CERN physics programme and neutrinos

E.Elsen

Director of Research and Computing

VII International Pontecorvo Neutrino Physics School, August 20 - September 1, 2017, Prague Czech Republic

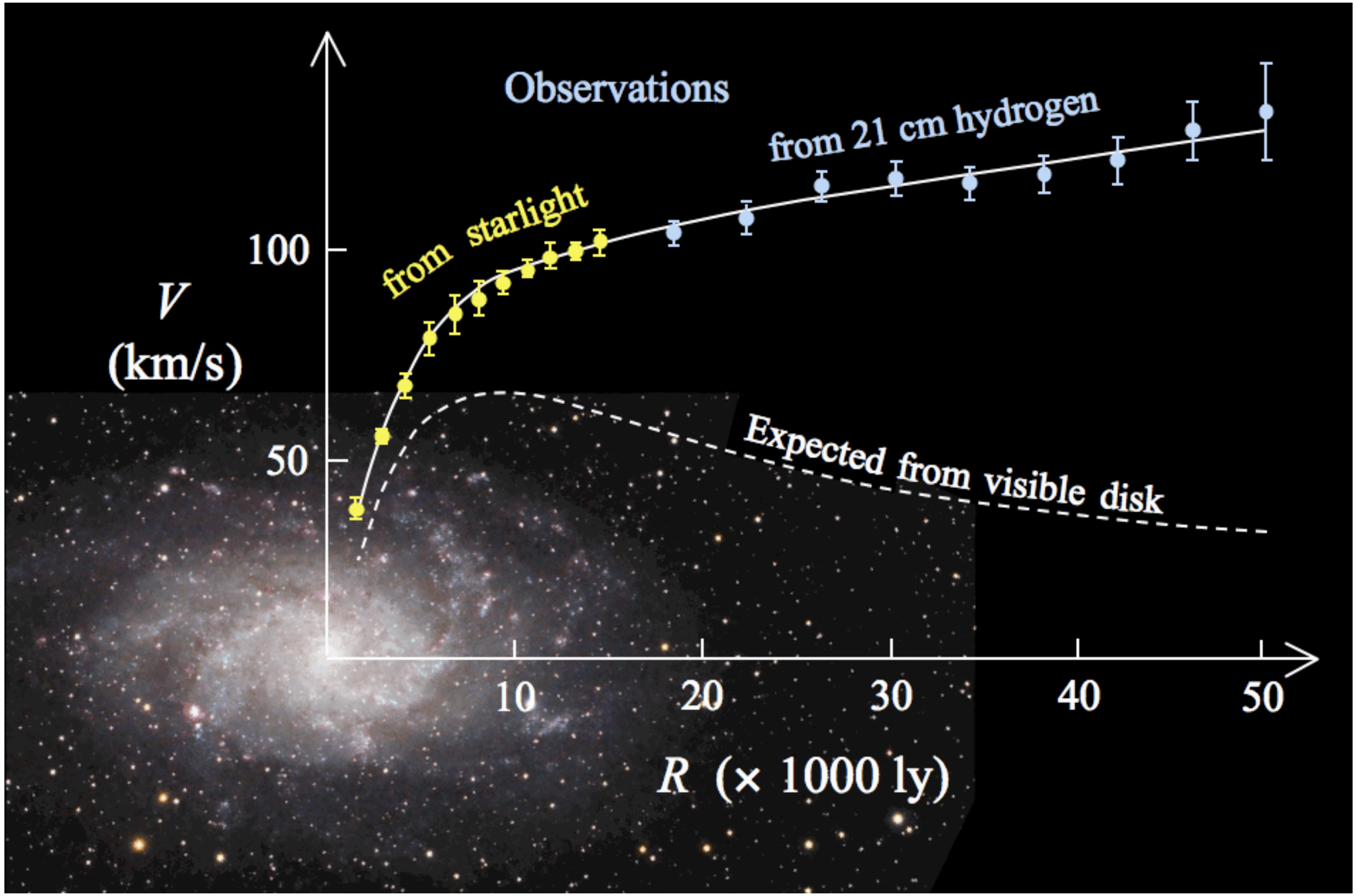
There must be more than the Standard Model…

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
PLANCK
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
today

Rotational Curves of Galaxies

- Outer rim of galaxies is seen to rotate faster than expected from Newtonian mechanics
    - there is more mass than is seen interacting

Dark Matter

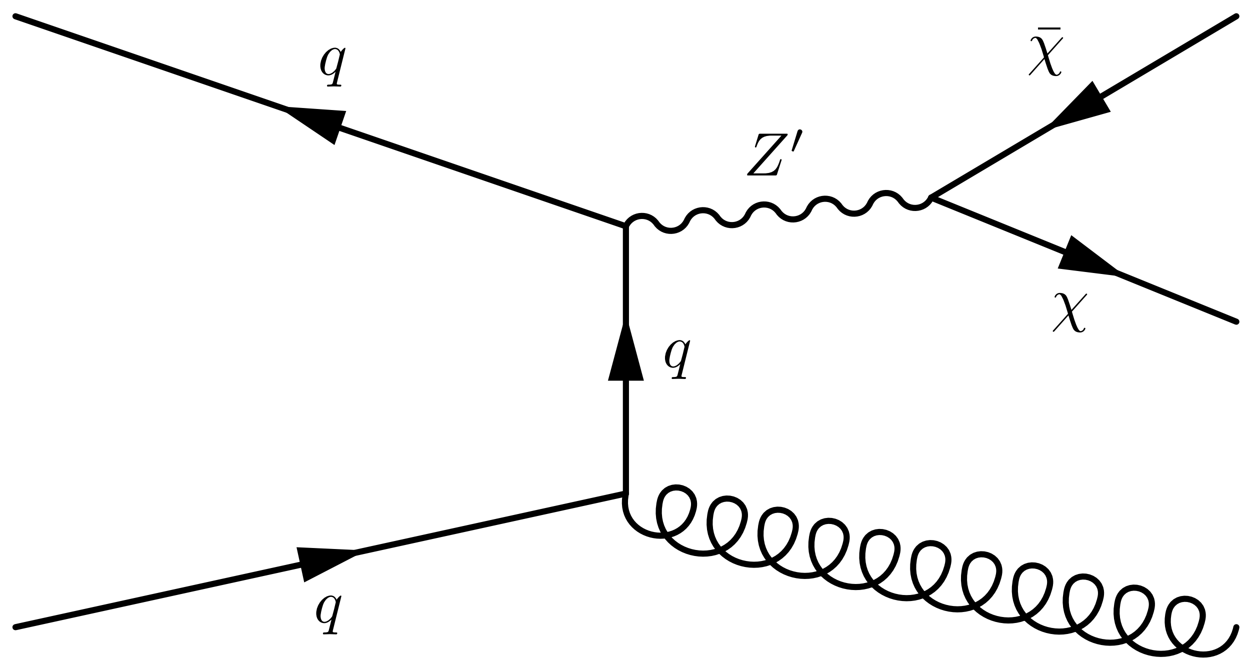


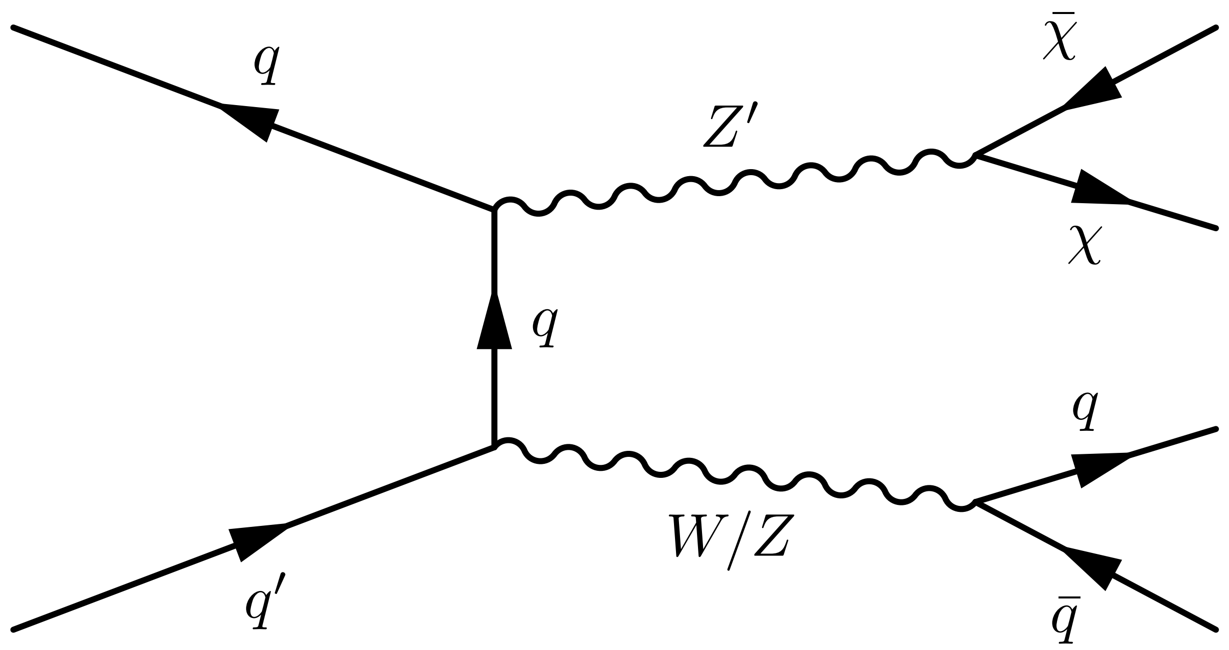
…executing the ongoing (worldwide) Strategy for Particle Physics

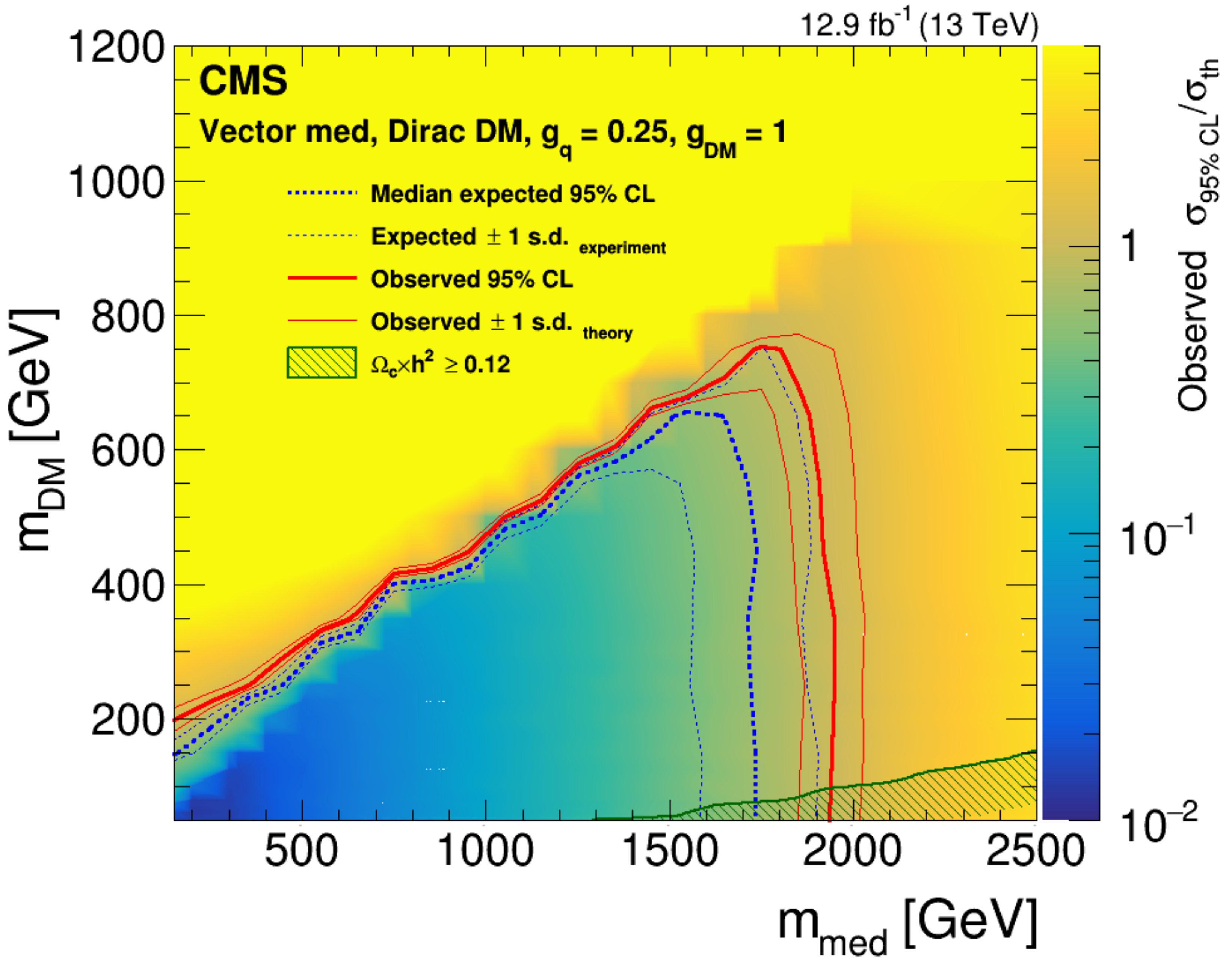
LHC as #1 tool…

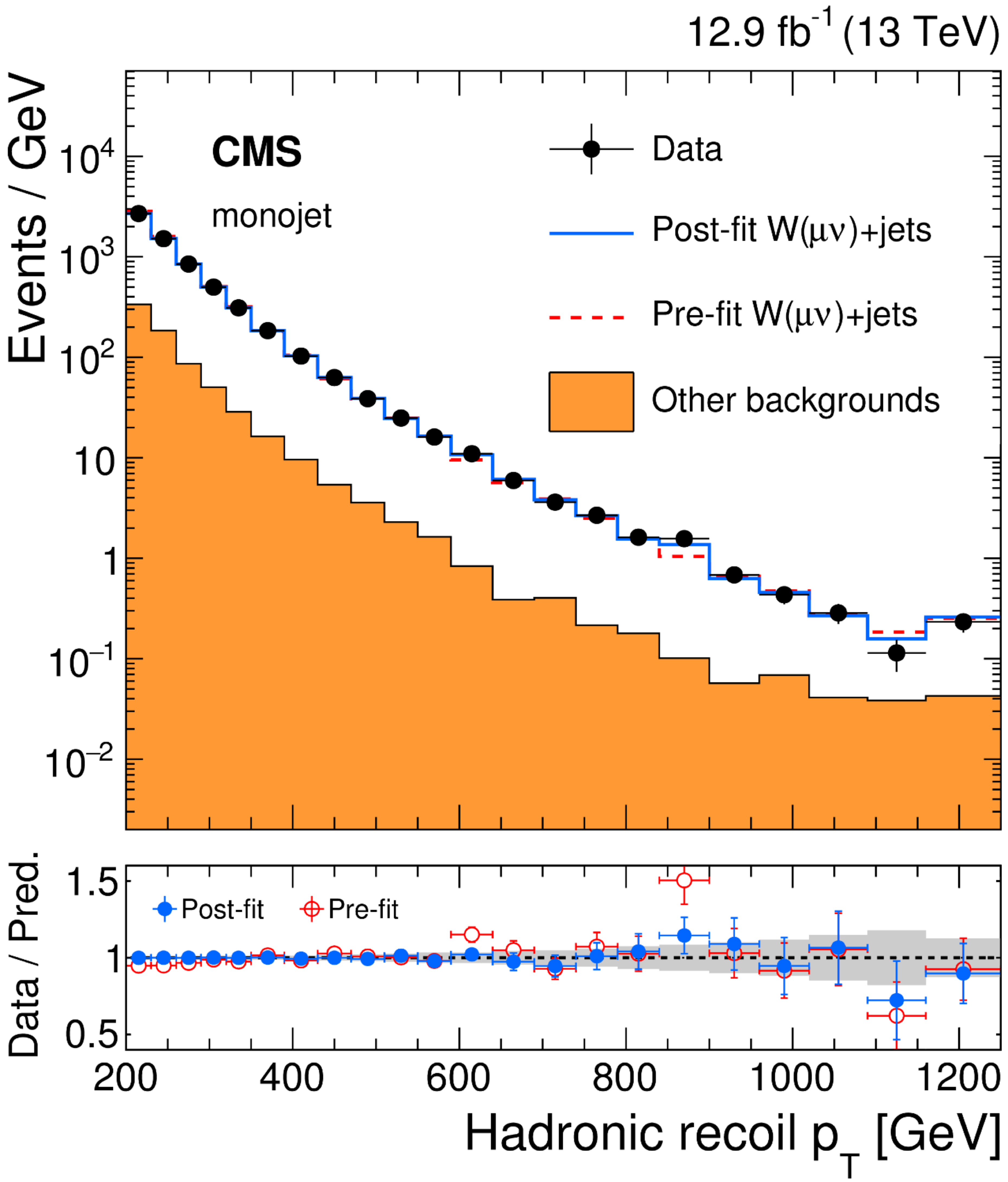

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Example of Dark Matter Search at the LHC









LHC Physics Programme in a broader context

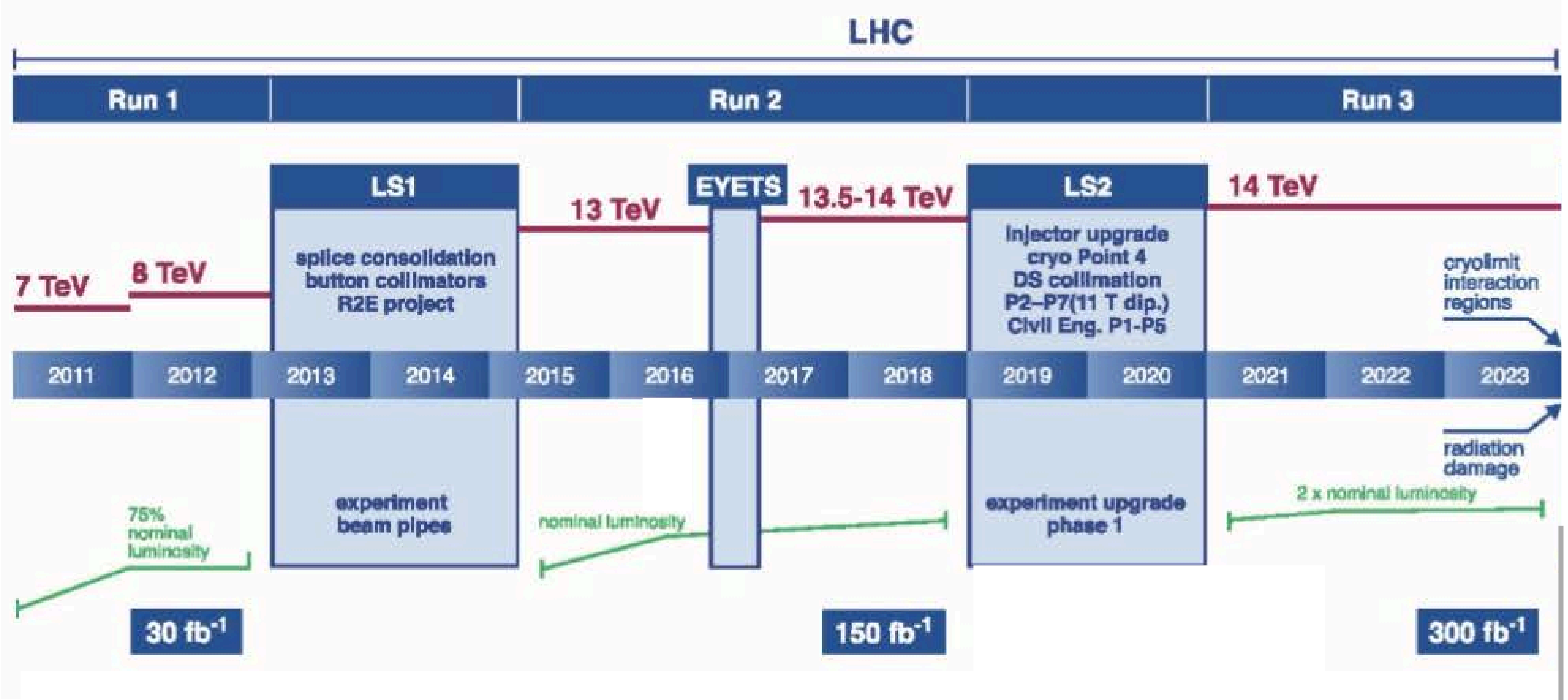
Goal of LHC – Identify the Physics beyond the Standard Model

- Explore an energy regime that has not been chartered before
    - have entered 13 TeV regime in *production* mode
- Look for small deviations (small couplings) from the Standard Model
    - Precision measurements of (rare) processes

Luminosity need in both cases

- 14 TeV *after* Long Shutdown 2 and possibly 15 TeV (study group)
- Higgs particle as a portal

LHC schedule



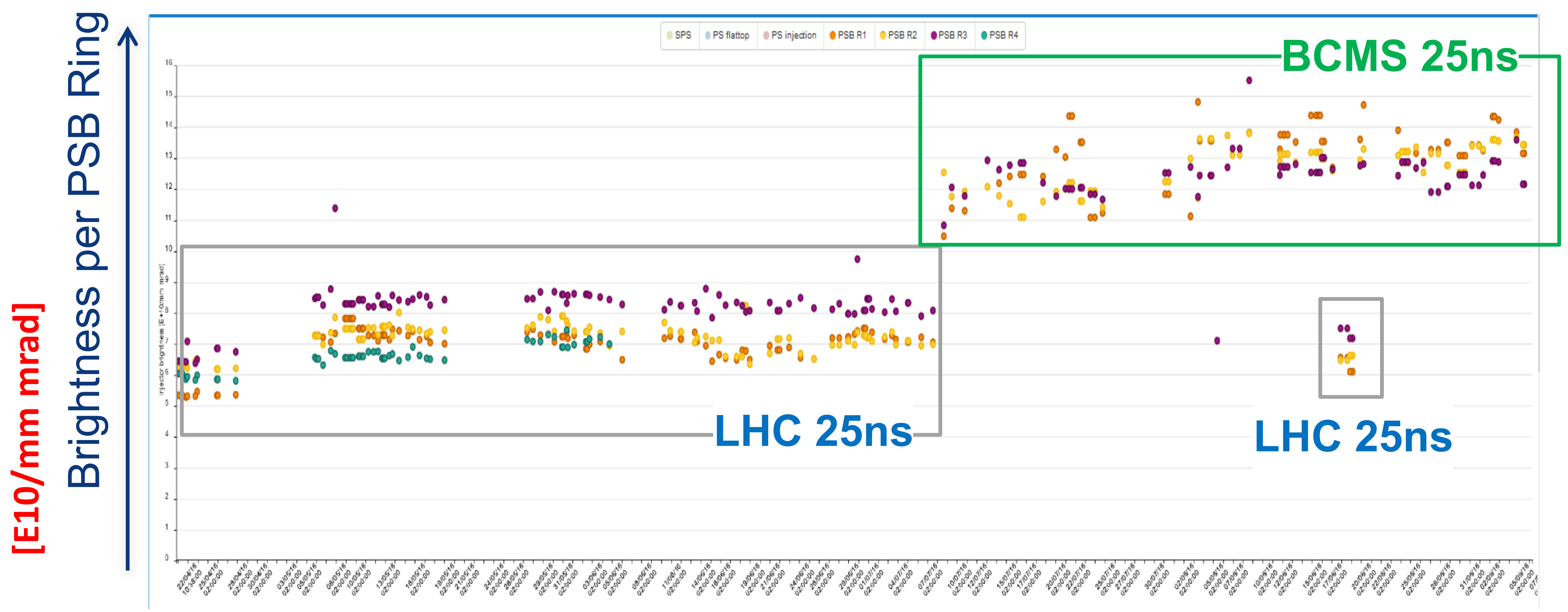
HL-LHC
High
Luminosity
Phase of LHC

Substantial upgrades for ALICE and LHCb; preparatory upgrades for ATLAS and CMS including civil construction

end of original LHC

Extraordinary LHC Performance in 2016

- Batch Compression Merging and Splitting scheme is boosting bunch brightness: bunches collide more effectively → increased pile-up

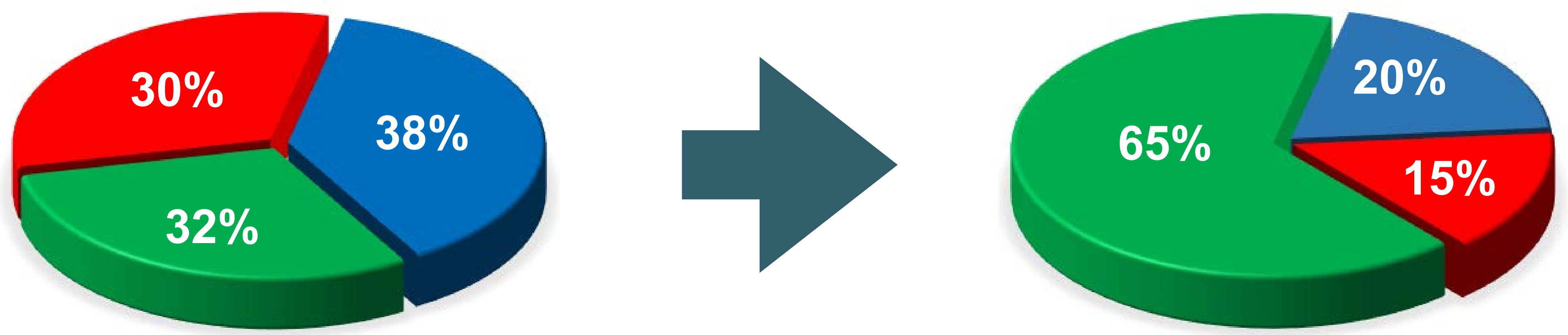


- Machine availability has essentially doubled (meticulous attention to operation)

- Considerably more physics data to digest

LHC Status

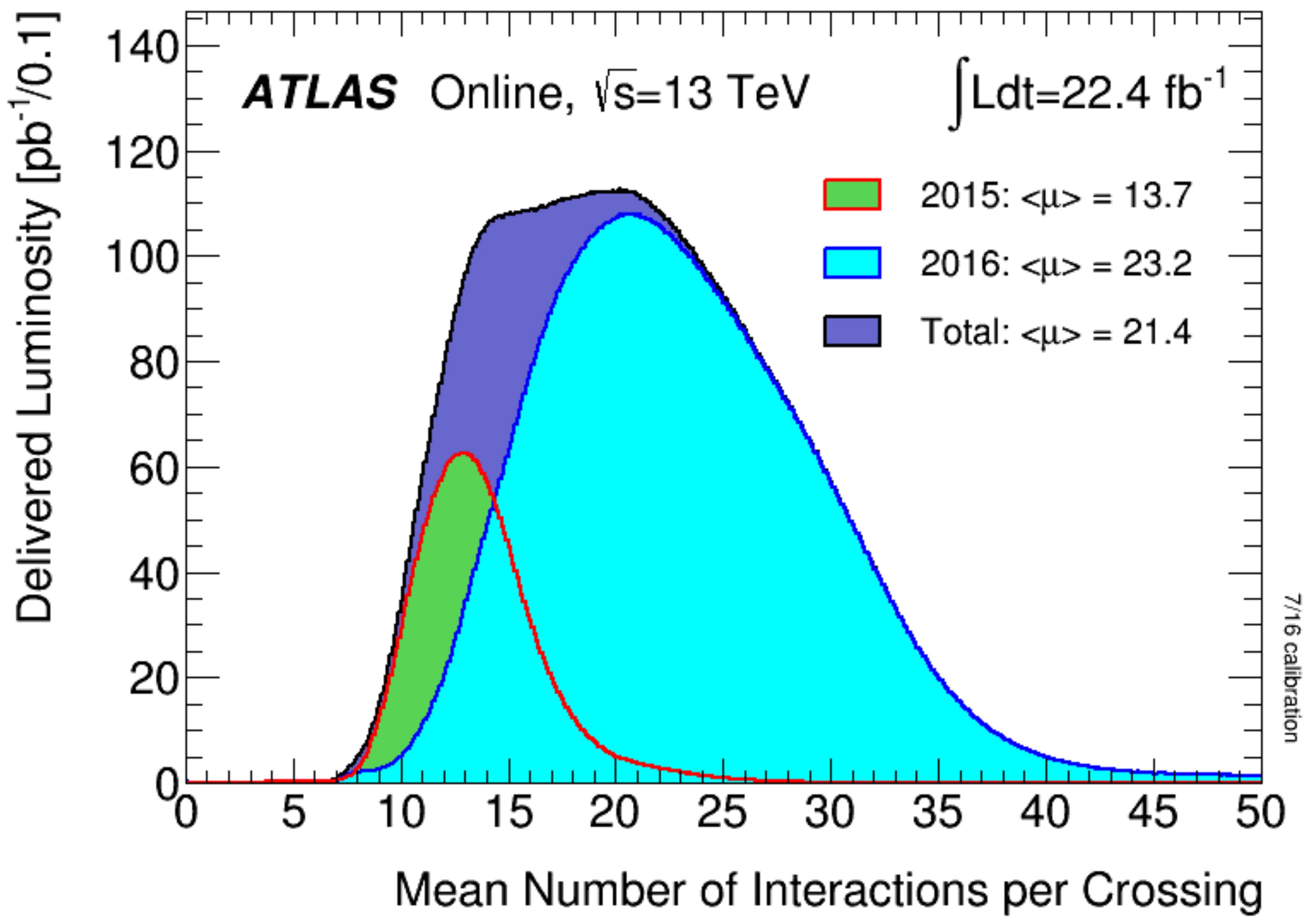
- Stable beam
- Faults
- Preparation and Injection

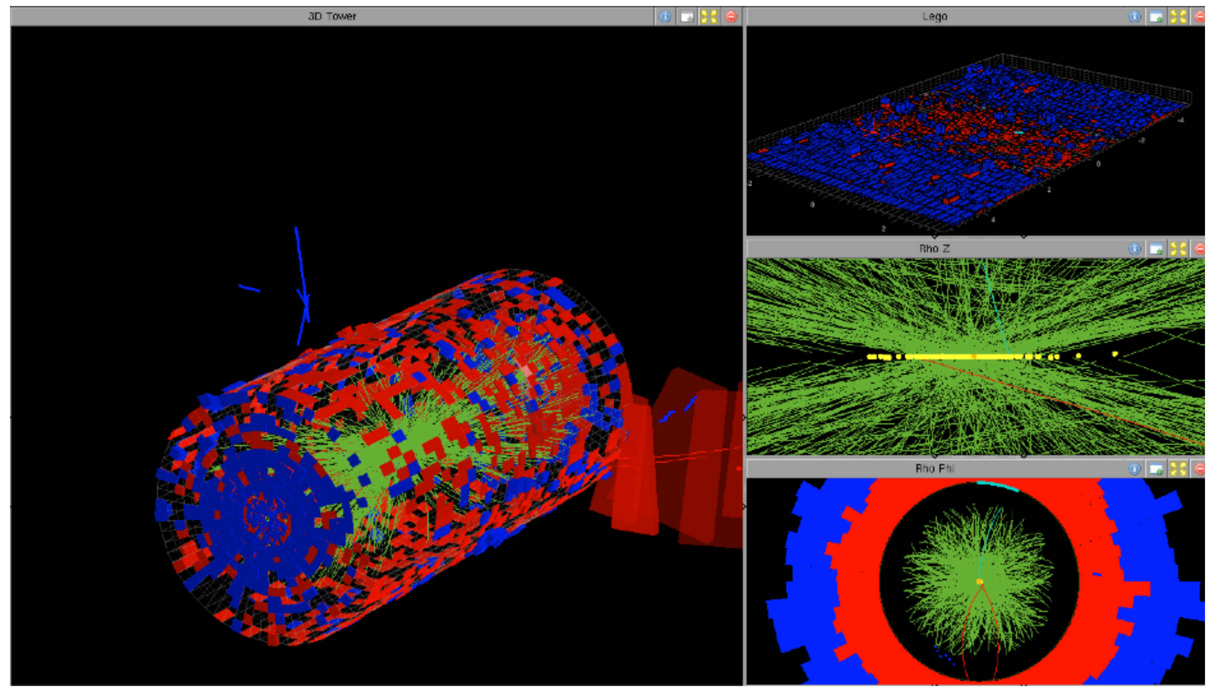


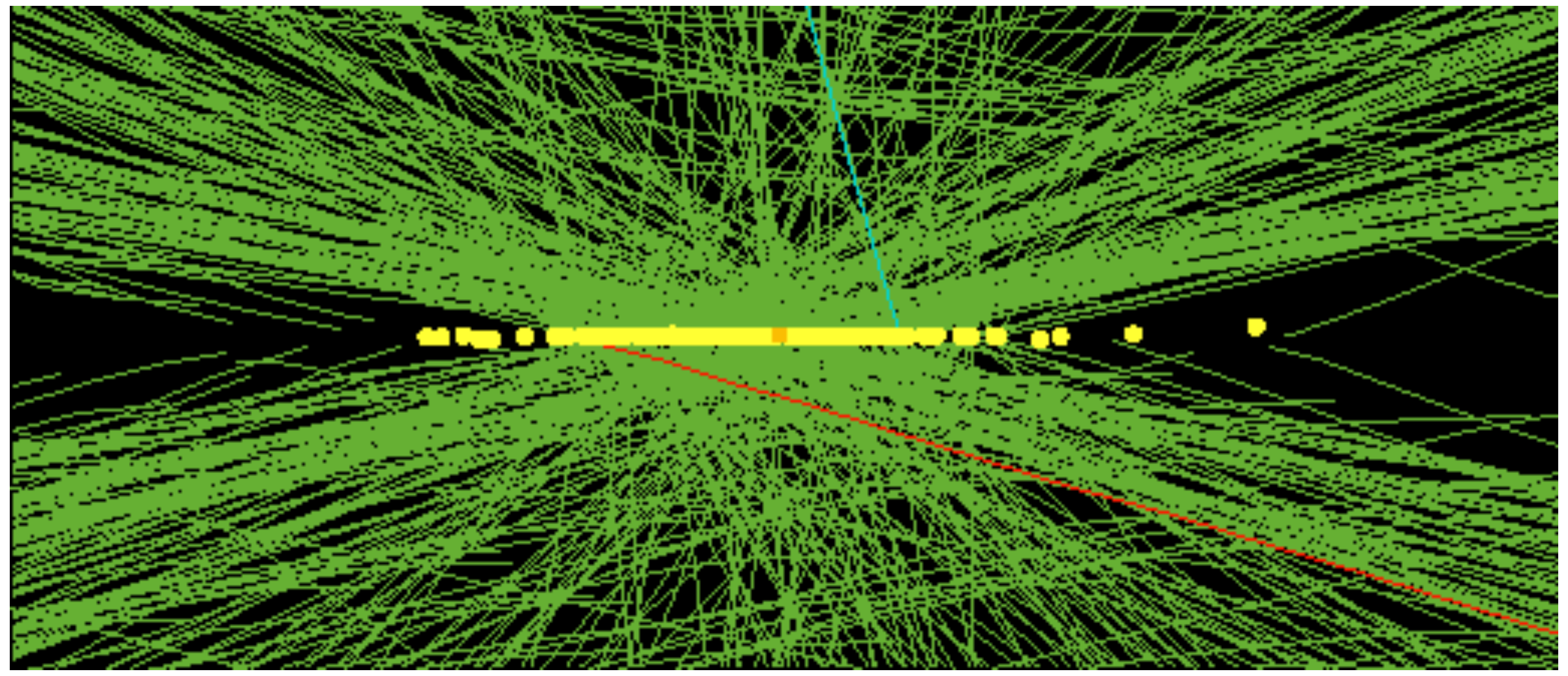
2015 first part of 2016

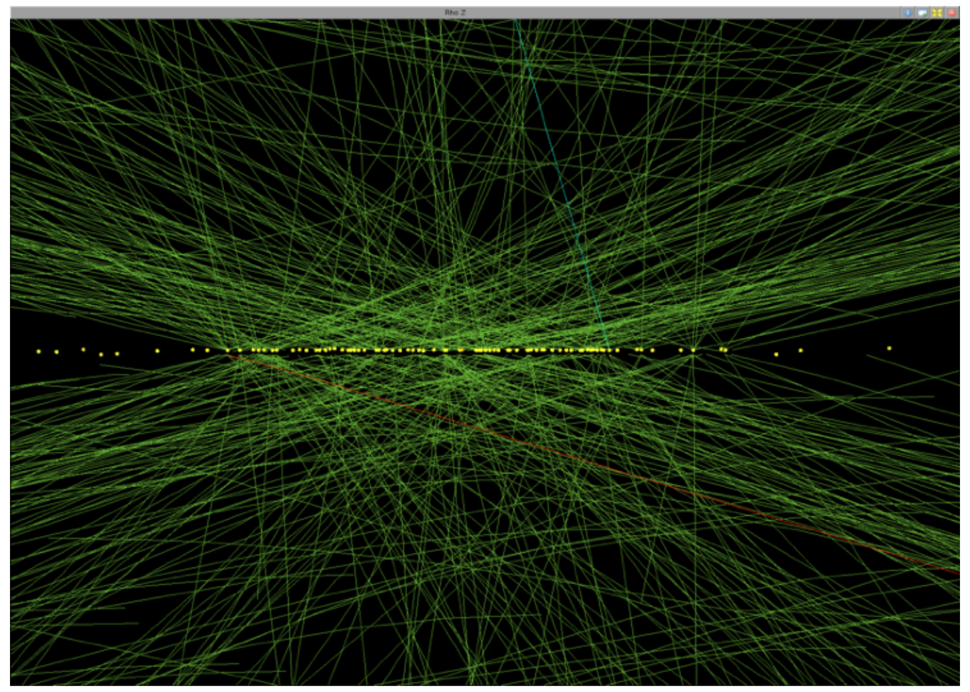
Experimental challenge - pile-up

- With every hard interaction of protons many other protons in the bunch collide
  - Experiments have to separate hard processes from the rest



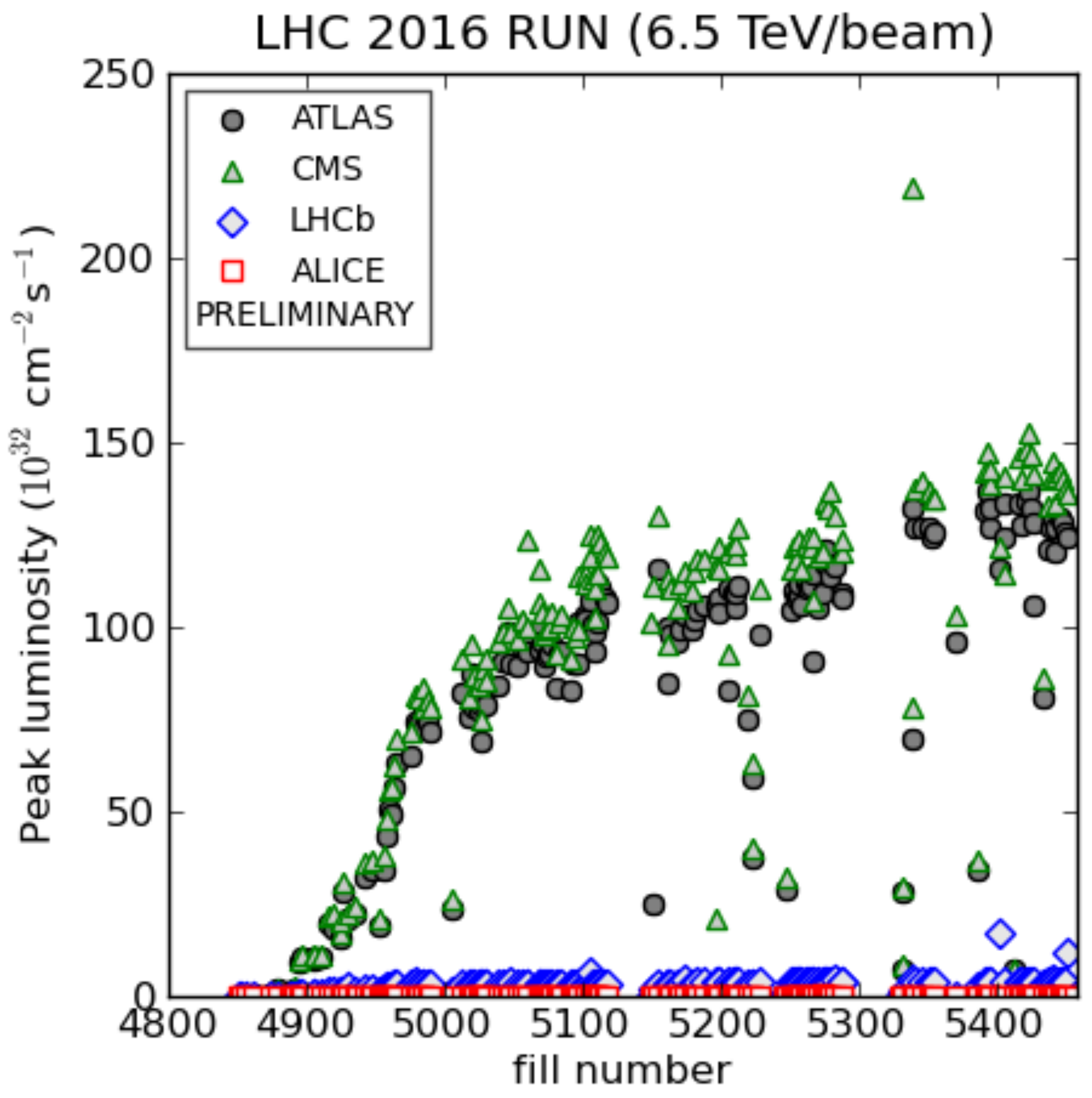


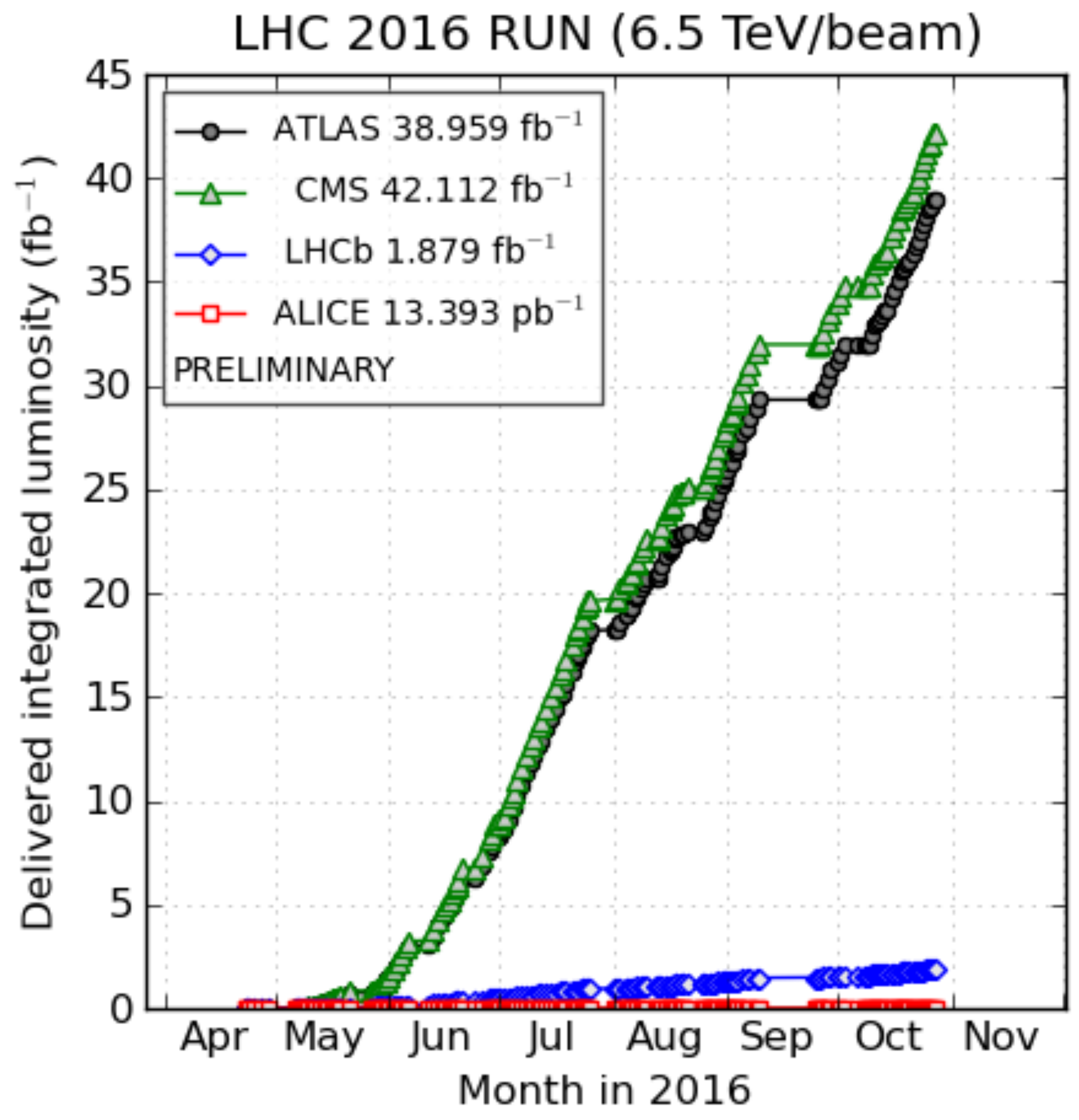


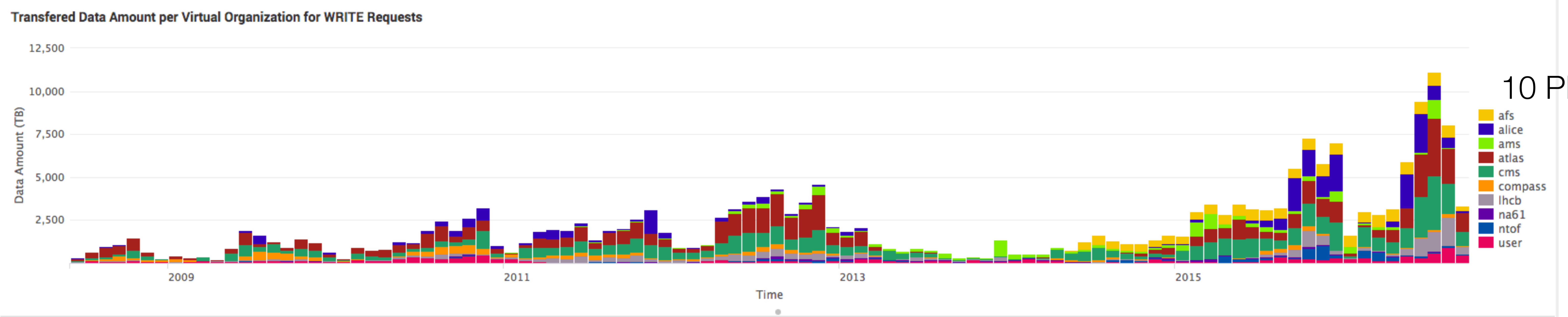


LHC Luminosity 2016 in pp

- Instantaneous (peak) luminosity drives pile-up
- Availability leads to increased computing and data transfer rates
    - >10 PB/month

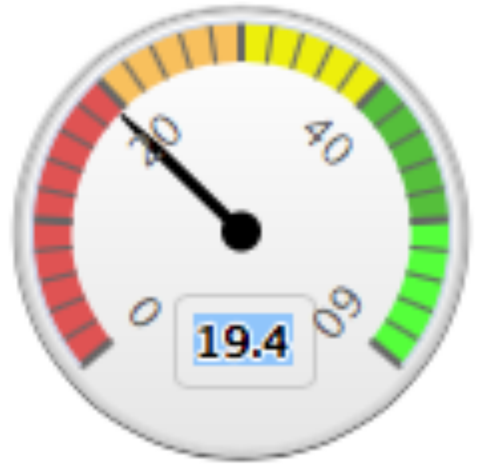




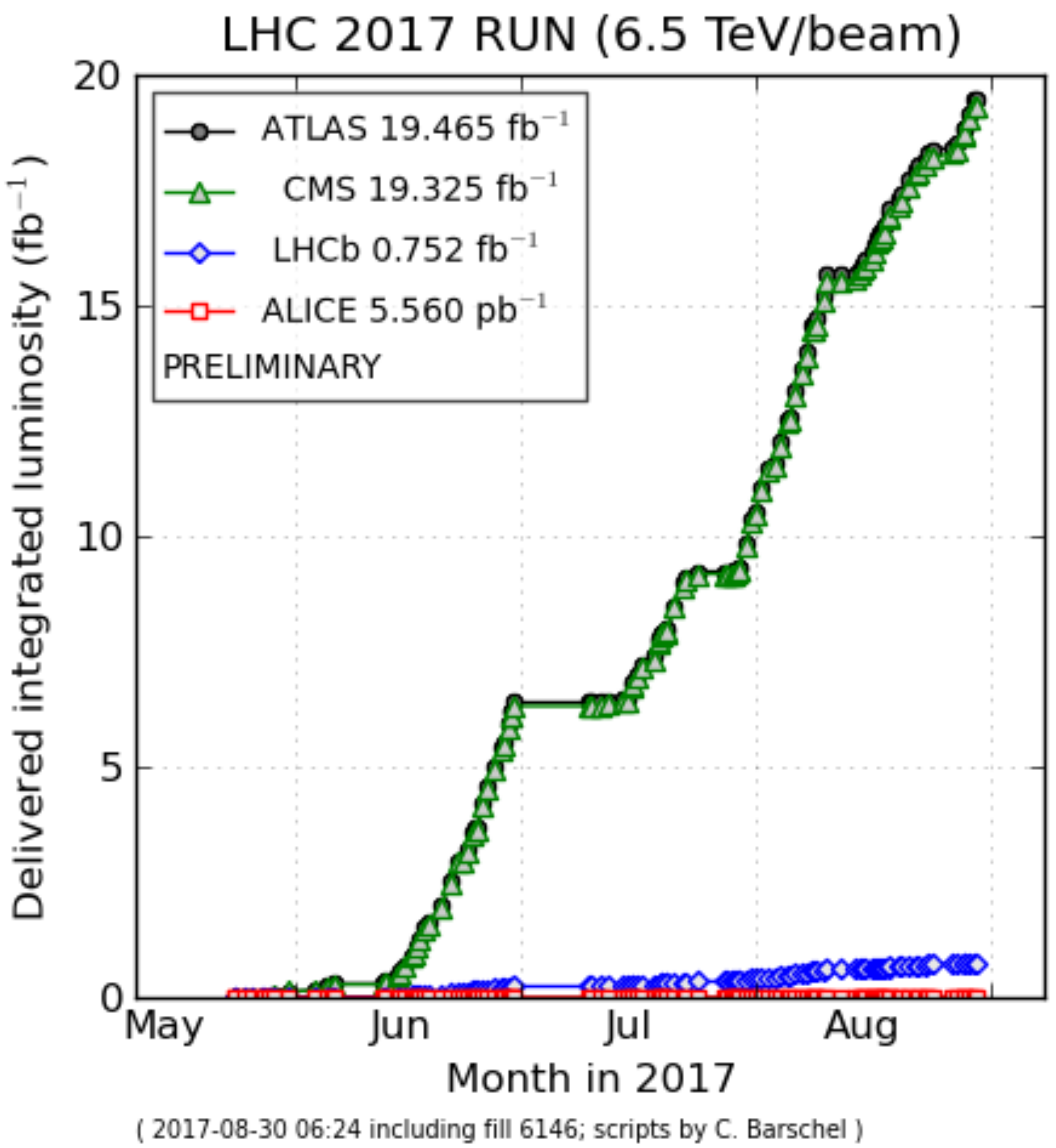


10 PB/m

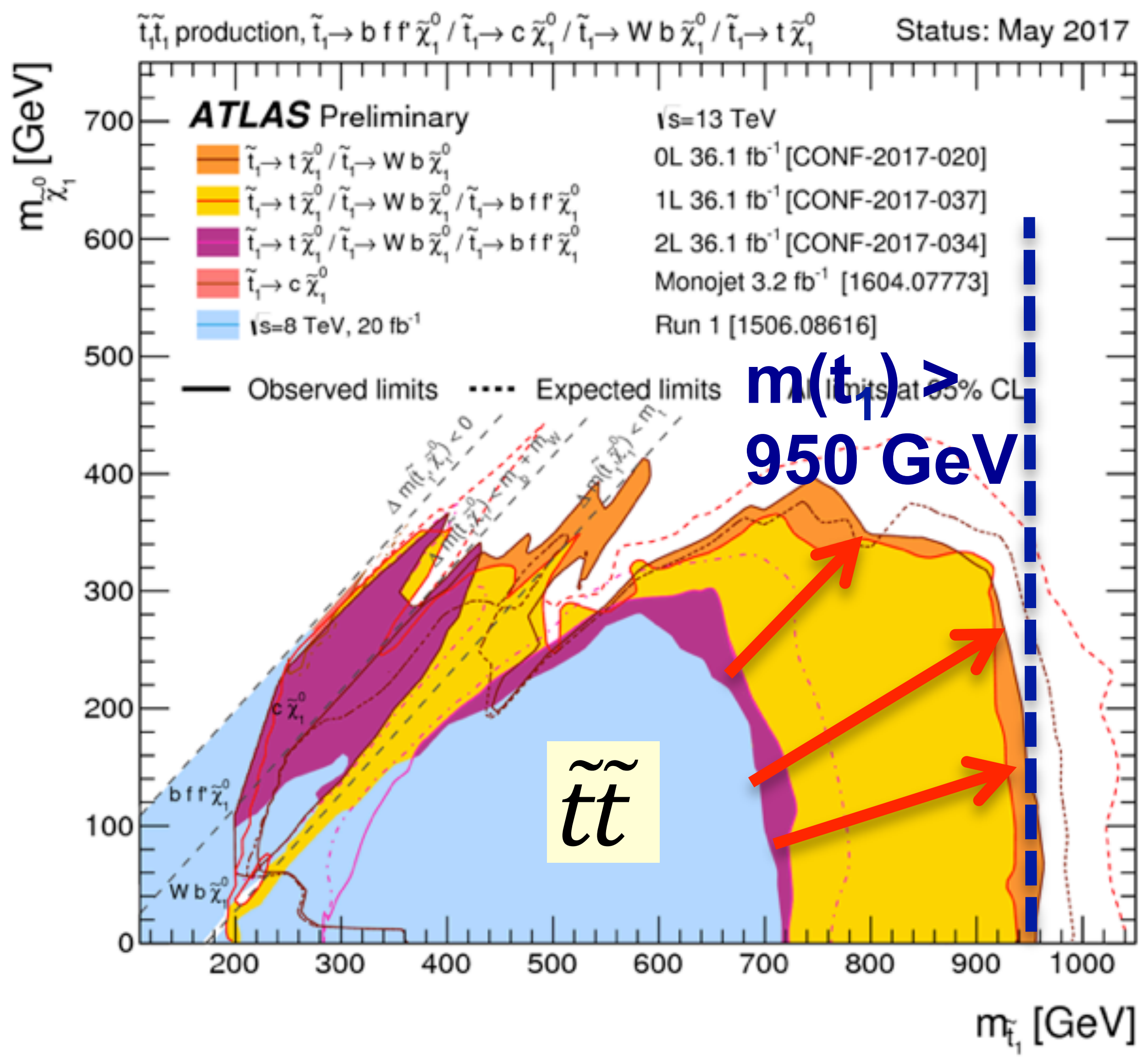
LHC Run 2017 in full swing

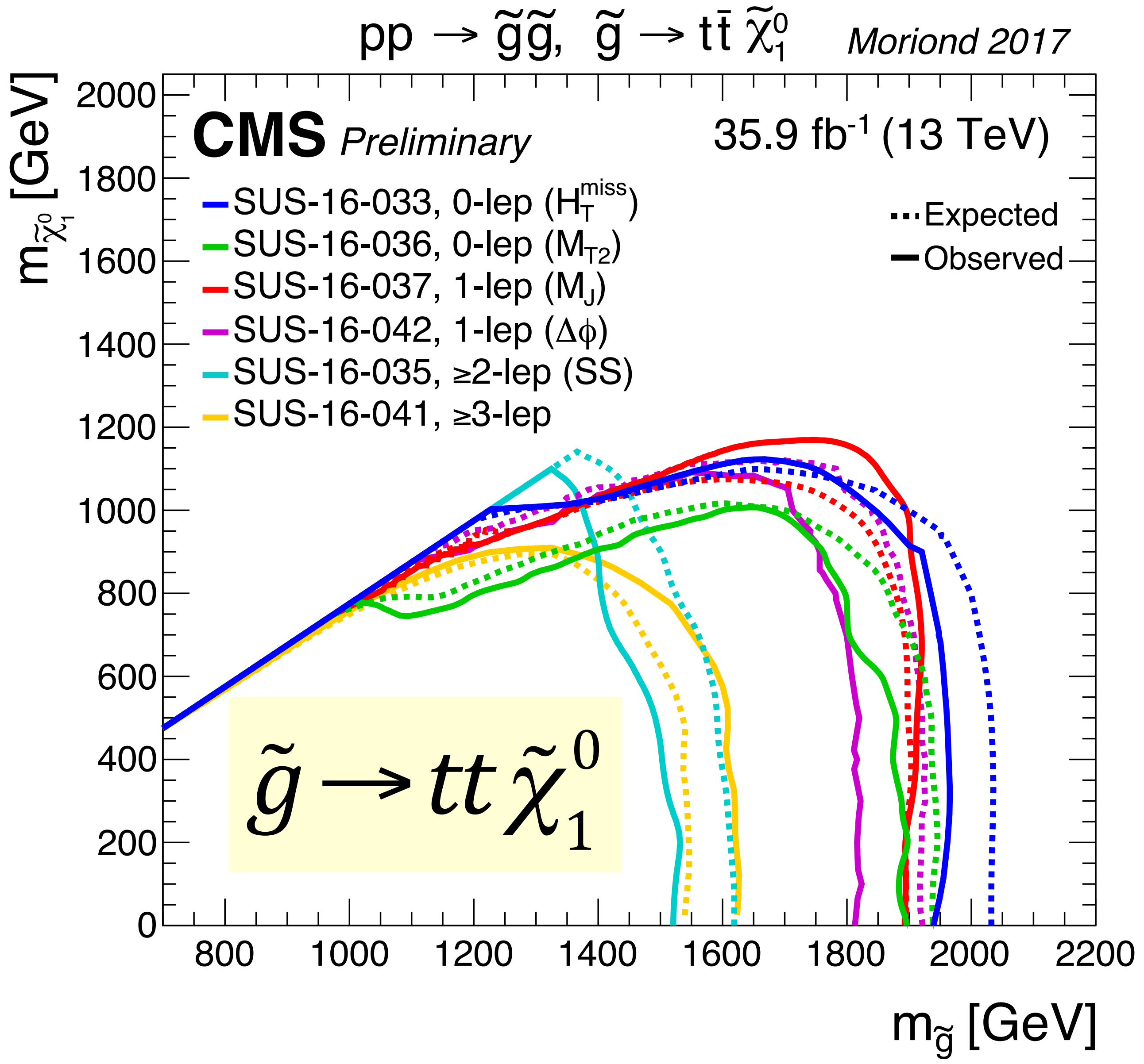


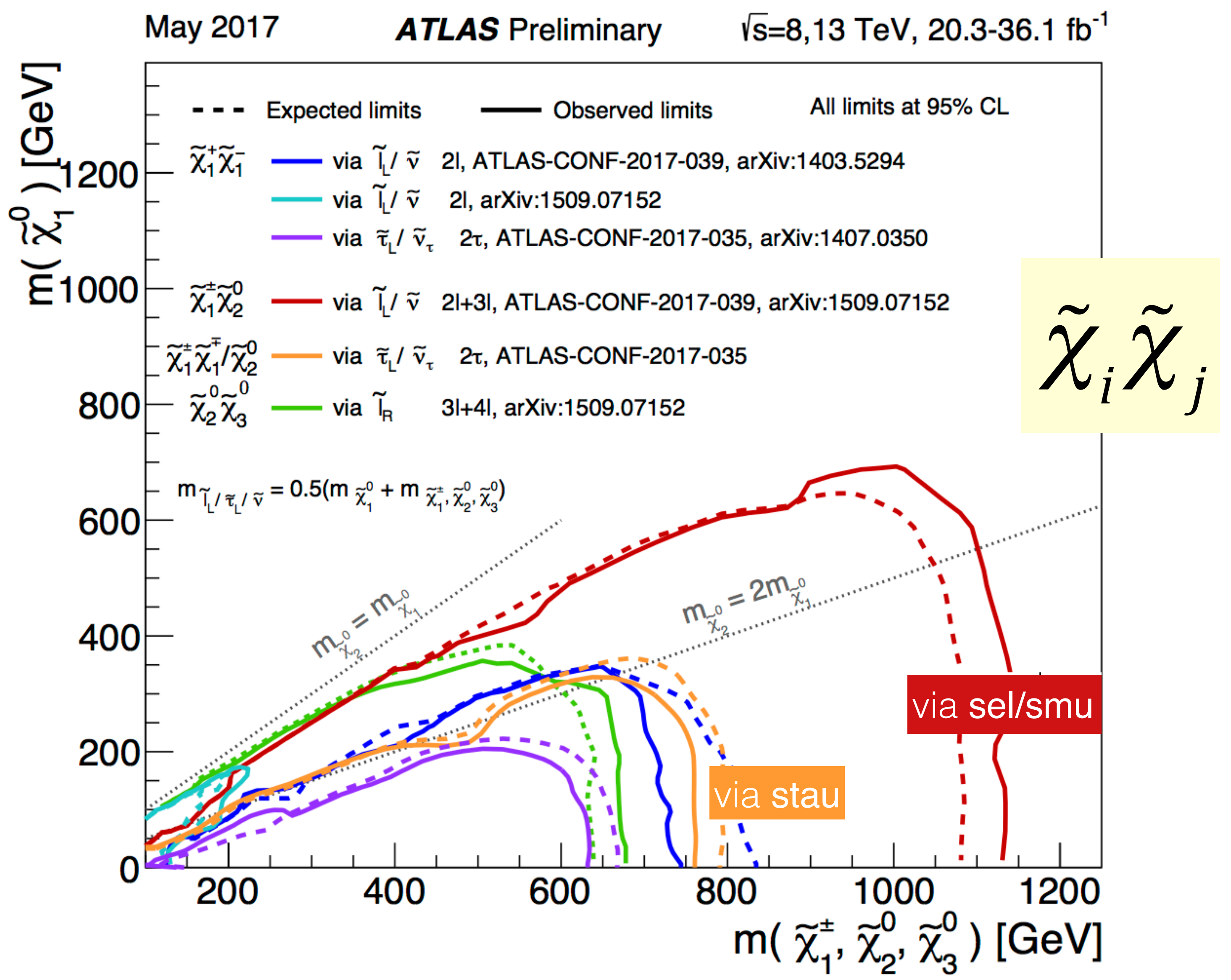
- LHC resumed full operation after extended winter stop which saw replacement of
    - SPS dump (vacuum leak)
    - *sick* LHC dipole in sector 12
- but observe sudden background bursts near quadrupole 16L2 leading to occasional dumps probably due to residual N_2 (intensity limitation)
- Experiments carried out their upgrades
    - CMS pixel detector, etc.

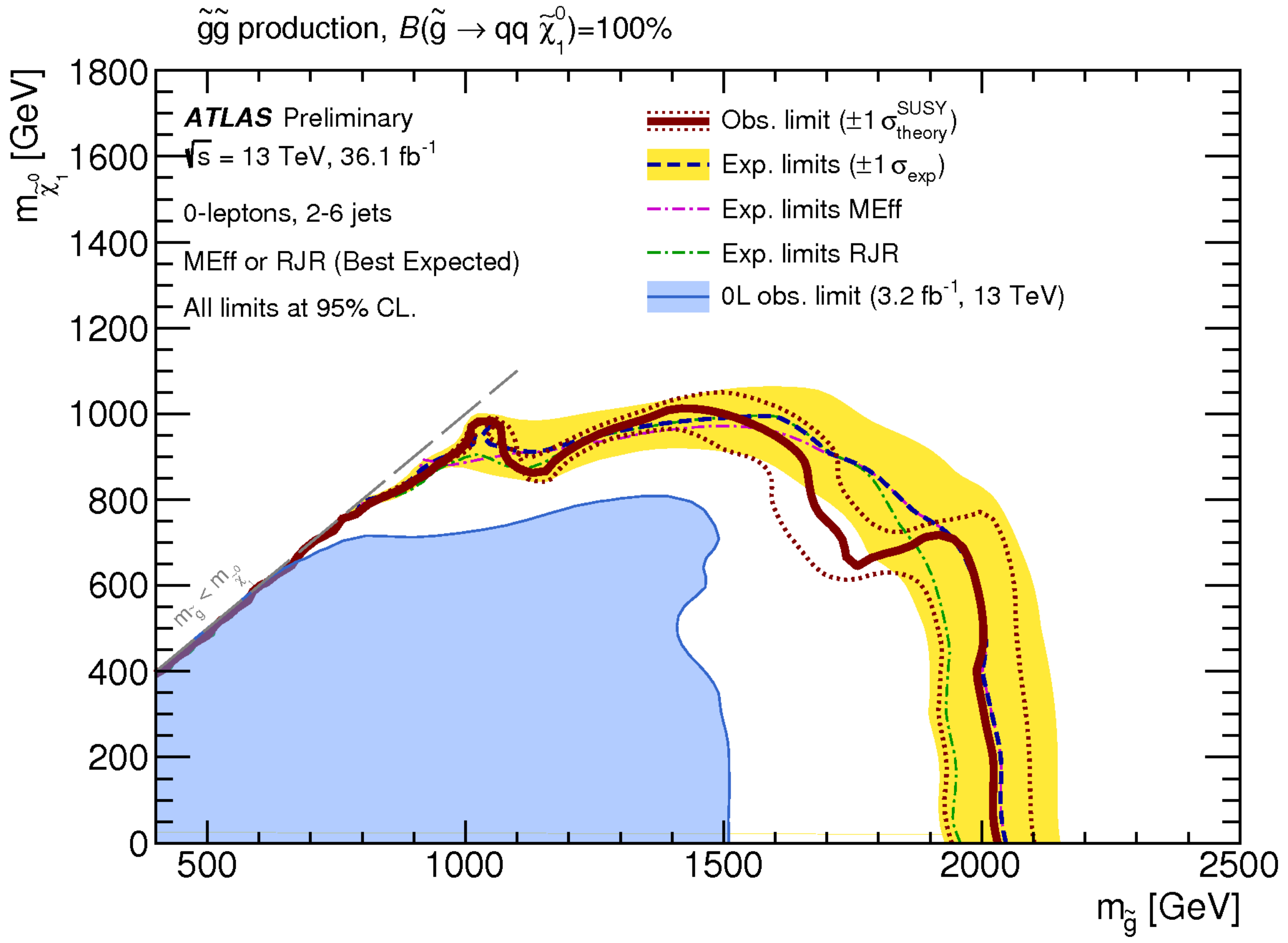


Extending mass reach – example searches for Supersymmetry

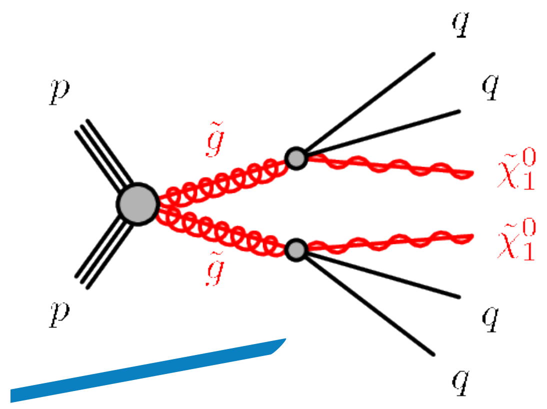








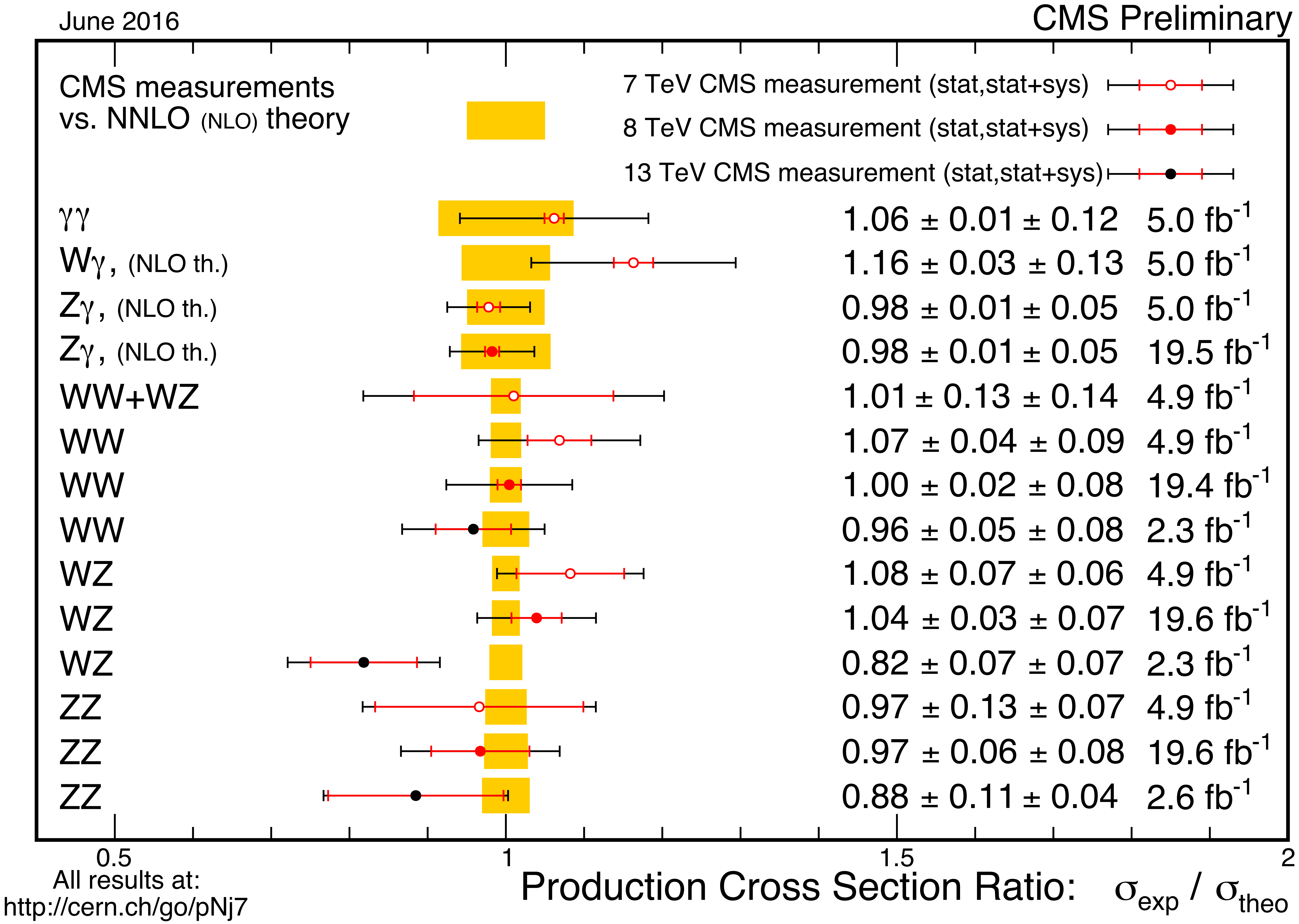
ATLAS-CONF-2017-022



reaching well into TeV region

Vector boson and theoretical understanding

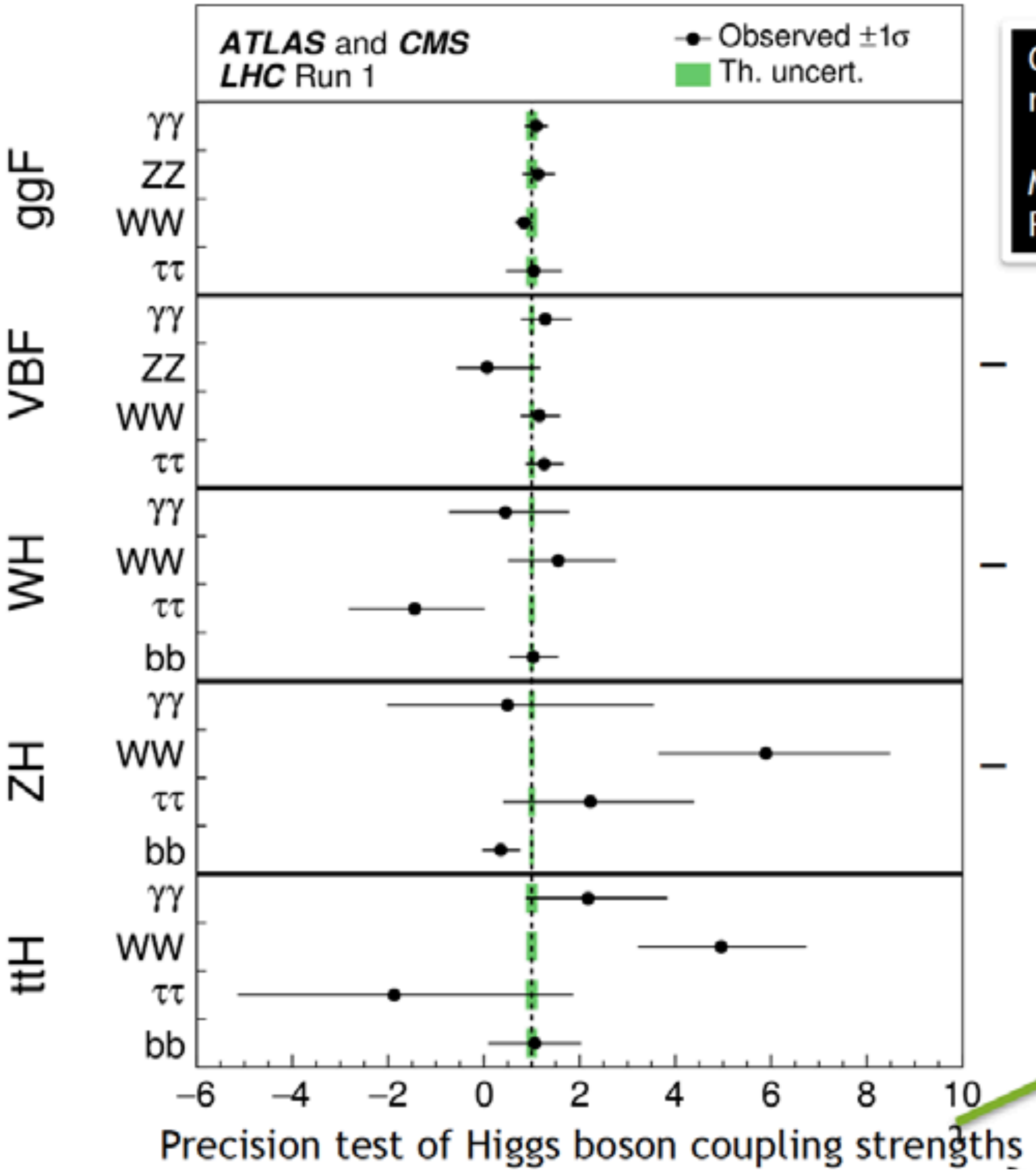
- Rate of interaction, i.e. the cross section for pp-collisions varies dramatically
  - high mass cross sections are of very low rate
  - requires very high selectivity (trigger, event selection)



Higgs Boson at 7 and 8 TeV (Run 1)

ATLAS and CMS have combined their Run 1 data to extract precise measurement of Higgs coupling

Higgs (125 GeV) compatible with SM



CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803
Rates and couplings: arXiv:1606.02266

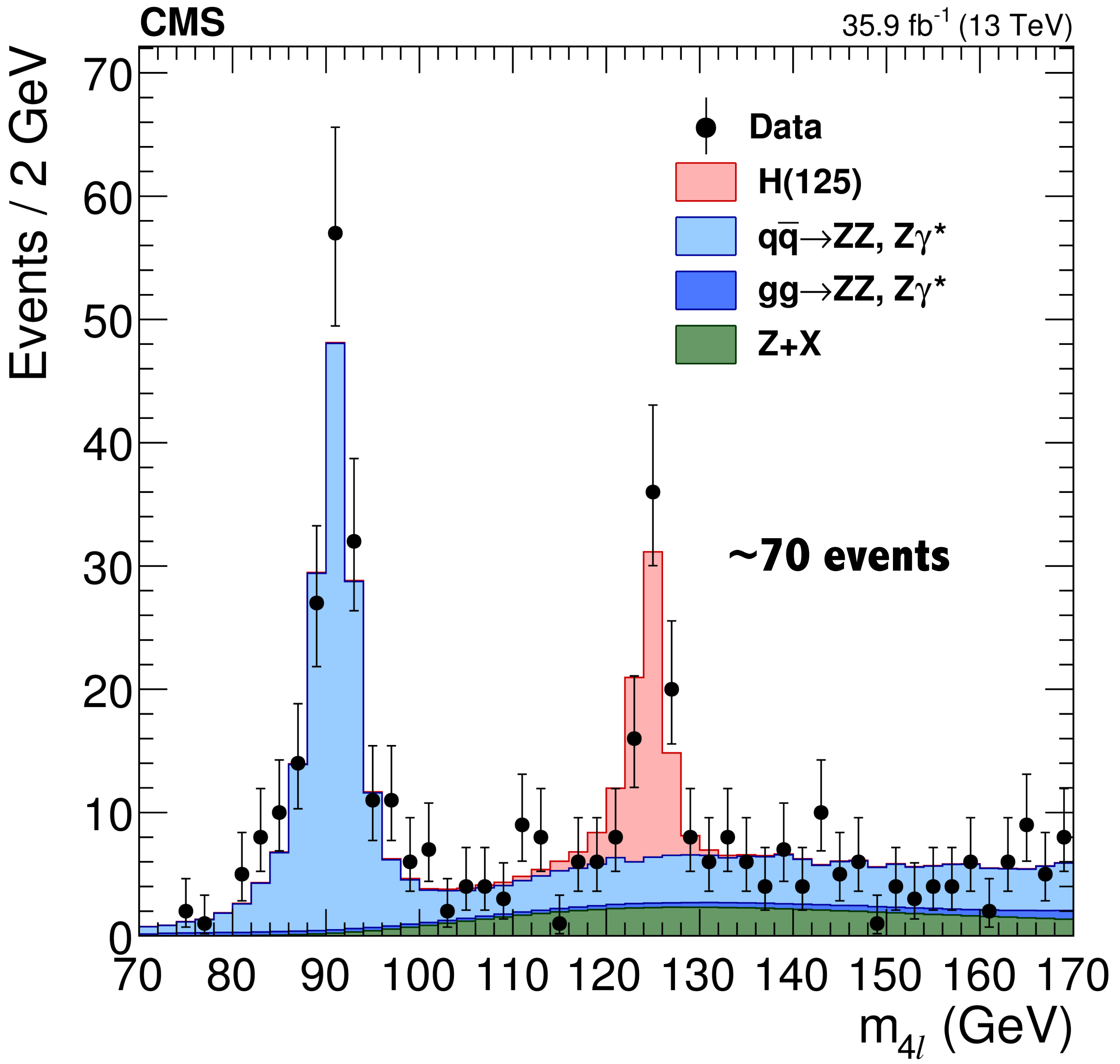
- Mass has been measured to 0.2% precision m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths

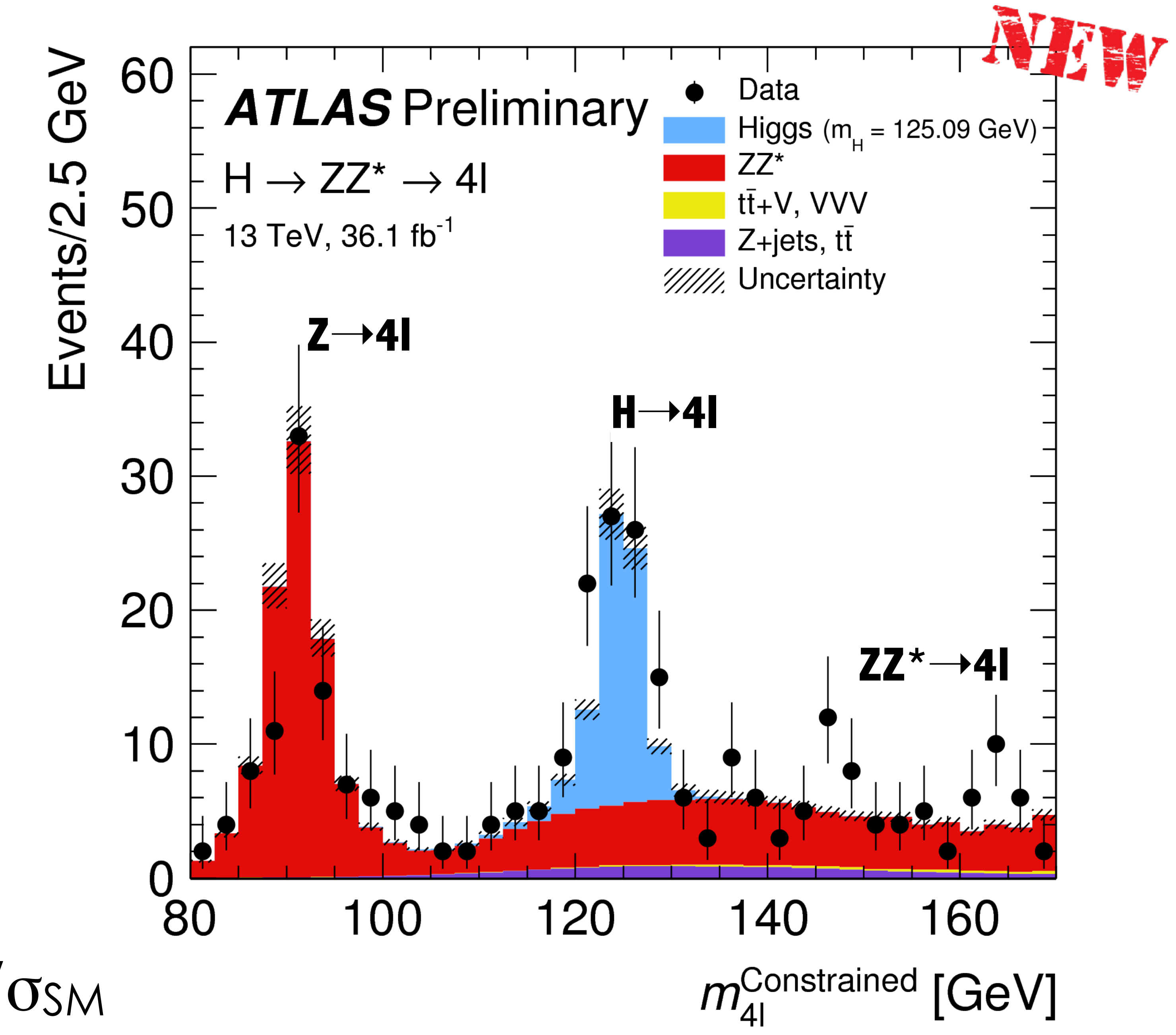
$$\mu = \frac{\sigma}{\sigma_{SM}}$$

H → 4 ℓ and combination with H → γγ

CMS arXiv:1706.09936 Submitted to JHEP



ATLAS-CONF-2017-043



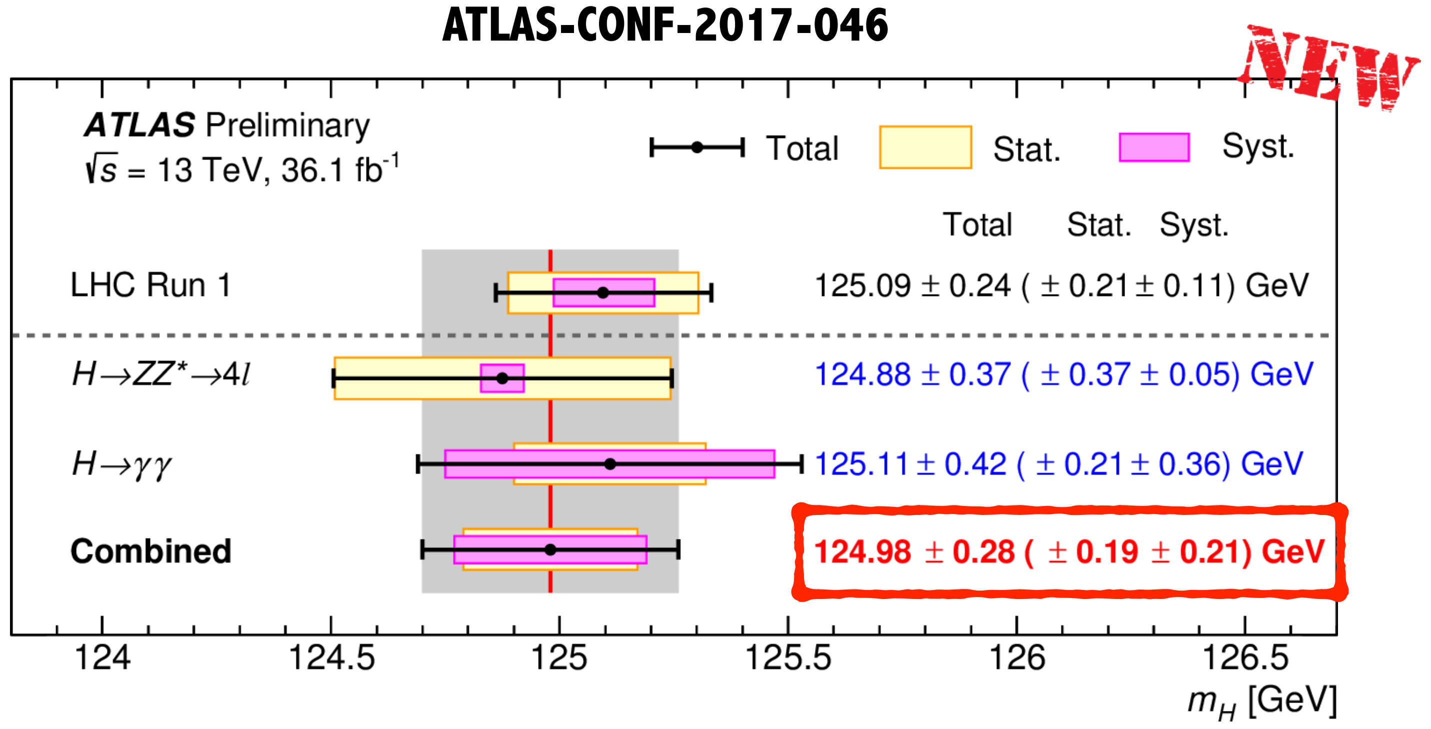
μ=σ/σ_{SM}

$$\mu = 1.05^{+0.15}_{-0.14}(\mathrm{stat})^{+0.11}_{-0.09}(\mathrm{syst})$$

$$\mu = 1.28^{+0.18}_{-0.17}(\mathrm{stat})^{+0.08}_{-0.06}(\mathrm{exp})^{+0.08}_{-0.06}(\mathrm{theo})$$

$$\mu = \sigma/\sigma_{SM}$$

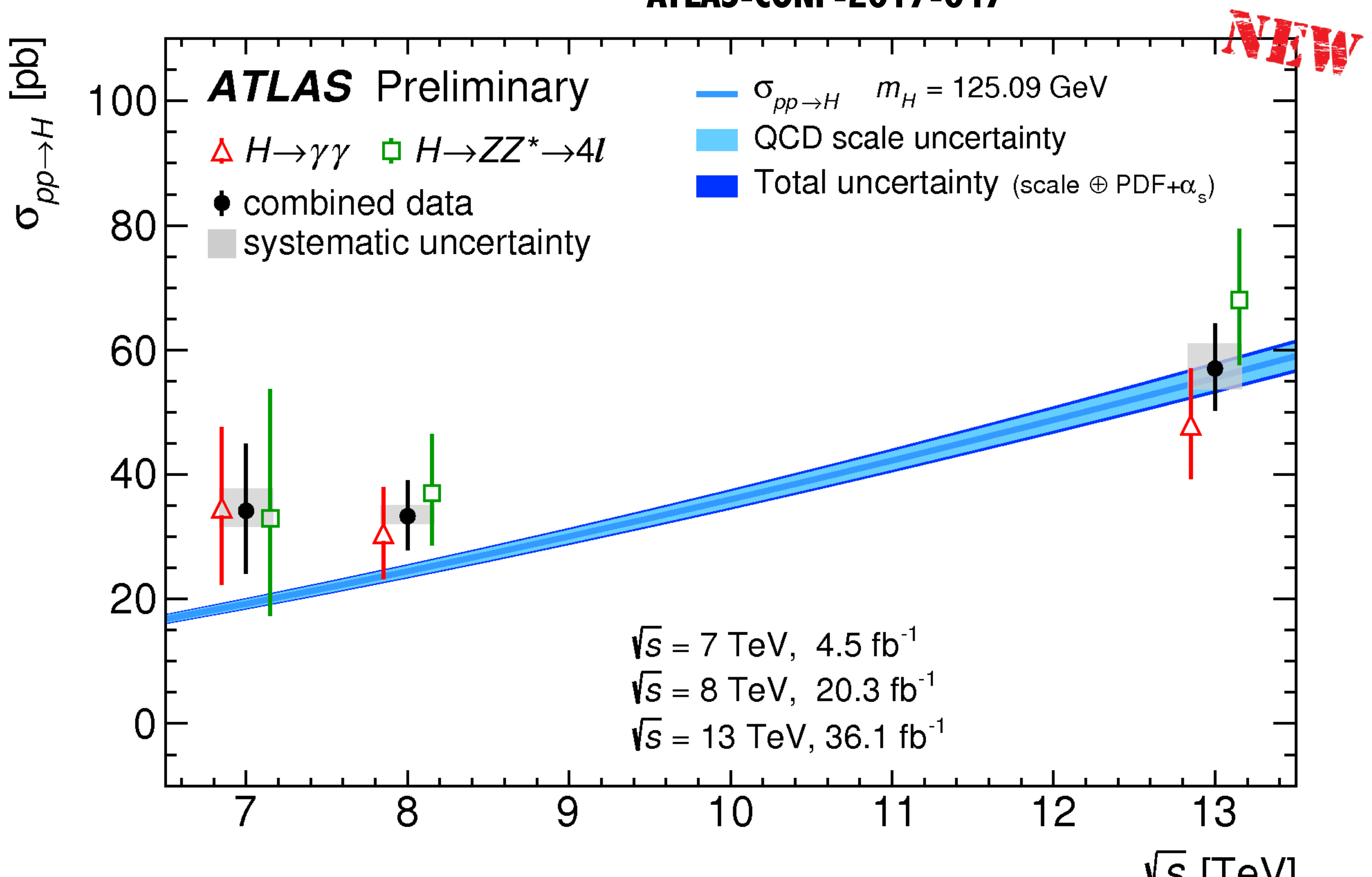
ATLAS-CONF-2017-046



CMS arXiv:1706.09936

$$m_H = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{GeV}$$

ATLAS-CONF-2017-047



H → fermions

$$H \rightarrow \tau\tau$$

$$H \rightarrow b\bar{b}$$

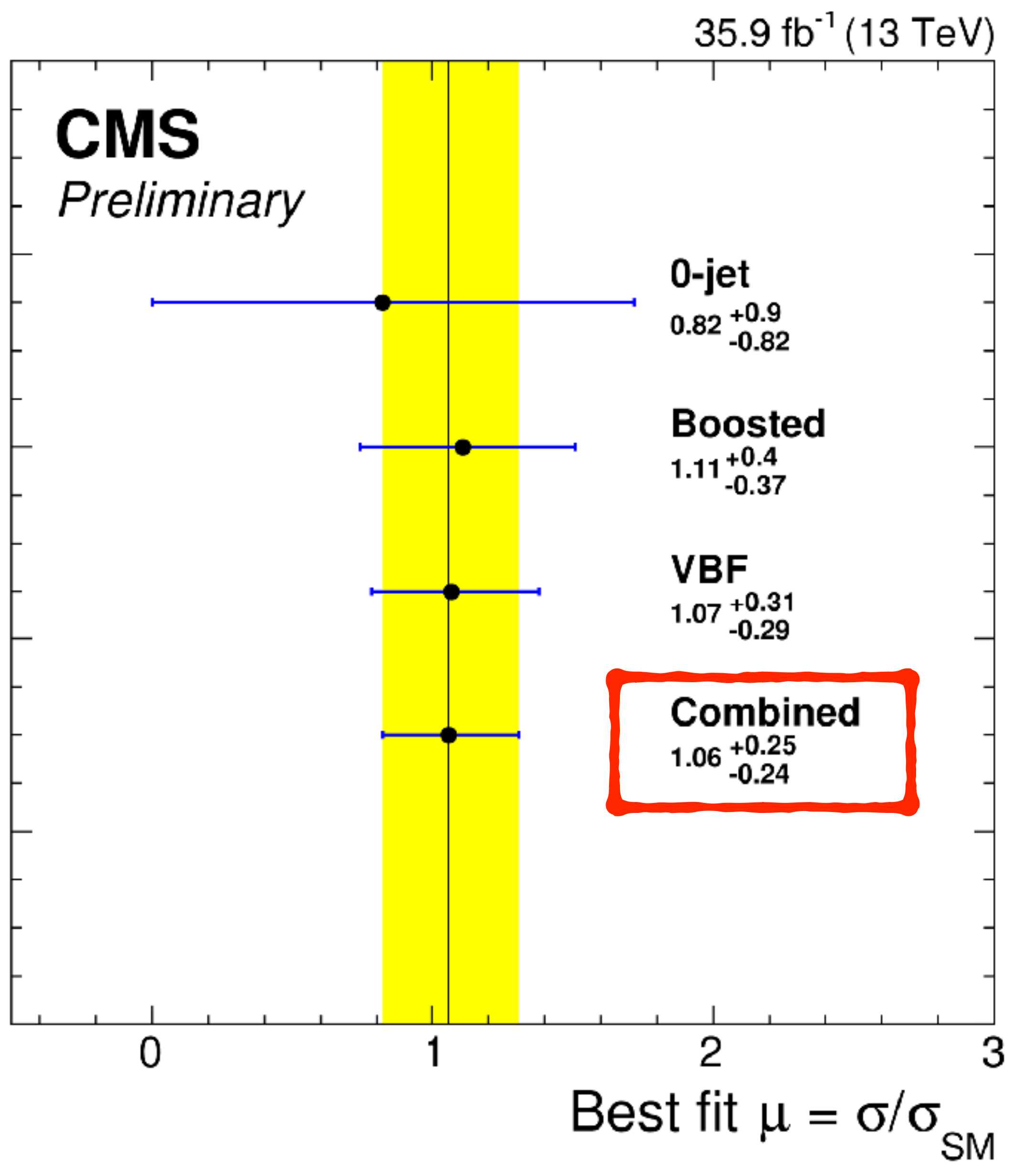
Using

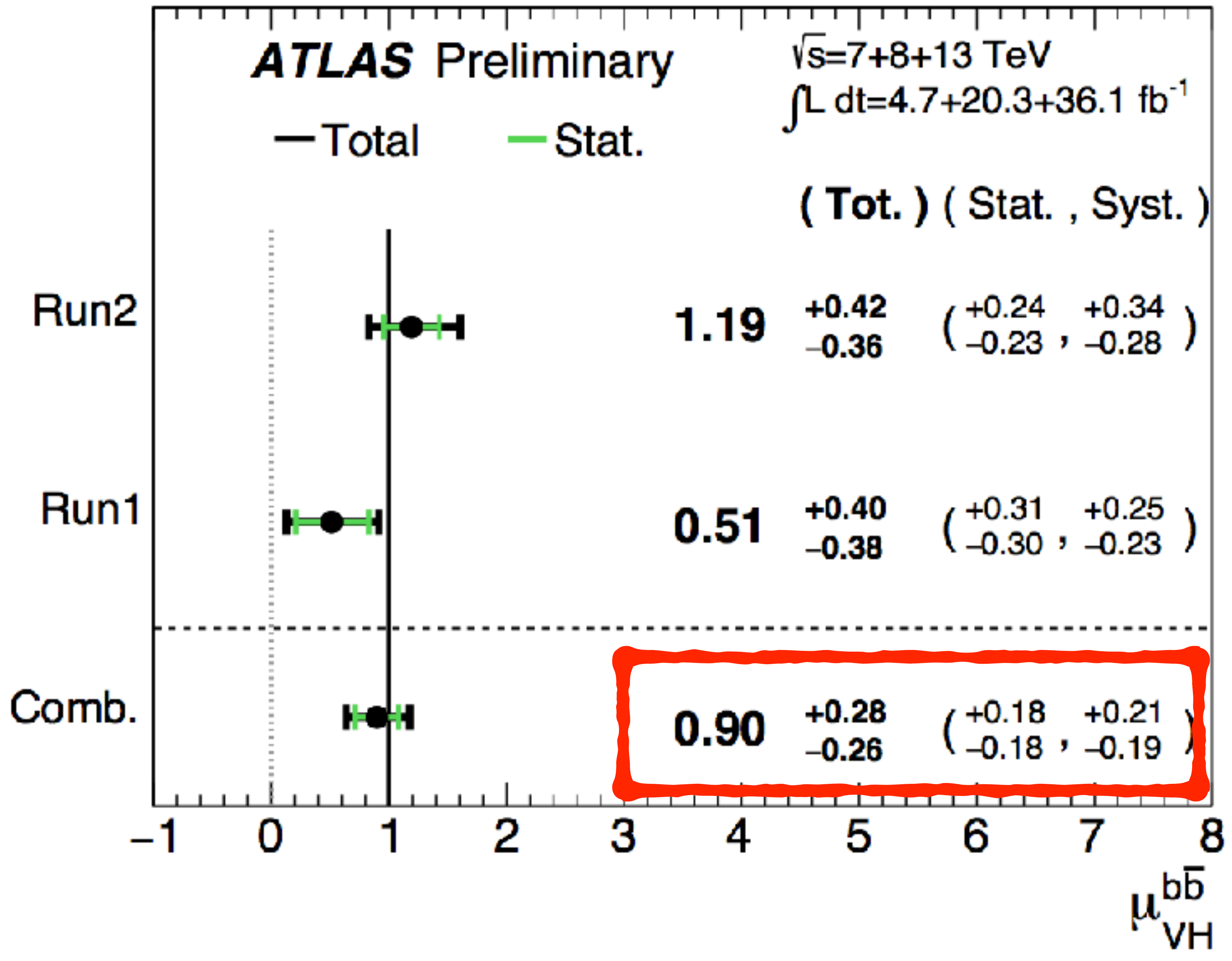
$\tau_h\tau_h$

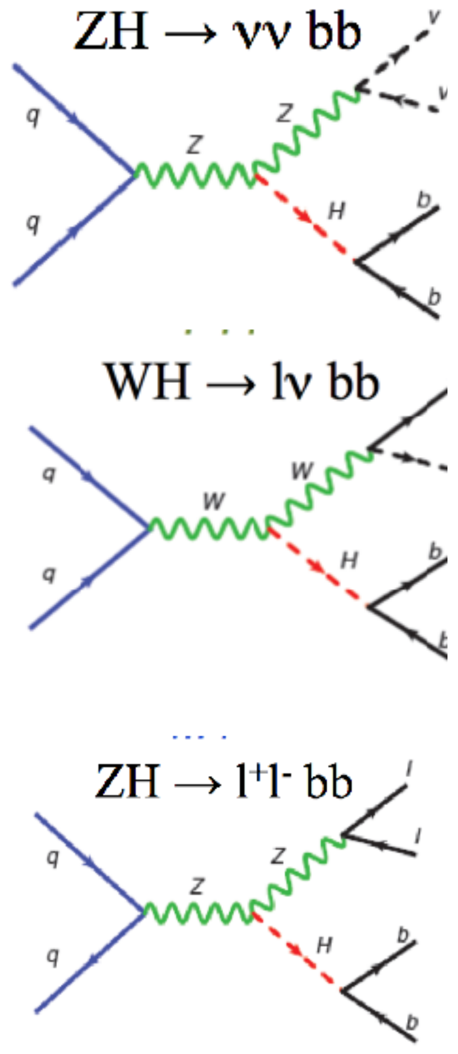
$e\tau_h$

$\mu\tau_h$

$e\mu$

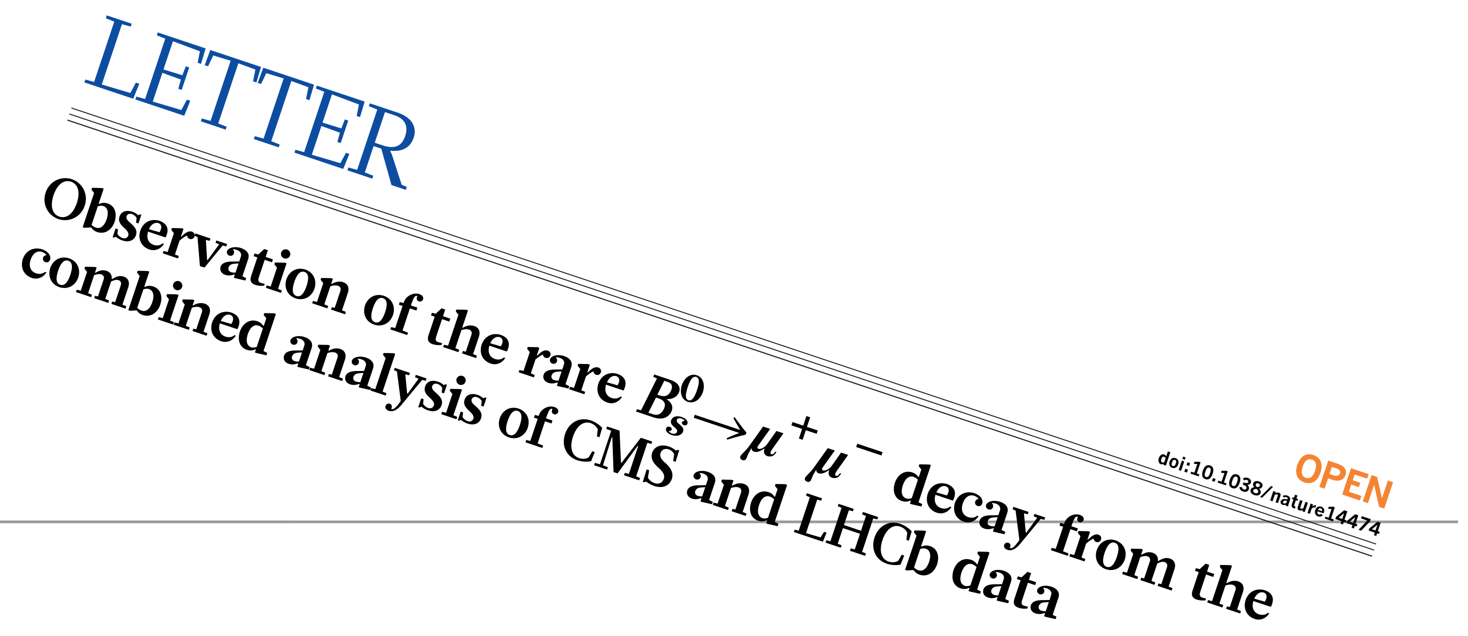




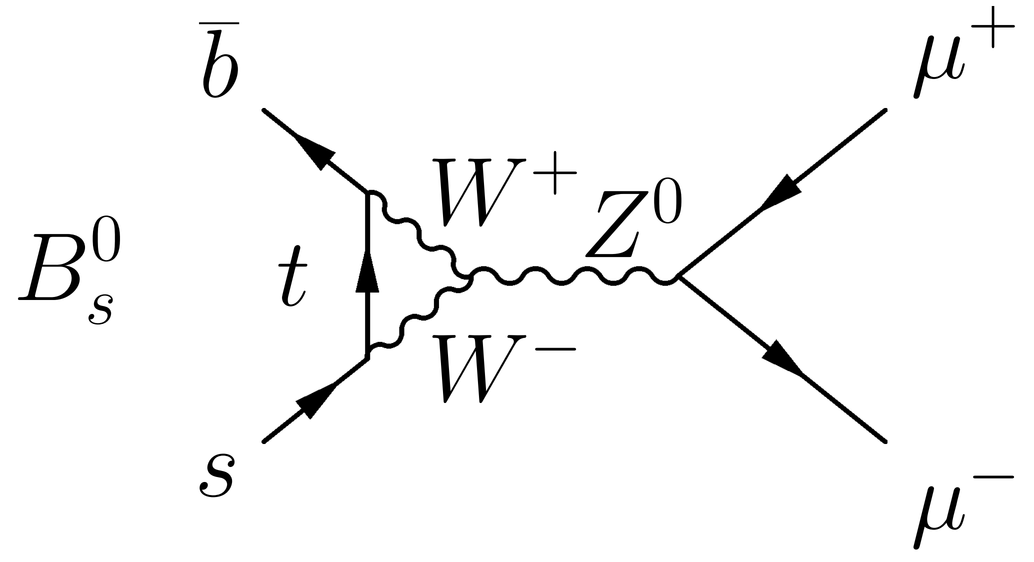


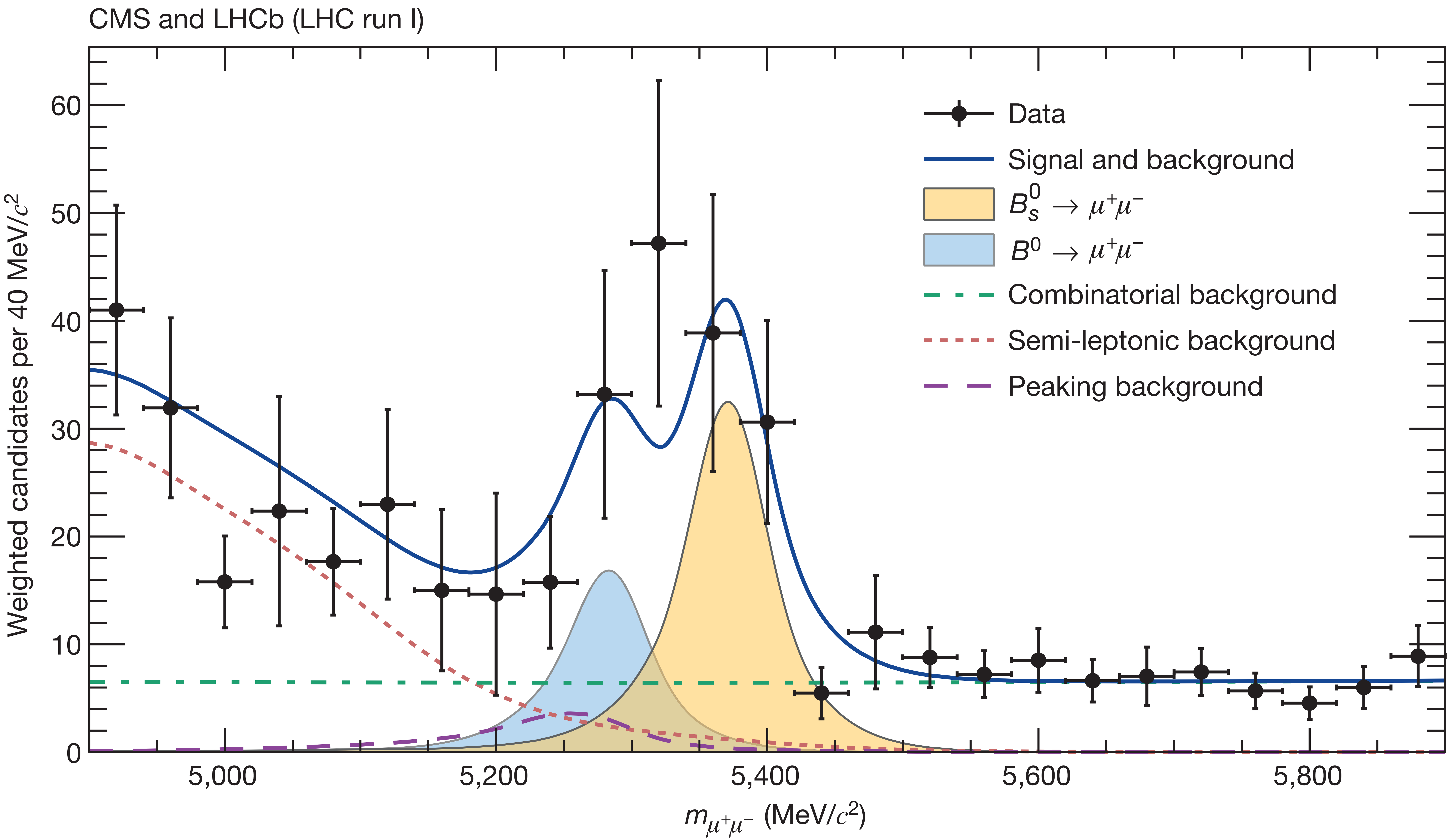
4.9 σ   from run 2   3.5 σ

$B^0 \rightarrow \mu\mu$

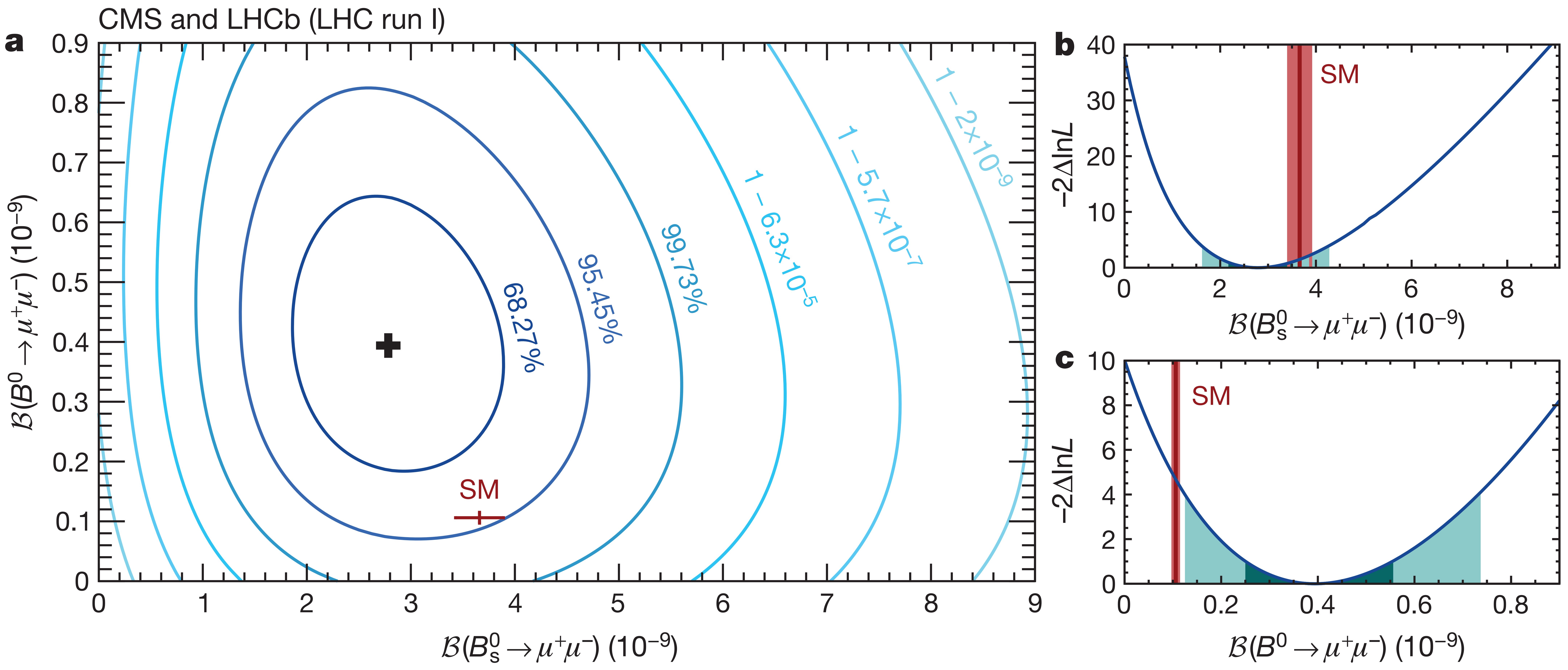


Extremely rare decay in Standard Model





$B^0 \rightarrow \mu\mu$ combined result of CMS and LHCb

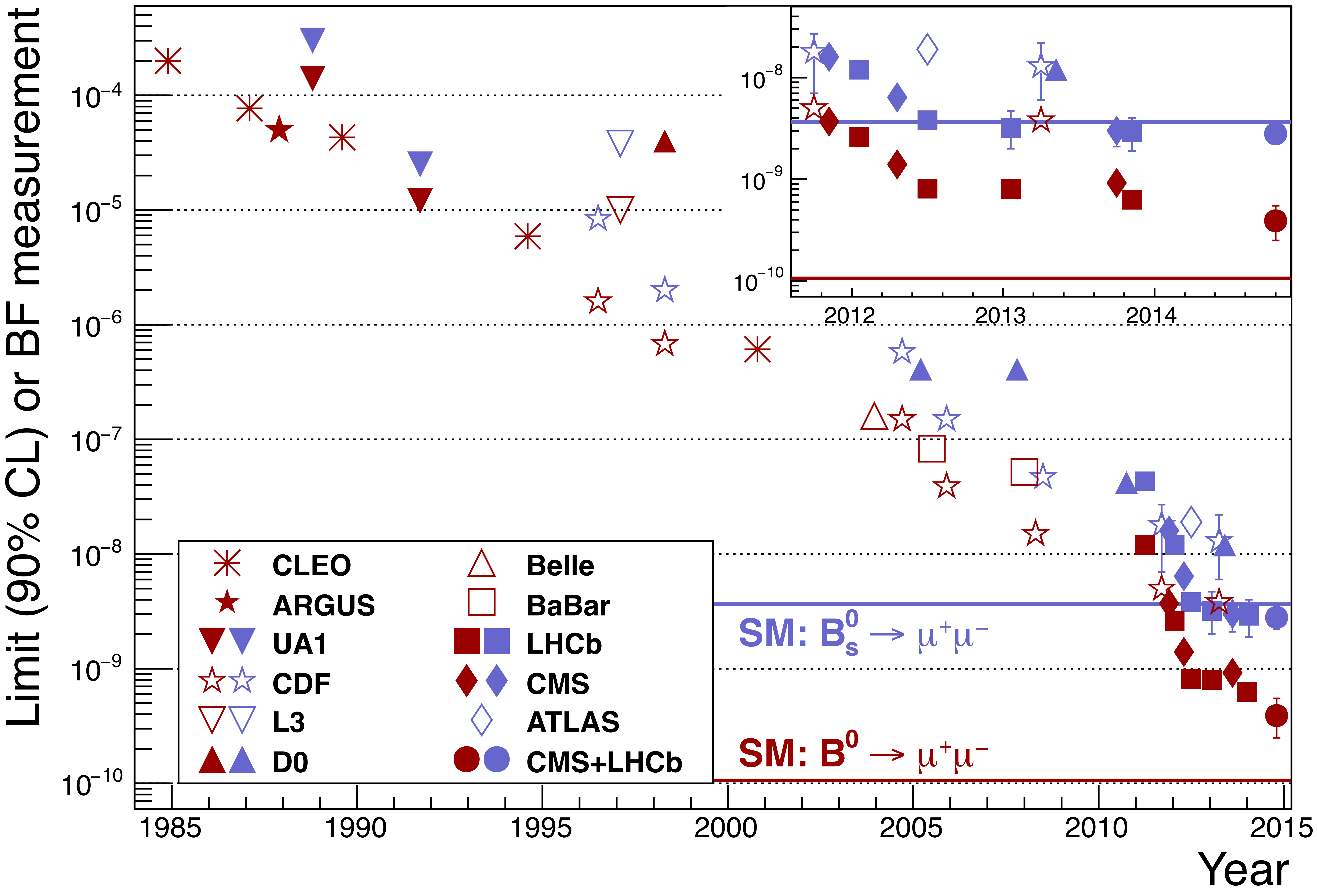


From limit to measurement for $B^0 \to \mu\mu$

The rare decay was known to be particularly sensitive for new physics.

25 years of experimental research to reach SM sensitivity.

Compatible with SM – new physics not hiding here?

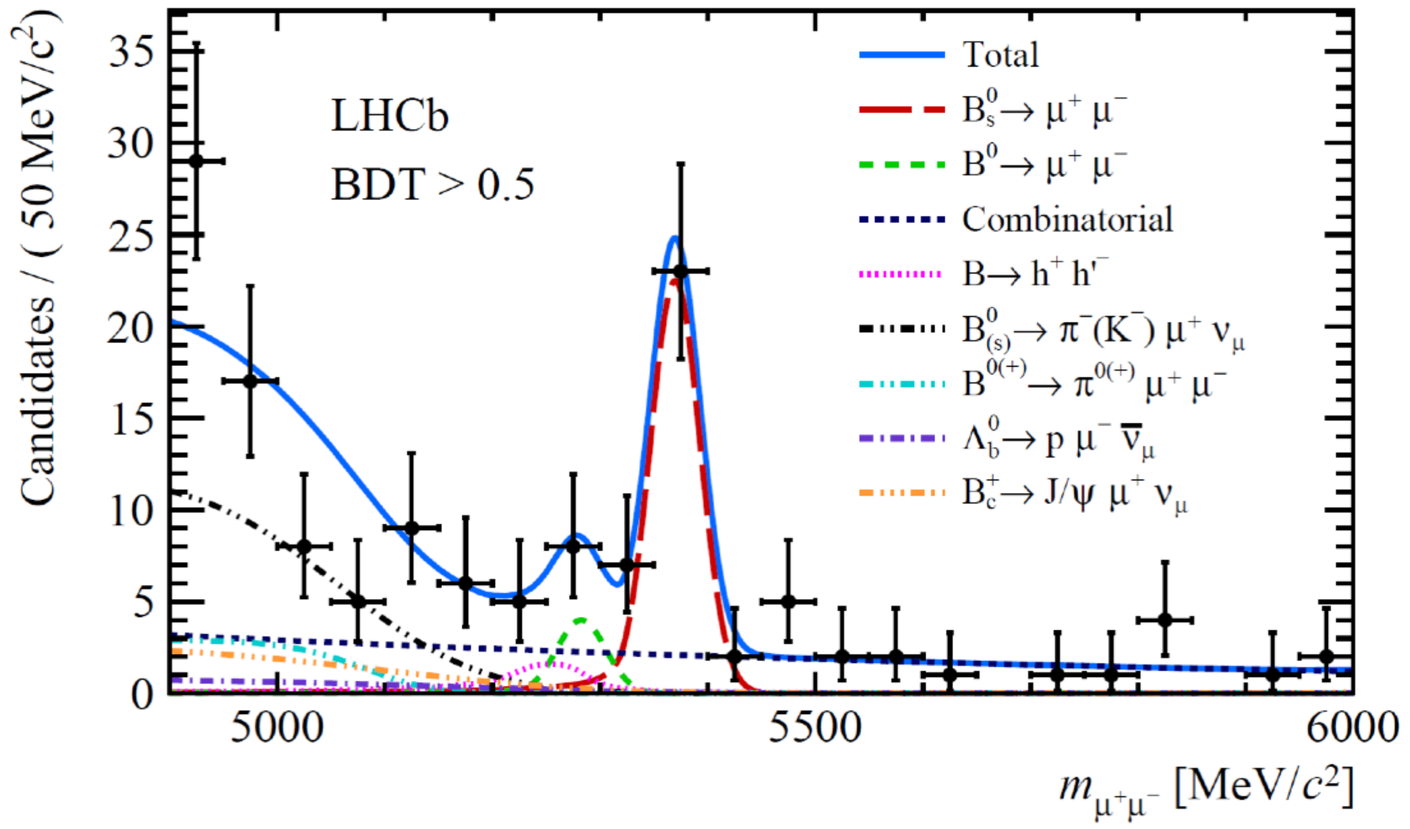


Measurement of BR($B_s \to \mu\mu$) and search for $B_d \to \mu\mu$

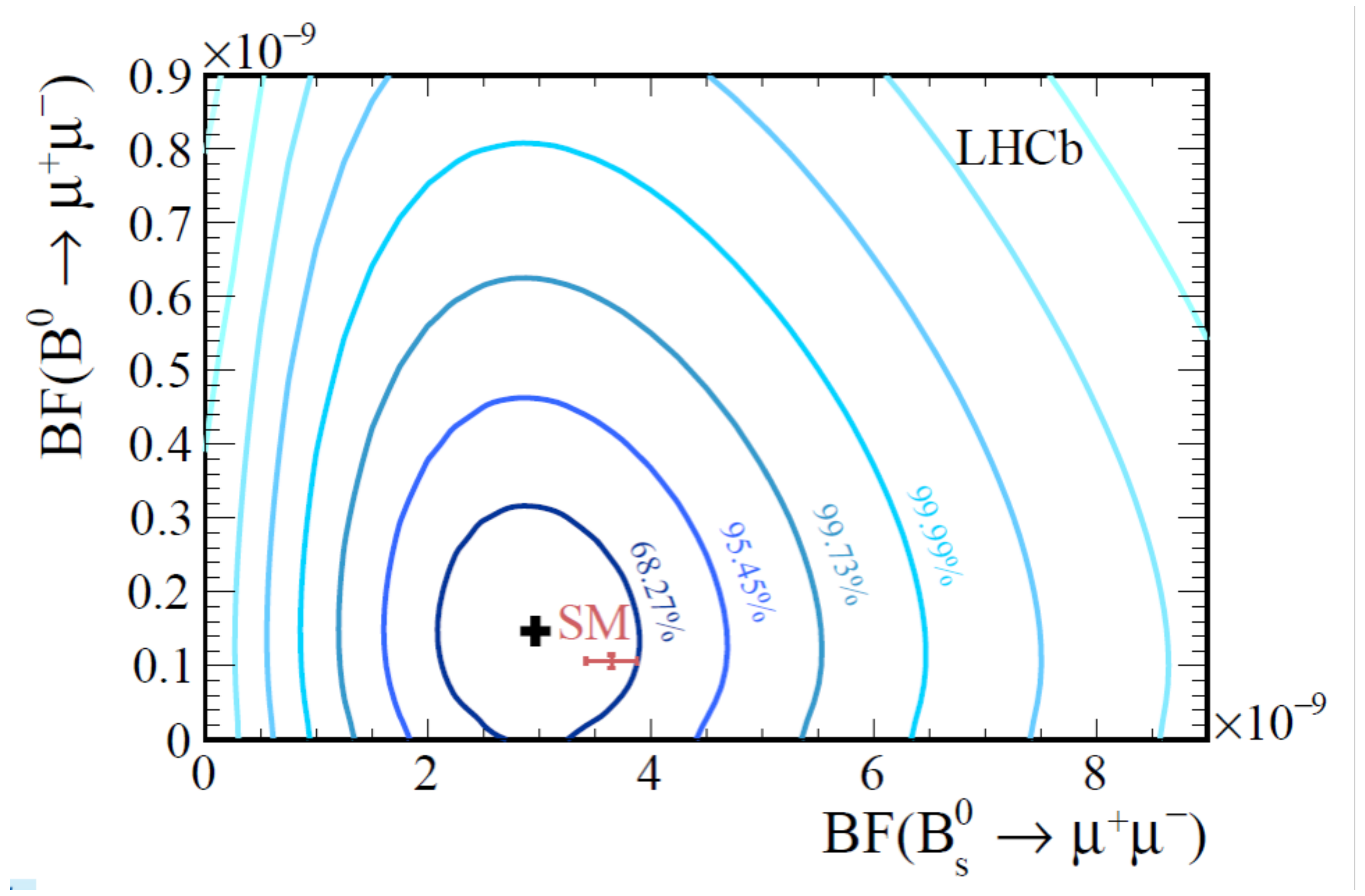
Recent result from LHCb alone

- Re-analyse Run 1 data with improved selection (background halved) and add 1.4 fb^{-1} of Run 2 data
- First single-experiment observation of $B_s \to \mu\mu$ mode; measurement of BR has same precision as previous Run 1 LHCb-CMS combined analysis [Nature 522 (2015) 68].

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})) \times 10^{-9} \qquad (7.8\sigma)$$



$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \quad @\,95\,\%\text{ C.L.}$$



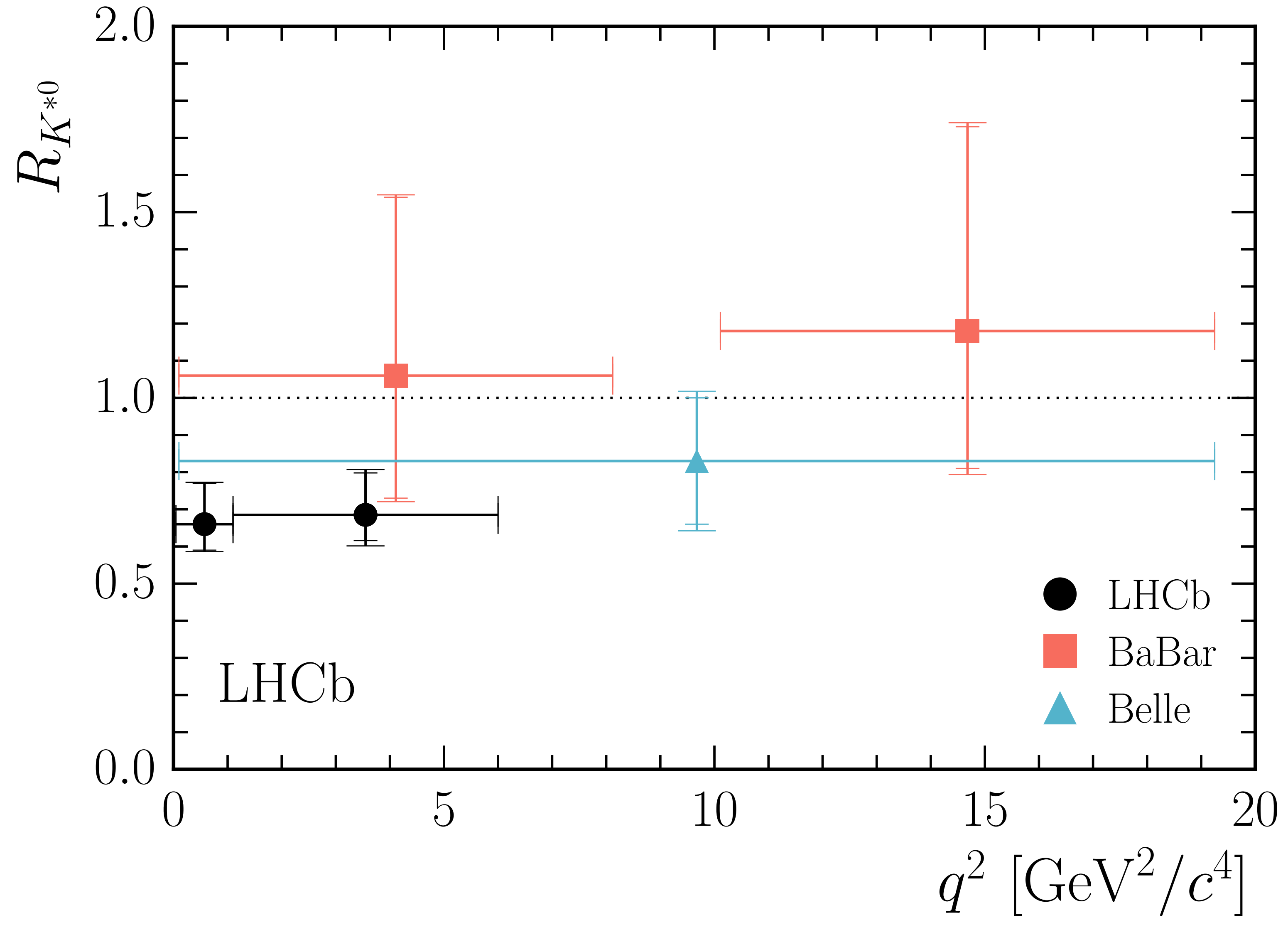
Measurement of R_{K^*}

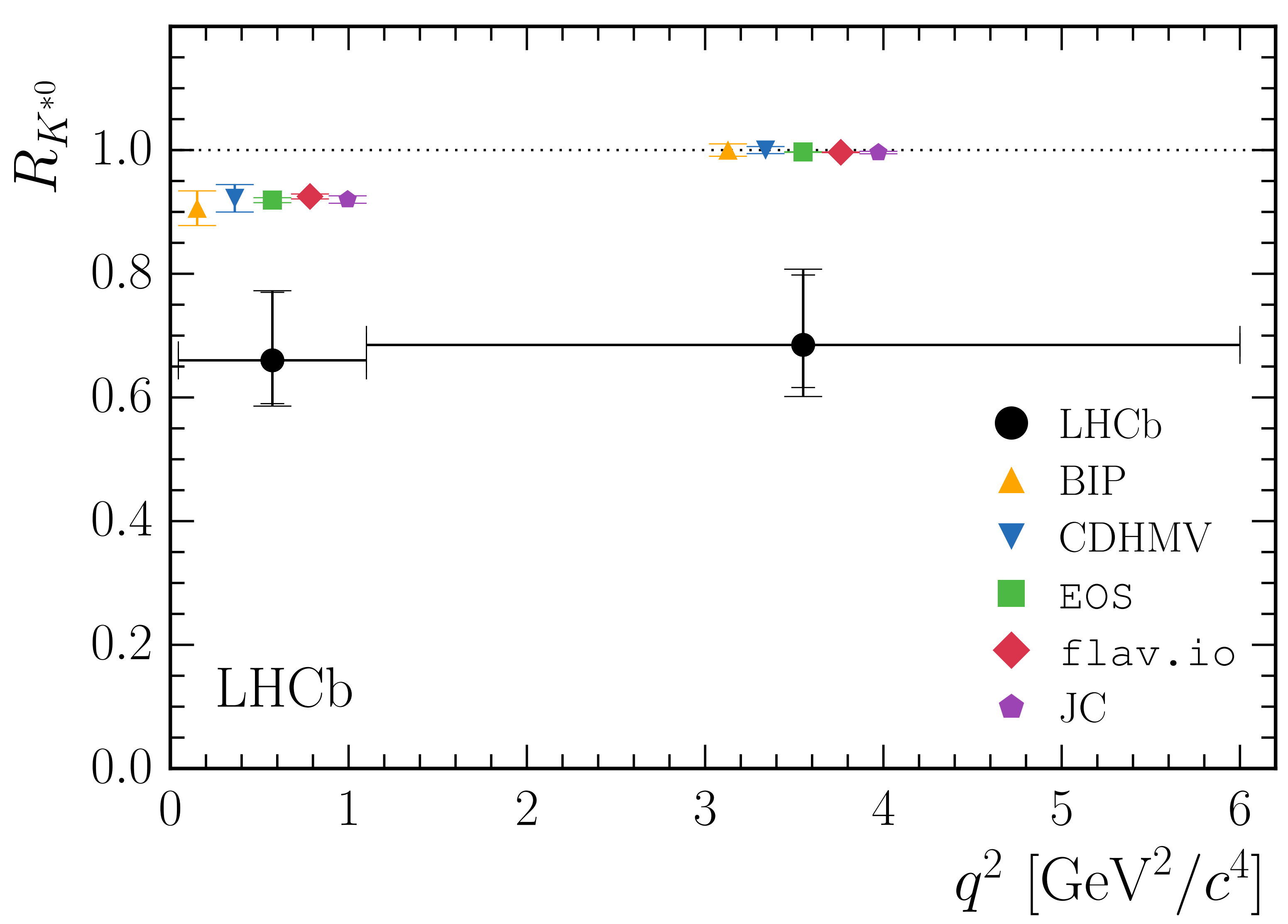
Expect μμ and ee-branchings to be the same – apart from well understood mass contributions

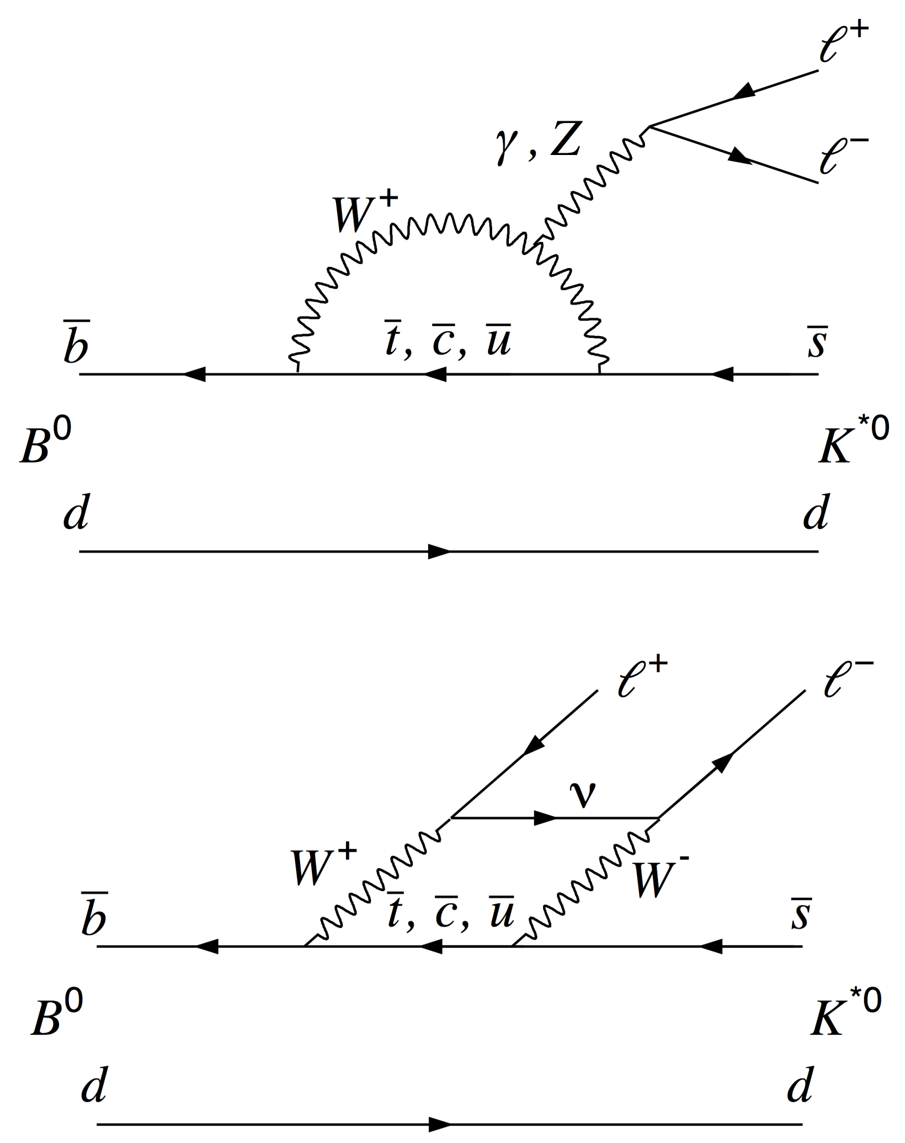
LHCb-Paper-2017-013

So far a ~2.5 σ effect

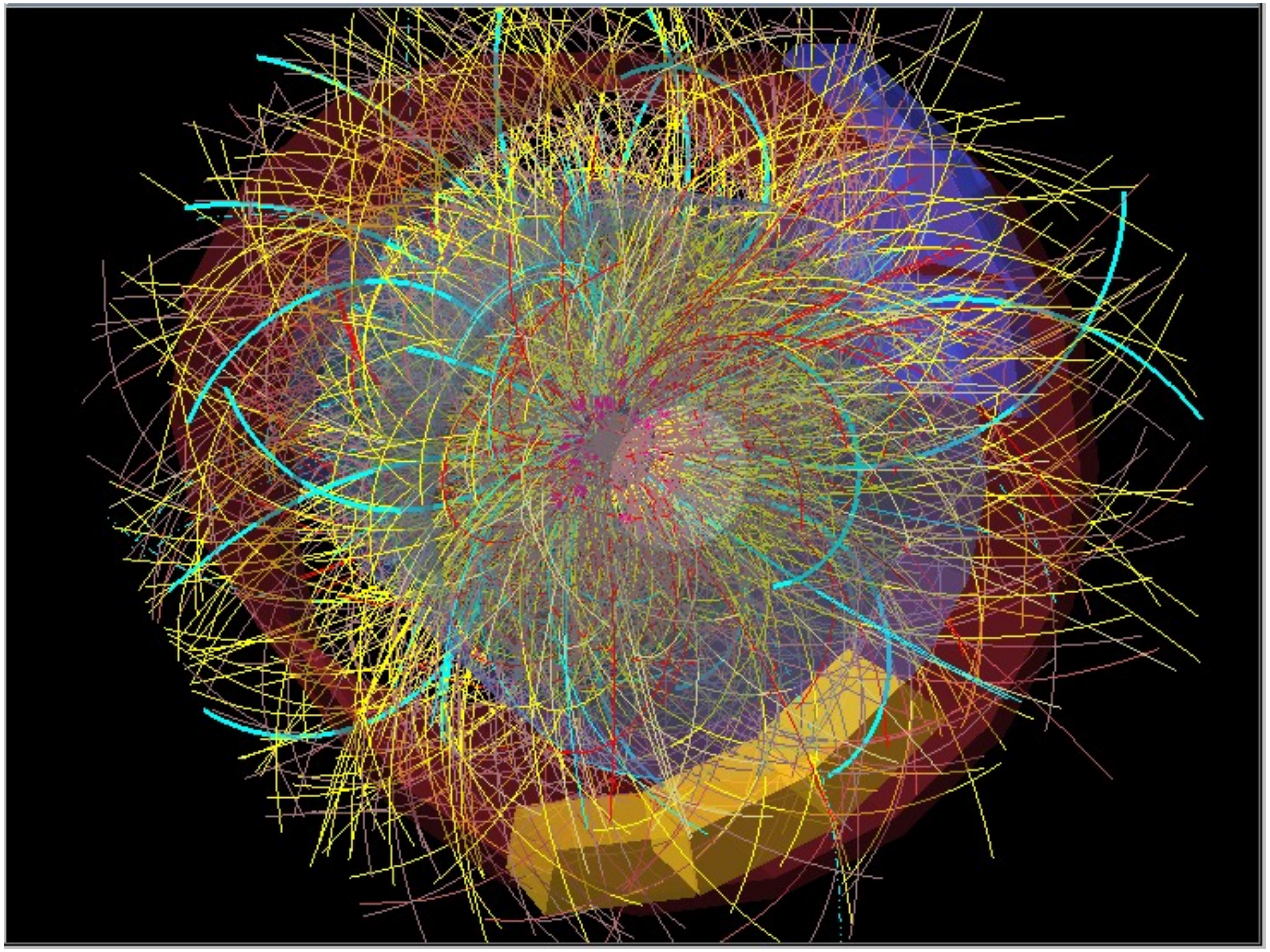
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$







Heavy Ion Physics



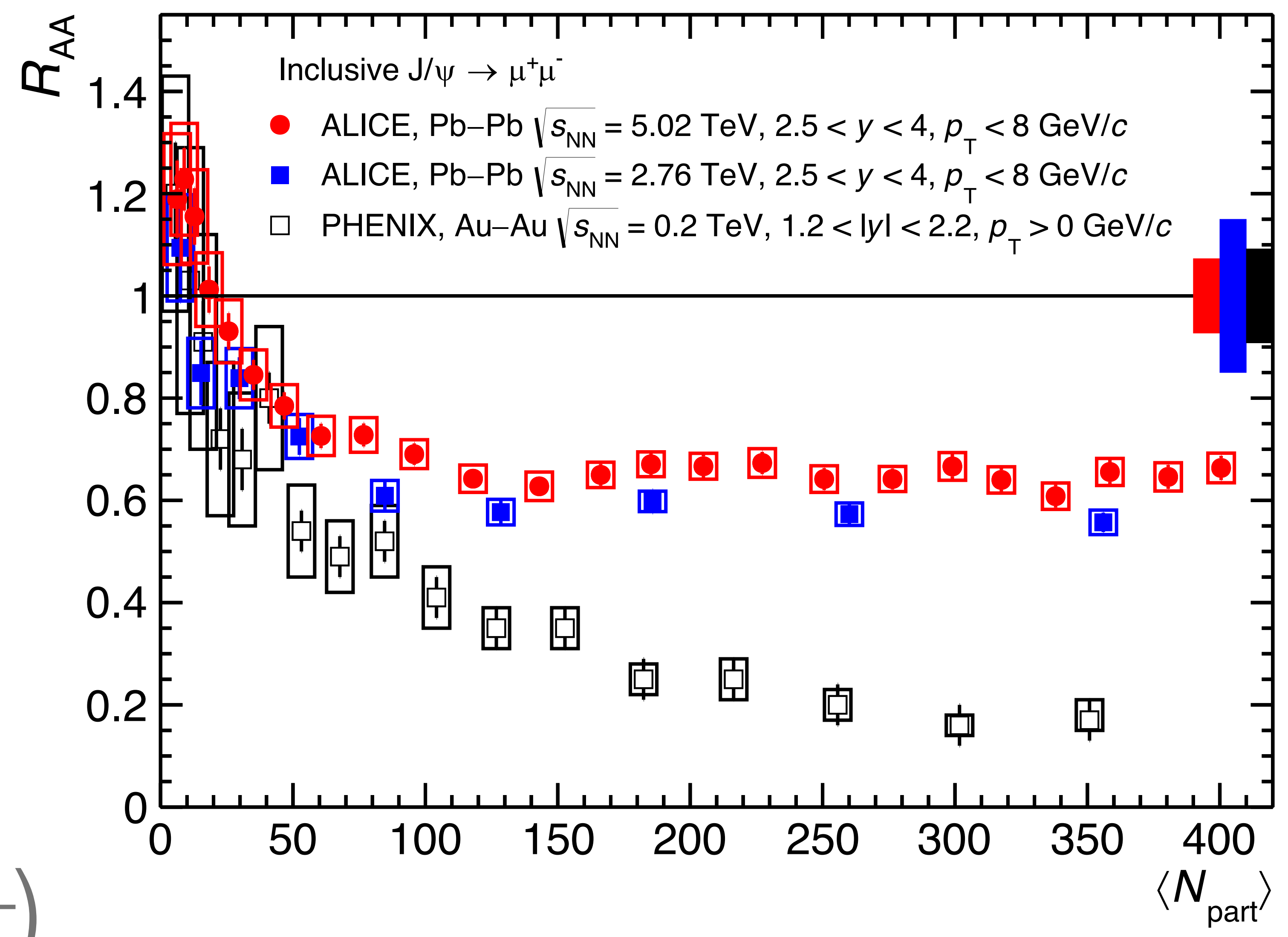
Pb-Pb: J/ψ suppression at 5 TeV

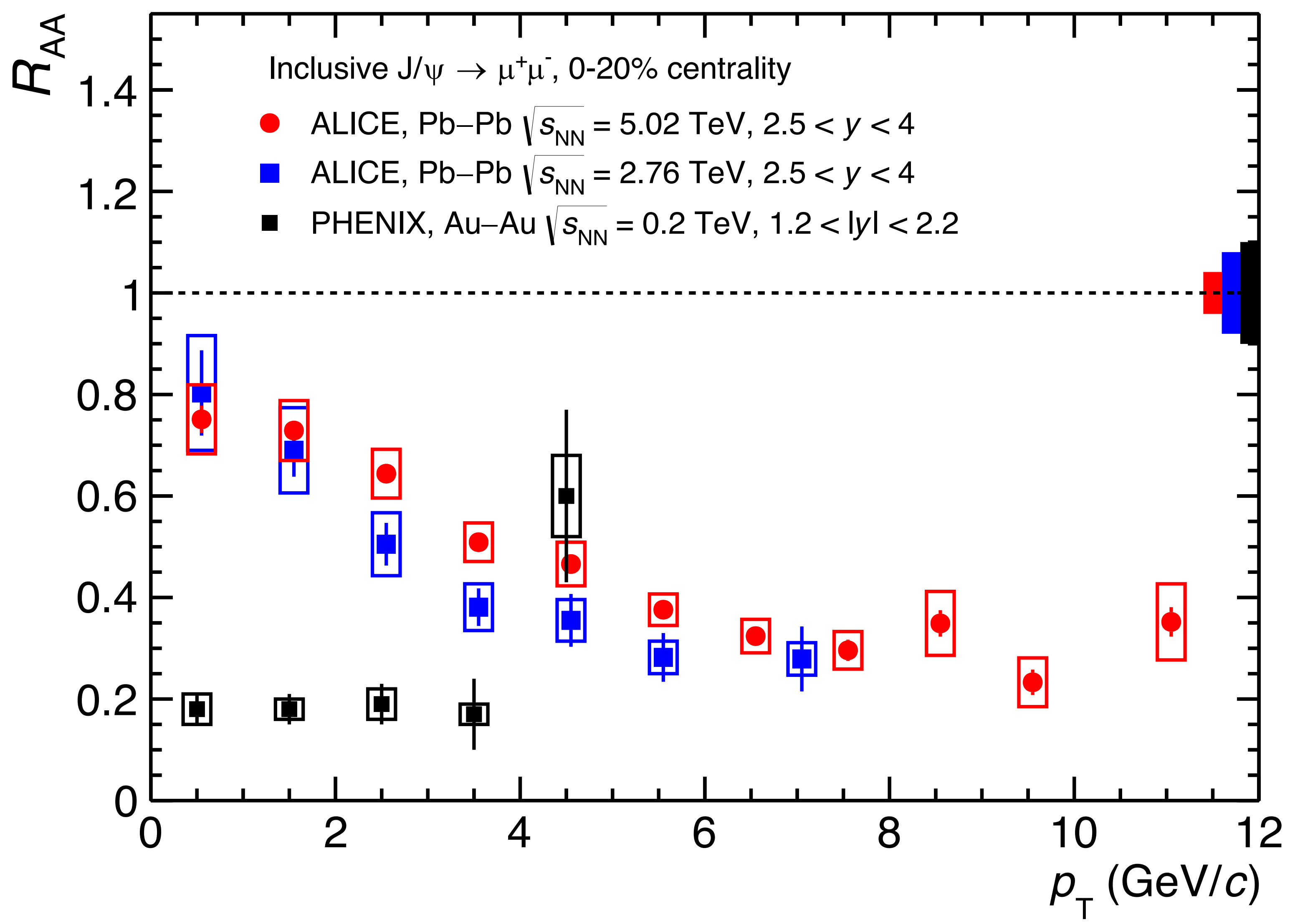
- nuclear modification factor R_{AA}:

$$R_{AA} = \frac{N(J/\psi)_{AA}}{\langle N_{bin} \rangle N(J/\psi)_{pp}}$$

- very different behaviour between LHC and RHIC (vs both centrality and p_T)

- most straightforward explanation: c-cbar recombination at LHC



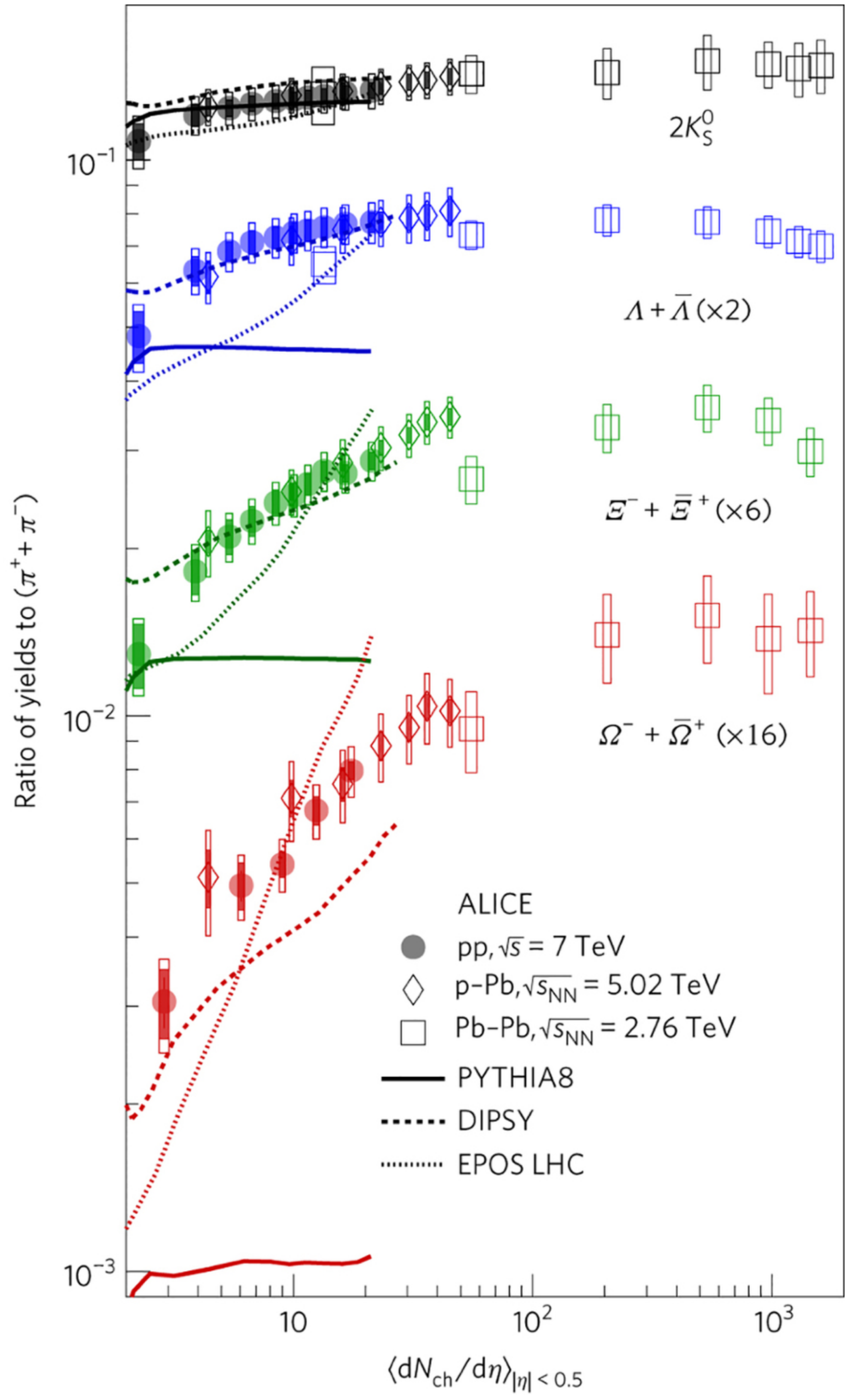


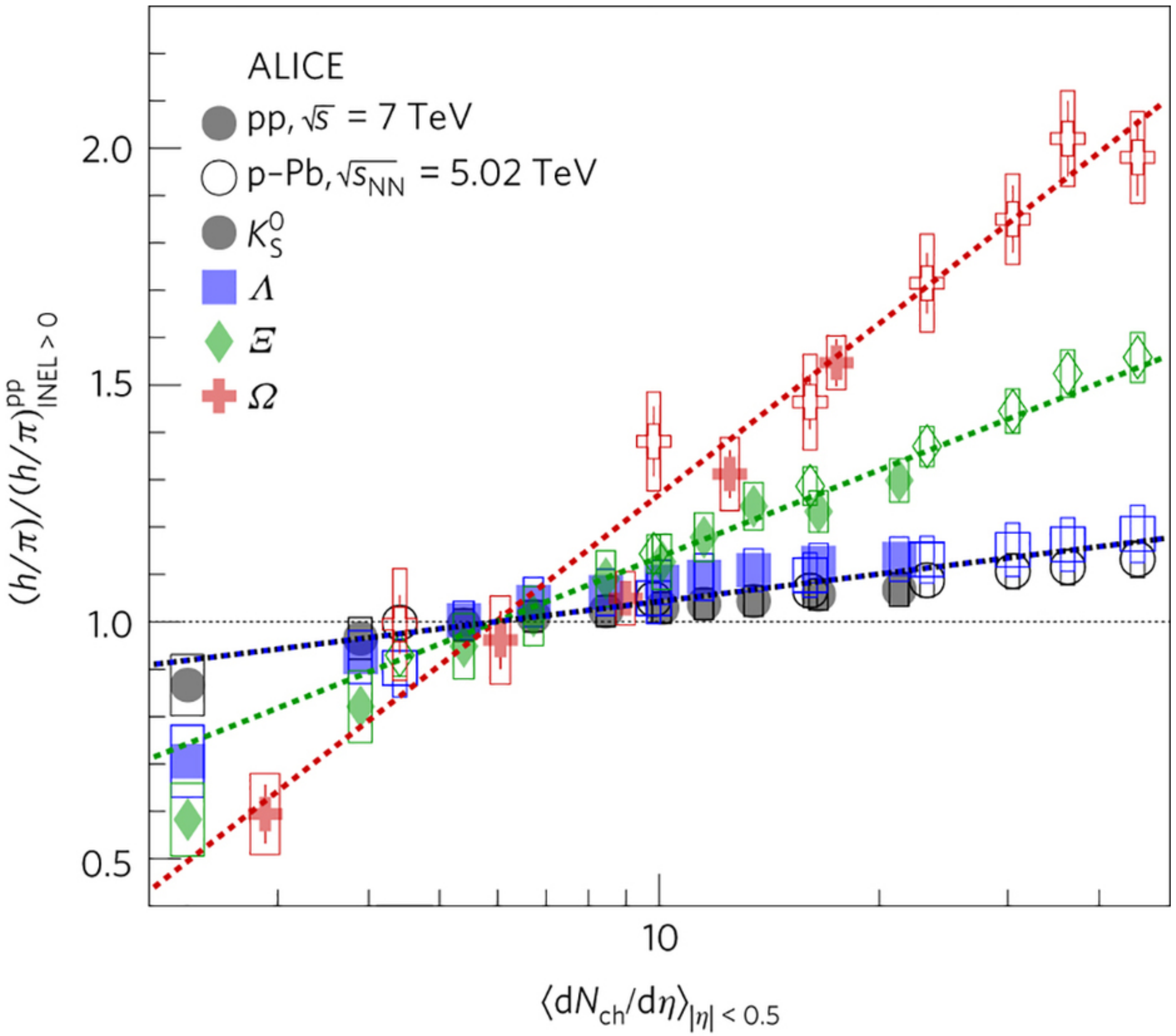
New and precise 5 TeV data support even further increase

Strangeness production in high-energy pp

Strangeness increases in high-multiplicity pp-collisions

Evidence for Quark-Gluon plasma in pp collisions





High Luminosity LHC

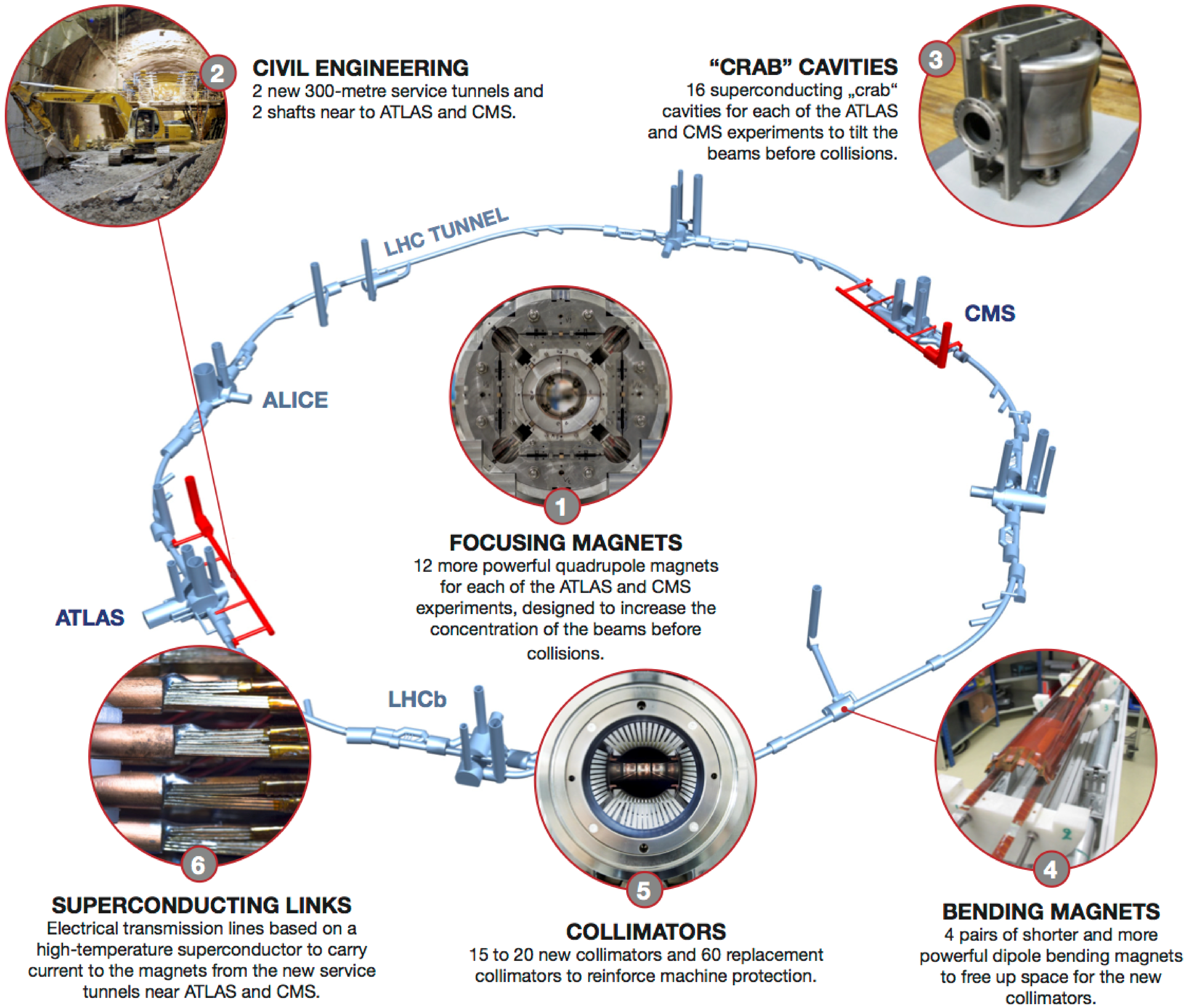
High-Luminosity LHC approved by Council in 2016

High-Luminosity (HL-LHC)

- $5x10^{34}$ $cm^{-2}s^{-1}$ levelled; i.e. factor 5 over design
    - to yield 3 ab^{-1} by ~2035

requires

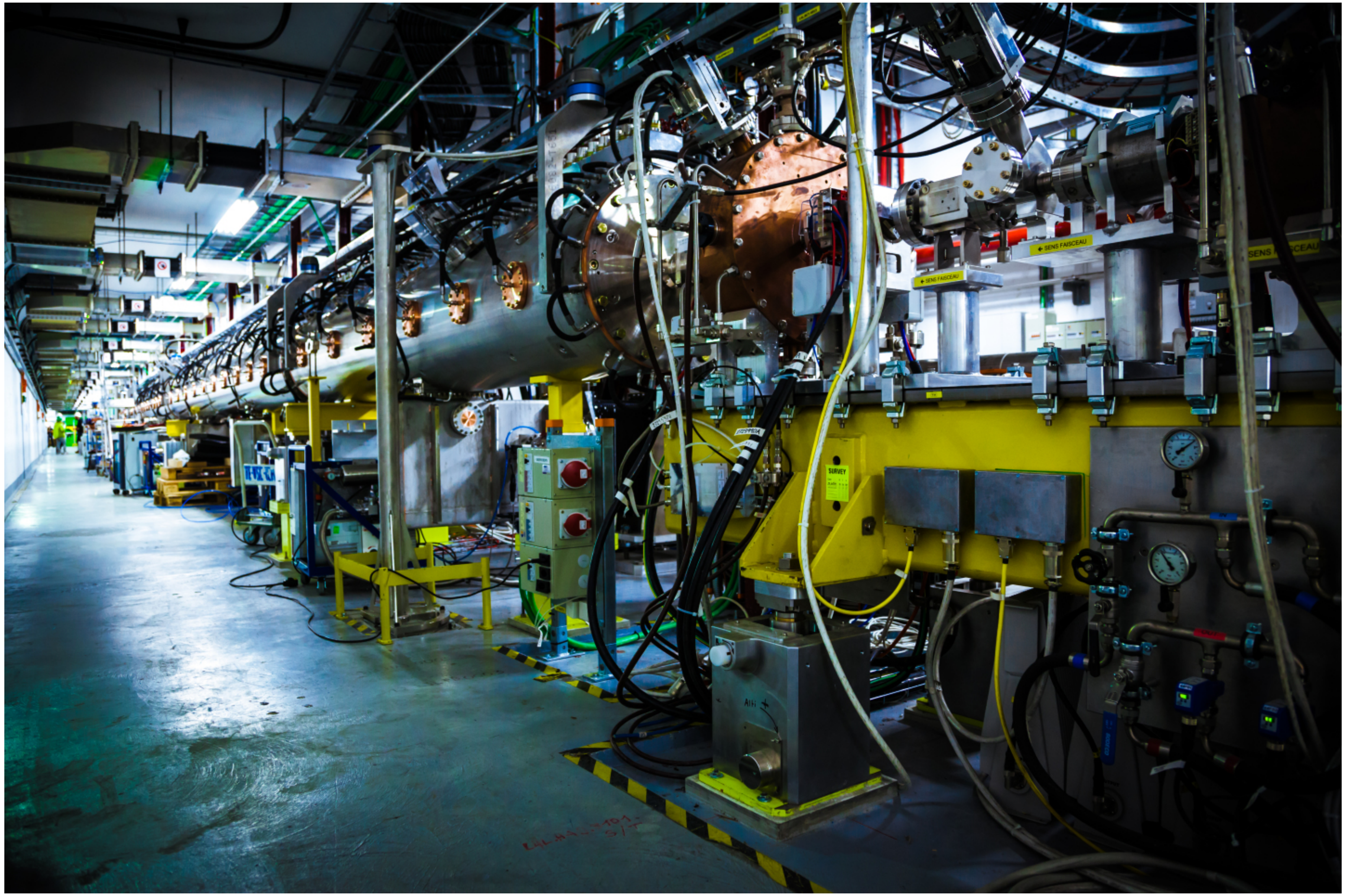
- focussing β^*=15 cm
- crab crossing



LHC-Injector upgrades – Linac 4 taken into operation*

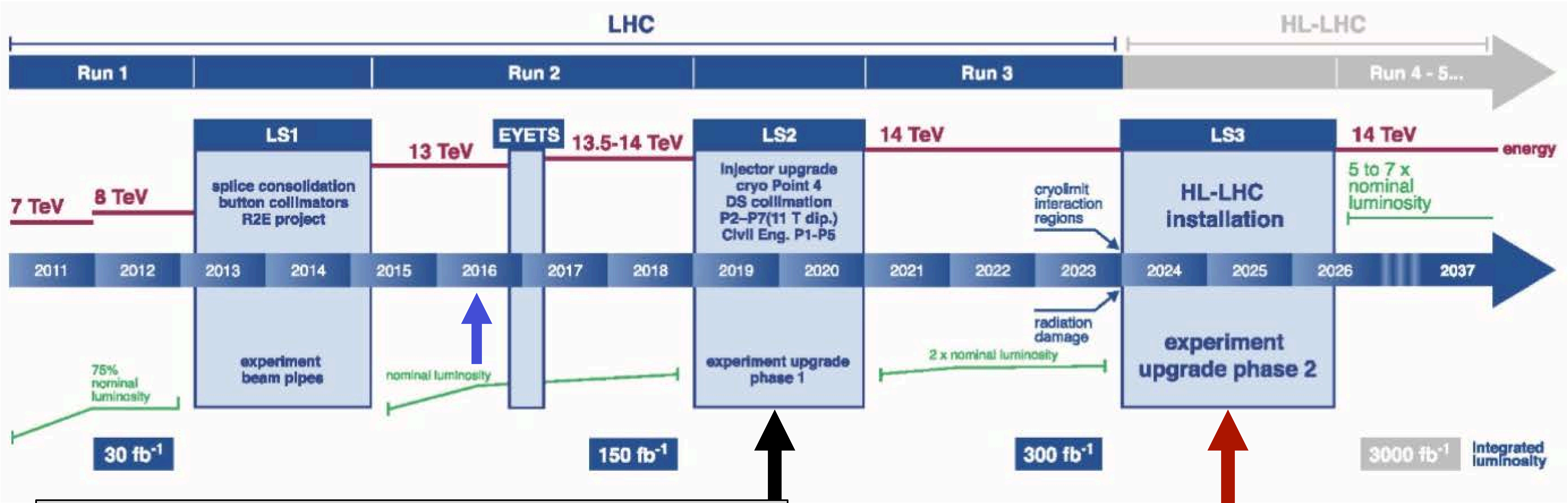
- Commissioning started 2014
- protons have been accelerated to 160 MeV
- using π-mode structures PIMS for high energy acceleration

Inauguration 9.5.2017



*not yet connected to booster

HL-LHC schedule



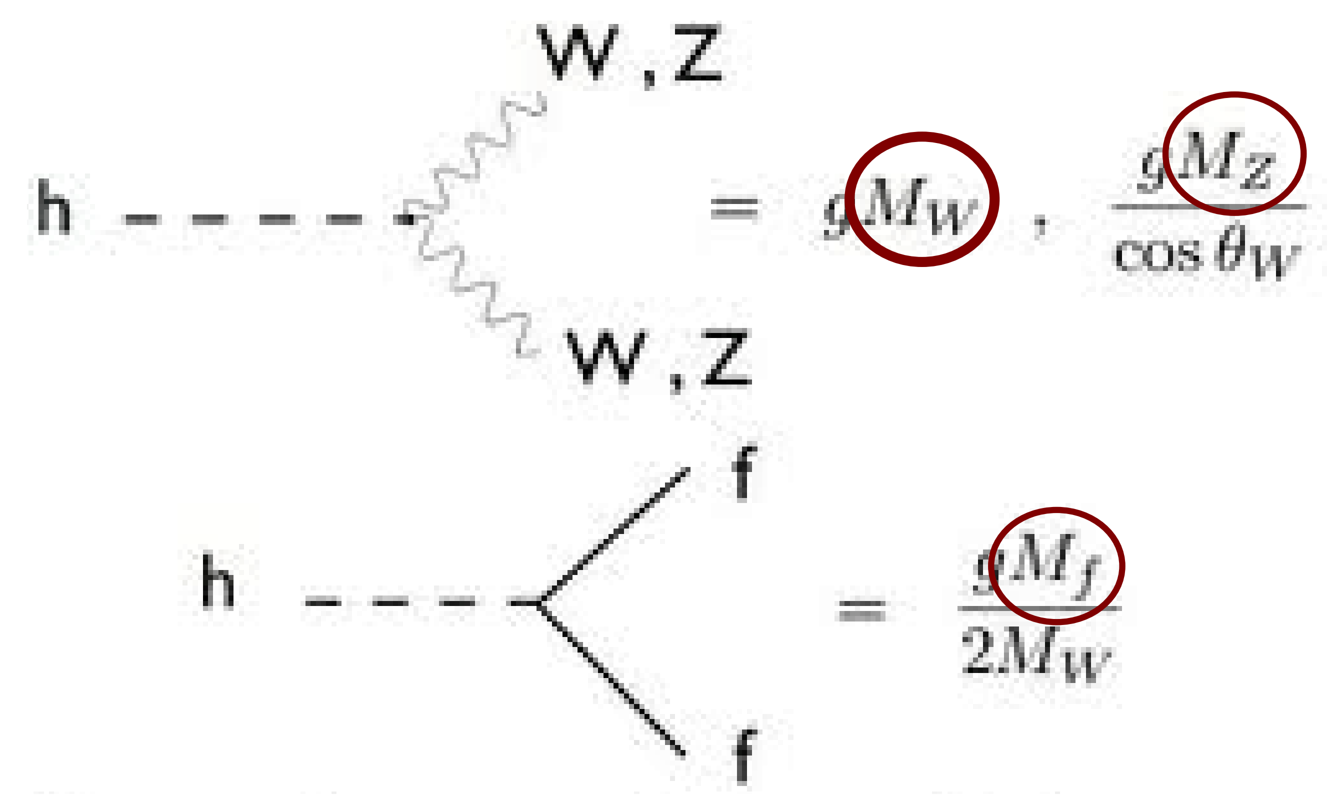
LS2 (2019-2020):
- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

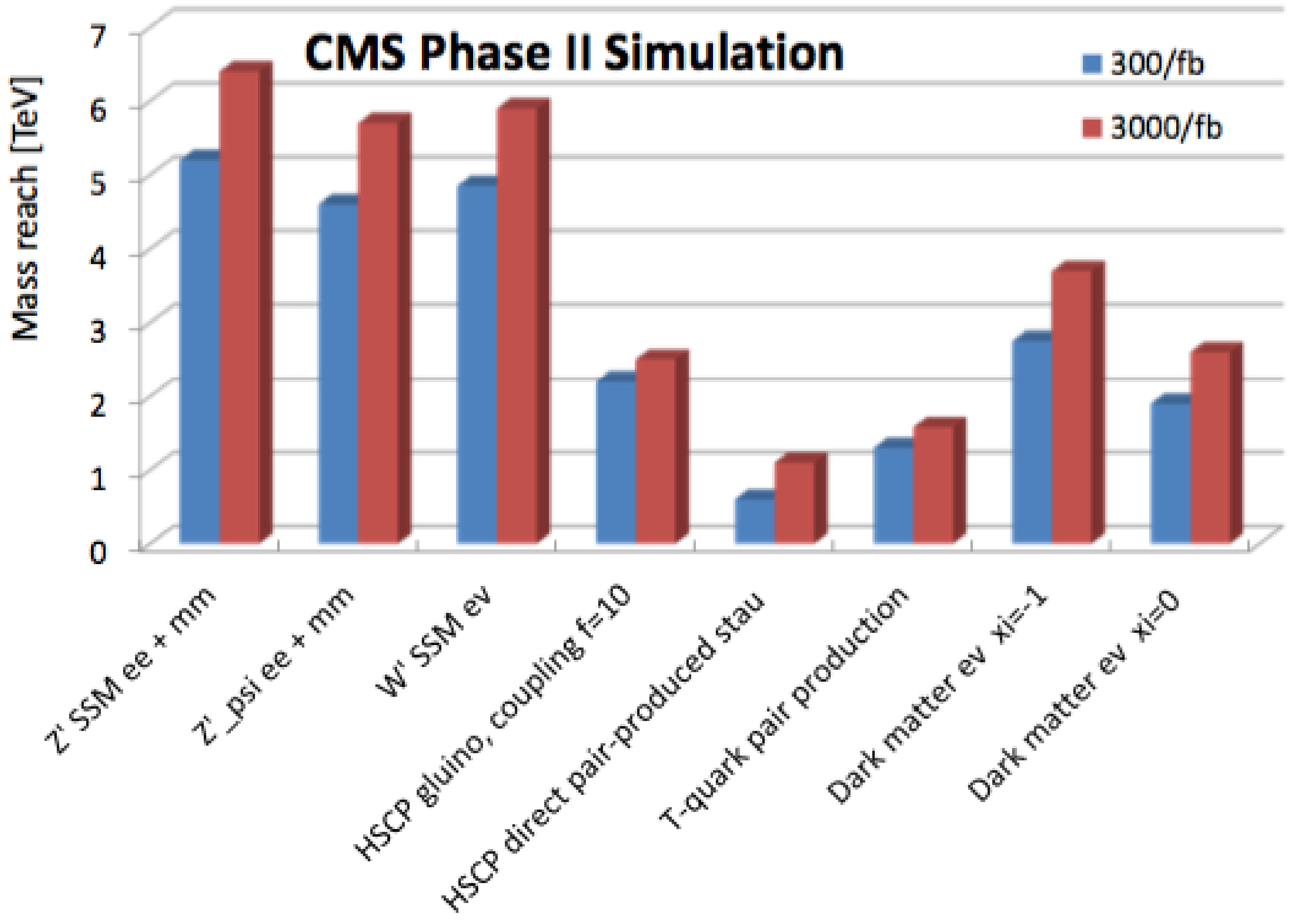
LS3 (2024-2026):
- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Schedule driven by radiation damage to inner triplet (eol: 2023)

A few physics example for HL-LHC

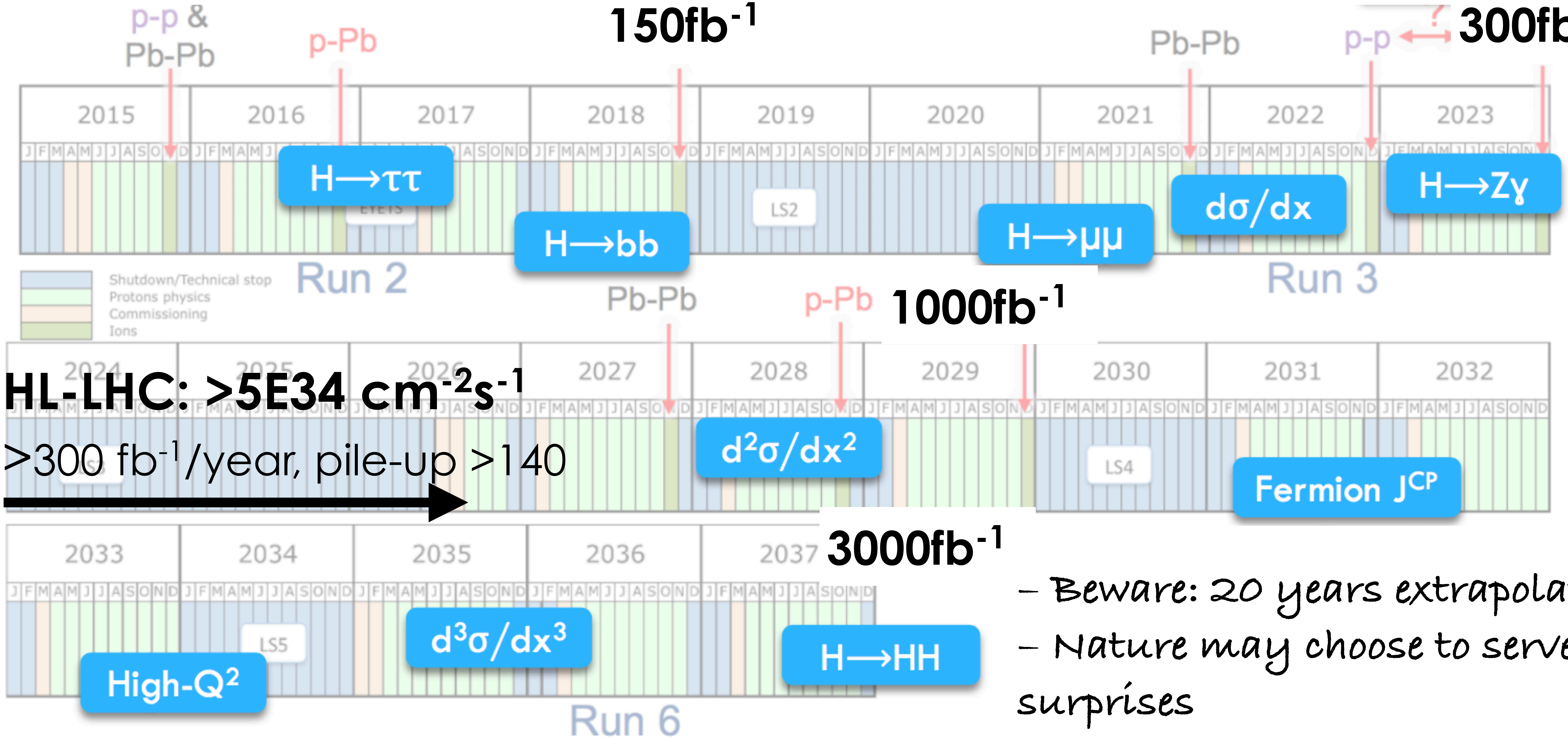
- measurement of Higgs couplings
  - deviations may be at the few %-level
  - access to second generation couplings H→μμ
- 20-30% larger discovery potential (8 TeV)
  - precision measurements





SM Physics Menu on the LHC and HL-LHC Running Schedule

Credits: A. David @ GRC 2017



– Beware: 20 years extrapolation

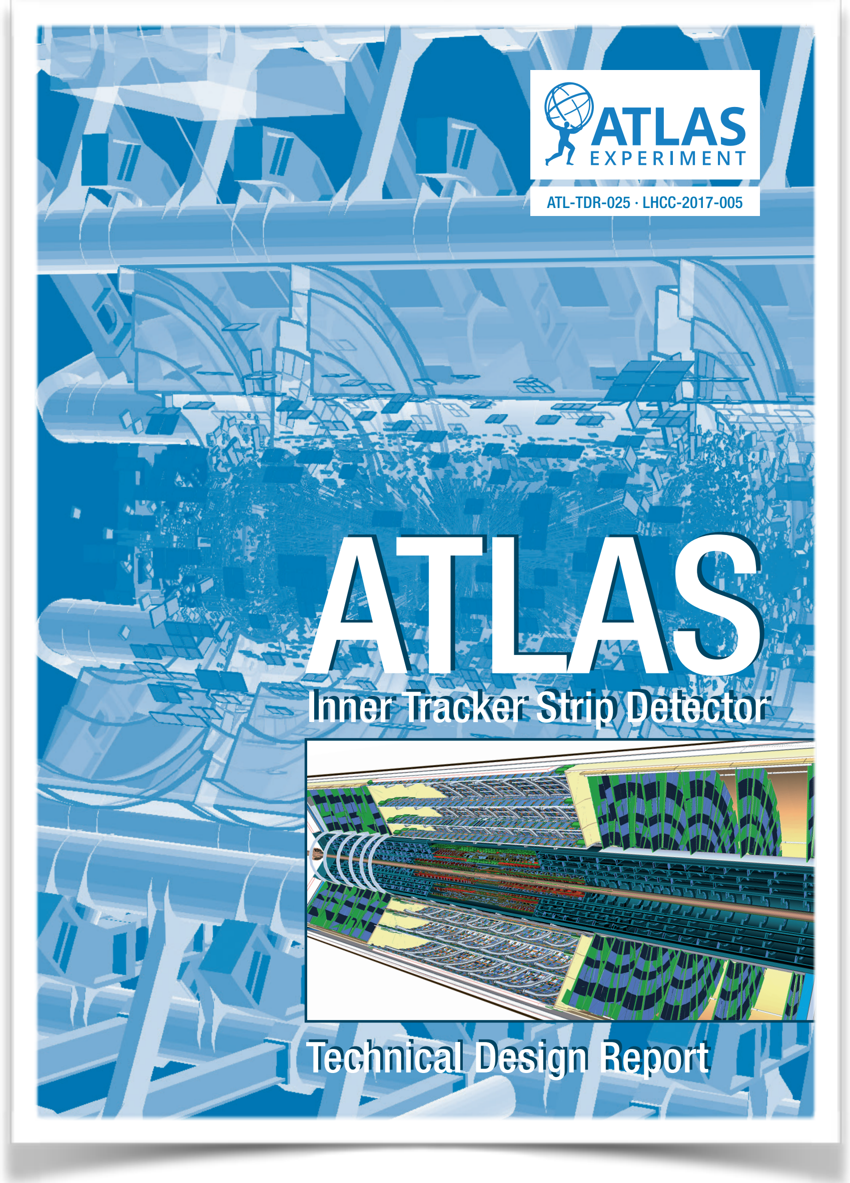
– Nature may choose to serve surprises

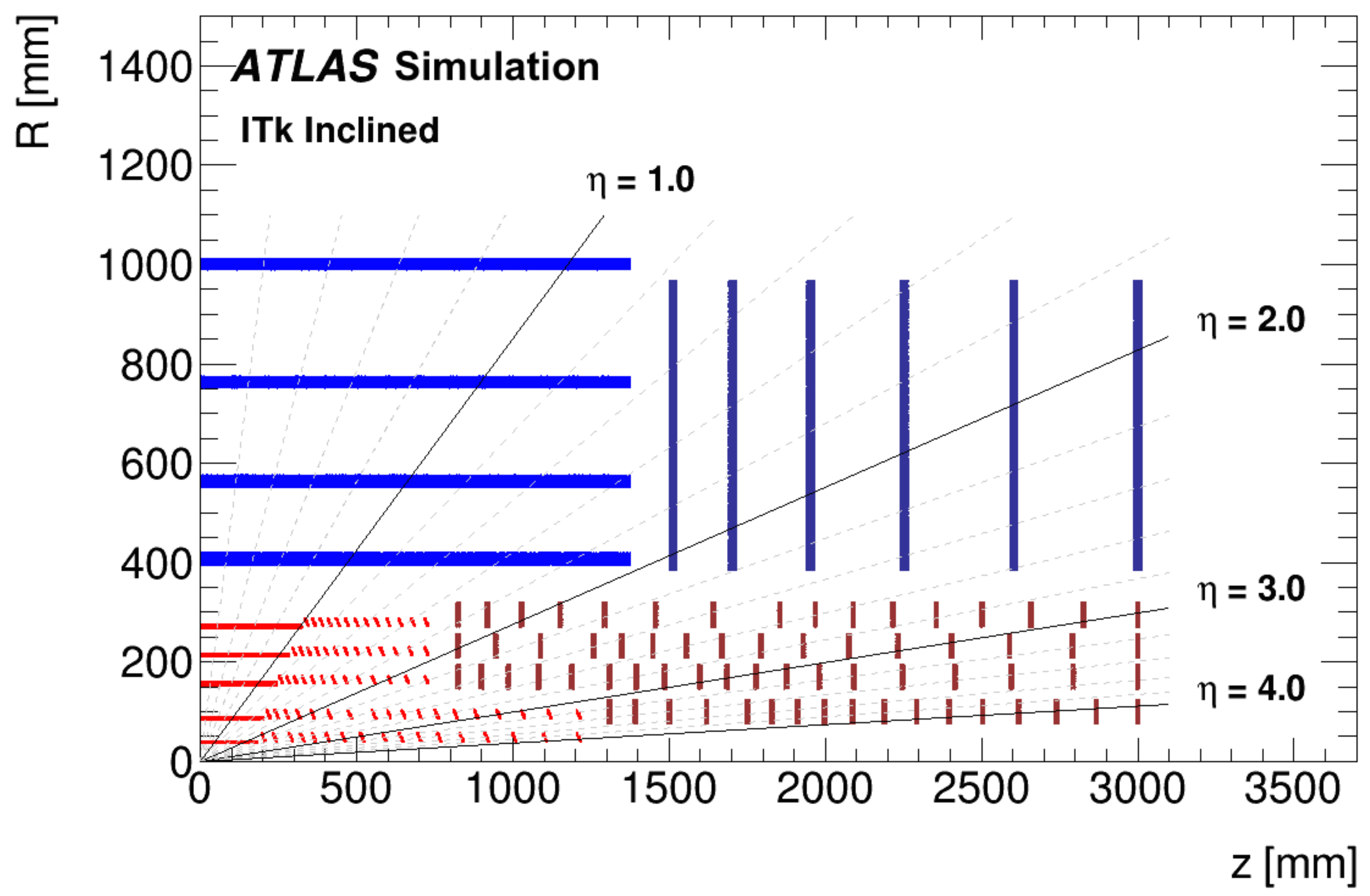
Phase II Detector upgrades

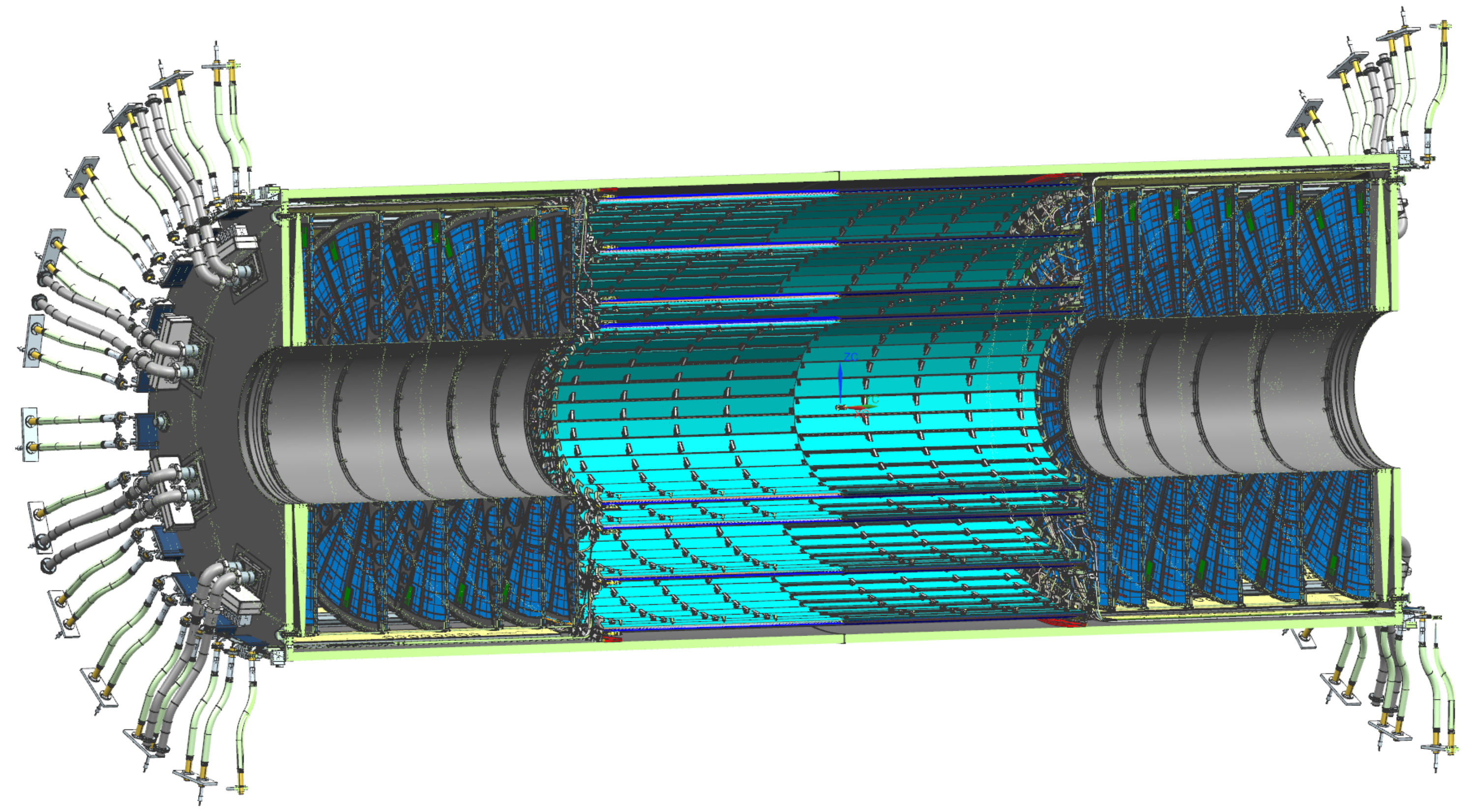
– replace radiation-damaged components
– enable detectors to withstand the rates at phase I performance

ATLAS ITk strips TDR (Phase II Upgrade)

- Settled on 5 pixel + 4 strips system
- Only the strips are evaluated in TDR – although status of pixel mentioned
- The pixel TDR will follow at the end of 2017
- Large document (>500 pages)







Planned deluge of Technical Design Reports (TDRs)

Experiment	System	Date	CORE MCHF	SOURCE
ATLAS	ITkStrip	Dec-16	61	TDR ITkStrip
ATLAS	Muon	Jun-17	34	SD
ATLAS	LAr	Sep-17	36	SD - sFCal
ATLAS	Tile	Sep-17	9	SD
ATLAS	TDAQ	Dec-17	43	SD
ATLAS	ITkPixel	Dec-17	59	SD
CMS	Tracker	Jul-17	112	SD
CMS	Barrel Cal	Sep-17	11	SD
CMS	Muon	Sep-17	25	SD
CMS	Endcap Cal	Nov-17	64	SD
CMS	Trigger DAQ/HLT	>2019	24	SD

SD=
Scoping Documents

ATLAS
Letter of Intent + Scoping Document
CERN-LHCC-2012-022
CERN-LHCC-2015-020

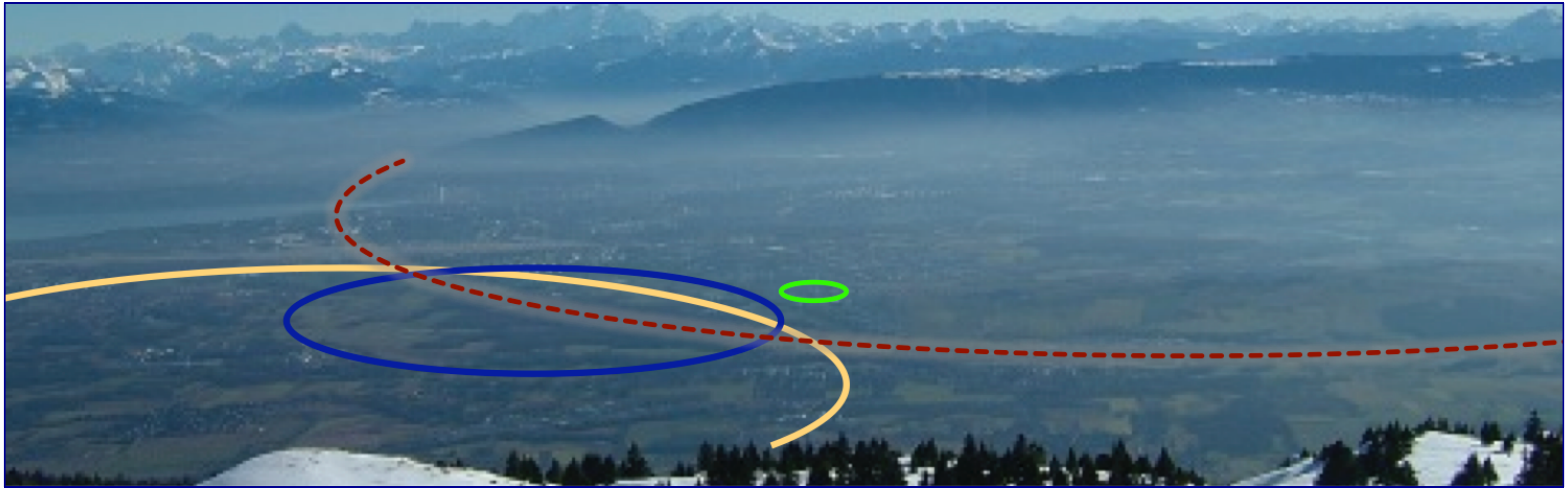
CMS
Technical Proposal + Scoping Document
CERN-LHCC-2015-010
CERN-LHCC-2015-019

Highest energy hadron colliders

From European Strategy of Particle Physics

CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

Future Circular Collider FCC



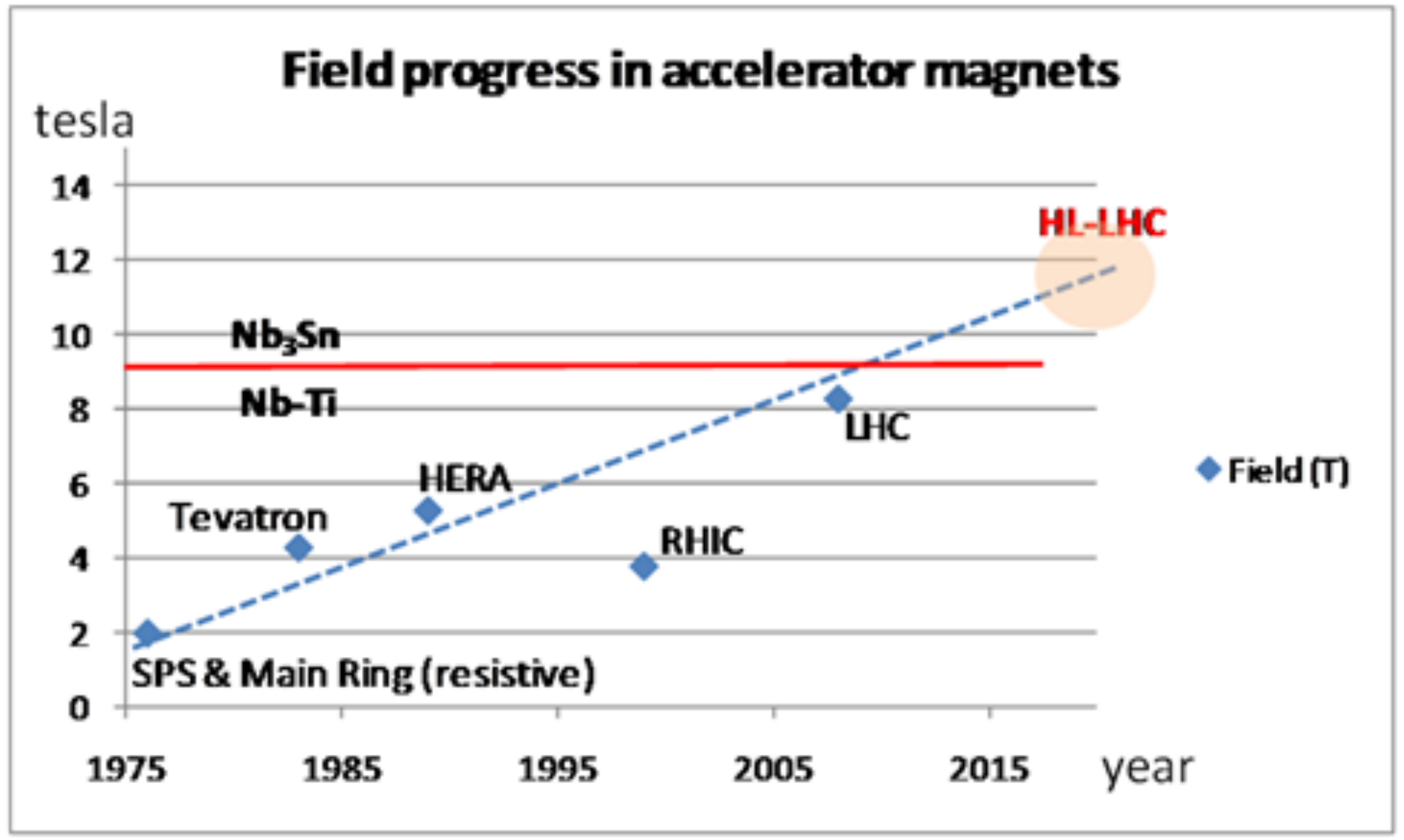
- Study for A 100 km ring providing collisions at 100 TeV cm
  - employs injector chain of CERN

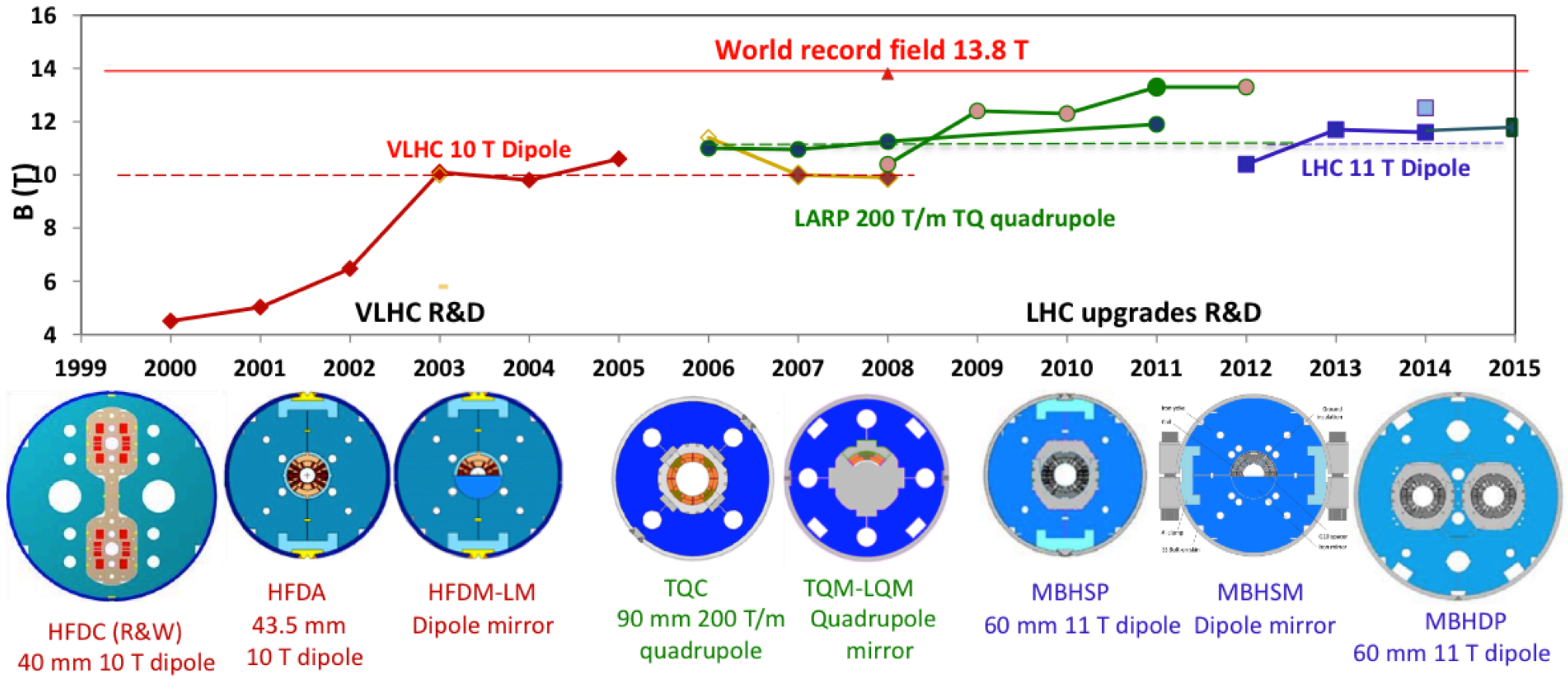
High-field magnets

- Key to high energies
  - FCC and
  - HE-LHC = use of high field magnets in existing LHC ring
- Technology
  - Nb_3Sn allows ~16 T magnets that need to be developed (size, cost, industry…)
    - HL-LHC magnets provide a ~1.2 km test of the technology (11 T magnets)
  - an insert of HTS may increase field to 20 T (requires considerable research)

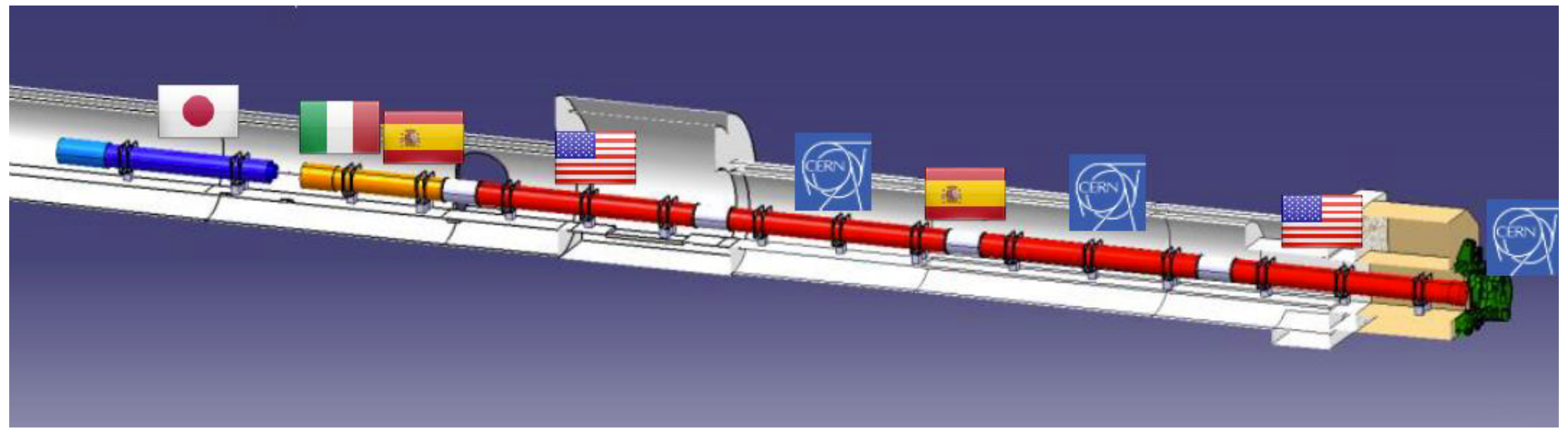
International Collaboration on Magnet Development

- Nb_3Sn magnets: international R&D programme
    - several European countries and US LARP programme and its successor



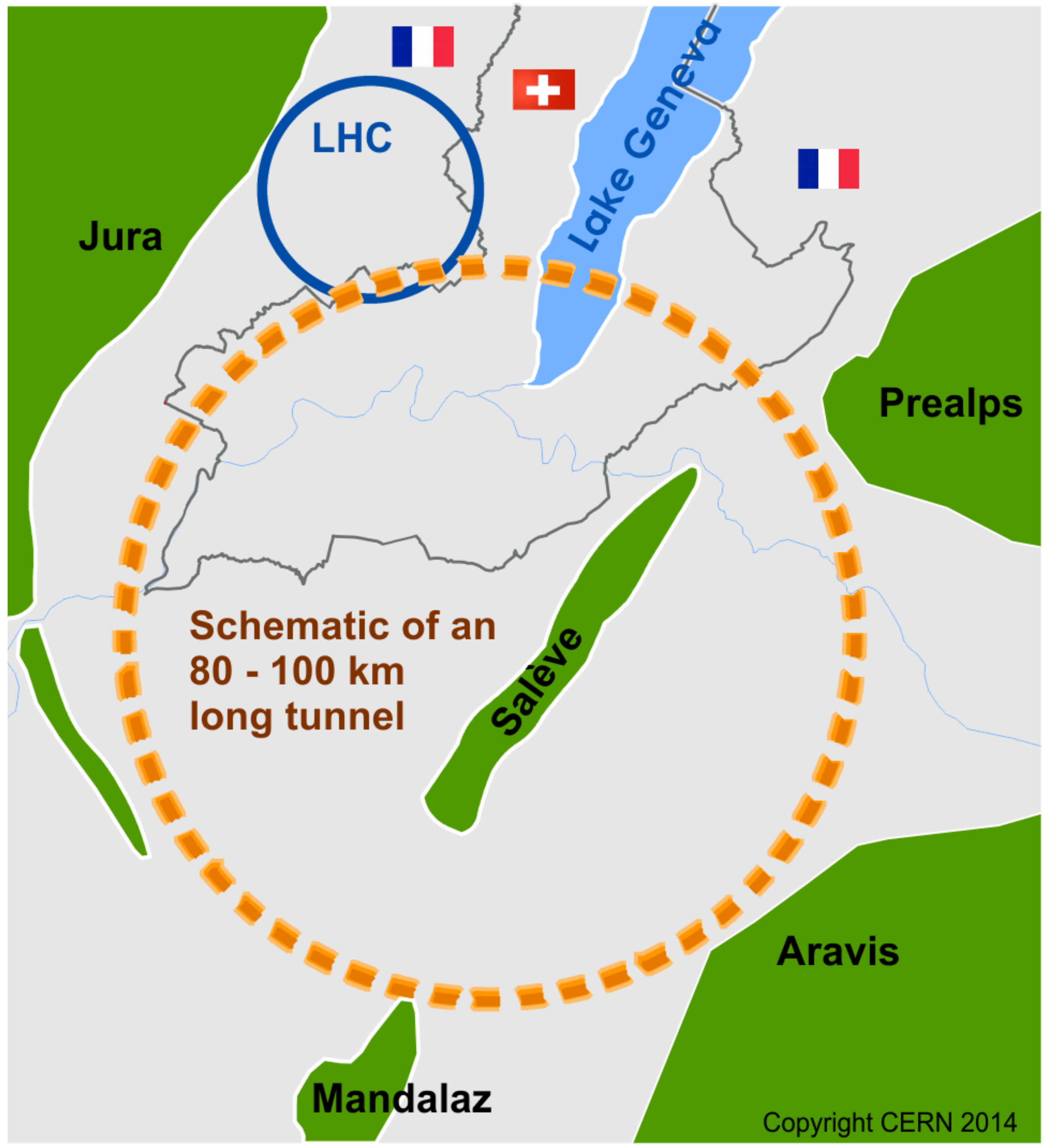


1.2KM of LHC modified



FCC Conceptual Design Report by end 2018

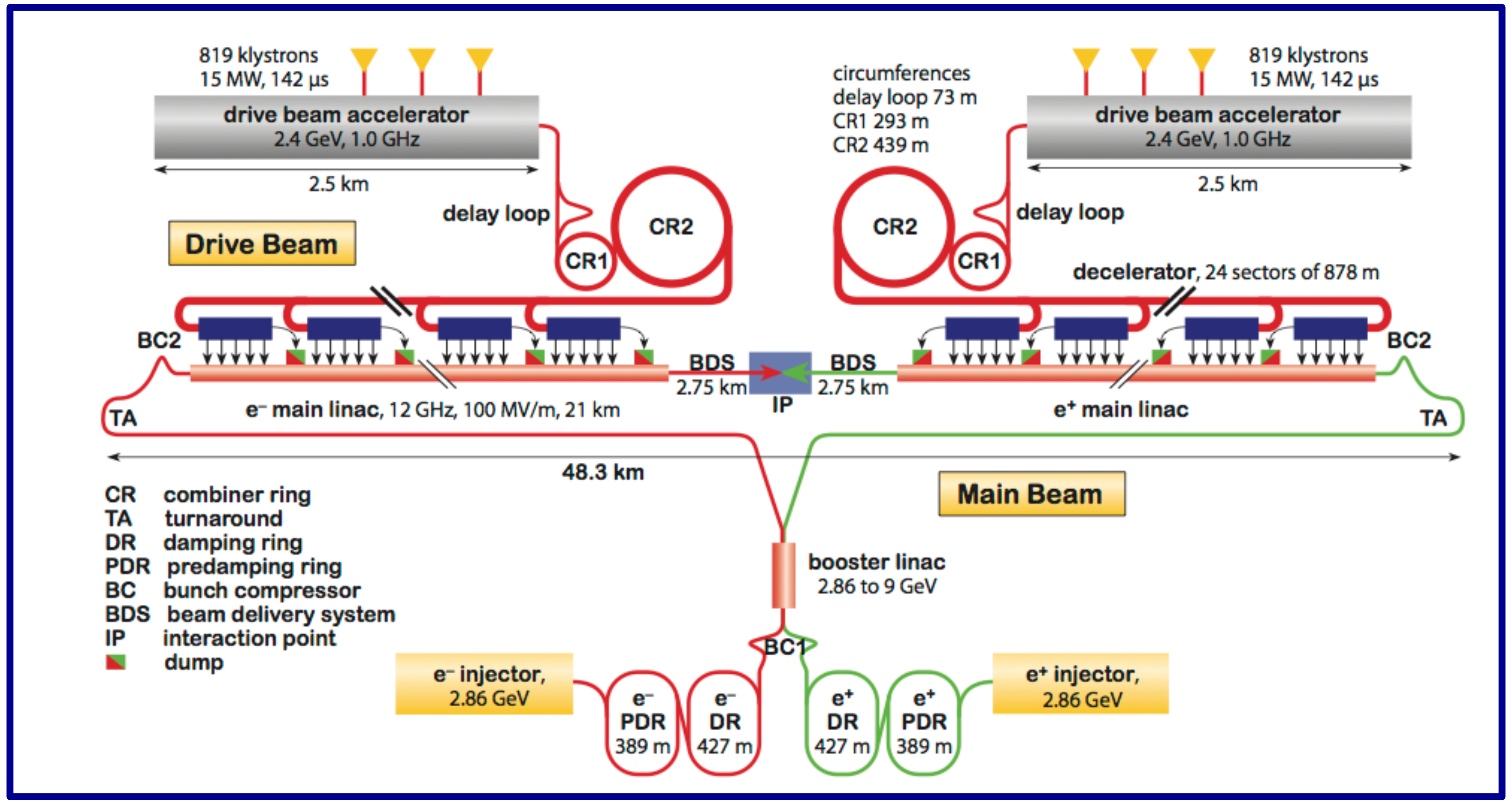
- **pp-Collider (FCC-hh) – sets the boundary conditions**
  - **100 km ring, $\sqrt{s}$=100 TeV, L~2x10^{35}**
  - **HE-LHC is included (~28 TeV)**
- e^+e^--Collider as a possible first step
  - $\sqrt{s}$= 90 - 350 GeV,
    L~1.3x10^{34} at high E
- eh-Collider as an option
  - $\sqrt{s}$=3.5 TeV, L~10^{34}



Highest energy with lepton colliders

Compact Linear Collider CLIC

- e^+e^- collider 1-3 TeV
- currently only option for the TeV region
- 380 GeV study has been completed both for 2-beam and klystrons approach; now explore 250 GeV
- decisive input to next update of European Strategy for Particle Physics



- CDR 2013
- CTF3 has provided key results
  - experimental programme ended 2016
- ready for a demonstrator

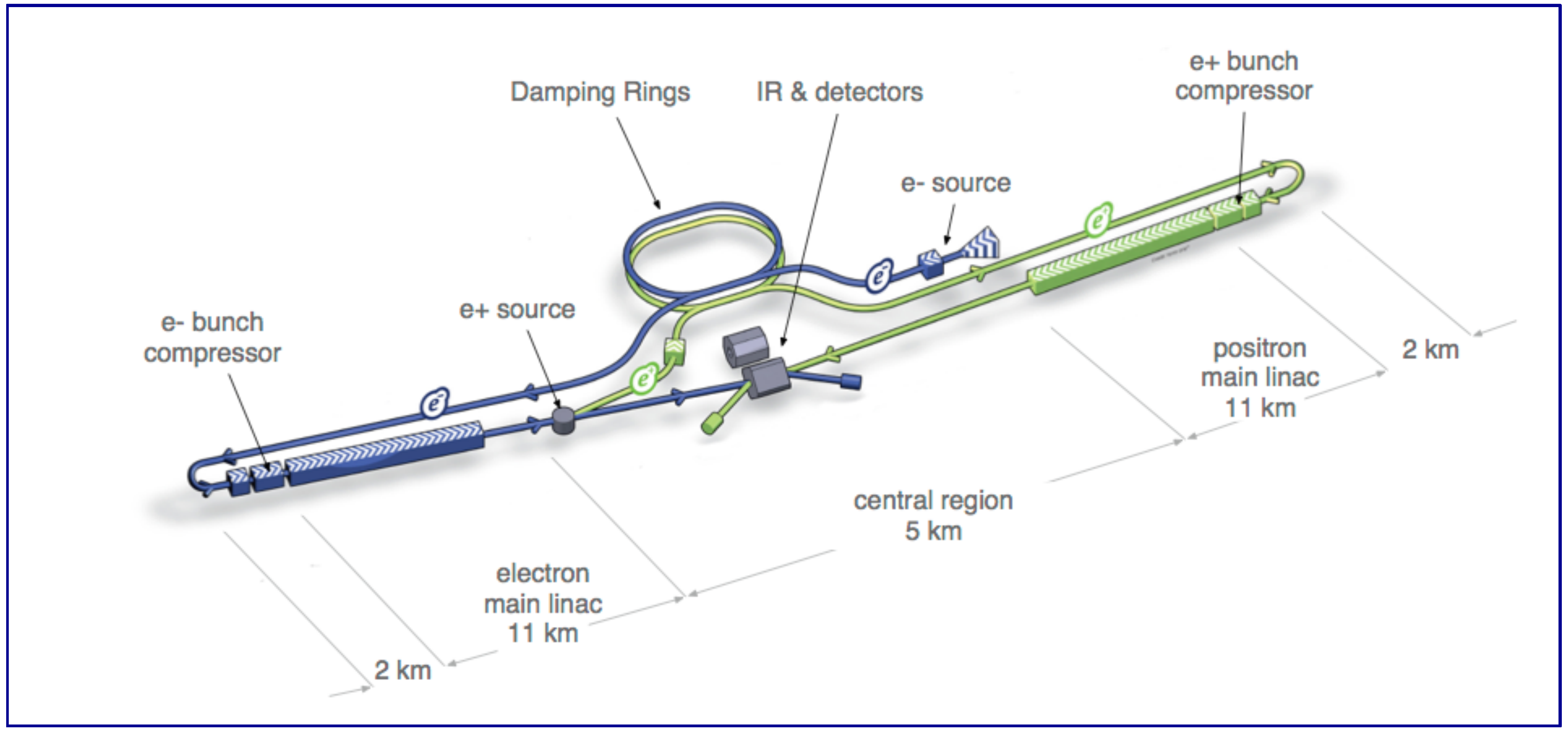
e^+e^- collider

From European Strategy of Particle Physics
There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.

Europe looks forward to a proposal from Japan to discuss a possible participation.

International Linear Collider ILC

- e^+e^- collider $\sqrt{s}$ = 0.5 TeV (upgradeable to 1 TeV)
    - staged version for $\sqrt{s}$ = 0.25 TeV being promoted
- precision Higgs (and Top) programme and beyond
- Ministry MEXT continues to evaluate the implications of hosting ILC in Japan w.r.t. cost, manpower (skills)



- Project is mature (TDR 2012)
- hosting evaluated by Japanese government
- expect (some) statement by the end of 2018

ν-physics

From European Strategy of Particle Physics

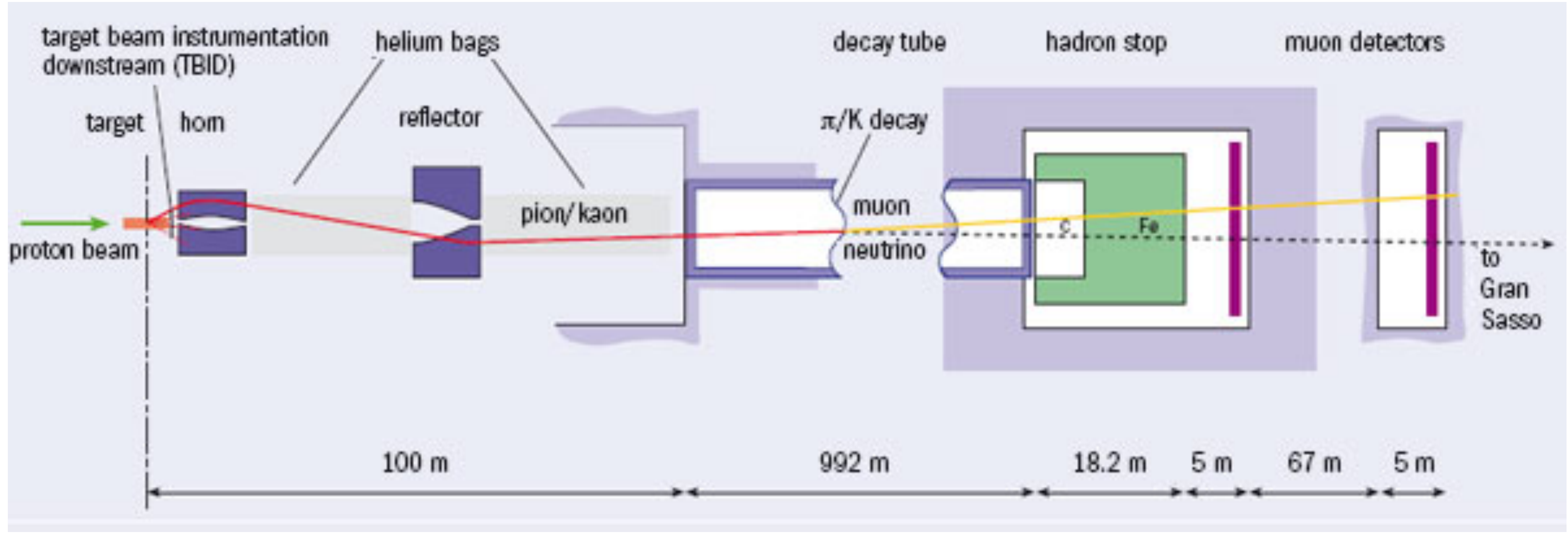
Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

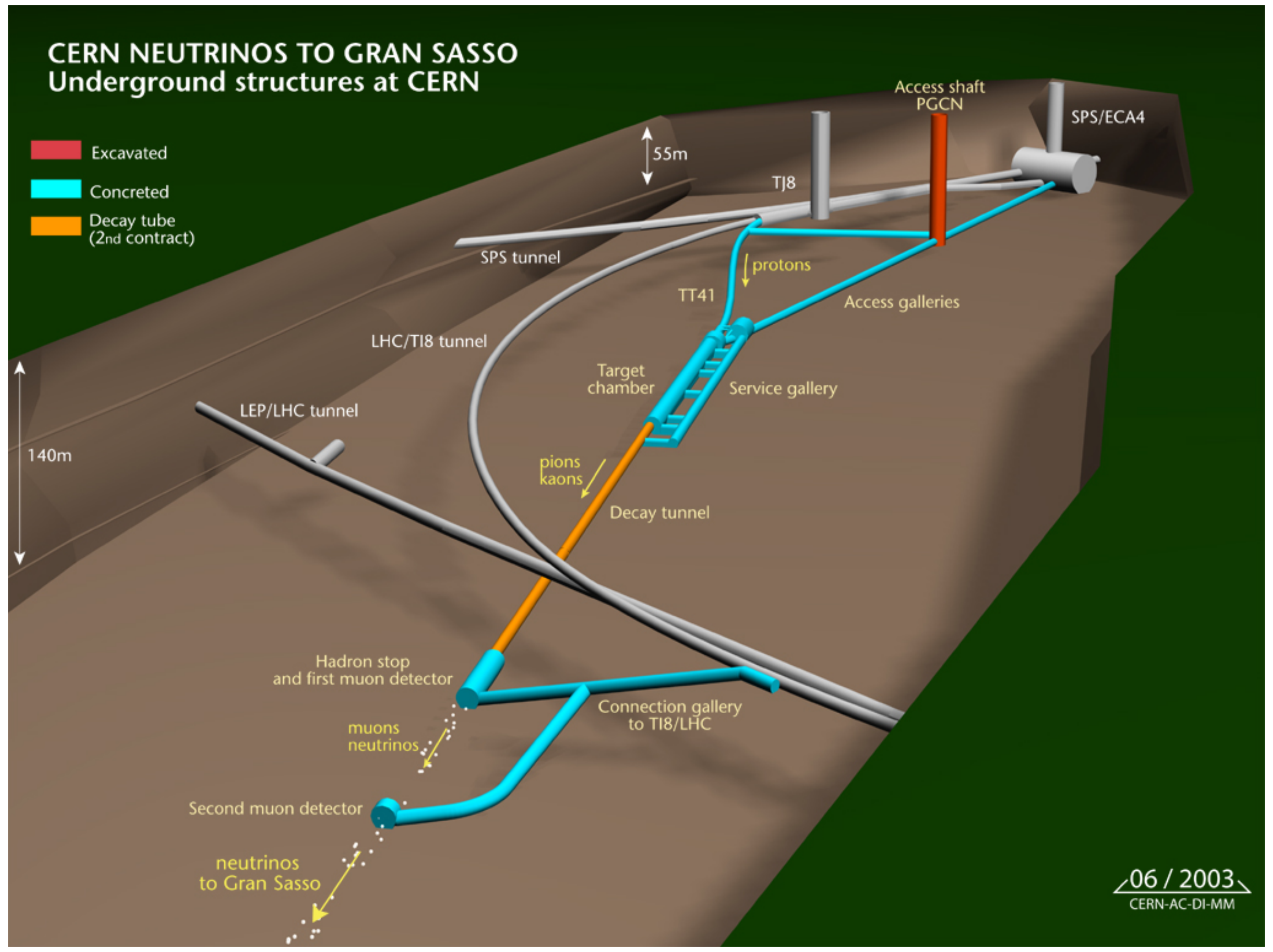
Neutrinos at CERN

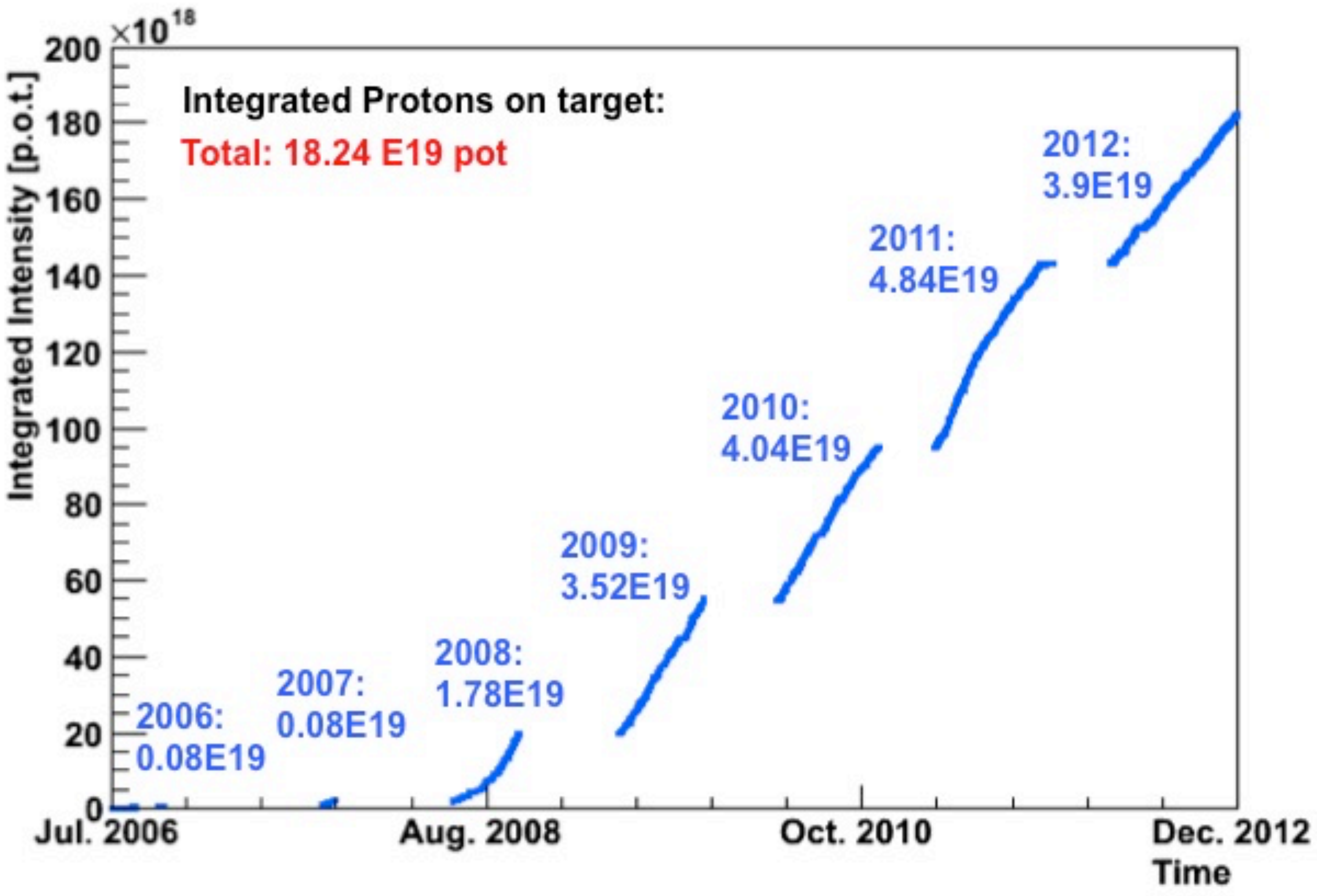
- Long tradition
  - detection of neutral currents at Gargamelle in 1973
  - CDHS and CHARM…
- More recently
  - CNGS
    - sending neutrinos from CERN to Gran Sasso

CNGS 2006 - 2012

- CERN ν-beam to Gran Sasso



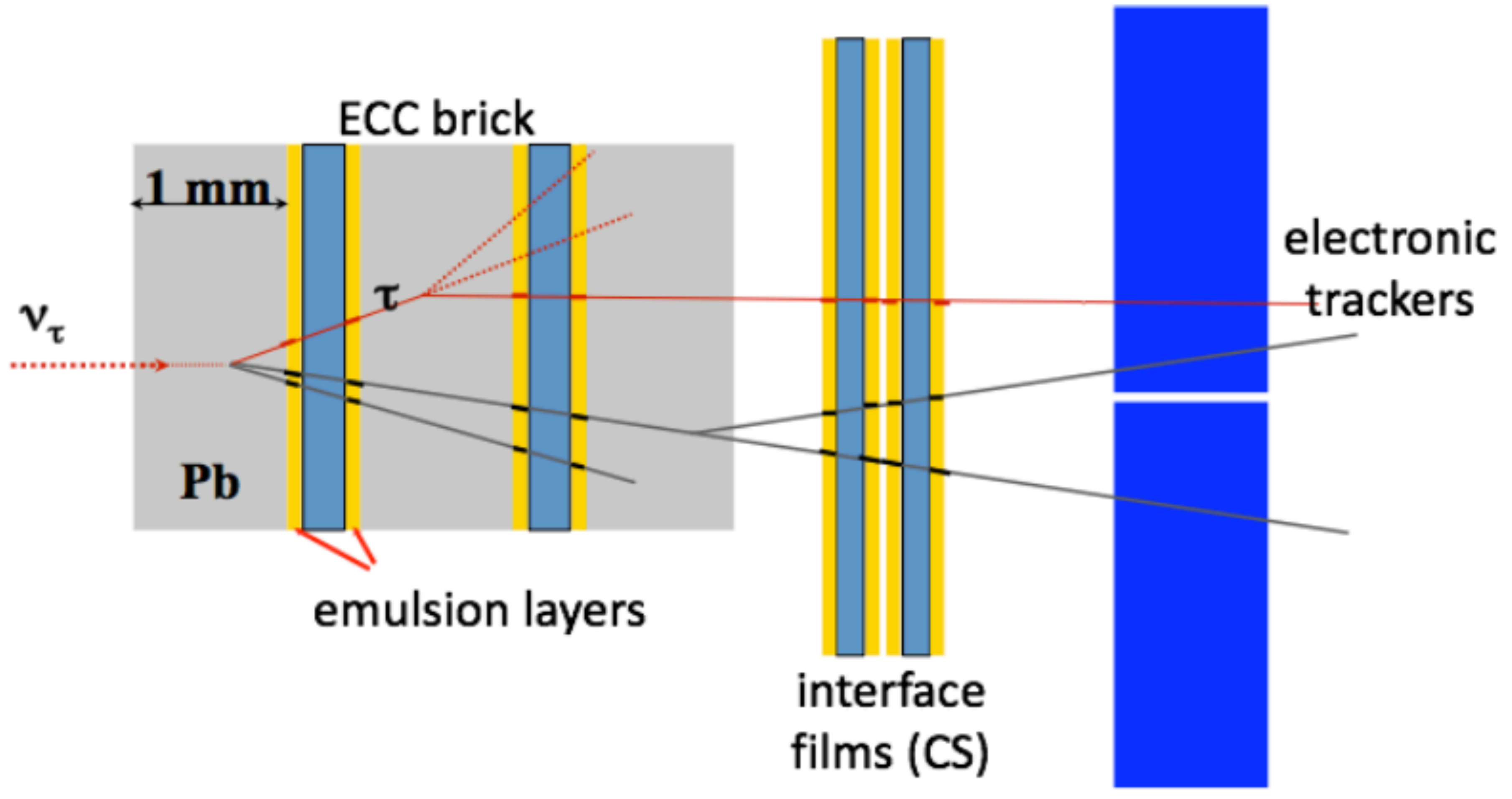


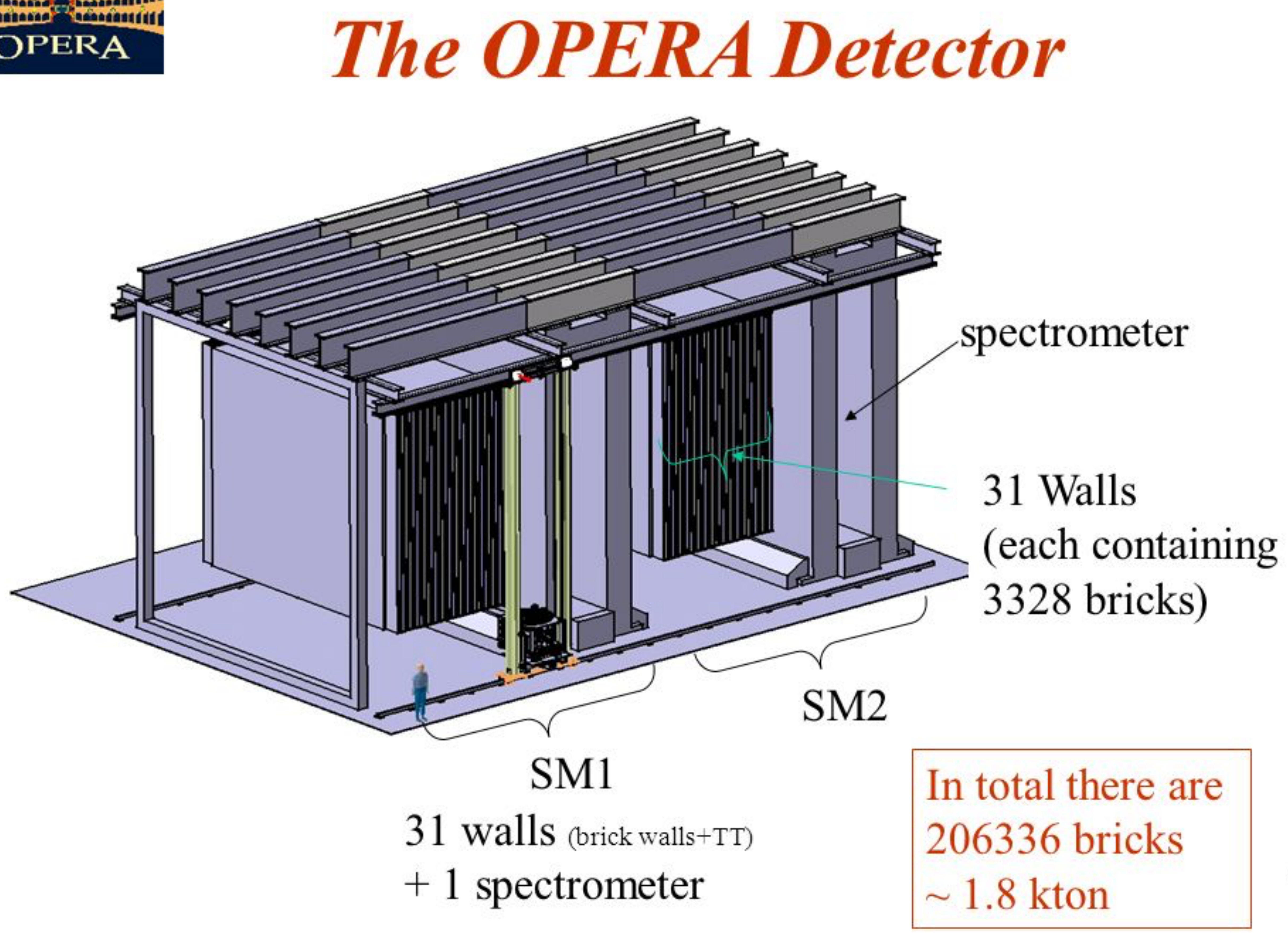


1.8×10^{20} p.o.t.

OPERA

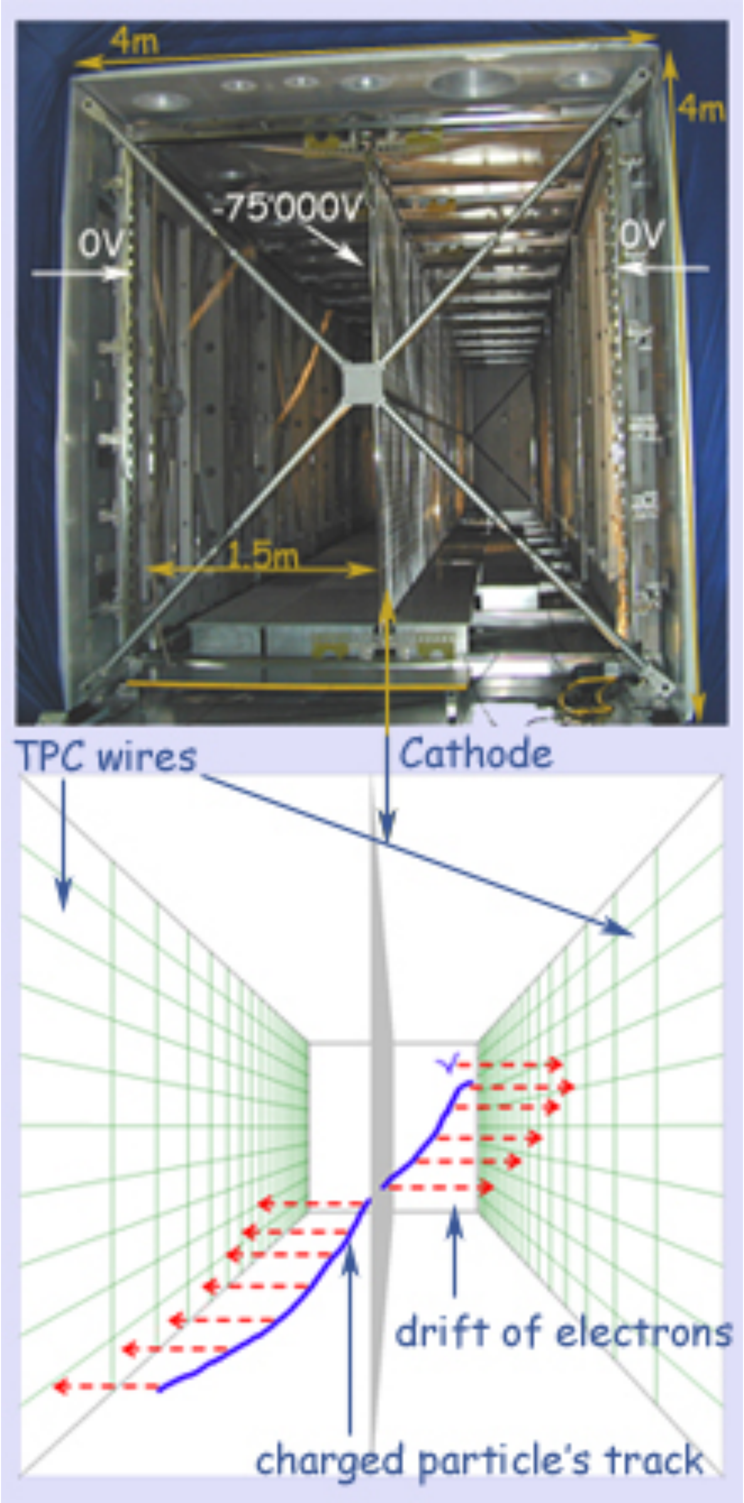
- 5 ν_τ were detected in emulsion detector
    - Detection of $\nu_\mu \to \nu_\tau$ oscillations

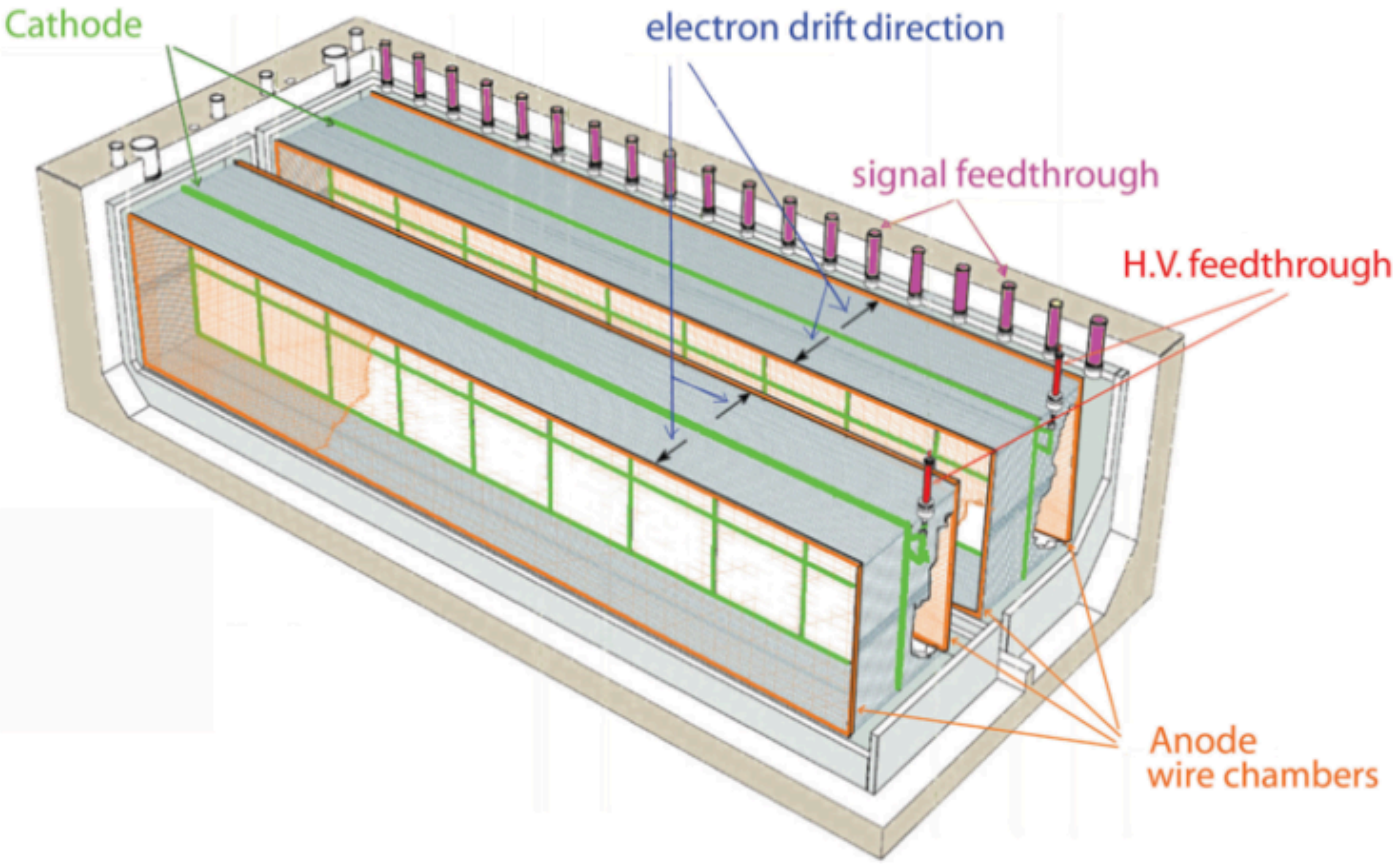




ICARUS at Gran Sasso

- LArTPC
  - search for $\nu_\mu \rightarrow \nu_e$ oscillations and LSND effect
    - $P_{\nu\mu\rightarrow\nu e} \leq 5.4 x 10^{-3}$ @ 90%CL
  - search for $\nu_\mu \rightarrow \nu_\tau$ oscillations





Neutrino Physics at CERN in the LHC era

- with the ESPP of 2012…
  …decision to end CNGS in 2012
- Establishment of a Neutrino Platform at CERN
  - as a springboard for European Physicists to engage in accelerator based neutrino physics in the US and in Japan
  - Detector development (initial emphasis on Lar TPC)
  - Extension of EHN1 hall

Charged particles from SPS available

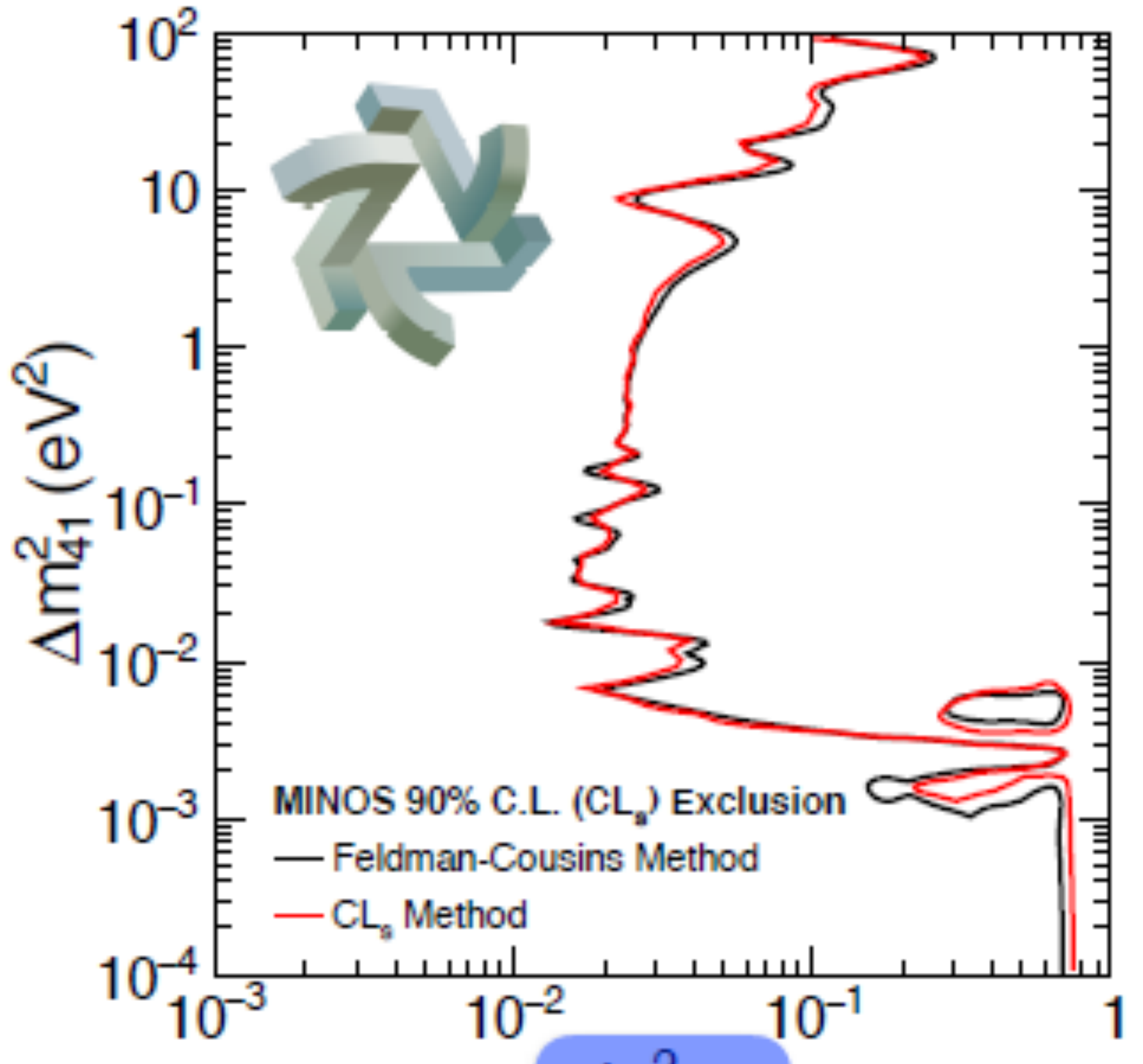
Fast entry into Short Baseline Programme at Fermilab

- ICARUS
    - ended data taking at LNGS
    - pioneered LarTPC technology
    - space at LNGS had to be cleared

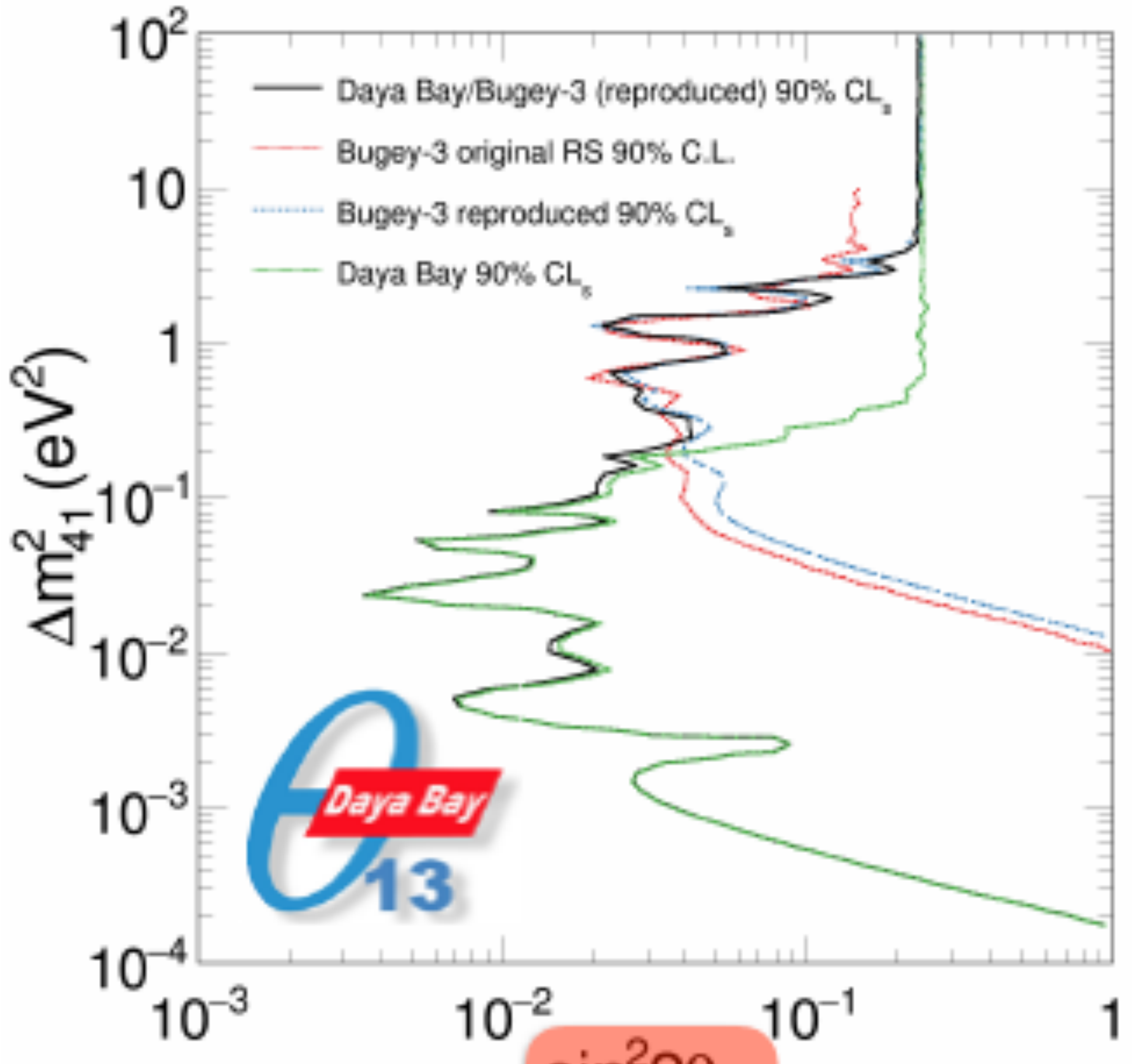
ICARUS overhaul at CERN (WA104 - NP01)

- Detector upgrade
  - more PMTs
  - new cathode, inner cabling
  - new electronics
- Scintillator layer (cosmic tagger)
- New cryostat and cryogenic plant
- Reassembly of the 2 T300 modules inside cryostats and shipment to Fermilab

Sterile neutrino search



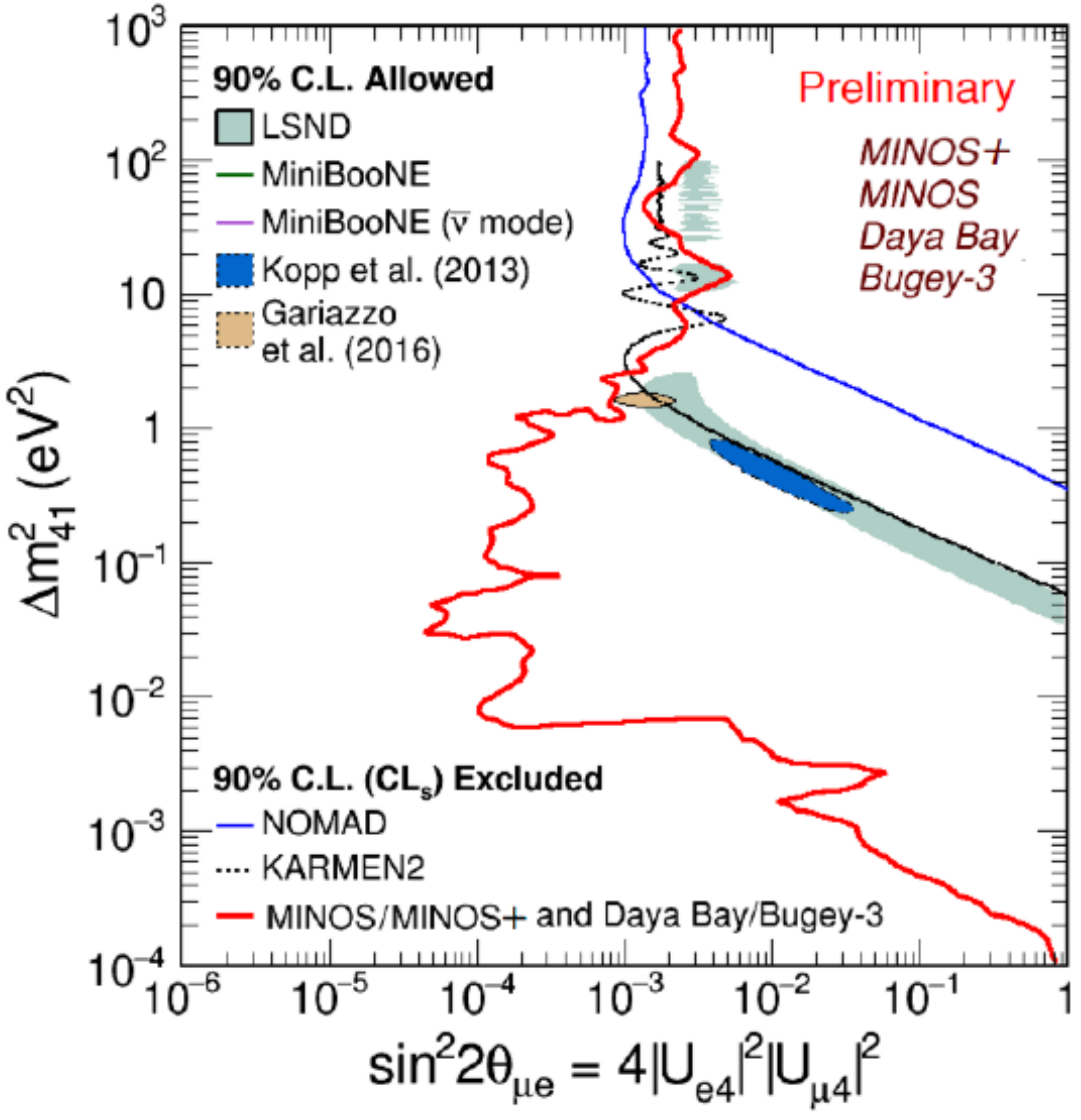
sin$^2\theta_{24}$



sin$^22\theta_{14}$

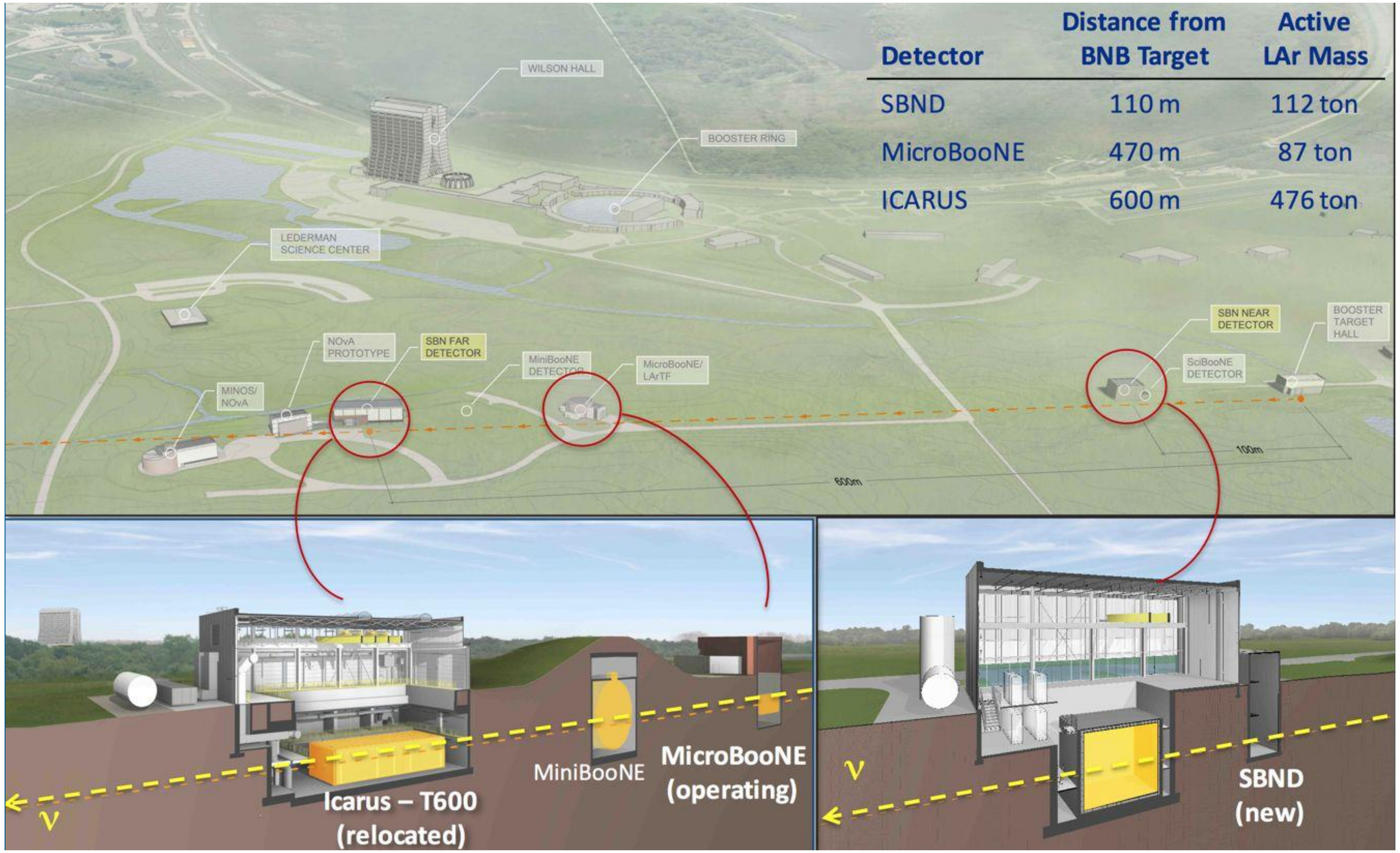
LSND & MiniBooNE

$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$



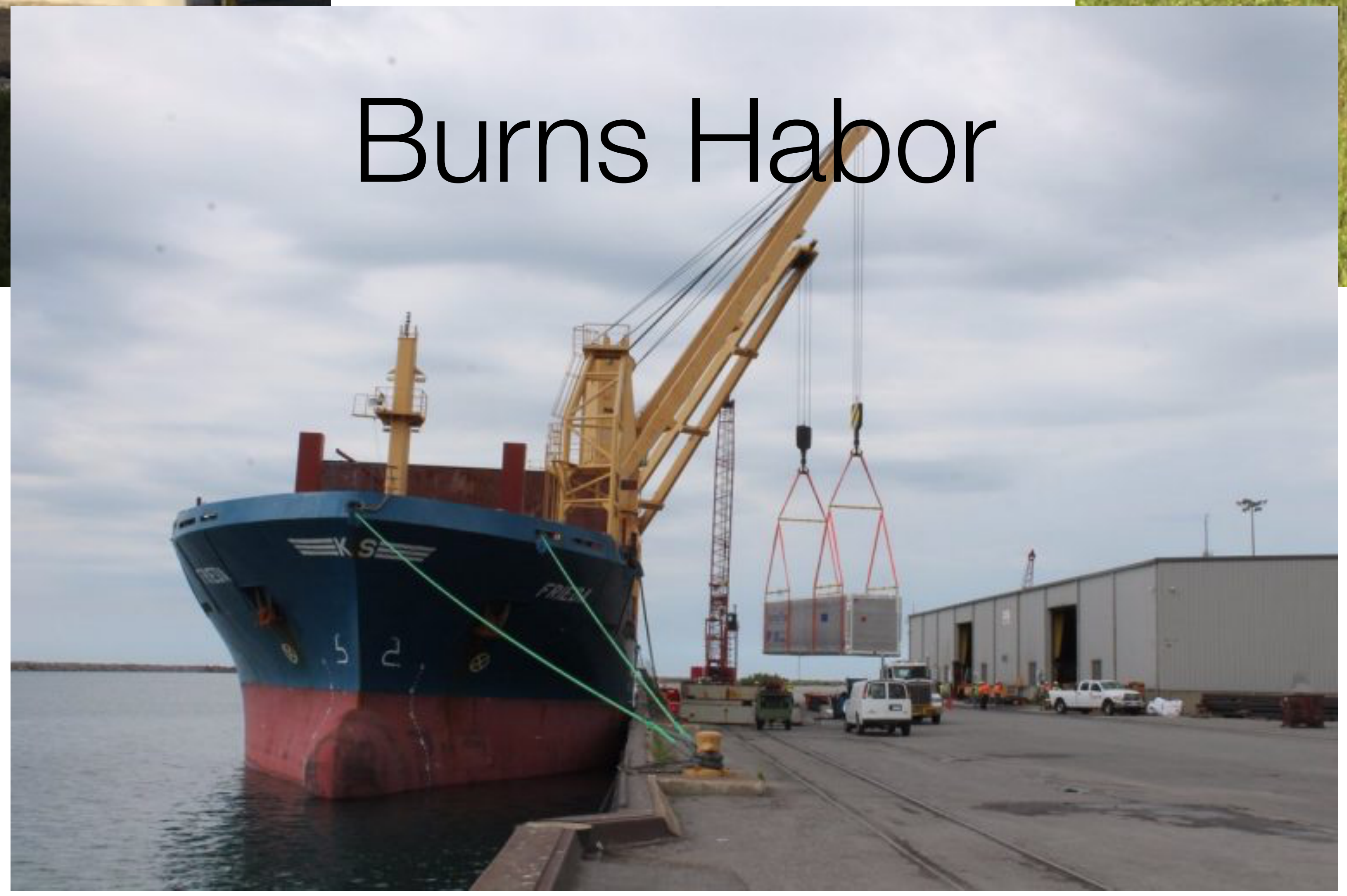
Short baseline programme at Fermilab

- To resolve experimental inconsistencies in the measured ν-spectrum
  - SBND (near detector)
  - MicroBooNE (operating)
  - MiniBooNE
  - refurbished ICARUS arrived at Fermilab



ICARUS Trip

Burns Habor



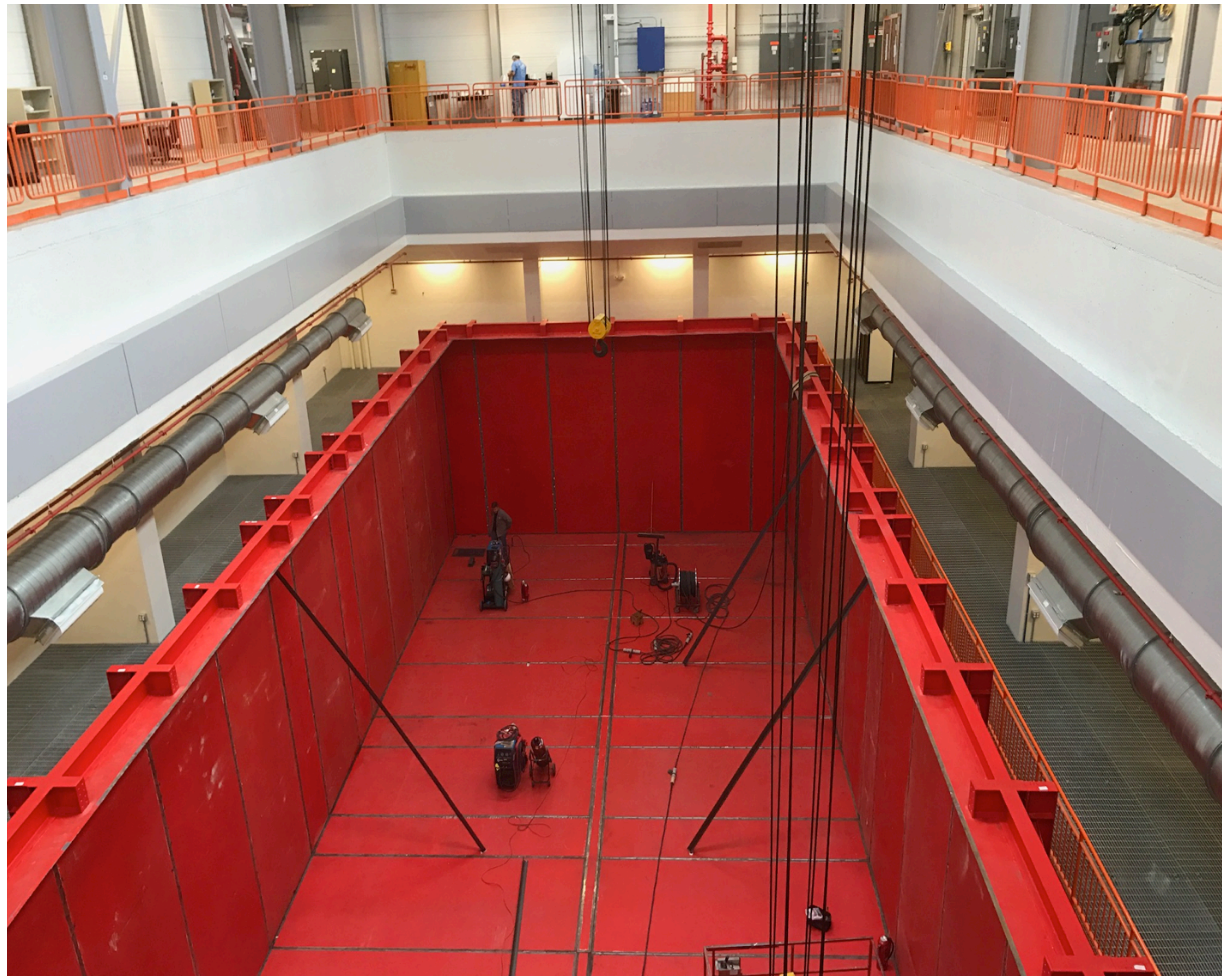
CERN

Fermilab

ICARUS arrival at Fermilab

- Novel cryostat technology for ICARUS
    - based on GTT technology well established for vessels carrying liquid gases
    - much more demanding on stability

Route Planning	Route Schedule
Dep. CERN	12 June 2017
↓ truck	
Arr. Basel (CH)	14 June 2017
Dep. Basel (CH)	15 or 16 June 2017
↓ barge	
Arr. Antwerp (NL)	21 June 2017
Dep. Antwerp (NL)	earliest/latest on 23/30 June 2017
↓ ship	
Arr. Burns Arbor (USA, IN)	appr. 23-24 days after departure from Antwerp
↓ truck	
FERMILAB	appr. 2 days after dep. from Burns Arbor



J-PARC at Neutrino Platform

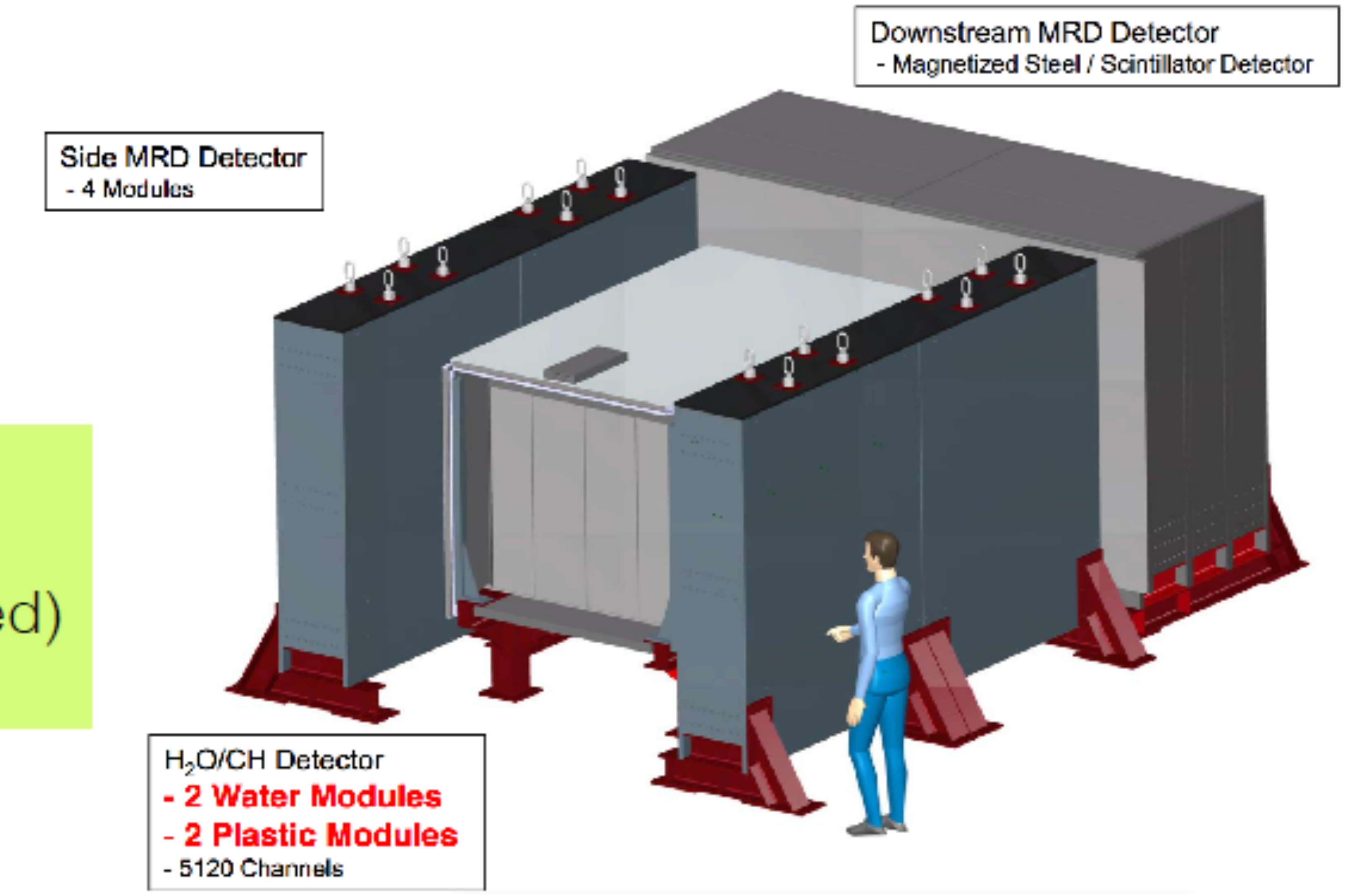
- 3% precision H_2O/C_nH_n cross-section ratio
- Study of ν_μ energy reconstruction
- wide angle θ coverage
- complementary to ND280

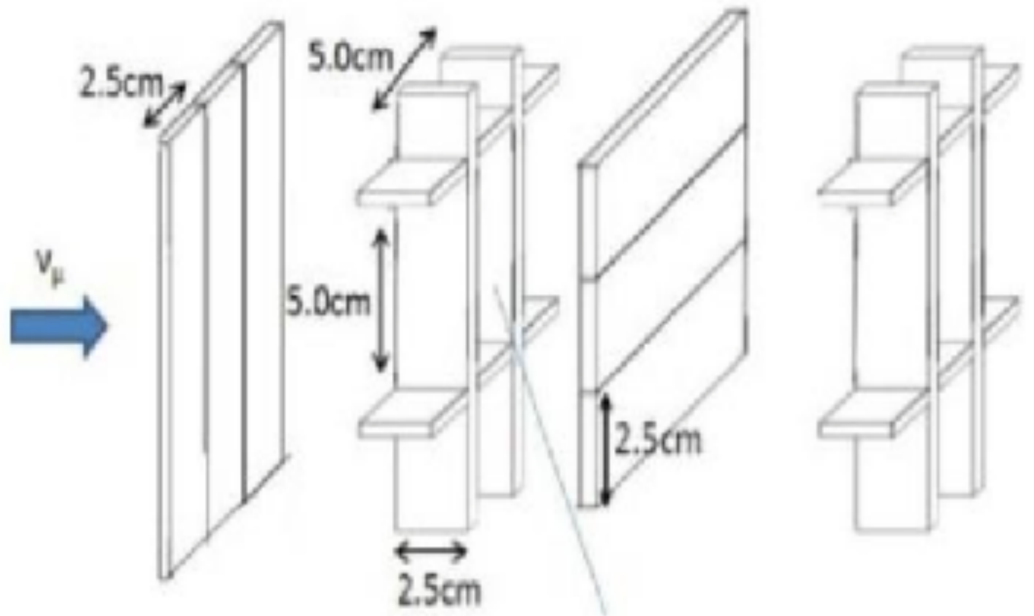
3% precision H_2O / CH x-section ratio

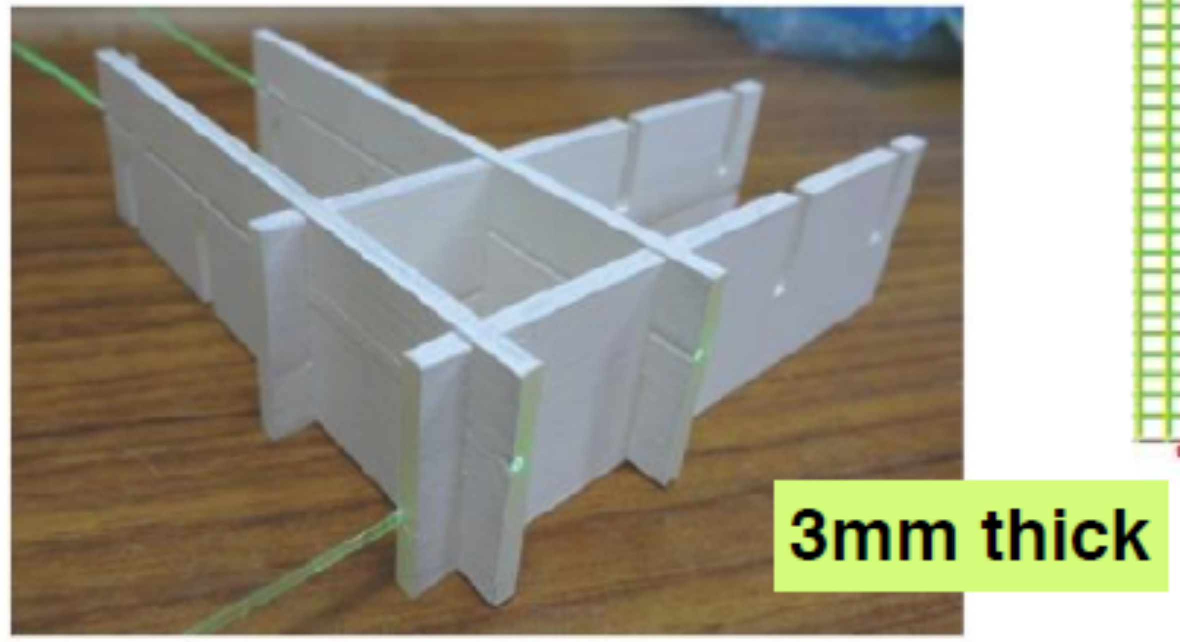
Wagasci

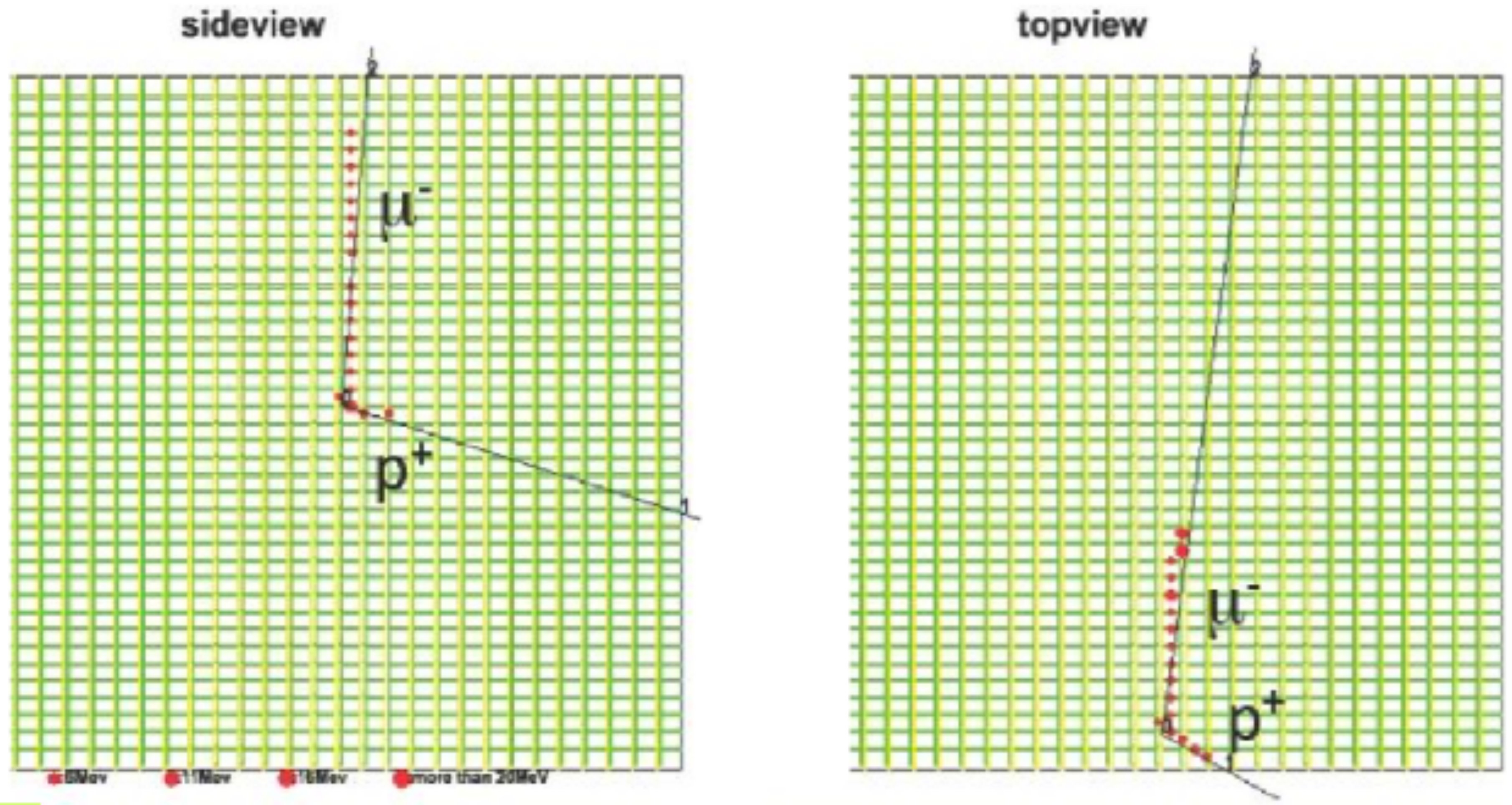
Wagasci collaboration

‘The B2 experiment’
- 3D scintillator grid filled with water
- Side MRDs and end MRD (magnetized)
- Excellent phase space coverage







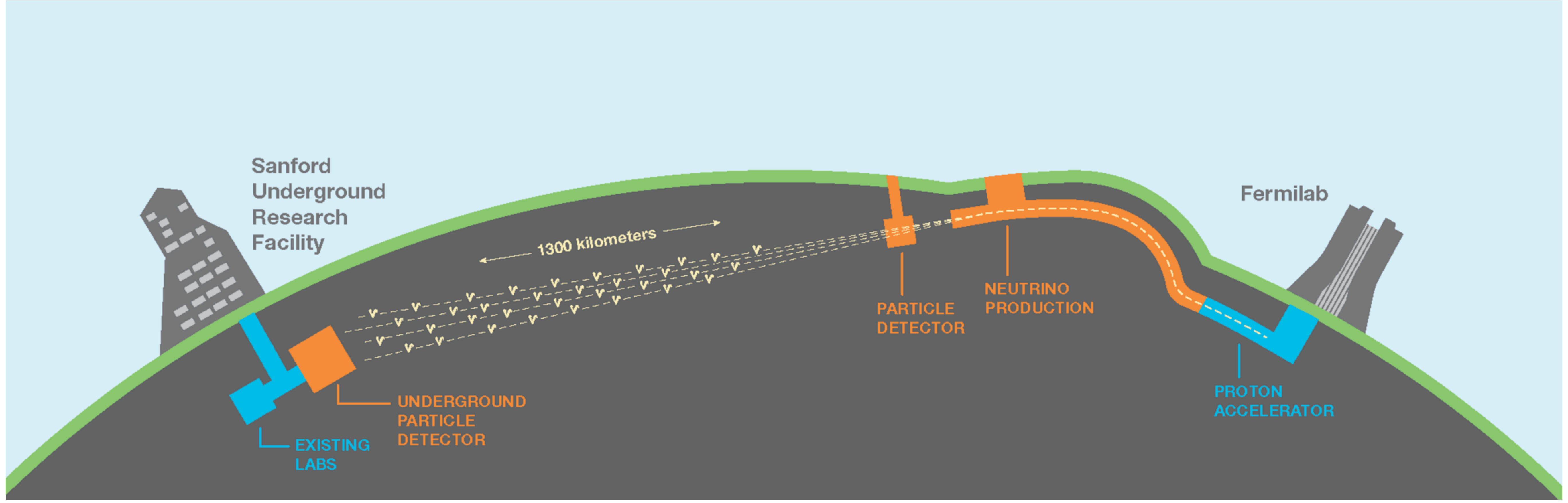


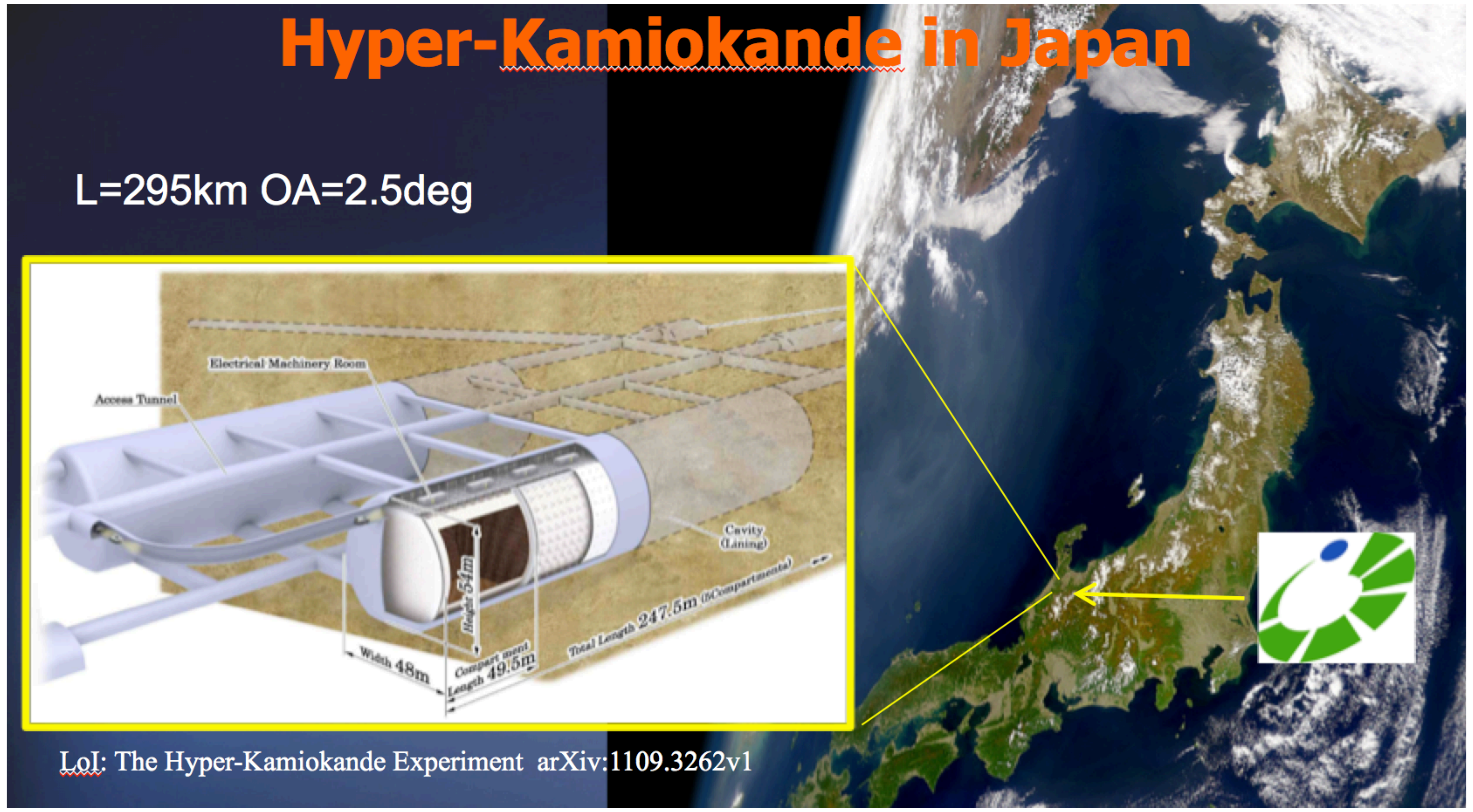
Long baseline neutrino programmes

- Fermilab is constructing a long baseline neutrino facility (LBNF), a wide band neutrino beam to the DUNE experiment (40 kt LArTPC) in South Dakota

- Tokyo is considering Hyper-K (water Cherenkov detector) at Kamioka

- Goals: neutrino-oscillation parameters, mass hierarchy and CP-violation, …

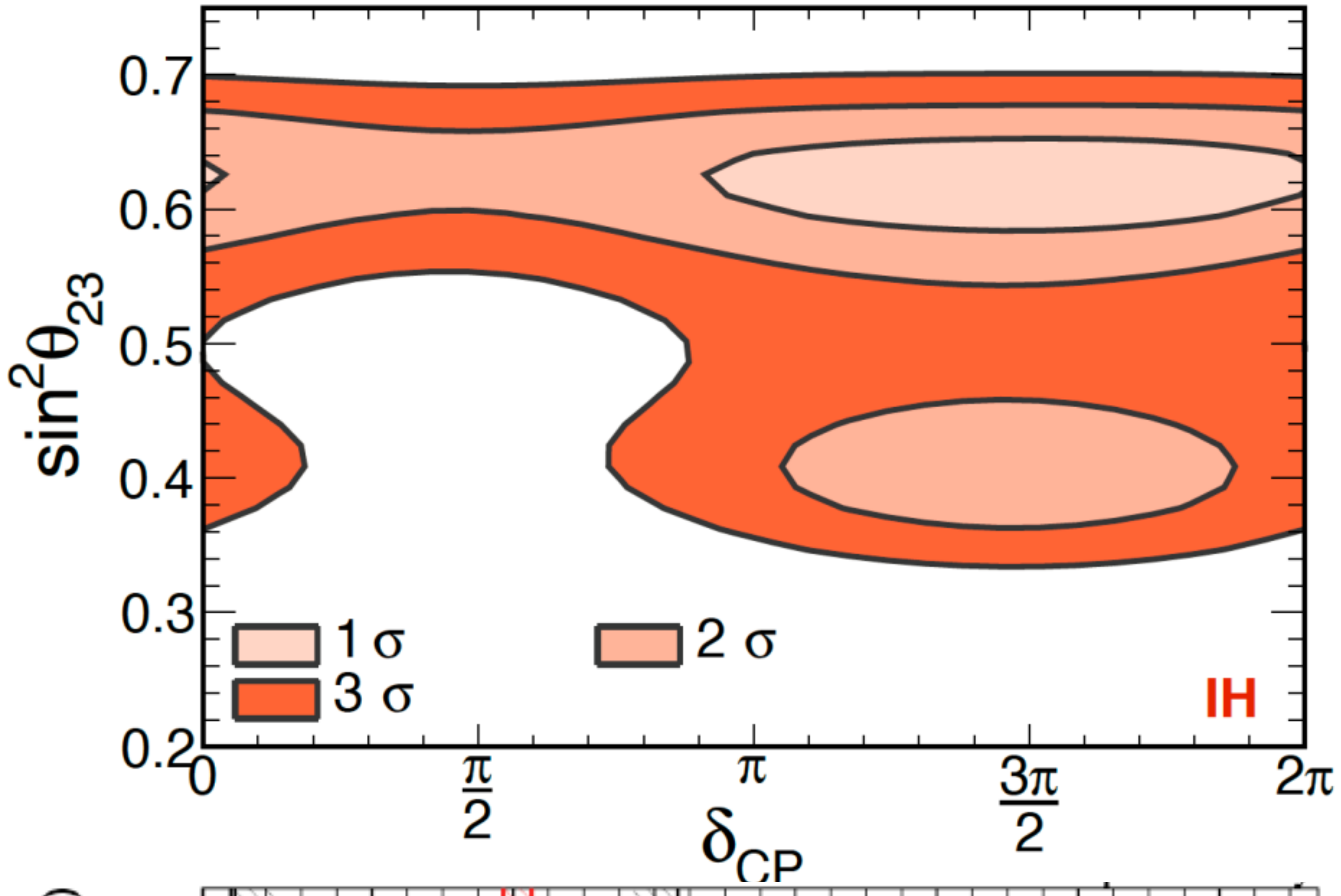




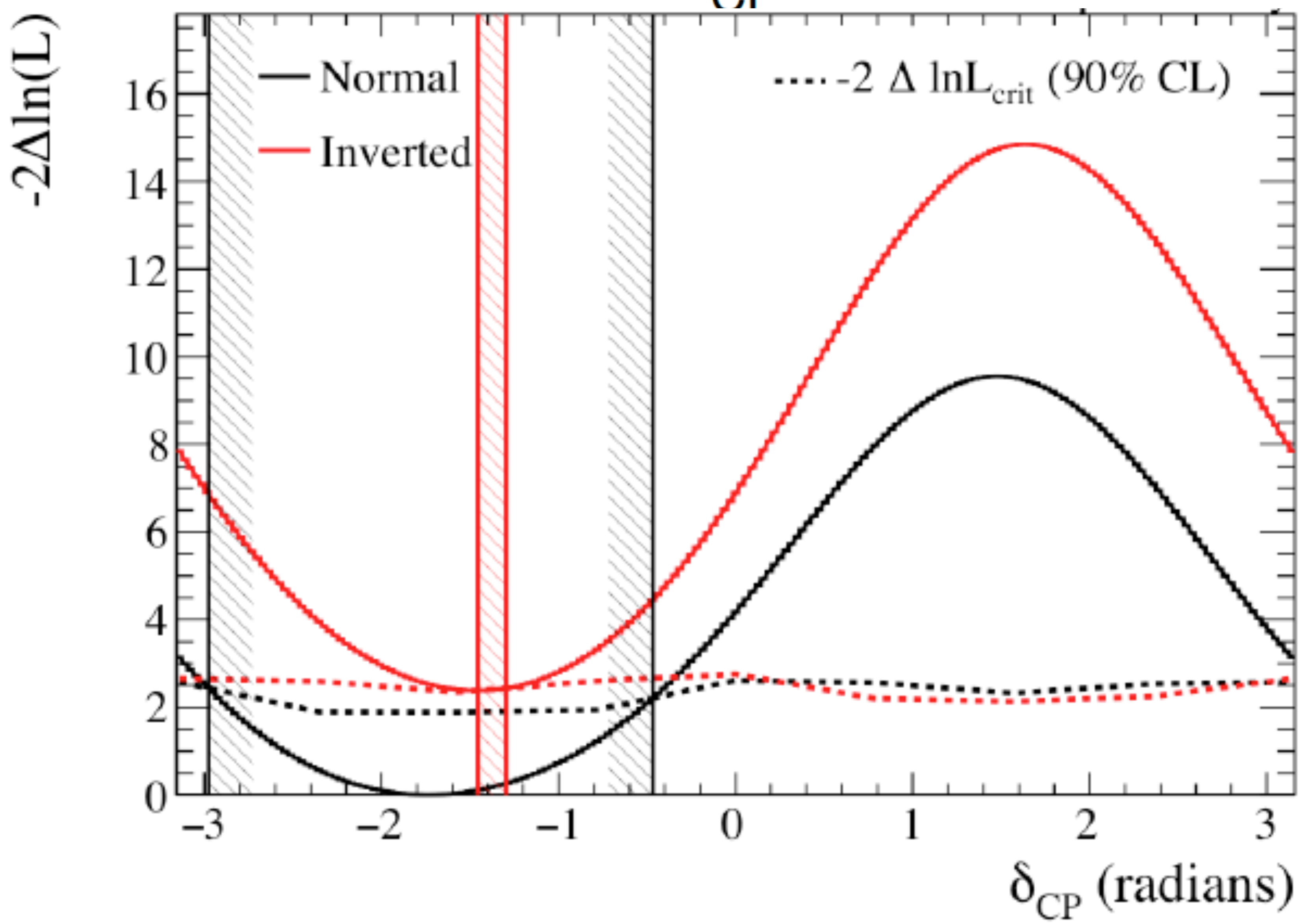
CP violation

- Both Nova and T2K see slight preference for CP violation in neutrino sector
  - angle around 270°
  - good prospects for large mass detectors

Nova

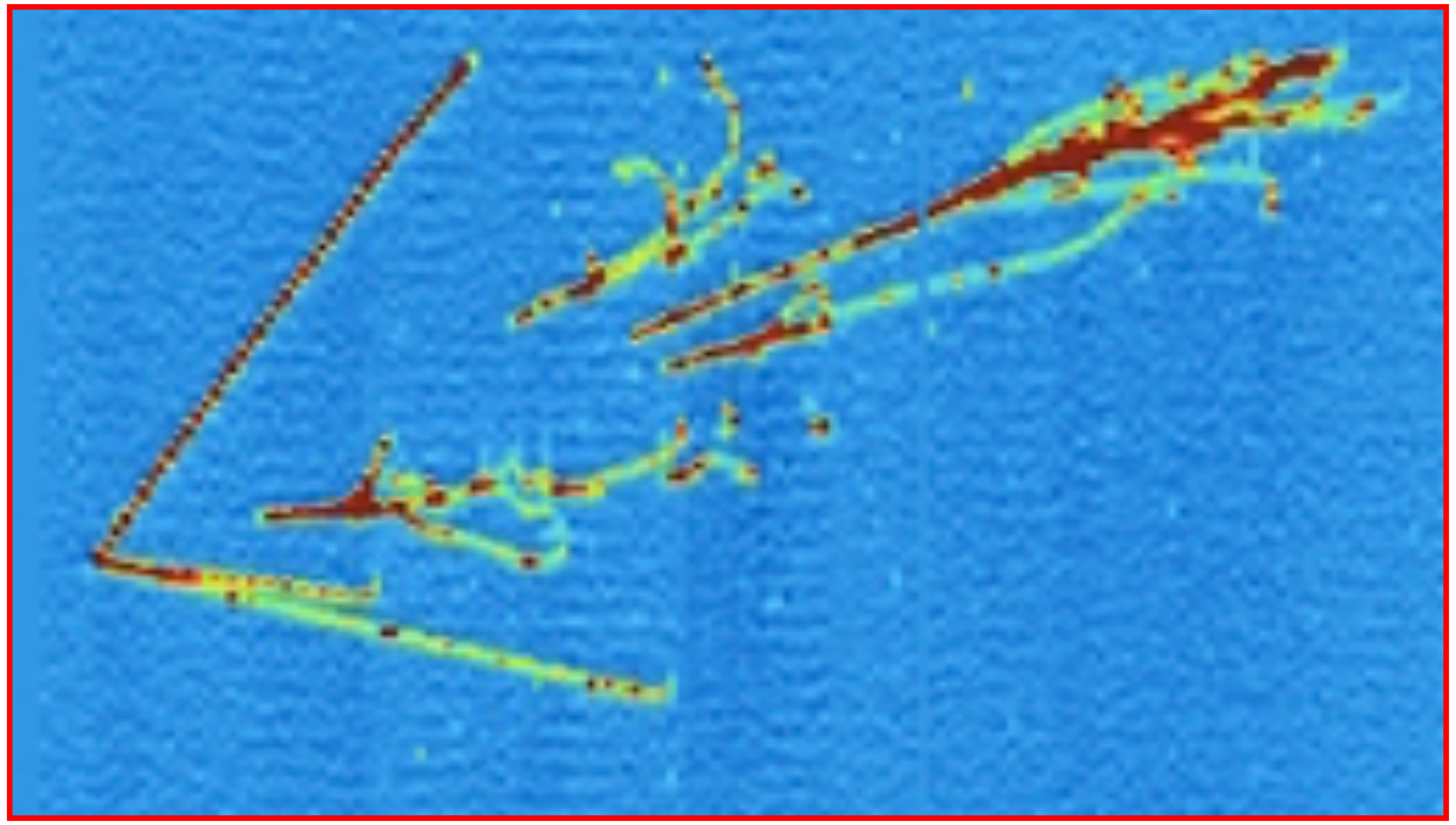


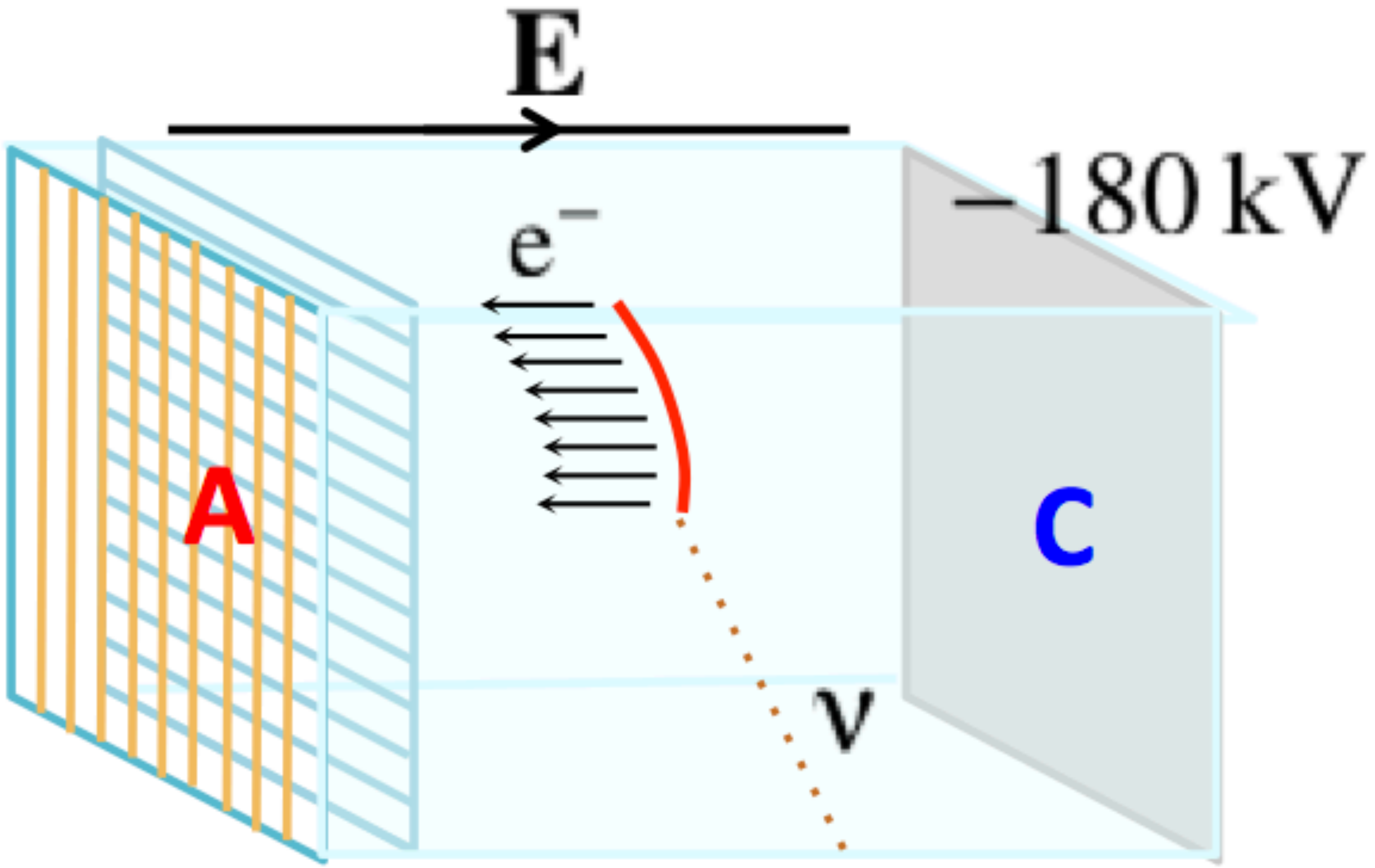
T2K



LAr Technology

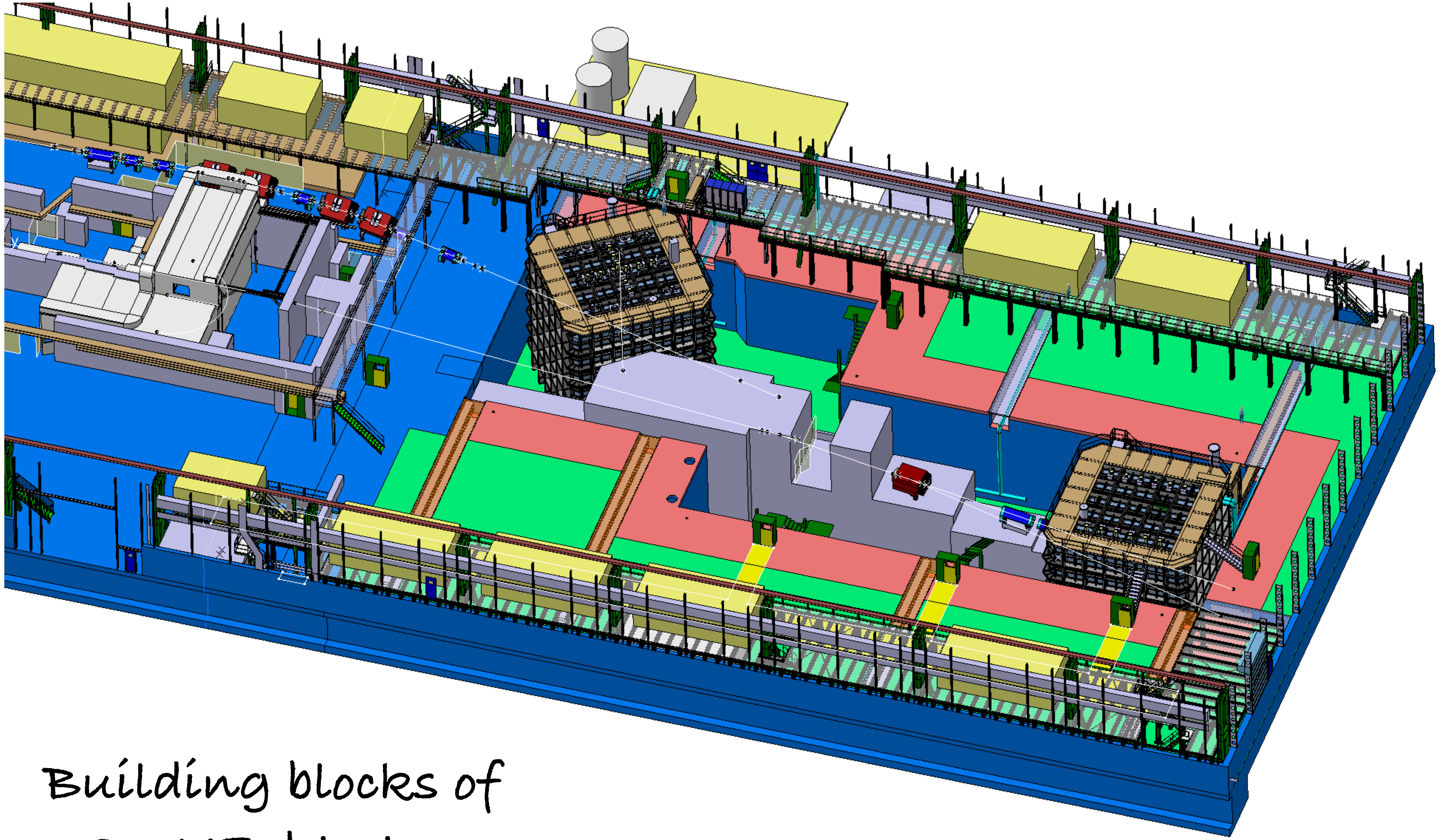
- LarTPC large scale active detectors
    - few mm precision
    - good energy resolution





Neutrino Platform at CERN

To develop experimental techniques, e.g. protoDUNE
– single phase LArTPC
– double phase LArTPC



Building blocks of DUNE detector

Preparing the protoDUNE cryostat structures at CERN

preparing the cryostat inner structures

active volume 6x6x6 m^3

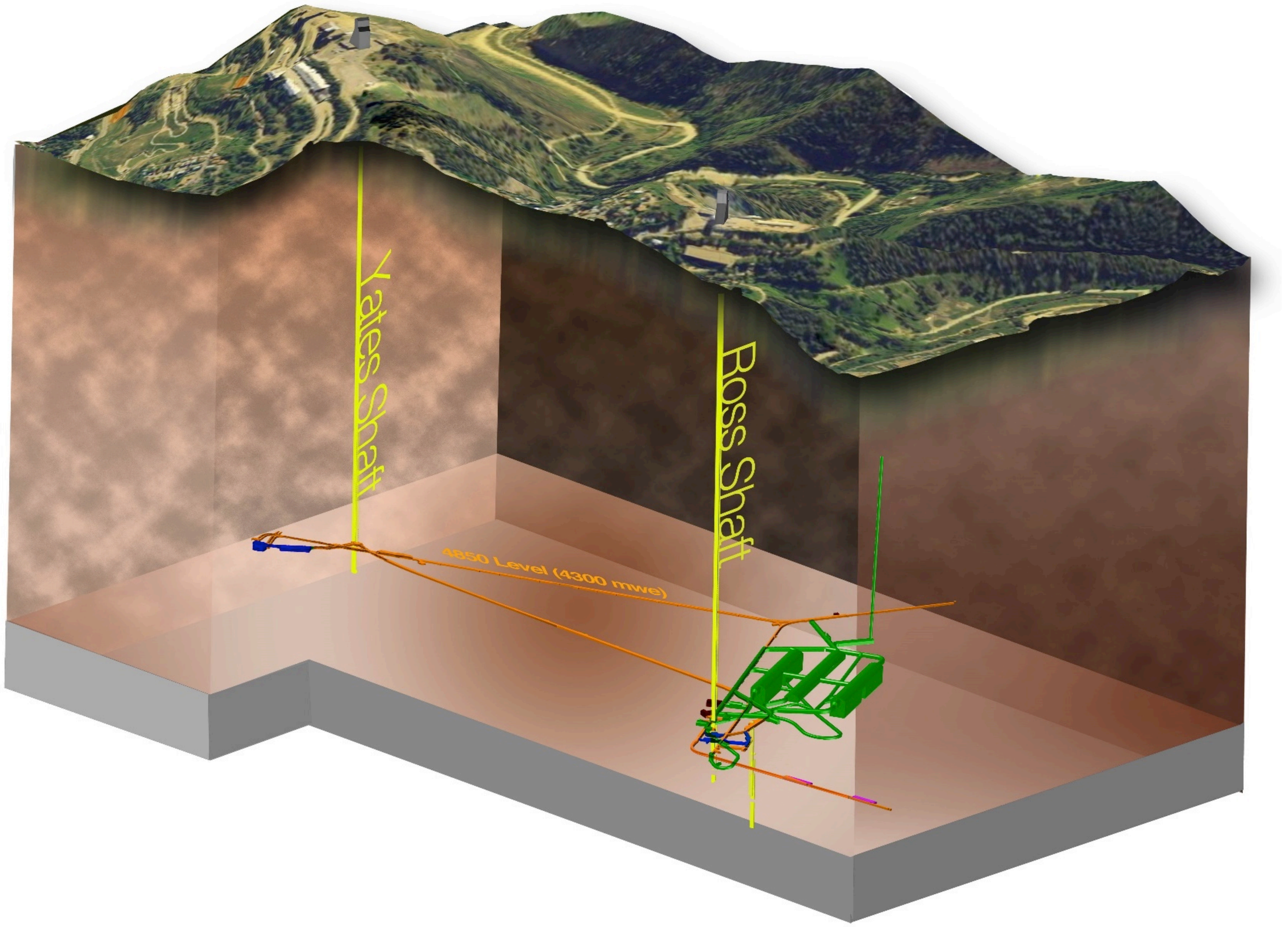
at the neutrino platform

DUNE Collaboration

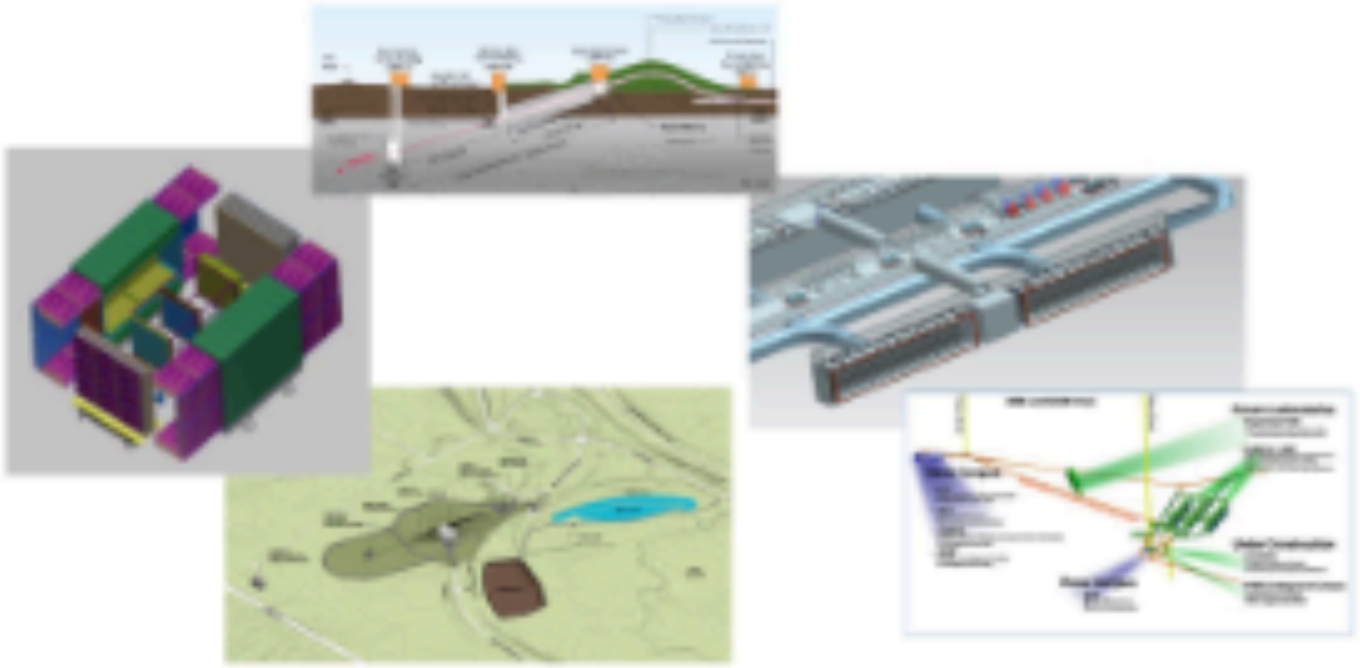
Groundbreaking of SURF July 2017

LBNF / DUNE - far detector

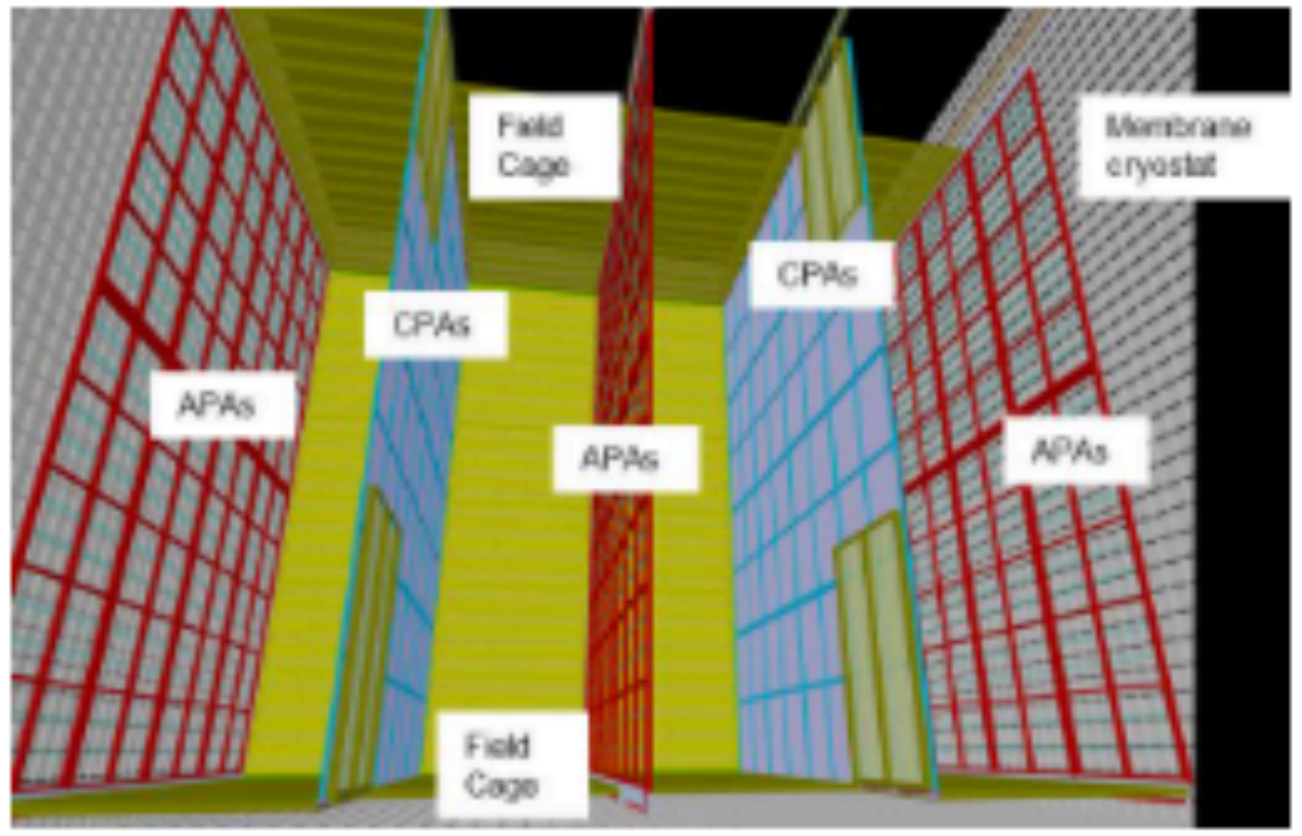
- Sanford Lab Reliability FY16 – 18 (~30M$)
  - Ross shaft rehab; Hoist motor rebuild…
- Pre-Exc Construction FY17 – 18 (~15M$)
  - Rock disposal systems
  - Ross headframe upgrade, more…
- Excavation & Surface Construction FY19 – 22 (~300M$)
- Cryostats/Cryogenic Systems FY20 – 25 (In kind)



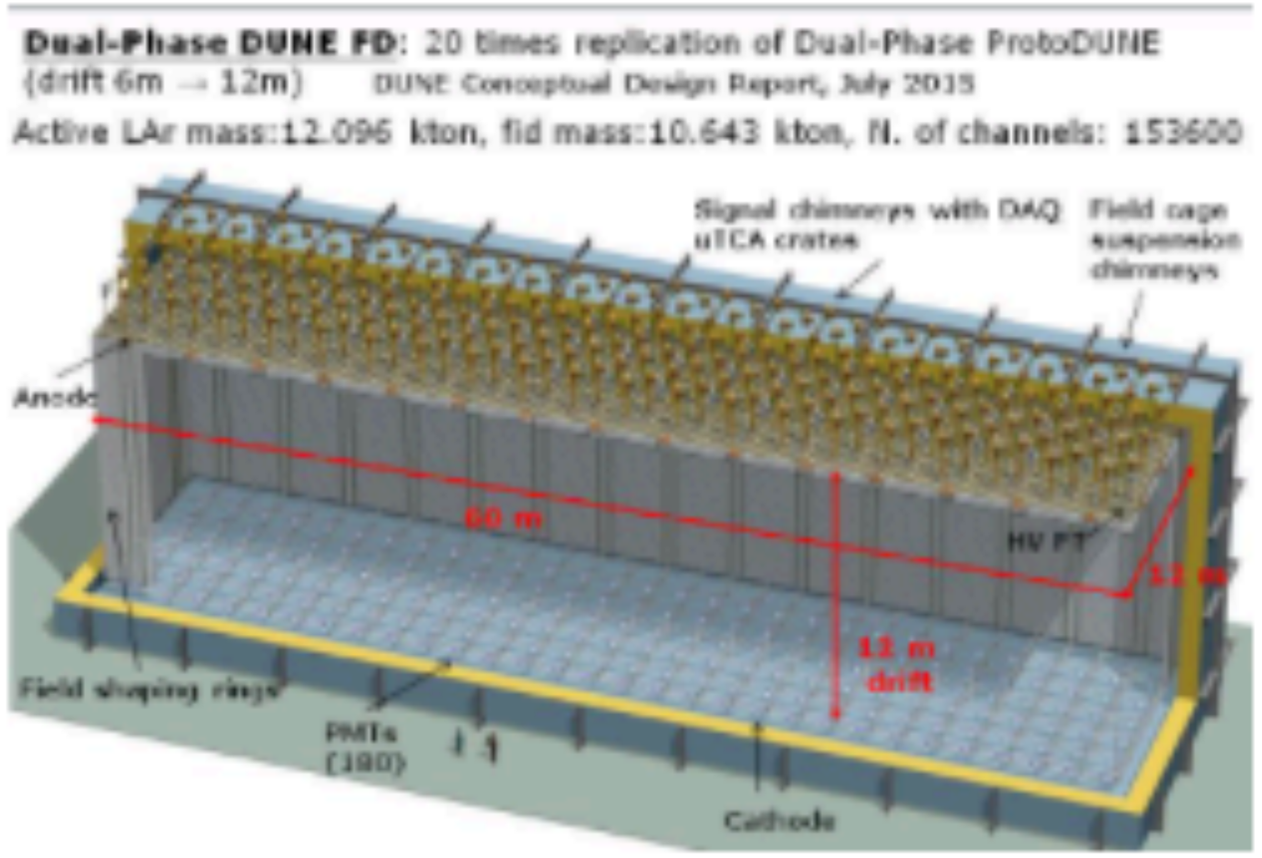
International DUNE Project



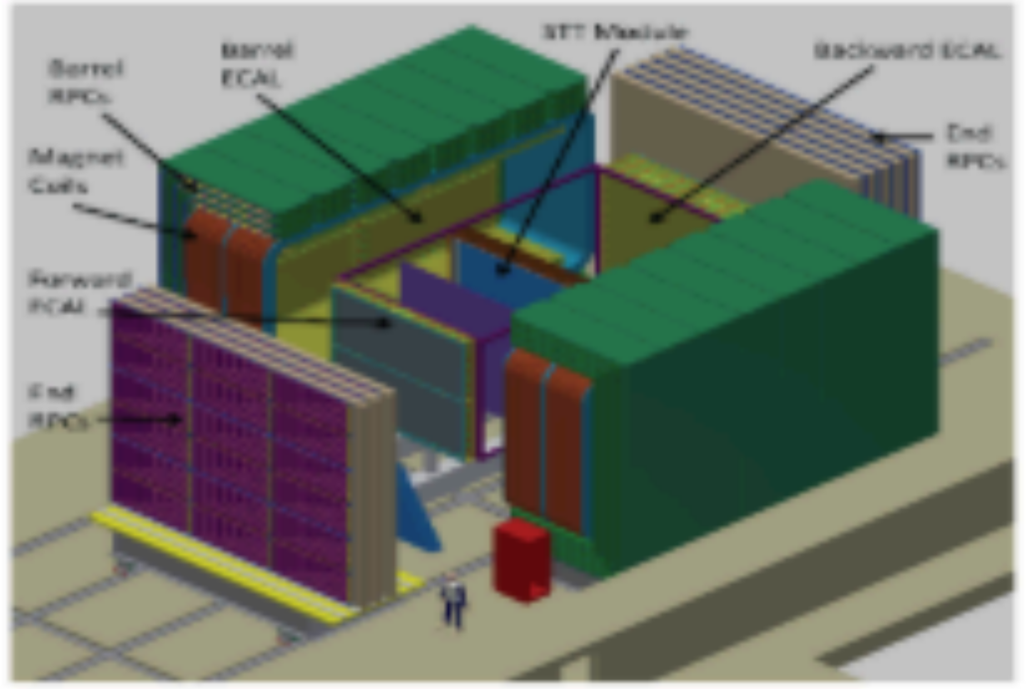
DUNE project Office
Installation and Integration



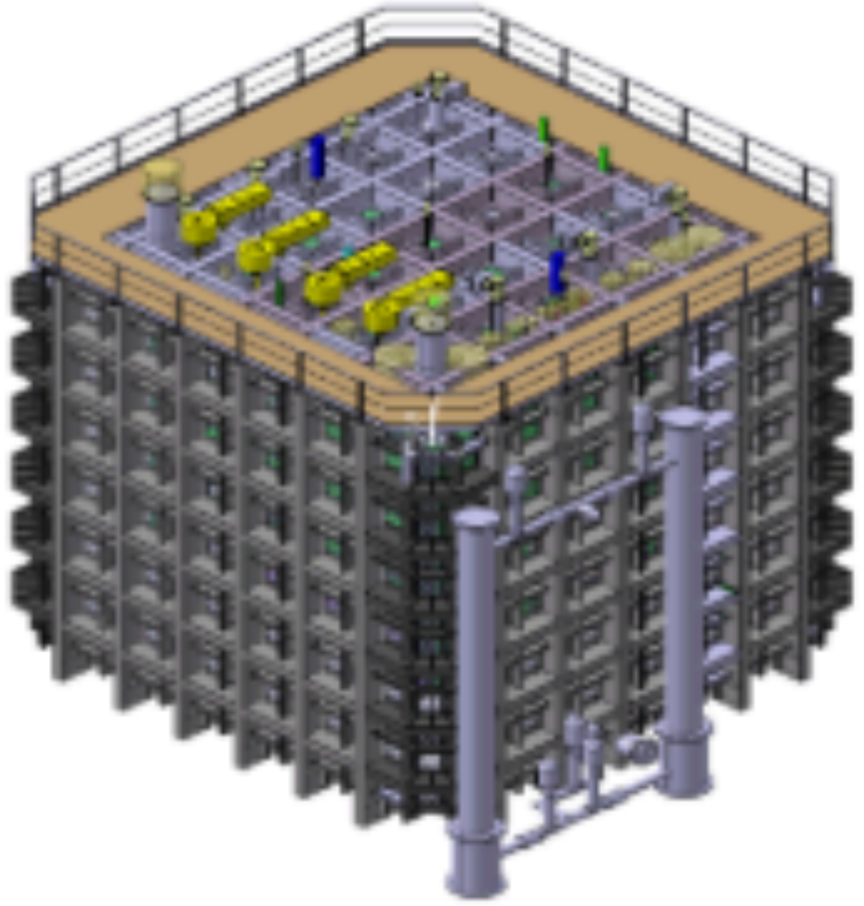
FAR DETECTOR - Single Phase



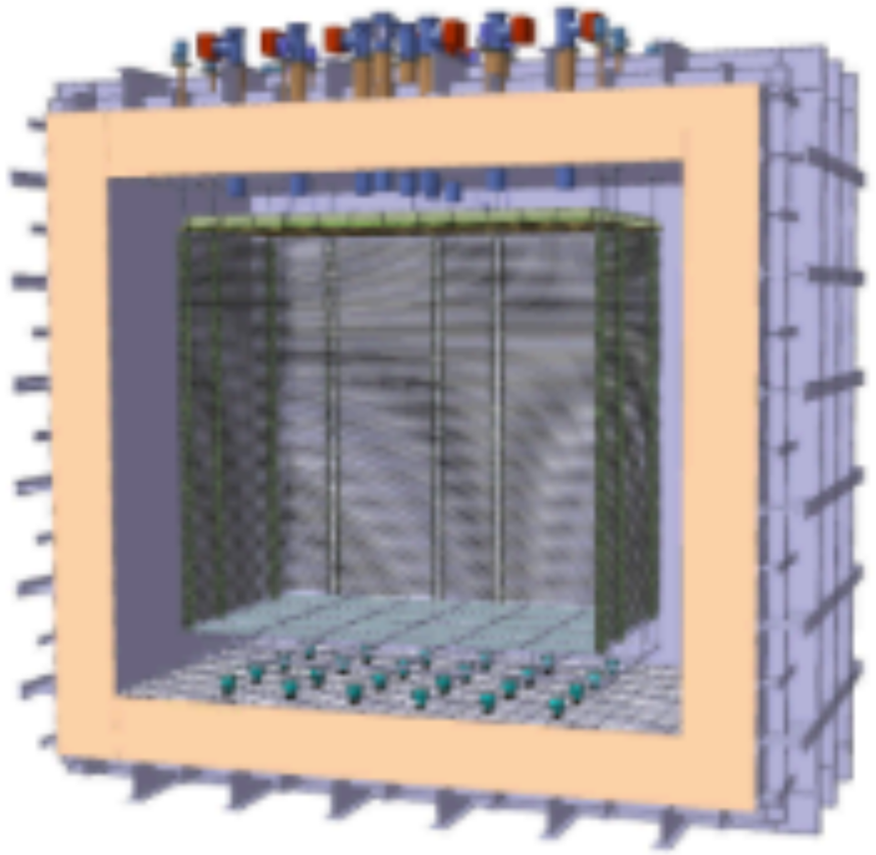
FAR DETECTOR - Dual Phase



NEAR DETECTOR



ProtoDUNE-SP
CERN Twiki, CENF, FNAL Wiki, BNL Wiki



ProtoDUNE-DP

Summary Neutrino Platform

- CERN offers a platform for Neutrino detectors R&D and later construction. CERN is supporting this platform in an active way both for the infrastructure and for the detectors construction, installation and commissioning

- A large neutrino test area (EHN1-1 extension) with charged beams capabilities has been constructed and is being made operational

- CERN will assist the EU neutrino community in their long term common plans. We are reacting on demands from the community, in particular for many R&D aspects.

- In the short term, the CERN Platform is helping in getting a Short Baseline operational at FNAL with an agreed physics program … and later a Long Baseline. Near detectors are now appearing as new R&D projects.

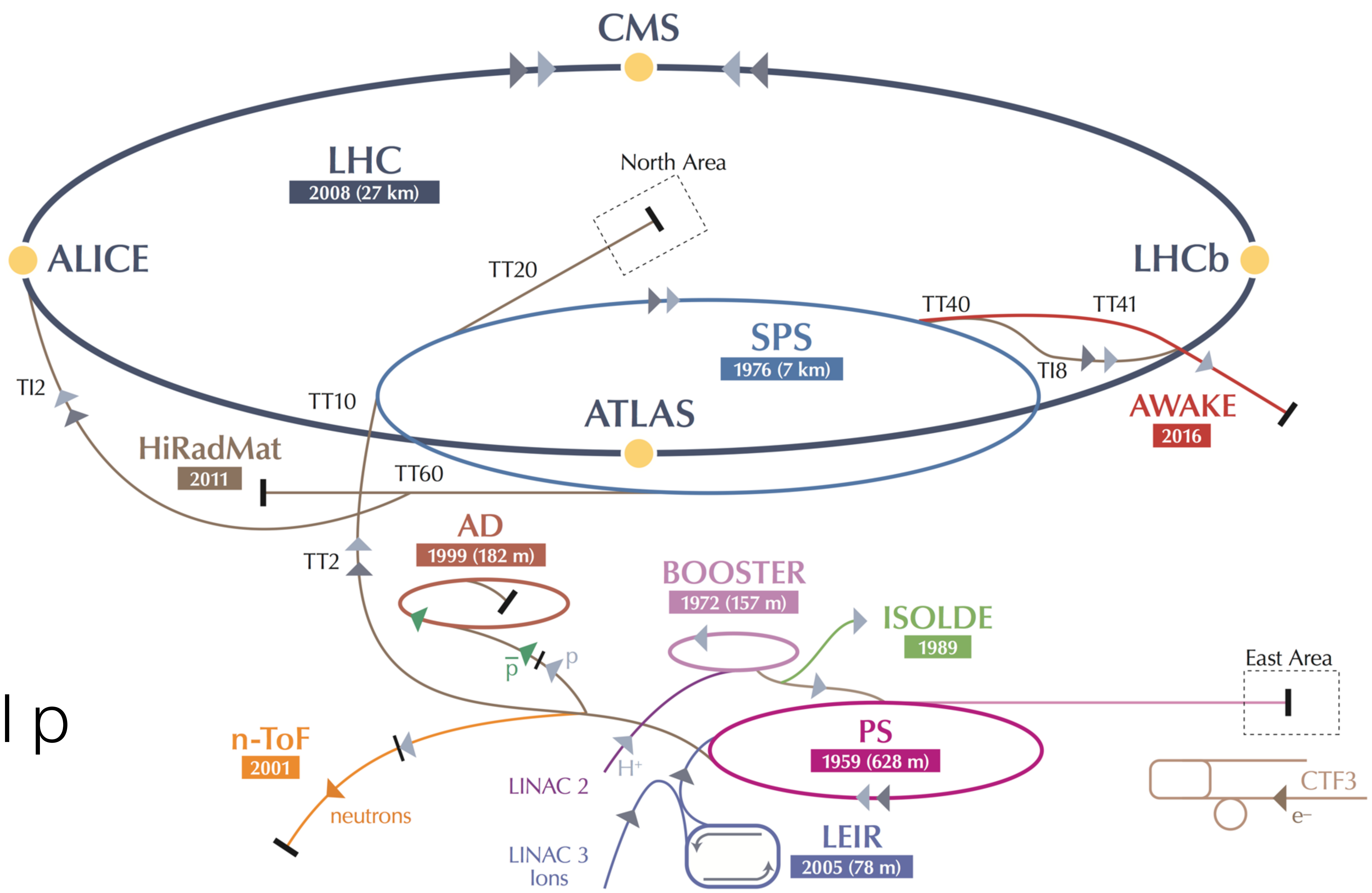
Towards 2020 Update of European Strategy for Particle Physics

– LHC and HL-LHC exploitation (√)
– Prepare for the next step at the energy frontier
– Rich diversity programme…

LHC and its injector chain used for physics

- LHC
  - ongoing Run 2 @ 13 TeV
- Injectors supporting
  - Fixed target programme
  - ISOLDE (isotopes)
  - n-ToF
  - AD-programme

} 75% of all p

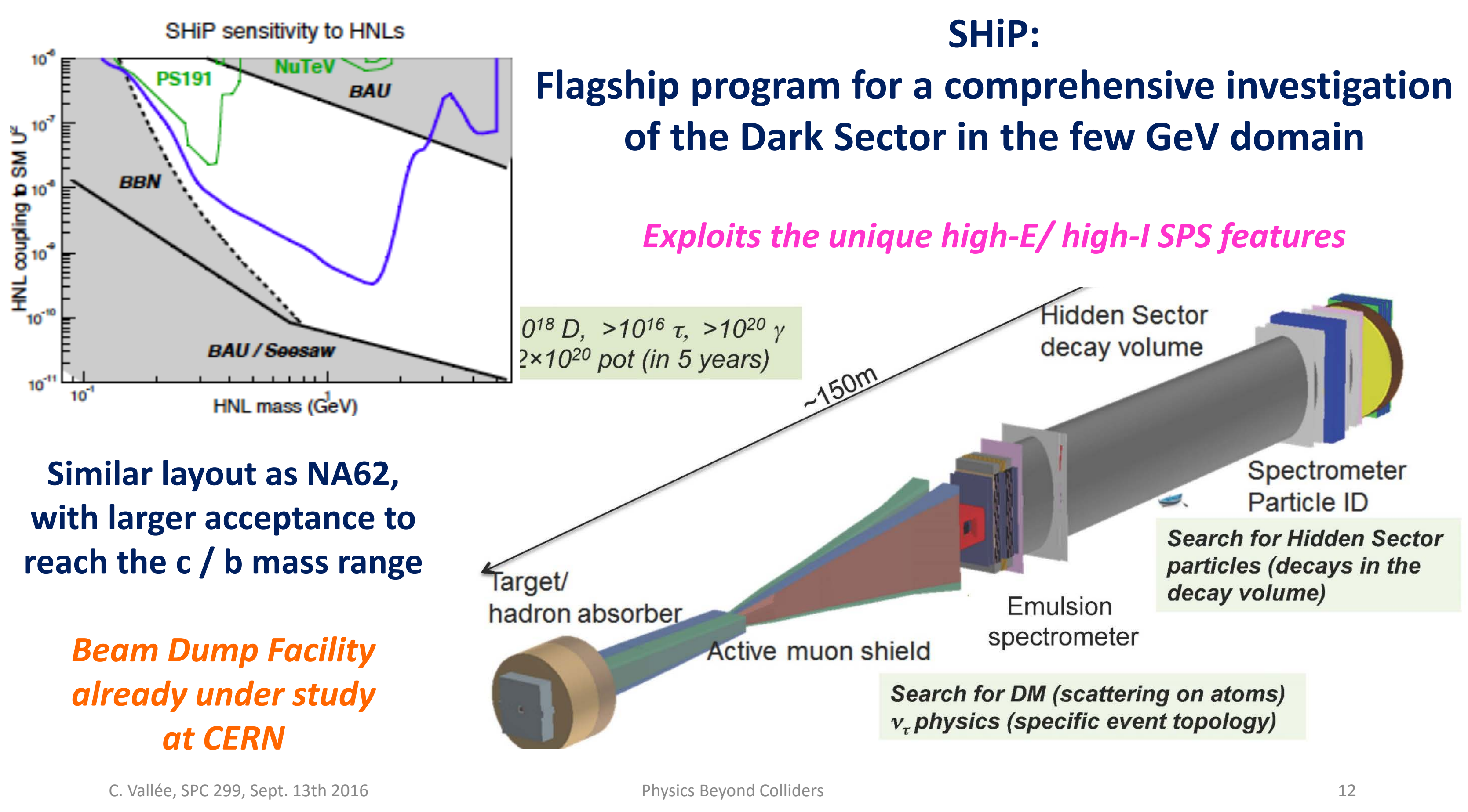


Physics Beyond Collider Study

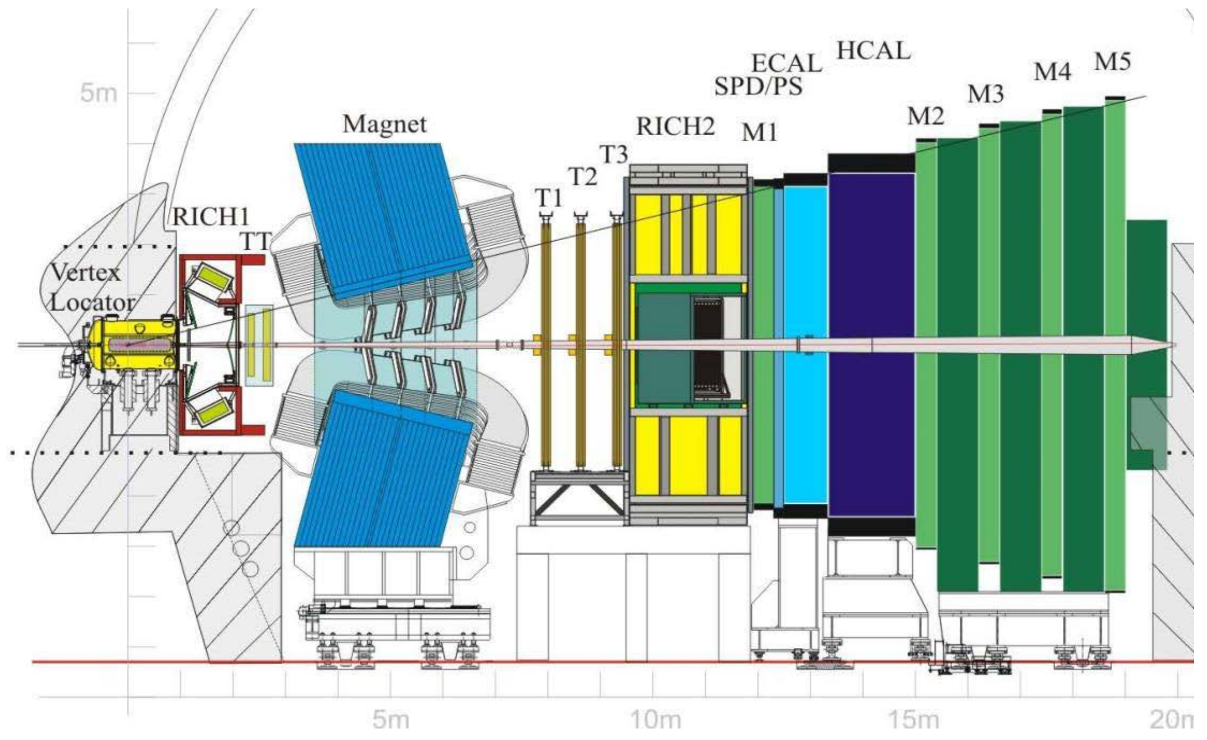
- Kickoff meeting held in September 2016
  Follow-up in November 2017

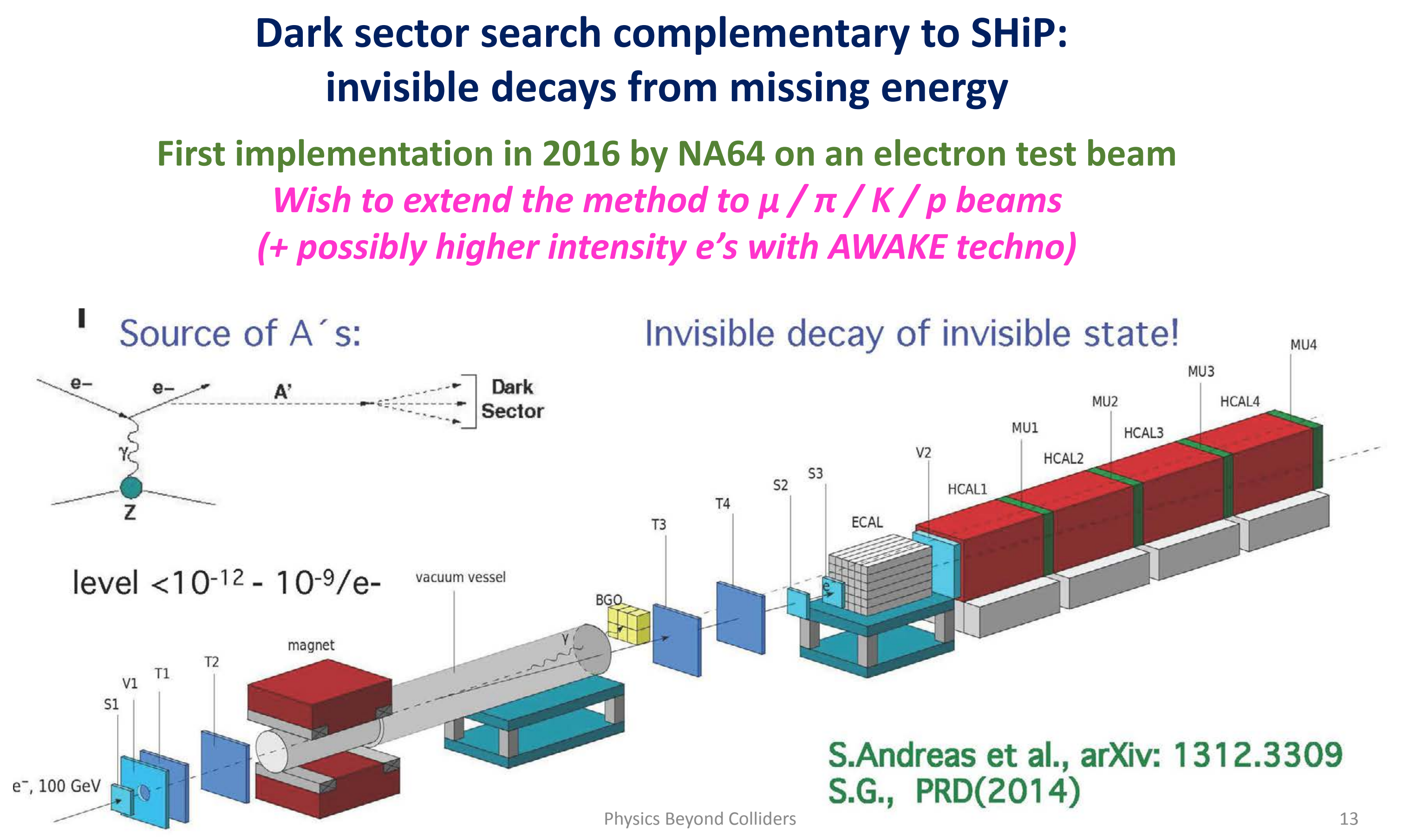
  - Study of fixed target programme

    …even with LHC beams



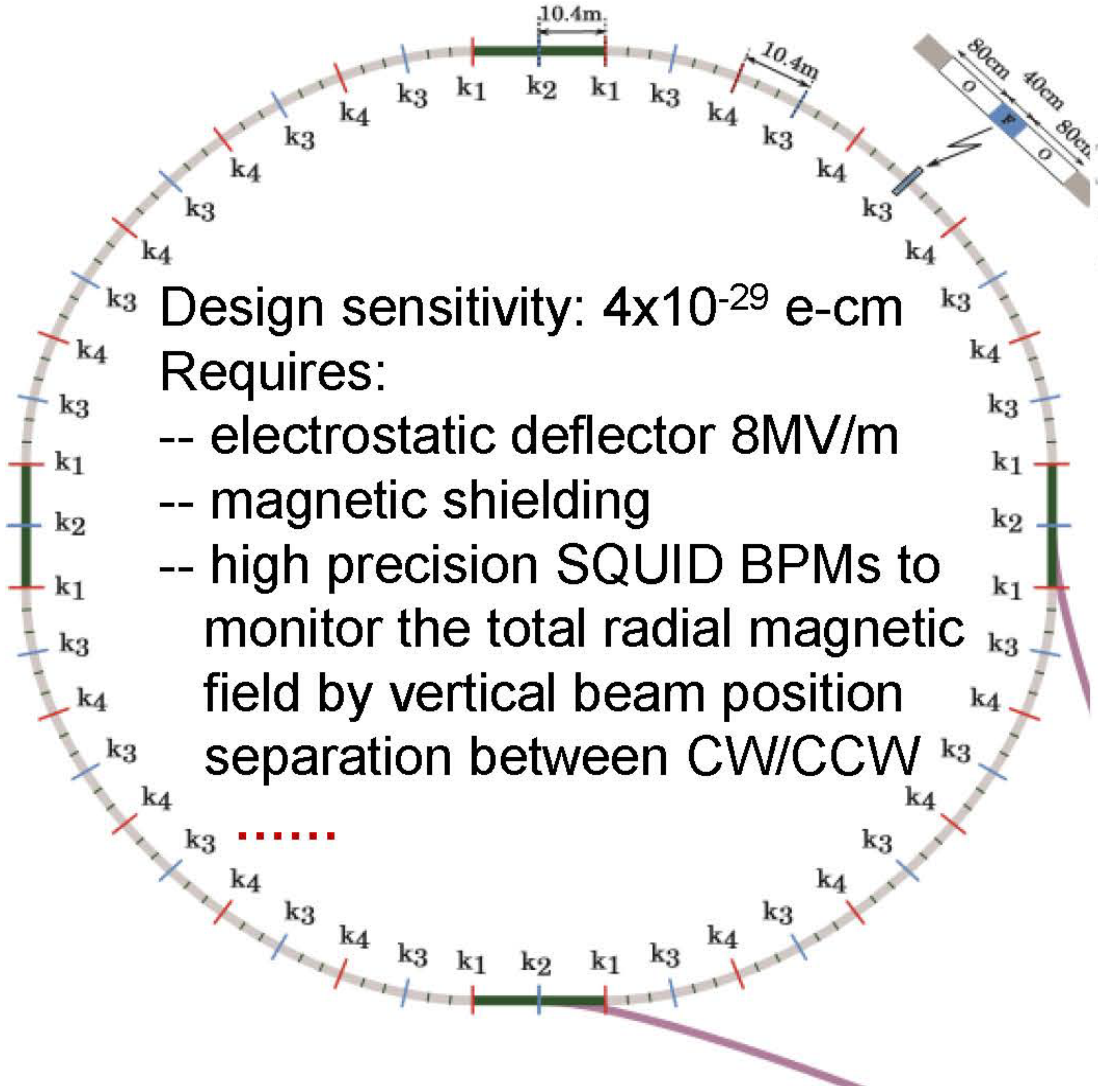
SMOG



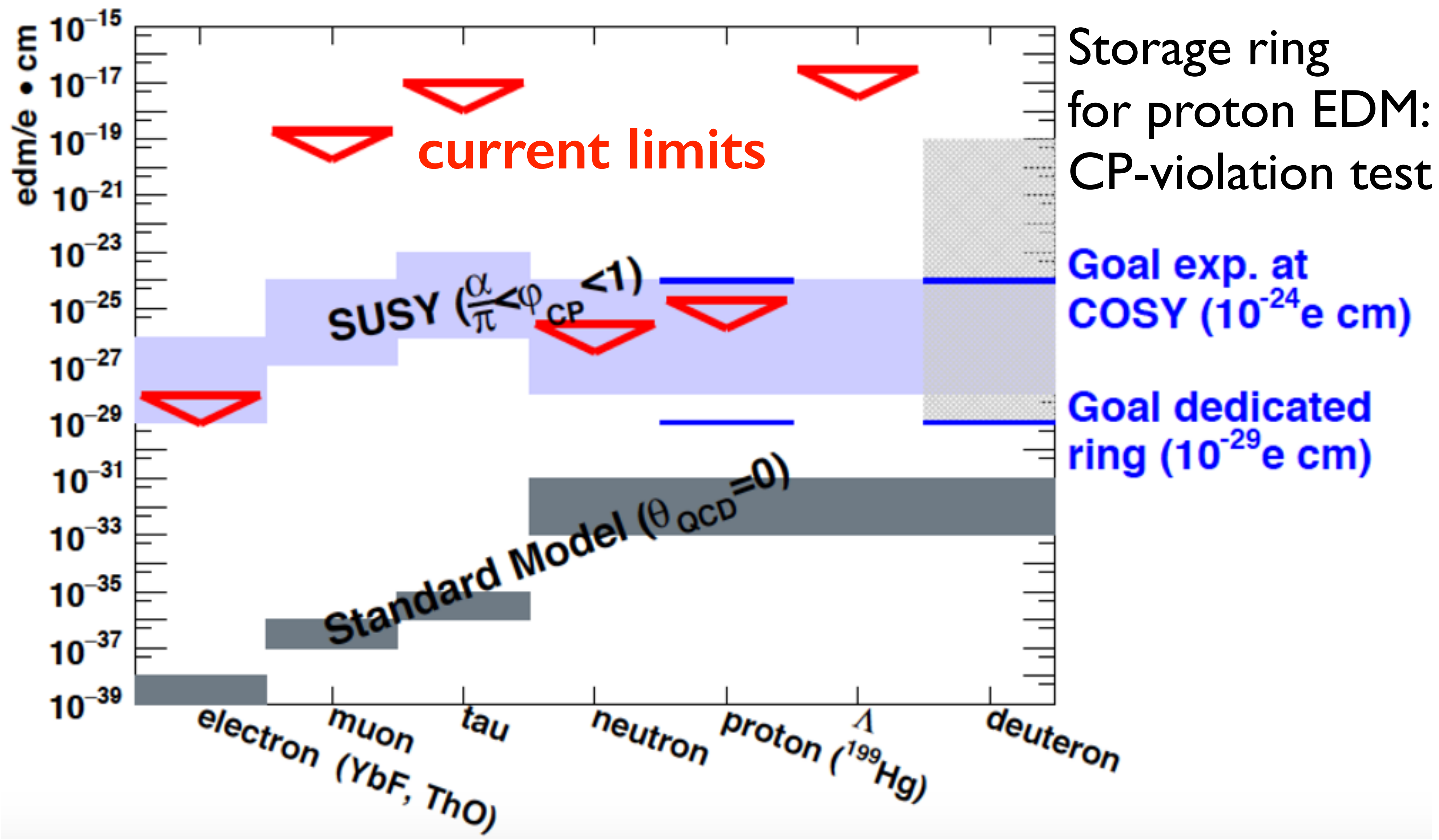


Physics Beyond Collider Study cont'd

Study of an all-electric storage ring



Design sensitivity: 4×10^{-29} e-cm
Requires:
-- electrostatic deflector 8MV/m
-- magnetic shielding
-- high precision SQUID BPMs to monitor the total radial magnetic field by vertical beam position separation between CW/CCW
……



Sensitivity of 10^{-29} e-cm corresponds to 100 TeV for new physics scale

Summary

- Experimental Programme of LHC extremely rich; long range experimental programme guarantees physics return
    - by exploring the highest energies
    - by searching for violations of the SM in (highly sensitive) rare decays
- Preparing Update of the European Strategy for Particle Physics
  - LHC and HL-LHC
  - Energy Frontier (FCC / CLIC)
  - Accelerator based neutrino programme (US & Japan) via neutrino platform
  - Vibrant physics programme Beyond Colliders

2018 (end): reports on Physics
2019: community discussion with input from other regions