\gamma$?	
ss	$H \rightarrow \phi\gamma$?	$H \rightarrow \phi\gamma$?	
ee	**ee → H**		
HH	30%	**~3%**	20%
inv, exo	<0.45%	**10^{-3}**	5%



NB this is an ‘impression plot’ not the consistent result of a Higgs coupling fit!

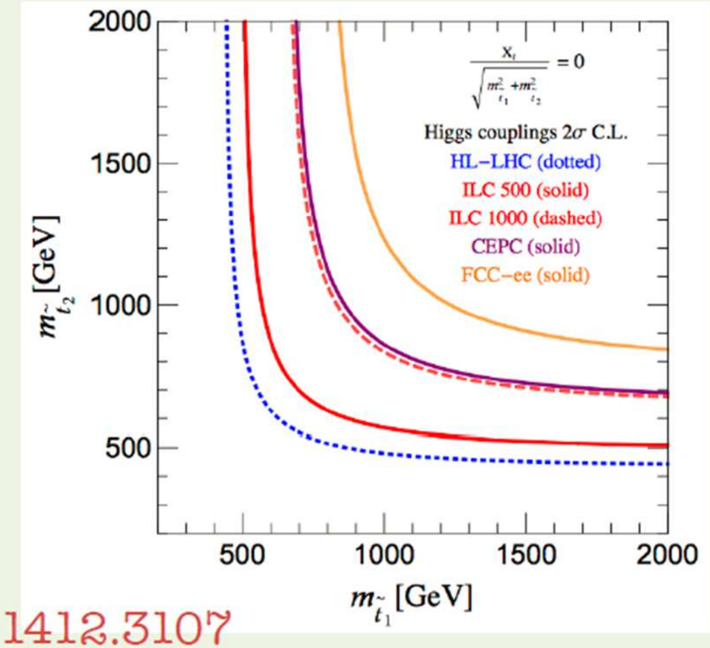
hh, eh precisions assume SM or ee measurements!

Supersymmetry

In supersymmetry top partner is “stop squark”.

FCC-ee

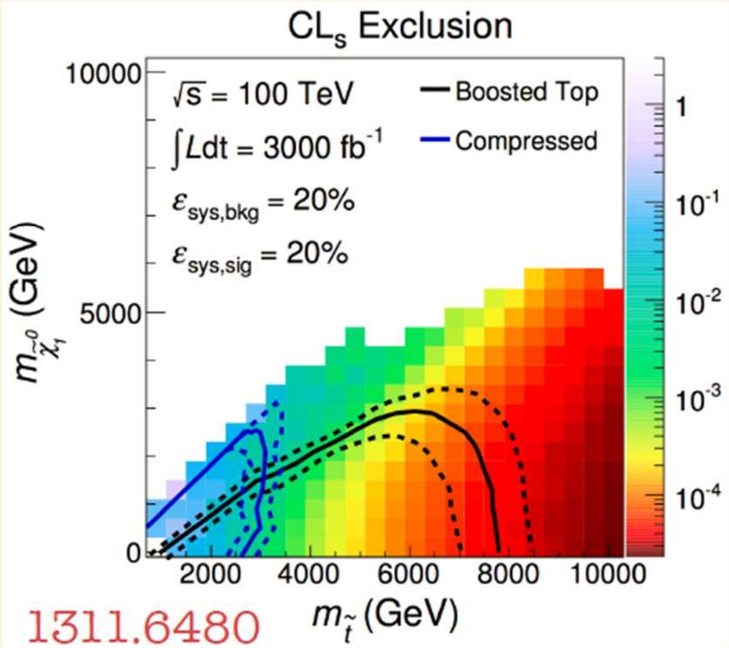
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:



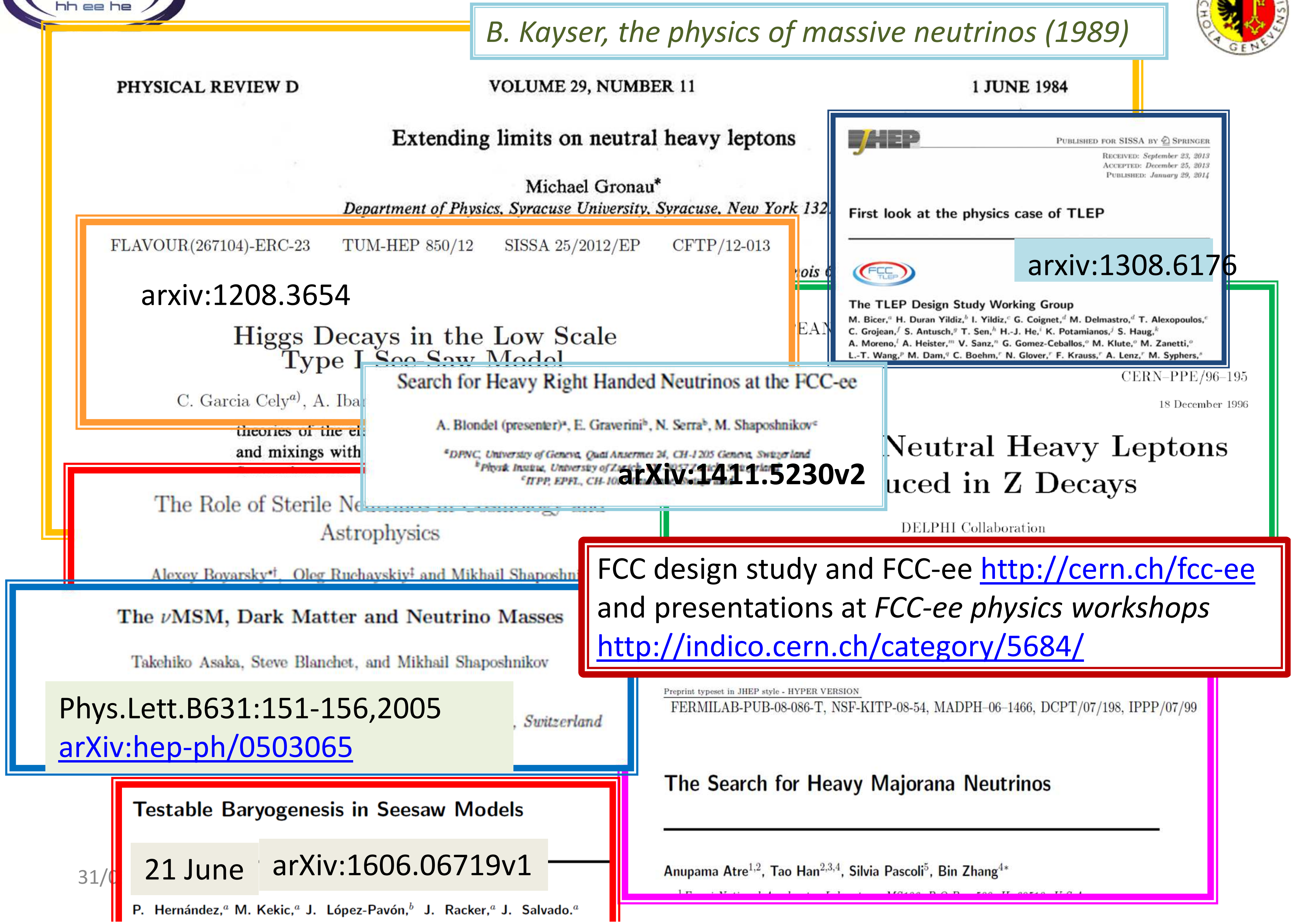
1311.6480

FCC-ee: Indirect, but more “spectrum independent”, for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

The Hunt for right-Handed Neutrinos at the FCCs

courtesy J. Wenninger

A few REFERENCES



B. Kayser, the physics of massive neutrinos (1989)

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

Department of Physics, Syracuse University, Syracuse, New York 132

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a], A. Iba

and mixings with

JHEP PUBLISHED FOR SISSA BY SPRINGER

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PUBLISHED: *January 29, 2014*

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s]

Search for Heavy Right Handed Neutrinos at the FCC-ee

A. Blondel (presenter)[a], E. Graverini[b], N. Serra[b], M. Shaposhnikov[c]

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[b]*Physik Institut, University of Z*
[c]*ITPP, EPFL, CH-10*

arXiv:1411.5230v2

CERN–PPE/96–195

18 December 1996

Neutral Heavy Leptons uced in Z Decays

DELPHI Collaboration

The Role of Sterile Ne Astrophysics

Alexey Boyarsky[*†], Oleg Ruchayskiy[‡] and Mikhail Shaposhni

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Switzerland

Phys.Lett.B631:151-156,2005
arXiv:hep-ph/0503065

FCC design study and FCC-ee http://cern.ch/fcc-ee
and presentations at *FCC-ee physics workshops*
http://indico.cern.ch/category/5684/

Preprint typeset in JHEP style - HYPER VERSION

FERMILAB-PUB-08-086-T, NSF-KITP-08-54, MADPH–06–1466, DCPT/07/198, IPPP/07/99

The Search for Heavy Majorana Neutrinos

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

Testable Baryogenesis in Seesaw Models

21 June

arXiv:1606.06719v1

P. Hernández,[a] M. Kekic,[a] J. López-Pavón,[b] J. Racker,[a] J. Salvado.[a]

Some Recent papers:

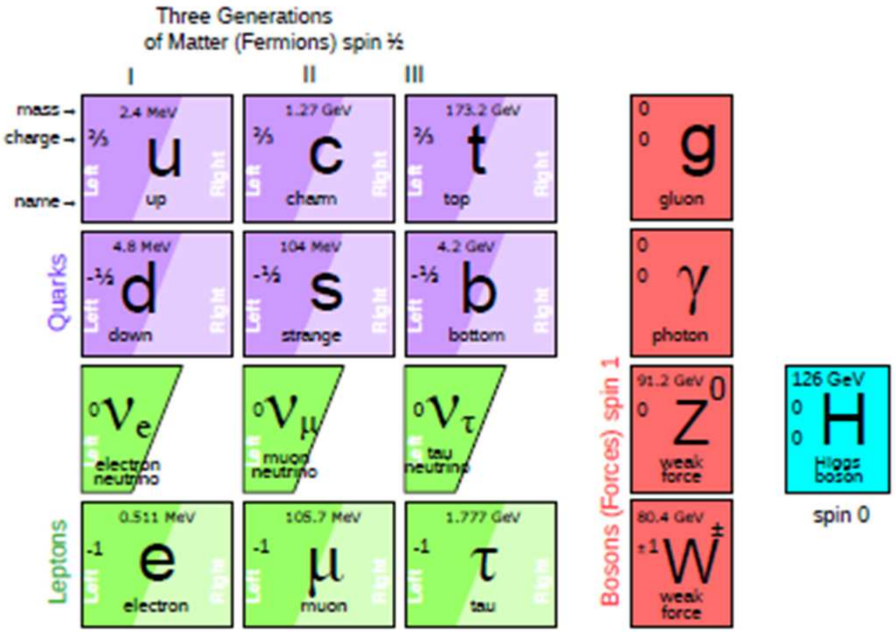
The seesaw path to leptonic CP violation
A. Caputo, P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Salvado **arXiv:1611.05000**

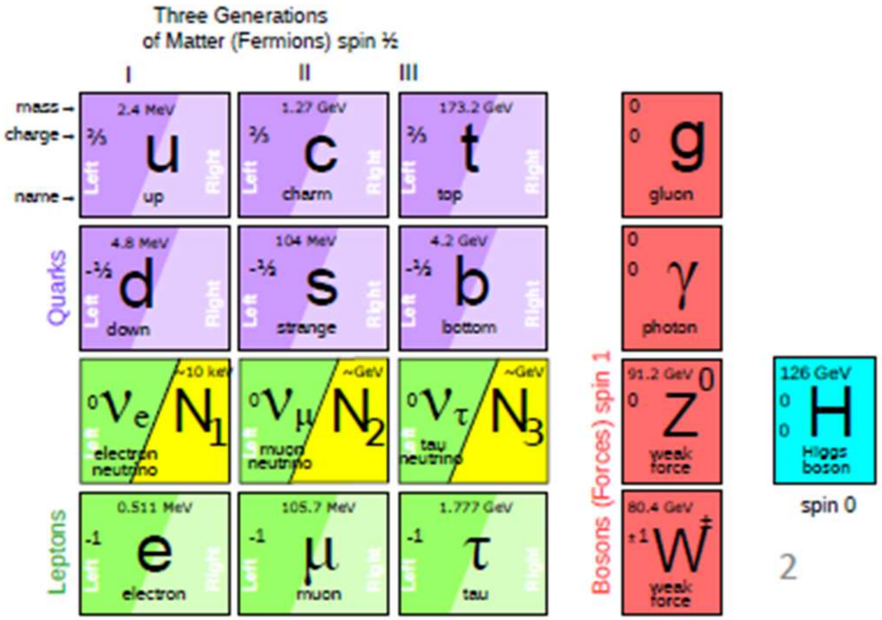
Sterile neutrino searches at future e−e+, pp, and e−p colliders
Stefan Antusch, Eros Cazzato, Oliver Fischer **arXiv:1612.02728v2**

things are moving fast!

THE STANDARD MODEL IS COMPLETE .....

But at least 2 or 3 pieces are still missing





neutrinos have mass...

and this very probably implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

.... but could perhaps explain: DM, BAU, small ν-masses

Introduction / disclaimer

As you have seen in the lectures by S. Bilenki, B. Kayser S. Kind, C. Giunti and J. Link

1. there are several (many) ways to build massive neutrinos onto the Standard Model

2. the word Sterile has been used mostly for a possible observation at a scale of 1 eV
   of phenomena that could be interpreted as a fourth, sterile neutrino
   (given that at LEP we meaasured that there are only the three known active neutrinos
   but it generally extends to neutrinos that have no weak isospin.

3. here I will discuss only the first, simplest case of type I see-saw as an example of how to look for 'sterile' right-handed neutrinos at high energy colliders.

4. this is a case in point that all physics to be discovered is not just a replica of phenomena that are known today.

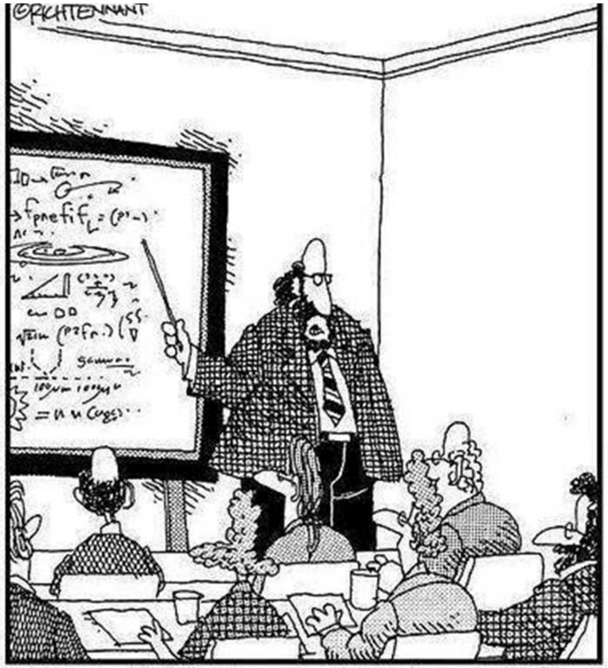
Electroweak eigenstates

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

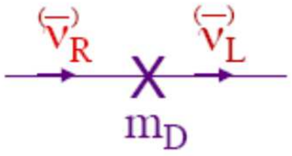
Also called 'sterile'



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

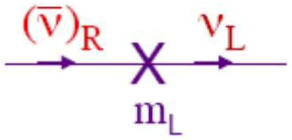
$m_D \nu_L \overline{\nu_R}$ $\quad$ $m_D \overline{\nu_L} \nu_R$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> prevents adding then a term like

$$m_M \overline{\nu_R{}^c} \nu_R$$



and this simply means that a neutrino turns into a antineutrino

It is perfectly conceivable ('natural'?) that both terms are present.

Dirac mass term + Majorana mass term ➔ 'see-saw'

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw type I, one family :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

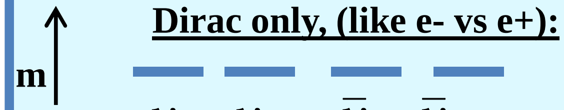
$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):



	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

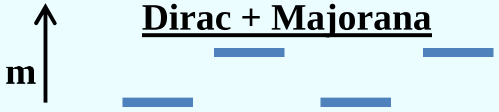
	ν_L	$\bar{\nu}_L$
I_{weak}=	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ see-saw

Dirac + Majorana



dominantly:

	ν	N	$\bar{\nu}$	$\bar{N}$
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$\boldsymbol{m_\nu} \approx \frac{\boldsymbol{m_D}^2}{\boldsymbol{M}}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$

$$\boldsymbol{\nu} = \boldsymbol{\nu_L} \cos\theta - \boldsymbol{N^c_R} \ \mathbf{sin}\theta$$

$$\boldsymbol{N} = \boldsymbol{N_R} \cos\theta + \boldsymbol{\nu_L}^c \sin\theta$$

what is produced in W, Z decays is:

$$\boldsymbol{\nu_L} = \boldsymbol{\nu} \cos\theta + \boldsymbol{N} \sin\theta$$

$\boldsymbol{\nu}$ = light mass eigenstate
N = heavy mass eigenstate
$\neq \boldsymbol{\nu_L}$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences

-- if very light (eV) , possible effect on neutrino oscillations

-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- possibly measurable effects at High Energy

If N is heavy it will decay in the detector (not invisible)

→ PMNS matrix unitarity violation and deficit in Z «invisible» width

→ Higgs, Z, W visible exotic decays $H \rightarrow \nu_i \ \bar{N}_i$ and $Z \rightarrow \nu_i \ \bar{N}_i$, $W \rightarrow l_i \ \bar{N}_i$

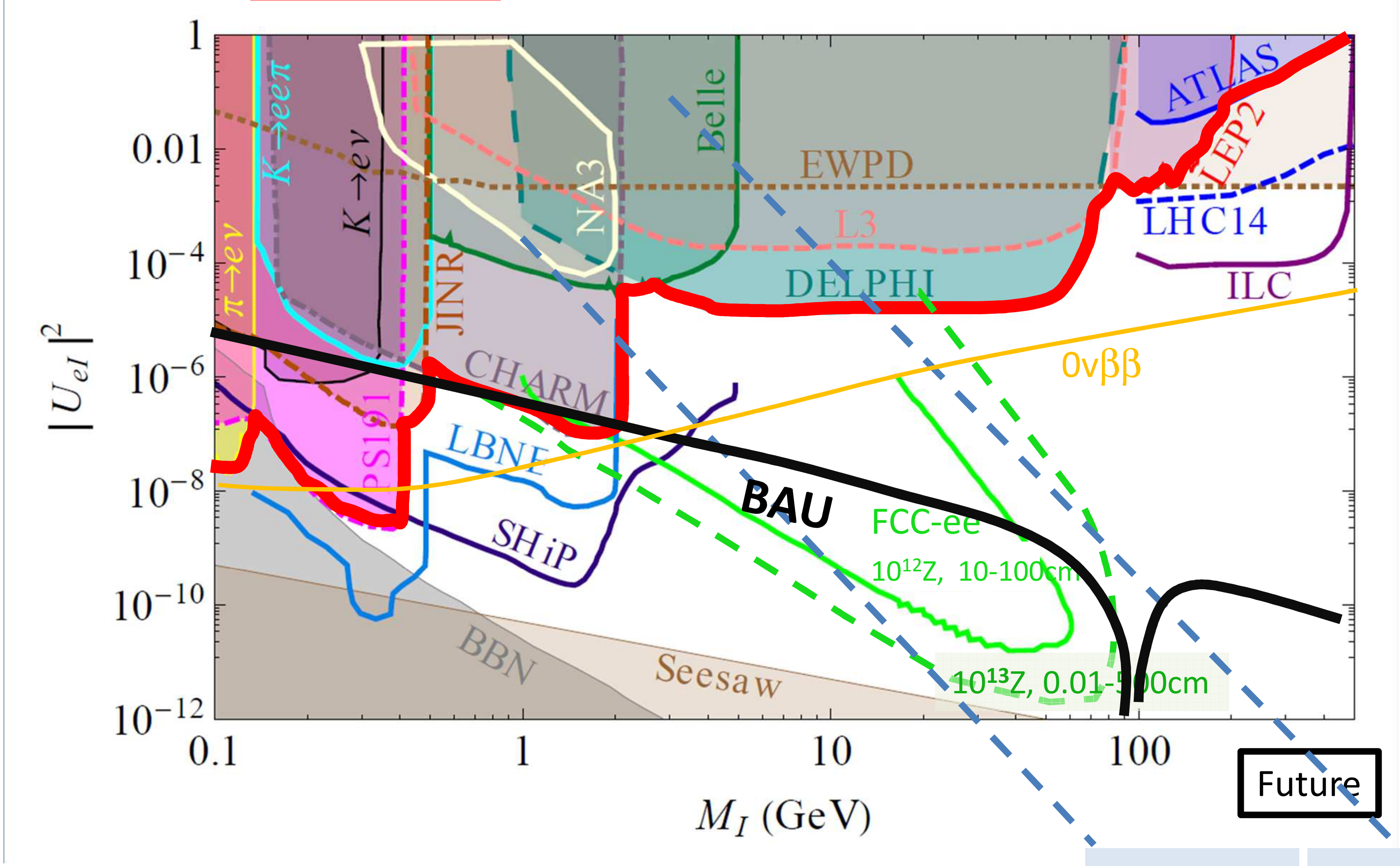
→ also in K, charm and b decays via $W^* \rightarrow l_i^{\pm} \ \bar{N}$, $N \rightarrow l_j^{\pm}$
with any of six sign and lepton flavour combination

→ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

-- Couplings are very small ($\boldsymbol{m_\nu} / m_N$) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Present limits



Future

$L_{decay} \approx$10m

L_{decay} =1mm

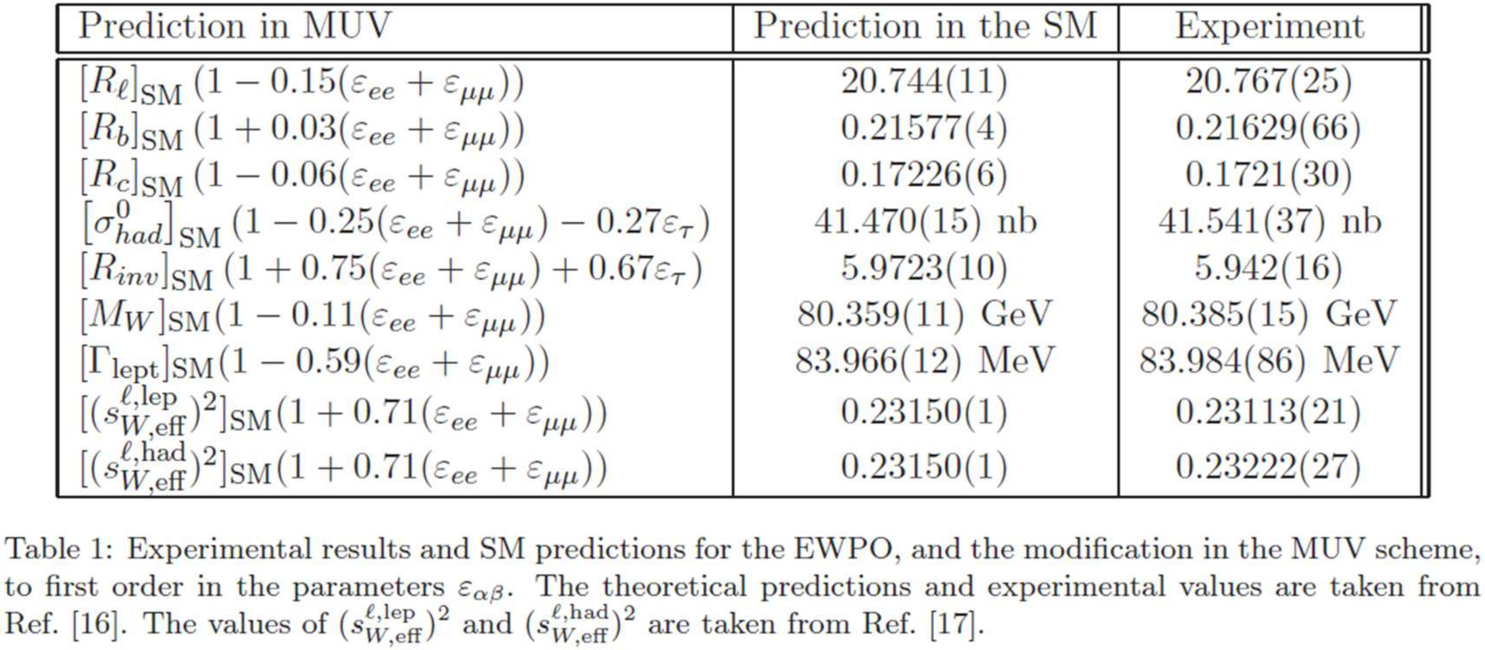
Based on arXiv:1504.04855v1 'SHIP physics paper'

And Pilar Hernandez, HEP-EPS Vienna

(indirect) Effect of right handed neutrinos on EW precision observables

The relationship $|U|^2 \propto \theta^2 \approx m_\nu / m_N$ is valid for one family see-saw.
For two or three families the mixing can be larger (*Shaposhnikov*)
Antush and Fisher have shown that a slight difference in Majorana mass between generations can generate larger mixing between the left- and right-handed neutrinos. ***Worth exploring.***

«$\nu_L = \nu\cos\theta + N\sin\theta$» → $(\cos\theta)^2$ becomes parametrized as $1+\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative)
the coupling to light neutrinos is typically suppressed.
In the G_F, M_Z α_{QED} scheme, G_F (extracted from $\mu \to e\nu_e\nu_\mu$) and g should be increased
This leads to *correlated* variations of all predictions upon e or mu neutrino mixing.
Only the 'number of neutrinos' (R_{inv} and σ_{had}^{peak}) is sensitive to the tau-neutrino mixing.



Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\rm SM}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\rm SM}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,{\rm had}}_{W,{\rm eff}})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2$ and $(s^{\ell,{\rm had}}_{W,{\rm eff}})^2$ are taken from Ref. [17].

Other quantities that could be sensitive to the light-heavy mixing

1. the tau life time would be sensitive to $\varepsilon_{\tau\tau}$

→ how well can we measure the tau life time with 10^{11} $\tau\tau$?

$\tau_\tau = (290.3 \pm 0.5) \times 10^{-15}$ s $c\tau_\tau = 87.03$ µm

Mass m = 1776.86 ± 0.12 MeV limits the sensitivity to 0.3 10^{-4}

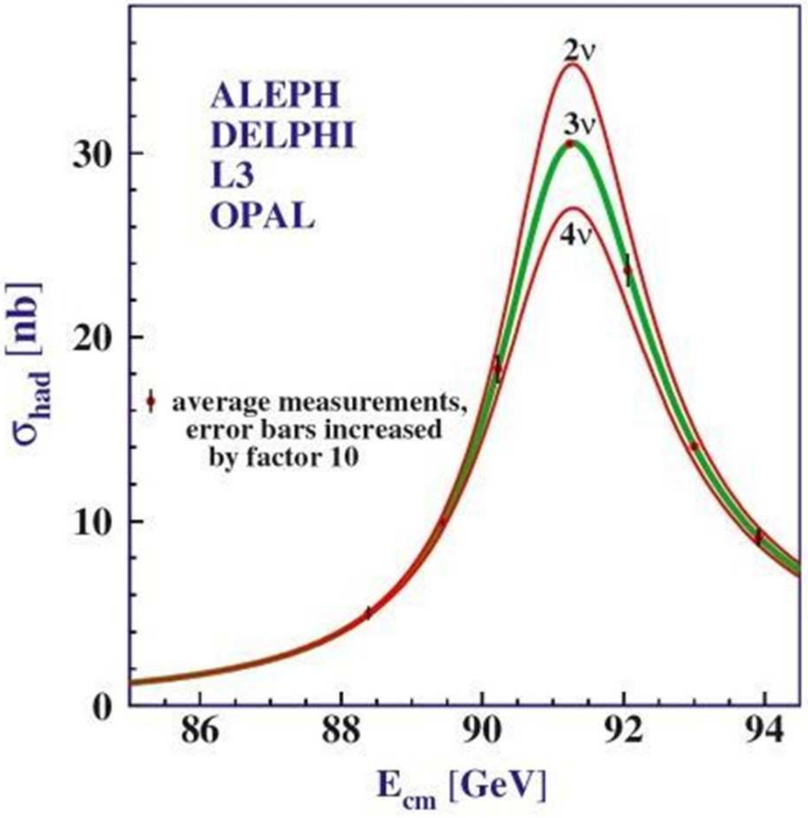
2. the measurement of the 'number of neutrinos'

At the end of LEP:

Phys.Rept.427:257-454,2006

$N_\nu = 2.984 \pm 0.008$

- 2 σ :^) !!

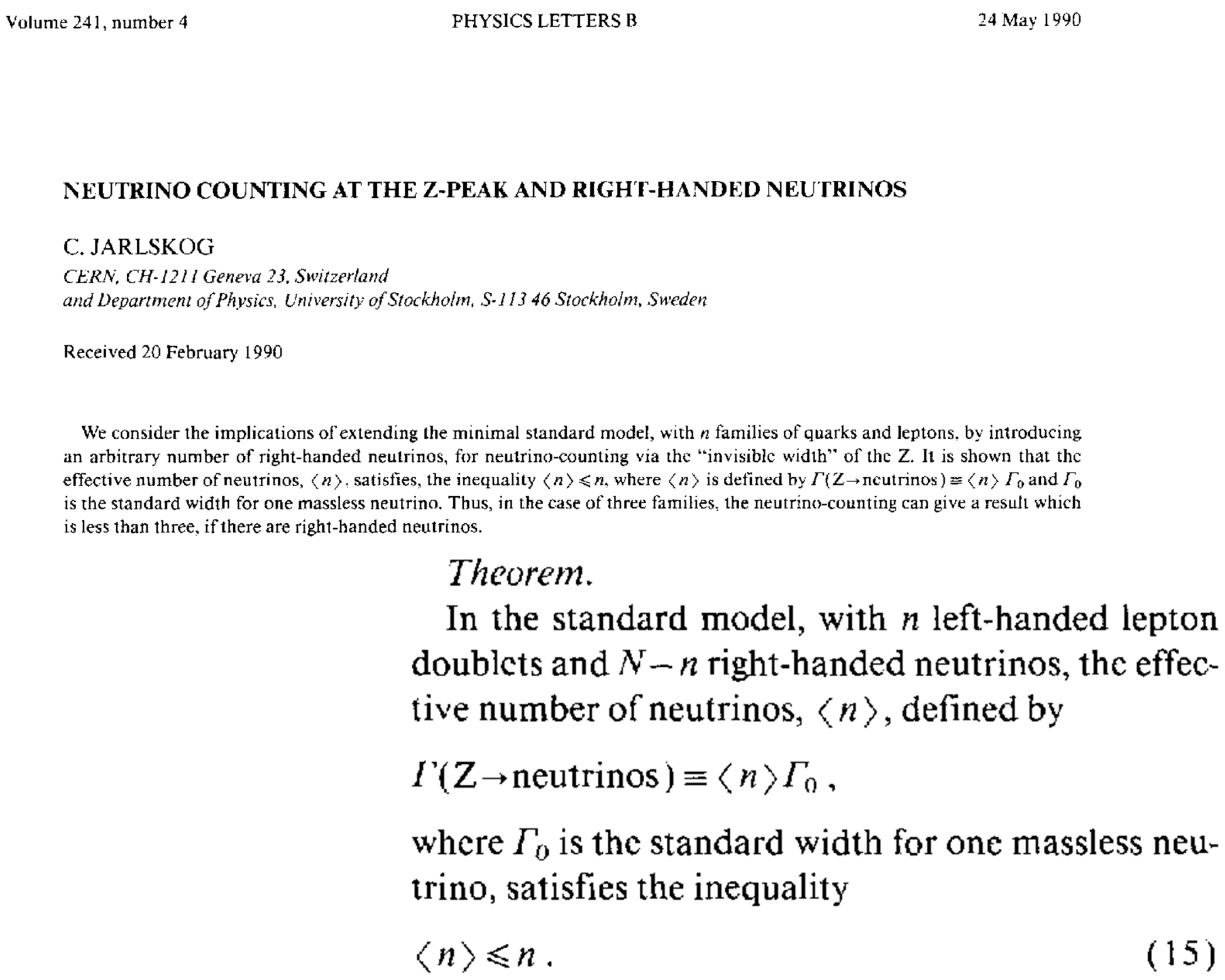


This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔ little parametric dependence

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) and QED effects which represents an error of ±0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation

Error may decrease to 0.002….



Volume 241, number 4 PHYSICS LETTERS B 24 May 1990

NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

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and Department of Physics, University of Stockholm, S-113 46 Stockholm, Sweden

Received 20 February 1990

We consider the implications of extending the minimal standard model, with n families of quarks and leptons, by introducing an arbitrary number of right-handed neutrinos, for neutrino-counting via the "invisible width" of the Z. It is shown that the effective number of neutrinos, $\langle n \rangle$, satisfies, the inequality $\langle n \rangle \leqslant n$, where $\langle n \rangle$ is defined by $\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0$ and Γ_0 is the standard width for one massless neutrino. Thus, in the case of three families, the neutrino-counting can give a result which is less than three, if there are right-handed neutrinos.

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \tag{15}$$

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e,\mu}\,(SM)}$$

The common γ **tag** allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of O(10^{12}) Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}(SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for |cosθ_γ| <0.95

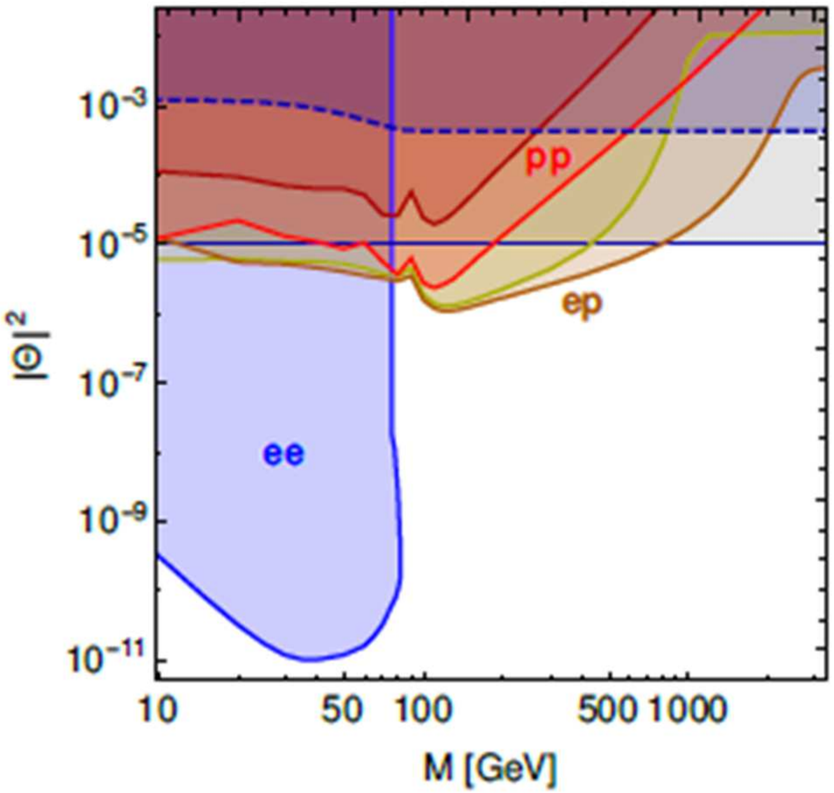
161 GeV (10^7 s) running at 1.6×10^{35}/cm²/s x 4 exp ➔ 3×10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

A better point may be 1 125GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?

The interest of these 'indirect' tests

They constrain the coupling to the RH neutrinos independently of their mass

-- very high mass sensitivity if one assumes large coupling **(10^{-4})**



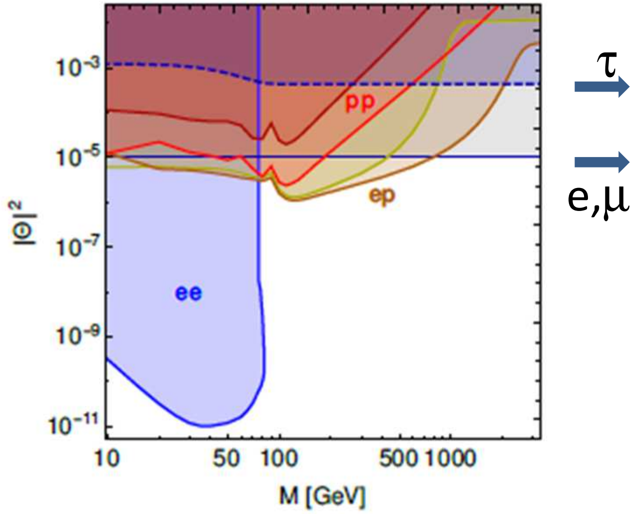


Figure 16: Summary of selected estimated sensitivities of the FCC-ee, -hh, and -eh colliders, including the HL-LHC and the LHeC. The best sensitivity for heavy neutrino masses $M < m_W$ is obtained from the displaced vertex searches at the Z pole run of the FCC-ee shown by the blue line, which are sensitive to $|\theta|^2 = |\theta_e|^2 + |\theta_\mu|^2 + |\theta_\tau|^2$. For heavy neutrino masses above m_Z the pp colliders (red: FCC-hh, dark-red: HL-LHC) and e^-p colliders (brown: FCC-eh, yellow: LHeC) have the best prospects for discovering sterile neutrinos via the LFV signatures. The lepton-dijet signature at the pp colliders with final states $\ell_\alpha^\pm \ell_\beta^\mp jj$, $\alpha \neq \beta$ yields sensitivities to the active-sterile mixing parameter combinations $|\theta_\alpha\theta_\beta|^2/|\theta|^2$, and it is shown by the red lines. The lepton-trijet signature at the e^-p colliders with final states $\ell_\alpha^- jjj$, $\alpha \neq e$ is sensitive to $|\theta_e\theta_\alpha|^2/|\theta|^2$, and it is shown by the brown lines. Finally, for very large heavy neutrino masses the best sensitivity is given by the EWPO measurements at the FCC-ee. The solid and dashed horizontal blue line denotes the sensitivity to $|\theta_e|^2 + |\theta_\mu|^2$ and $|\theta_\tau|^2$, respectively.

arXiv:1612.02728v2

Experimentally some new requirements

-- tau life time measurement?

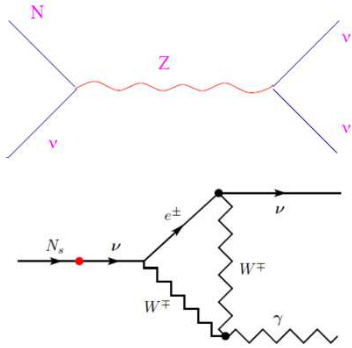
-- Single gamma N_ν counting needs to be included

Direct searches

Search Processes (I)

m_N Below m_π:

N→ 3ν; N→ νγ w $E_\gamma = m_N/2$



$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

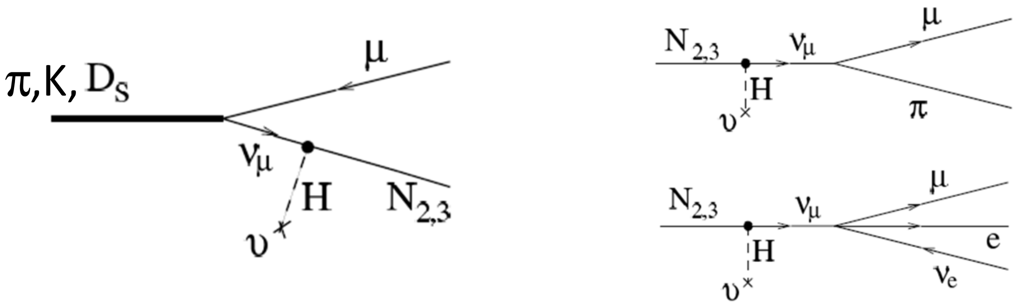
Long life, **dark matter candidate**

Equilibrium with neutrinos produced in the stars

→ Search for gamma emission line (such as 3.5 keV line)

Drewes et al; arXiv:1602.04816v1

Meson decay (π,K: neutrino beams) examples:



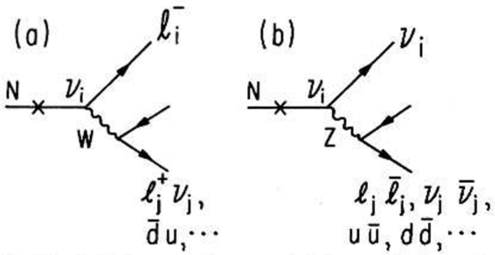


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\,(m_{\nu_m}(\text{GeV}/c^2))^6} \times \frac{P_\nu}{45GeV/c}$$

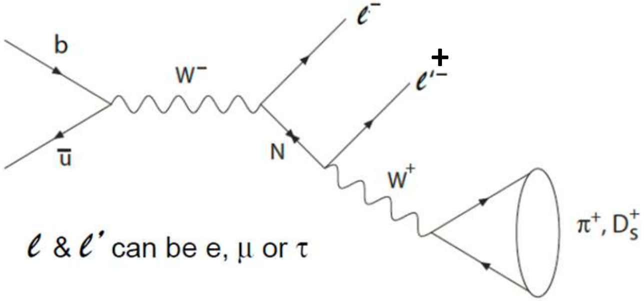
Decay via W gives at least two charged particles, and amounts to ~60% of decays.

Searches for long lived decays in neutrino beams PS191, NuTeV, CHARM; SHIP and DUNE proposals

Processes (II)

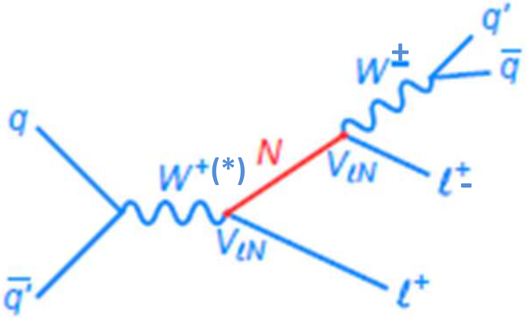
Search for heavy right-handed neutrinos in collider experiments.

B factories



ℓ & ℓ' can be e, μ or τ

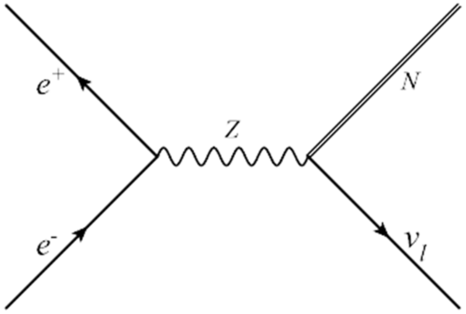
Hadron colliders



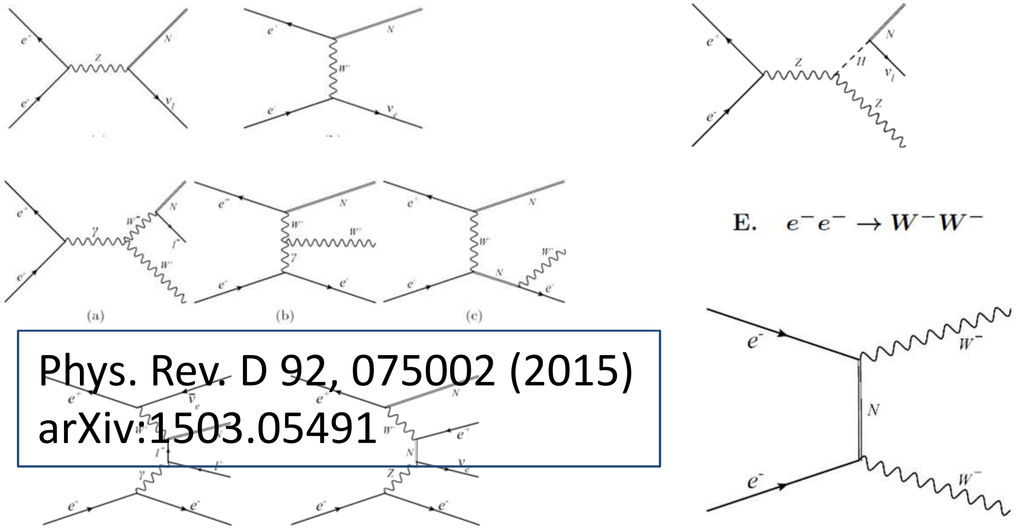
or $l^{\pm}\nu$

Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



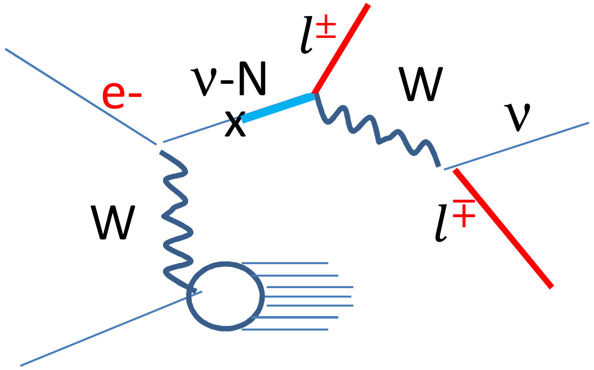
HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)

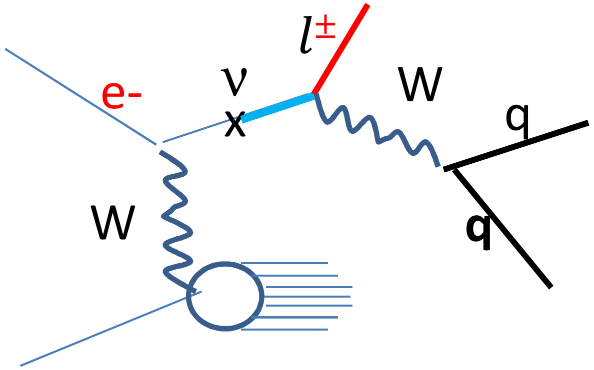


Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

FCC-ep

Clearly the ep collisions produce abundant numbers of neutrinos, which will be mixed with RH neutrinos.





hard lepton can have ‘wrong sign’!

A question more than a statement: does this cause any problem of trigger? acceptance? background?

Searches for heavy neutrinos ν_h in B decays

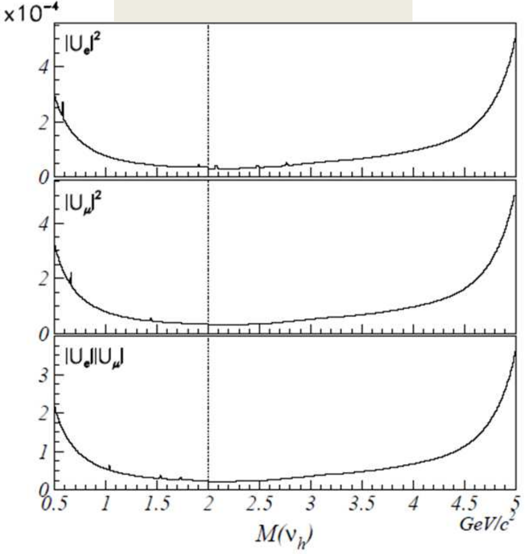
-- **BELLE** *Phys. Rev. D. 87, 071102 (2013), arXiv:1301.1105*

7.8 10^8 B mesons at Y_{4s}!

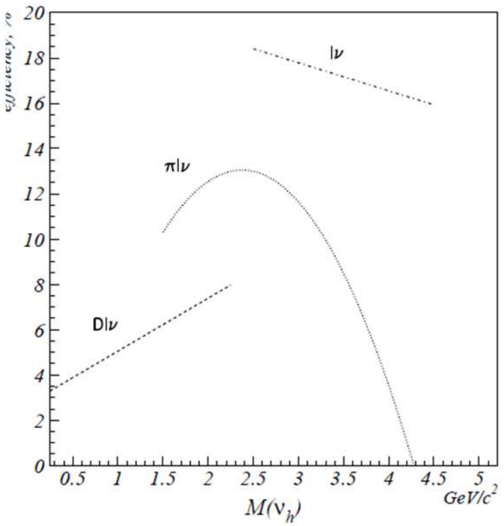
Search for $\ell_2 + (\ell_1 \pi)$, where ℓ_1 and π have **opposite charge and displaced vertex**
for $M(\nu_h)$ =1GeV/c2 and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$ the flight length is $c\tau \simeq 20$m.

➔ charge and flavour of $\boldsymbol{\ell_2 \ell_1}$ can be **any combination of e, μ, + or -** because the heavy neutrino is assumed to be Majorana. (If Dirac fermion, -> opposite charges only).
A few signal events, no ‘peak’.

90% CL limits



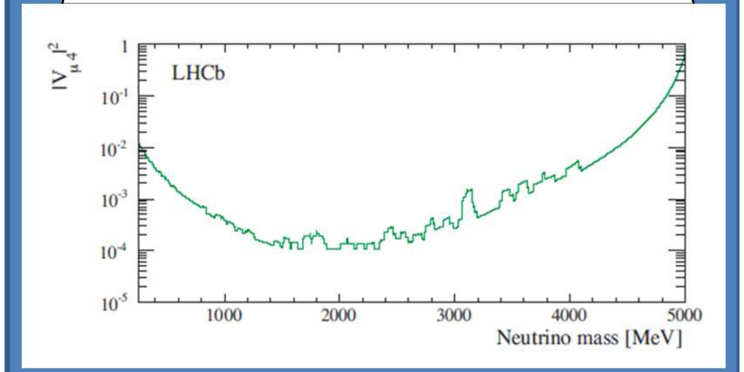
Efficiency for the search



Scope for 10-100x improvement at SuperKEKb

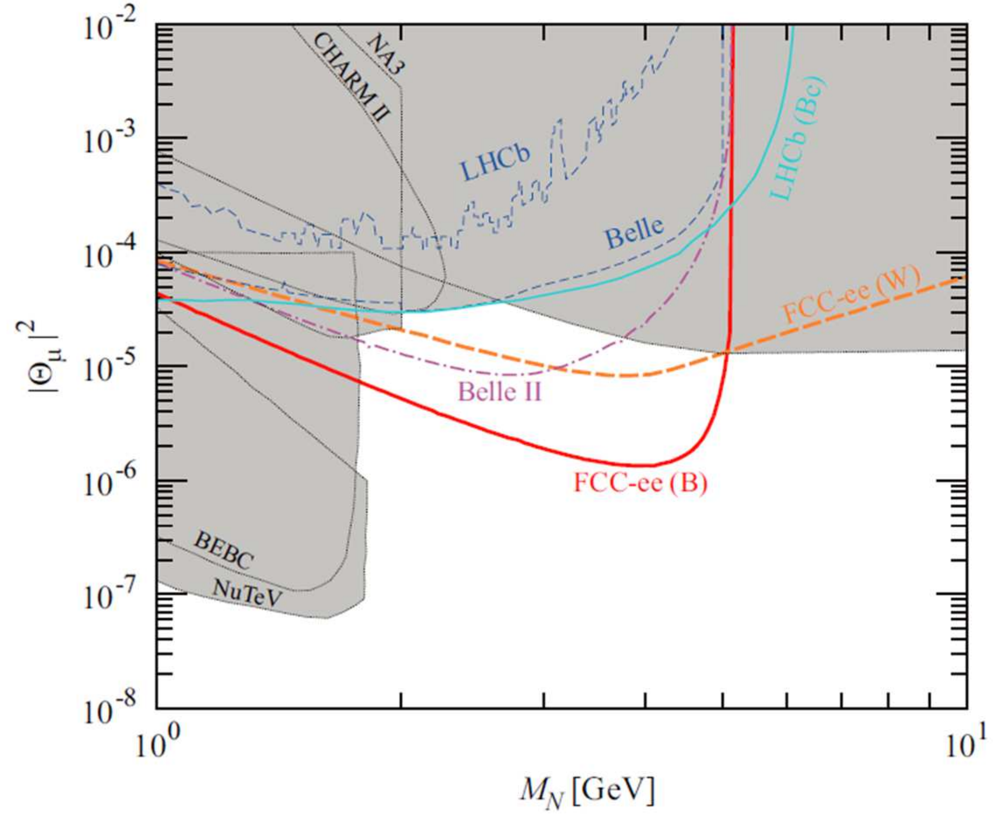
LHCb collaboration,
PRL 112, 131802 (2014)

$$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9} \text{ at } 95\%$$



Scope for much improvement
at 13TeV&HL-LHC!

SuperKEKb (soon) and FCC-ee (Z-> $\bar{b}b$)

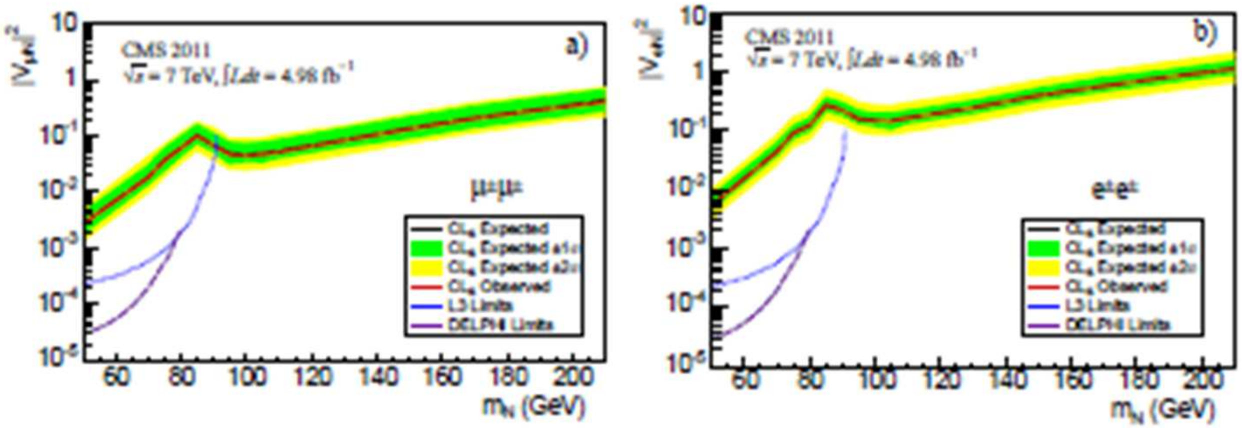


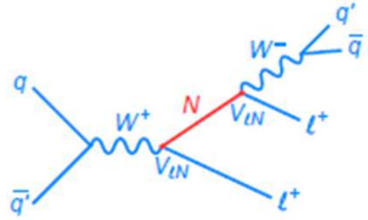
1609.06113v2

Figure 2: The sensitivity limits on $|\Theta_\mu|^2$ from the LNV decay $B^+ \to \mu^+\mu^+\pi^-$ due to heavy neutrino at Belle II with $N_B = 5 \times 10^{10}$ (magenta dot-dashed line) and at FCC-ee with $N_Z = 10^{13}$ (red solid line). The orange long-dashed line is the limit from $W^+ \to \mu^+\mu^+\pi^-$ at FCC-ee with $N_W = 2 \times 10^8$. For comparision we also show the limit from the LNV decays $B_c^+ \to \mu^+\mu^+\pi^+$ at LHCb for LHC run 3 [24] (cyan solid line). The blue dashed lines are the upper bounds from the LNV B decays by LHCb [30] and Belle [29]. The gray region is excluded by search experiments: DELPHI [32], NA3 [33], CHARM II [34], BEBC [35], and NuTeV [36].

NB it will be better since HNL decays mix both charges and flavour this should be investigated.

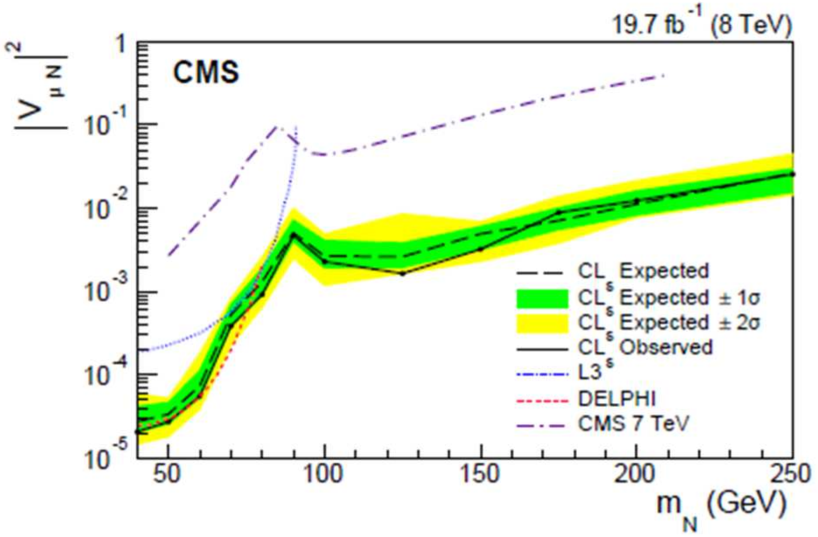
CMS search for same sign muon pairs or electron pairs at the LHC





CMS arXiv:1207.6079.

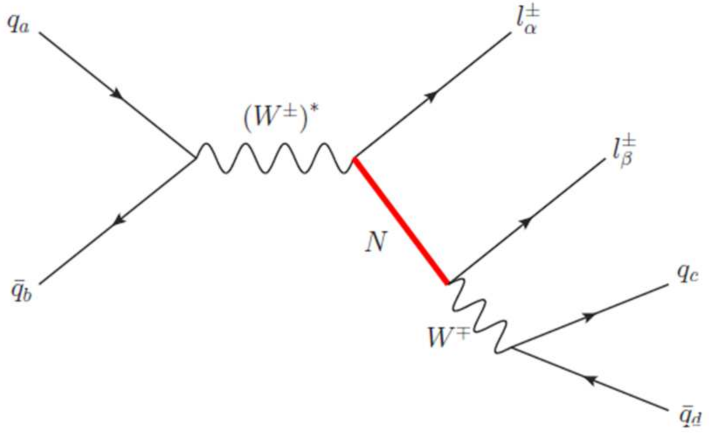
arXiv:1501.05566



Begin to match/superseed the DELPHI limit.

limits at $|U|^2 \sim 10^{-2-5}$ level

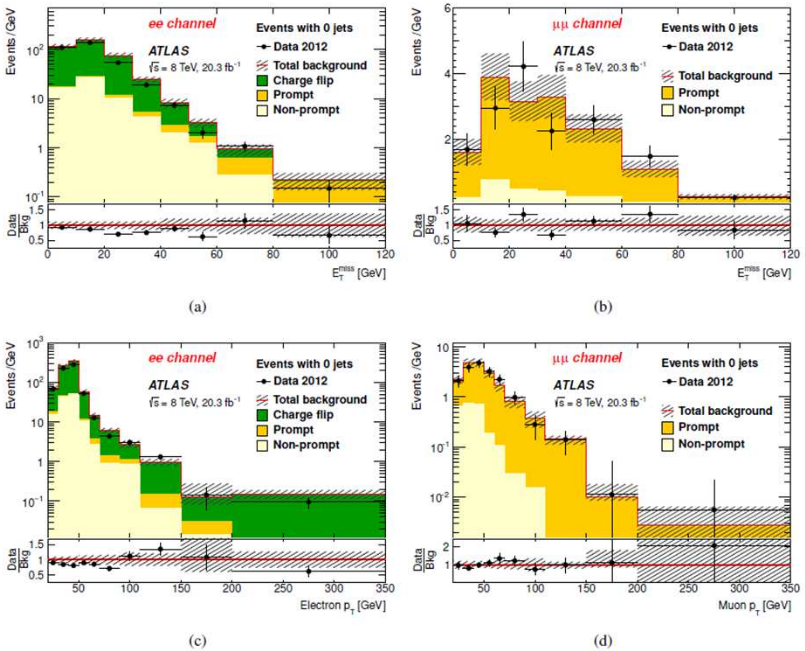
ATLAS search for Heavy Neutrinos at LHC *JHEP07(2015)162 arXiv:1506.06020*

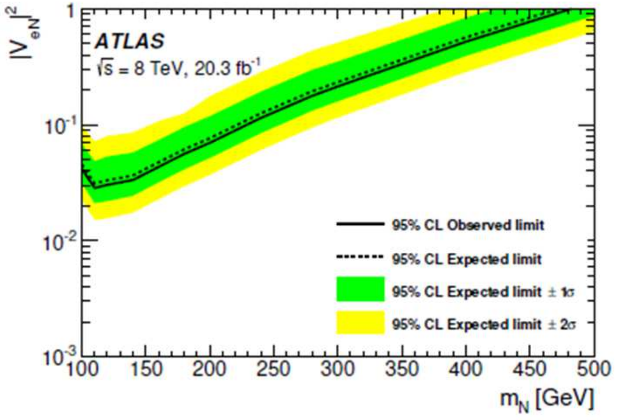


or lν

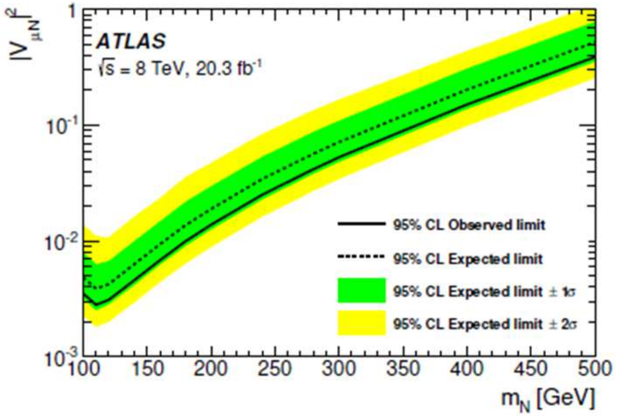
e^-e^-, e^+e^+, $\mu^-\mu^-$, $\mu^+\mu^+$ final states
(like sign, like flavour leptons)
Concentrates on m_N>100 GeV
'because <100 GeV excluded by LEP'

Charge flip significant bkgd for ee channel





(b)



LHC prospects

~10^9 vs from W decays in ATLAS and CMS with 25 fb^{-1} @8 TeV

Signals of RH neutrinos with mass $\leq m_W$ could be visible if mixing angle $O(10^{-7,8})$

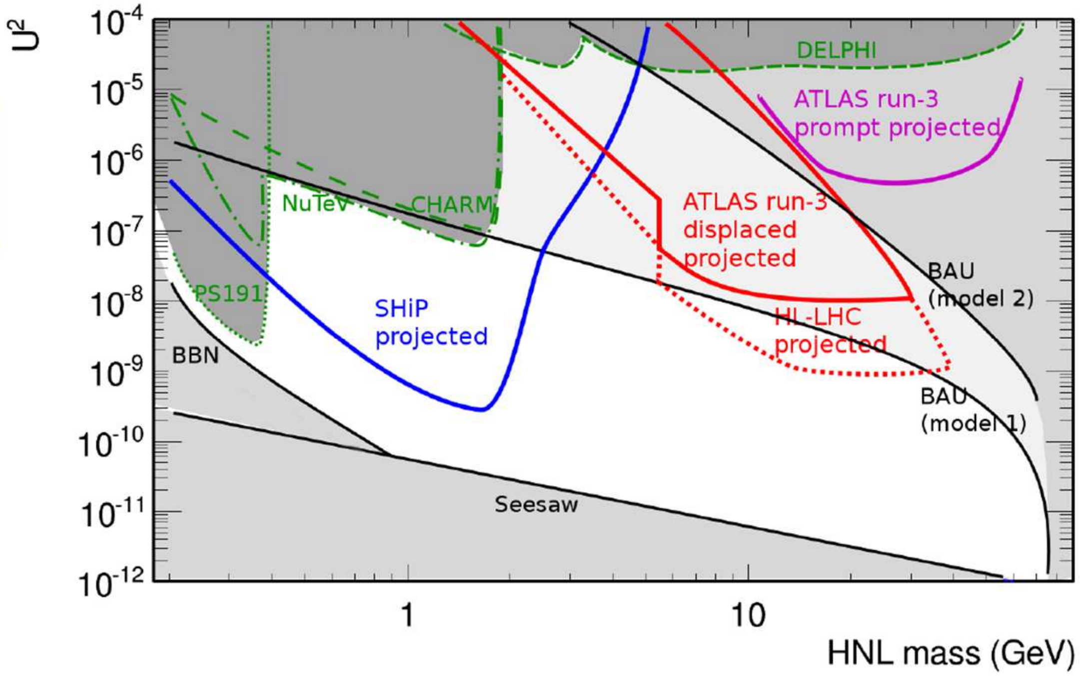
The keys for that region of phase space

-- require **displaced vertex**
-- allow leptons of different charge and flavour
-- constrain to W mass.

If lifetime is short
require triple lepton signature

Hope for considerable improvement
in W decays at LHC!

Ph. Mermod



RHASnu’s production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\overline{\nu}\right)|U|^2 \left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

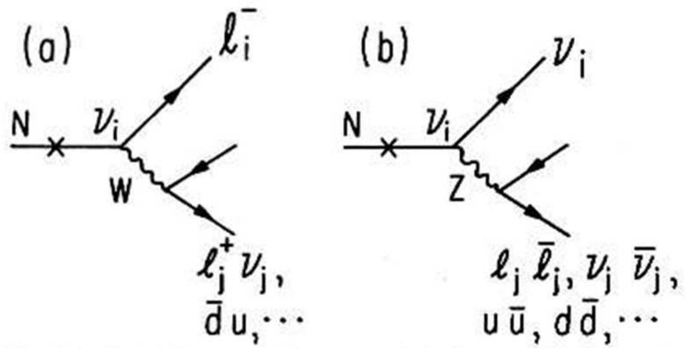


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

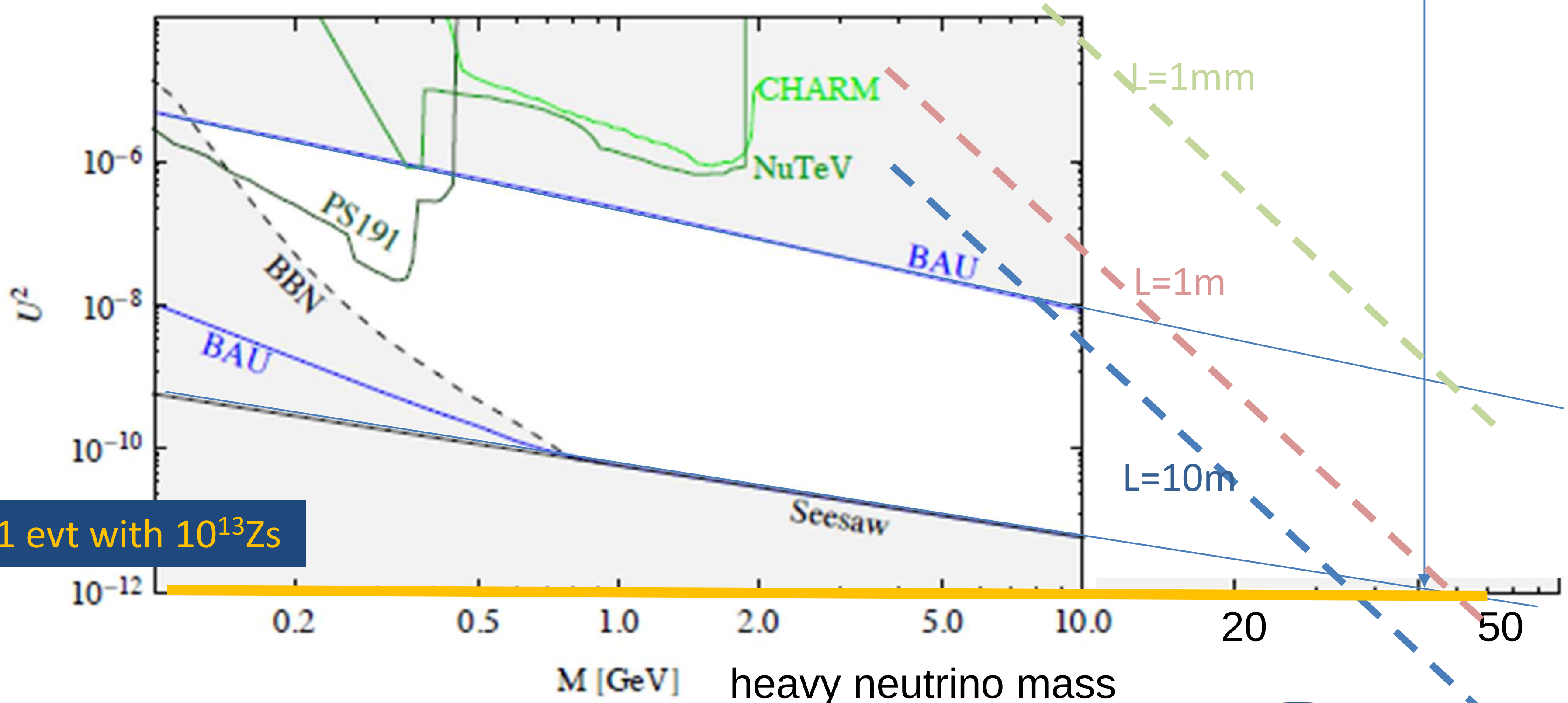
$$L \approx \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to ≥ 2 charged tracks

Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → Z*(νν) + (Z/γ)*

Decay length

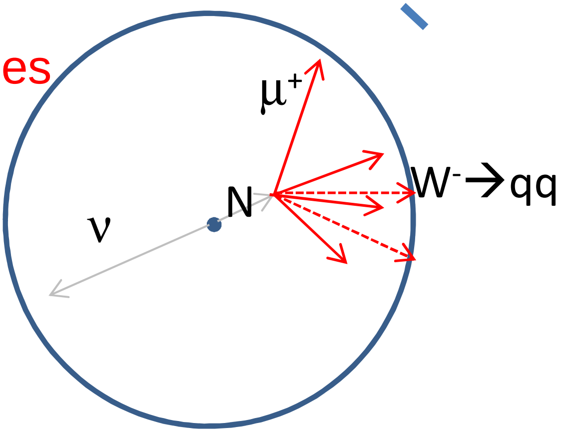
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



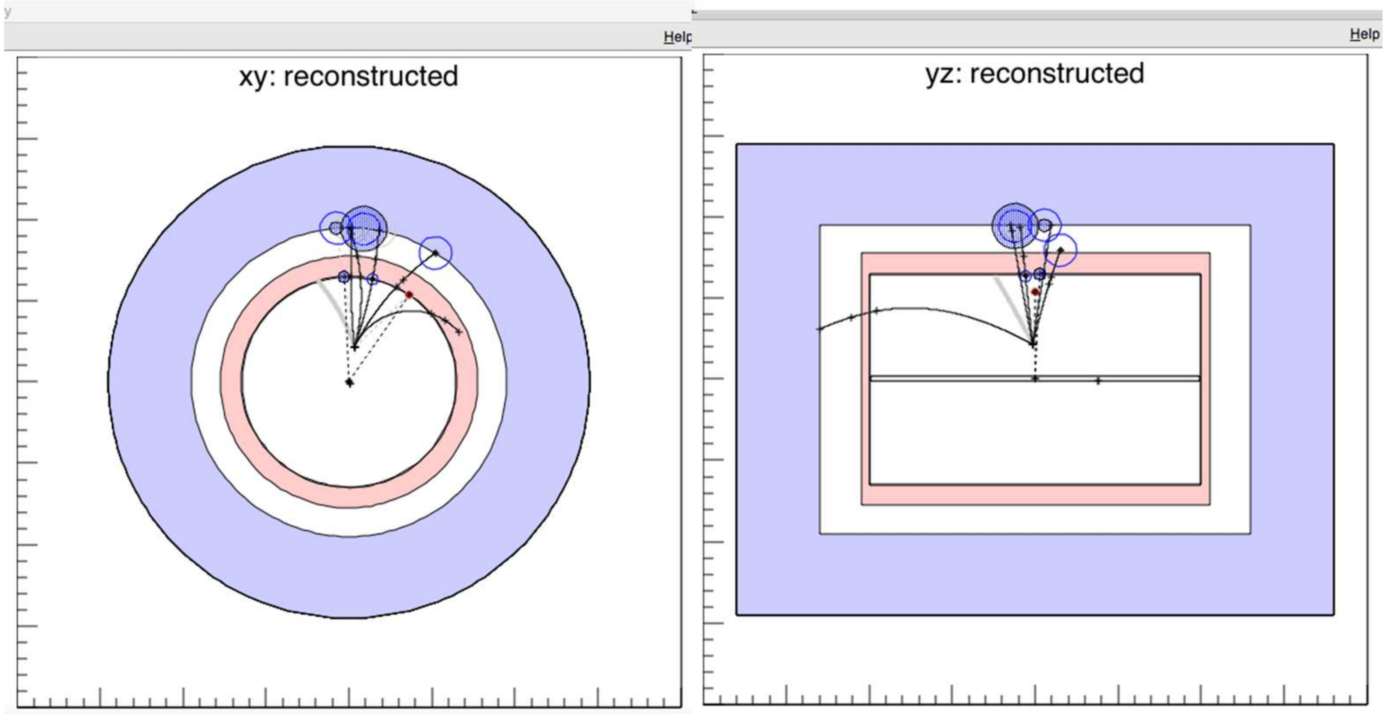
a large part of the interesting region will lead to detached vertices

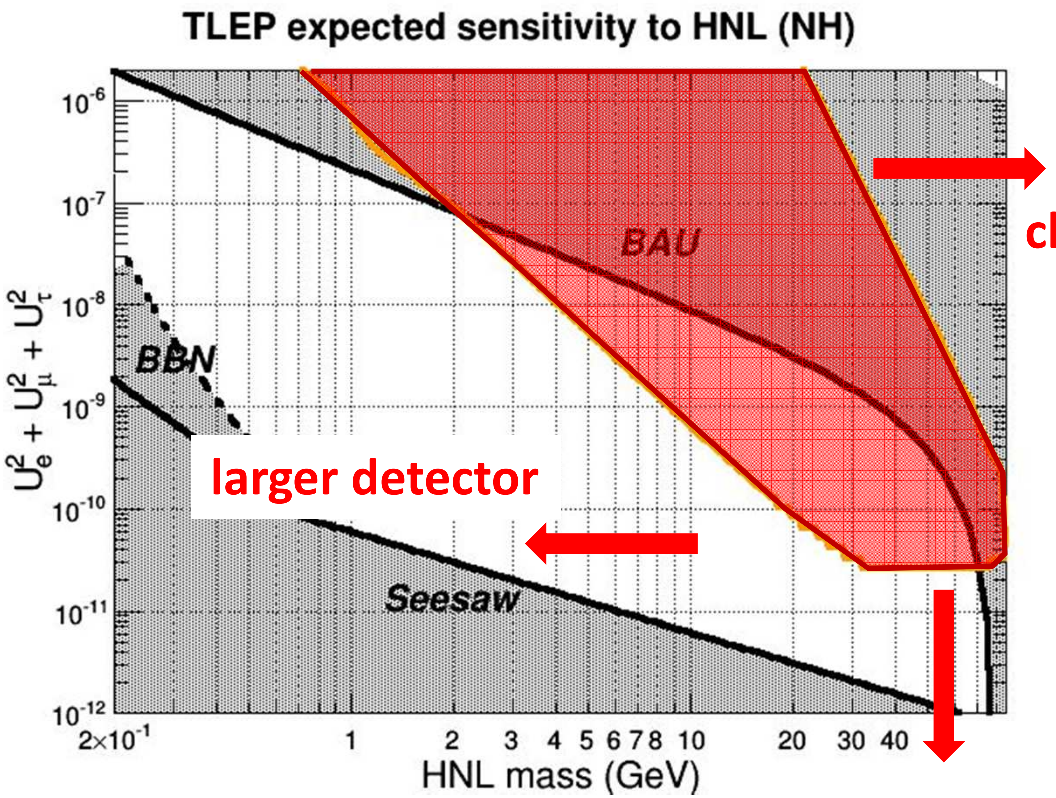
... ➔very strong reduction of background!

Exact reach domain will depend on detector size
and details of displaced vertex efficiency & background



Simulation of heavy neutrino decay in a FCC-ee detector





$N_Z = 10^{12}$ 1mm<L<1m

closer vertexing

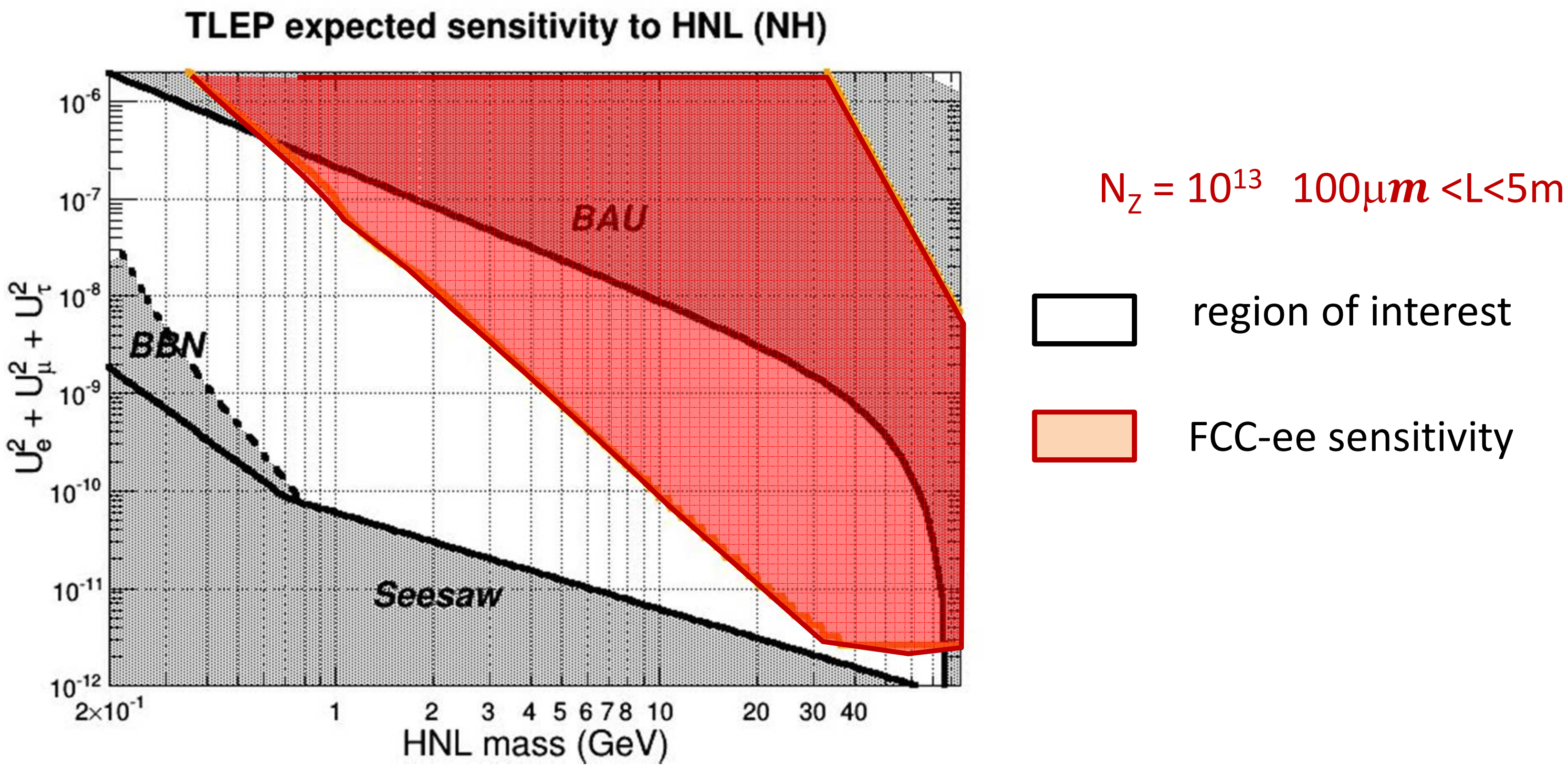
larger detector

more luminosity

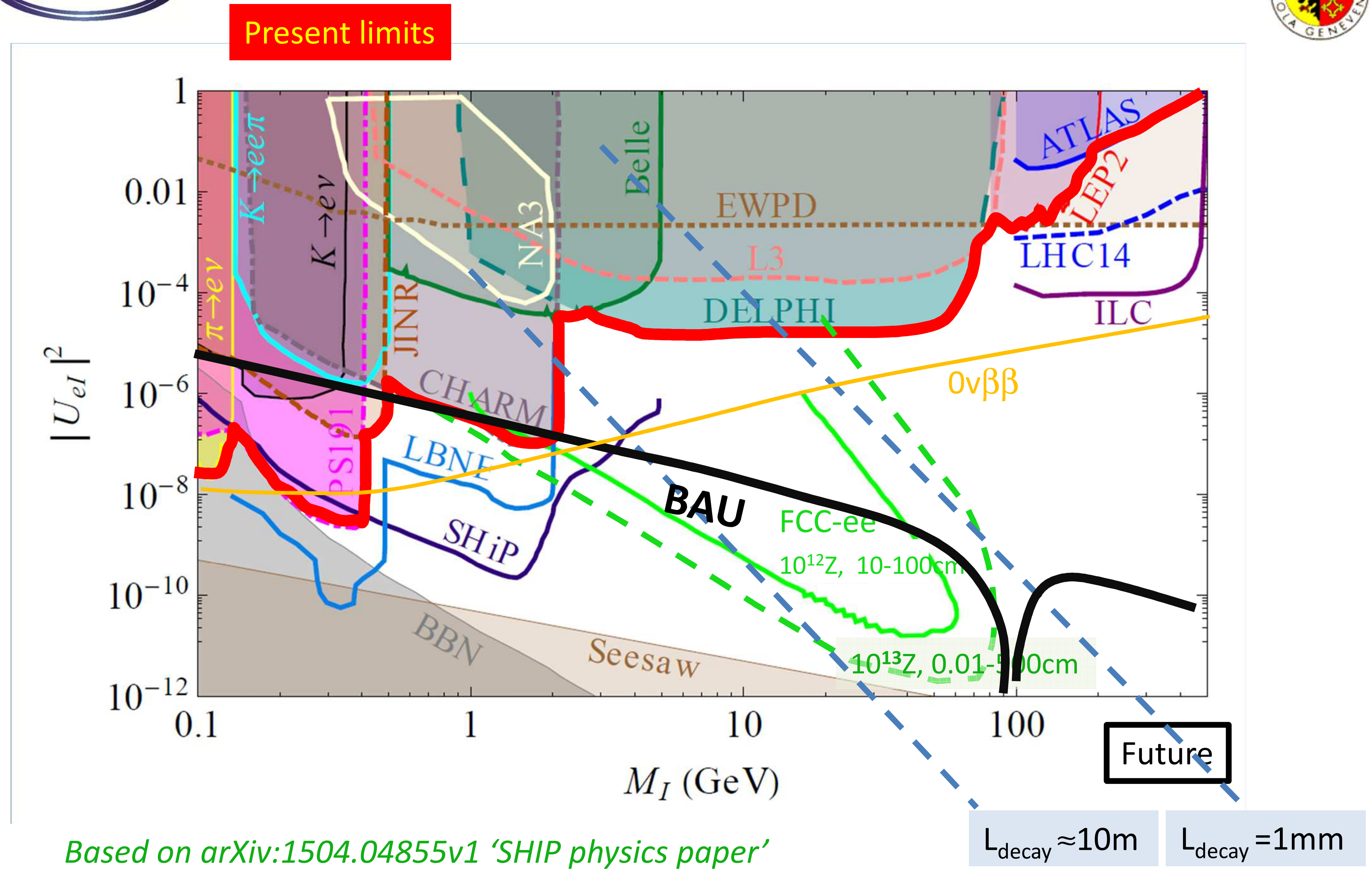
☐	region of interest
🟥	FCC-ee sensitivity

A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov **arXiv:1411.5230**

contrary to bb or pp, like sign lepton does not occur.



the **blind region** between 5 and ~20 GeV is reduced directly as function of the size of the detector.
8m radius? Under evaluation in the FCC-ee detector group



Based on arXiv:1504.04855v1 ‘SHIP physics paper’
And Pilar Hernandez, HEP-EPS Vienna

Testable Baryogenesis in Seesaw Models

P. Hernández,[a] **M. Kekic,**[a] **J. López-Pavón,**[b] **J. Racker,**[a] **J. Salvado.**[a]

[a] *Instituto de Física Corpuscular, Universidad de Valencia and CSIC, Edificio Institutos Investigación, Catedrático José Beltrán 2, 46980 Spain*

[b] *INFN, Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy*

ABSTRACT: We revisit the production of baryon asymmetries in the minimal type I seesaw model with heavy Majorana singlets in the GeV range. In particular we include for the first time "washout" effects from scattering processes with gauge bosons and higgs decays and inverse decays, besides the dominant top scatterings. We show that in the minimal model with two singlets, and for an inverted light neutrino ordering, future measurements from SHiP and neutrinoless double beta decay could in principle provide sufficient information to predict the matter-antimatter asymmetry in the universe up to a sign. We also show that SHiP measurements could provide very valuable information on the PMNS CP phases.

KEYWORDS: Beyond Standard Model, Cosmology of Theories beyond the SM, Neutrino physics, CP violation

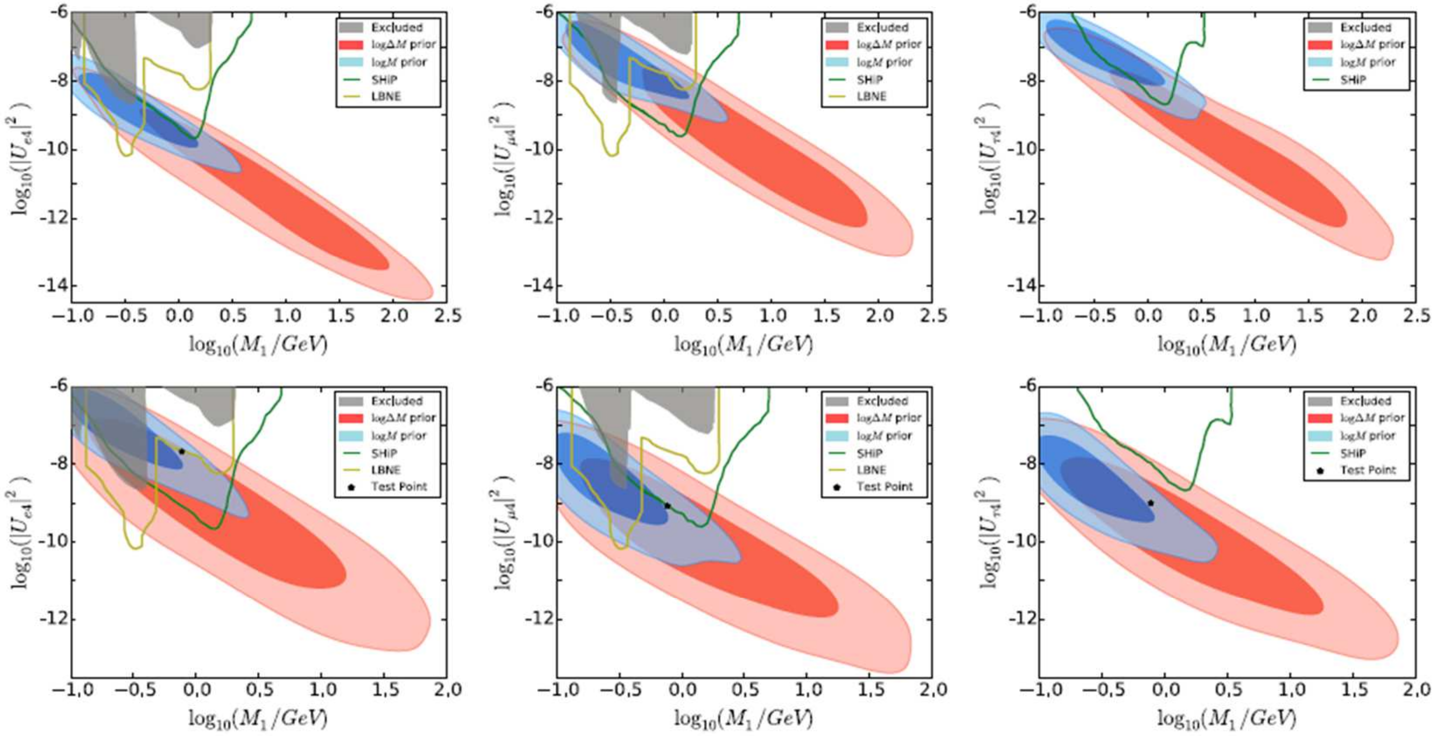
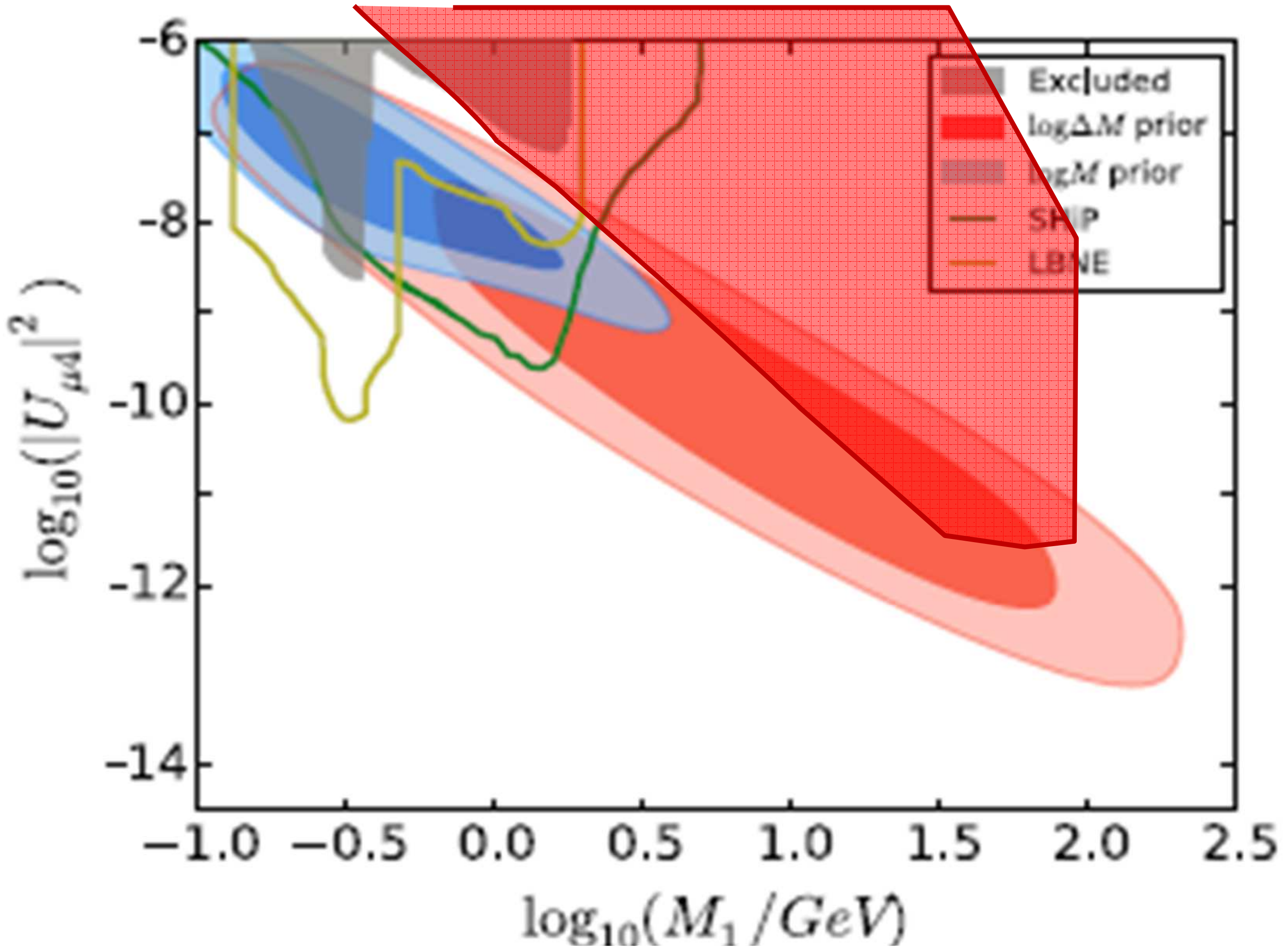


Figure 6. Comparison of the posterior probability contours at 68% and 90% on the planes mixings with e, μ, τ versus masses, with the present (shaded region) and future constraints from LBNE and SHiP for NH (up) y IH (down).

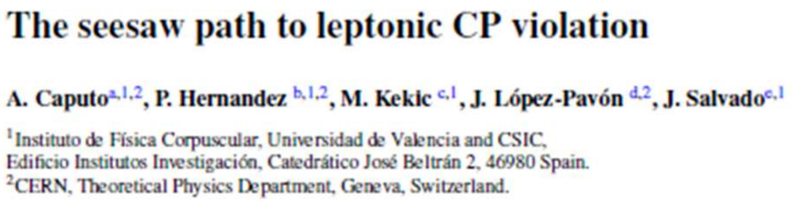
☐ region of interest

🟧 FCC-ee sensitivity

$N_Z = 10^{13}$ $100\mu m < L < 5m$



CP violation!

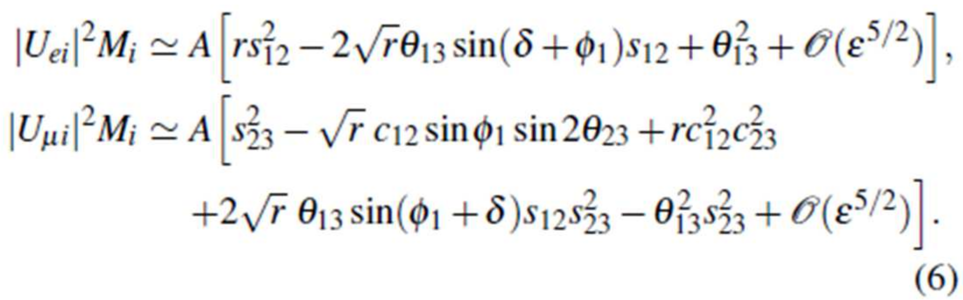


The seesaw path to leptonic CP violation

A. Caputo[a,1,2], **P. Hernandez** [b,1,2], **M. Kekic** [c,1], **J. López-Pavón** [d,2], **J. Salvado**[e,1]

[1]Instituto de Física Corpuscular, Universidad de Valencia and CSIC,
Edificio Institutos Investigación, Catedrático José Beltrán 2, 46980 Spain.
[2]CERN, Theoretical Physics Department, Geneva, Switzerland.

arXiv:1611.05000v1 (SHIP, B factory, Z factory)



$$|U_{ei}|^2 M_i \simeq A\left[r s_{12}^2 - 2\sqrt{r}\theta_{13}\sin(\delta+\phi_1)s_{12} + \theta_{13}^2 + \mathcal{O}(\varepsilon^{5/2})\right],$$

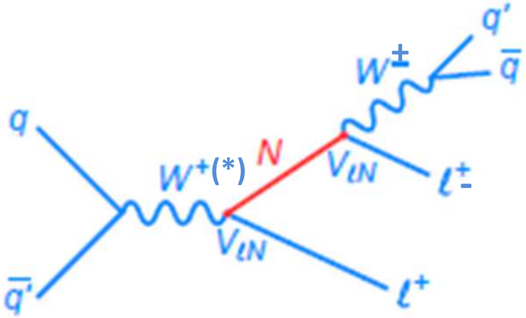
$$\begin{aligned}|U_{\mu i}|^2 M_i \simeq A\Big[& s_{23}^2 - \sqrt{r}\, c_{12}\sin\phi_1 \sin 2\theta_{23} + r c_{12}^2 c_{23}^2 \\ & + 2\sqrt{r}\,\theta_{13}\sin(\phi_1+\delta)s_{12}s_{23}^2 - \theta_{13}^2 s_{23}^2 + \mathcal{O}(\varepsilon^{5/2})\Big].\end{aligned} \tag{6}$$

The ratio of decays in muons to electrons is directlly related to the ratio of phases (and the known PMNS angles)

➔ *the discovery of a massive neutrino and the measurement of its mass and its mixings to electrons and muons can result in a 5σ CL discovery of leptonic CP violation in very significant fraction*
of the CP-phase parameter space (> 80%/>60%) for IH/NH
for mixings above O(10^{-8}) in SHiP and above O(10^{-10}) in FCC-ee.

Outlook for FCC-hh

or $l^{\pm}\nu$



or $l^{\pm}\nu$

We have seen that the Z factory offers a clean method
for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders

At the 100 TeV pp W is the dominant particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

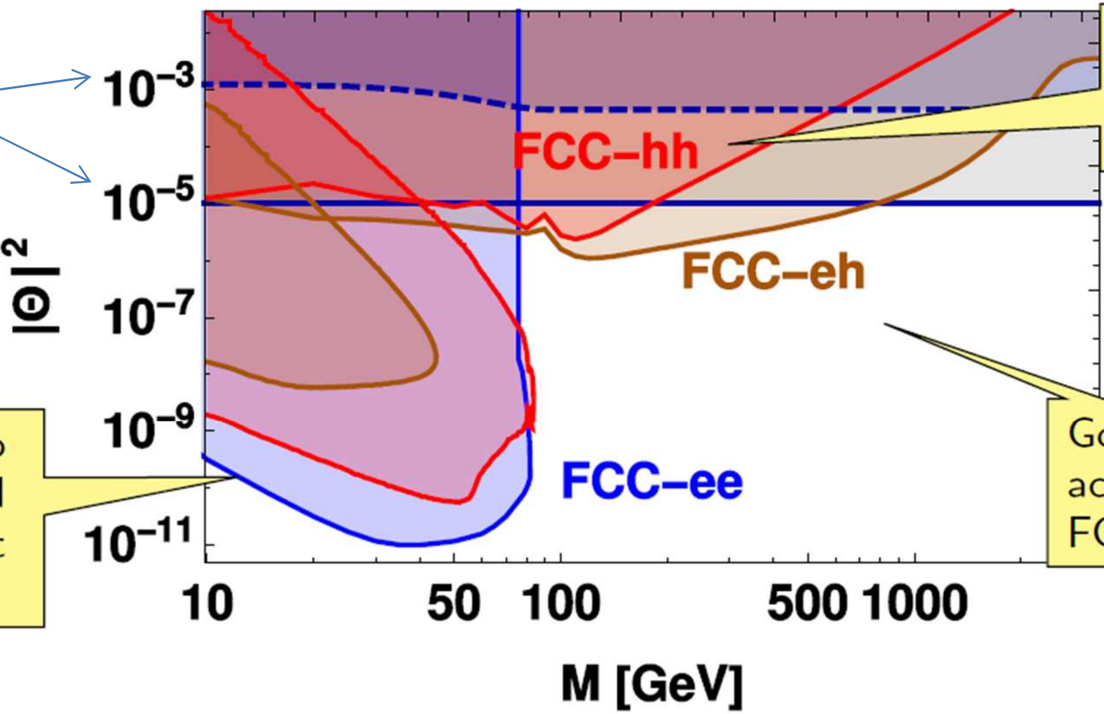
VERY interesting... **to be further investigated.**
Requirements: displaced vertex trigger or triple lepton signature

Summary

Another example of Synergy
while ee covers a large part of space very cleanly ,
its either ‘white’ in lepton flavour or the result of EWPOs etc
Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO



FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

Conclusion

The quest for the right-handed neutrinos is very well motivated
…. we have already seen the tail of the dinosaur!

The three FCCs can have their say:

-- precision EW observables, and number of neutrinos at FCC-ee give limits up to very high masses
but limited to reletively high couplings

-- direct searches for RH neutrinos :
mass below Z mass down to very low couplings (relevant to BAU) at FCC-ee in clean environment
similarly in FCC-hh iff detached vertices can be triggered on or in triple lepton final state
in FCC-eh access to ν_e-mixed RH neutrino allows direct reach to higher masses (larger mixing)

→ different regions of phase space, different capabilities.

CONCLUSIONS

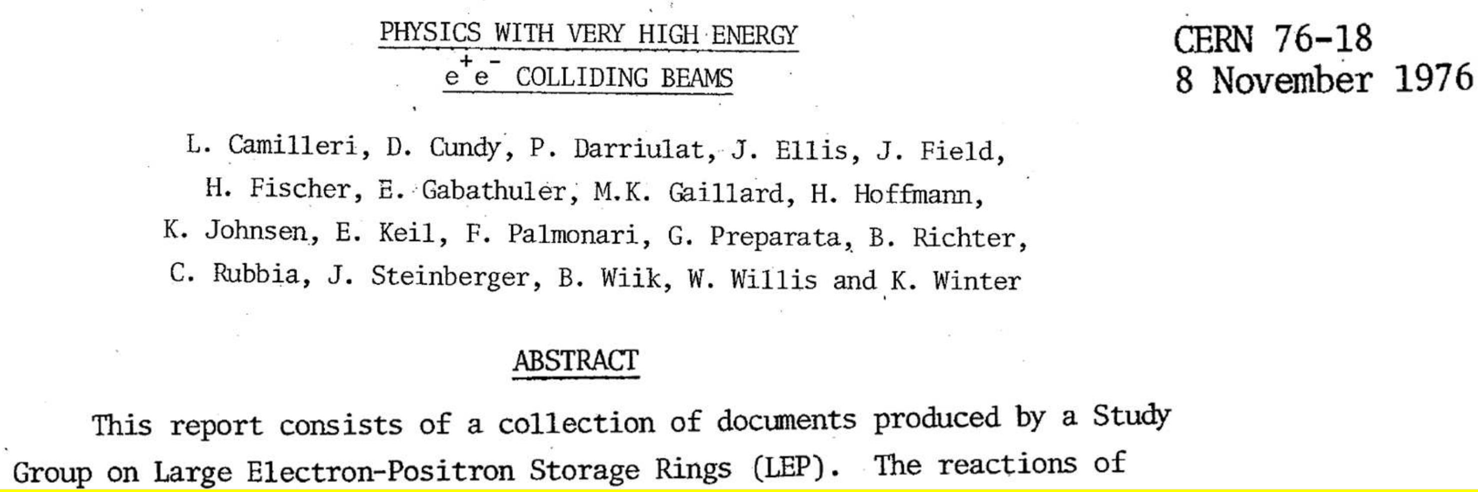
-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

-- Both FCC-ee and FCC-hh have outstanding physics cases
  -- each in their own right
  -- the sequential implementation of FCC-ee, FCC-hh, FCC-eh would maximise the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

-- the FCC are shaping up as the most natural, complete and powerful aspiration of HEP for its long-term future

A successful model!



CERN 76-18
8 November 1976

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

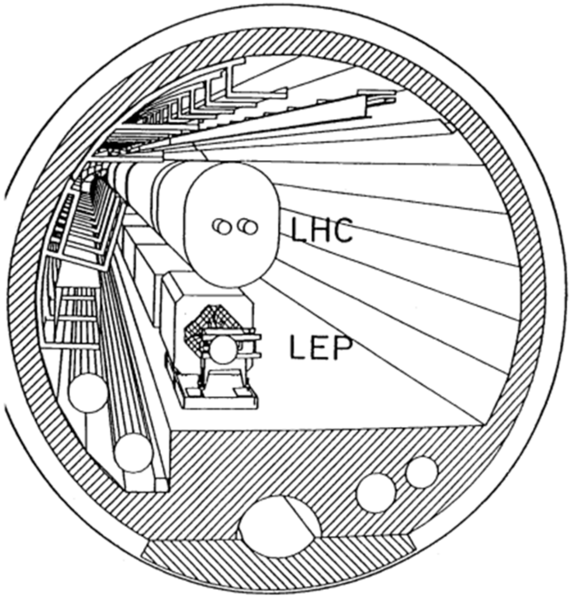
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

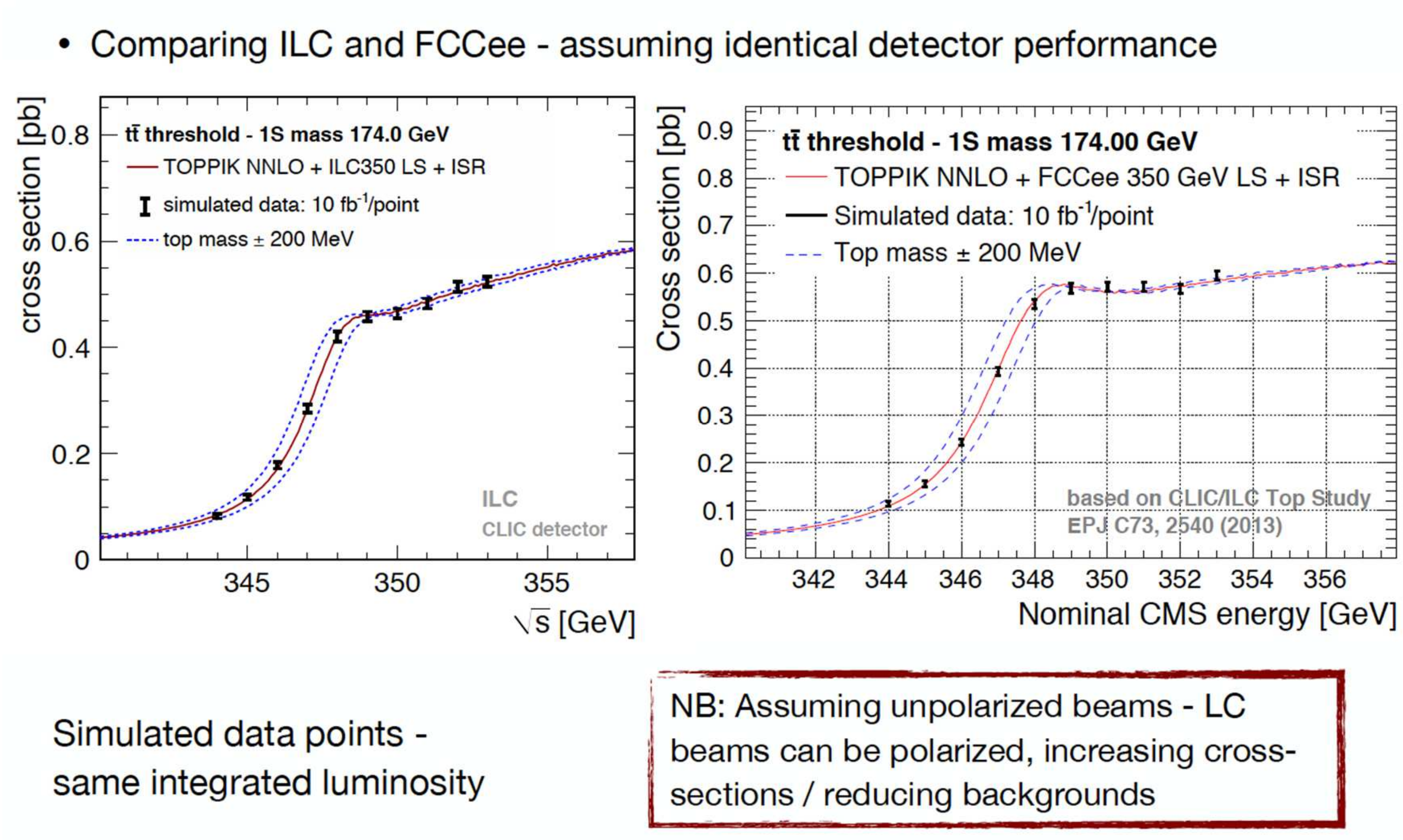
Vol. I

p p 2009-2039

Let's not be SHY!

350 GeV: the top mass

- **Advantage of a very low level of beamstrahlung in circular machines**
- **Could potentially reach 10 MeV uncertainty (stat) on m_{top}**
- **The main issue is relation ship between tt threshold and the loop corrections**



- Comparing ILC and FCCee - assuming identical detector performance

Simulated data points - same integrated luminosity

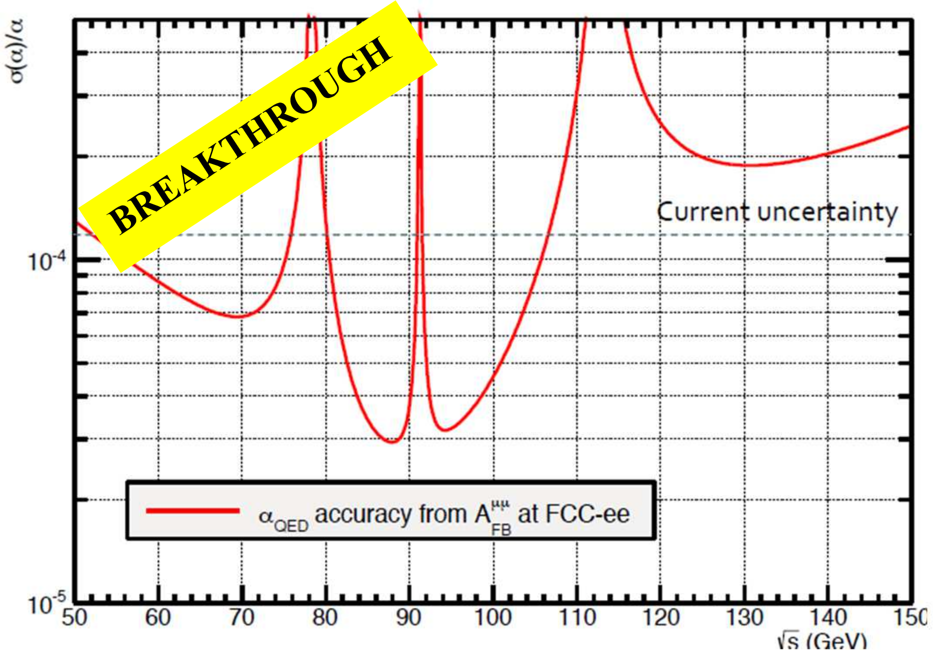
NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

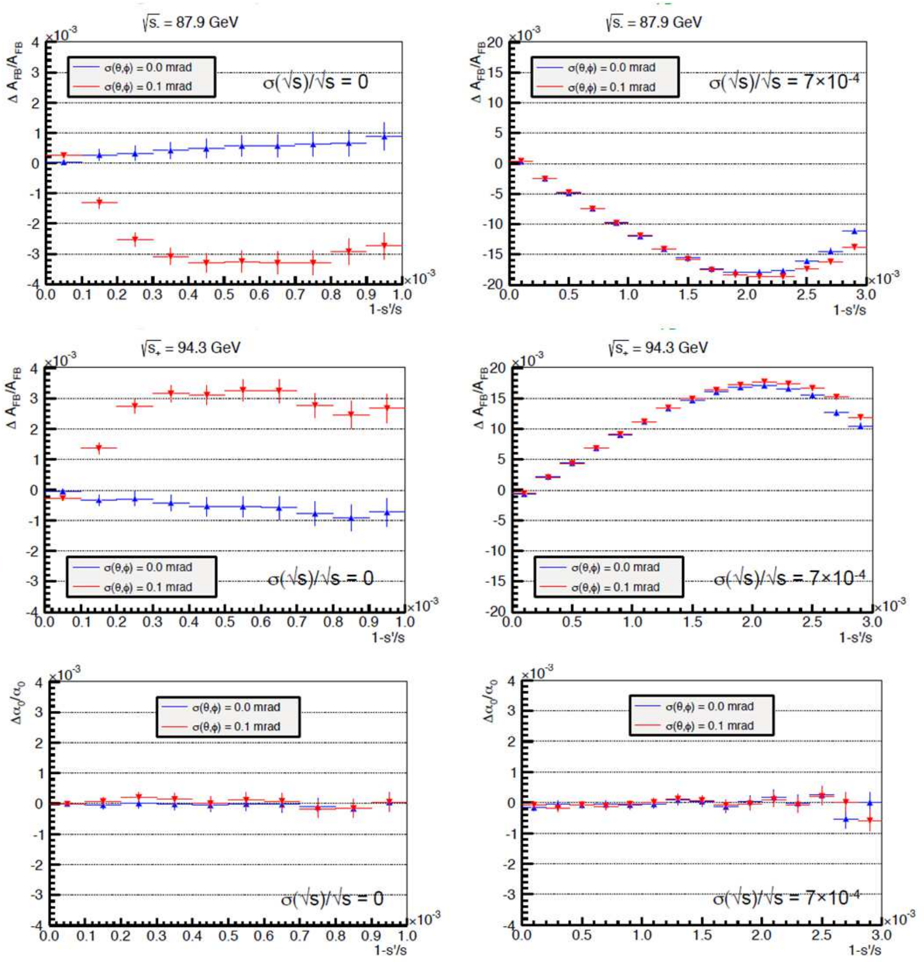
From Frank Simon, presented at 7th TLEP-FCC-ee workshop, CERN, June 2014

Unwanted error

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,M_Z^2}\;\frac{1}{1+\Delta\rho}\;\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

Physics discoveries





P. Janot discovered that one can measure $\Delta\alpha_{QED}(m_z)$ from measuring $A_{FB}^{\mu\mu}$ at +- 3 GeV from the Z peak. (Nice Z lineshape scan)

Further studies with S. Jadach shows error cancellation of +3 vs -3 points.

- Total bias on $\alpha_{QED}(m_Z^2)$ of the order of 8×10^{-6}

Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise $\alpha_s(m_Z)$ measurement was derived from the Z decay ratio $R_l = \Gamma_{had}/\Gamma_l$. Reinterpreting this measurement in light of: i) new N_3LO calculations; ii) improved m_{top}; and iii) knowledge of the m_{Higgs}, the uncertainty is now something like:

$$\boxed{\delta\,(\alpha_s(m_Z))_{LEP} = \pm\, 0.0038\ (\text{exp.}) \pm 0.0002\ (\text{others})}$$

R_l measurement was statistics dominated: Foresee a factor ≥25 improvement at FCC-ee. From the Z-pole, therefore a resonable experimental target is

$$\boxed{\delta\,(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm\, 0.00015}$$

Similarly, from the WW threshold, $\alpha_s(m_W)$ can be derived from the high stats measurement of $B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$

$$\boxed{\delta\,(\alpha_s(m_W))_{FCC\text{-}ee} = \pm\, 0.00015}$$

Combining the two above, a realistic target precision would be

$$\boxed{\delta\,(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm\, 0.0001}$$

Present W.A.

$\alpha_s(M_Z) = 0.1181 \pm 0.0013$

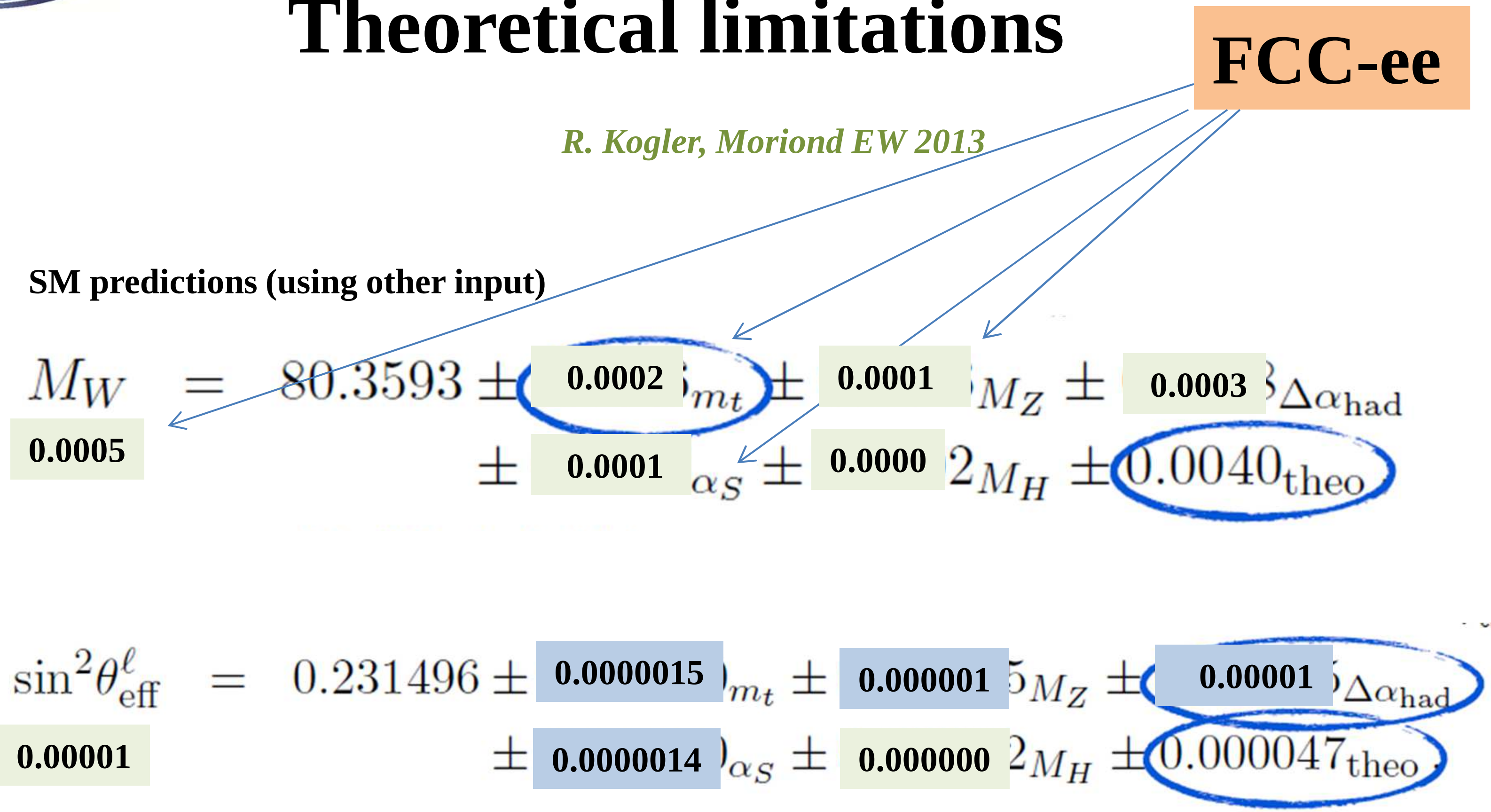
D. Enterria

Workshop on α_S sept 2015

D. d'Enterria, P.Z. Skands (eds.)

arXiv:1512.05194

Theoretical limitations



R. Kogler, Moriond EW 2013

SM predictions (using other input)

$M_W = 80.3593 \pm$ **0.0002** $_{m_t} \pm$ **0.0001** $_{M_Z} \pm$ **0.0003** $_{\Delta\alpha_{\mathrm{had}}}$

$\pm$ **0.0001** $_{\alpha_S} \pm$ **0.0000** $2_{M_H} \pm 0.0040_{\mathrm{theo}}$

0.0005

$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.231496 \pm$ **0.0000015** $_{m_t} \pm$ **0.000001** $_{M_Z} \pm$ **0.00001** $_{\Delta\alpha_{\mathrm{had}}}$

$\pm$ **0.0000014** $_{\alpha_S} \pm$ **0.000000** $2_{M_H} \pm 0.000047_{\mathrm{theo}}$

0.00001

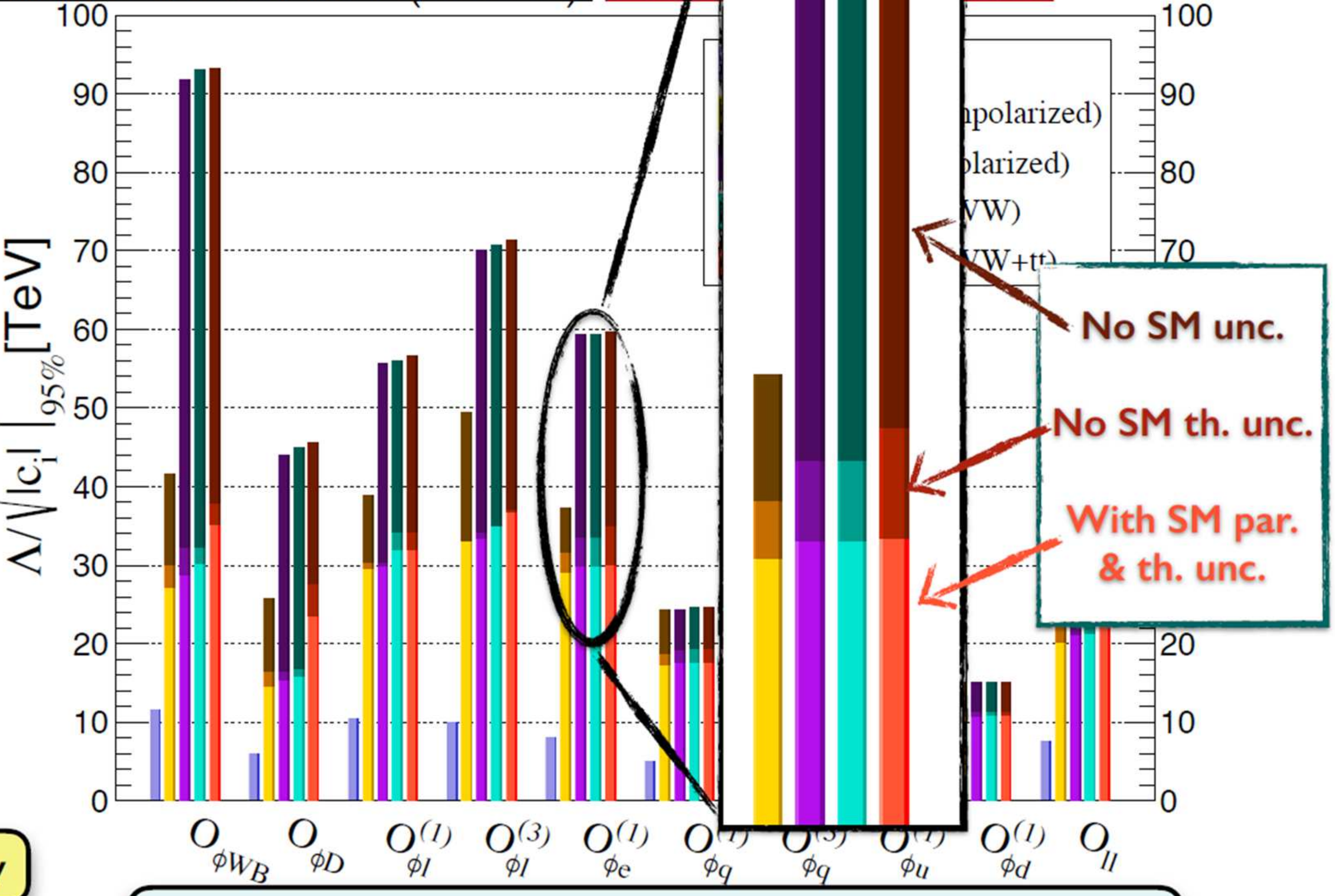
Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
Suggest including manpower for theoretical calculations in the project cost.

EWPO AT FUTURE COLLIDERS: SENSITIVITY TO NP

- Dimension six SMEFT (EWPD): **Pres ture**

1 operator at a time. Flavor universal.



No SM unc.

No SM th. unc.

With SM par. & th. unc.

Preliminary

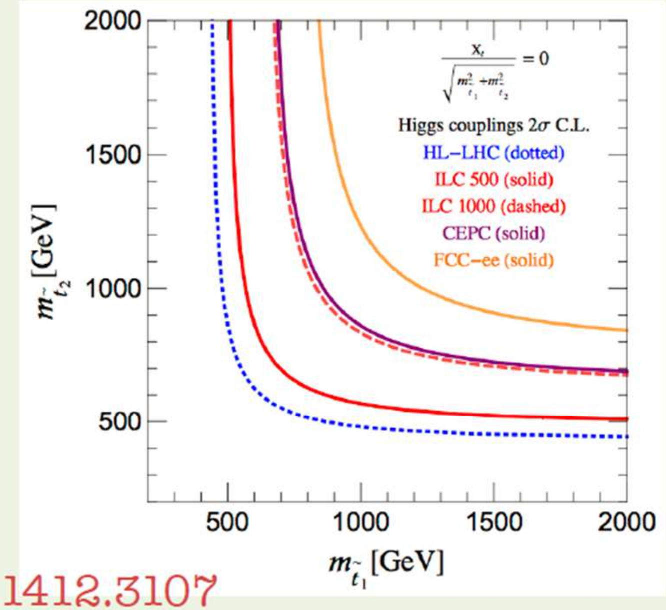
LARGE impact of SM uncertainties

Comprehensive Complementarity

In supersymmetry this is the "stop squark".

FCC-ee

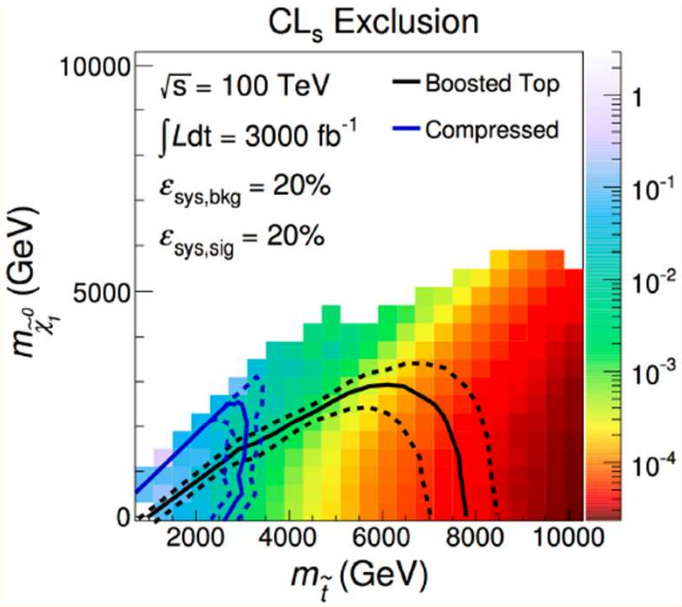
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:



FCC-ee: Indirect, but more "spectrum independent", for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

McCullough

Systematic Complementarity

Thus returning to the third notion of complementarity: “Different FCC Colliders enhance the exploratory power of one another, when a measurement at one reduces a systematic uncertainty in another.”

One can see that the estimated FCC-ee determination, from runs at the Z-pole and at higher energies, of

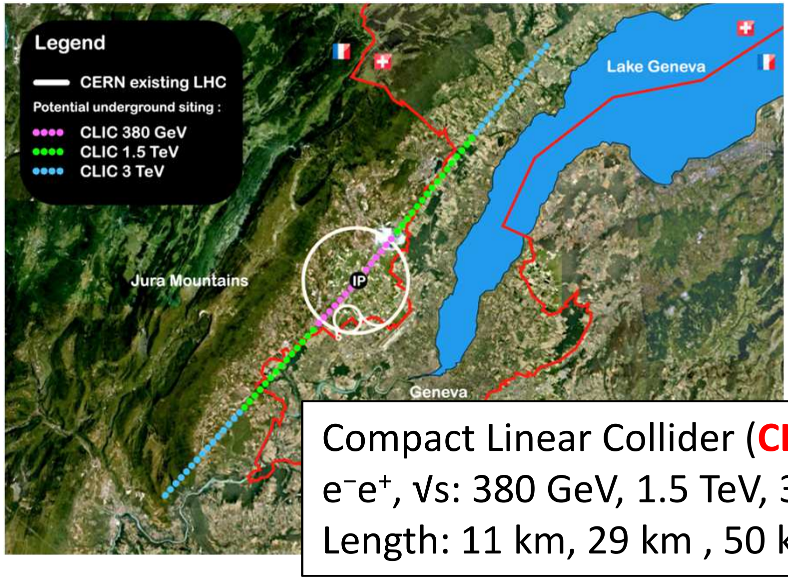
$$\Delta\alpha_S(M_Z^2) \sim \pm 0.0001(0.08\%)$$

Would reduce systematic uncertainties in BSM searches at FCC-hh, both direct (e.g. extra dimensions) and indirect (e.g. Higgs couplings).

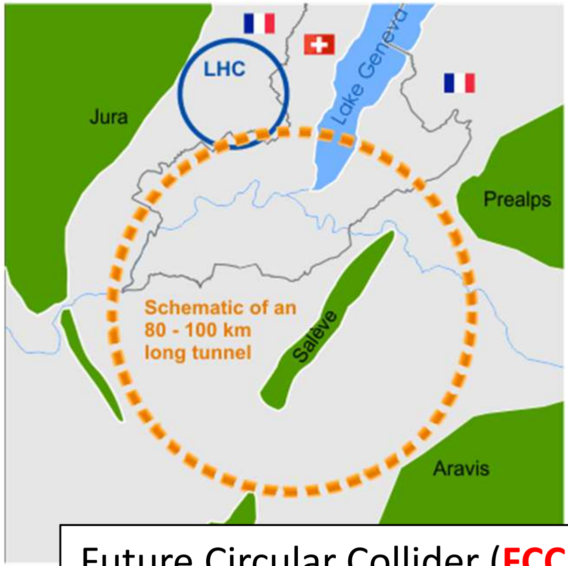
-- need to understand how measurement of R_b would reduce model dependence of extraction of α_s from R_{had} -- also meast from Ws.

-- FCC-ep can also contribute at level of $3\ 10^{-4}$

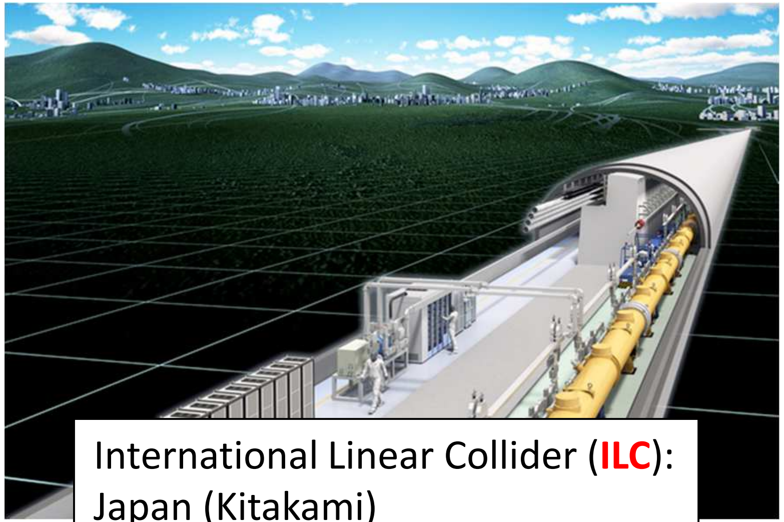
studies of high-energy e^+e^- colliders



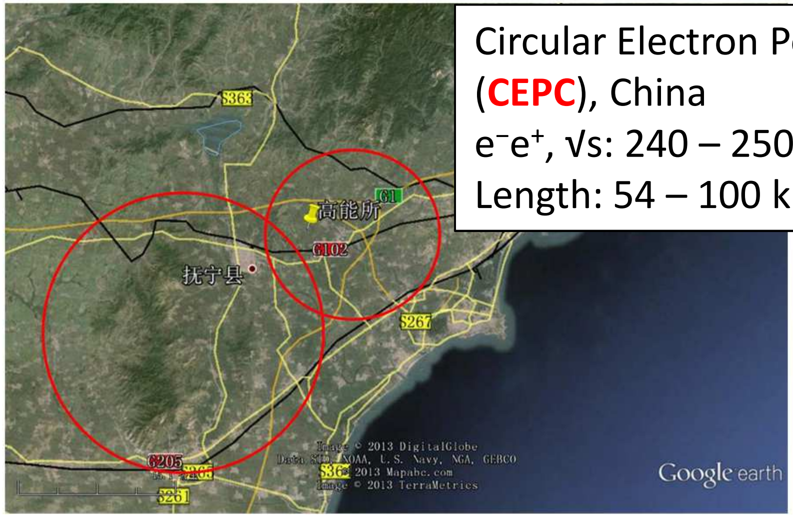
Compact Linear Collider (**CLIC**): CERN
e^-e^+, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC**): CERN
e^-e^+, $\sqrt{s}$: 90 - 350 GeV; pp, $\sqrt{s}$: ~100 TeV
Circumference: 90 - 100 km

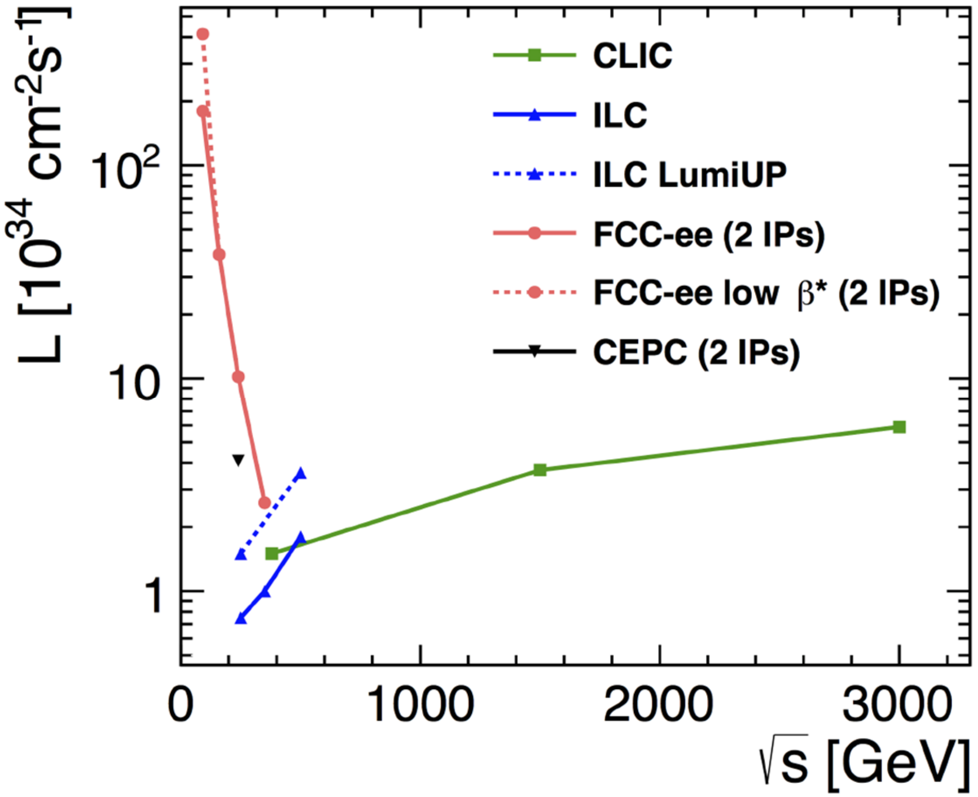


International Linear Collider (**ILC**):
Japan (Kitakami)
e^-e^+, $\sqrt{s}$: 500 GeV (1 TeV)
Length: 31 km (50 km)



Circular Electron Positron Collider (**CEPC**), China
e^-e^+, $\sqrt{s}$: 240 – 250 GeV; SPPC pp,
Length: 54 – 100 km

luminosity performance e^+e^- colliders



Linear colliders:

- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

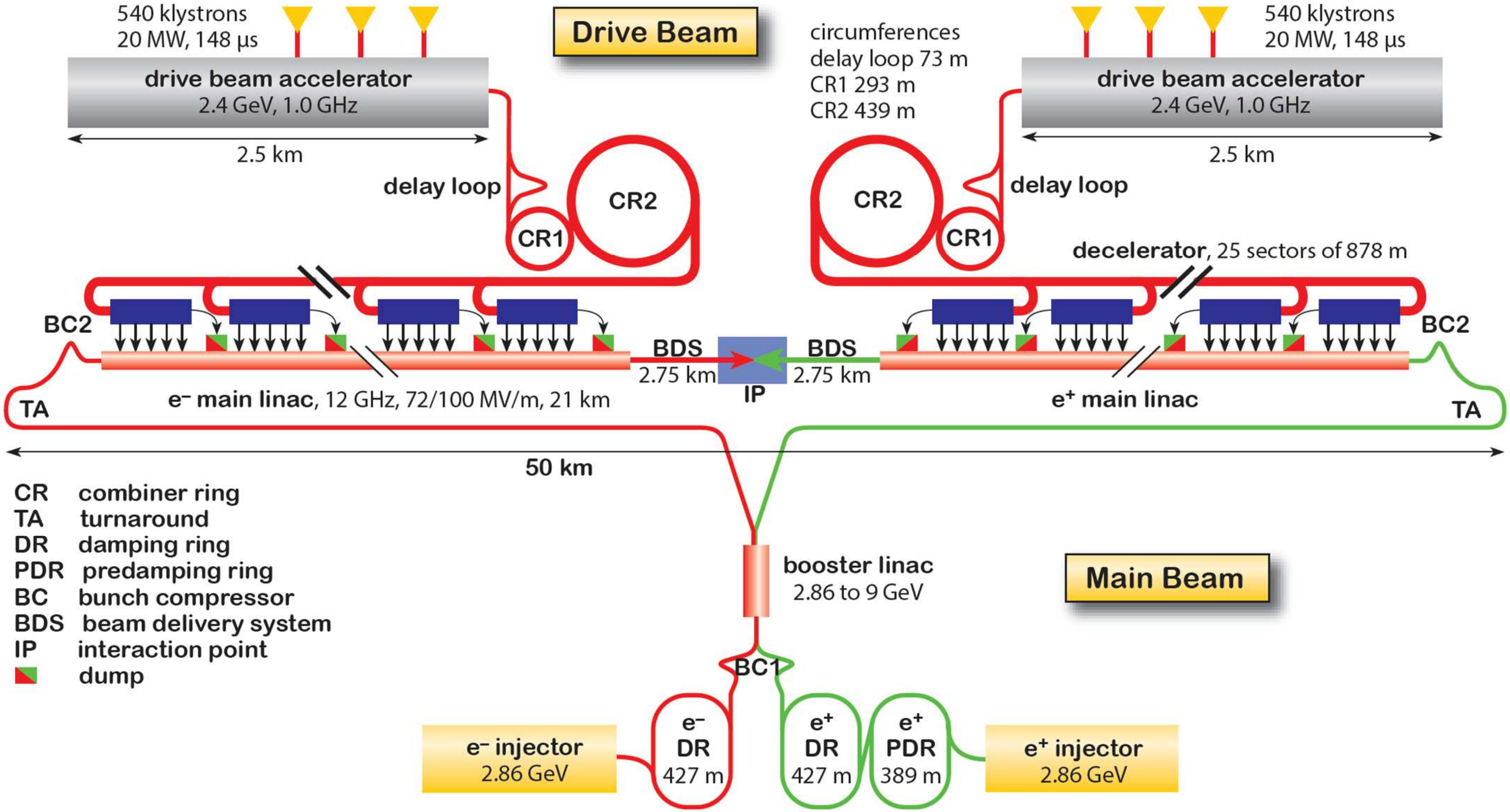
Circular colliders:

- Large luminosity at lower energies
- Luminosity decreases with energy
- Exquisite Beam energy calibration

CLIC and the circular machines are very complementary.

Note: Peak luminosity at LEP2 (209 GeV) was ~10^{32} cm^{-2}s^{-1}

CLIC layout at 3 TeV



540 klystrons
20 MW, 148 μs

Drive Beam

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

540 klystrons
20 MW, 148 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

CR2

CR1

delay loop

CR2

CR1

decelerator, 25 sectors of 878 m

BC2

BDS
2.75 km

IP

BDS
2.75 km

BC2

TA

e⁻ main linac, 12 GHz, 72/100 MV/m, 21 km

e⁺ main linac

TA

50 km

booster linac
2.86 to 9 GeV

Main Beam

BC1

e⁻ injector
2.86 GeV

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector
2.86 GeV

CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
◩	**dump**

CLIC 2-beam acceleration scheme

High centre-of-mass energy requires high-gradient acceleration

- High gradients feasible in normal conducting structures with high RF frequency (12 GHz)
- Initial transfer from wall plug to beam (klystron) is efficient at lower frequency (~1 GHz)
- To keep power low, apply RF power only at the time when the beam is there.

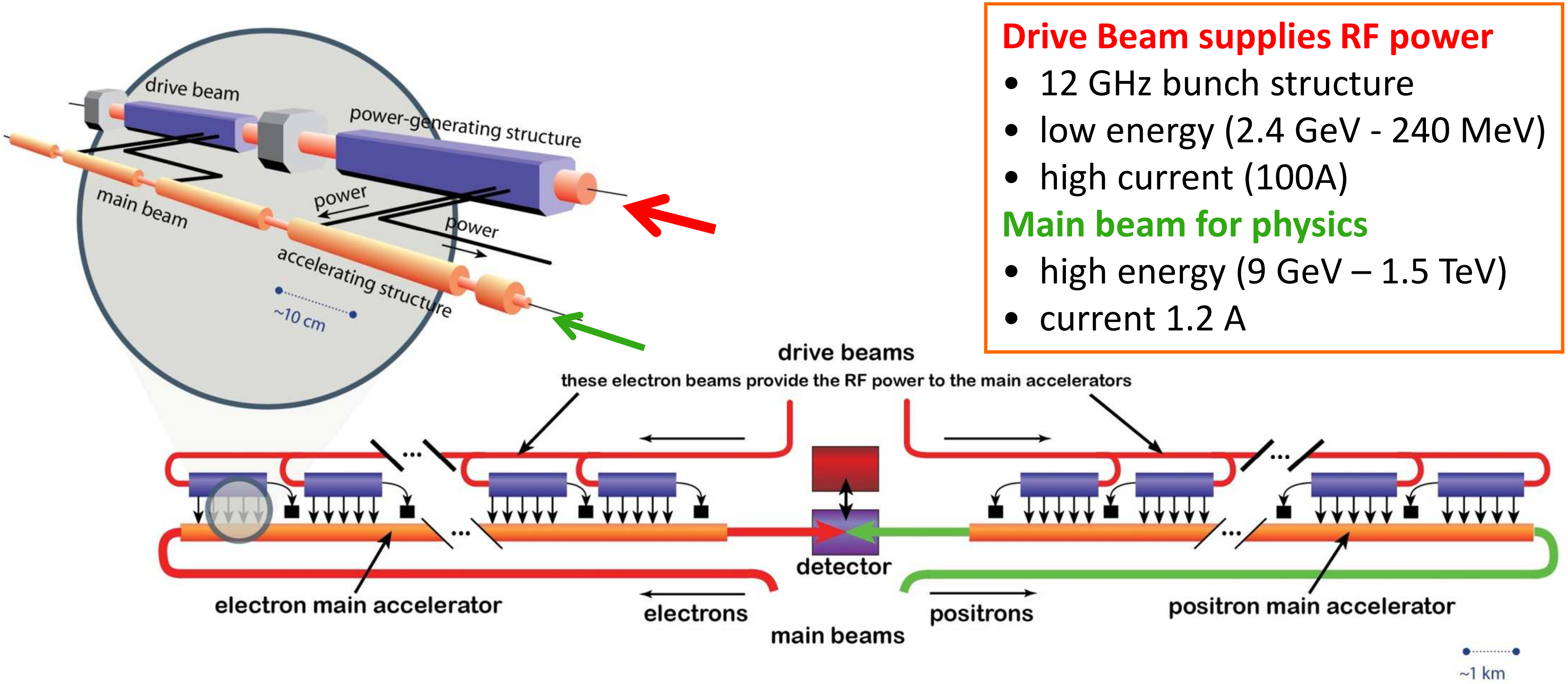
➡ **CLIC uses a 2-beam acceleration scheme at 12 GHz, gradient of 100 MV/m**

Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

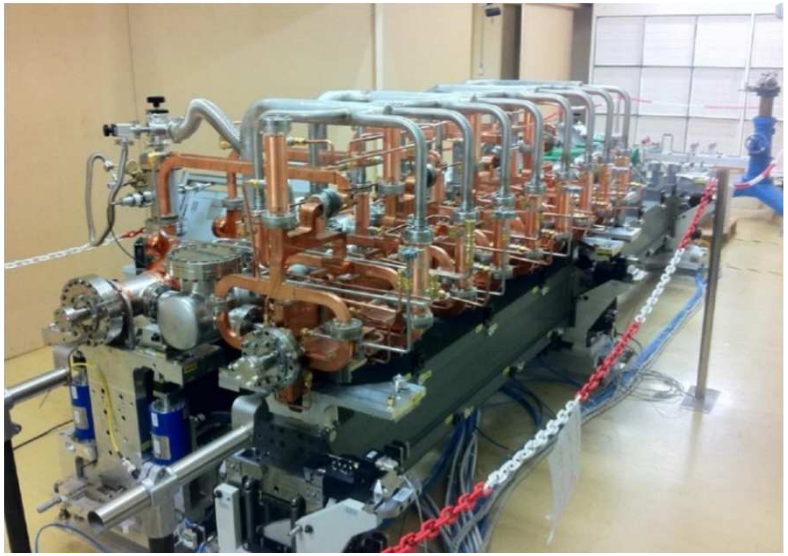
Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

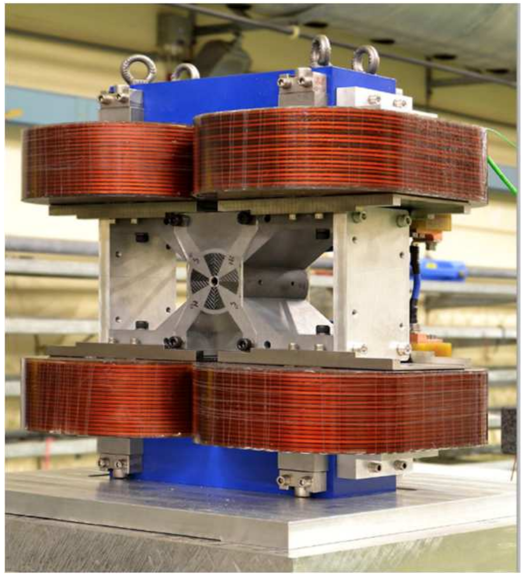


CLIC accelerator, some pictures

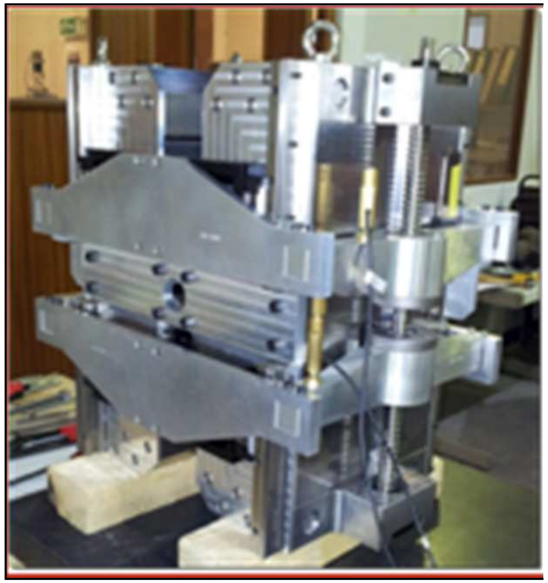
CLIC mechanical tests of 2-beam module



prototype final focus quadrupole

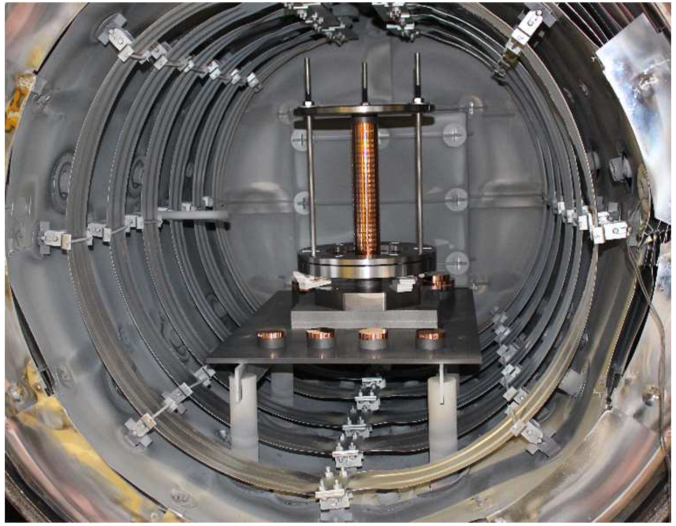


tunable permanent magnet



accelerator structure, 1 disk

brazing of a CLIC structure



cut through a CLIC acceleration structure

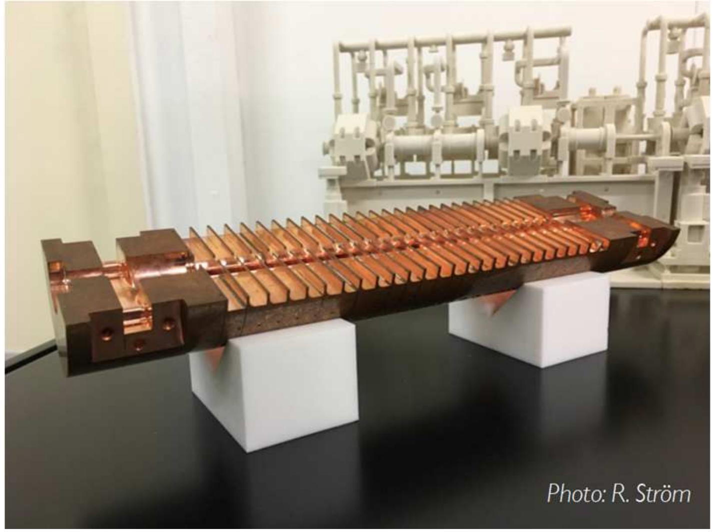


Photo: R. Ström

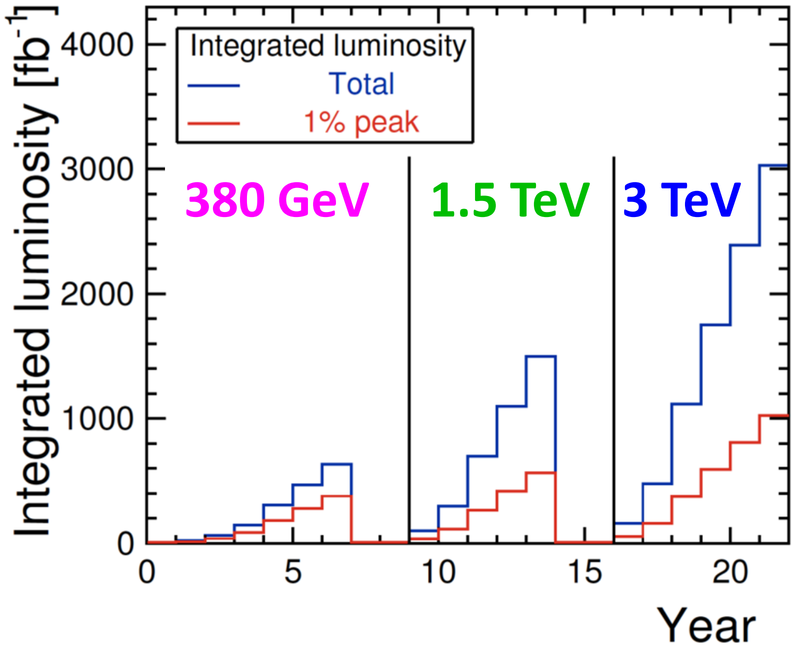
CLIC staging scenario

New CLIC staging baseline: CERN yellow report: CERN-2016-004

With “affordable” first stage at 380 GeV, focused on Higgs physics and top quark physics

Physics potential best exploited in a staged approach:

- **380 GeV (350 GeV)**, 600 fb^{-1} : precision Higgs and top physics (including top threshold scan)
- **1.5 TeV**, 1.5 ab^{-1} : BSM searches, precision Higgs, ttH, HH, top physics
- **3 TeV**, 3 ab^{-1} : BSM searches, precision Higgs, HH, top physics



Integrated luminosity including commissioning with beam and stops for energy upgrades

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

Dedicated to top mass threshold scan

Staging can be adapted to possible LHC discoveries

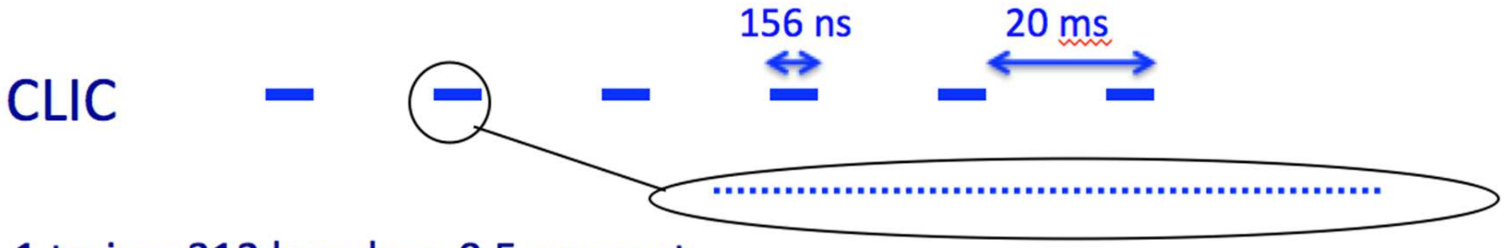
CLIC accelerator parameters

Parameter	**380 GeV**	**1.5 TeV**	**3 TeV**
Luminosity L (10^{34}cm^{-2}sec^{-1})	1.5	3.7	5.9
L above 99% of $\sqrt{s}$ (10^{34}cm^{-2}sec^{-1})	0.9	1.4	2.0
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	11.4	29	50
Repetition frequency (Hz)	50	50	50
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	70	44	44
Estimated power consumption* (MW)	252	364	589

scaled from CDR, with room for improvement

Drives timing requirements for CLIC detector

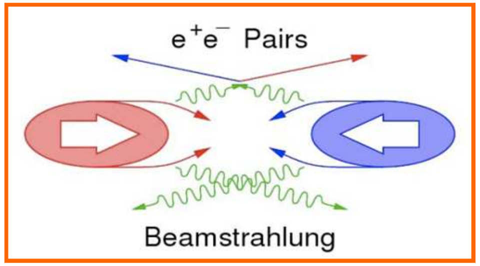
Very small beam



1 train = 312 bunches, 0.5 ns apart

- not to scale -

CLIC accelerator environment



Beam-beam background at IP:

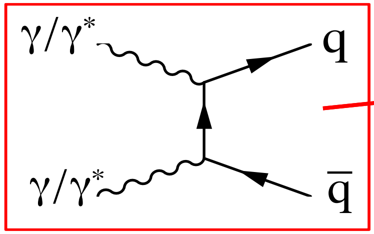
- Small beams => very high E-fields
  - ♦ **Beamstrahlung**
  - ♦ **Pair-background** → Design issue (small cell sizes)
    - ♦High occupancies
  - ♦ **γγ to hadrons** → Impacts on the physics / Needs suppression in data
    - ♦Energy deposits

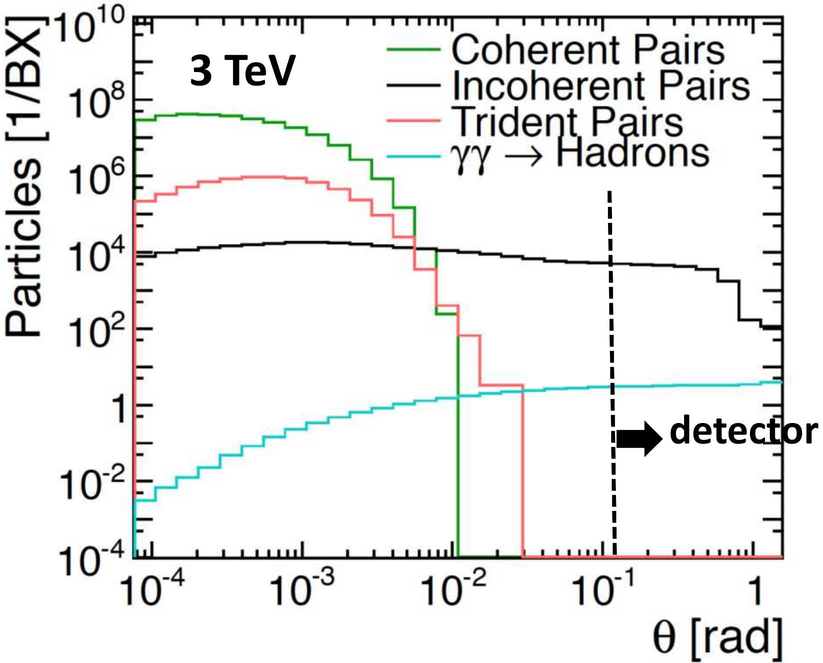
Simplified picture:

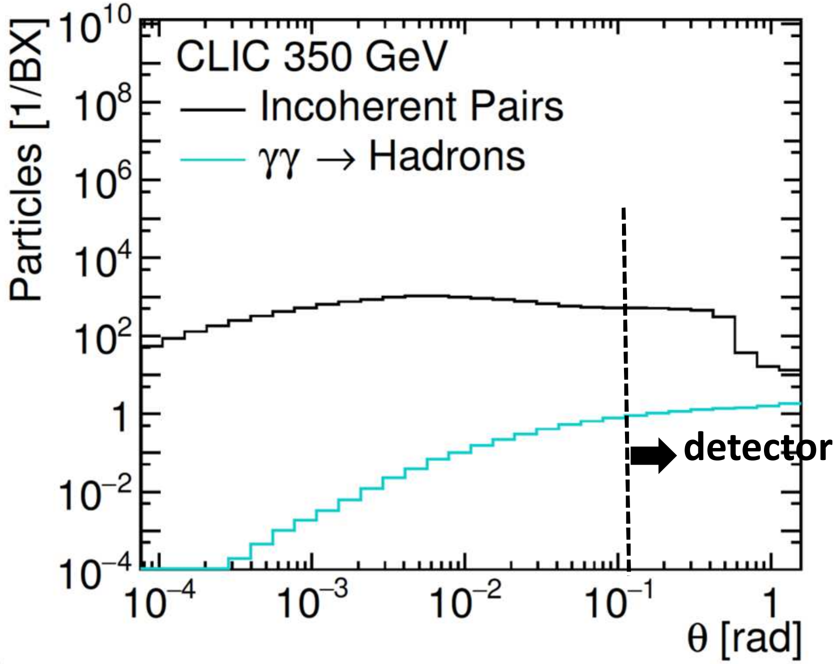
Design issue (small cell sizes)

Impacts on the physics

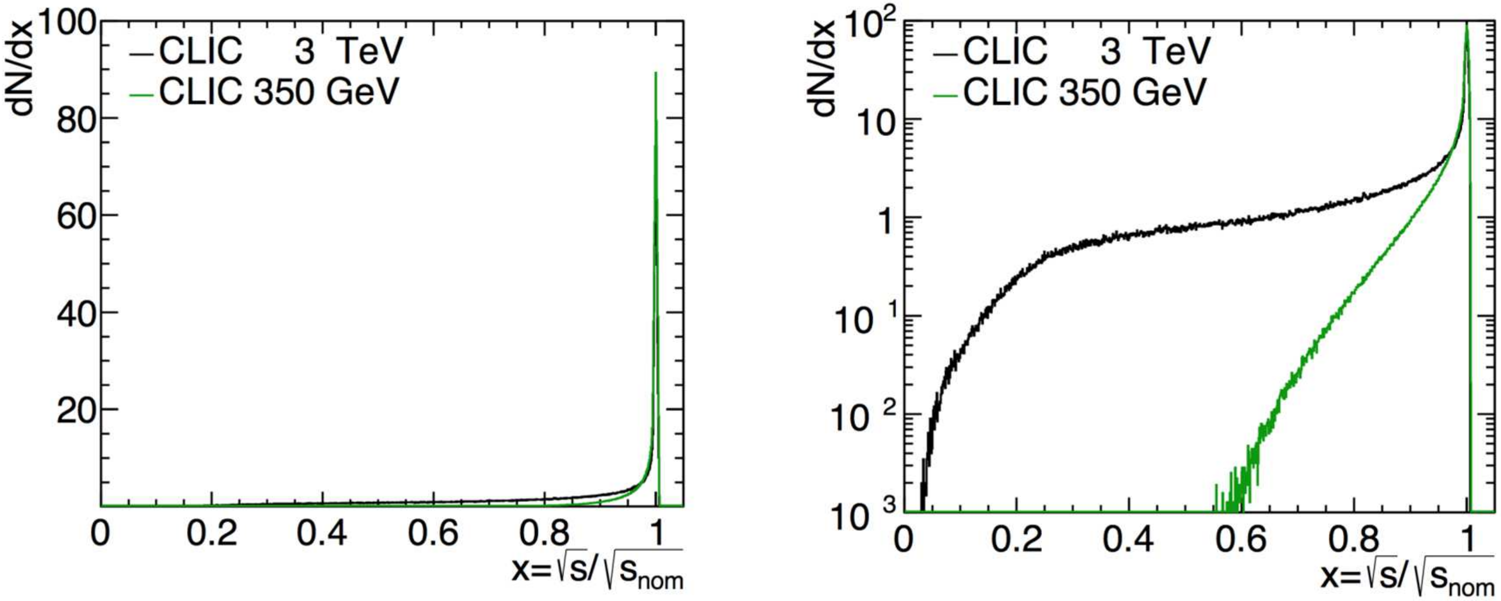
Needs suppression in data







luminosity spectrum



Beamstrahlung ➔ important energy losses right at the interaction point

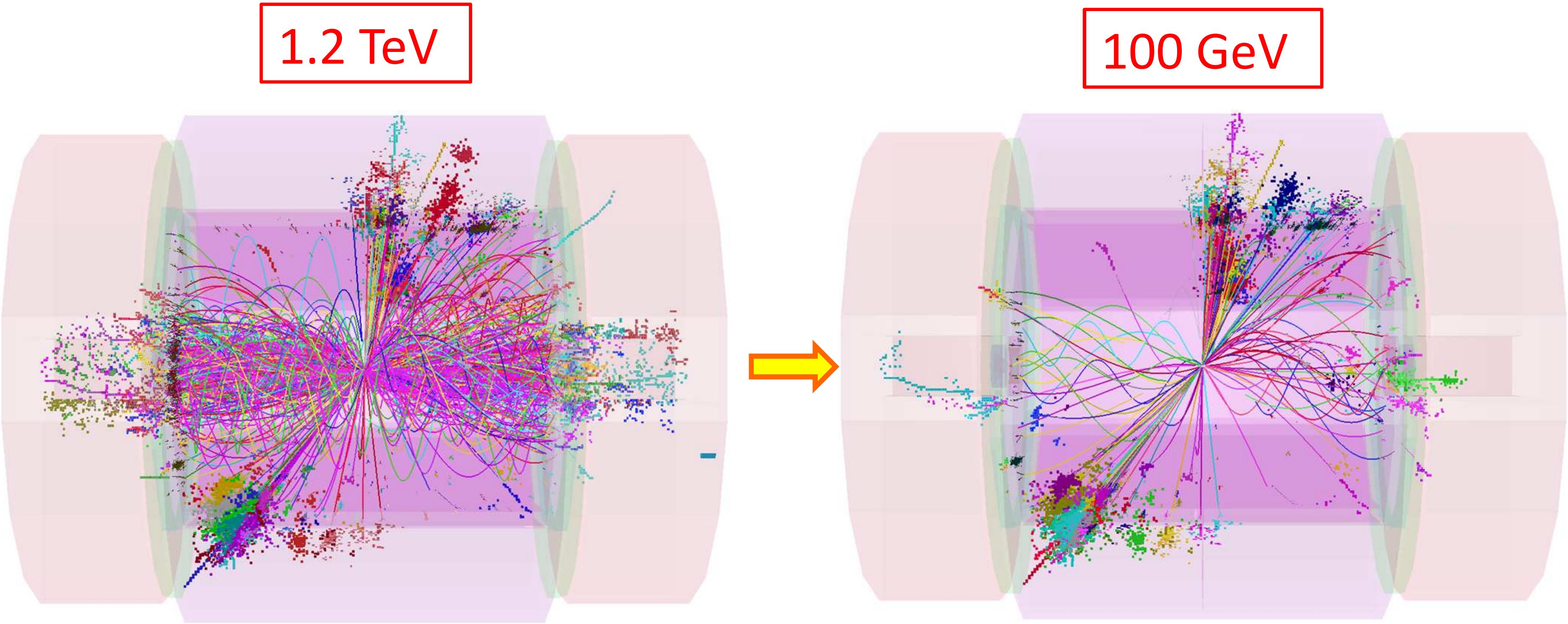
Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ
using large-angle Bhabha scattering events,
to 5% accuracy at 3 TeV
Eur.Phys.J. C74 (2014) no.4, 2833

Fraction $\sqrt{s}/\sqrt{s_{nom}}$	**350 GeV**	**3 TeV**
>0.99	68%	36%
>0.9	95%	57%
>0.8	99.1%	68%
>0.7	99.9%	77%
>0.5	~100%	88%

beam-induced background rejection (1)

Beam-induced background from γγ ➔ hadrons can be efficiently suppressed by applying ***p_t* cuts and timing cuts on individually reconstructed particles** (particle flow objects)

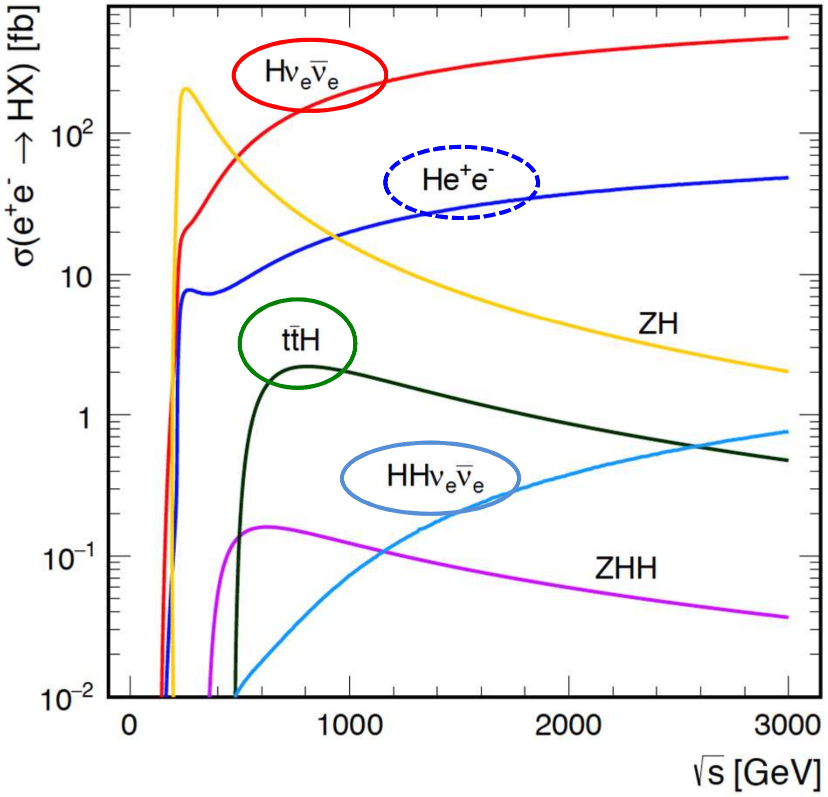


$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8 \text{ jets}$$

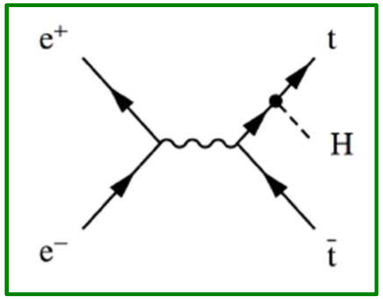
1.2 TeV background in reconstruction window (>=10 ns) around main physics event

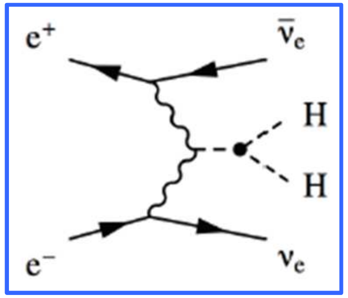
100 GeV background after tight cuts

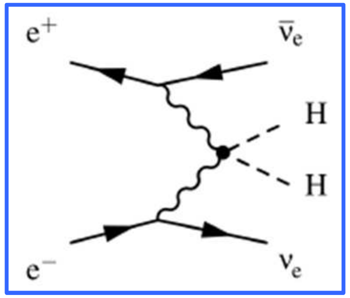
Higgs physics above 1 TeV



Vector boson fusion:
$e^+e^- \rightarrow H\nu\nu$, $e^+e^- \rightarrow He^+e^-$
High σ + increased luminosity
Gives access to rare Higgs decays







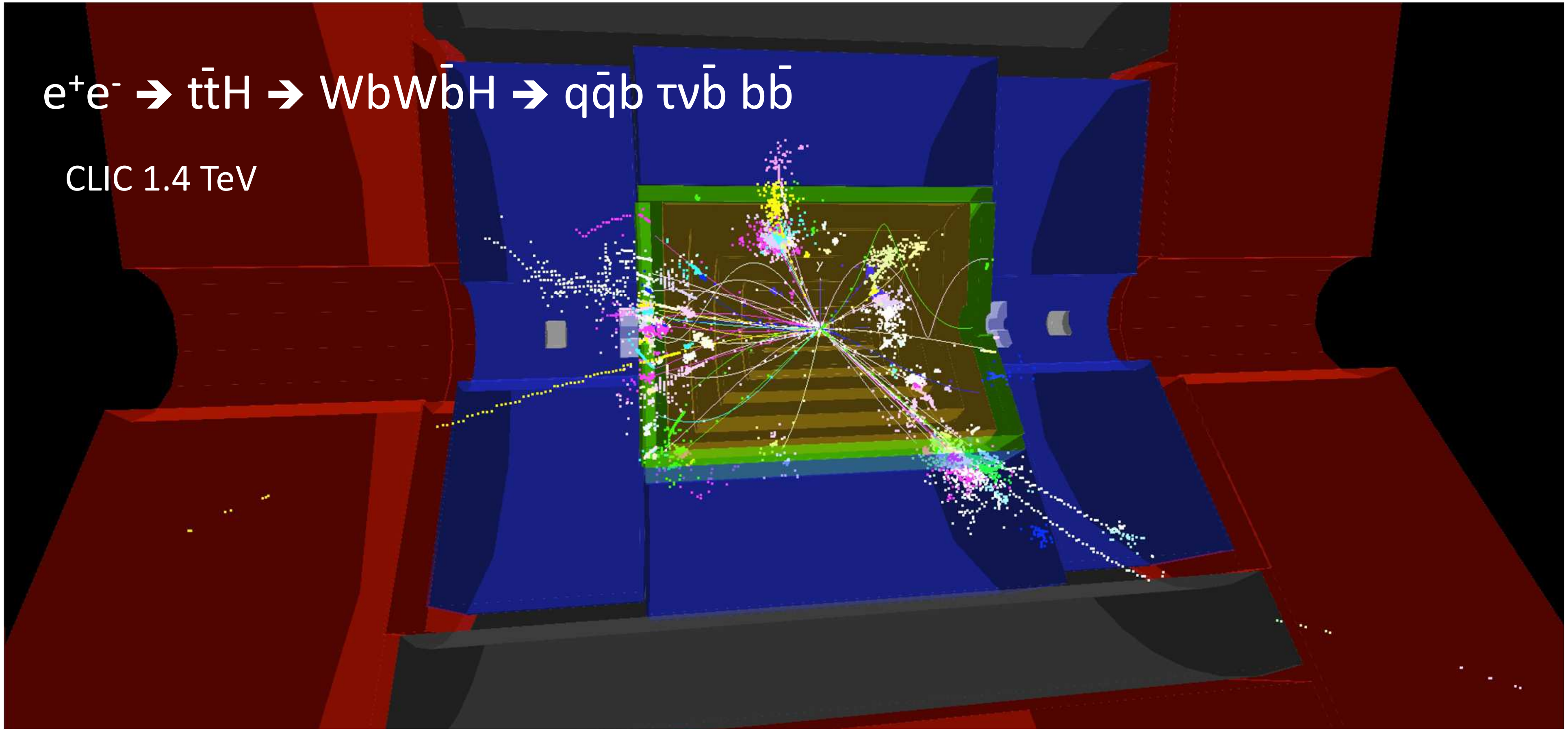
$t\bar{t}H$ production:
- Extraction of Yukawa coupling y_t
- Best at √s above 700 GeV

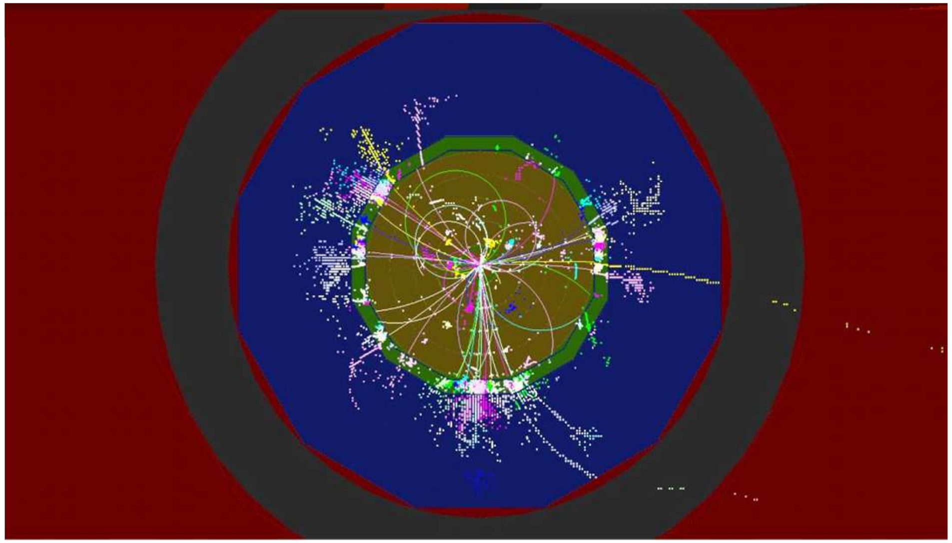
Studied at 1.4 TeV, 1.5 ab^{-1}
- Fully hadronic (8 jets)
- Semi-leptonic (6 jets + lepton + ν)

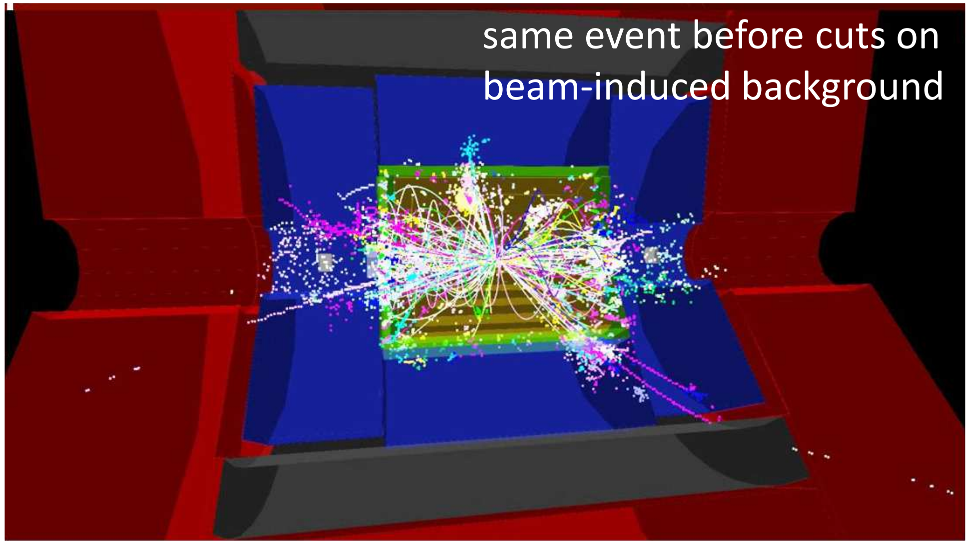
Statistical accuracy:
- **$\Delta(g_{Htt})$ = ±4.4%** at 1.4 TeV

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV

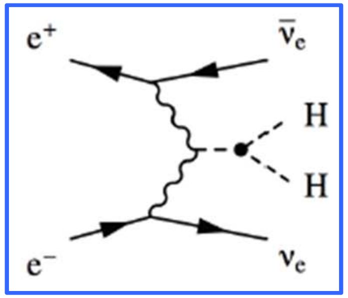


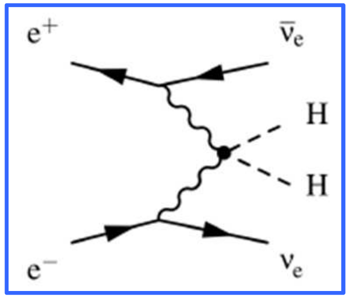




same event before cuts on beam-induced background

double Higgs production

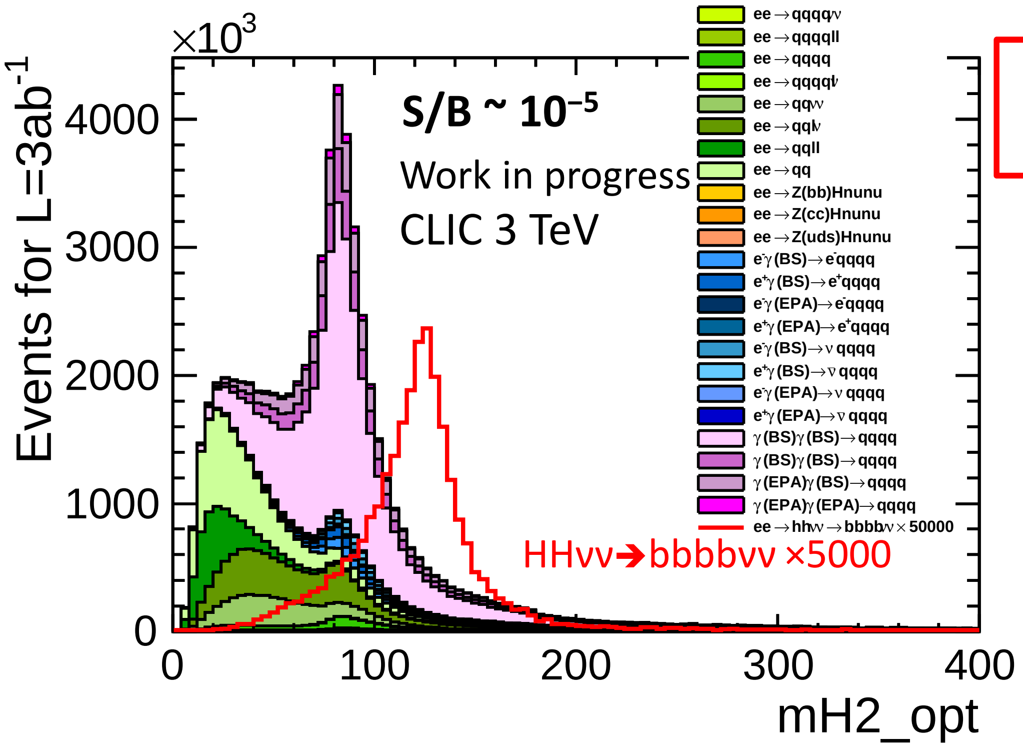




- Cross section sensitive to g_{HHH} and g_{WWHH}
- Small cross section (225/1200 evts @ 1.4/3 TeV)
- Large backgrounds

$\Rightarrow$ **Requires high energy and high luminosity**

Most promising final states:
*bbbbνν and bbWW*νν*



S/B ~ 10^{-5}

Work in progress
CLIC 3 TeV

HHνν➔bbbbνν ×5000

$\Rightarrow$ **$\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$**

for operation at 1.4 TeV + 3 TeV with polarisation

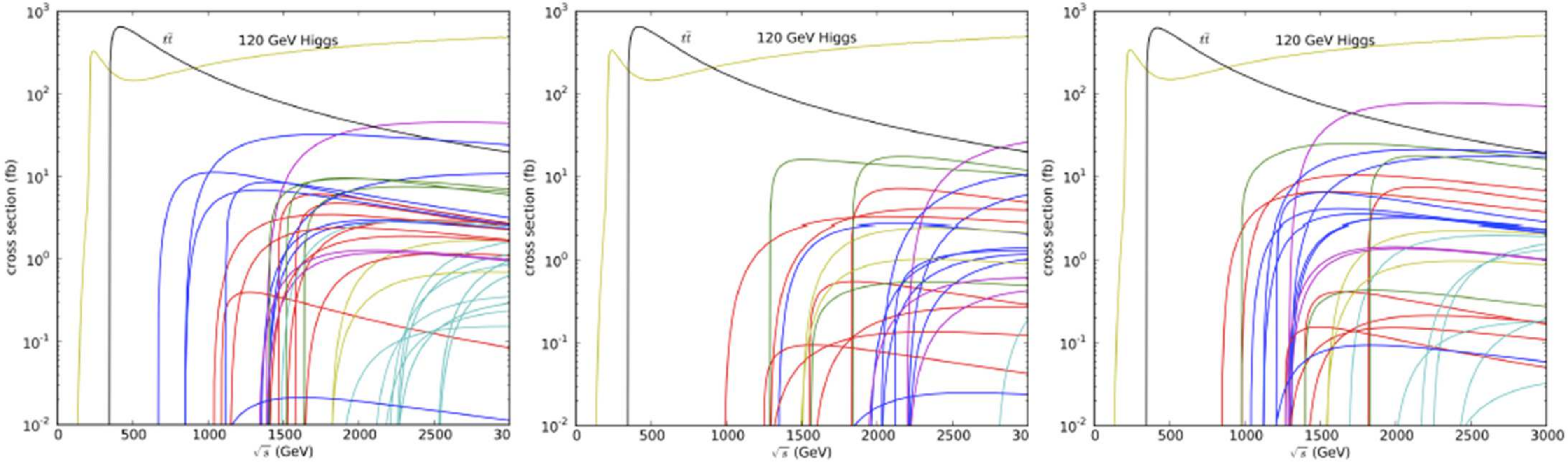
Process with strong sensitivity to BSM

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

arXiv:1305.6397

direct BSM sensitivity

using SUSY as a benchmarking tool



"model I", 3 TeV:

- Squarks
- Heavy Higgs

"model II", 3 TeV:

- Smuons, selectrons
- Gauginos

"model III", 1.4 TeV:

- Smuons, selectrons
- Staus, Gauginos

— Higgs
— $\tilde{\tau}, \tilde{\mu}, \tilde{e}$
— charginos
— squarks
— SM tt̄
— $\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e$
— neutralinos

Wider capability than only SUSY: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"

→ In general, **O(1%)** precision on masses and production cross sections found

CERN-2012-003 CERN-2012-007

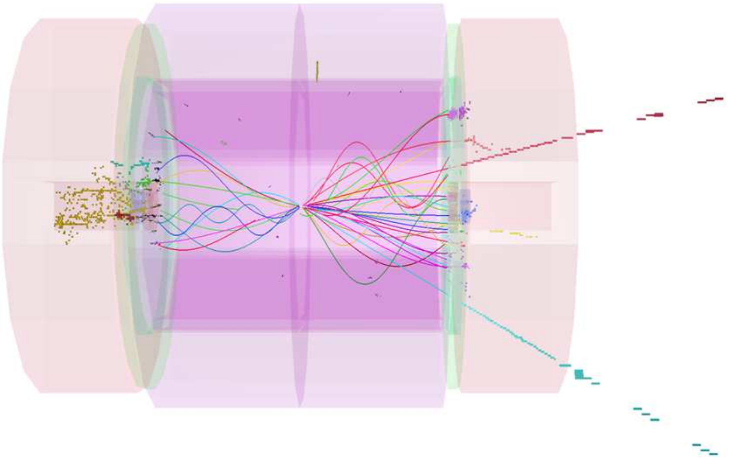
the simplest case: slepton at 3 TeV

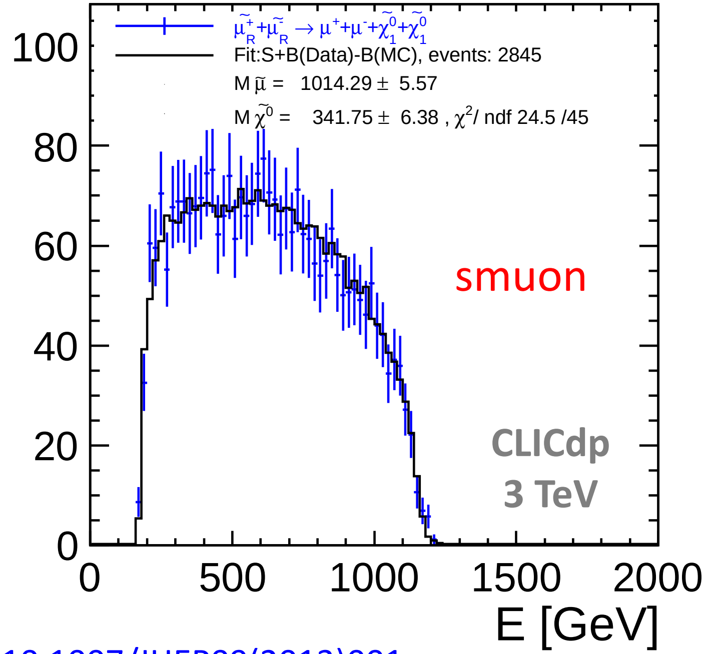
Slepton production at CLIC very clean

slepton masses ~ 1 TeV

Investigated channels include

- $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\ \tilde{\chi}_1^0\,\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\ \tilde{\chi}_1^0\,\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^-\ \tilde{\chi}_1^0\,\tilde{\chi}_1^0$





10.1007/JHEP09(2013)001

- Leptons and missing energy
- Masses from analysis of endpoints of energy spectra

result: $\Delta m/m \leq 1\%$

$m(\tilde{\mu}_R)$: ± 5.6 GeV
$m(\tilde{e}_R)$: ± 2.8 GeV
$m(\tilde{\nu}_e)$: ± 3.9 GeV
$m(\tilde{\chi}_1^0)$: ± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$: ± 3.7 GeV

Systematics due to uncertainty on luminosity spectrum studied:
syst. well below stat. error

di-jet masses: gauginos at 3 TeV

Chargino and neutralino pair production

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

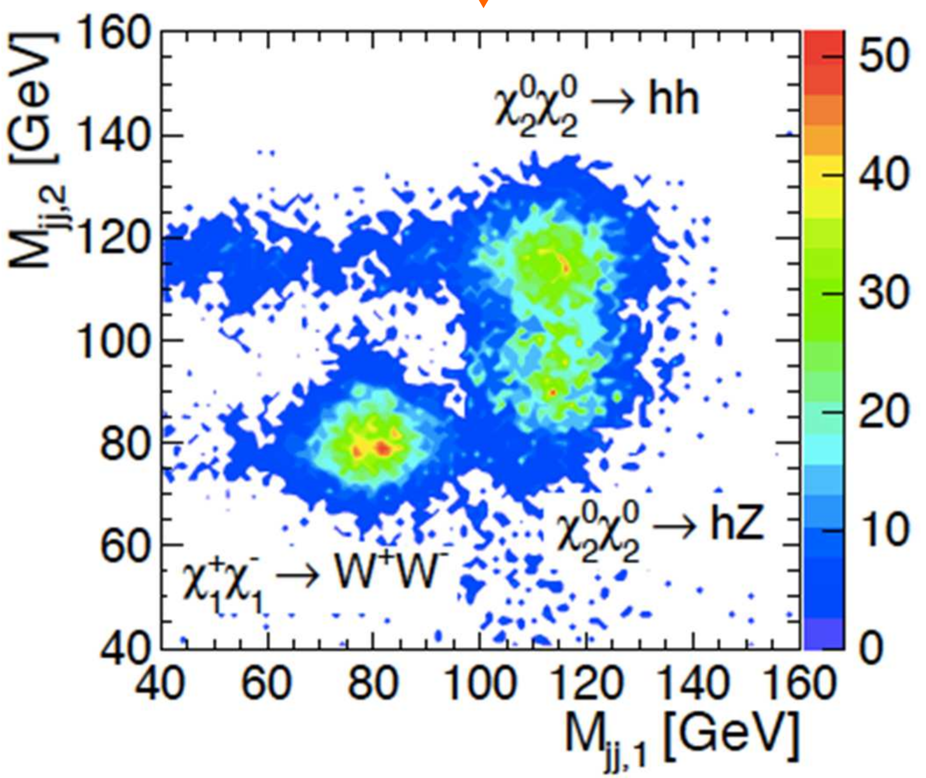
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\,\%$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\,\%$$

$$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$$

- separation using di-jet invariant masses (test of PFA)



$$m(\tilde{\chi}_1^\pm) \;:\; \pm 7\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0) \;:\; \pm 10\,\mathrm{GeV}$$

use slepton study result

$$m(\tilde{\chi}_1^0) \;:\; \pm 3\,\mathrm{GeV}$$

result: $\Delta m/m \leq 1\%$

LCD-Note-2011-037

results of SUSY benchmarks

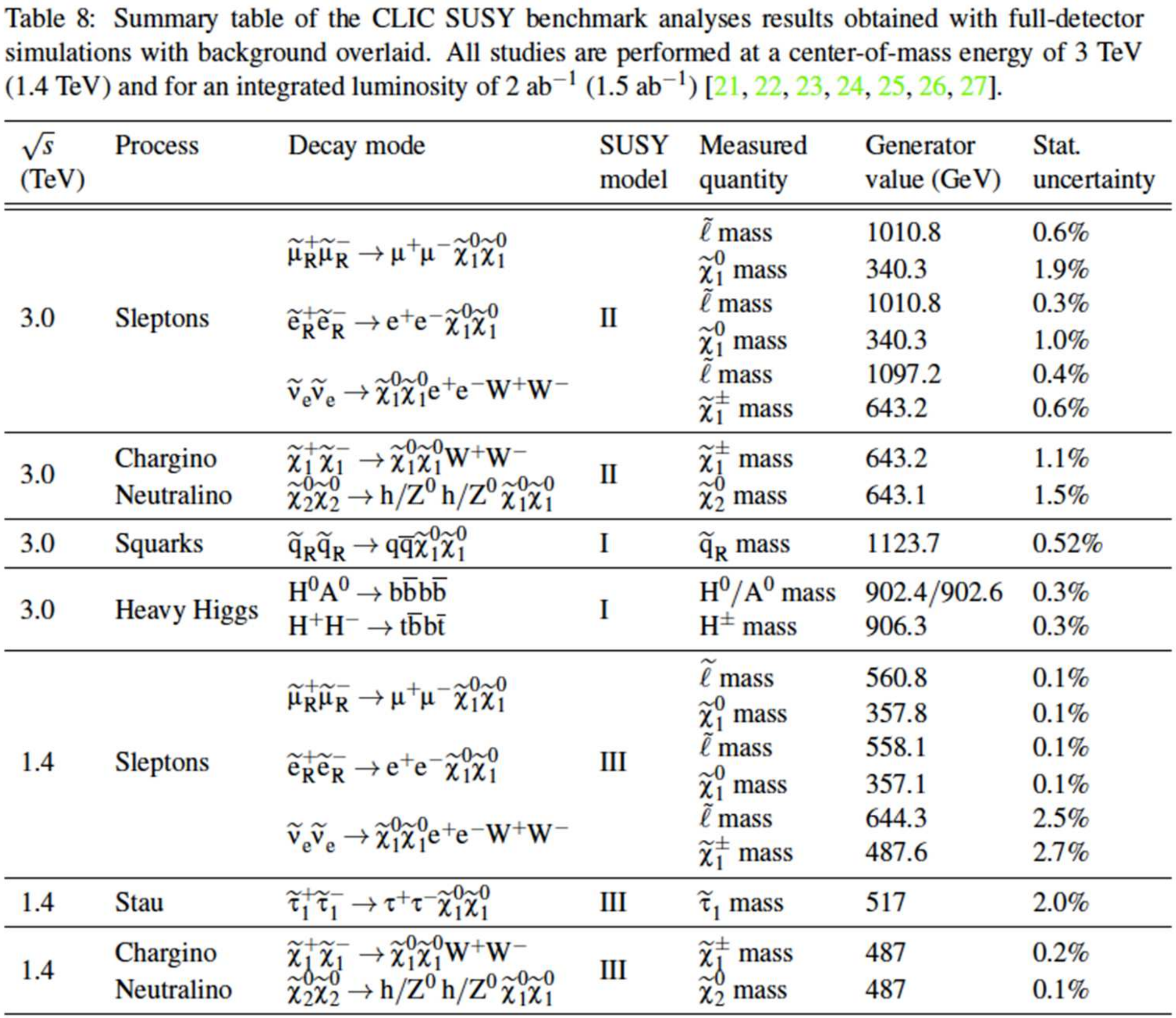


Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Large part of the SUSY spectrum measured at <1% level

CERN-2012-007

test of QED: precision study of $e^+e^- \rightarrow \gamma\gamma$

Possible deviations from QED cross sections and angular γγ spectrum can test extension of QED (finite electron size, extra dimension, mass of excited electrons..)

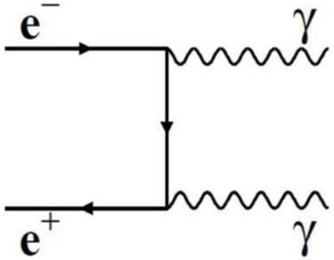
Finite electron size => energy cut off Λ

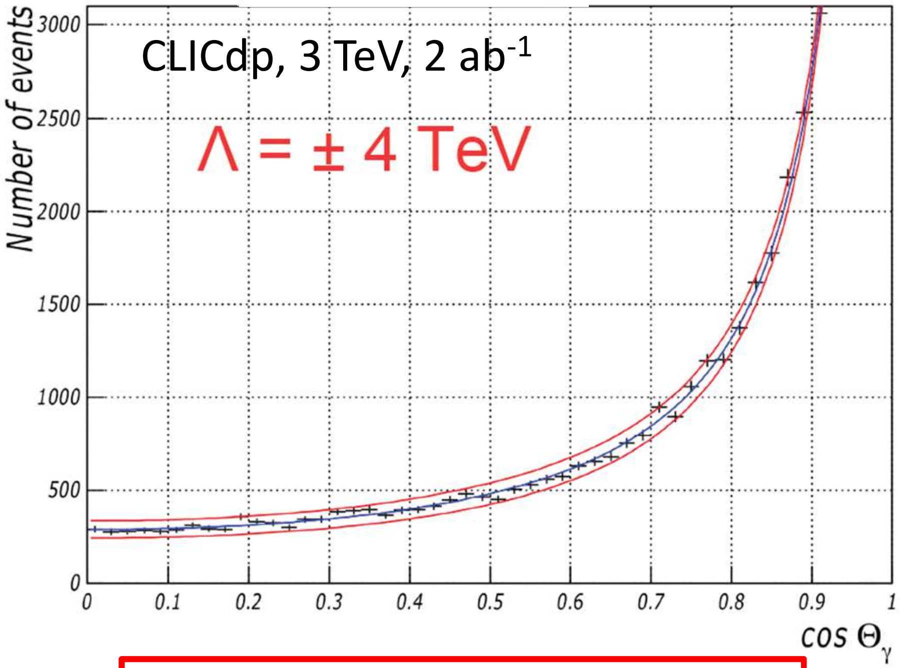
$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)$$

=> ***two back-to-back photons***

Events selected with small energy loss due to Beamstrahlung and ISR

Main backgrounds:
ee → ee and eγ → eγ
So e/γ identification in forward region is important





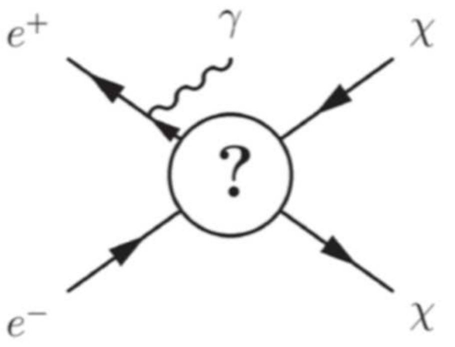
Fit result: Λ > 6.33 TeV
(or electron size < 3.1×10^{-18} cm)

Combined LEP data: Λ > 431 GeV
(or electron size < 4.6×10^{-17} cm)

I. Boyko @ CLIC'16

further indirect assessments

$ee \rightarrow \gamma + E_T^{miss}$



Generic

Dark matter study

Only observable:

ISR photon

Benchmark study ongoing

SM Effective Field Theory (SM EFT)

Dimension-6 operators, model-independent approach

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Using e+e- ➔ ZH, Hνν and W^+W^-

At three CLIC energy stages

- Study shows high-energy CLIC as a powerful indirect probe for new physics
- Importance of studying ***HZ at high energy***

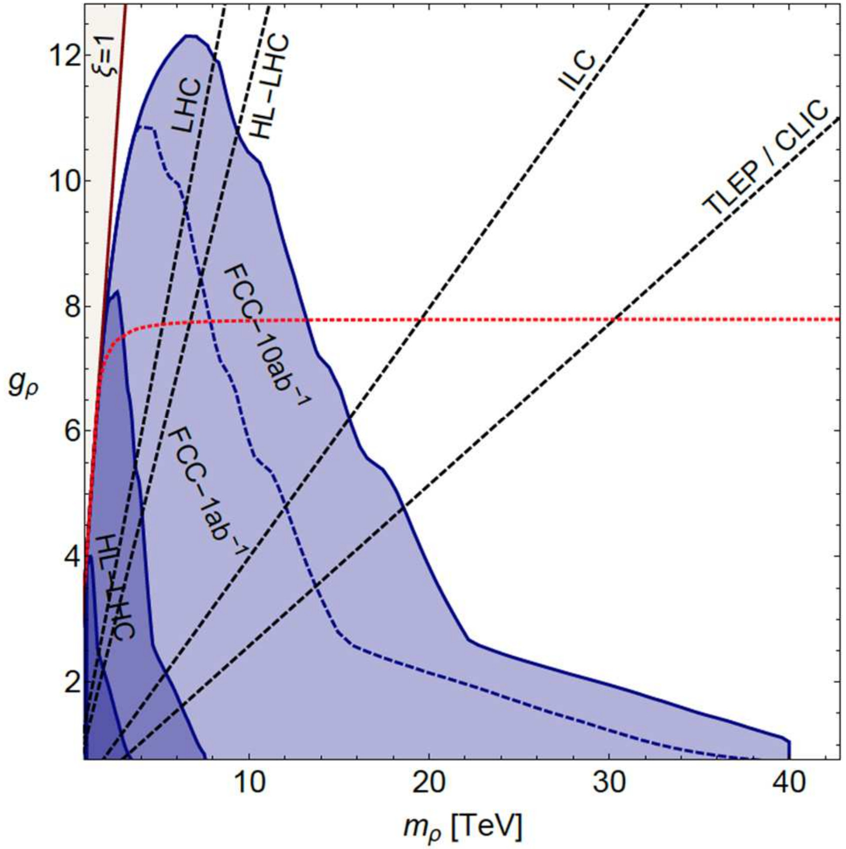
arXiv:1701.04804

Minimal Composite Higgs scenario

2-parameter model:

Resonance mass m_ρ

Coupling SM fermions to EW gauge bosons, g_ρ



Comparison of direct and indirect measurements

Allowed region above the dashed lines

CLIC/FCC-ee very sensitive to large g_ρ

arXiv:1502.01701

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

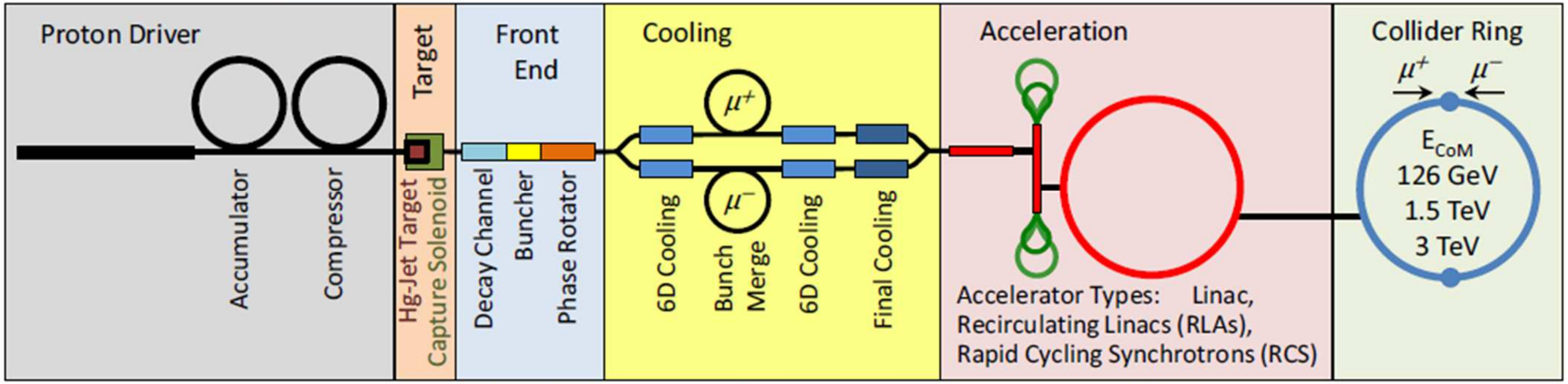
2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

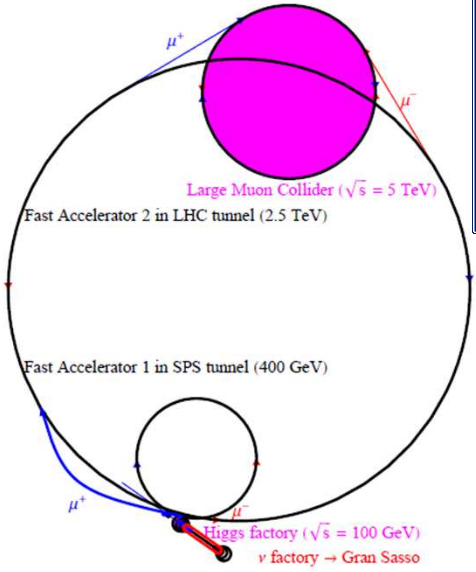
Muon colliders



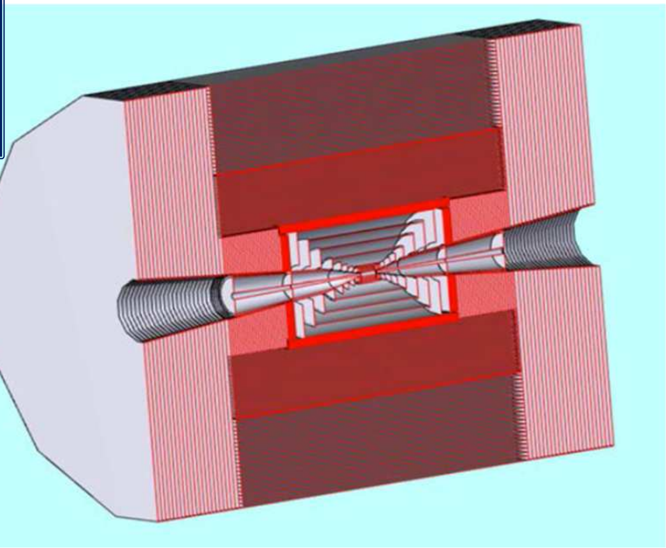
arxiv:1308.0494

U.S. Muon Accelerator Program

- Higgs physics
- Precision measurements
- Higher masses
- Experimental environment
- What can a muon collider do .... and not do?



CERN-YELLOW-99-02, CERN-2004-002 ; ECFA-04-230



Muon colliders | General features for experiments

1. Basic limitation from number of muons @ given proton driver power
2. Luminosity grows like E^2 for given muon source (normalized emittance) in optimized ring

   ! The winner for E.C.M. above 2 TeV !

   in a given ring it grows like E^3 :

   ex: top factory E_{CM}=350 GeV, L=6 10^{33} ➔ @Z 10^{32} ; @WW 6 10^{32} ; @ZH 2 10^{33} ; @H 3 10^{31}
3. ! energy spread can be reduced to 3 10^{-5}
4. ! beam energy and beam energy spread calibration is exquisite
5. rep rate > 1μs , typically 15(fills)x10^3 (turns/fill) → no pile-up
6. large fraction of power in cooling!

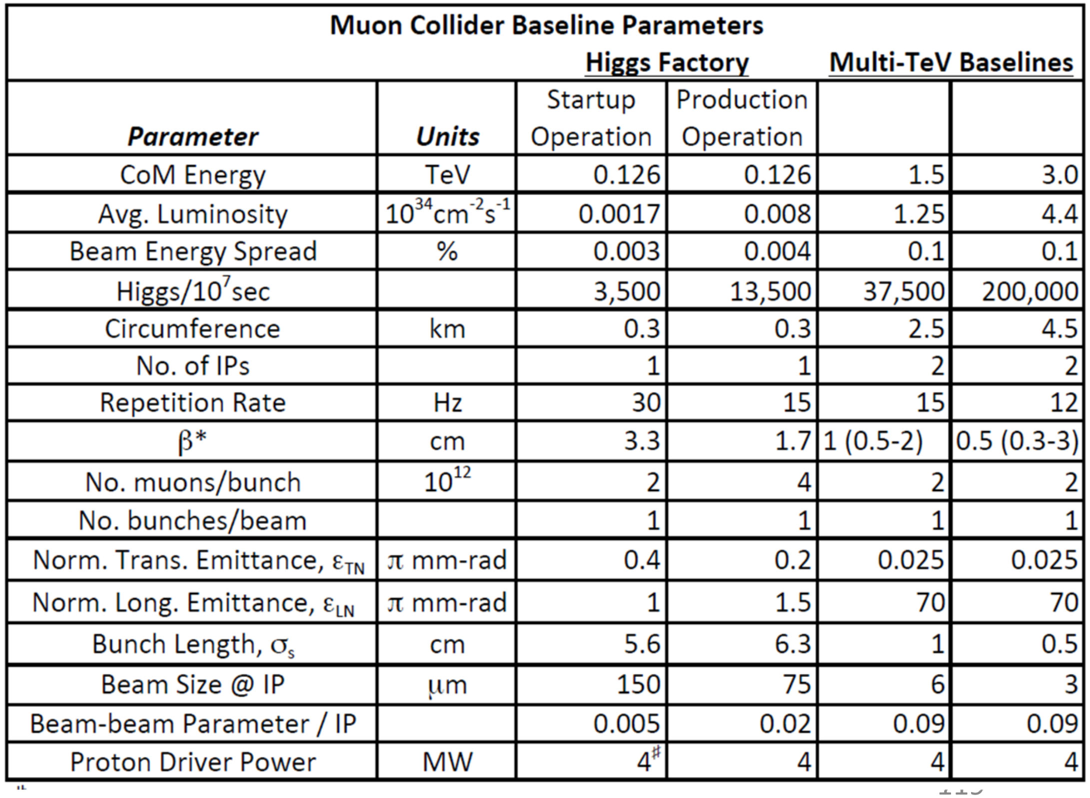
   → wall power increases slowly with E_{CM}
7. muons decay ! 10^{12} muons : $\mu \rightarrow e\nu\nu$

   → e/γ background at IP

7'. ν from muon decay give radiation

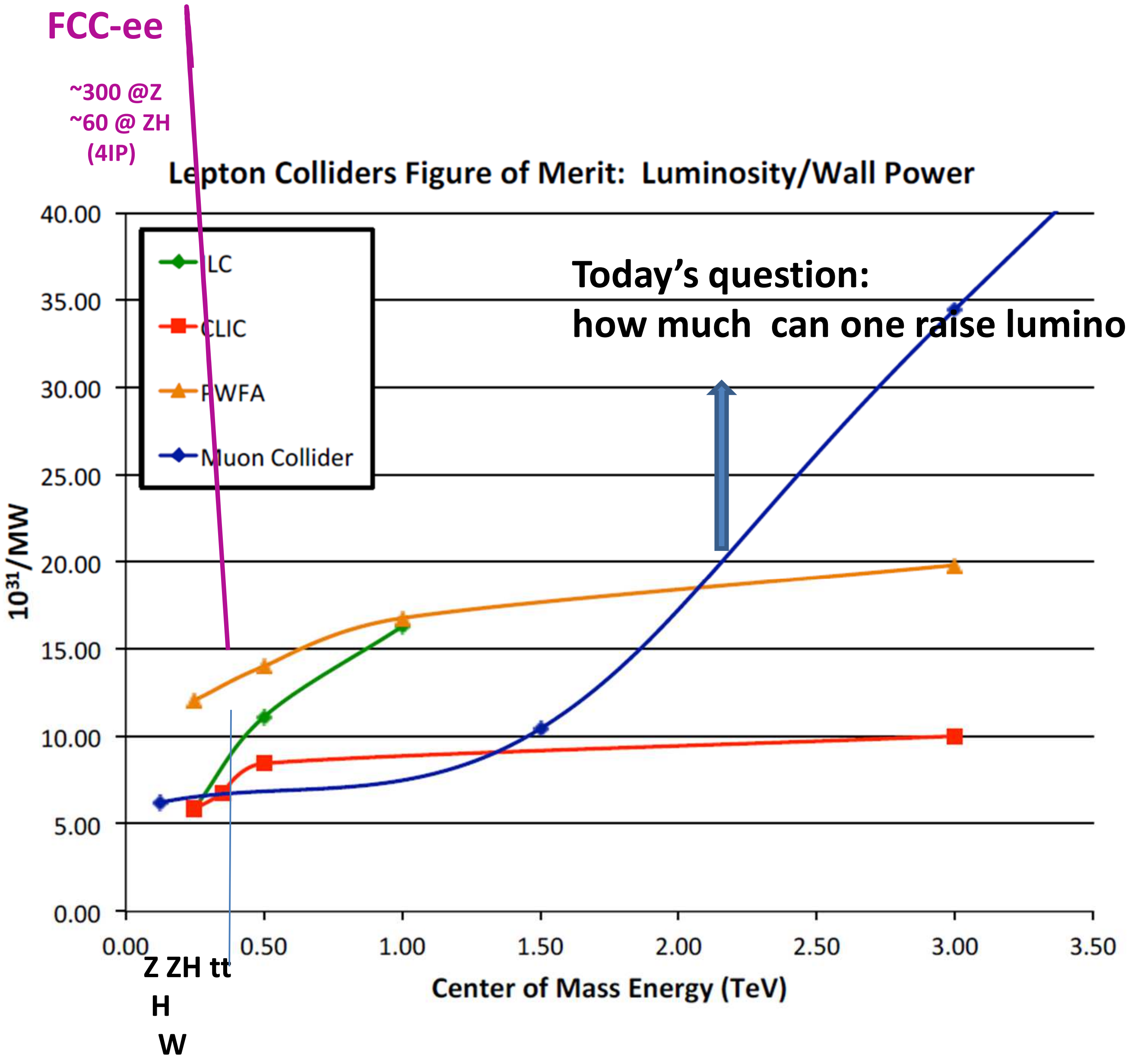
at point of exit → grows as E^4

limits applicability to ~E_{CM}= 10 TeV



Muon Collider Baseline Parameters

Parameter	***Units***	**Higgs Factory** Startup Operation	**Higgs Factory** Production Operation	**Multi-TeV Baselines**	**Multi-TeV Baselines**
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4



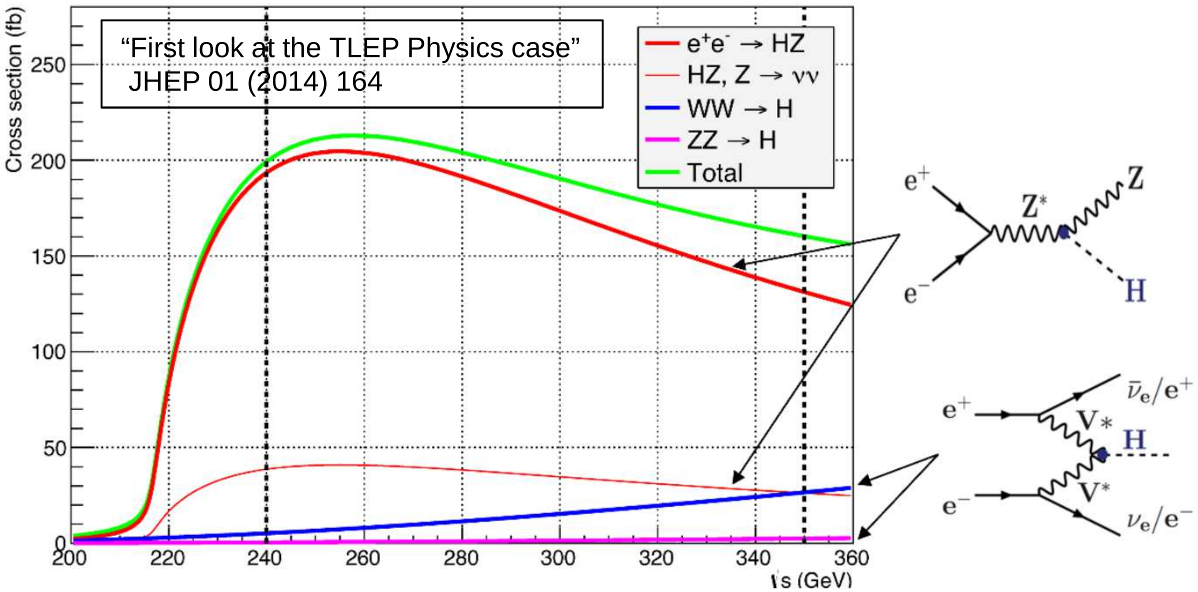
FCC-ee

~300 @Z
~60 @ ZH
(4IP)

Today's question:
how much can one raise luminosity?

Higgs boson production (1)

- **Muons are leptons, like electrons**
  - Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:

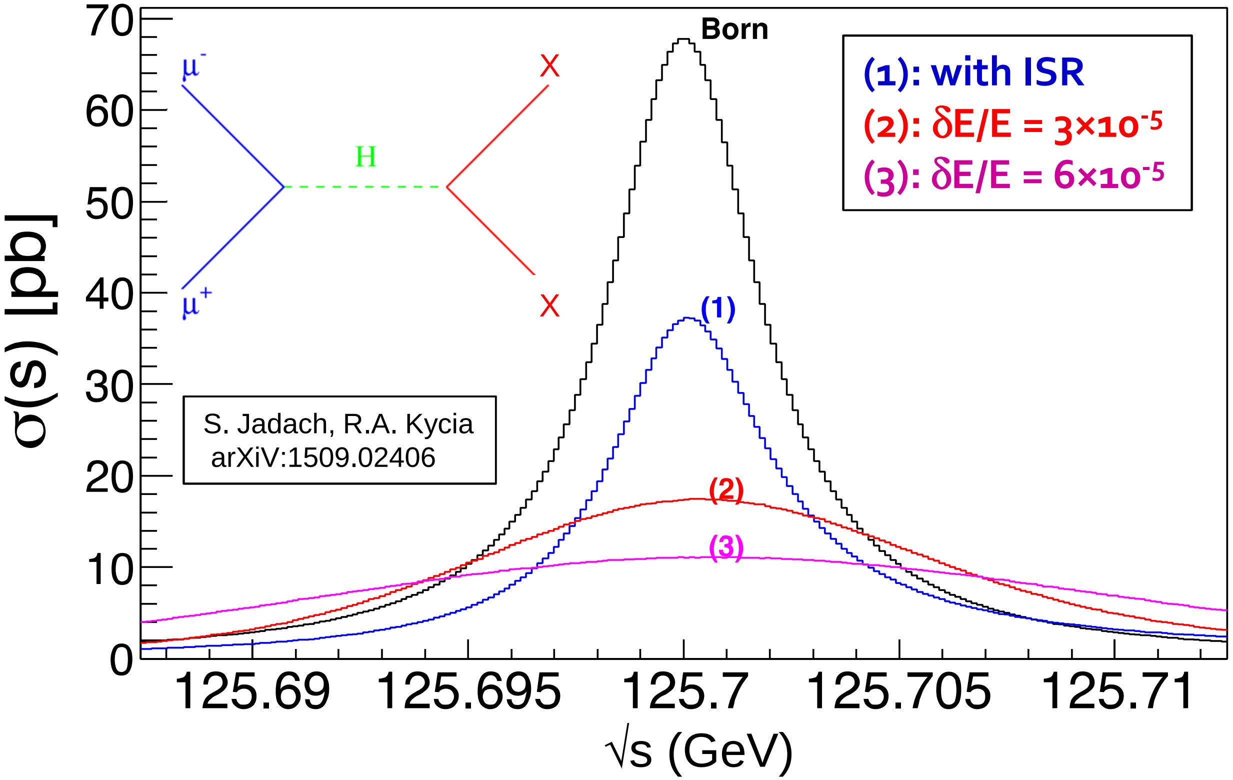


"First look at the TLEP Physics case"
JHEP 01 (2014) 164

  - However, for a similar beam energy spread ($\delta E/E \sim 0.12\%$) at $\sqrt{s}$ = 240-350 GeV
    - FCC-ee luminosity: 0.5 – 1.1 × 10^{35} $cm^{-2}s^{-1}$ / IP and up to 4 IPs
    - Muon collider luminosity: few× 10^{33} $cm^{-2}s^{-1}$ / IP
  - Precision on branching ratios, couplings, width, mass, etc. , with 2 IPs
    - A factor 10 better at FCC-ee (and twice better at ILC) than at a muon collider

Higgs boson production (2)

- Muons are heavy, unlike electrons: $m_\mu/m_e \sim 200$
  - Large direct coupling to the Higgs boson: $\sigma(\mu^+\mu^- \rightarrow H) \sim 40{,}000 \times \sigma(e^+e^- \rightarrow H)$
  - Much less synchrotron radiation, hence potentially superb energy definition
    - $\delta E/E$ can be reduced to $3\text{-}4 \times 10^{-5}$ with more longitudinal cooling
      - ➔ Albeit with equivalent reduction of luminosity: $2 - 8 \times 10^{31}$ cm^{-2}s^{-1}



(1): with ISR
(2): $\delta E/E = 3\times10^{-5}$
(3): $\delta E/E = 6\times10^{-5}$

S. Jadach, R.A. Kycia
arXiV:1509.02406

- $\sigma(\mu^+\mu^- \rightarrow H) \sim 15$ pb
  (ISR often forgotten…)
- 200 – 800 pb^{-1} / yr
- 3000 – 12000 Higgs / yr

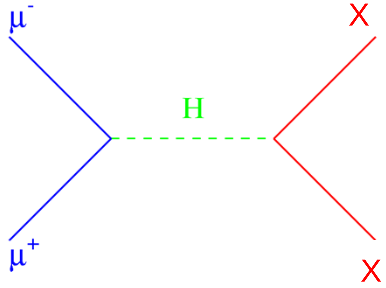
Reminder: At FCC-ee
400,000 to 800,000 Higgs/yr

Not quite there, even with factor 10

Scan of the SM Higgs resonance (1)

- **Resonant production**

$$\sigma(\mu^+\mu^- \to H^0) = \frac{4\pi\Gamma_H^2 Br(H^0 \to \mu^+\mu^-)}{(\hat{s}-M_H^2)^2 + \Gamma_H^2 M_H^2}$$



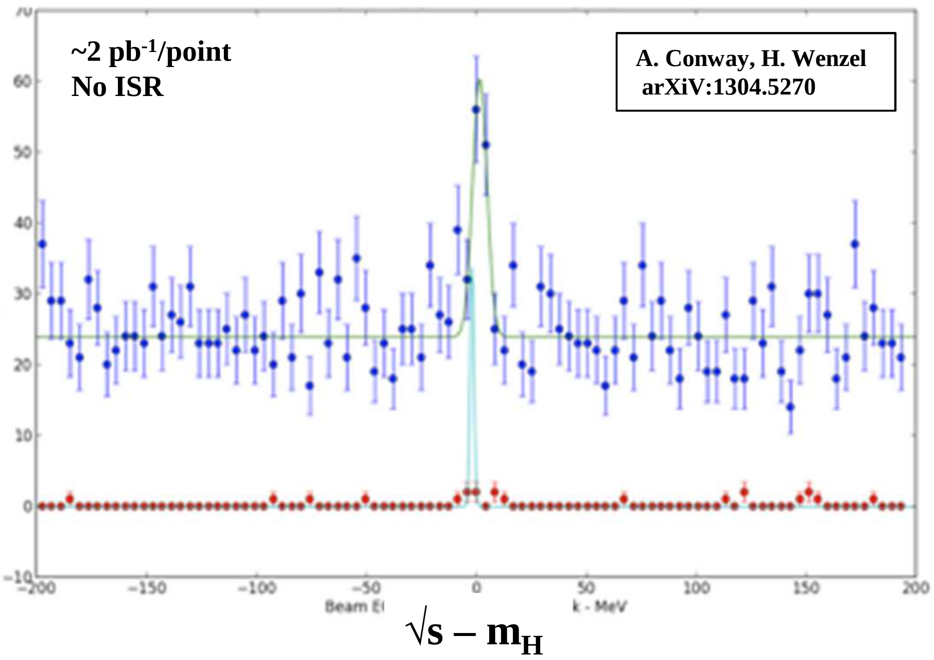
Major background:
$\mu^+\mu^- \to Z/\gamma^* \to XX$

- Convoluted with
  - Beam energy spectrum
  - Initial state radiation (ignored in most studies)

- The measurement of the lineshape gives access to
  - The Higgs mass, m_H
  - The Higgs width, Γ_H
  - The branching ratio into $\mu^+\mu^-$, BR($H \to \mu\mu$)
    - ➔ Hence, the coupling of the Higgs to the muon, $g_{H\mu\mu}$
  - Some branching fractions and couplings, with exclusive decays

Scan of the SM Higgs resonance (2)

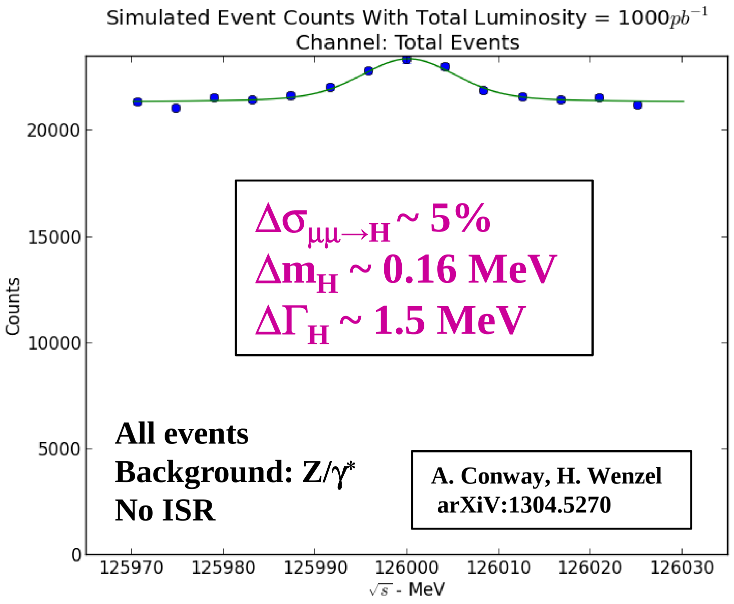
- Finding the resonance (Γ_H = 4.2 MeV ~ δE)
  - Today, m_H is known to ±250 MeV
    - Improves to ±100 MeV (LHC14), ±30 MeV (ILC), or ±8 MeV (FCC-ee)
  - Scan the $\sqrt{s}$ region of interest in optimal bins of 4.2 MeV
    - Count the number of bb and semi-leptonic WW events (see next slides)
  - Without ISR, needs about 2 pb^{-1} / point for a 5σ significance
    - Reduced to 3σ when ISR is included
      - ➔ Probably enough
  - Total luminosity needed for 3σ
    - 300 pb^{-1} (1.5 yr) for ±300 MeV
    - 90 pb^{-1} (6 months) for ±90 MeV
    - 25 pb^{-1} (2 months) for ± 24 MeV
      - ➔ With L = 2×10^{31} $cm^{-2}s^{-1}$
  - Can be long …
    - … but feasible
      - ➔ Especially after ILC / FCC-ee



Scan of the SM Higgs resonance (3)

❑ Measurement of the lineshape

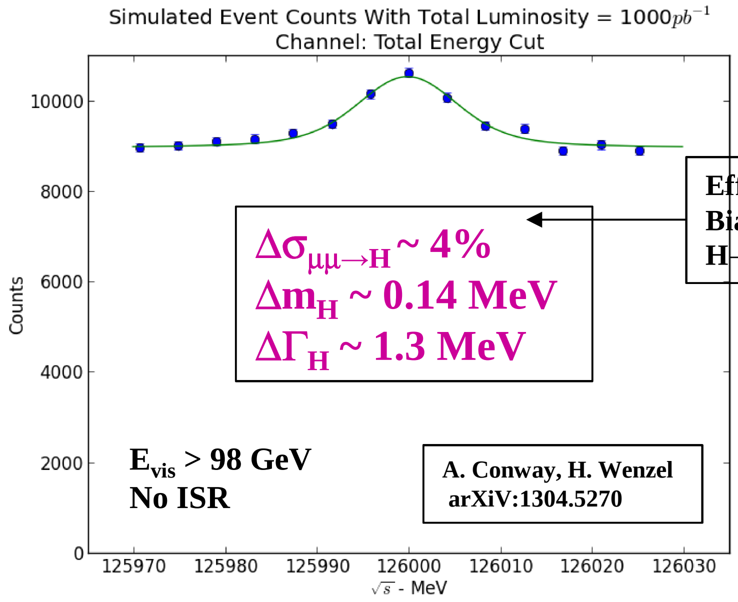
- Assume 1 fb^{-1} (5 yrs at 2×10^{31} and ≥ 1 yr at 8×10^{31}) : 70 pb^{-1} / point around m_H
  - The detector is assumed to have the performance of an ILC detector
  - **No beam background (e.g., from muon decays) was simulated**
- Count either all events, or only those with E_{vis} > 98 GeV [reject Z(γ) events]



$\Delta\sigma_{\mu\mu\to H}$ ~ 5%
Δm_H ~ 0.16 MeV
$\Delta\Gamma_H$ ~ 1.5 MeV

All events
Background: Z/γ*
No ISR

A. Conway, H. Wenzel
arXiV:1304.5270



$\Delta\sigma_{\mu\mu\to H}$ ~ 4%
Δm_H ~ 0.14 MeV
$\Delta\Gamma_H$ ~ 1.3 MeV

E_{vis} > 98 GeV
No ISR

A. Conway, H. Wenzel
arXiV:1304.5270

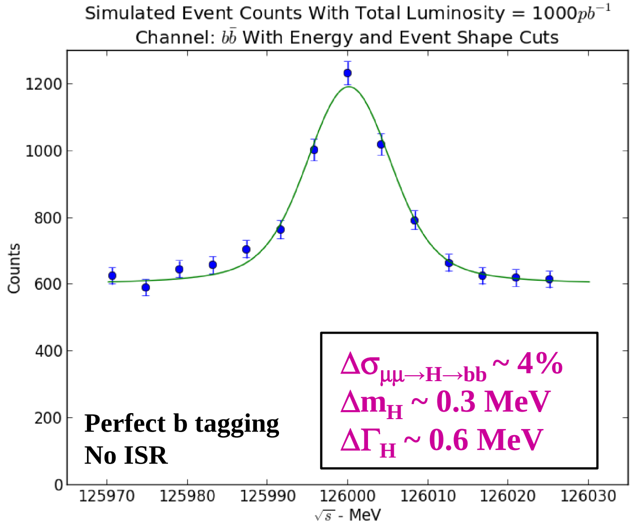
Efficiency ~ 80%
Biased against
H→ττ,WW,ZZ,…

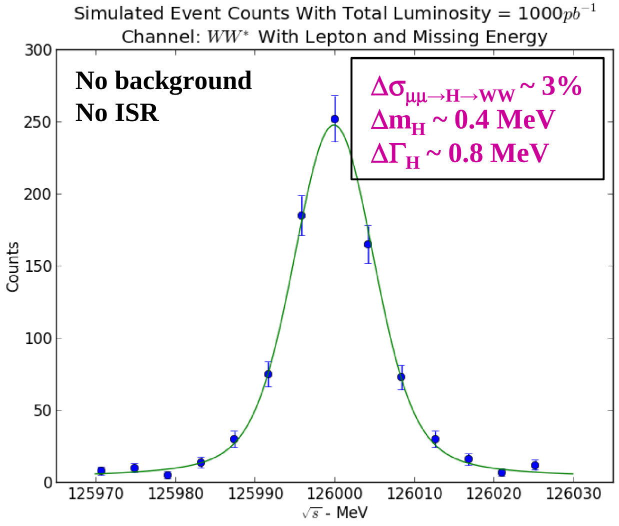
- ISR reduces the signal by a factor 2 (but not the background)
  - ➔ All errors to be increased by a factor 2
- m_H and Γ_H measurements require knowledge of E and δE with great precision

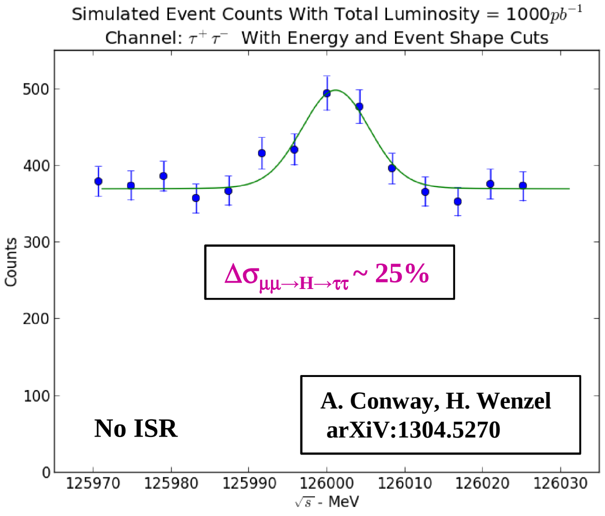
Scan of the SM Higgs resonance (4)

❑ Exclusive decays

- ◆ H ⟶ bb   H ⟶ WW ⟶ lνqq   H ⟶ ττ







- ◆ **Notes**
  - Some optimism in these numbers (perfect b tag, only Z bkgd, no beam bkgd…)
  - Errors to be increased to account for ISR
  - A better scan strategy should be designed (less in the sides, more in the peak)
  - The numbers are for 5 years at low luminosity, and 1.2 year after lumi upgrade
    - ➔ Combined numbers (next slide) given for 5 (low lumi) + 5 (upgrade) years.

Beam energy and beam-energy spread (1)

- **Muons are naturally 100% polarized (from π± decays)**
  - It is hoped that ~20% of this polarization can be kept in the collider ring
    - Then, the spin precesses around B with a frequency ν_0
      - ➔ For m_H = 125 GeV, ν_0 = 0.68967593(35)
    - Without energy spread, P_L oscillates between -20% and +20%
    - With energy spread, P_L gets diluted turn after turn

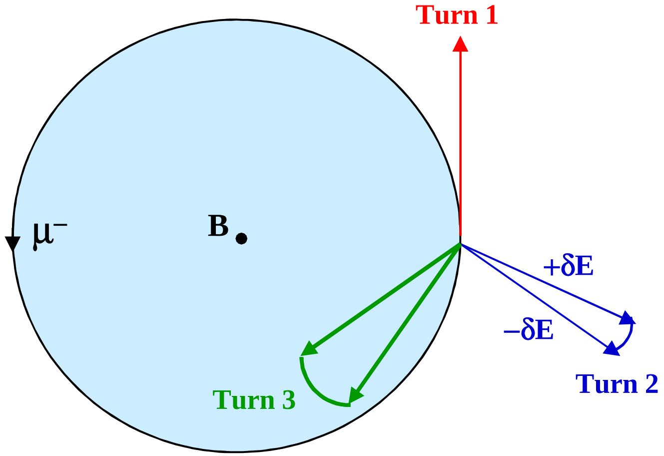
$$\nu_0 = \frac{g_\mu - 2}{2} \times \frac{E_{\text{Beam}}}{m_\mu}$$

$$P_L(T) = P_0 \int_0^\infty \cos(2\pi\nu T) S(\nu) \mathrm{d}\nu$$

➔ $P_L(T)$ is the Fourier transform of $S(\nu)$

- For example, with a Gaussian energy spread

$$P_L(T) = P_0 \cos(2\pi\nu_0 T) \exp\left\{ -\frac{1}{2} \left[2\pi\nu_0 T \frac{\delta E}{E} \right]^2 \right\}$$

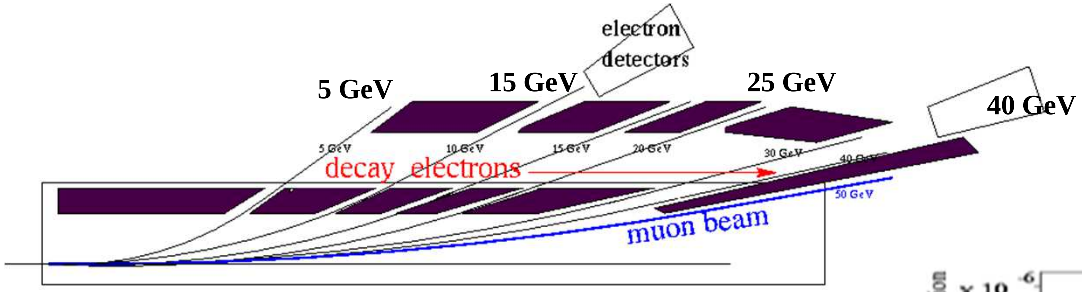


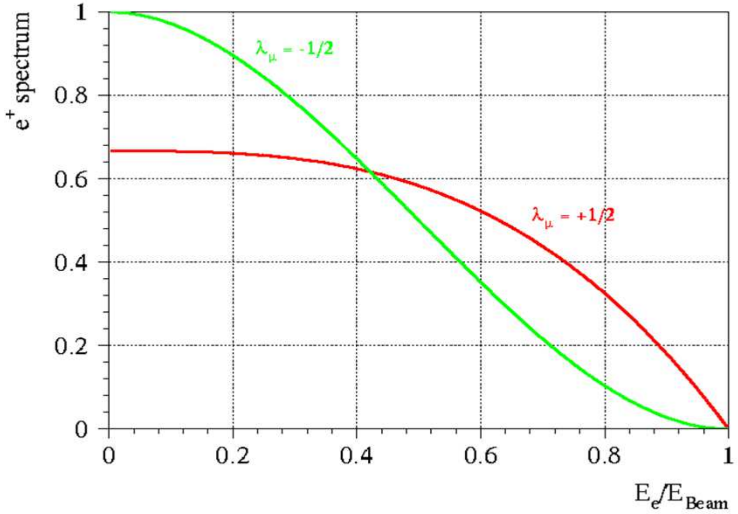
- Experimentally, measure P_L at each turn T
  - ➔ And deduce the complete beam energy spectrum by inverse Fourier transform

i.e., δE/E for a Gaussian energy spread

Beam energy and beam-energy spread (2)

- Use decay electrons to measure $P_L(T)$
  - Energy distribution depends on the muon helicity
    - $N_e(E) / N_{tot}$ oscillates according to P_L
      - ➔ Count electrons in the first dipole:

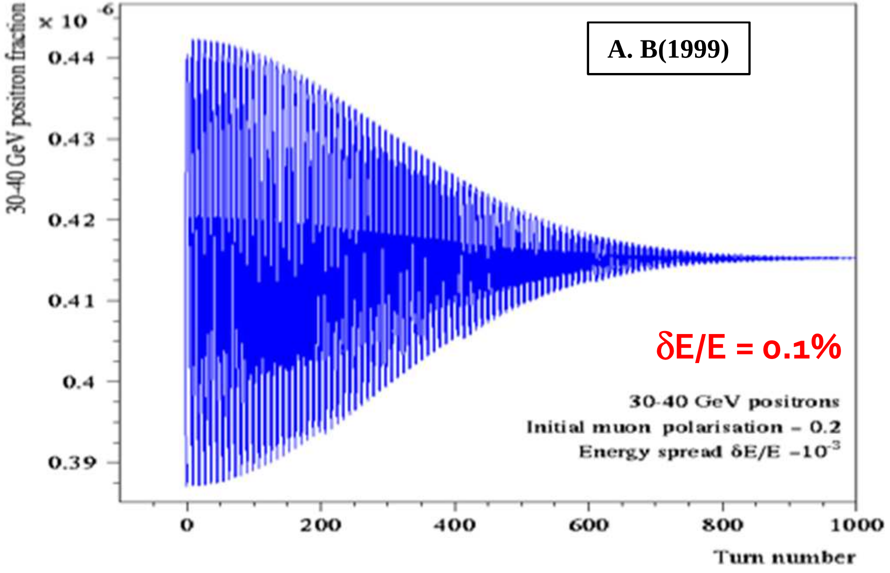




  - Fraction of e^+ from 30 to 40 GeV

$$P_L(T) = P_0 \cos(2\pi\nu_0 T)\exp\left\{-\frac{1}{2}\left[2\pi\nu_0 T\frac{\delta E}{E}\right]^2\right\}$$

    - The amplitude gives P_0
    - The frequency gives ν_0 (E_{Beam})
    - **The damping gives $\delta E/E$**



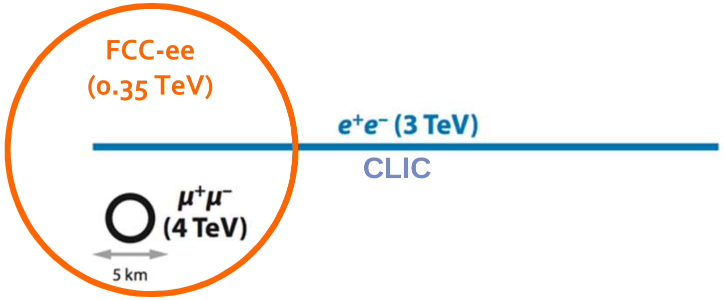
Beam energy and beam-energy spread (3)

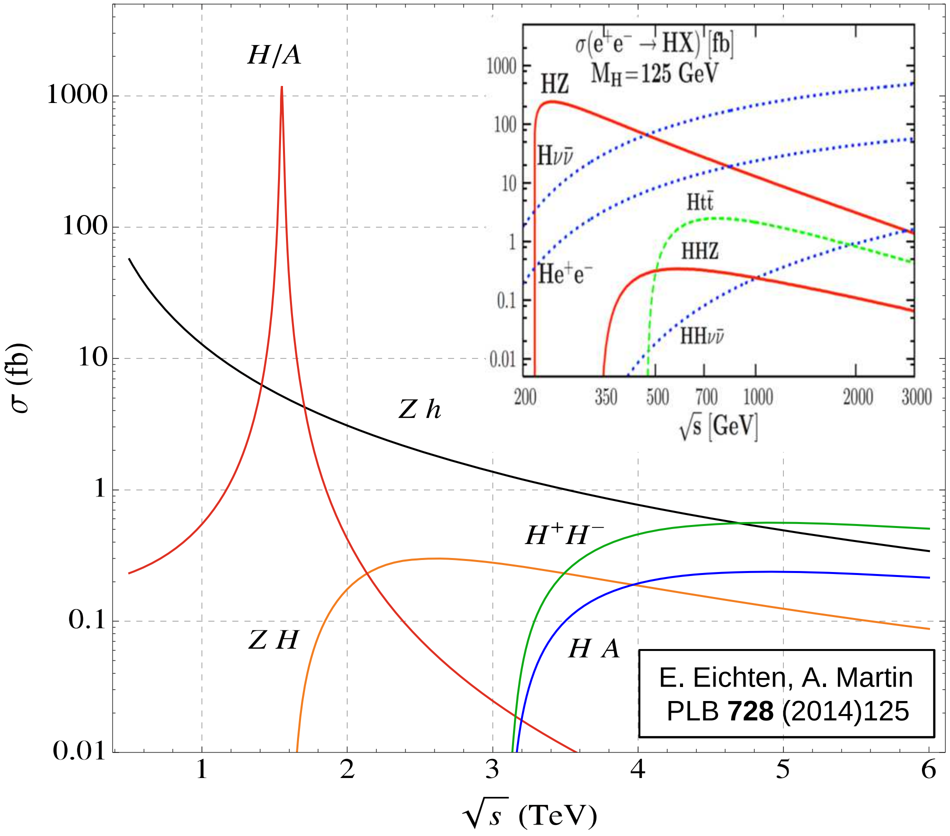
Expected statistical accuracy of the method

- For L = 2×10^{31} cm^{-2}s^{-1} and $\delta E/E = 3\times10^{-5}$, for each "fill" (i.e., 1000 turns)
  - 10^{-7} on the beam energy (6 keV)
    - ➔ Limited to 5×10^{-7} (30 keV) by the precision on $g_\mu-2$ (!)
  - $3\cdot10^{-7}$ on the beam energy spread $\delta E/E$ (1%)
    - ➔ Corresponds to a systematic uncertainty of 0.5% on $\sigma(\mu\mu\rightarrow H)$
    - ➔ Corresponds to a systematic uncertainty of 50 keV on Γ_H
  - 10^{-4} on the polarization value
    - ➔ Negligible impact on $\sigma(\mu\mu\rightarrow H)$
- These uncertainties are appropriately smaller than the statistical precision
  - On the Higgs mass (60 keV)
  - On the Higgs width (170 keV)
  - On the production cross section (1.5%)

Higgs boson production (3)

- **Muons are heavy, similar to protons**
  - Limited synchrotron radiation
    - Can reach very high energy in small rings





E. Eichten, A. Martin
PLB **728** (2014)125

Luminosity

- Similar to linear colliders for $\sqrt{s} > 1$ TeV
  - HHH coupling with similar precision
    - (Also done at FCC-hh)

Energy

- Can go to higher energy
  - Advantage for 2HDM (e.g., SUSY)
    - Heavy Higgs with $\mu^+\mu^- \to$ H,A

- $\sqrt{s} \sim 6$ TeV possible in the Tevatron tunnel

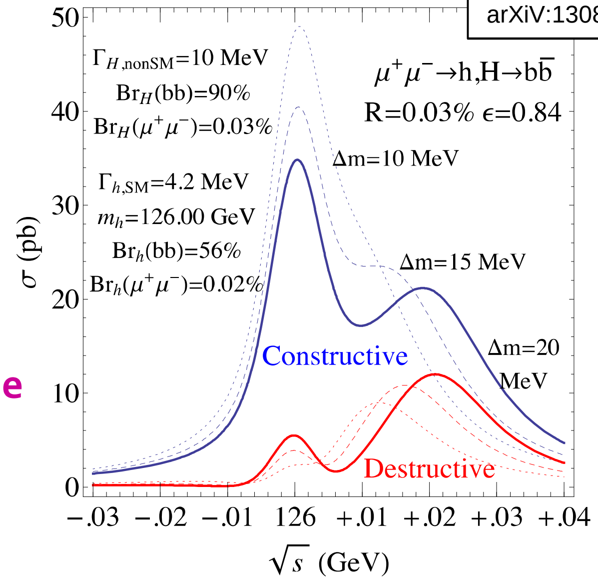
Additional Higgs bosons (1)

- **Is H(125) made of several quasi-degenerate Higgs bosons ?**
  - At LHC, the typical m_H resolution in the $H \to ZZ^* \to \mu\mu$ channel is ~1 GeV
    - Two quasi-degenerate Higgs bosons difficult to infer if ΔM < few 100 MeV

Similar at FCC-ee (Recoil mass)

  - Would be a piece of cake at a muon collider
    - Examples shown for
      - ➔ ΔM = 10, 15, 20 MeV
      - ➔ Destructive/constructive interference
      - ➔ Similar coupling to muons and b quarks
      - ➔ might be visible at FCC-ee (ZH) by difference in recoil mass for different decay modes.

Snowmass 2013
arXiV:1308.2143



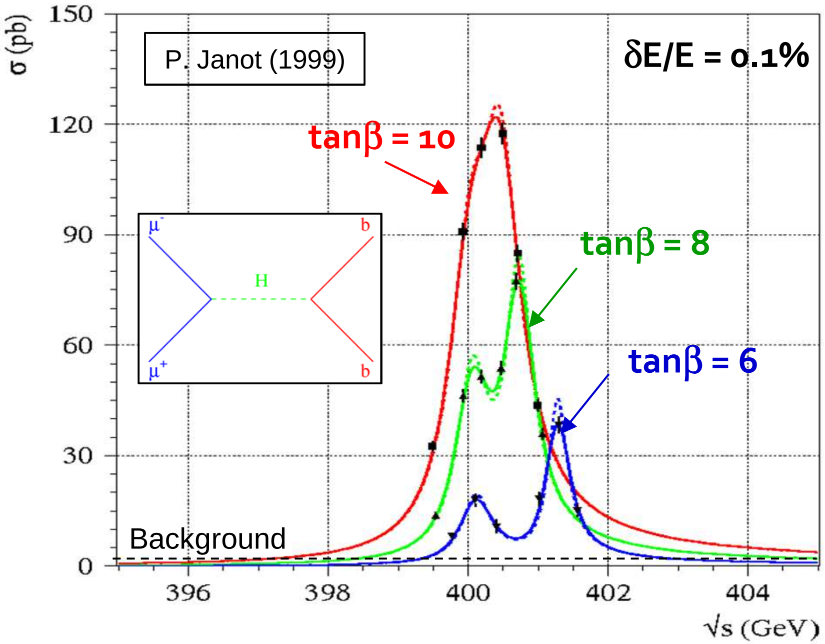
    - Lineshape sensitive to ΔM ~ MeV
      - ➔ If both Higgs bosons couple to μ and b/W
  - Probably observable at ILC FCC-ee via pair production with √s > 250 GeV (to be studied)
    - $e^+e^- \to$ hA present at tree level with large cross section (A pseudoscalar)
    - [$e^+e^- \to$ hH only at loop level with a few ab cross section (H scalar)]
      - ➔ A small mass difference is not measurable this way

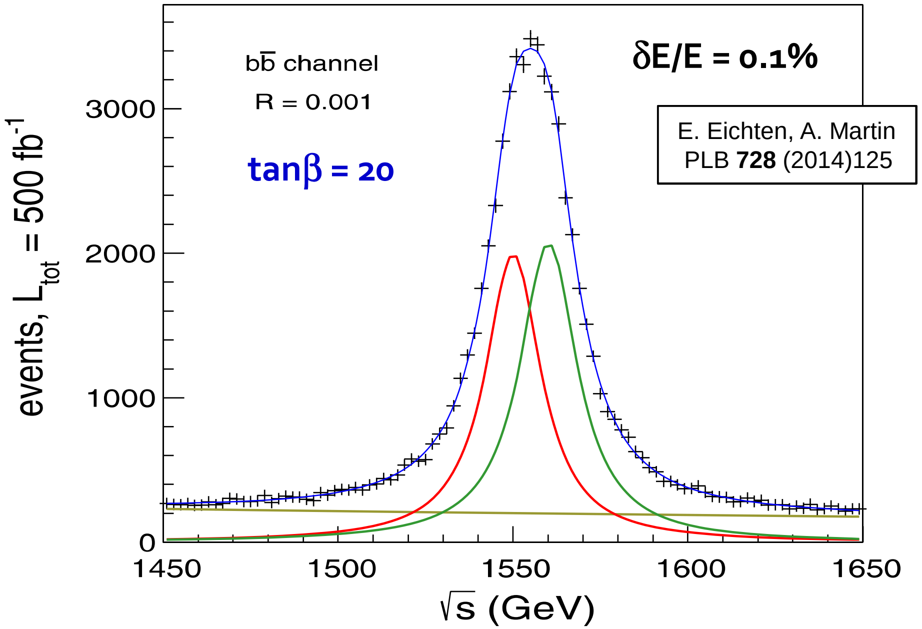
A. Djouadi et al.
PRD **54** (1996) 759

... but the pair production proves the existence of two (three) states

Additional Higgs bosons (2)

- Can be applied to heavier H and A in 2HDM (e.g., from SUSY)
  - Example 1: m_A = 400 GeV Example 2: m_A = 1.55 TeV


P. Janot (1999)


E. Eichten, A. Martin PLB **728** (2014)125

- Notes:
  - Higgs width of the order of 0.1 to 1% of the Higgs mass
    - ➔ δE/E ~ 0.1% enough, large integrated luminosities (100's fb^{-1} or ab^{-1}) possible
  - Each value of m_A correspond to a specific ring diameter
    - ➔ Need to know the mass before designing the ring!

FUTURE FACILITIES

-- my personnal conclusions

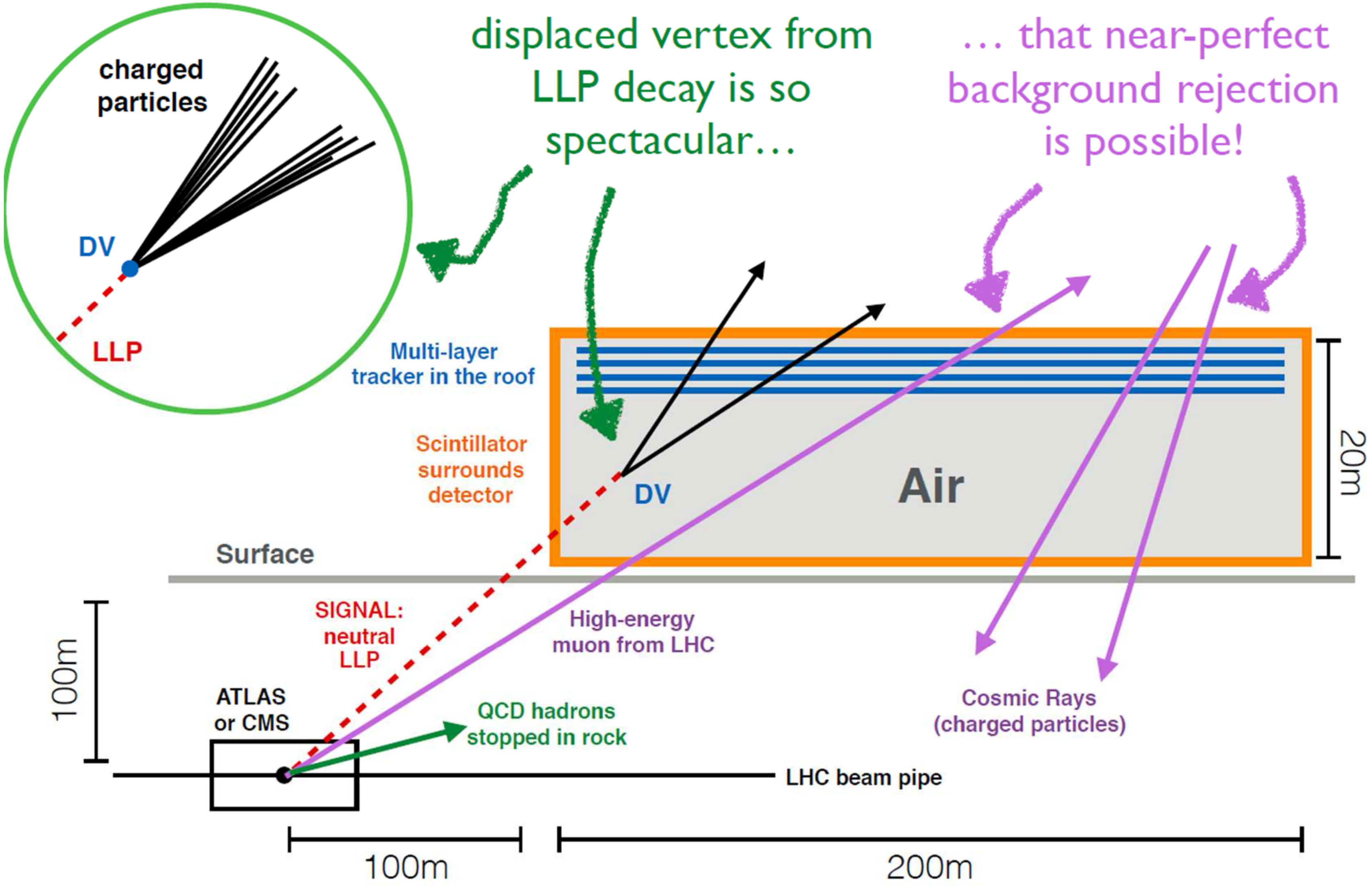
1. The present physics landscape is dominated by large uncertainties about the next energy scale.
   This is true for all scenarios including the very likely one of right-handed neutrinos

2. High precision measurements of the known heavy particles of the SM (Z, W, H, top) have the potential to reveal the presence of new physics at energies of up to 100 TeV and sometimes more. *This is the main physics case for the circular e+e- machines.*
   The circumference has to be larger than ~80km
   They also offer the best potential for particles with very small couplings.

3. A high energy hadron collider offers very large statistics and can complete the precision measurements (e.g. g_{HHH}) and offer unequalled search for particles with SM couplings
   This requires a large energy step such as that proposed by the FCC-hh
   The synergies and complementarities offered by the FCC ee/hh/AA/eA are remarkable

4. If a new particle with SM couplings is found by a hadron collider the case for a linear e+e- collider or a muon collider may become very strong.

Long Lived Particles will be hunted actively!



NB this is recent – there was no mention of this at the kick-off meeting in Geneva!

Curtin

Dark matter searches

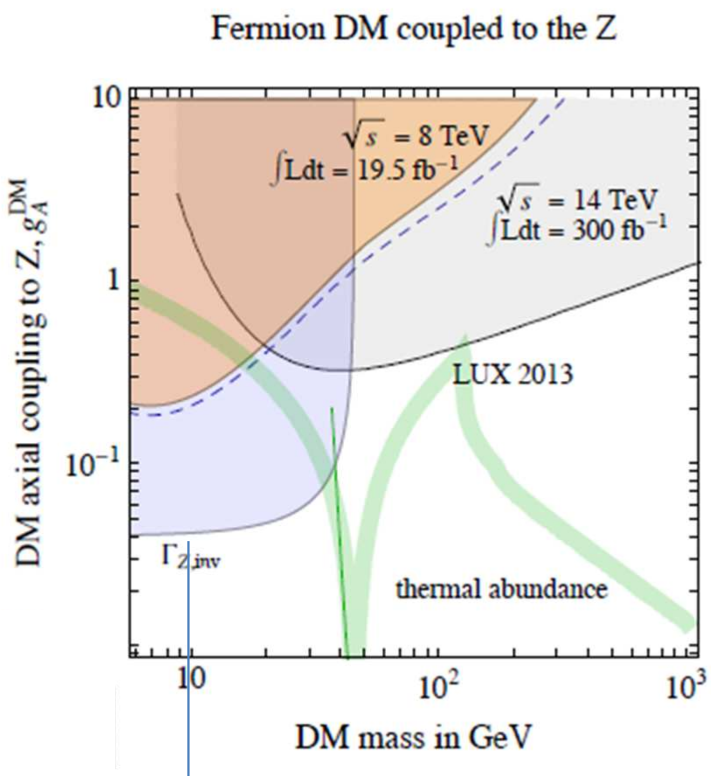
‘sterile neutrinos’

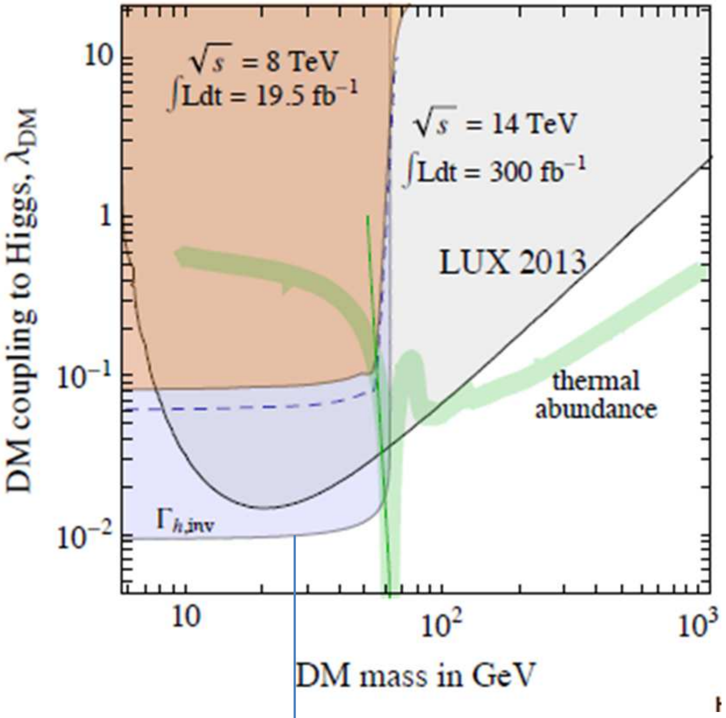
’invisible Higgs’ decay   work in progress: what systematics are needed at FCC-hh to match the e+e- measurement. Can one improve on either (tag ZH with Z-> light quarks + inv)

‘LSP searches etc…’ FCC-ee unbeatable for SUSY like couplings
– do we understand the gaps etc…?

Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

(Giudice)





$\Delta N_\nu = 0.0004$?
from e+e-→$Z\gamma$

Will improve these by large factors!

$\Delta\Gamma_{h,inv}/\Gamma_{tot} < 0.19\%$

We are making significant progress towards a demonstration that

The combination of the FCC machines offers outstanding discovery potential by exploration of new domains of

-- both **direct search**,

and

-- **precision**

  - -- at high energy and
  - -- at very small couplings