Moriond Electroweak Interactions & Unified Theories

La Thuile, 23 Mar 2019

EW - Main Topics

- The Standard Model: precision tests
- Search for the Higgs Boson
- Beyond the Standard Model: searches, supersymmetry, rare processes, extradimensions, ...
- Flavour physics and CP violation (in the hadronic and leptonic sectors)
- Neutrino physics
- Axions
- Dark matter searches and Dark energy candidates
- Astroparticles and cosmological observations and their implications

Shahram Rahatlou

Executive Summary

- ▻ LHCb experiment at CERN stole the show this year at Moriond EW
  Observation of CP Violation in charm mesons by LHCb !!!
- ▻ Flavor anomalies are still alive after updated result by LHCb
  – x2 more data still to be looked at by LHCb
  – Heads up to BELLE, CMS, and ATLAS
- ▻ Neutrino experiments on track to tackle CP Violation as well
- ▻ Rich program across energy and mass scales to detect rare processes – indirect search for New Physics
- ▻ Standard Model physics at colliders entering New Physics territory
- ▻ Vibrant and diversified direct search program for New Particles
- ▻ Multi-prong approach to Dark Matter expanding
  – Not just WIMPs but also very light or exotic candidates pursued

CP Violation

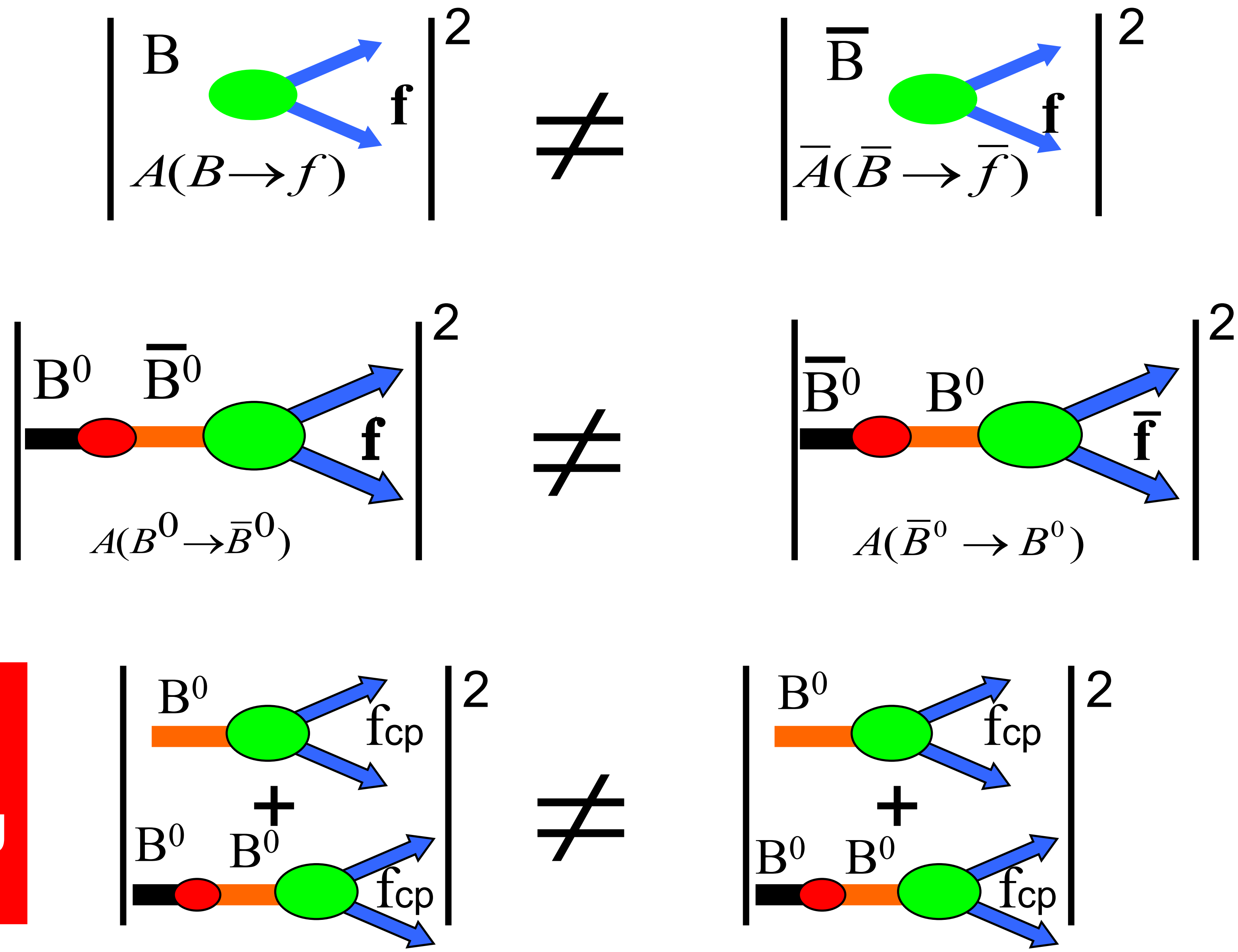
Matter - anti–matter Asymmetry

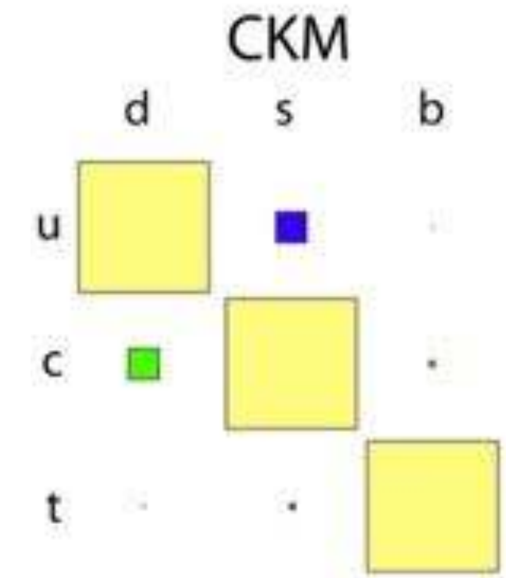
CP Violation

CP Violation
in Decay
a.k.a.
Direct CPV

CP Violation
in Mixing

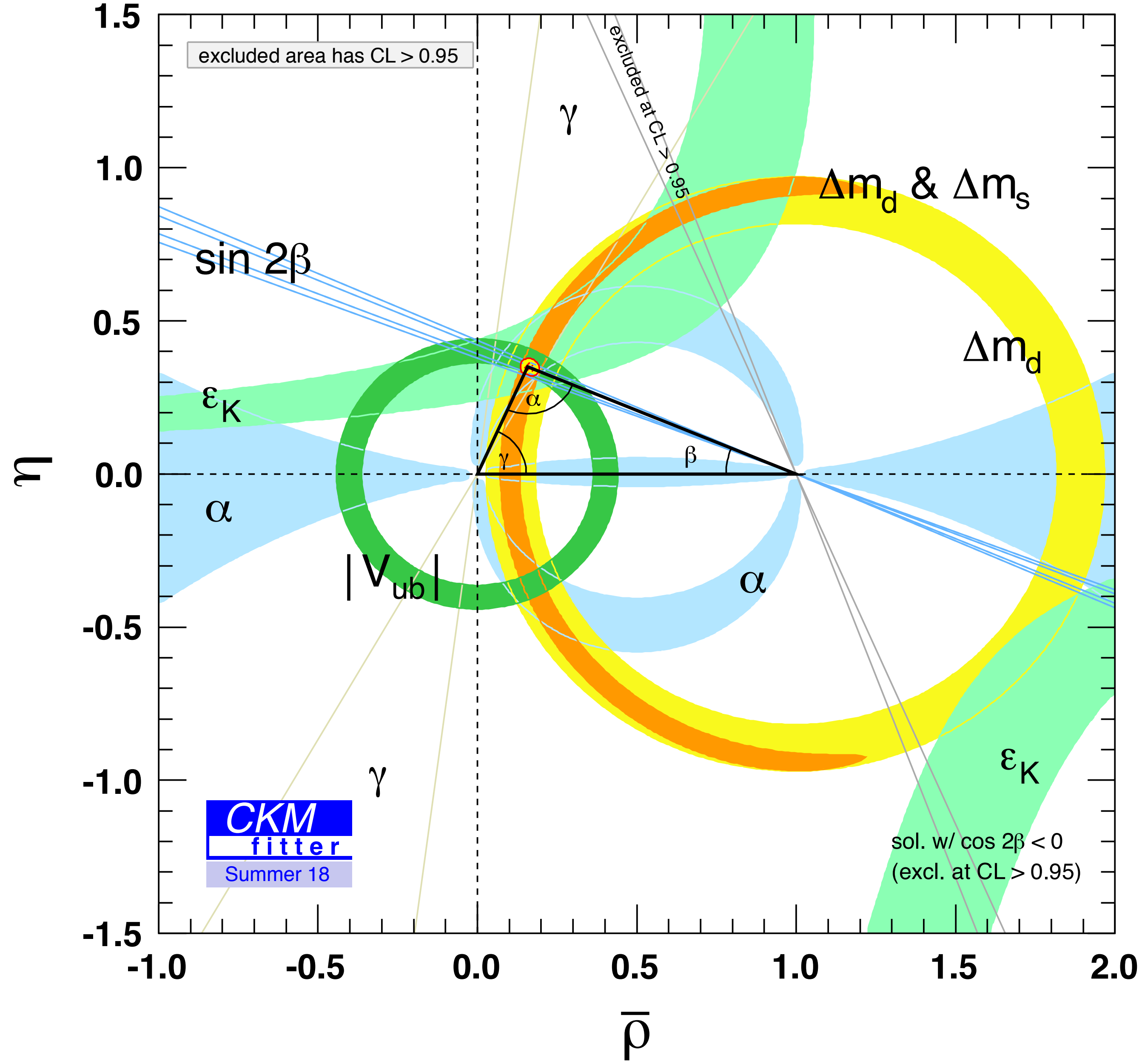
CP Violation
in interference
between Mixing
and Decay



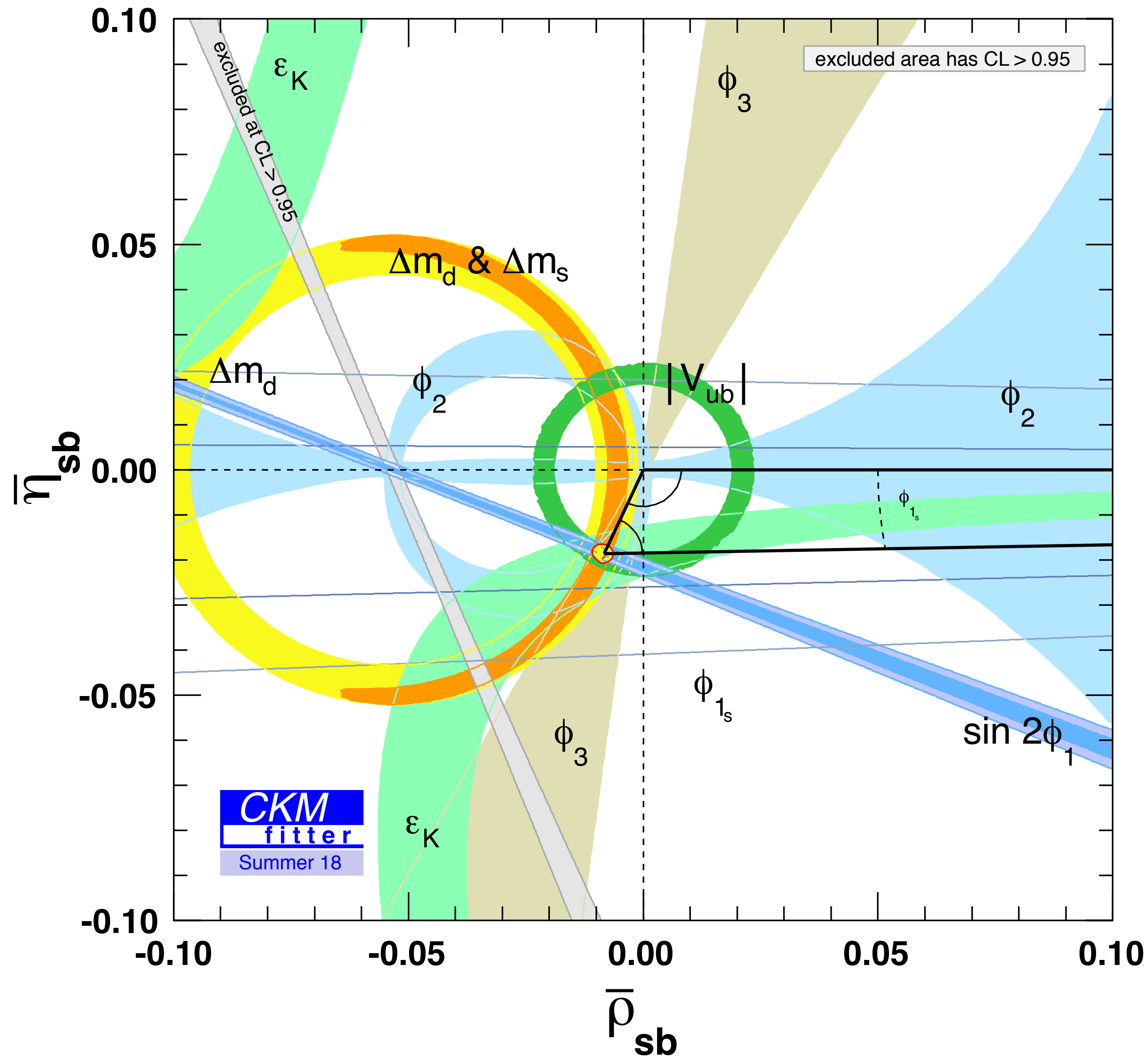


Unitarity Triangle(s)

B_d



B_s



$$\phi_s^{SM} \approx -2\arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.03686^{+0.00096}_{-0.00068}\ \text{rad}$$

- Probing new physics as enhancement in B_s CP Violation

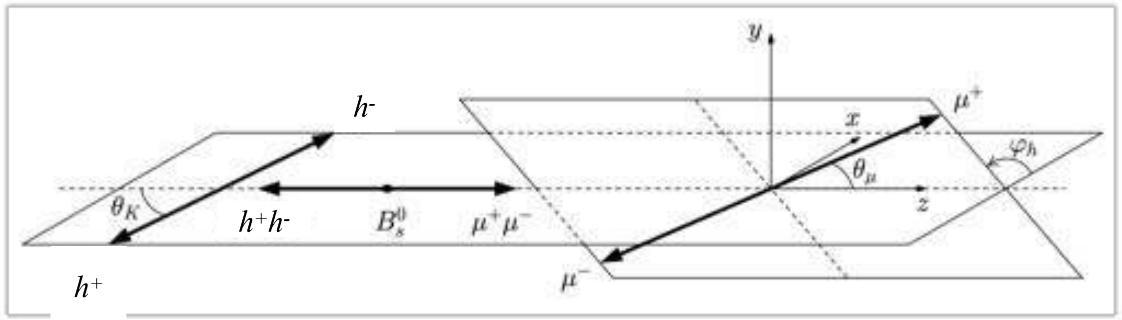
CP Violation in $B_s \to J/\Psi KK$

Ekaterina Govorkova, LHCb
Jennifer Zonneveld, LHCb

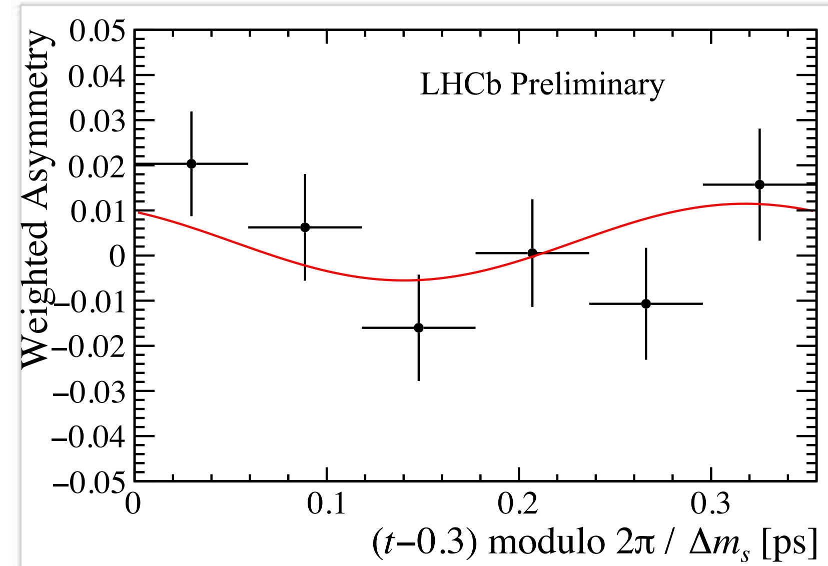
- Updated time-dependent angular analysis by adding 2016 data

$B^0_s \to J/\psi K^+K^-$
[LHCB-PAPER-2019-013]
in preparation

$B^0_s \to J/\psi \pi^+\pi^-$
arXiv:1903.05530

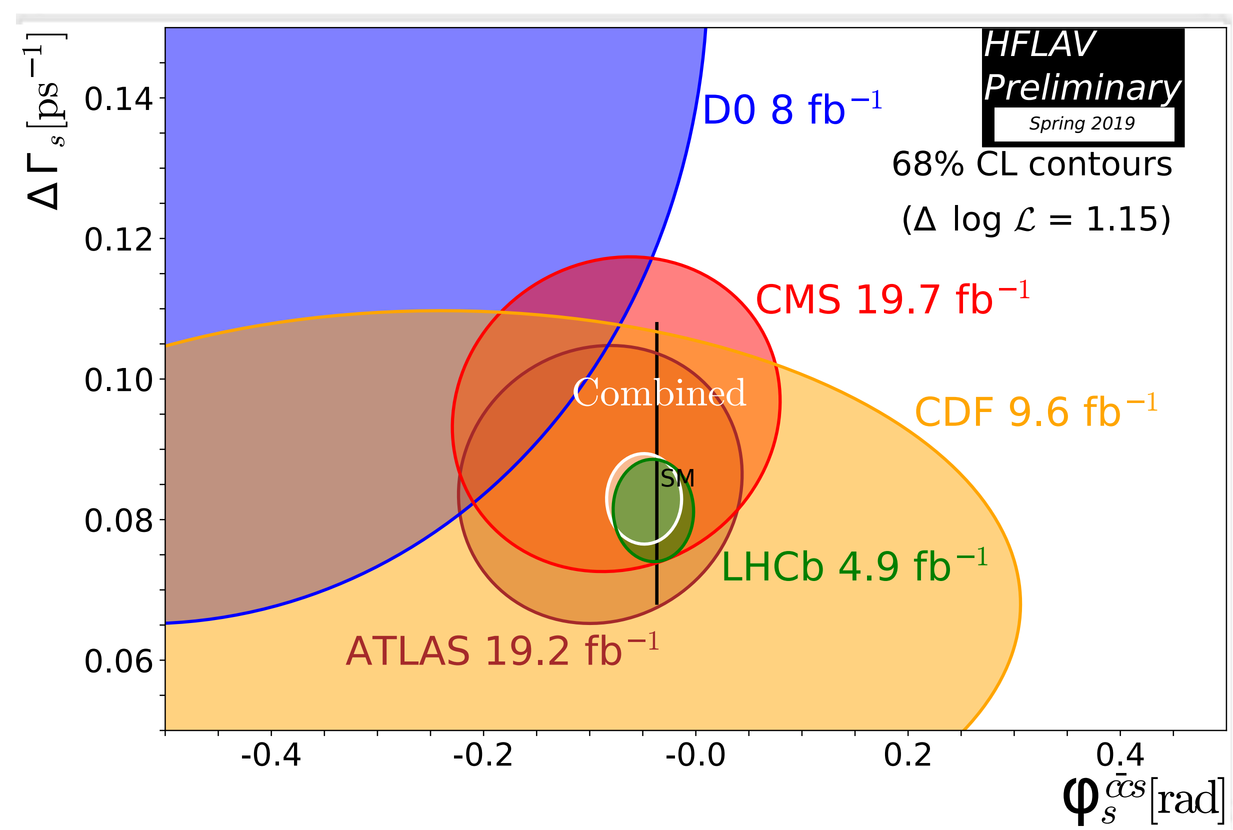


$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_s \to f}(t) - \Gamma_{B^0_s \to f}(t)}{\Gamma_{\bar{B}^0_s \to f}(t) + \Gamma_{B^0_s \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$



- Combination with other B_s decays for most precise measurement of Φ_s

$\phi_s = -0.040 \pm 0.025$ [rad]
$|\lambda| = 0.991 \pm 0.010$
$\Delta\Gamma_s = 0.0813 \pm 0.0048$ [ps^{-1}]
$\Gamma_s - \Gamma_{B^0} = -0.0024 \pm 0.0018$ [ps^{-1}]

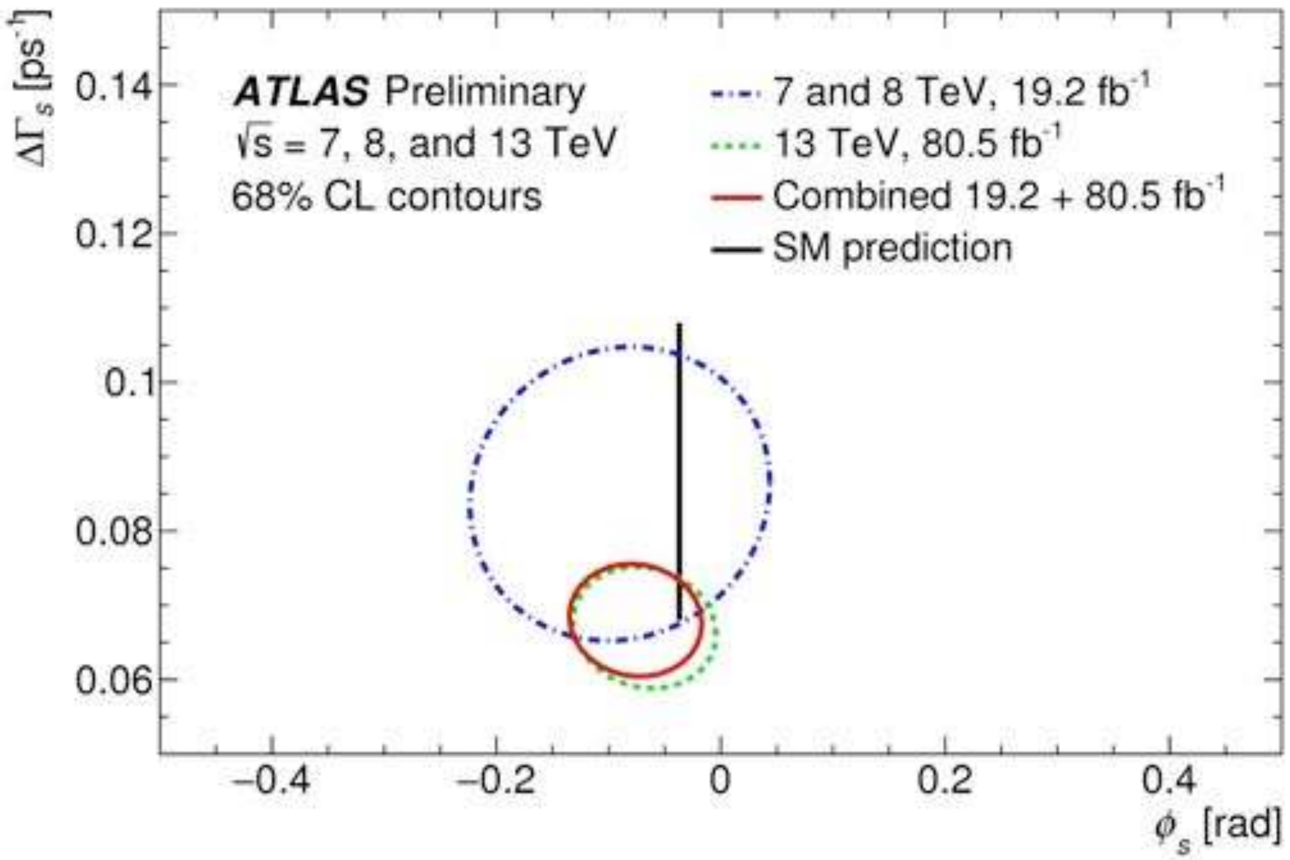


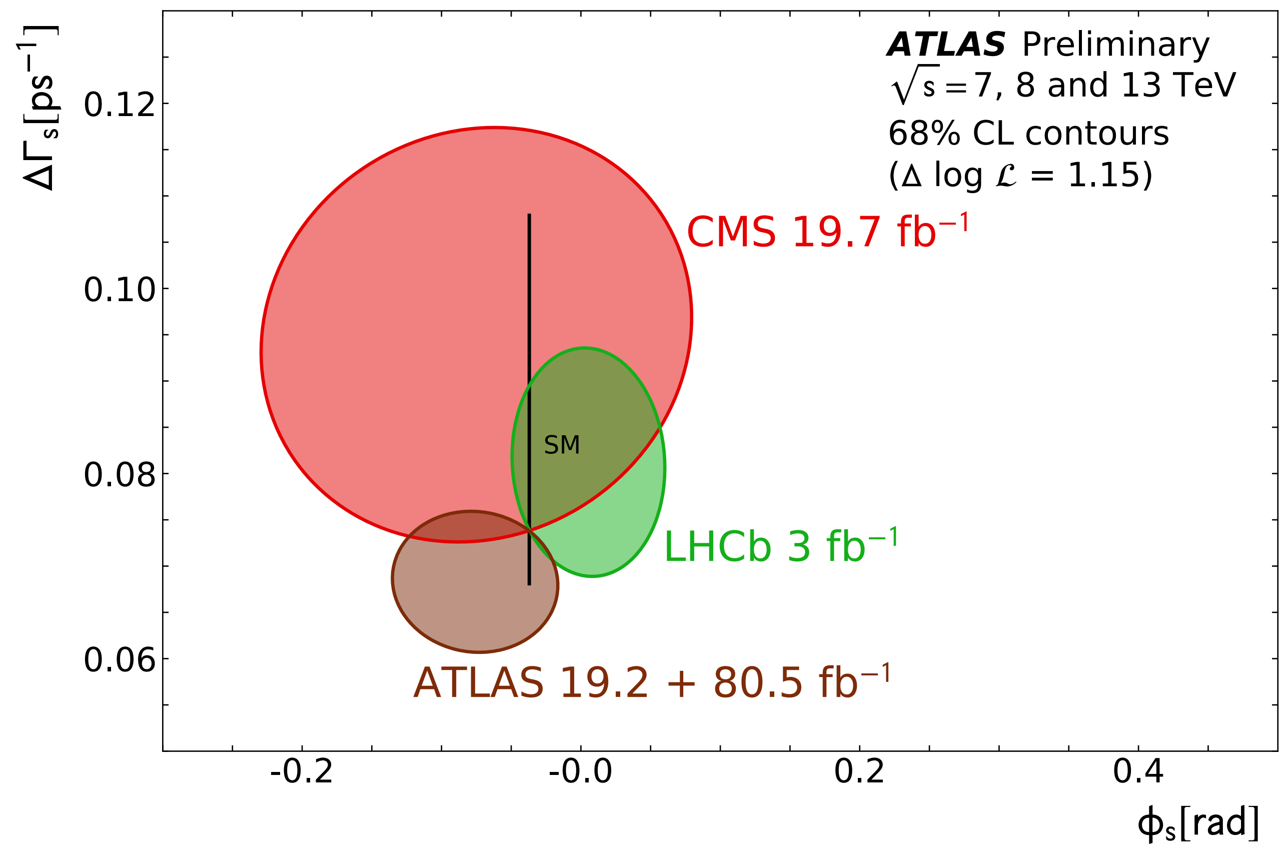
- No evidence for direct CPV
- Width and interference consistent with expectations

CP Violation in $B_s \to J/\Psi\ \phi$

Olga Igonkina, ATLAS

- Time-dependent angular analysis with 80 fb^{-1} collected in 2015-2017
- *Uncertainties competitive with latest LHCb results*





ATLAS: Run1 + Run2

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.076	0.034	0.019
$\Delta\Gamma_s$[ps^{-1}]	0.068	0.004	0.003
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\|A_{\parallel}(0)\|^2$	0.220	0.002	0.002
$\|A_0(0)\|^2$	0.517	0.001	0.004
$\|A_S\|^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_\parallel$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	−0.216	0.037	0.010

LHCb: JpsiKK

$\phi_s = -0.040 \pm 0.025$ [rad]

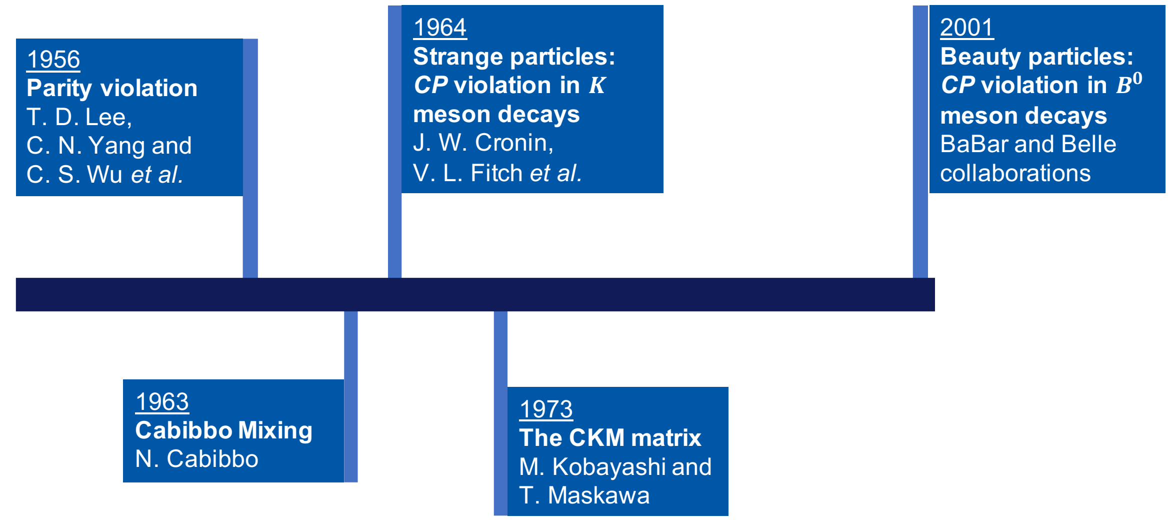
$|\lambda| = 0.991 \pm 0.010$

$\Delta\Gamma_s = 0.0813 \pm 0.0048$ [ps^{-1}]

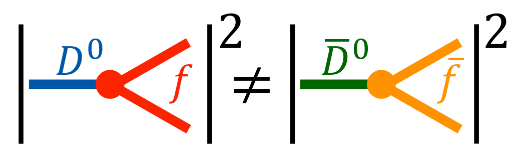
$\Gamma_s - \Gamma_{B^0} = -0.0024 \pm 0.0018$ [ps^{-1}]

Probing CP Violation in Charm

- CP violation in Standard Model expected at ~ $10^{-3} - 10^{-4}$ in charm mesons
  - compare to O(1) in B mesons!



$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}$$



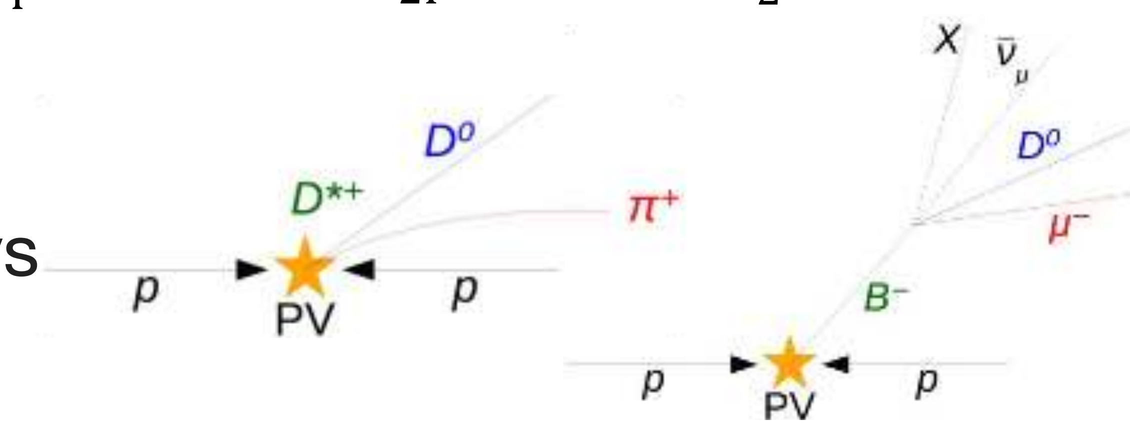
f =K^+K^-,$\pi^-\pi^+$

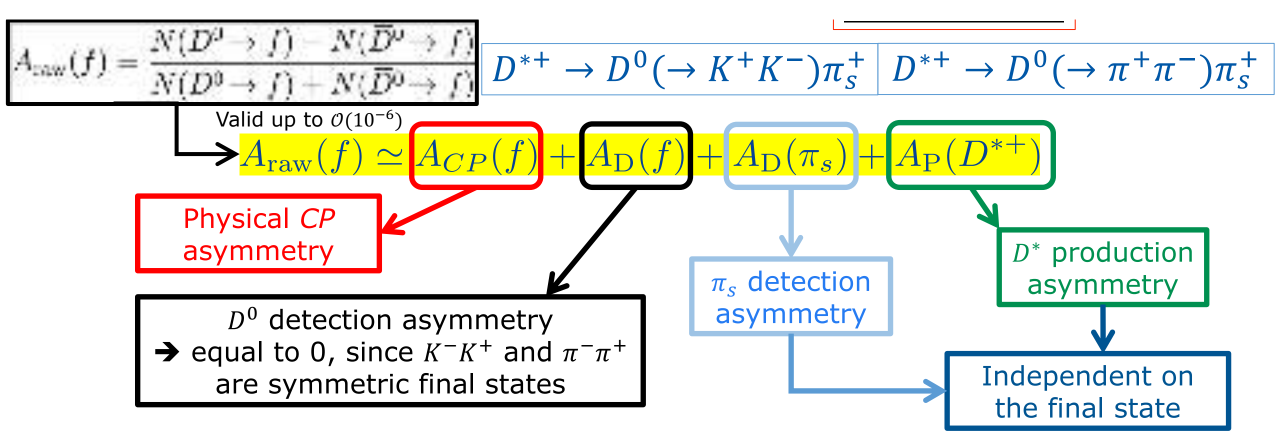
$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^-\pi^+)$$

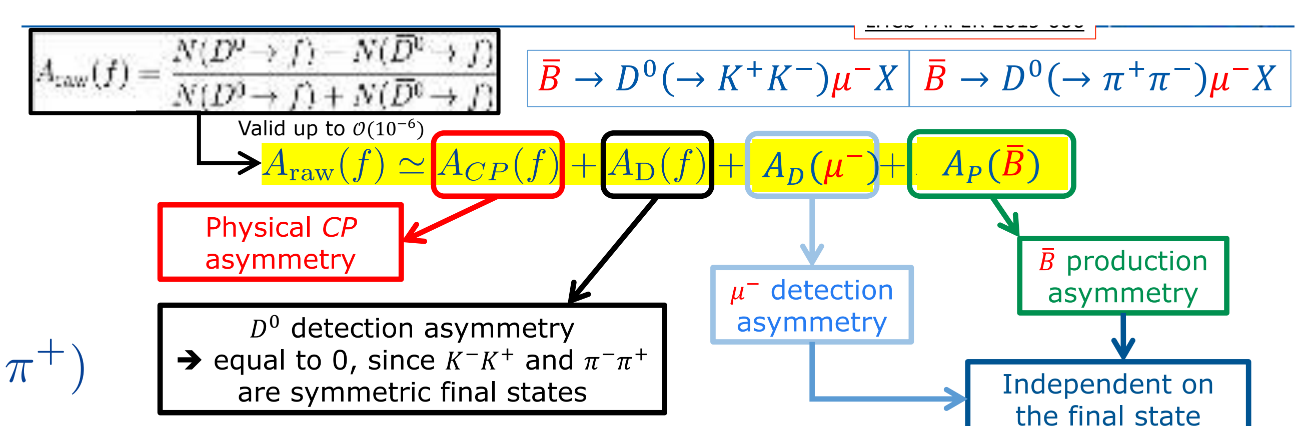
$$\simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle t \rangle}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{ind}$$

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Flavor tagging with soft pion from prompt charm and muons from semi-leptonic decays







$$A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$$

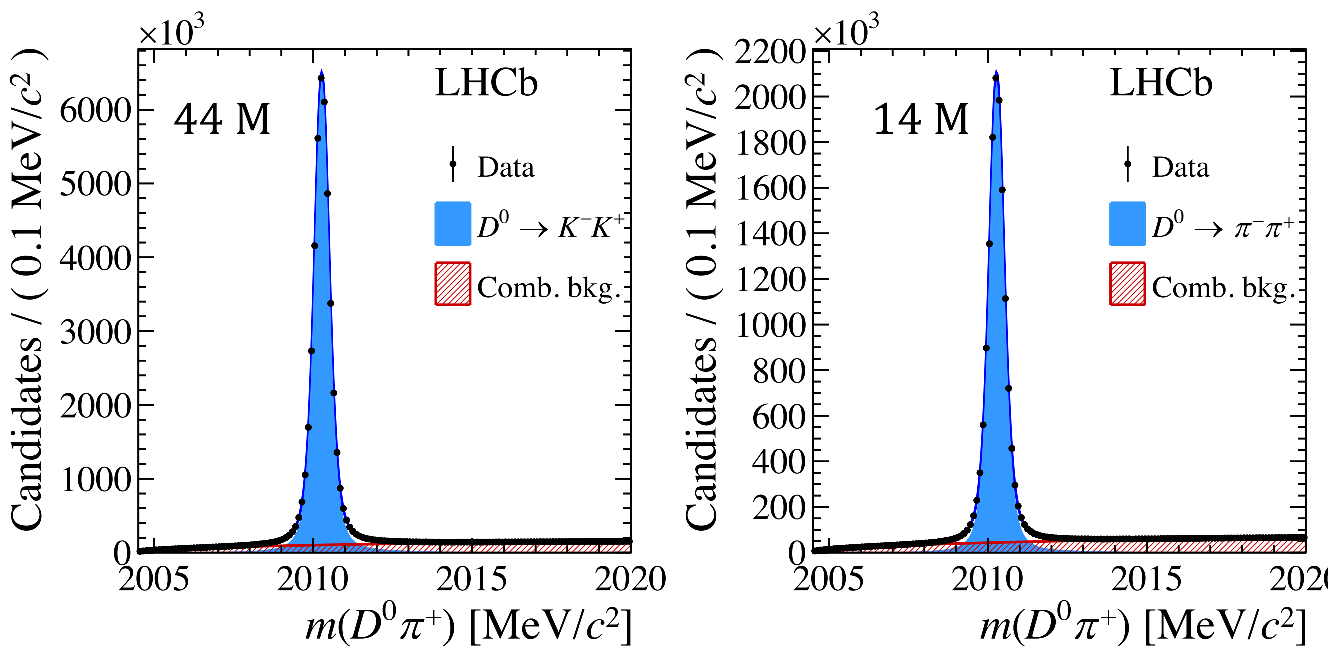
Observation of CPV in Charm (at last)

- Dedicated TURBO stream with online calibration and reconstruction of events
  - Increased event rate and faster turn around for critical measurements

Federico Betti, LHCb

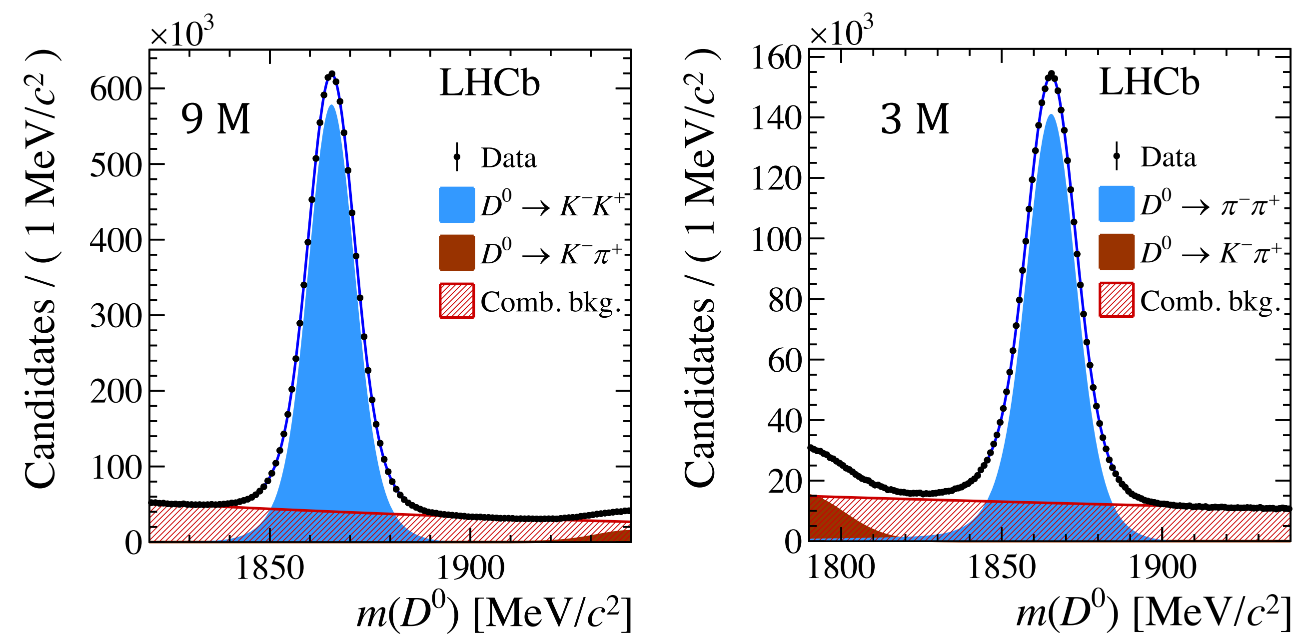
LHCb-PAPER-2019-006

soft pion tag



Run2 only

muon tag



Run2 + Run1

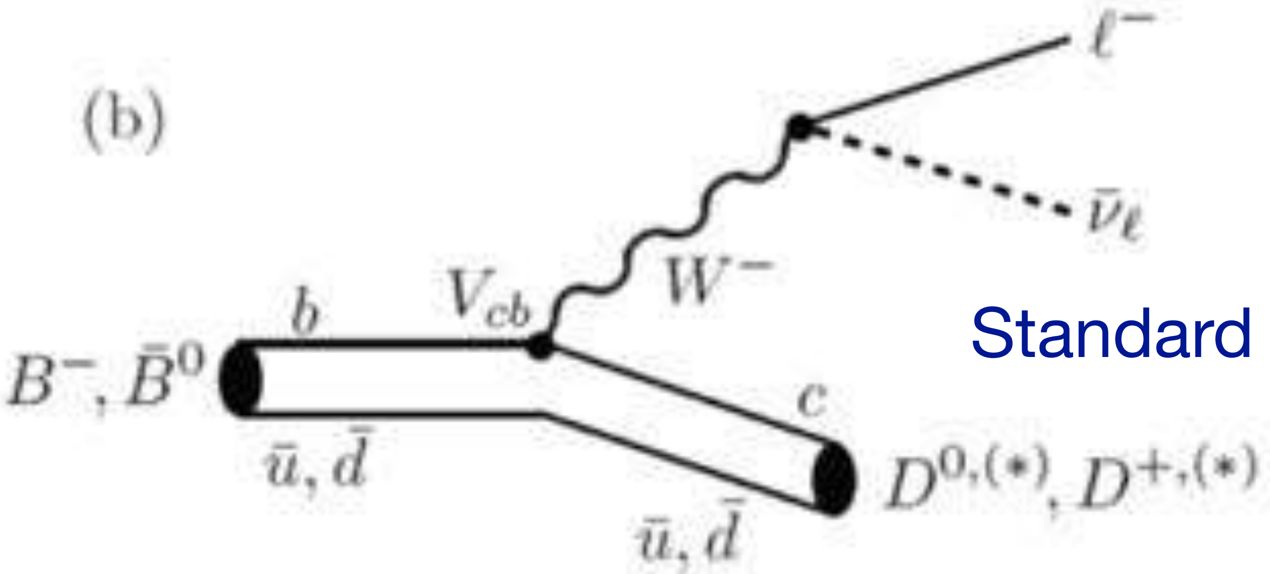
$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$

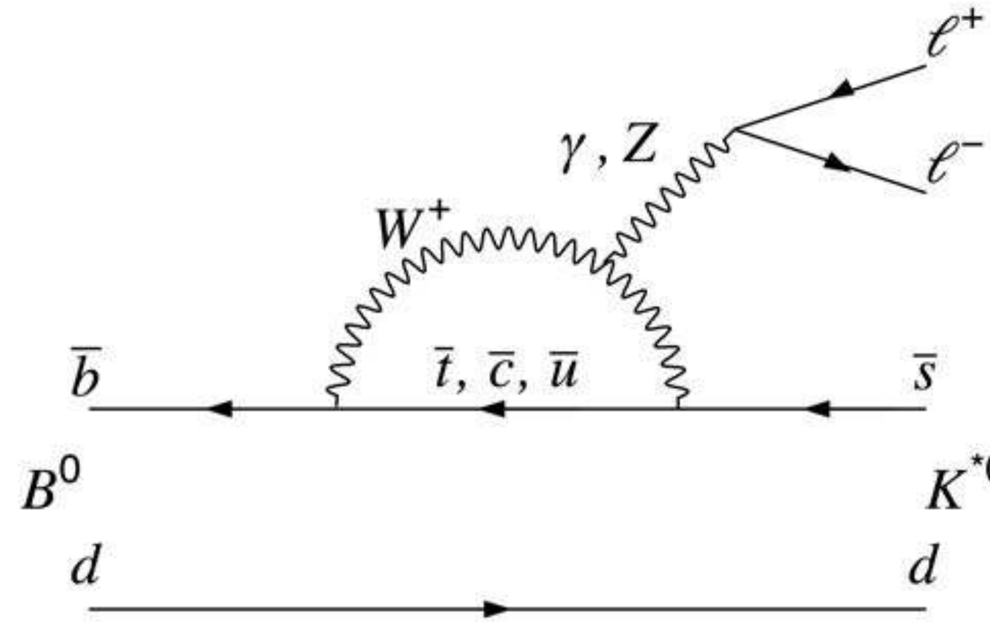
CP violation observed at $\mathbf{5.3\sigma}$!!

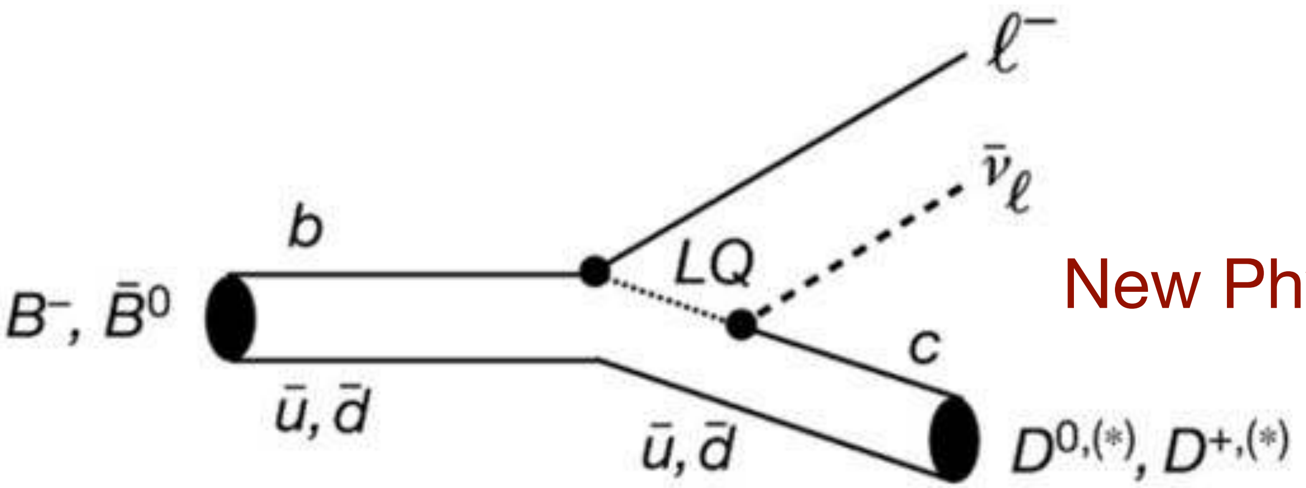
- Probing also $D^0 \to K_S K_S$ but no CPV yet

Giulia Tuci, LHCb

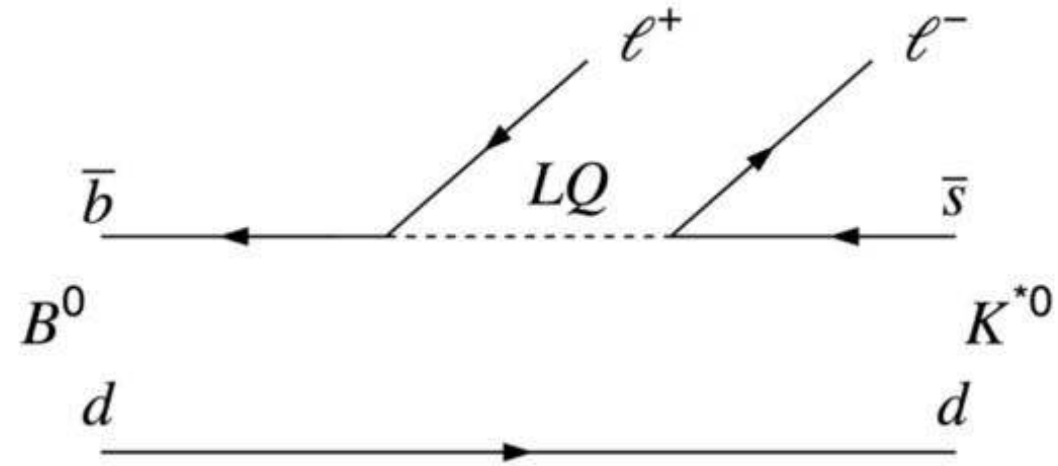


Standard Model





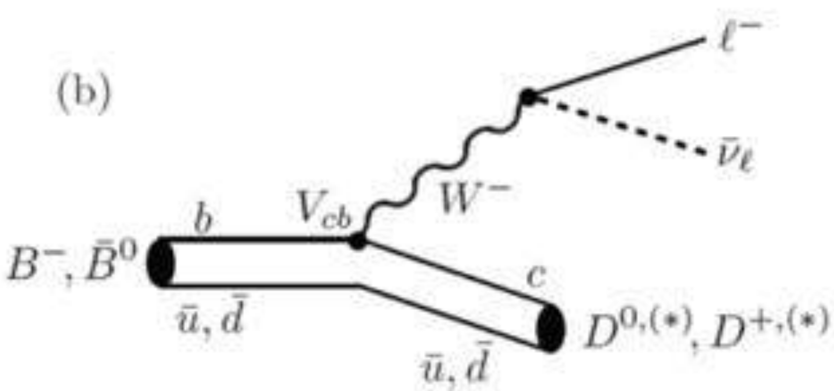
New Physics



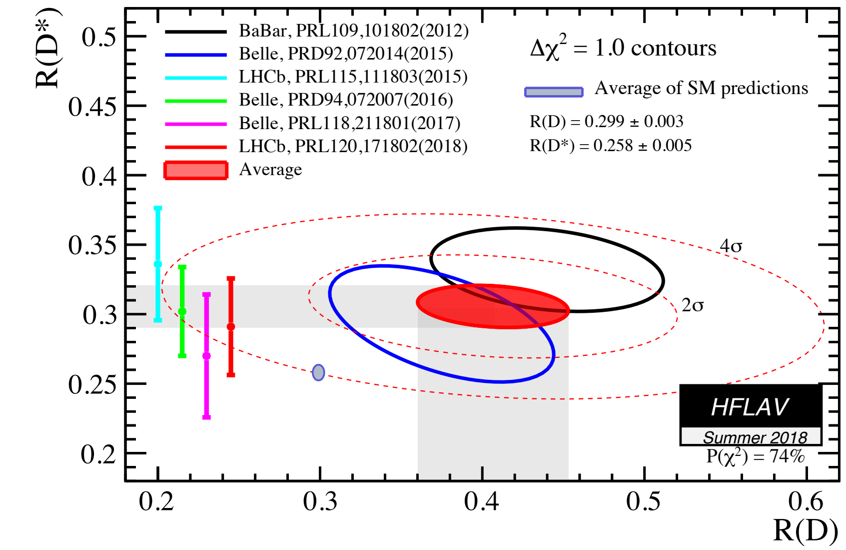
Lepton Flavor Universality

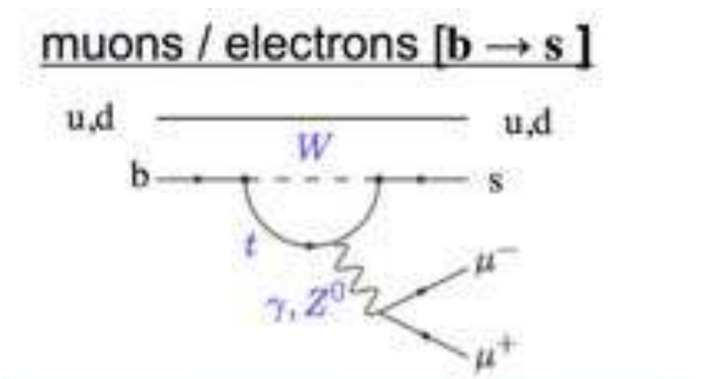
Indirect New Physics

Long Standing Anomalies

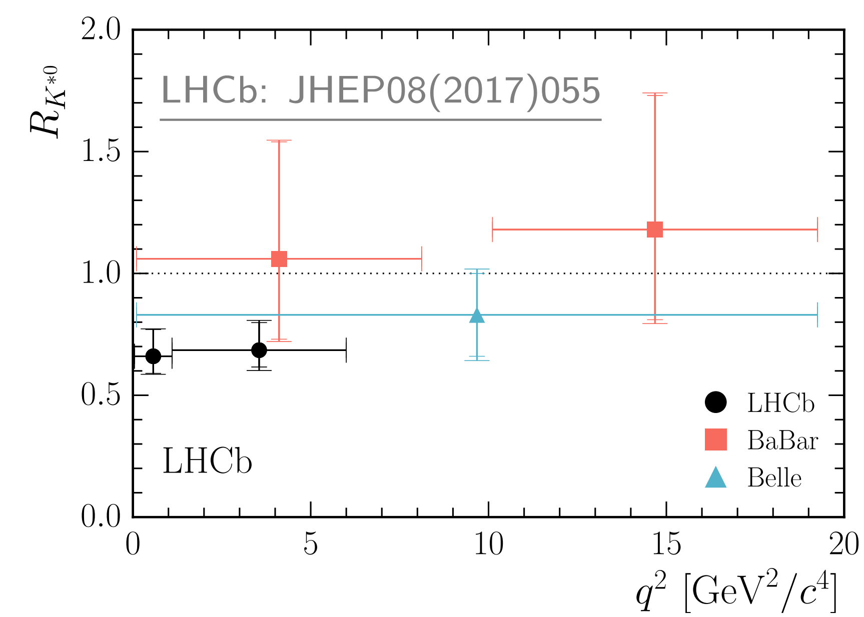


$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$

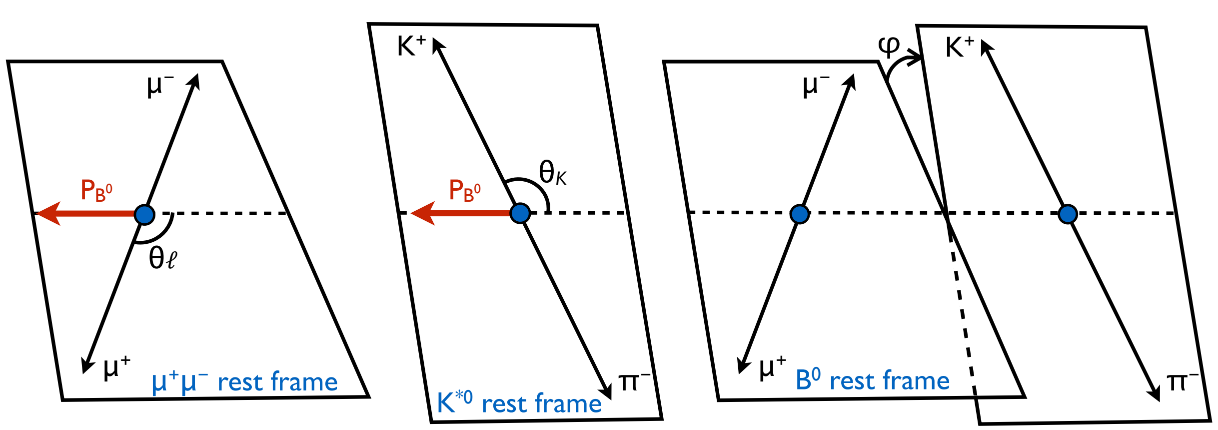


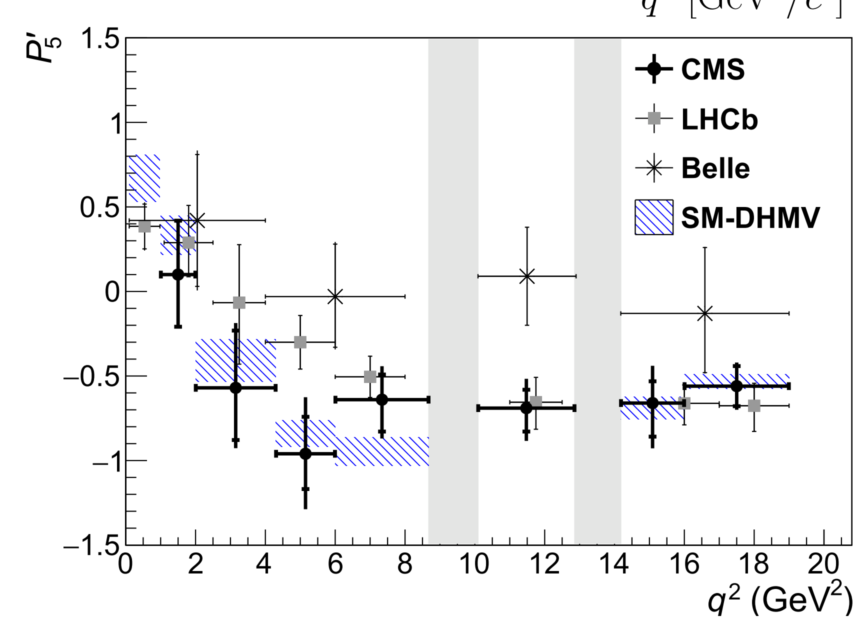


$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$



$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$

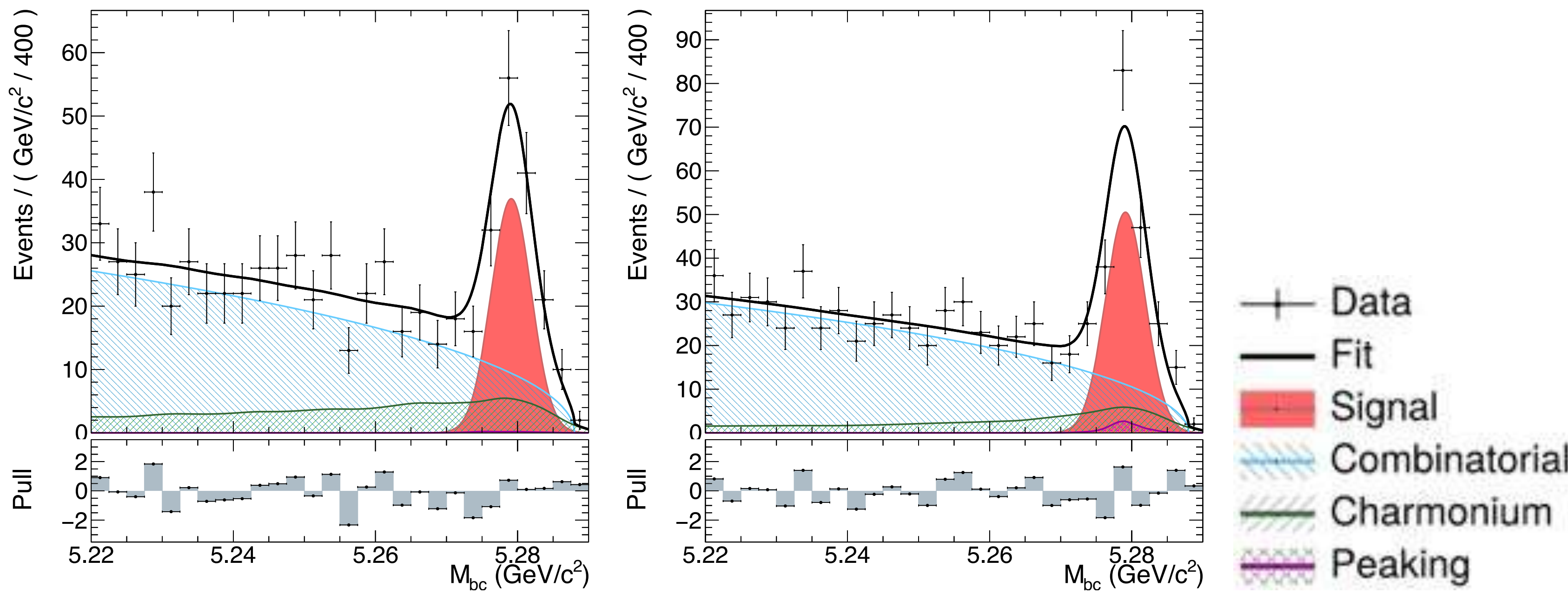


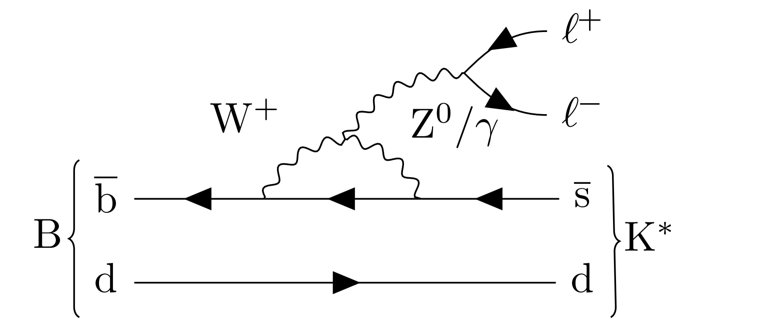


R(K*) and R(K*+) by BELLE

Markus Prim, BELLE

- Updated R(K*) and first measurement of R(K*+) with 711 fb^{-1} of data collected ion Y(4s) resonance





$B^0 \to K^{*0}\ell^+\ell^-$

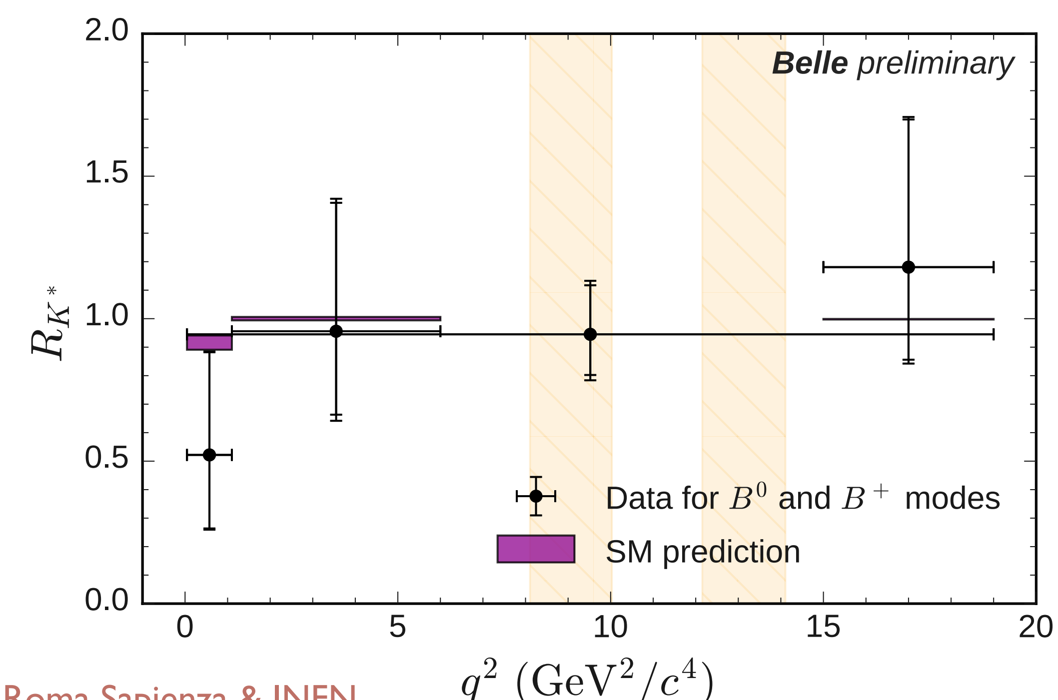
$B^+ \to K^{*+}\ell^+\ell^-$

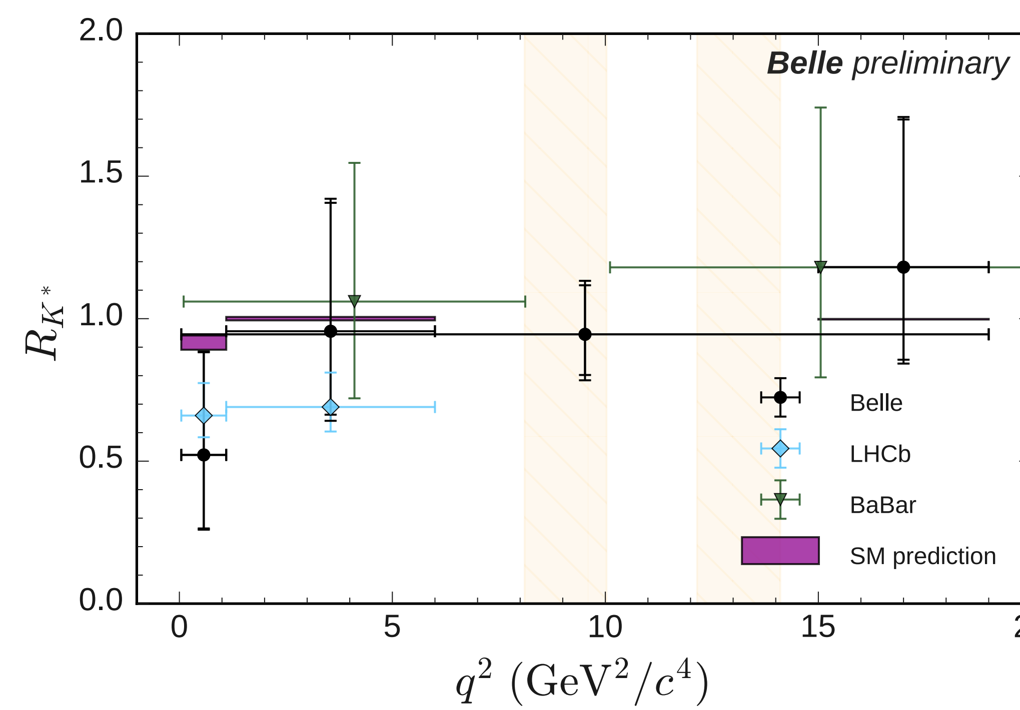
$K^{*0} \to K^+\pi^-$

$K^{*+} \to K^+\pi^0$

$K^{*+} \to K^0_S\pi^+$

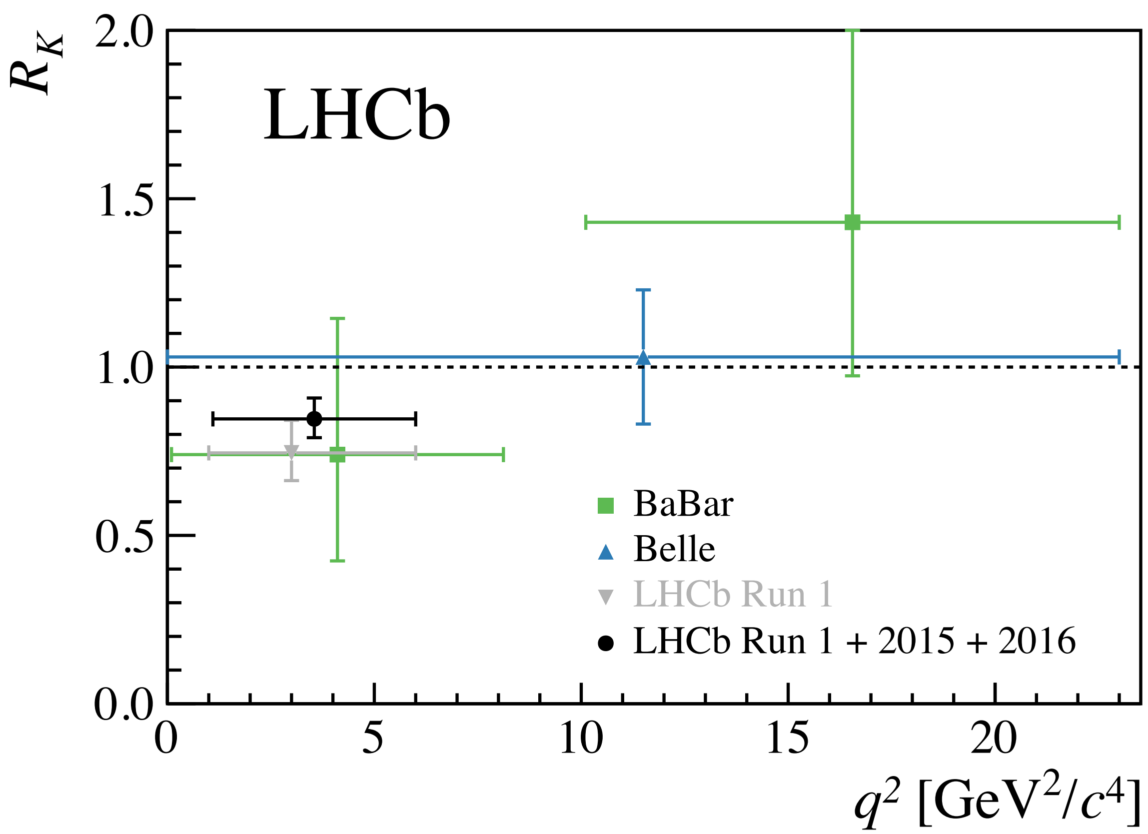
- No deviation from SM predictions
  - dominated by statistical uncertainty





Anomaly is still out there

Thibaud Humair, LHCb



Combined Run1 + Run2

$$R_K = 0.846\ ^{+0.060}_{-0.054}\,(\mathrm{stat.})\ ^{+0.016}_{-0.014}\,(\mathrm{syst.})$$

$\sim$ **2.5 σ** from SM.

$R^{\mathrm{new}}_{K\ \mathrm{Run\ 1}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}$, $R_{K\ \mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017}$;

$R^{\mathrm{old}}_{K\ \mathrm{Run\ 1}} = 0.745^{+0.090}_{-0.074} \pm 0.036$ (PRL113(2014)151601) ,

~70% of events in common between old and new Run1 analysis

LHCb-paper-2019-009

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\,\sigma$
- Run 1 result vs. Run 2 result: $1.9\,\sigma$.

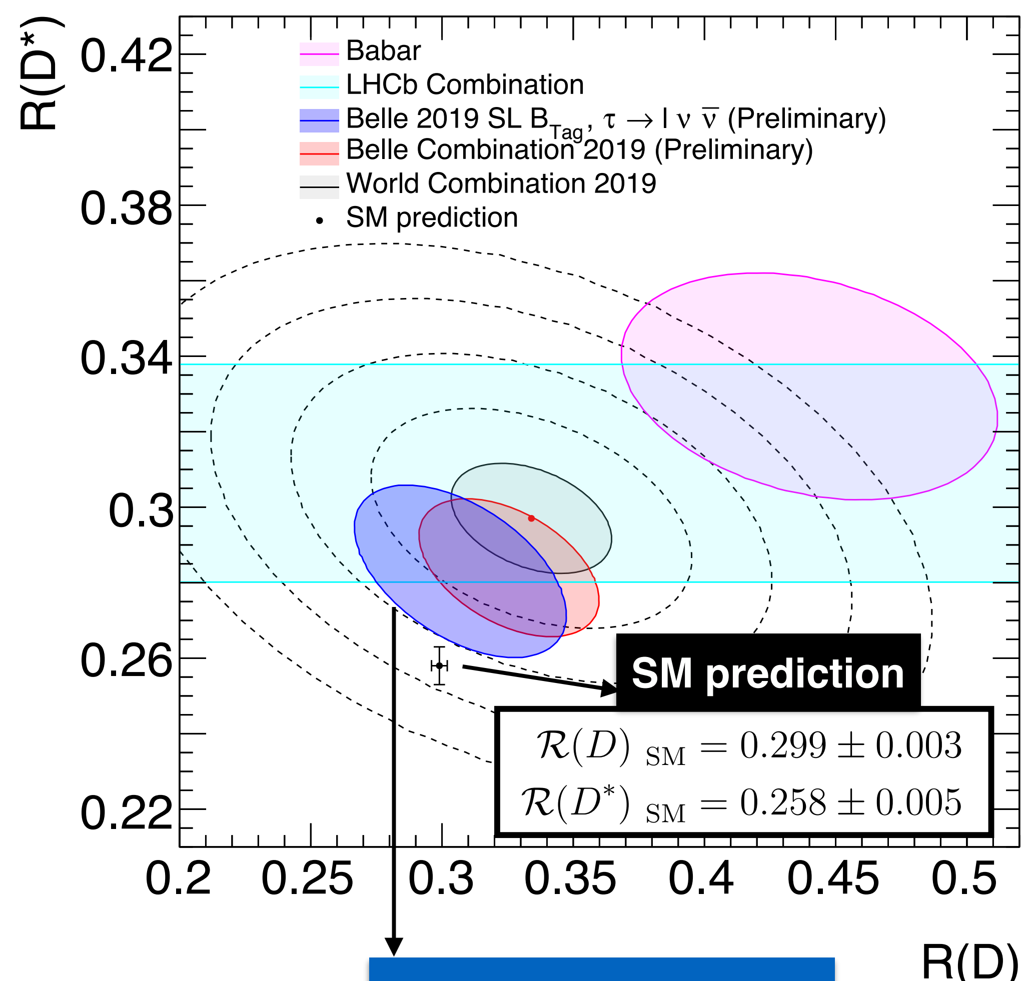
- Prospects
  - LHCb still has x2 data to analysis (2017 and 2018)
  - Additional measurements with B_s, B_c and Λ_b will be useful to understand the puzzle
  - Updated R(K*) still to come
  - Updated R(D) and R(D*) could also help understand differences between charged and neutral currents (written before Friday PM session)
  - Input from BELLE-II and other LHC experiments most welcome

R(D) and R(D*) from BELLE

Giacomo Caria, BELLE

- Simultaneous measurement of R(D) and R(D*) and their correlation with 2D fit to both D and D* samples

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



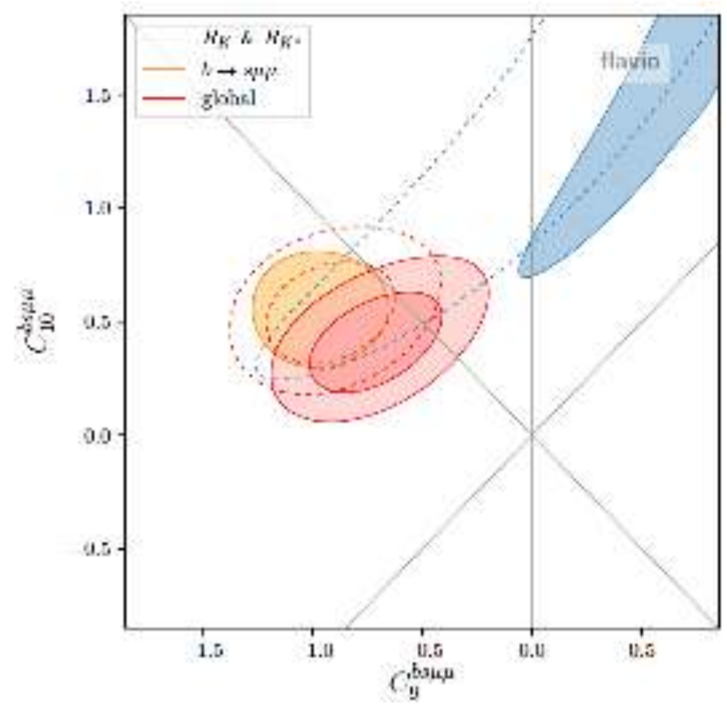
This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

- Eagerly awaiting the release of the paper or conference note!

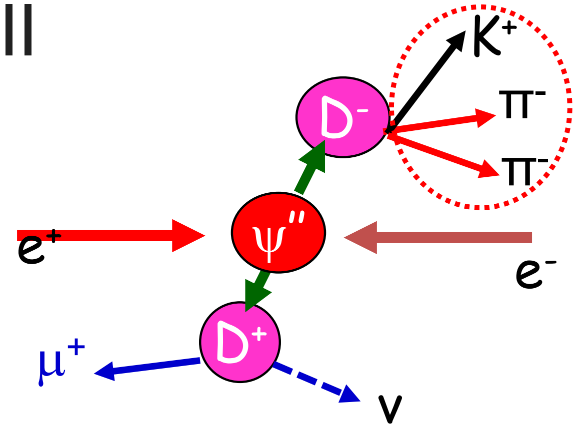
Thanks, David, updates made in LaThuile Straub

Coeff.	Dirac structure	best fit	1σ	pull
$C_9^{bs\mu\mu}$	$L \otimes V$	-0.95	$[-1.10, -0.79]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.09$	$[-0.07, +0.24]$	0.5σ
$C_{10}^{bs\mu\mu}$	$L \otimes A$	$+0.73$	$[+0.59, +0.87]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.19	$[-0.30, -0.07]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.20$	$[+0.05, +0.35]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$L \otimes L$	-0.53	$[-0.62, -0.45]$	6.5σ



LFUV in charm decays

- Probing LFUV with semi-leptonic decays of charm mesons and baryons at BES-III



- **Most precise measurements**

Constant	Syst. error (%)	Stat. error (%)	
		Now	Exp.
f_{D+}	~0.9	2.6	1.3
f_{Ds+}	~1	1.2	0.6
$f^{D\to K}_{+}(0)$	~0.5	0.35	0.18
$f^{D\to\pi}_{+}(0)$	~0.7	1.26	0.63
$\vert V_{cs}\vert^{Ds+\to l+v}$	~1	1.2	0.6
$\vert V_{cs}\vert^{D0\to K-e+v}$	2.5 (2.4^{LQCD})	0.35	0.18
$\vert V_{cd}\vert^{D+\to\mu+v}$	~0.9	2.6	1.3
$\vert V_{cd}\vert^{D0\to\pi-e+v}$	4.5 (4.4^{LQCD})	1.26	0.63

- **No LFU violation in charm decays**

Decays	Syst. Error (%)	Stat. error (%)	
		Now	Exp.
$D^+\to l^+v$ [μ/τ]	~10	20	10
$D_s^+\to l^+v$ [μ/τ]	~3	4	2
$D^0\to K^-l^+v$ [e/μ]	~1	0.7	0.35
$D^0\to\pi^-l^+v$ [e/μ]	~2	3.3	1.7
$D_s^+\to\phi l^+v$ [e/μ]	~4	6	3
$D_s^+\to\eta l^+v$ [e/μ]	~3	4	2
$\Lambda_c^+\to\Lambda l^+v$ [e/μ]	~4	17	5

Now: Current D/D_s/Λ_c analyses are based 2.9/3.2/0.567 fb^{-1} data at 3.773/4.178/4.6 GeV

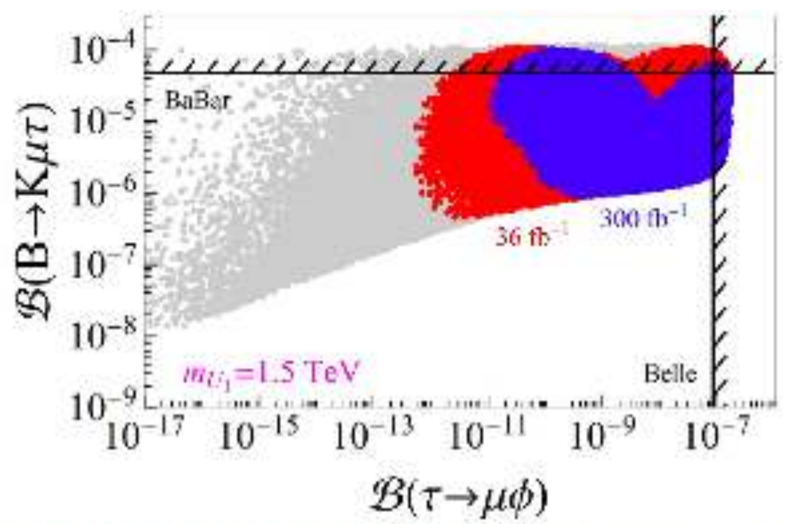
Exp.: Expected precision is based on 12/12/5 fb^{-1} data at 3.773/4.178/4.65 GeV

Single leptoquark solution

minimal, predictive: Vector LQ, for R_K and R_D "just around the corner" Angelescu

Which Single-LQ Model?

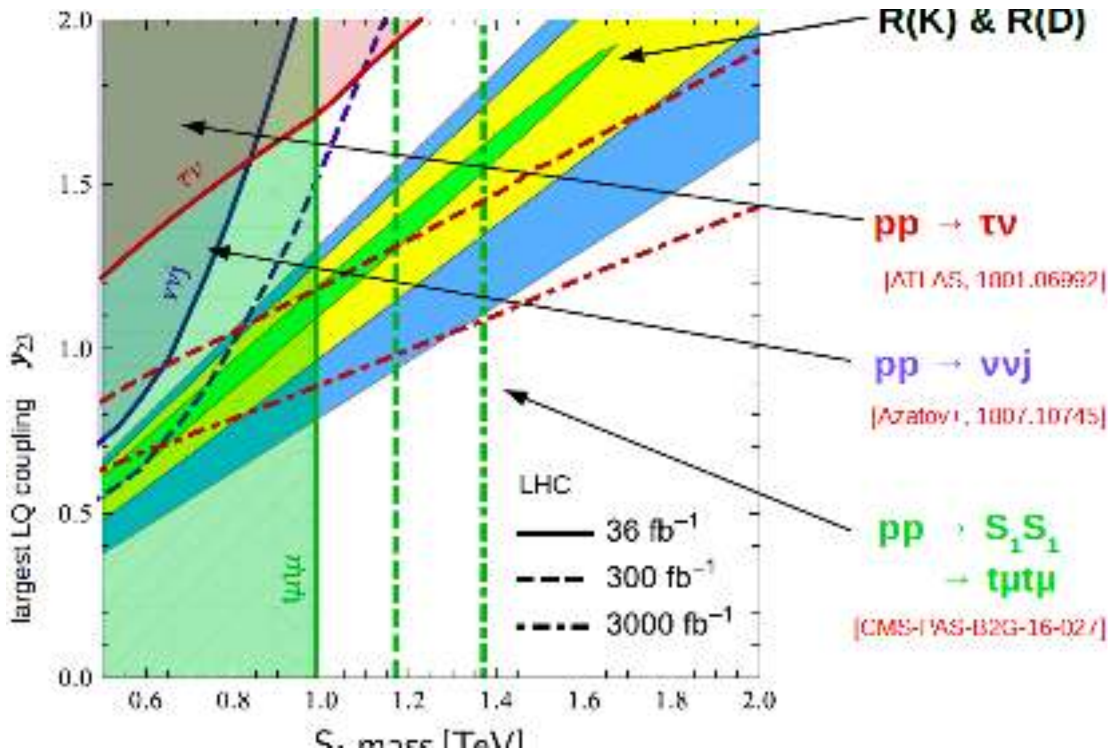
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗*	✓	✗*
$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗*	✓	✗
$\widetilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

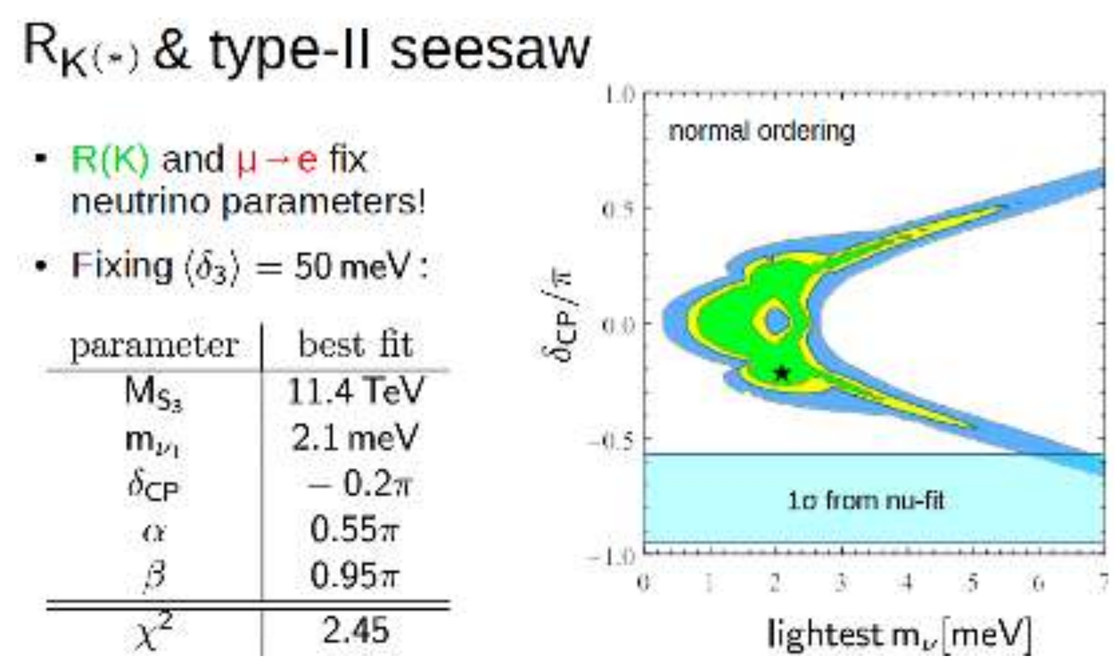


Lower bound on LFV pushed upwards by $pp \to \ell\ell$ for any m_{U_1}! (see backup)

Pati-Salam leptoquark solution

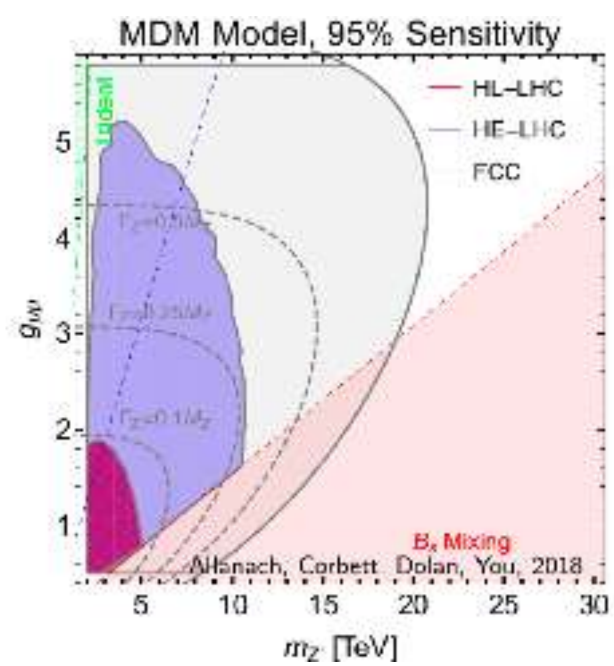
Heeck Pati-Salam LQ's for R_K and R_D and seesaw II with NO





2 scalar LQs, S_1 "just around the corner"

2LQs Hati connecion with (radiative) m_ν, dark matter and LFV simplified $L_Z = (\bar{Q}\lambda^Q\gamma_\mu Q + \bar{L}\lambda^L\gamma_\mu L)Z'^\mu$ Collider reach depends on up-vs down flavor in couplings $\lambda^{Q,L}$ in mass basis; third familly hypercharge $U(1)'$; anomaly cancllation



Angelescu

Unique Solution

$F_{Q'_i} = 0$	$F_{u'_{Ri}} = 0$	$F_{d'_{Ri}} = 0$	$F_{L'_i} = 0$
$F_{e'_{Ri}} = 0$	$F_H = -1/2$	$F_{Q'_3} = 1/6$	$F_{u'_{R3}} = 2/3$
$F_{d'_{R3}} = -1/3$	$F_{L'_3} = -1/2$	$F_{e'_{R3}} = -1$	$F_\theta \neq 0$

$$\mathcal{L} = Y_t \overline{Q'_{3L}} H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + Y_\tau \overline{L'_{3L}} H^c \tau'_R + H.c.,$$

- First two families massless at renormalisable level
- Their masses and fermion mixings generated by small non-renormalisable operators

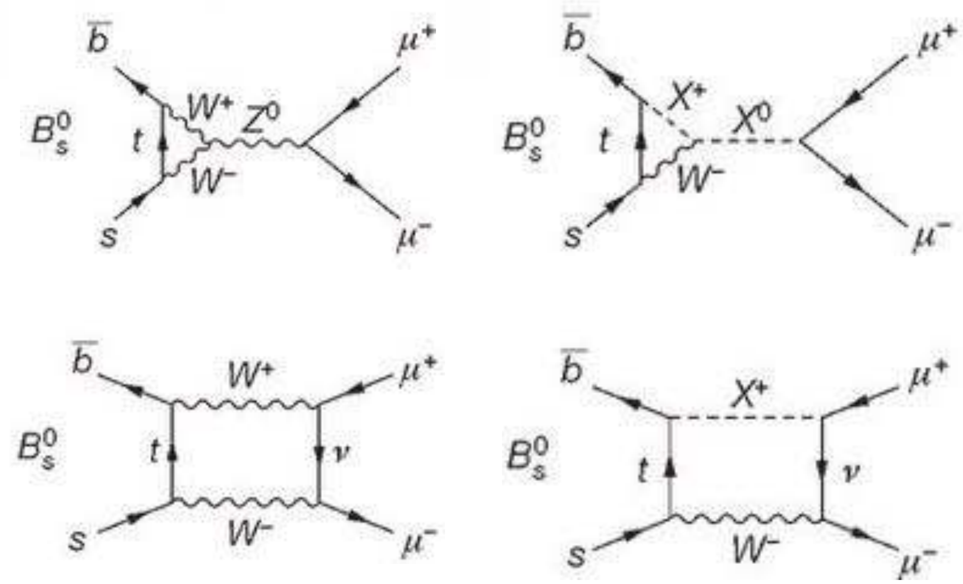
Planck/GUT scale framework, m_ν seesaw, with VL fermions King

Rare Processes

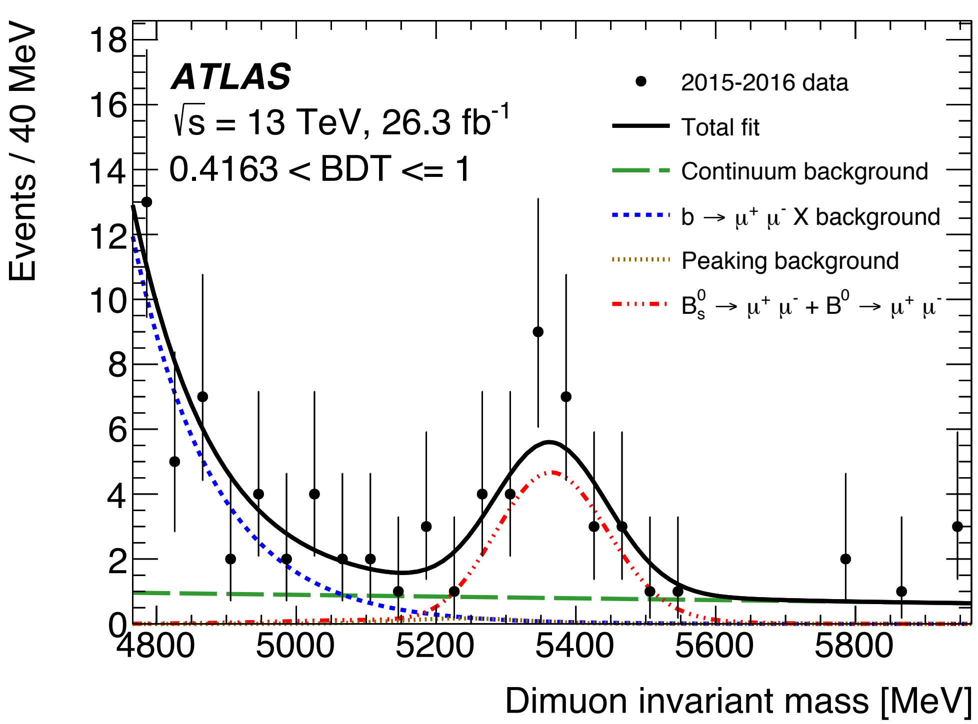
$B_s \rightarrow \mu\mu$ with ATLAS

Olga Igonkina, ATLAS

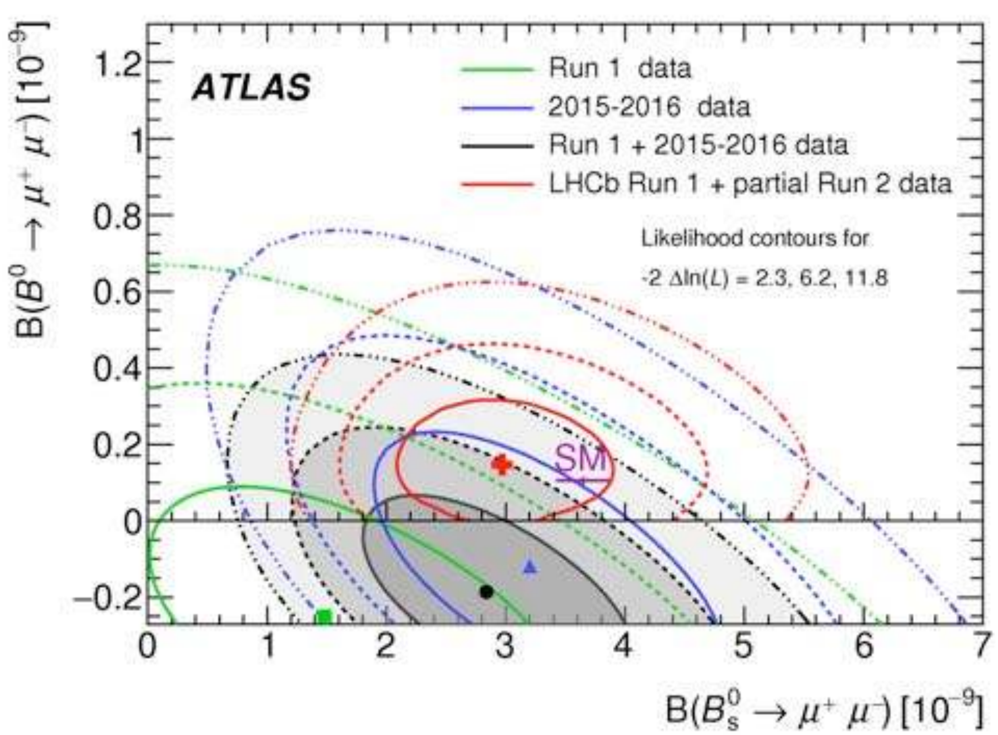
- Standard Model BF = 3 x 10^{-9} sensitive to BSM enhancements
- 26 fb^{-1} of data collected in 2015-2016
- Abundant sample of J/psi K^+ as reference



$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)] \times \frac{f_u}{f_{d(s)}}$$



Mass spectrum in best S/B category



SM :

$Br(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

$Br(B^0 \rightarrow \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

Best fit of Run 2 data :

$Br(B_s \rightarrow \mu\mu) = (3.2 \pm 0.9) \times 10^{-9}$

$Br(B^0 \rightarrow \mu\mu) = (-1.3 \pm 2.1) \times 10^{-10}$

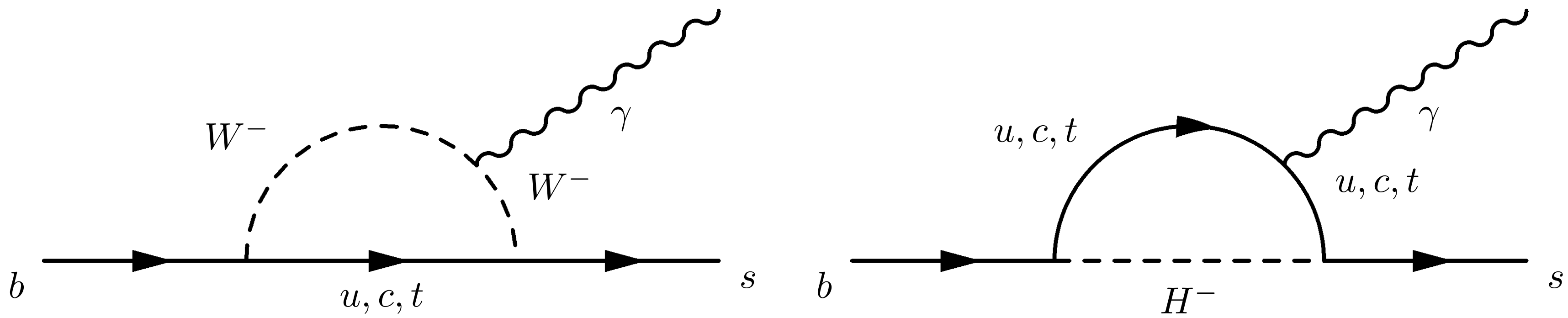
Run 1 + Run 2 result @ 95% CL

$Br(B_s \rightarrow \mu\mu) = (2.8 \pm 0.8) \times 10^{-9}$

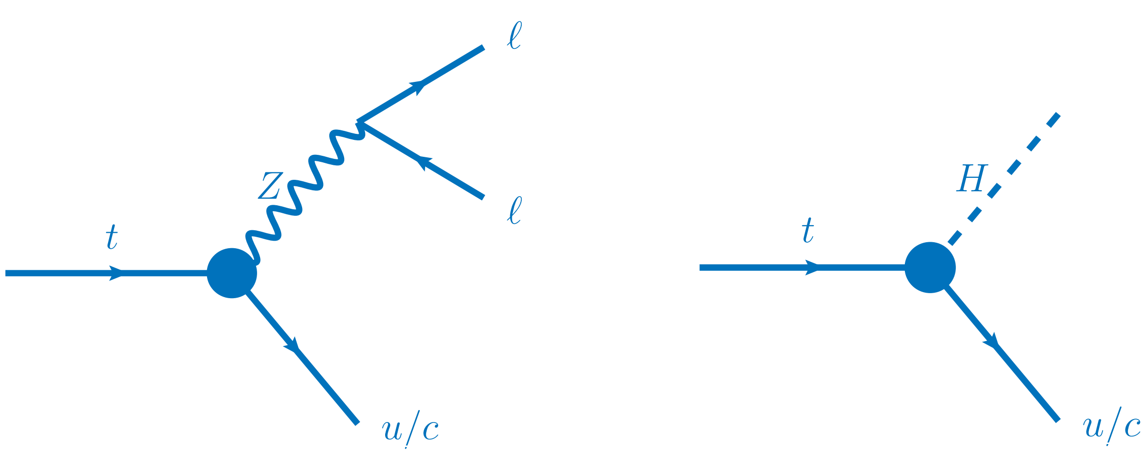
$Br(B^0 \rightarrow \mu\mu) < 2.1 \times 10^{-10}$

First theoretical implications already shown yesterday afternoon!
(see theory summary)

Flavor **C**hanging **N**eutral **C**urrents



- Forbidden in Standard Model at tree level
- Typically small predicated rates and hence sensitive to new particles in strong and electroweak penguin loops
- Rich area of probe in b, c, s, and now also top decays



$\mathrm{BR}(t \to qH) \sim 10^{-15}$

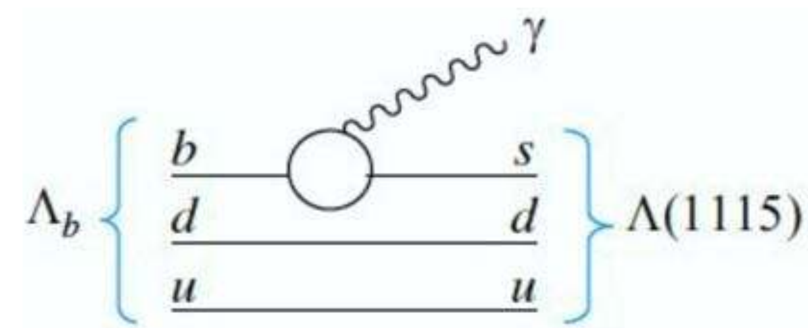
$\mathrm{BR}(t \to qZ) \sim 10^{-14}$

Loïc Valéry, ATLAS

FNCN with radiative decay $\Lambda_b \rightarrow \Lambda\gamma$

Carla Marin , LHCb

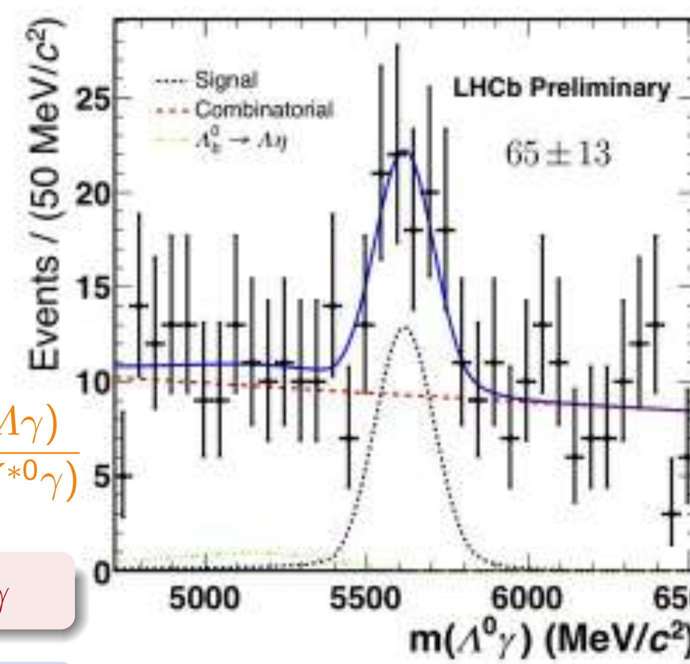
- Rare radiative decays sensitive to new physics

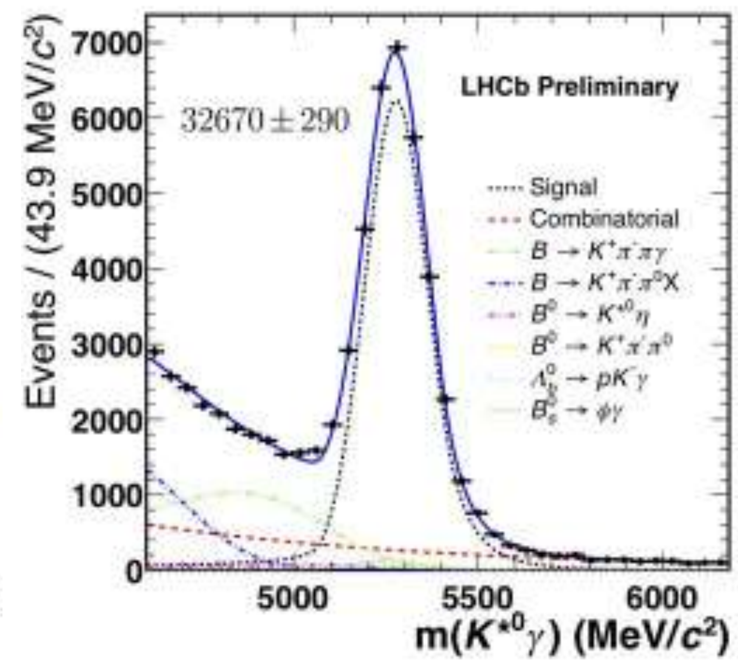


- Only theoretical prediction affected by large uncertainties: 10^{-5} — 10^{-7}
  - Experimental limit CDF: $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) < 1.9 \times 10^{-3}$ at 90% CL

- Machine learning techniques to reduce combinatorial background and improved particle identification
  - 99.8% background rejection with 1/3 signal efficiency

$$\frac{N(\Lambda_b^0 \rightarrow \Lambda\gamma)}{N(B^0 \rightarrow K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma)}{\mathcal{B}(B^0 \rightarrow K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda \rightarrow p\pi^-)}{\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)} \times \frac{\epsilon(\Lambda_b^0 \rightarrow \Lambda\gamma)}{\epsilon(B^0 \rightarrow K^{*0}\gamma)}$$





Signal excess with 5.6 σ significance $\rightarrow$ first observation of $\Lambda_b^0 \rightarrow \Lambda\gamma$

Branching fraction measurement within range of SM predictions

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

- *Begging for new theoretical calculation*

- LHCb also investigating other such radiative decays

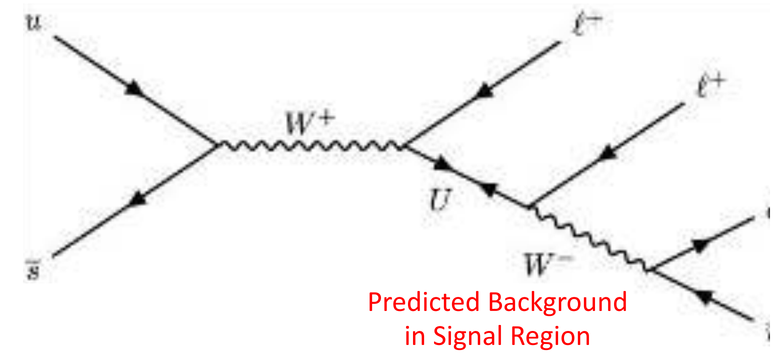
Latest results from LHCb

- Best world limit on $B^+ \rightarrow \mu^+\mu^-\mu^+\nu_\mu$
- Full angular analysis of $\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$: compatible with SM

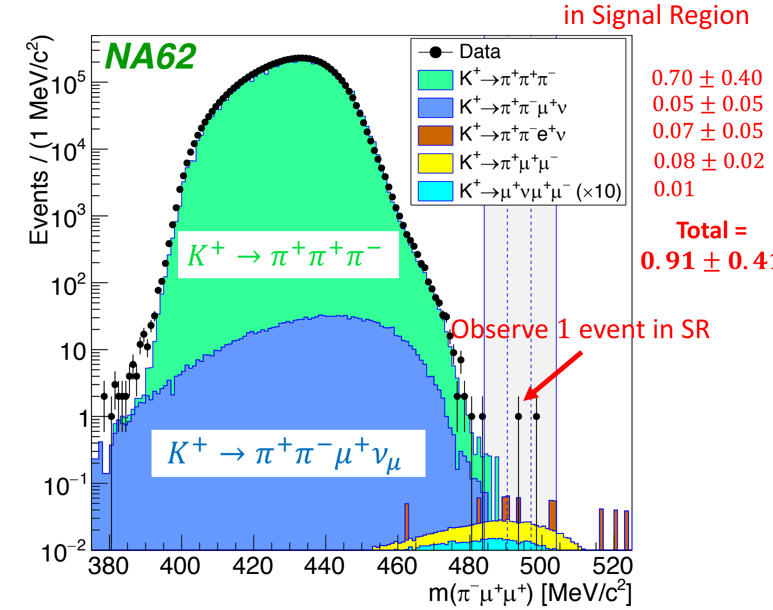
Lepton Flavor Violation

Joel Swallow, NA62

- Neutrino-less double beta-decay a prime probe of LFV
- NA62 at CERN reported on $K^+ \to \pi^- l^+ l^+$ with of 2017 data
  - measurement normalised to similar FNCN mode $K^+ \to \pi^+ l^+ l^-$

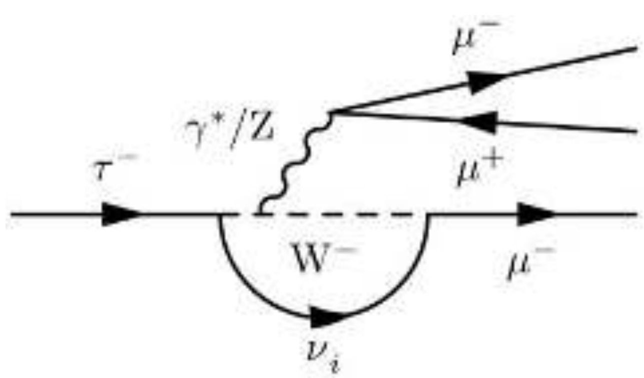


Decay	BR UL @ 90% CL	PDG (2018) UL @ 90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11}



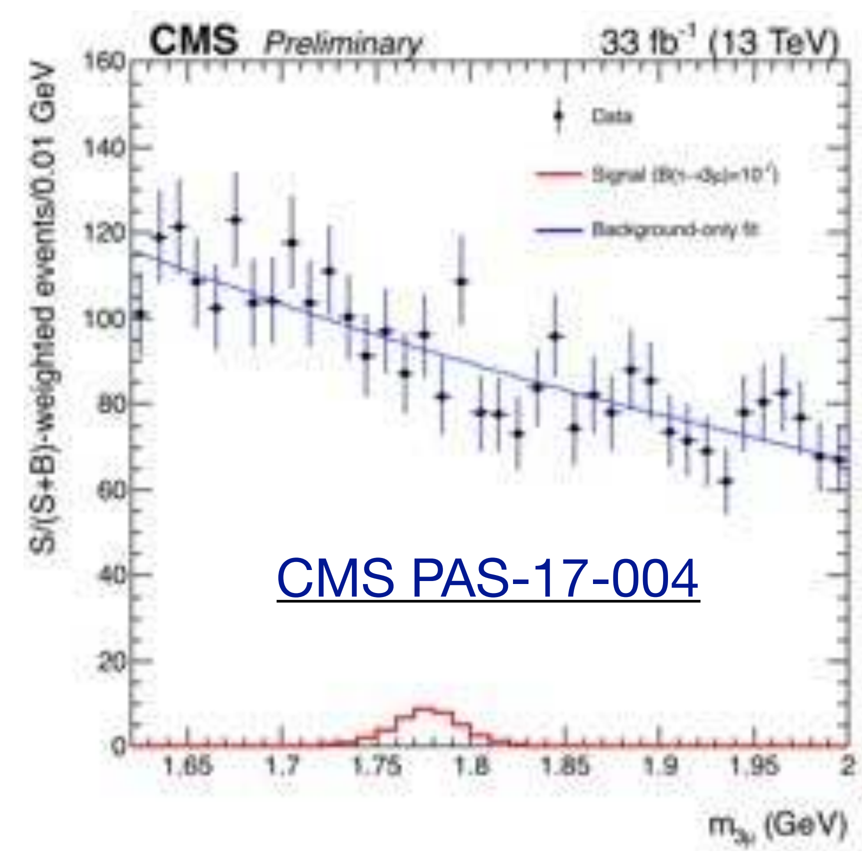
Alessio Boletti, CMS

- Search for τ→3μ in copious sample of leptons from B and D decays in 2016 data at 13 TeV
  - $D_s^\pm \to \phi\pi^\pm \to \mu^+\mu^-\pi^\pm$ used as reference sample



Most stringent limit (Belle): $BF < 2.1 \cdot 10^{-8}$ (90% CL)

CMS $BF(\tau \to 3\mu) < 8.9 \cdot 10^{-8}$

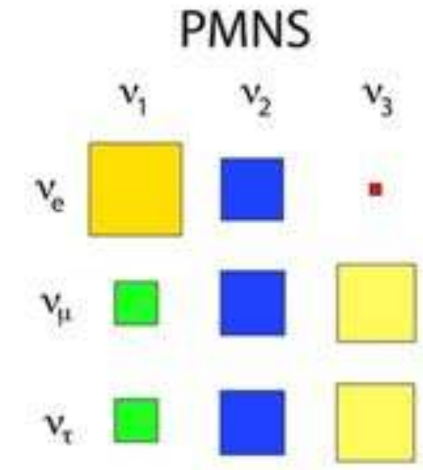


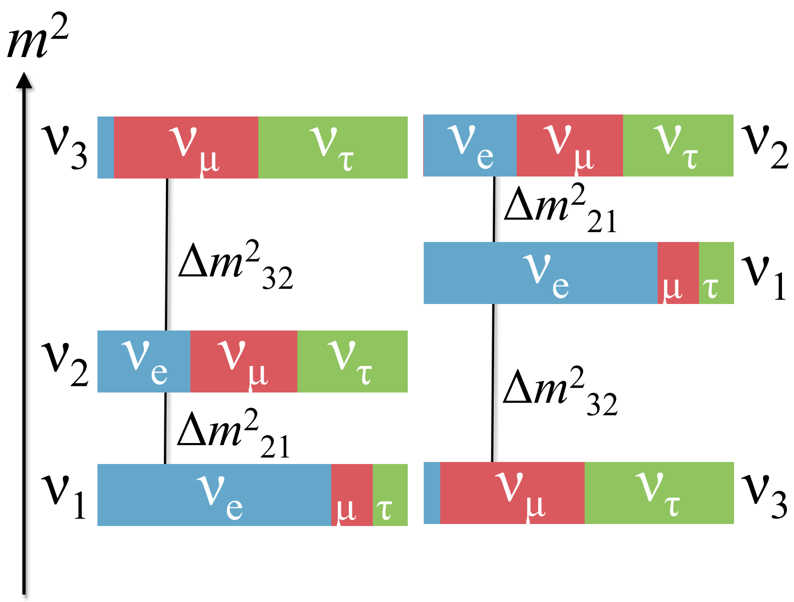
CMS PAS-17-004

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

CP phase δ_{CP}





Normal Hierarchy **Inverted Hierarchy**

Mass squared difference $\Delta m^2_{21}, \Delta m^2_{32}$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

Neutrinos

Neutrinos

- Only confirmed proof of Physics Beyond Standard Model (BSM)
  - mass term confirmed by oscillation experiments but not predicted in SM
- Open Questions
  - origin of the mass and nature of neutrinos
  - overall mass scale
  - mass hierarchy of 3 generations
  - mixing angles
  - CP violation
  - existence of new (possibly sterile) neutrinos
    - and how to detect them
  - anomalies in flux of anti-neutrinos
- Experimental approach
  - appearance and disappearance of each generation
    - NOvA, T2K, Day Bay, Ice Cube
  - Investigation of flux anomaly at reactors
    - Daya Bay, STEREO, PROSPECT, CONUS

ν-fits Update PMNS, masses

PMNS matrix parametrization

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

NO: $m_1 < m_2 < m_3$

IO: $m_3 < m_1 < m_2$

$\Delta m^2_{21} \ll |\Delta m^2_{31}| \sim |\Delta m^2_{32}|$ where $\Delta m^2_{ij} = m^2_i - m^2_j$

$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 & \text{for NO,} \\ \Delta m^2_{32} < 0 & \text{for IO} \end{cases}$$

Hernandez

With current data (up to Fall 2018)

θ_{12} : 14% , θ_{13} : 8.9% ,

θ_{23} : 27% [24%] , δ_{CP} : 100% [92%] ,

Δm^2_{21} : 16% , $|\Delta m^2_{3\ell}|$: 7.8% [7.6%] ,

θ_{12}, θ_{23}, θ_{13} & δ_{CP},

$\Delta m^2_{sol} \ll \Delta m^2_{atm}$ (Mass ordering)

- NO is favour over IO, $\Delta\chi^2 = 4.7(9.3)$
- $\sin^2\theta_{23}$ 2^o octant $\Delta\chi^2 = 4.4(6.0)$
- CP violation, $\Delta\chi^2 = 1.5(1.8)$

Some tensions (Kamland 2σ -Δm^2_{21}, NOvA-T2K (δ_{CP}), Normal ordering favored

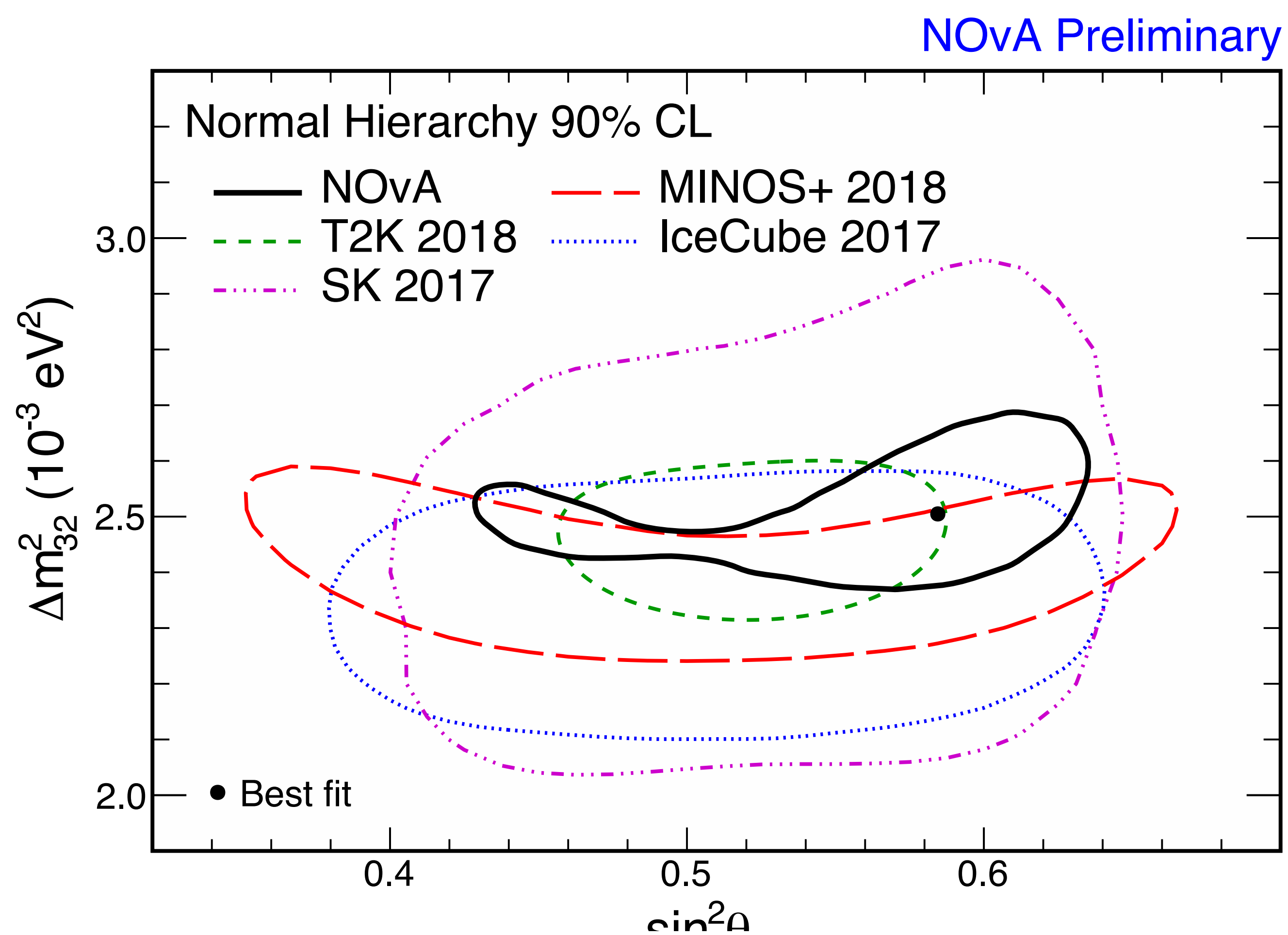
Neutrino Mixing and Mass Hierarchy

- Taking advantage of both appearance and disappearance
- NOvA: 2 detectors using NuMI beam from FNAL with narrow energy spectrum
  - First anti-neutrino data: Total analysis exposure 6.90x1020 (antineutrino) + 8.85x1020 (neutrino) POT
  - Additional antin-antis-neutrino data collected and to be added

Diana Mendez, NOvA

Alain Blondel, T2K

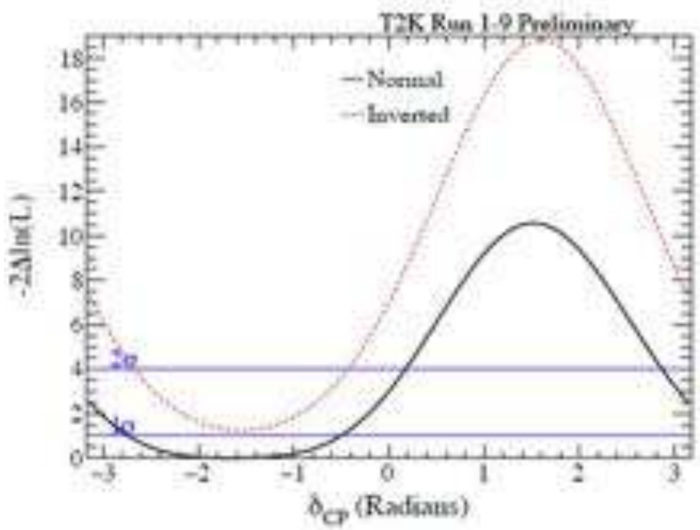
- T2K: 2 detectors using narrow energy beam from J-PARC
  - recent run mostly in anti-neutrino (50% more statistics wrt neutrino 2018 results)
  - best year of data taking in 2017~2018
- Both experiments **favor maximal mixing** for neutrinos and **Normal Hierarchy** for mass
- Slight preference for Normal Hierarchy also by IceCube DeepCore
  - limited sensitivity



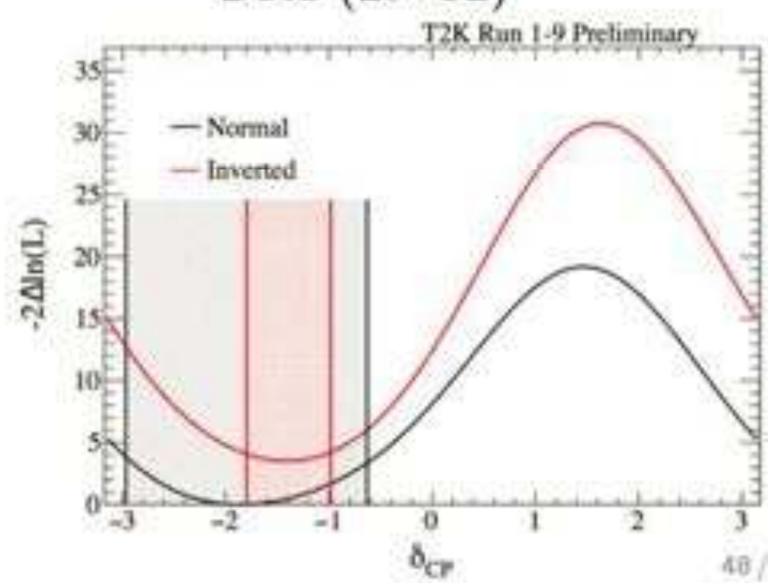
CP Violation in Neutrinos

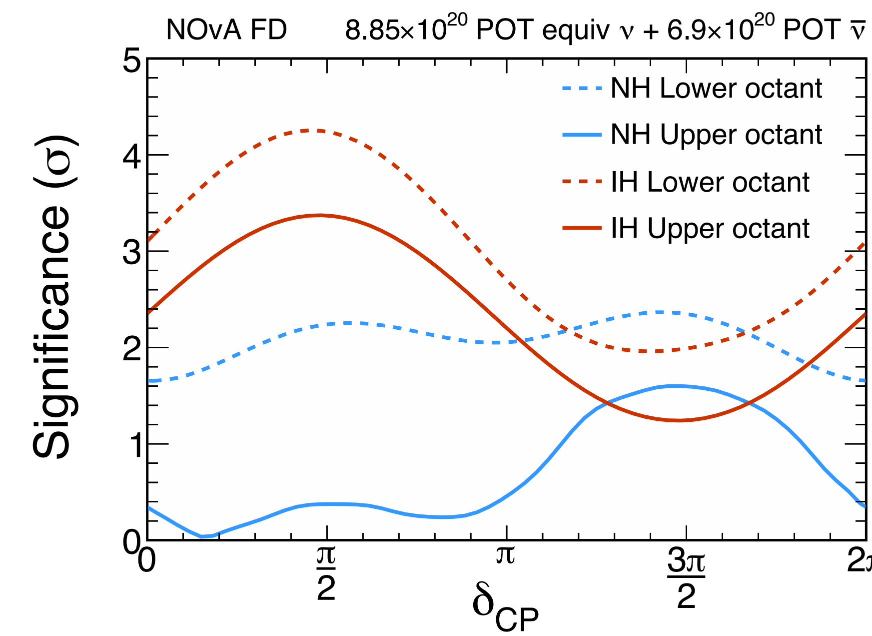
- CP conserving values $(0, \pi)$ fall outside of the 2σ CL intervals !
  - Still fall within the 3σ CL intervals
  - Suggestive result, but need more data

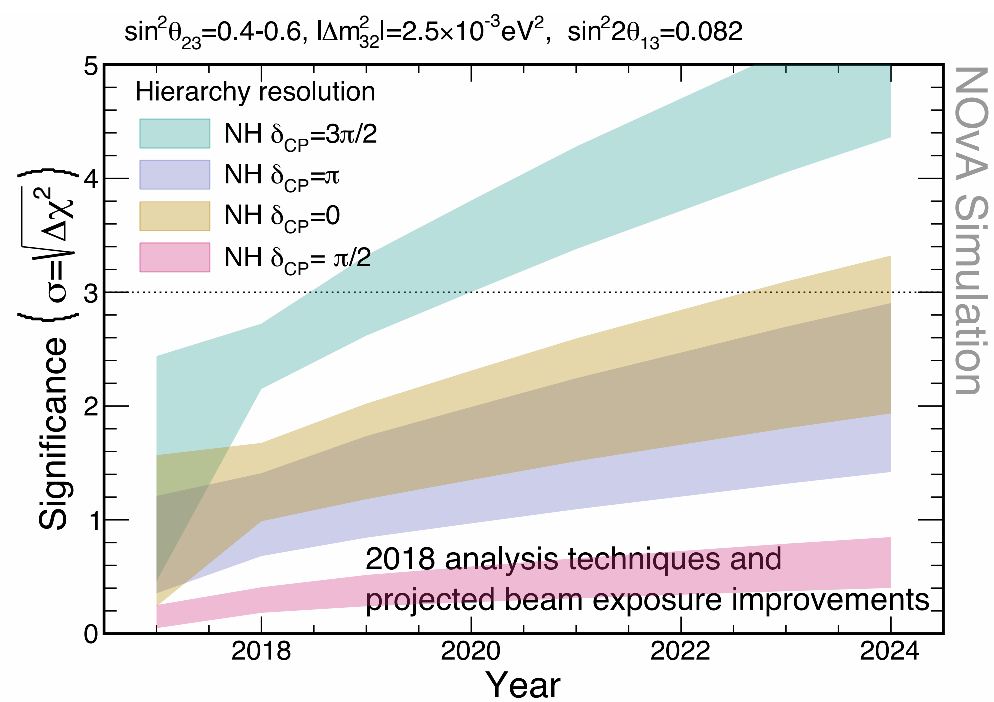
Sensitivity



Data (2σ CL)







nt best fit with 15.75 x 10^{20} POT-equivalent

$\delta_{CP} = 0.17\pi$

NH preferred by 1.8 σ
Exclude $\delta_{CP} = \pi/2$ in IH at 3 σ

- Analysis improvements and accelerator for up to 900 kW
- 2σ sensitivity to CP violation for favourable parameters by 2024
- Possible hierarchy determination at 3σ in 2020
- Joint NOvA-T2K analysis efforts ramping up

Diana Mendez, NOvA

Alain Blondel, T2K

Neutrino Mass Scale

▹ Oscillation measurements not sensitive to neutrino mass scale

Cosmology

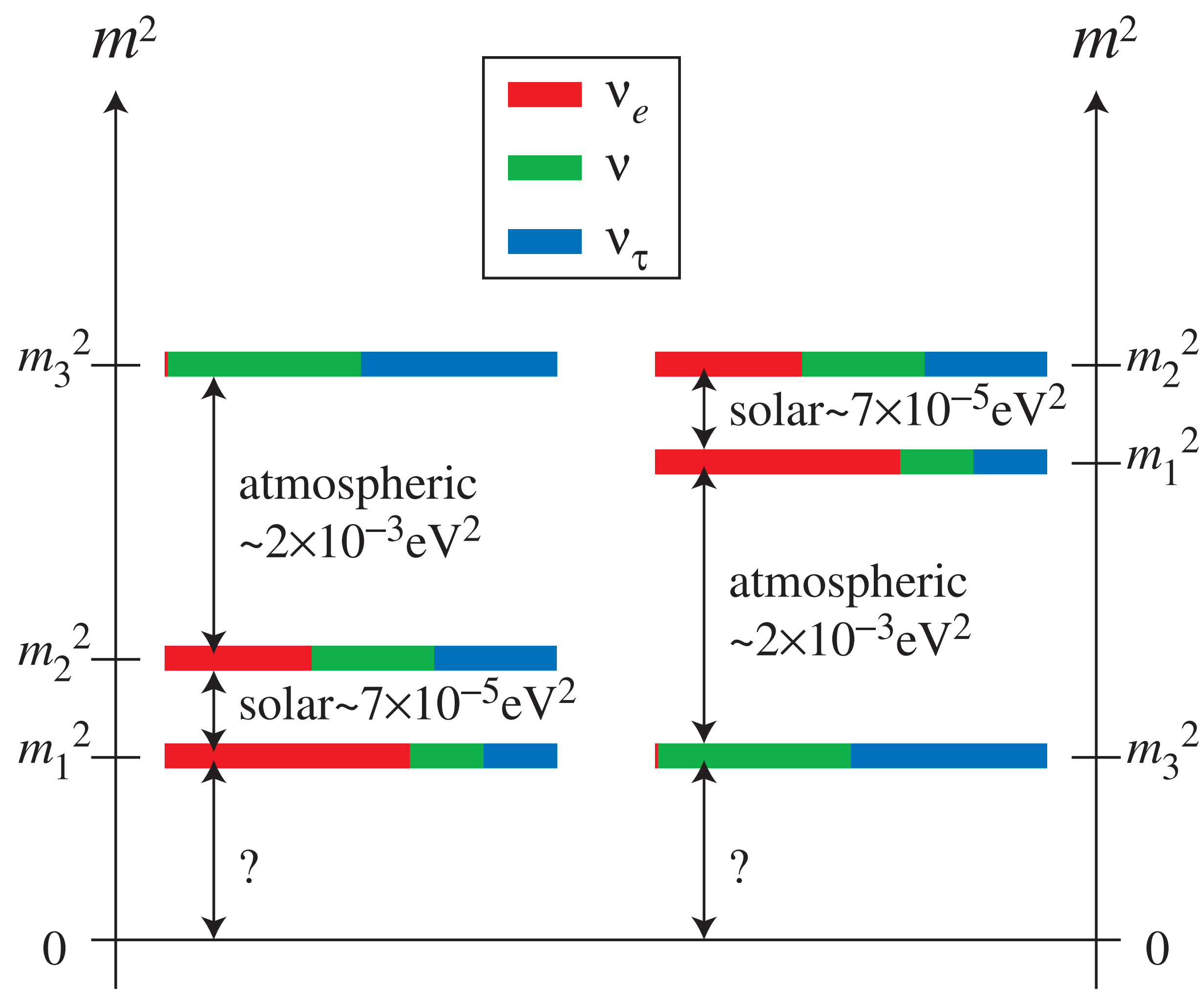
- ΛCDM
- $\sum_i m_i < 0.12 - 1$ eV

$0\nu\beta\beta$

- Majorana phases
- Matrix elements
- $\left|\sum_i U_{ei}^2 m_i\right| < 0.2 - 4$ eV

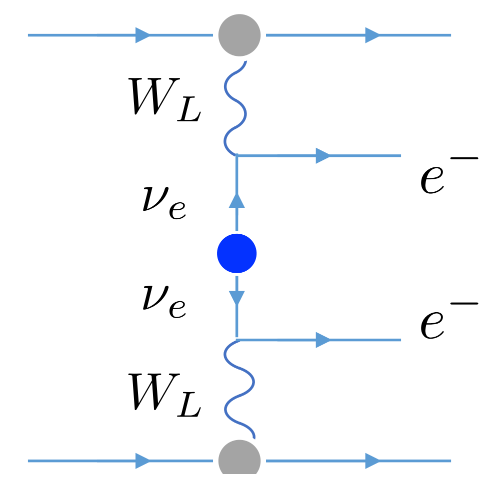
β-decay & EC

- Final states
- $\sqrt{\sum_i |U_{ei}|^2 {m_i}^2} < 2$ eV



Neutrinoless Double β-Decay (0νββ)

- Rare process in Standard Model sensitive to
  - Nature of neutrinos
  - lepton number violation
  - absolute neutrino mass scale



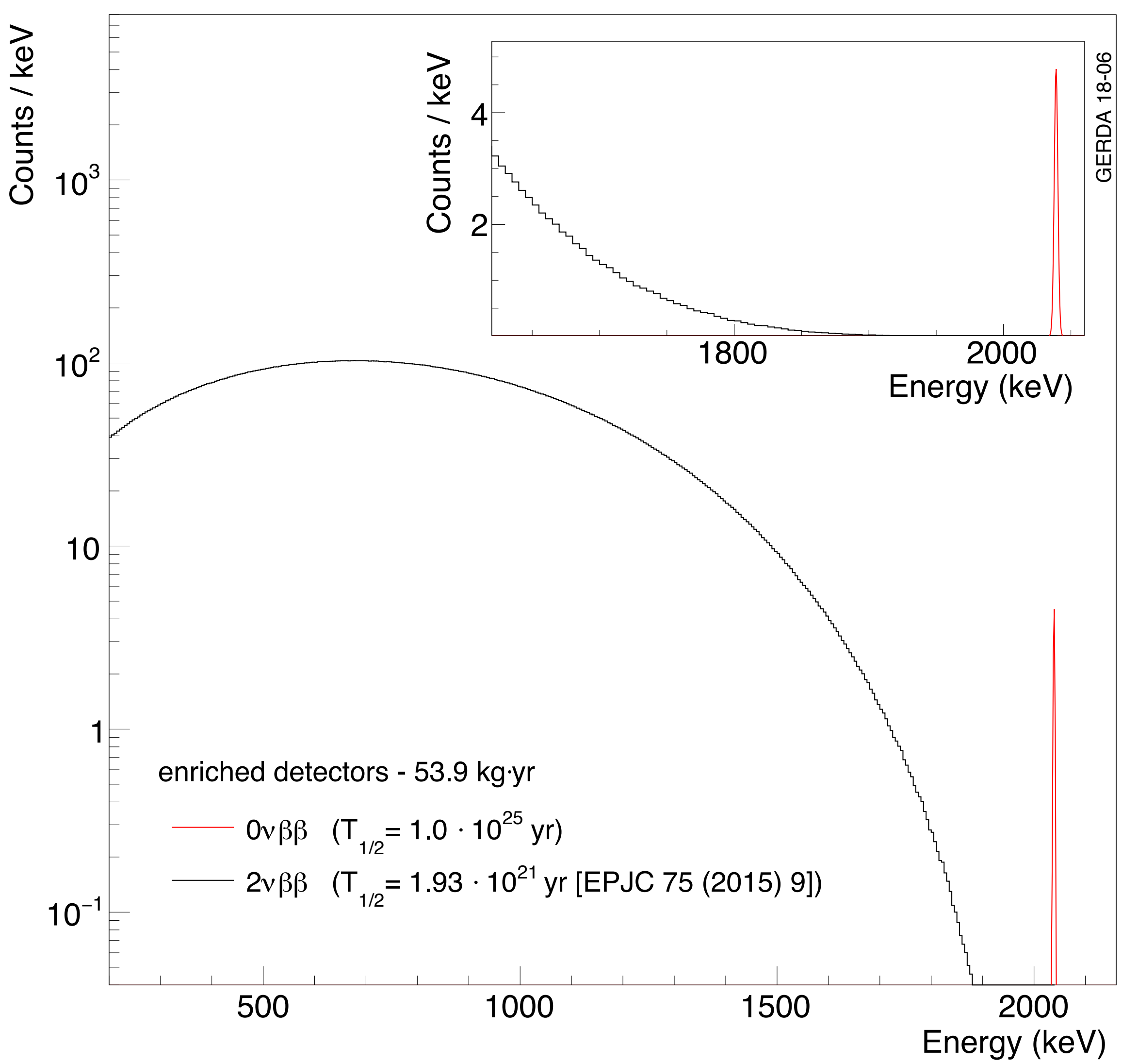
Half life of $0\nu\beta\beta$ (in case of light Majorana neutrino exchange):

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \times |M_{0\nu}|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

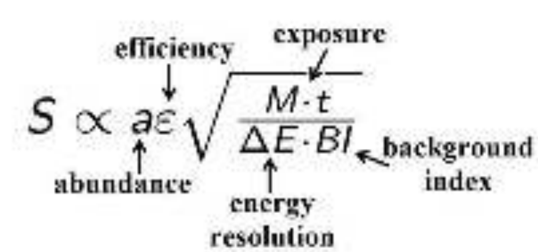
Phase Space Integral: well known quantity

Nuclear Matrix Element: most critical ingredient, produces uncertainty in the determination of $m_{\beta\beta}$ (quenching problem)

Neutrino Effective Mass: by measuring $T_{1/2}^{0\nu}$, $m_{\beta\beta}$ can be estimate



Experimental sensitivity



$$S \propto a\varepsilon\sqrt{\frac{M\cdot t}{\Delta E\cdot BI}}$$

in case of background-free:
($N_{bkg} < 1$ at full exposure)

$$\boxed{S \propto a\varepsilon \cdot M \cdot t}$$

Aim at background-free experiment

0νββ with CUORE detector at Gran Sasso

- Cryogenic detector of 750 kg of high-purity TeO2 crystals readout by bolometers

^{130}Te is an ideal candidate for the $0\nu\beta\beta$ search

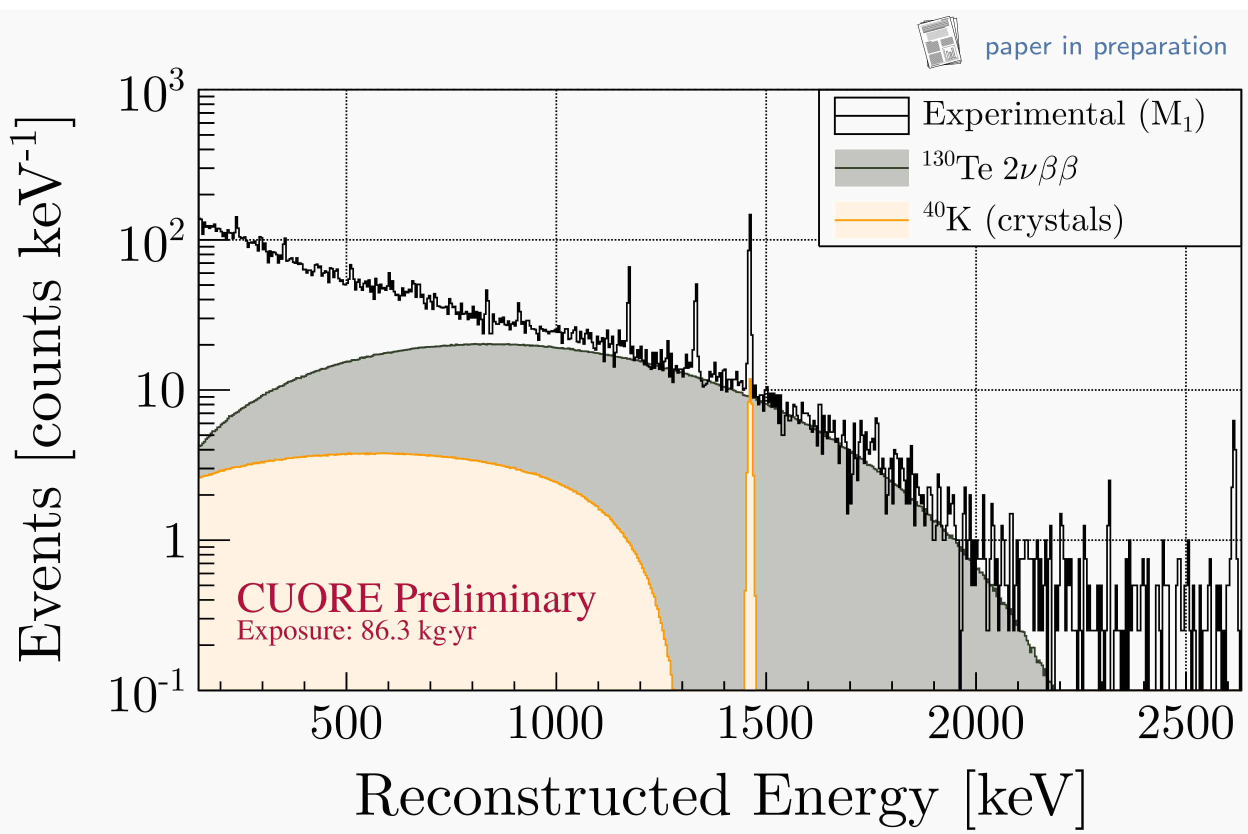
- $Q_{\beta\beta}$ moderately high: (2527.515 ± 0.013) keV (between the ^{208}Tl peak and Compton edge)
- large natural abundance: $(34.167 \pm 0.002)\%$

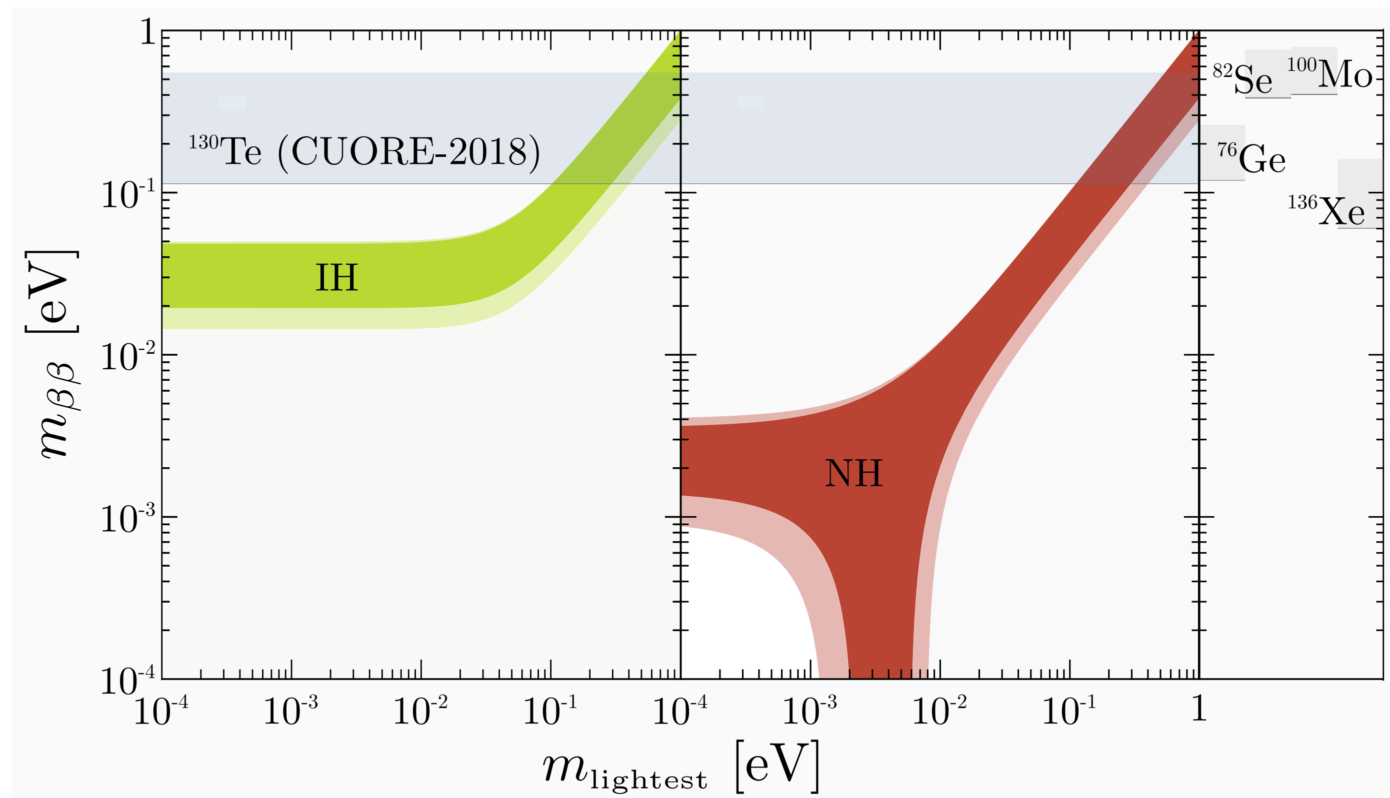
- Most precise 2νββ measurement
  - now almost the only source of background

$$t_{1/2}^{0\nu} > 1.5 \cdot 10^{25}\ \text{yr @ 90\% C. L.}$$

- Energy resolution of 7.7 keV currently

$$m_{\beta\beta} > (110 - 520)\ \text{meV}$$





Stefano Dell'Oro, CUORE

- Ambitious goal of 9 x 10^{25} yr @ 90% C.L.

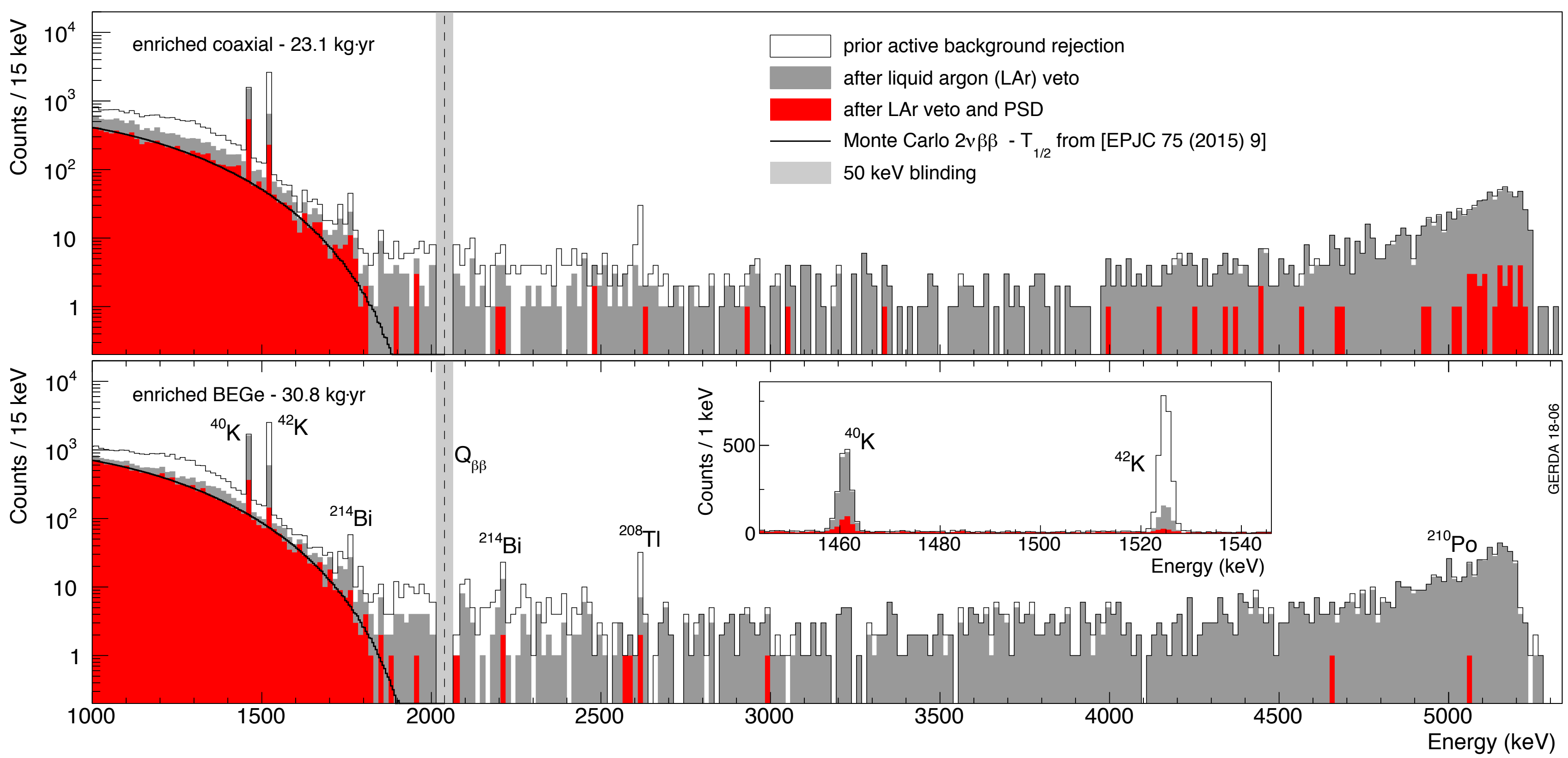
0νββ with LEGEND detector

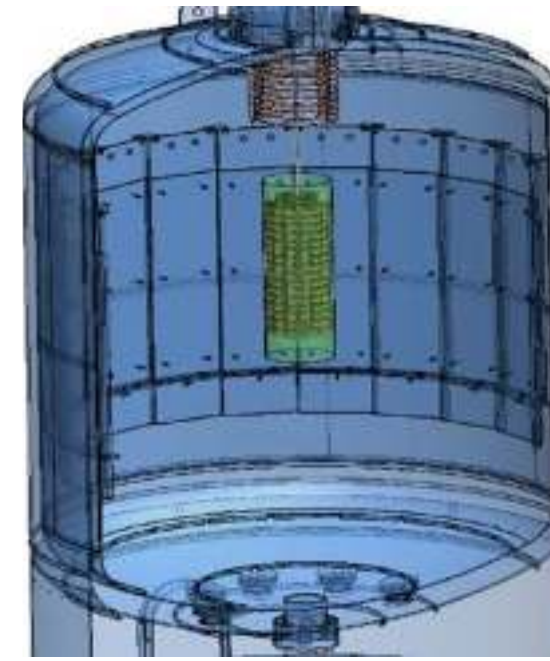
- Successor of GERDA and MAJORANA detectors using ^{76}GE
  - First stage with 200 kg of ^{76}GE aiming for 0.6 counts/t/yr
- Outstanding performance for GERDA and MAJORANA

energy resolution $\sim 0.1\%$ **at** $Q_{\beta\beta}$

lowest background ever achieved: $6 \cdot 10^{-4}$ cts/(keV·kg·yr)

exploration of the $0\nu\beta\beta$ **decay at the** 10^{26} **yr scale**

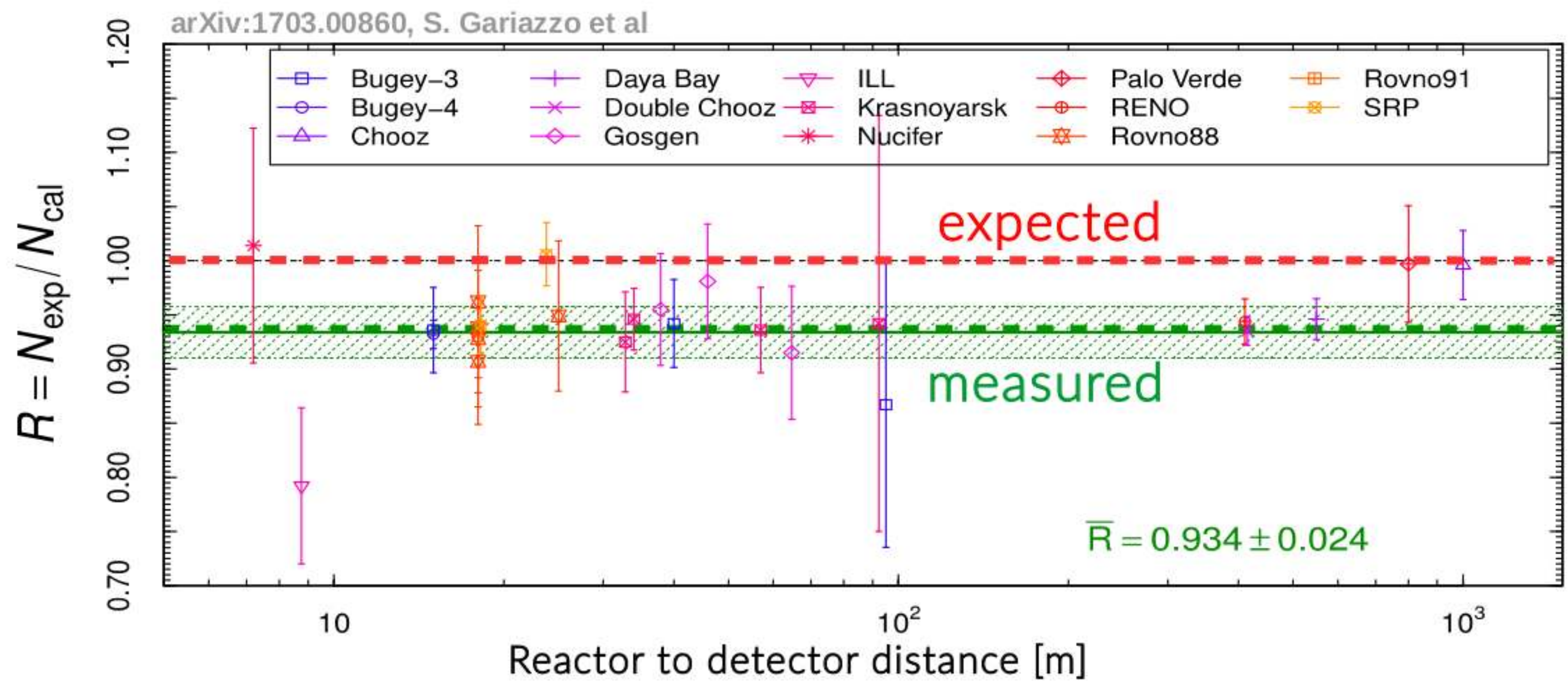




Valerio D'Andrea, LEGEND

- LEGEND aims at sensitivity of 10^{27} yr and neutrino effective mass limit of ~10 meV

isotope	$T^{0\nu}_{1/2}$ [10^{25} yr]	$S^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]	experiment
^{76}Ge	9	11	104–228	GERDA
^{76}Ge	2.7	4.8	157–346	MAJORANA
^{130}Te	1.5	0.7	162–757	CUORE
^{136}Xe	1.8	3.7	93–287	EXO-200
^{136}Xe	10.7	5.6	76–234	KamLAND-Zen

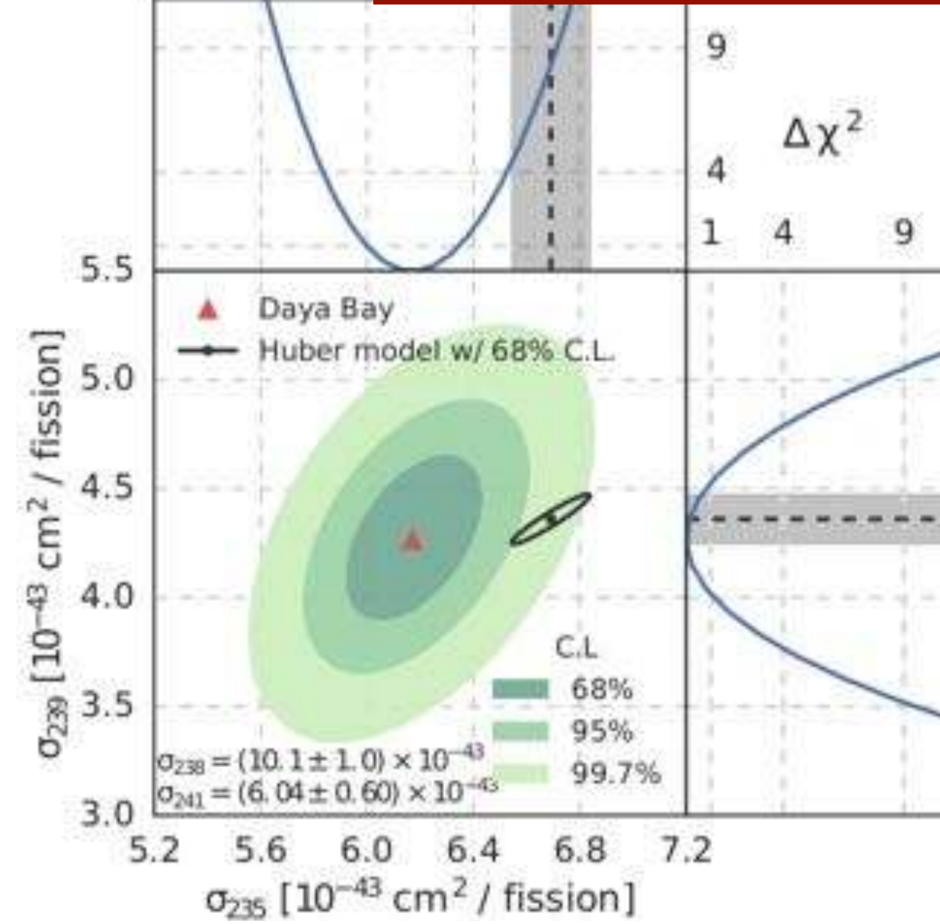


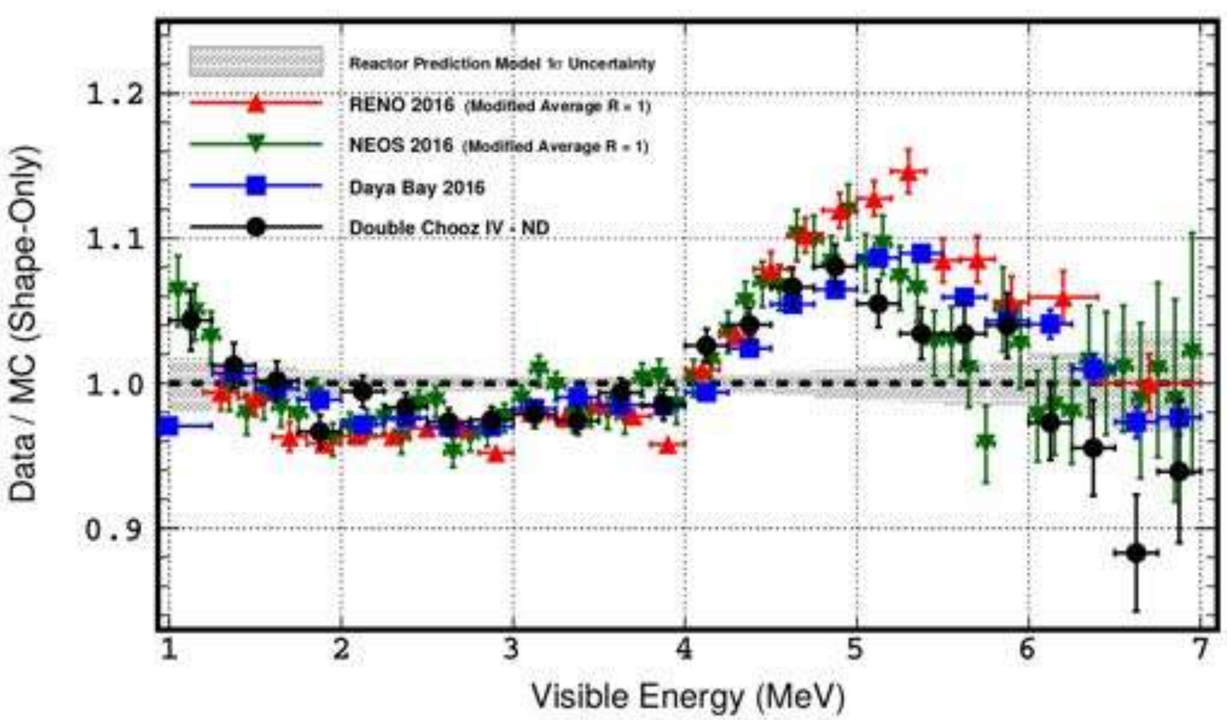
Reactor Anti-Neutrino Flux Anomaly (RAA)

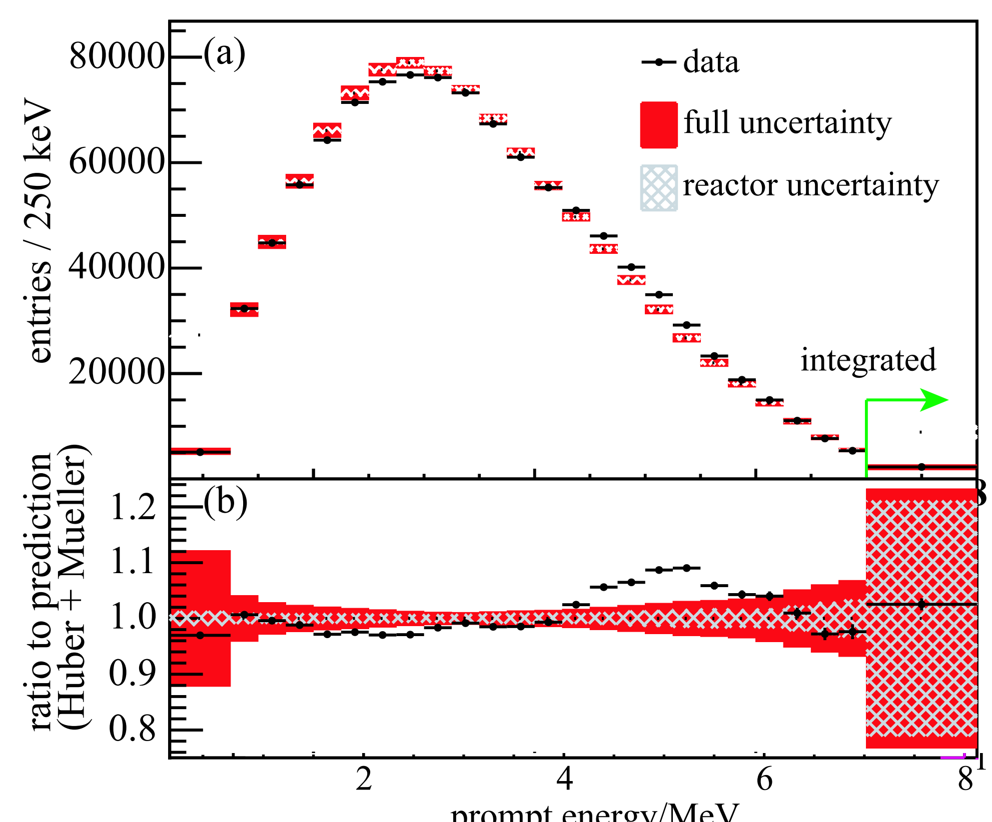
Flux Anomaly at Daya Bay

Liang Zhan, Daya Bay
Jianrun Hu, Daya Bay

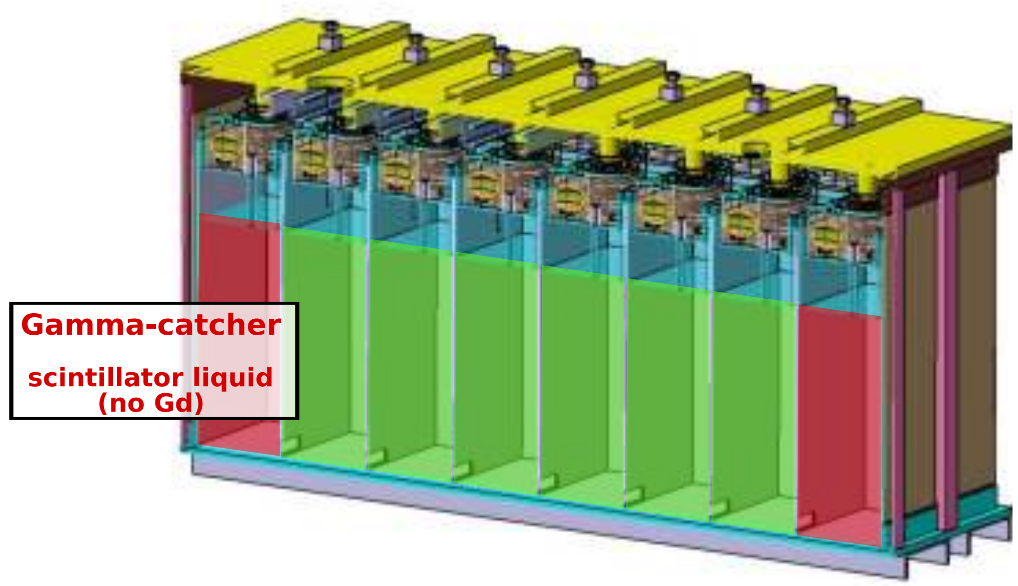
- Day Bay confirms 5% deficit in flux of anti-neutrinos WRT Huber-Mueller expectation
- Fuel composition of 4 primary isotopes: ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu
  - ^{235}U believed to be the largest contribution
    - Typically makes up 50-60% of fuel
  - but composition evolves in time
- In addition, investigating discrepancy also in spectral shape of prompt energy around 4-6 MeV
  - reported also by other experiments







RAA with STEREO at Grenoble



- Probe anomaly through measurement of distortion of anti-neutrino energy spectrum as a function of distance
  - independent from prediction
- Spectral shape: significant deviation in the 6-7 MeV range to be investigated with more data and complementary experiments
- Best-fit hypothesis of Sterile neutrino preferred by RAA rejected at ~99.8% C.L.

RAA with PROSPECT at Oak Ridge

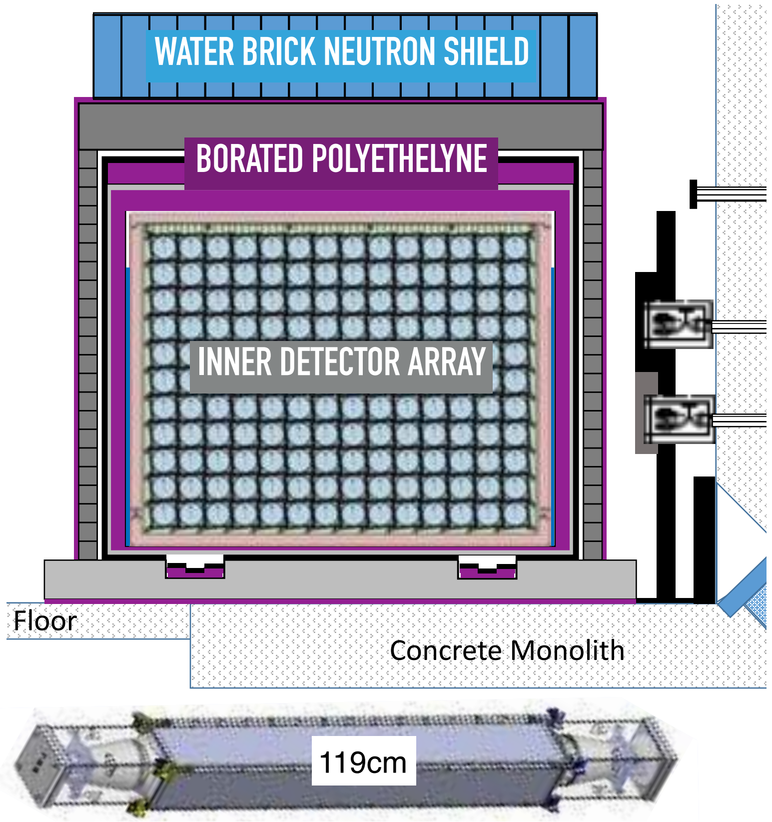
>99% of flux from ^{235}U

Single 4,000 L **^{6}Li-loaded liquid scintillator** (3,000 L fiducial volume)

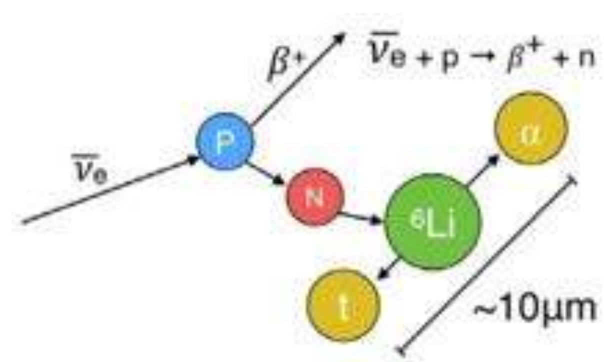
11 x 14 (154) **array of optically separated segments**

Very low mass separators (1.5 mm thick)
Corner support rods allow for full *in situ* calibration access

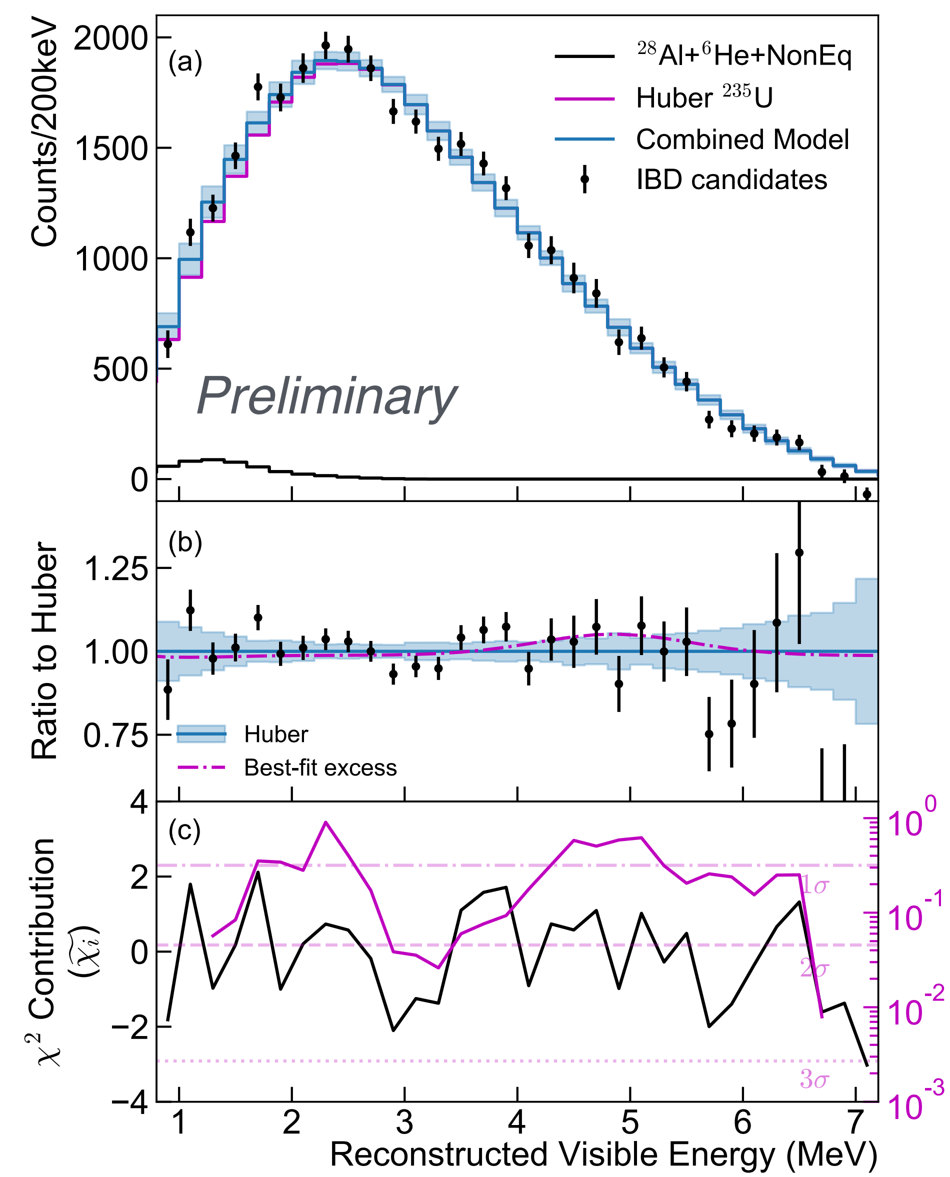
Double ended PMT readout, with light concentrators
good light collection and energy response
~5%√E energy resolution
full X,Y,Z event reconstruction

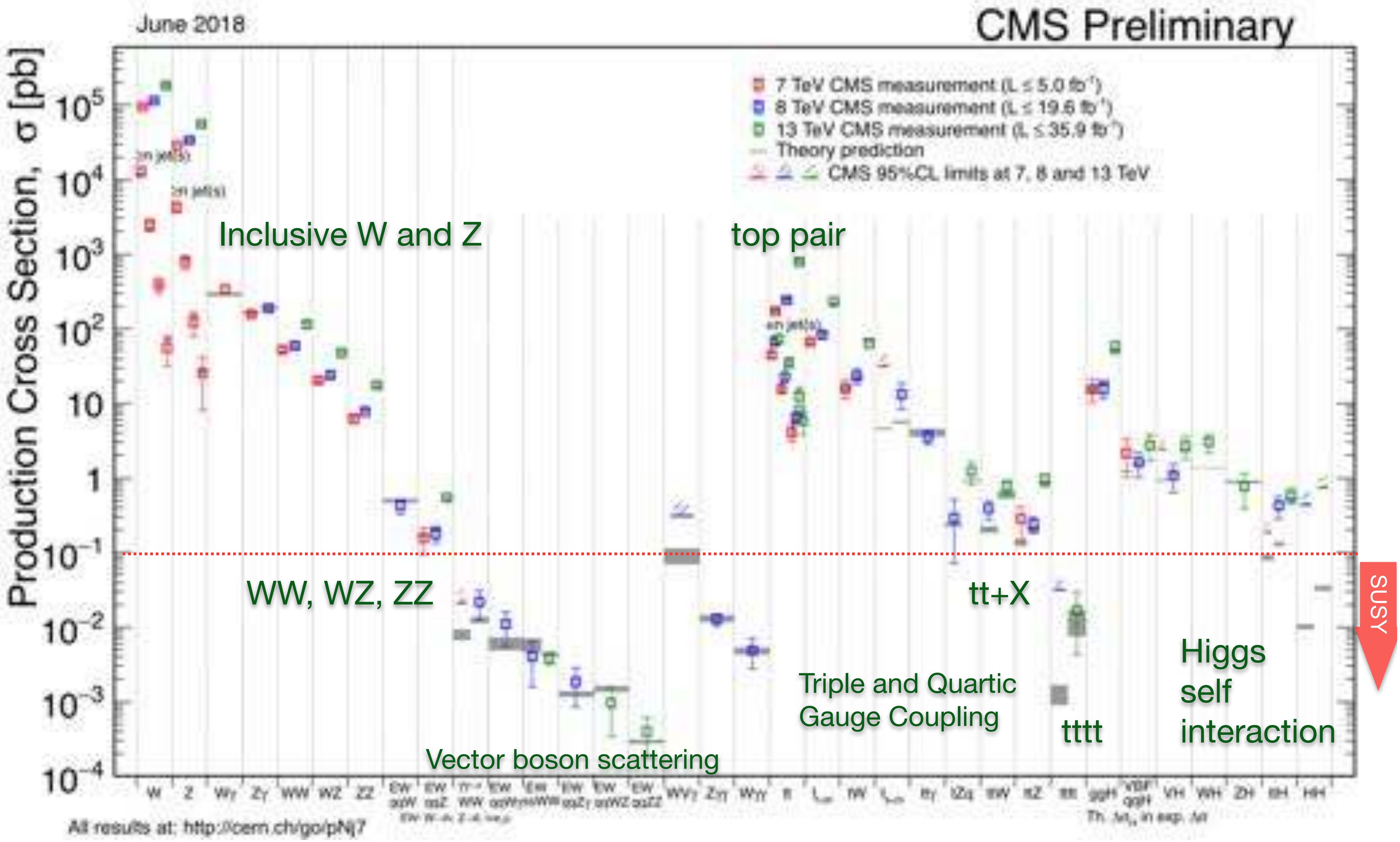


Karsten Heeger , PROSPECT



- Same approach as STEREO via spectral distortion
- Spectral shape: Huber model broadly agrees with spectrum but exhibits large chi2 and not a good fit
- Best-fit hypothesis of Sterile neutrino preferred by RAA disfavoured at >95% C.L.





Standard Model

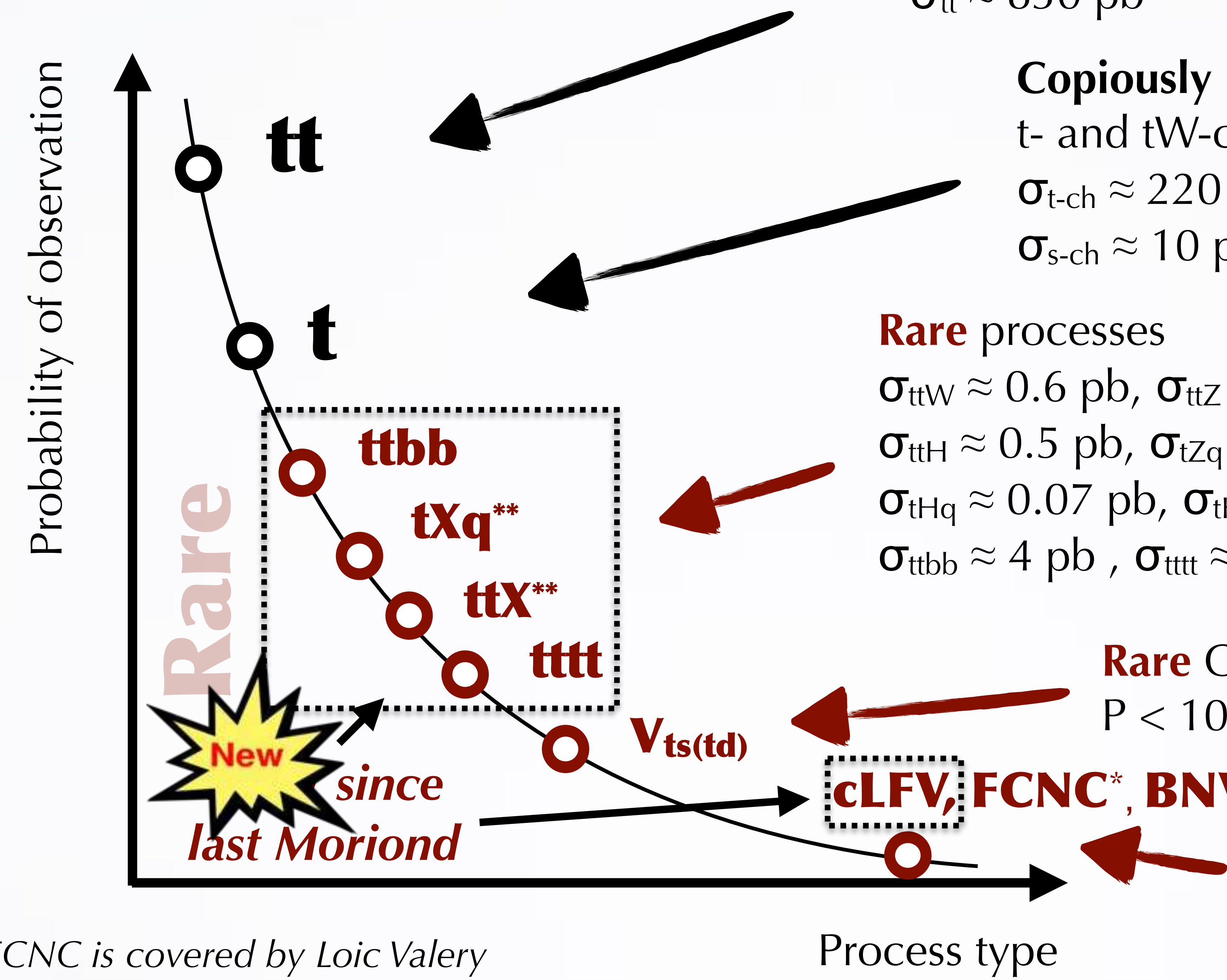
New Physics through Precision

Precision top physics

▹ LHC is a top factory

Kiril Skovpen, CMS

The LHC world @13TeV



Most abundant production mechanism of top quarks $\sigma_{tt} \approx 830$ pb

Copiously produced via t- and tW-channels $\sigma_{t\text{-}ch} \approx 220$ pb, $\sigma_{tW\text{-}ch} \approx 70$ pb, $\sigma_{s\text{-}ch} \approx 10$ pb

Rare processes
$\sigma_{ttW} \approx 0.6$ pb, $\sigma_{ttZ} \approx 0.8$ pb, $\sigma_{tt\gamma} \approx 0.2$ pb,
$\sigma_{ttH} \approx 0.5$ pb, $\sigma_{tZq} \approx 1$ pb, $\sigma_{t\gamma q} \approx 3$ pb,
$\sigma_{tHq} \approx 0.07$ pb, $\sigma_{tHW} \approx 0.02$ pb,
$\sigma_{ttbb} \approx 4$ pb , $\sigma_{tttt} \approx 0.01$ pb

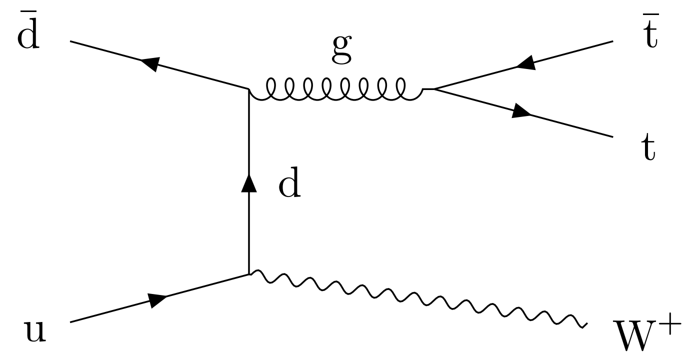
Rare CKM-suppressed decays
$P < 10^{-3}$

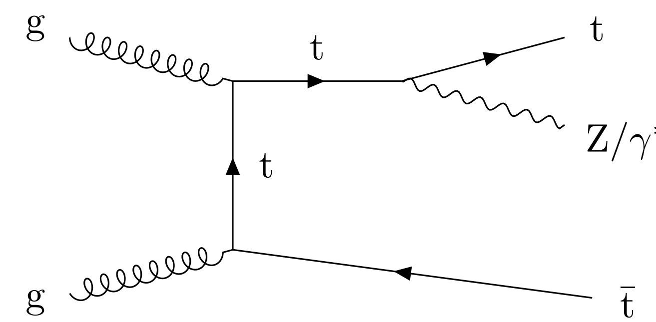
Not reachable at the LHC
$P_{FCNC} < 10^{-12}$
$P_{BNV} < 10^{-27}$
$P_{cLFV} < 10^{-55}$

(*) *FCNC is covered by Loic Valery*
(**) *Higgs results are covered by Stephane Cooperstein*

Top agreement with theory

- Cross section of ttbar + V measured by both experiments with 2016 data





CMS

14% precision

$\sigma(t\bar{t}Z) = 0.99^{+0.09}_{-0.08}\,(\text{stat})^{+0.12}_{-0.10}\,(\text{syst})\,\text{pb}$

$\sigma(t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})\,\text{pb}$ 22% precision

Good agreement with NLO predictions

2019/03/17 Kirill Skovpen - Moriond EW 2019

ATLAS

$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08_{\text{stat.}} \pm 0.10_{\text{syst.}}\,\text{pb}$ 13% precision

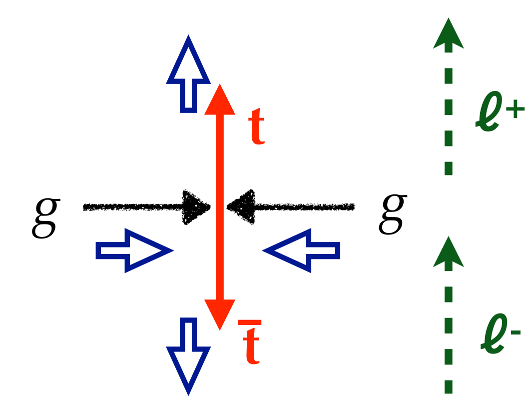
$\sigma_{t\bar{t}W} = 0.87 \pm 0.13_{\text{stat.}} \pm 0.14_{\text{syst.}}\,\text{pb}$ 22% precision

Good agreement with NLO predictions

- Differential cross section of ttZ now better precision than NLO calculations

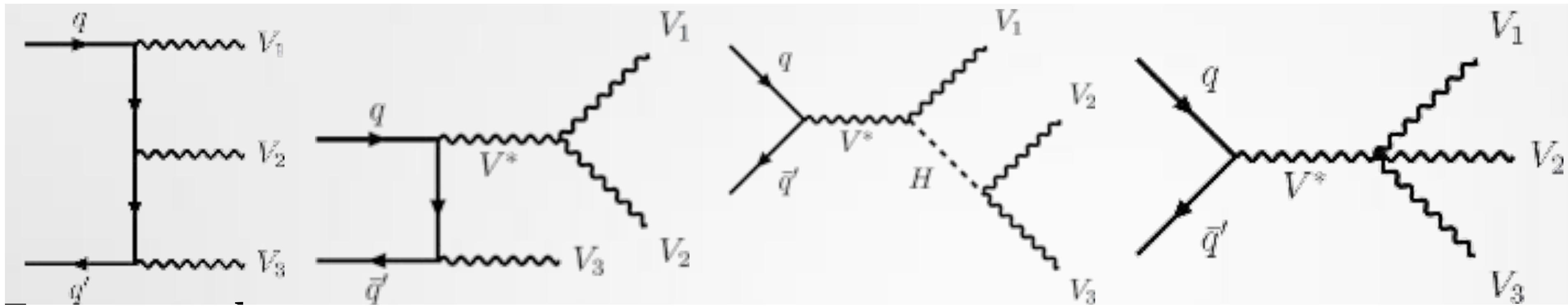
- tt+bb production now exceeding theoretical knowledge!
  - Important background in study of top-Higgs Yukawa coupling

- Top spin correlations also provide valuable comparison with theory
  - NNLO predictions needed to mitigate discrepancies up to 3σ wrt simulations

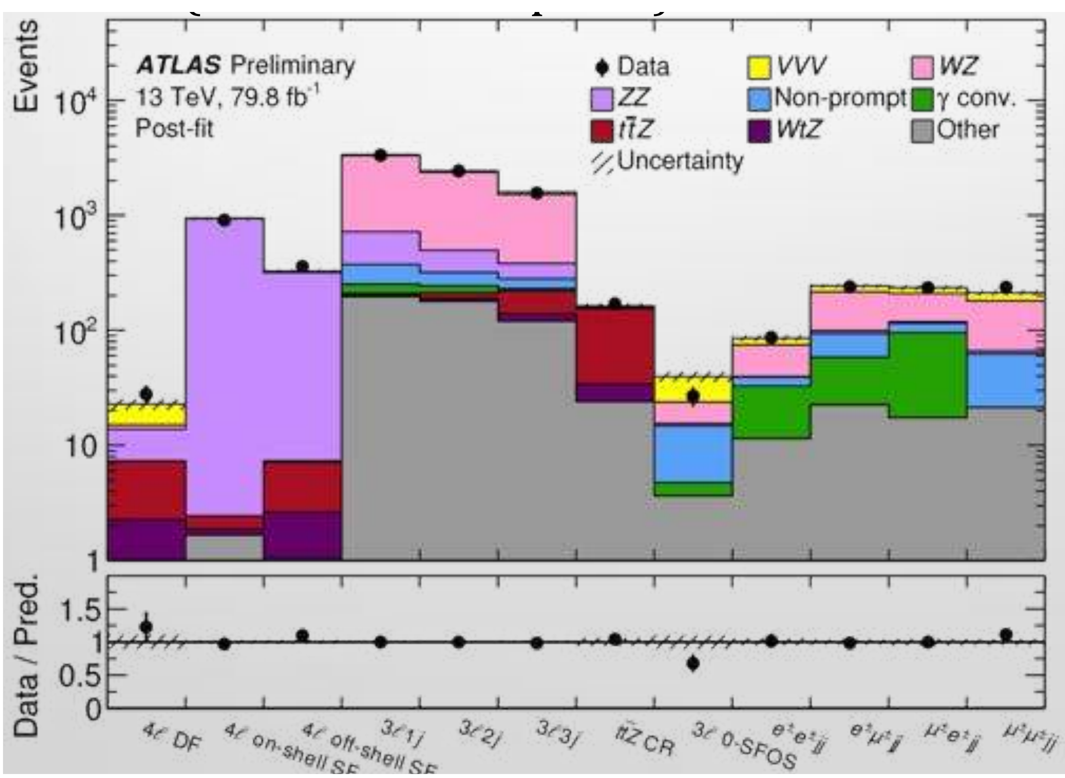


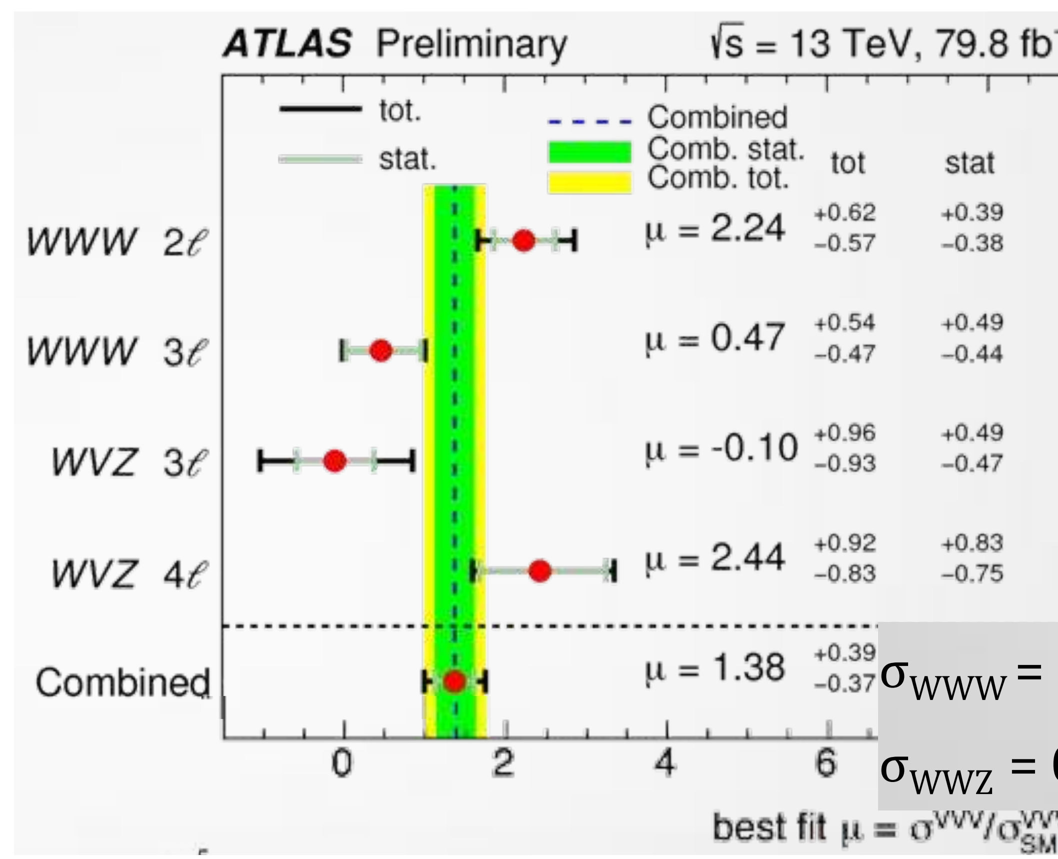
Jacob Linacre, CMS

Triple Gauge Boson Production



- Search at ATLAS (79 fb^{-1}) and CMS (36 fb^{-1}) for WWW in final states with 3 leptons or at least 2 same-sign leptons + jets
  - ATLAS also considering WWZ and WZZ and reporting first evidence for VVV





$\sigma_{WWW} = 0.68\,^{+0.23}_{-0.21}$ pb

$\sigma_{WWZ} = 0.49\,^{+0.20}_{-0.18}$ pb

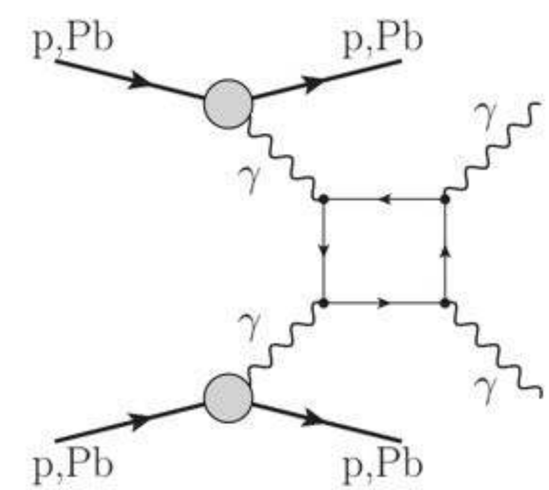
- *Multiboson domain finally accessible thanks to high luminosity of LHC*

Aleksandra Dimitrievska, ATLAS

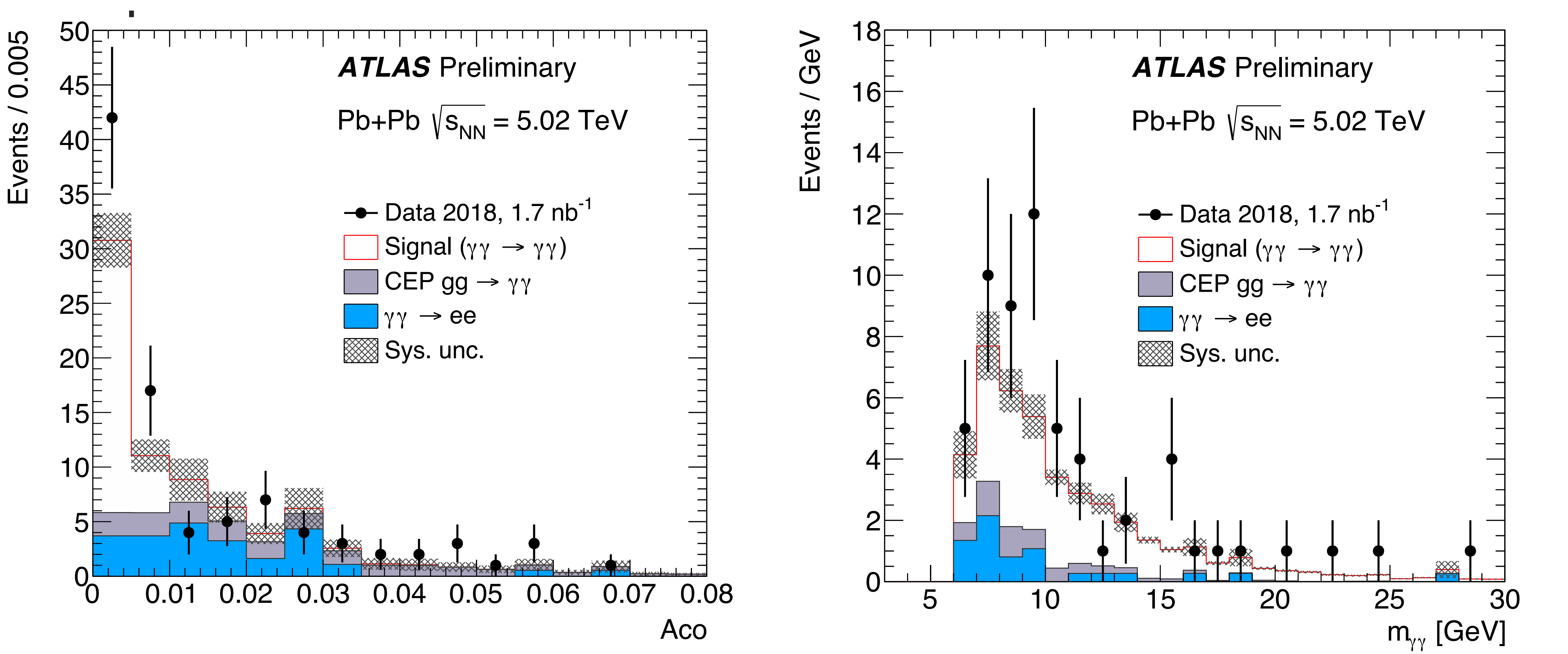
Alberto Belloni, CMS

Observation of Light-by-Light Scattering

- Forbidden process at tree level enhanced in Pb-Pb collisions
  - Cross section proportional to Z^4
  - Another probe of anomalous gauge couplings and BSM contributions
  - Evidence had been reported already



- First observation by ATLAS in collisions recorded in Nov 2018
  - better trigger and enhanced identification of photons

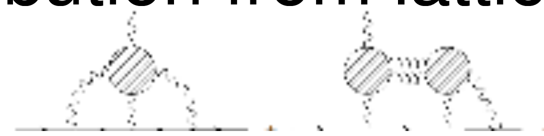


σ_{ATLAS} = 78 ±13 (stat) ±8 (sys) nb

SM predictions: **49 ±5 nb**

Mateusz Dyndal, ATLAS

Hadronic light by light contribution from lattice QCD

Blum 

Experiment - Theory

SM Contribution	Value ± Error ($\times 10^{11}$)	Ref	notes
QED (5 loops)	116584718.951 ± 0.080	[Aoyama et al., 2012]	
HVP LO	6931 ± 34	[Davier et al., 2017]	$\to 3.5\sigma$
	6932.6 ± 24.6	[Keshavarzi et al., 2018]	$\to 3.7\sigma$
	6925 ± 27	[Blum et al., 2018]	lattice+R-ratio (FJ17), $\to 3.7\sigma$
HVP NLO	-98.2 ± 0.4	[Keshavarzi et al., 2018]	
		[Kurz et al., 2014]	
HVP NNLO	12.4 ± 0.1	[Kurz et al., 2014]	
HLbL	105 ± 26	[Prades et al., 2009]	
HLbL (NLO)	3 ± 2	[Colangelo et al., 2014]	
Weak (2 loops)	153.6 ± 1.0	[Gnendiger et al., 2013]	
SM Tot	116591820.5 ± 35.6	[Keshavarzi et al., 2018]	
Exp (0.54 ppm)	116592080 ± 63	[Bennett et al., 2006]	
Diff (Exp − SM)	259.5 ± 72	[Keshavarzi et al., 2018]	$\to 3.7\sigma$

main messages: QCD errors dominate, Δ HLbL ∼ Δ HVP, discrepancy is large

FNAL E989 running, goal to reduce BNL 821 error by 1/4

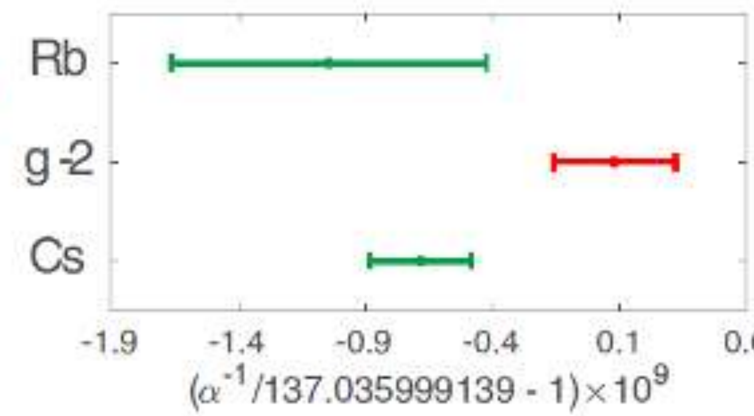
"Prel. QED$_L$ $a \to 0, L \to \infty$ limits taken; QED$_\infty$ w.i.p. Unlikely that HLBL will rescue SM"

- Last year:
  - New measurement of α in **Cs** Parker et al. 2018

$$a_e^{\text{exp}} = 1{,}159{,}652{,}180.73(28) \times 10^{-12}$$

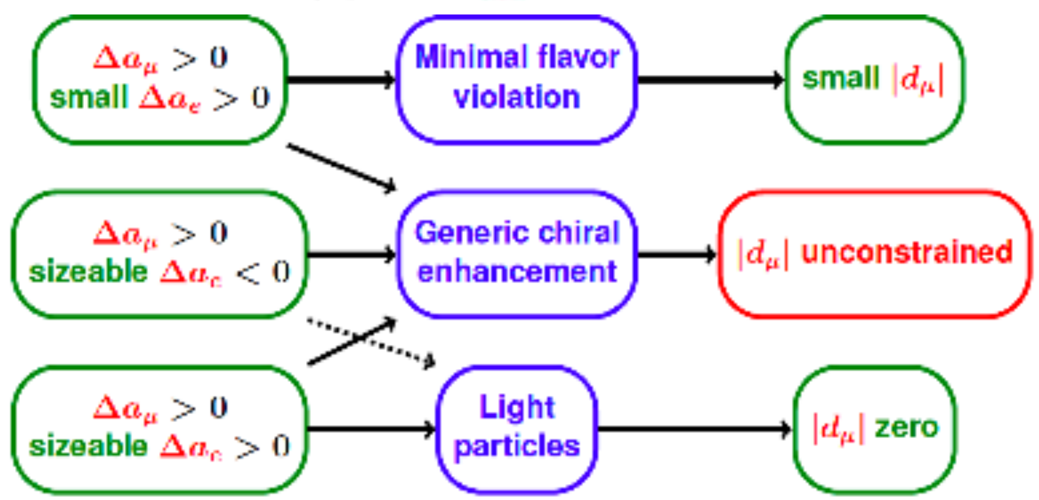
$$a_e^{\text{SM}} = 1{,}159{,}652{,}181.61(23) \times 10^{-12}$$

$$\hookrightarrow \Delta a_e = -0.88(36) \times 10^{-12}\ [2.5\sigma]$$

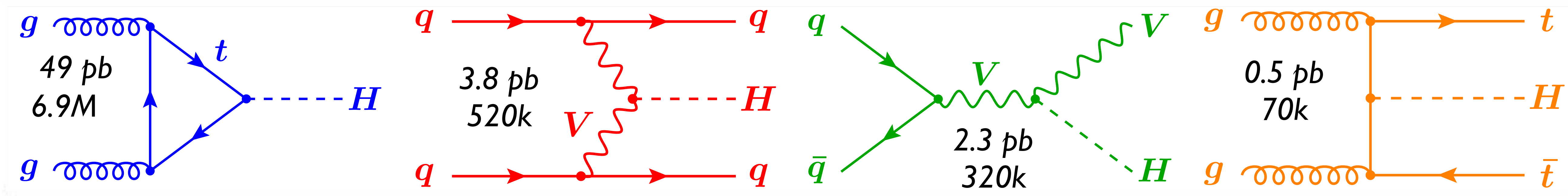


  - Dominant uncertainty now in a_e^{exp}

Hoferichter

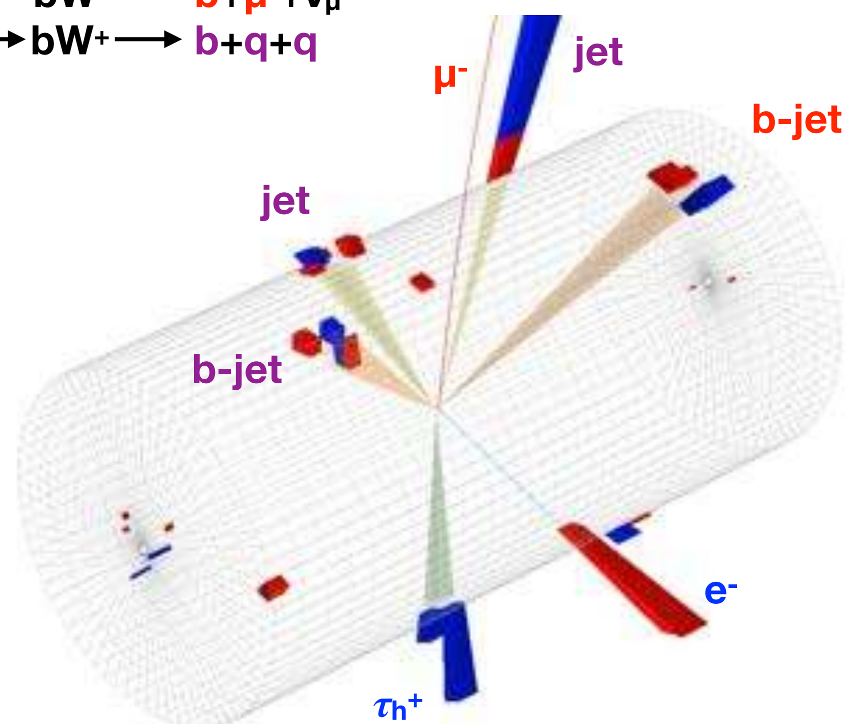


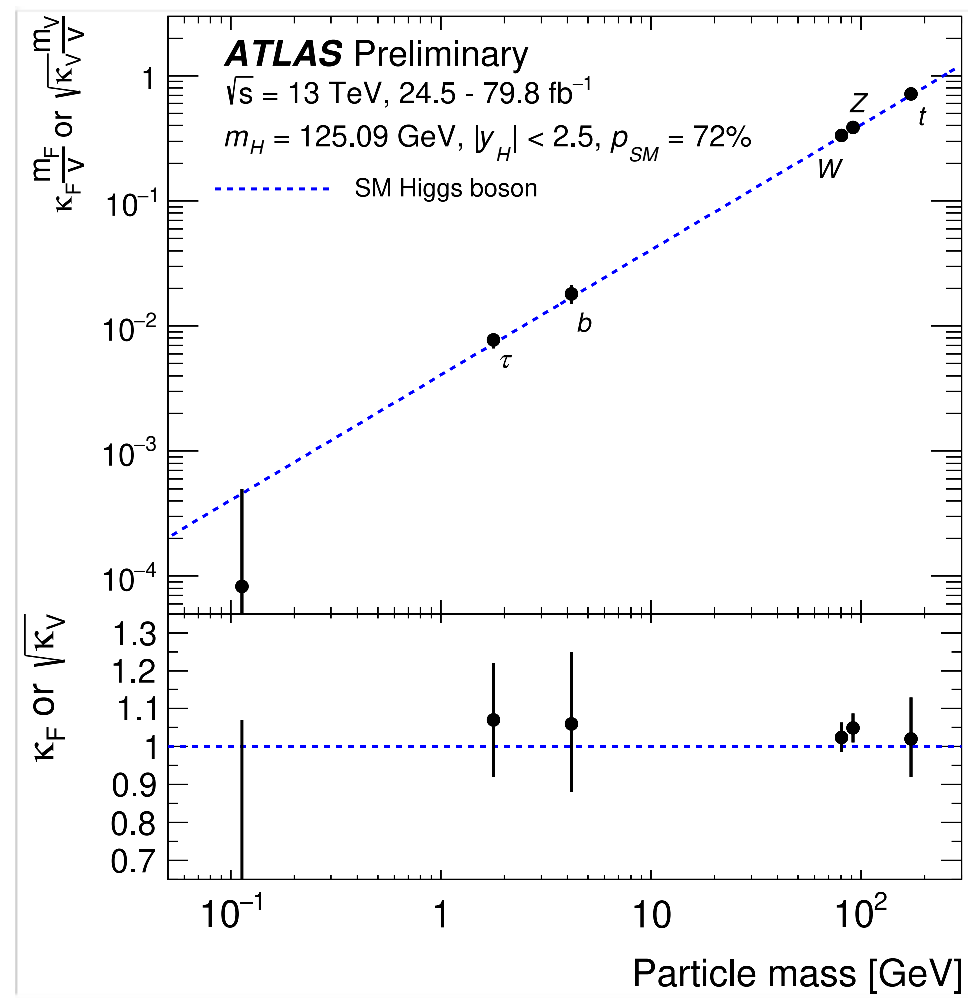
Note, $\Delta a_\mu > 0$; possible correlation with $\mu \to e\gamma$, and muon EDM. ”[Model with VL fermions] works for a_e but tensions with a_μ”. Modification with extra scalar (for a_μ) and a_e from Higgs work – interesting lepton flavor structure beyond $(m_e/m_\mu)^n$ scaling Hormigos



σ [pb]
#Higgs produced during Run-2

pp → t$\bar{t}$H
→ ττ → $e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$
→ $\bar{b}W^-$ → $\bar{b} + \mu^- + \bar{\nu}_\mu$
→ bW^+ → b+q+q





Higgs

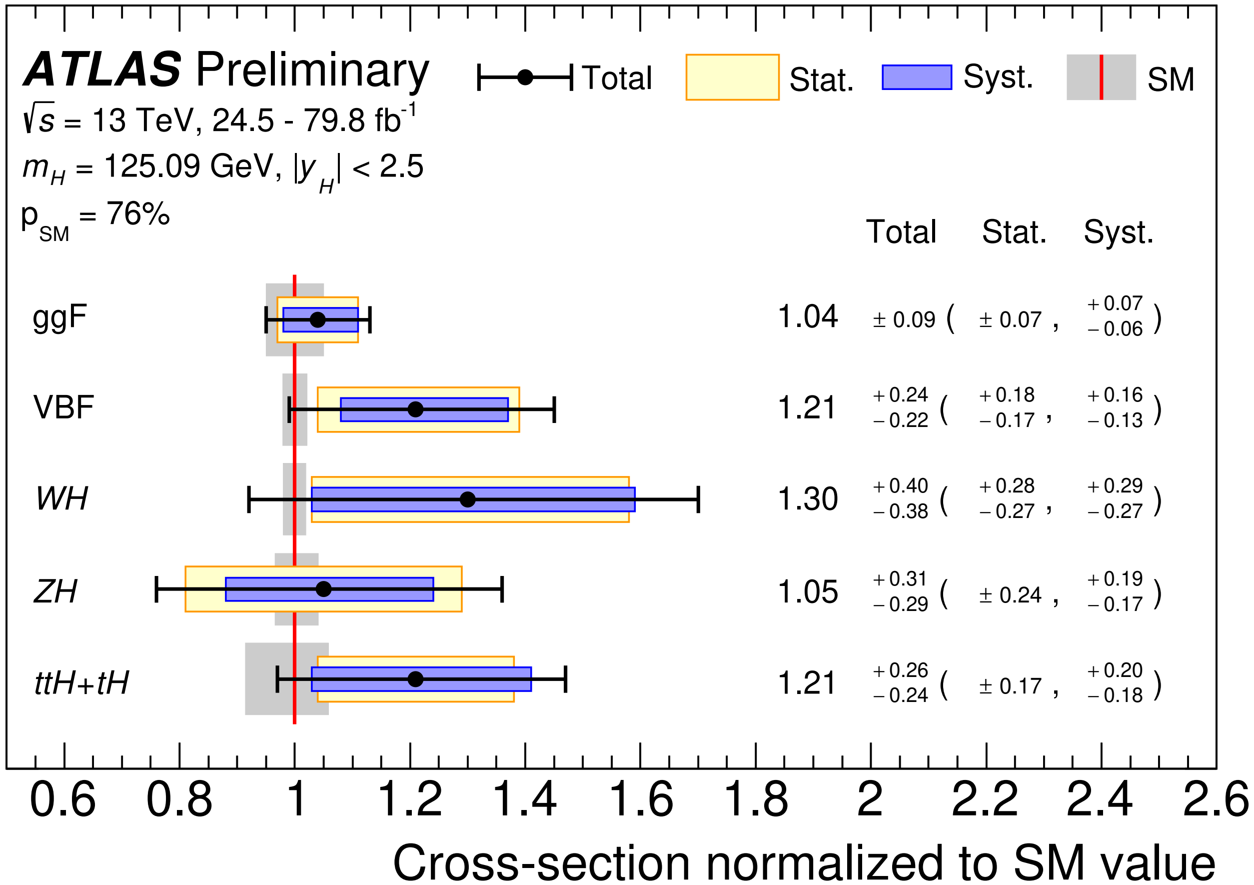
From Discovery to Precision

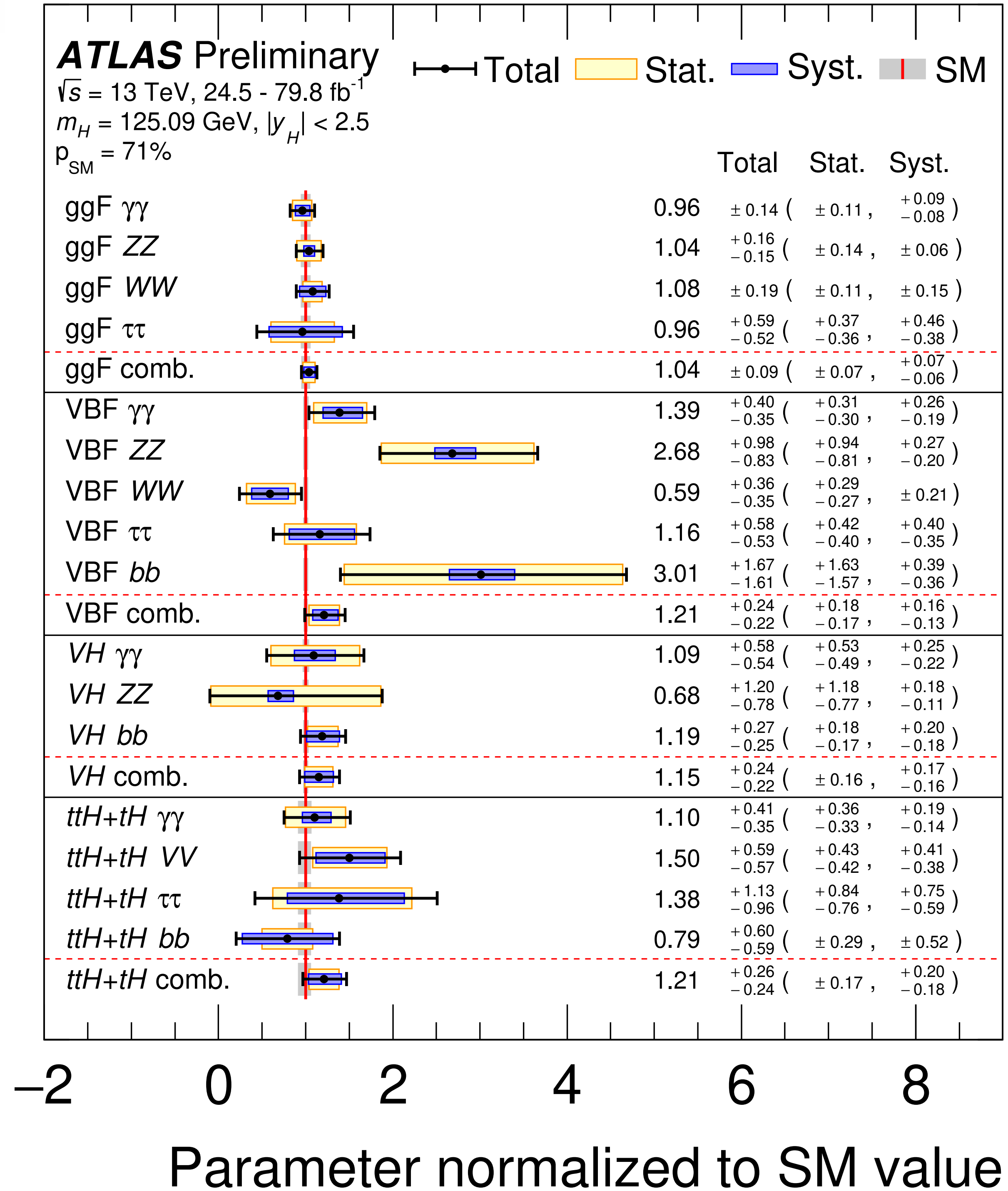
$Y_{ij}\psi_i\psi_j\phi$

Higgs Properties

Heather Gray, ATLAS

- Similar performance for ATLAS and CMS





- Experimental precision approaching theory precision even before using full statistics of Run2

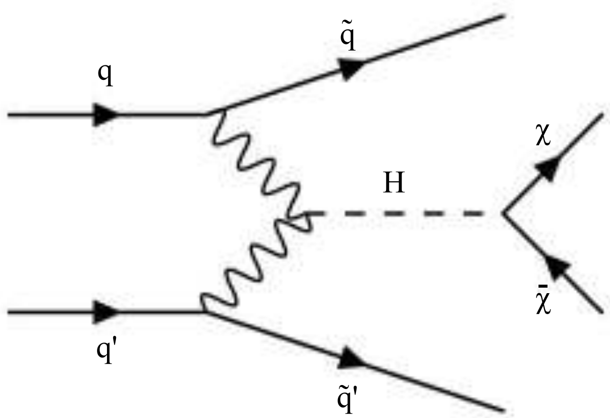
$$\sigma/\sigma_{SM} = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.})\,^{+0.03}_{-0.03}\,(\text{bkg. th.})$$

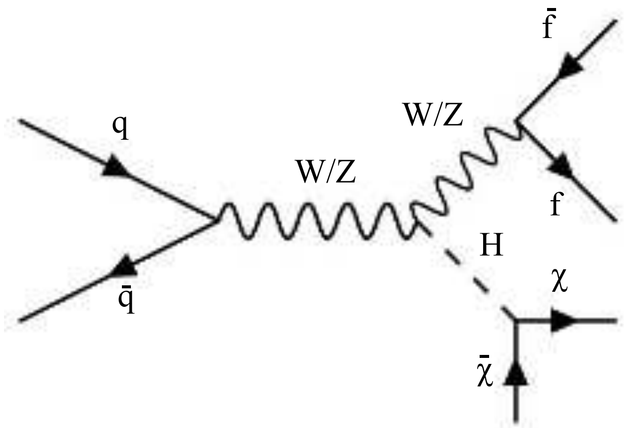
- Also extensive measurement of differential cross sections

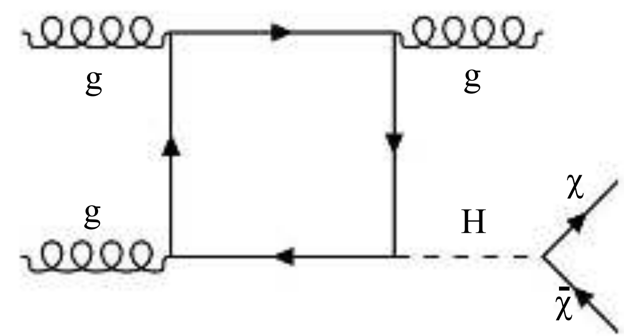
Yacine Haddad, CMS

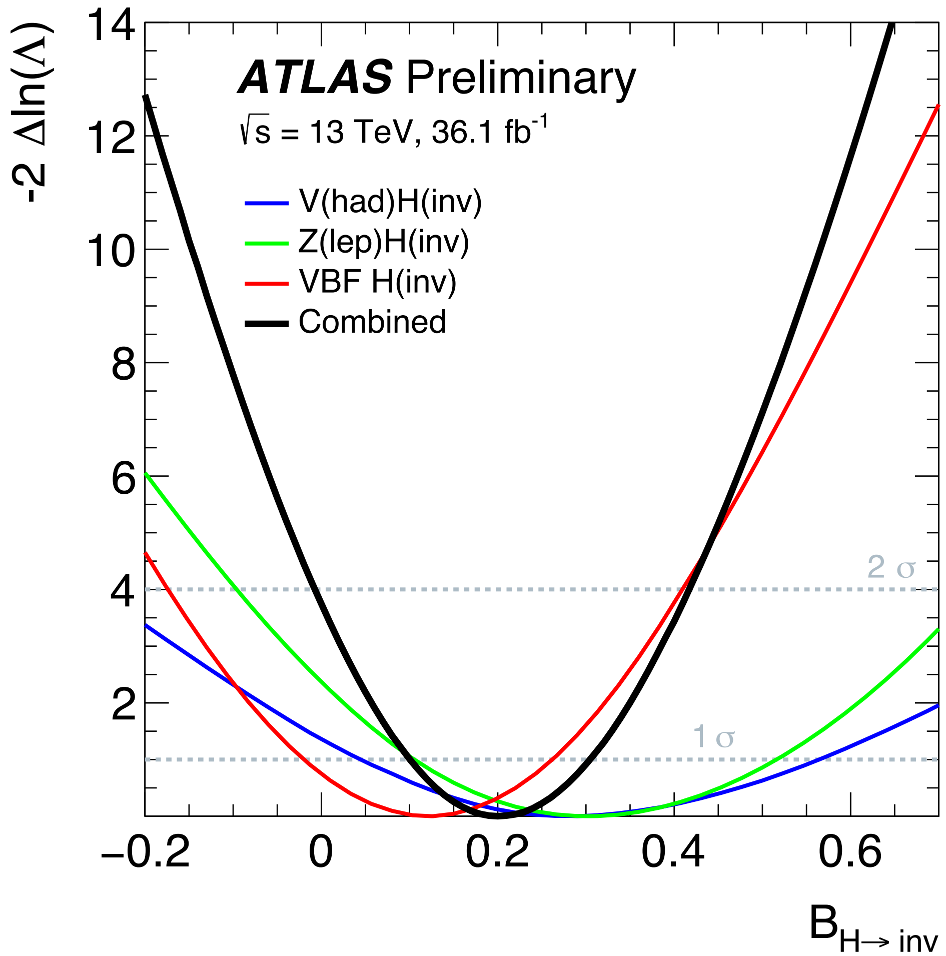
Fabio Cerutti, ATLAS

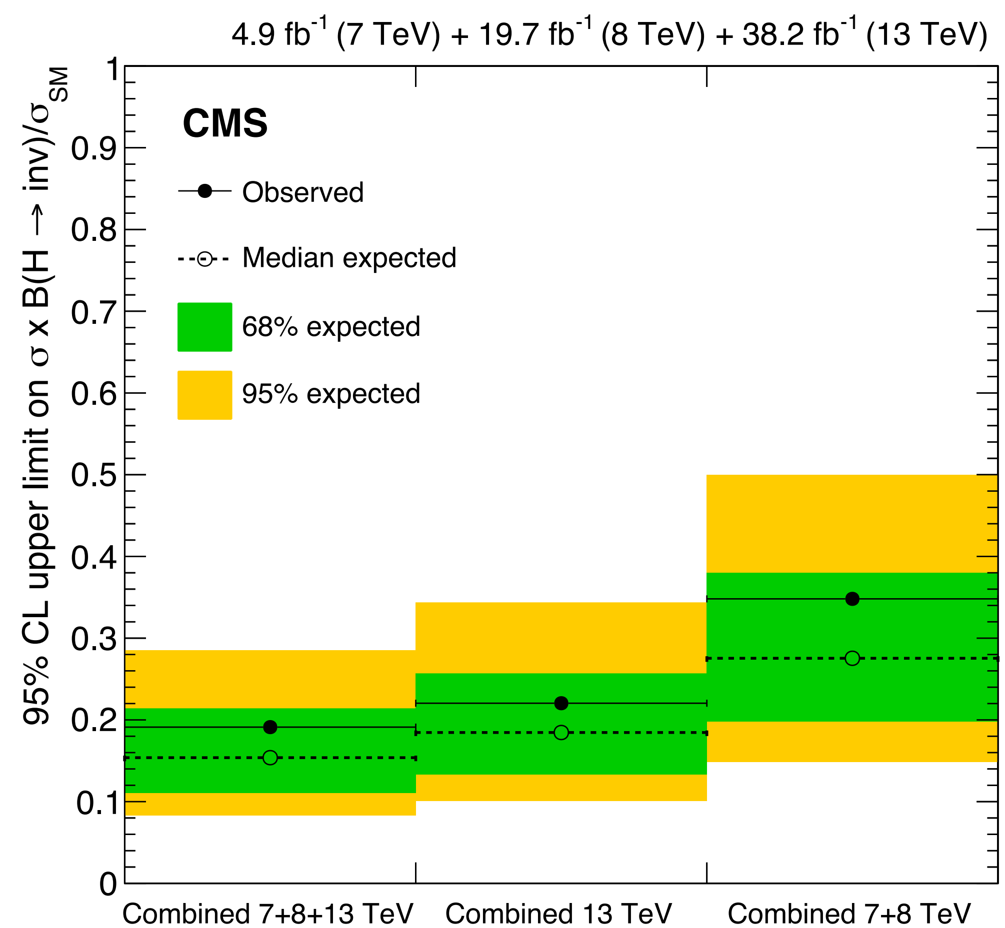
H → invisible







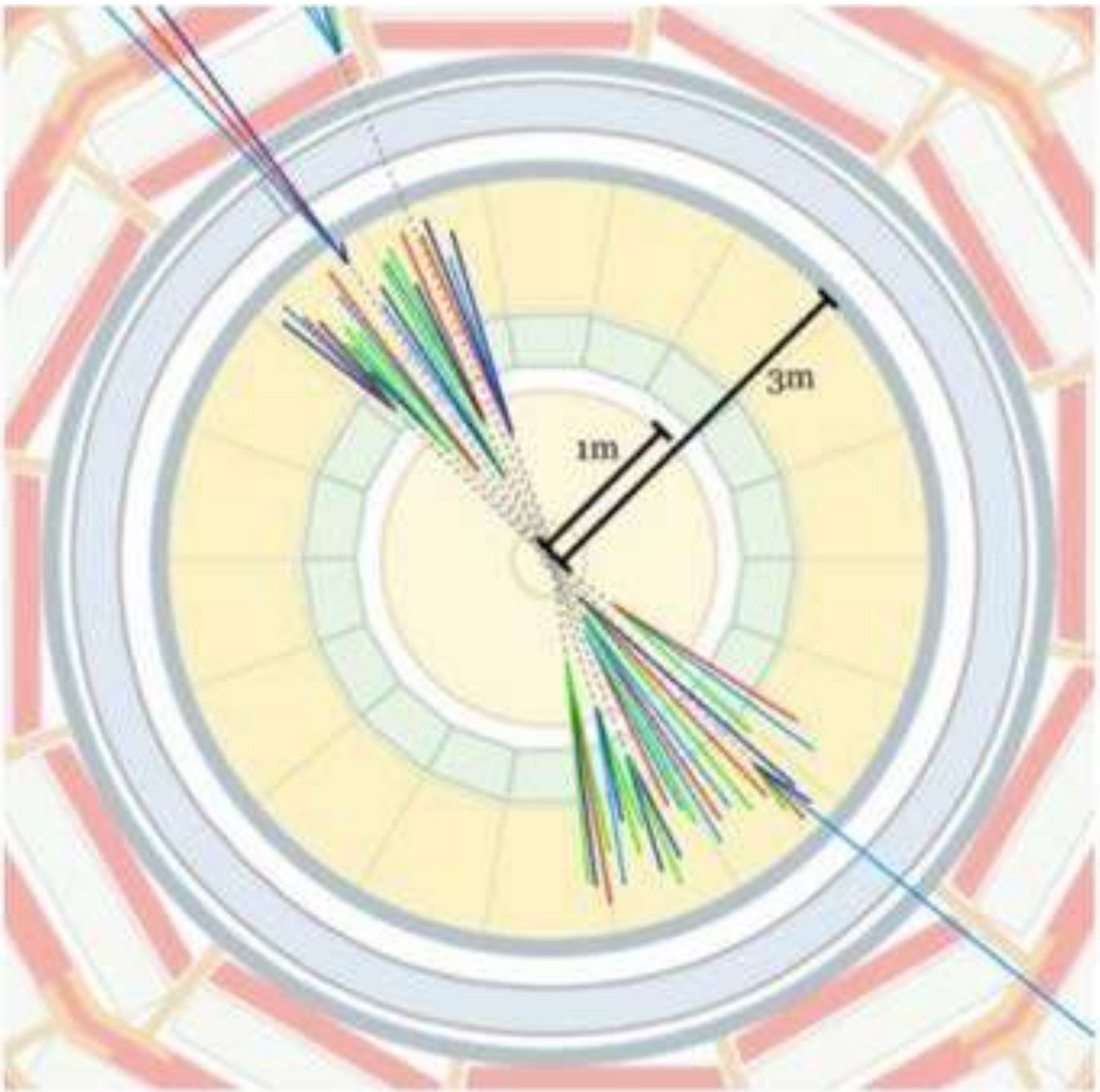


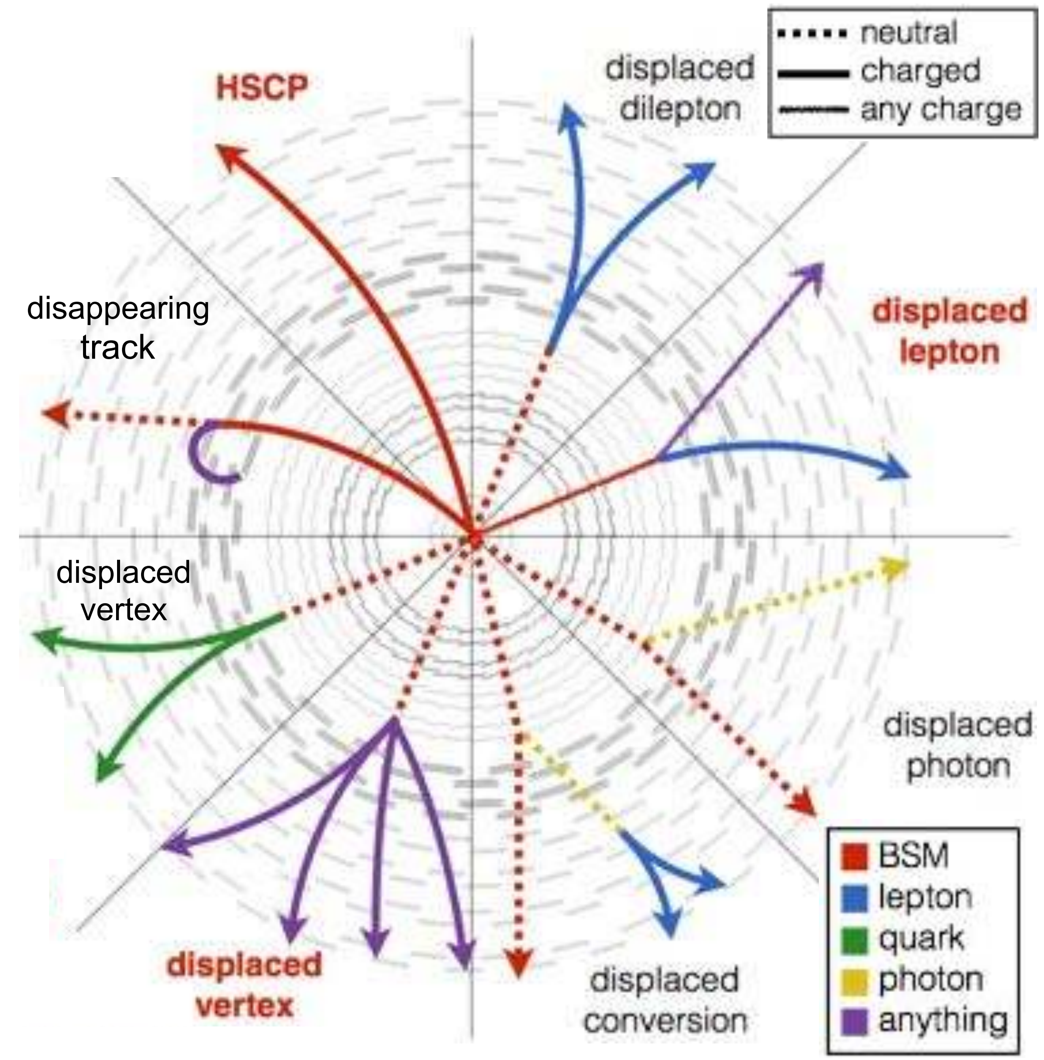


$B(H\rightarrow inv) < 0.26\ (0.17^{+0.07}_{-0.05})$ @ 95% CL

$B_{inv} < 0.19\ (0.15)$

- Aiming for 2-3% limit at High-Luminosity LHC with 3000 fb^{-1}



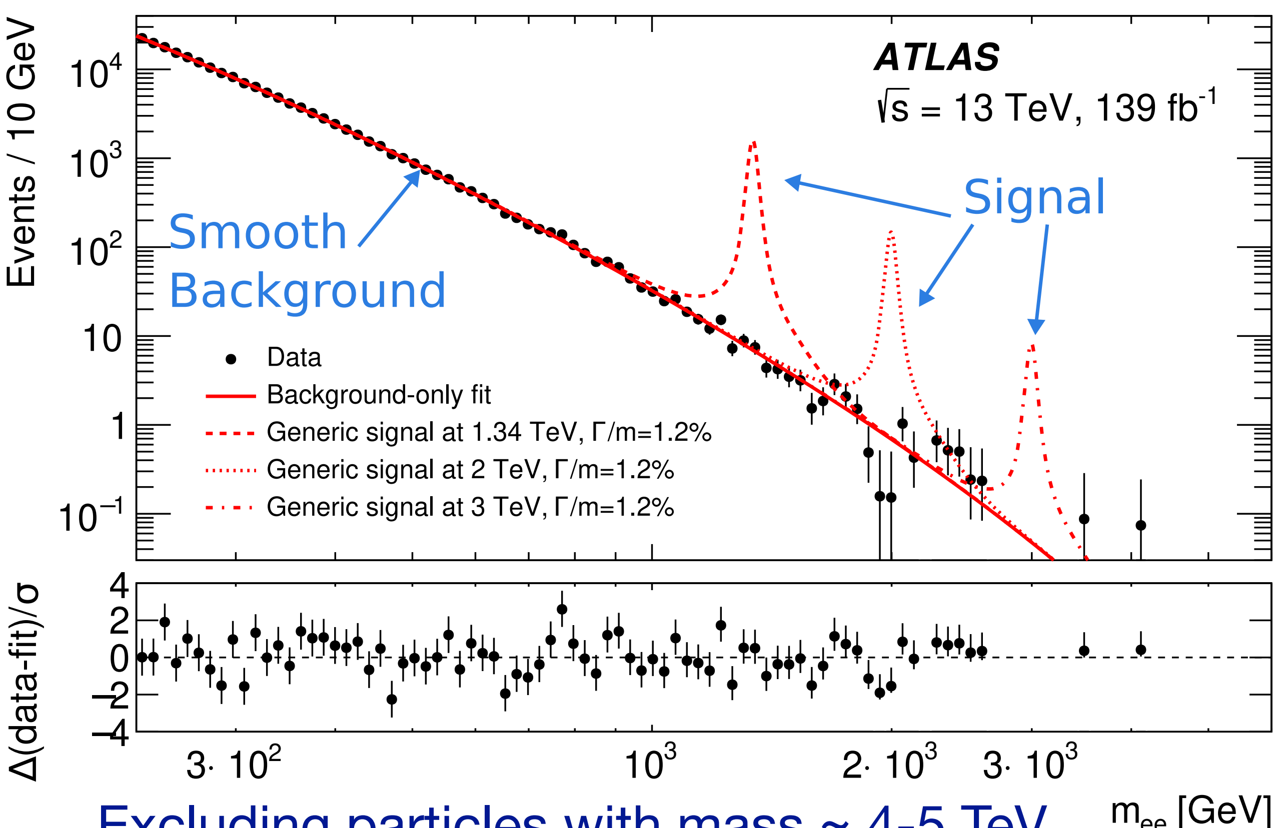


Credits: J. Antonelli

Exotic Phenomena

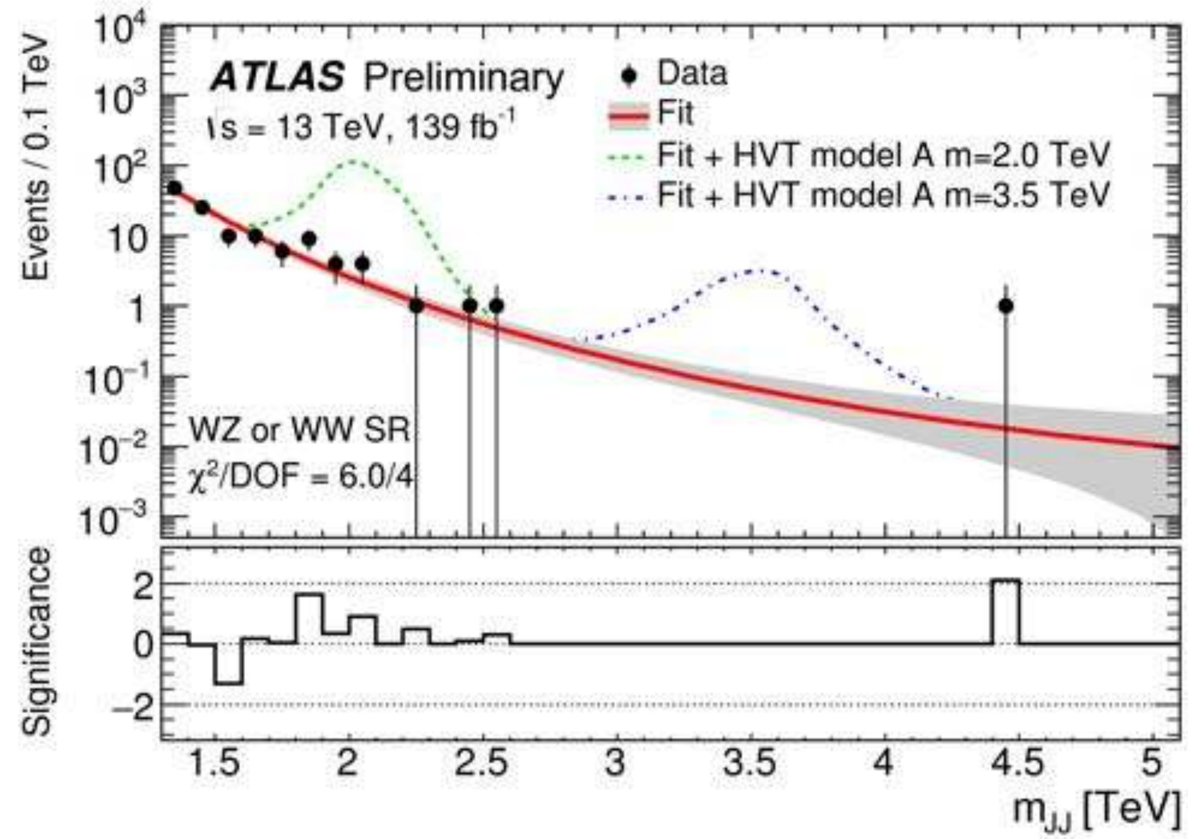
Heavy Resonances

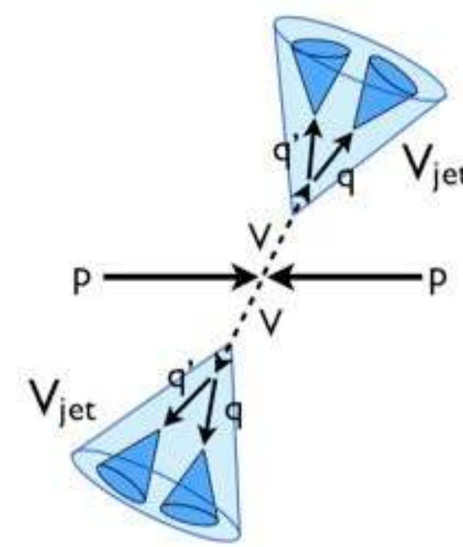
Z’ in dileptons



Excluding particles with mass ~ 4-5 TeV

Diboson resonance using boson tagging with substructure





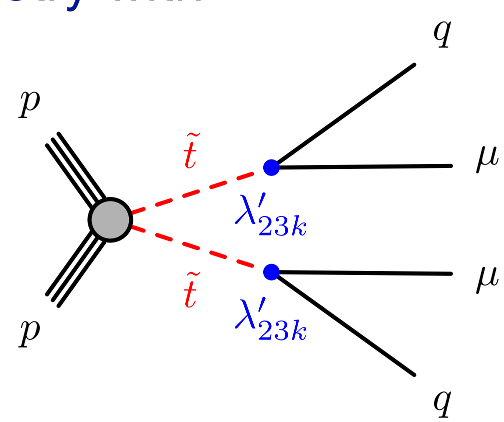
- Also updated ATLAS diet bump hunt with full Run2
  - Addition of full Run2 data extends exclusion limits by ”just” 700 GeV

Savanna Shaw, ATLAS

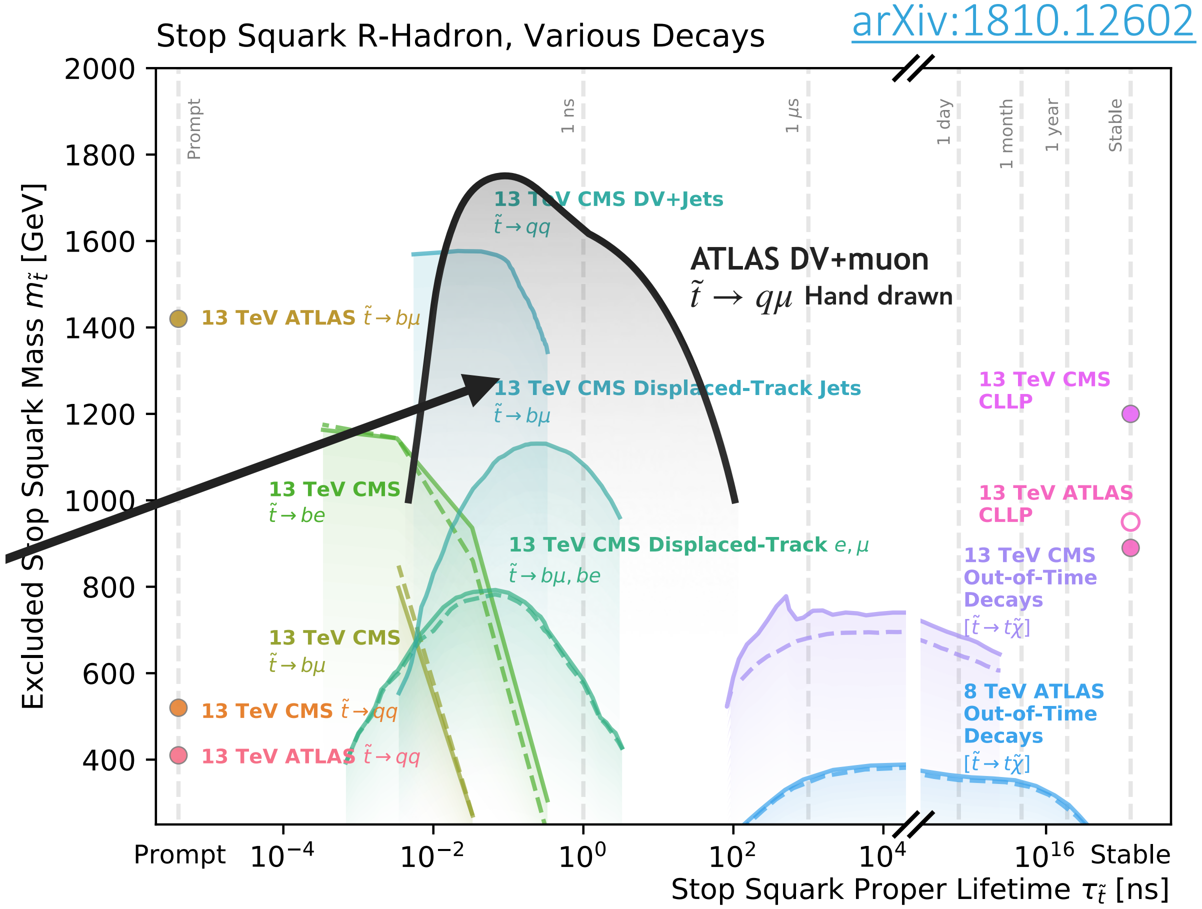
Alberto Zucchetta, CMS

Long-Lived Particles

Search for supersymmetry with displaced vertex



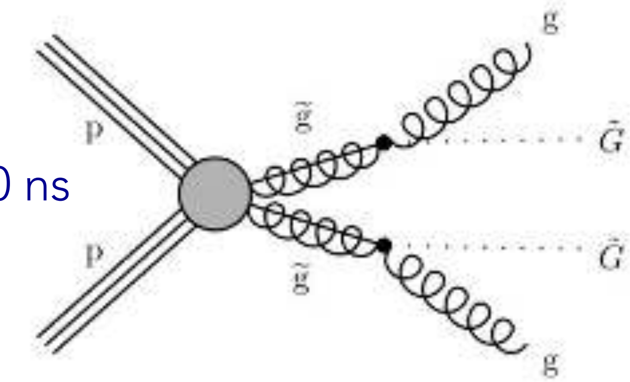
[arXiv:1810.12602]

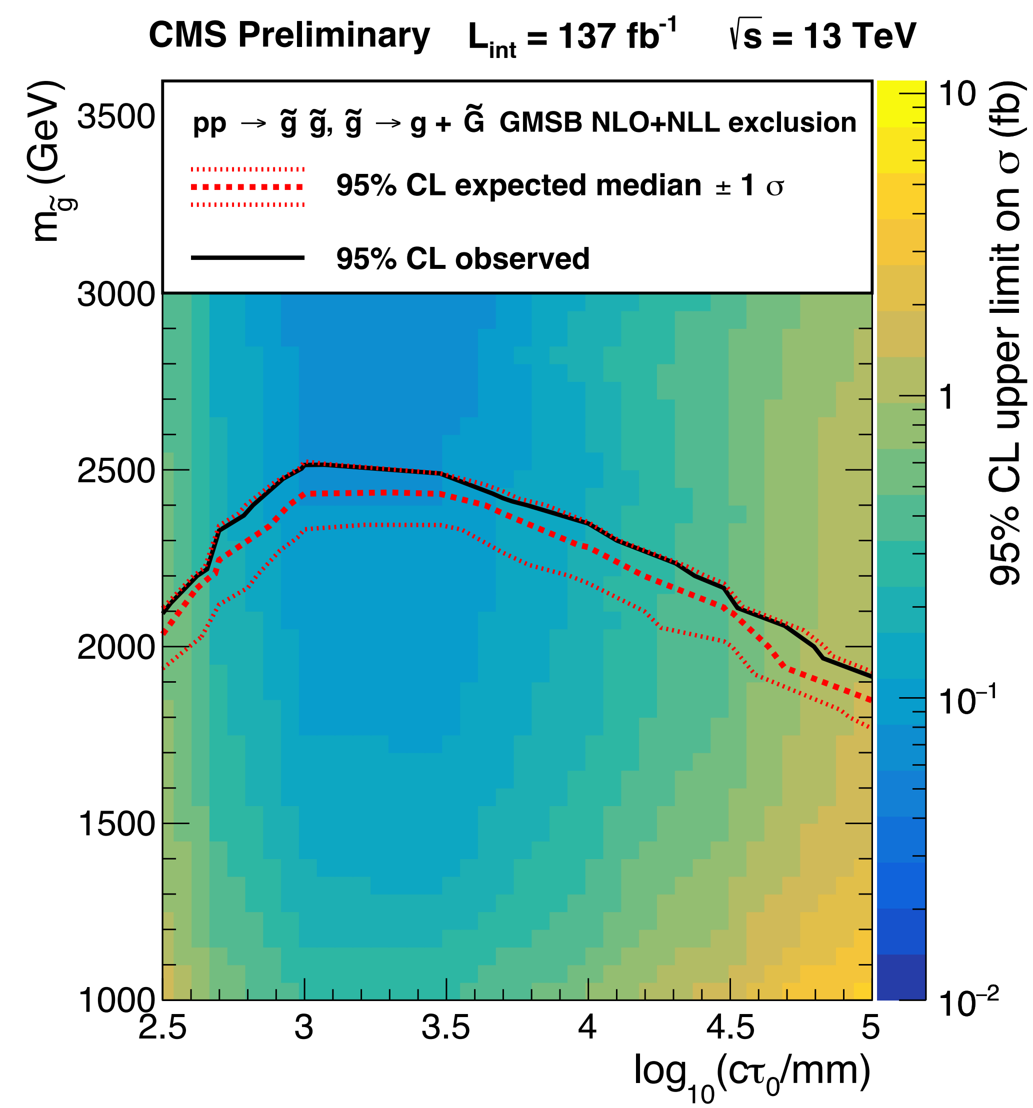


Nora Pettersson, Karri Folan DiPetrillo, ATLAS

Search for supersymmetry with delayed jets

3 ns < t_{jet} < 20 ns

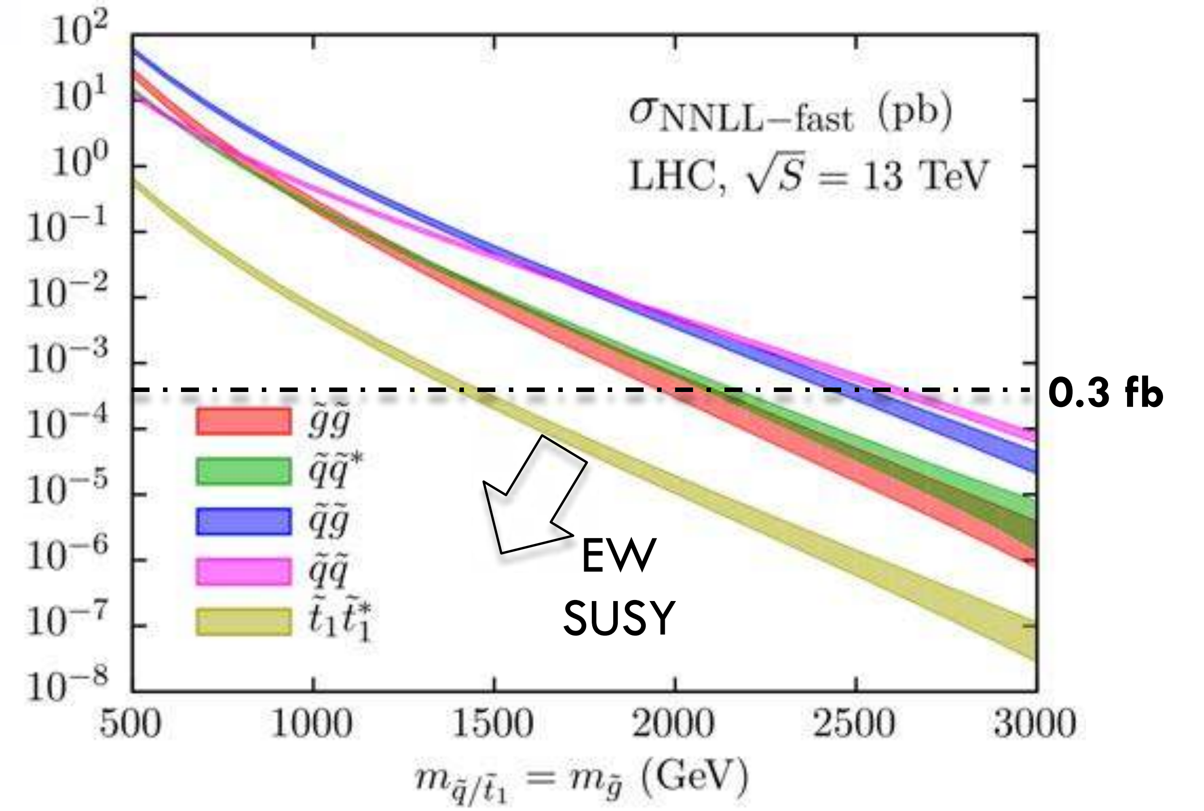


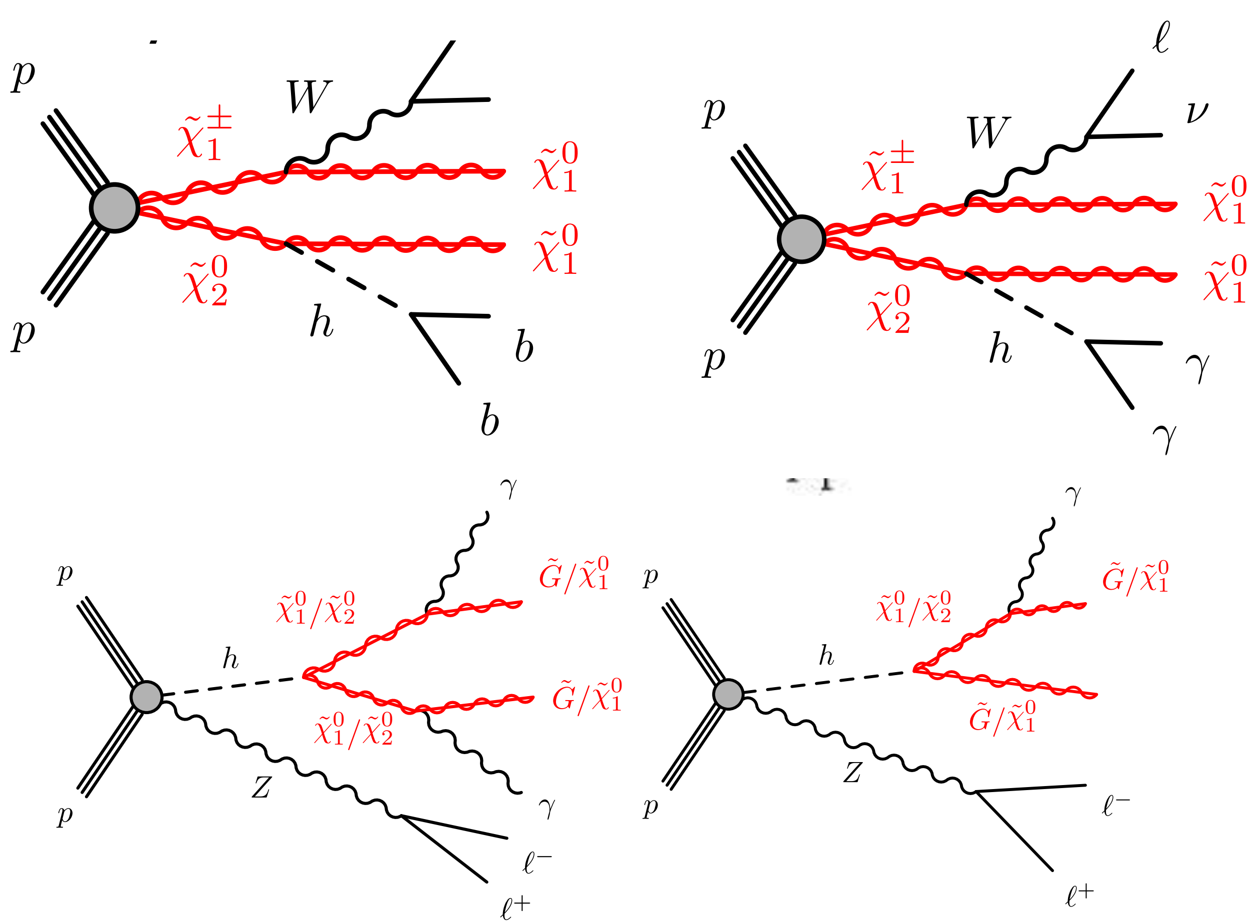


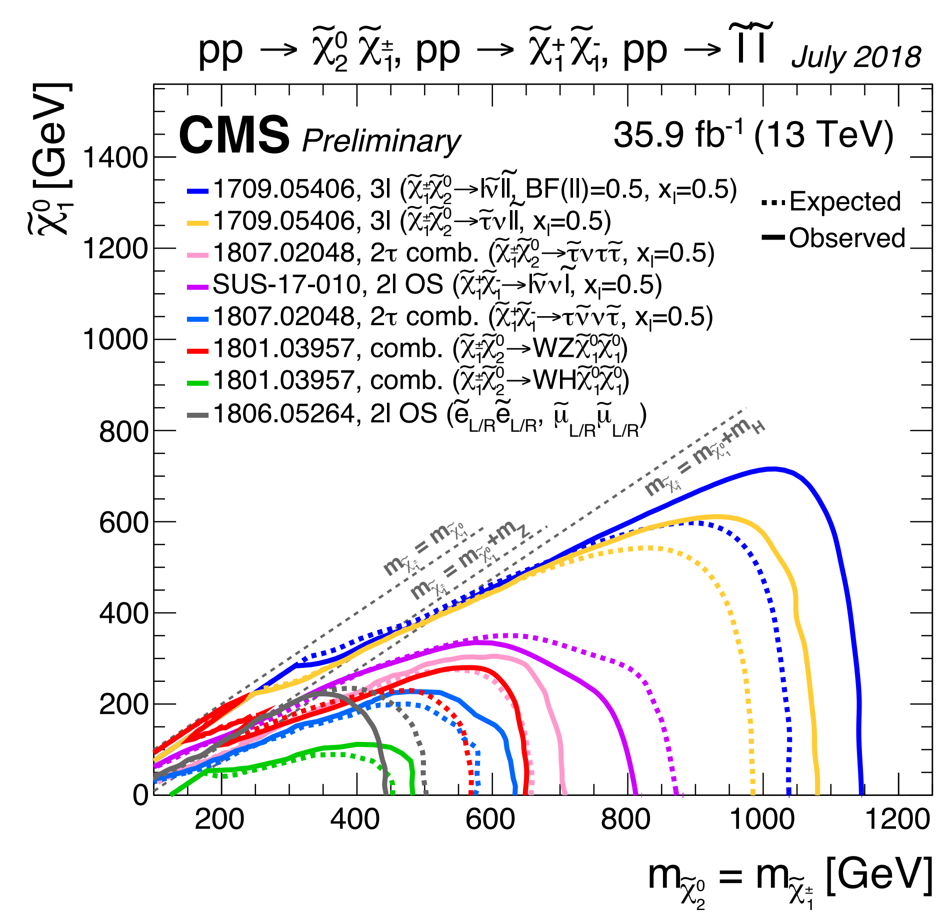
▹ Extremely quick turn-around for long-lived particle search

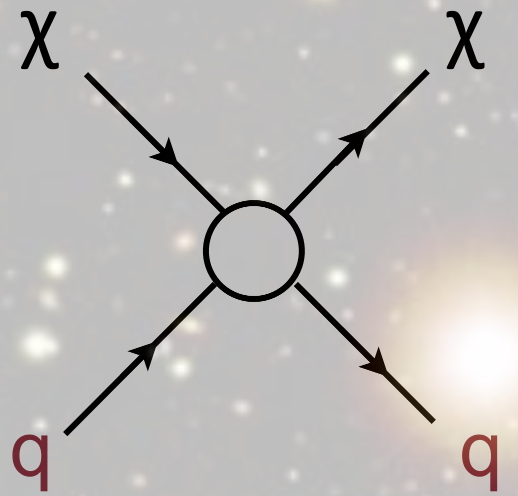
Supersymmetry

- Many new searches targeting both strong and electroweak production
  - No significant excess observed so far
- Strong SUSY searches targeting masses ~ 2 TeV
- Searches now using also H→γγ and exotic Higgs decays in electroweak production

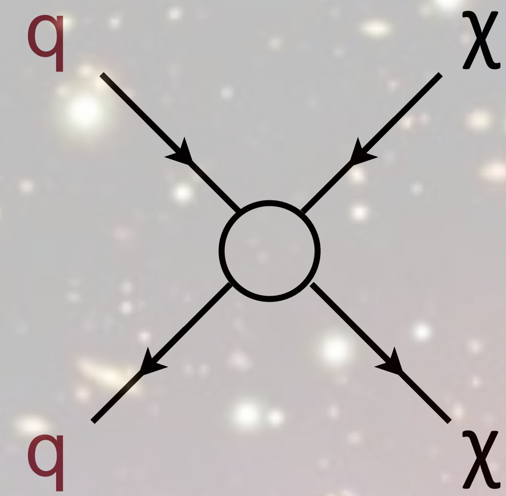




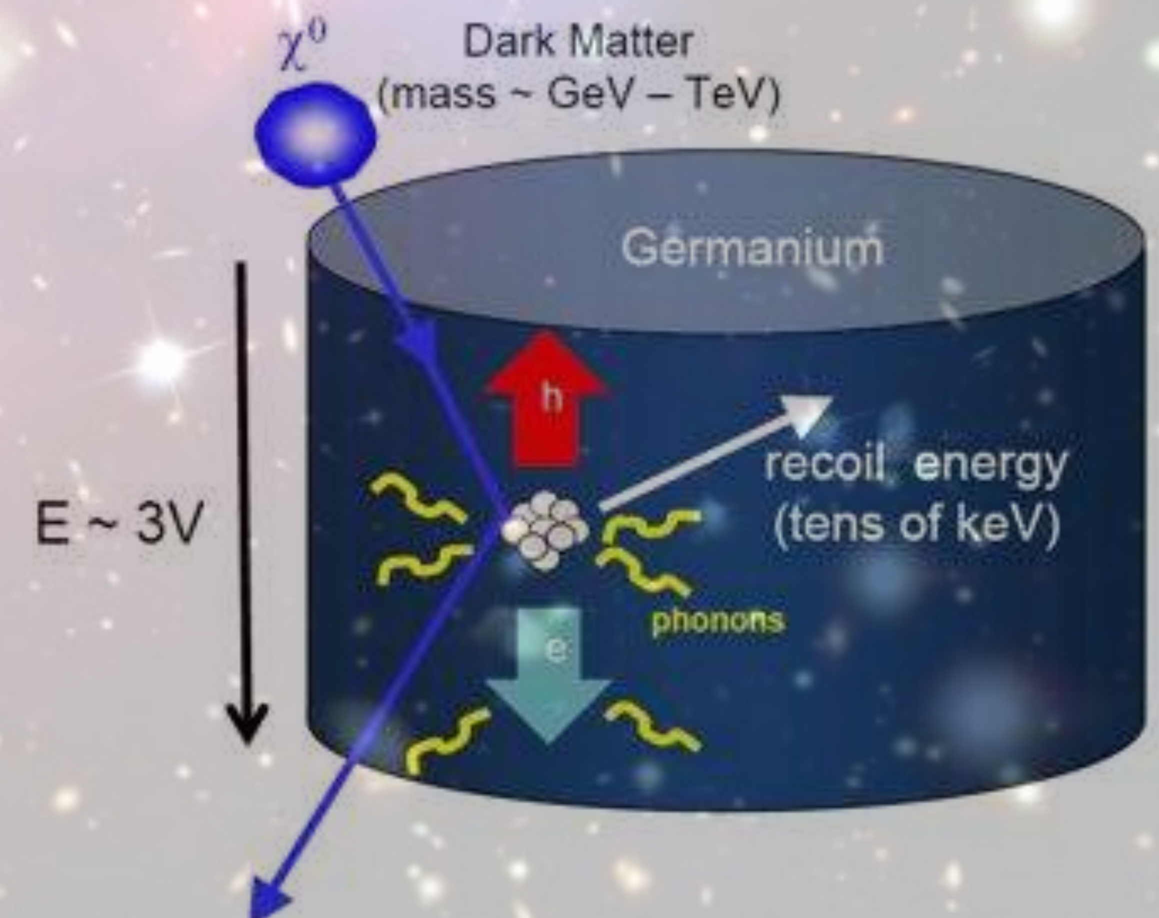




Direct Detection



Production at Colliders

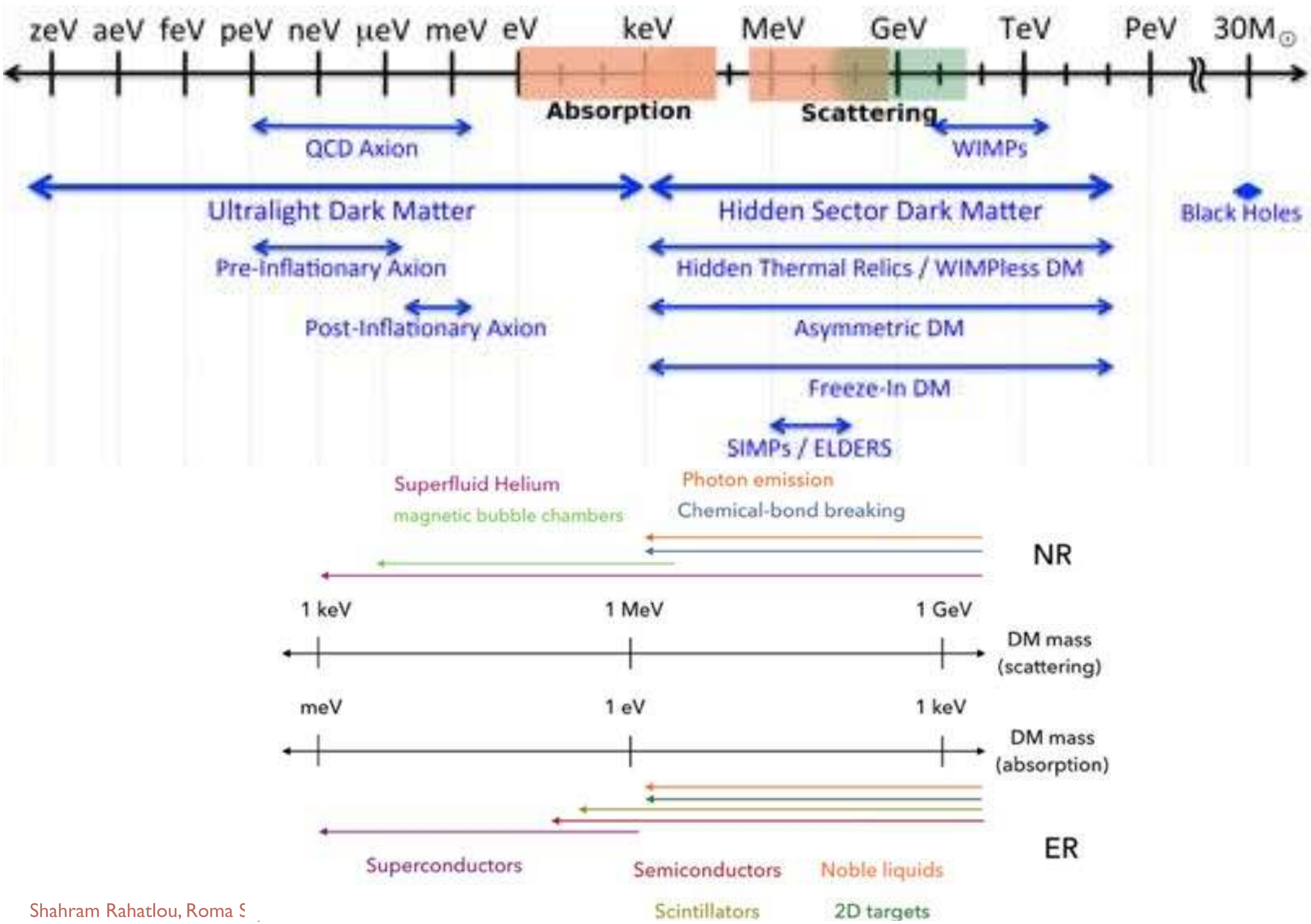


Dark Matter

The known unknown

Dark Matter Mass Spectrum

Enectalí Figueroa-Feliciano, CDMS



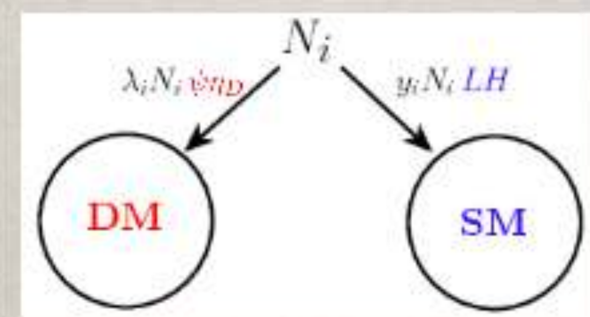
asymmetric dark matter scen. $m_{DM} \sim 5 m_p$ gives $\Omega_{DM} \simeq 5\Omega$;
"minimal" 2 RH neutrinos, SM$\times SU(2)_D \times Z_3$

Covi

Let us consider a minimal model for leptogenesis with two RH neutrinos to explain the neutrino masses and give the correct mixing matrices, as well as leptogenesis.
The particle content of the model is given by

Gauge Group	Fermion Fields							Scalar Fields		
	$\Psi_{1L} = (\psi_1, \psi_2)^T_L$	ψ_{1R}	ψ_{2R}	$\Psi_{2L} = (\psi_3, \psi_4)^T_L$	ψ_{3R}	ψ_{4R}	N_i	ϕ_h	ϕ_D	η_D
$SU(3)_c$	1	1	1	1	1	1	1	1	1	1
$SU(2)_L$	1	1	1	1	1	1	1	2	1	1
$SU(2)_D$	2	1	1	2	1	1	1	1	2	2
Z_3	ω	ω	ω	ω^2	ω^2	ω^2	1	1	1	ω

The decay of the lightest RH neutrino generates at the same time an asymmetry in leptons and DM:



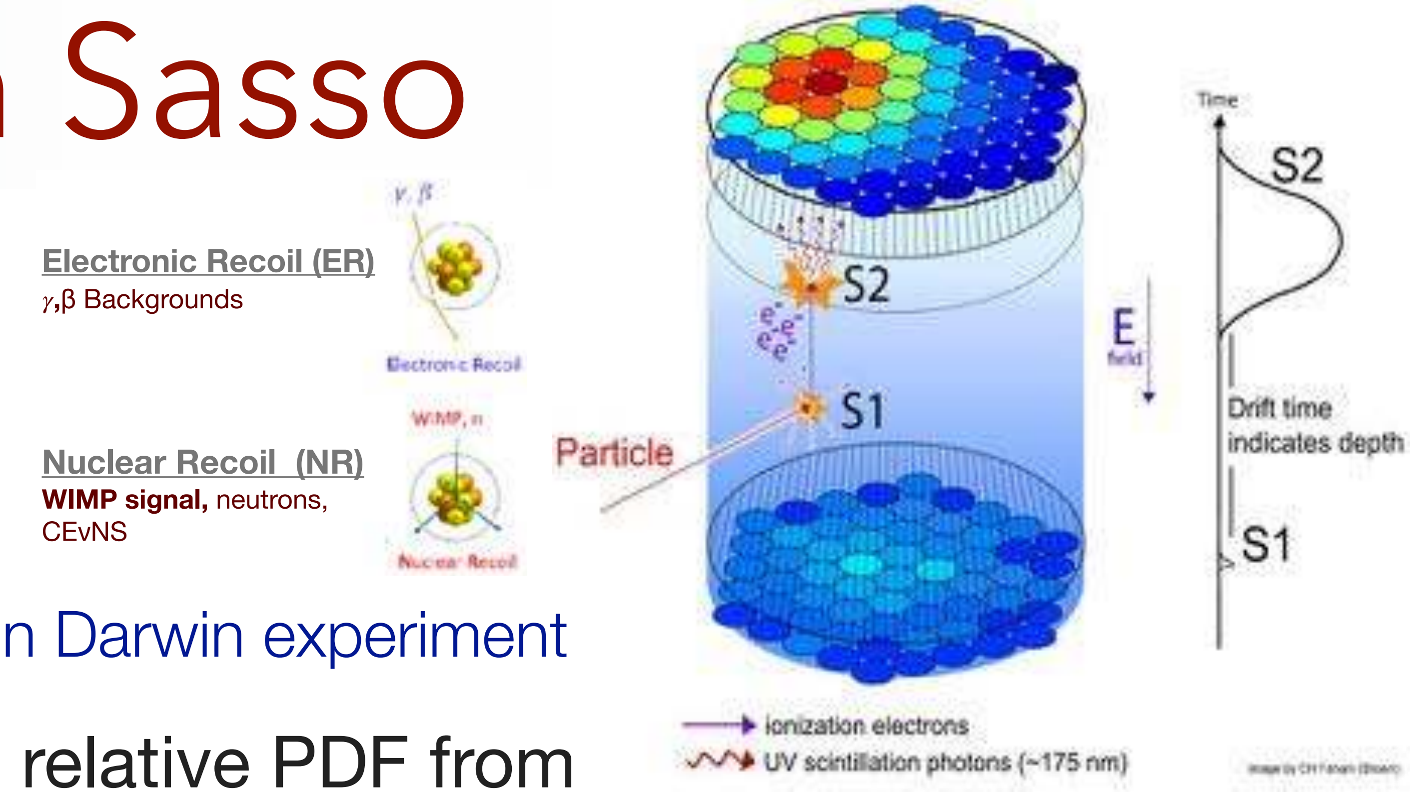
Need similar CP violation in both sectors !

Works with Yukwas with large CP-phase; only one Majoranaphase a low enery; effective mass

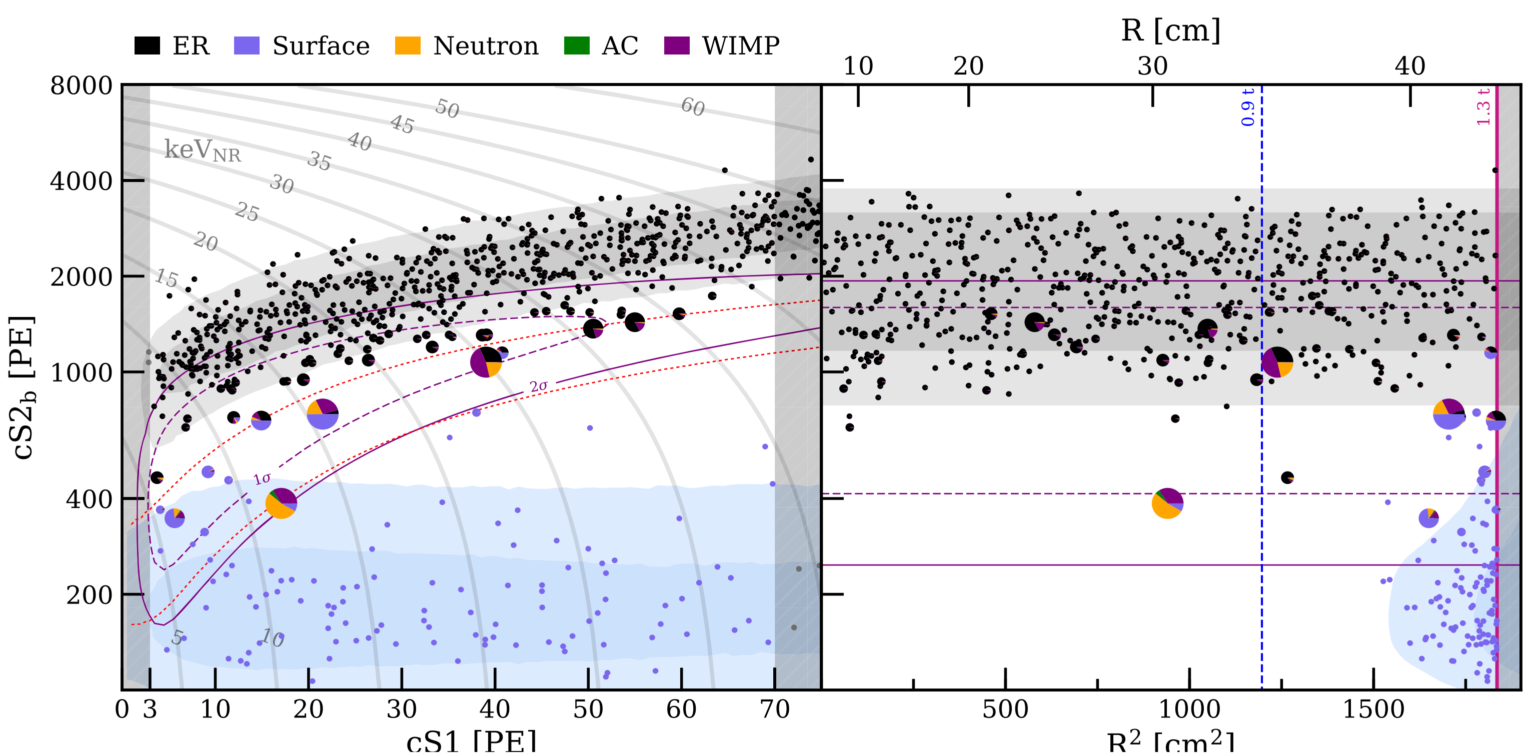
$m_{eff} = |\sum m_i U_{ei}^2|$ within few meV.

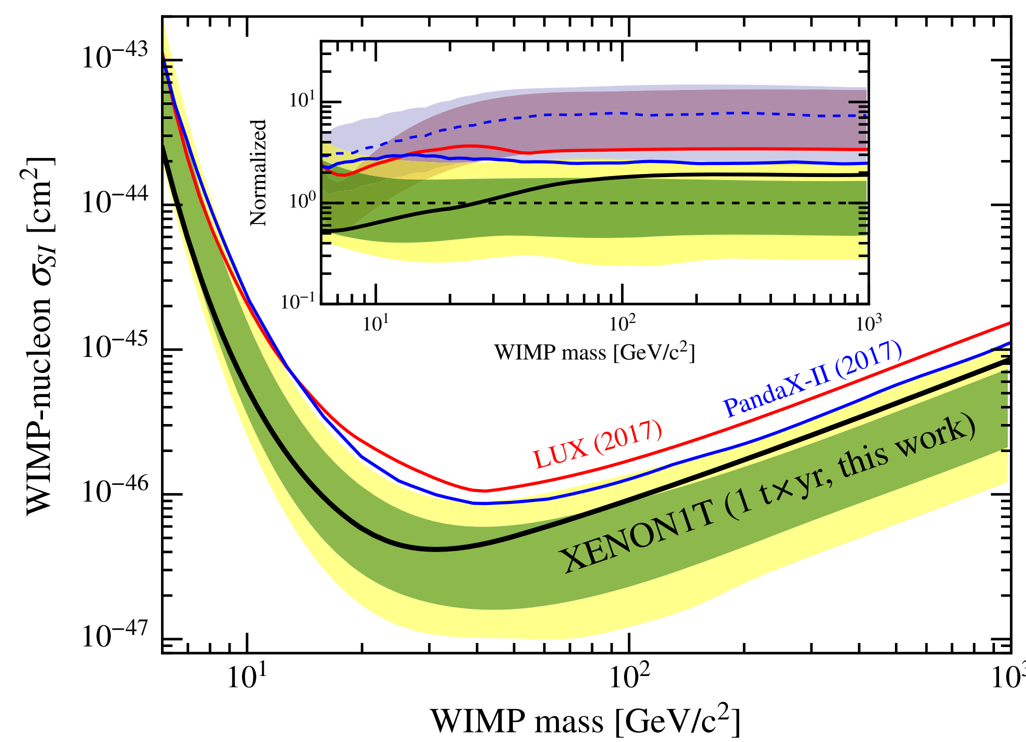
Xenon-1T at Gran Sasso

- Dual phase time projection chamber
  - Using s1/s2 discrimination instead of pulse shape
- CEvNS: subdominant background
  - will be more important in next generation Darwin experiment
- Events shown as pie charts showing relative PDF from each component for the best fit model of a 200 GeV WIM



Jacues Pienaar, Xenon



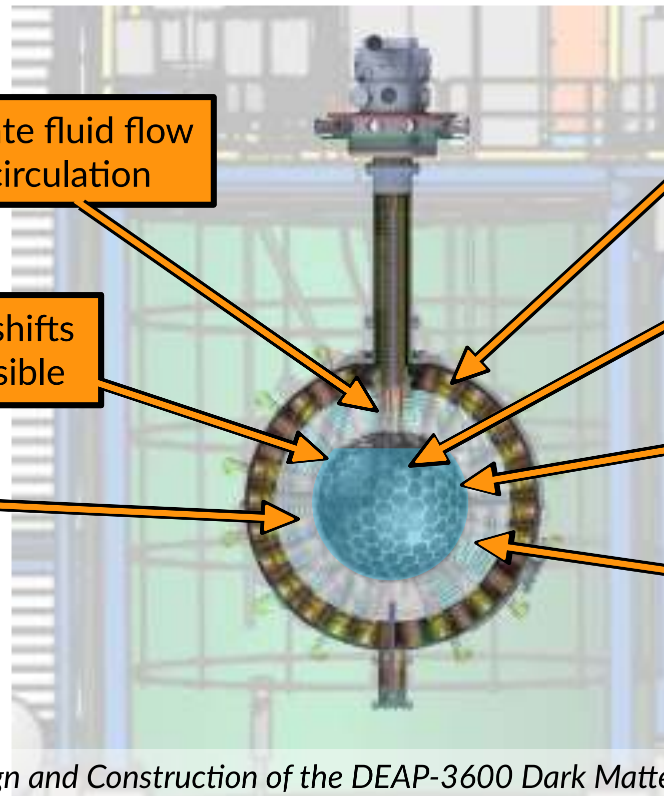


- Limits with 1 year of exposure
  - p-value of ~0.2 for m >= 200 GeV does not disfavor a signal hypothesis

DEAP-3600 at SNOLAB

Shawn Westerdale, DEAP

- Single phase LAr using pulse shape discrimination



Acrylic flow guides facilitate fluid flow during filling, potential recirculation

3 µm thick TPB coating shifts UV LAr scintillation to visible

45 cm long acrylic light guides transport light to PMTs, provide thermal insulation and shielding

255 8” PMTs

3.3 tonnes of LAr with a ~30 cm GAr layer

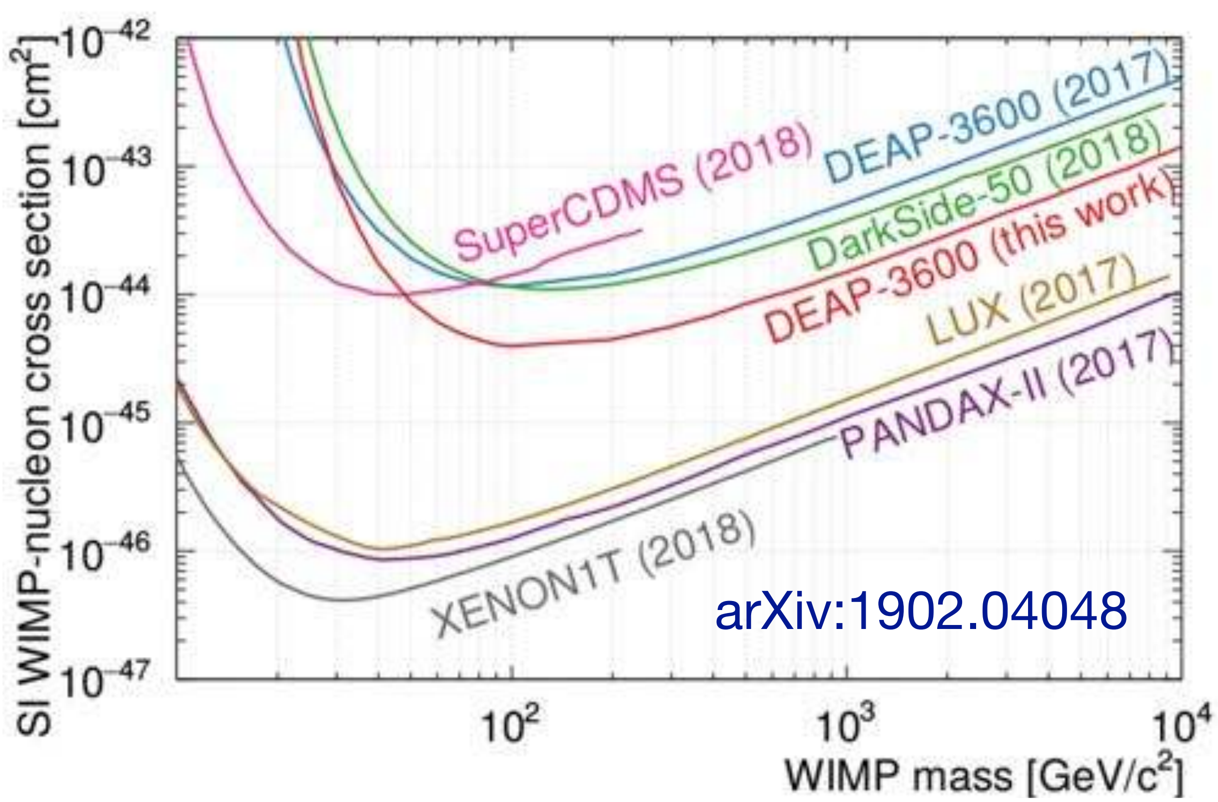
5 cm thick acrylic shell contains the LAr

Foam filler blocks between light guides provide further insulation and shielding

The DEAP Collaboration, *Design and Construction of the DEAP-3600 Dark Matter Detector*, Astropart. Phys. 108, 1 (2019).

- WIMP scatters on argon nucleus
- Singlet and triplet Ar dimers form
- Singlets decay (~6 ns), create 128 nm photons
- TPB shifts light to visible, detected by PMTs
- Triplets decay (~1.3 µs), create 128 nm photons
- TPB shifts light to visible, detected by PMTs

By looking for events with a large fraction of fast scintillation light, we identify nuclear recoils, which may be caused by WIMPs



231 live days after run selection and deadtime corrections

824 kg fiducial mass

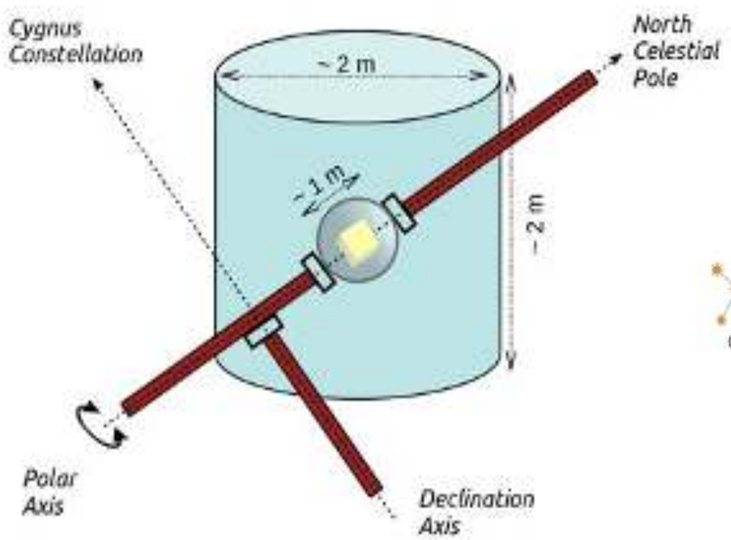
0 events in ROI

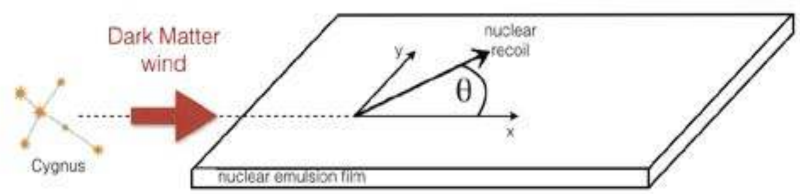
Exclude S.I. WIMP-nucleon cross sections above 3.9×10^{-45} cm^2 for 100 GeV/c^2 WIMP mass

Directional Detection

Valerio Gentile, NEWSdm

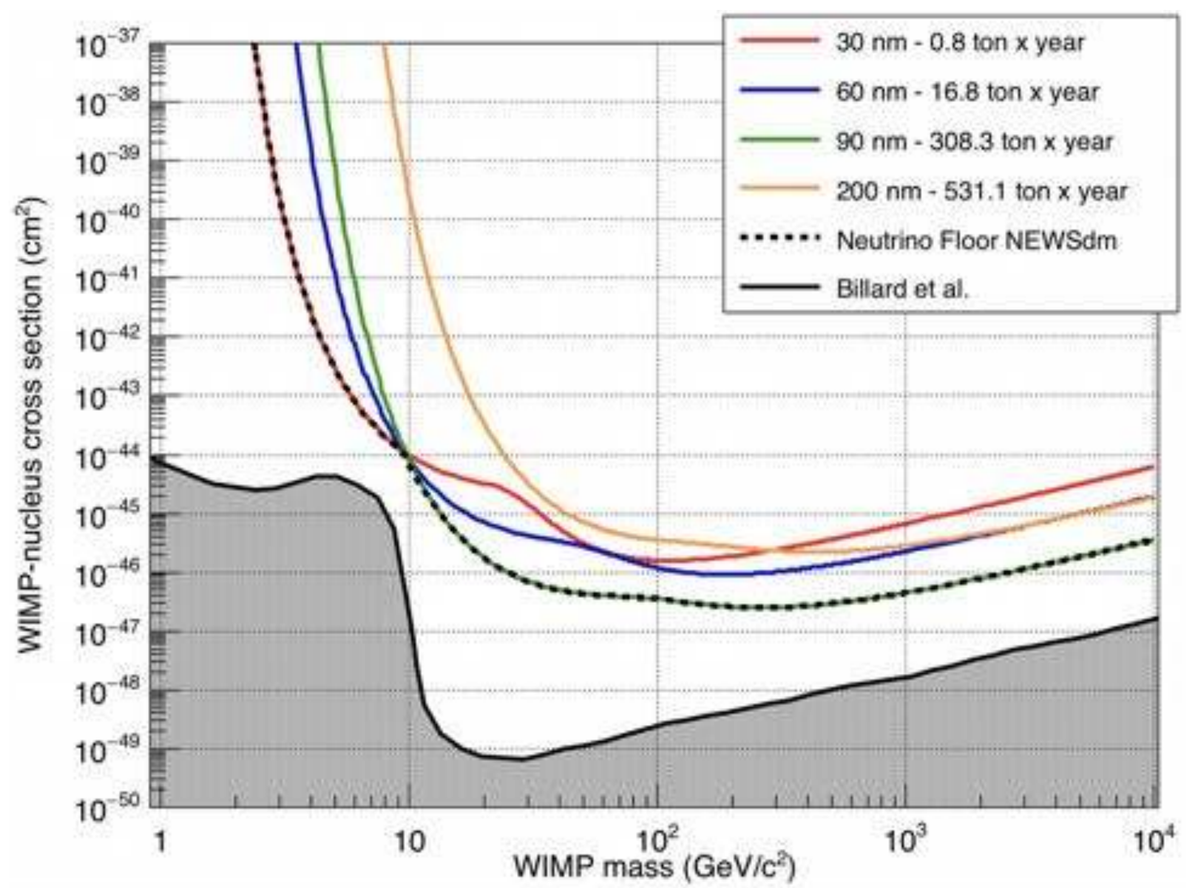
- Nuclear Emulsion based detector acting both as target and tracking device





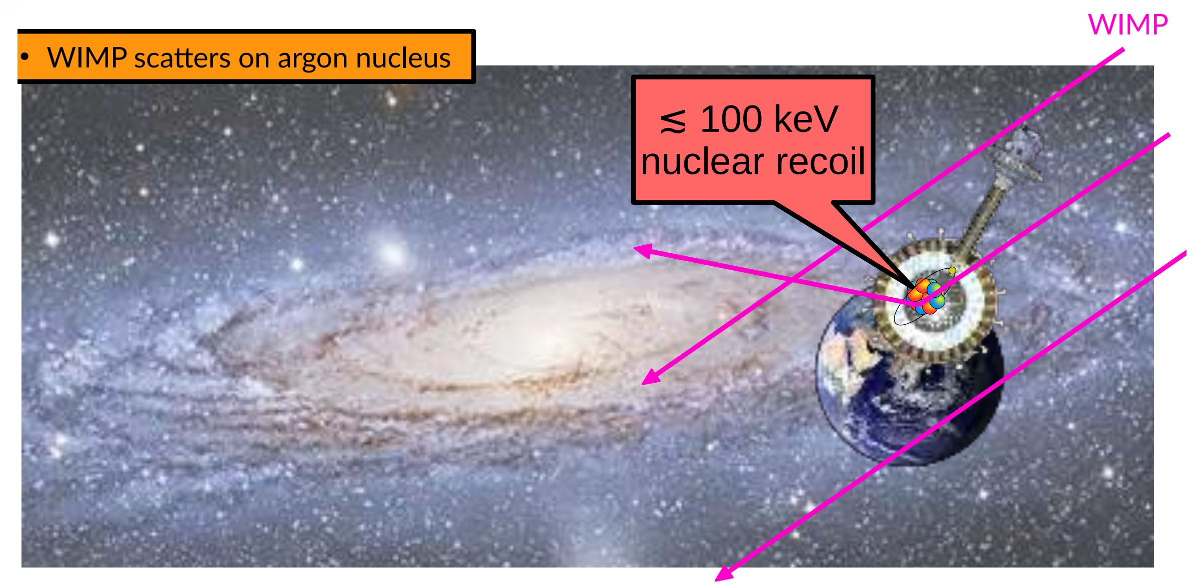
Aim: detect the direction of nuclear recoils produced in WIMP interactions
Background reduction: shielding surrounding the target
Fixed pointing: target mounted on equatorial telescope constantly pointing to the Cygnus Constellation
Directionality: Unambiguous proof of the galactic origin of Dark Matter
Location: Gran Sasso underground laboratory

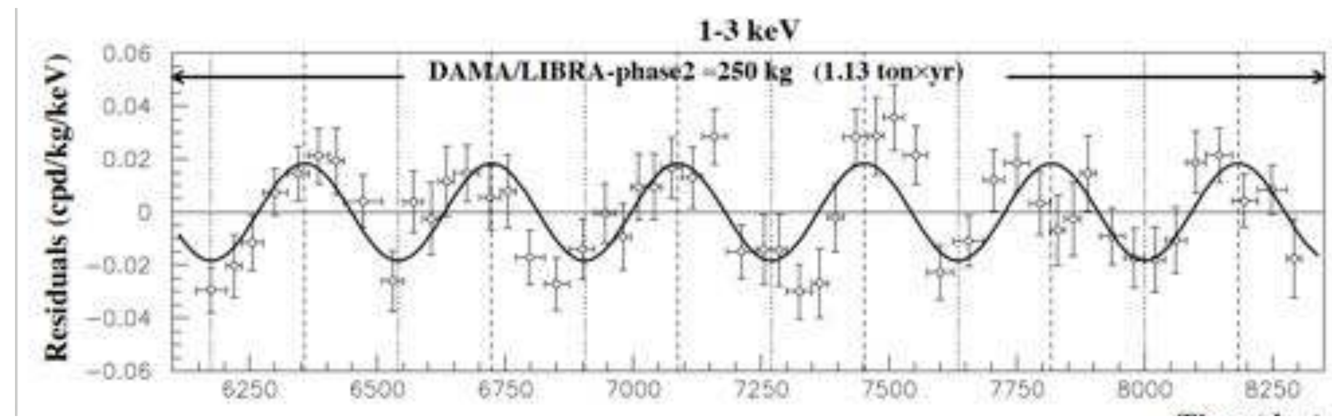
- Potential to overcome the ***neutrino floor***, where coherent neutrino scattering creates an irreducible background
- Plans (if funded)
  - 2020: construction
  - 2021: data taking
  - 2020: analysis



Annual WIMP Modulation

- Strong signal reported by DAMA/LIBRA
  - pure NaI crystals
  - Not confirmed by any other experiment
  - Excluded by many other experiments using different technologies and methods





Modulation persists in DAMA Phase 2

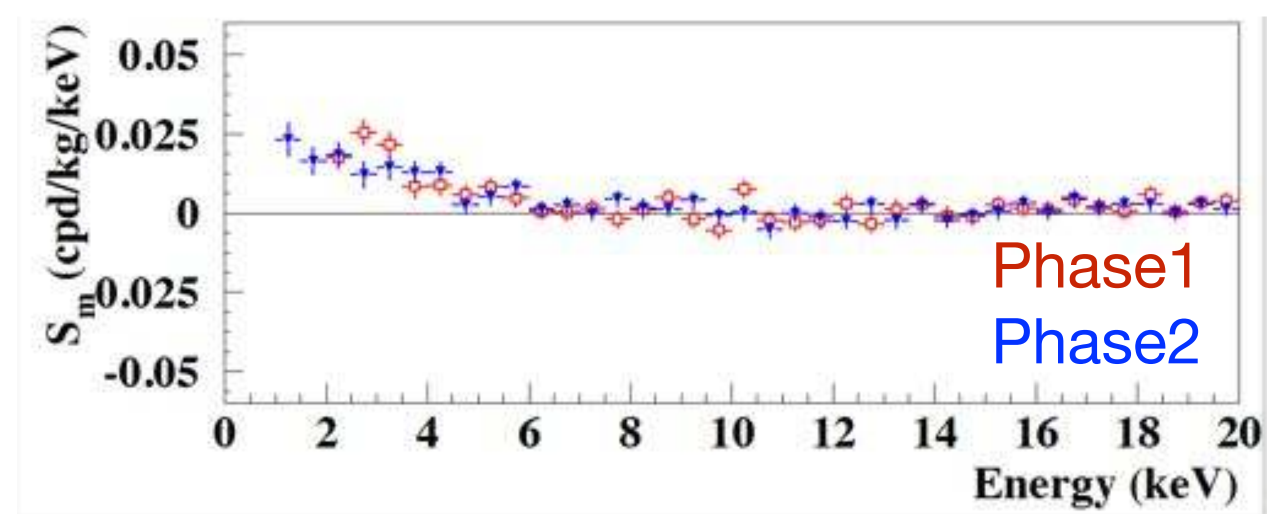
- 6+ additional years / 1.13 ton-year
- Threshold lowered to 1 keV

(1 – 6) keV: 9.5σ from 1.13 ton- year

(2 – 6) keV: 12.9σ from 2.46 ton-year

Signal consistent with Dark Matter

- Mod'n amp.: 0.0103 ± 0.0008 cpd/kg/keV
- Phase: (145 ± 5) days
- period: (0.999 ± 0.001) year

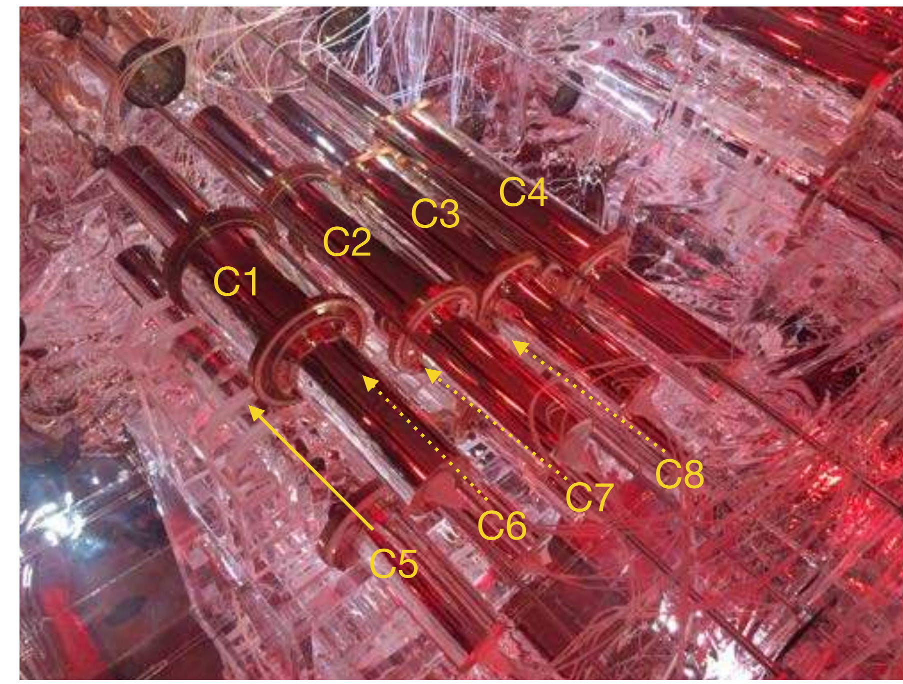


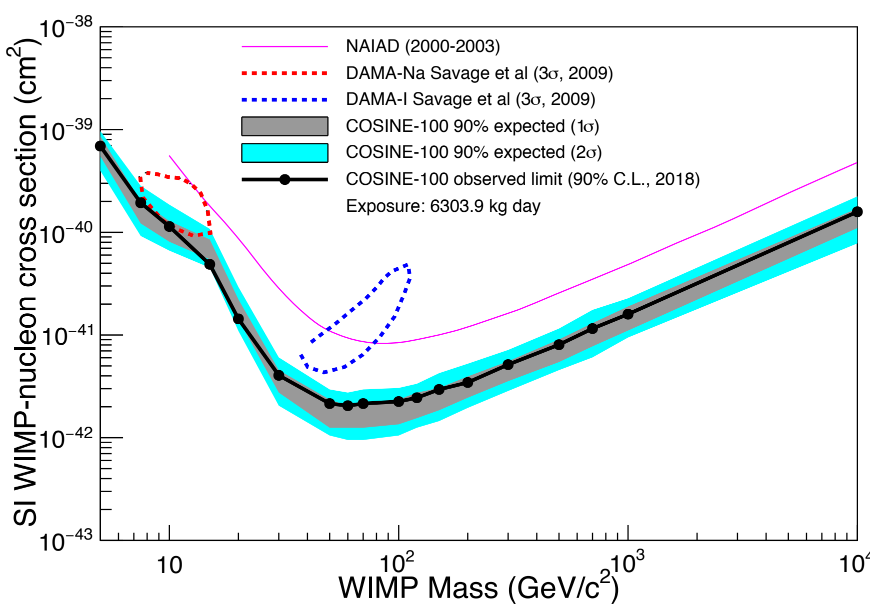
- *Galileo (the physicist) would suggest at least one other experiment to reproduce results as closely as possible*

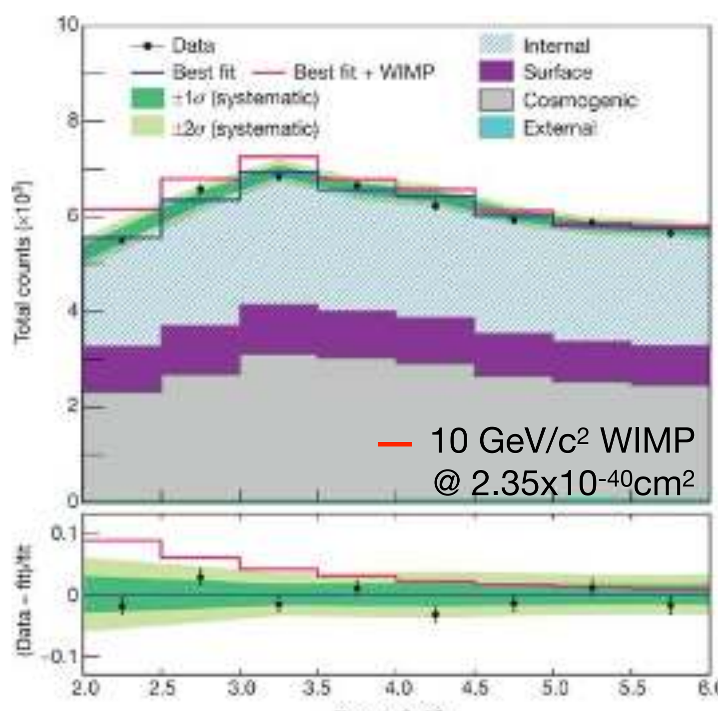
COSINE-100 at Yang Yang Lab (Korea)

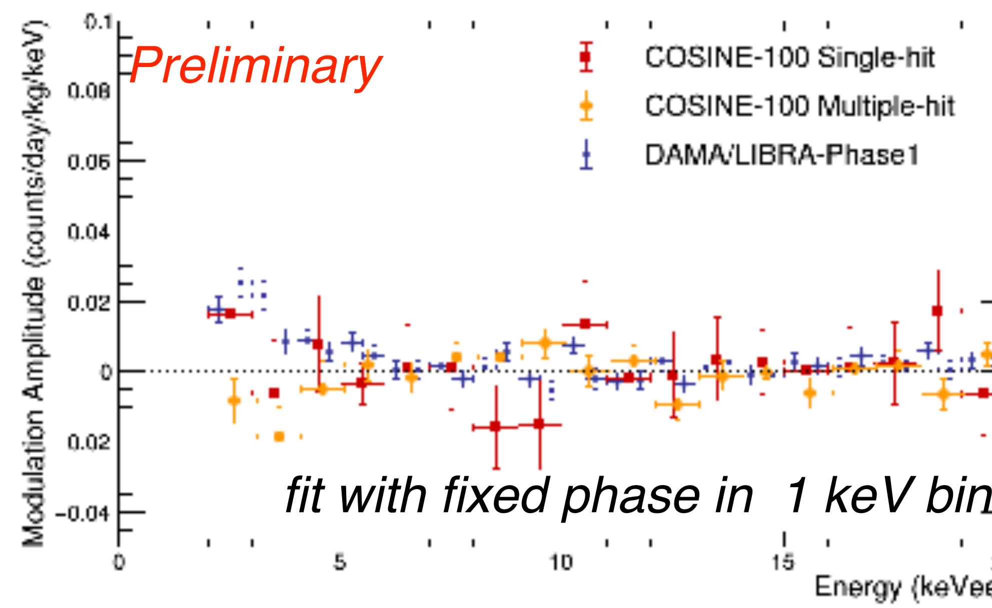
- 8 copper encapsulated NaI(Tl) crystals,106 kg total
  - Detailed Geant4 simulation; BDT background rejection
  - Currently background ~ x 2-4 DAMA
- First results with 2 years of exposure
  - disfavors standard spin-independent WIMP interaction with NaI(Tl) as explanation for DAMA/LIBRA
- Effort underway for COSINE-200 with ultra pure crystals
  - 5 year of data needed to confirm DAMA with 3σ

Reina Maruyama, COSINE

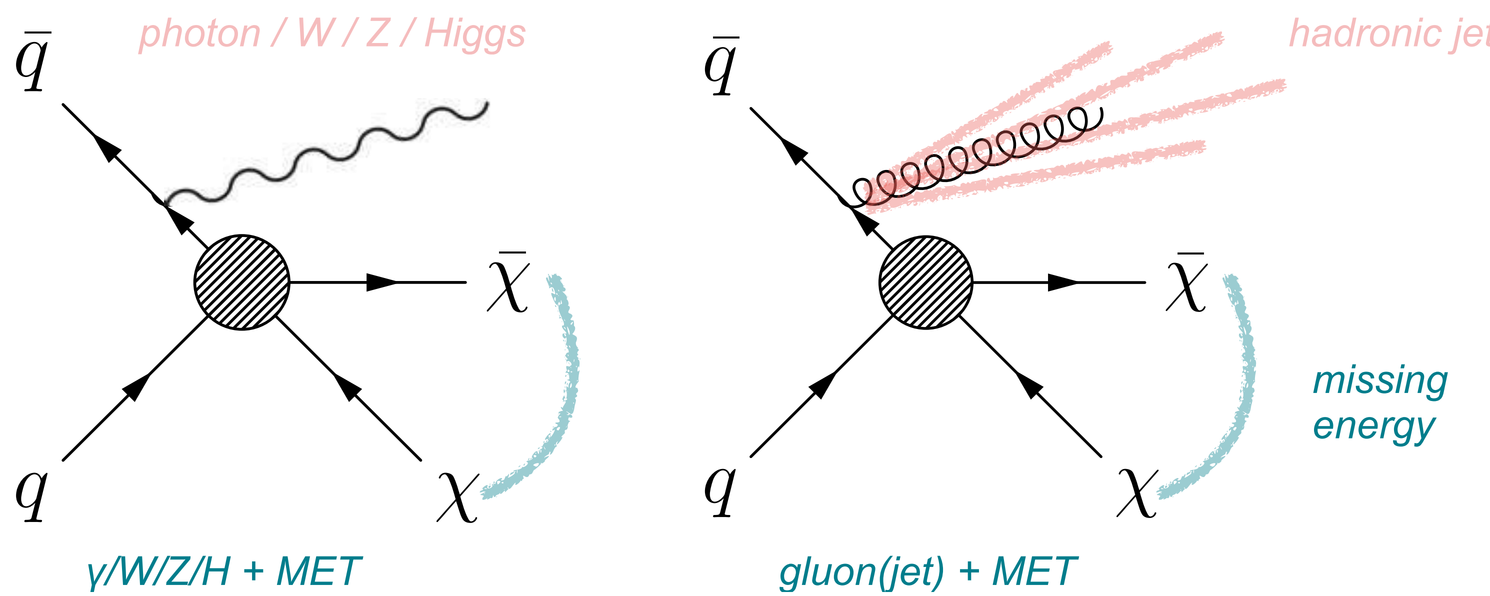


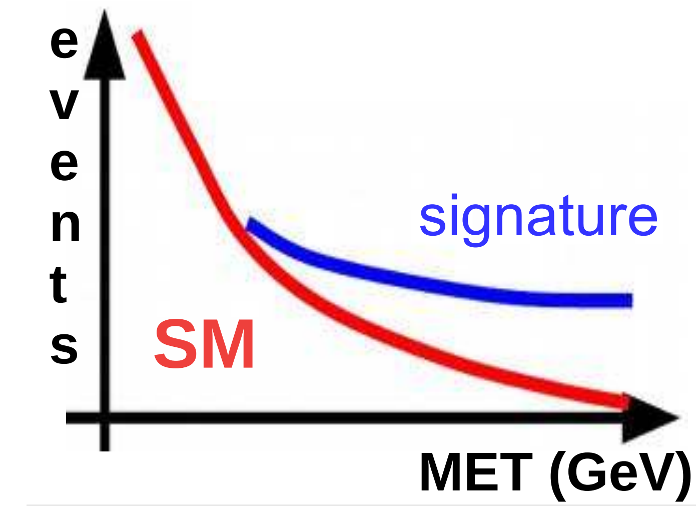




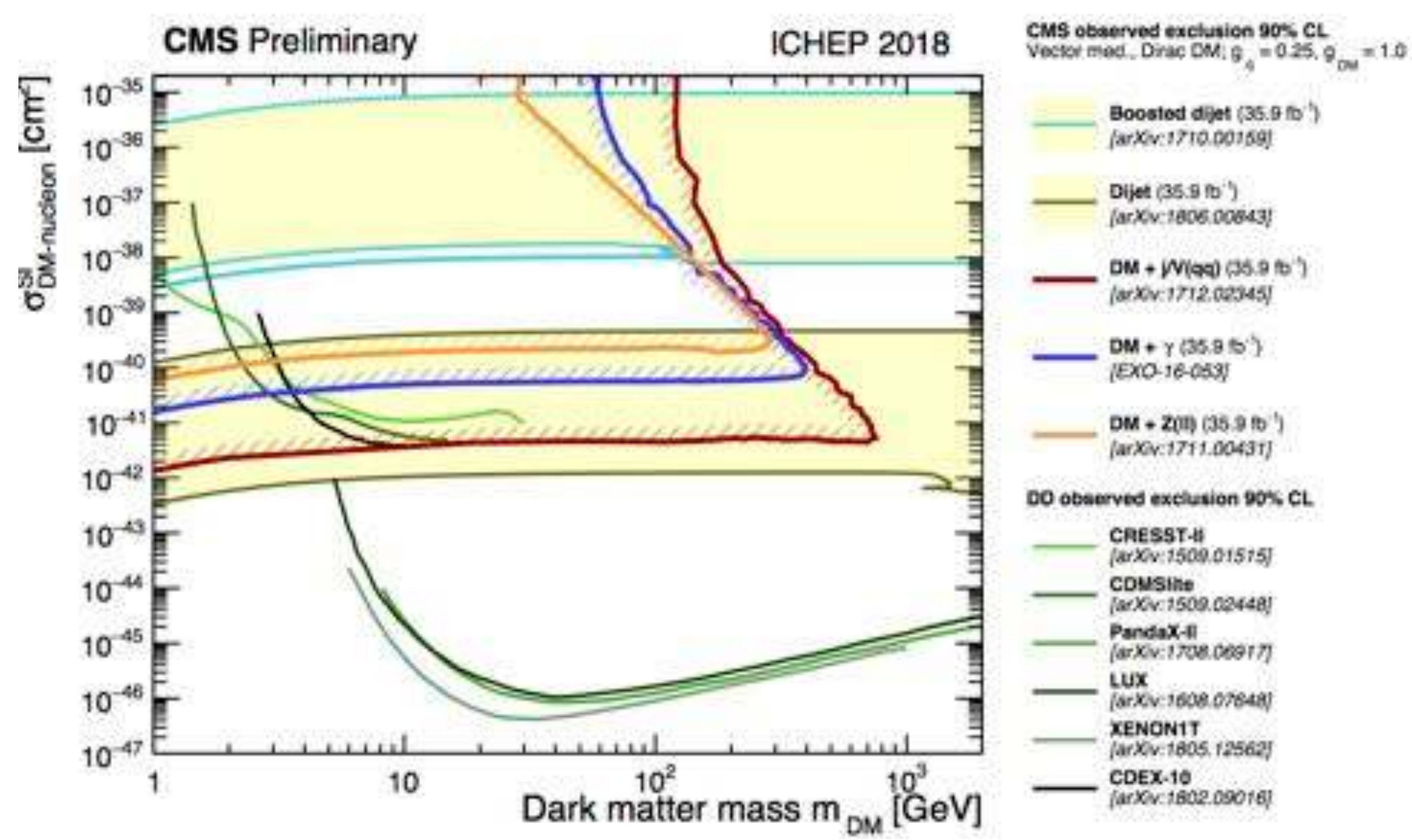


WIMP at LHC





- In addition to classic MET + mono-object search, also constraining mediator mass and coupling in simplified models
- No excess reported
  - Significant reduction of both experimental and theoretical background systematics



Sergei Chekanov, ATLAS

Outlook

- Standard Model still stands strong after Moriond EW
- Observation of CP Violation in D mesons another victory for Standard Model
- Flavor anomaly still there and to be pursued at low and high mass
  - Redundant measurements and revamped interest for Z' and LQ

- My desiderata or wish list for near future (~ 5 years) based on this week
  - Resolution of flavor anomaly
    - possibly still standing and confirmed by heavy new particles
  - Verification of DAMA/LIBRA by NaI experiments
    - Possibly also in the southern hemisphere with SABRE
  - Reaching the neutrino floor at low mass with superCDMS
  - First evidence for coupling of Higgs to second generation fermions
  - Updated heavy neutrino searches at LHC