Experimental Summary

Shahram Rahatlou

Moriond Electroweak Interactions & Unified Theories

La Thuile, 23 Mar 2019

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

Rencontres de Moriond since 1966

Experience as Summary Speaker

picture: by me

X-files poster by theendivechronicles.com

Caveats

- 54 experimental talks
- 12 experimental YSF talks
  - congratulations to young**er** colleagues for very interesting and well prepared presentations
- Number of new results, ideas, upgrades, exceeded by far the number of minutes allocated for this talk!
  - … and my absorption rate
- The following is a very *personal and non-comprehensive* ***selection*** of what I see as a concerted effort to explain our universe
  - apologies if your favorite result is not included

Many thanks to all speakers for providing the material for this talk

*Any name omission is purely due to **sleep deprivation** and will be fixed in the public version on the conference website*

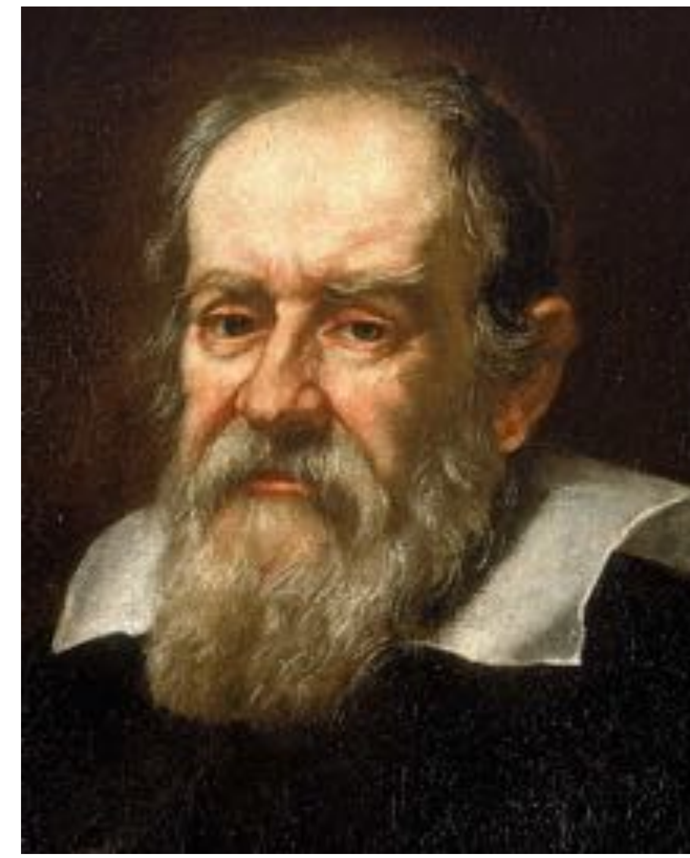
Executive Summary

- LHCb experiment at CERN stole the show this year at Moriond EW
  - Last experimental YSF talk from BELLE a pleasant surprise!
- 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
- *Observation of CP Violation in charm mesons by LHCb*
- 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

What is the goal of experimental program?

Scientific Method

- Galileo was the father of the scientific method
  - Observe **phenomena** in Nature with experiments
  - Make **hypothesis** about laws of Nature (models)
  - Make quantitative **predictions**
  - Verify predictions with new **experiments**
  - Successful predictive models promoted to be a new **theory**
  - Never stop **verification and falsification** of existing theories
    - taking advantage of theoretical and technological advancements



XVI Century

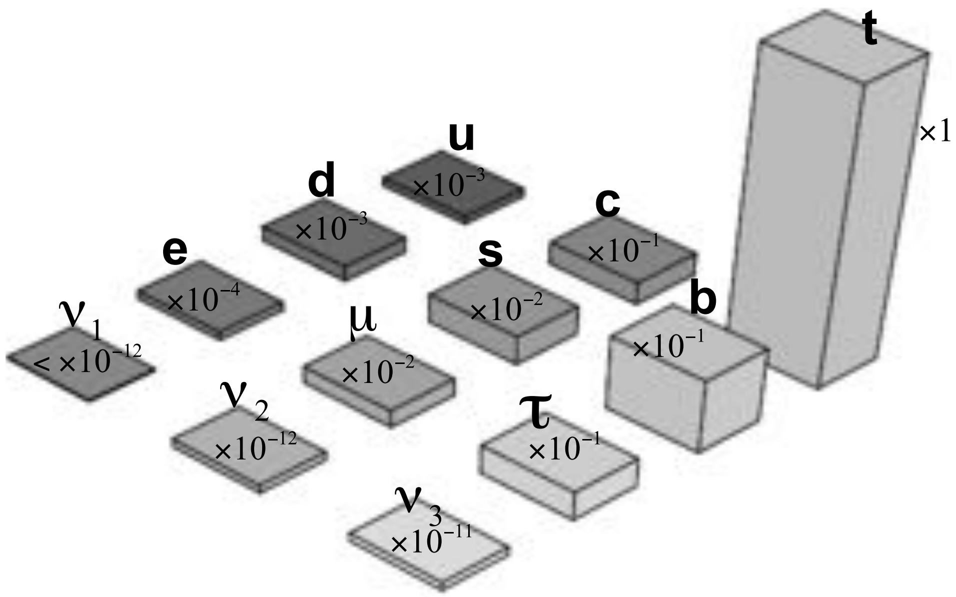
Falsification of Standard Model is as relevant as ever

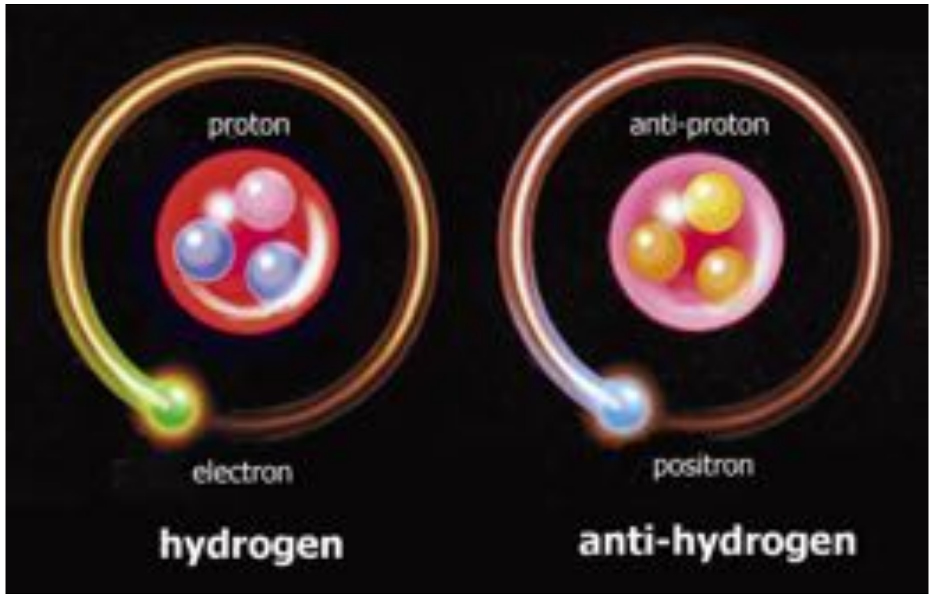
Standard Model

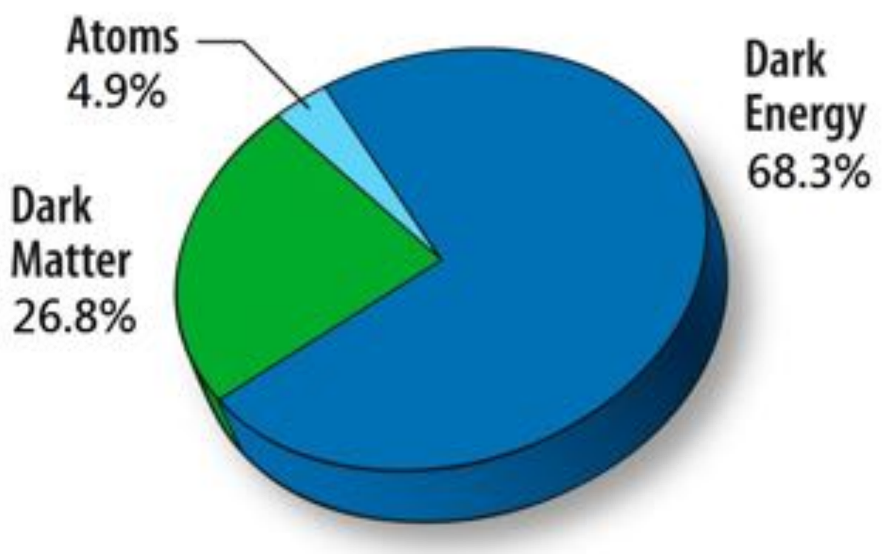
- Extremely predictive theory since its inception
- Last missing piece discovered just 7 years ago
  - Compare to gravitational waves and general relativity
- Has successfully resisted 50 years of falsification
- *We already know it is incomplete*
  - Neutrinos are massive
- It cannot address some basic curiosities and questions about our Universe

A few questions and curiosities

- What is the origin of mass?
- Have we found ***the*** Higgs boson?
- What is the origin of mass hierarchy?
- Where is all the anti-matter in our Universe?
- What is Dark Matter?







Means of Falsification

- Multiple and redundant measurements of well known quantities
  - different methods
  - different contexts
  - different technologies

The Known Knowns

- Measurement of very small and precise predictions
  - variety of such observables across the spectrum
  - typically referred to as indirect search for New Physics
  - At LHC now merging with standard Physics thanks to amount of data

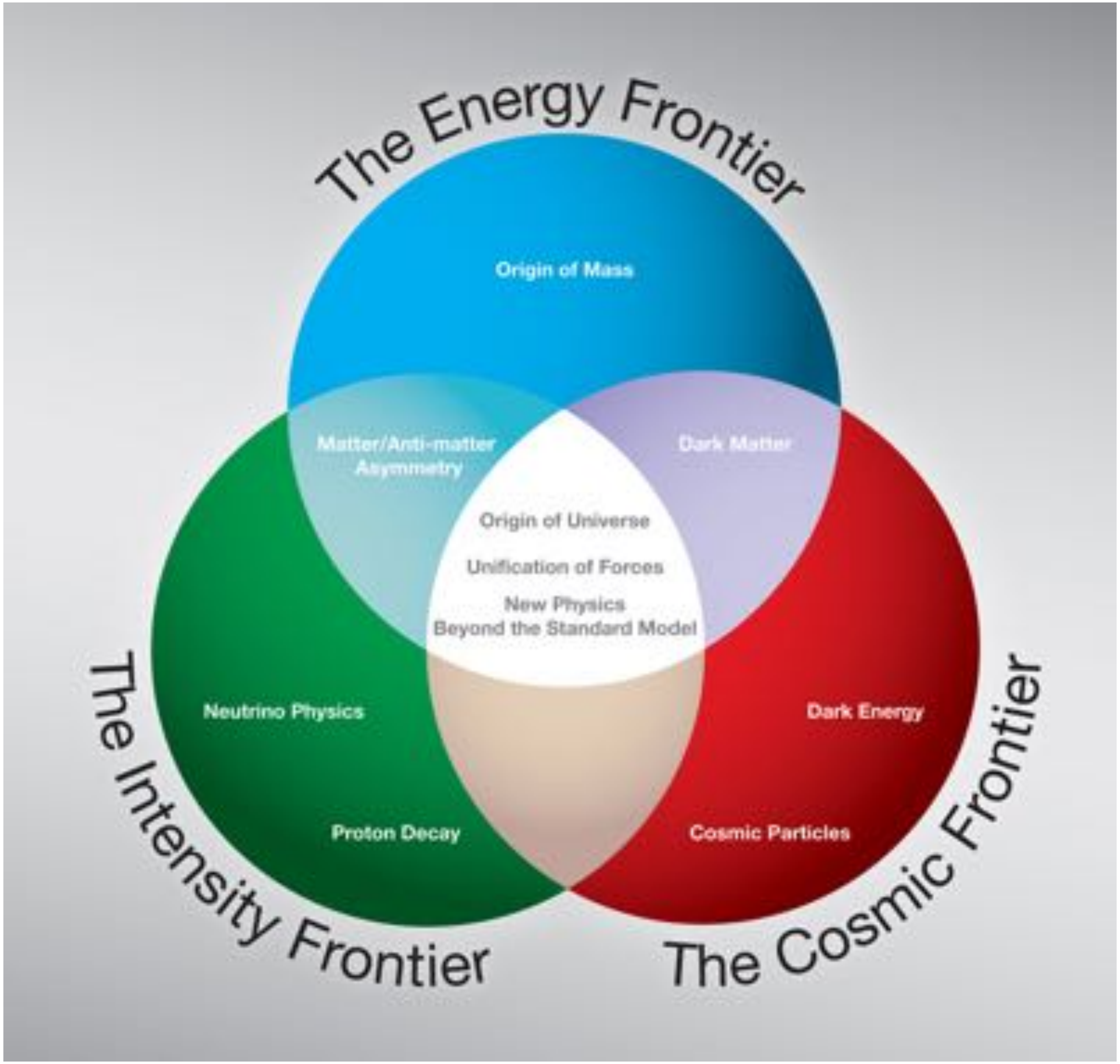
The Known Unknowns

- Search for the exotic
  - chasing more or less crazy ideas by theory friends
    - often motivated by some big question
  - Taking advantage of capabilities of detectors for unconventional signatures

The Unknown Unknowns

- New computational tools for more efficient data mining and increasing sensitivity
- New technologies to improve detection techniques and try new avenues

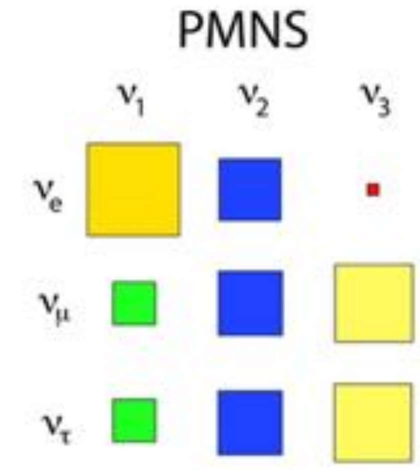
Multi-prong Approach

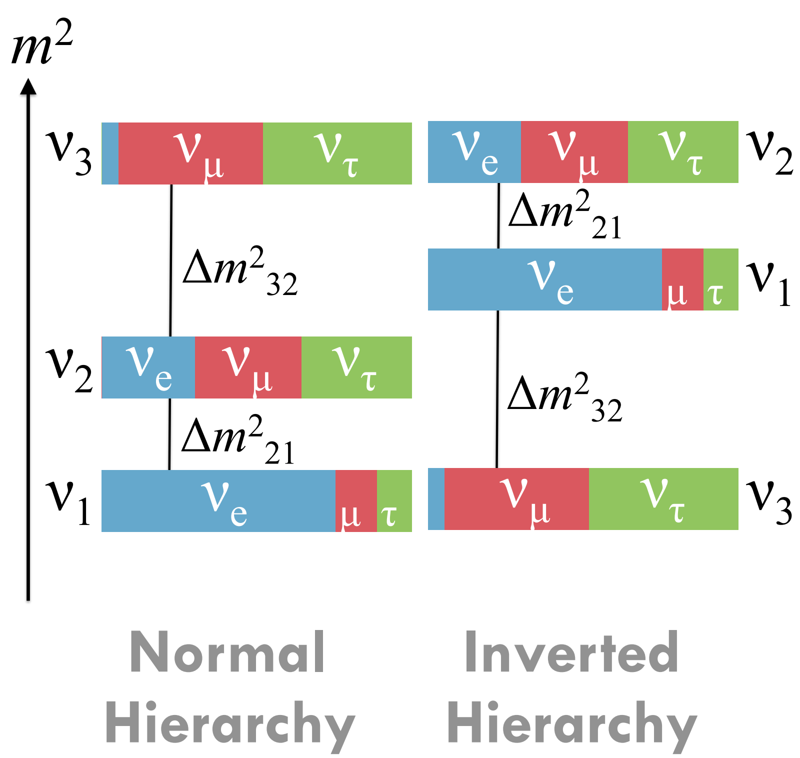


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

CP phase: δ_{CP}





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

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

Neutrinos

The known unknown

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

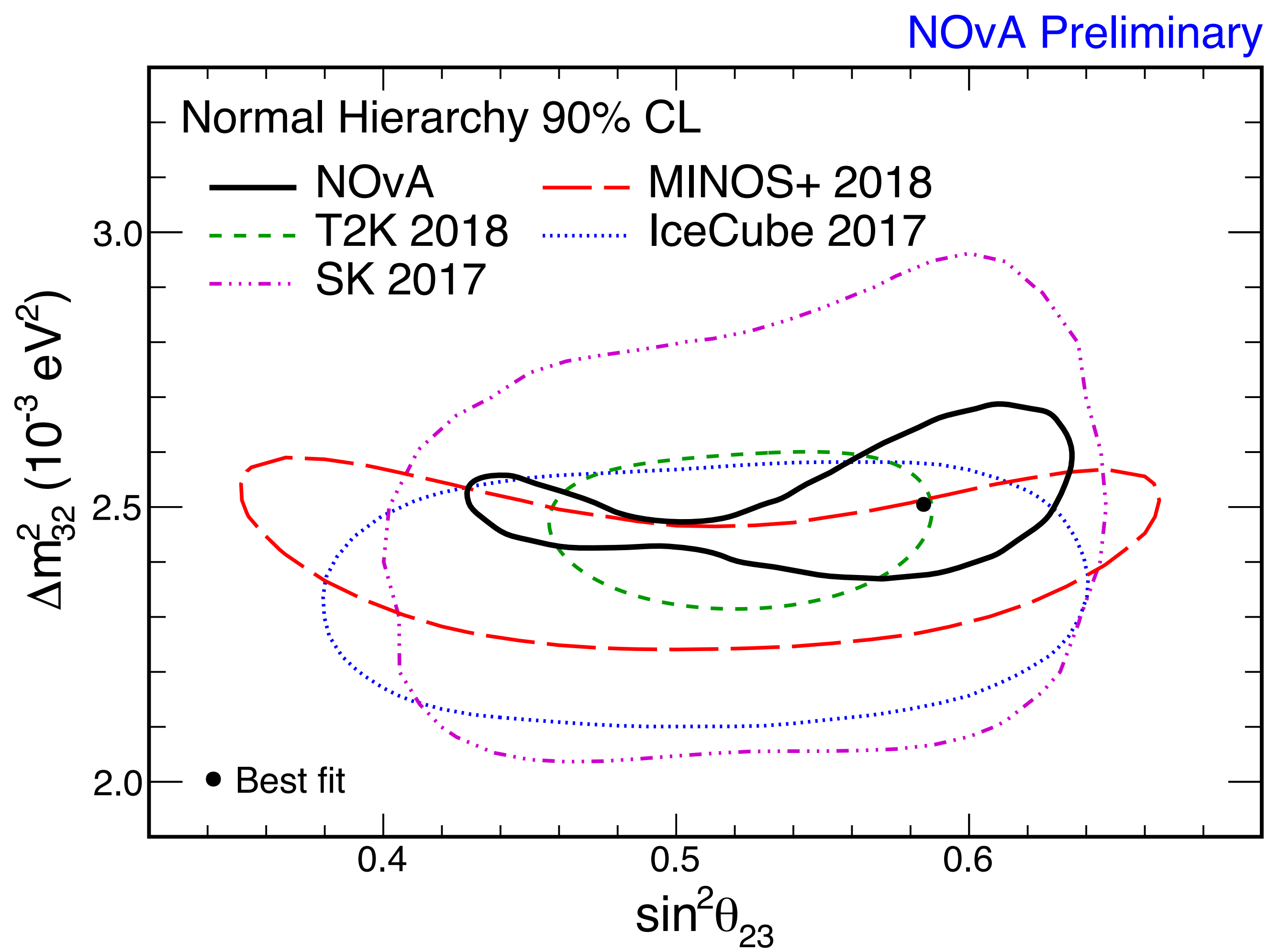
Neutrino Mixing and Mass Hierarchy

- 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

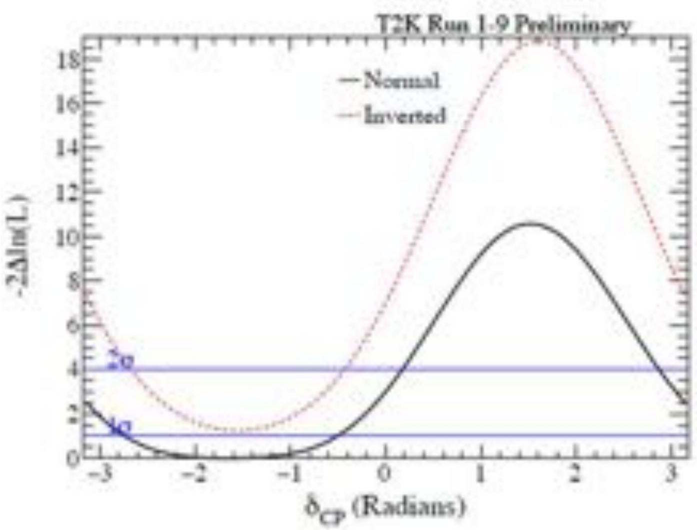
- T2K: 2 detectors using narrow energy beam from J-PARC
  - recent run mostly in anti-neutrino (50% more statistics wrt neutrino 2018 results)
  - best year of data taking in 2017~2018
- Both experiments **favor maximal mixing** for neutrinos and **Normal Hierarchy** for mass
- Slight preference for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



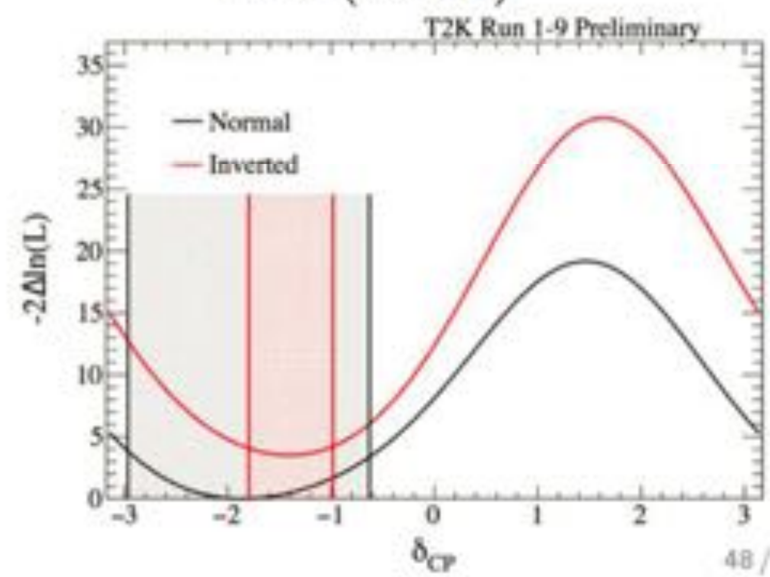
CP Violation in Neutrinos

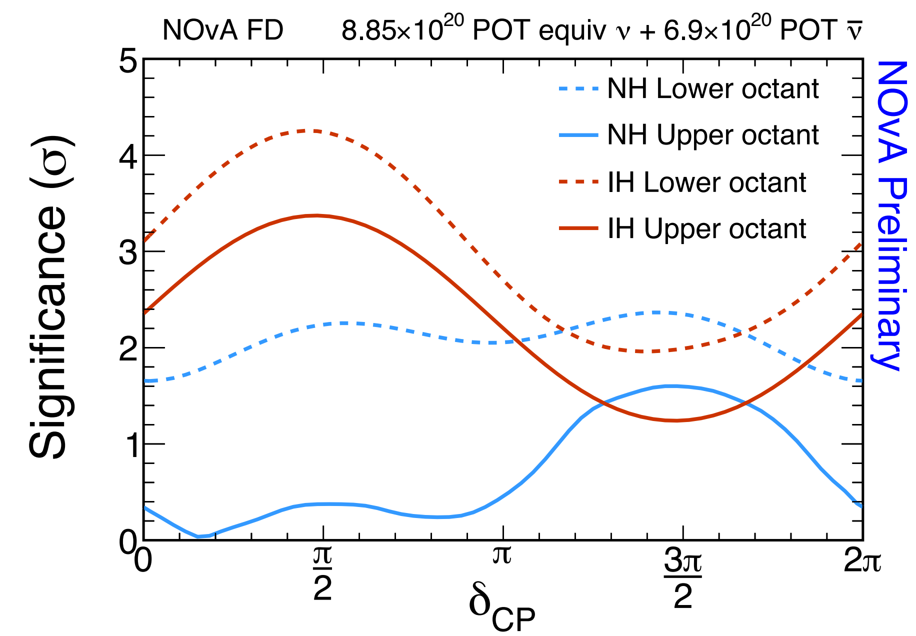
- CP conserving values (0, π) fall outside of the 2σ CL intervals !
  - Still fall within the 3σ CL intervals
  - Suggestive result, but need more data

Sensitivity



Data (2σ CL)

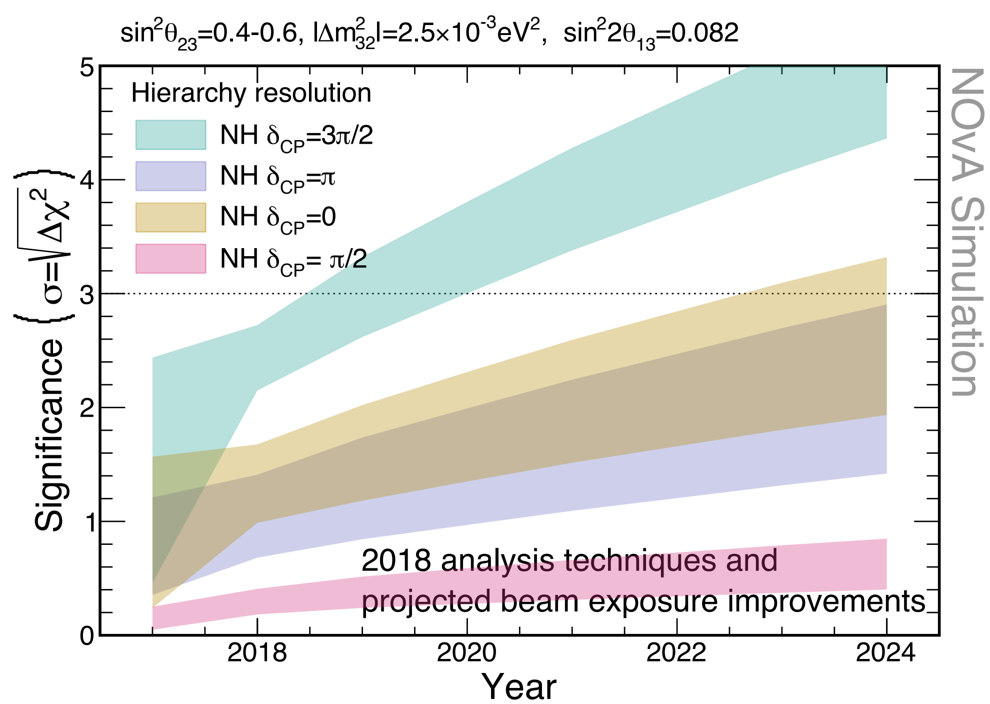




nt best fit with 15.75 x 10^{20} POT-equivalent

$$\delta_{CP} = 0.17\pi$$

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

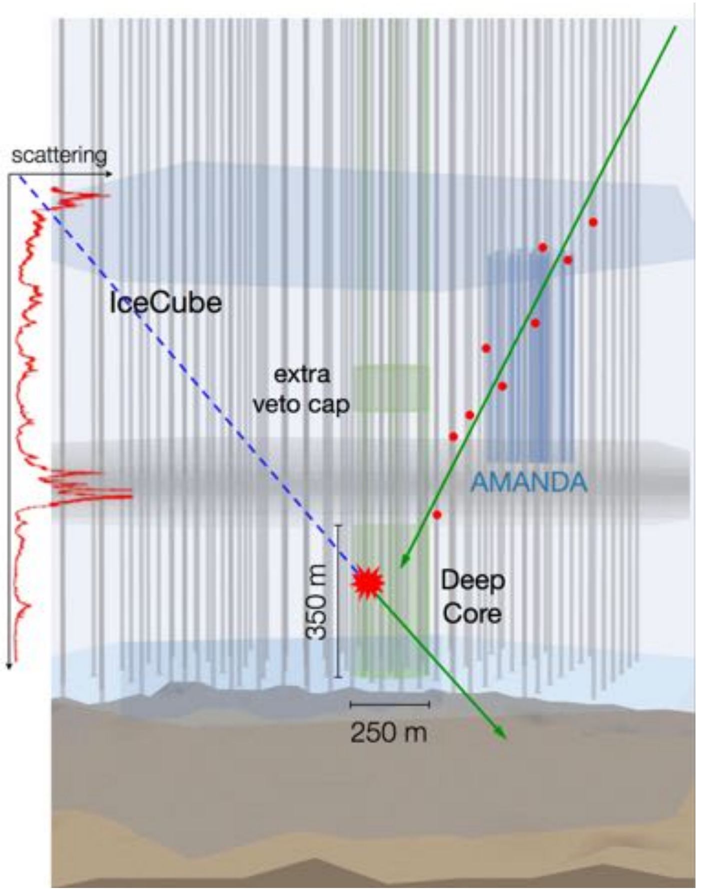


Diana Mendez, NOvA

Alain Blondel, T2K

- 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

Tau Neutrino Appearance

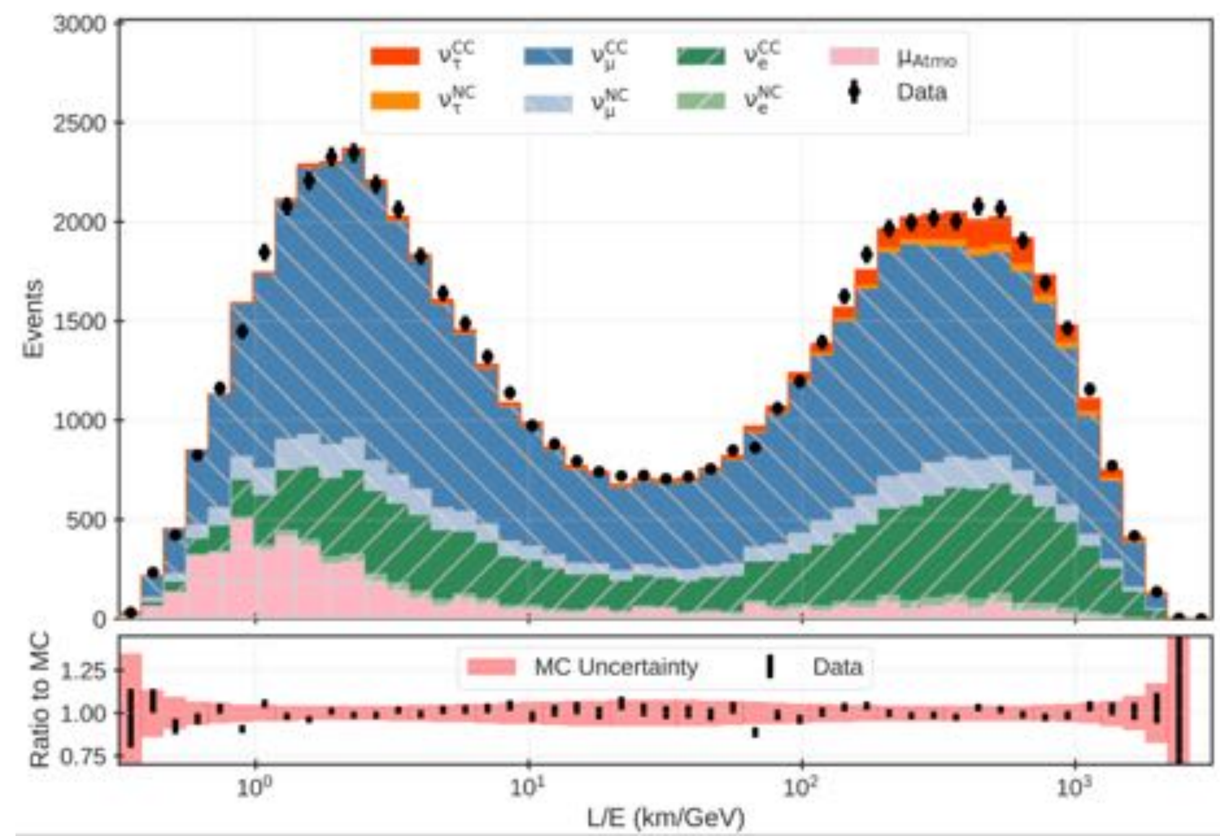


IceCube

- 5160 PMTs
- 17 m vertical spacing
- 86 strings
- 125 m string spacing
- 1 km^3 volume

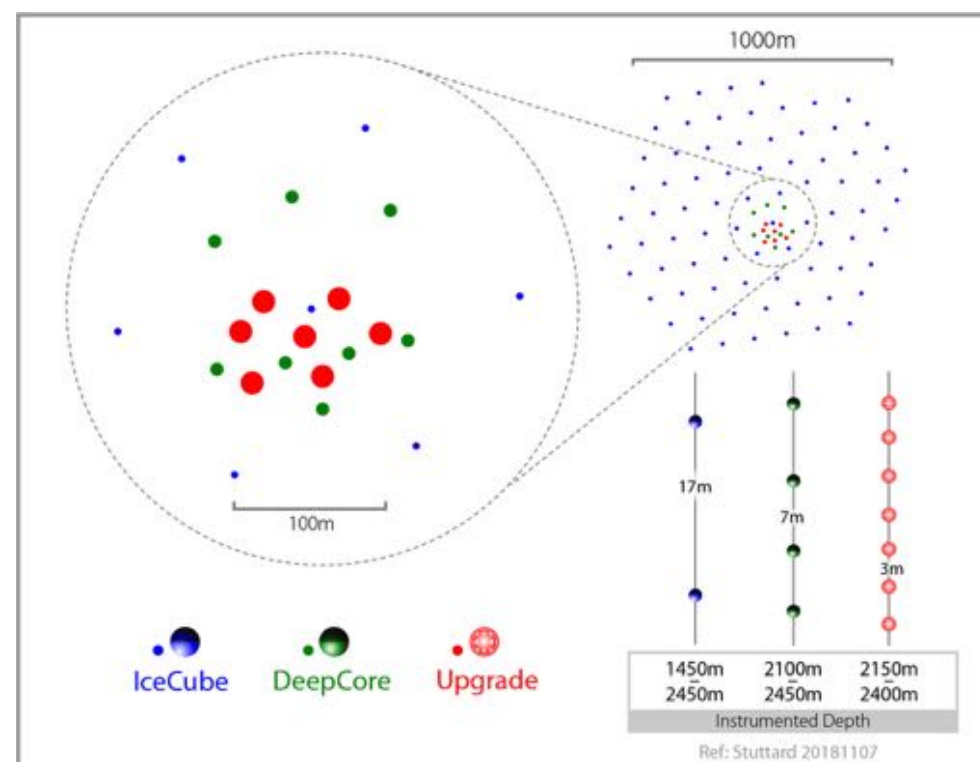
[2]

ν_τ appearance rate consistent with standard neutrino oscillations



Justin Evans, IceCube

- Important to constrain PMNS matrix unitarity in tau sector
  - not yet as constrained as e and μ sectors
- Upgraded IceCube detector expected to further enhance this program



Neutrino Mass Scale

- Oscillation measurements not sensitive to neutrino mass scale

Cosmology

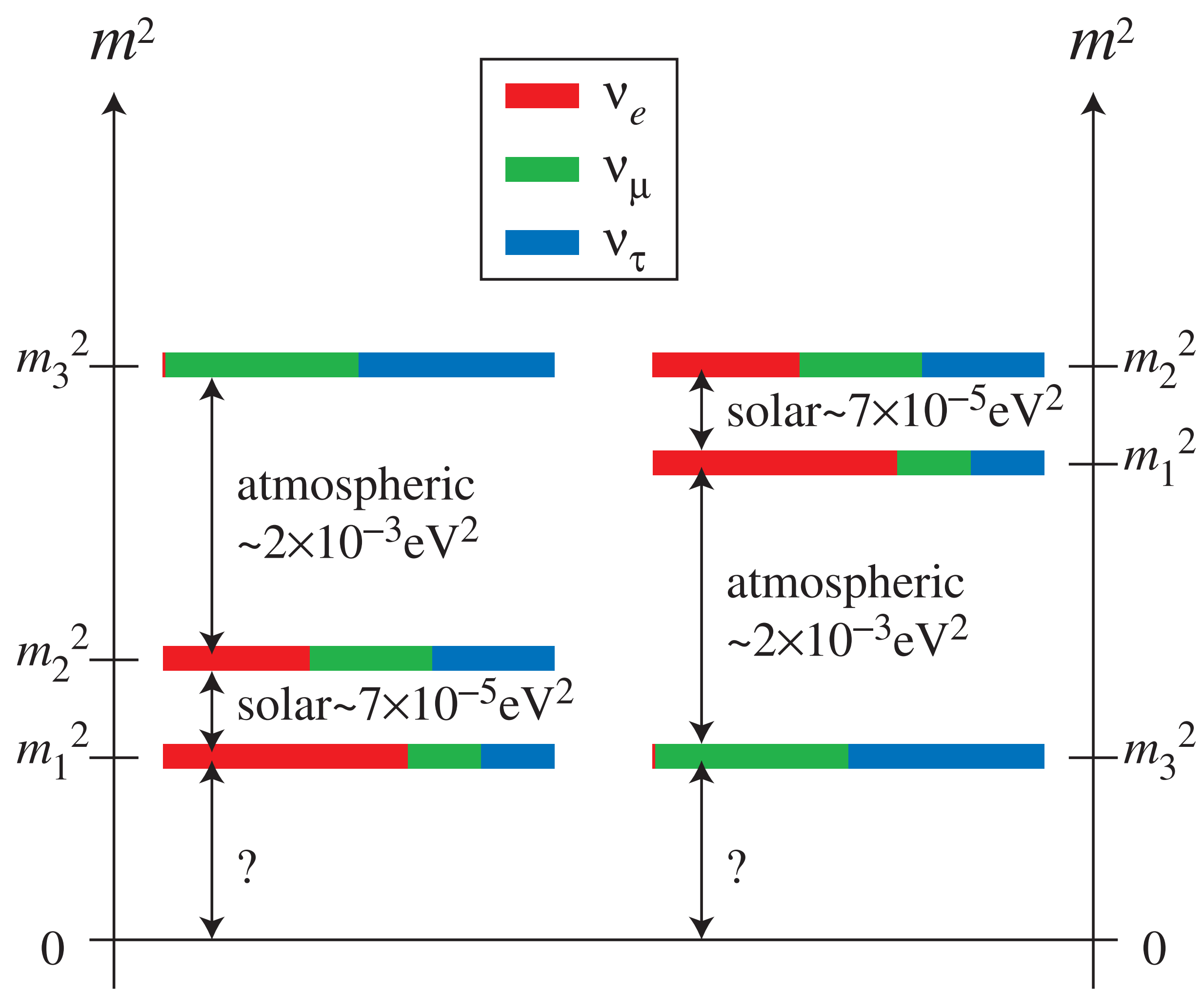
- ΛCDM
- $\sum_i m_i < 0.12 - 1$ eV

$0\nu\beta\beta$

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

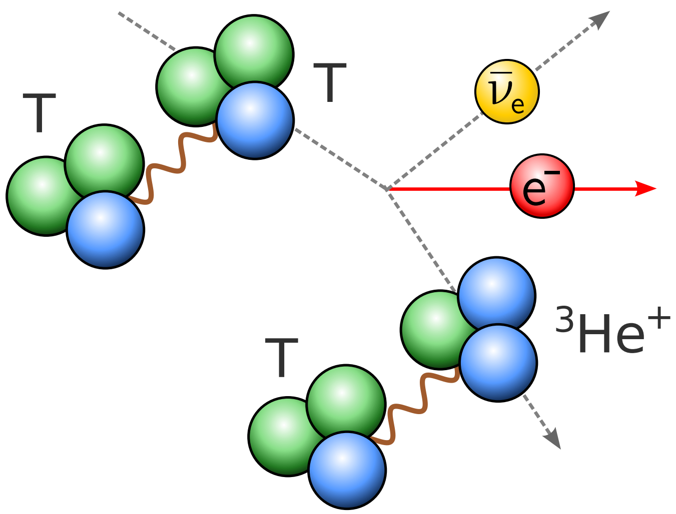
β-decay & EC

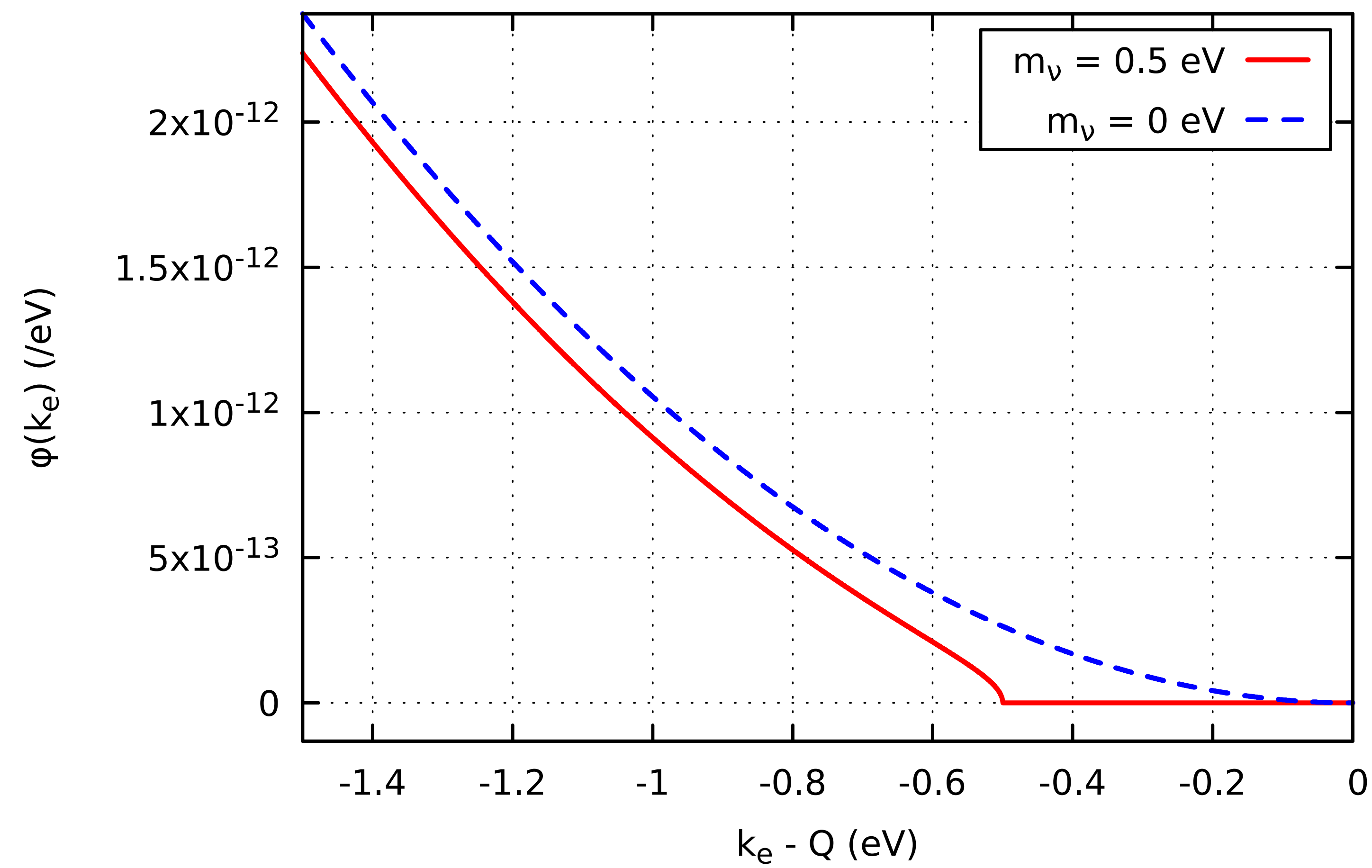
- Final states
- $\sqrt{\sum_i |U_{ei}|^2 {m_i}^2} < 2$ eV



Karlsruhe Tritium Neutrino experiment

- Analyse electron energy spectrum from molecular tritium β-decay
  - take advantage of vibrational and rotational energy





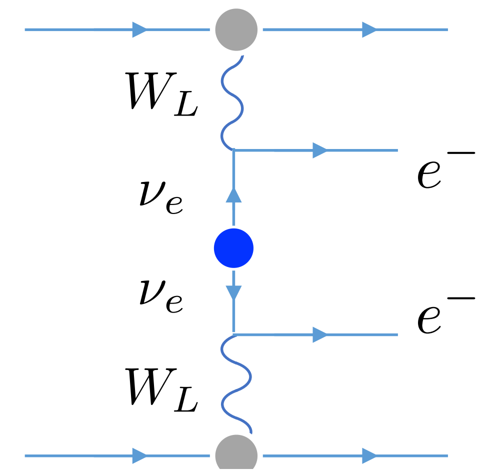
- 3-h run used to
  - test analysis framework
  - optimise source and spectrometer parameters
  - refine systematics

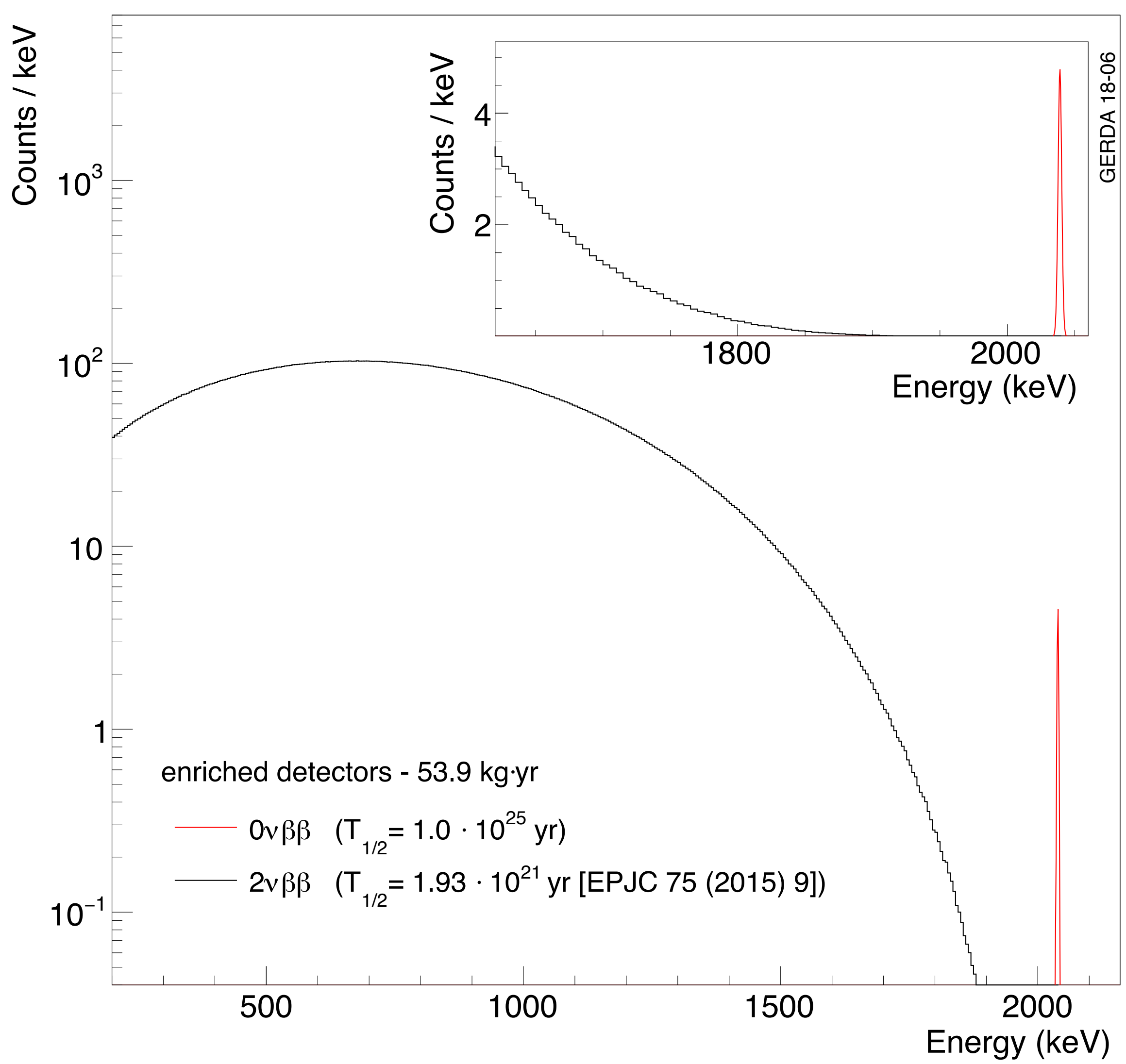
Valérian Sibille, KATRIN

- *Aim at sub-eV sensitivity*

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):

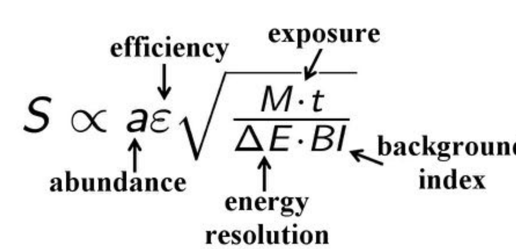
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \times \ |M_{0\nu}|^2 \times \ \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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



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: $(34.167 \pm 0.002)\%$

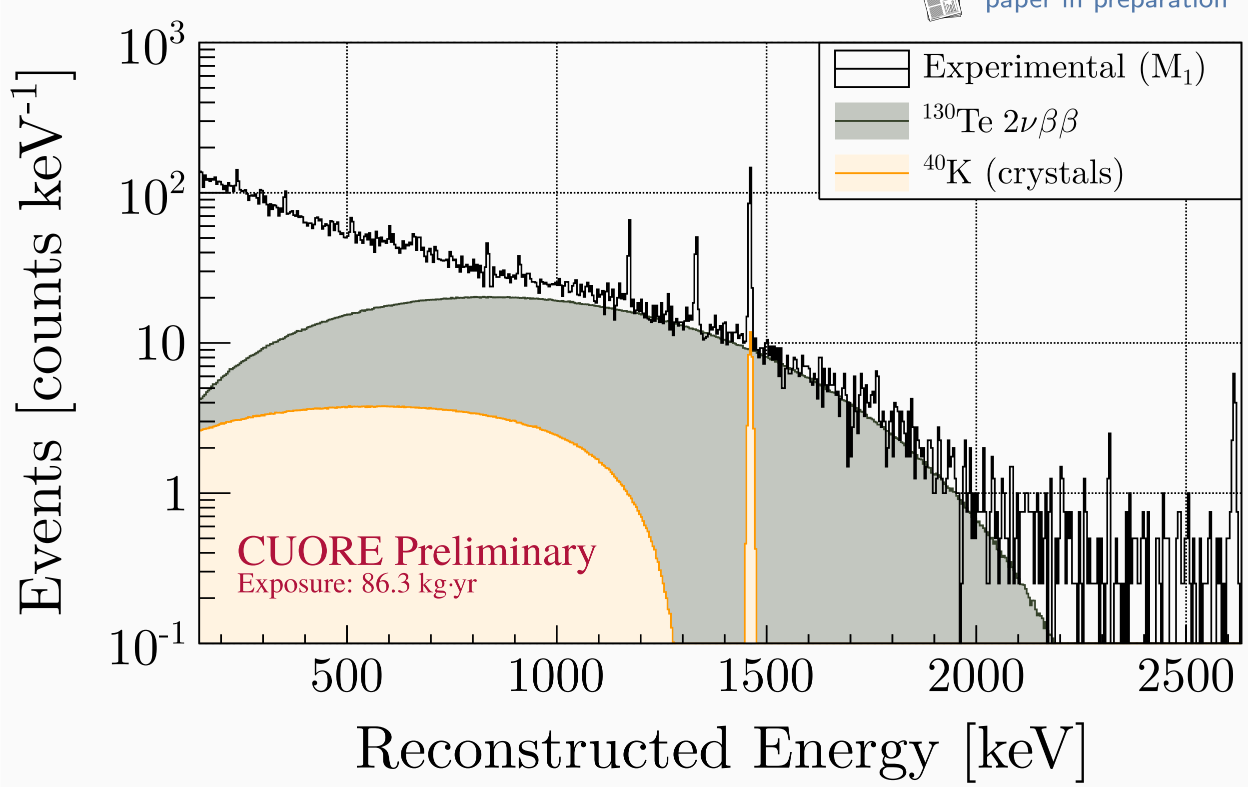
- Most precise 2νββ measurement
  - now almost the only source of background

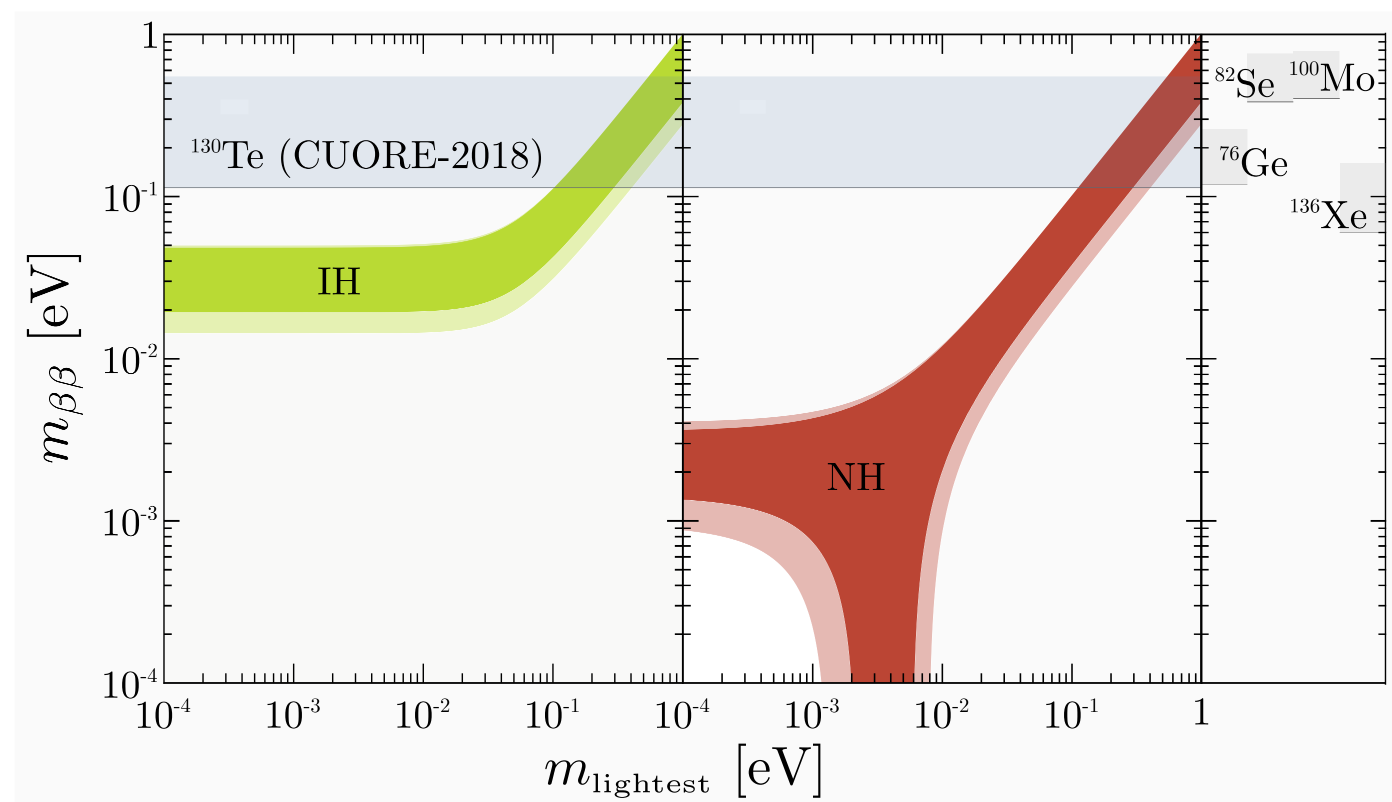
$t^{0\nu}_{1/2} > 1.5 \cdot 10^{25}$ yr @ 90% C. L.

- Energy resolution of 7.7 keV currently

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

paper in preparation





Stefano Dell'Oro, CUORE

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

0νββ with LEGEND detector

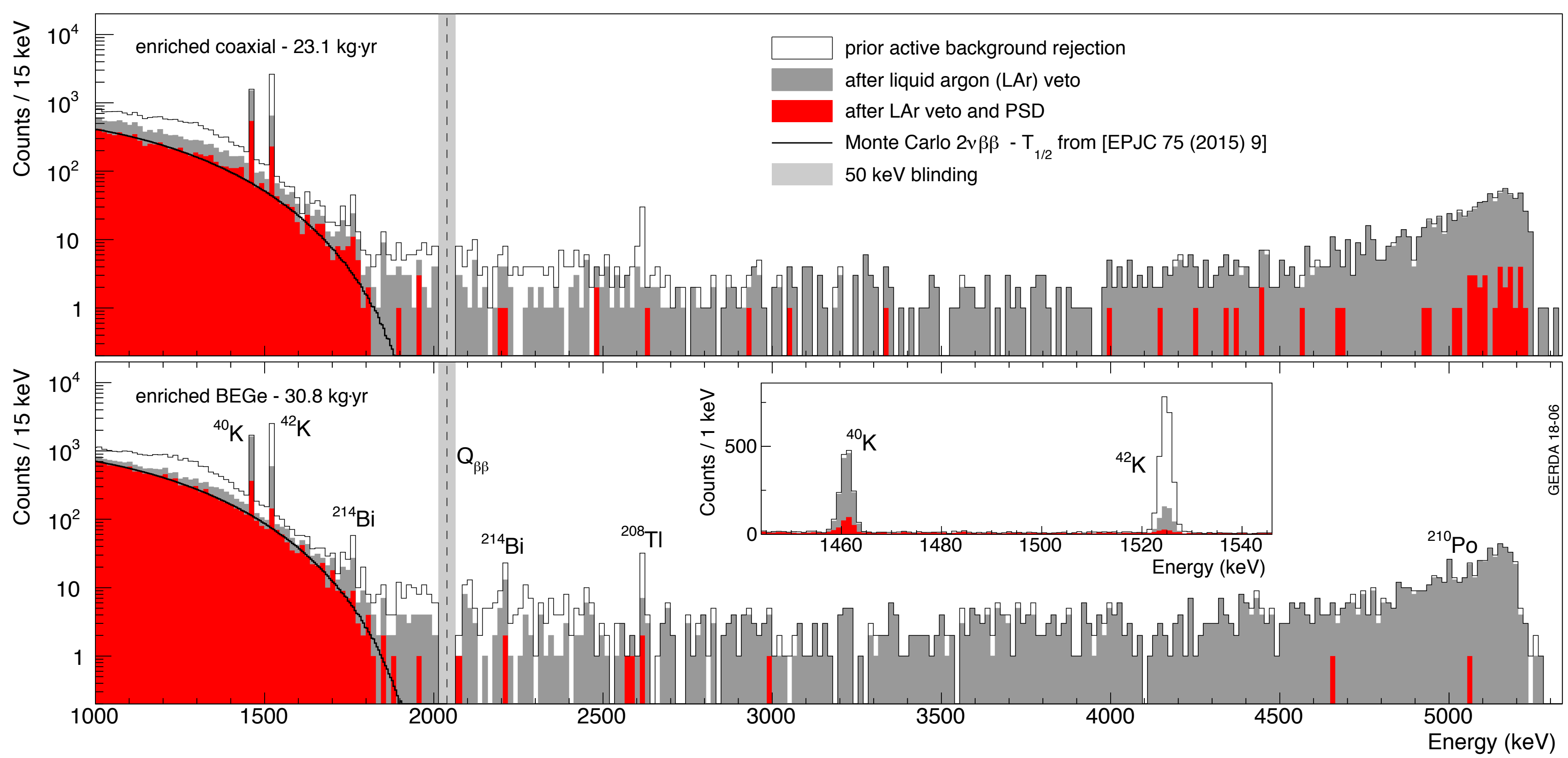
- Successor of GERDA and MAJORANA detectors using ^{76}GE
  - First stage with 200 kg of ^{76}GE aiming for 0.6 counts/t/yr

- Outstanding performance for GERDA and MAJORANA

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

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

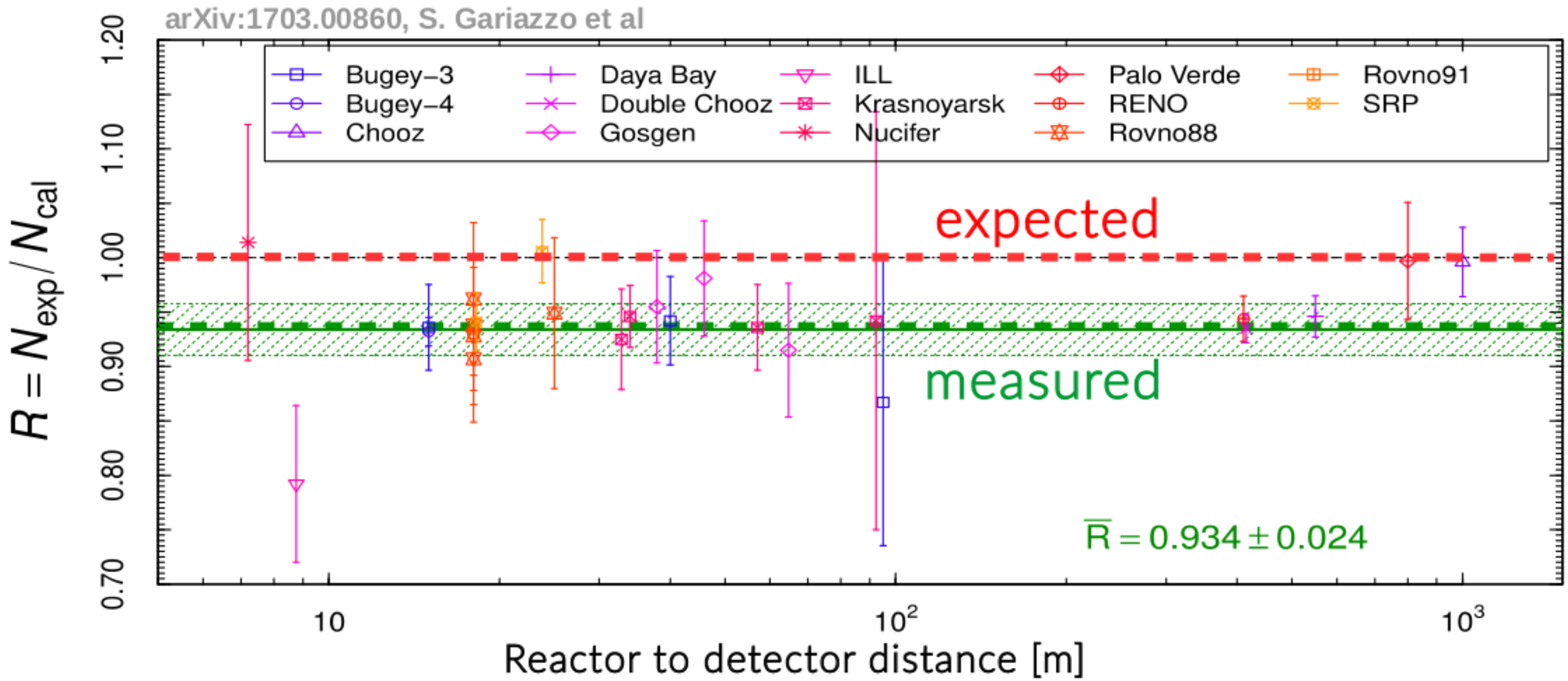
exploration of the $0\nu\beta\beta$ **decay at the** 10^{26} **yr scale**



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

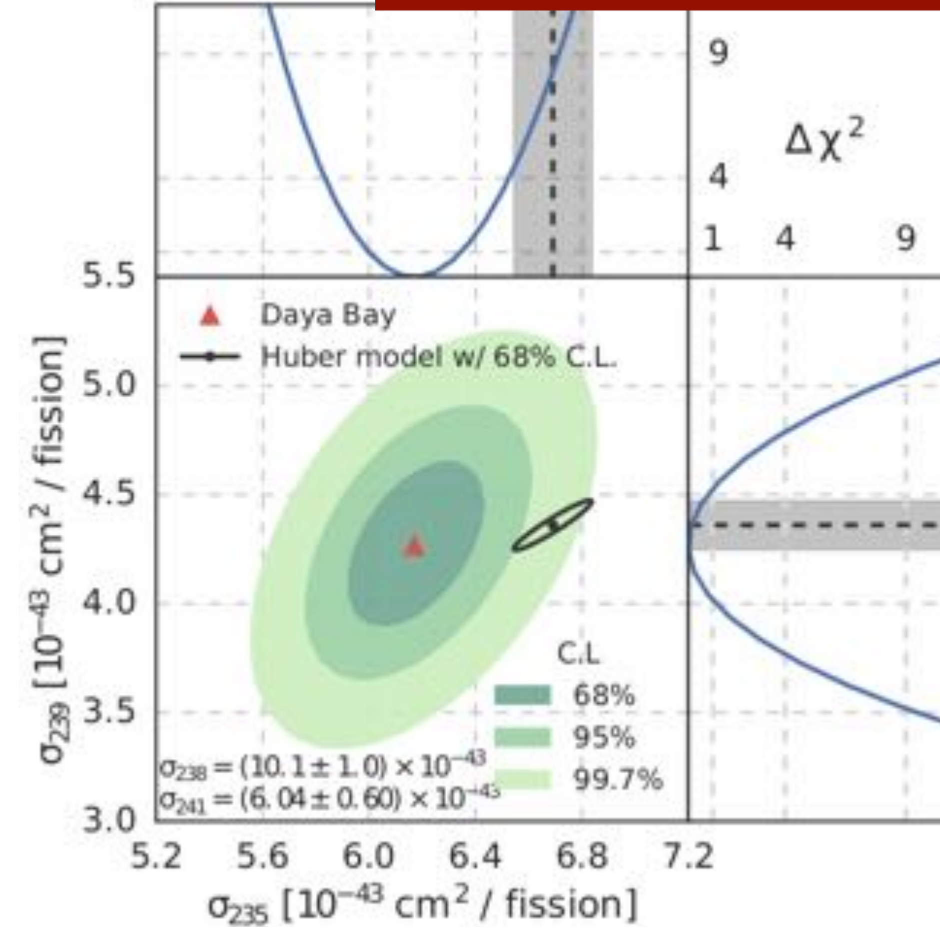


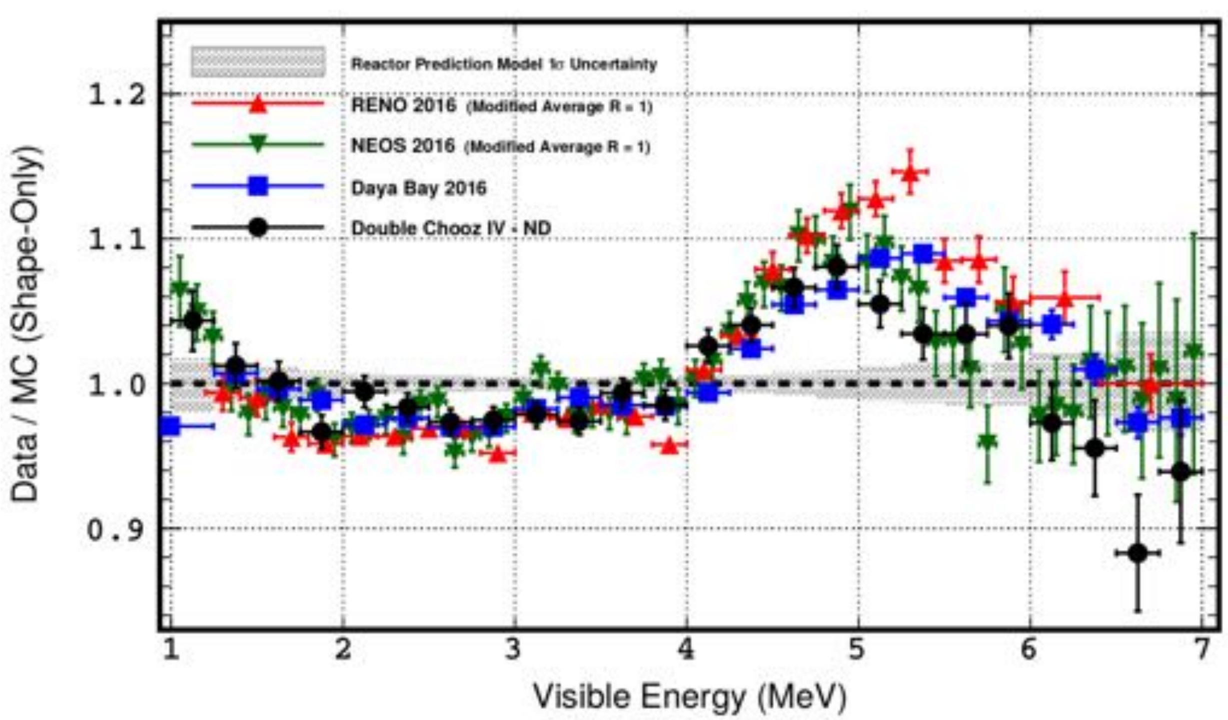
Reactor Anti-Neutrino Flux Anomaly (RAA)

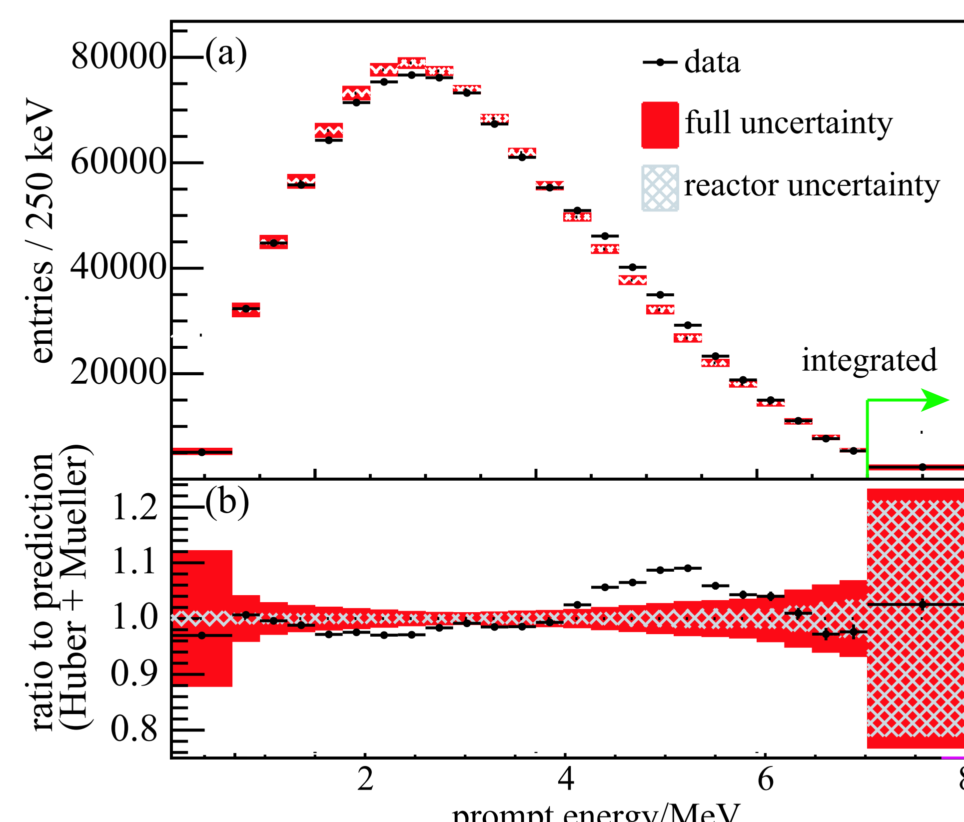
Flux Anomaly at Daya Bay

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







Sterile Neutrino as source of RAA

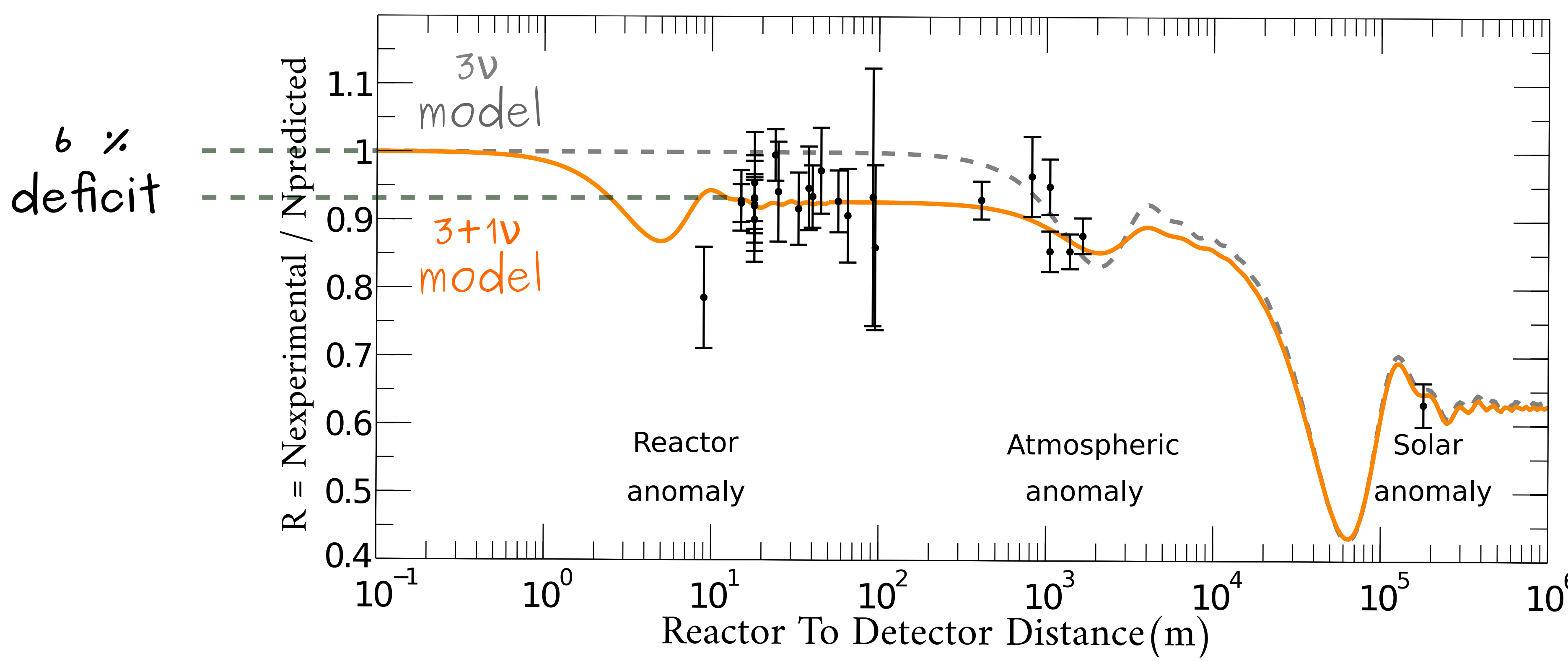
Introduction of a 4th neutrino adds a mixing with the $\bar{\nu}_e$:

$$P_{\overline{\nu}_e \to \overline{\nu}_e}(E_{\overline{\nu}_e}, L) = 1 - \sin^2(2\theta_{new}) \sin^2\left(1.27 \frac{\Delta m^2_{new}[eV^2] L[km]}{E_{\overline{\nu}_e}[MeV]}\right)$$

Suggested oscillation parameter best fit by RAA :

- $\Delta m^2_{new} = 2.3$ eV^2
- $\sin^2(2\theta_{new}) = 0.14$

3+1 scenario fits better the experimental data points :



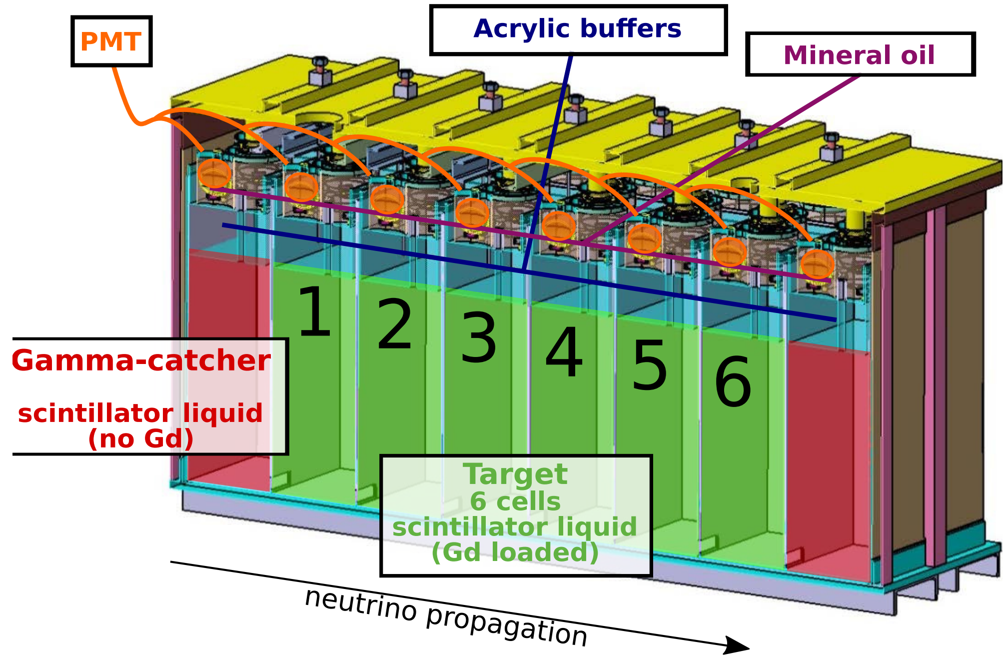
Laura Bernard, MORIOND, March 19, 2019

▹ Addressing RAA provides a mean to verify the sterile neutrinos hypothesis

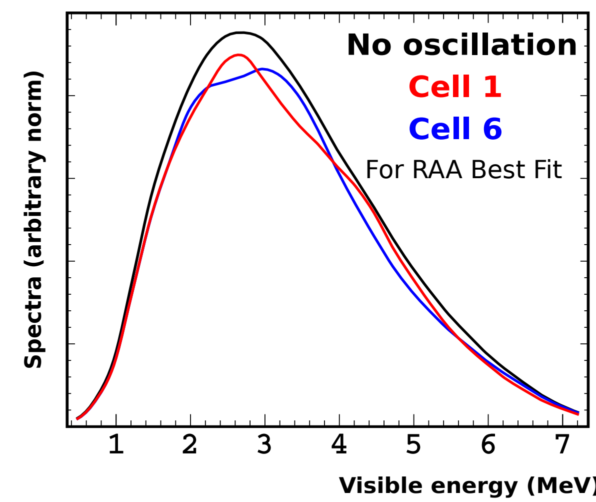
RAA with STEREO at Grenoble

Research reactor core $\sim$ 58 MW_{th}
$\rightarrow 10^{19}\ \bar{\nu}_e\ s^{-1}$

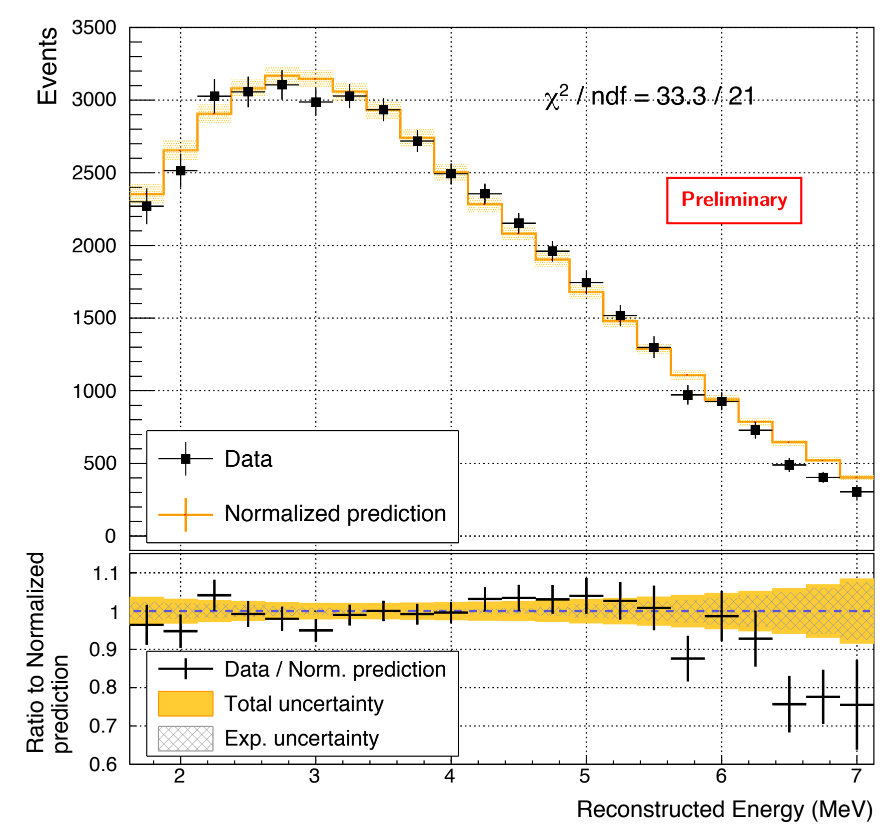
- **Compact** core (⌀40cm × 80cm)
- **Highly enriched** ^{235}**U** (93%)
- **Short baseline** measurement: 9.4m $< L_{core} <$ 11.2m



Laura Bernard , STEREO



- ▷ 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.



Perspectives toward even higher accuracy:

- ☐ Refined tuning of the MC
- ☐ Complementary calibration observable (source at 6 MeV (Am-C), Boron 12 spectrum ...)
- ☐ Improved background rejection (NN for cuts optimization)

RAA with PROSPECT at Oak Ridge

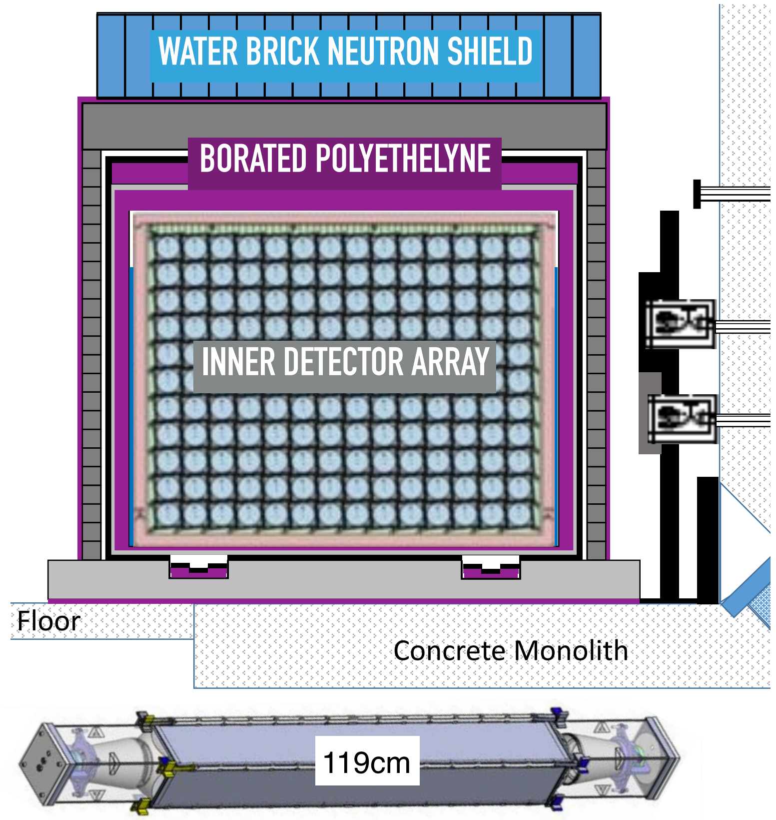
>99% of flux from ^{235}U

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

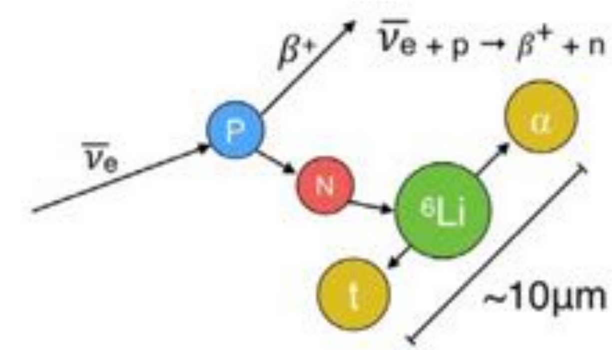
11 x 14 (154) array of optically separated segments

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

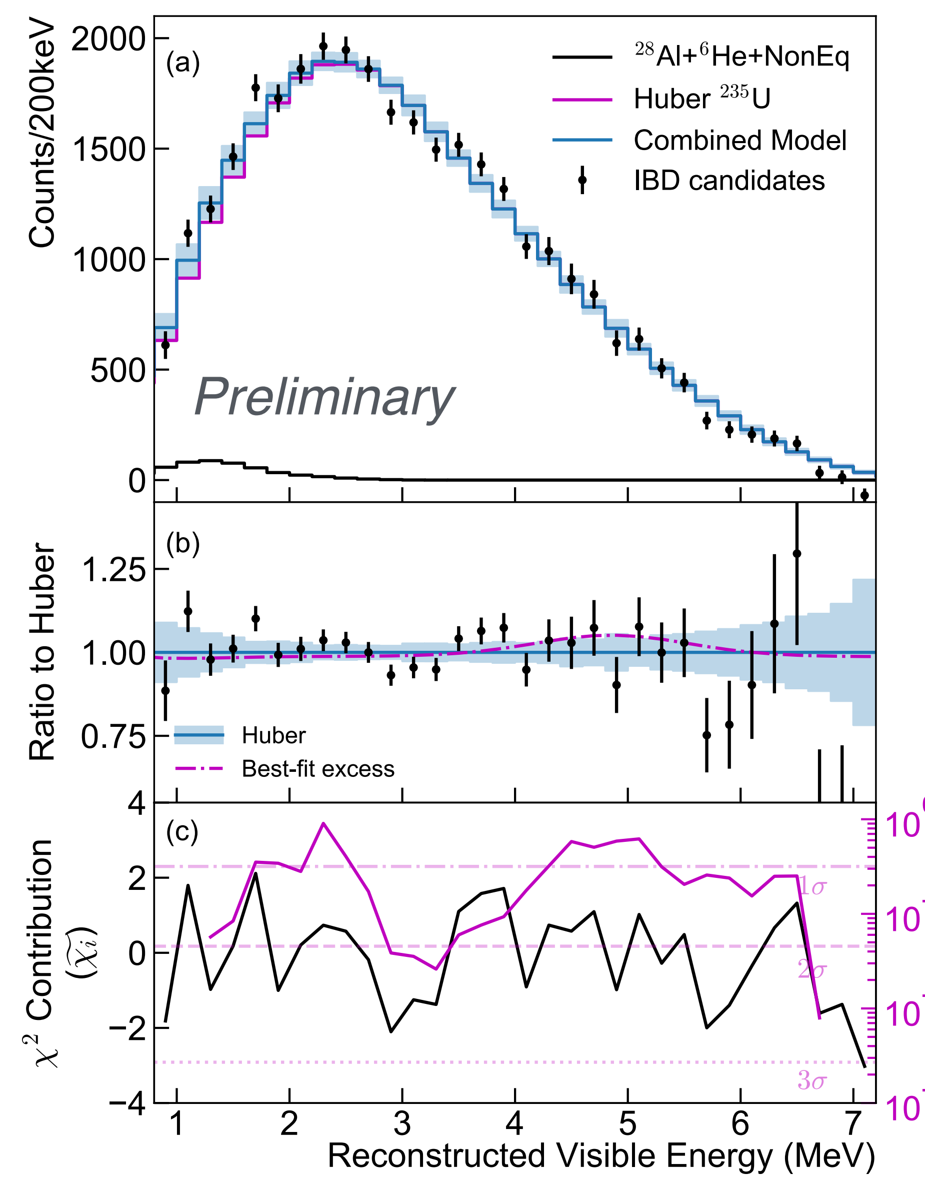
Double ended PMT readout, with light concentrators
good light collection and energy response
~5%√E energy resolution
full X,Y,Z event reconstruction



Karsten Heeger , PROSPECT

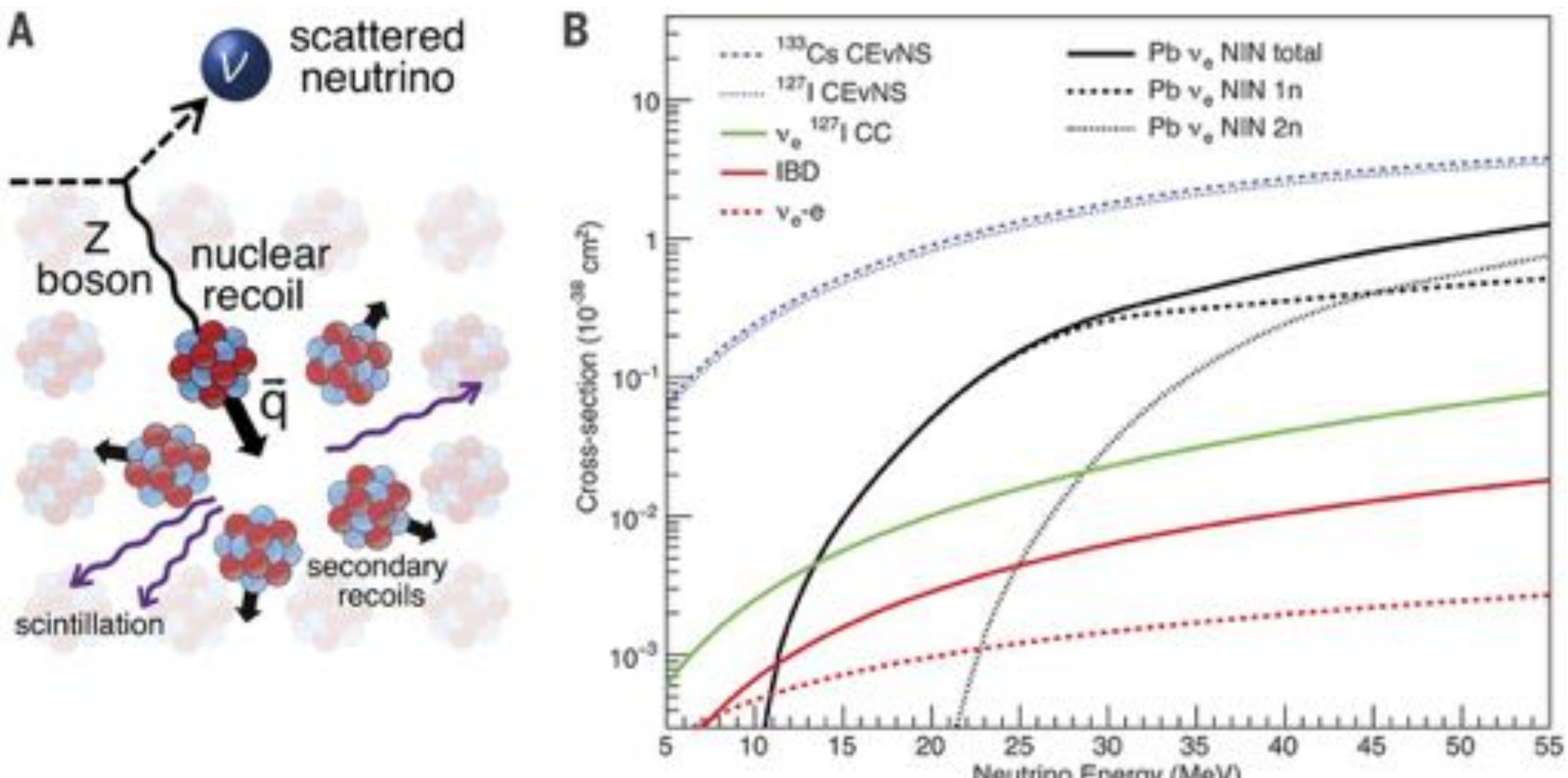


- Same approach as STEREO via spectral distortion
- Spectral shape: Huber model broadly agrees with spectrum but exhibits large chi2 and not a good fit
- Best-fit hypothesis of Sterile neutrino preferred by RAA disfavoured at >95% C.L.



CEvNS: **C**oherent **E**lastic **v**eutrino **N**ucleus **S**cattering

- A different process that can be used to investigate the flux anomaly
  - coherent scattering of low-energy neutrons
- Predicted in 1974 and measured in 2017 by COHERENT experiment

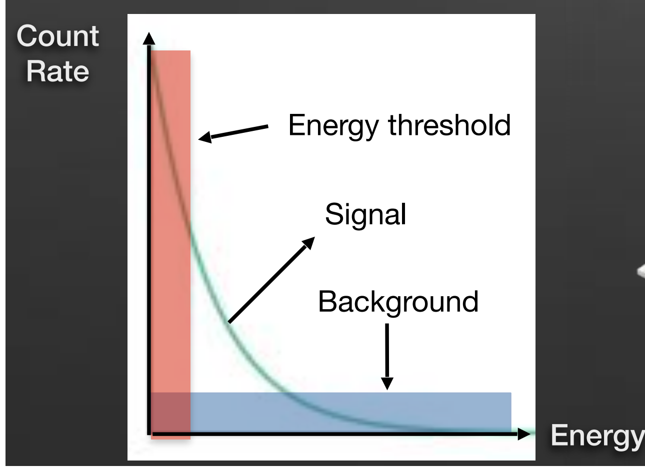


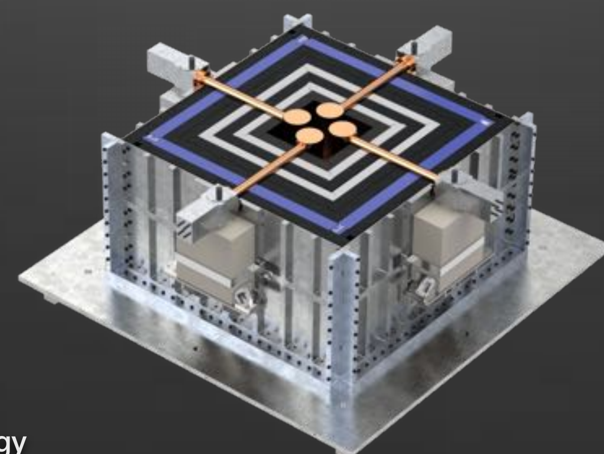
D. Akimov et al. Science 2017;357:1123-1126

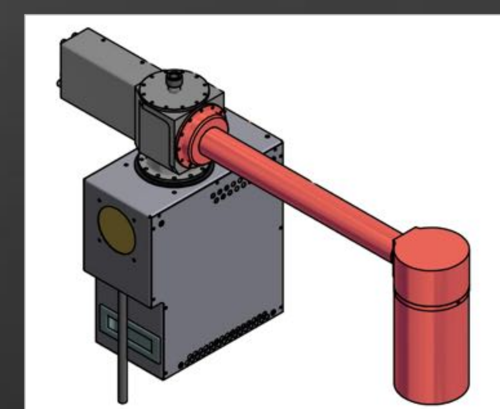
- An important background for Dark Matter experiments
  - currently a sub-dominant background for Xenon-1T
  - But can become important for next generation Darwin experiment

RAA with CONUS at Brokdorf (GE)

2. Low background environment (material selection, shielding)
3. Low energy threshold (~keV): Scintillating crystals, Ge-spectrometer, liquid noble gases







- ▹ Results still statistically limited

Preliminary

Counting analysis (~300-550 keV)	Counts
Reactor OFF (65 kg d)	354±19
Reactor ON (417 kg d)	2405±49
ON-OFF **New**	133±130

Prediction for quenching factor 0.25: 117 counts

- ▹ Unlikely to tackle RAA due to small mass

Christian Buck, CONUS

Energy (and Intensity) Frontier

High-Luminosity Colliders

Energy Frontier after Higgs Discovery

- Intense scrutiny of Higgs and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak and QCD

$$+|D_\mu\phi|^2 - V(H)$$

Higgs properties
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \mathrm{h.c.}$$

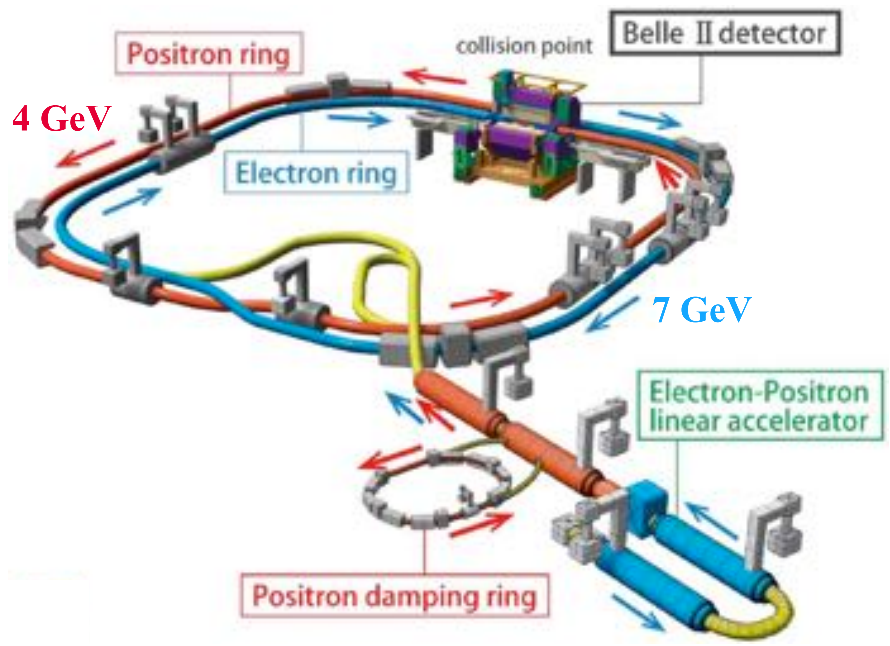
Higgs coupling to bosons and fermions
CKM matrix and CP Violation

- While keeping a wide open eye on new phenomena

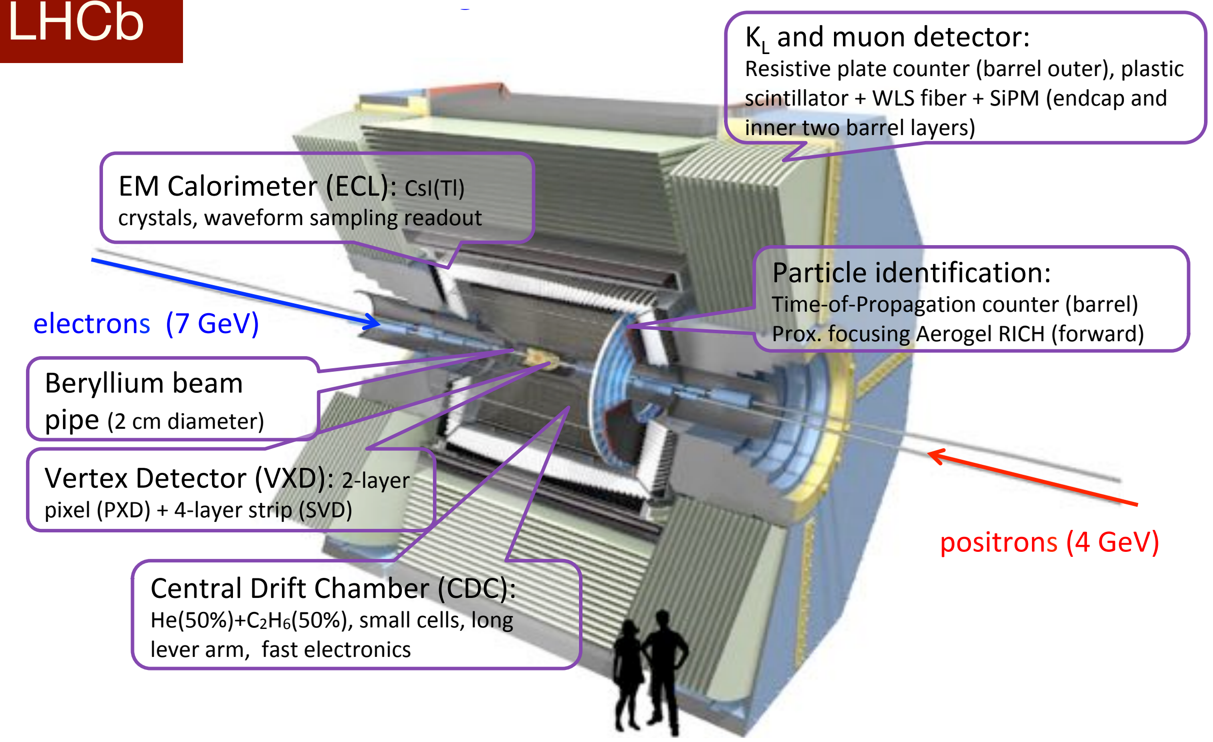
$$+\mathcal{L}_{New}$$

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

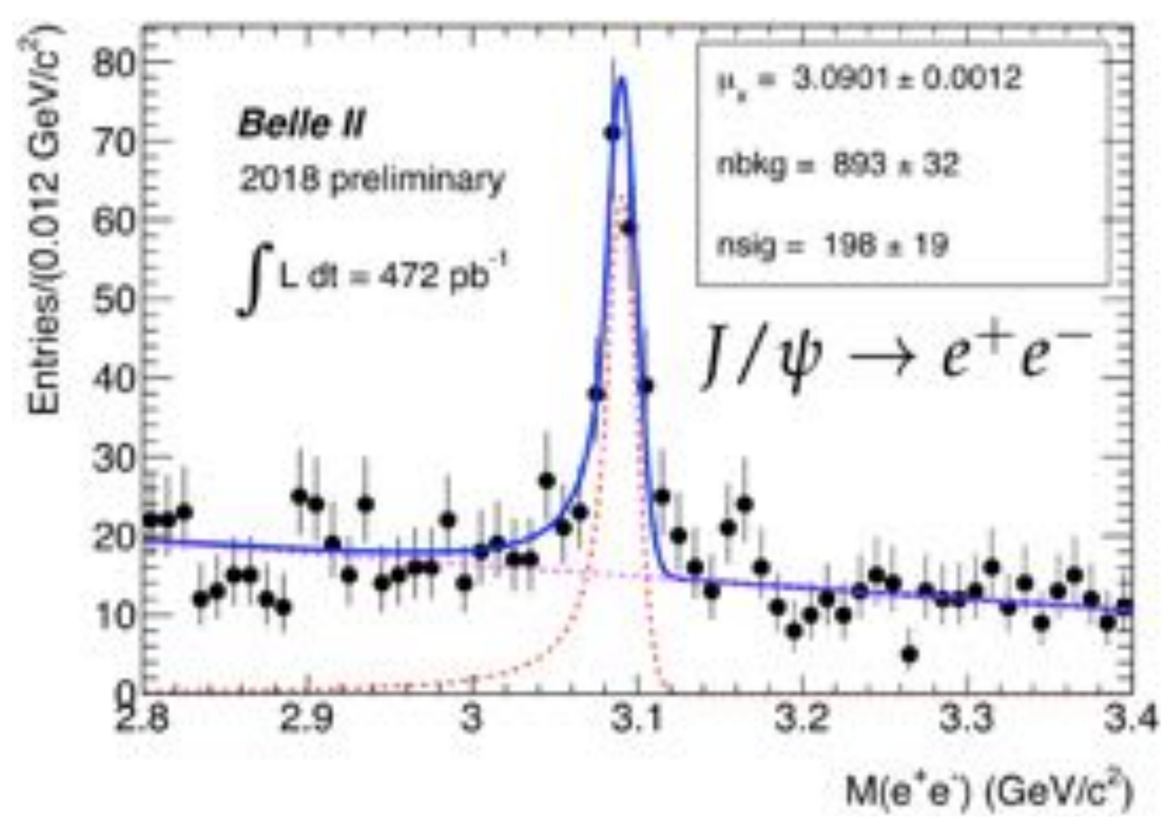
BELLE-II at SuperKEKB getting ready

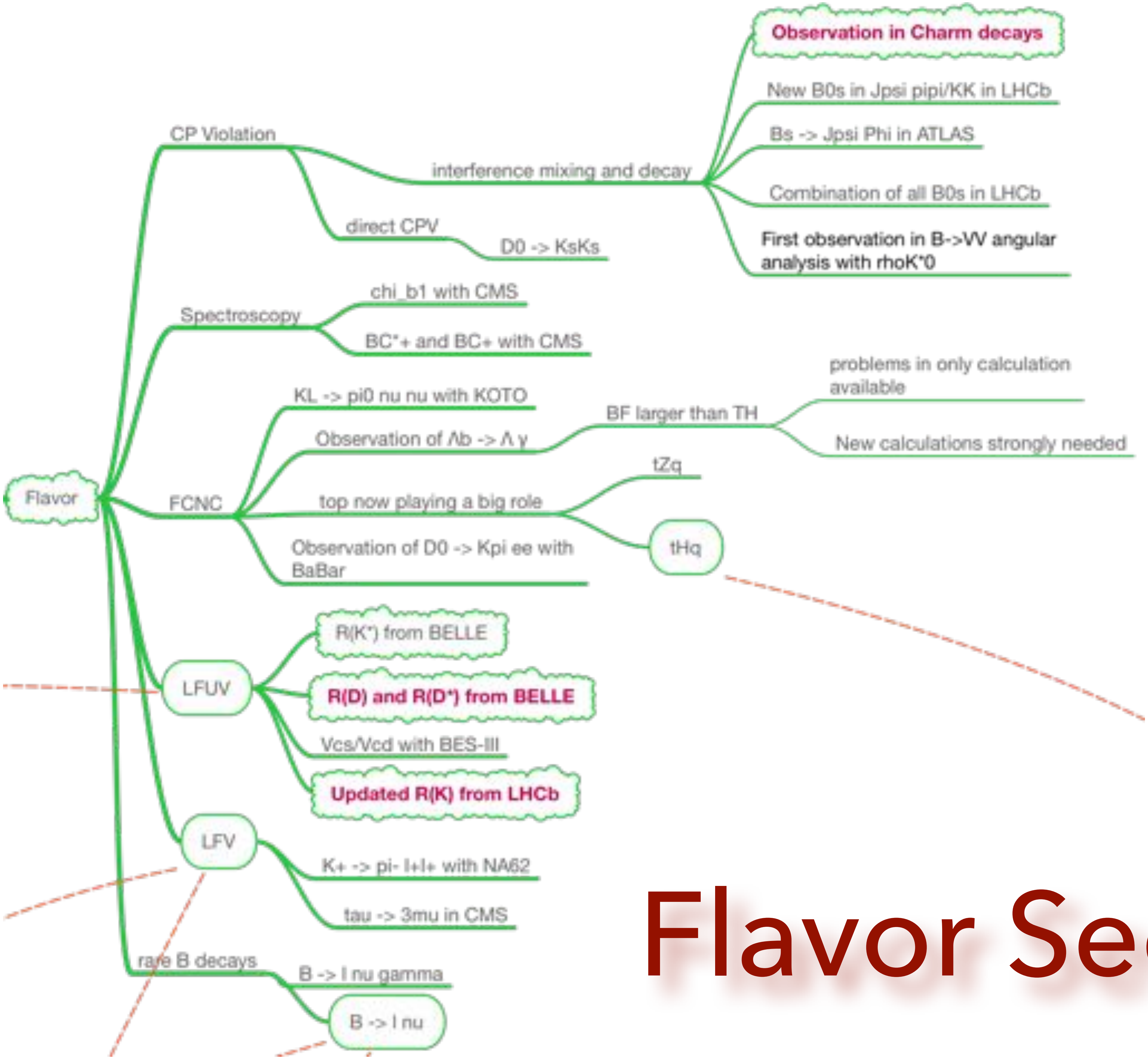


Gagan Mohanty , LHCb



- First new particle collider after LHC!
- Commissioning run in 2018 with partial vertex detector
  - new collisions by end of this week
  - Aiming for 10 fb^{-1} by Summer 2019 and 50 fb^{-1} within next 12 months
  - Reaching design instantaneous luminosity of 8 x 10^{35} cm^{-2} s^{-1} in 4 years by 2024
- Performance of charged and neutrals in agreement with simulations
- Ambitious physics program targeting search for new phenomena with first 10 fb^{-1}



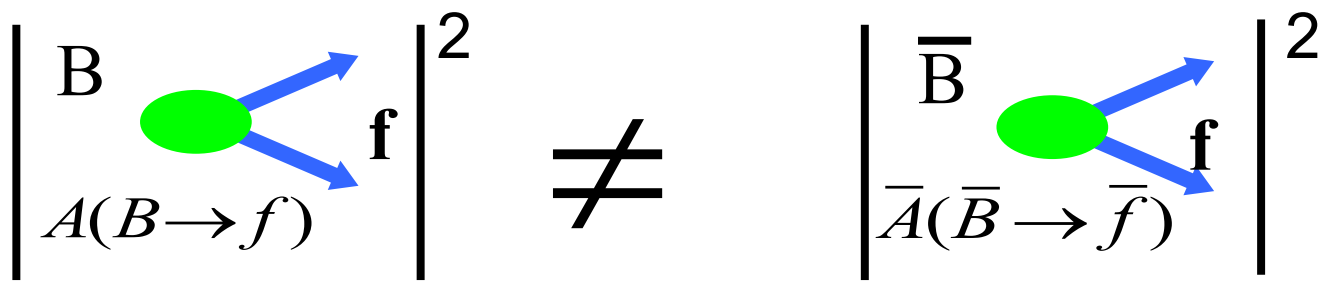


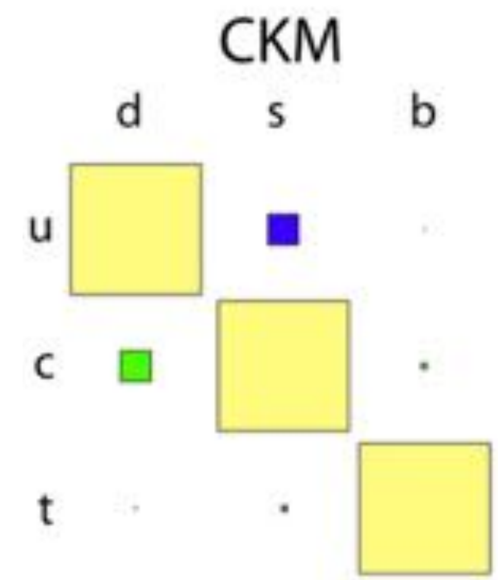
Flavor Sector

Matter - anti–matter Asymmetry

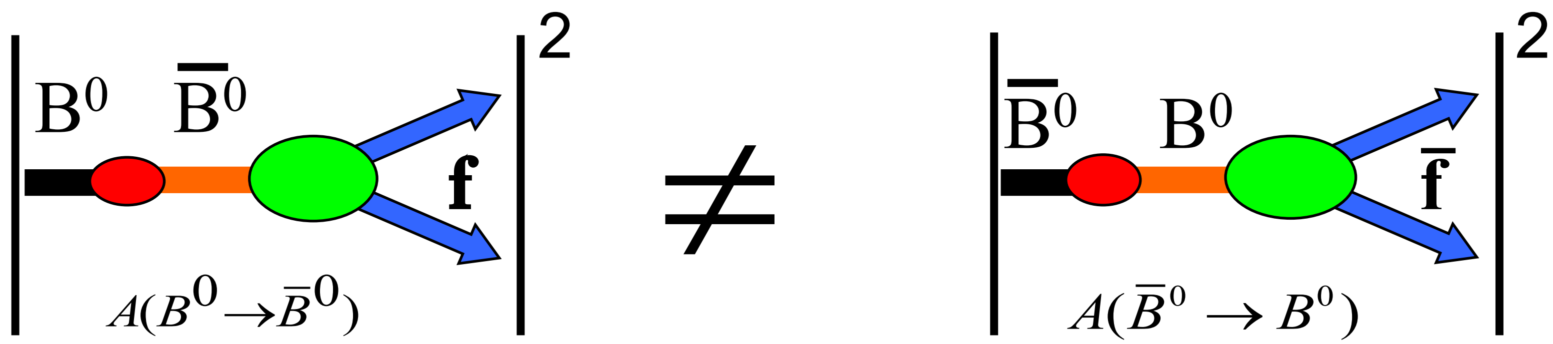
CP Violation

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

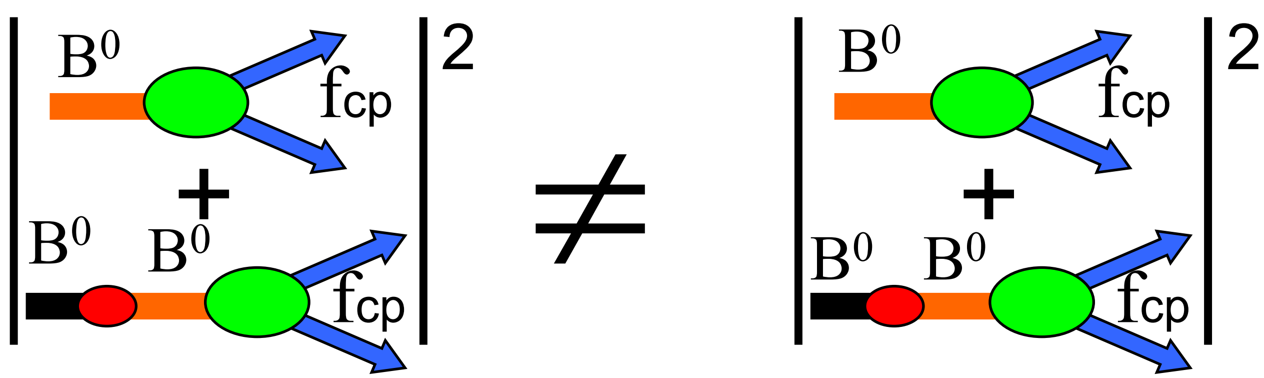




CP Violation in Mixing

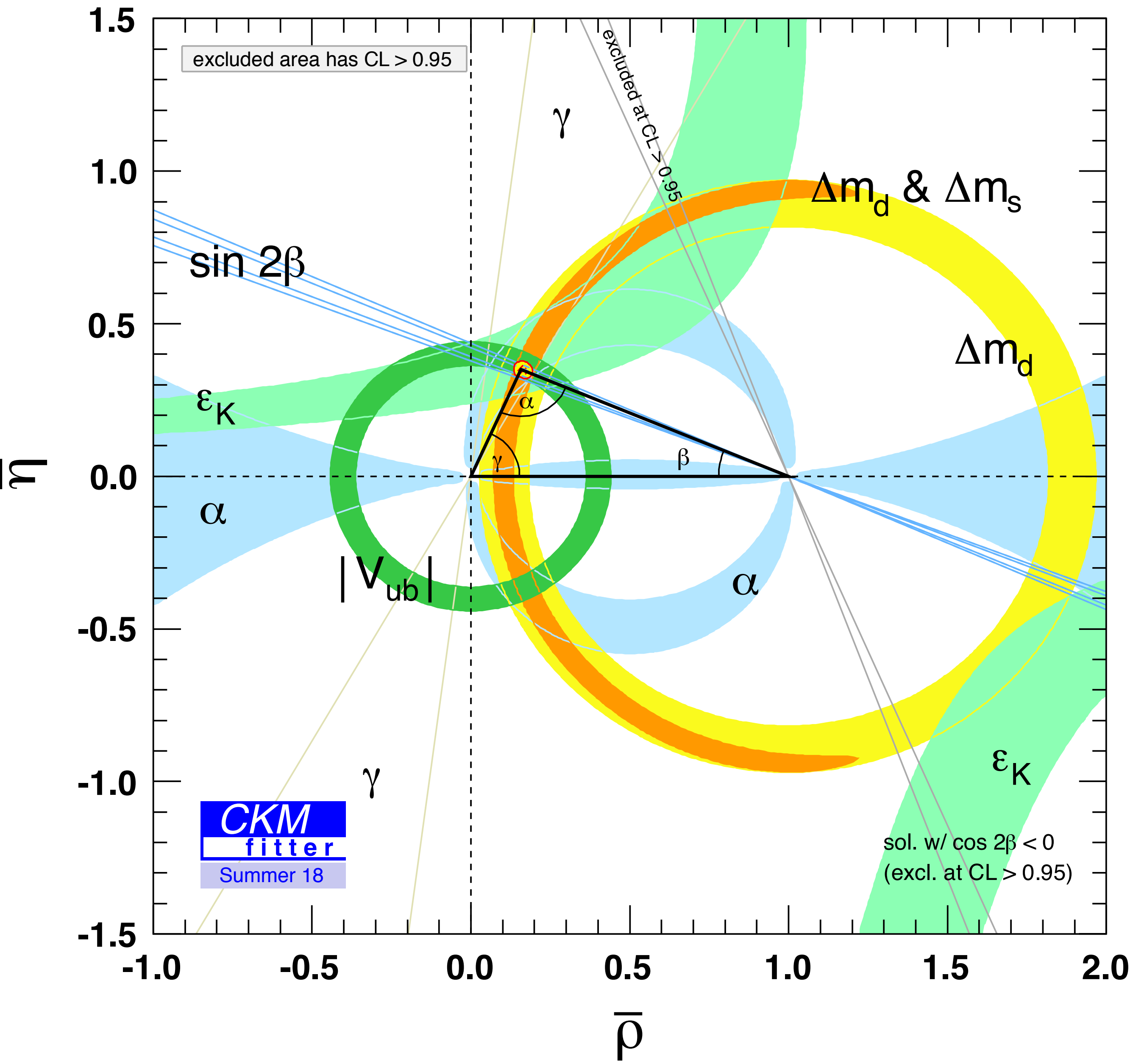


CP Violation in interference between Mixing and Decay

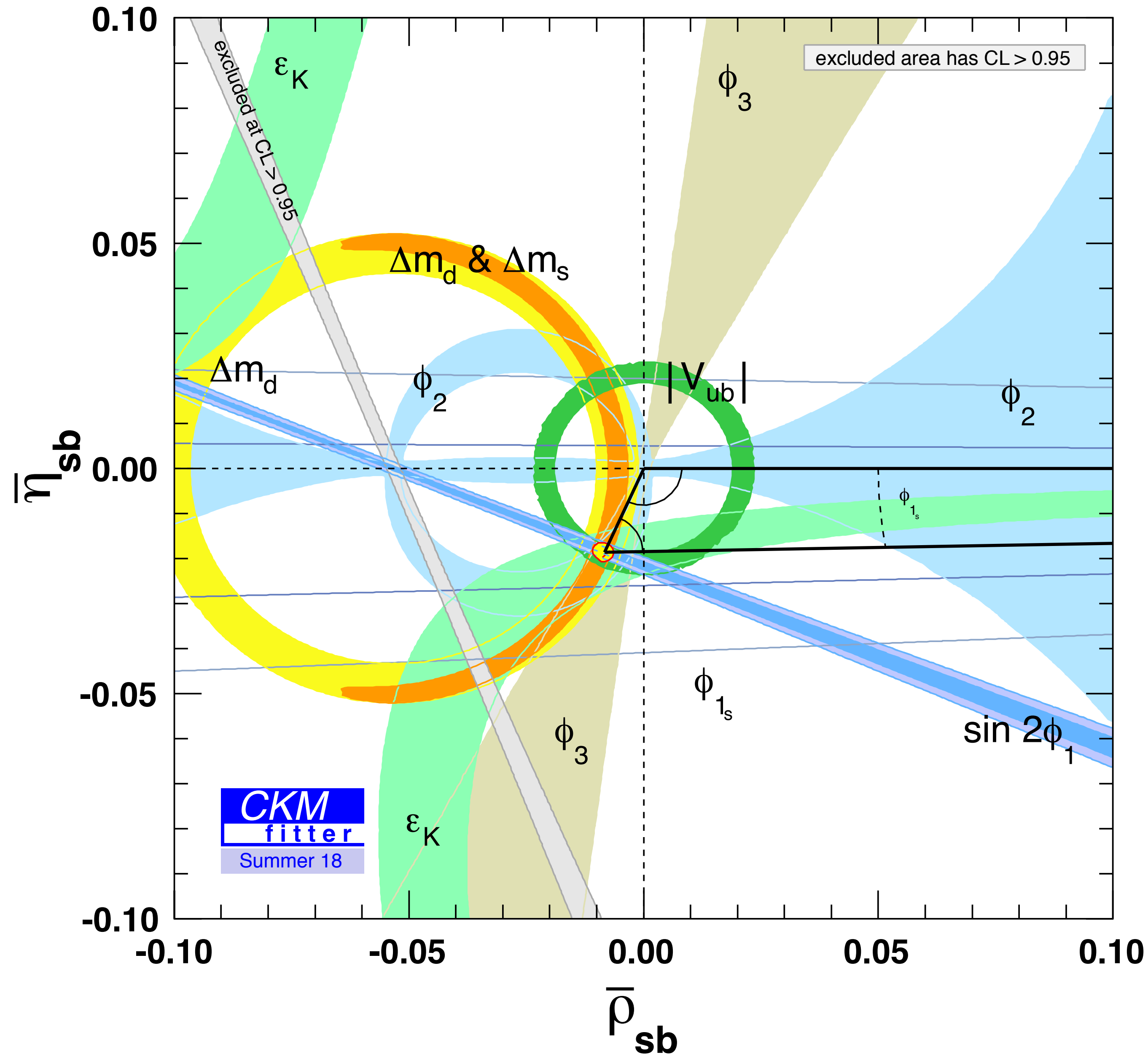


Unitarity Triangle(s)

B_d



B_s



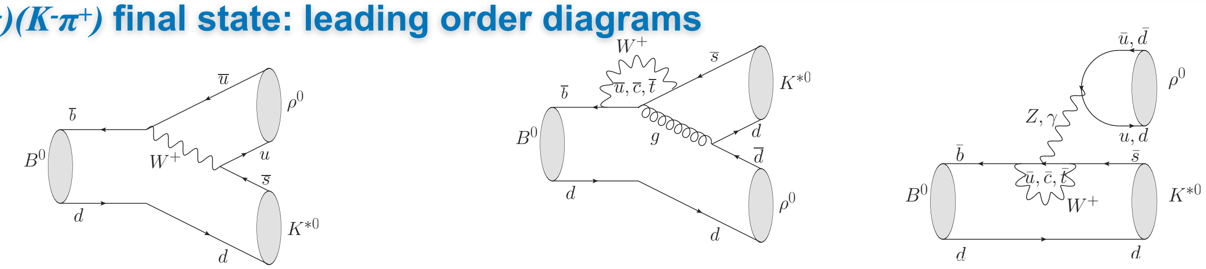
$$\phi_s^{SM} \approx -2\arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.03686\,^{+0.00096}_{-0.00068}\ \mathrm{rad}$$

- Probing new physics as enhancement in B_s CP Violation

Time-integrated CP Violation

- Full amplitude analysis in challenging final state $B^0 \to \rho^0 K^*(892)^0$
  - sensitive to gluon and electroweak penguins
  - challenging combinatorial background and pollution from $B^0 \to a_1(1260)^- K^+$

$(\pi^+\pi^-)(K^-\pi^+)$ final state: leading order diagrams



Doubly Cabibbo suppressed Tree | **Gluonic-penguin** | **Electoweak-penguin**

Dominant contribution

Small longitudinal polarisation fraction

$$\tilde{f}^L_{\rho K^*} = 0.164 \pm 0.015 \pm 0.022$$

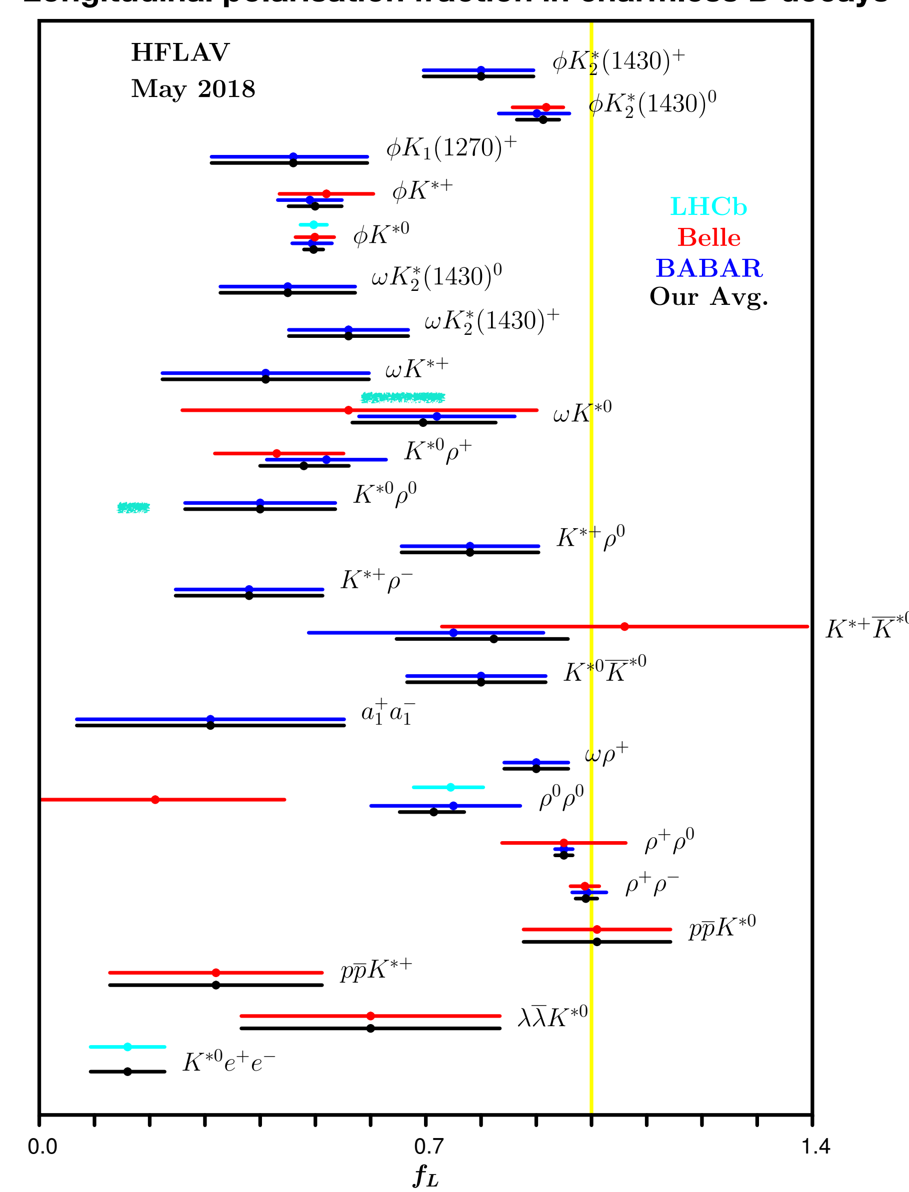
Large CP asymmetry: **first significant observation (5σ) of CP asymmetry** in angular distributions of B→VV decays

$$A^L_{\rho K^*} = -0.62 \pm 0.09 \pm 0.09$$

⇒ hint for a relevant contribution from the EW penguin diagram.

arXiv:1812.07008

Longitudinal polarisation fraction in charmless B decays



- Probing also direct CP violation in baryons
  - no experimental evidence so far compared to 20% theoretical prediction
- No hint of CPV in phhh (h=π,k) final states of Λ^0_b and Ξ^0_b

Emilie Bertholet, LHCb

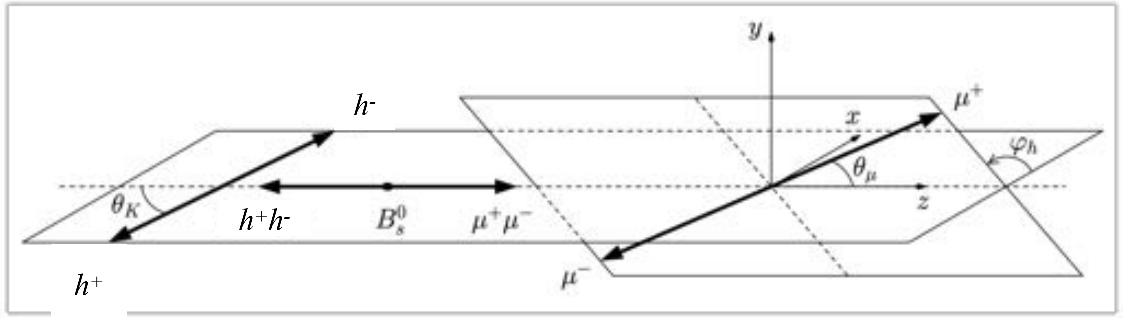
CP Violation in $B_s \to J/\Psi KK$

Ekaterina Govorkova, LHCb
Jennifer Zonneveld, LHCb

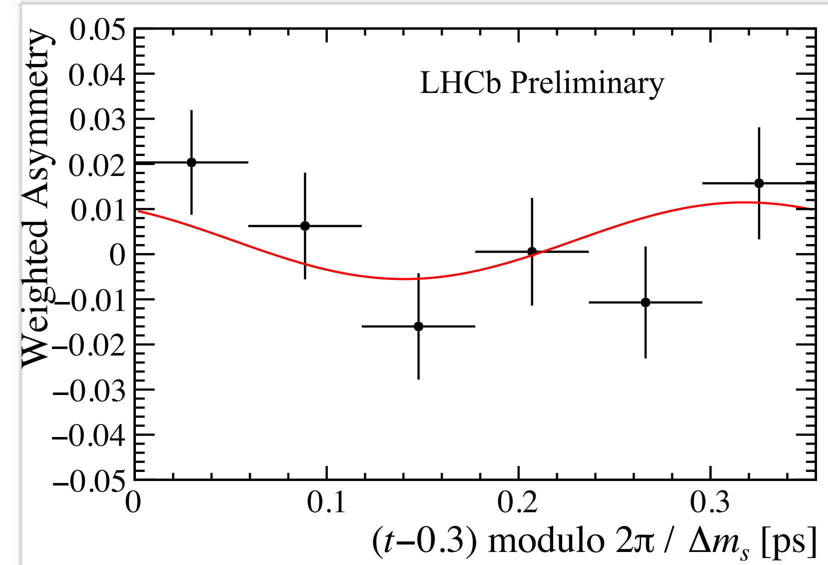
- Updated time-dependent angular analysis by adding 2016 data

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

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

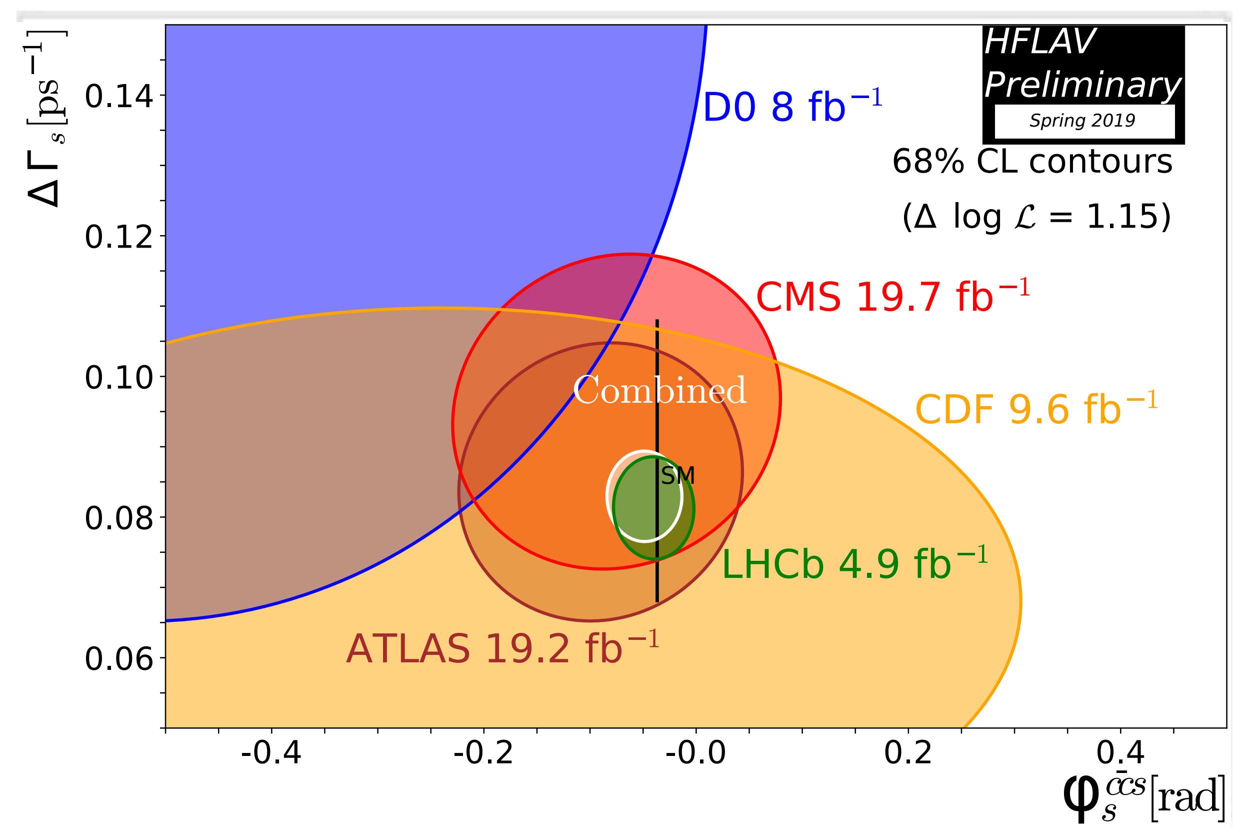


$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_s \to f}(t) - \Gamma_{B^0_s \to f}(t)}{\Gamma_{\bar{B}^0_s \to f}(t) + \Gamma_{B^0_s \to f}(t)} \sim \sin(\phi_s)\sin(\Delta m_s t)$$



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

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

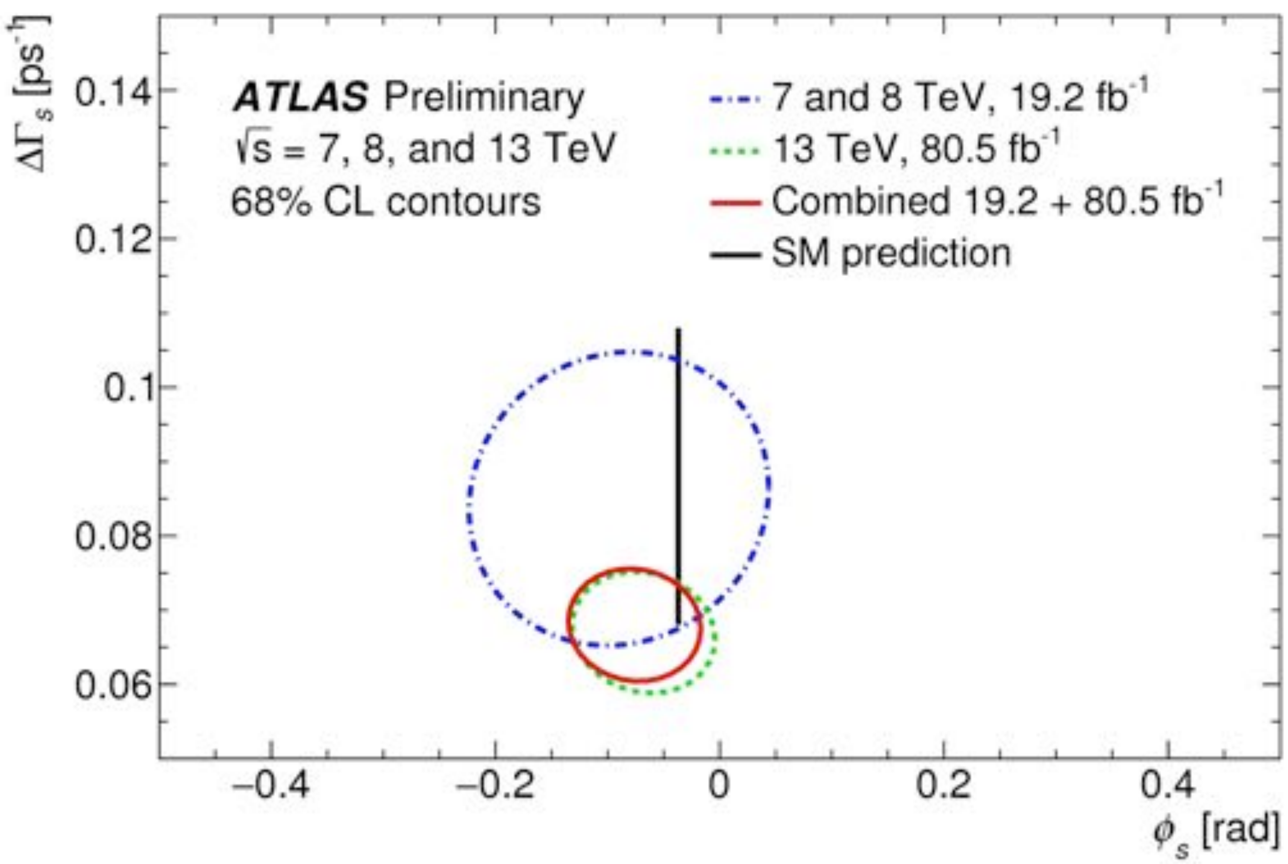


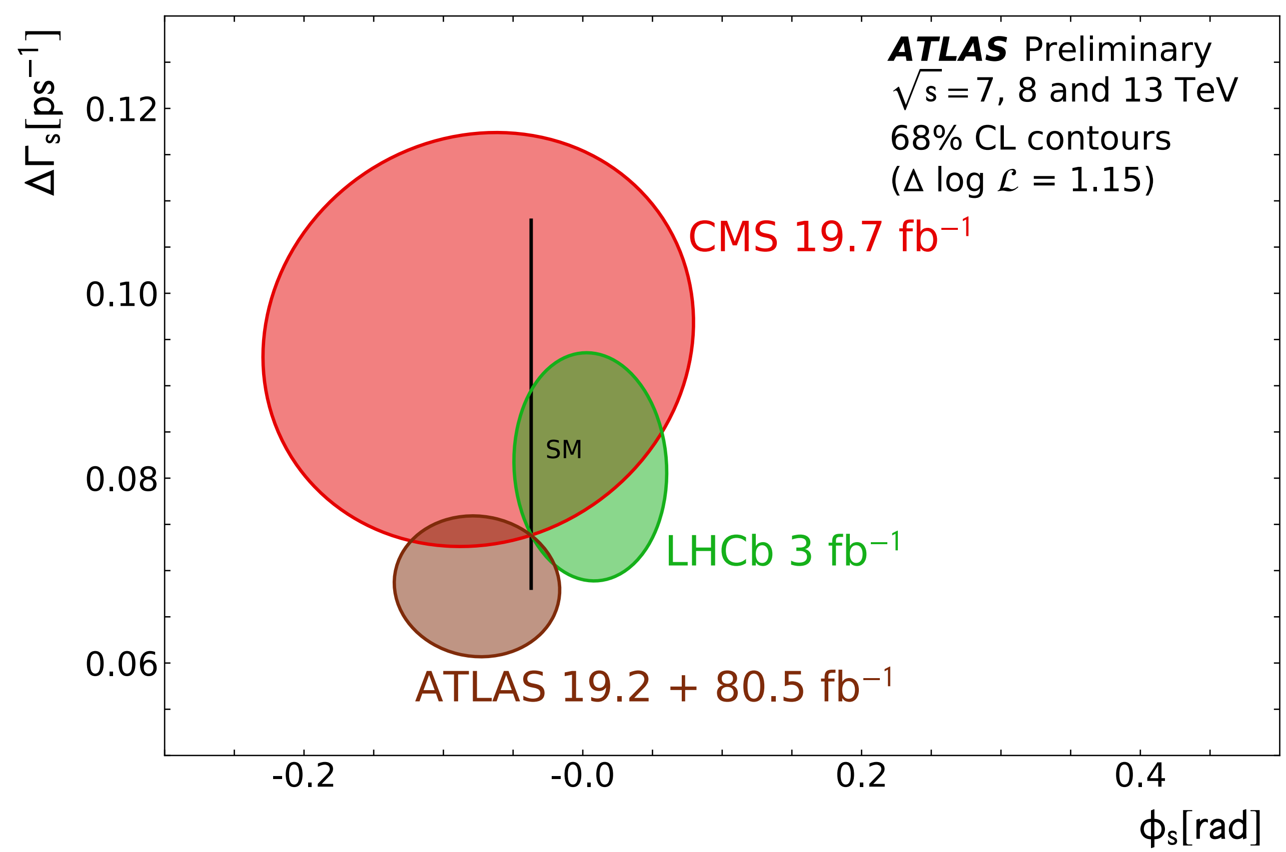
- No evidence for direct CPV
- Width and interference consistent with expectations

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*





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}]

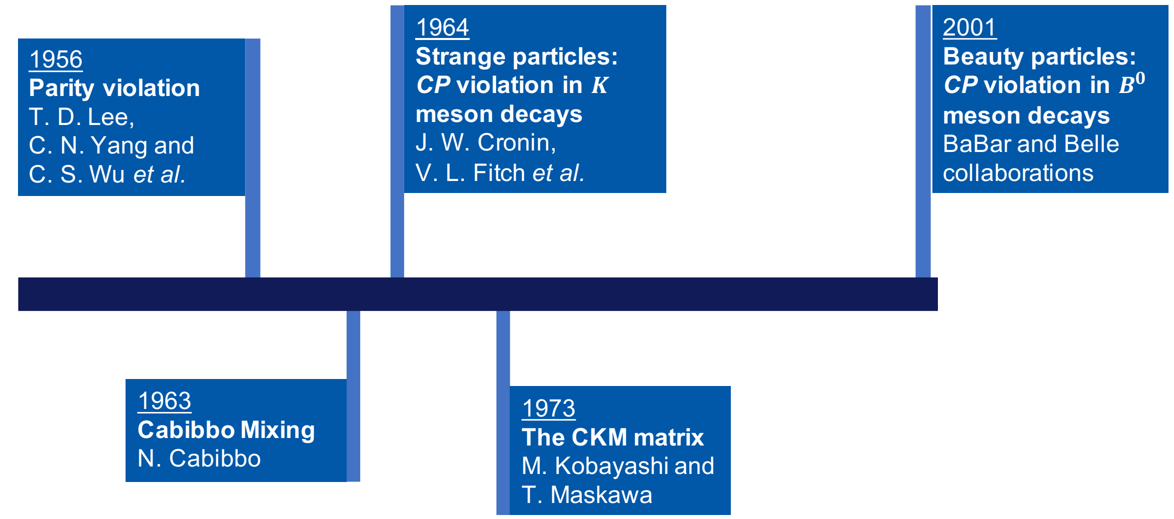
$\Gamma_s - \Gamma_{B^0} = -0.0024 \pm 0.0018$ [ps^{-1}]

ATLAS: Run1 + Run2

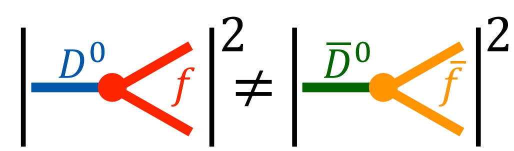
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.076	0.034	0.019
$\Delta\Gamma_s[ps^{-1}]$	0.068	0.004	0.003
$\Gamma_s[ps^{-1}]$	0.669	0.001	0.001
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S\rvert^2$	0.043	0.004	0.004
$\delta_\perp$ [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

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!



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

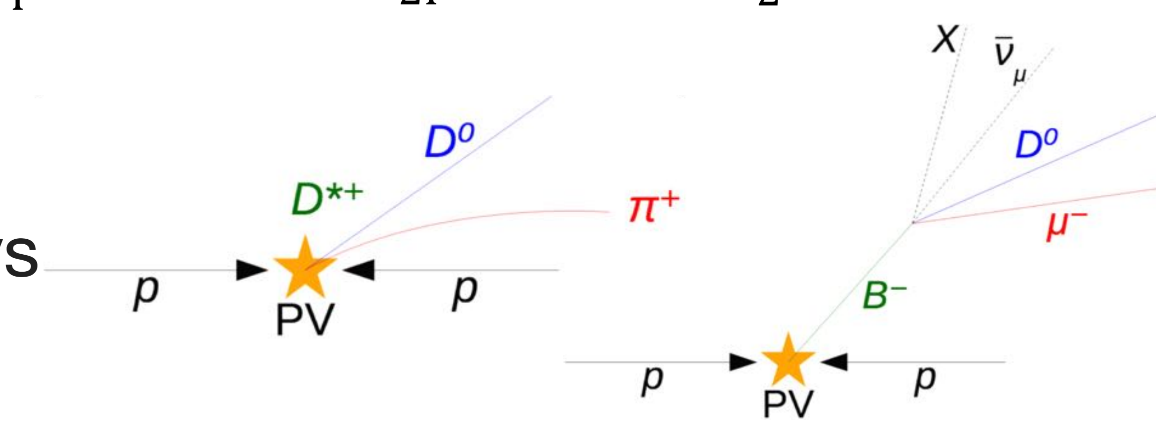


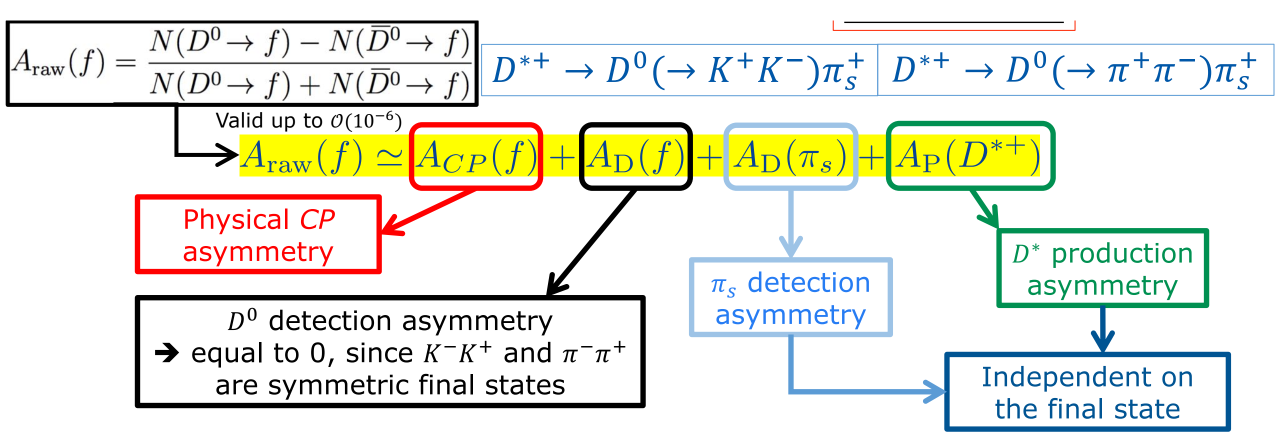
f =K⁺K⁻,π⁻π⁺

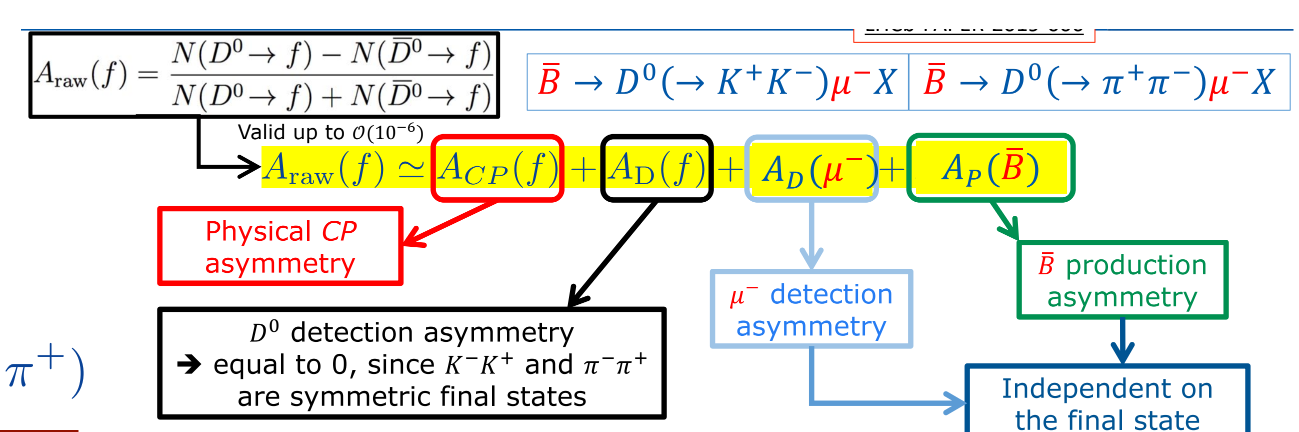
$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$
$$\simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle t \rangle}{\tau(D^0)} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{ind}$$

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

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







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

Federico Betti, LHCb

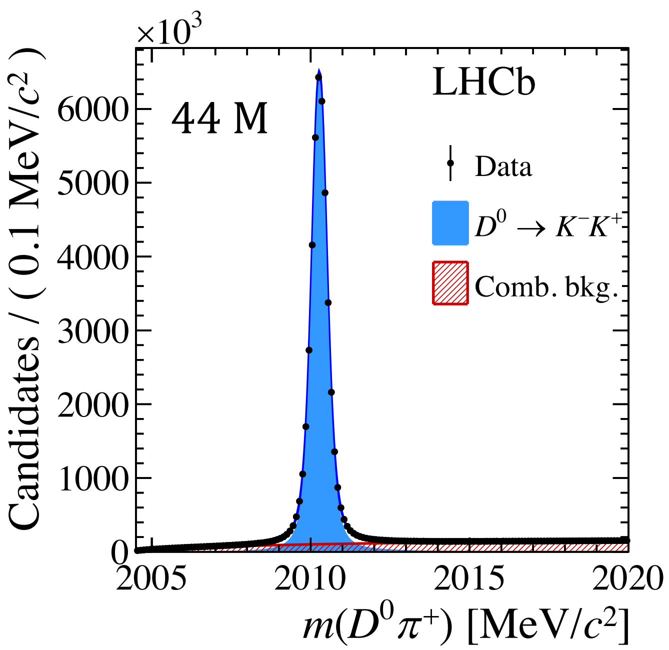
Observation of CPV in Charm (at last)

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

Federico Betti, LHCb

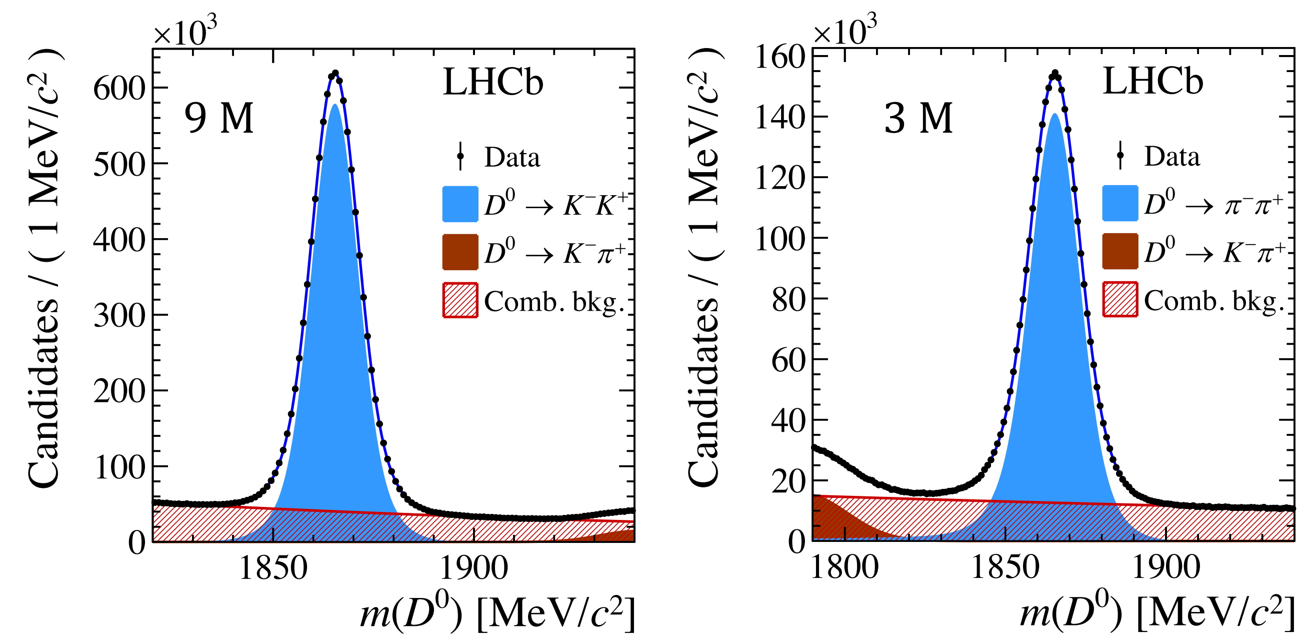
LHCb-PAPER-2019-006

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

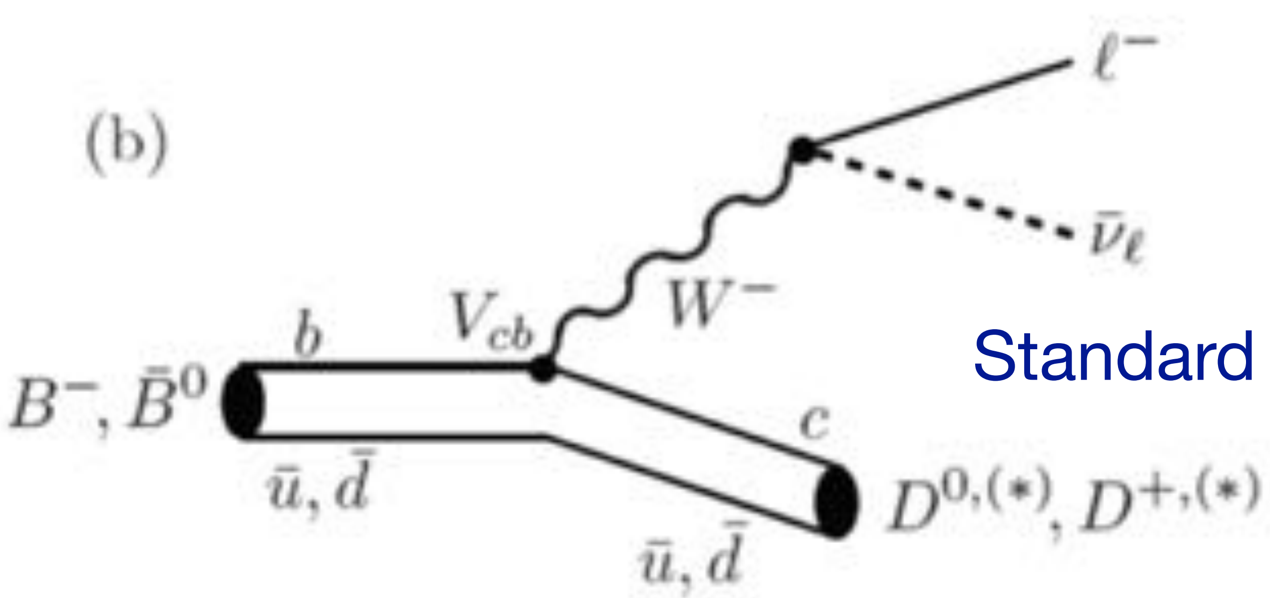
Giulia Tuci, LHCb

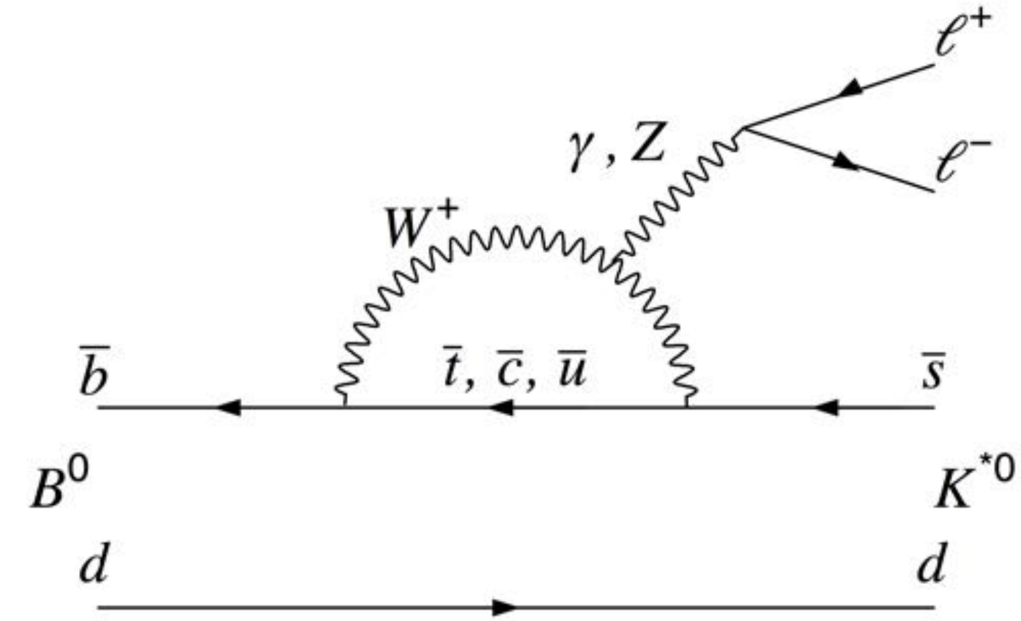
CP Violation From Beauty to Charm

15 Feb 2002
… in time for Moriond EW

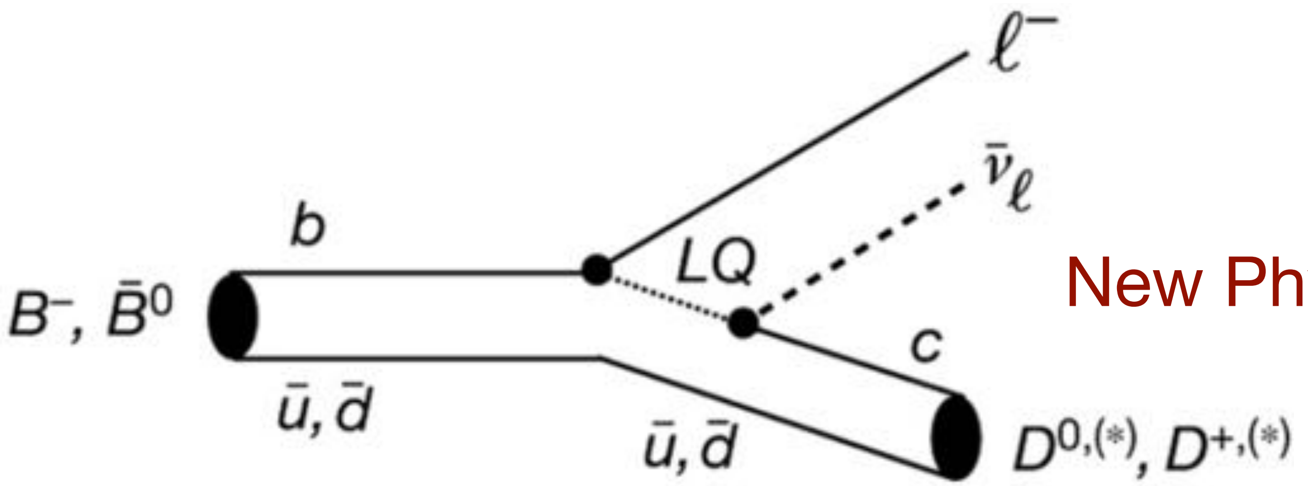
… and end of 9th season of X-Files

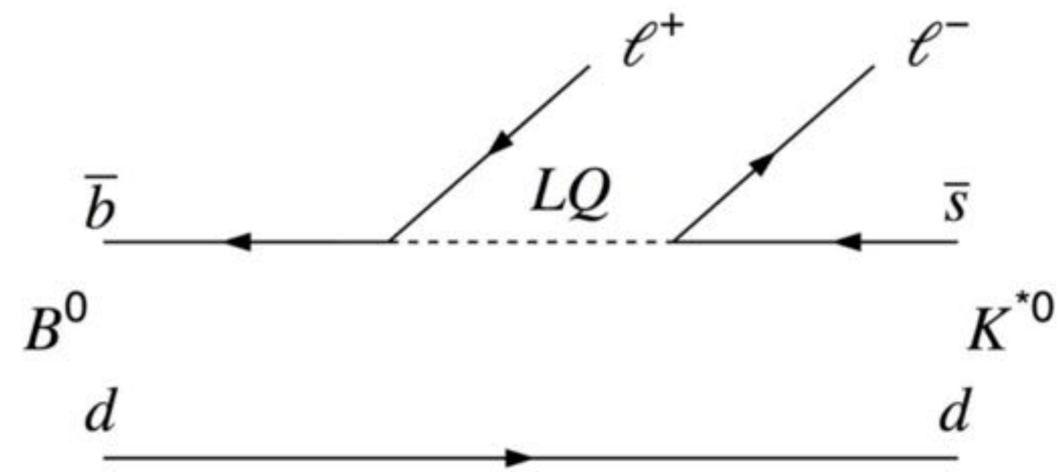
21 Mar 2019





Standard Model



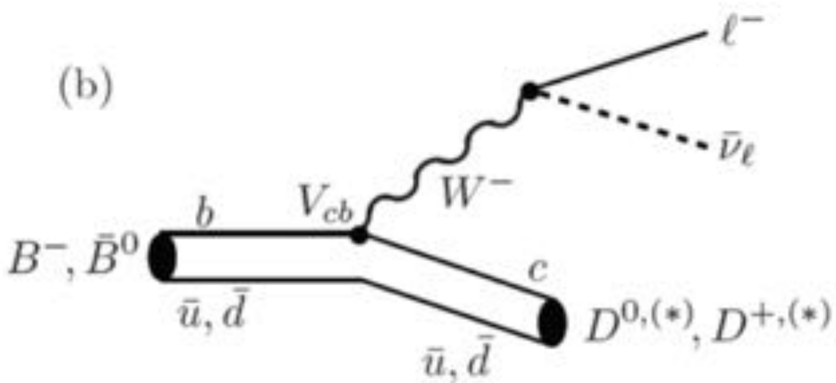


New Physics

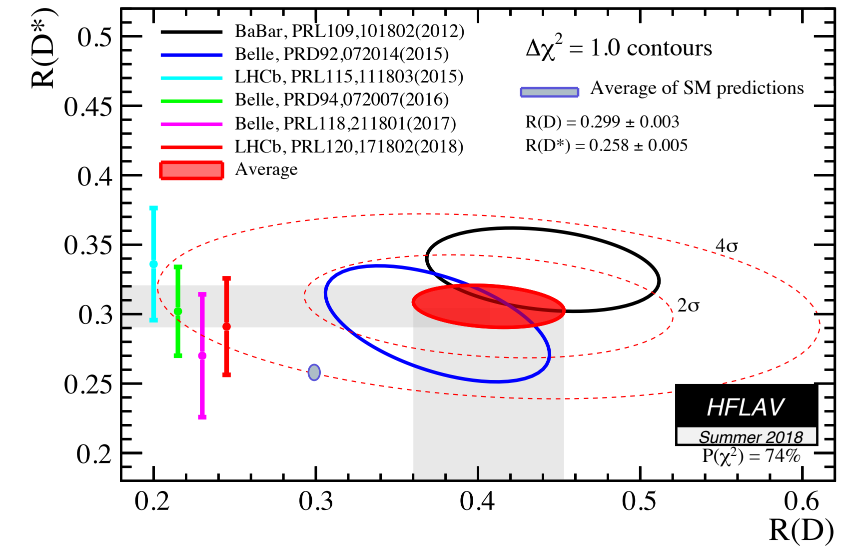
Lepton Flavor Universality

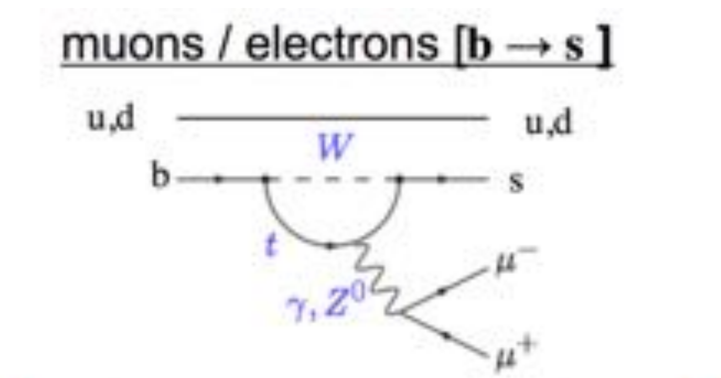
Indirect New Physics

Long Standing Anomalies

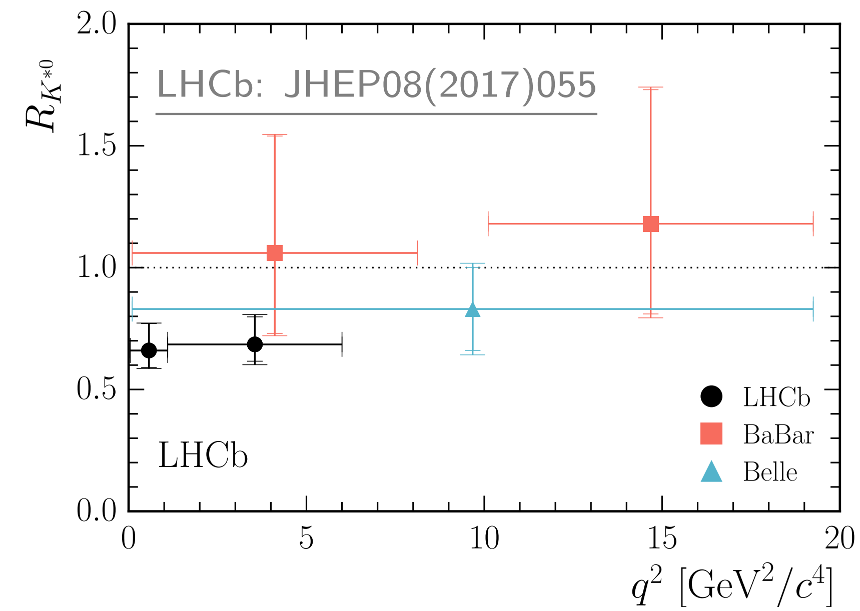


$$R(D^*) = \frac{BF(B \to D^* \tau \nu)}{BF(B \to D^* \mu \nu)}$$

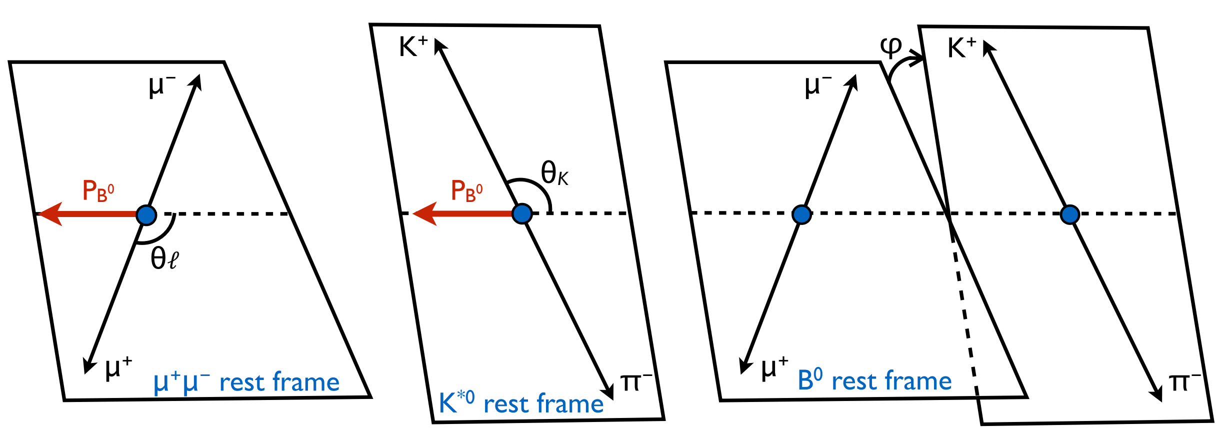


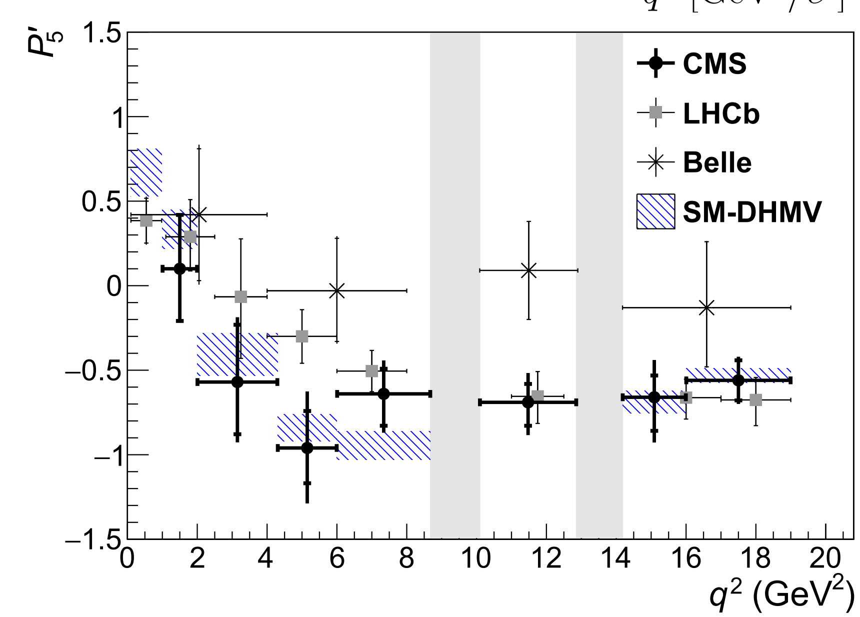


$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$



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

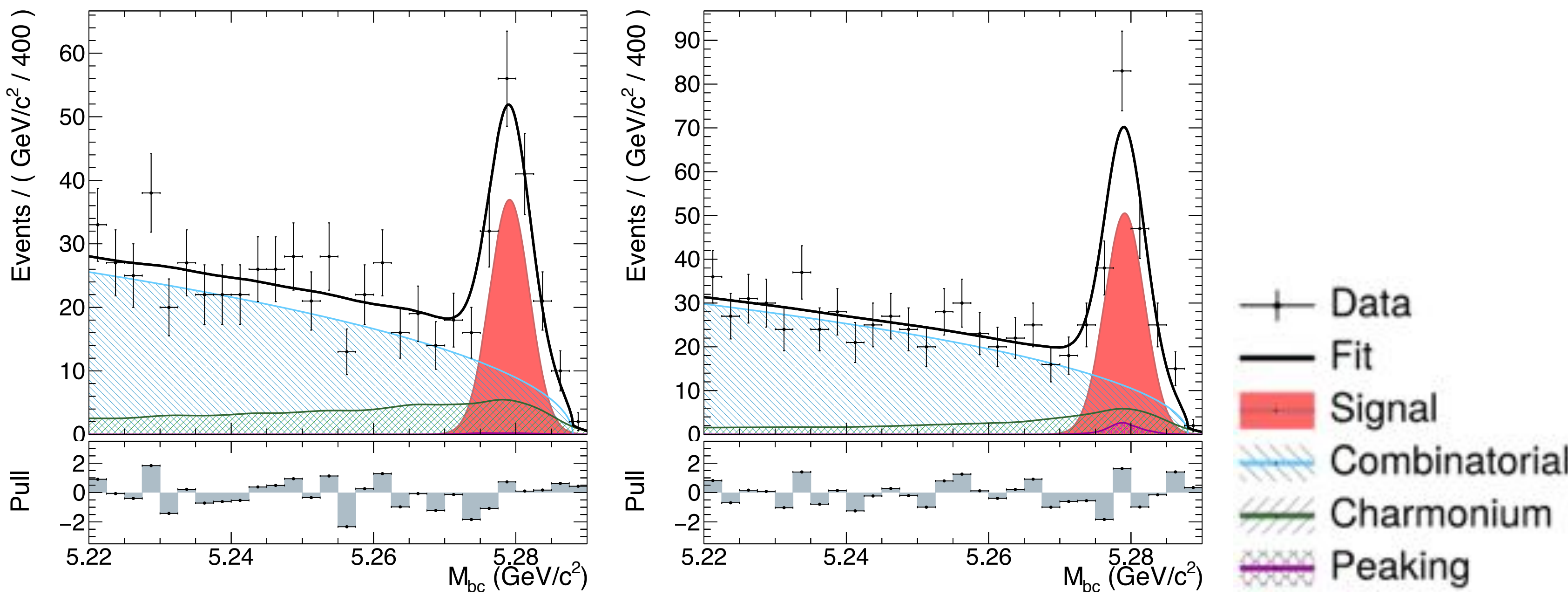


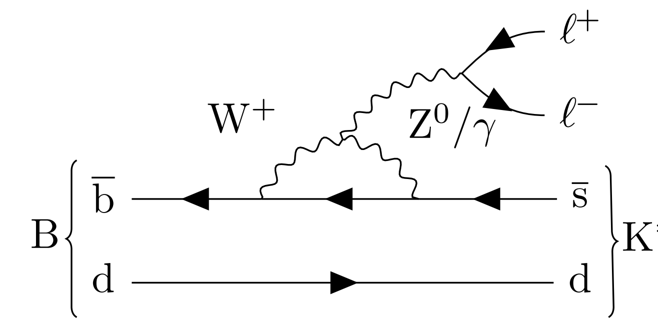


R(K*) and R(K*+) by BELLE

Markus Prim, BELLE

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





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

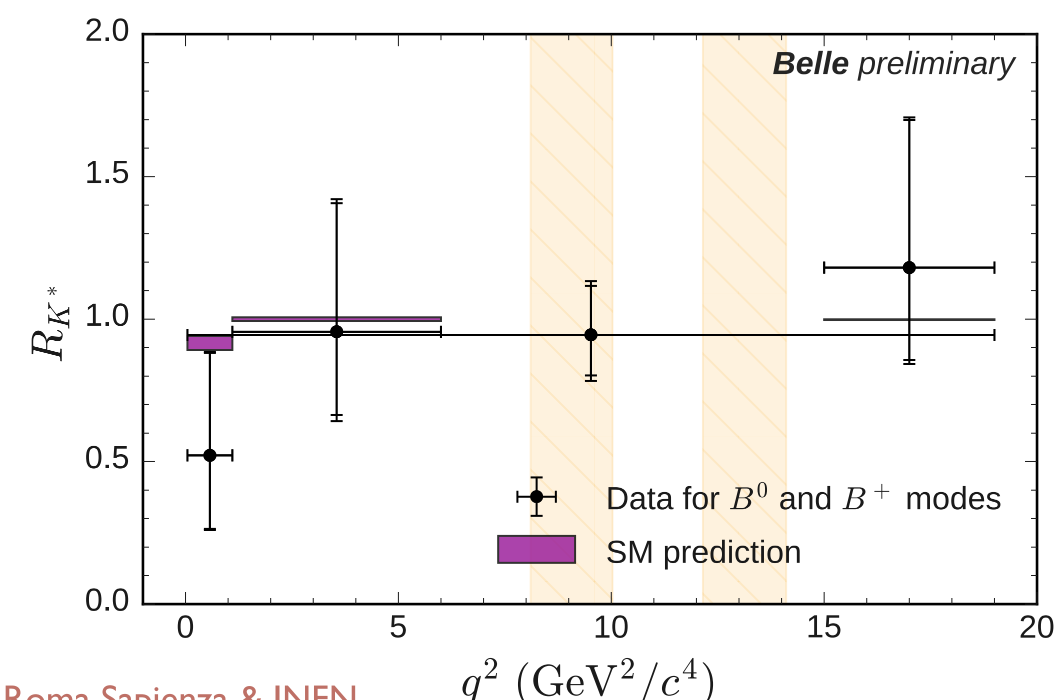
$B^+ \to K^{*+}\ell^+\ell^-$

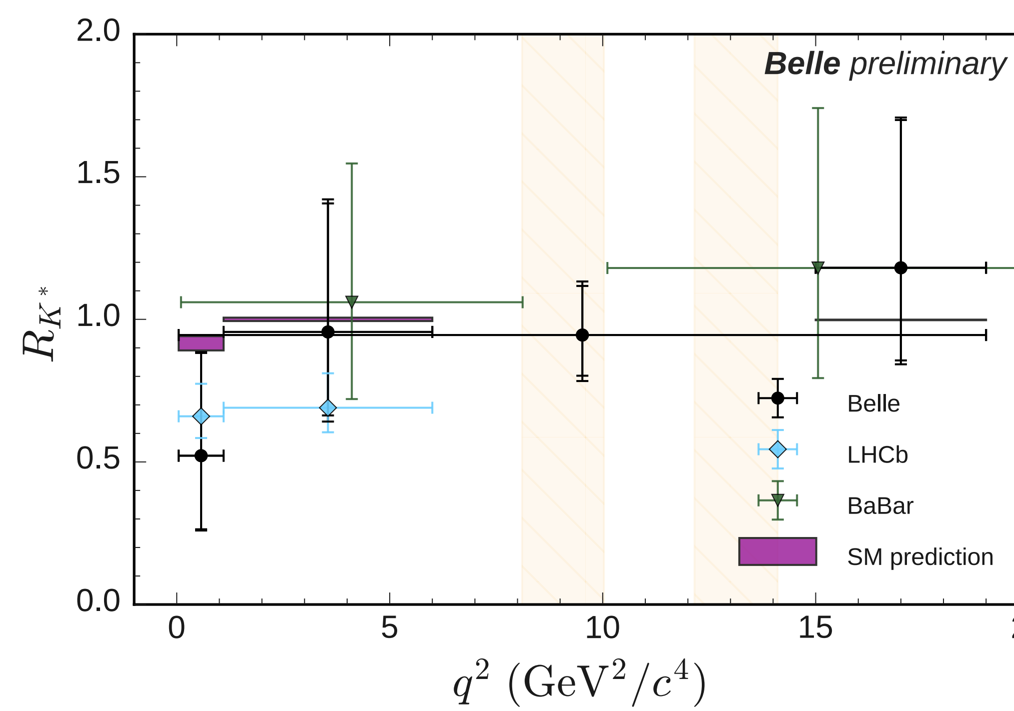
$K^{*0} \to K^+\pi^-$

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

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

- No deviation from SM predictions
  - dominated by statistical uncertainty

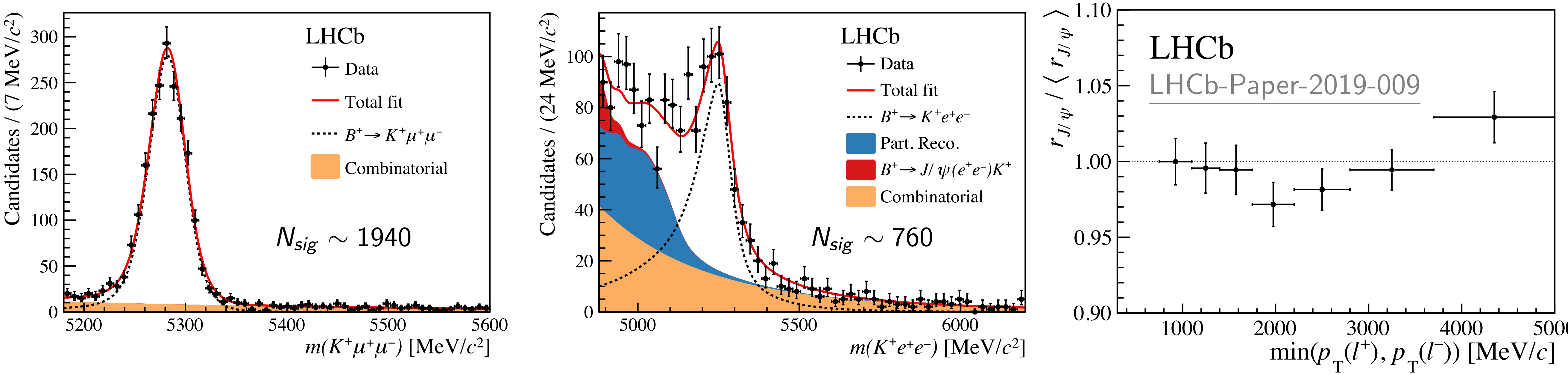




Updated R(K) by LHCb

- Addition of 2016 data and re-analysis of Run1 data
  - x2 increase in number of B mesons
  - x2 reduction in systematic uncertainty
    - better trigger and particle identification
  - double ratio to reduce electron/muon differences

Thibaud Humair, LHCb



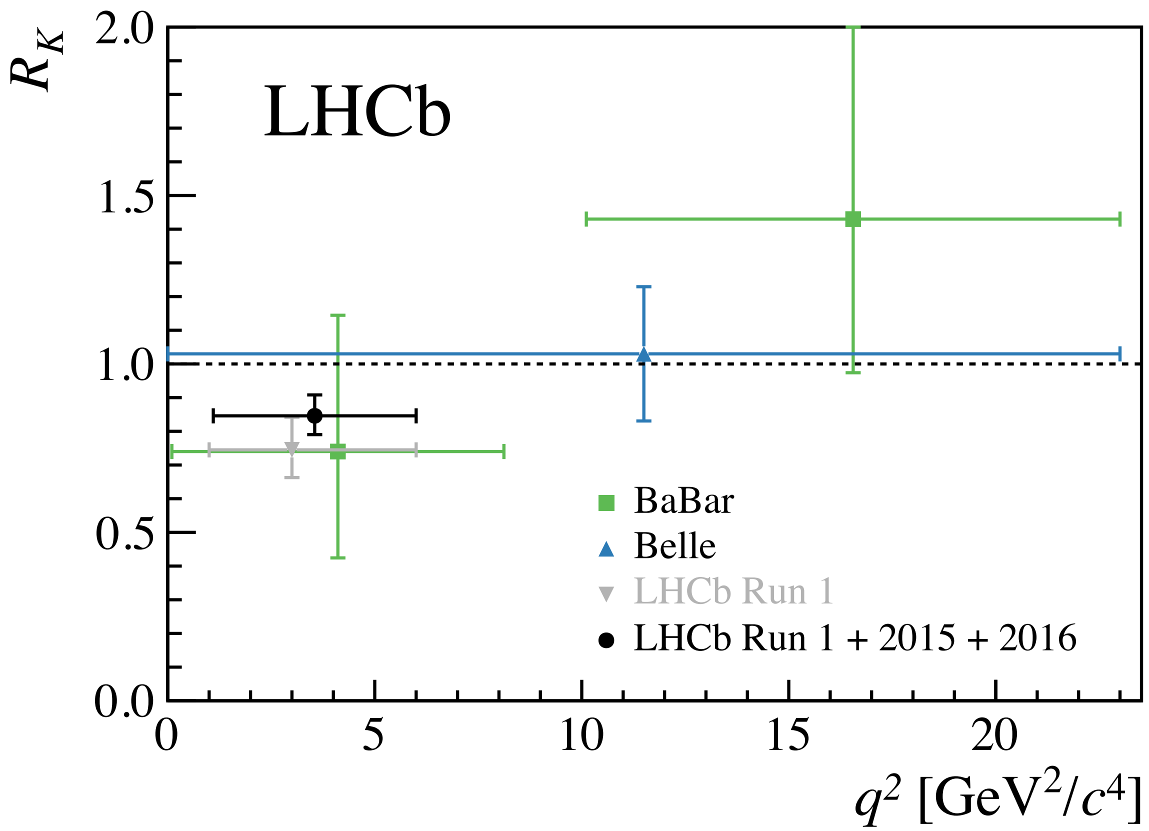
$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+ J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+ J/\psi(ee))} = 1.014 \pm 0.035 \text{ (stat. + syst.)}$$

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$

$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

Anomaly is still out there

Thibaud Humair, LHCb



Combined Run1 + Run2

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

$\sim$ **2.5 σ** from SM.

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

$R^{\text{old}}_{K\ \text{Run 1}} = 0.745^{+0.090}_{-0.074} \pm 0.036$ (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

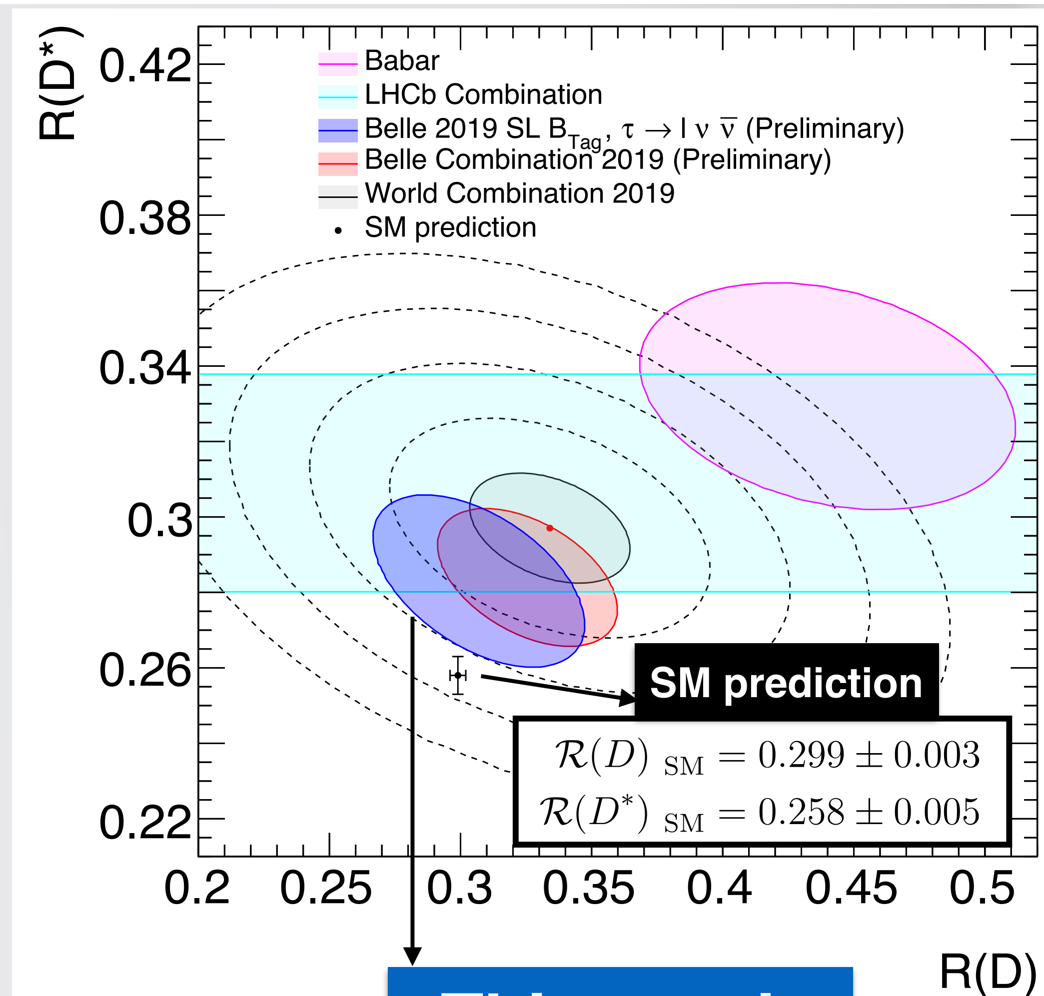
- LHCb still has x2 data to analysis (2017 and 2018)
- Additional measurements with B_s, B_c and Λ_b will be useful to understand the puzzle
- Updated R(K*) still to come
- Updated R(D) and R(D*) could also help understand differences between charged and neutral currents (written before Friday PM session)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



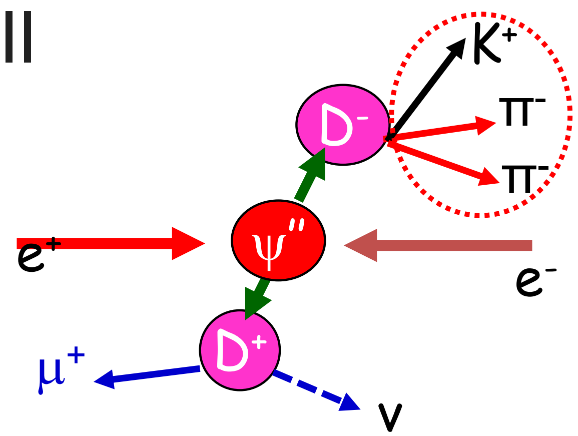
This result

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

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

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
$\|V_{cs}\|^{Ds+\to l+v}$	~1	1.2	0.6
$\|V_{cs}\|^{D0\to K-e+v}$	2.5 (2.4^LQCD^)	0.35	0.18
$\|V_{cd}\|^{D+\to\mu+v}$	~0.9	2.6	1.3
$\|V_{cd}\|^{D0\to\pi-e+v}$	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

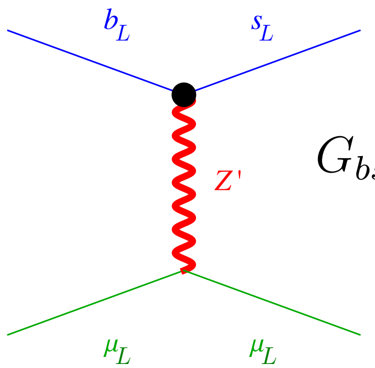
Now: Current D/D_s/Λ_c analyses are based 2.9/3.2/0.567 fb^{-1} data at 3.773/4.178/4.6 GeV

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

Probing Anomalies at High Mass

- Several models proposing new heavy Z' or leptoquarks as possible source

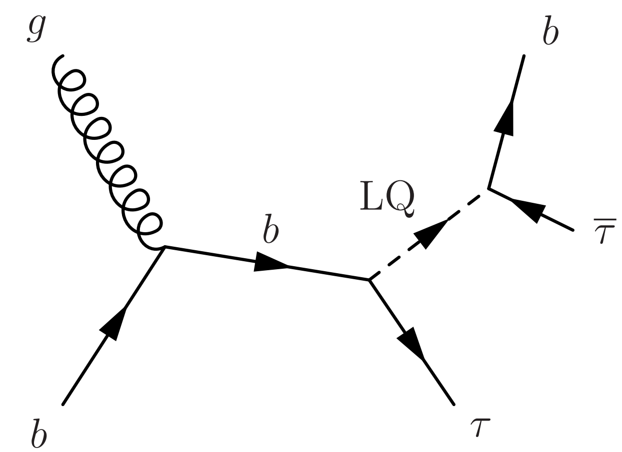
Steve King, Ben Allanach, Julian Heeck, Andrei Angelescu



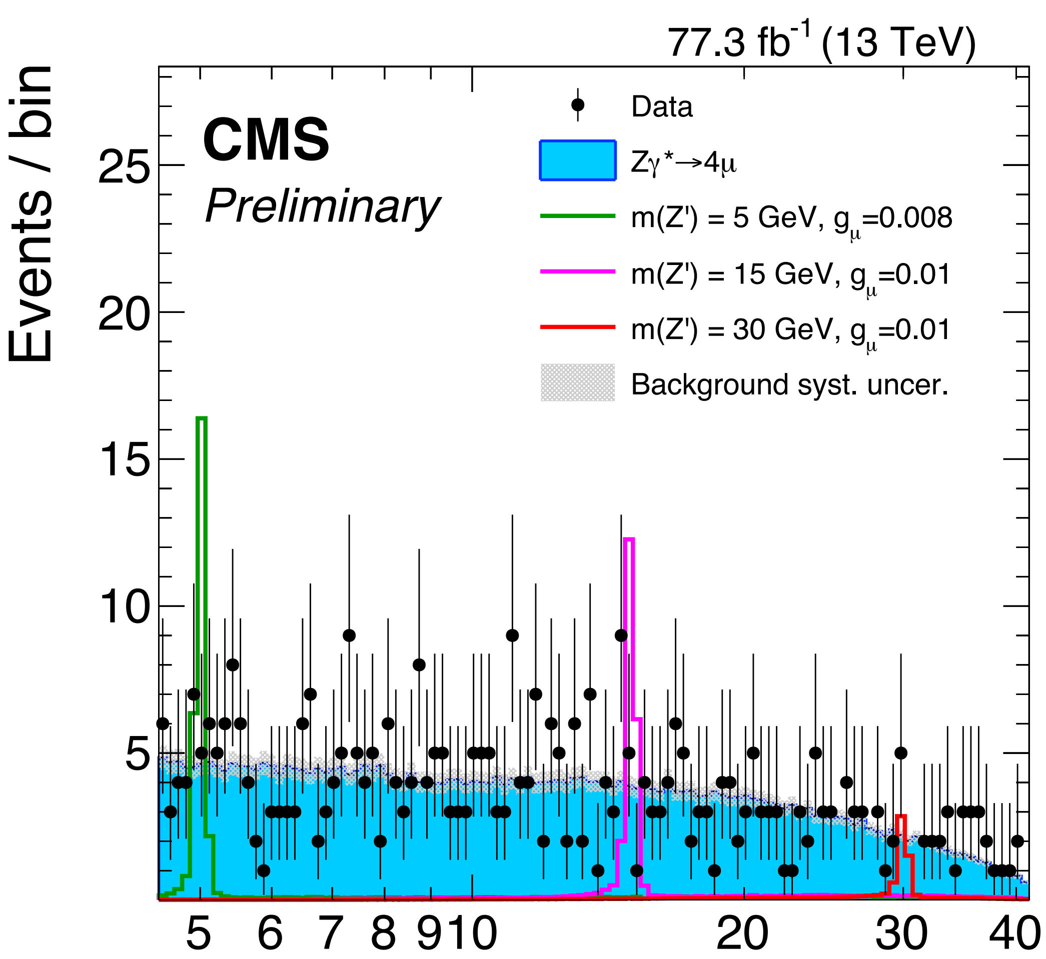
$V_{ts} \sim -0.04$

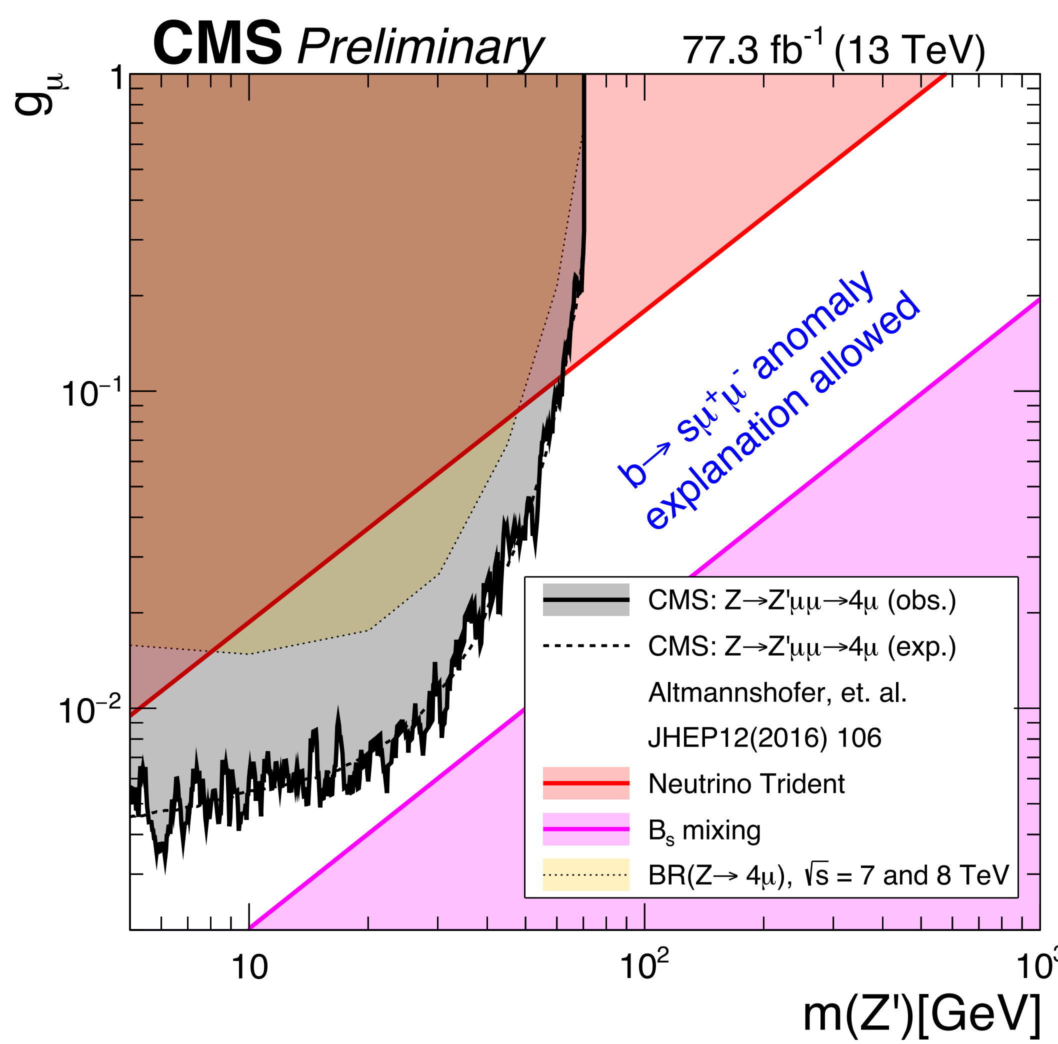
$$G_{bs\mu} = -\frac{g_{bs}g_{\mu\mu}}{M_{Z'}^2} = -\frac{V_{ts}g_{bb}g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(31.5\ \text{TeV})^2}$$

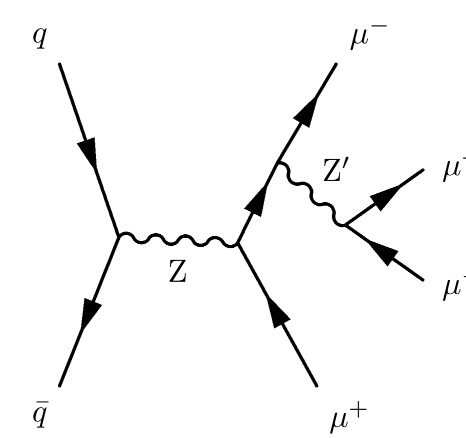
$$\frac{g_{bb}g_{\mu\mu}}{M_{Z'}^2} \approx \frac{1}{(6.4\ \text{TeV})^2}$$



- Active program of direct searches underway at CMS and ATLAS







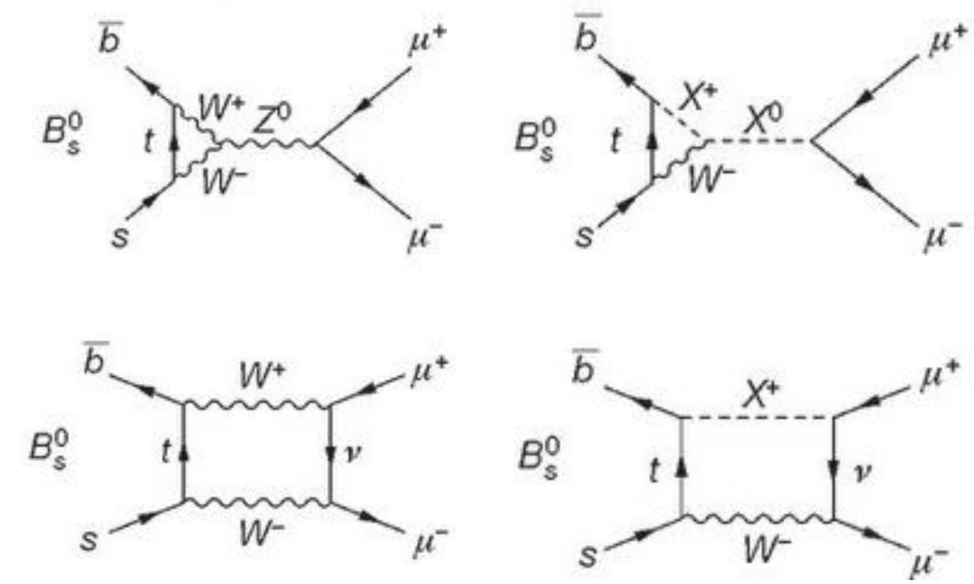
arXiv:1808.03684 accepted by PLB

Rare Processes

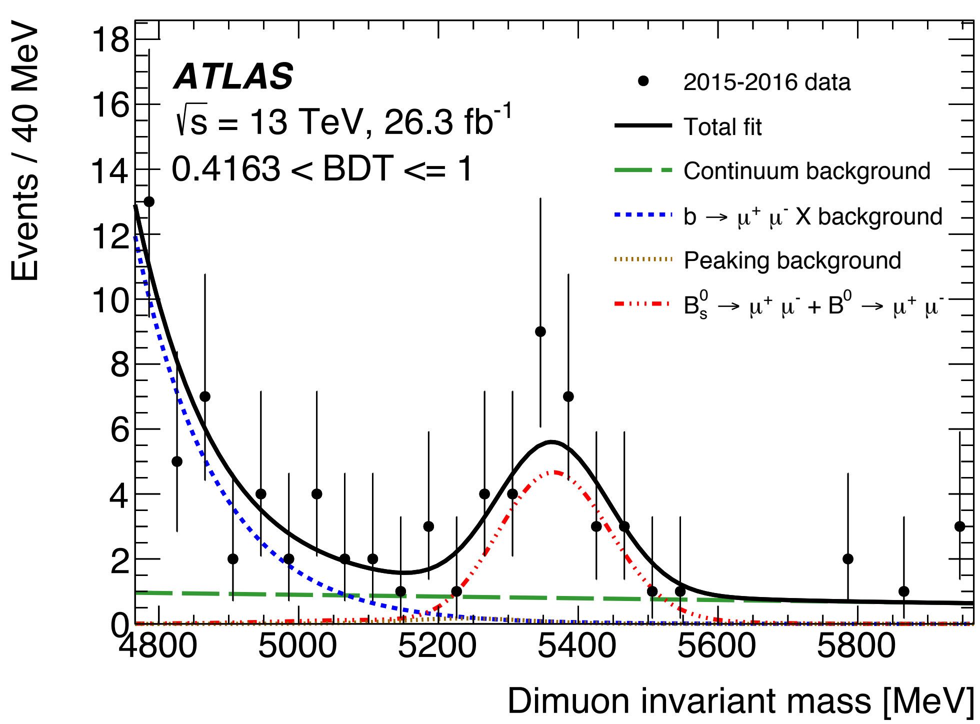
$B_s \to \mu\mu$ with ATLAS

Olga Igonkina, ATLAS

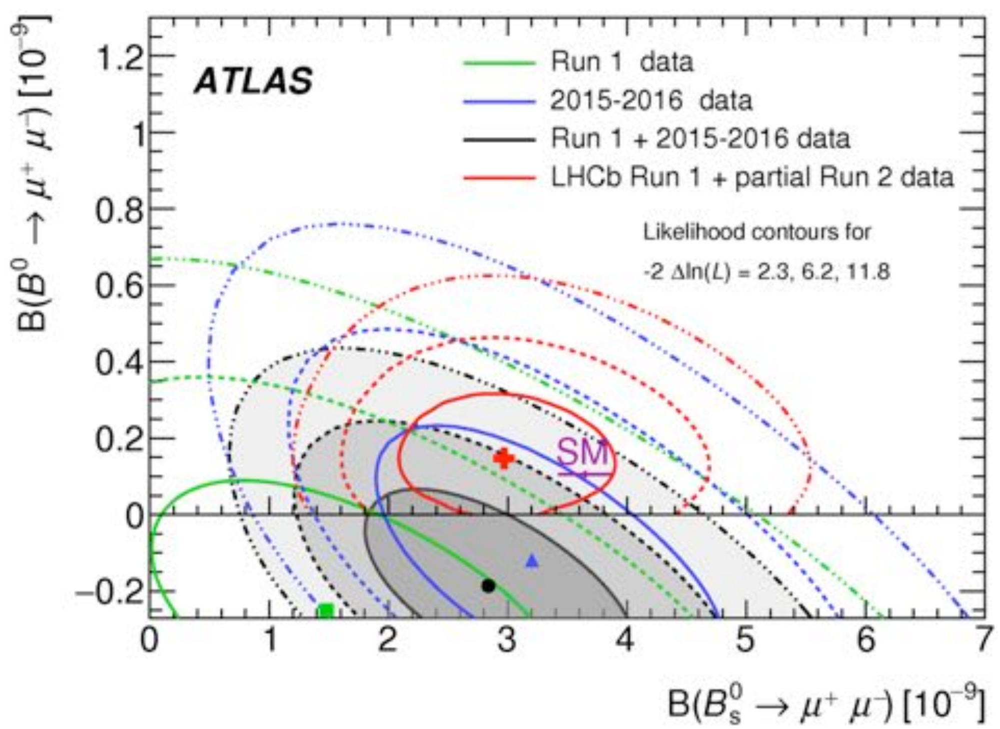
- Standard Model BF = 3 x 10^{-9}
  sensitive to BSM enhancements
- 26 fb^{-1} of data collected in 2015-2016
- Abundant sample of J/psi K^+ as reference



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



Mass spectrum in best S/B category



SM :

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

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

Best fit of Run 2 data :

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

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

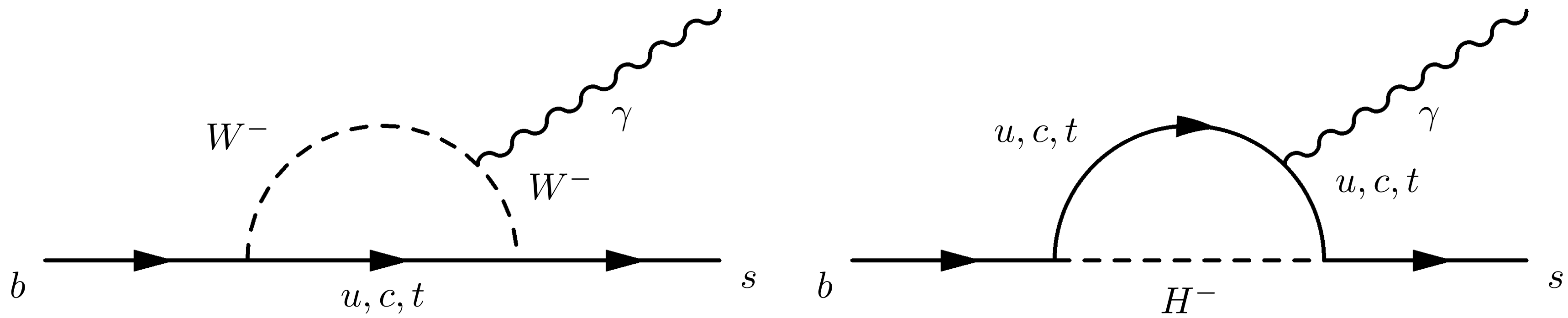
Run 1 + Run 2 result @ 95% CL

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

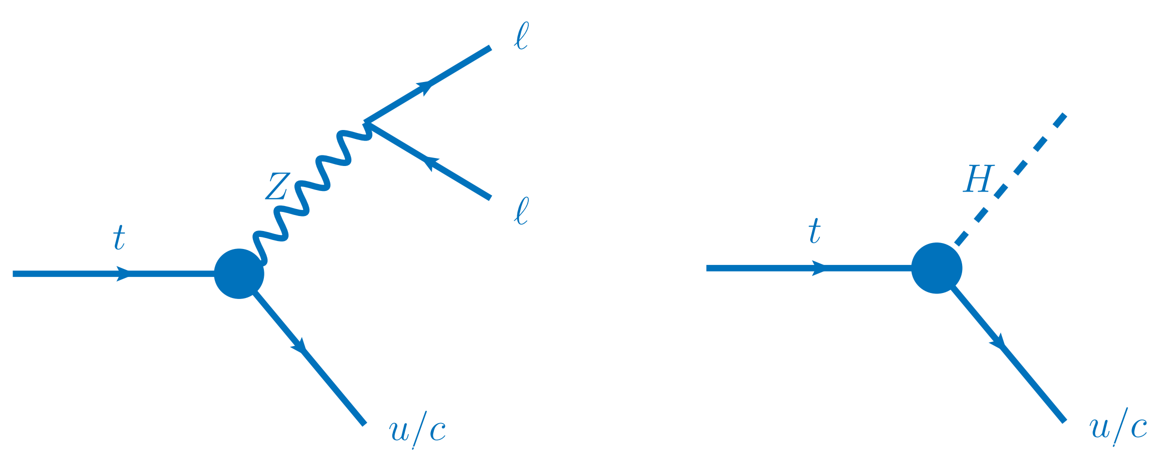
$Br(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$

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

Flavor Changing Neutral Currents



- 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



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

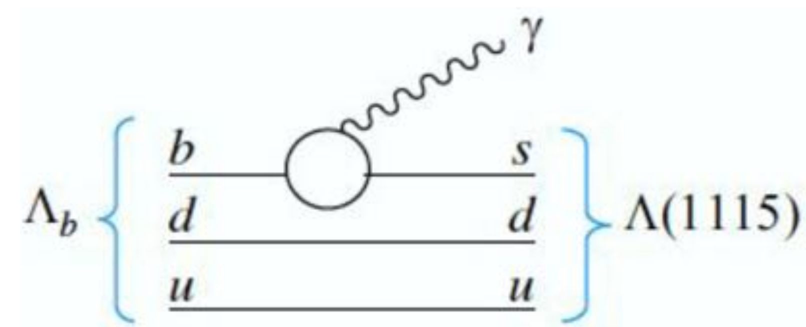
BR($t \to qZ$) ~ 10^{-14}

Loïc Valéry, ATLAS

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

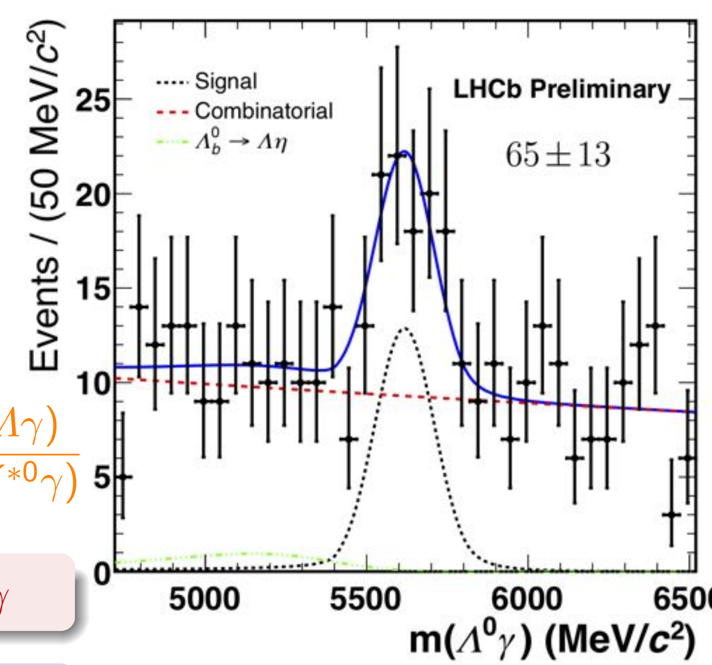
Carla Marin , LHCb

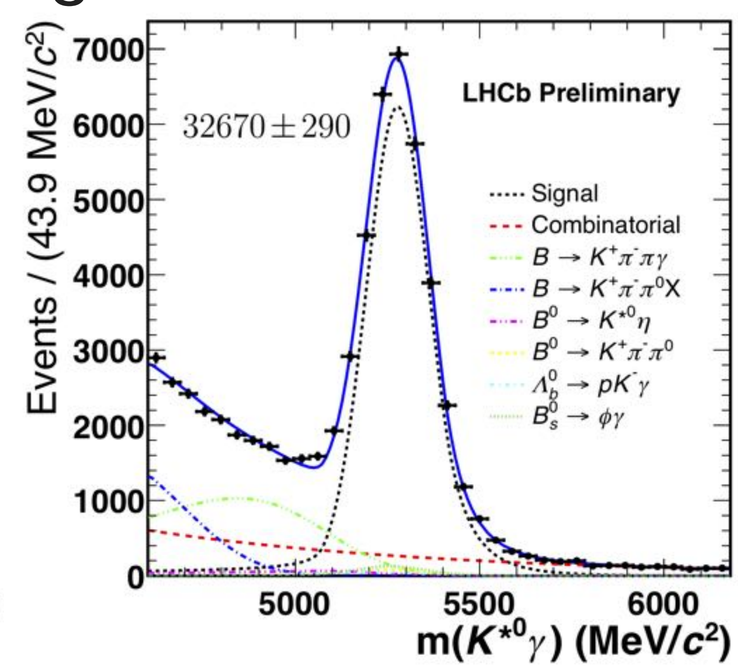
- Rare radiative decays sensitive to new physics
- Only theoretical prediction affected by large uncertainties: 10^{-5} — 10^{-7}
  - Experimental limit CDF: $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) < 1.9 \times 10^{-3}$ at 90% CL



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

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





Signal excess with $5.6\,\sigma$ significance $\to$ first observation of $\Lambda_b^0 \to \Lambda\gamma$

Branching fraction measurement within range of SM predictions

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

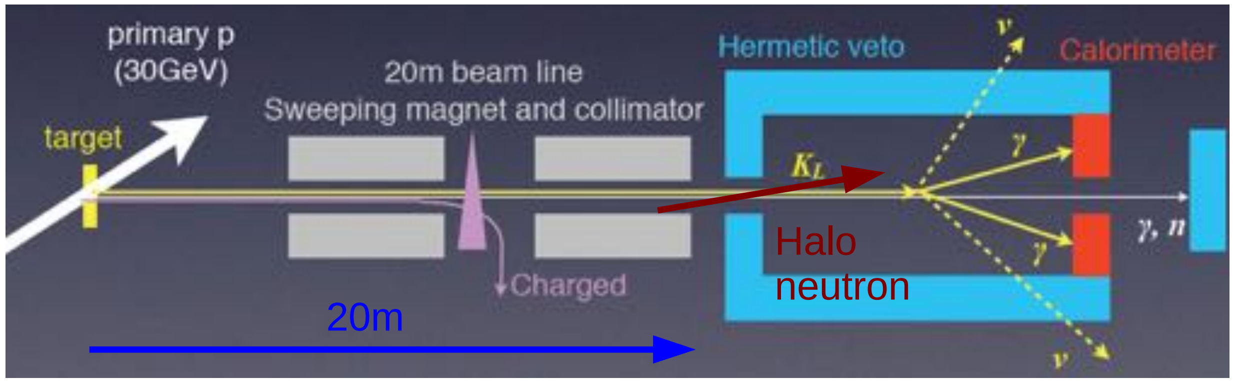
- *Begging for new theoretical calculation*
- LHCb also investigating other such radiative decays

Latest results from LHCb

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

FCNC with charm and strange

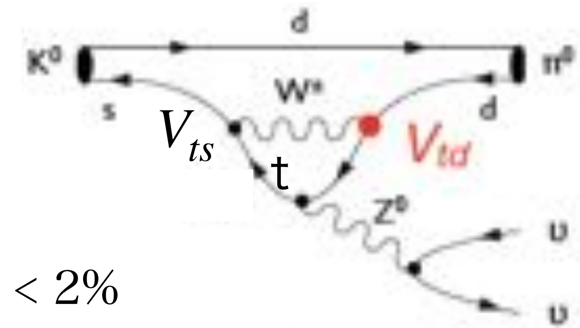
- KOTO detector at J-PARC with collimated beam of K^0



Hajime Nanjo, KOTO

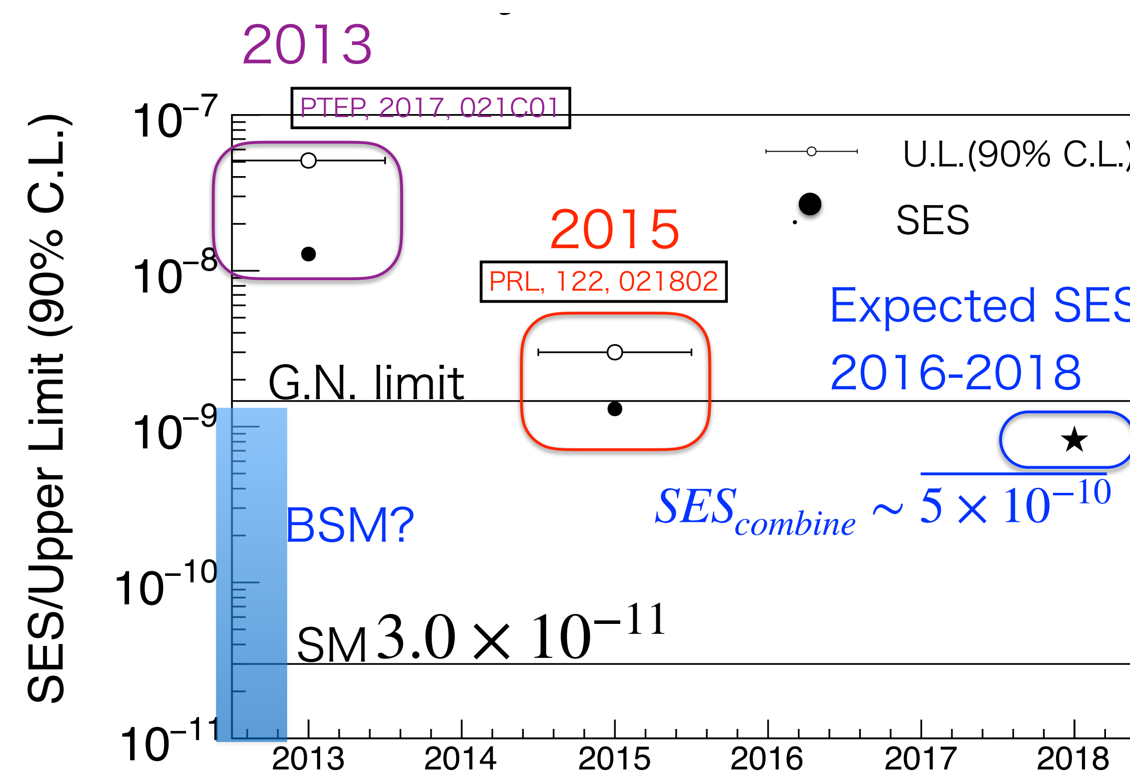
Standard Model : FCNC

- Rare: $BR(SM) = 3 \times 10^{-11}$
- Accurate:
  - theoretical uncertainty < 2%

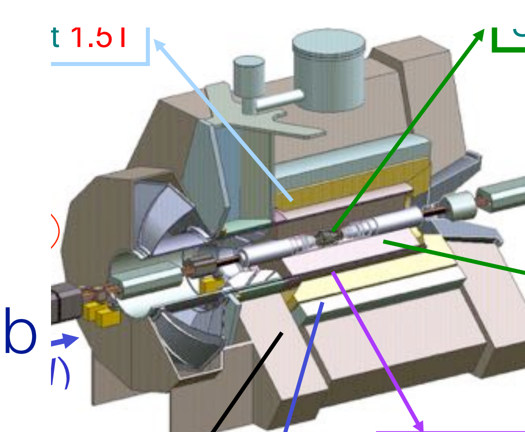


- Best upper limit in 2015
  - Still taking data and planning an upgraded detector to dive into New Physics realm

$$B_{K_L \to \pi^0 \nu \bar{\nu}} < 3.0 \times 10^{-9} (90\,\%\,\mathrm{C.L.})$$



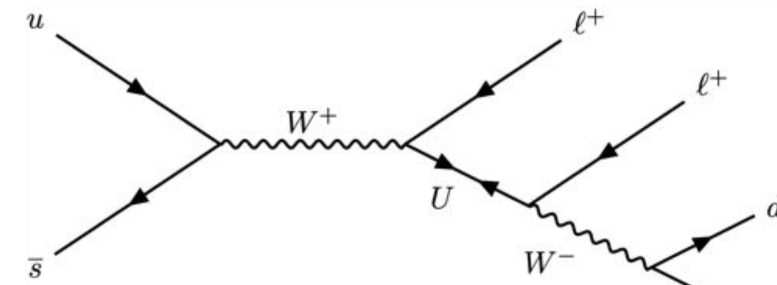
Eli Ben-Haim, BaBar



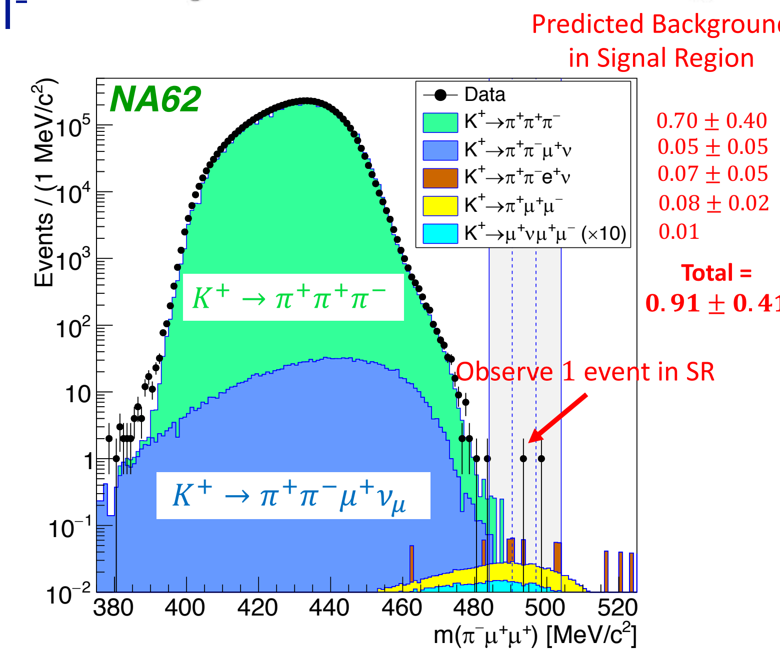
- BaBar reported a new search in $K \to \tau\nu$ and observation of $D^0 \to K^-\pi^+e^+e^-$ final state
  - but no deviations from SM when compared to $D^0 \to K^-\pi^+\mu^+\mu^-$ from LHCb

Lepton Flavor Violation

Joel Swallow, NA62



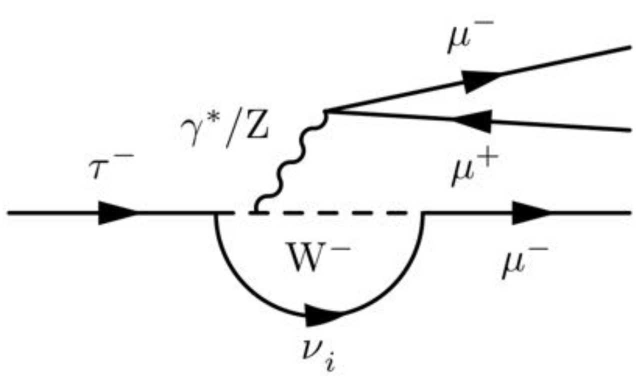
- Neutrino-less double beta-decay a prime probe of LFV
- NA62 at CERN reported on $K^+ \to \pi^- l^+ l^+$ with of 2017 data
  - measurement normalised to similar FNCN mode $K^+ \to \pi^+ l^+ l^-$



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}

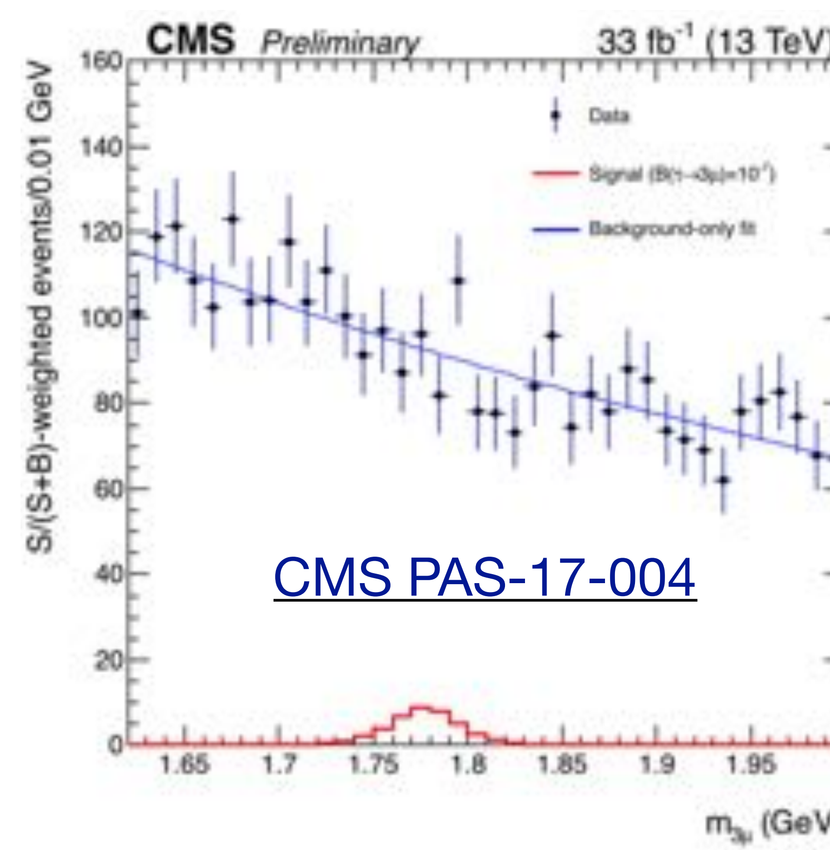
Alessio Boletti, CMS

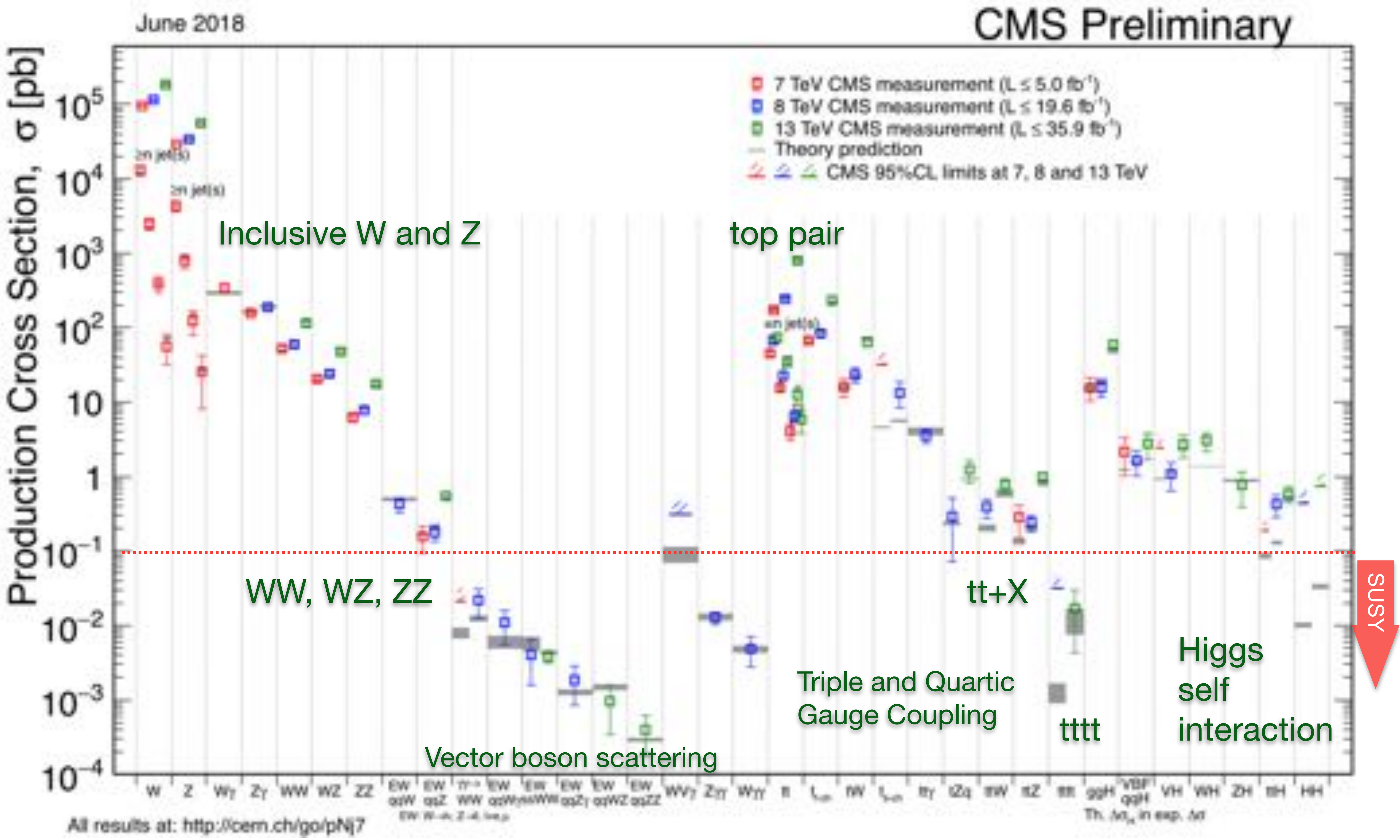
- Search for $\tau \to 3\mu$ in copious sample of leptons from B and D decays in 2016 data at 13 TeV
  - $D_s^\pm \to \phi\pi^\pm \to \mu^+\mu^-\pi^\pm$ used as reference sample



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

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





Standard Model

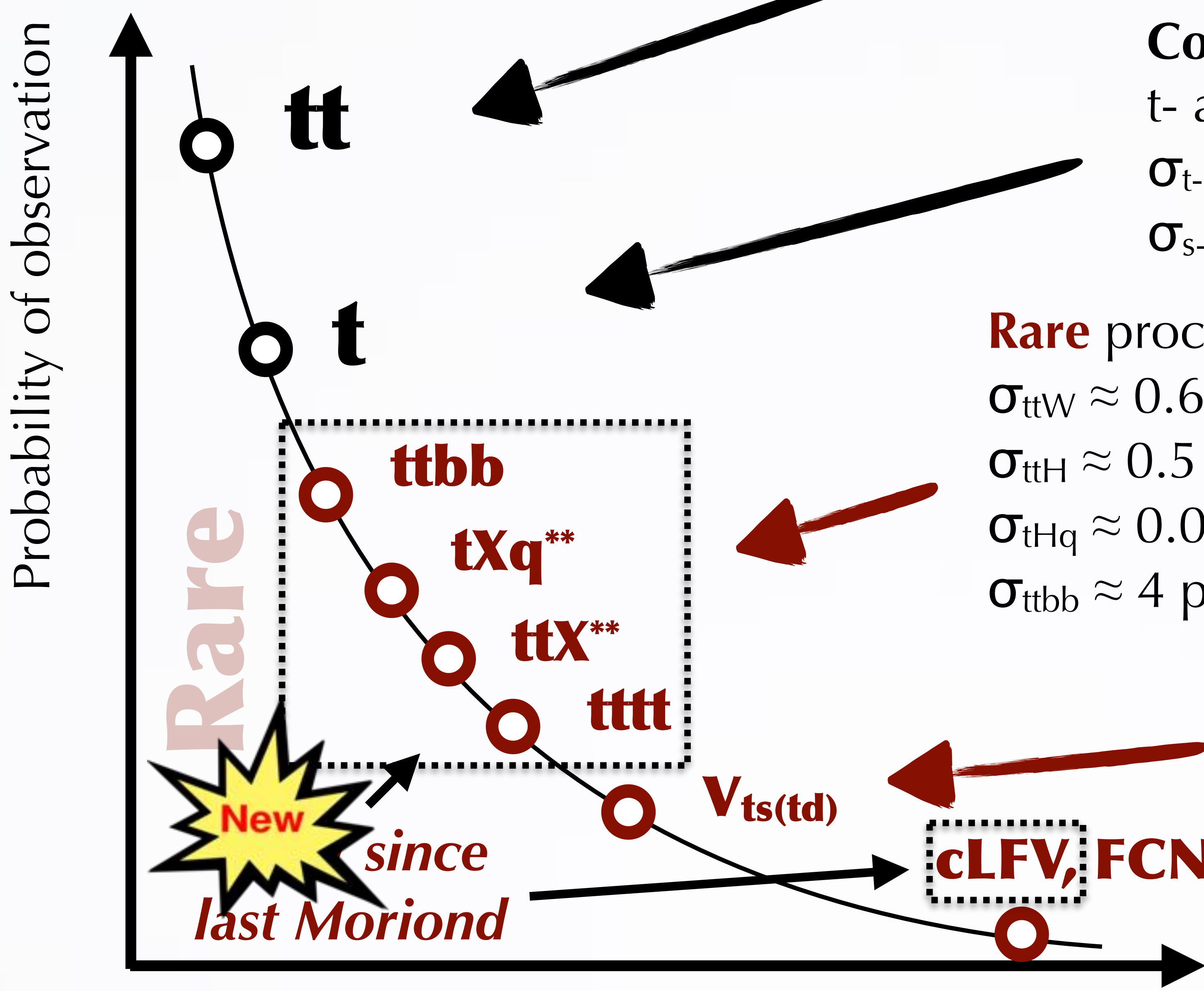
New Physics through Precision

Precision top physics

- LHC is a top factory

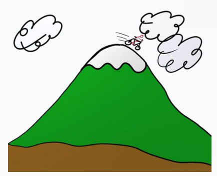
Kiril Skovpen, CMS

The LHC world @13TeV

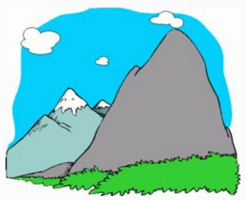


Most abundant production mechanism of top quarks
$\sigma_{tt} \approx 830$ pb

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



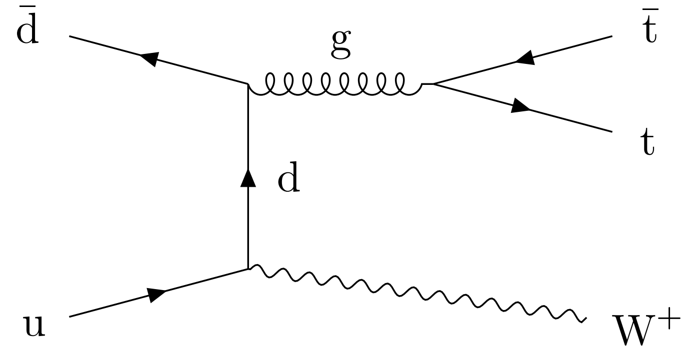
Rare CKM-suppressed decays
$P < 10^{-3}$

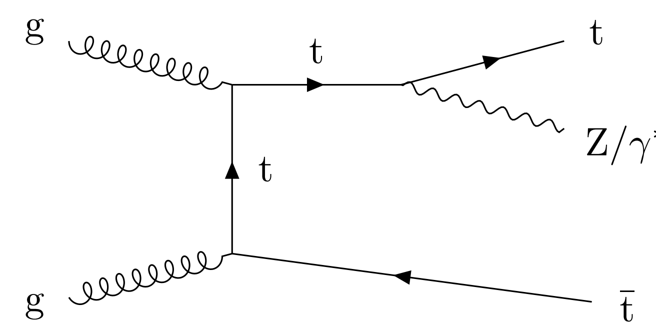
Not reachable at the LHC
$P_{FCNC} < 10^{-12}$
$P_{BNV} < 10^{-27}$
$P_{cLFV} < 10^{-55}$

(*) 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

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

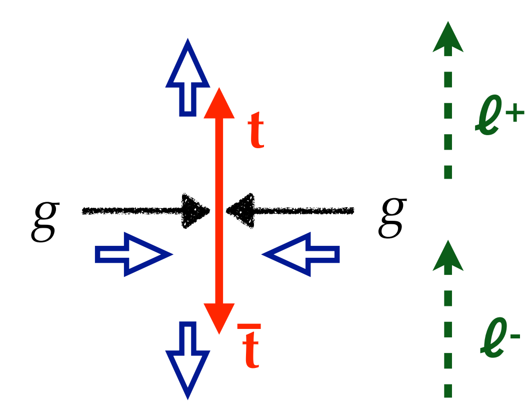
13% precision

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

22% precision

Good agreement with NLO predictions

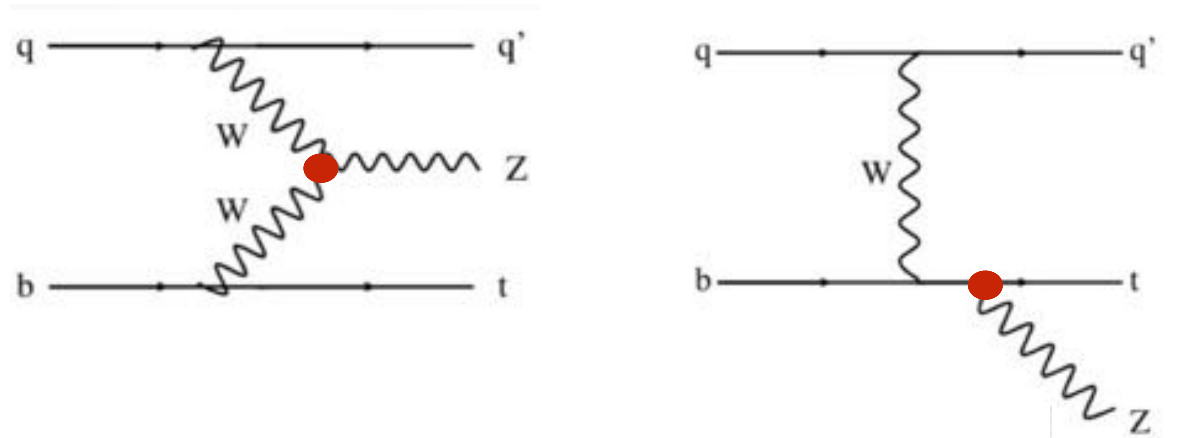
- Differential cross section of ttZ now better precision than NLO calculations
- tt+bb production now exceeding theoretical knowledge!
  - Important background in study of top-Higgs Yukawa coupling
- Top spin correlations also provide valuable comparison with theory
  - NNLO predictions needed to mitigate discrepancies up to 3σ wrt simulations



Jacob Linacre, CMS

Rare top production

- Observation of rare single-top production tZq

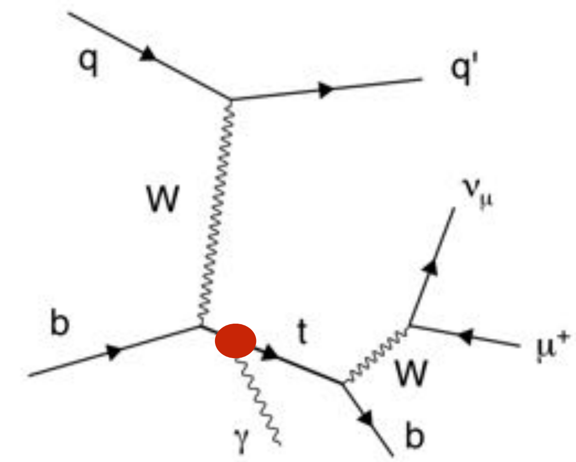


15% precision

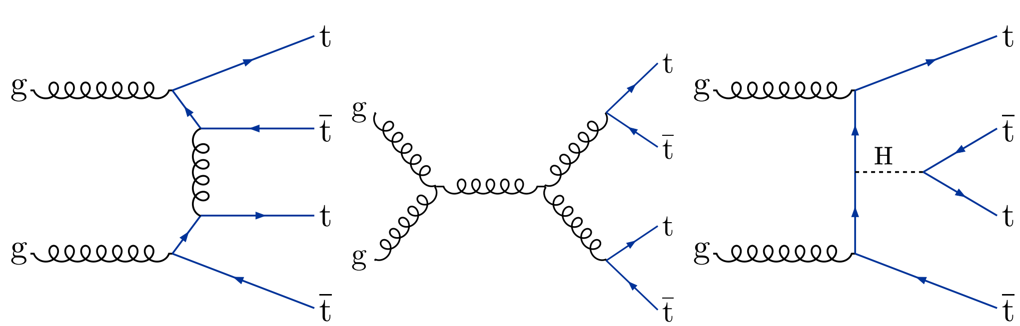
$$\sigma(pp \to tZq \to t\ell^+\ell^-q) = 111 \pm 13\,(\text{stat})\,^{+11}_{-9}\,(\text{syst})\ \text{fb}$$

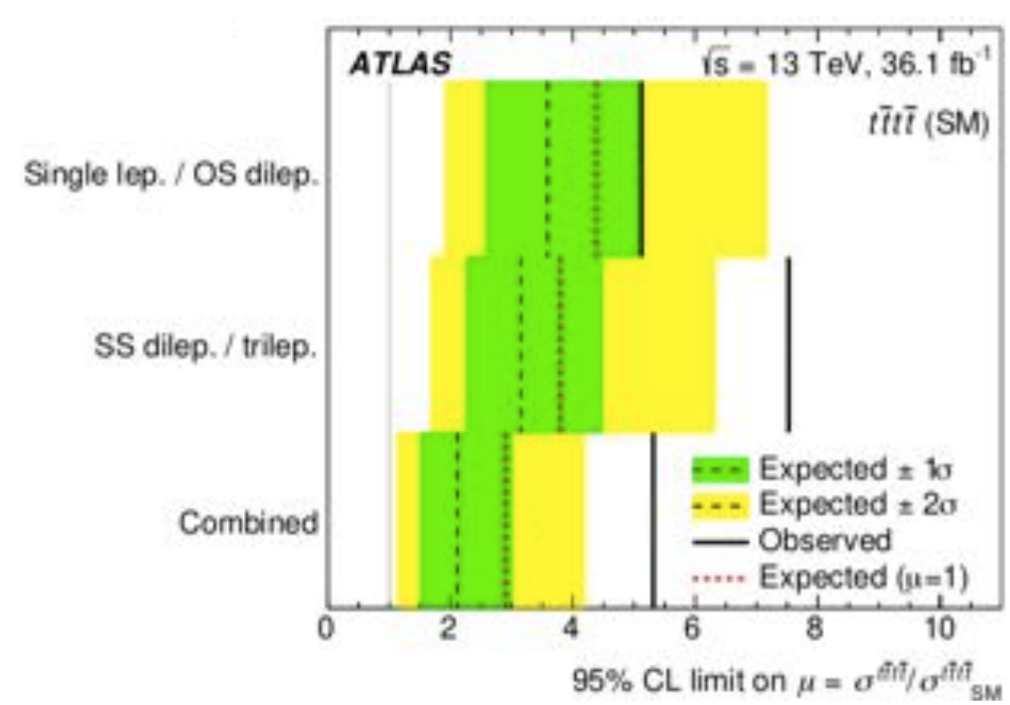
- Evidence for tγq with 30% precision

$$\sigma(pp \to t\gamma j)\mathcal{B}(t \to \mu\nu b) = 115 \pm 17\,(\text{stat}) \pm 30\,(\text{syst})\ \text{fb}$$

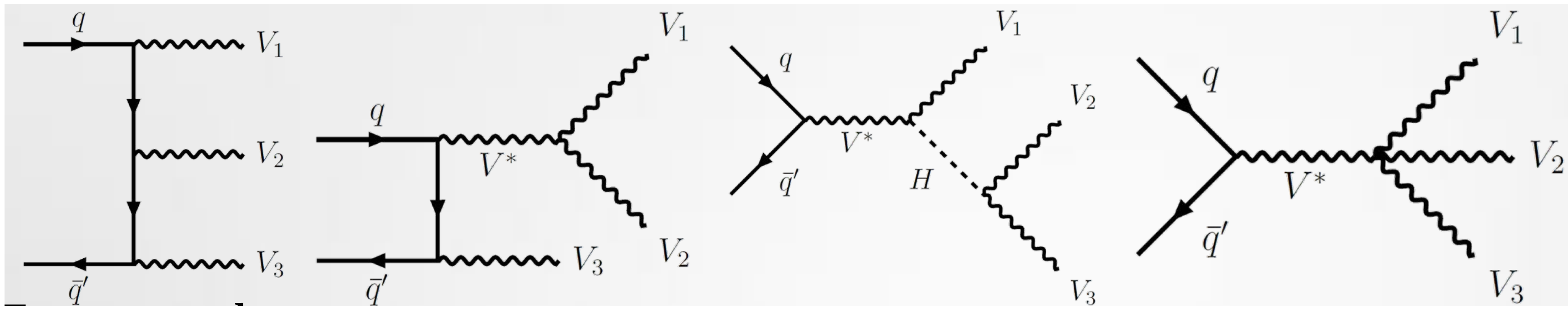


- Search for tttt production
  - same sensitivity for both experiments
    - expected significance of ~1σ
  - over fluctuation in ATLAS

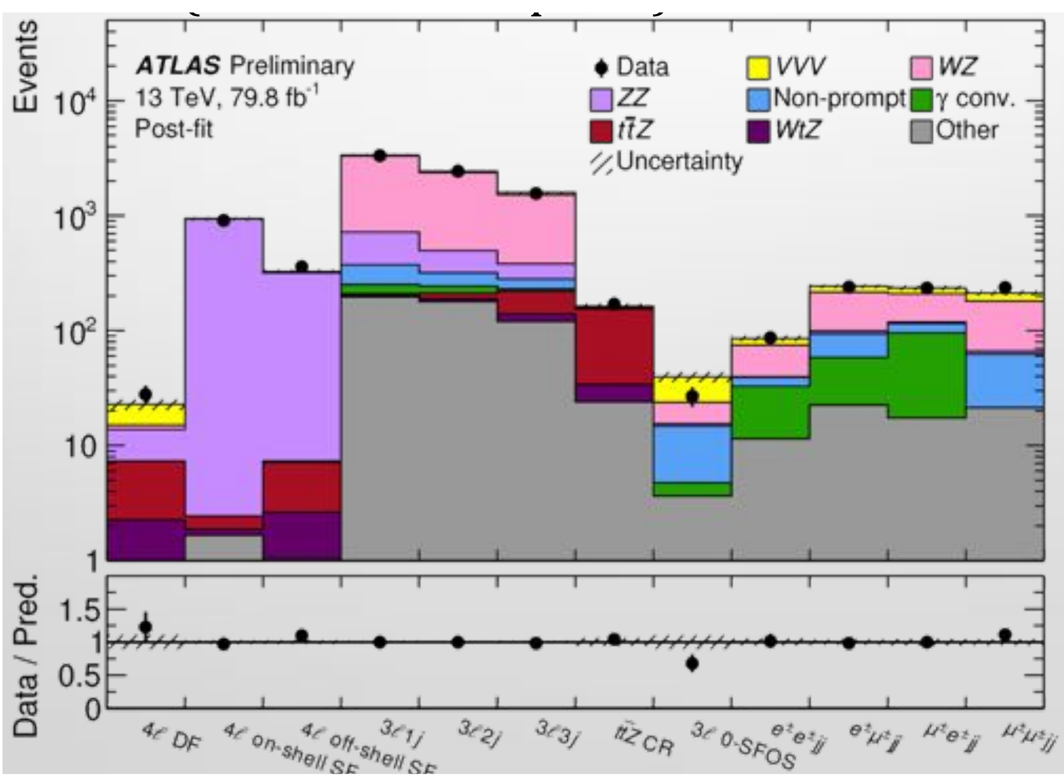


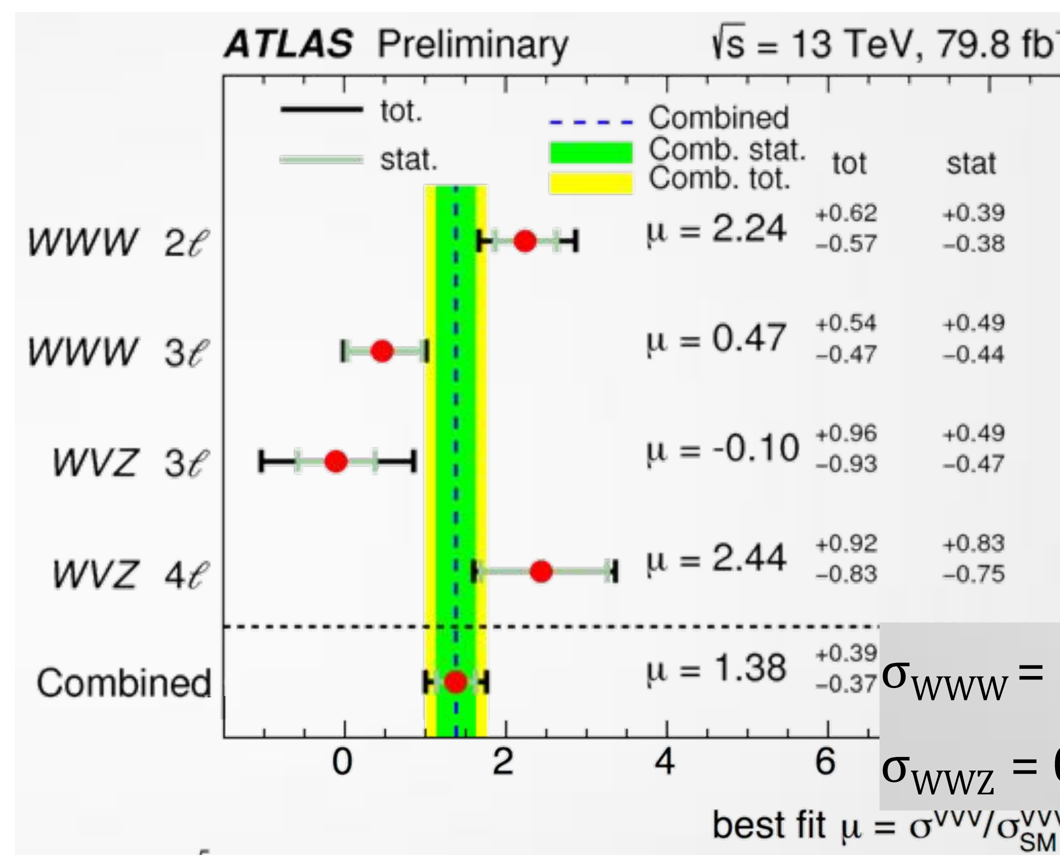


Triple Gauge Boson Production



- 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

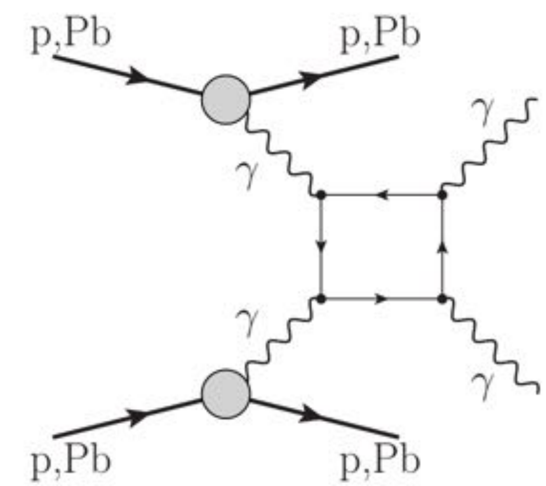
- *Multiboson domain finally accessible thanks to high luminosity of LHC*

Aleksandra Dimitrievska, ATLAS

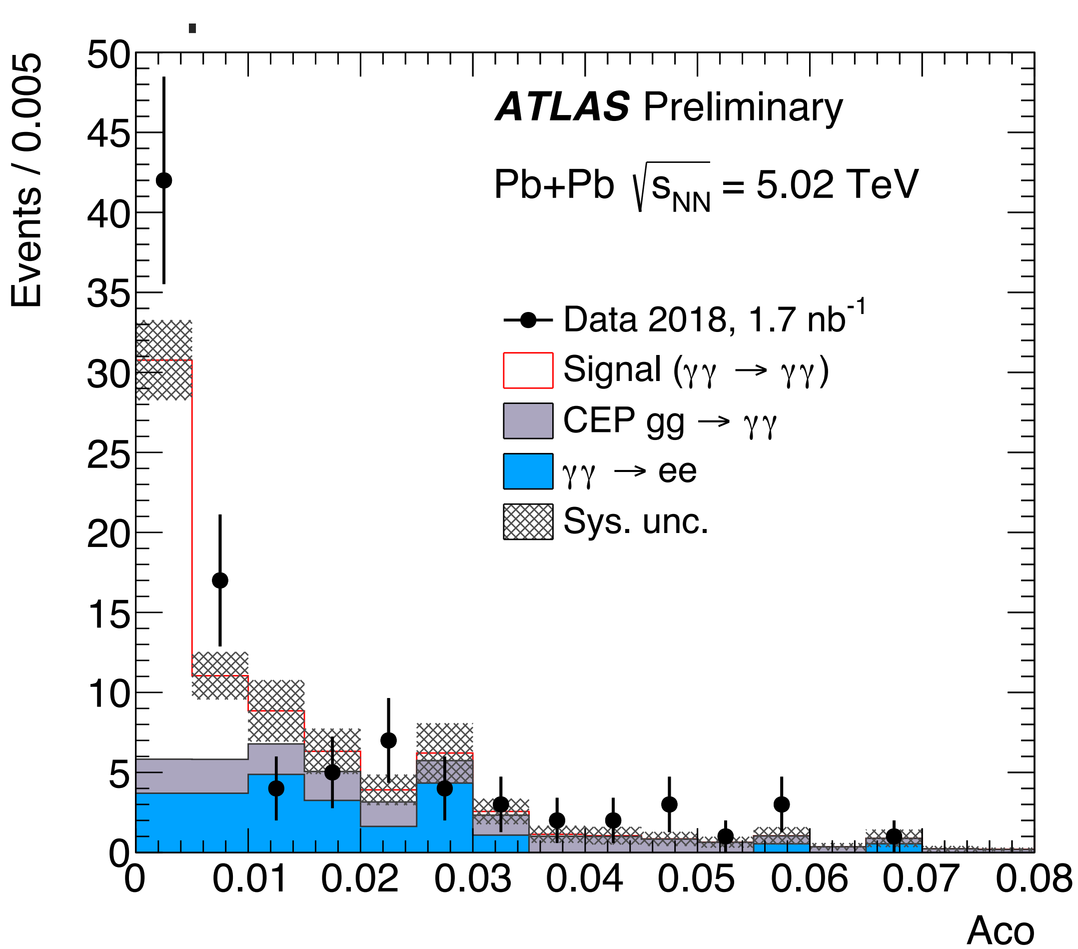
Alberto Belloni, CMS

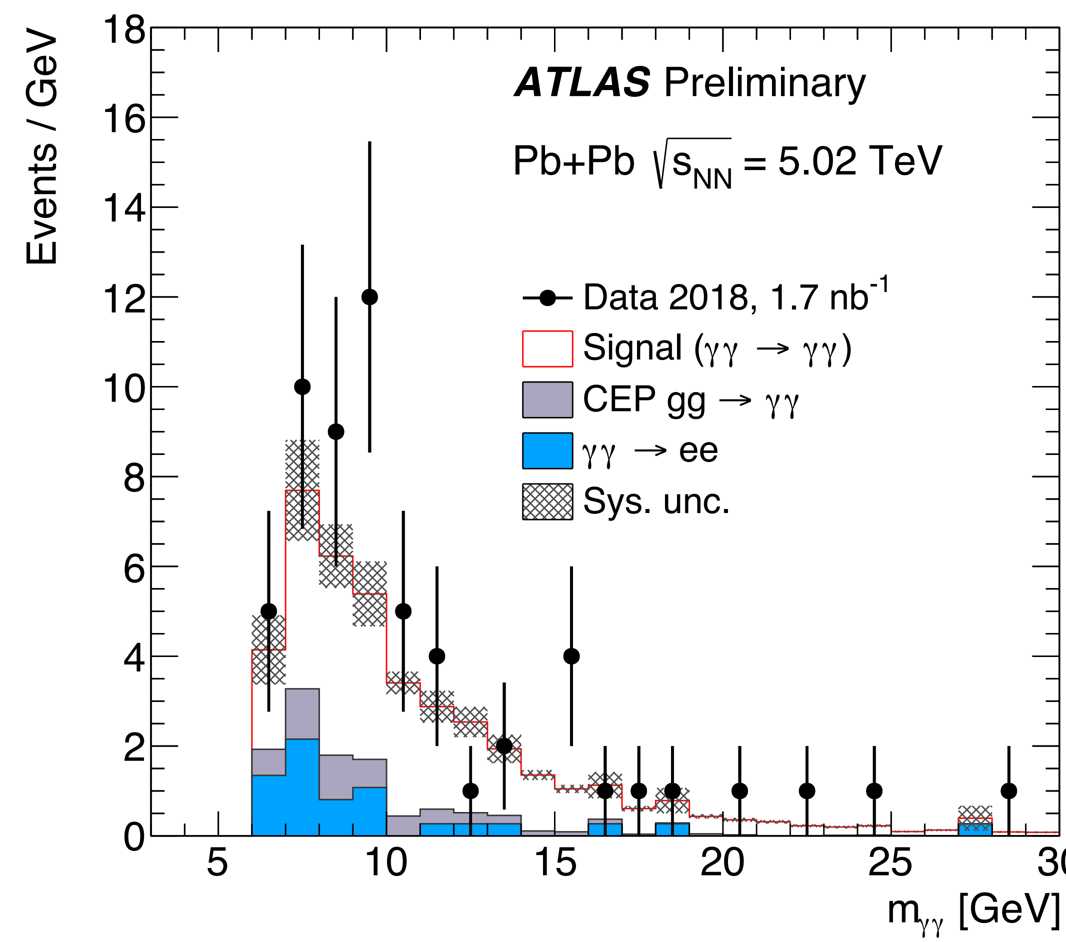
Observation of Light-by-Light Scattering

- 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

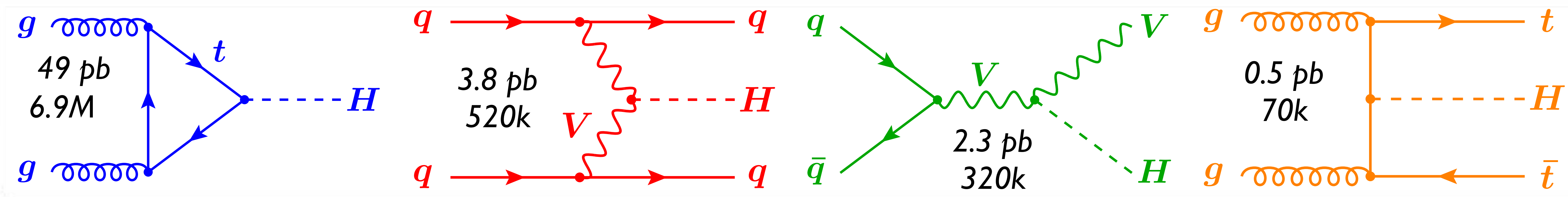




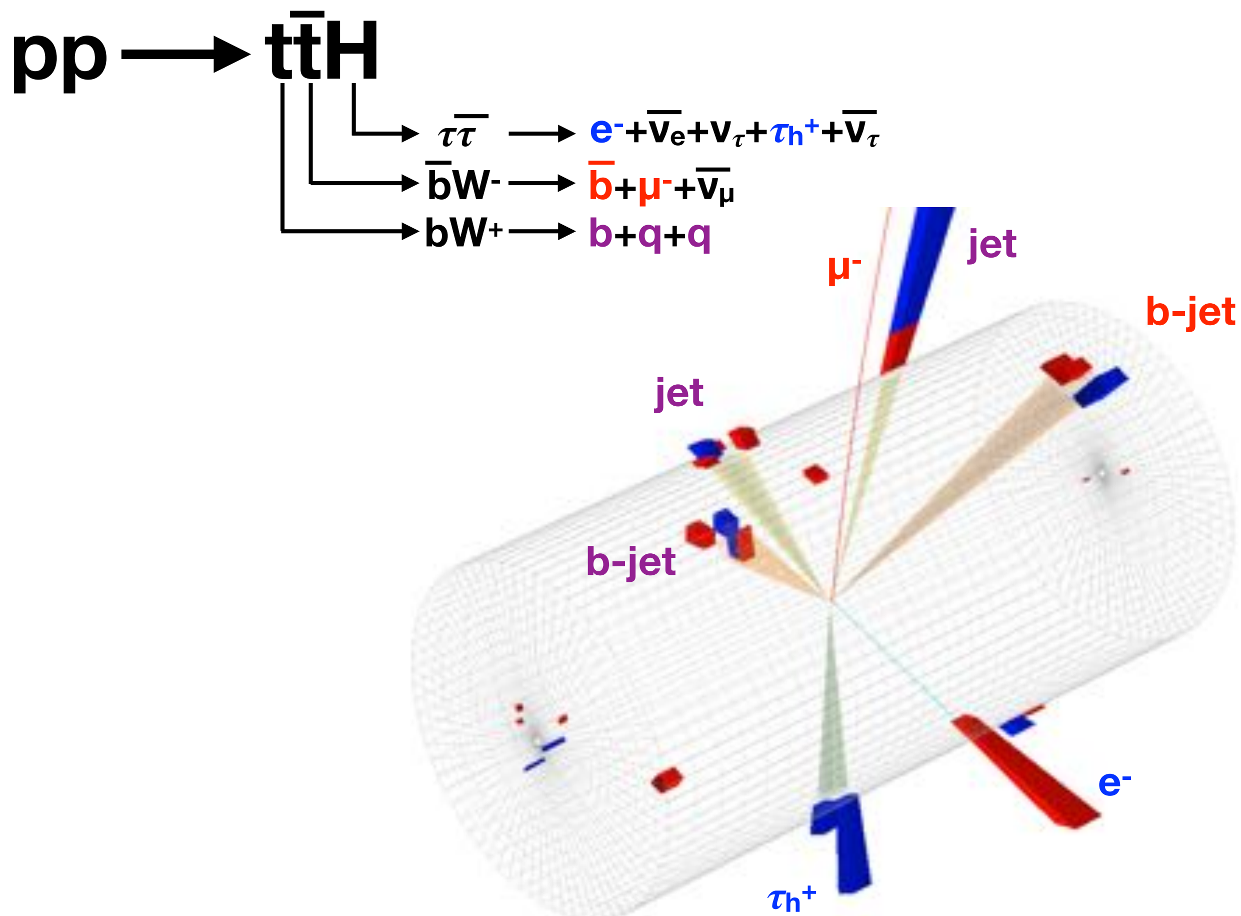
σ_{ATLAS} = **78 ±13 (stat) ±8 (sys) nb**

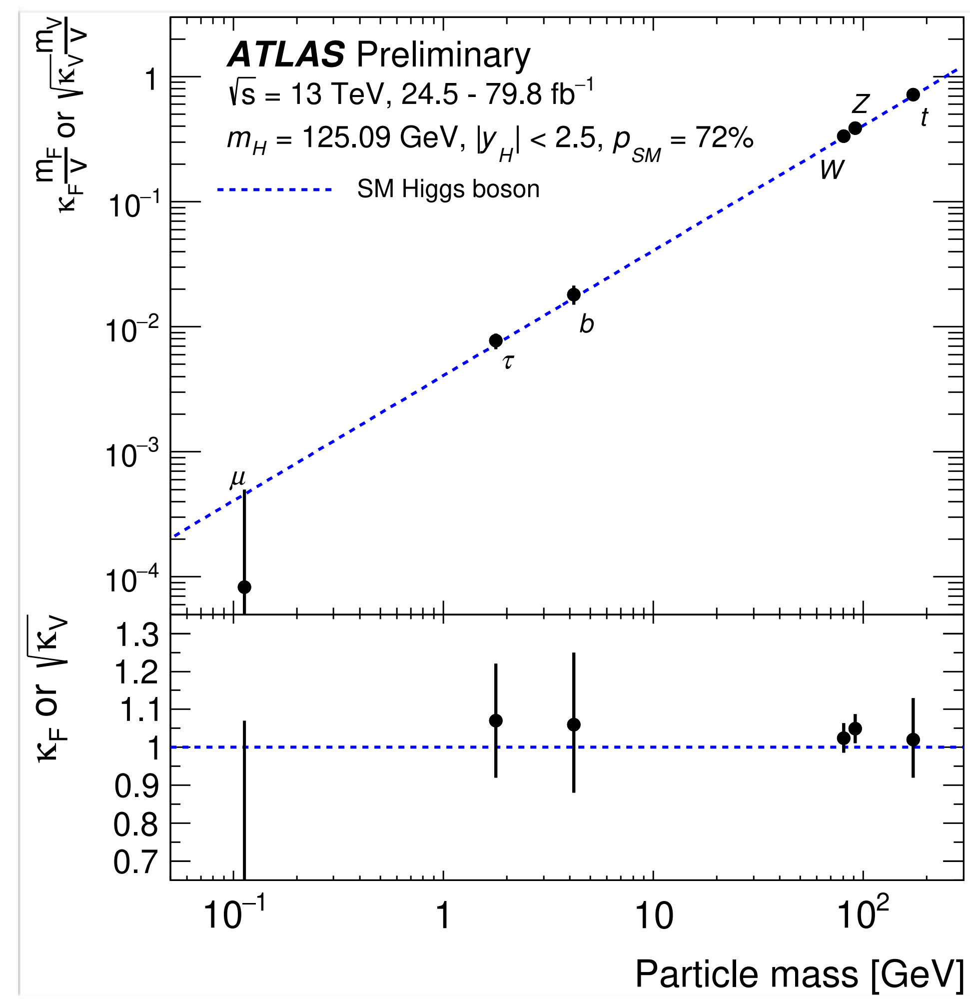
SM predictions: **49 ±5 nb**

Mateusz Dyndal, ATLAS



σ [pb]
#Higgs produced during Run-2





Higgs

From Discovery to Precision

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

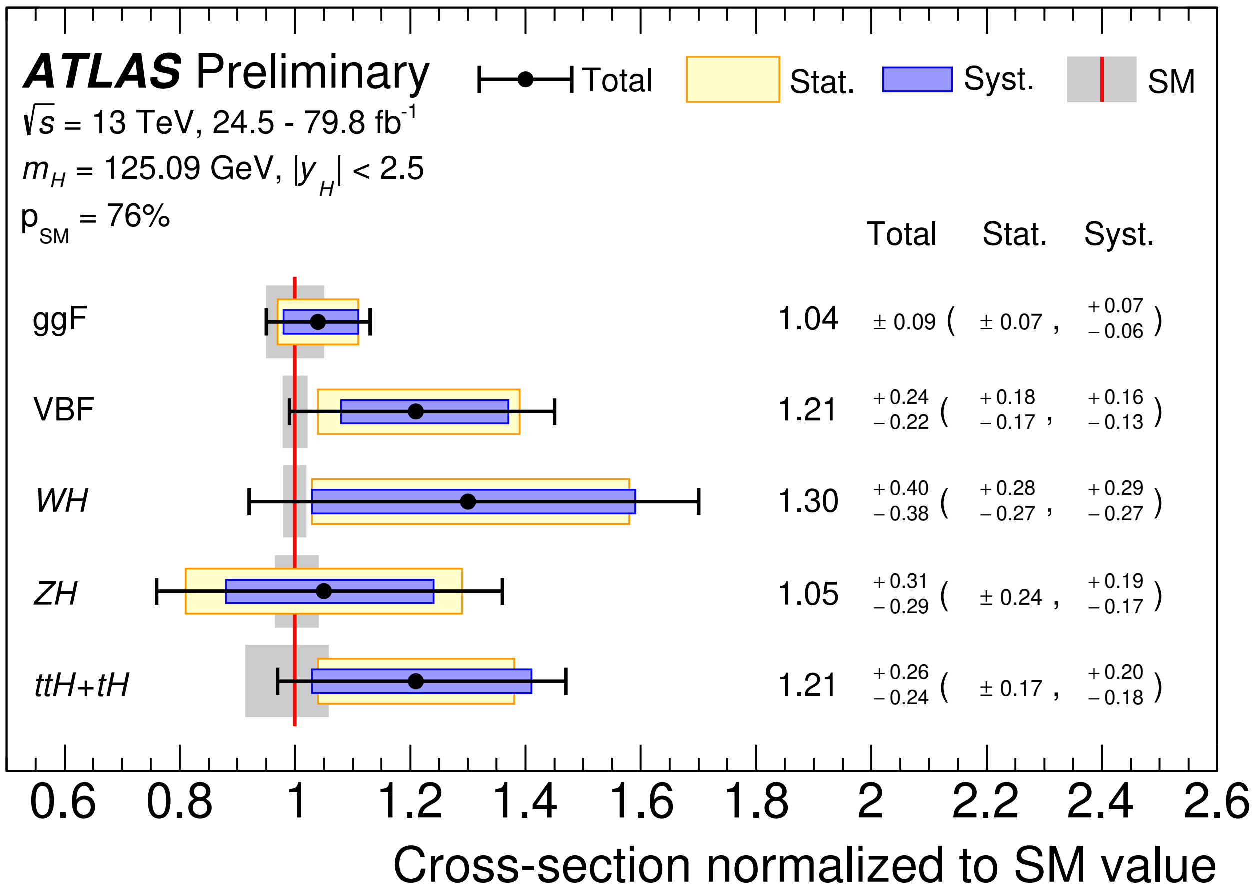
Higgs Physics in 2019

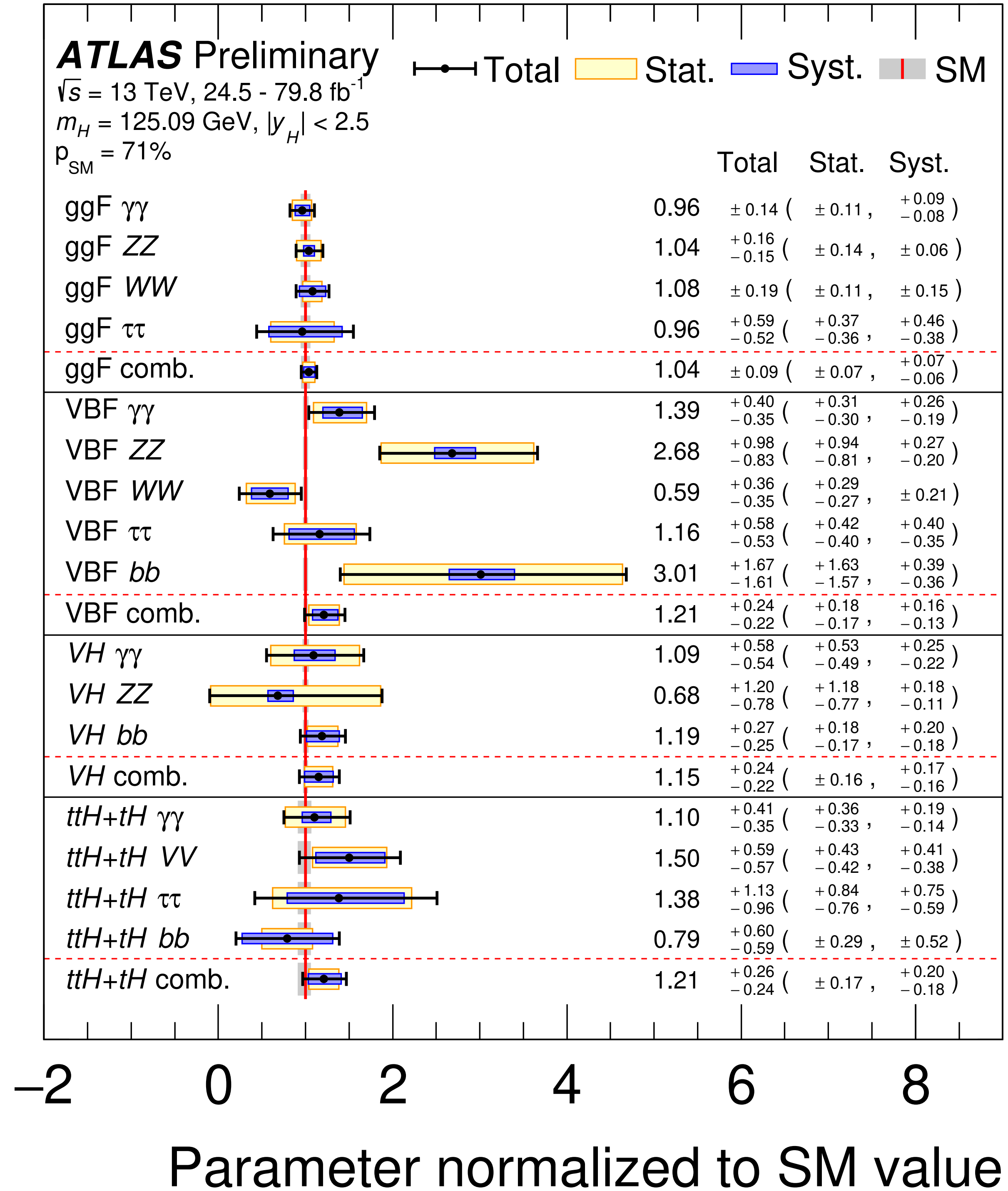
- A standard candle of Standard Model in just 7 years since its discovery
  - compare to top, W, and Z
- Higgs now used as a probe in searches for new phenomena
  - FCNC in top decays
  - Search for Supersymmetry
  - Search for Dark Matter WIMP candidates
  - Decay of heavy new particles to H+X
- Couplings to 3rd generation established in past 2 years
  - taus in 2017, top and b in 2018
- So far it walks and talks like the Standard Model Higgs
- *Falsification of the Higgs mechanism a critical component of High Energy Frontier program*

Higgs Properties

Heather Gray, ATLAS

- Similar performance for ATLAS and CMS





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

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

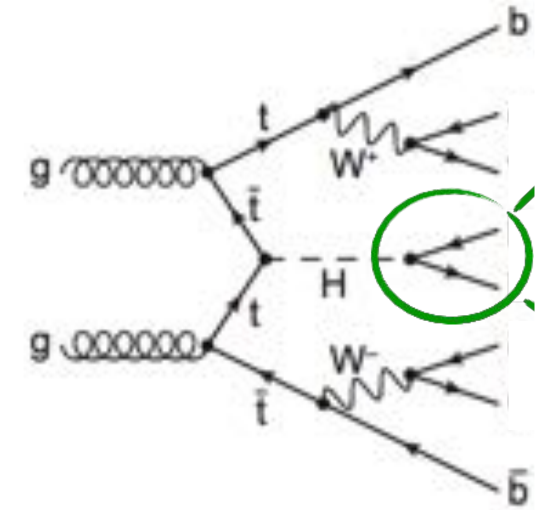
- Also extensive measurement of differential cross sections

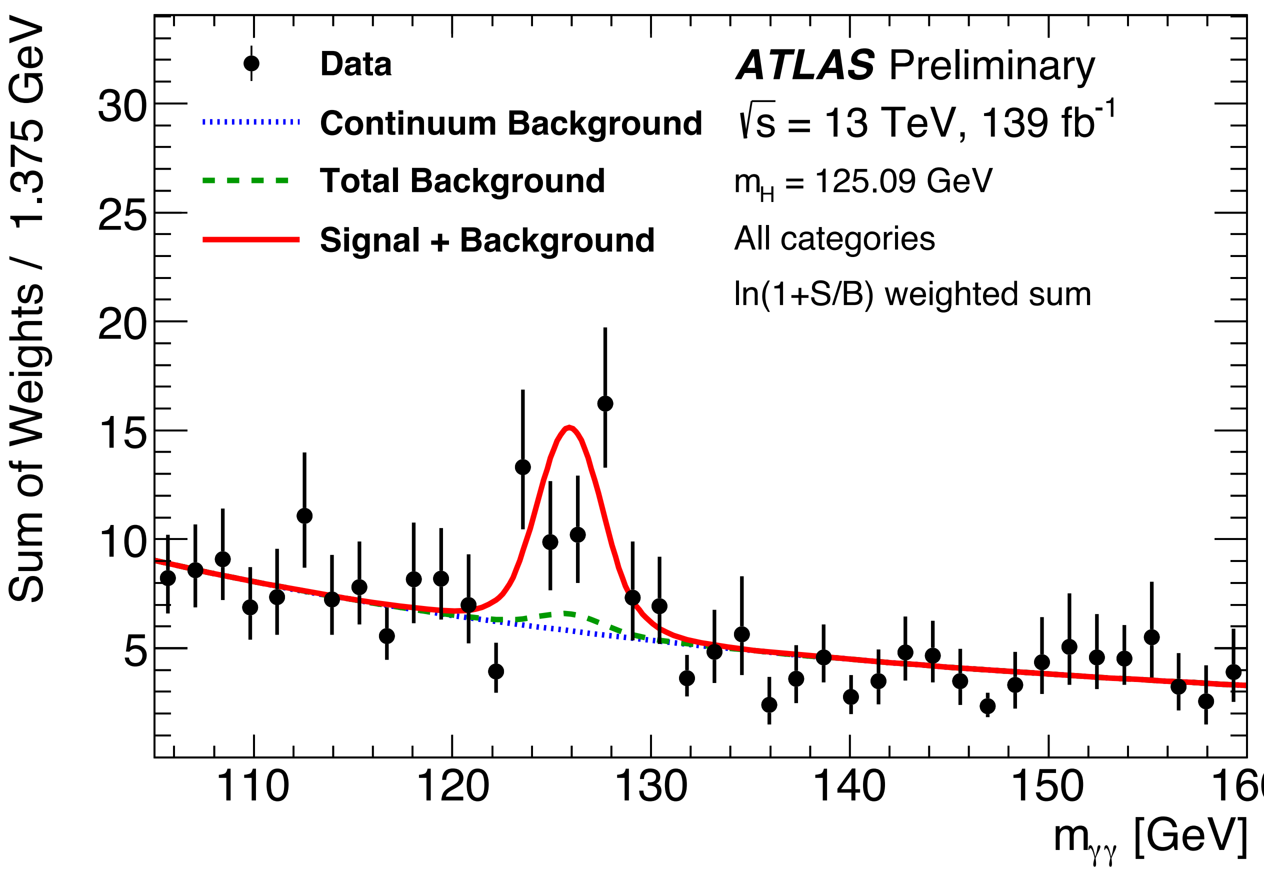
Yacine Haddad, CMS

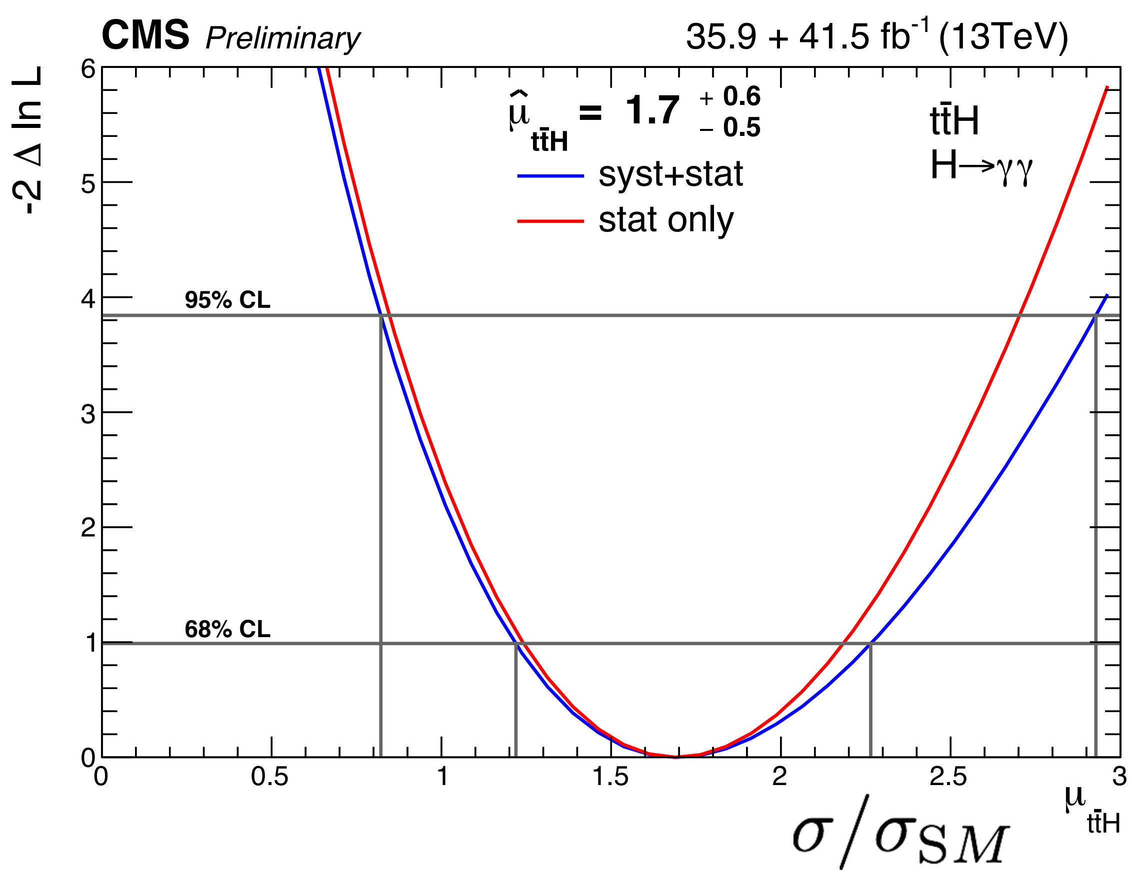
Fabio Cerutti, ATLAS

Updated Higgs-Top Coupling

- Updated study of top-Higgs coupling in H→γγ
  - ATLAS using full Run2 sample
  - CMS using 2016+2017 sample





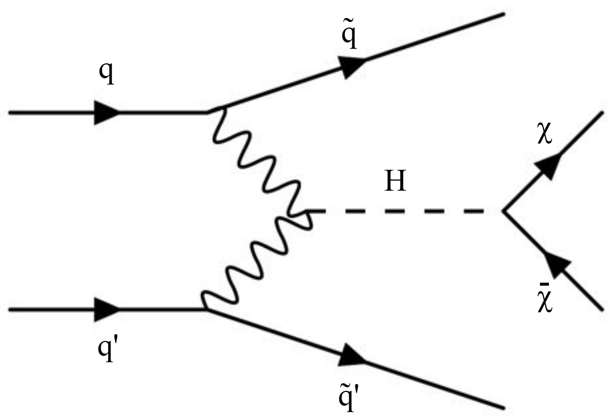


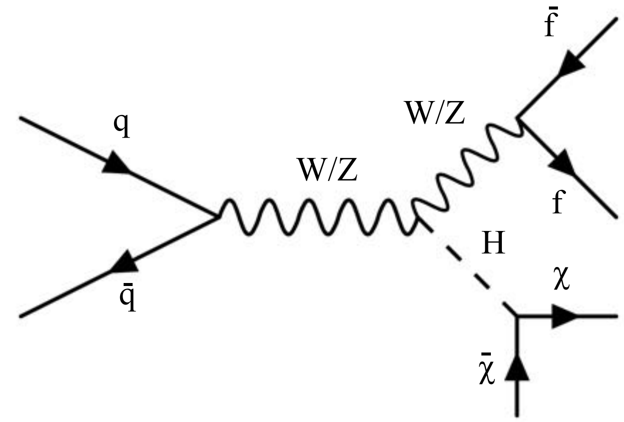
ATLAS $$\sigma/\sigma_{SM} = 1.38\,^{+0.41}_{-0.36} = 1.38\,^{+0.33}_{-0.31}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{exp.})\,^{+0.22}_{-0.14}\,(\text{theo.})$$

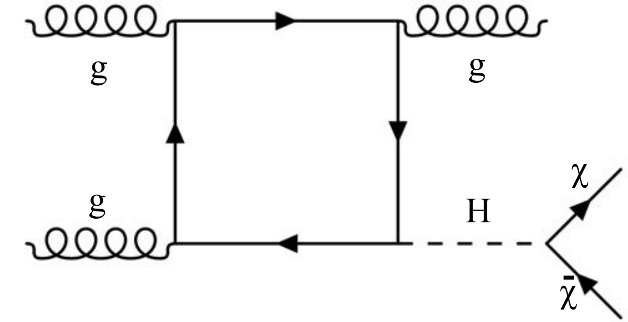
Haichen Wang, Jennet Dickinson, ATLAS

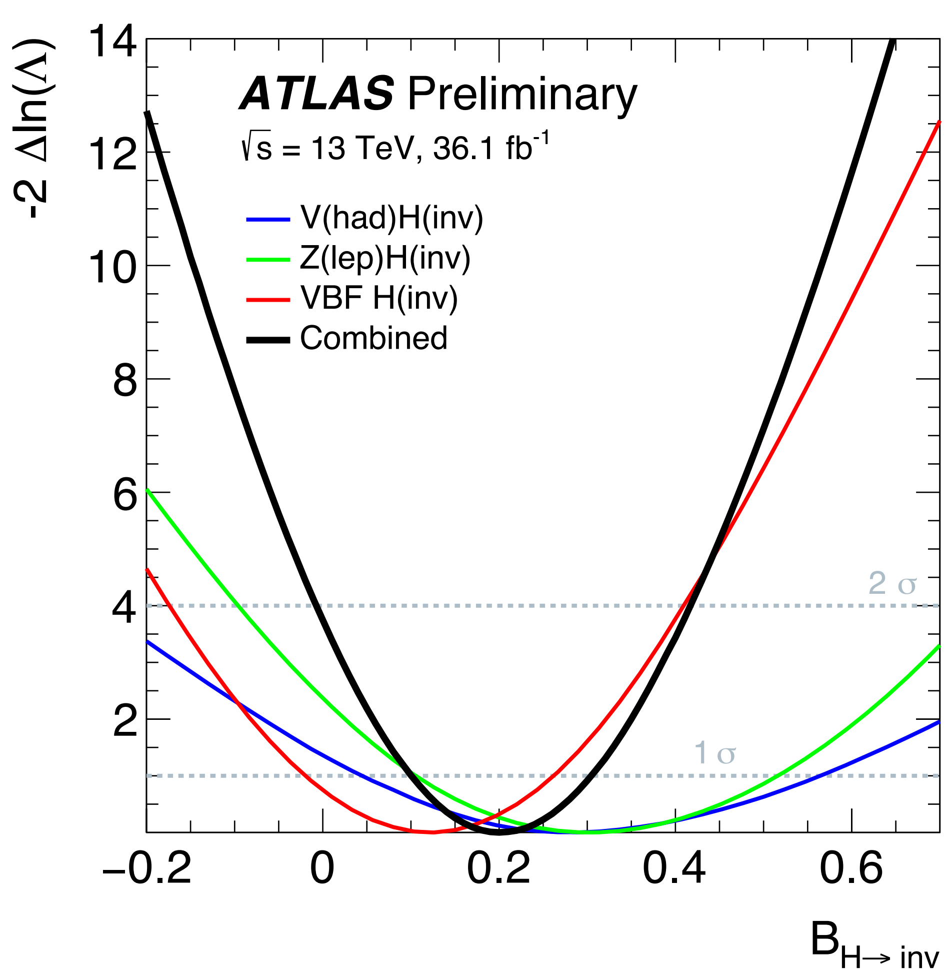
Stephane Cooperstein, CMS

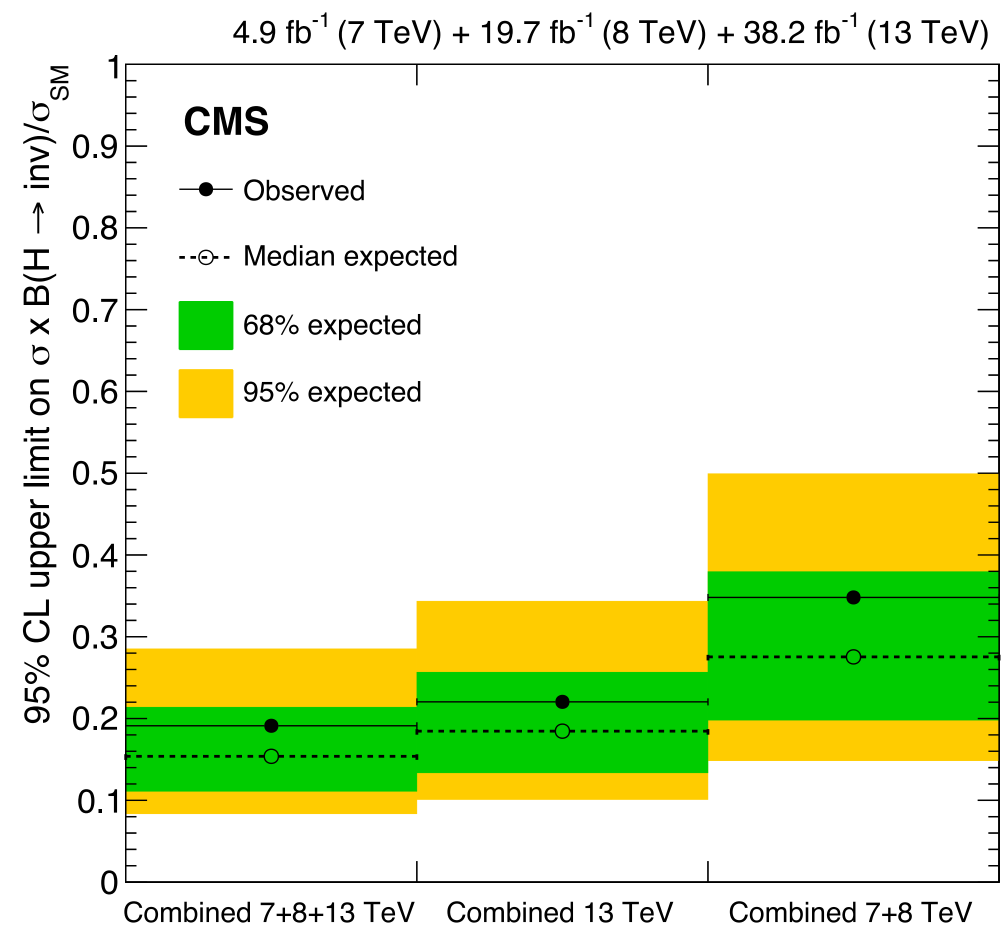
H → invisible











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

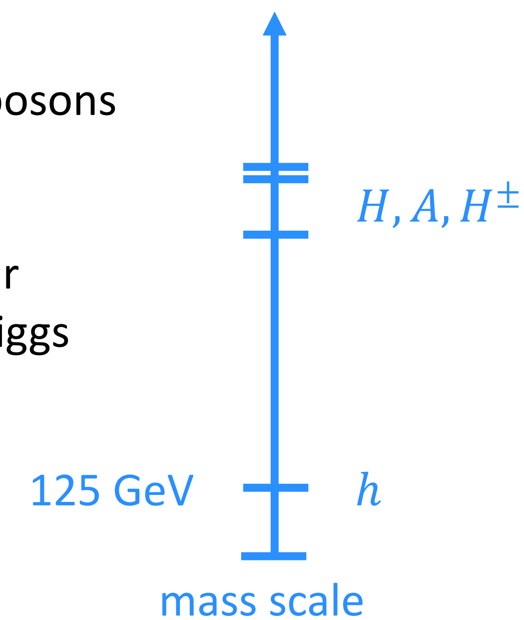
$B_{inv} < 0.19\ (0.15)$

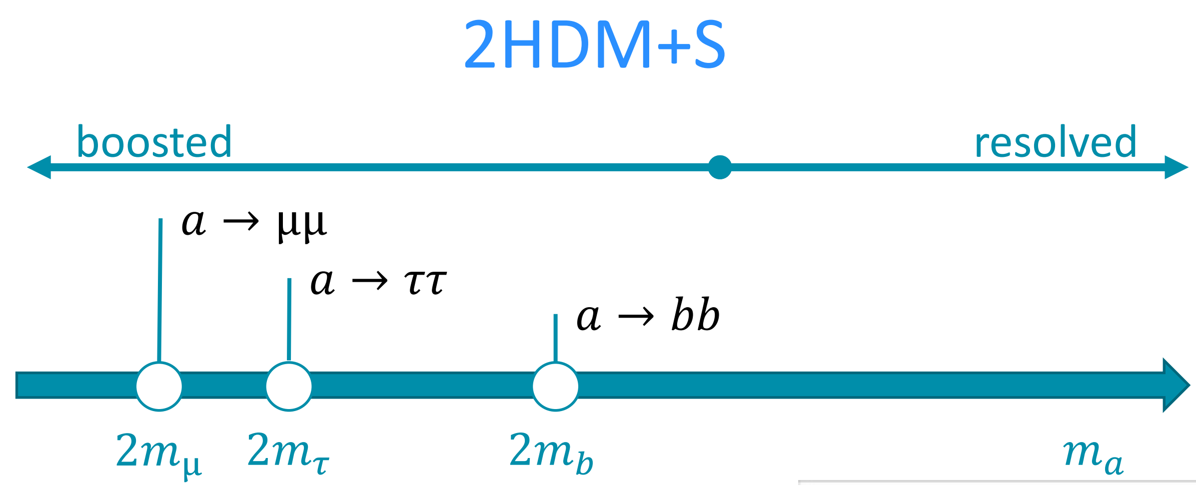
- Aiming for 2-3% limit at High-Luminosity LHC with 3000 fb^{-1}

The Higgs or *A* Higgs?

- In BSM models with more Higgs bososn, the lightest can resemble *the* Higgs
- Direct search for additional light and heavy Higgs bosons with up to 80 fb^{-1}

2HDM has 5 Higgs bosons
- h: "SM" Higgs
- H: heavy Higgs
- A: pseudoscalar
- $H^{\pm}$: charged Higgs





- So far no excess or evidence and only exclusion in theory parameter space

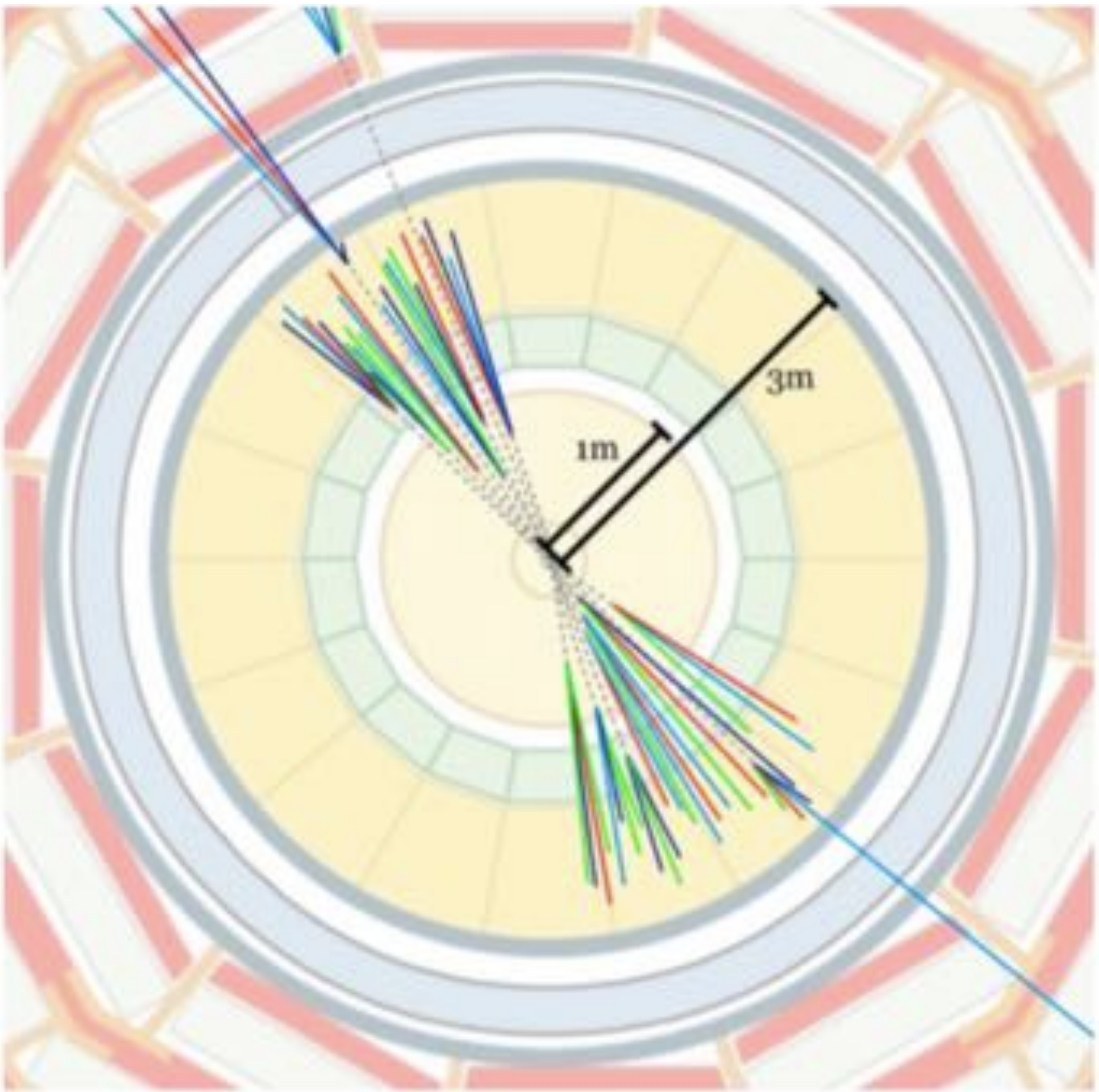
$$H/A \rightarrow \tau\tau,\ \mu\mu,\ bb,\ ZZ,\ WW,\ hh,\ Zh$$

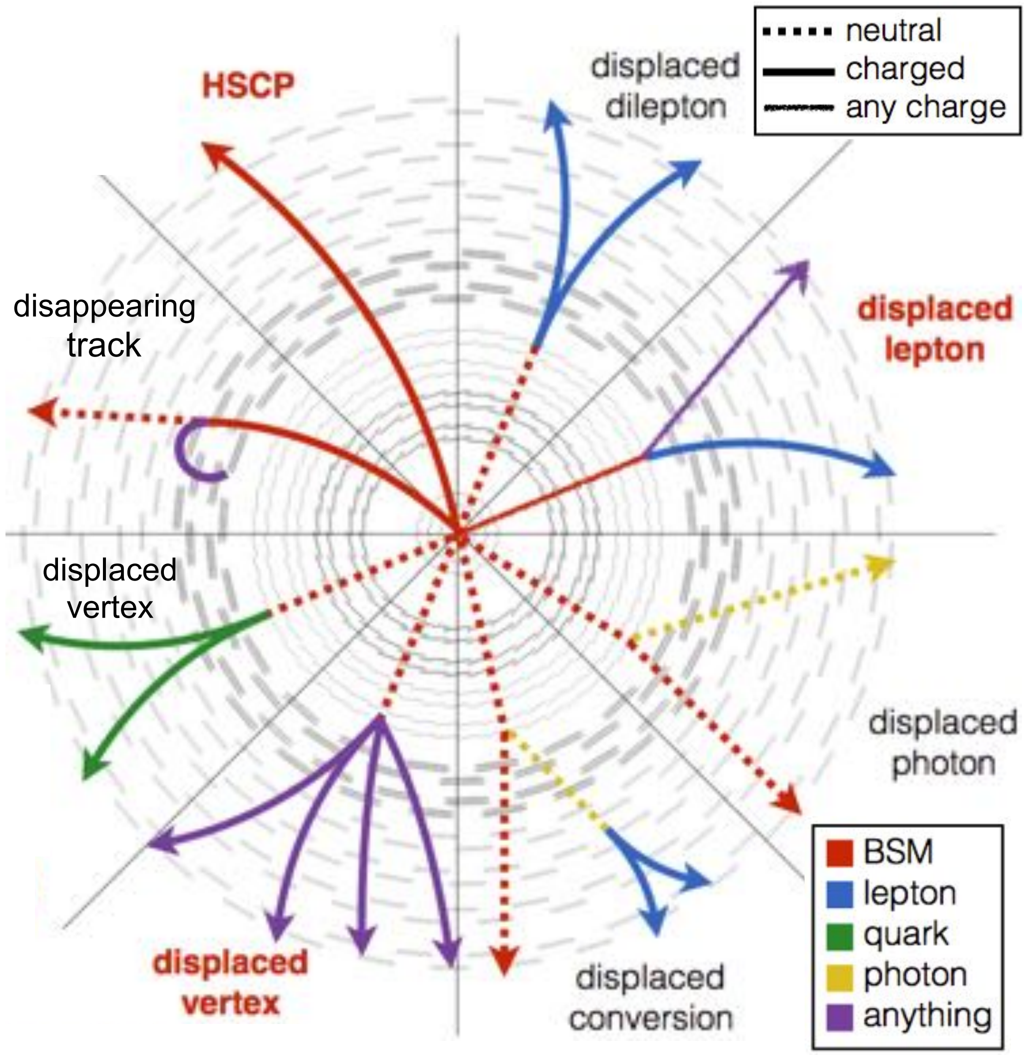
$$H^{+} \rightarrow \tau\upsilon,\ t\bar{b},\ W^{+}A,\ W^{+}Z$$

$$h \rightarrow aa \rightarrow 4\mu,\ 4\tau,\ \mu\mu\tau\tau,\ bb\mu\mu,\ bb\tau\tau,\ 4b$$

- High-Luminosity LHC two provide x20 increase in statistics to answer this question

Devin Taylor, CMS





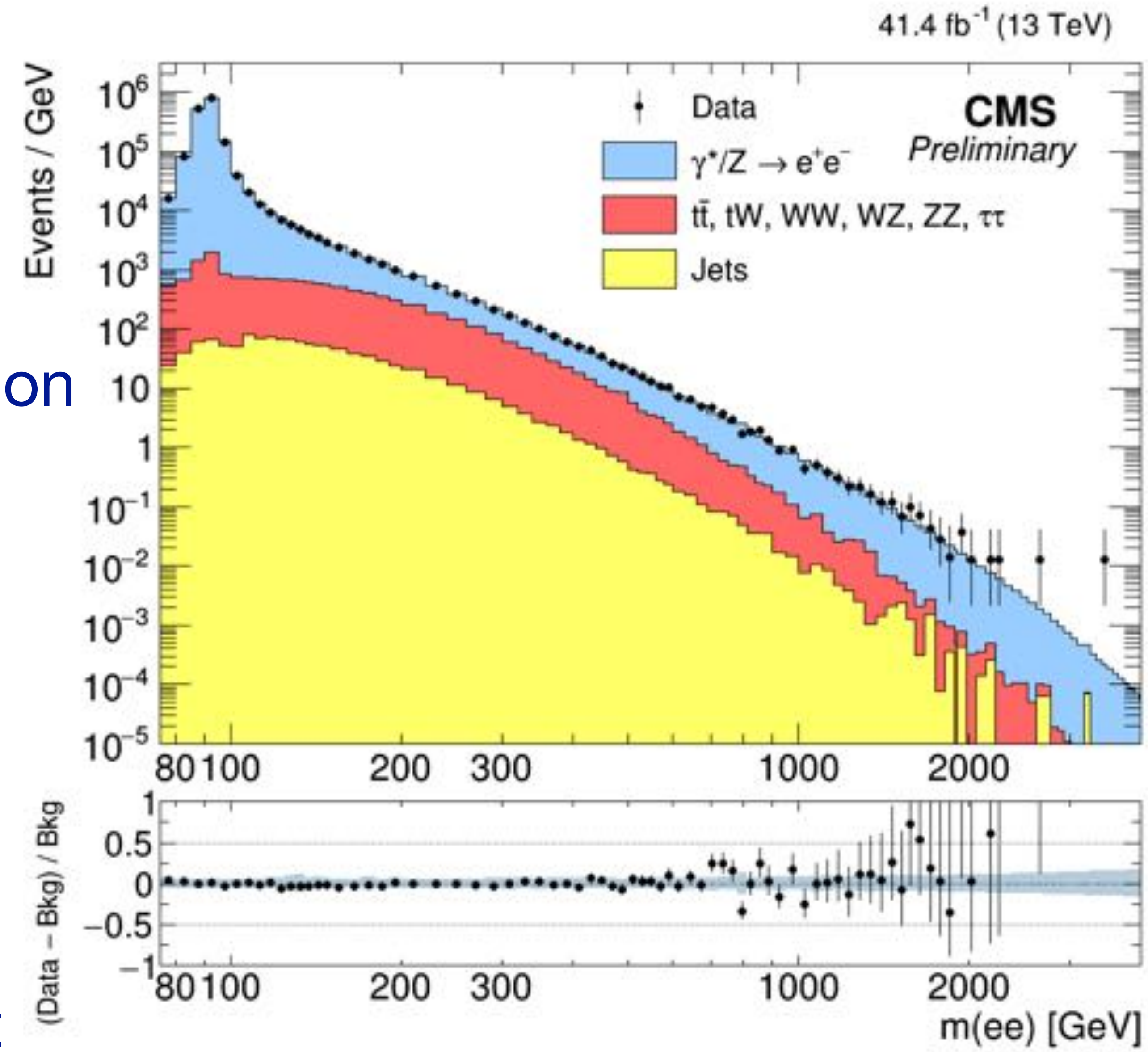
Credits: J. Antonelli

Exotic Phenomena

Exotica Timeline

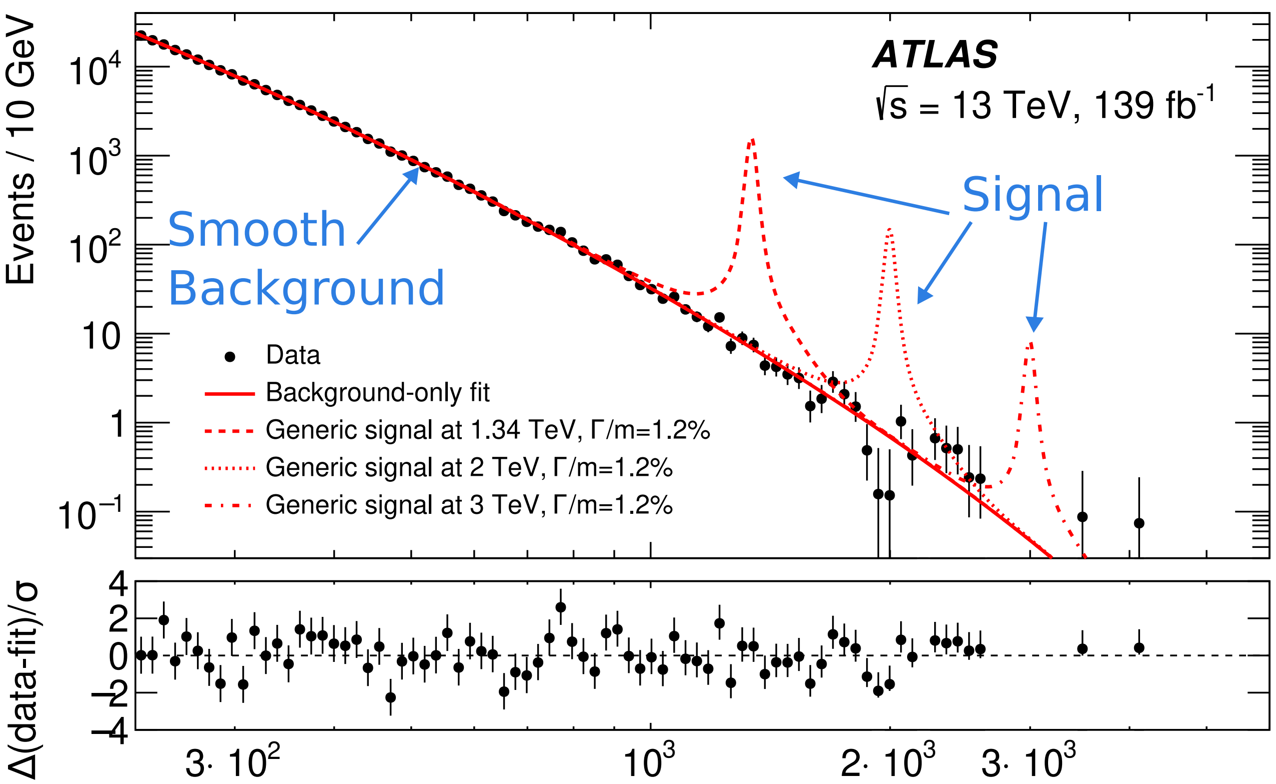
Detector Understanding (time)

- Two-body resonances from day one: leptons, photons, jets
  - detector effects not critical
  - sensitive to bumps right away
- Increase complexity and multiplicity of final state
  - better understanding and calibration of detector
- Final states with X + MET
- Really exotic signatures such as long-lived particles
  - control of detector conditions over longer period
  - ultimate calibration and alignment
  - optimisation of dedicated algorithms



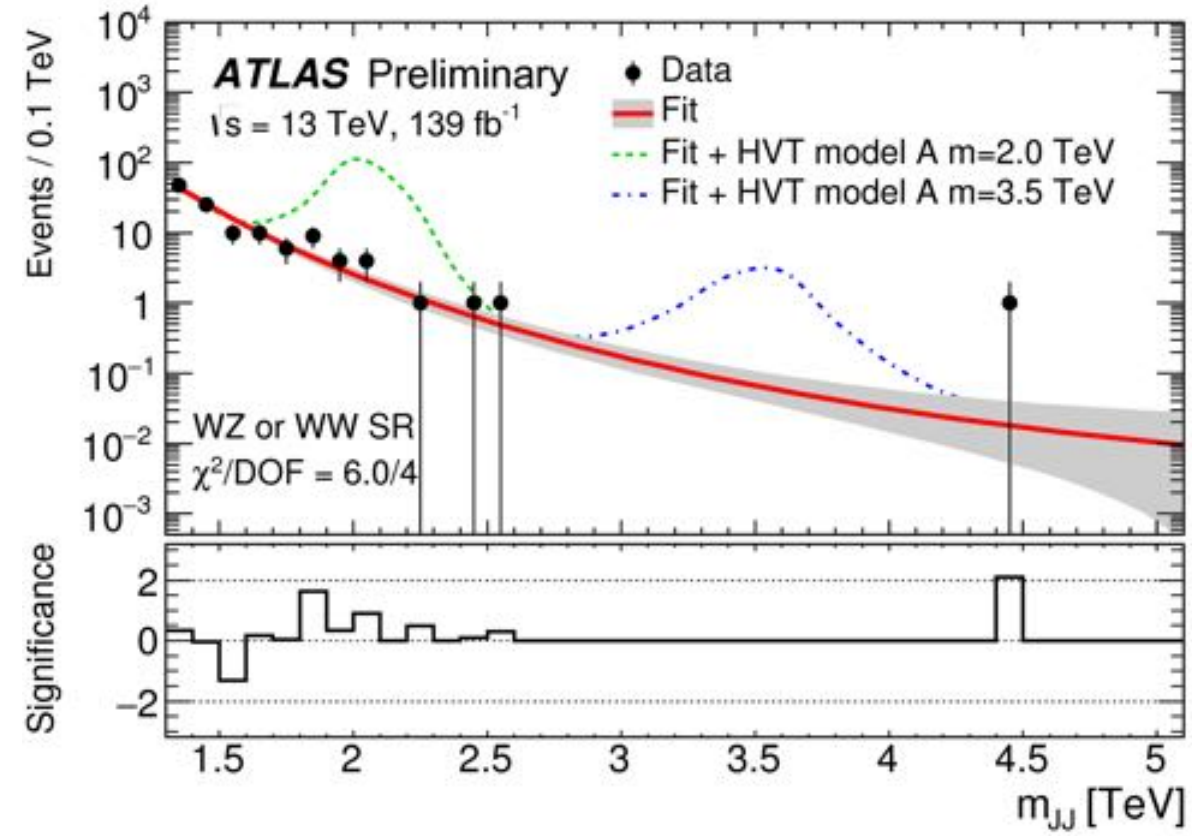
Heavy Resonances

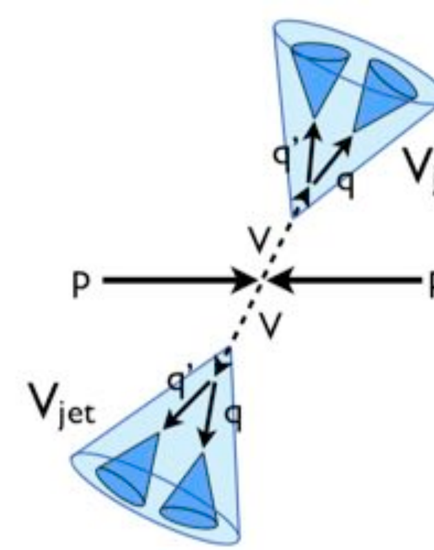
Z' in dileptons



Excluding particles with mass ~ 4-5 TeV

Diboson resonance using
boson tagging with substructure





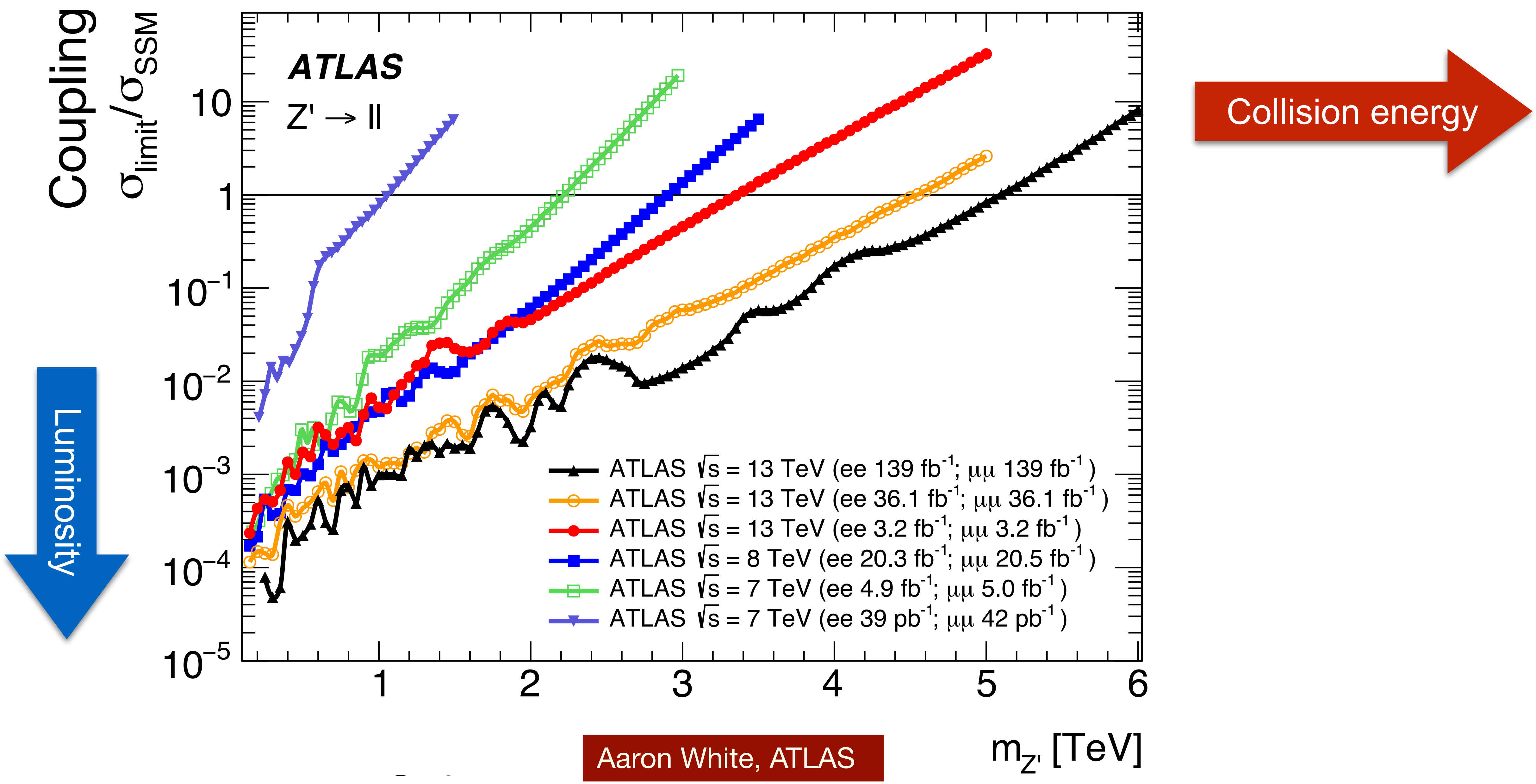
- Also updated ATLAS diet bump hunt with full Run2
  - Addition of full Run2 data extends exclusion limits by "just" 700 GeV

Savanna Shaw, ATLAS

Alberto Zucchetta, CMS

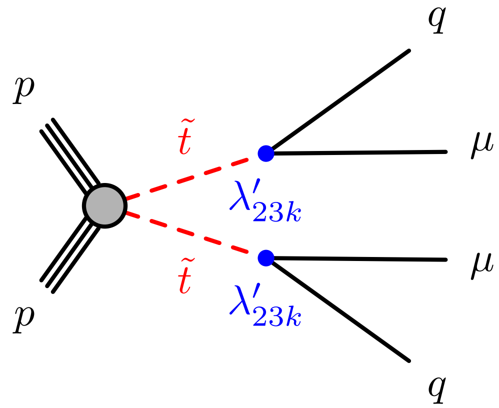
Energy vs Luminosity

- Biggest jump in mass limits with increased energy at start of Run2
  - Assuming maximal coupling to SM particles
  - Most searches published with 36 fb^{-1} of data
- With full Run2 data focus on exploring weakly coupled phenomena

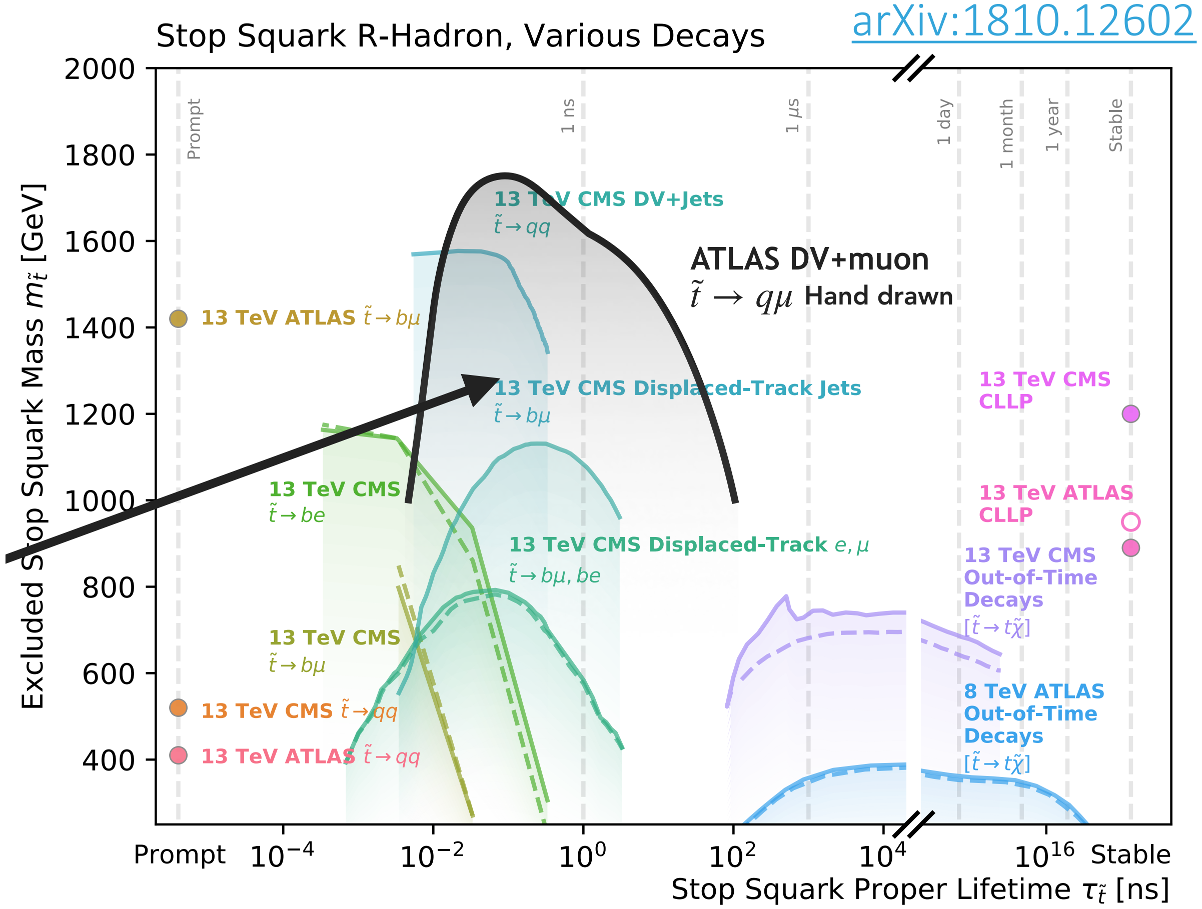


Long-Lived Particles

Search for supersymmetry with displaced vertex



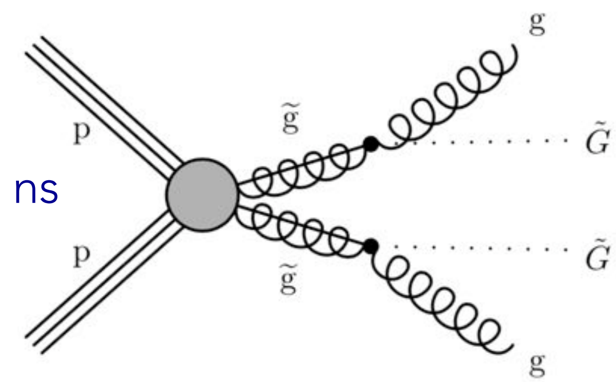
arXiv:1810.12602

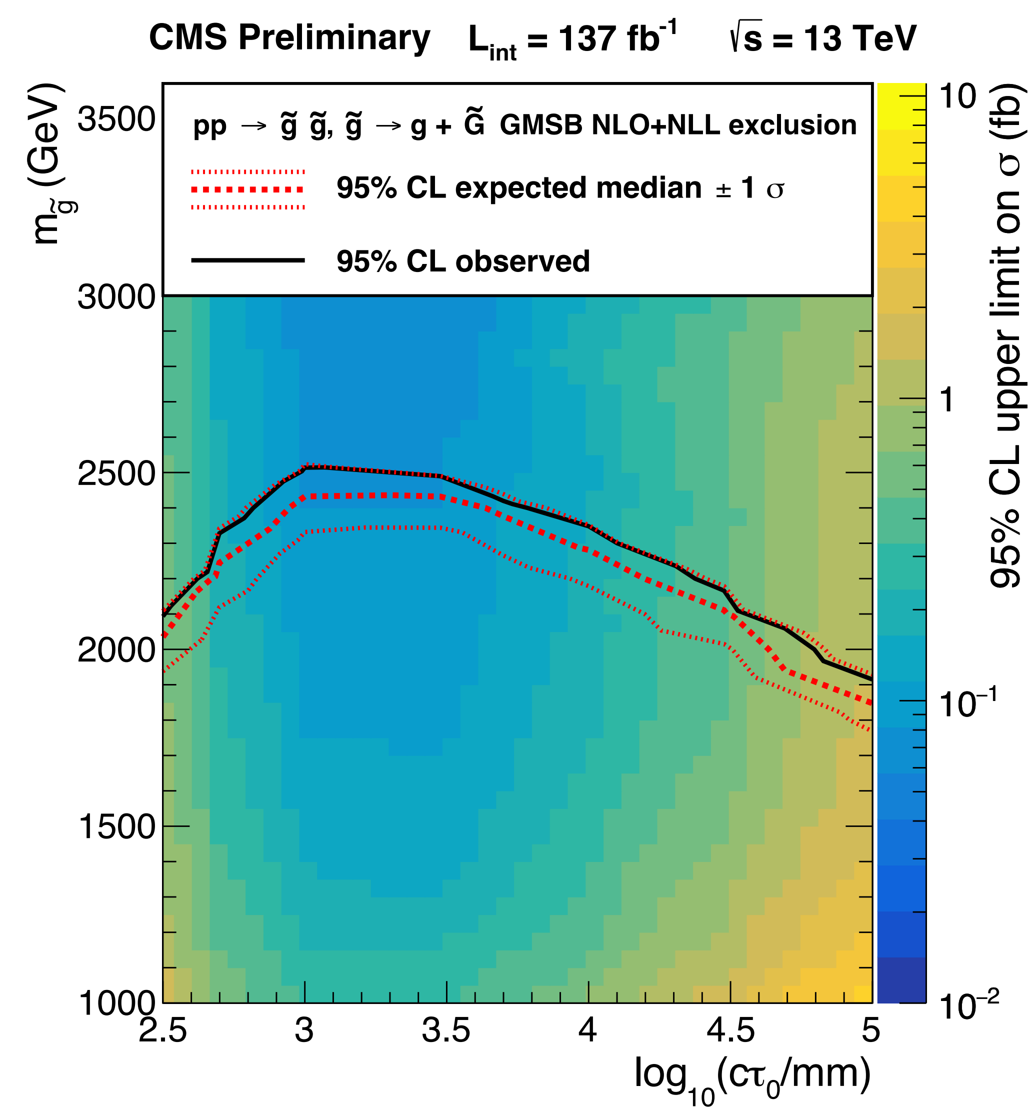


Nora Pettersson, Karri Folan DiPetrillo, ATLAS

Search for supersymmetry with delayed jets

3 ns < t_{jet} < 20 ns

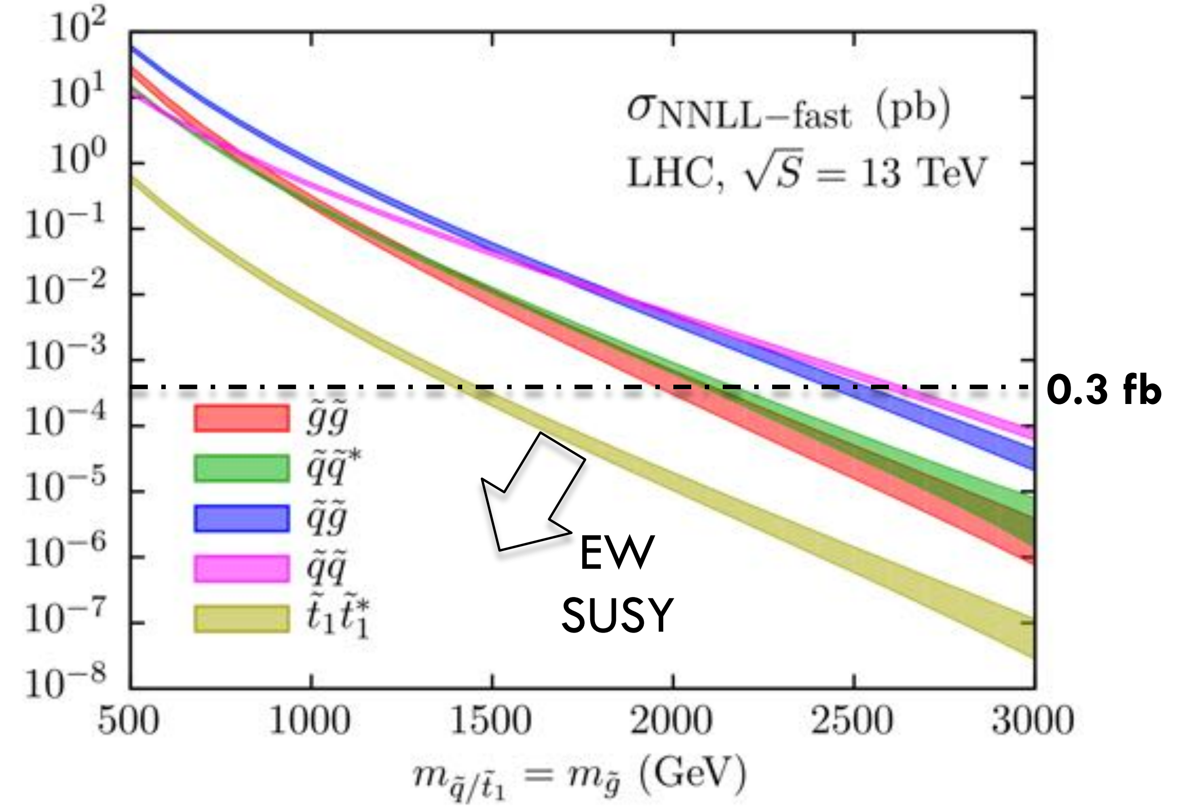


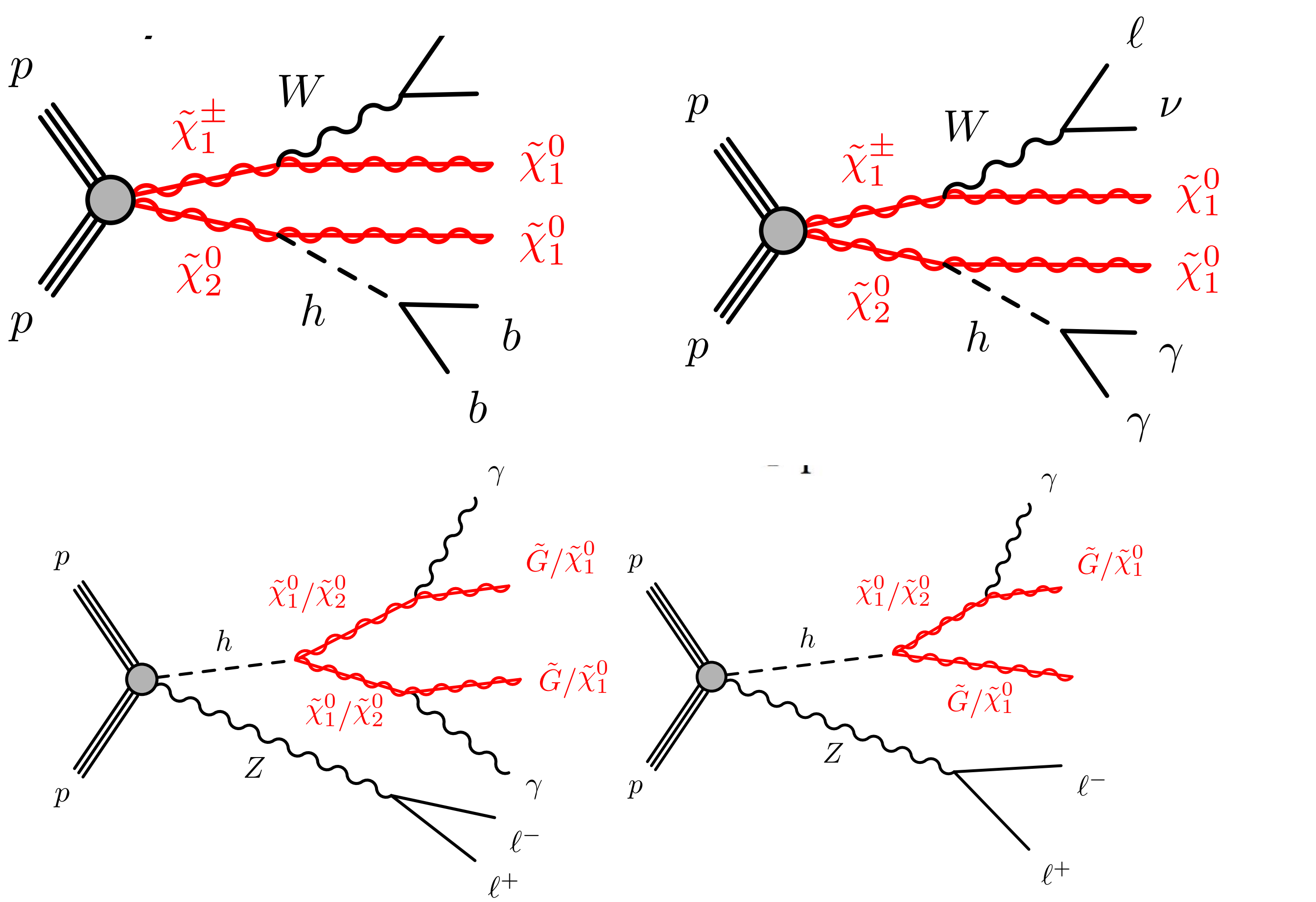


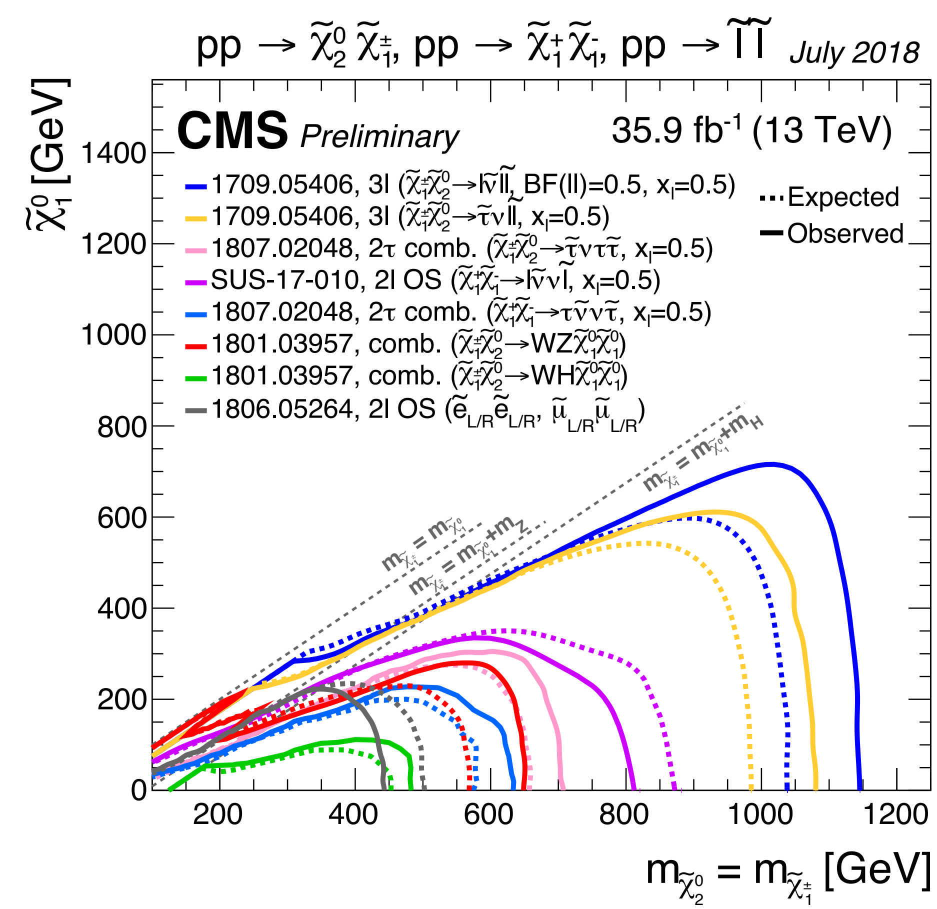
- ▹ Extremely quick turn-around for long-lived particle search

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

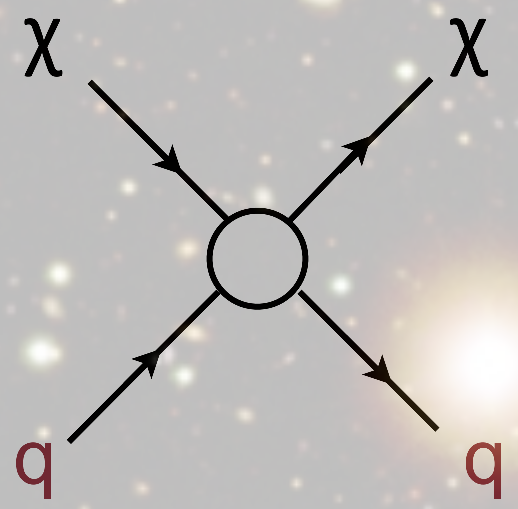




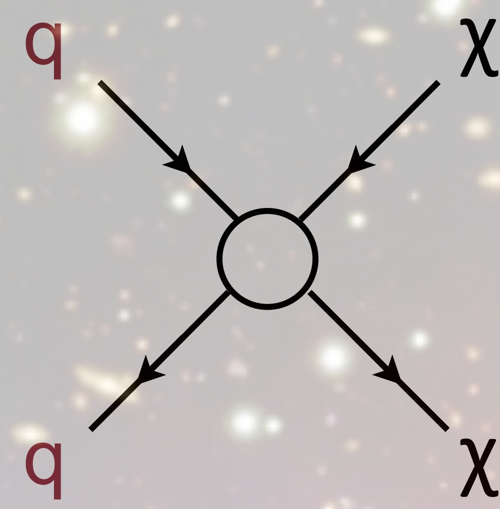


Marco Masciovecchio, CMS

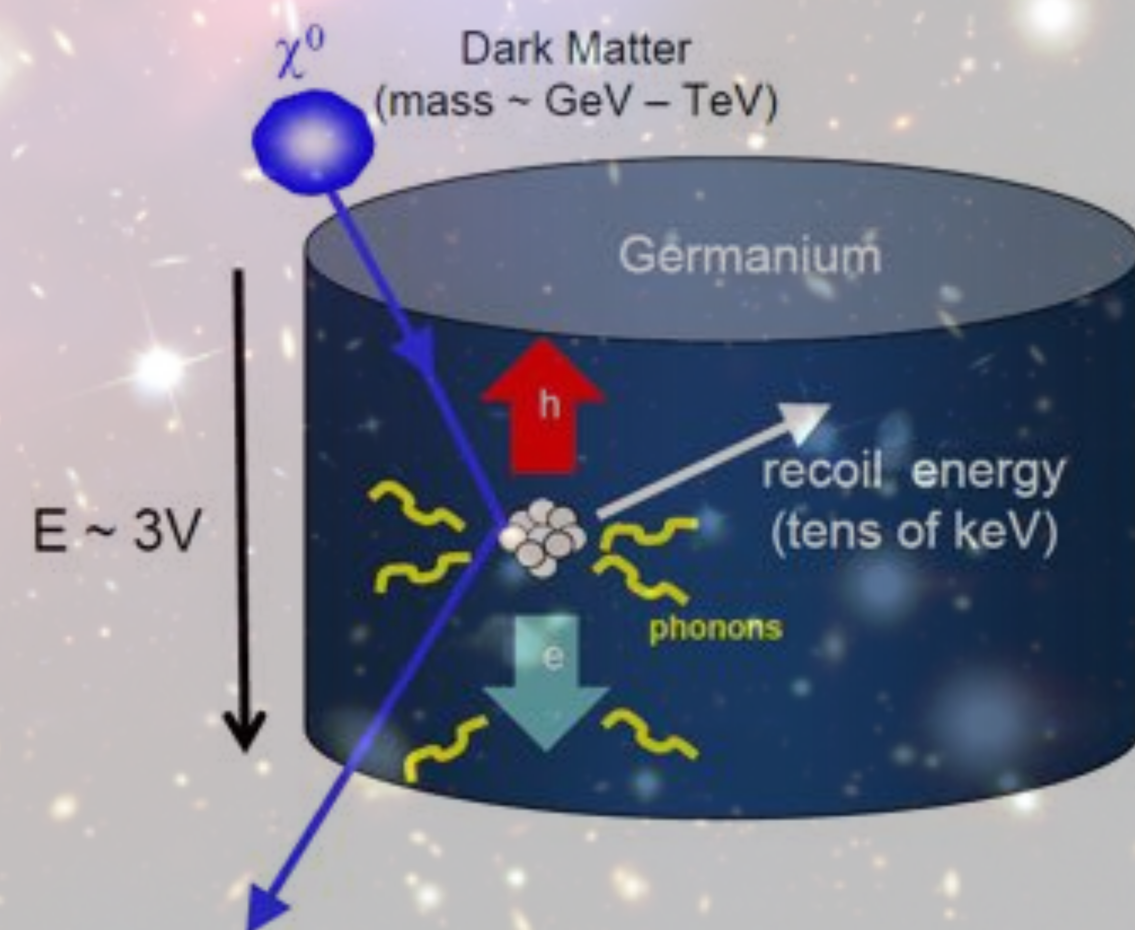
Matthew Gignac, ATLAS



Direct Detection



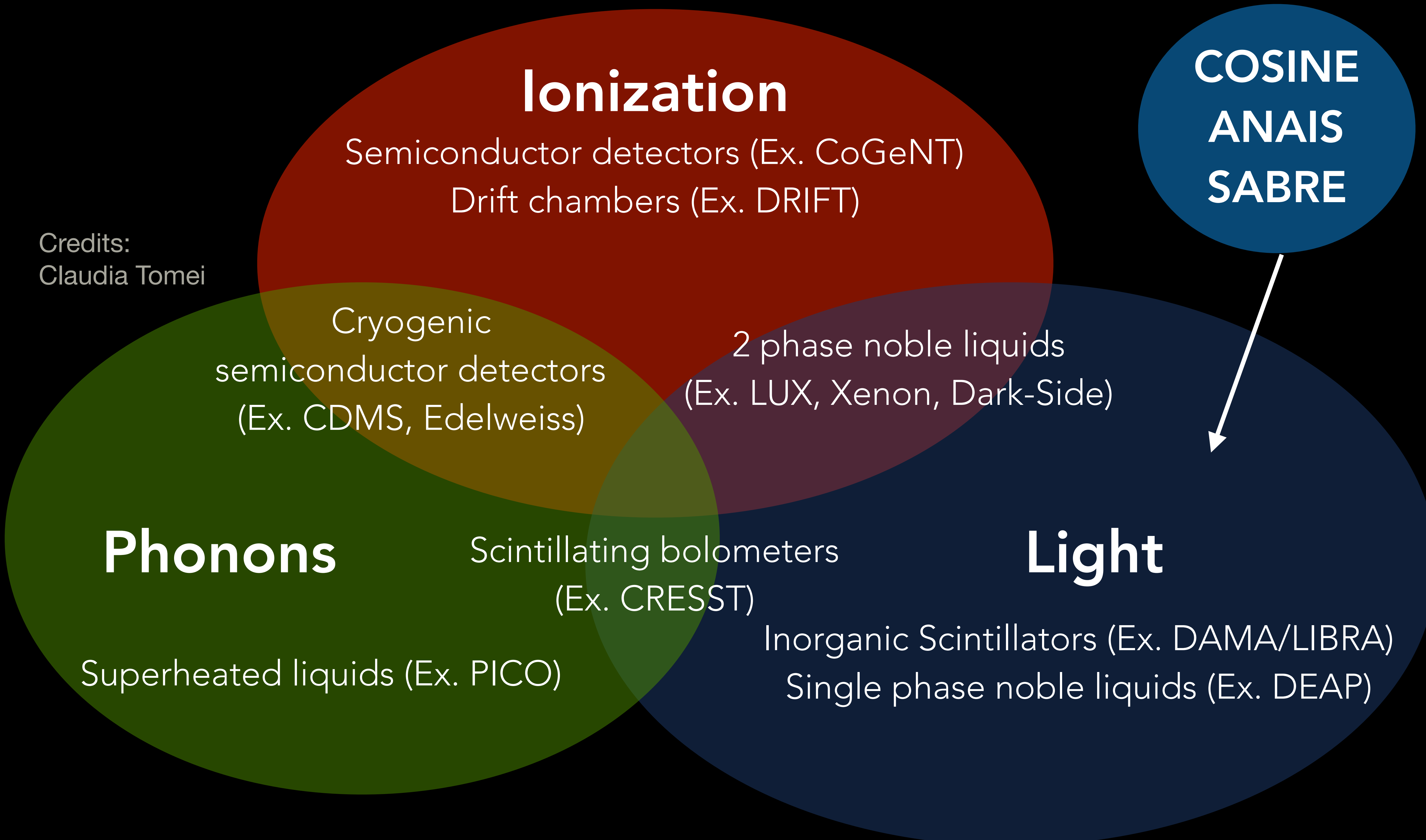
Production at Colliders



Dark Matter

The known unknown

Detection Techniques

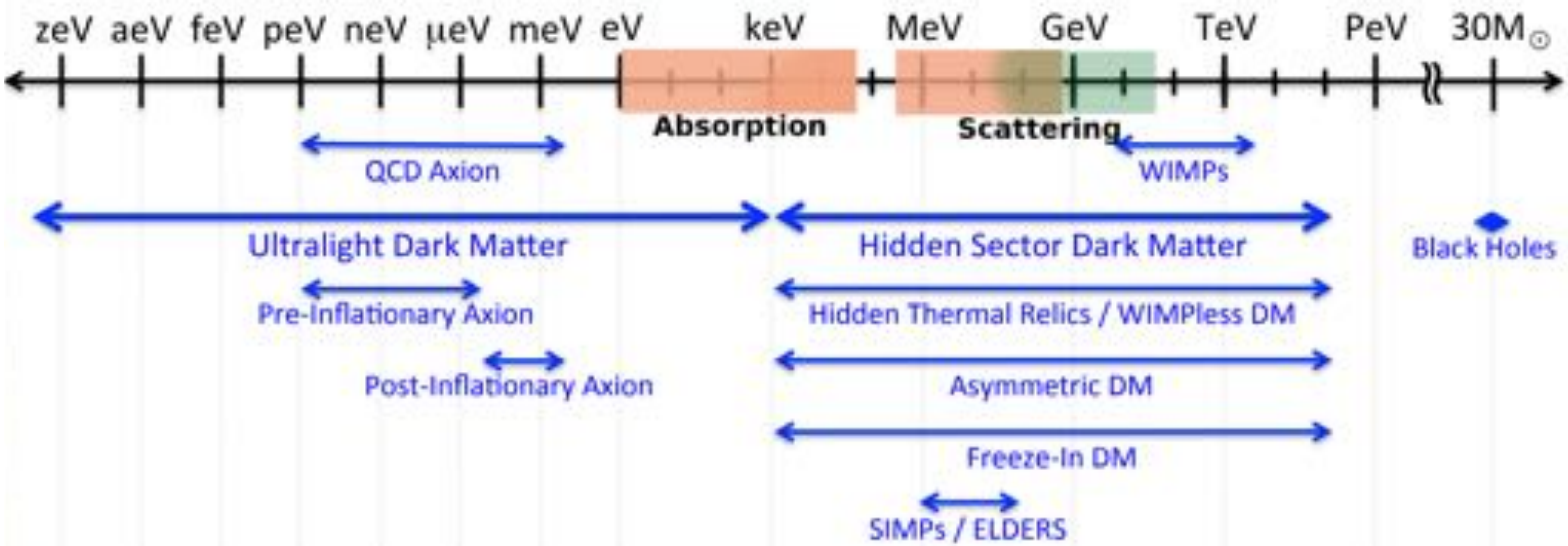


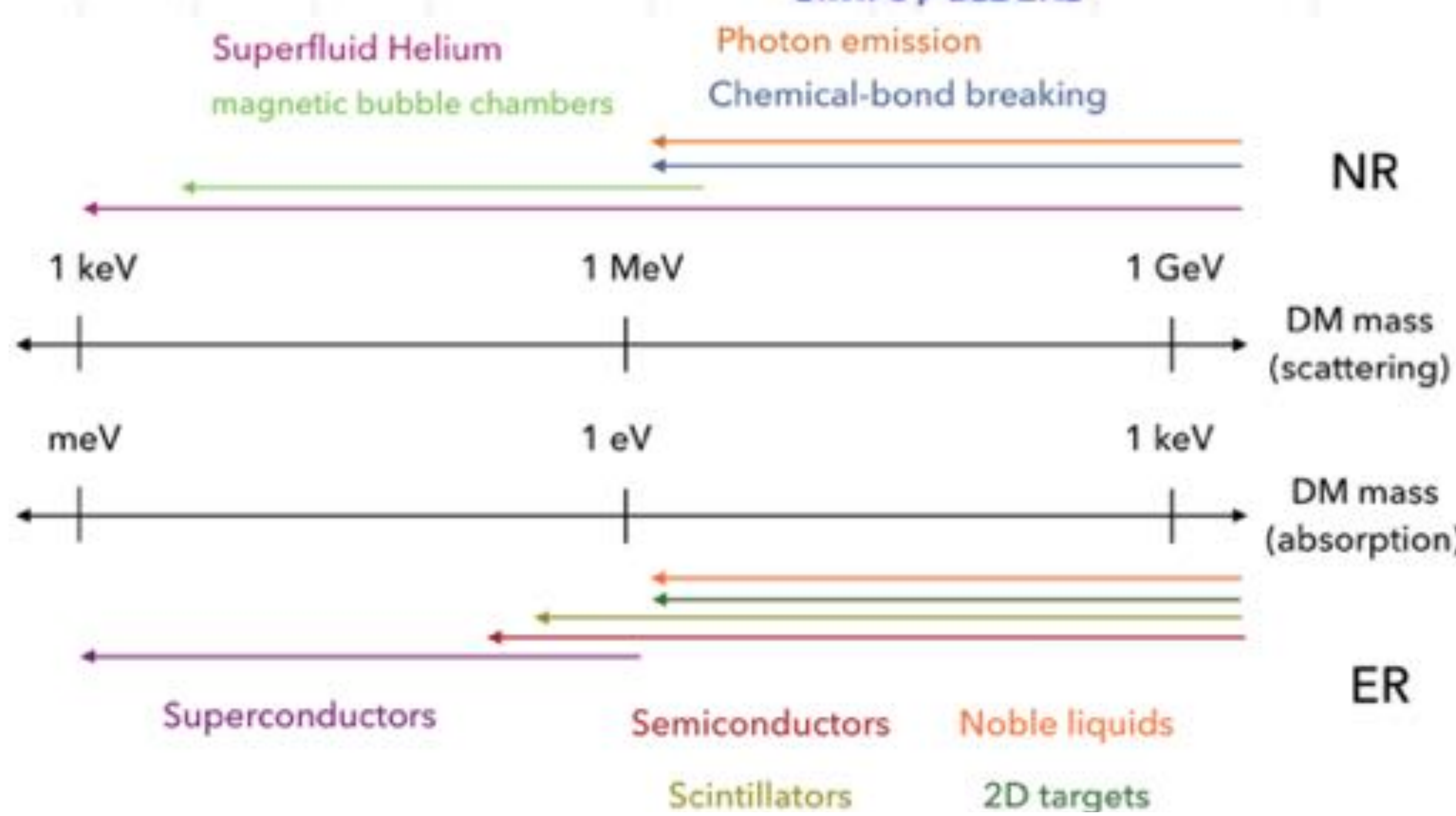
Credits:
Claudia Tomei

Radio pure material and clean environment critical for background reduction

Dark Matter Mass Spectrum

Enectalí Figueroa-Feliciano, CDMS



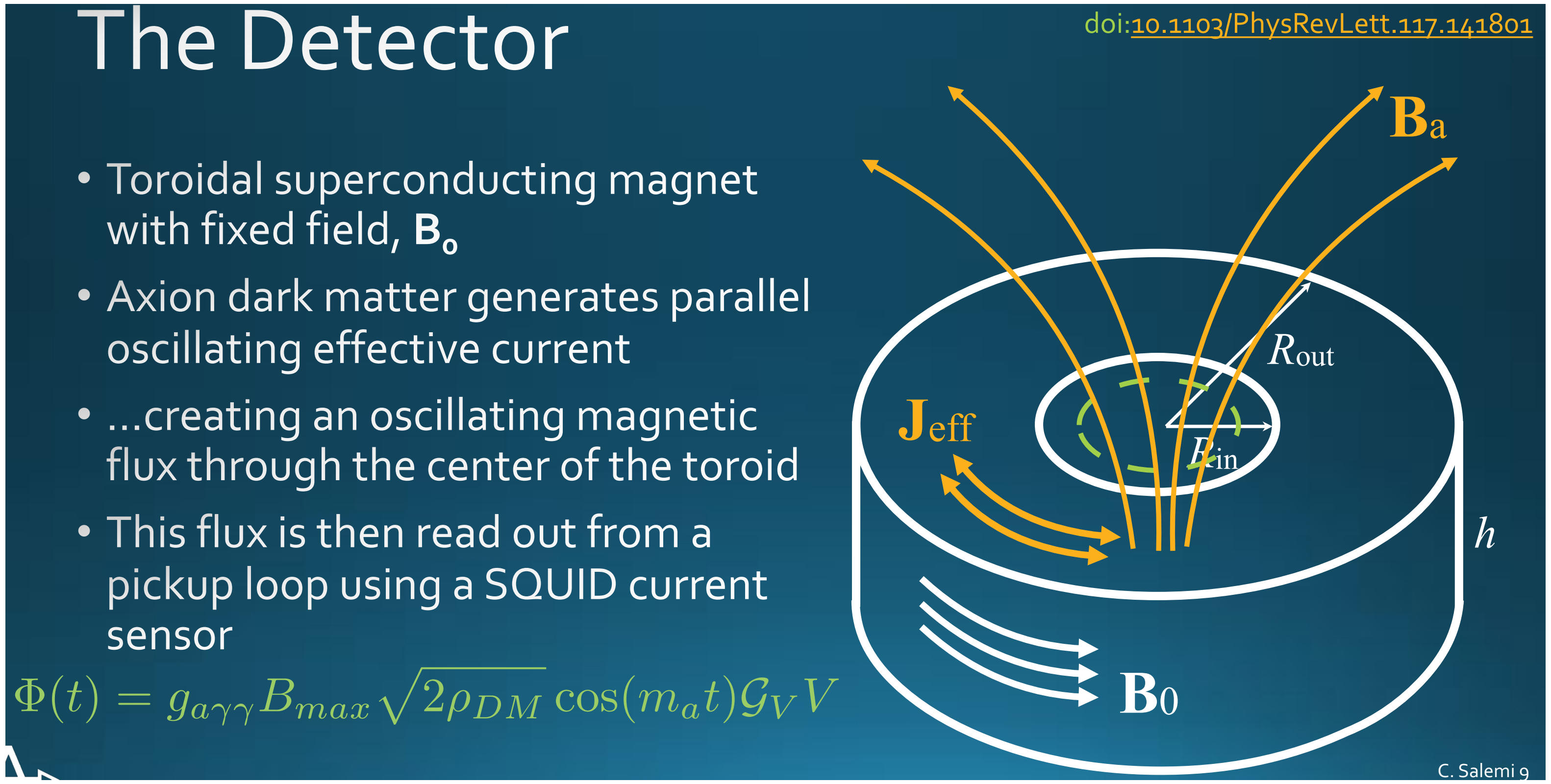


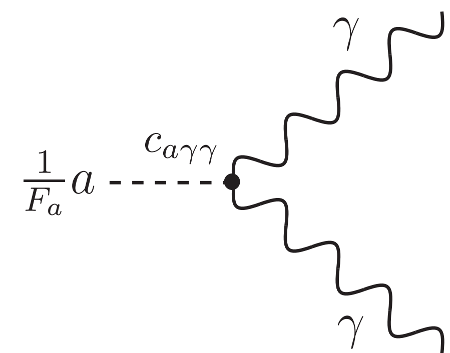
ABRACADABRA

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

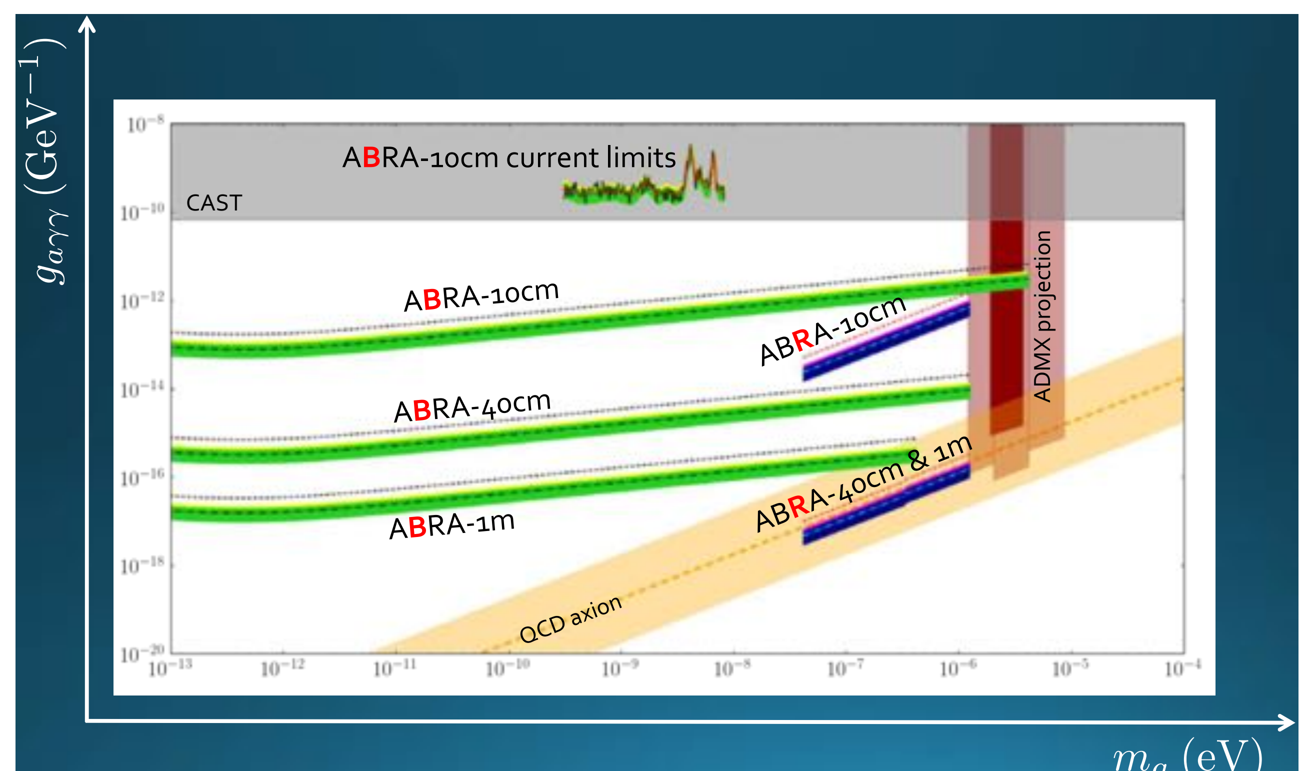
Chiara Salemi, ABRACADABRA

- Probing coupling of axions to SM particles





- Sensitivity currently reduced by x 6.5 WRT expectation due to parasitic inductance in the circuit
  - Low frequency noise due to mechanical vibration and some transient noise yet to be understood

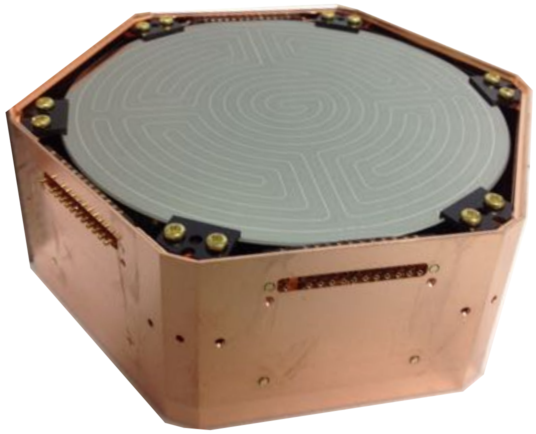


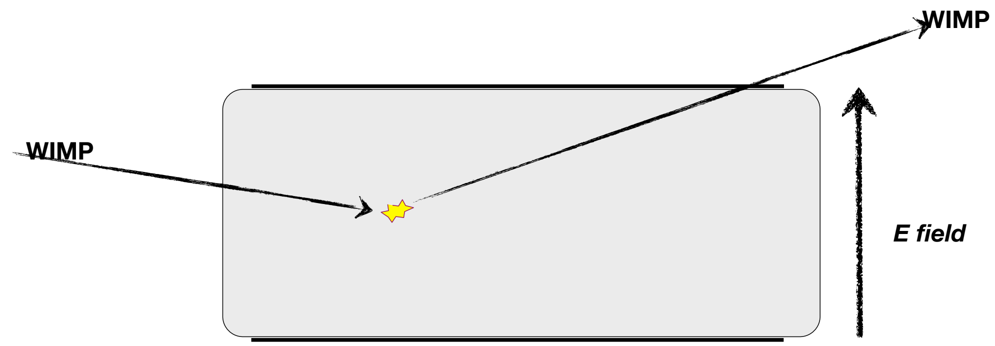
- Upgraded 40cm and 1m versions could probe axion space preferred by QCD

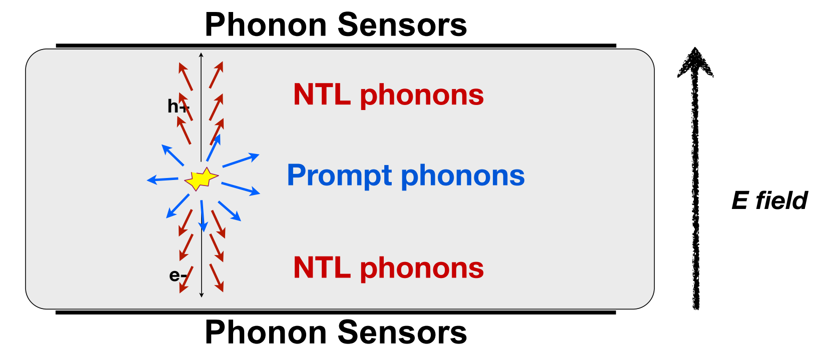
SuperCDMS at SNOLAB

Enectalí Figueroa-Feliciano, CDMS

- Ge-based detector with phonon-based charge amplification

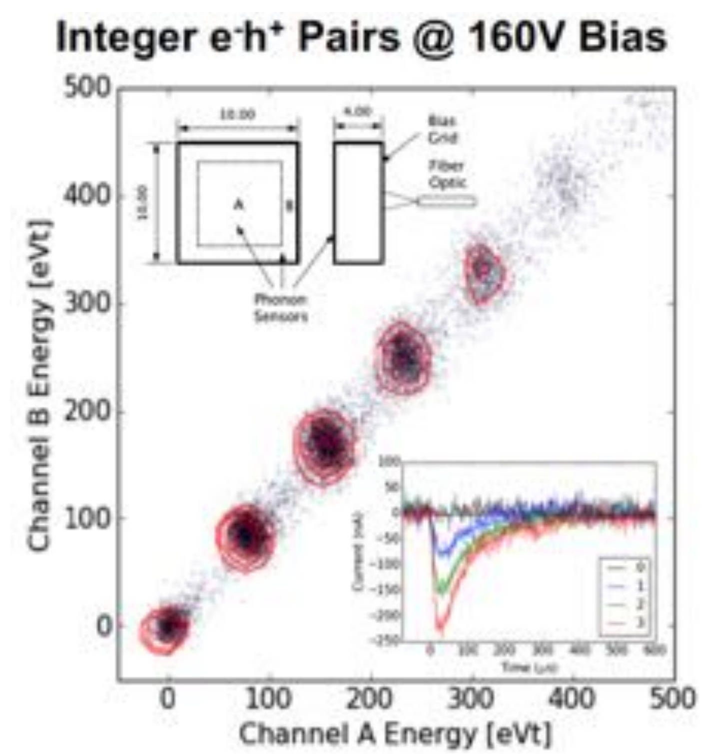




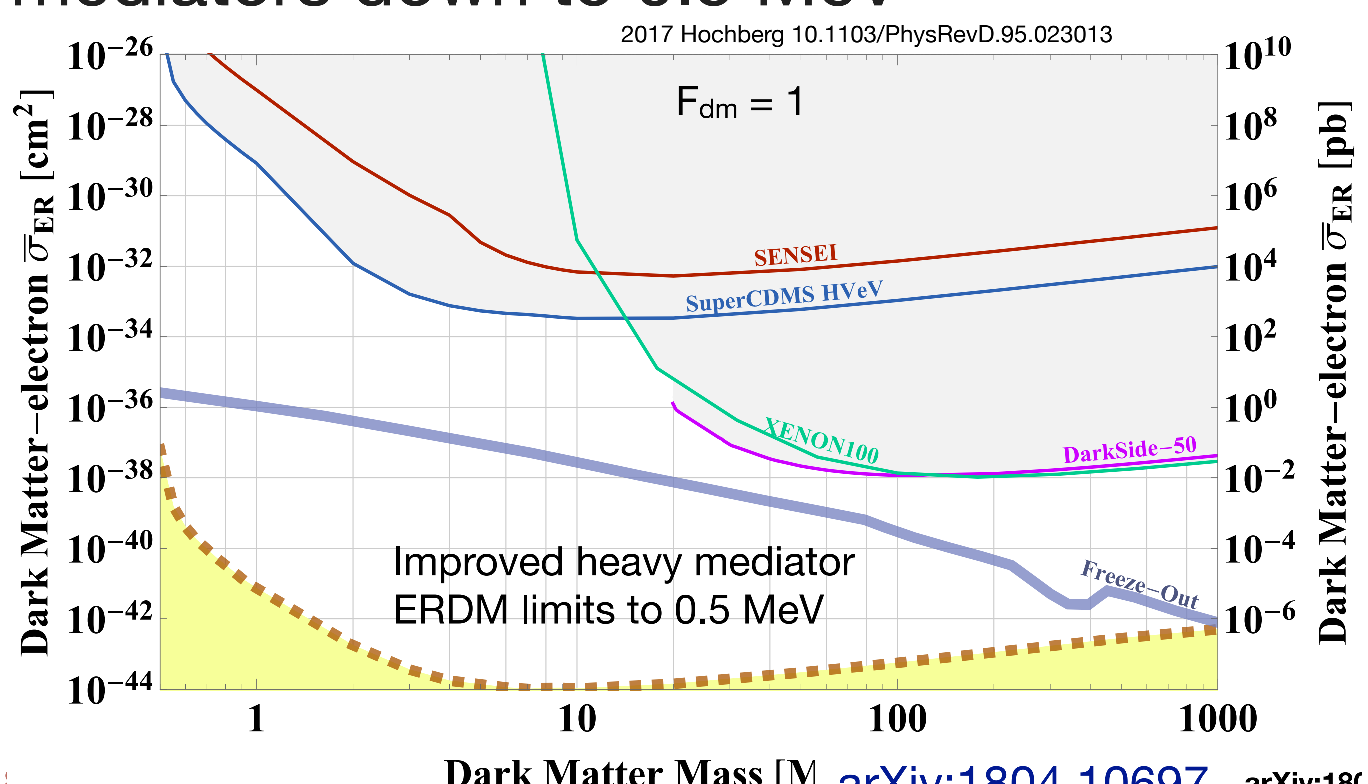


Phonon energy = E_{recoil} + E_{NTL}
= E_{recoil} + n_{eh} e^{-} V

- First observation of $e^{-}h^{+}$ pairs in Si crystal with phonon sensor (arXiv:1710.09335)
  - Reached also resolution of 0.06 $e^{-}h^{+}$



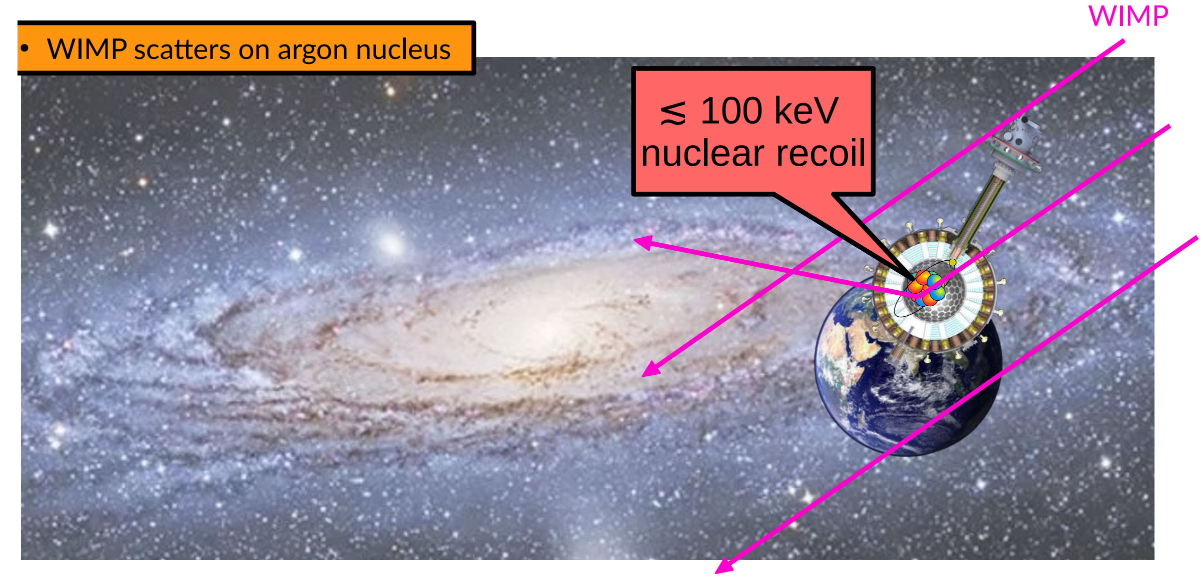
- Improved constraints on inelastic ERDM for both heavy and light mediators down to 0.5 MeV with 0.5 g.day!

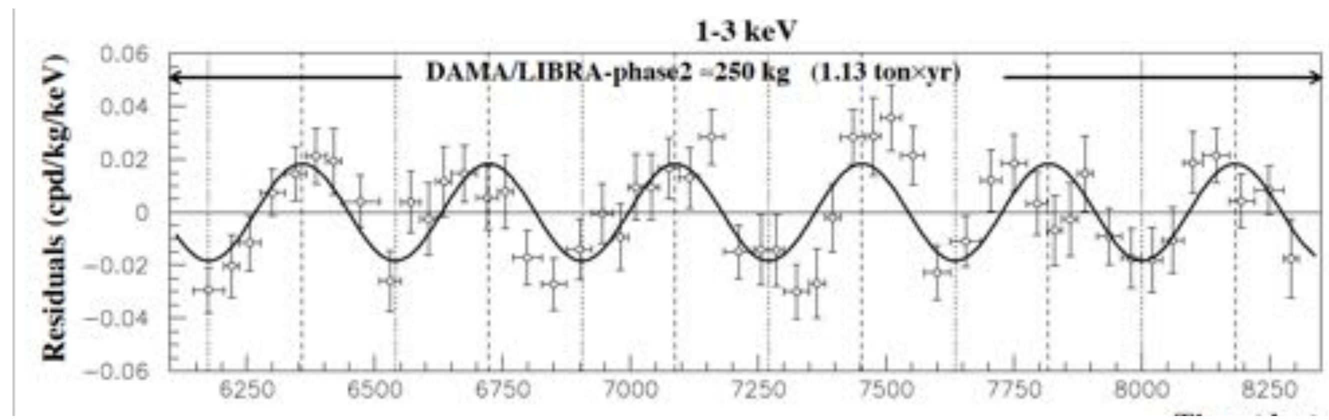


arXiv:1804.10697 arXiv:180

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

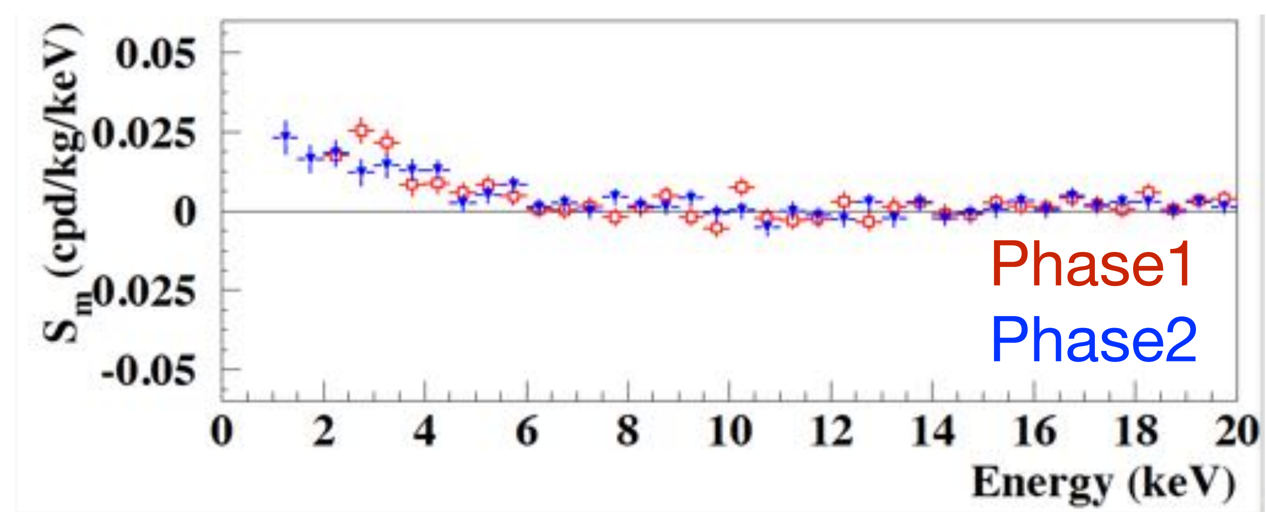
- 6+ additional years / 1.13 ton-year
- Threshold lowered to 1 keV

(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

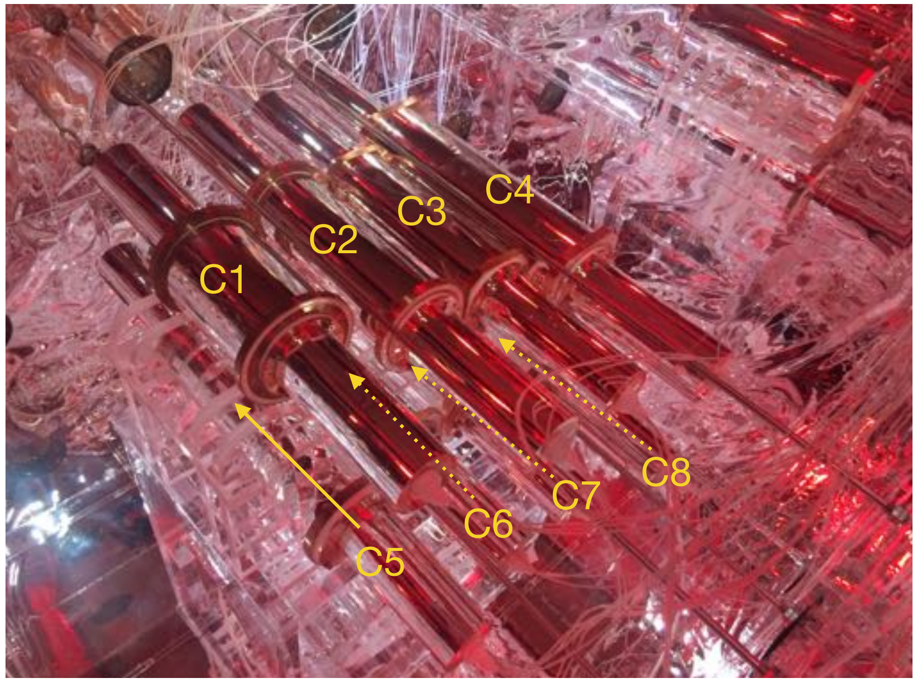


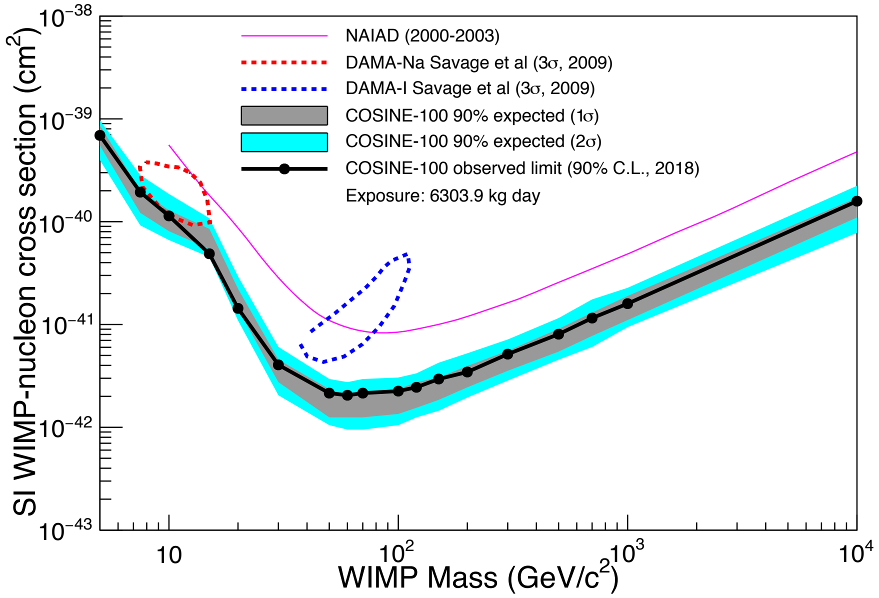
- *Galileo (the physicist) would suggest at least one other experiment to reproduce results as closely as possible*

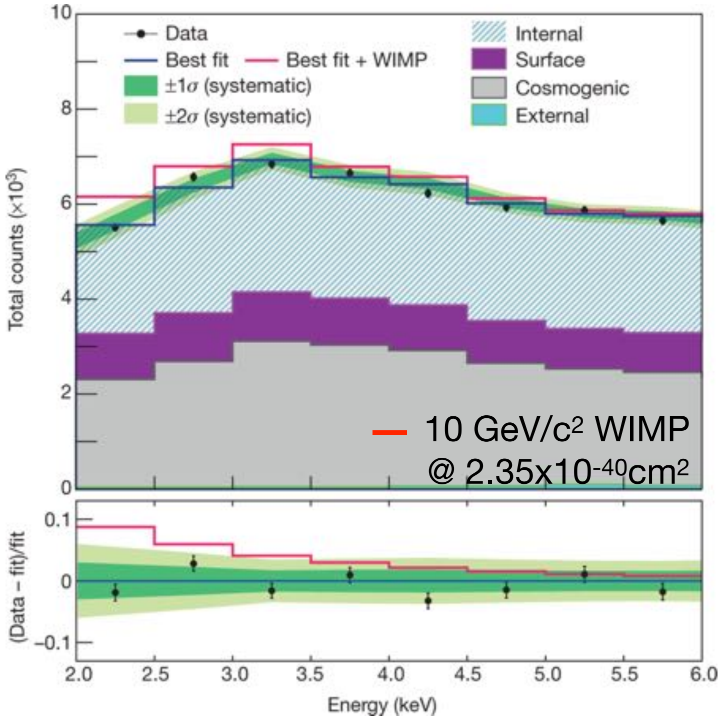
COSINE-100 at Yang Yang Lab (Korea)

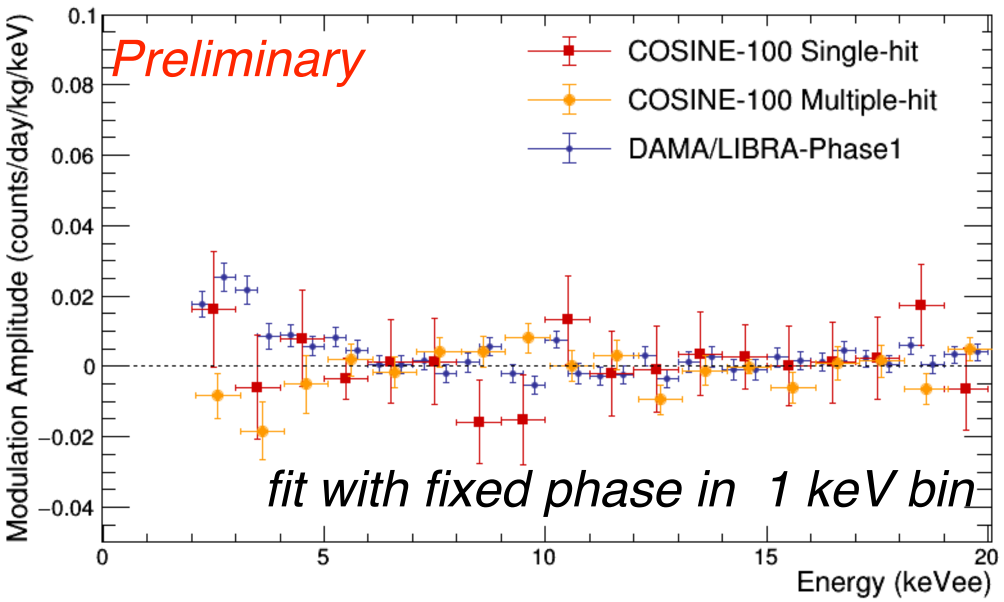
- 8 copper encapsulated NaI(Tl) crystals,106 kg total
  - Detailed Geant4 simulation; BDT background rejection
  - Currently background ~ x 2-4 DAMA
- First results with 2 years of exposure
  - disfavors standard spin-independent WIMP interaction with NaI(Tl) as explanation for DAMA/LIBRA
- Effort underway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

Reina Maruyama, COSINE



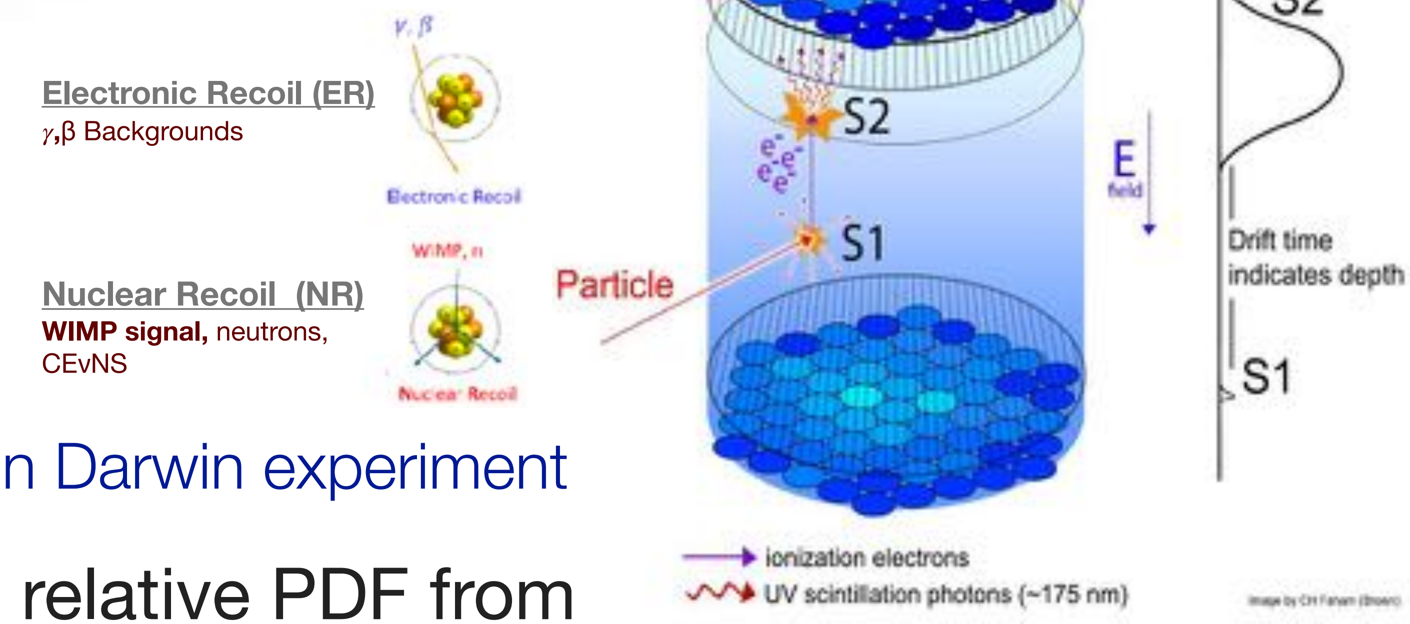






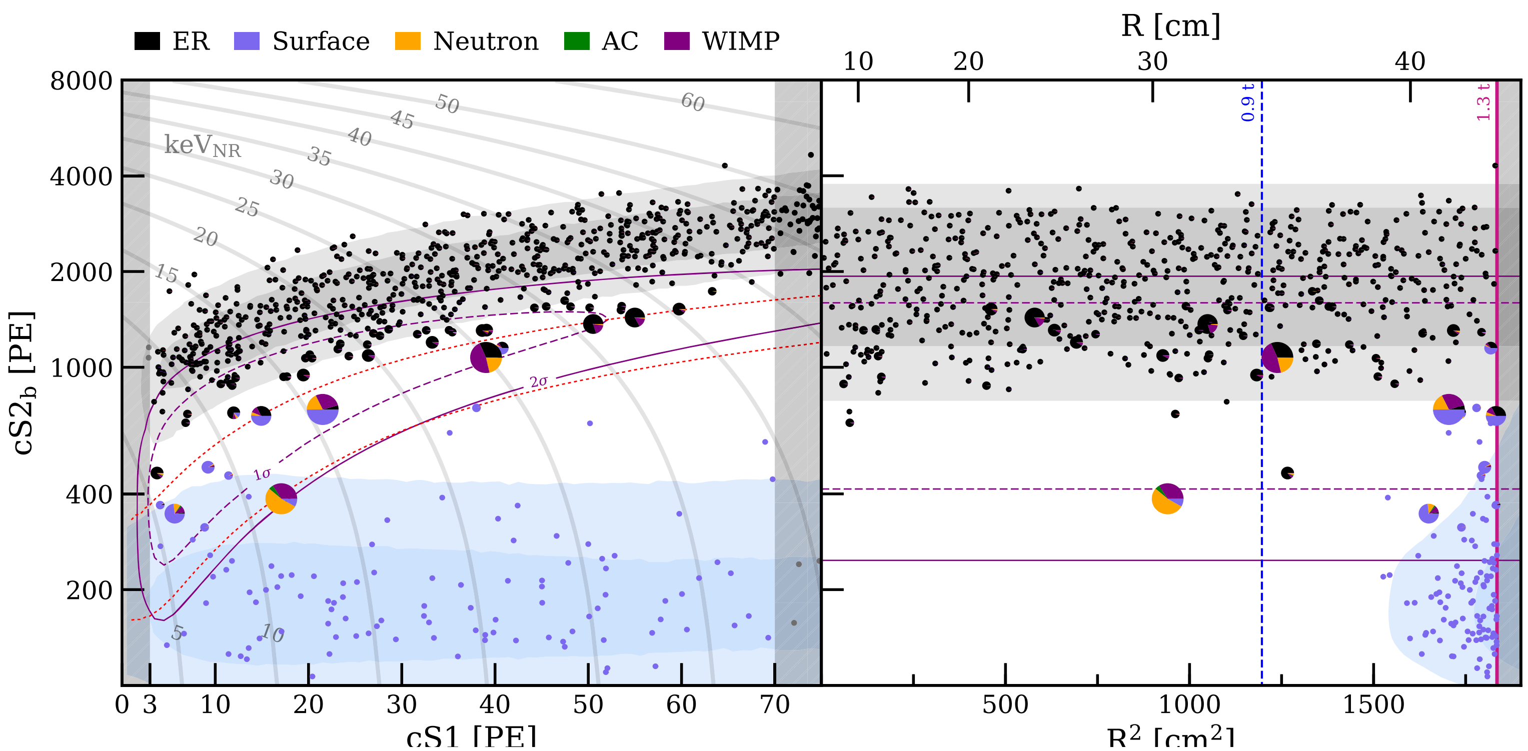
Xenon-1T at Gran Sasso

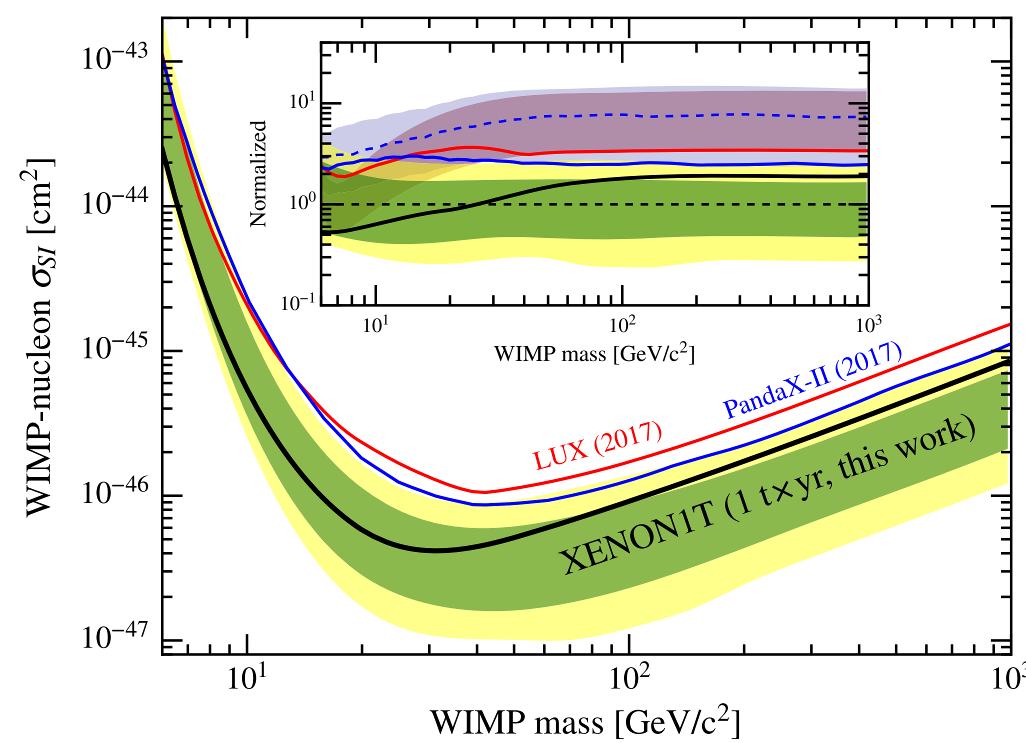
- Dual phase time projection chamber
  - Using s1/s2 discrimination instead of pulse shape



- 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



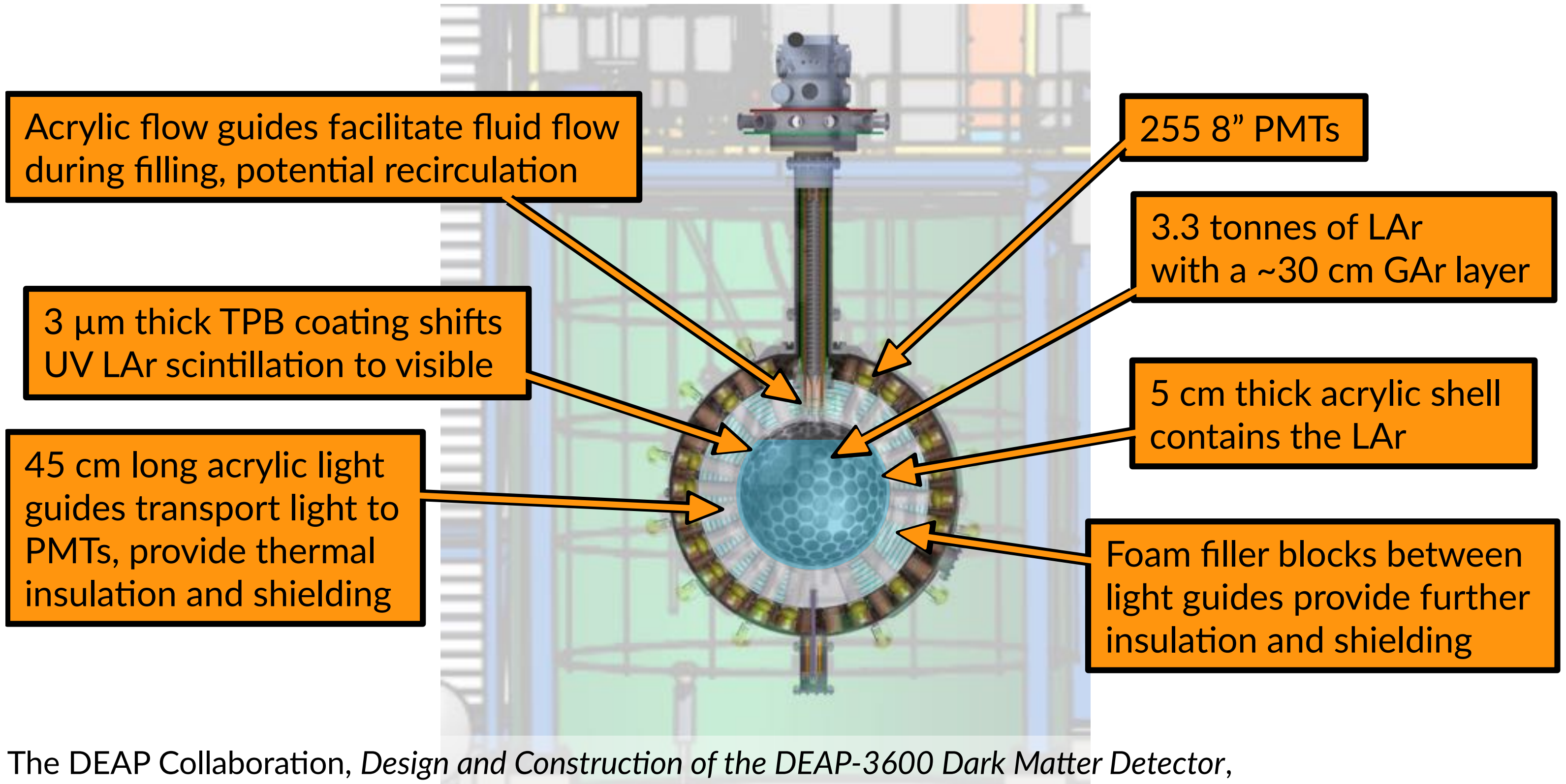


- Limits with 1 year of exposure
  - p-value of ~0.2 for m >= 200 GeV does not disfavor a signal hypothesis

DEAP-3600 at SNOLAB

Shawn Westerdale, DEAP

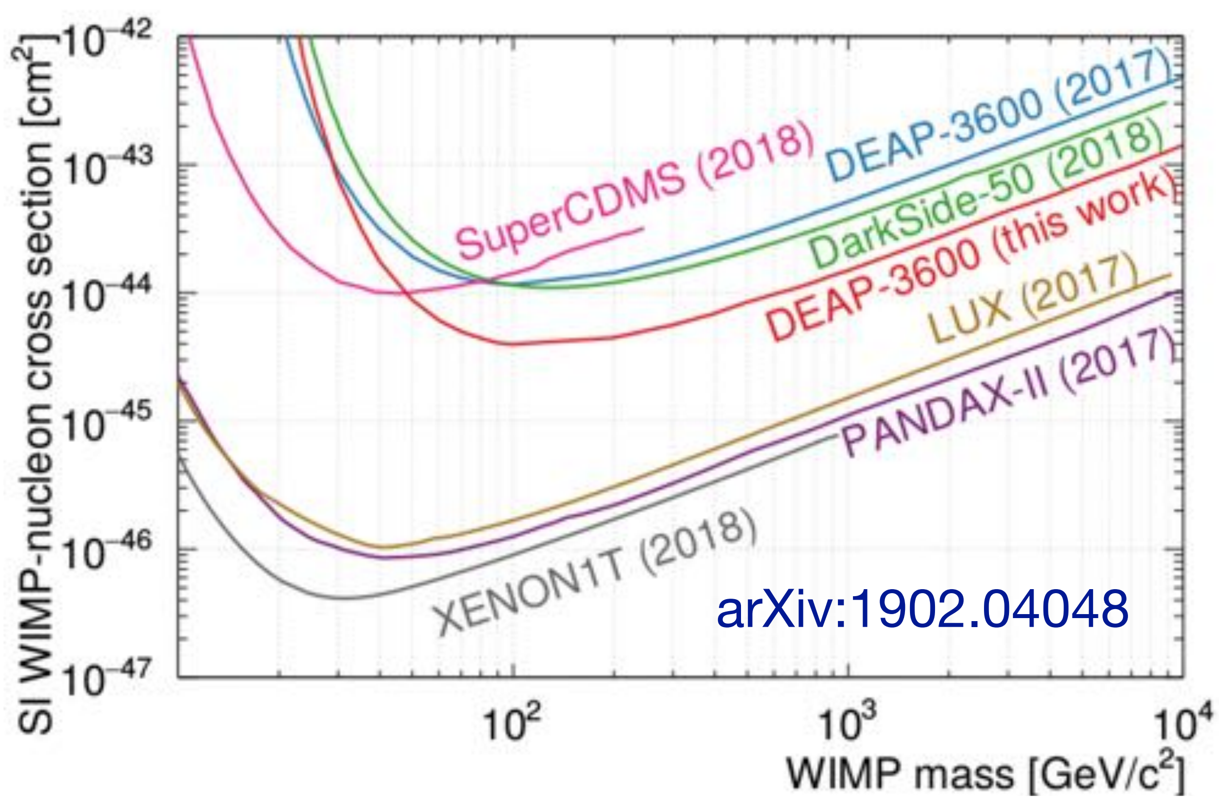
- Single phase LAr using pulse shape discrimination



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

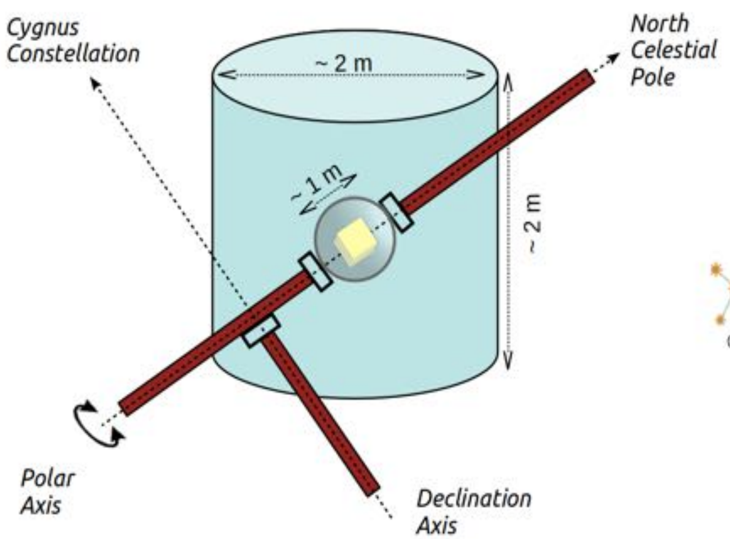
0 events in ROI

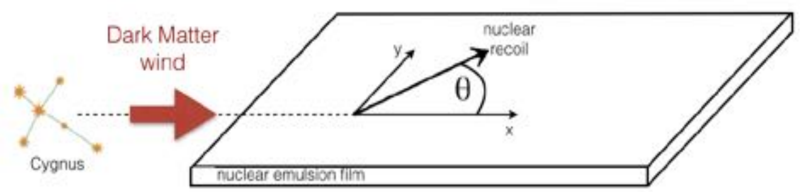
Exclude S.I. WIMP-nucleon cross sections above 3.9×10^{-45} cm^2 for 100 GeV/c^2 WIMP mass

Directional Detection

Valerio Gentile, NEWSdm

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

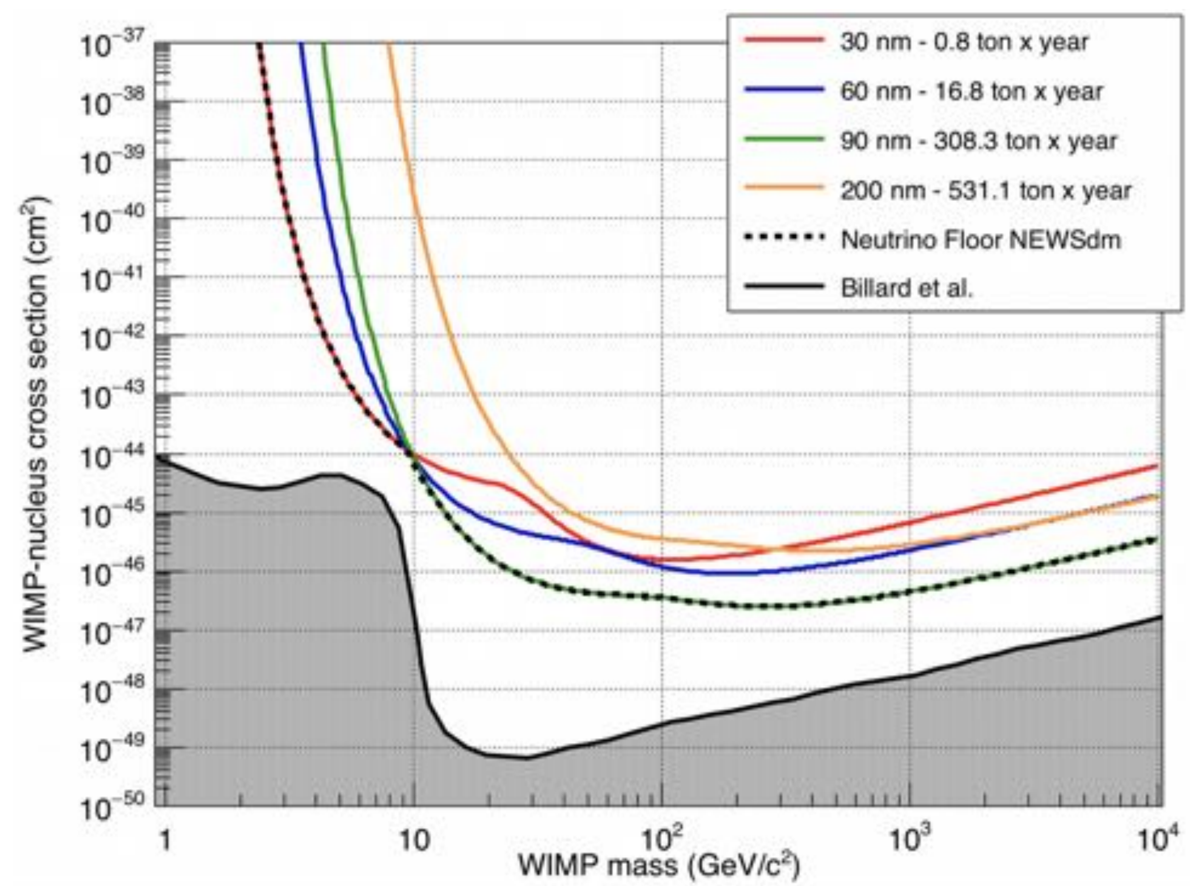




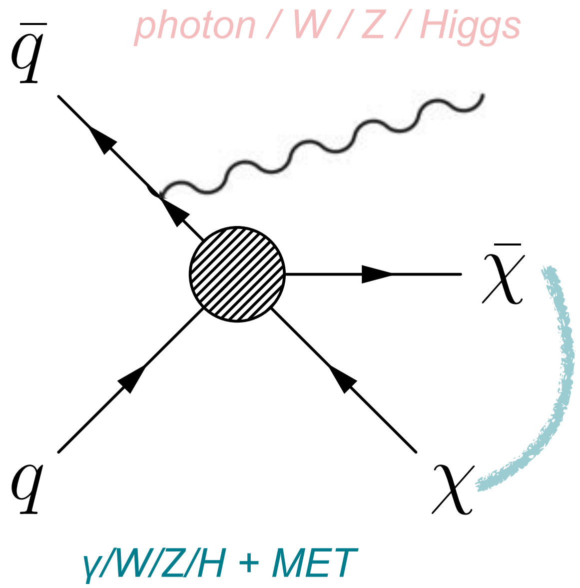
Aim: detect the direction of nuclear recoils produced in WIMP interactions
Background reduction: shielding surrounding the target
Fixed pointing: target mounted on equatorial telescope constantly pointing to the Cygnus Constellation
Directionality: Unambiguous proof of the galactic origin of Dark Matter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

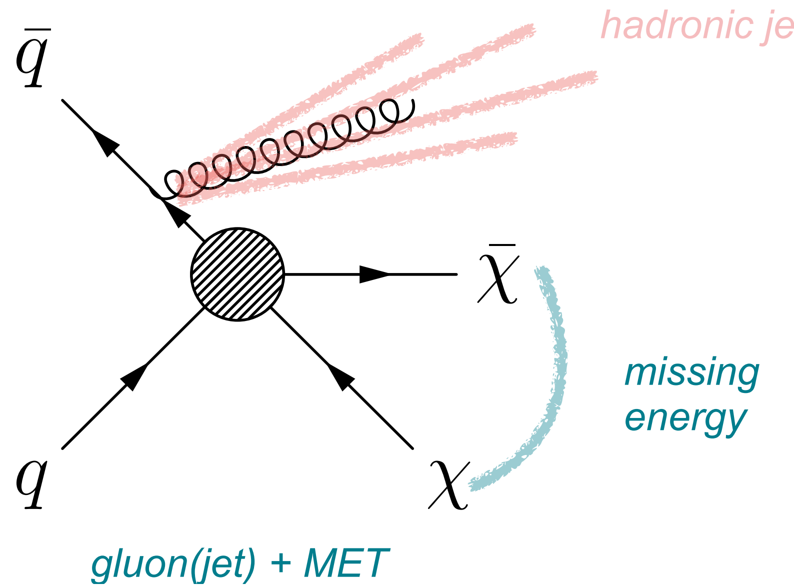
- Potential to overcome the ***neutrino floor***, where coherent neutrino scattering creates an irreducible background

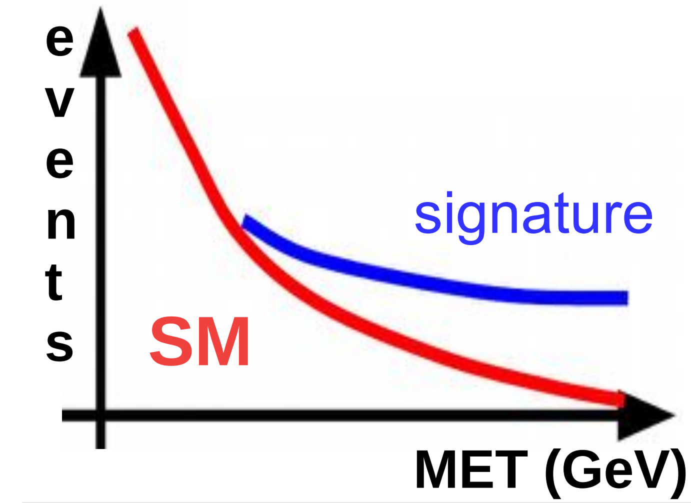
- Plans (if funded)
  - 2020: construction
  - 2021: data taking
  - 2020: analysis



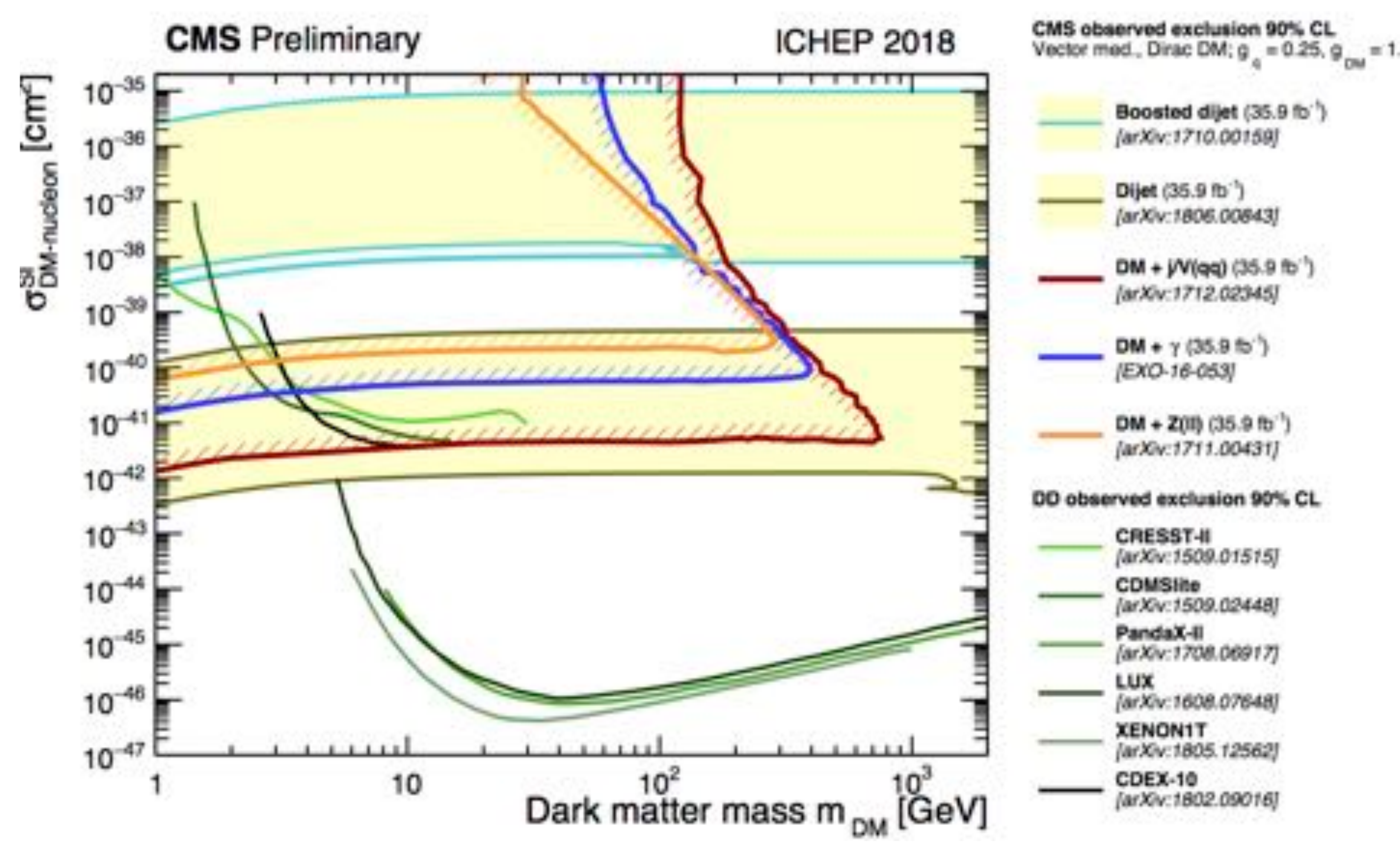
WIMP at LHC







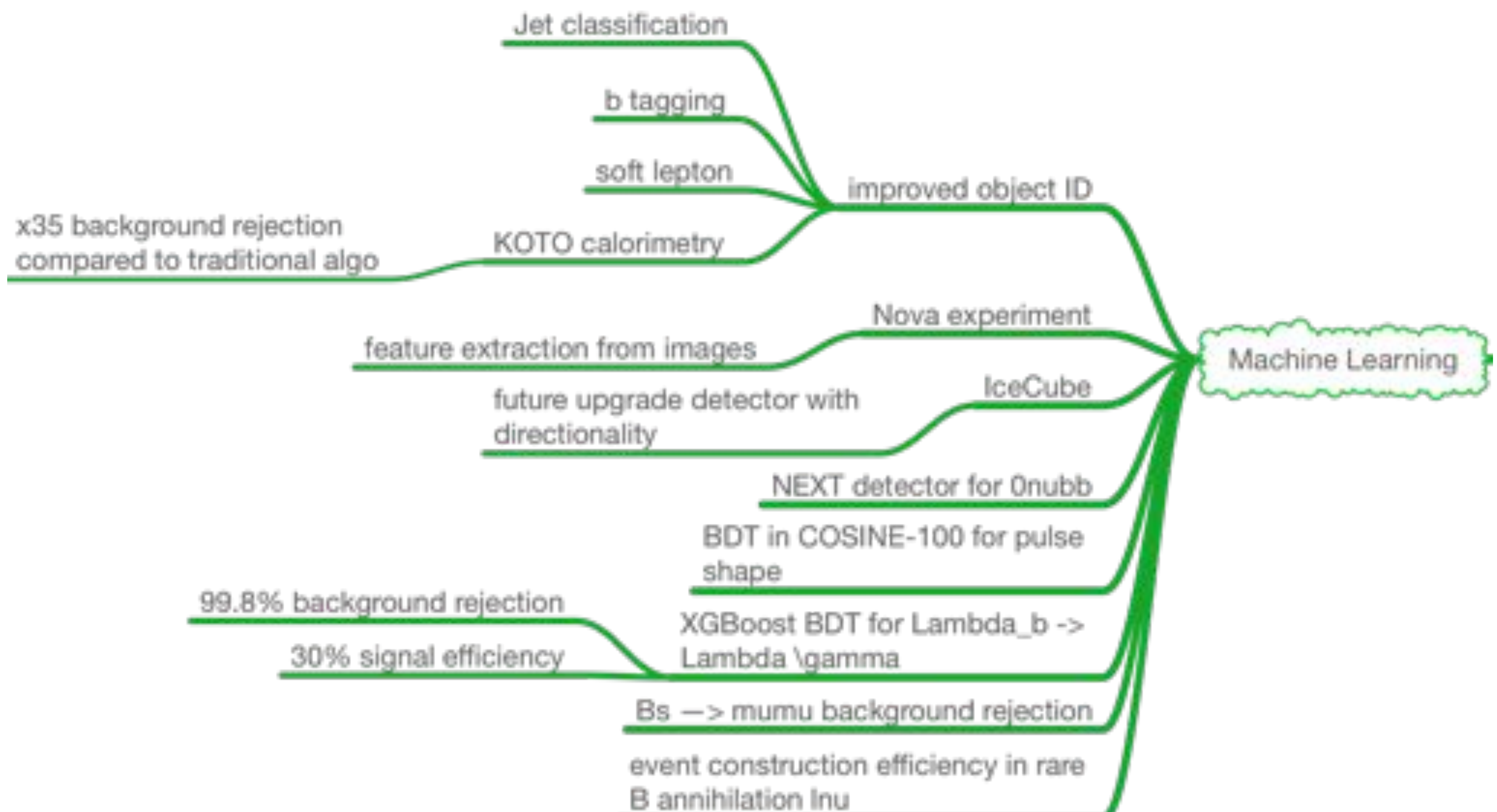
- In addition to classic MET + mono-object search, also constraining mediator mass and coupling in simplified models
- No excess reported
  - Significant reduction of both experimental and theoretical background systematics



Sergei Chekanov, ATLAS

Machine-Assisted Intelligence

- Machine-Learning methods percolating data analysis at fast rate
- Not always the choice of artificial intelligence is an intelligent decision
  - Modest gains of 1-5% by using methods at late stages of analysis
  - Countered by painful and complicated systematic assessment
- Highest pay-off for deployment at low level to better understand detector response and particle or event identification



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
  - And more importantly… some sleep!