Conference Summary and Highlights

A breathtaking overview of High Energy Physics

A wealth of new results!

Soshi Asai - “Lets enjoy our physics!”

281 posters, 918 parallel talks, 40 plenary talks.

1388 Participants

Selected Highlights

Sincere apologies to those whose superb result(s) are not presented!

Thank you to all the speakers for their availability to discuss their results!

Marumi Kado
Max Planck Institute for Physics

The General Framework

Raymond Volkas

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c.$$

Simplicity, governed by symmetries only 3 (EW) and 2 (QCD) parameters!

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. \quad + \frac{c_{ij}}{\Lambda} L_i L_j H H \ ?$$

$$+ |D_\mu \phi|^2 - V(\phi) \quad + \Lambda^4 \ ?$$

Not governed by symmetries and with **26 parameters set by "hand" of experiments!**

Open problems

Hierarchies

- Gauge Hierarchy and Naturalness
- Flavour hierarchy including neutrino masses

The strong CP problem

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$$

From neutron electric dipole moment

The existence of Dark Matter (new field?)

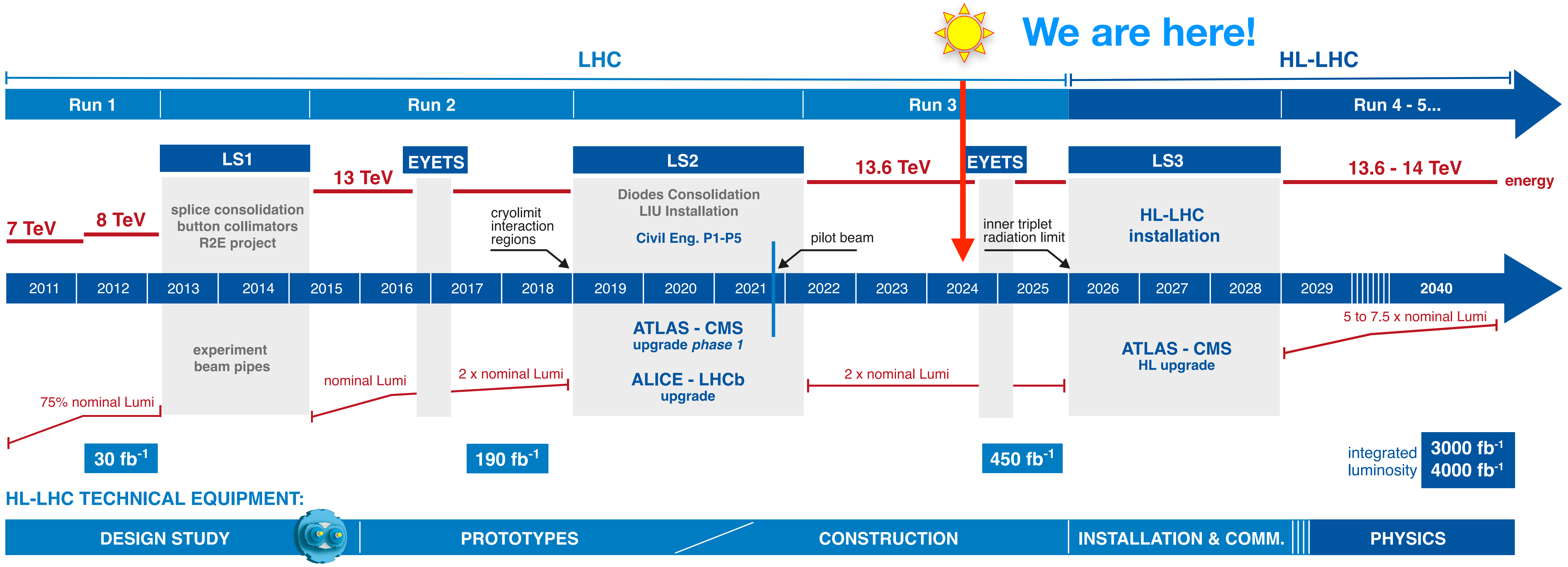
The nature of Dark energy

Open questions

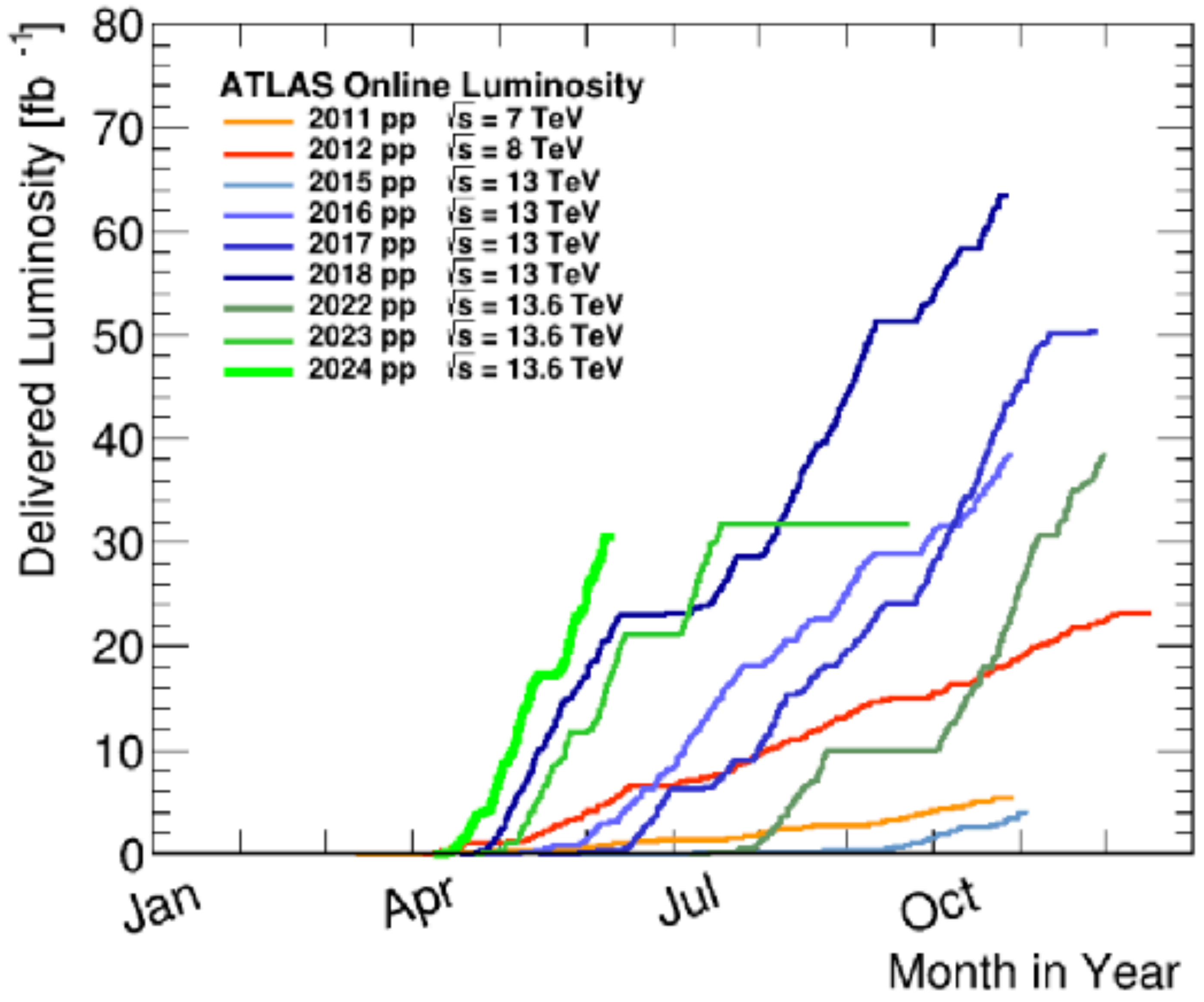
- What is the origin of the asymmetry between matter and anti-matter in the universe?
- What are the properties of QCD confinement?
- Why do electrons have precisely the same charge as the protons?

Main Colliders - Experimental Landscape

- LHC is refining its results on a **clean and well calibrated dataset of ~140** fb^{-1} at 13 TeV the Run 3 nearly equaling the Run 2 dataset ~120 fb^{-1} at 13.6 TeV.



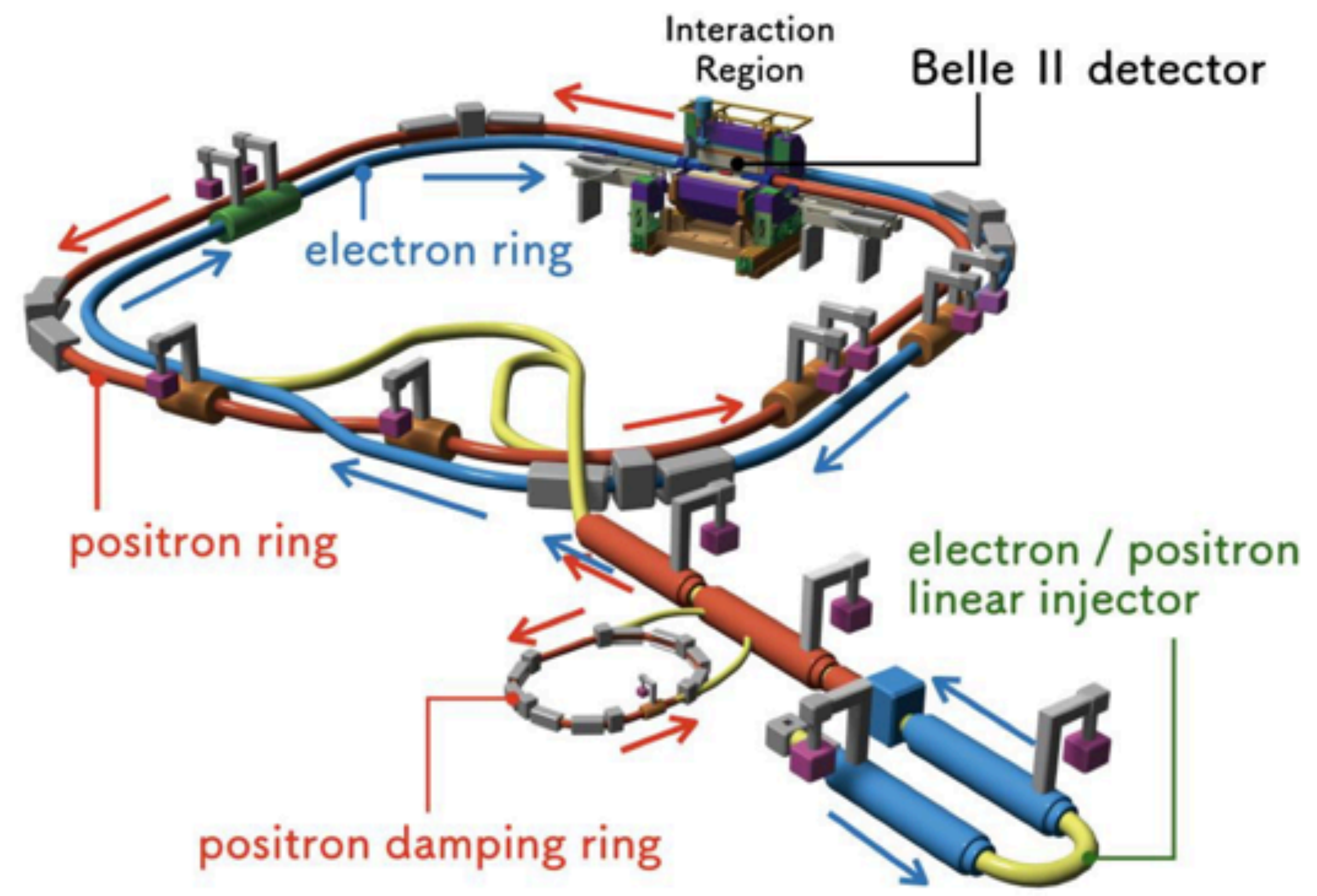
2024 - High availability operation, Full mastery of considerable inherent operational risks



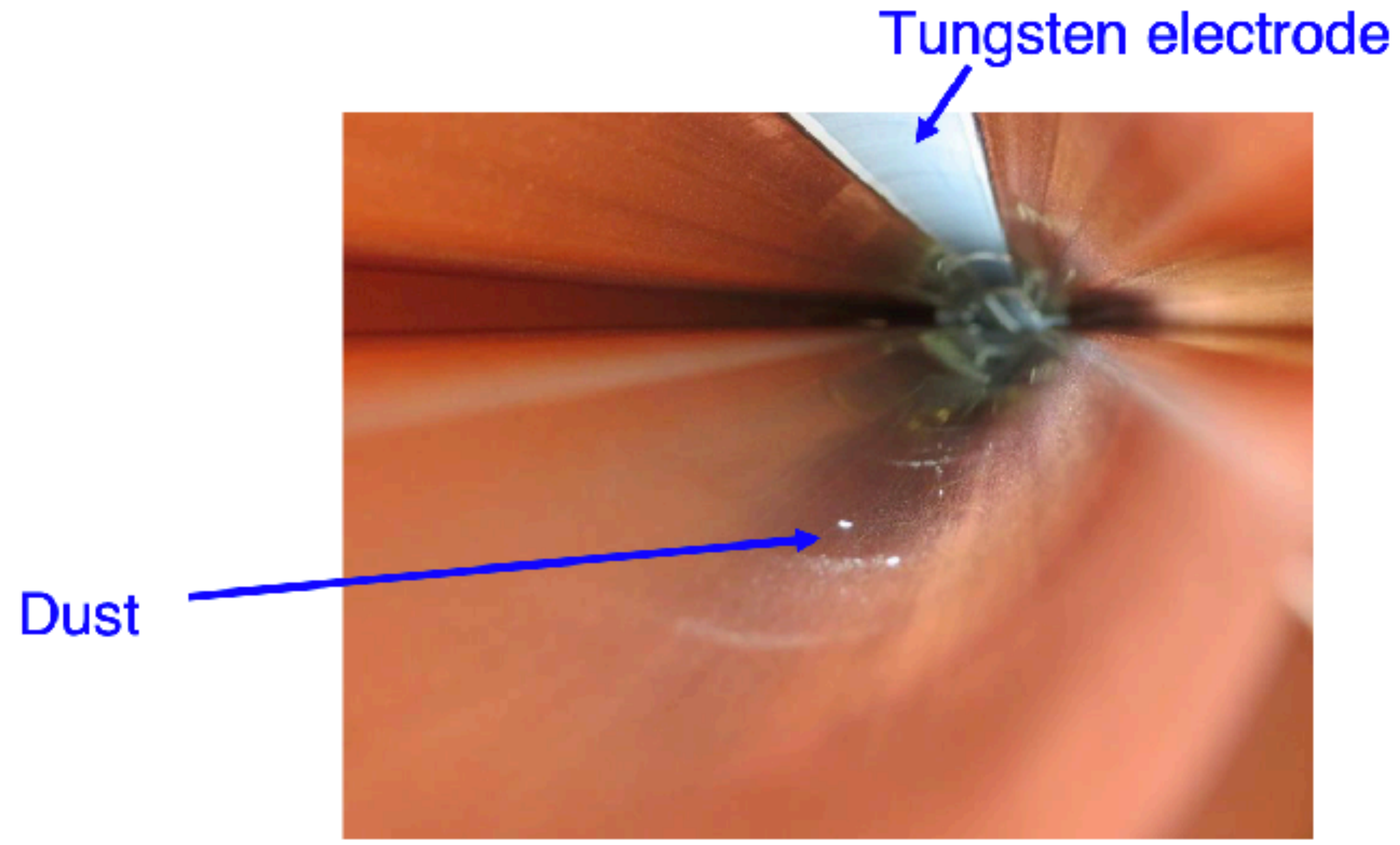
- Currently about half way into entire LHC operations schedule, **Major upgrades leading** to the High Luminosity during the third long shutdown now on the horizon! (See backup for more details)

Approximately x10 Luminosity delivered (in terms of results x20)

Main Colliders - Experimental Landscape



- Super KEK-B and Belle II world's highest instantaneous luminosity (4.7x10^{34} cm^{-2}s^{-1}), difficult year with a focus on understanding **Sudden Beam Losses** (Belle II is currently running with VTX off).



Countermeasures to the SBL will be implemented during the 2024 summer maintenance period.

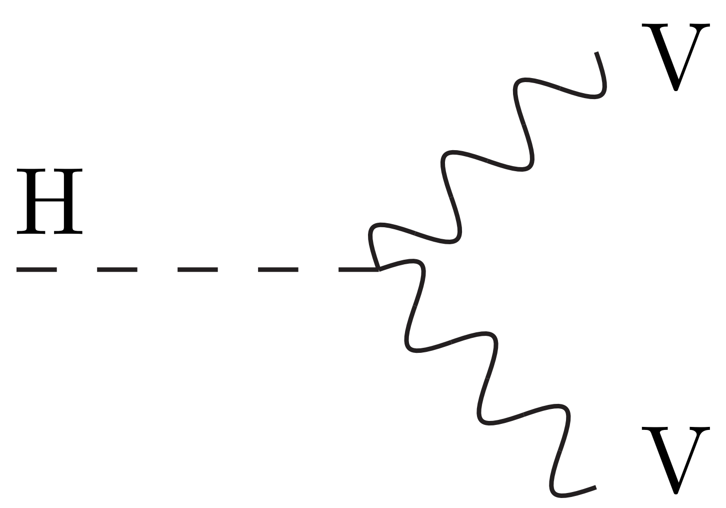
Sergei also discussed other facilities:

- RHIC AA (and future EIC, NICA)
- High intensity facilities Fermilab, JPARC, PSI, TRIUMF, CERN PS and SPS
- VEPP and BEPC continuing to bring very useful data (discussed in this talk).
- DAϕNE facility still brings physics potential (PADME) and progress in accelerator R&D!

The Higgs Sector - Pillars of Higgs physics

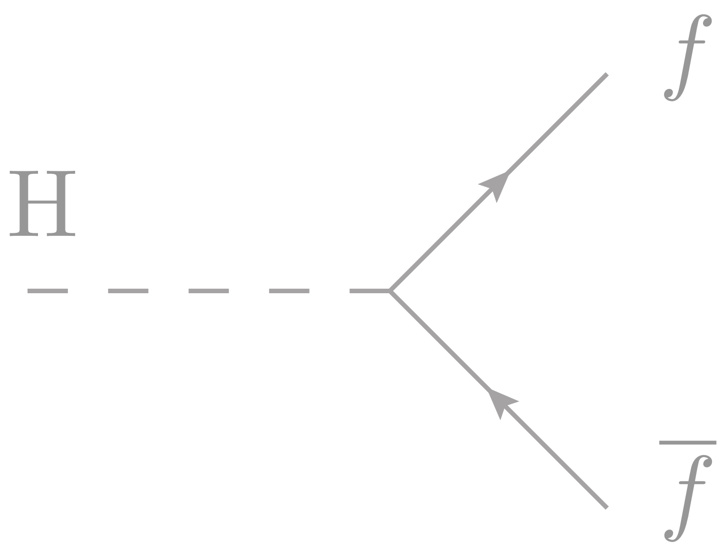
Nicolas Berger, Matthew McCullough

The pillars of Higgs physics:

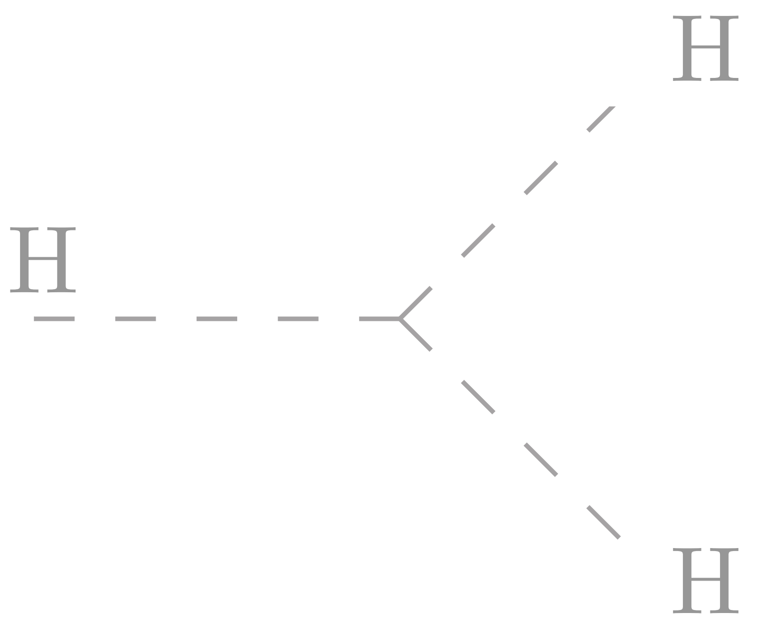


$\frac{2m_V^2}{v}$ $|D_\mu \phi|^2$

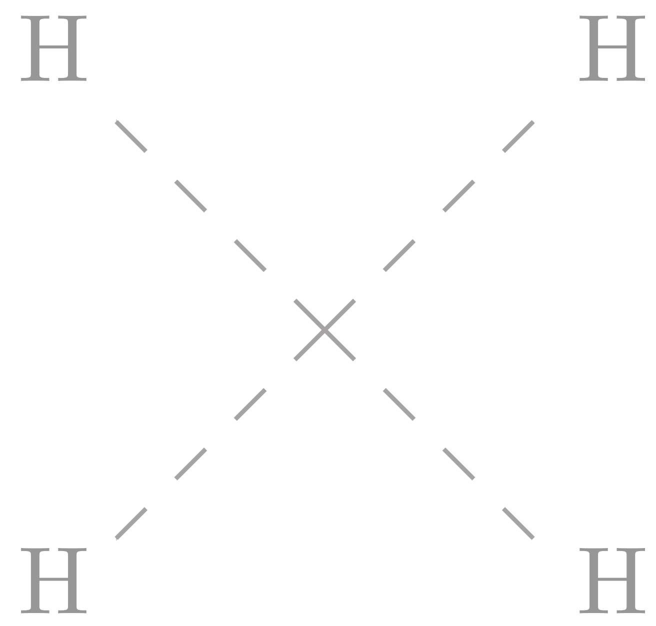
This term could not exist without a vev



$\frac{m_f}{v}$ $\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$



$\frac{3m_H^2}{v}$



$\frac{3m_H^2}{v^2}$ $V(\phi)$

Message 1 (Matthew McCullogh): It is of utmost importance to measure the most precisely measured coupling (hZZ) to probe the Higgs compositeness.

Unambiguous proof of the existence of the Higgs condensate!

	Current	HL-LHC	FCC (ee)
$\kappa_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

Most precisely known Higgs coupling tells us how elementary the Higgs boson is!

The Higgs could well be a pNGB as the pion!

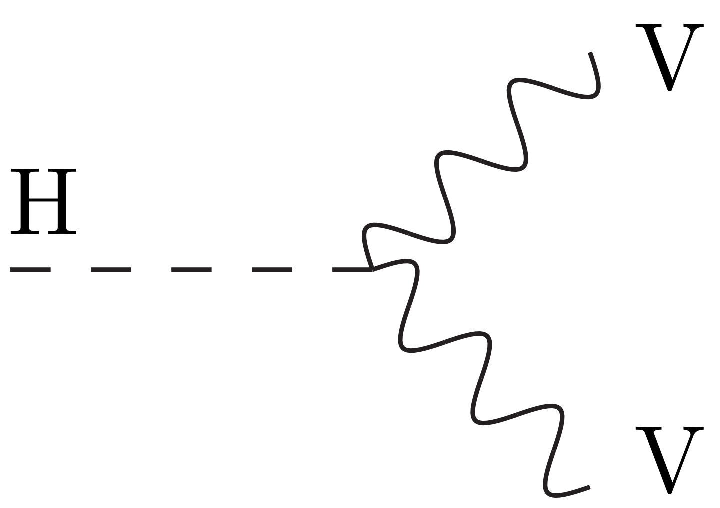
Message 2 (Matthew McCullough): Precision in Higgs physics is key.

Precision at HL-LHC is limited by TH (HO, PDFs and α_s)

The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Matthew McCullough, Sakura Schafer-Nameki

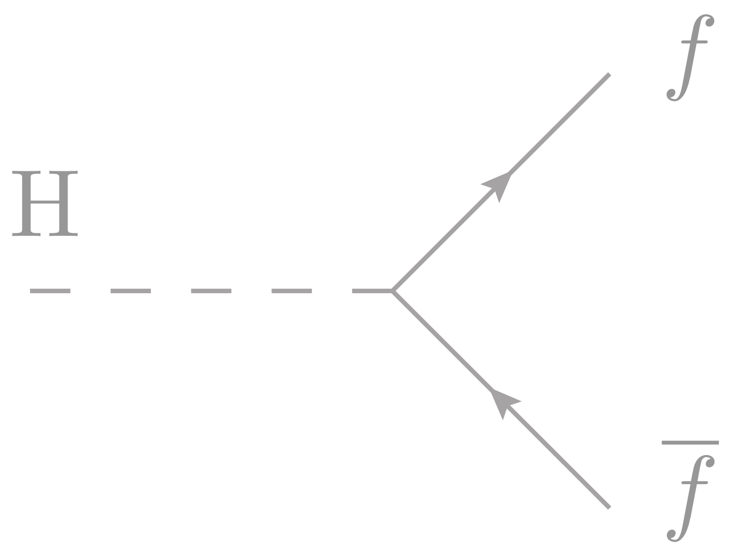
The pillars of Higgs physics:



$$\frac{2m_V^2}{v}$$

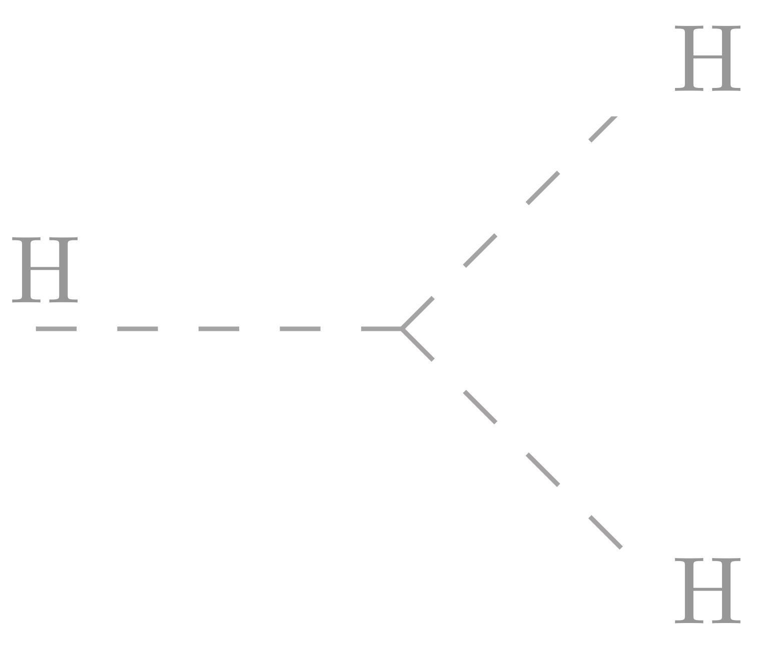
$$|D_\mu\phi|^2$$

This term could not exist without a vev

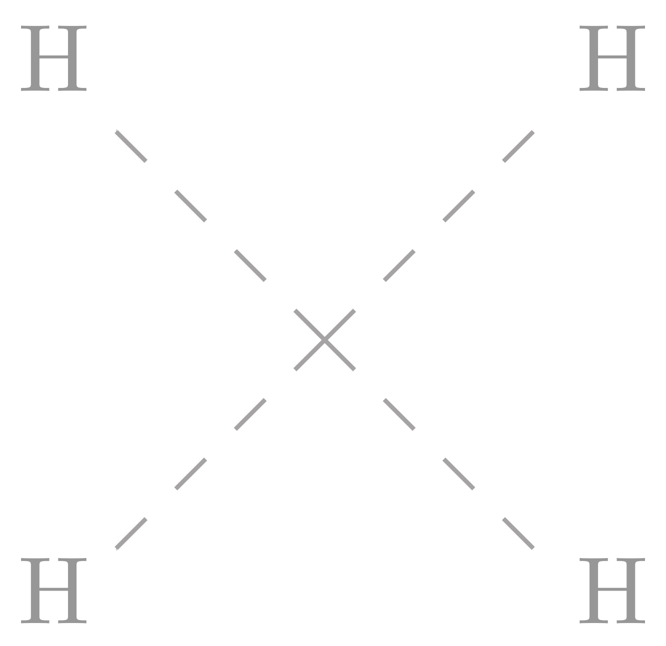


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



$$\frac{3m_H^2}{v}$$

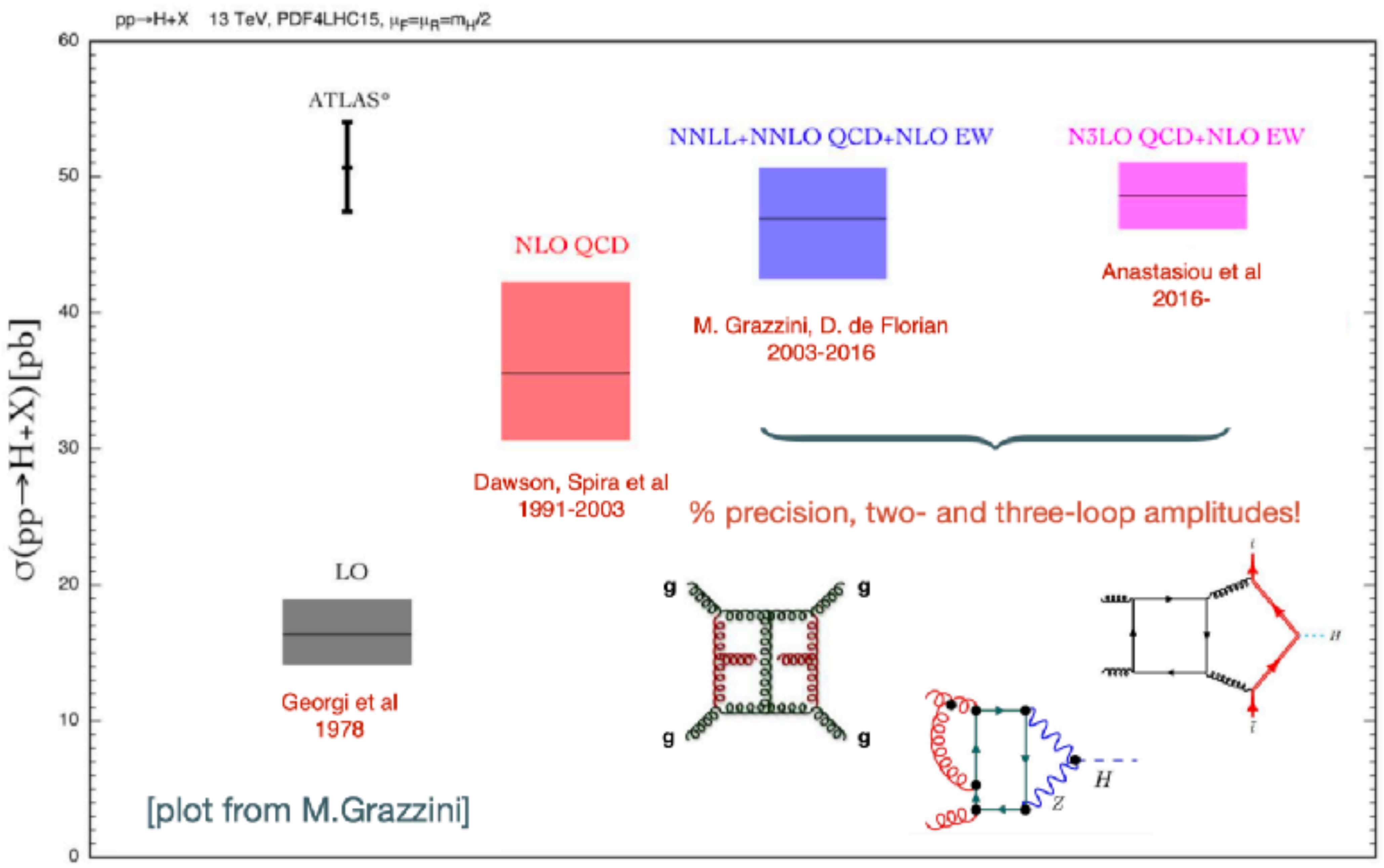


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

Message 1 (Matthew McCullogh): It is of utmost importance to measure the most precisely measured coupling (hZZ) to probe the Higgs compositeness.

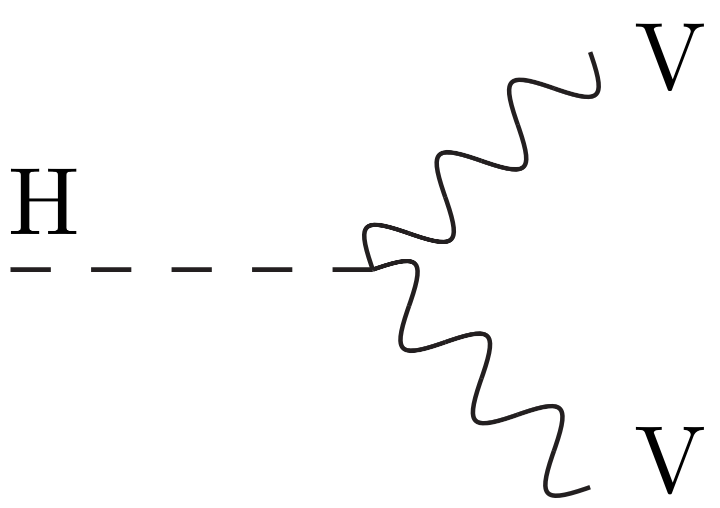
Message 2 (Sakura Schafer-Nameki): Much progress thanks to formal theory: **amplitudes**!



The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Matthew McCullough, Maurizio Pierini

The pillars of Higgs physics:



$$\frac{2m_V^2}{v}$$

$|D_\mu \phi|^2$

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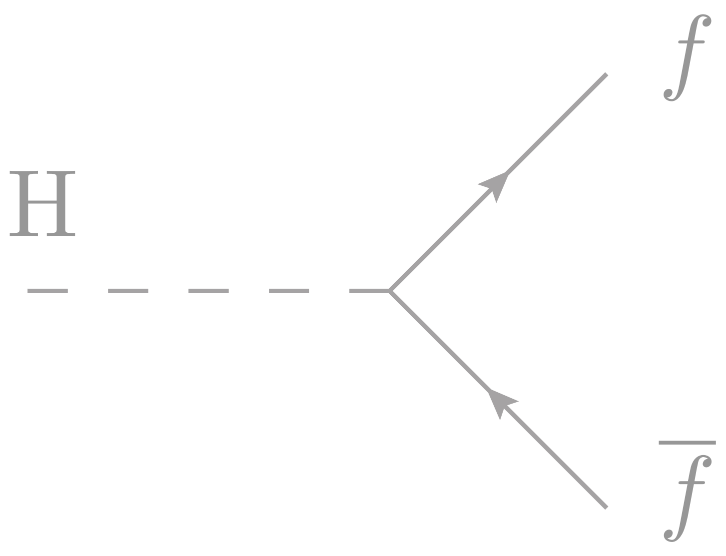
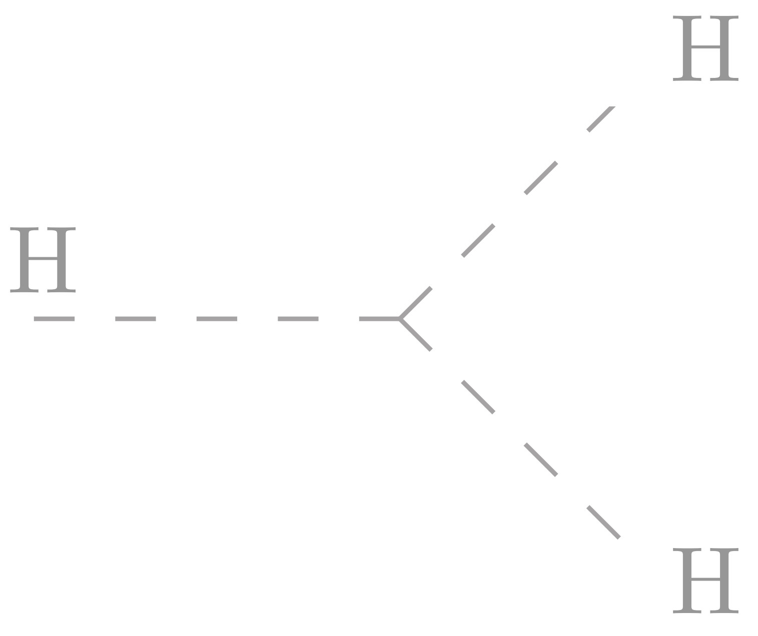
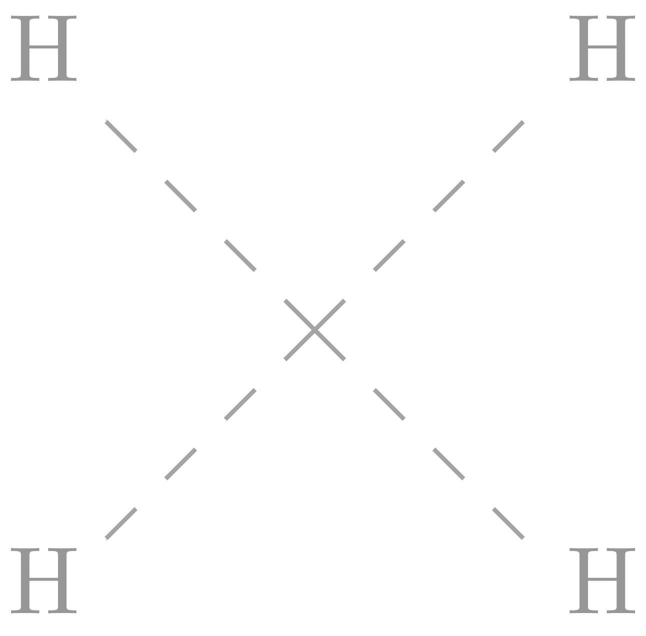


$$\frac{m_f}{v}$$

$\bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$



$$\frac{3m_H^2}{v}$$

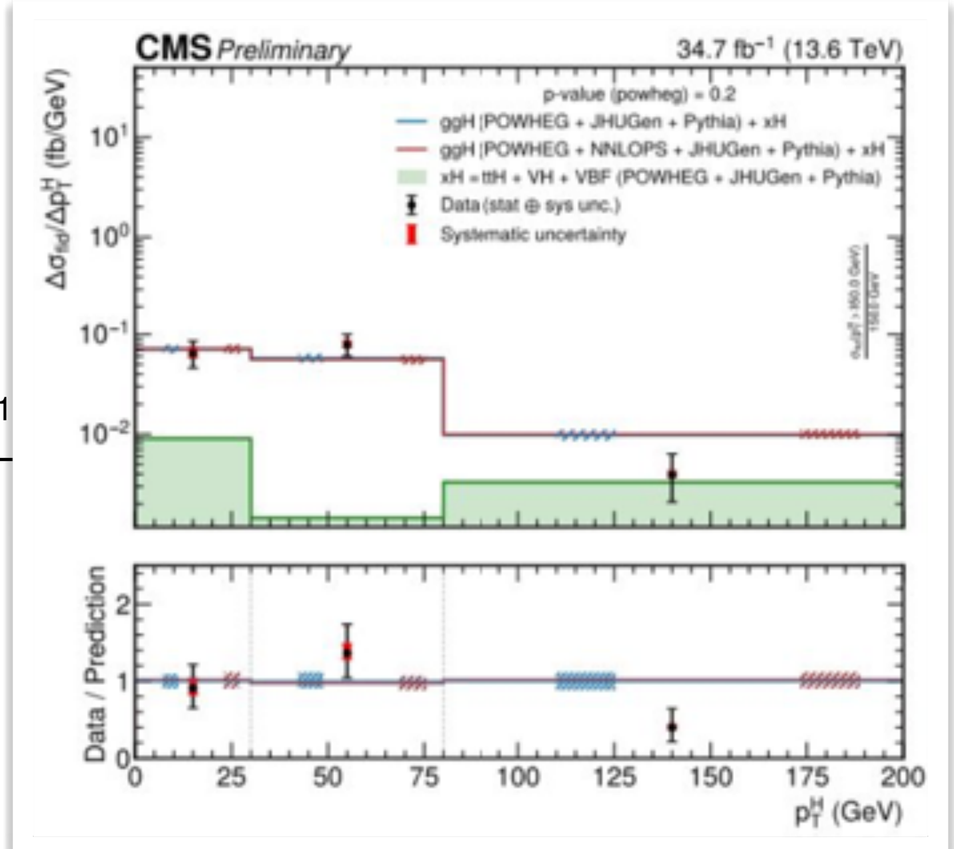


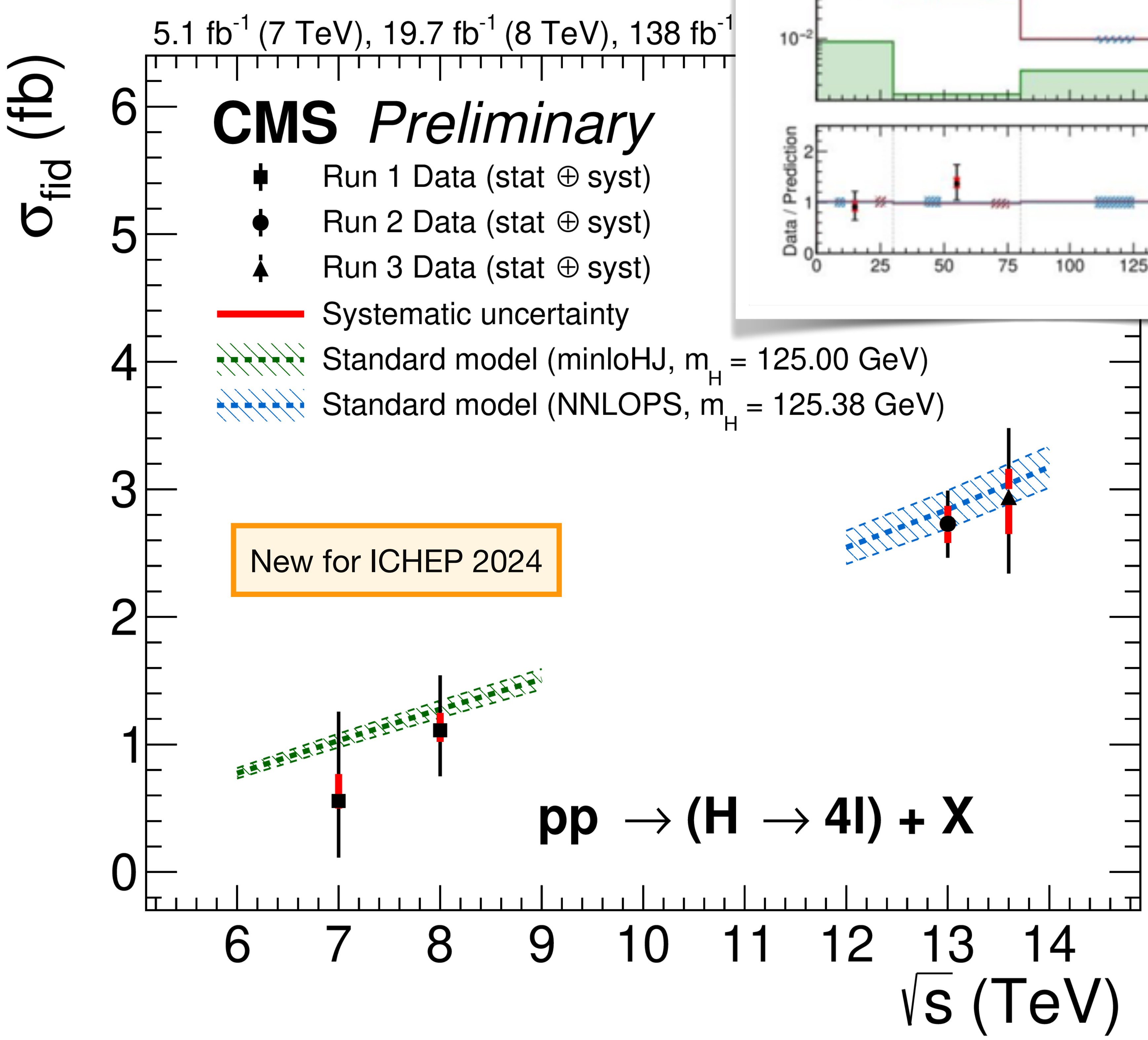
$$\frac{3m_H^2}{v^2}$$

$V(\phi)$

Message 1 (Matthew McCullogh): It is of utmost importance to measure the most precisely measured coupling (hZZ) to probe the Higgs compositeness.

New measurements at 13.6 TeV (Run 3)





The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Matthew McCullough

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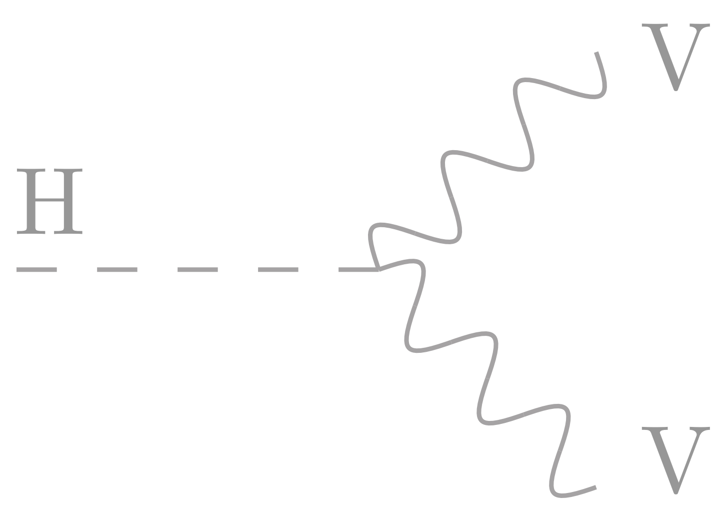

$$\frac{2m_V^2}{v}$$

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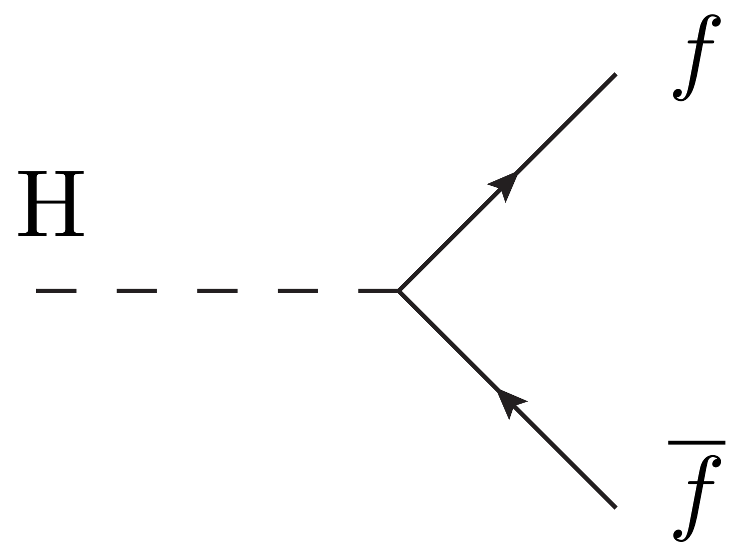

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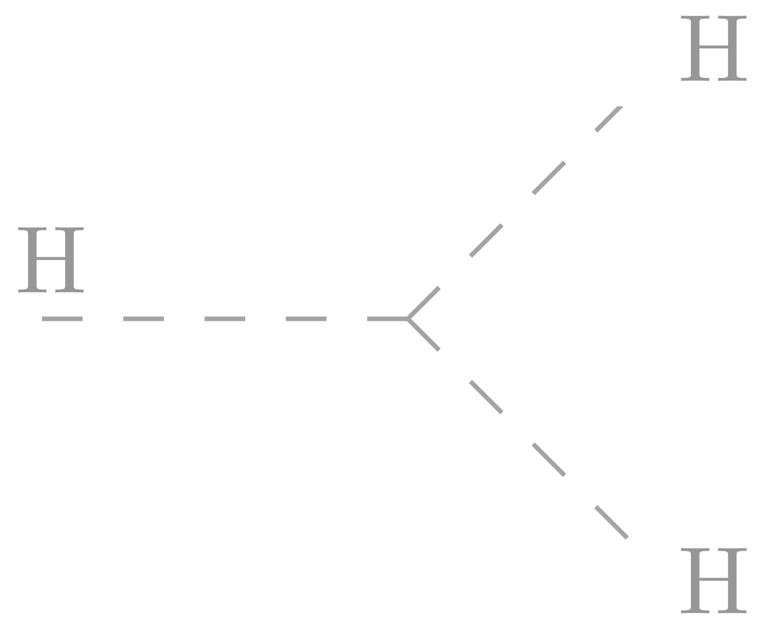

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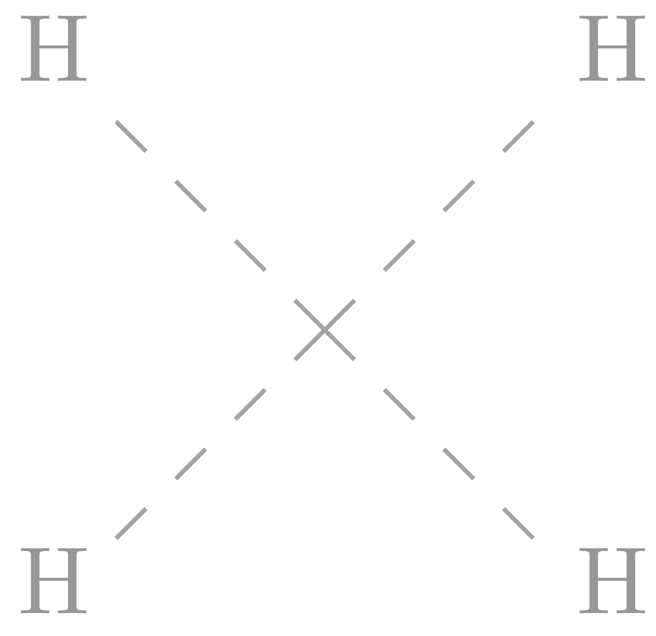
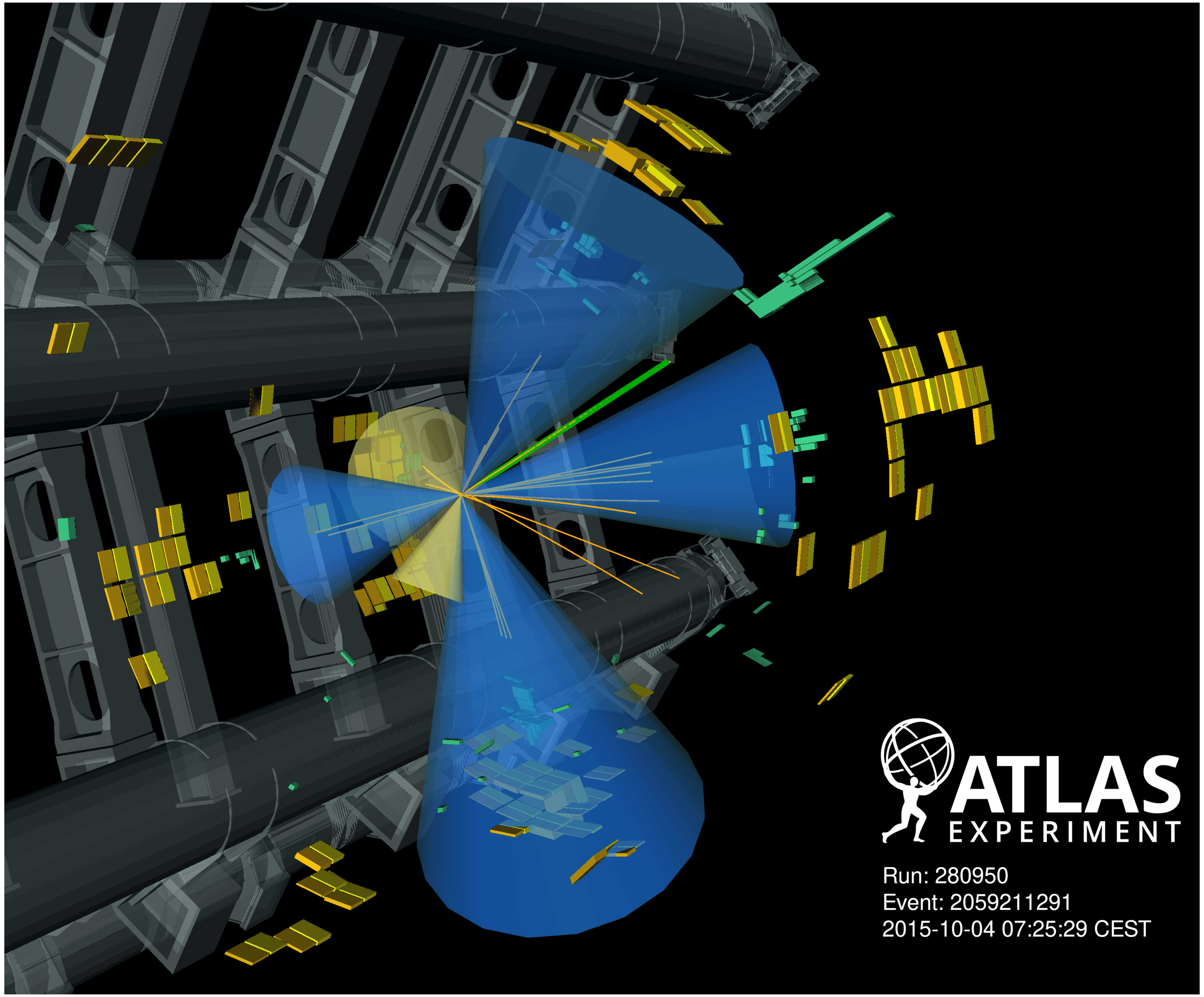


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

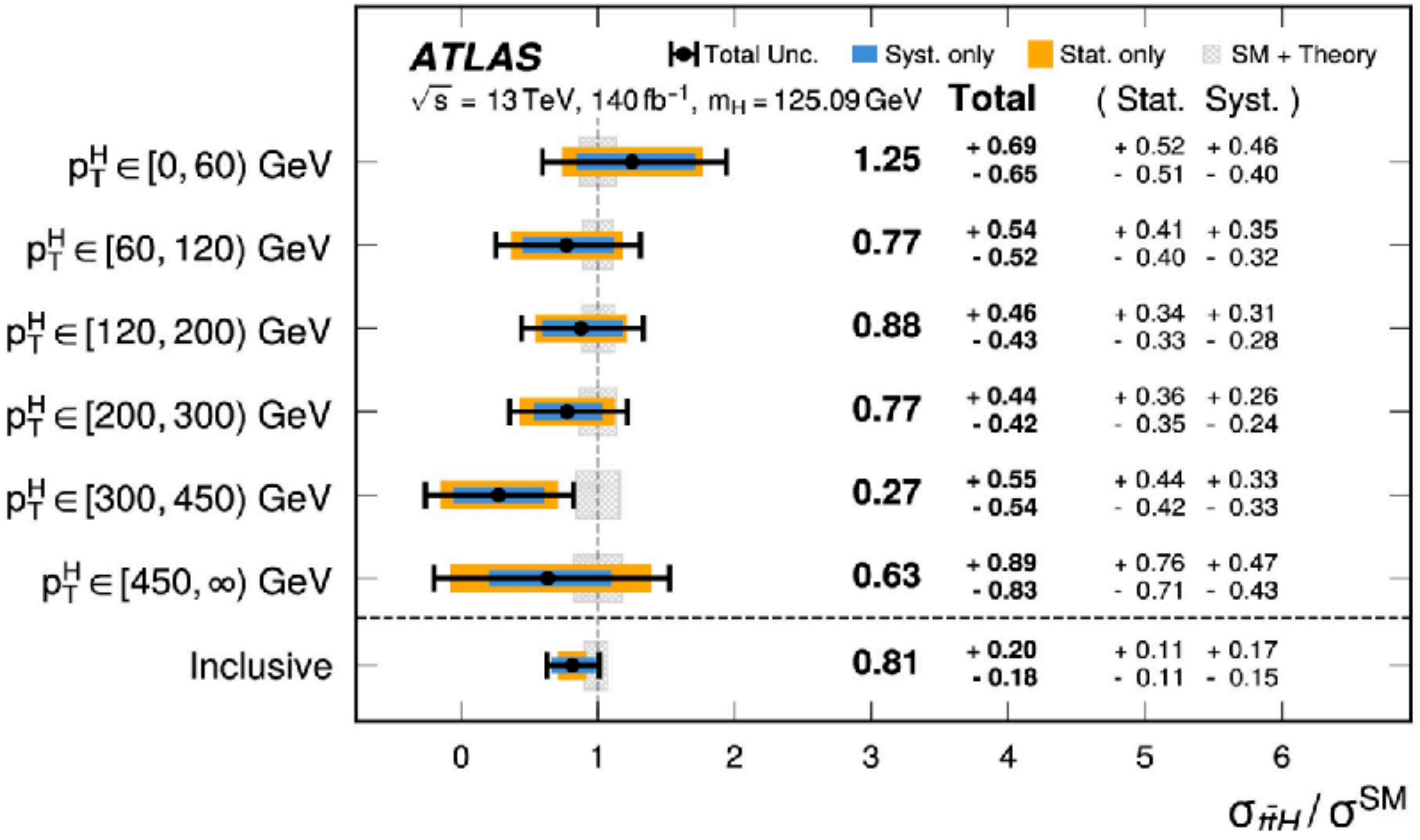
	Current	HL-LHC	FCC (ee)
$\kappa_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

	Current	HL-LHC	FCC (ee)	FCC (hh)
κ_t	11%	3.4%	-	1%
κ_b	11%	3.7%	0.7%	-
κ_τ	8%	1.9%	0.7%	-
κ_μ	20%	4.3%	8.9%*	



ttH news from ATLAS!

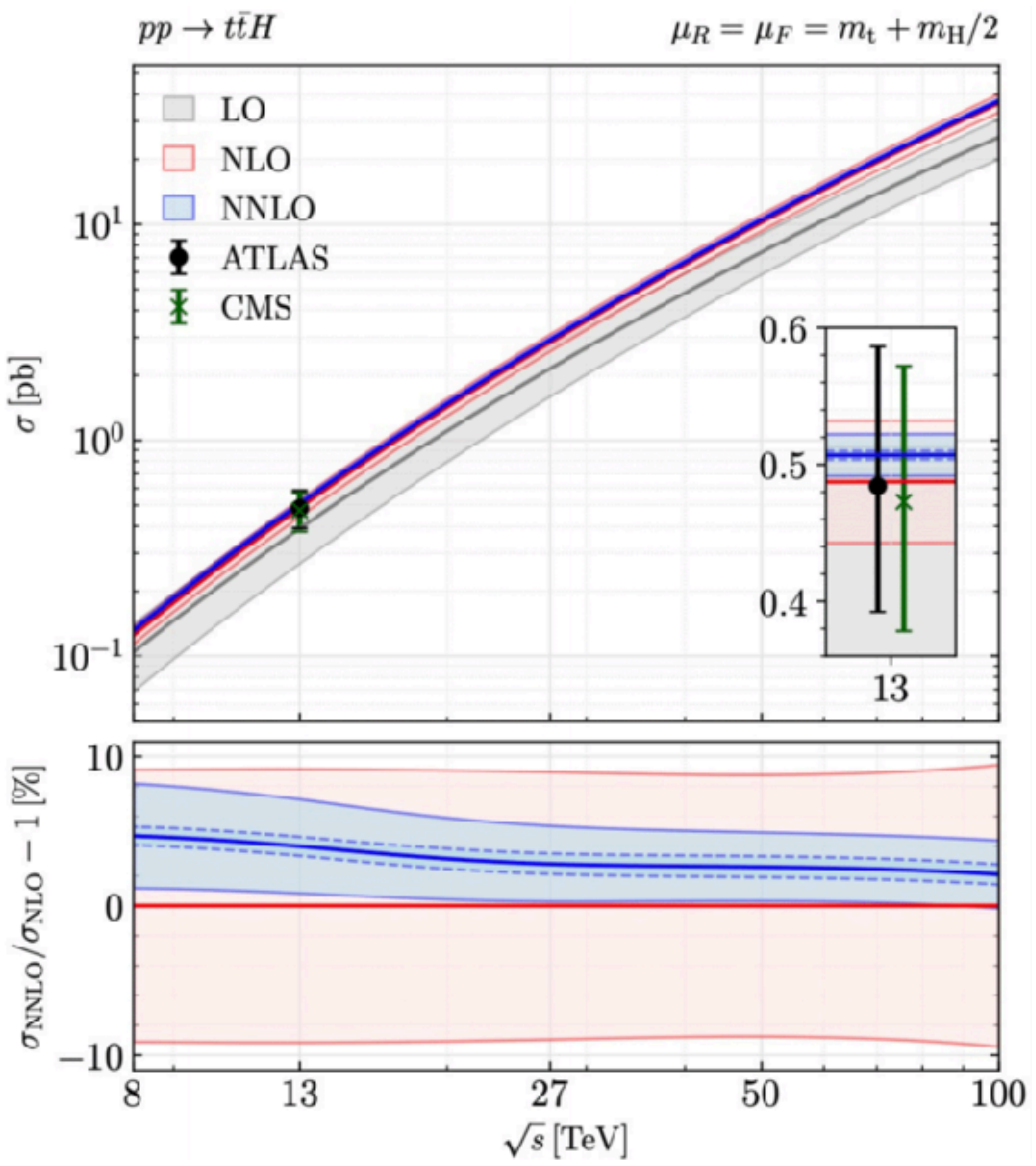
Very complex final state Main challenge: tt+bb background



Best single ttH measurement!
Overall uncertainty improved by factor 1.8, 4.6σ

Top Yukawa Coupling at the LHC

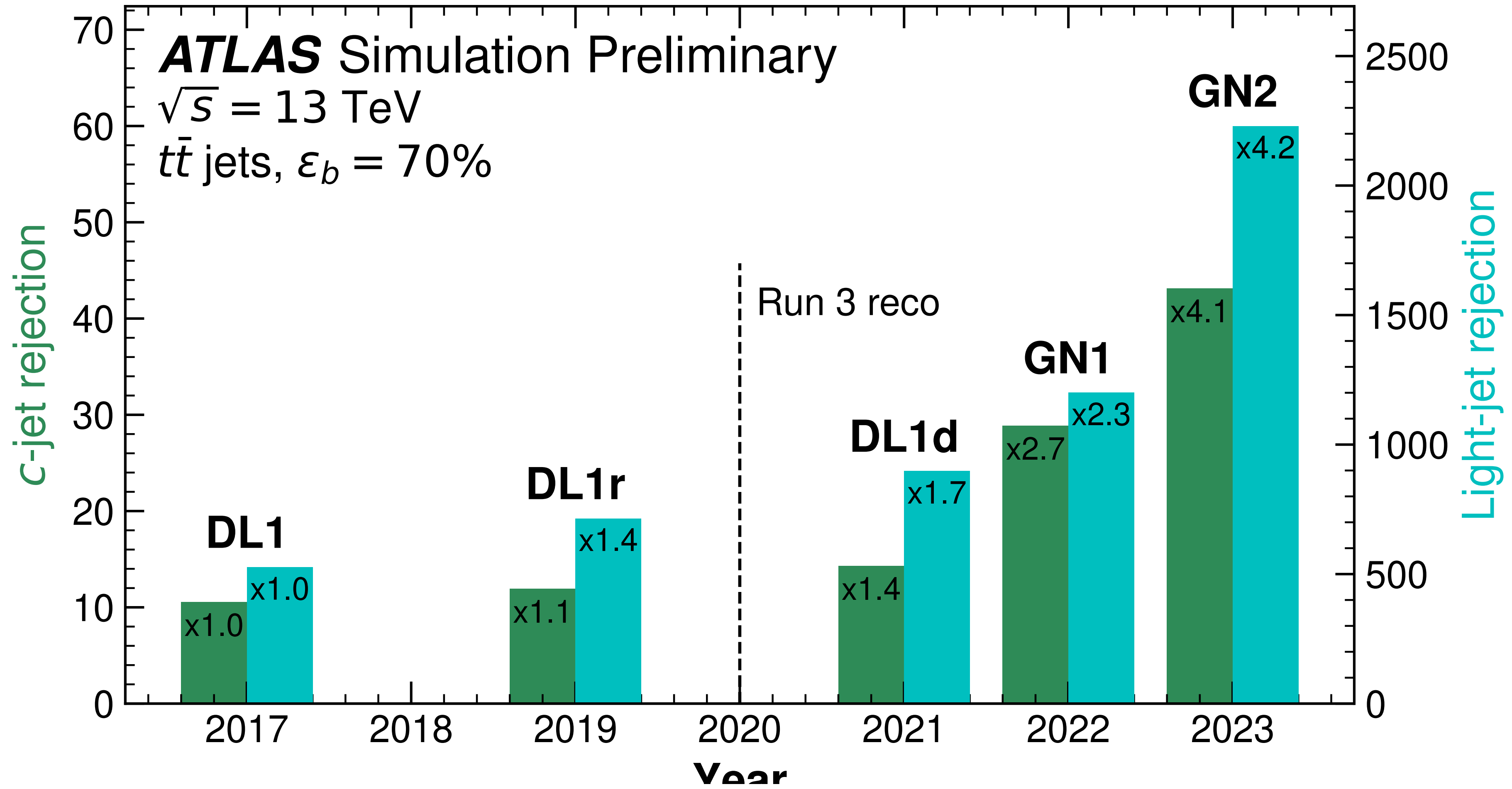
Recent example from Mathew (ttH)



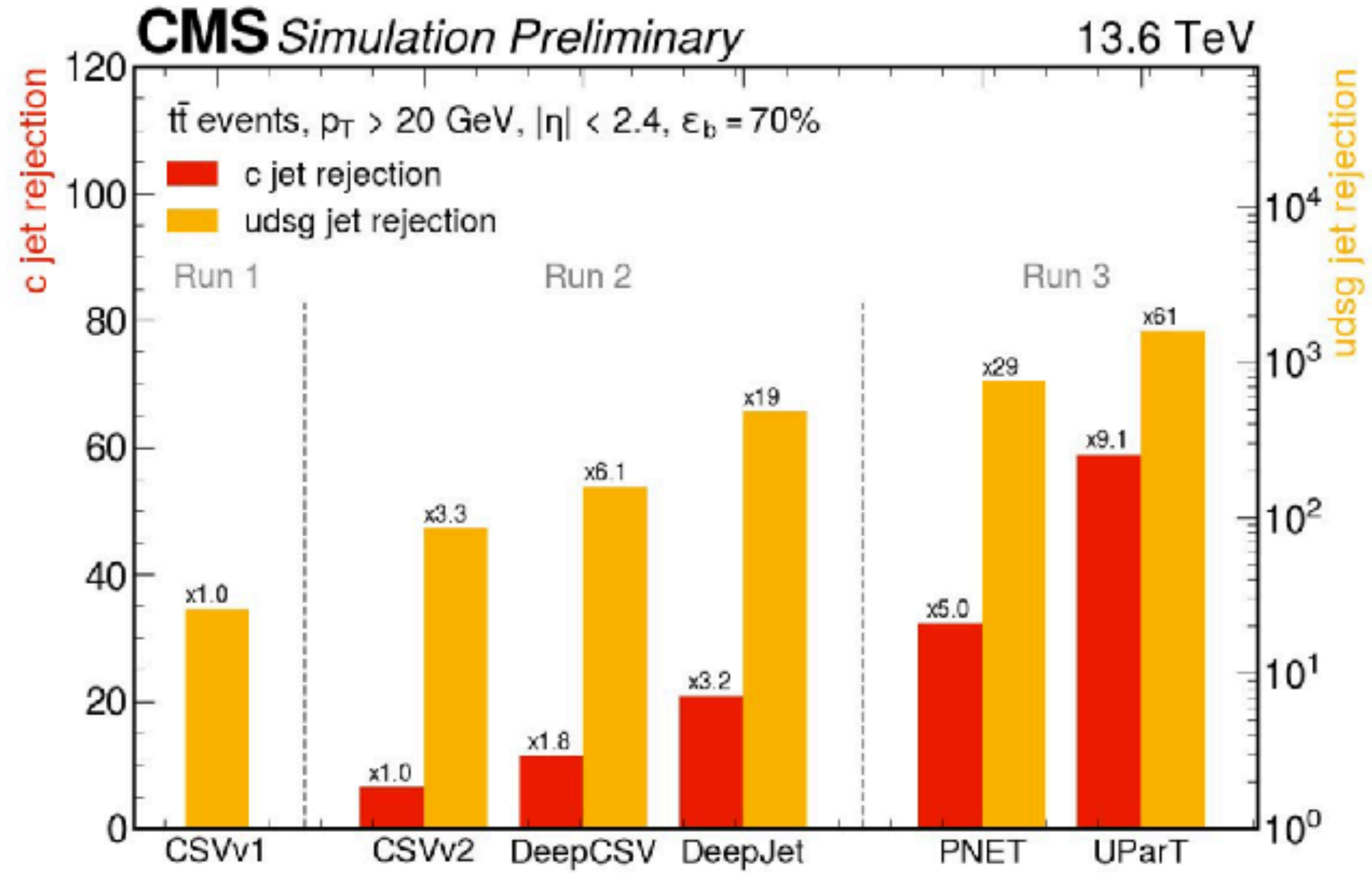
Message 2 (again) (Matthew McCullough):
Precision in Higgs physics is key.

ttH from ATLAS

AI in HEP reconstruction has a significant impact!

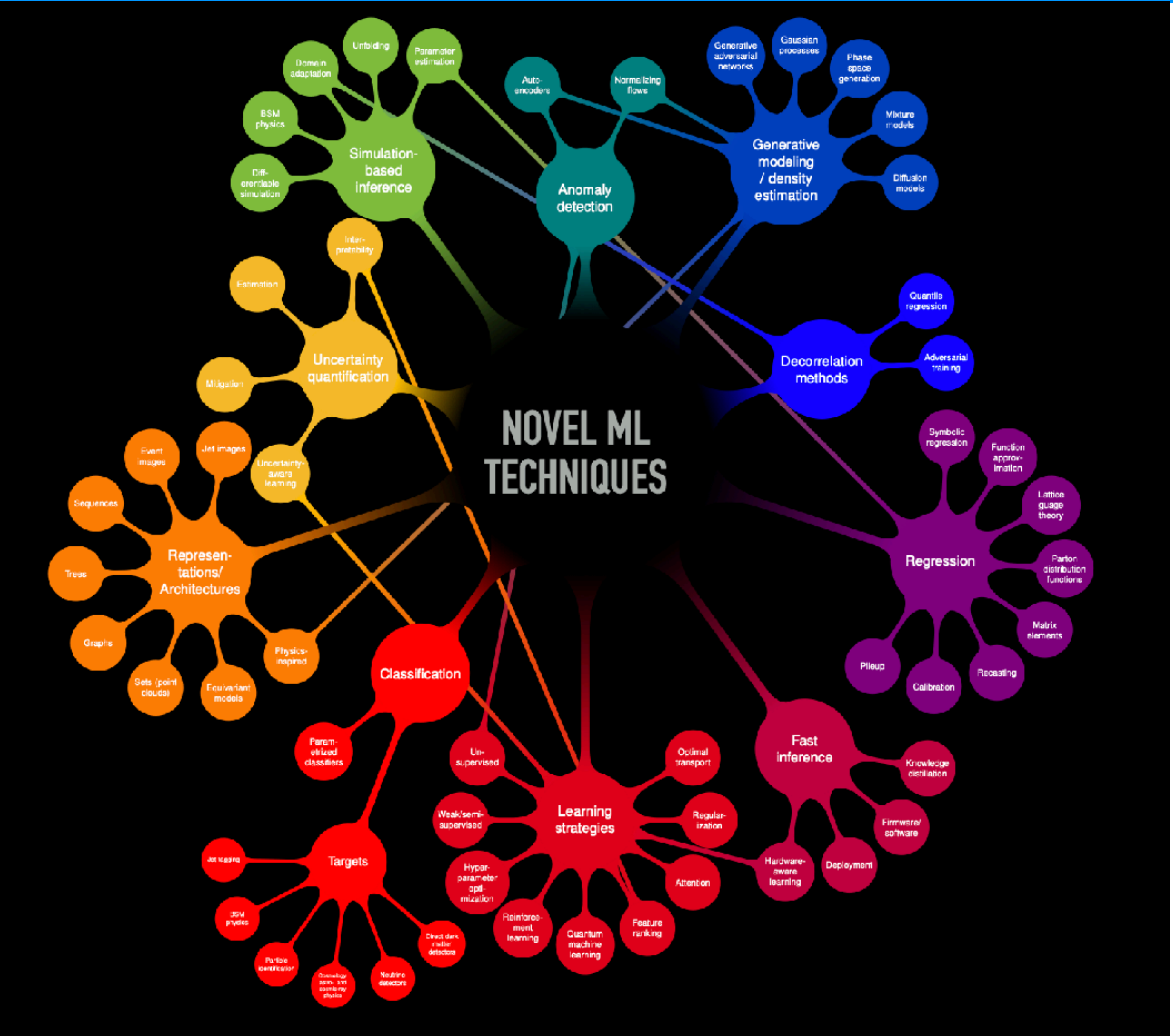


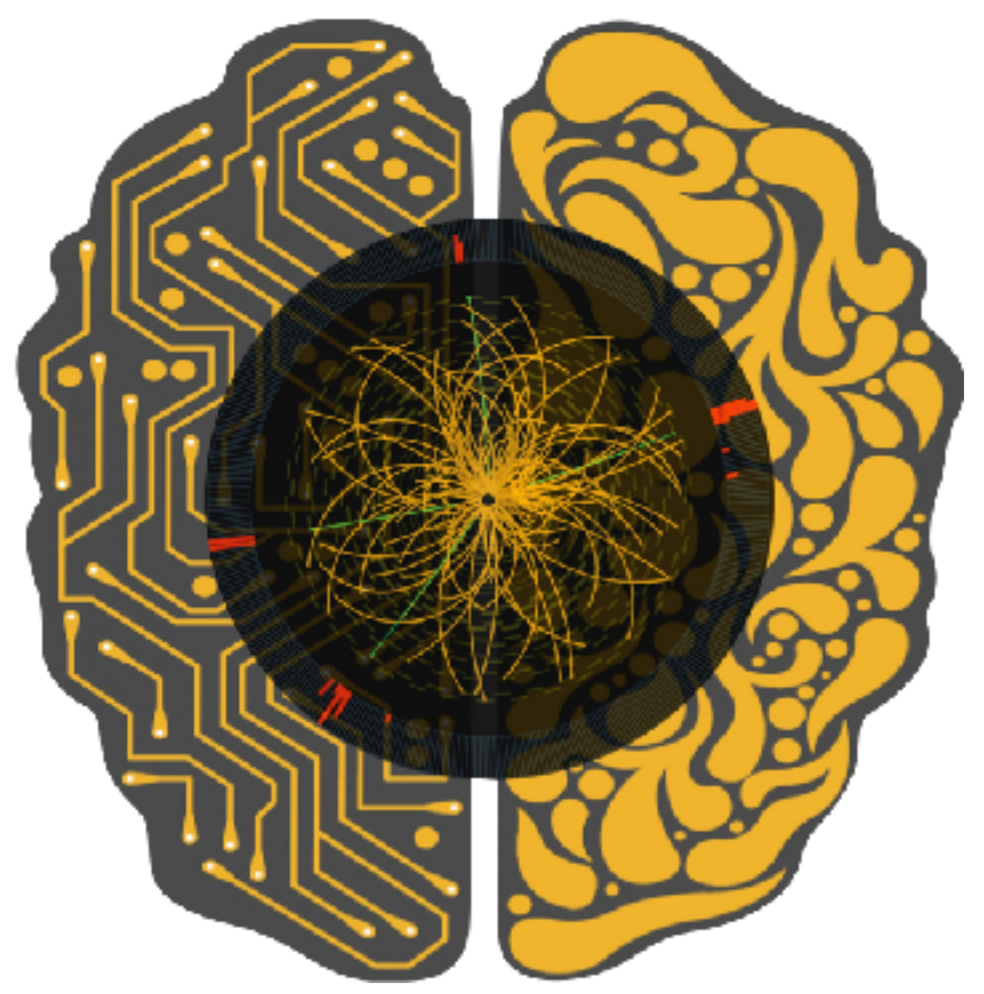
The most shown plot at this conference!



There are 4 b-quark jets in the ttH(bb) event topology!

AI in HEP



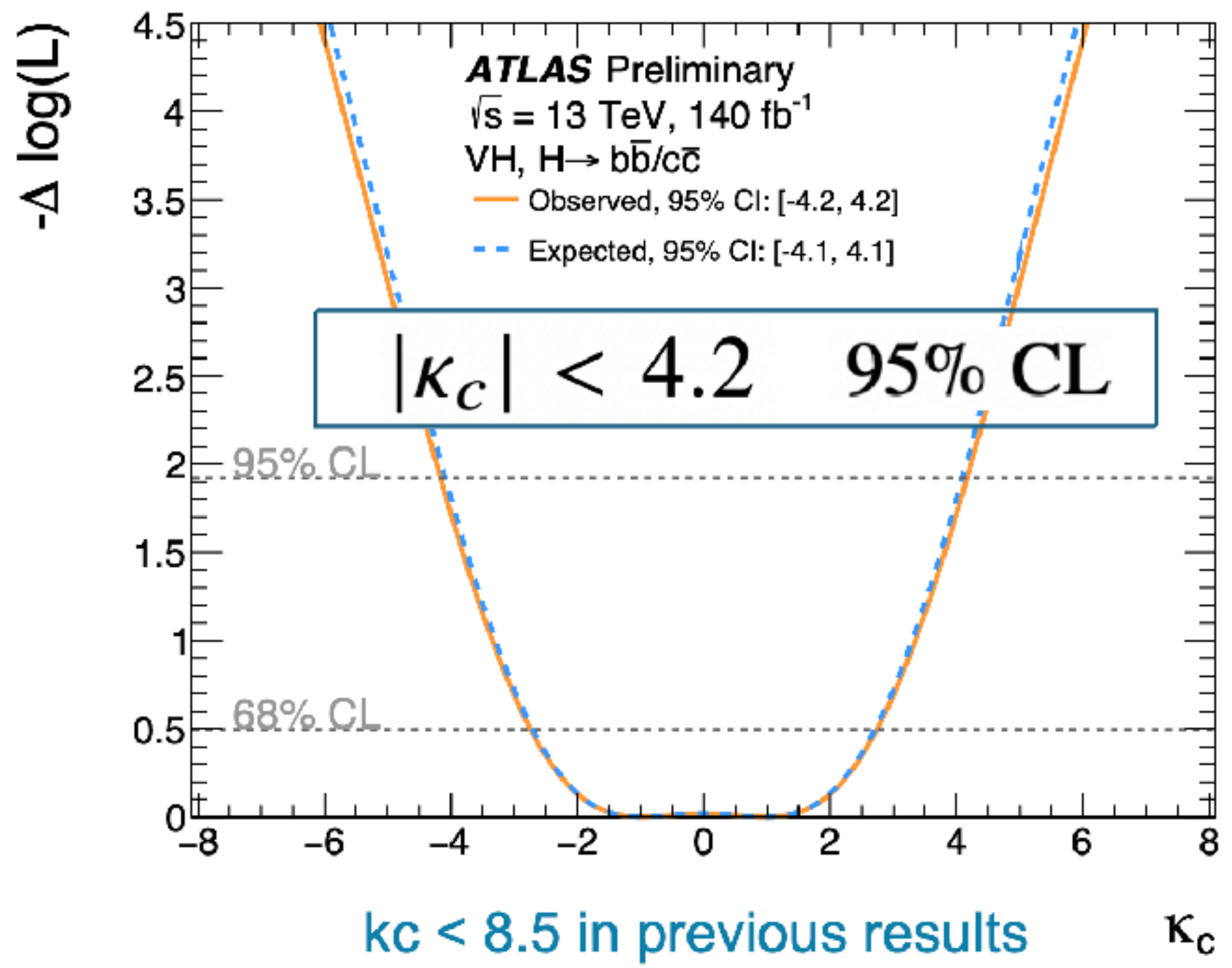


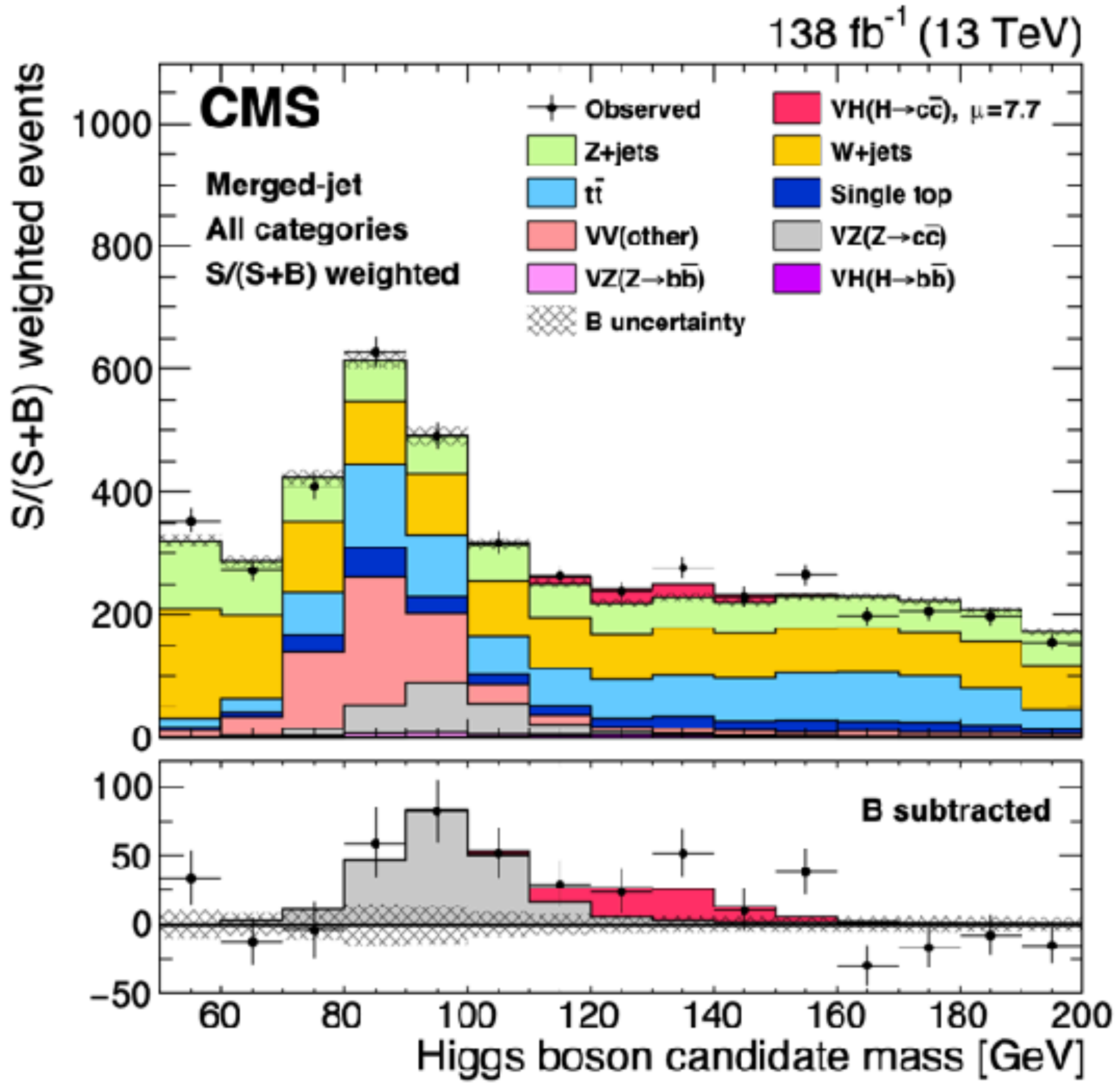
Array of ML opportunities beyond classification and regression, in simulation, unfolding, anomaly detection, etc.

New ideas also have to be concerned with **robustness and interpretability**

Refined analysis of Run 2 data with now Graph NN charm tagging!

Use of state-of-the-art ML techniques Particle Net uses Dynamic Graph CNN





$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.6}_{-3.5}\,(\text{syst.}).$$

Improvement by a factor of 2 w.r.t. previous result

Constraints on charm Yukawa $1.1 < \kappa_c < 5.5$

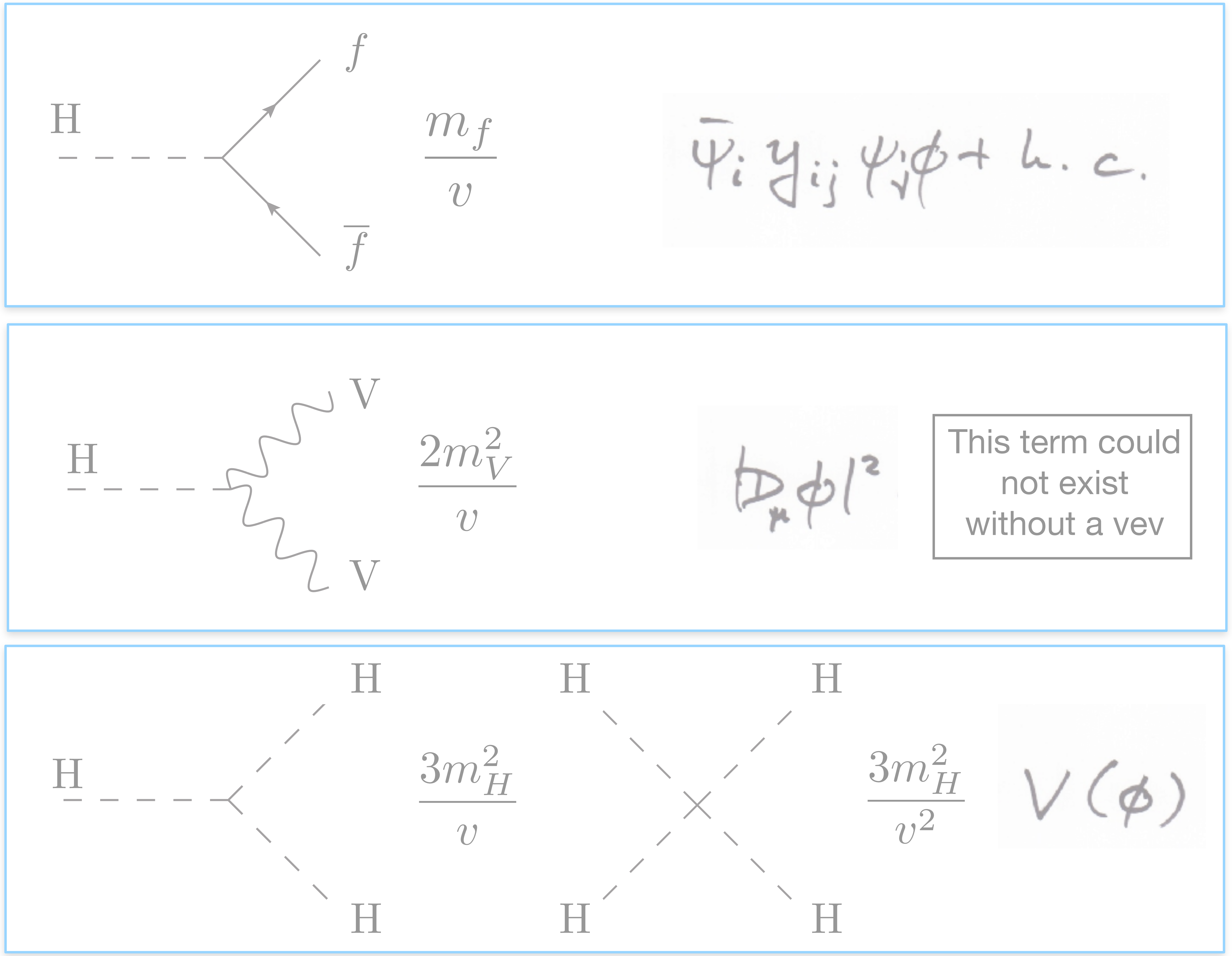
Yields a precision on κ_c of ~40% per experiment at HL-LHC

New perspective at the LHC!

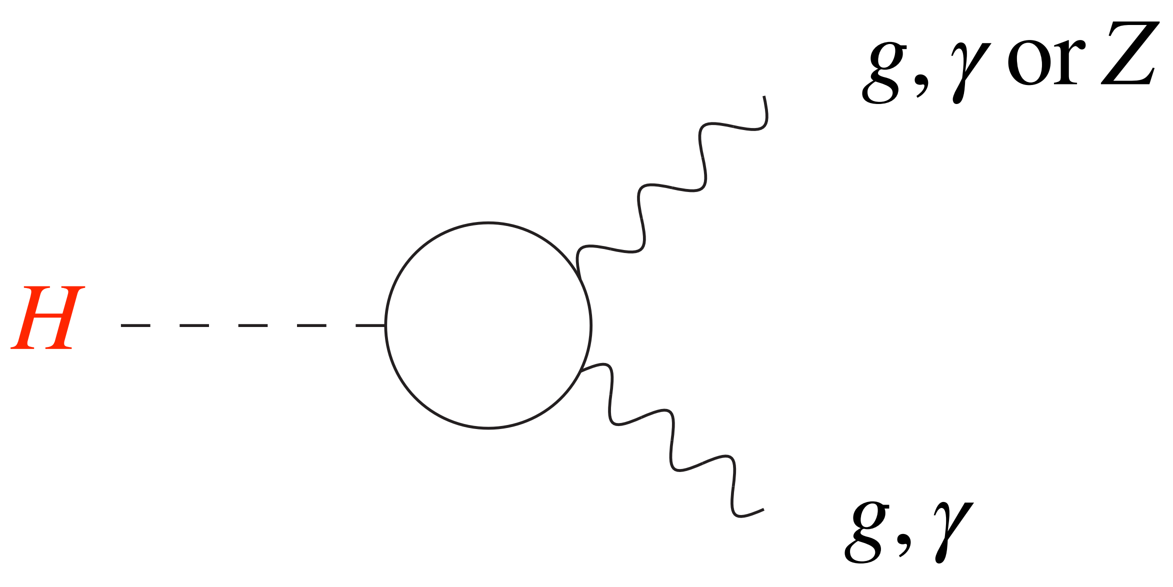
The Higgs Sector - Pillars of Higgs physics

Nicolas Berger, Francesco di Bello

The pillars of Higgs physics:



Probing new particles through loops in production and decays!

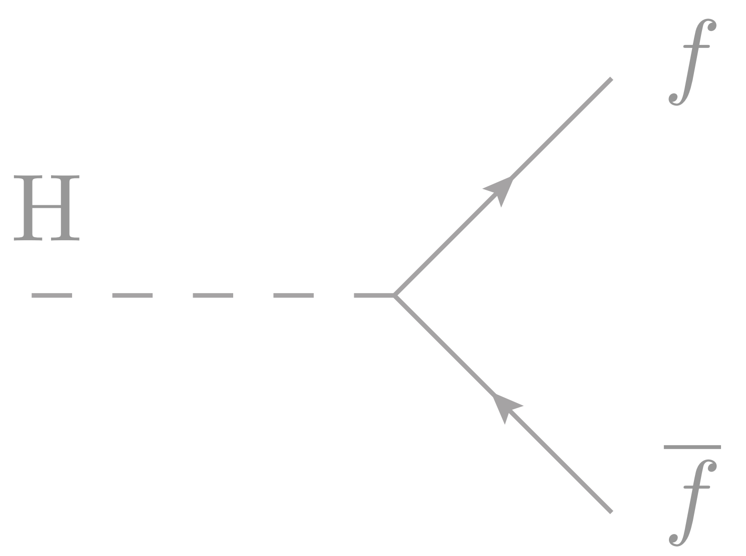


	Current	HL-LHC	FCC (ee)
κ_γ	6%	1.8%	3.9%
κ_g	7%	2.5%	1%
$\kappa_{Z\gamma}$	30%	9.8%	

The Higgs Sector - Pillars of Higgs physics

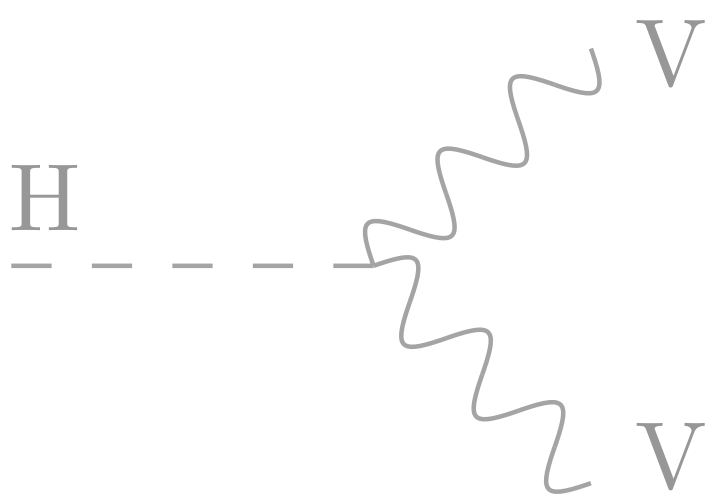
Cristina Mantilla-Suarez, Dilla Maria Portillo Quintero

The pillars of Higgs physics:



$$\frac{m_f}{v}$$

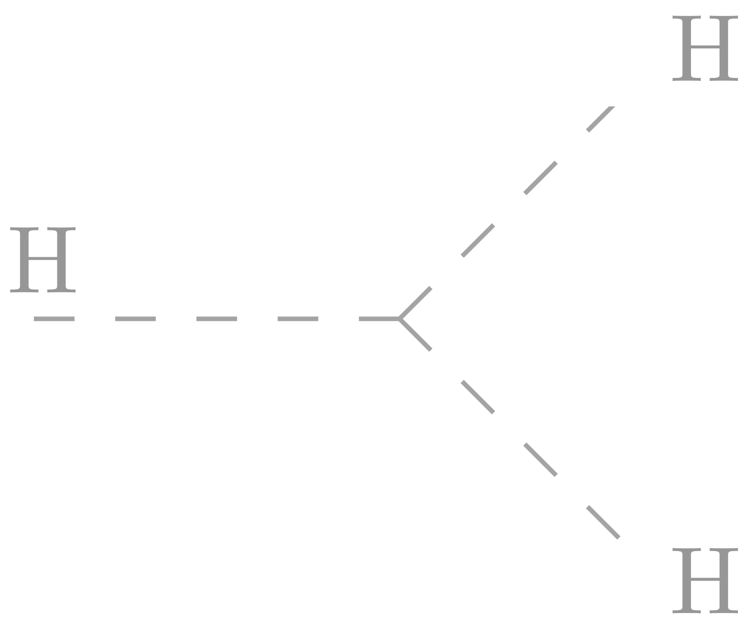
$$\bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$



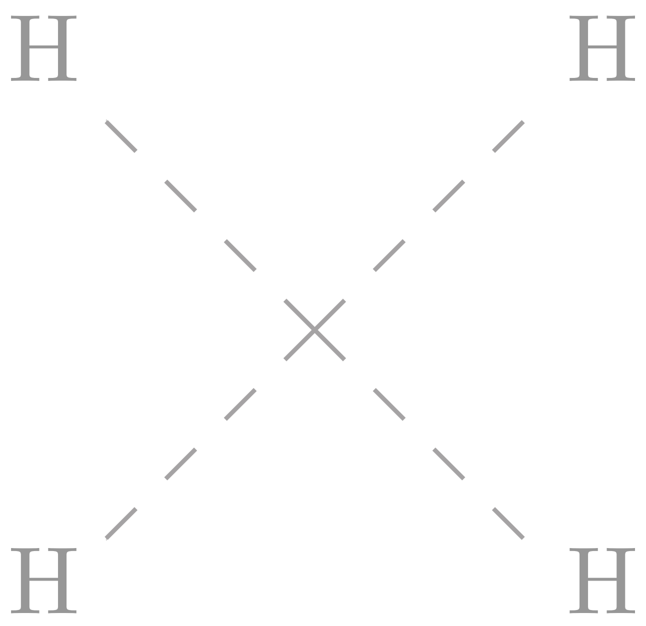
$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

This term could not exist without a vev



$$\frac{3m_H^2}{v}$$



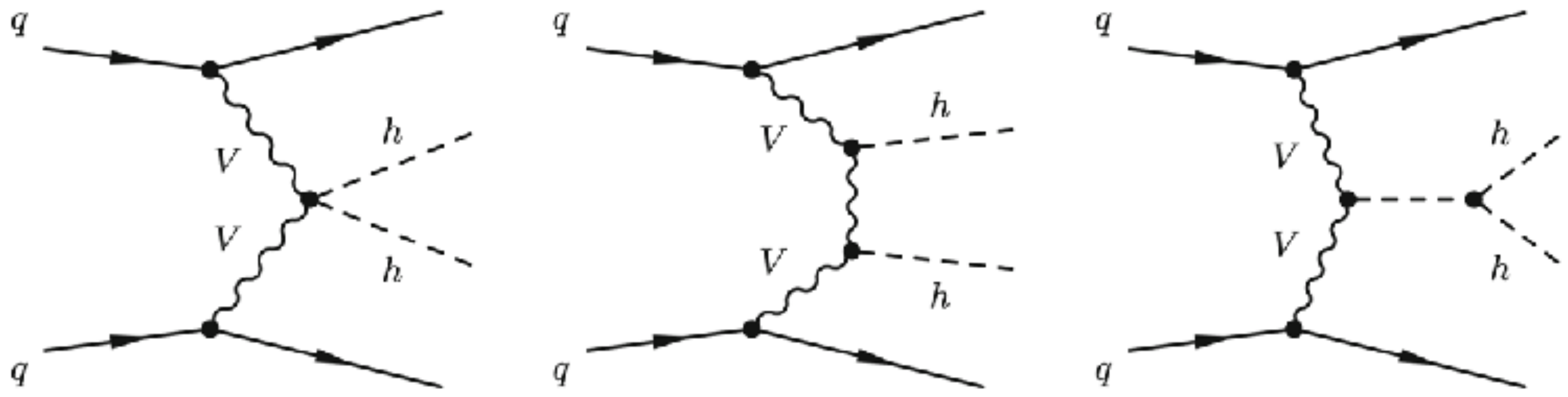
$$\frac{3m_H^2}{v^2}$$

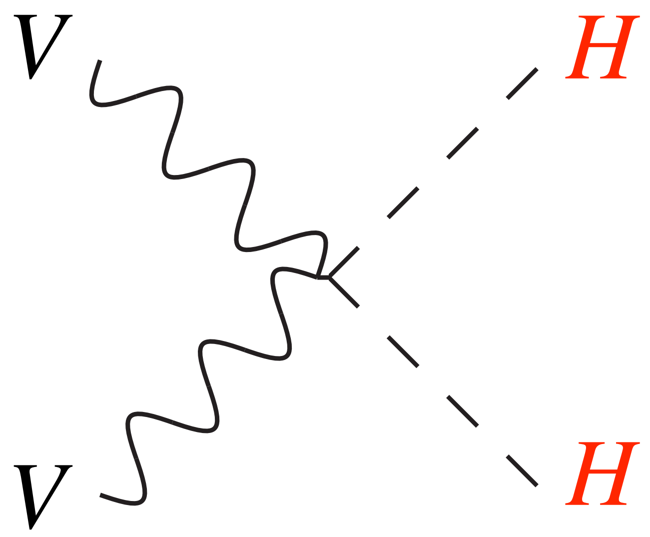
$$V(\phi)$$

Non vanishing di-Higgs (to VV) coupling!

Without observing HH production

Done in VBF(HH) production with a significant negative interference with





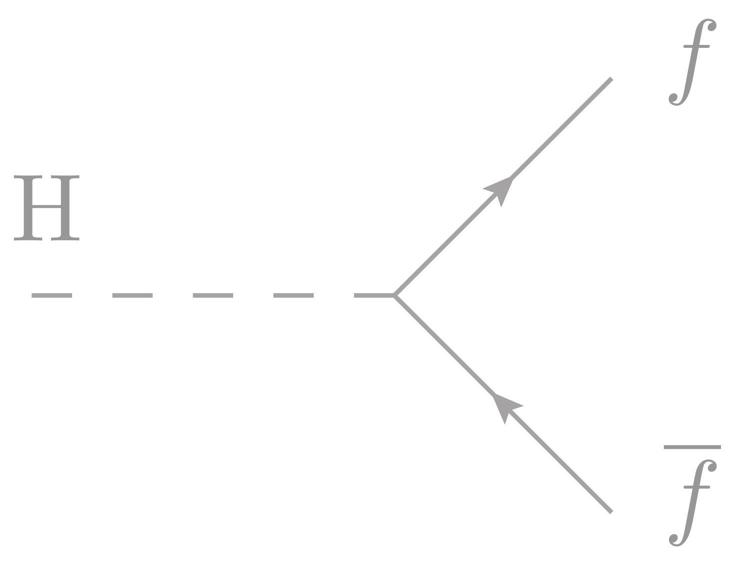
$$g_{HHVV} \sim \frac{2M_V^2}{v^2}$$

$\kappa_{2V} \in [0.67, 1.38]$ CMS result (ATLAS similar)

The Higgs boson self coupling!

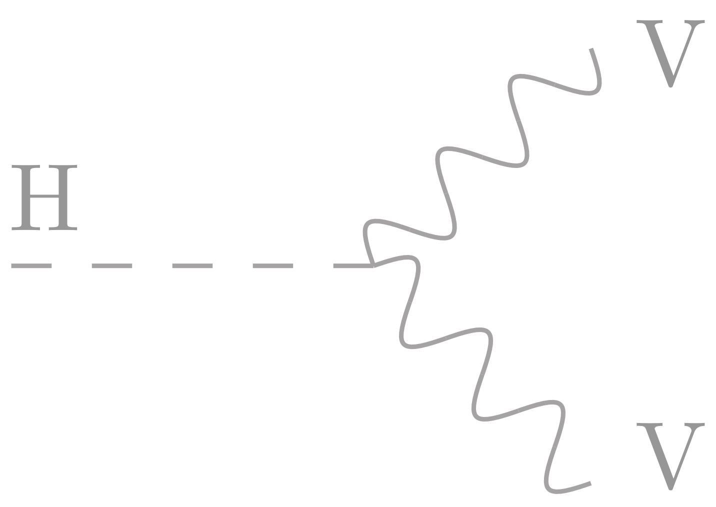
Nicolas Berger, Matthew McCullough

The pillars of Higgs physics:



$\frac{m_f}{v}$

$\bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$



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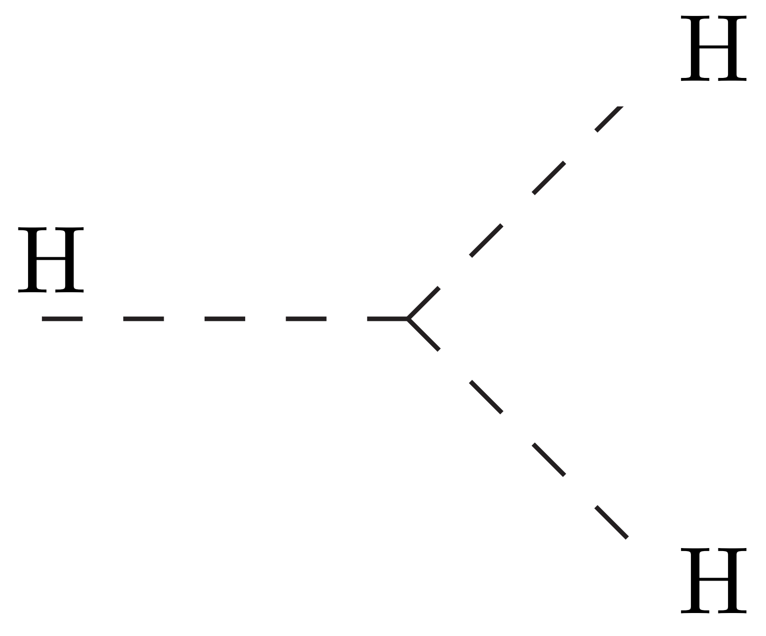

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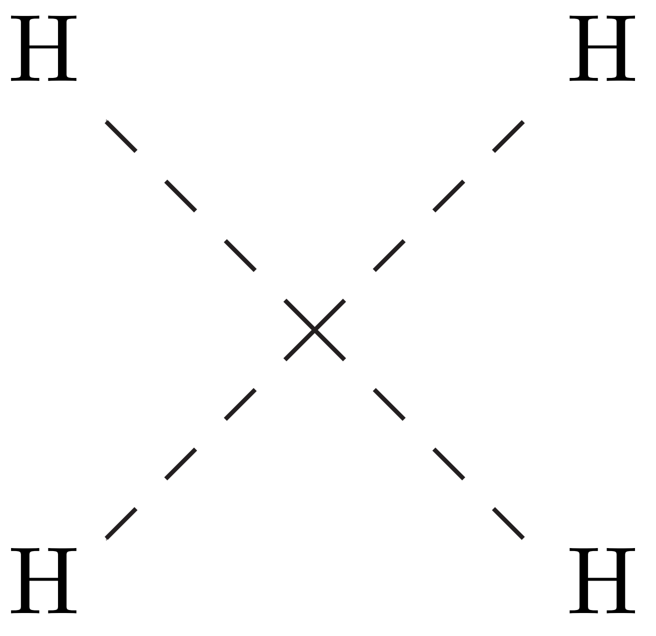


$\frac{3m_H^2}{v^2}$

$V(\phi)$

Despite the fact that in "Vanilla SUSY and vanilla composite models it is difficult to have large deviations in trilinear w.r.t. vector boson coupling"

Matthew McCullogh

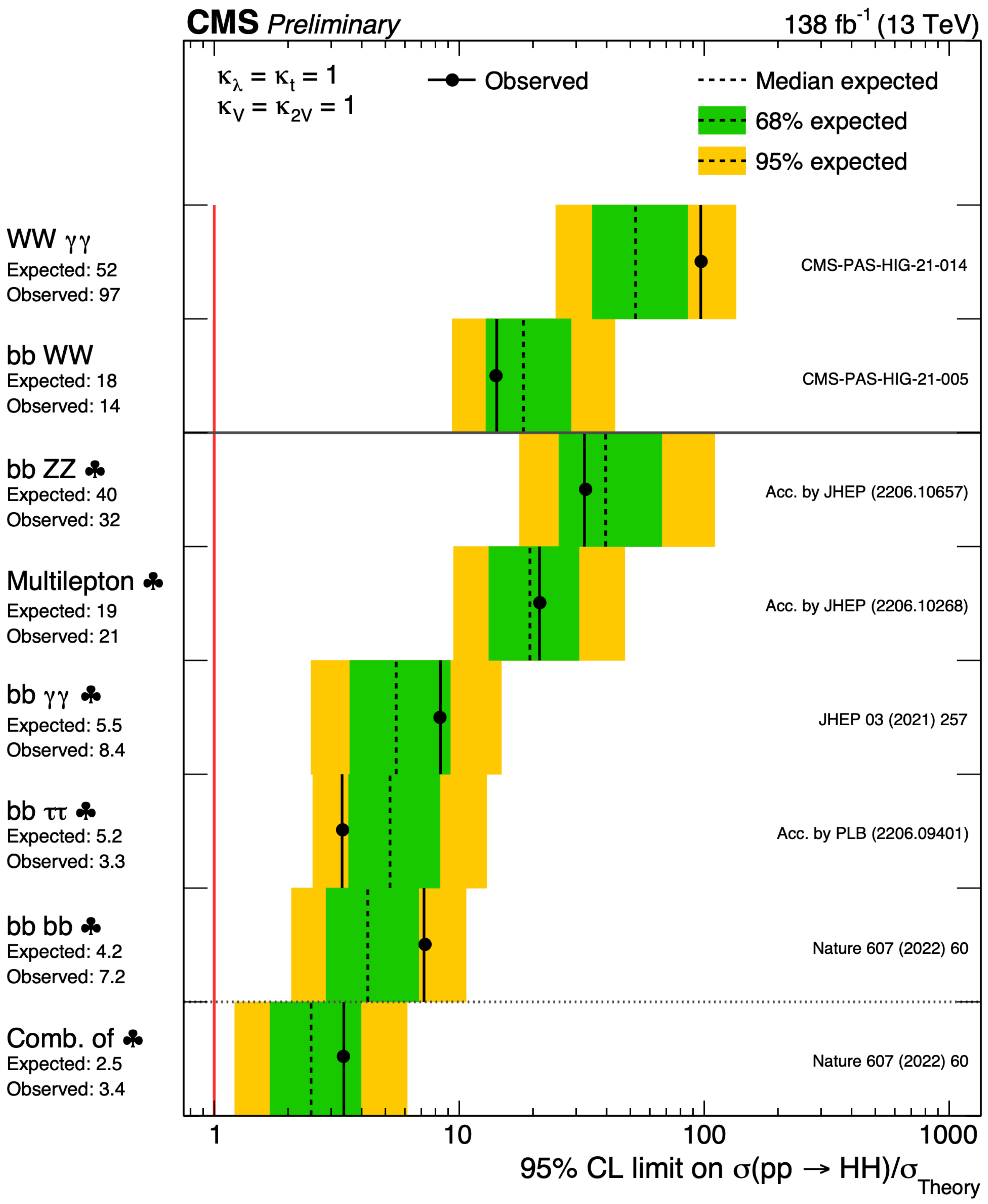
Message 3 (Matthew McCullogh - as well as Georg Weiglein in parallel session): Large trilinear deviations are possible while deviations of the Higgs to Z coupling remain small.

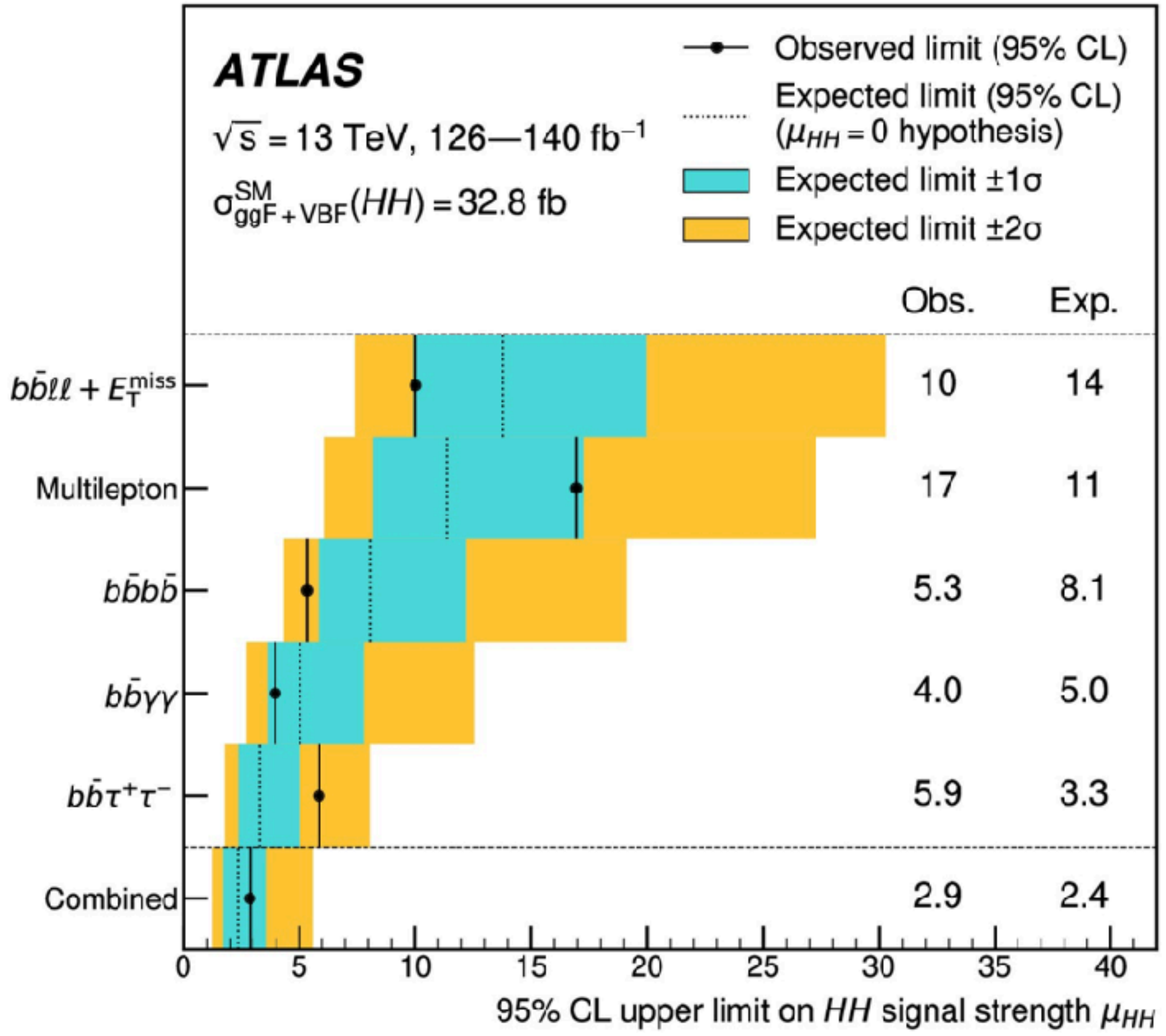
"Arguably the most important of them all!"

Higgs Self Coupling and HH Production

Nicolas Berger, Matthew McCullough

"Arguably the most important of them all!"





Observed limits start deviating from expectation!!

Both experiments have ~1σ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS ~1σ) with Run 2!!

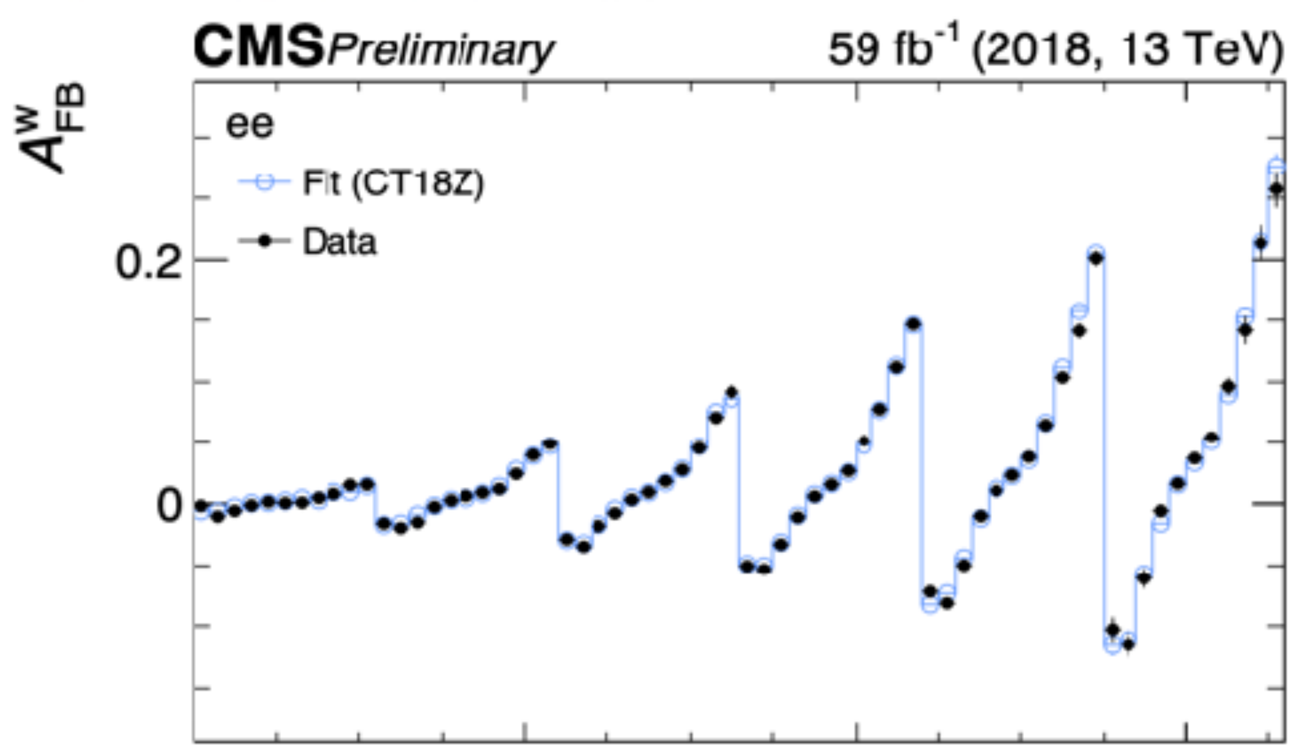
Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3σ**

The Gauge Sectors - LHC at Precision Frontier

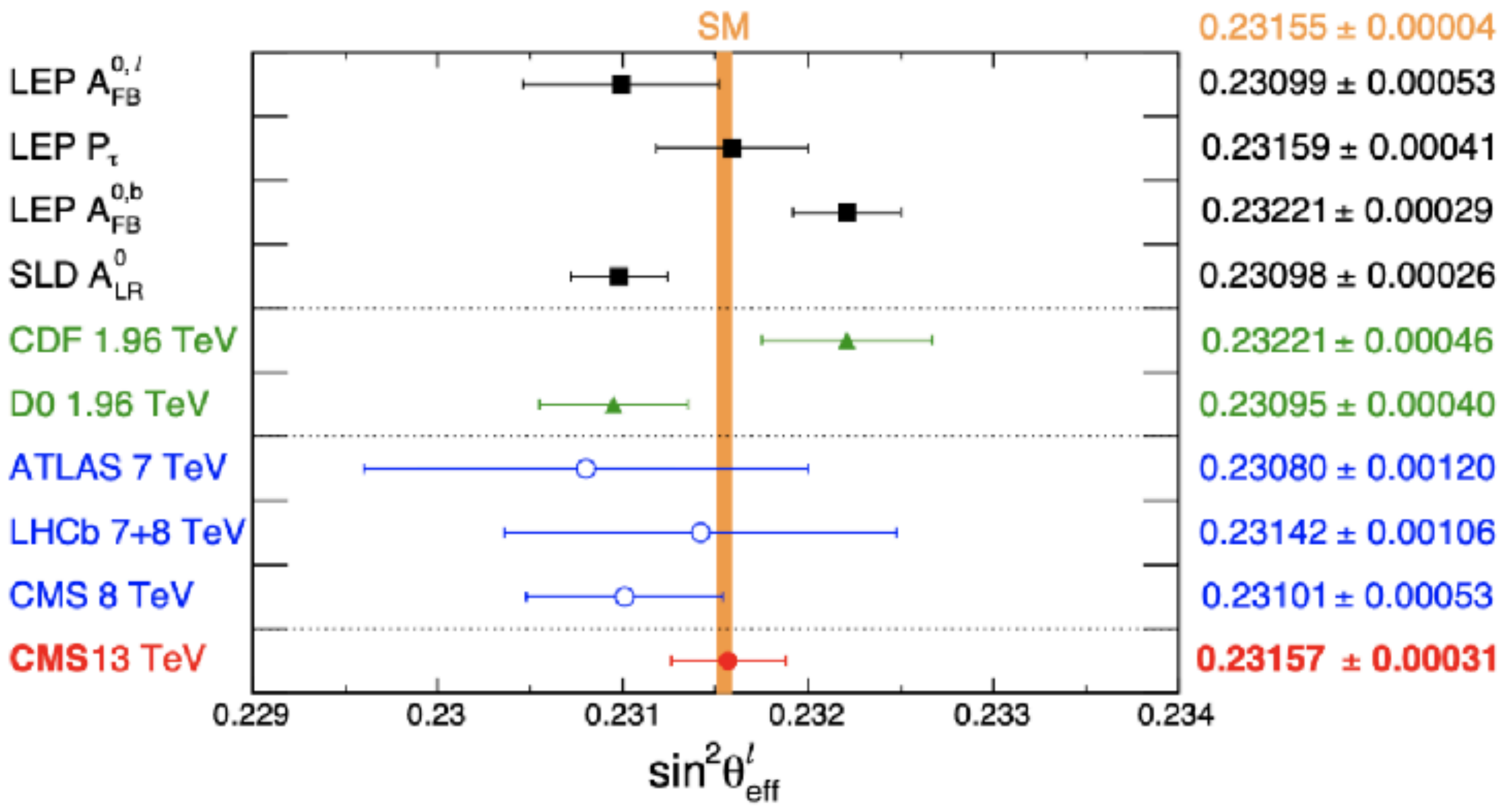
Maurizio Pierini, Yasmine Amhis

New measurements of $\sin^2\theta_W$ by CMS and LHCb through AFB

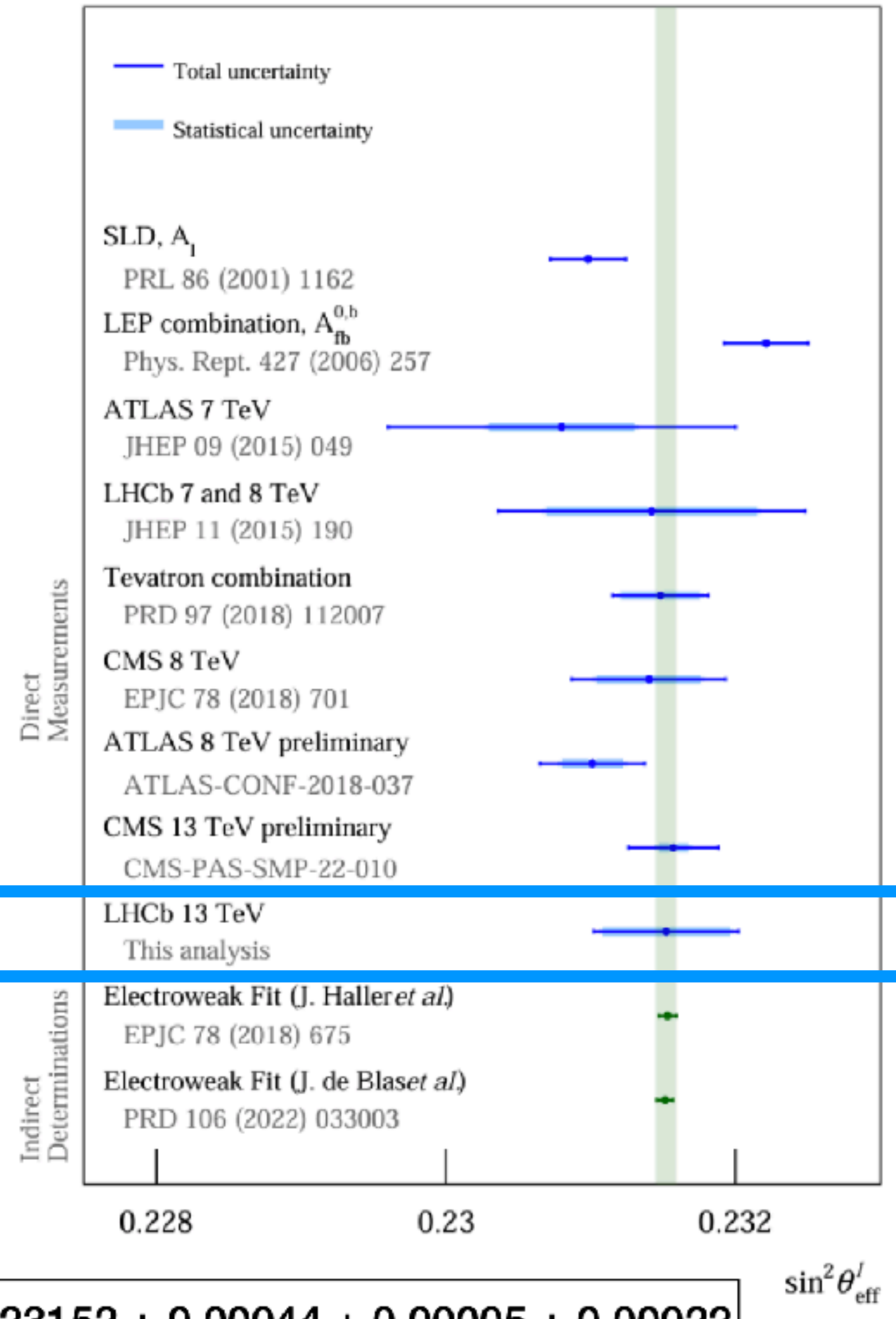
AFB in pp collisions is a tricky question, the forward region direction is given by the valence quark i.e. the system boost direction.



Precision comparable to the most precise single measurements at LEP A_{FB}^{b} and SLD A_{LR} determination



CERN Seminar yesterday! Link



$$\sin^2\theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$

Precise Determination of α_S using $Z \to \ell^+\ell^-$

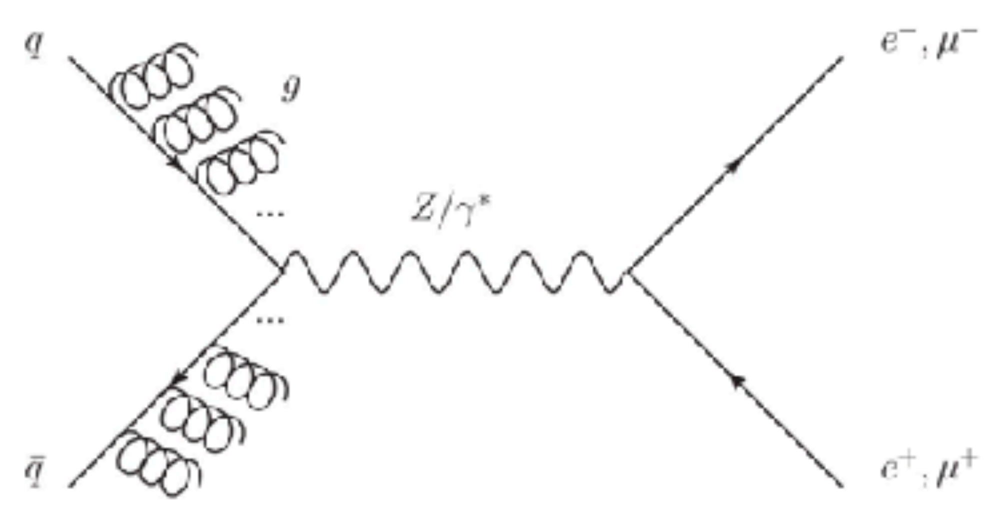
Conditions for a competitive measurement of α_S

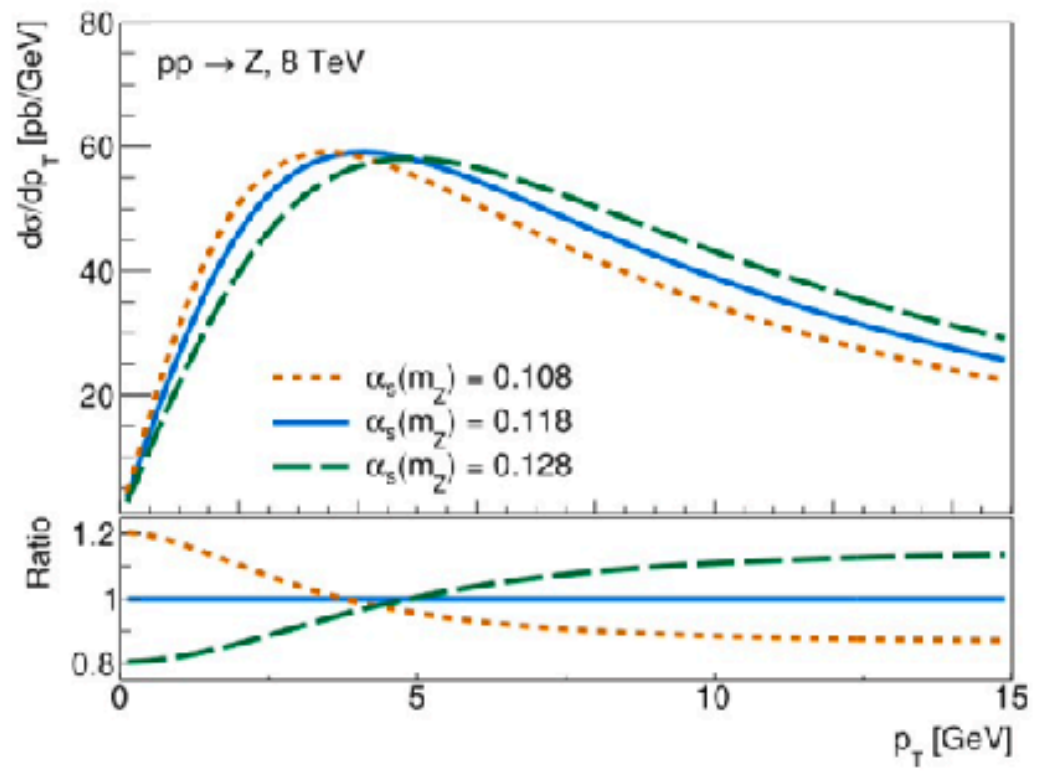
1) is proportional to the strong coupling constant;
2) can be predicted theoretically with a percent precision (NNLO and higher);
3) is independent (nearly independent) of poorly-known parton distribution functions;
4) refers to low(er) region of hard momentum region;
5) does not suffer from unknown non-perturbative effects.

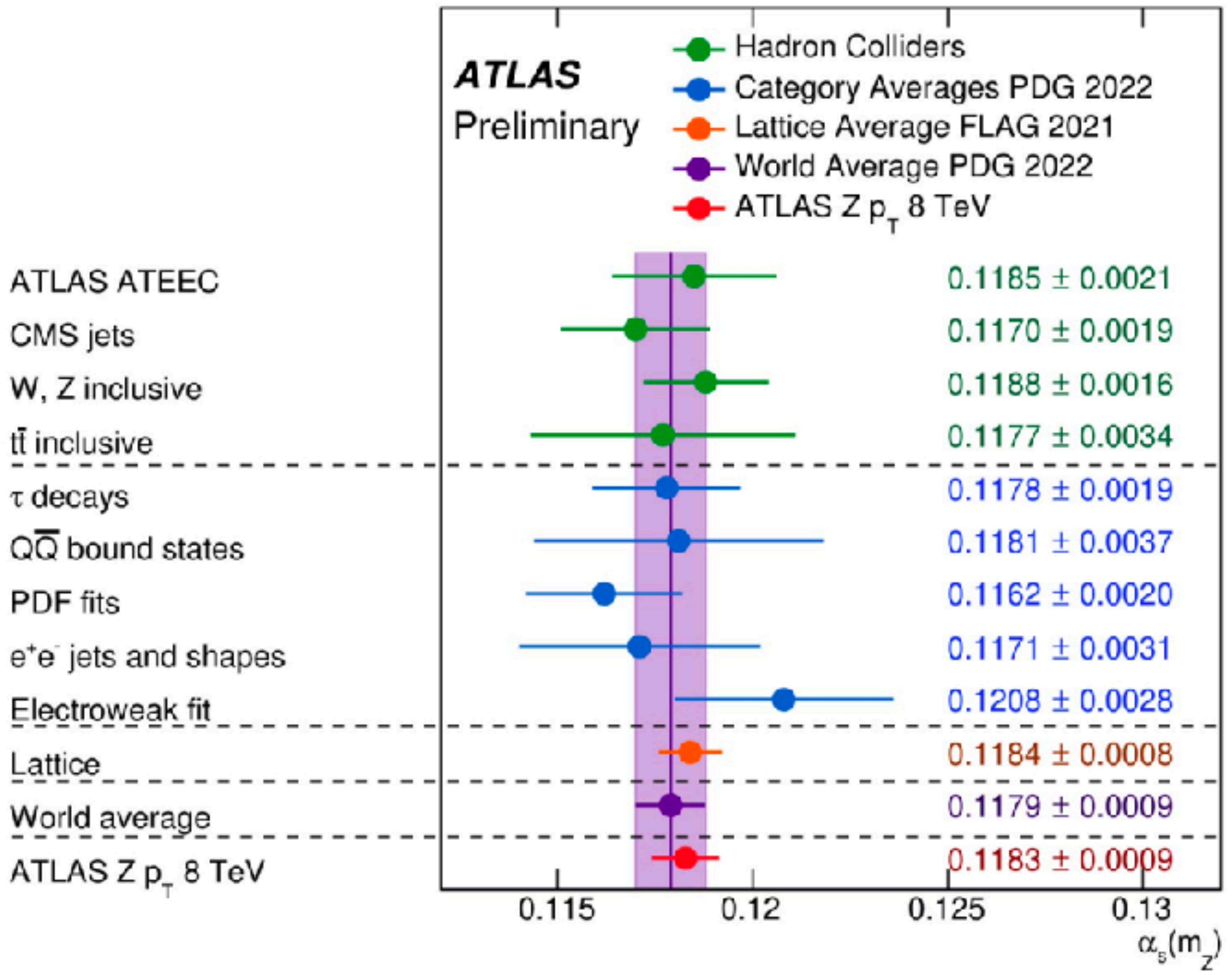
"Inclusive Z transverse momentum seems to fit the bill"!

$$\frac{d\sigma_Z}{\sigma_z dp_\perp} \sim \frac{\alpha_s(p_\perp)}{2\pi p_\perp} \ln \frac{M_Z}{p_\perp}$$

Using **Sudakof peak in pT**, based on **resummed calculations**

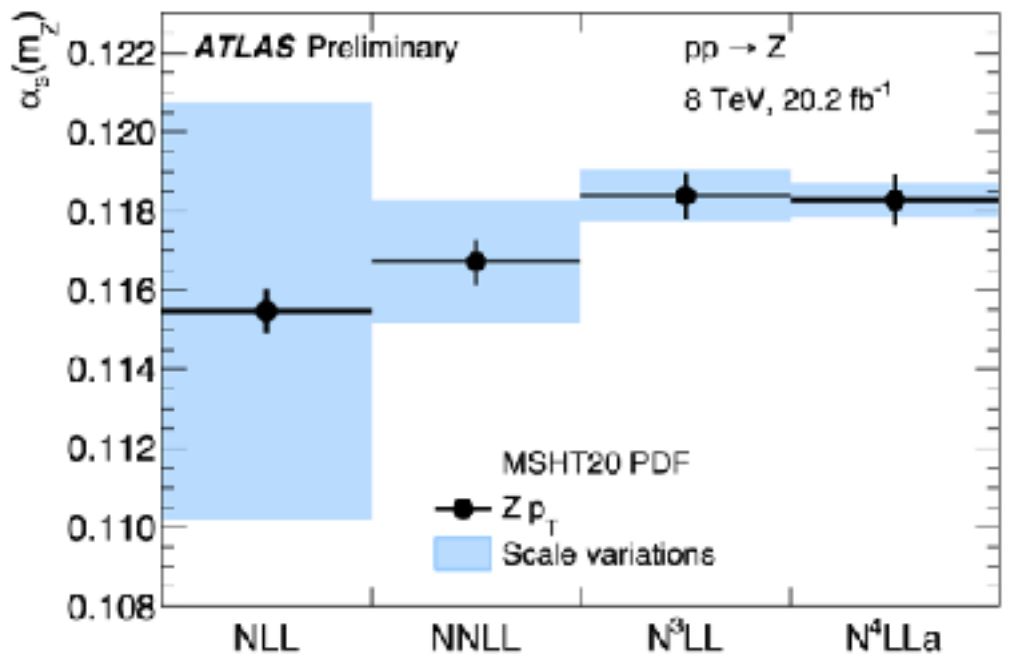






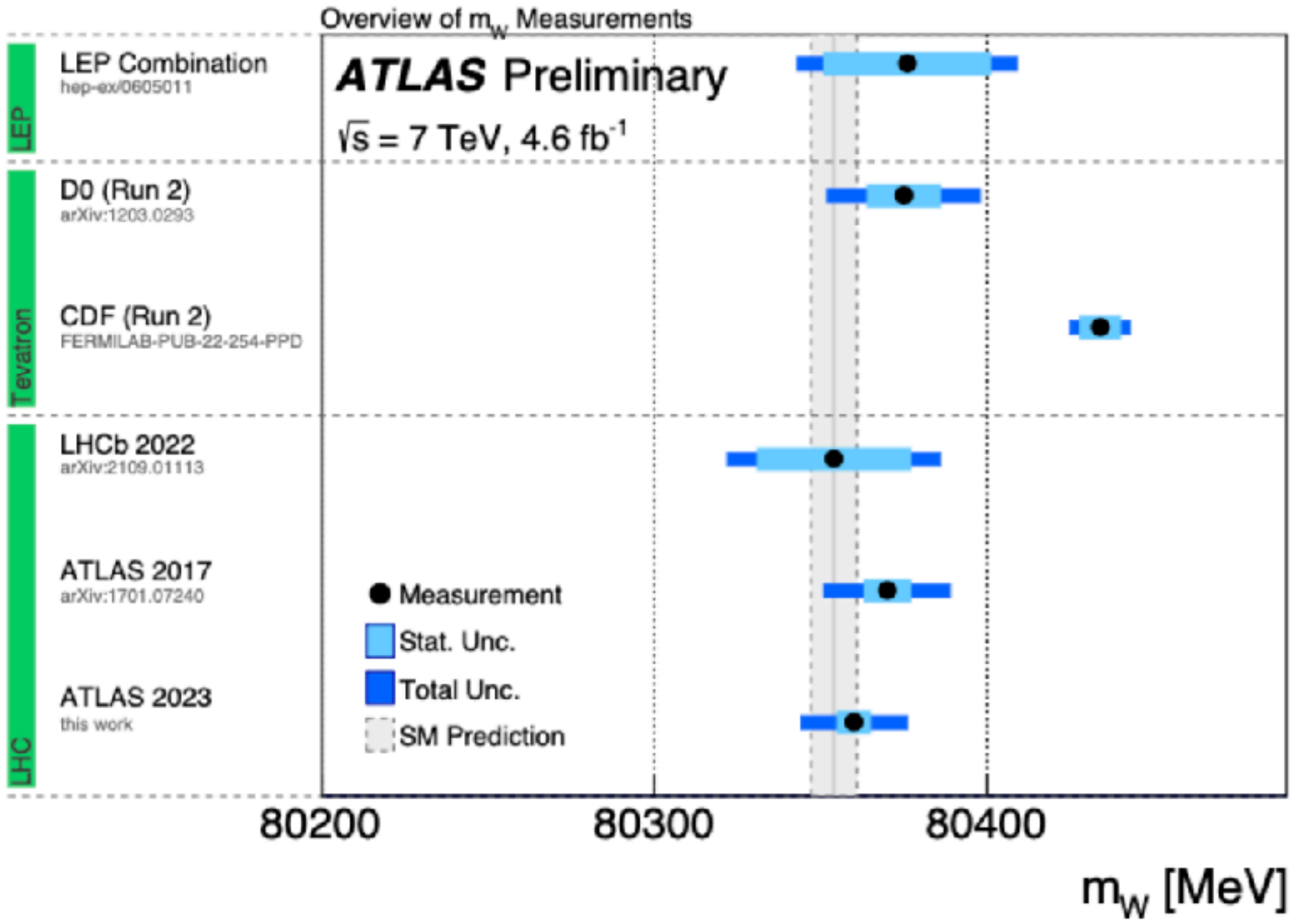
Precision on par with lattice QCD and world average!

Such precision would not be possible without precise TH predictions!



W Mass Puzzle

Measurements at LHC from ATLAS and LHCb



$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16$ MeV

CERN press release

The measurement relies on the ratio of W/Z pT (as noted by Kirill) non trivial QCD and EW corrections can modify this spectrum and bring correction of up to ~20 MeV

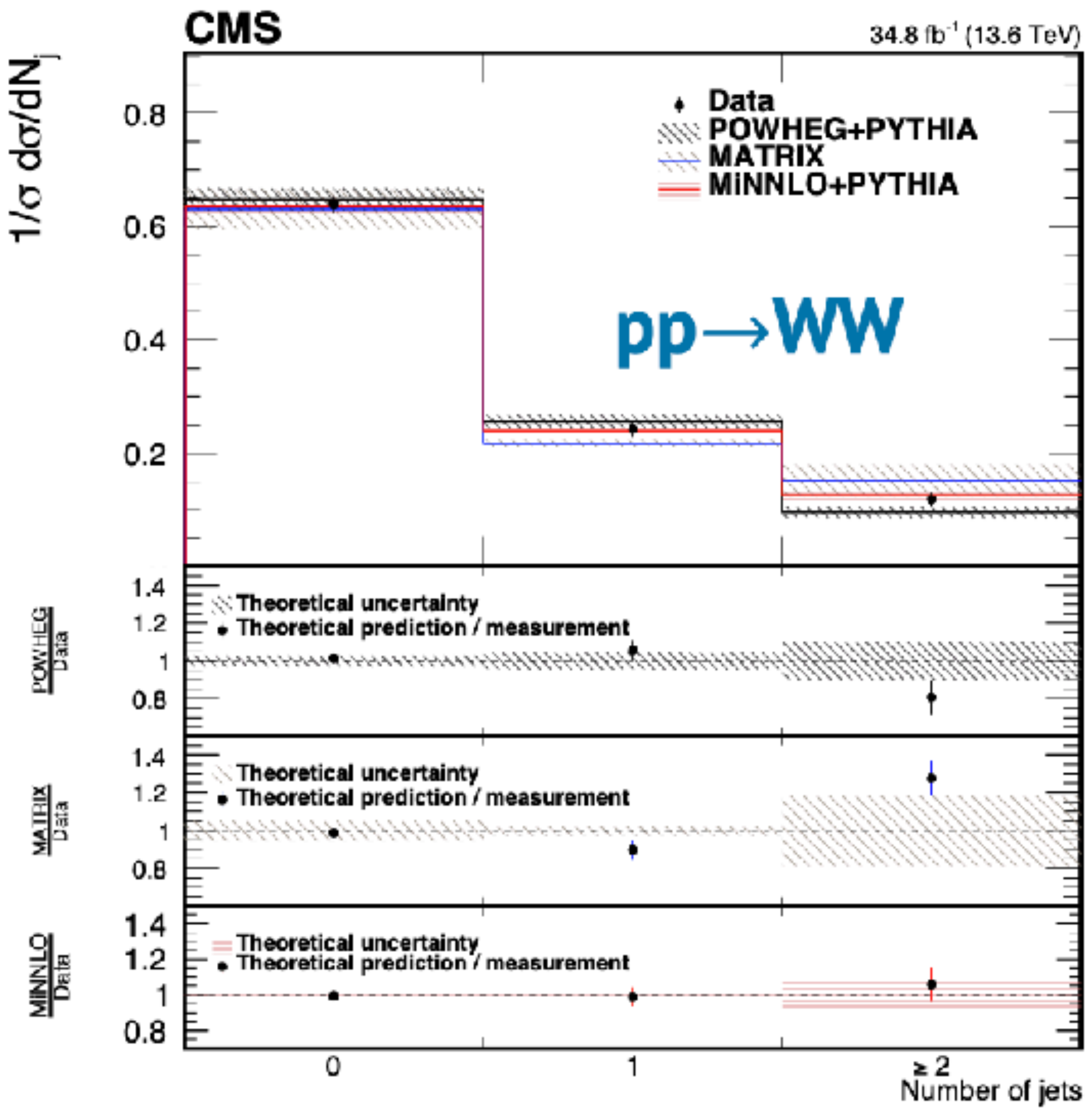
Before discussing the tension of the CDF measurement with the SM, need to address the tension between measurements!

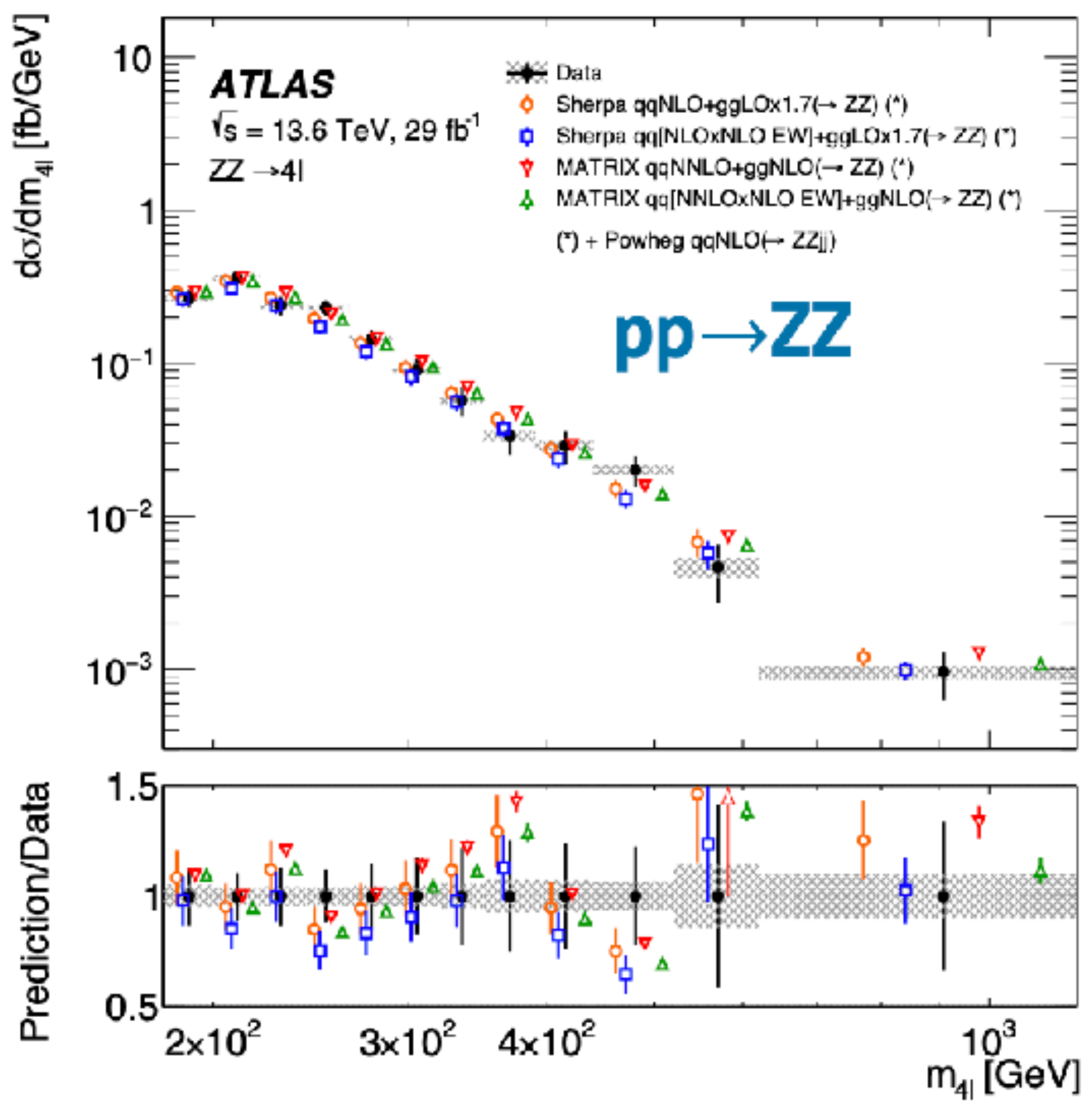
The tension between ATLAS and CDF W mass is of 4σ

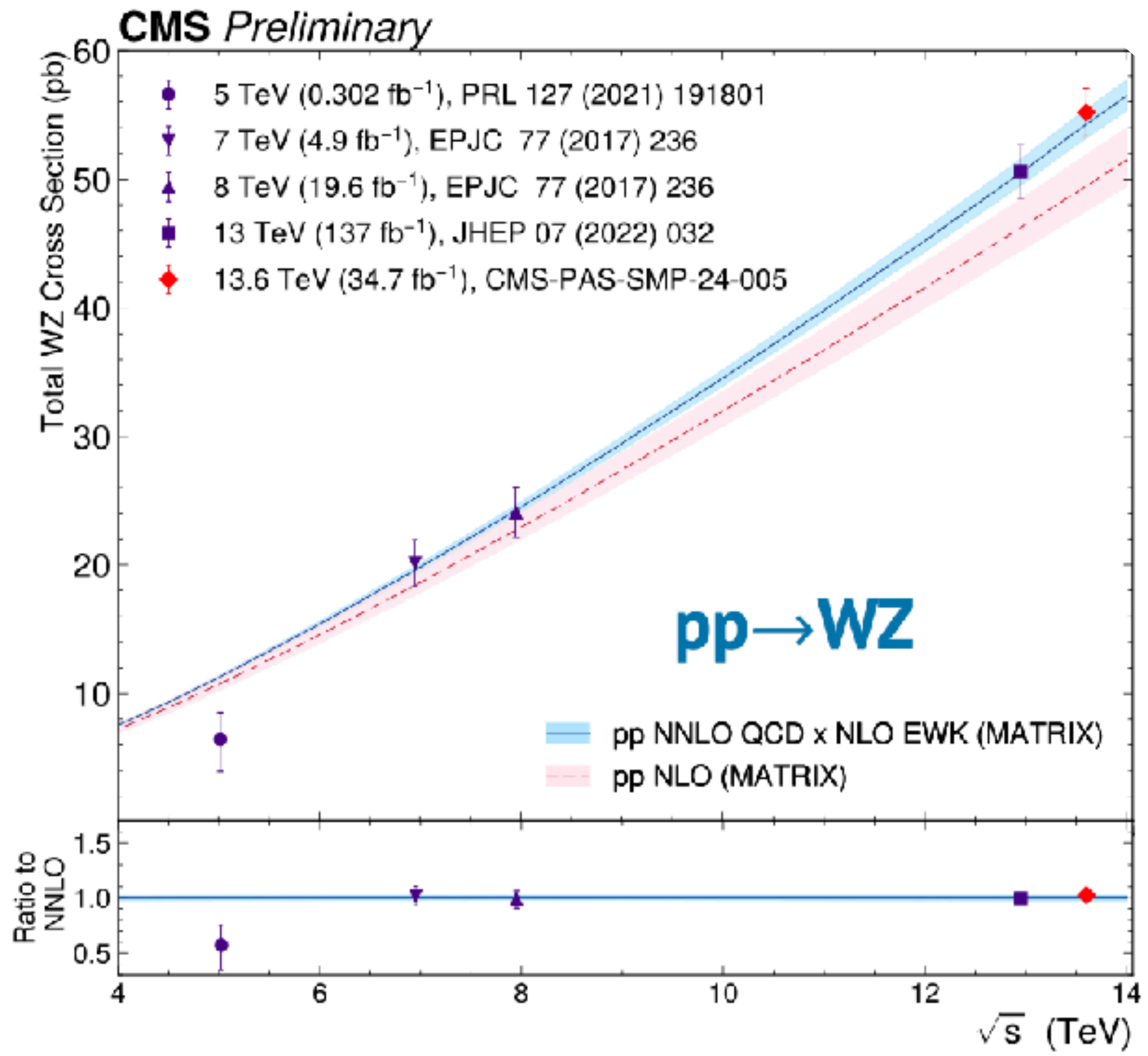
Significant evidence of measurement systematic bias!

First Measurements of di-boson production at Run 3

Monica Dunford, Philip Sommer







First measurements of the diboson processes at Run 3 (with 2022 data)

The Quark Sector - Top Entanglement

Maurizio Pierini, Didar Dobur

In top pair production at the LHC, top quarks are **not produced polarised,** however a **spin correlation** exists.

At threshold the $gg \to t\bar{t}$ production is dominated by the "singlet" spin configuration, **which is a pure, superposed and maximally entangled Bell state**:

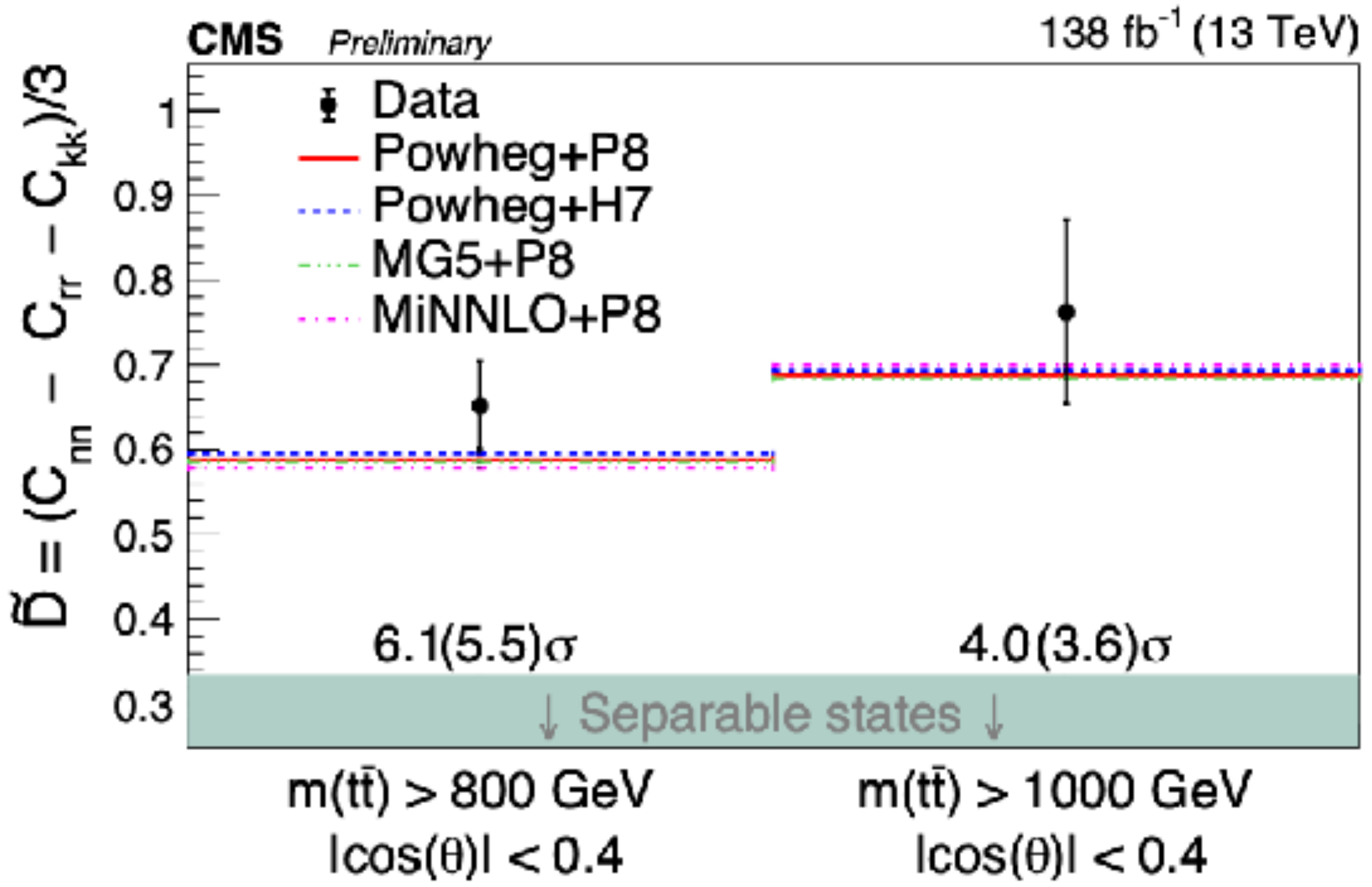
$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow> - |\downarrow\uparrow>\right)$$

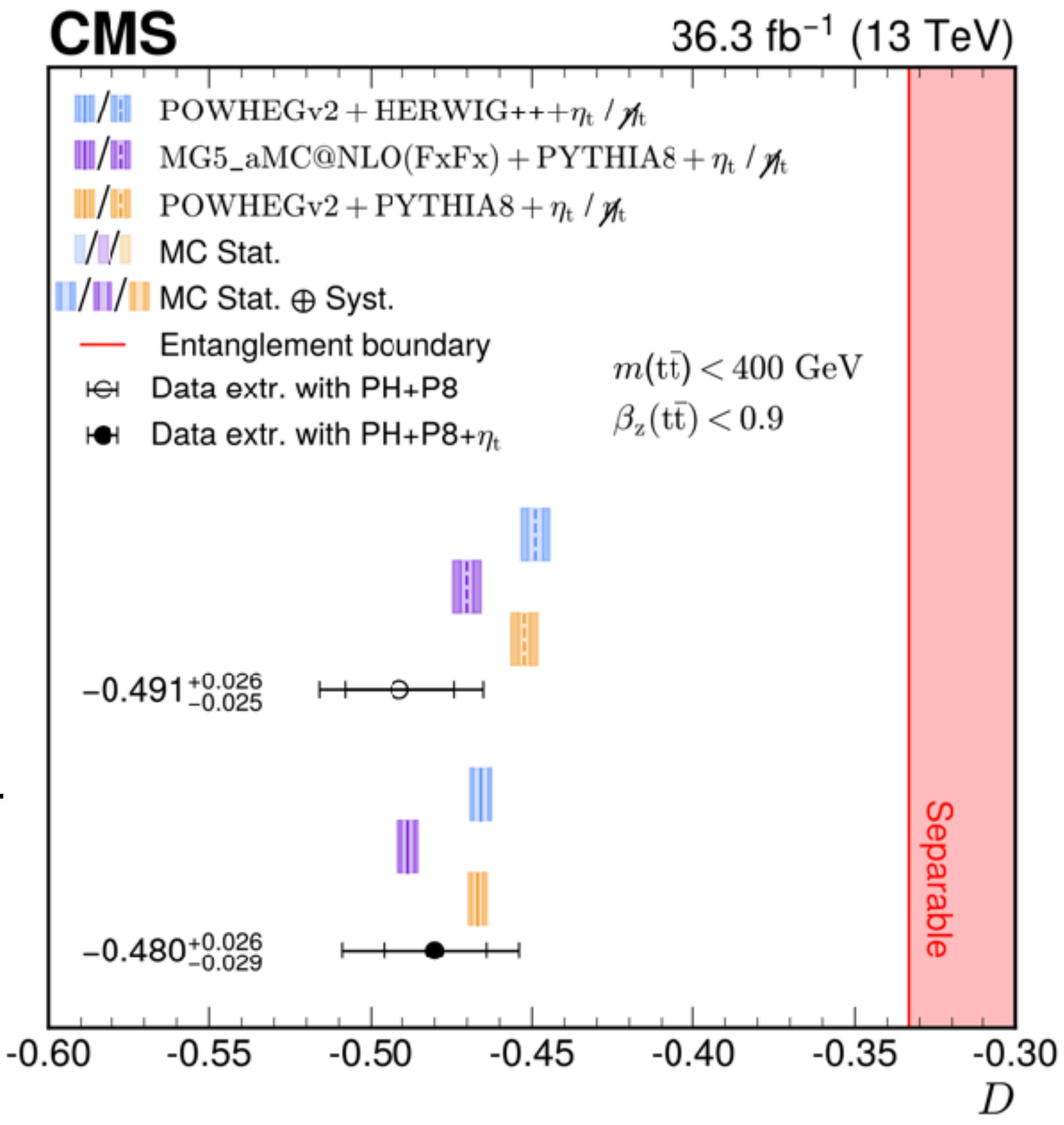
From the measurement of the spin density matrice we can probe whether this correlation is of quantum nature or not!

Initially measured near threshold where it is easier! CMS went beyond with:

- At production threshold in $t\bar{t} \to b\ell\nu b\ell\nu$ events

- At high m_{tt} with $t\bar{t} \to b\ell\nu bq\bar{q}$ events, (phase space dominated 90% by space-like events)



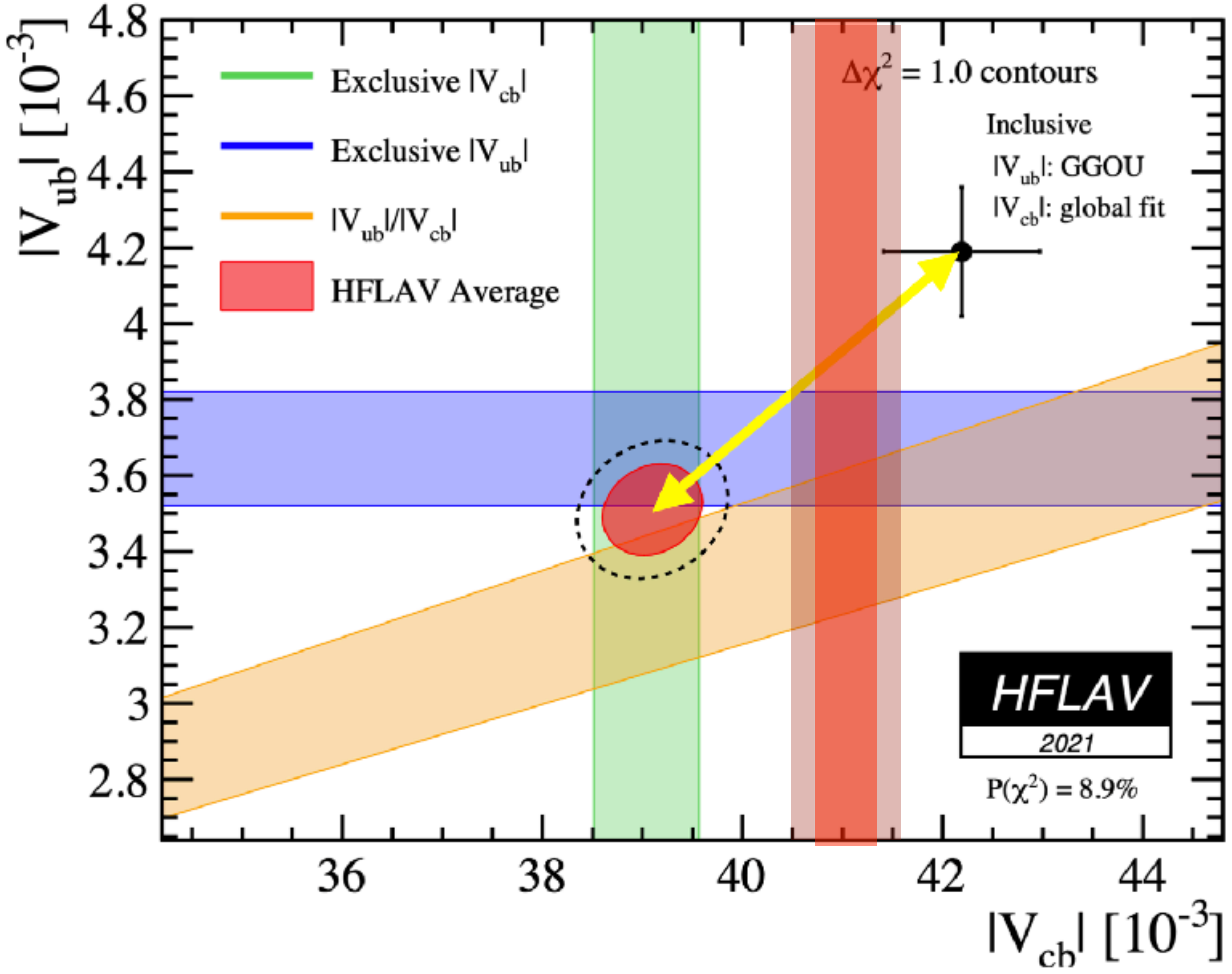


Very important elements (space-like) to go beyond entanglement towards the **violation of Bell Inequalities!** (With higher sensitivity)

The Vub and Vcb Puzzle

New measurements from Belle II and Babar

$|V_{cb}|$ and $|V_{ub}|$ discrepancy~3σ between exclusive and inclusive (have different TH uncertainties)!



Limiting factor in precision flavour physics!

Inclusive extraction from $B \to X_c \ell \nu$, where X_c goes to anything (Bernlochner et al. and Bordone et al.).

New exclusive |Vcb| results from BaBar and Belle II using fully differential information for the first time!

$B \to D \ell \nu$

$$|V_{cb}| = (41.1 \pm 1.2) \times 10^{-3}$$

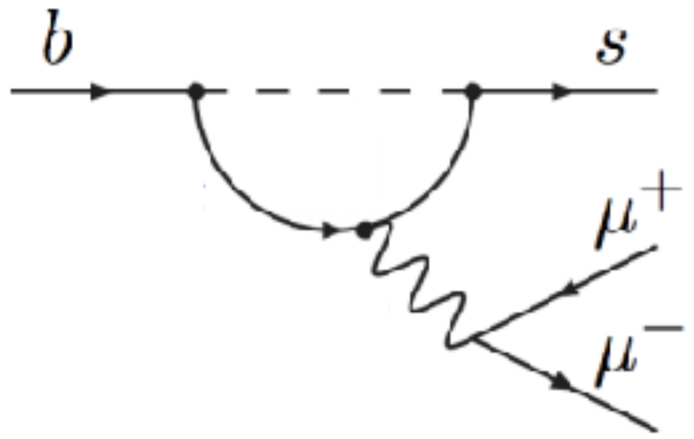
$B \to D^* \ell \nu$

$$|V_{cb}| = (41.0 \pm 0.7) \times 10^{-3}$$

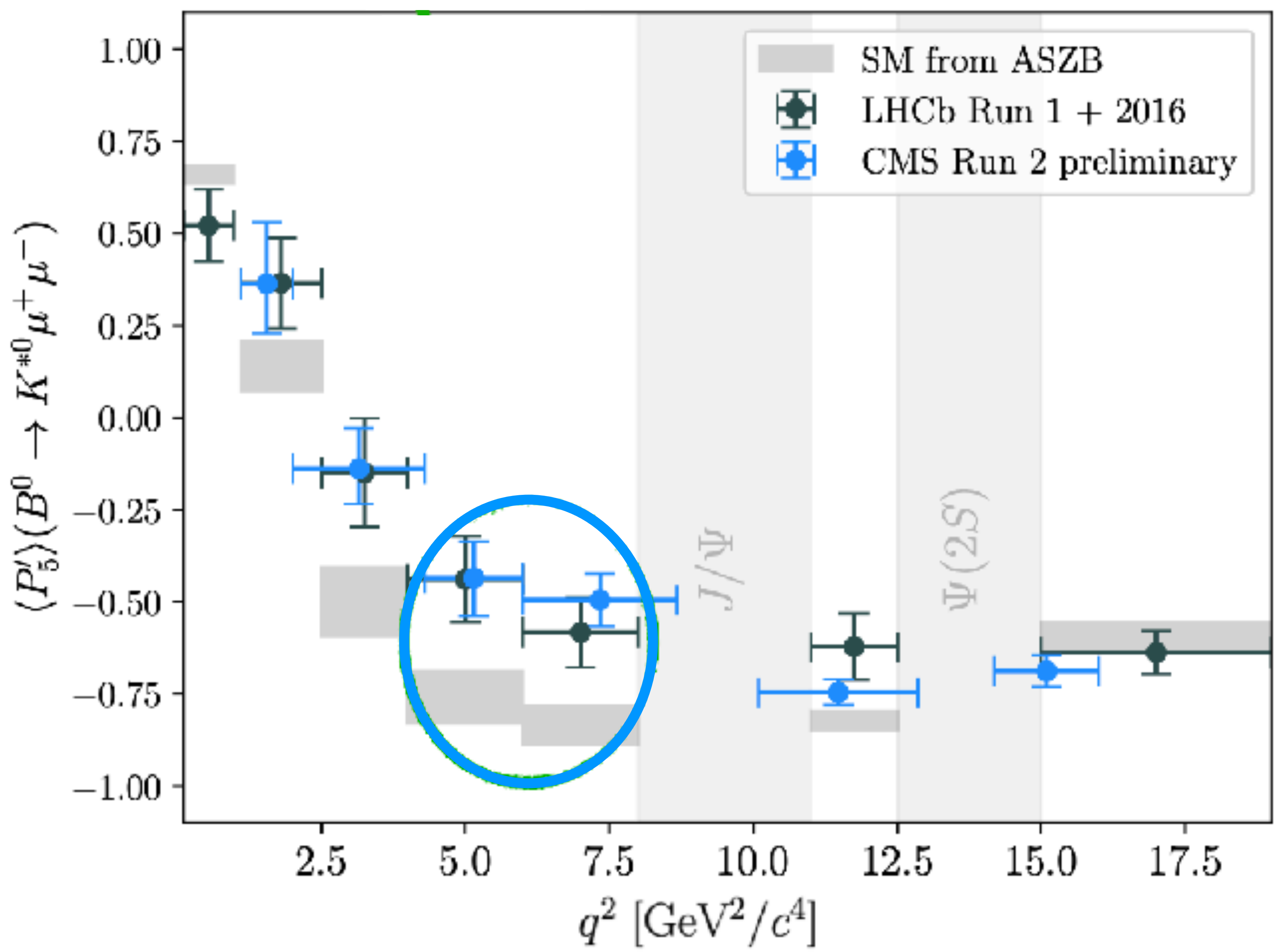
"Perhaps on the right path to resolve this puzzle"

RK* from LHCb cancelled end of 2022

Still a 2-3 Standard Deviation in the angular distribution and absolute branching fractions of $B^0 \to K^{0*}\mu^+\mu^-$ (paper)



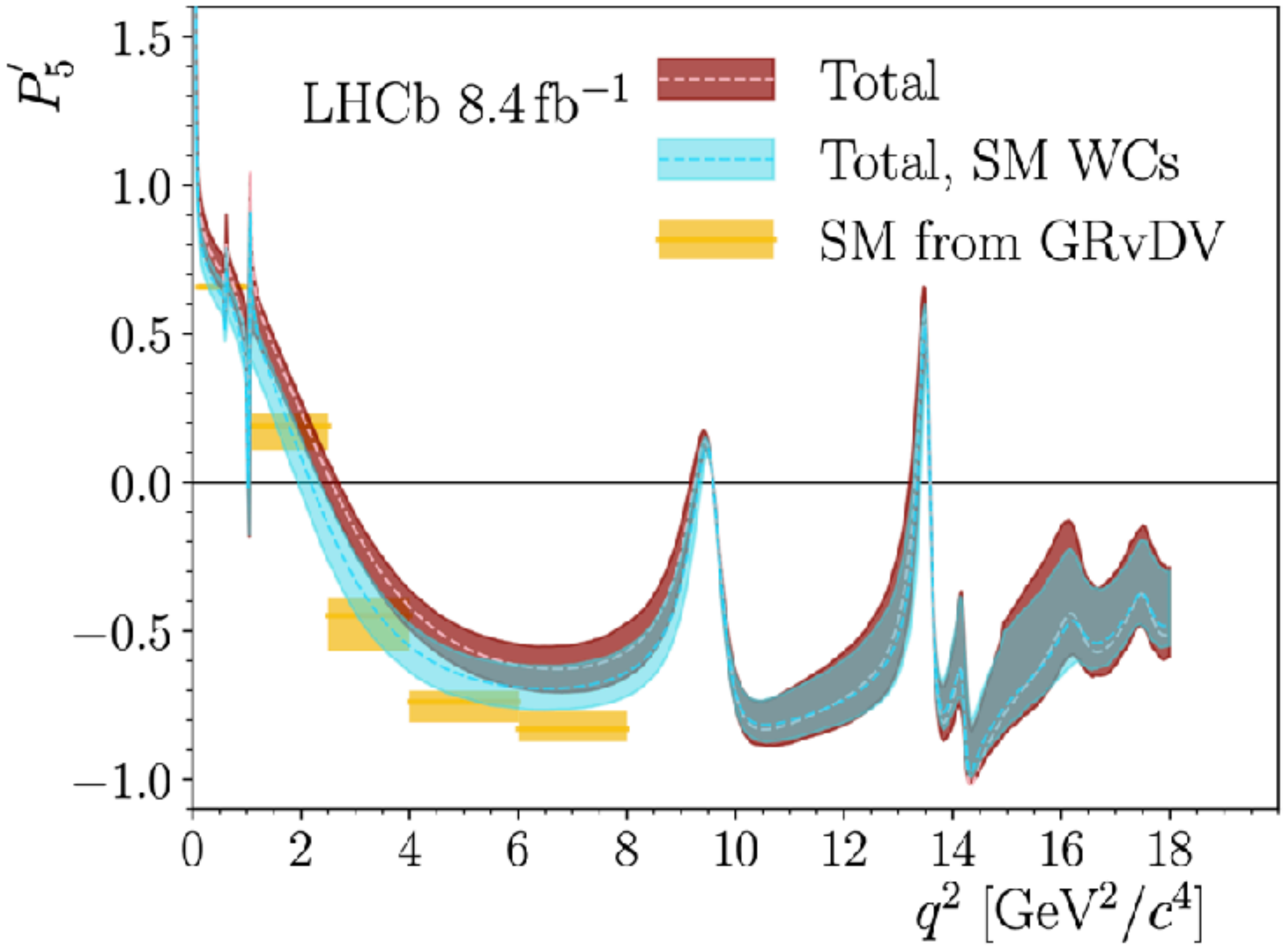
$B^0 \to K^{0*}\mu^+\mu^-$ **also from CMS**



P'$_5$ angular observable essentially free from form factor uncertainties.

Comprehensive analysis of local and nonlocal amplitudes $B^0 \to K^{0*}\mu^+\mu^-$ (paper)

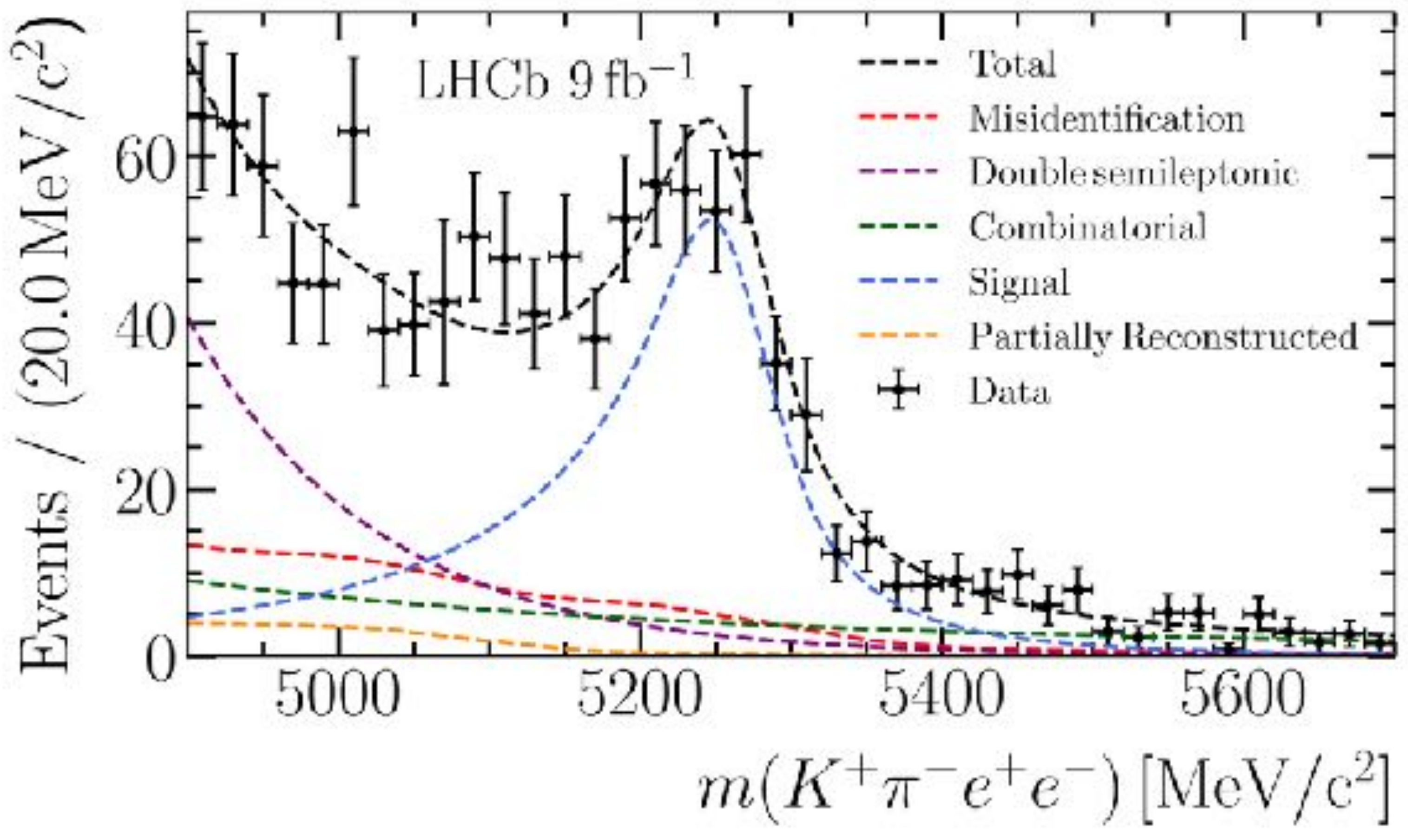
Careful long-distance contributions weaken these tensions are not considered

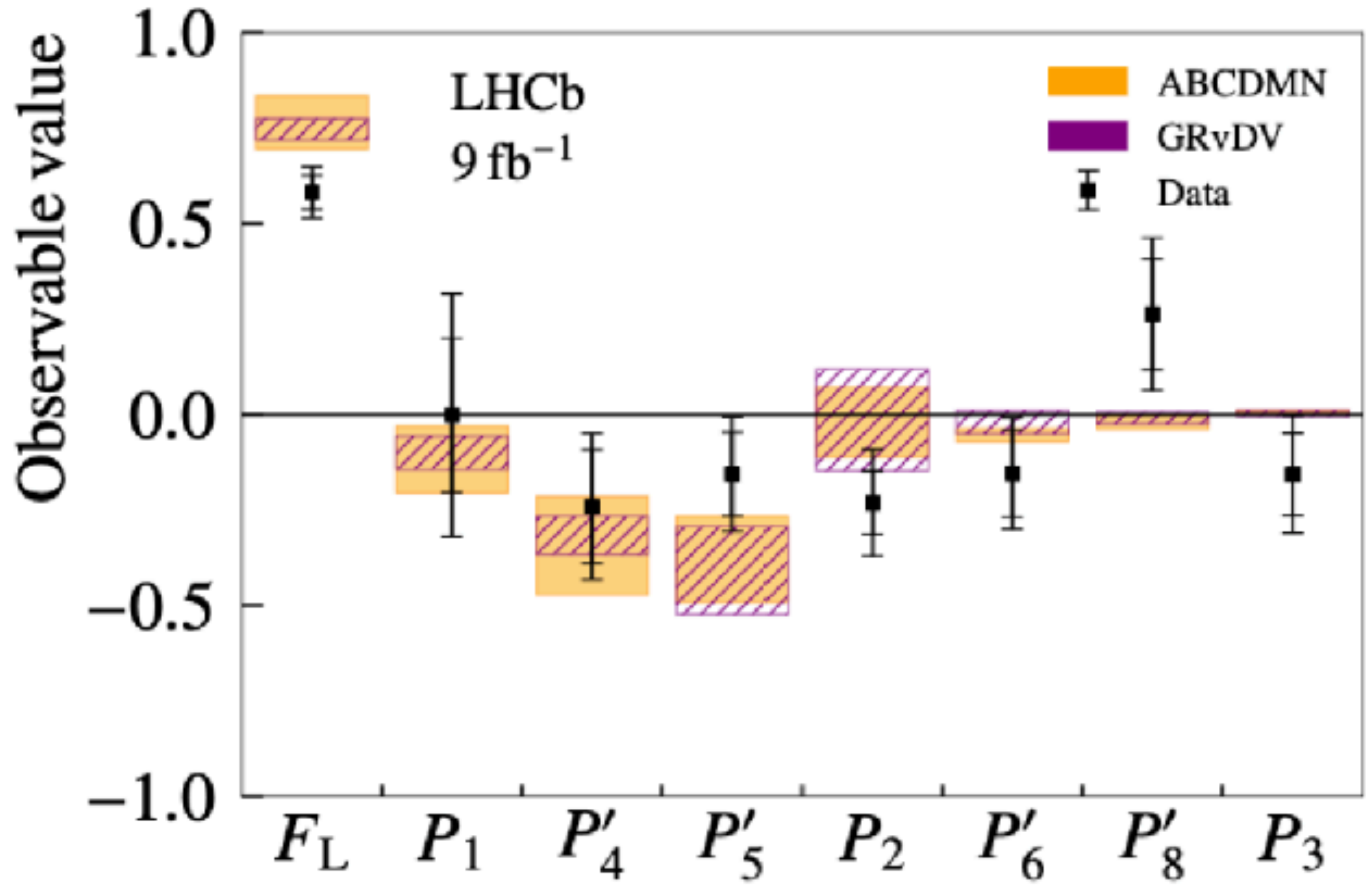


Tension now down to 2.1σ

Lepton Flavour Universality

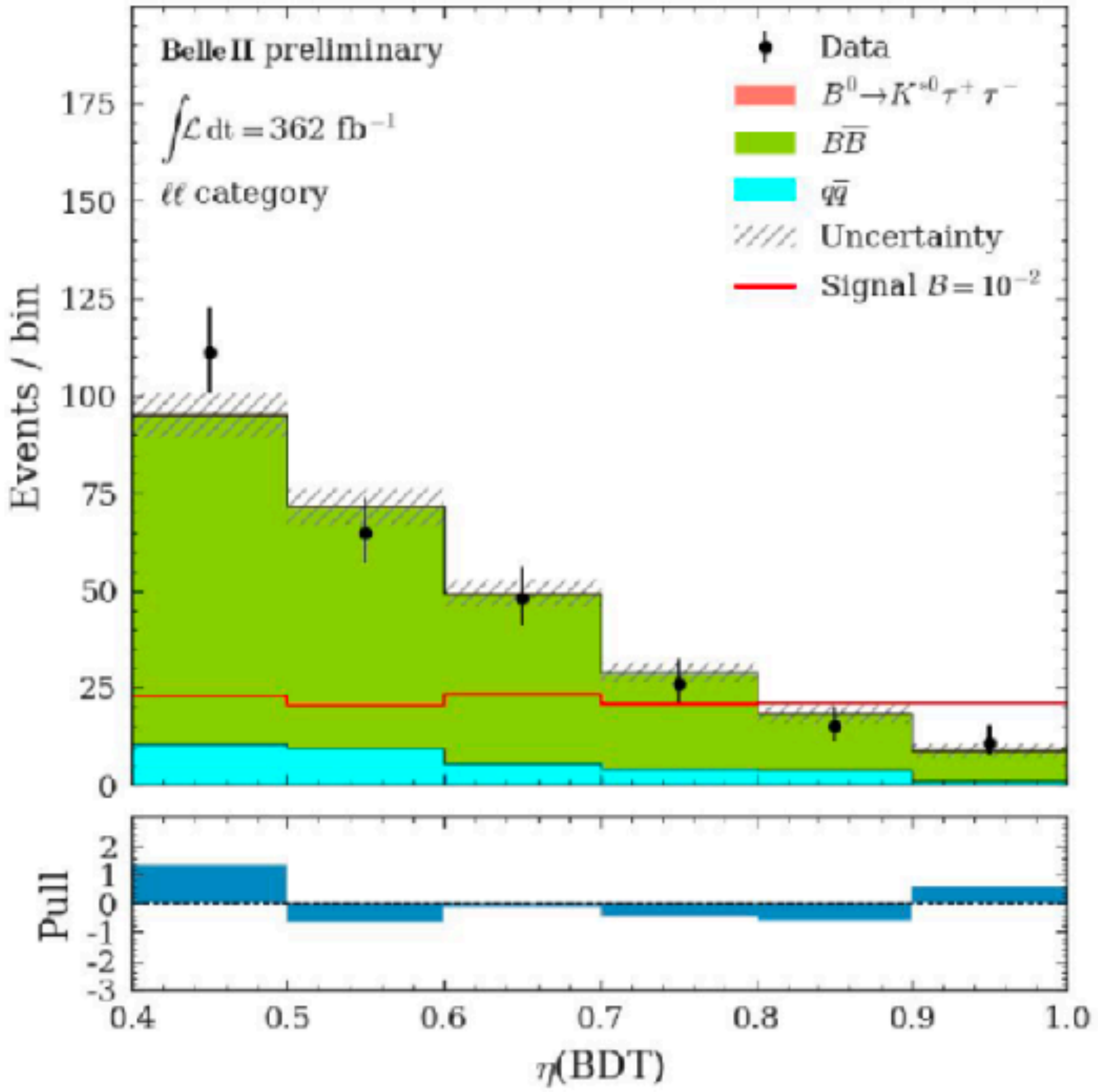
New $B^0 \to K^{0*}e^+e^-$ measurement from LHCb





New $B^0 \to K^{0*}\tau^+\tau^-$ measurement from Belle II

Analysis particularly sensitive to new physics affecting the $B^0 \to K^{0*}\mu^+\mu^-$ decay!



$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.73 \times 10^{-3}$$

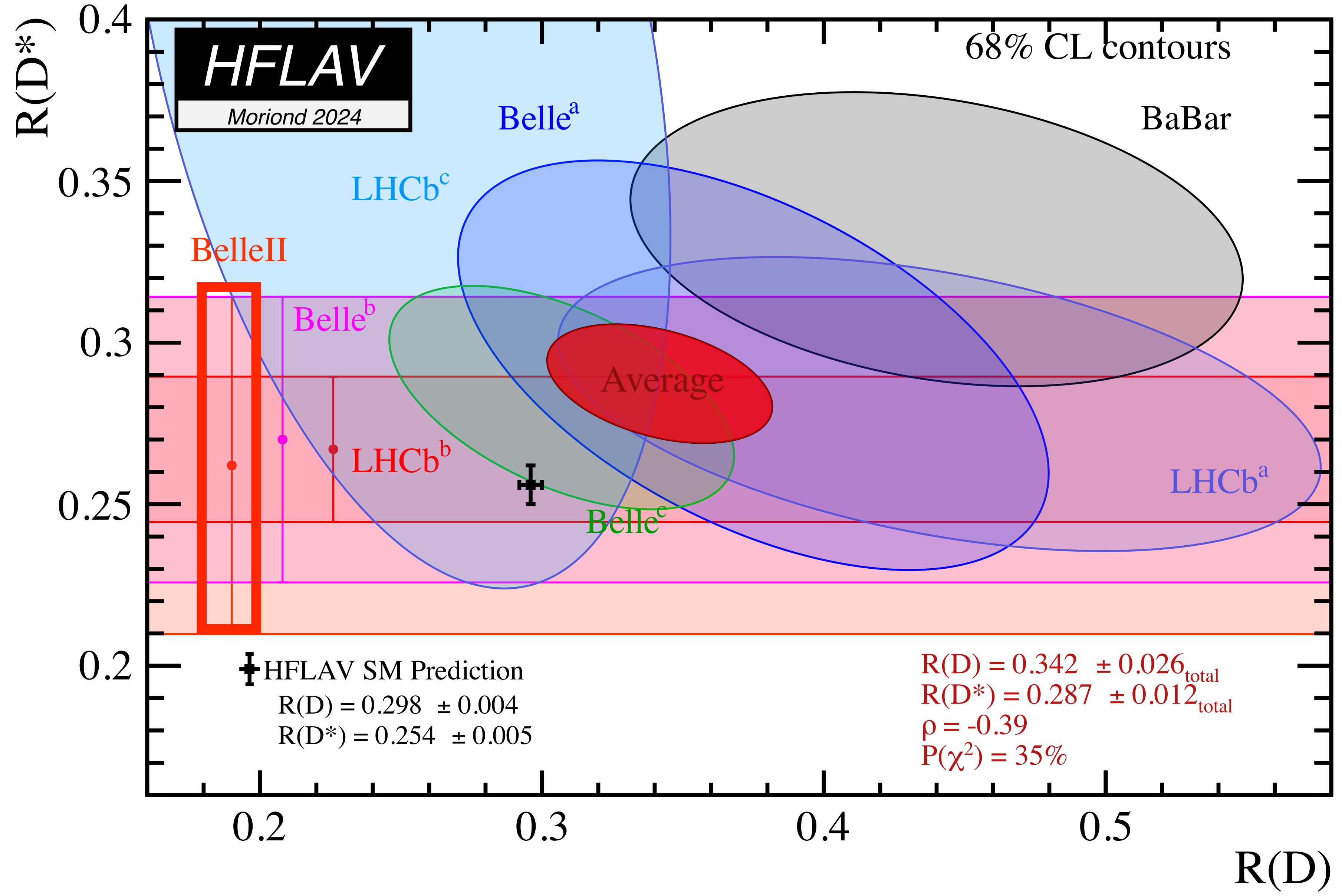
Limit twice improved over the Belle result!

Lepton Flavour Universality

First Belle II RD* measurement!

Both TH and EXP clean!

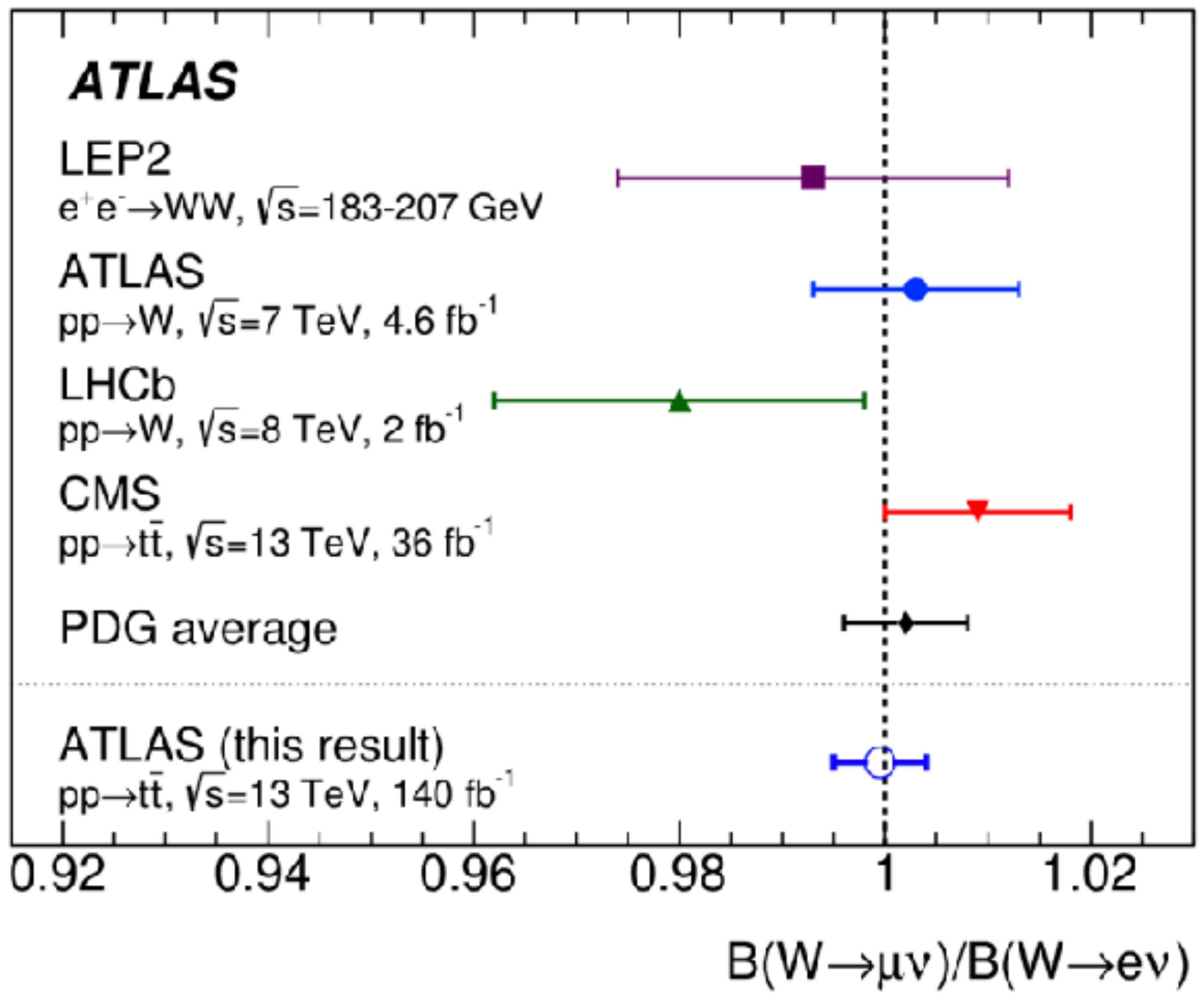
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$



$$R_D^* = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

- Systematic uncertainty related mainly to size of control samples
- Comparable precision to equivalent Belle result with 1/4 the sample

Lepton universality measurements for “on-shell” W bosons in top decays



ATLAS result more precise than current world average

Also with W decays from tops CMS measures |Vcs| !

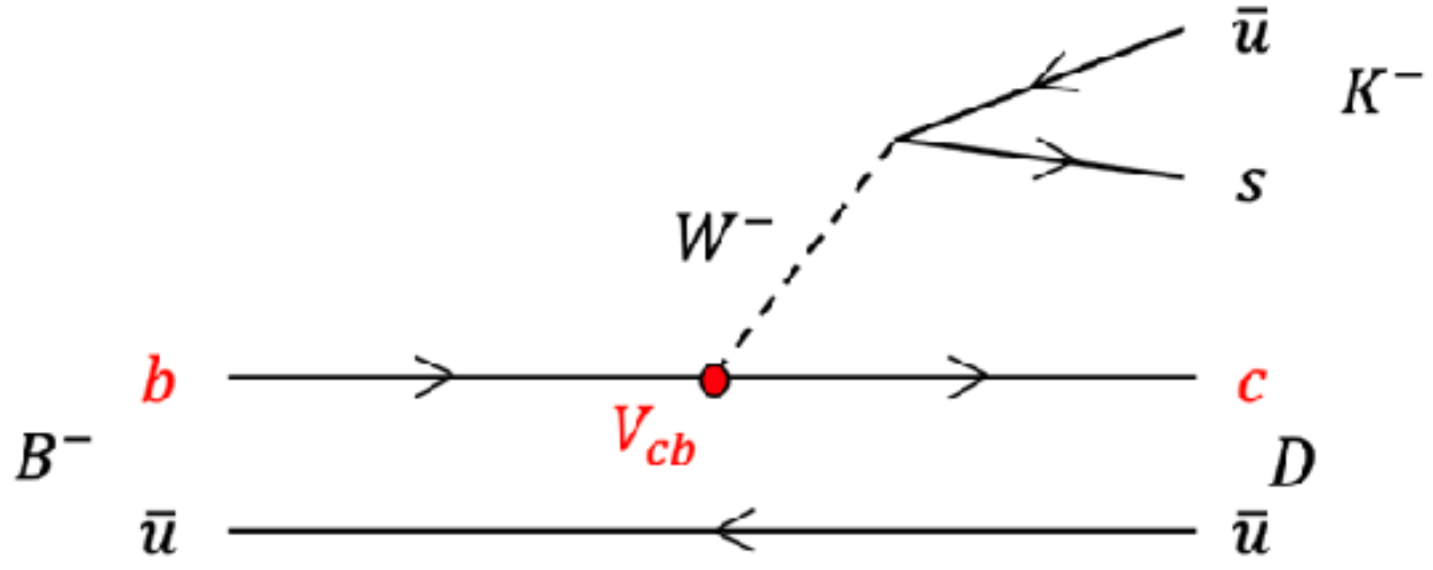
$$R_W^c = \frac{\mathcal{B}(W \to cq)}{\mathcal{B}(W \to cq)\mathcal{B}(W \to ud)} \qquad |V_{cs}| = 0.959 \pm 0.021$$

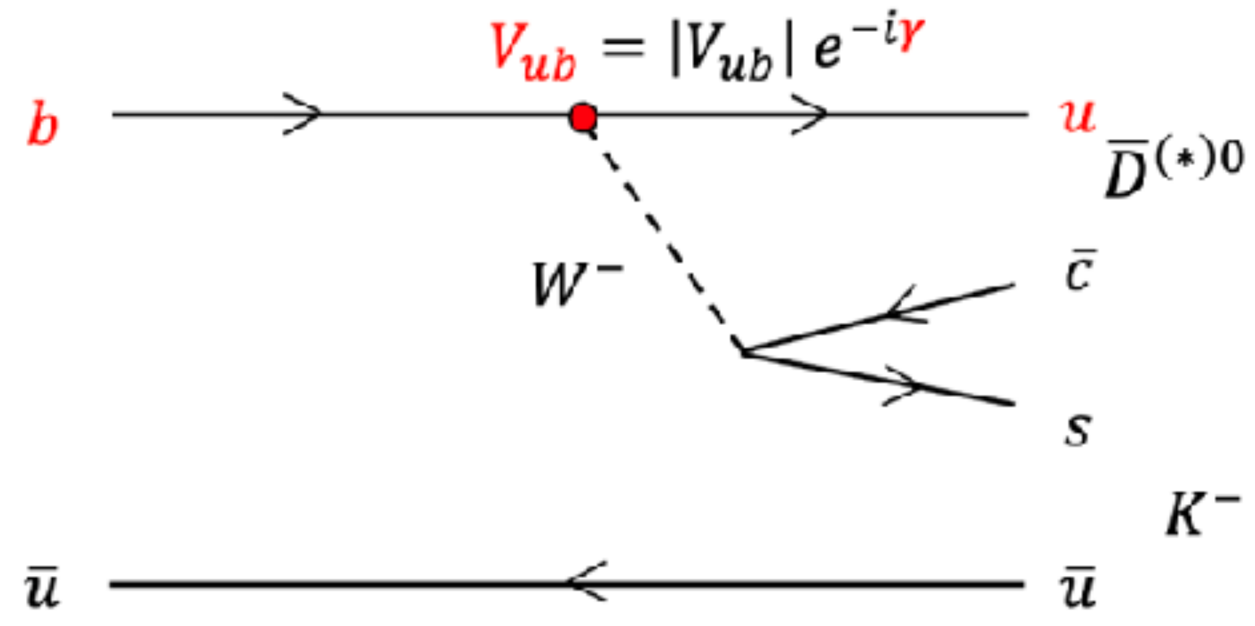
Latest CKM γ News (Belle II - LHCb)

Sneha Malde, Alakabha Datta

Recent Measurements of γ in the golden channel $B^{\pm} \to DK^{\pm}$

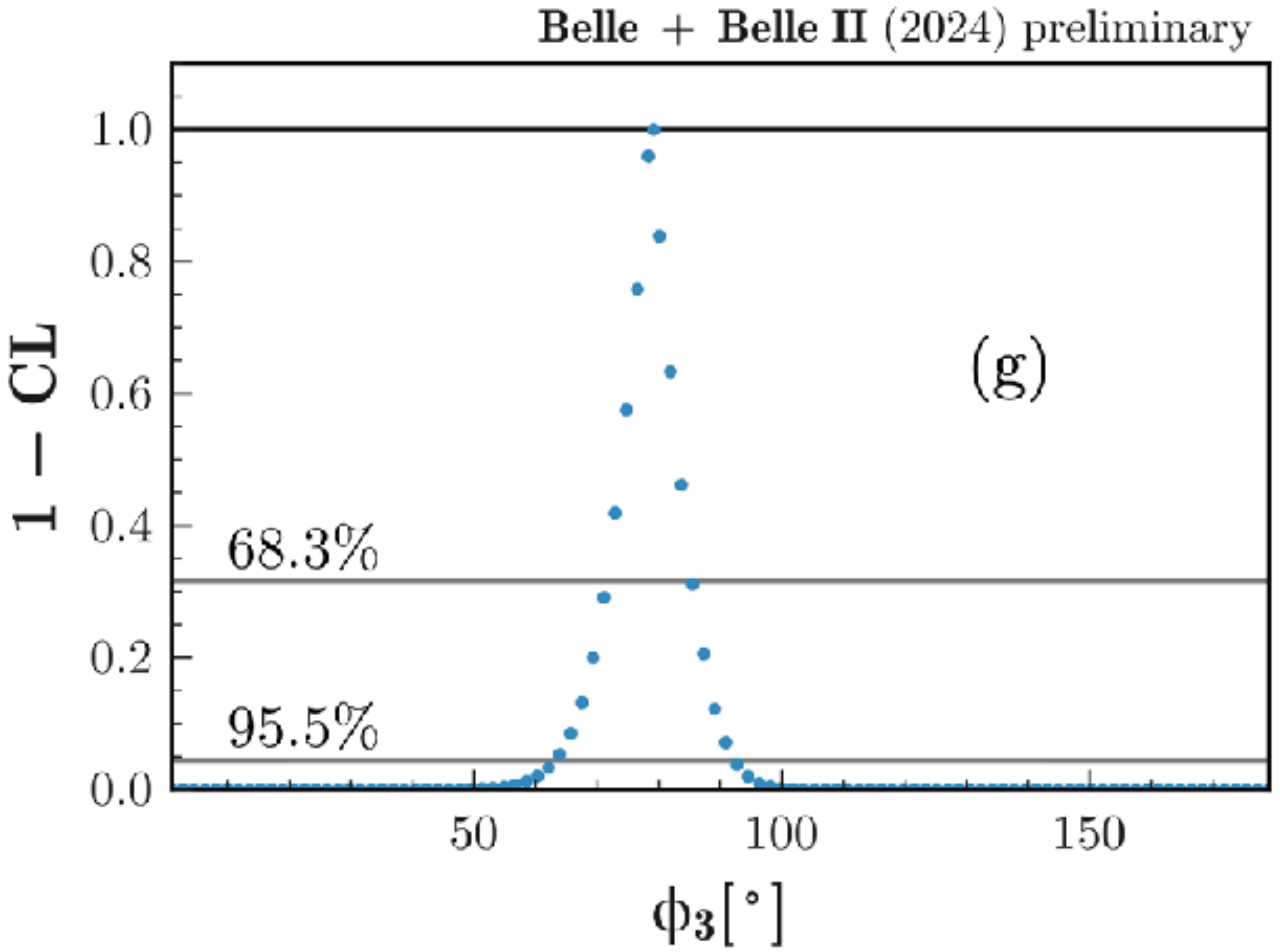
$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



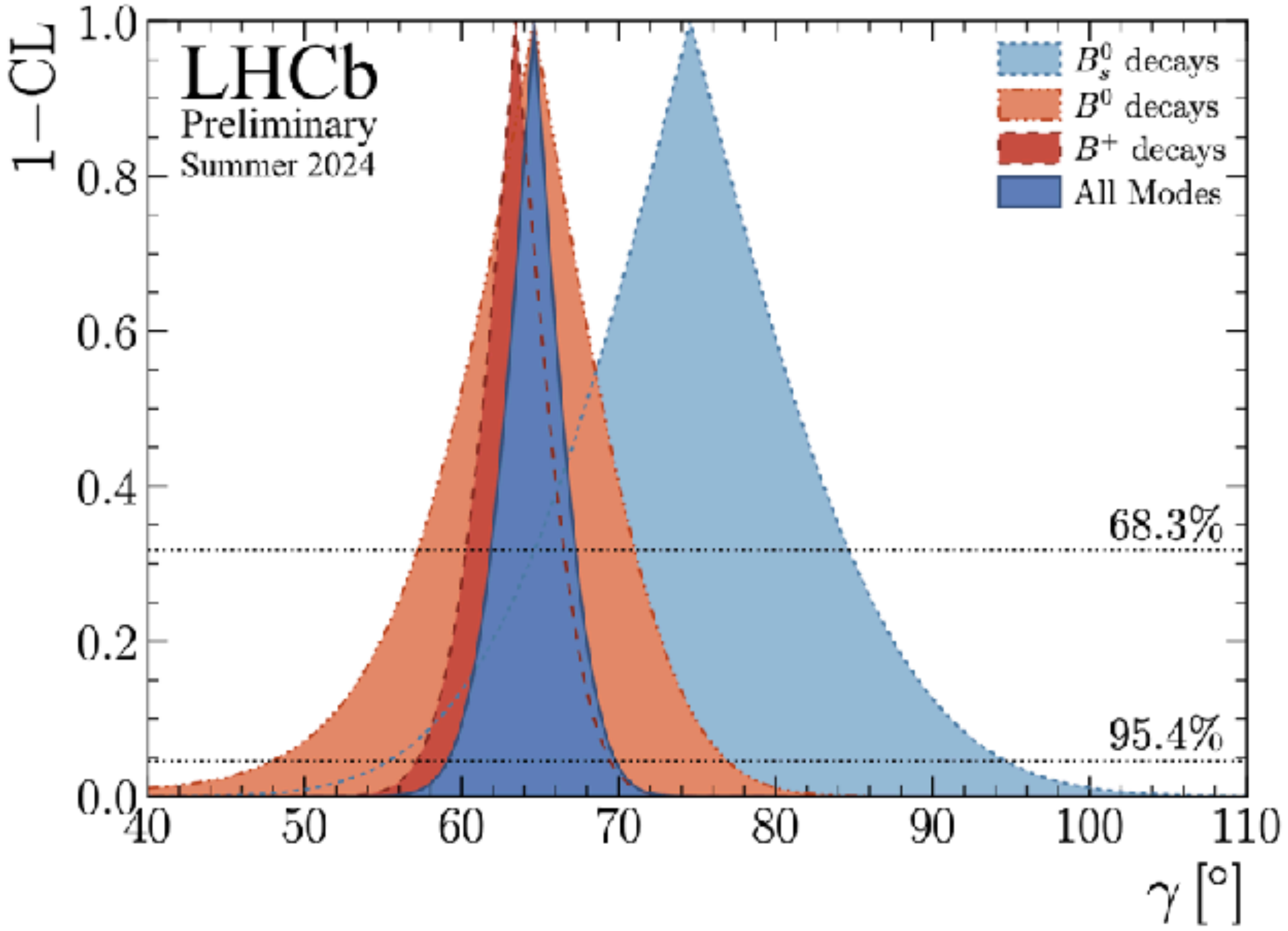


Lack of Lattice QCD needs makes it a "**pristine observable**" in flavour physics!

Charm input from BESIII/CLEO is critical



New for ICHEP 2024



Combination from Belle II

$$\gamma = (78.6^{+7.2}_{-7.3})^o$$

Combination from LHCb!

$$\gamma = (64.7 \pm 2.8)^o$$

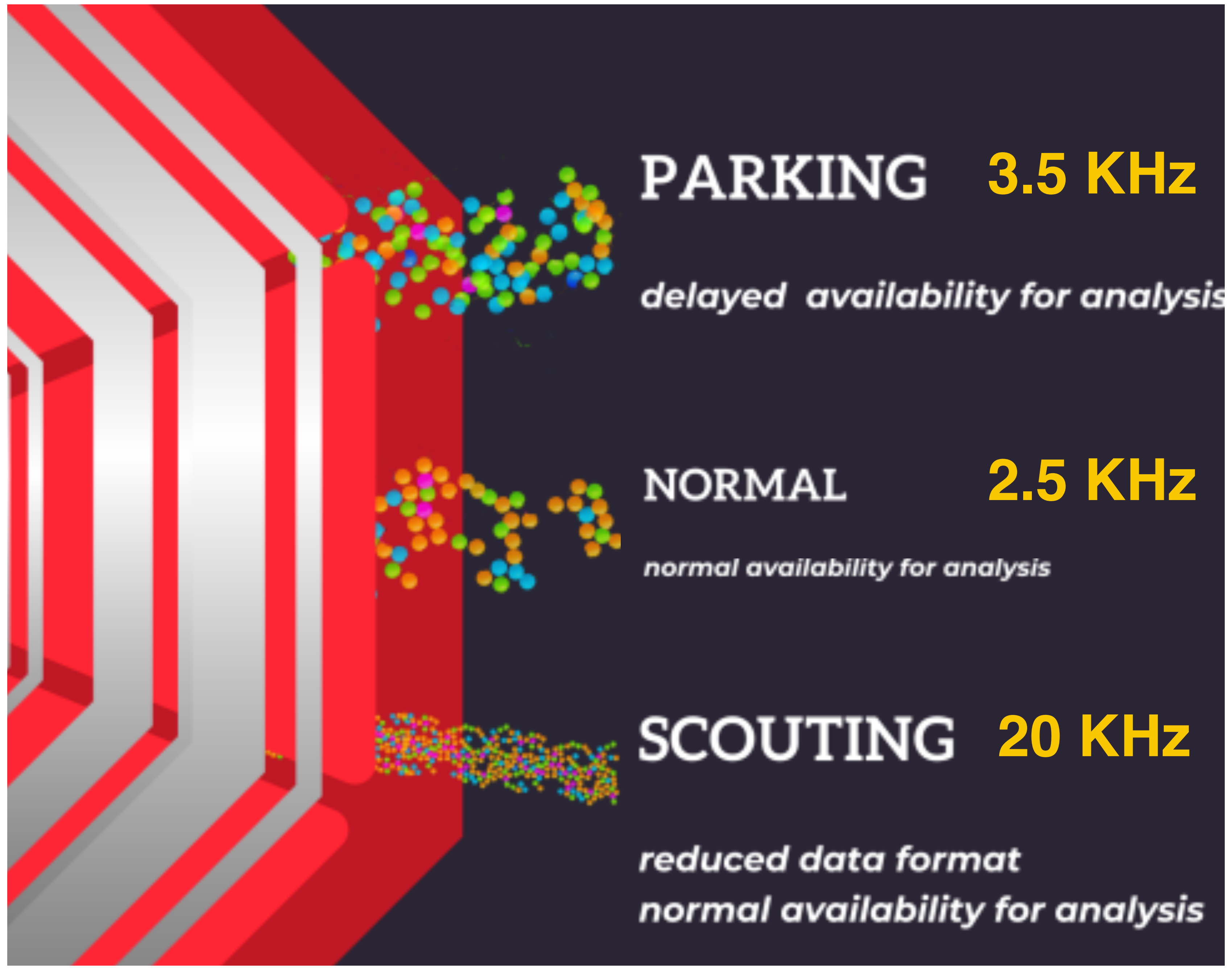
Measurement from LHCb has surpassed the target goal for Run 2!!

From CKM fitter $\gamma = (66.3^{+0.7}_{-1.9})^o$

Scouting, Parking and Trigger Improvements

Maurizio Pierini, David Rohr, Javier Duarte

CMS-EXO-23-007

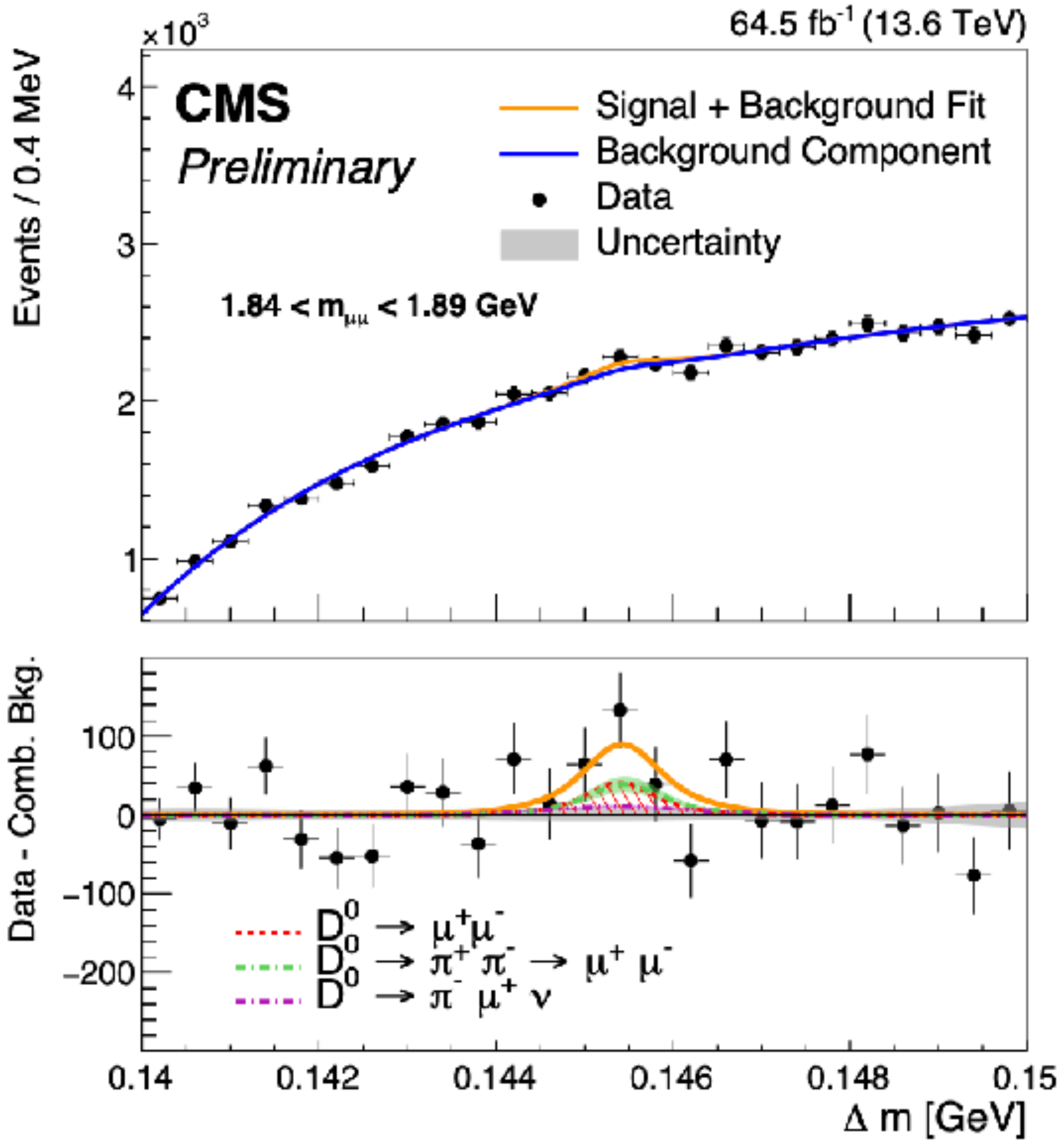


First Results using Run3 Parking

Search for $D^0 \rightarrow \mu^+\mu^-$ - improved by 35% over previous best limit

Further improvements foreseen!

CMS-BPH-23-008



NexTGen Next Generation Triggers

Large scale project to support the developments (with powerful hardware and software) to bring experiments to the next level with efficient data flows and structures, with ambitious and large ML models e.g. GNN tracking!

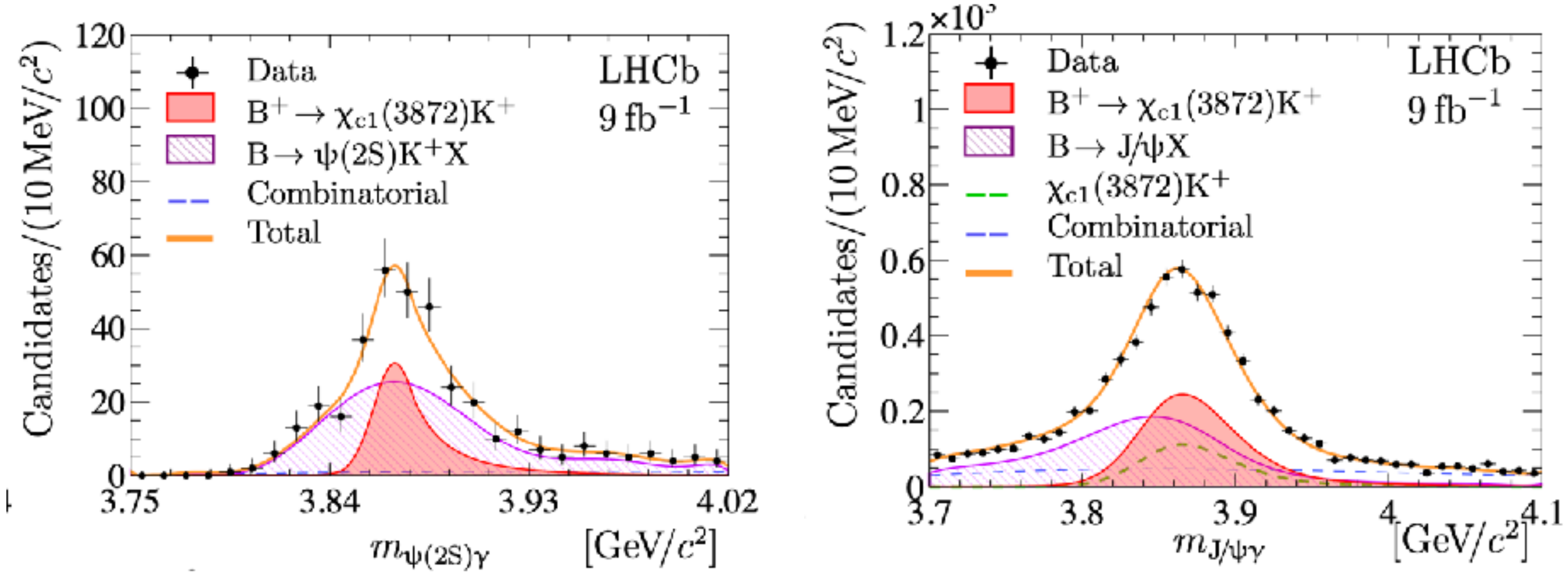
See talk by D. Rohr

Focus on New States

Observation of $\chi_c(3872)$ radiative decays at LHCb!

$\chi_c(3872)$ discovered 20 years ago, could it be D meson molecular state?

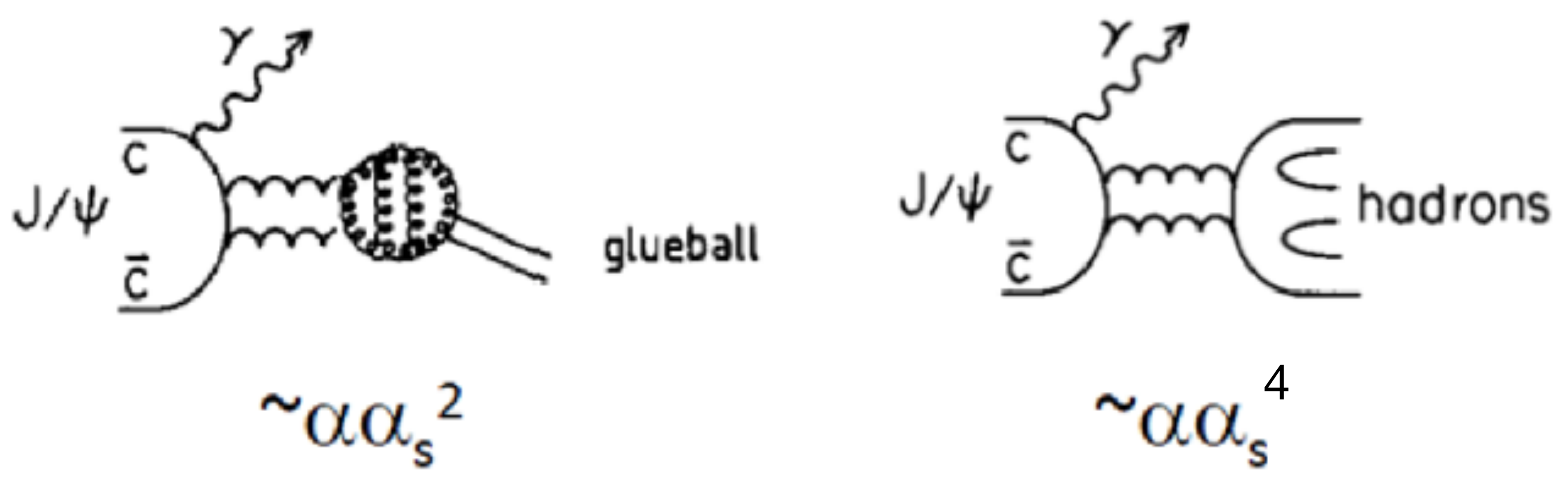
Now, the LHCb collaboration is closer to finding out what it is made up of!



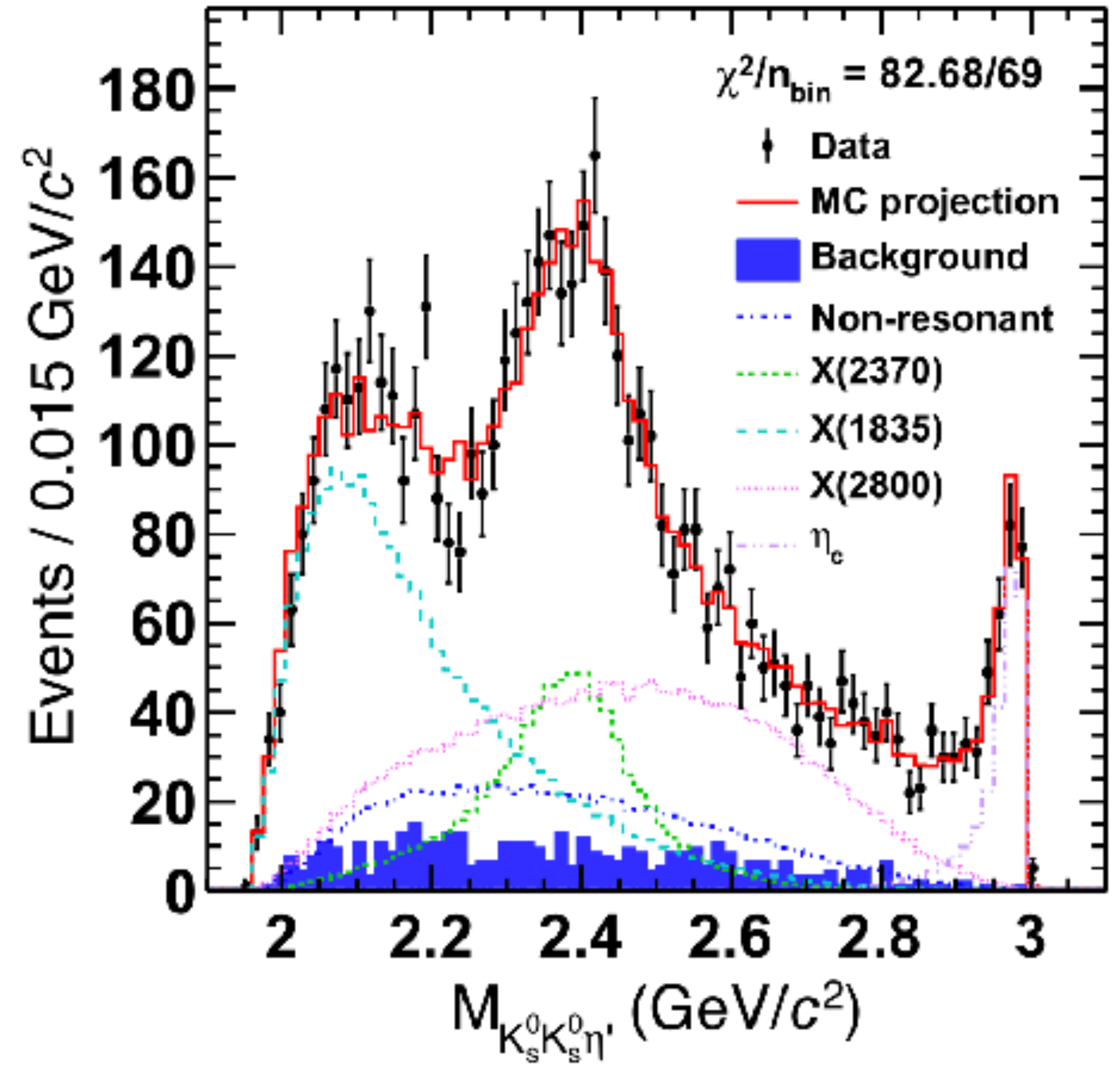
$$\mathscr{R}_{\psi\gamma} = \frac{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,.$$

Strong indication of a sizeable charmonium or tetraquark compact component of the X(3872)!

Discovery of a Glueball-like particle X(2370) at BESIII



Radiative J/ψ decays are gluon rich!

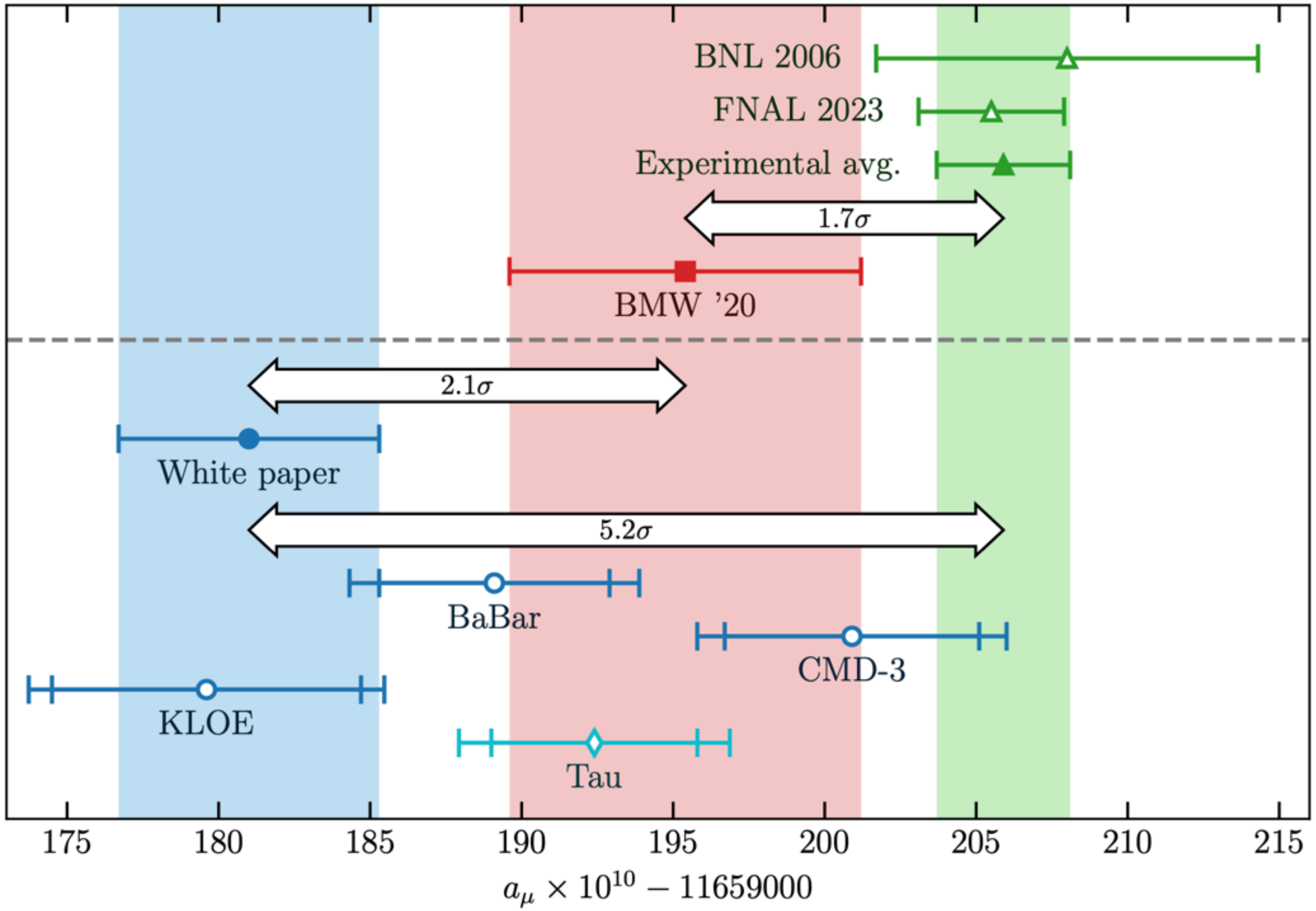


Candidate for elusive lightest pseudoscalar glueball predicted by LQCD

The Charged Lepton Sector

Toru Lijima, Bogdan Malaescu, Zoltan Fodor

Several important news from the front of $(g_\mu - 2)$ predictions from BaBar and Lattice in conjunction with data!



Scanning e+e– →π+ π – ECM = 0.32-2 GeV
CMD-3 at VEPP-2000 e+e- collider

Better detector performance Larger statistics (x30 CMD-2)

Muon Anomalous Magnetic Moment

Toru Lijima, Bogdan Malaescu, Zoltan Fodor

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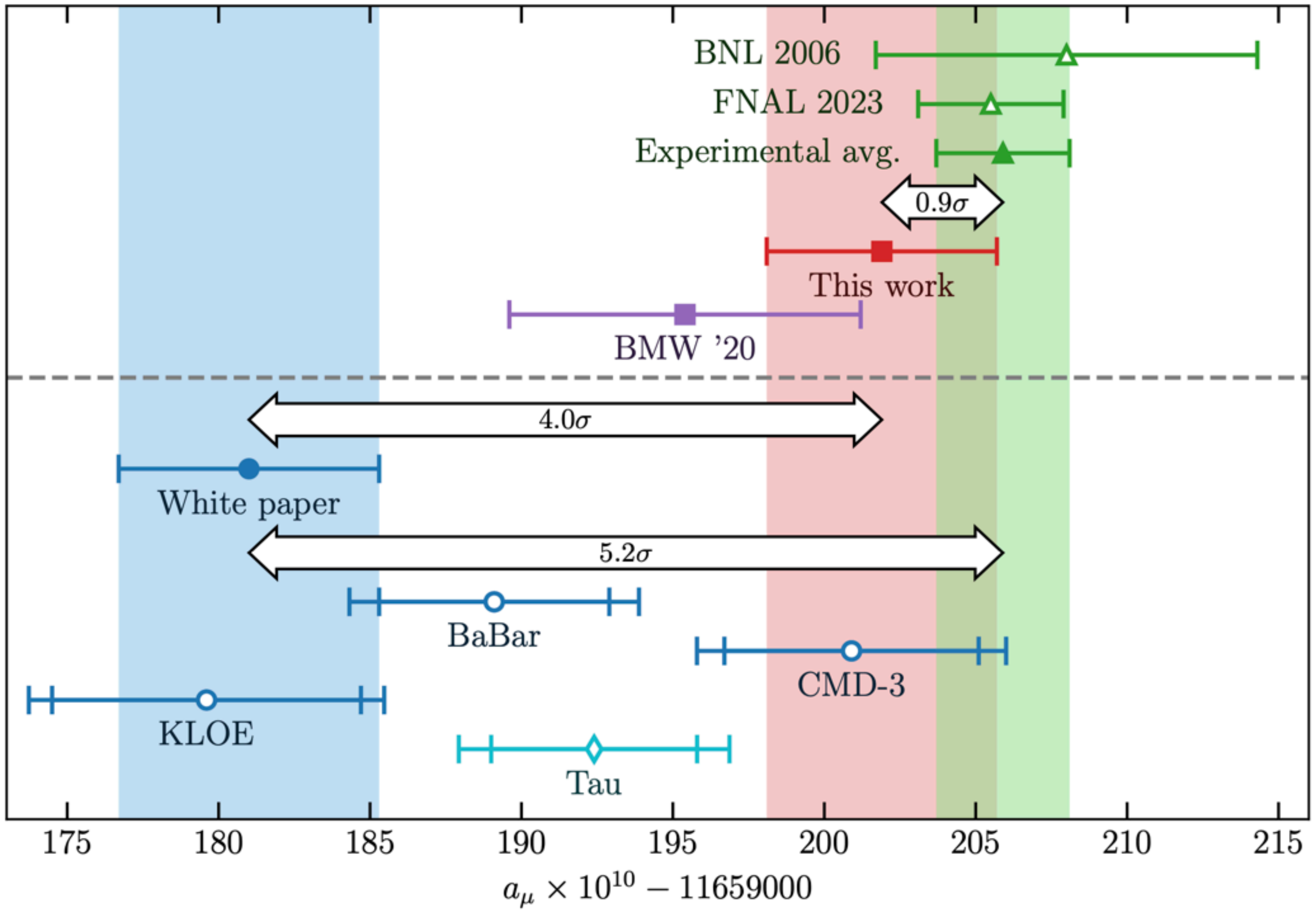


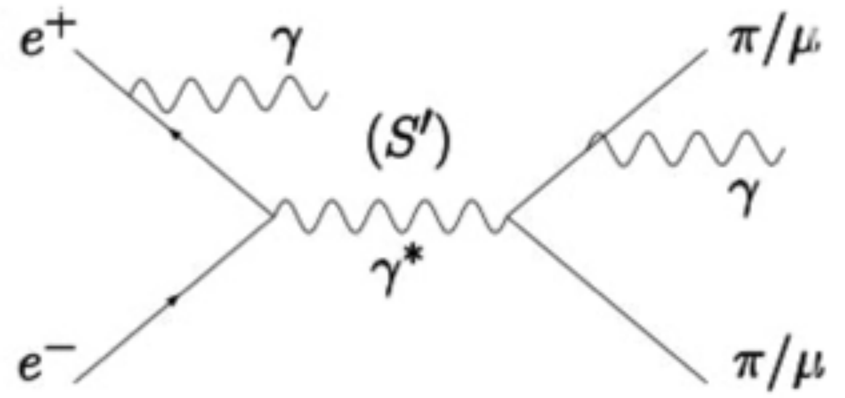
Scanning e+e– →π+ π – ECM = 0.32-2 GeV
CMD-3 at VEPP-2000 e+e- collider

Better detector performance Larger statistics (x30 CMD-2)

New BMW result including finer lattice and long distance effects from e^+e^- data!

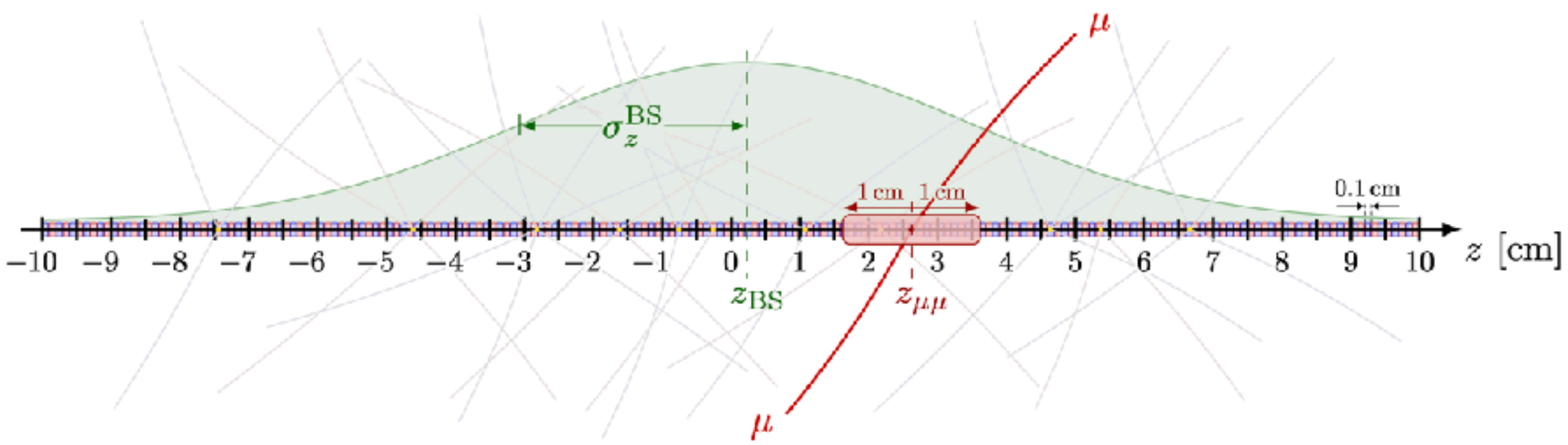
New BaBar studies of higher order radiation and impact on the vacuum polarisation predictions of (g-2)!

NNLO Radiative corrections need to be better understood and accounted in analyses!



Tau Anomalous Magnetic Moments

Toru Lijima, Maurizio Pierini

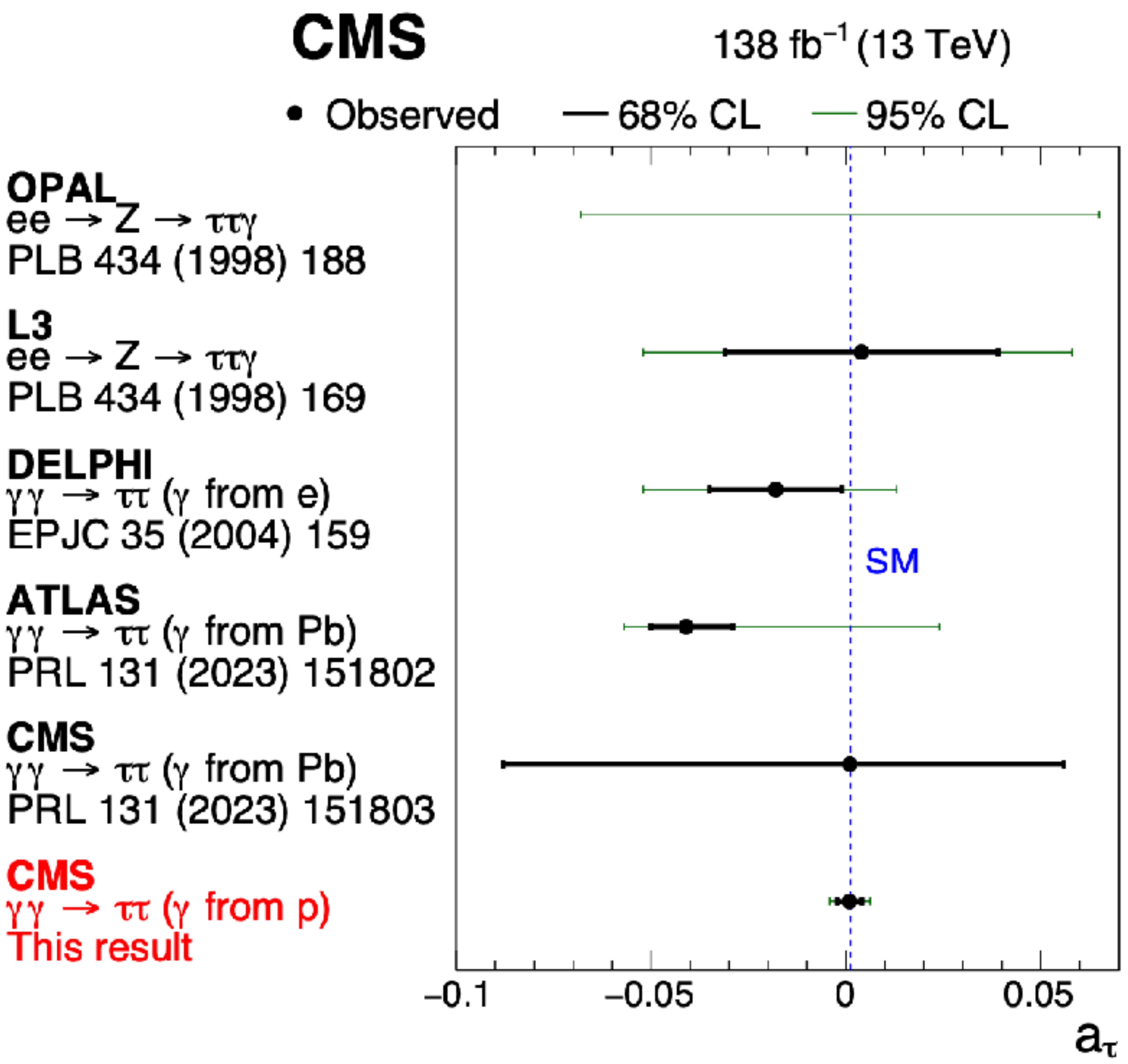


Beautiful analysis selecting isolated low multiplicity vertices, sensitive to photo-production of tau pairs!

Large gain in sensitivity! Only ~3 times larger than the Schwinger term (QED part)

However still almost 3-4 orders of magnitude above sensitive corrections e.g. EW!

$$
\begin{aligned}
a_\tau^{\rm QED} &= 1.1732 \times 10^{-3}, \\
a_\tau^{\rm had} &= 3.2(4) \times 10^{-6}, \\
a_\tau^{\rm EW} &= 4.7 \times 10^{-7}.
\end{aligned}
$$



$$a_\tau = \frac{g_\tau}{2} - 1 = 0.0009^{+0.0032}_{-0.0031}$$

The Neutrino Sector - Entering Precision Era

Accelerator Neutrino Oscillations

The current two main players ν_μ-beam experiments!

NOvA

Off Axis

Fermilab to Ash River

Improved sensitivity to mass ordering!

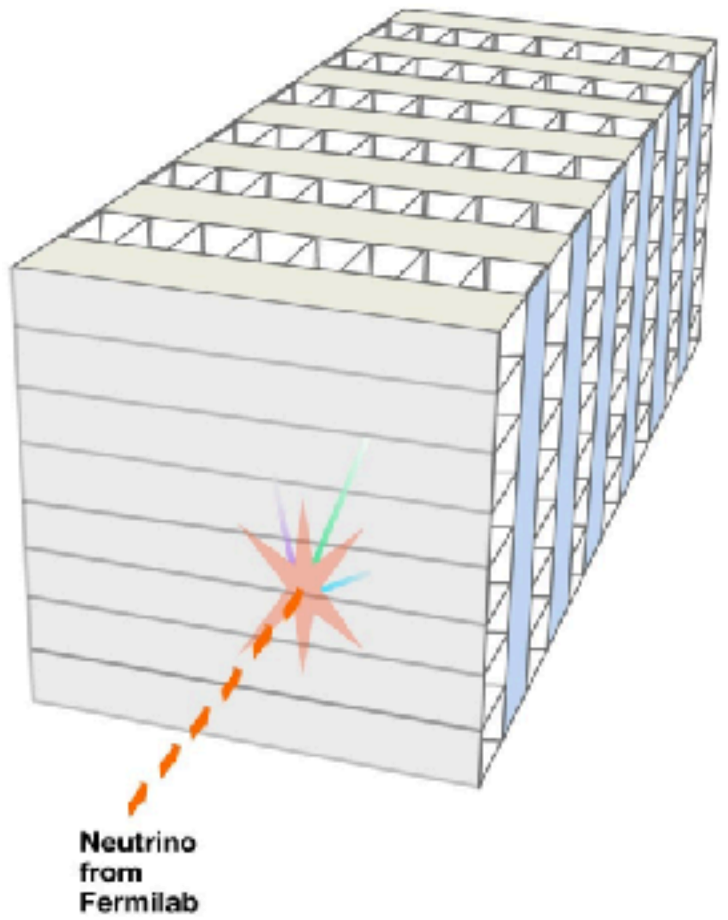
810 km/GeV - E 2 GeV - 0.8○ off-axis

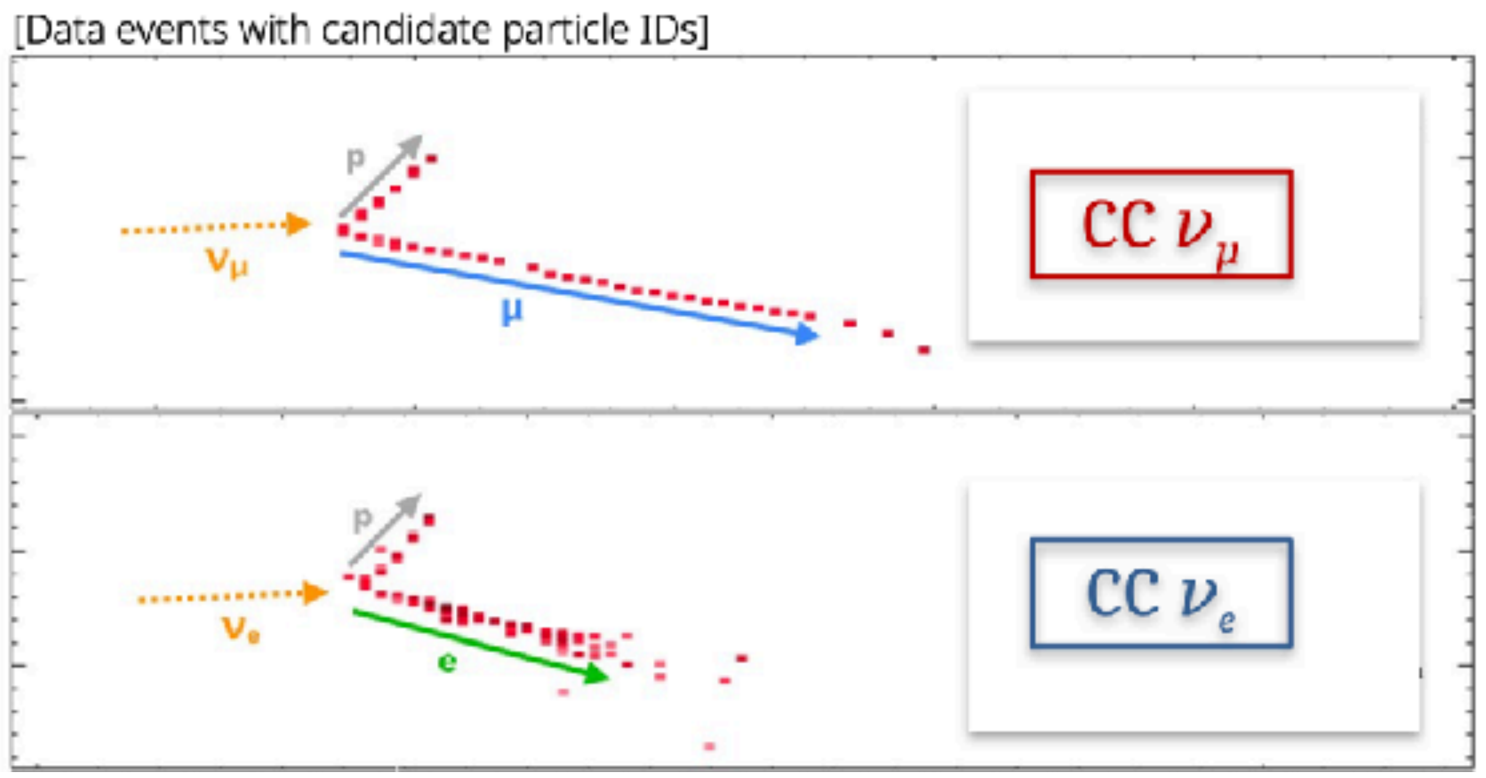
T2K

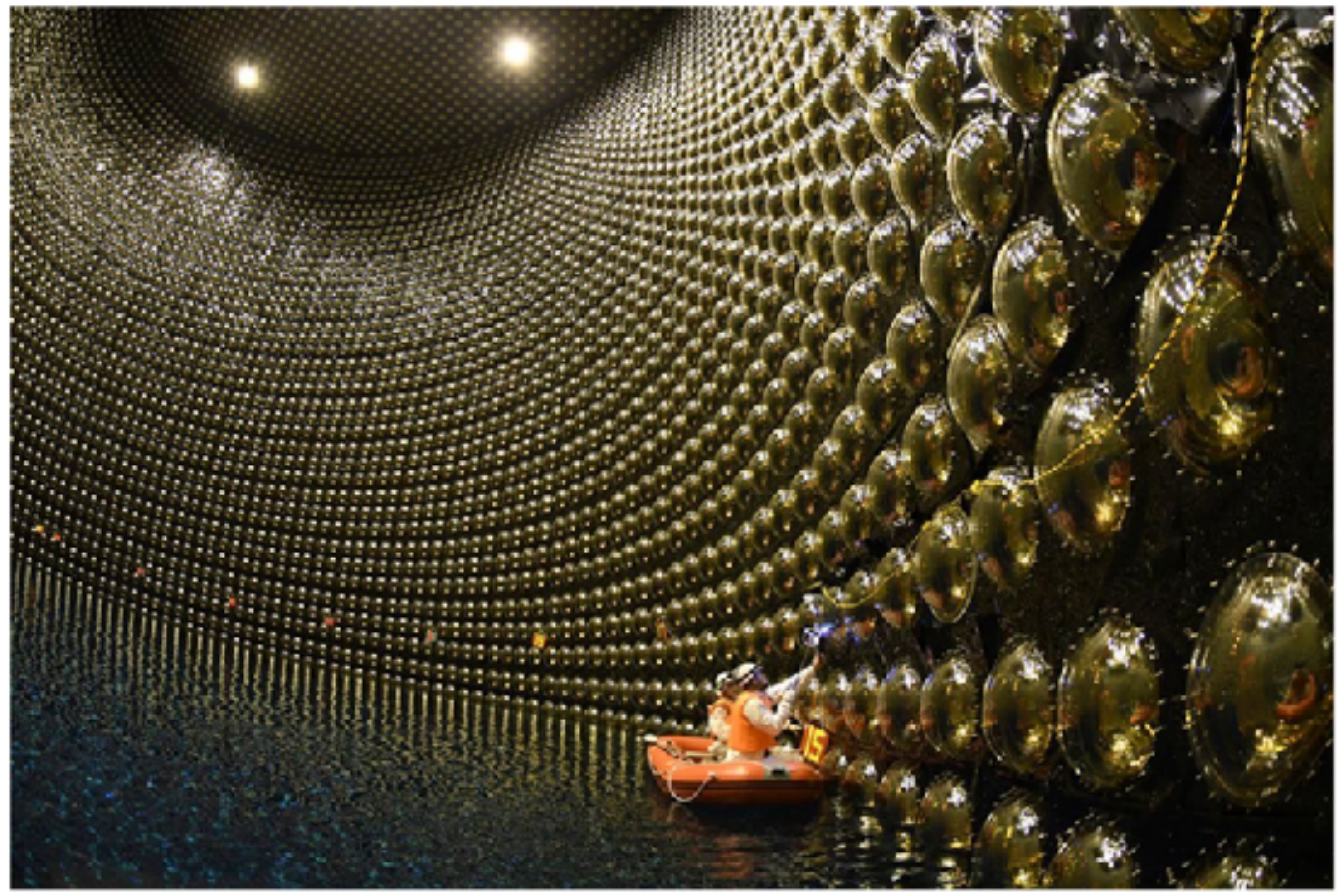
Slightly off axis (J-PARC to Super K)

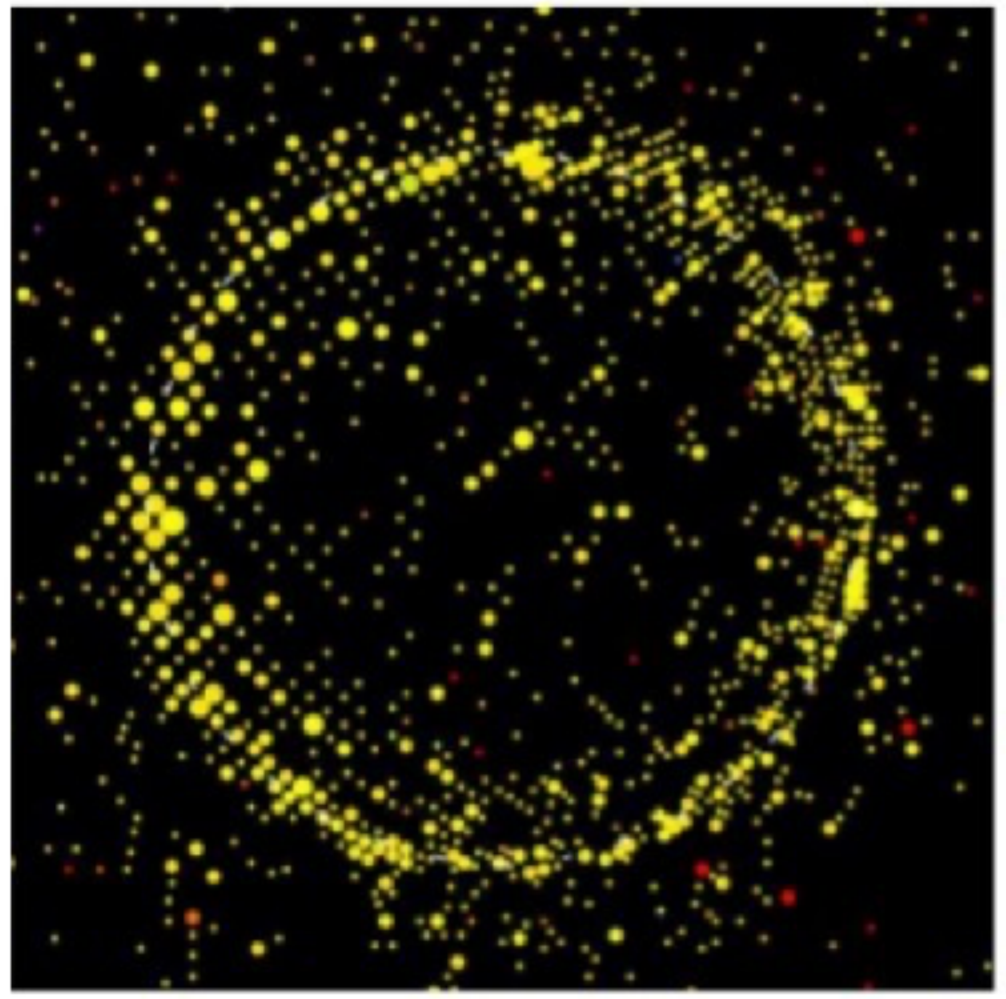
490 km/GeV - E 0.6 GeV - 2.5○ off-axis

Sensitive to ν_μ disappearance and ν_e appearance!









ν_e-like

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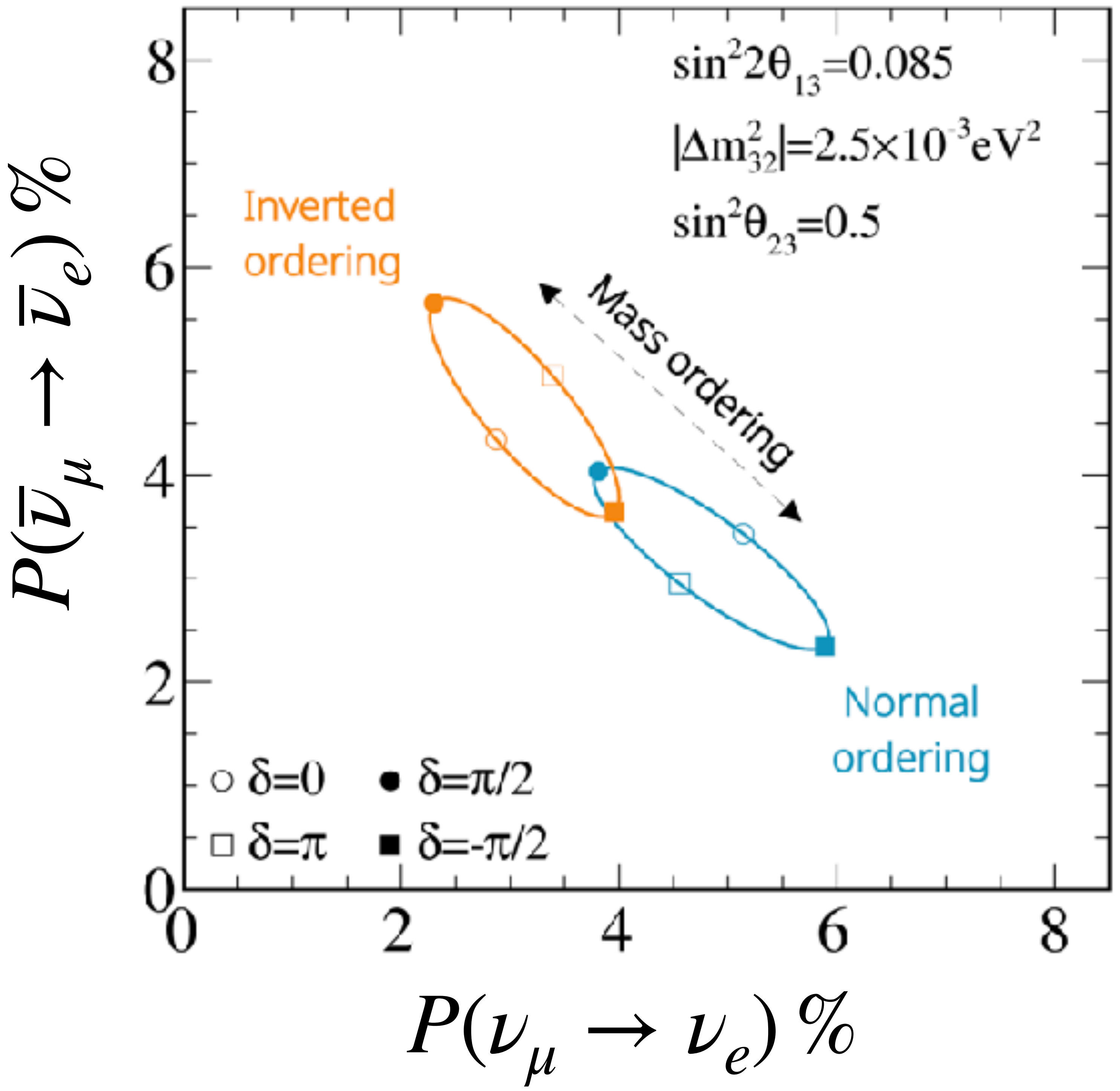

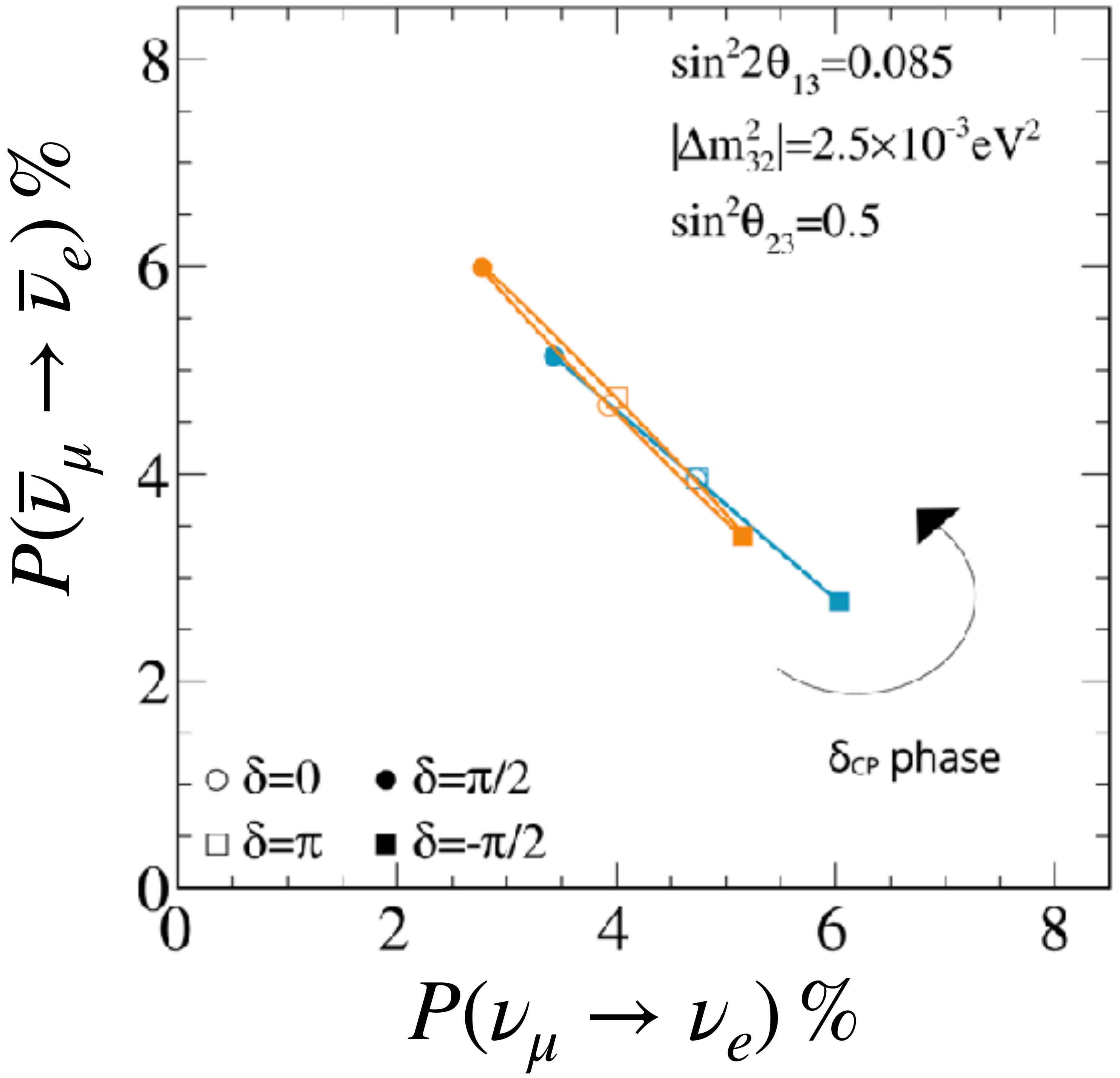

Accelerator Neutrino Oscillations

The current two main players ν_μ-beam experiments!

New combination of the two experiments for this conference!

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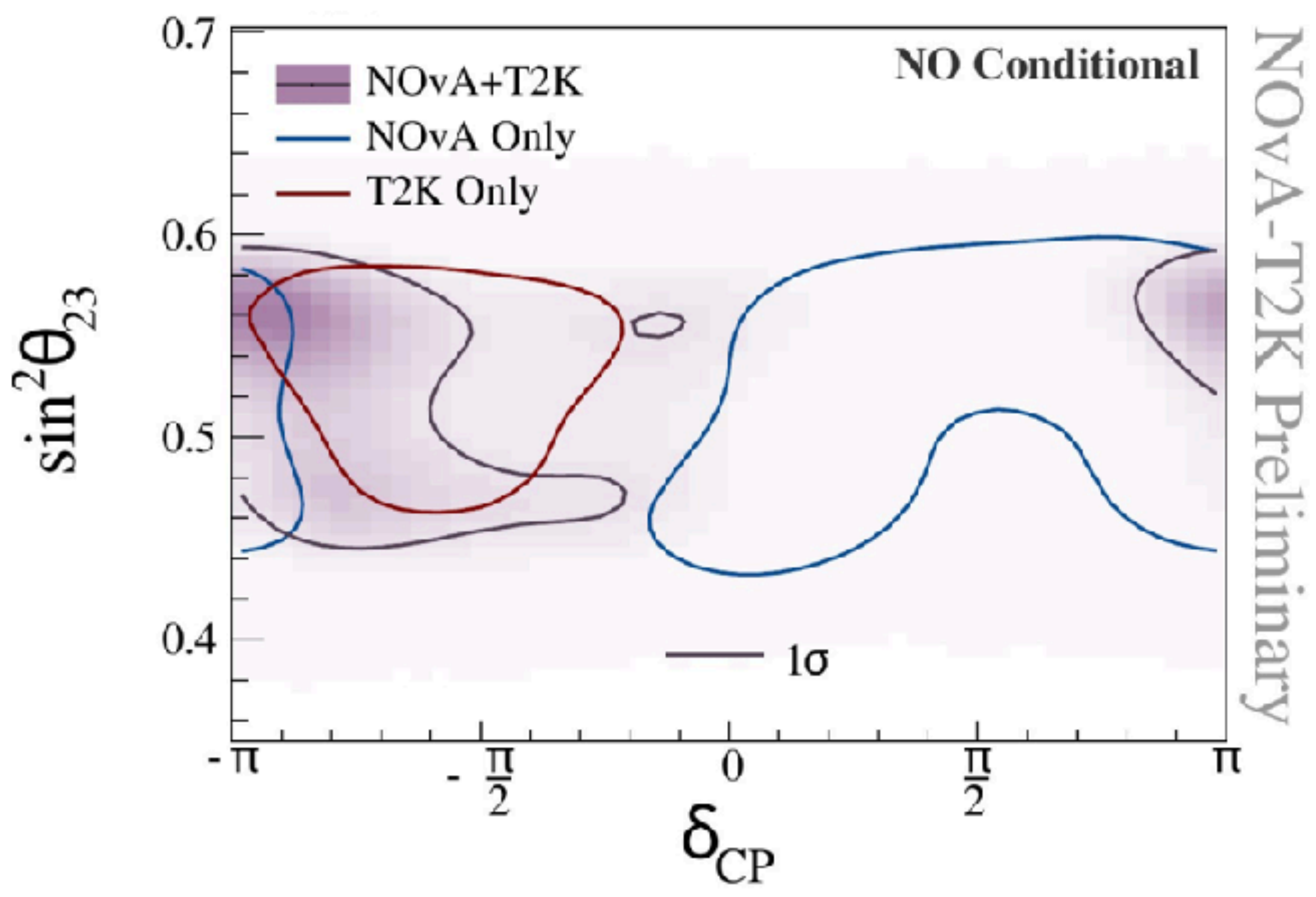
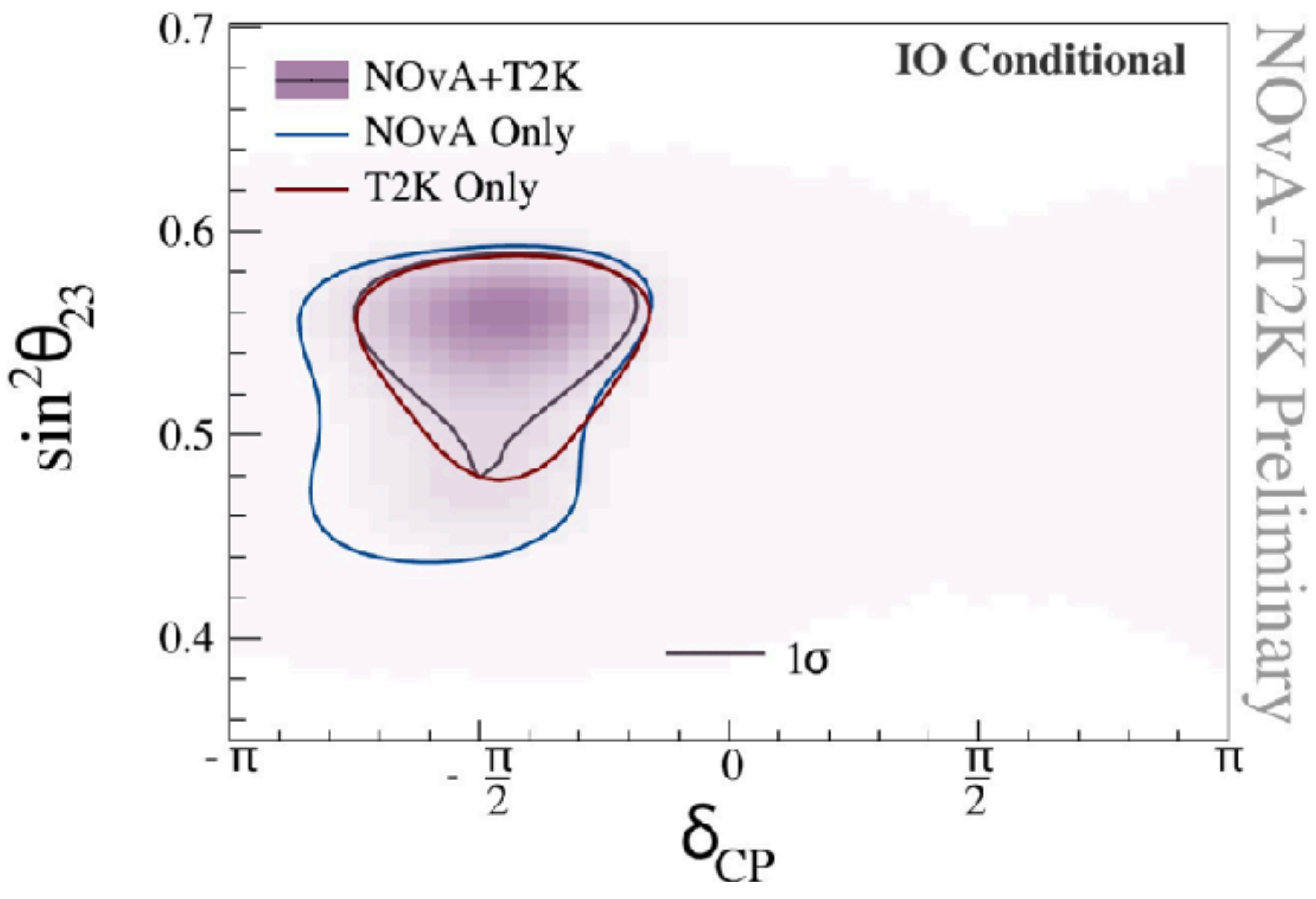


Mild preference for Inverted Ordering but influenced by θ_{13} constraint



CP-conserving points are *outside* 3σ intervals in IO

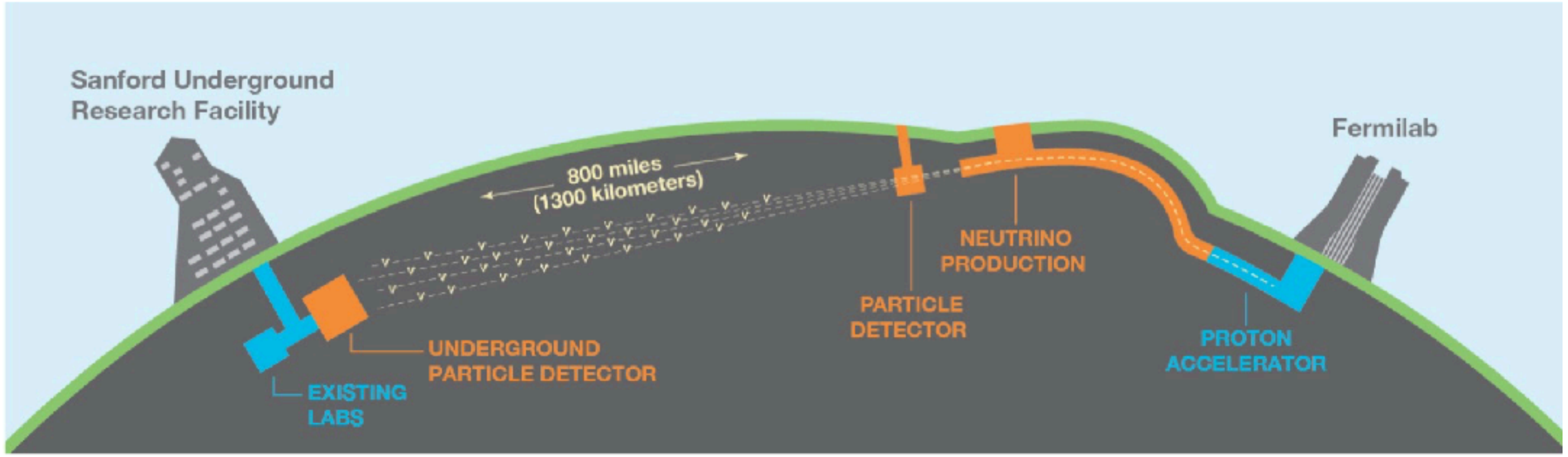
Expect CPV *if* ordering is inverted

Accelerator Neutrino Prospects

- Need definitive measurements! Two large next-generation projects are under preparation:

DUNE:

- > 2 MW beam
- Liquid-Argon TimeProjection Chamber (LArTPC) technology
- ≥ 40 kton far detector fiducial mass
- First physics in ~2029

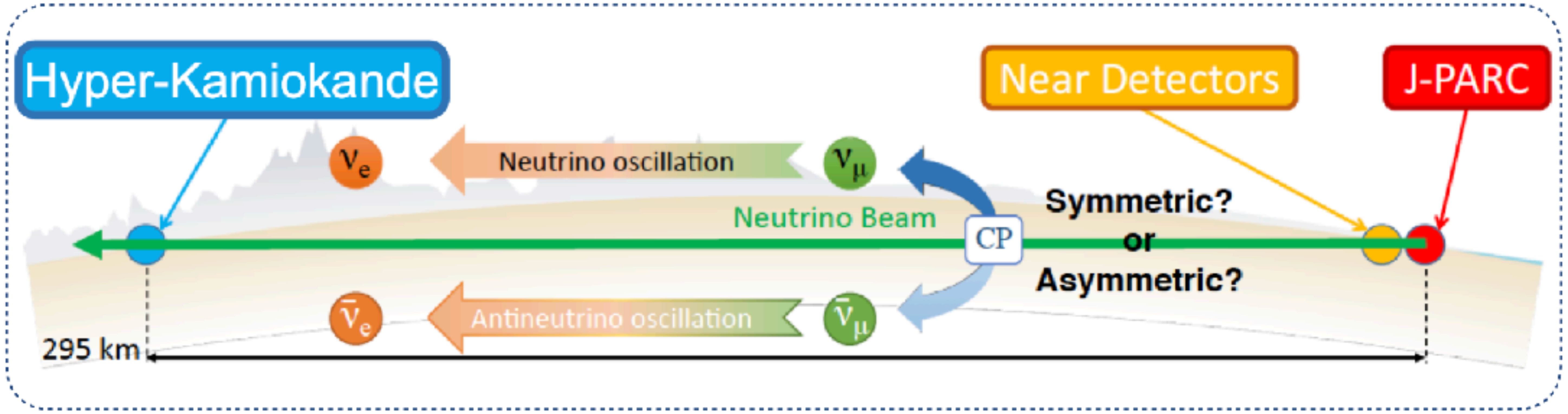


Large degree of complementarity:

	matter effects	energy spectrum	detection systematics
DUNE	large	wide band, higher energy	LArTPC
Hyper-K	small	narrow band, lower energy	Water Cherenkov

Hyper-Kamiokande:

- 1.3 MW beam
- Water Cherenkov far detector
- 190 kton far detector fiducial mass
- First physics in ~2027



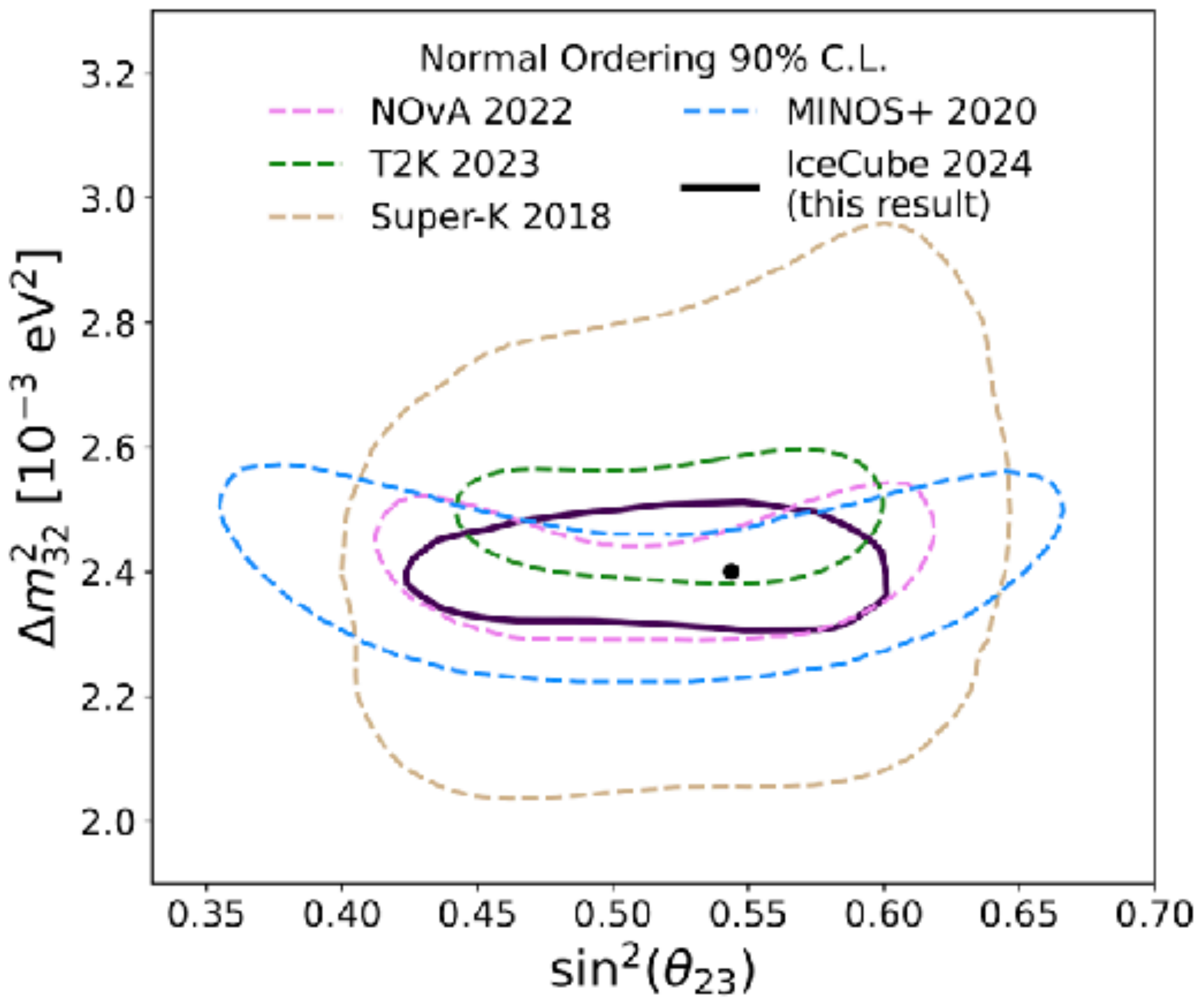
From T. Nakadaira's talk at ICHEP 2024

Atmospheric Neutrinos

ICECUBE and Deep Core

- 1km3 of ice instrumented with strings of Digital Optical Modules (DOMs), each with a PMT

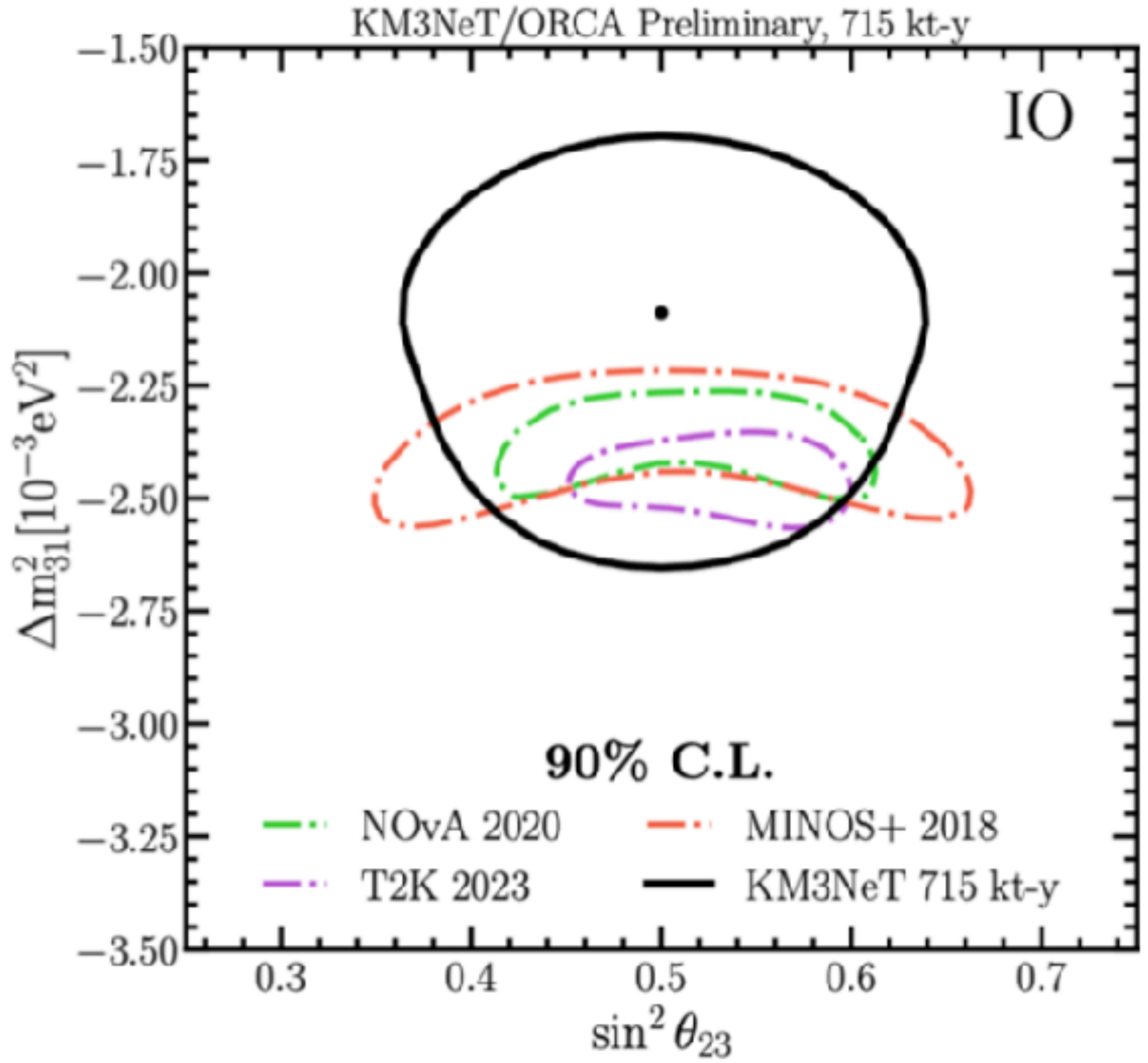
– DeepCore: 8 densely region at the center (threshold ~8 GeV)



- Comparable and compatible results between accelerator and atmospheric neutrinos.

Km3net and ORCA

- 115 strings optimized for neutrino oscillation measurements
- Each DOM has 31 3-inch PMTs
- About 20% of DOMs already installed



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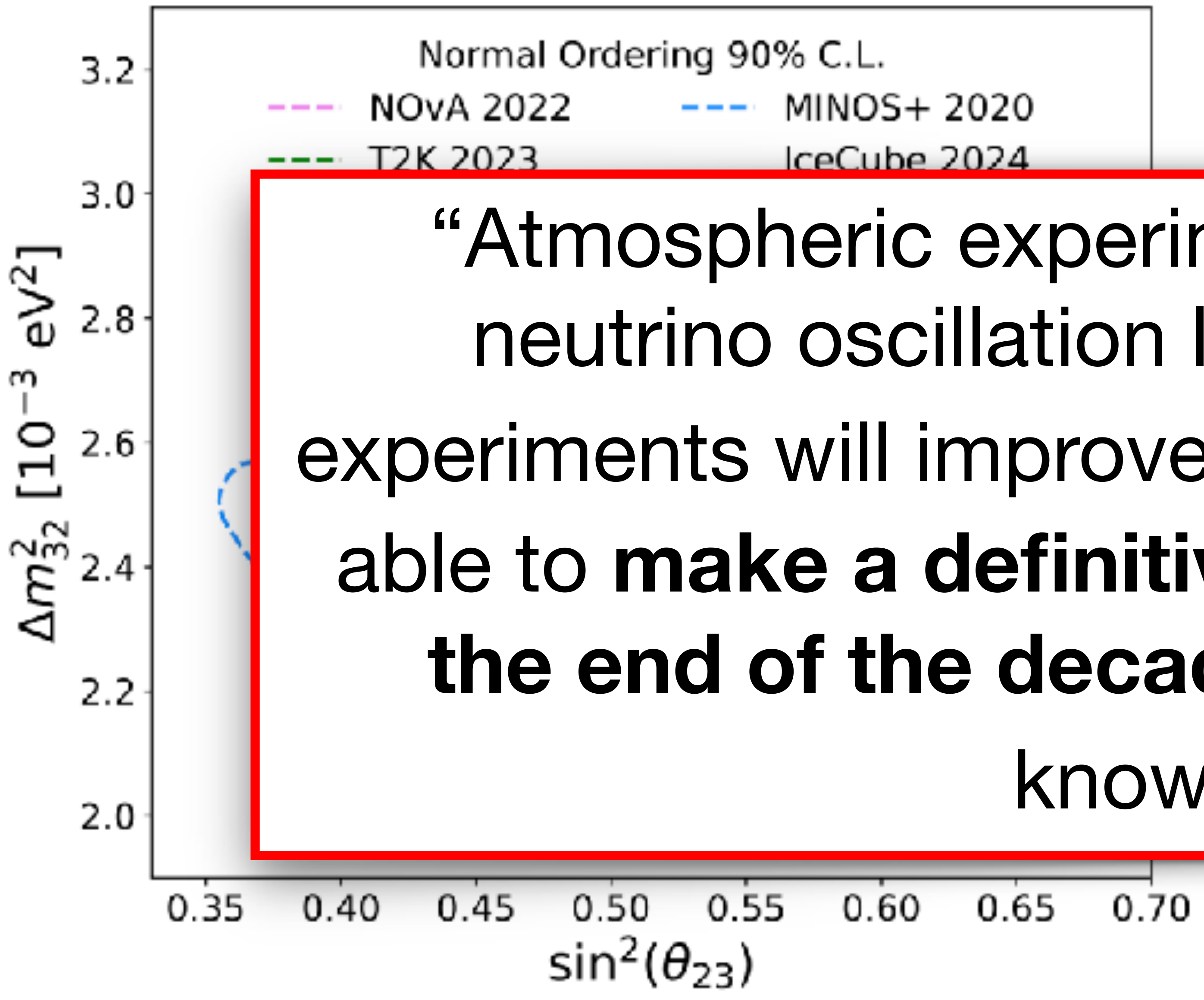

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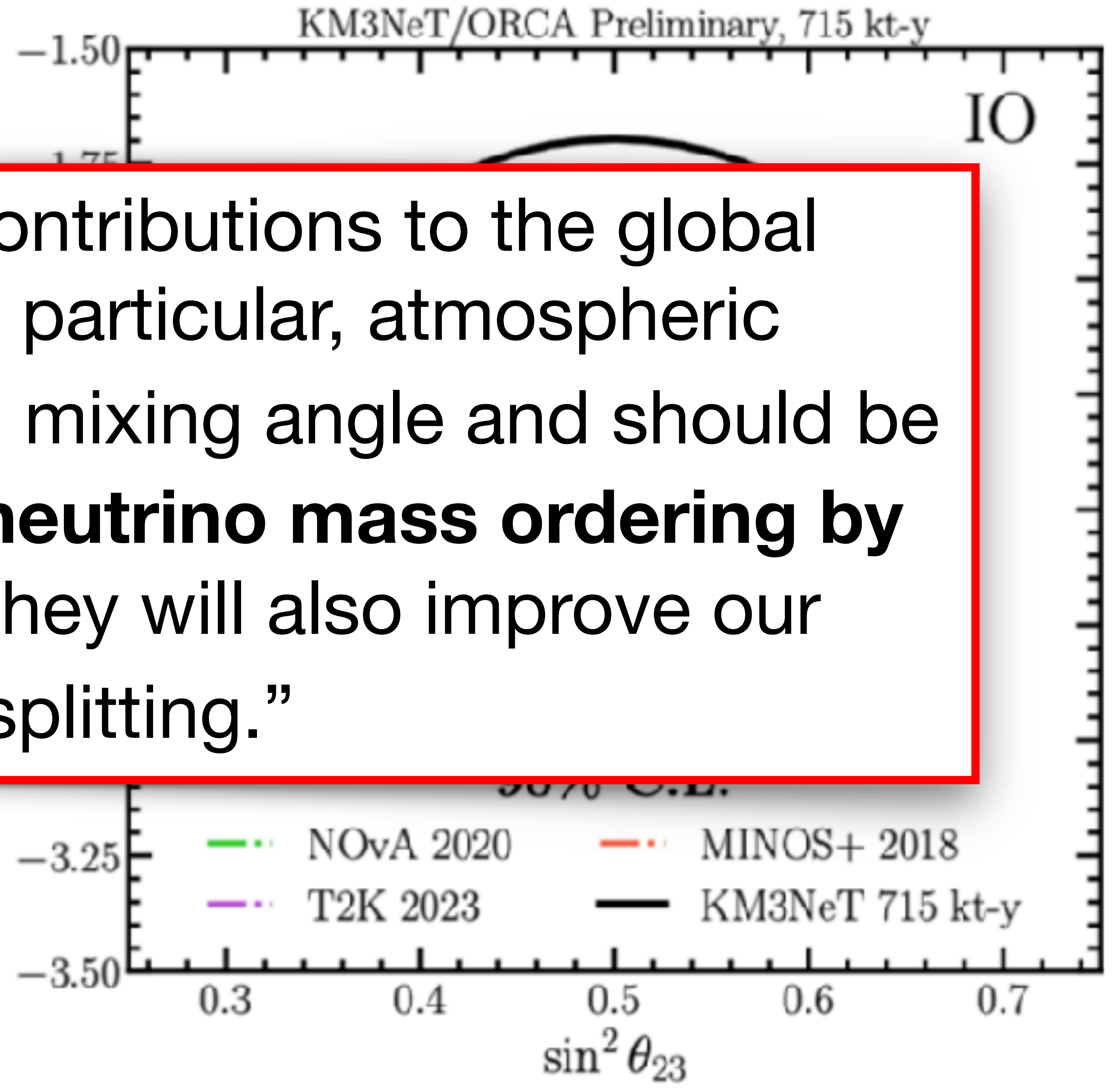
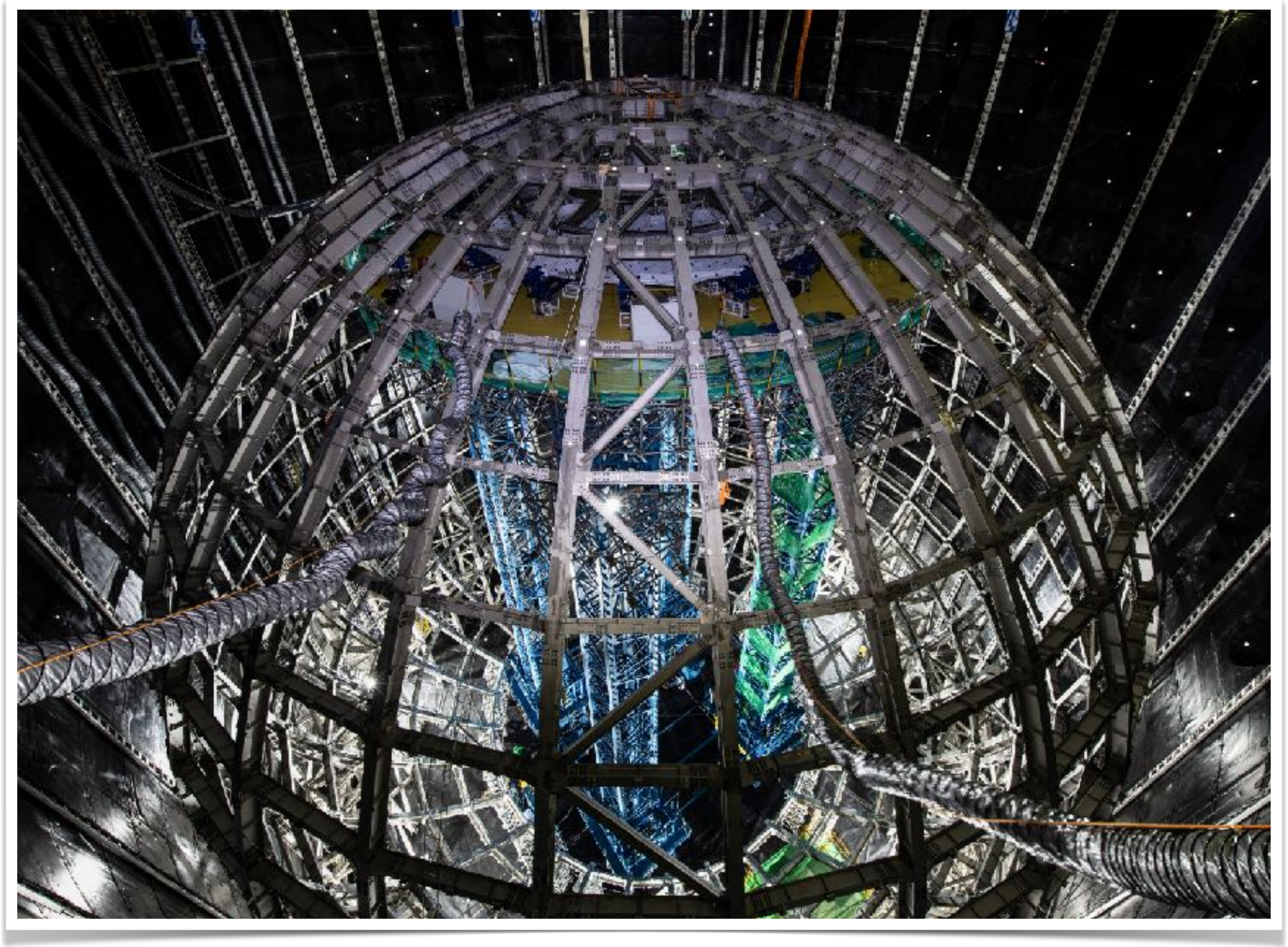
- About 20% of DOMs already installed



"Atmospheric experiments will make leading contributions to the global neutrino oscillation landscape before 2030. In particular, atmospheric experiments will improve our knowledge of the θ_{23} mixing angle and should be able to **make a definitive measurement of the neutrino mass ordering by the end of the decade**. Together with JUNO, they will also improve our knowledge of the Δm^2_{32} mass splitting."

Reactor Oscillations

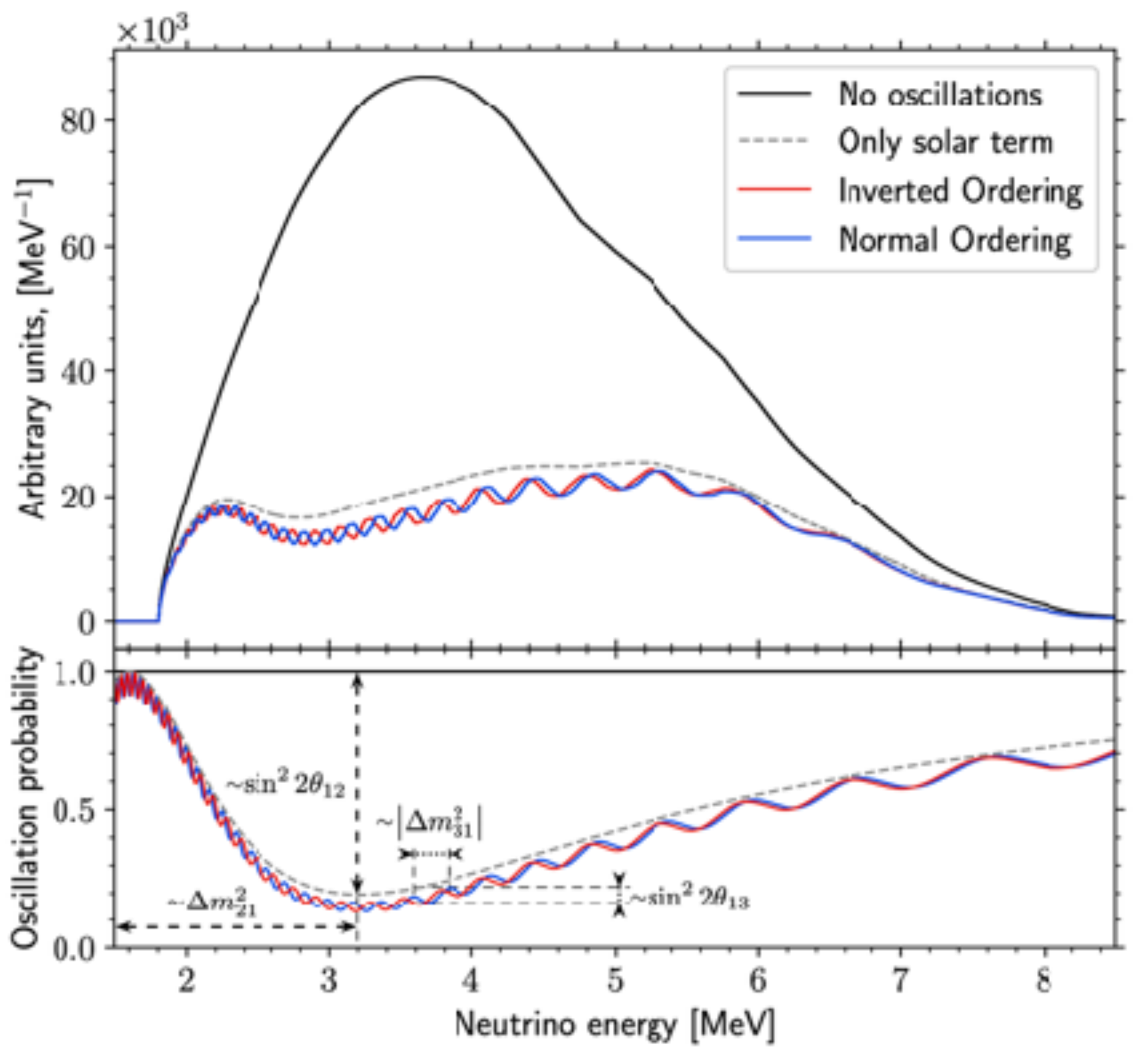


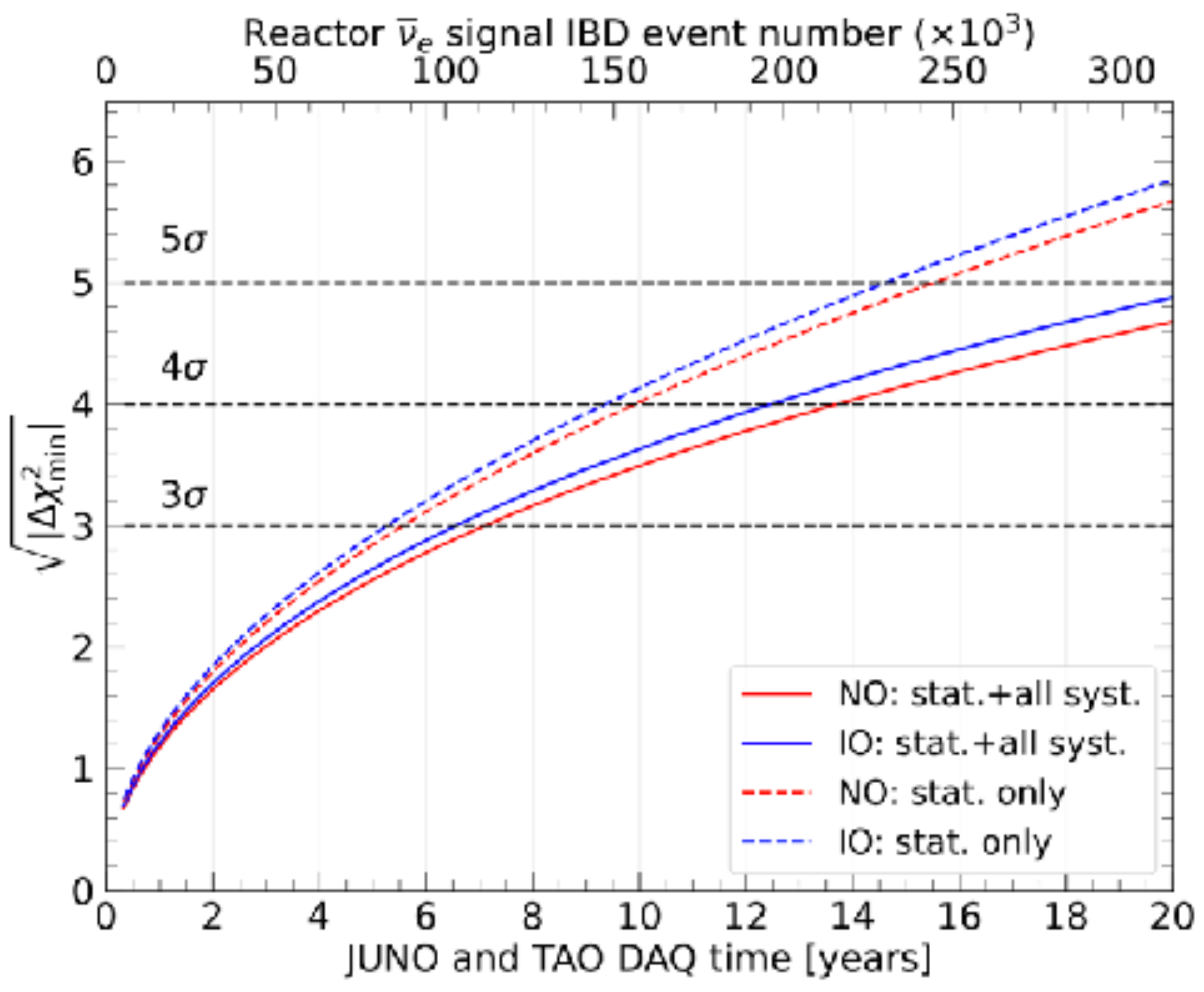
JUNO Medium baseline experiment

20-kton Liquid Scintillator neutrino observatory located in Southern China

Mass hierarchy from the electron anti-neutrino disappearance pattern through the interference effect of quasi-vacuum oscillation of reactor antineutrinos

JUNO reactor neutrino oscillation analysis alone provides a median 3σ sensitivity to NMO in 6.5 years!



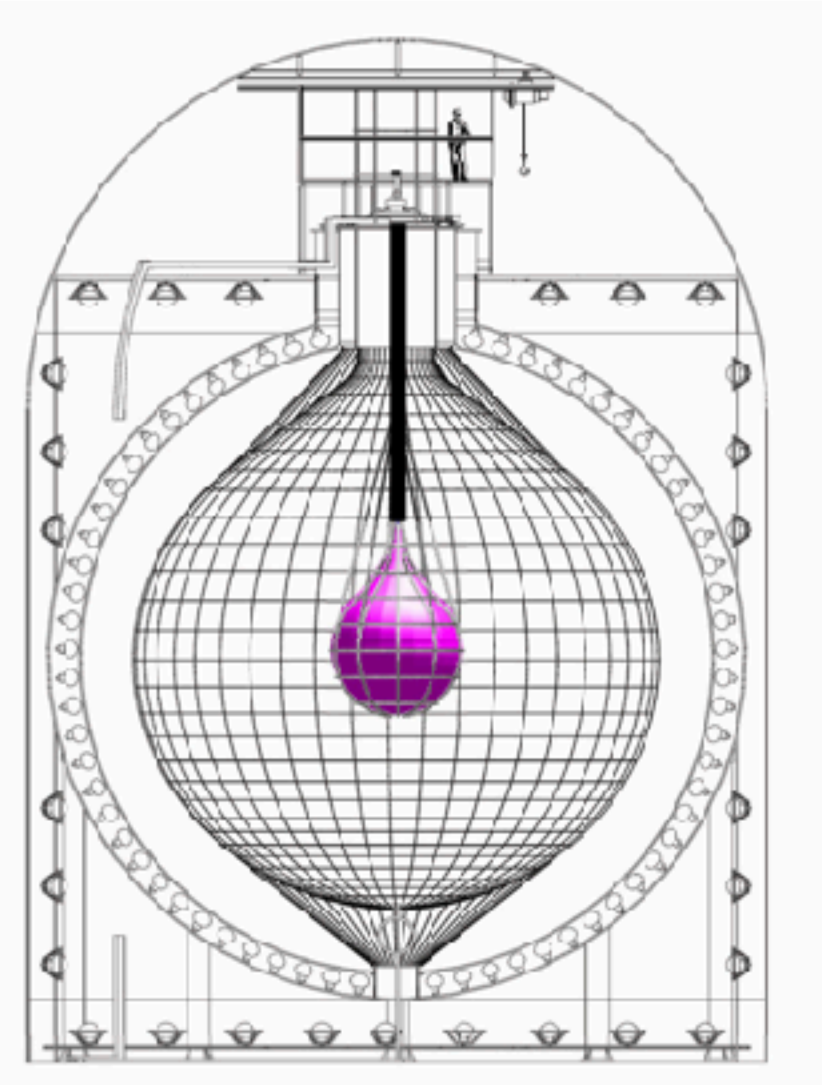


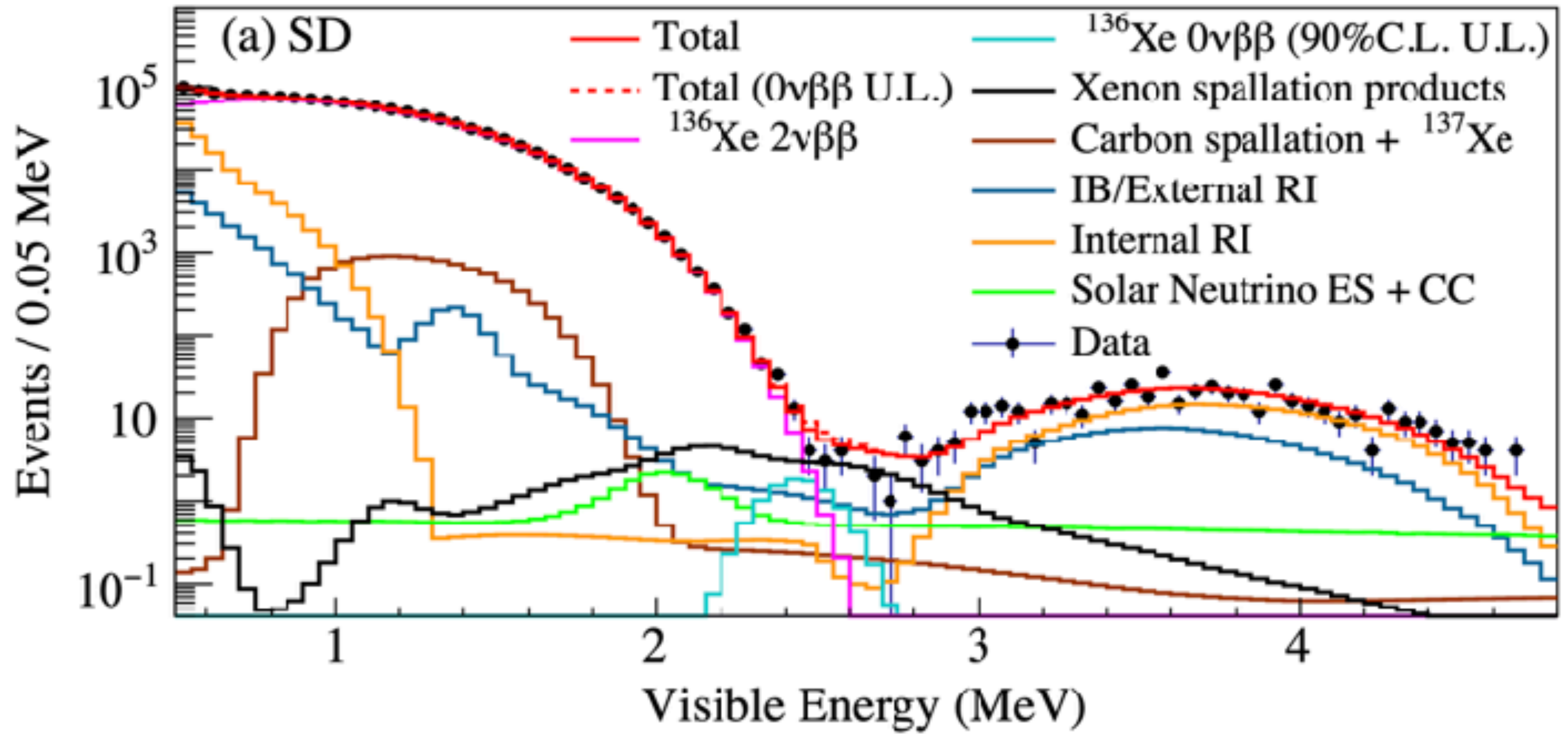
Neutrinoless double beta decay

KamLandZen

Mini-balloon Radius = 1.90 m
Xenon mass = 750 kg
Data taking started in 2019

The largest number of ββ nuclei. Low BG by distillation and filtration of both Liquid Scintillator and Xenon.





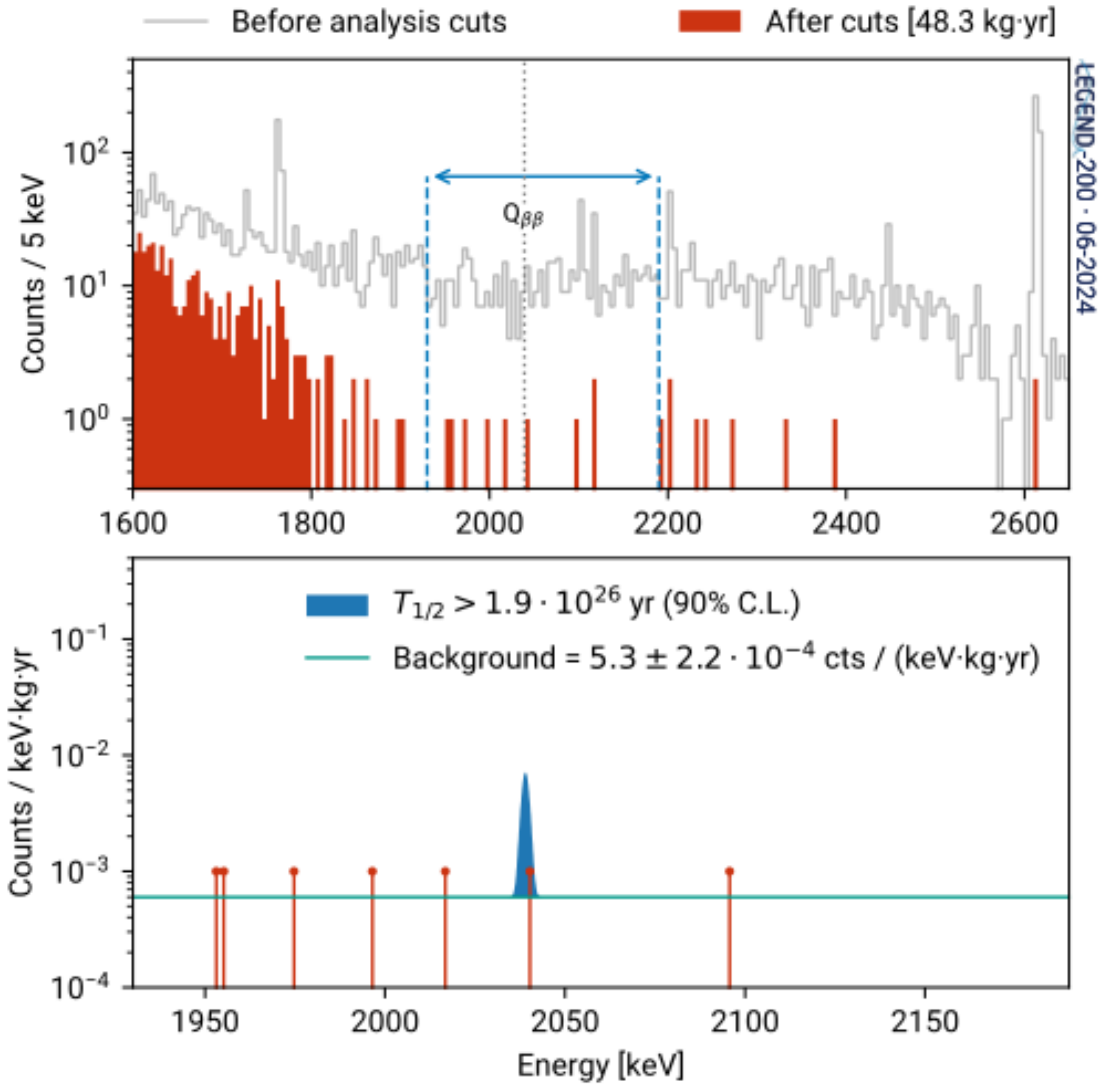
Limiting factor is the muon spallation of Xenon background.

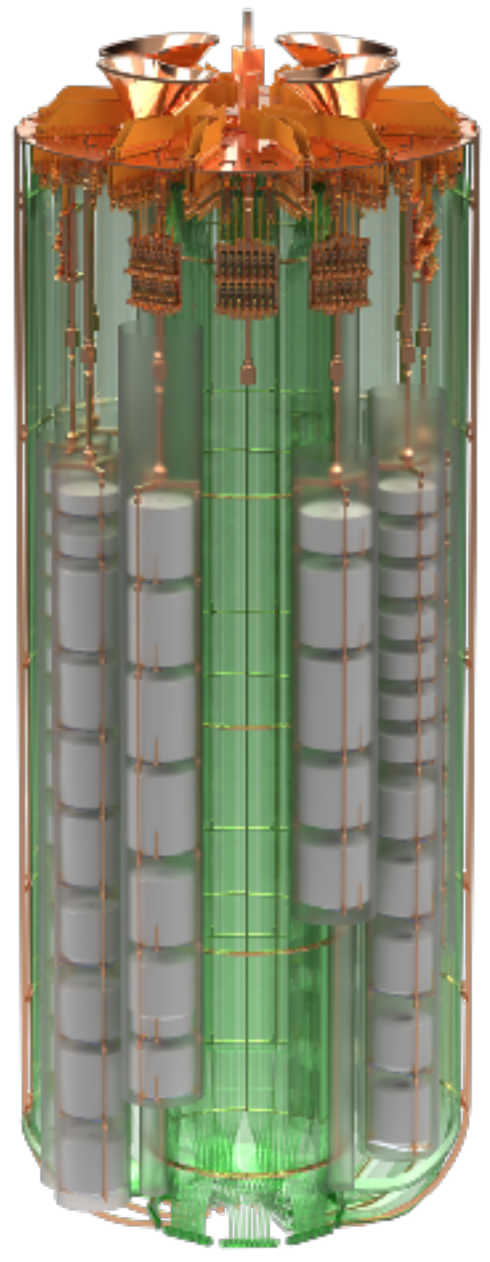
⟨mββ⟩ < 28 – 122 meV

KamLAND-ZEN-1T: ⟨mββ⟩ < ~20 meV

Legend-200

Germanium Semiconductor, with enrichment to > 90% in ^{76}Ge ($Q_{\beta\beta}$=2039 keVExcellent energy resolution (0.1 % FWHM @ $Q_{\beta\beta}$)





⟨mββ⟩ < 75 – 178 meV

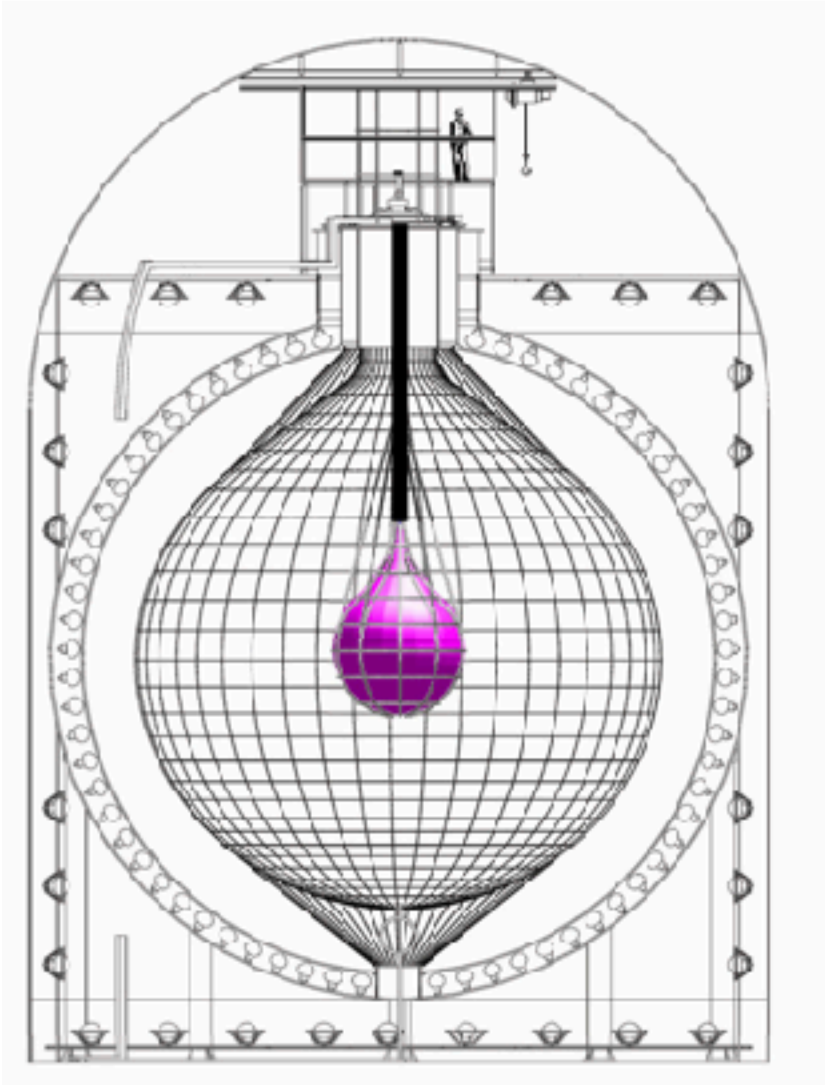
Legend 1000 ⟨mββ⟩ < ~20 meV

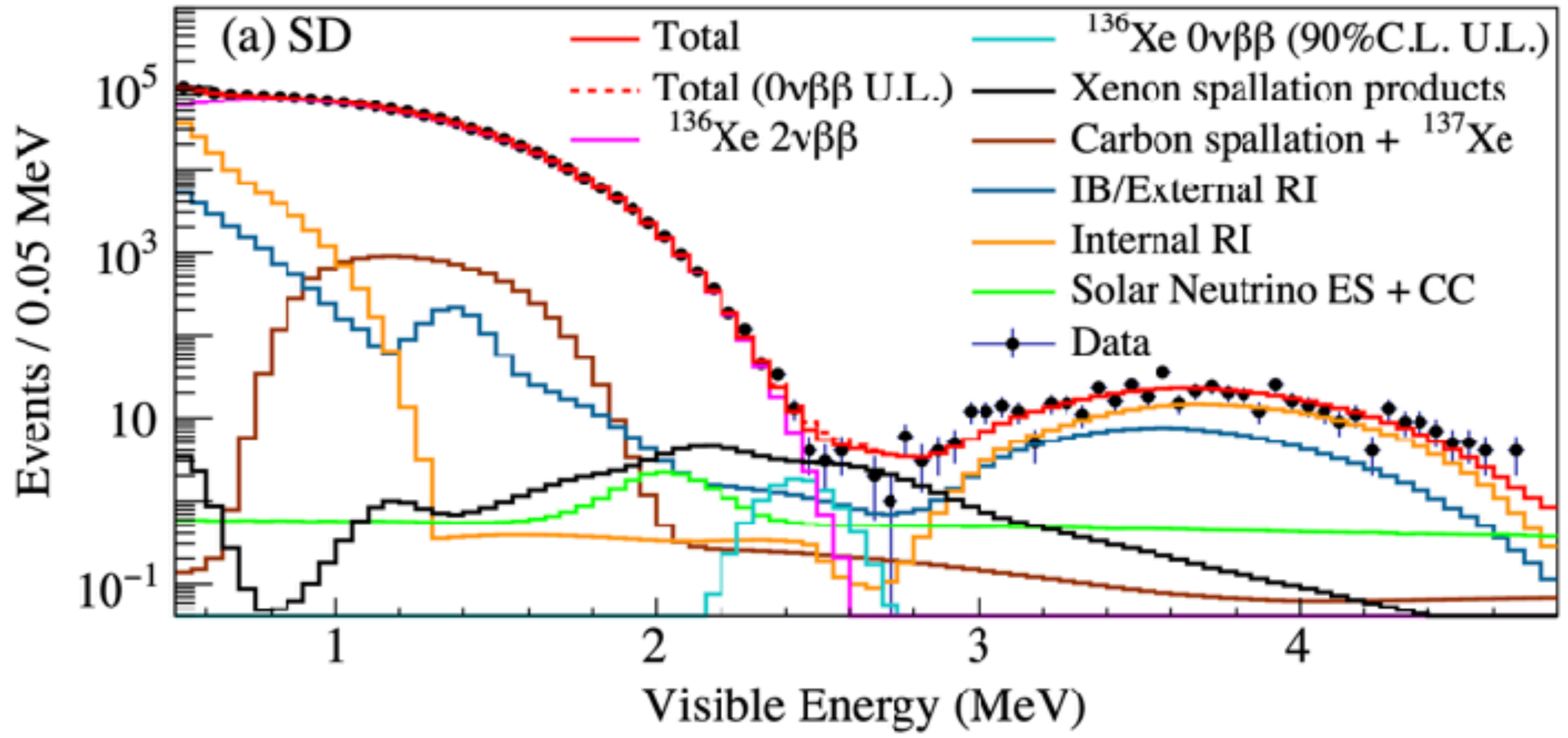
Neutrinoless double beta decay

KamLandZen

Mini-balloon Radius = 1.90 m
Xenon mass = 750 kg
Data taking started in 2019

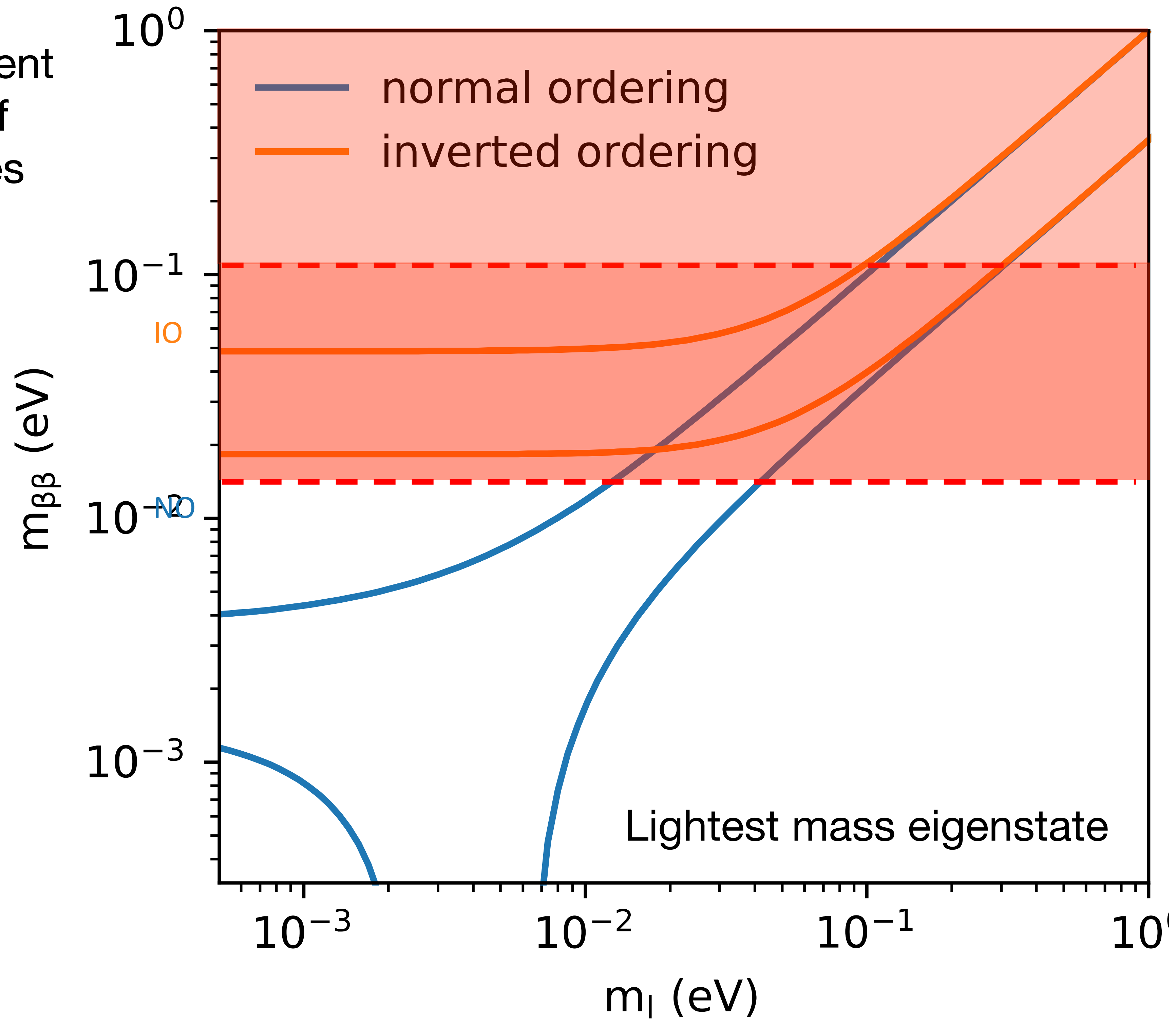
The largest number of ββ nuclei. Low BG by distillation and filtration of both Liquid Scintillator and Xenon.





Limiting factor is the muon spallation of Xenon background.

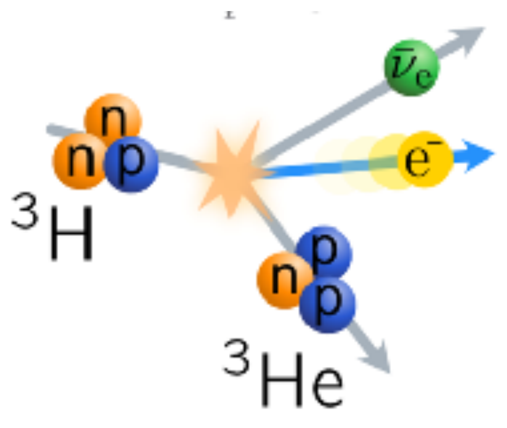
$\langle m_{\beta\beta} \rangle < 28 - 122$ meV



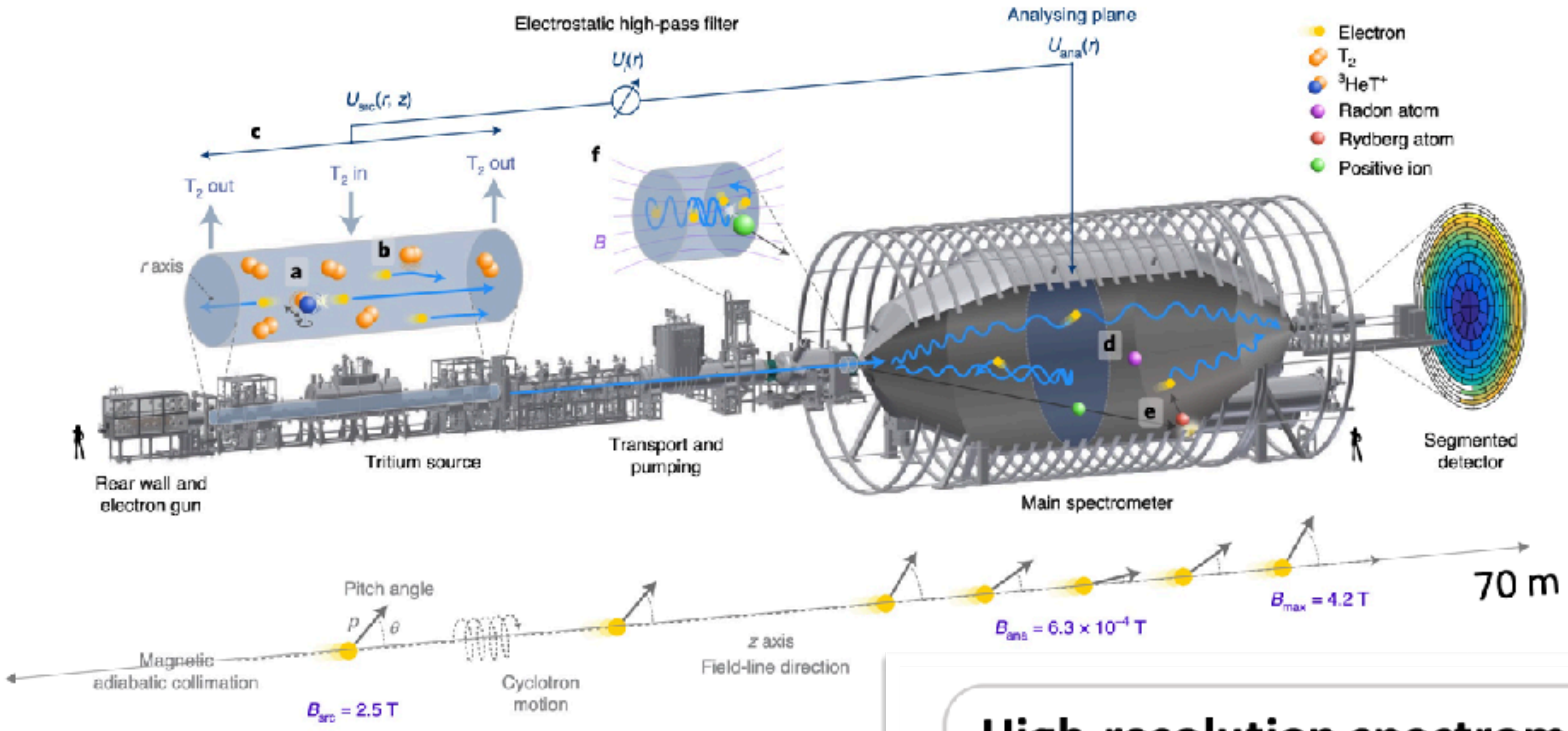
Next Generation experiments Legend-1000, KamLAND-ZEN-1T and nEXO will cover the inverted ordering!

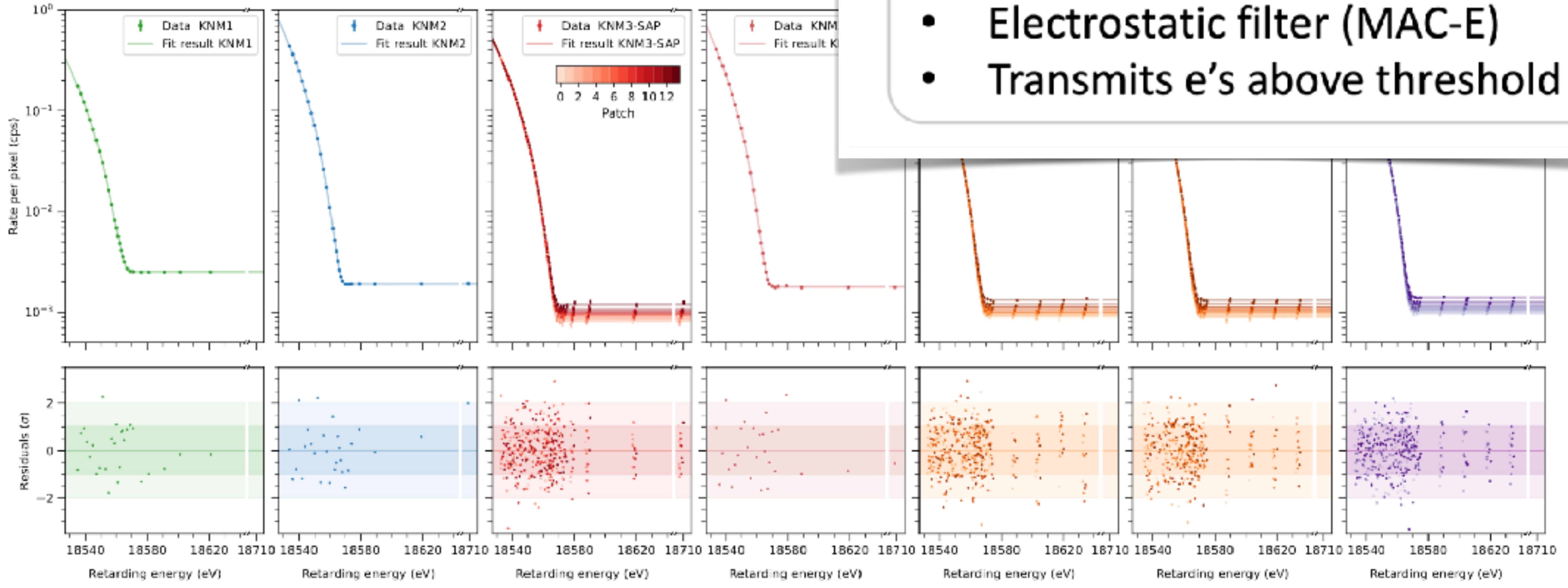
Absolute Neutrino Mass

KATRIN Experiment



High-activity tritium source
- 30 μg of gaseous T_2
- 10^{11} T_2 decays/s





High-resolution spectrometer
- Electrostatic filter (MAC-E)
- Transmits e's above threshold

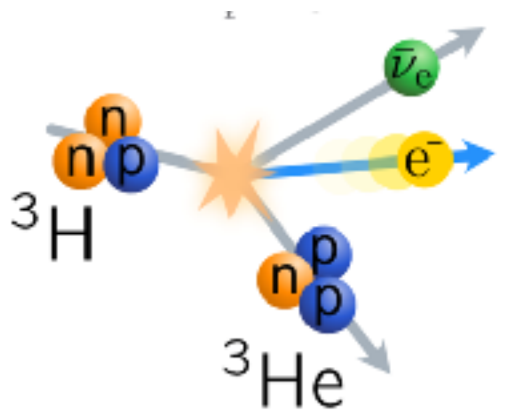
- Best fit:
  $m_\nu^2 = (-0.14^{+0.13}_{-0.15})$ eV² (stat. dom.)
- New limit:
  $m_\nu < 0.45$ eV (90% CL)
  Neutrino-24 (2024), arXiv:2406.13516 (2024)

Final goal (in 2026):

- < 0.3 eV sensitivity

Absolute Neutrino Mass

KATRIN Experiment



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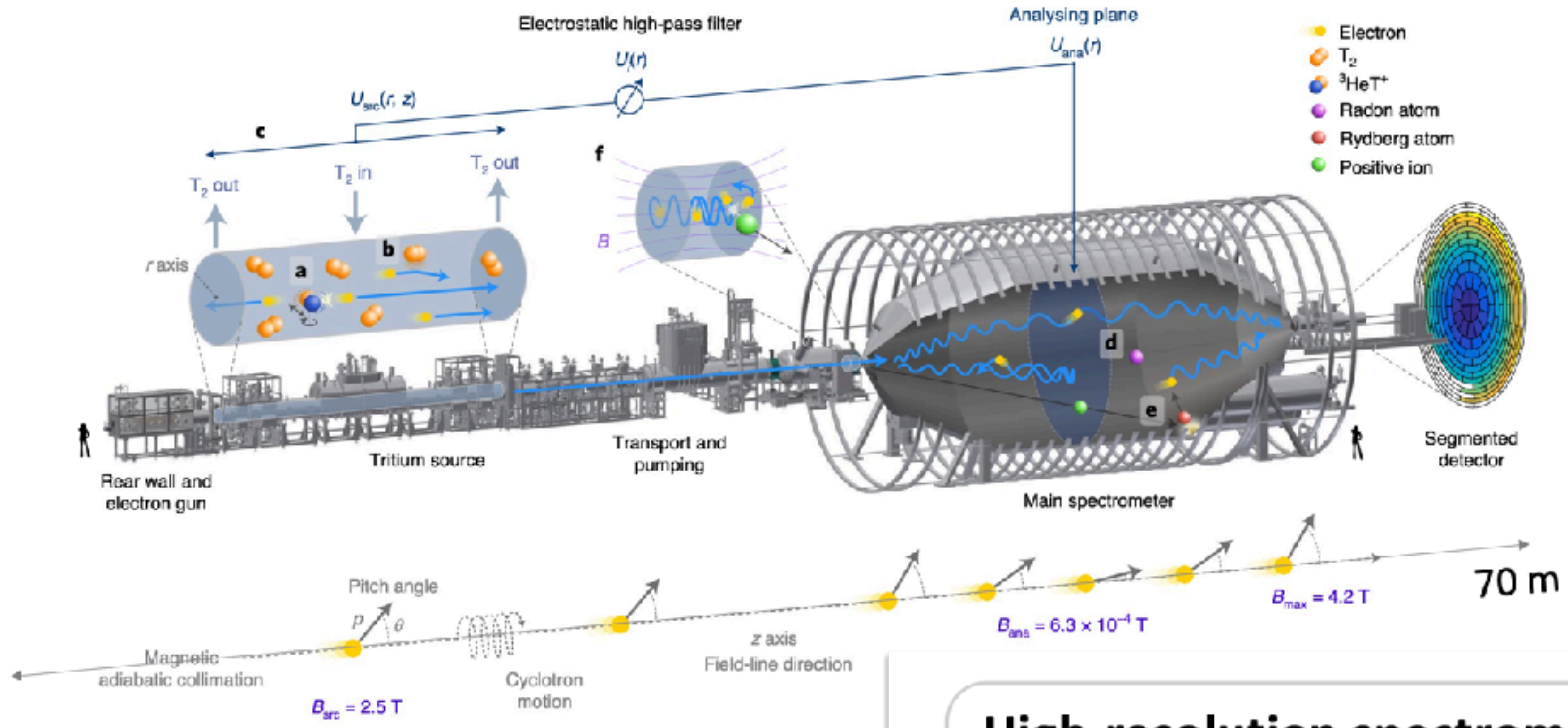

High-resolution spectrometer
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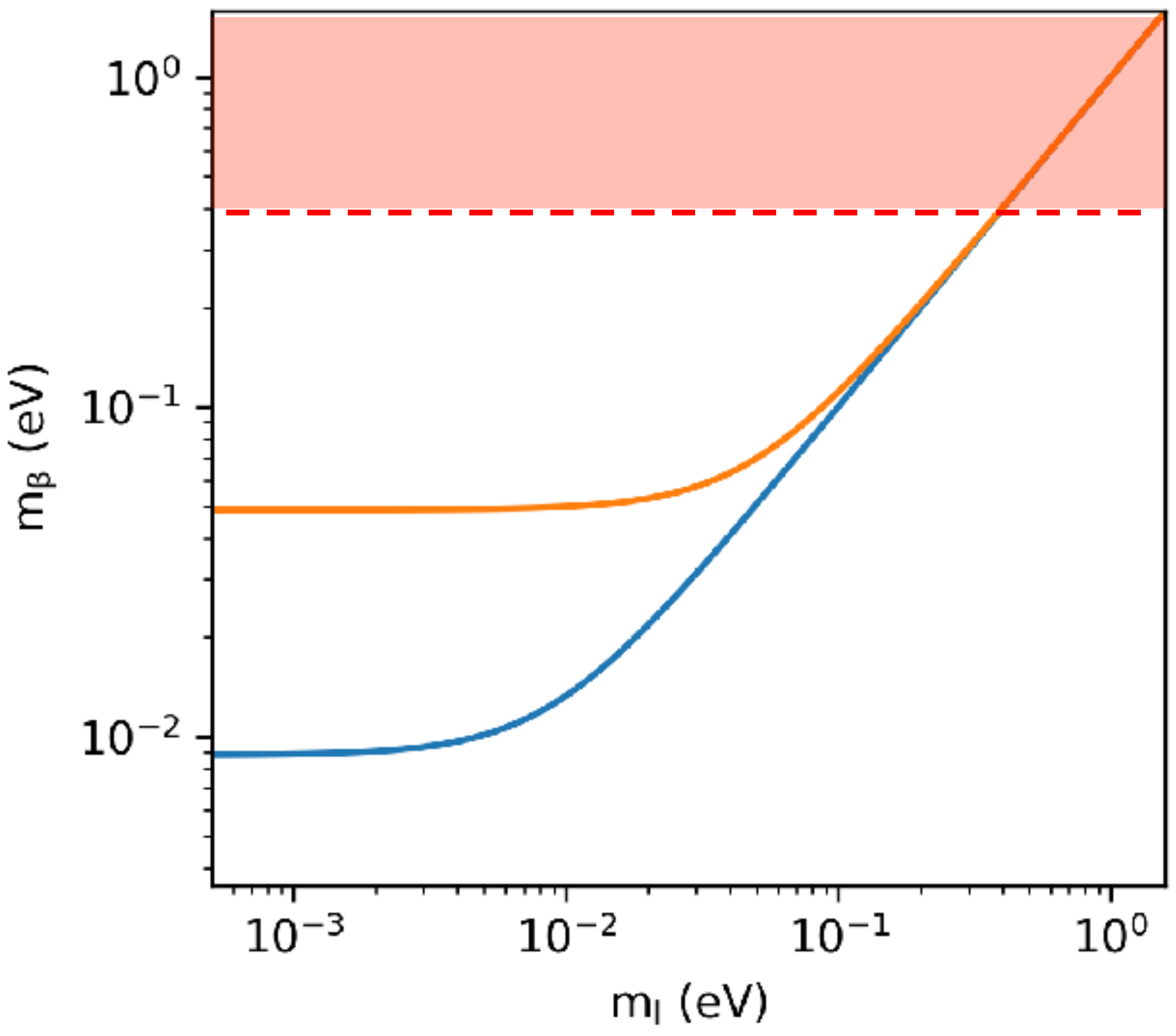
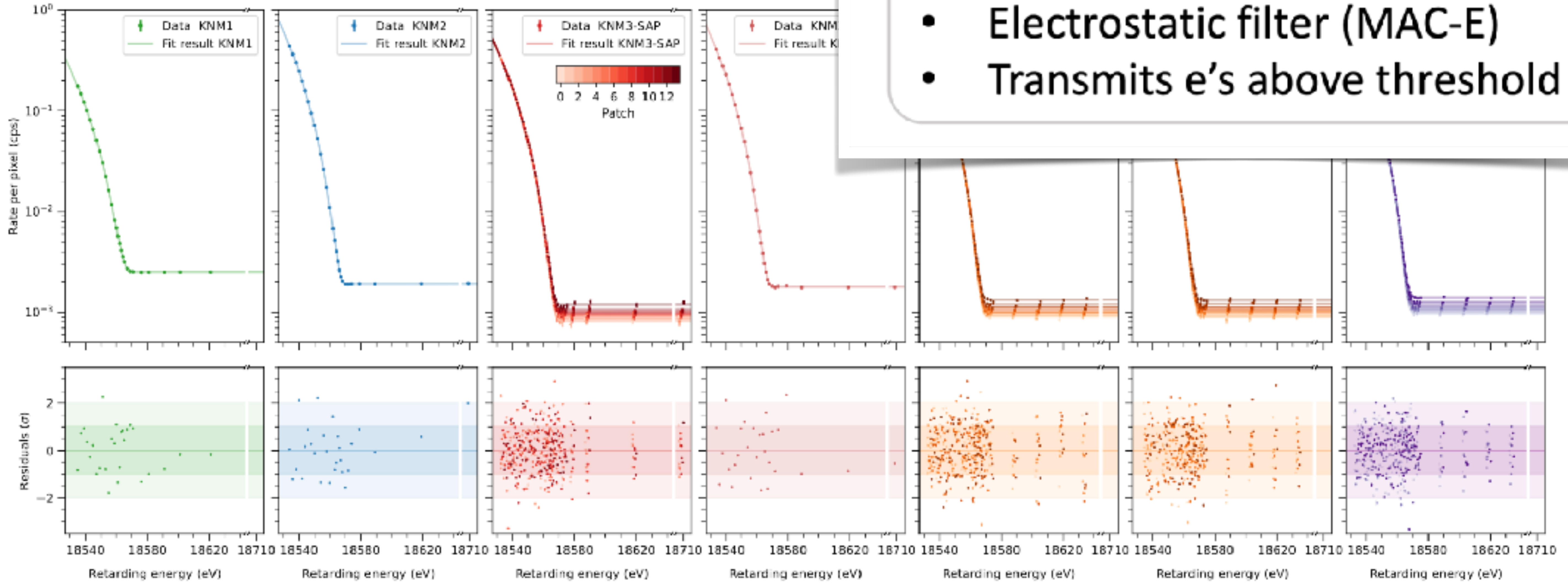
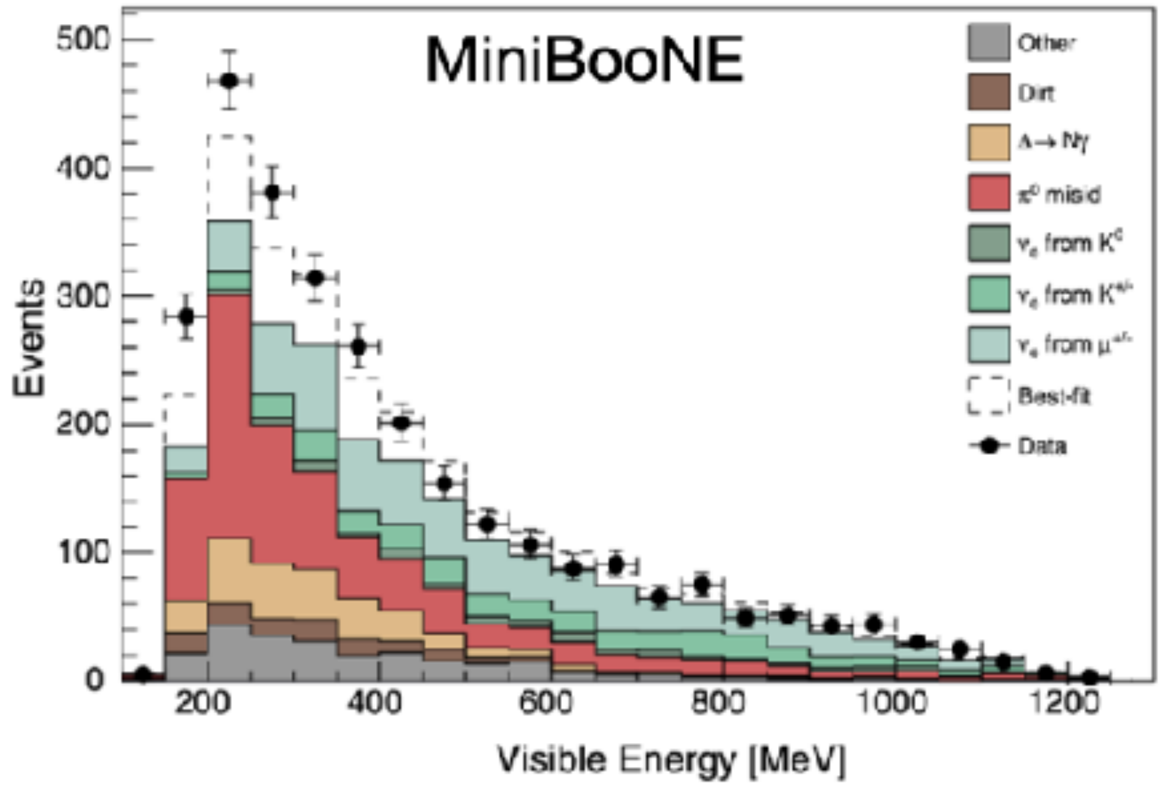


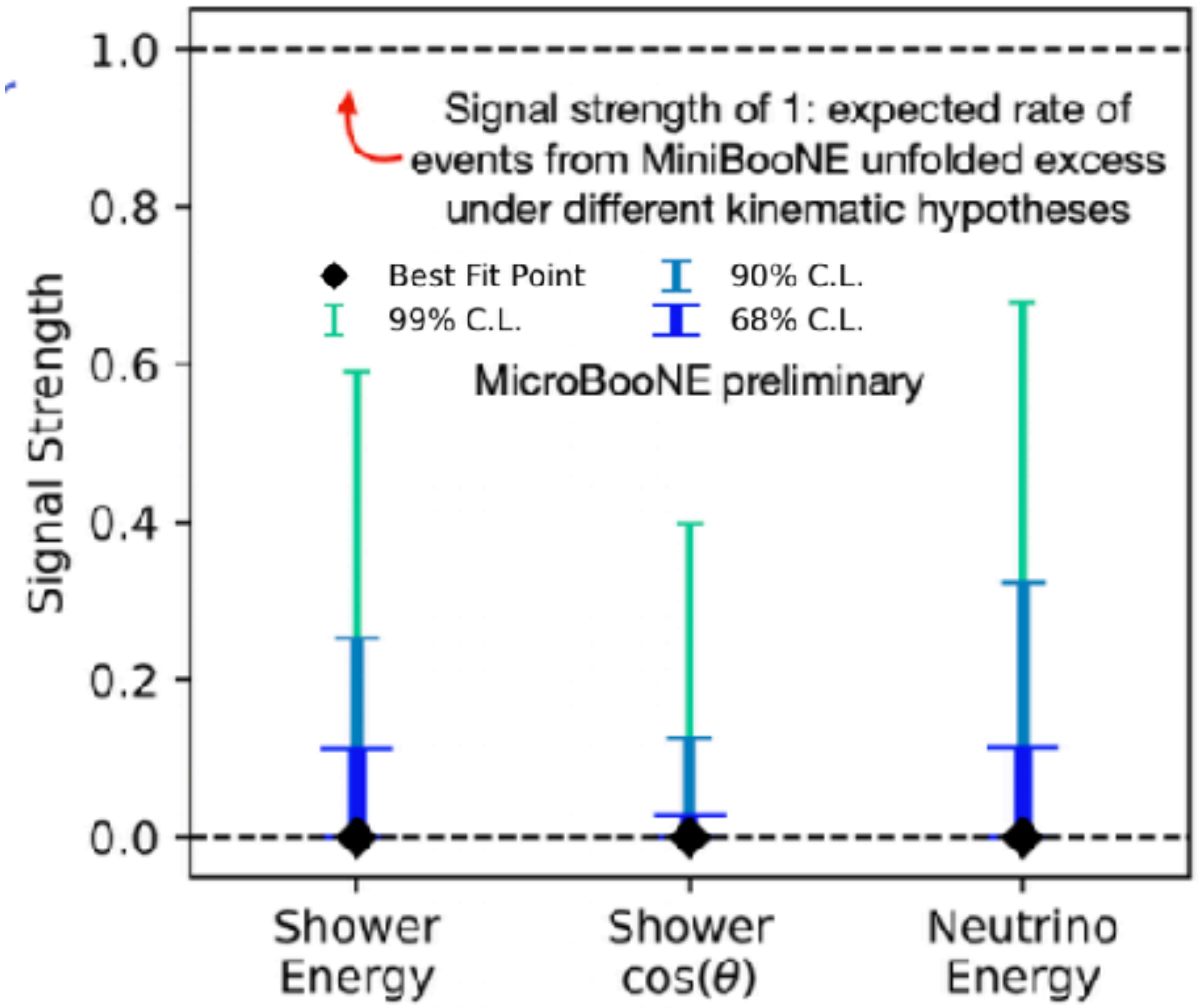


Neutrino Anomalies

LSND/MiniBooNE

LSND/MiniBooNE observed 6σ excess of electron (anti)neutrinos in muon (anti)neutrino beam!



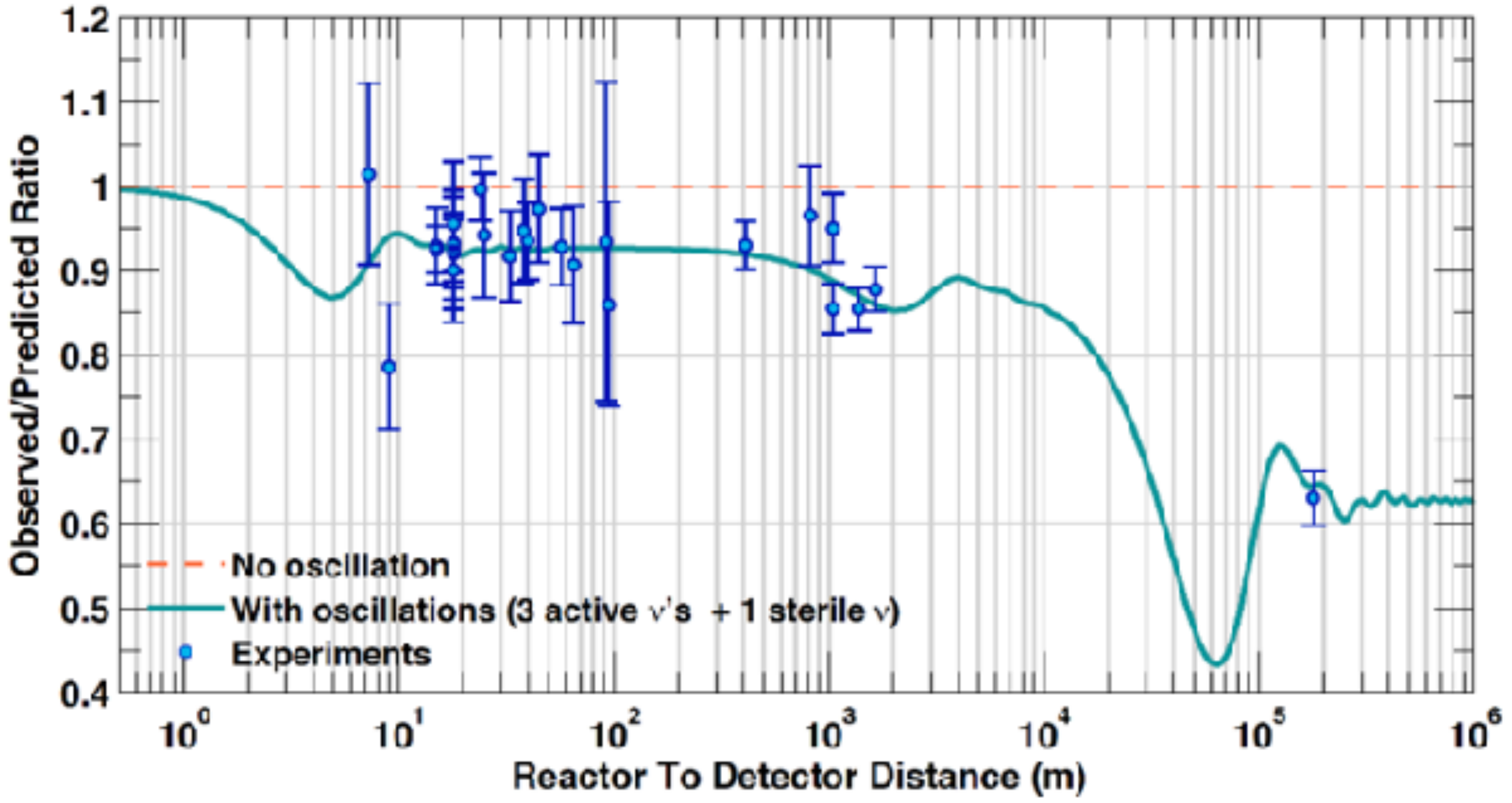


Excess not seen by MicroBooNE experiment

SBN program at Fermilab to completely settle the question!

Reactor anti-neutrino deficit

6% deficit of reactor anti-neutrinos ~3σ with respect to flux prediction models.

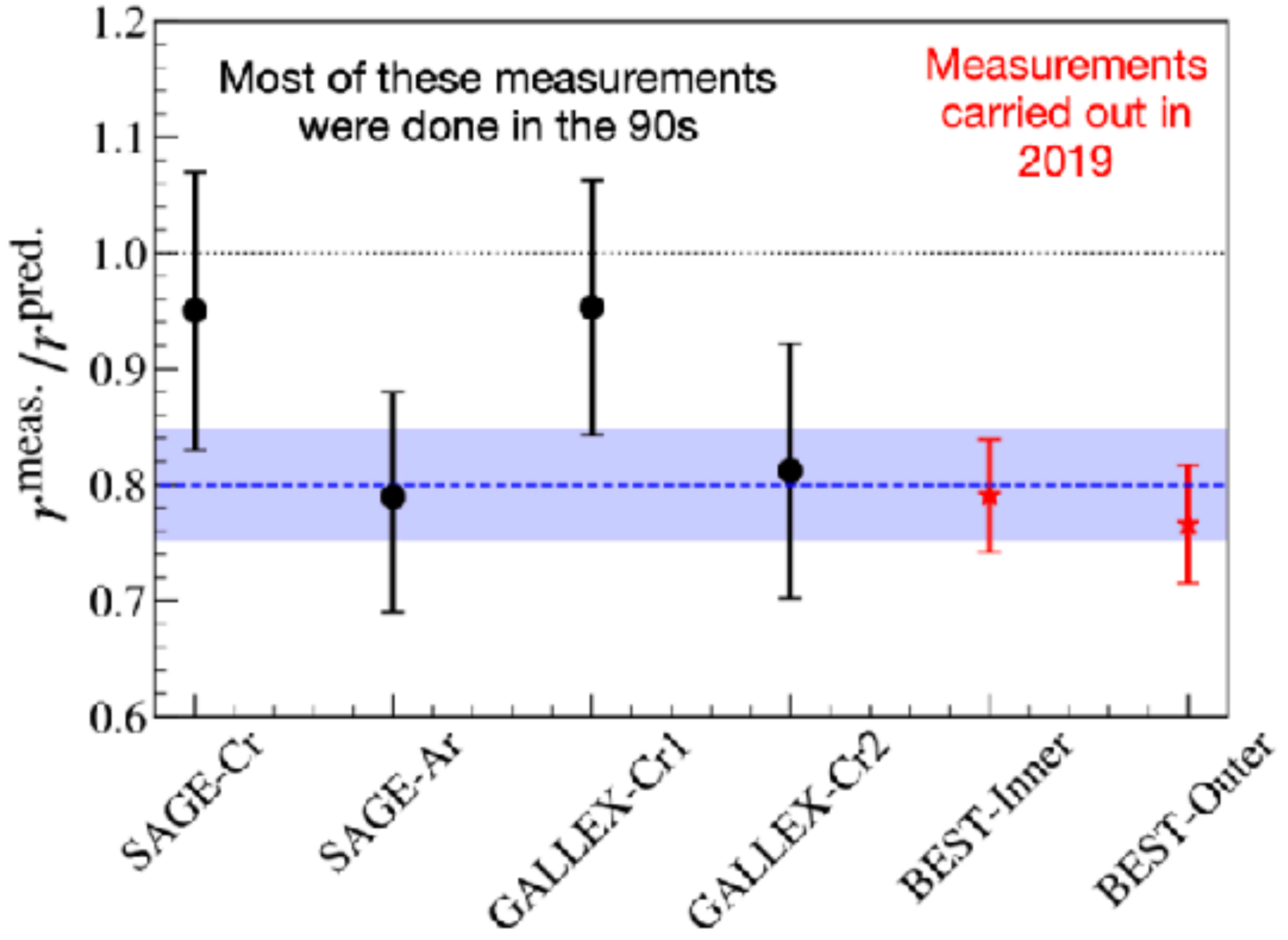


Recent fission data suggests that the flux were overestimated… by about the right amount!

Also essentially excluded by short baseline experiments searching for sterile neutrinos: DANSS, NEOS, PROSPECT, SoLid, STEREO.

Gallium anomaly

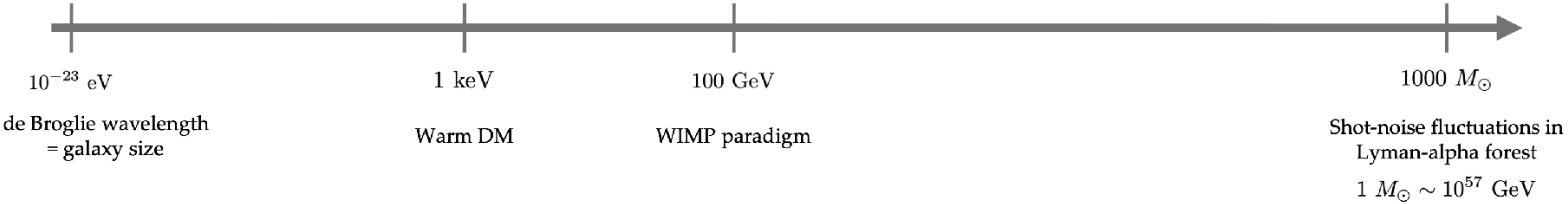
Seen by several experiments (including recent)



Also excluded by short baseline experiments.

Dark Matter and a Possible Dark Sectors

The Range of Possibilities is Stunning!



A clear roadmap!

Challenge #1: Fully Cover Electroweakino DM, e.g. with Cherenkov Telescopes

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection

Challenge #3: Build out the suite of axion searches

Challenge #4: Build out the suite of accelerator searches—high energy and intensity—for hidden sectors

Challenge #5: Cover the abundance-driven light DM models in direct detection

Challenge #6: Observe the Dark Matter Power on Small Scales

…

Jocelyn and Stefania have covered (#2 - #5) !

The Road Map

The Range of Possibilities is Stunning!

10^{-23} eV	1 keV	100 GeV	$1000\ M_\odot$
de Broglie wavelength = galaxy size	Warm DM	WIMP paradigm	Shot-noise fluctuations in Lyman-alpha forest
			$1\ M_\odot \sim 10^{57}$ GeV

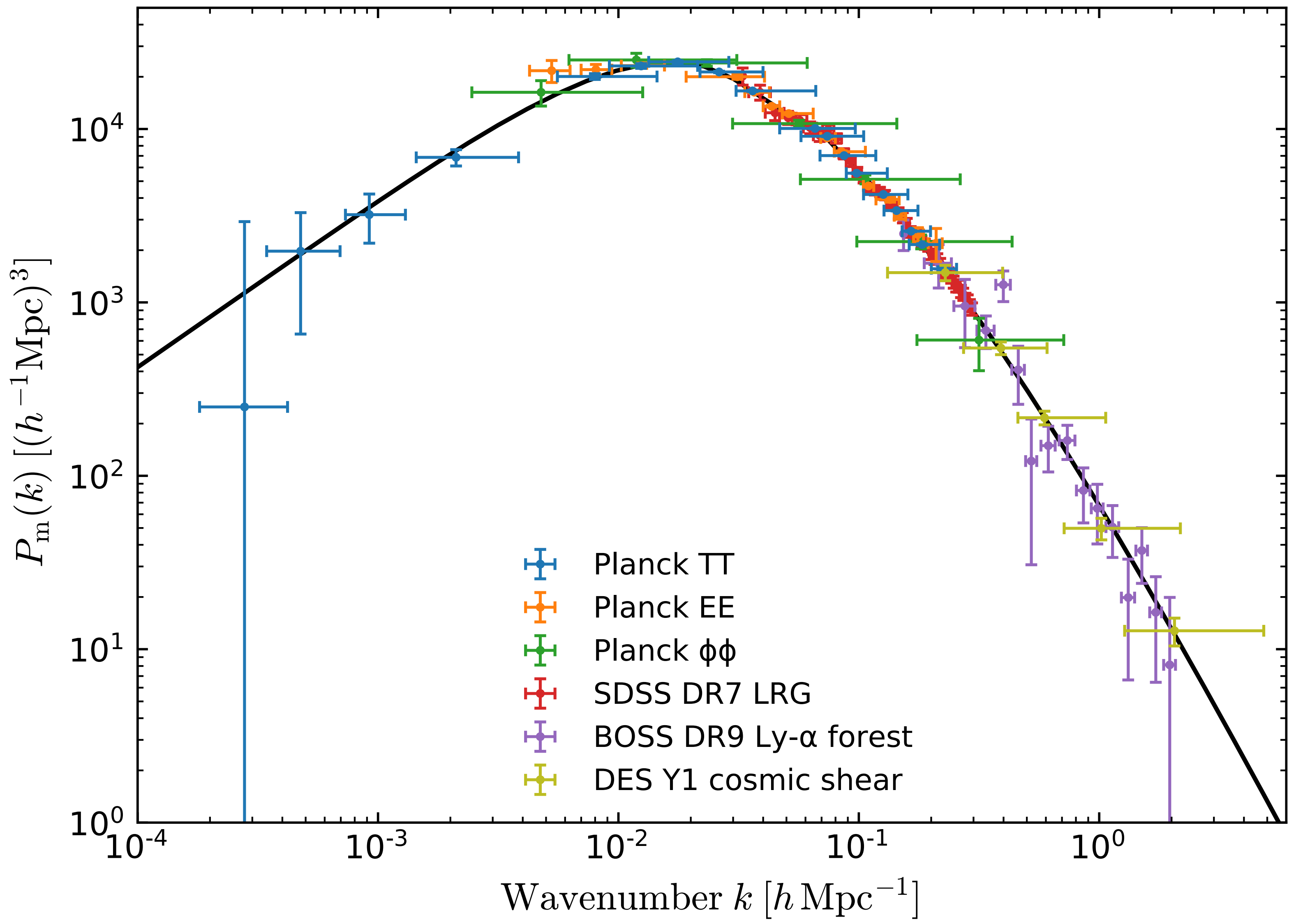
Challenge #1: Fully Cover Electroweakino DM, e.g. with Cherenkov Telescopes

- LHC is very sensitive to strongly produced SUSY particles, less so for pure electroweakinos
- Cherenkov telescopes can cover to larger masses!

Challenge #6: Observe the Dark Matter Power on Small Scales

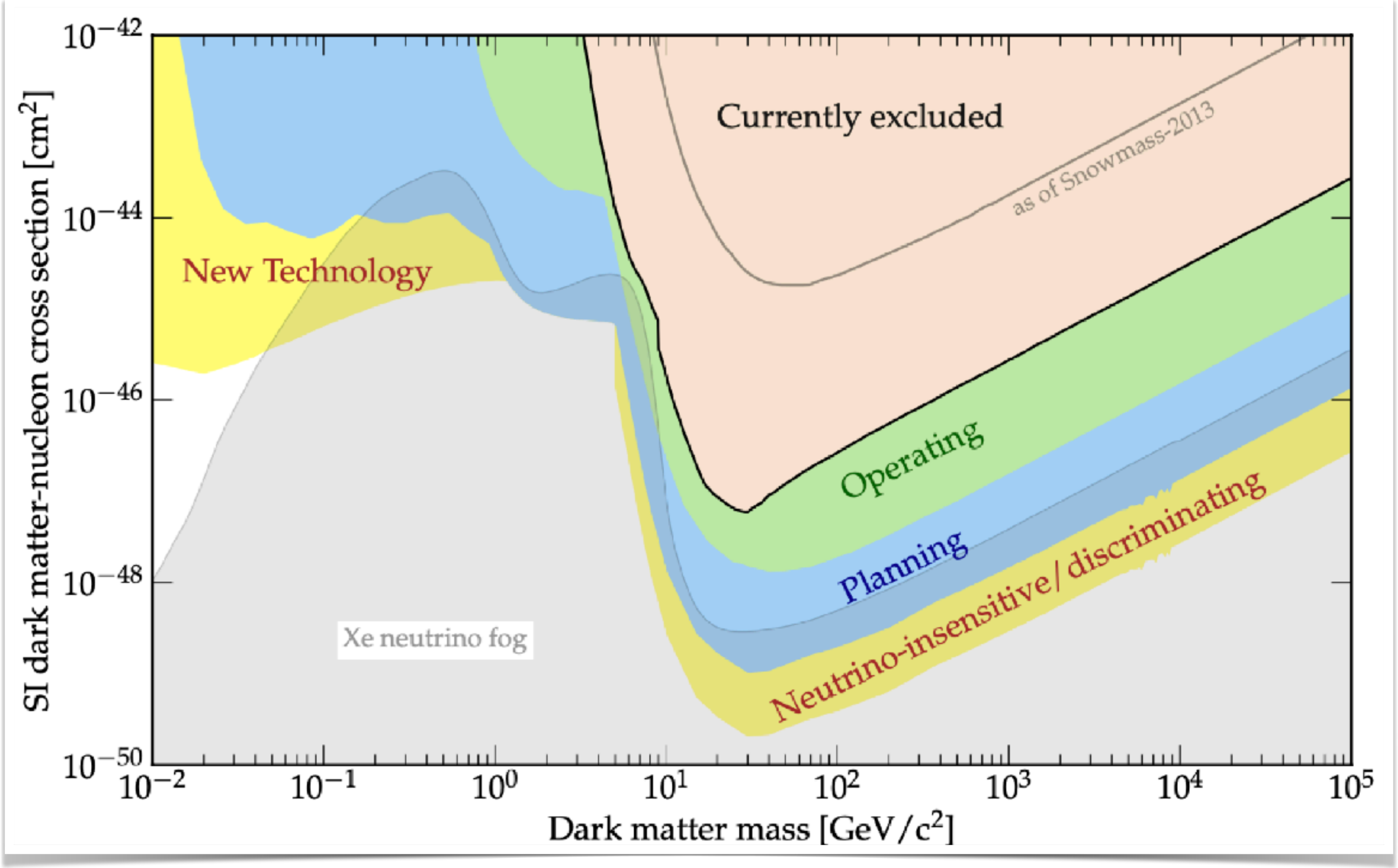
Theories as **PBH**, **axions**, predict different behavior than Λ_{CDM} at sub-halo scales, requiring new measurements of small scale!

(e.g. measuring the changes in the metric due to transiting DM substructure using Pulsar Timing Arrays)



Reaching the Neutrino Fog

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection

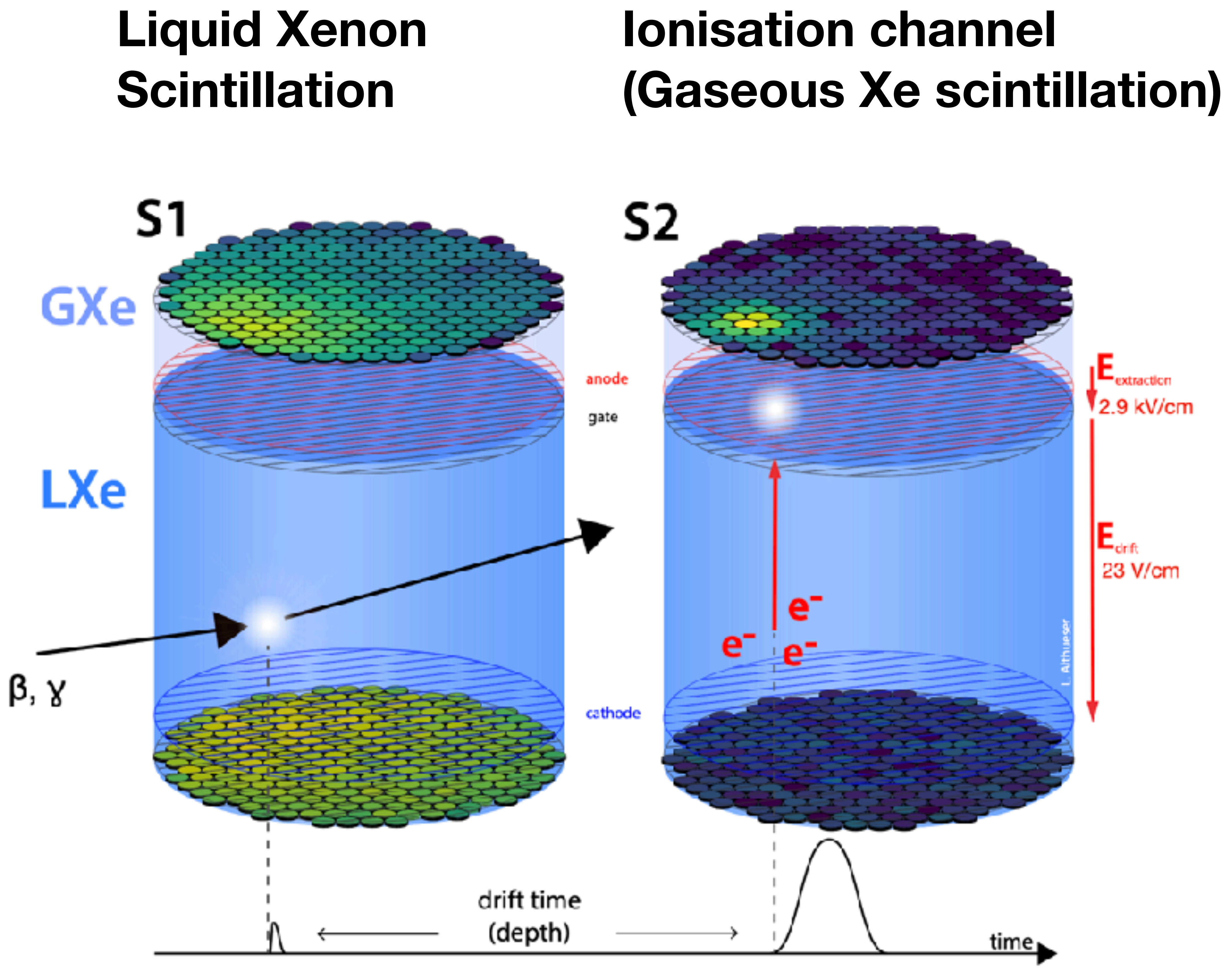


- **Currently operating detectors:**
  - Xenon nT, PandaX-4T, LZ-7T
  - Argon DarkSide
- **Next generation:**
  - PandaX-20T
  - Darwin XLZD 40-60T

Dual Phase Xenon TPC Experiments

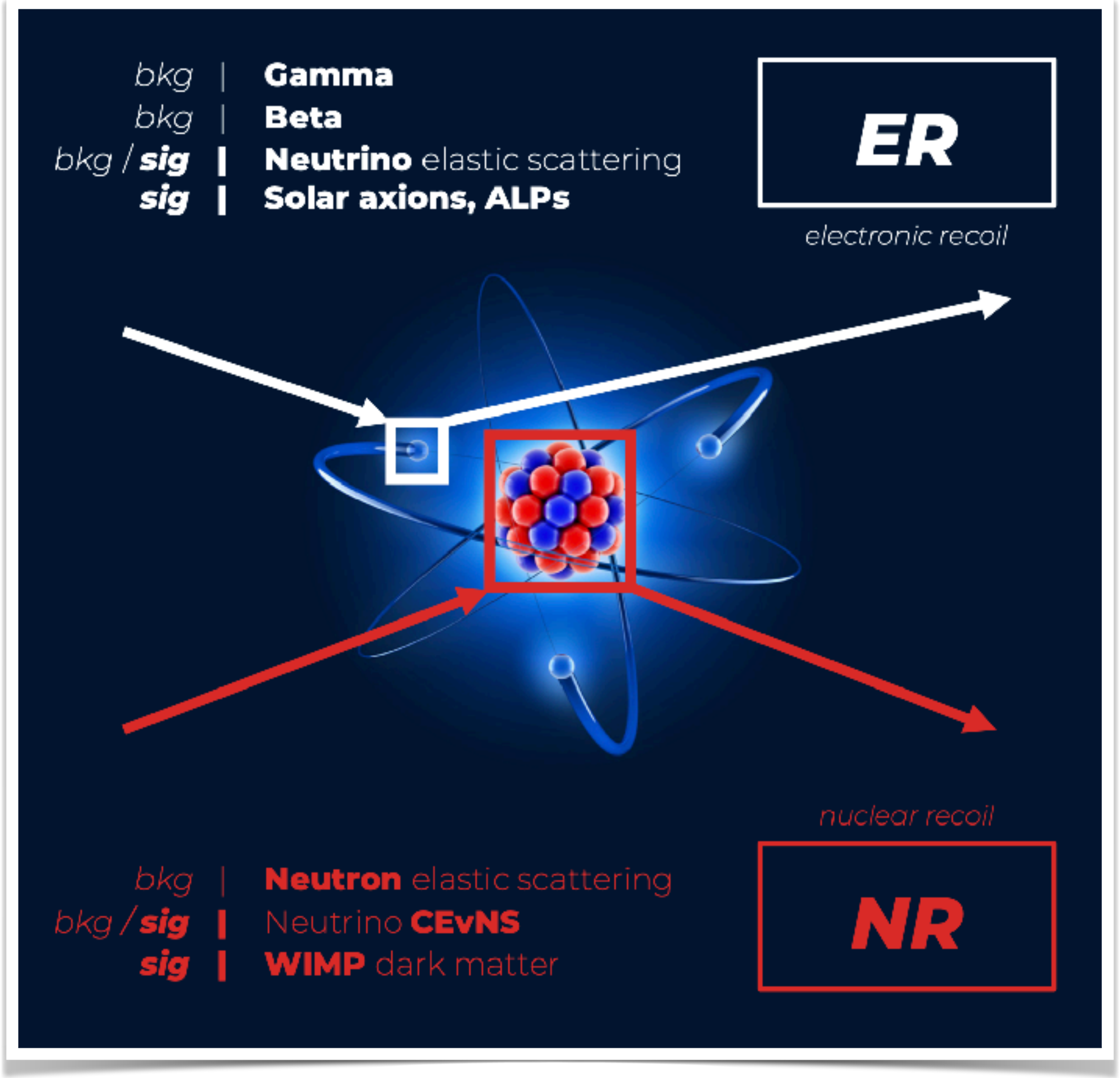
Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection

Xenon nT

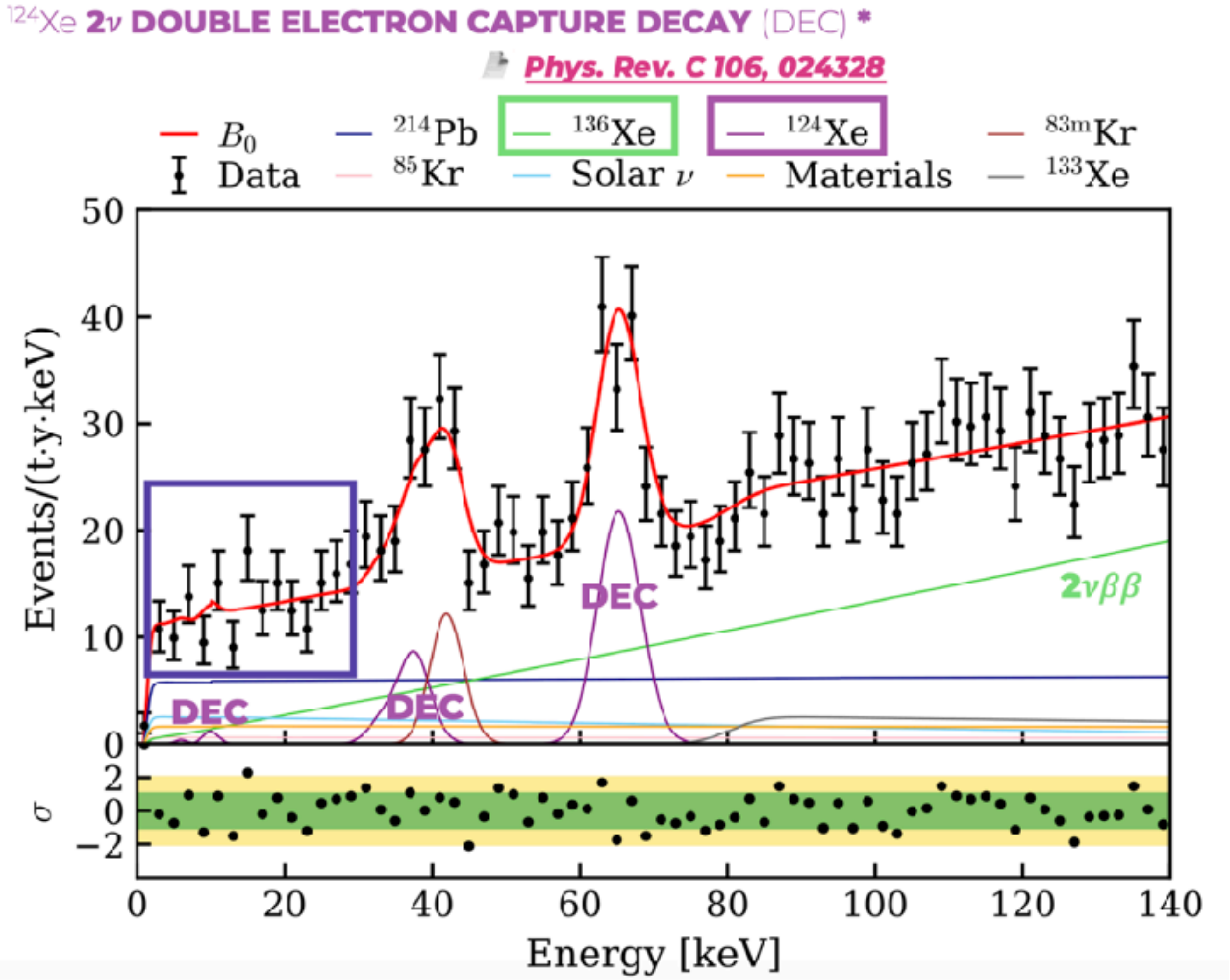


Electron Recoils

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection



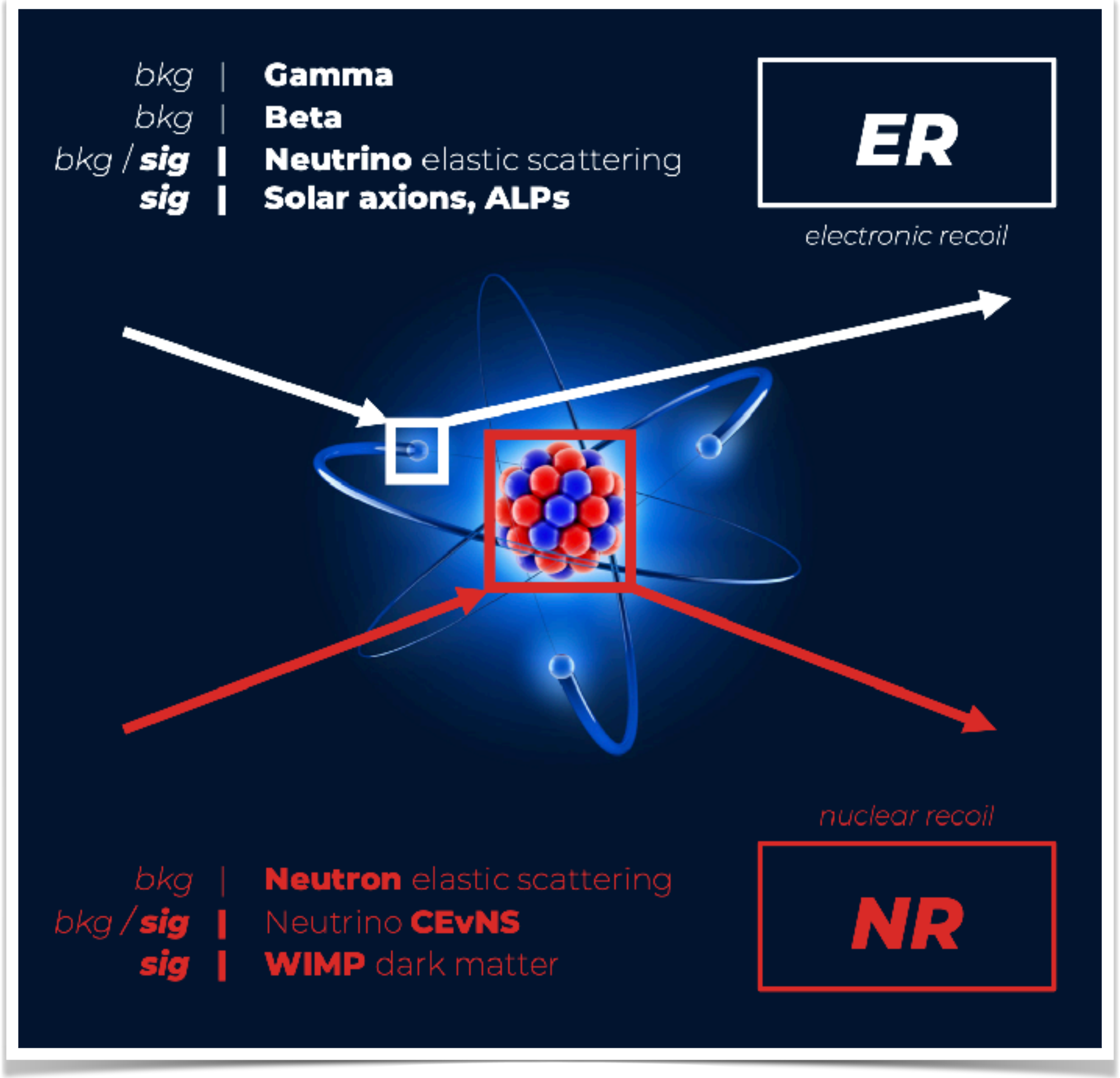
Electron Recoil in Xenon



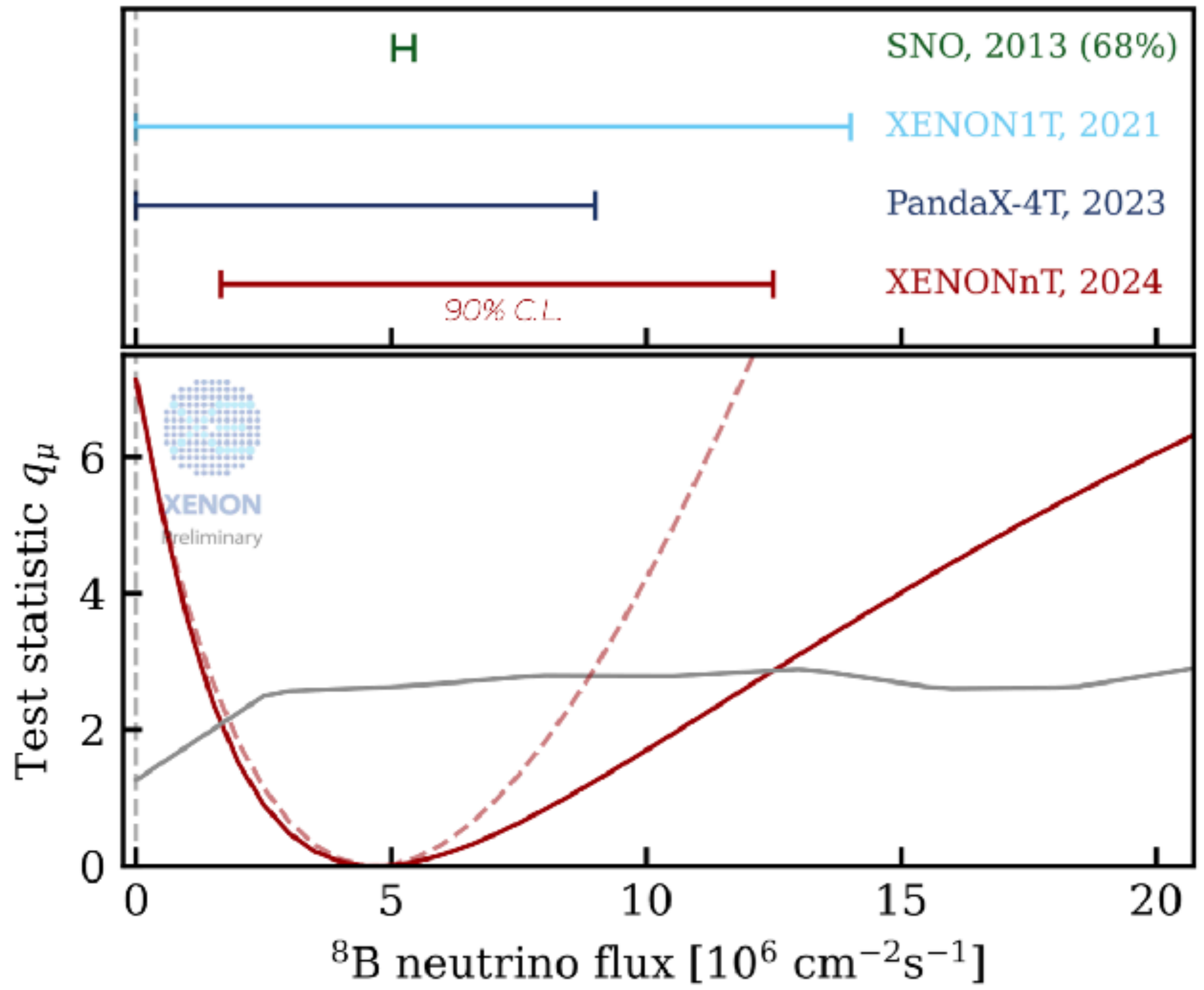
- Observation of DEC: Two of the orbital electrons are captured protons in the nucleus emission of 2 neutrinos
- Solar neutrinos background subdominant (backup PandaX-4T)

Reaching the Neutrino Fog

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection



Nuclear Recoils from ^{8}B solar neutrinos CEvNS in Xenon!



2.73 σ SIGNIFCANCE

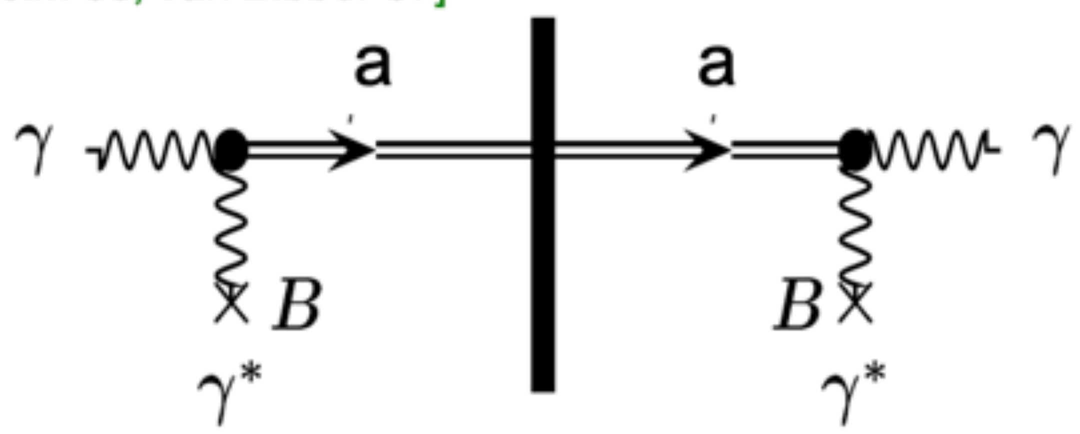
37 Events observed with 26 bkg and 11 signal expected!

Great achievement, but now need to learn how to fight it!

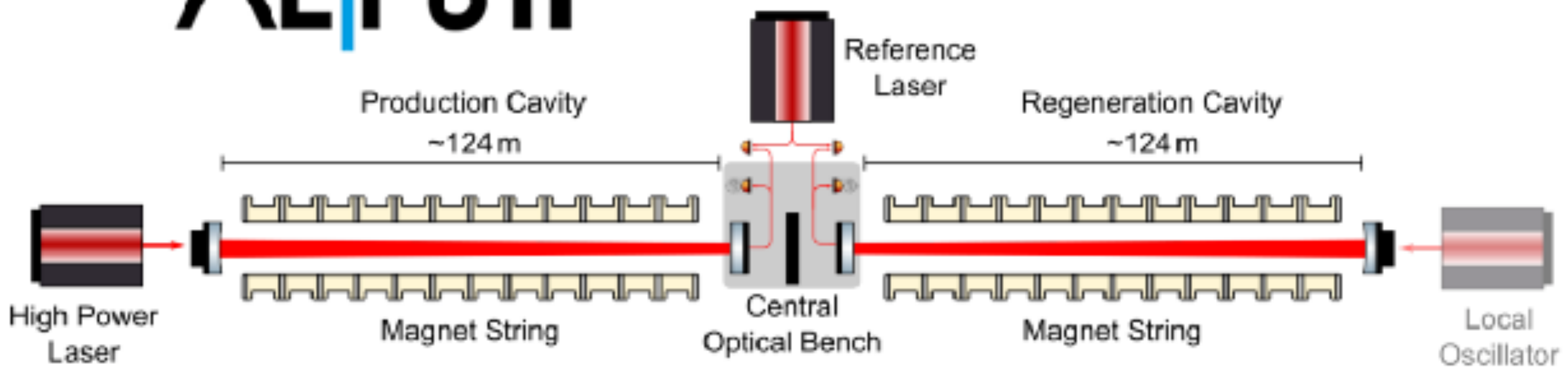
Axions an Ambitious Program

Challenge #3: Build out the suite of axion searches

Light shining through a wall (LSW)
[Anselm 85; van Bibber 87]

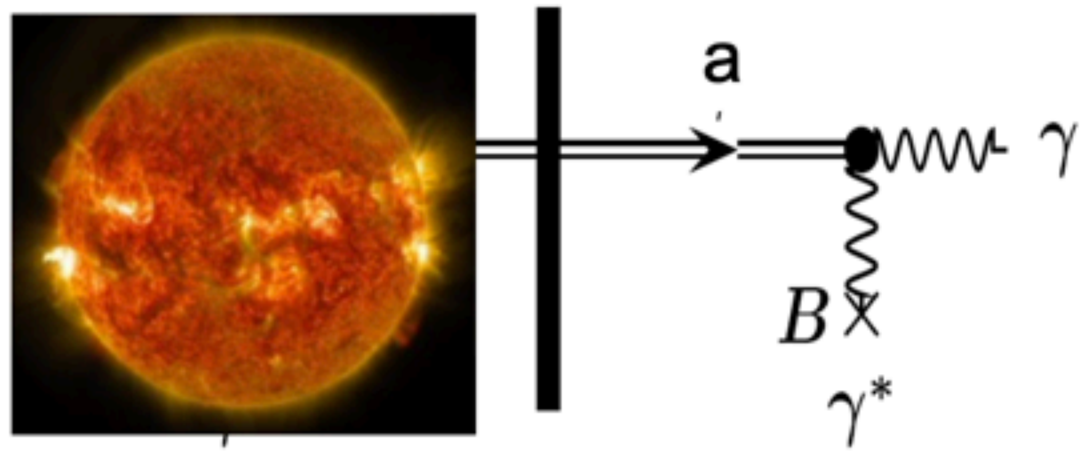


ALPS II



As well as **OSQAR**

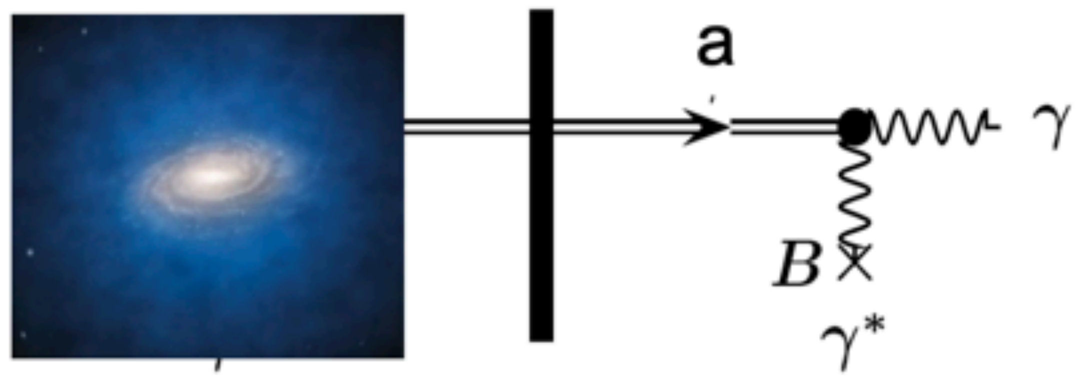
Helioscope: Sun shining through a wall
[Sikivie 83]



IAXO

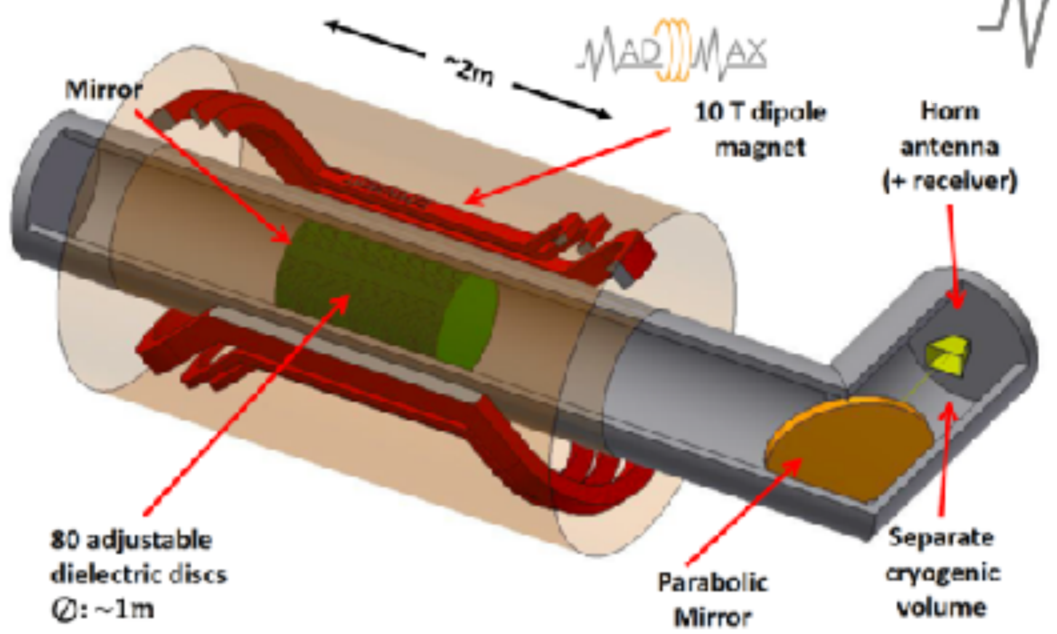
As well as **SUMICO**, and **CAST**

Haloscope: DM shining through a wall
[Sikivie 83]

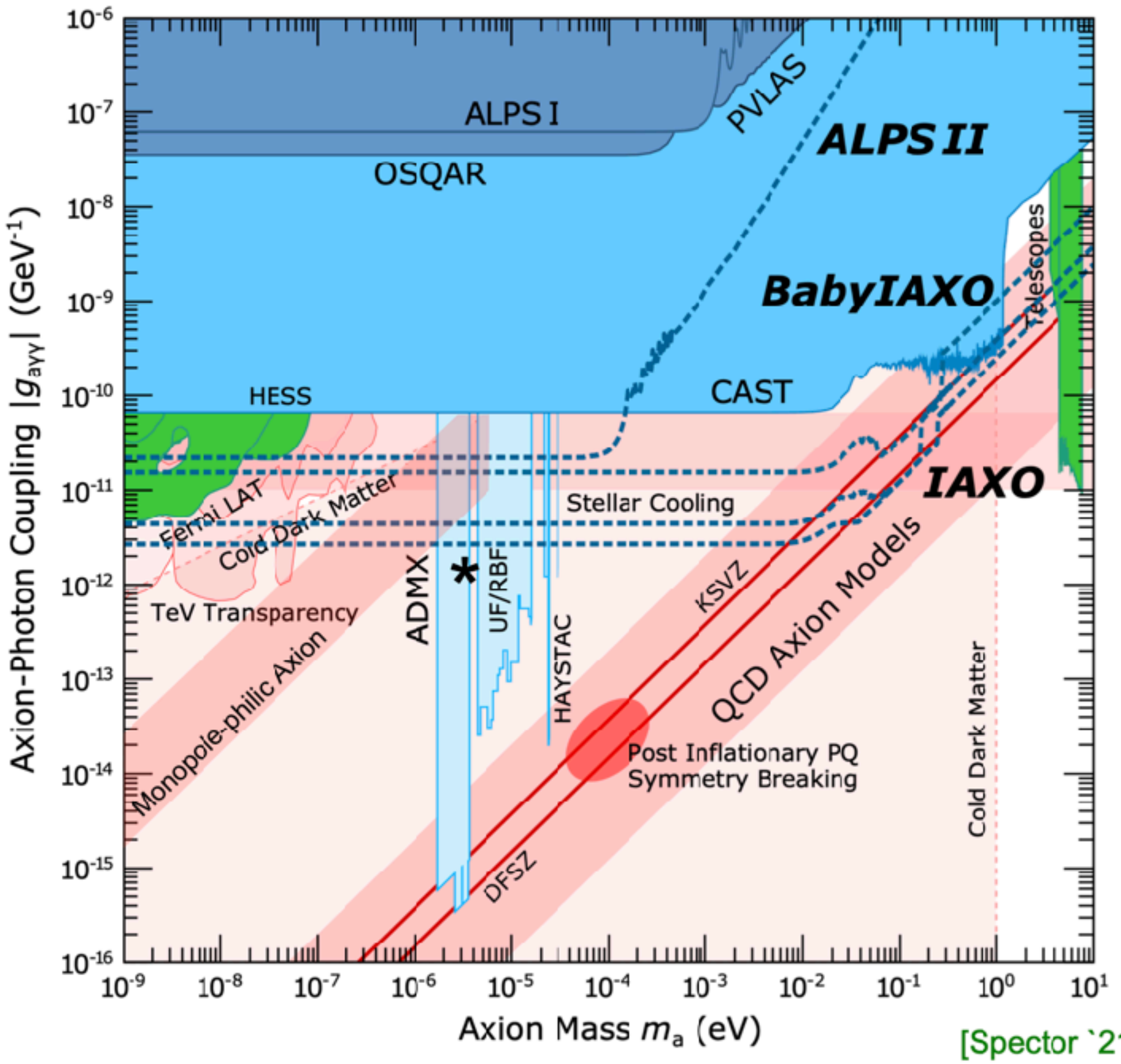


[Lindner]

MADMAX



As well as **ADMX**, **HAYSTAC**, **QUAX**, **CAST-CAPP**, **RADES**



[Spector `21]

Challenge #4: Build out the suite of accelerator searches—high energy and intensity—for hidden sectors

There are numerous gaps in the experimental exploration of dark sectors, both at the **electroweak-TeV** scale and at the **sub-GeV** scale.

NP particles can have a width that is suppressed by small mass splitting, multi-body final states, high NP scale small coupling, etc.

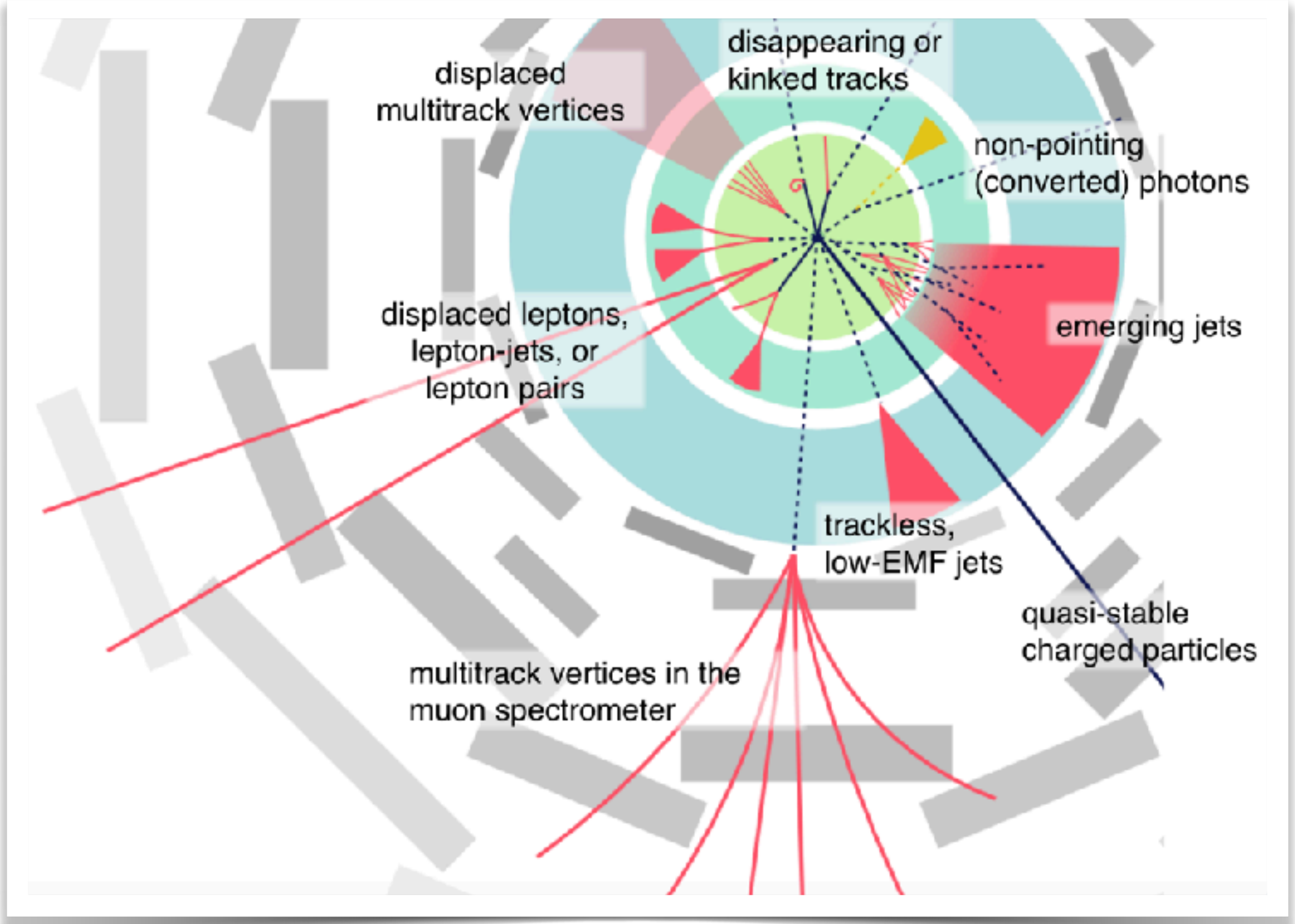
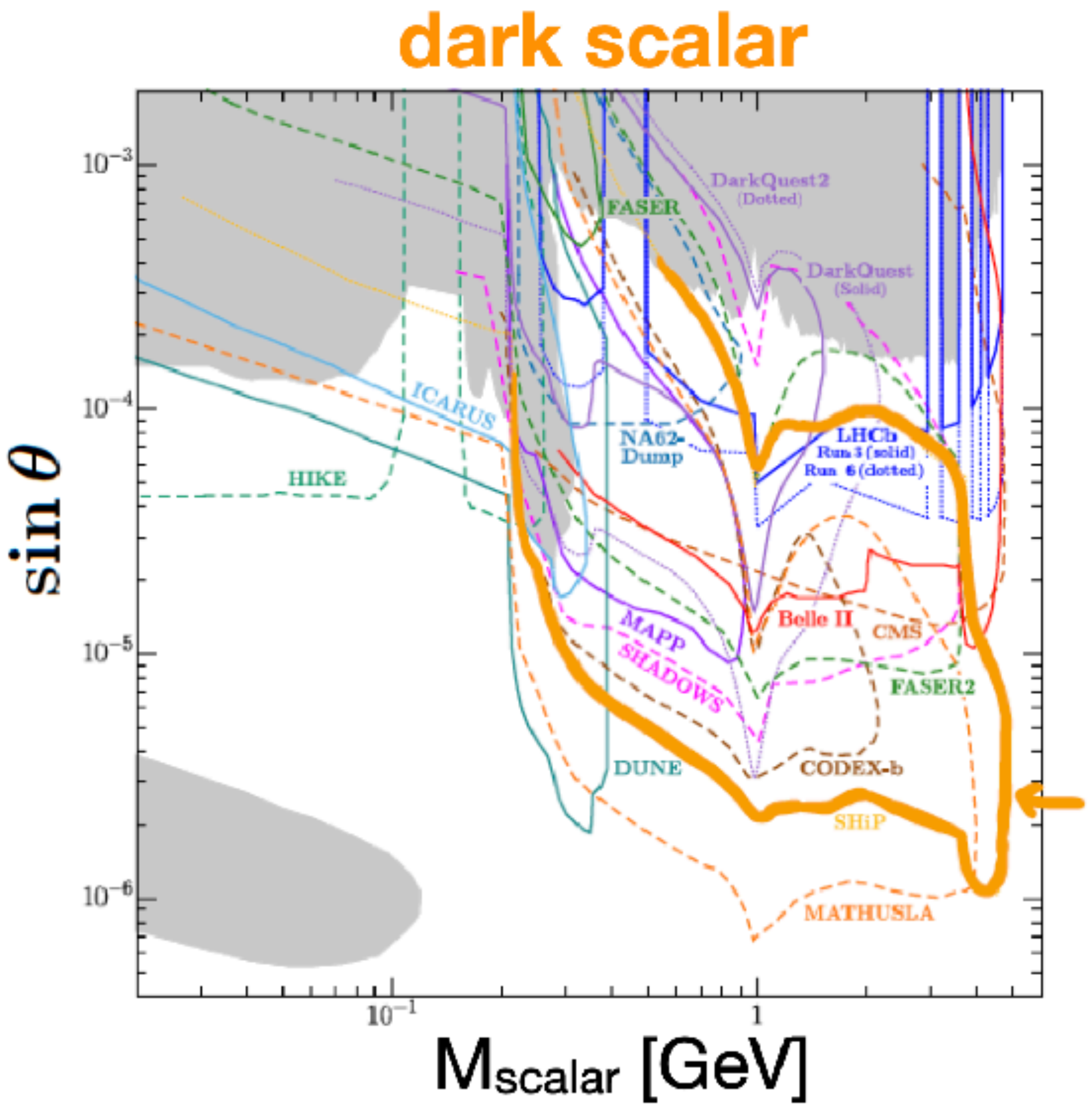


Image from H. Russel

Sub-GeV new physics motivates searches at high intensity facilities and Meson factories!



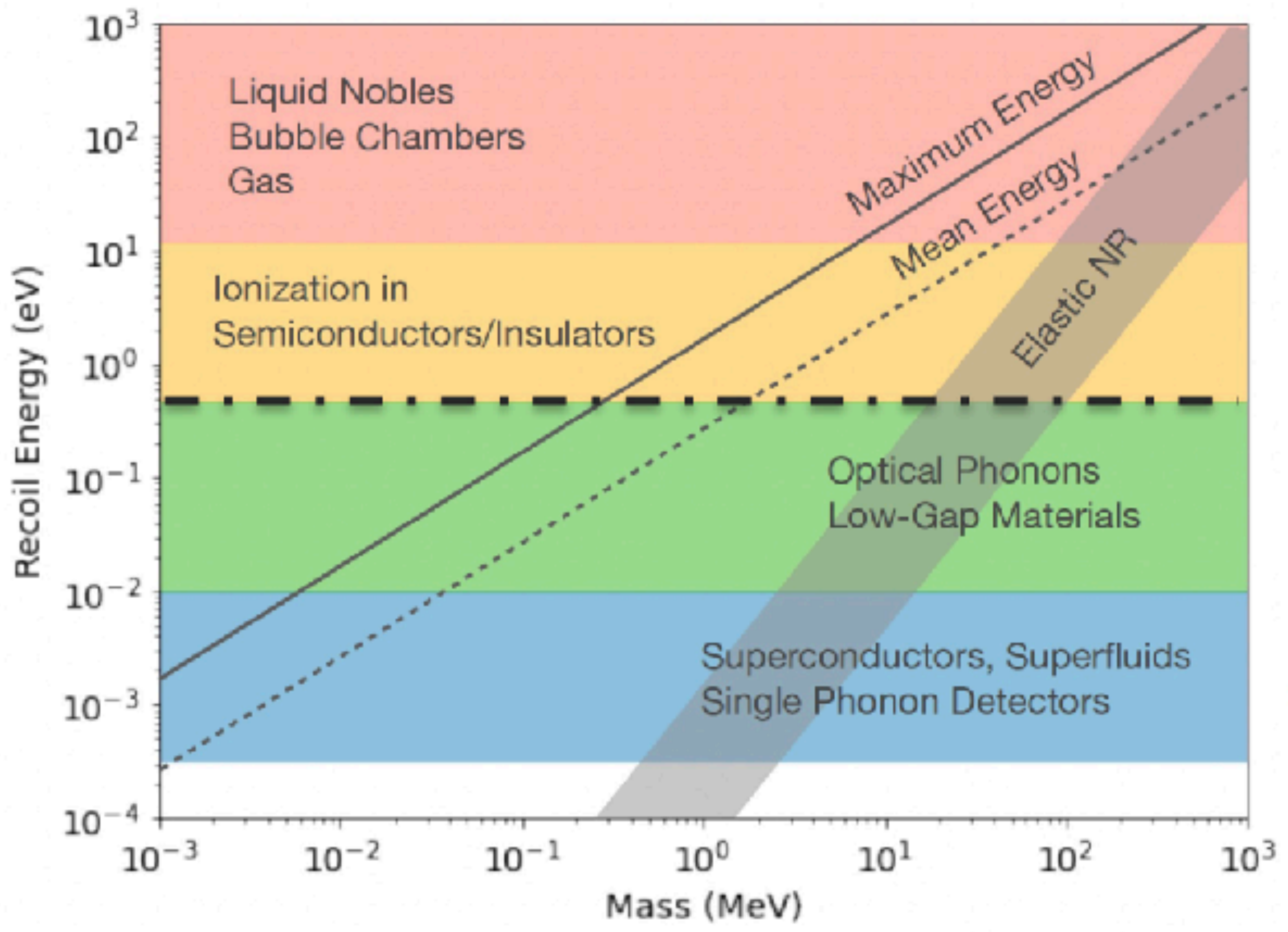
SHiP
(scalar from meson decays)

Complementarity with LHC auxiliary detectors + neutrino experiments

Challenge #5: Cover the abundance-driven light DM models in direct detection

Hidden sector DM: huge range of techniques… Models motivate from relic abundance can be tested w/1 kg-yr exposures!

Quantum sensors can go to sub-eV recoil energies (a blossoming filed!)



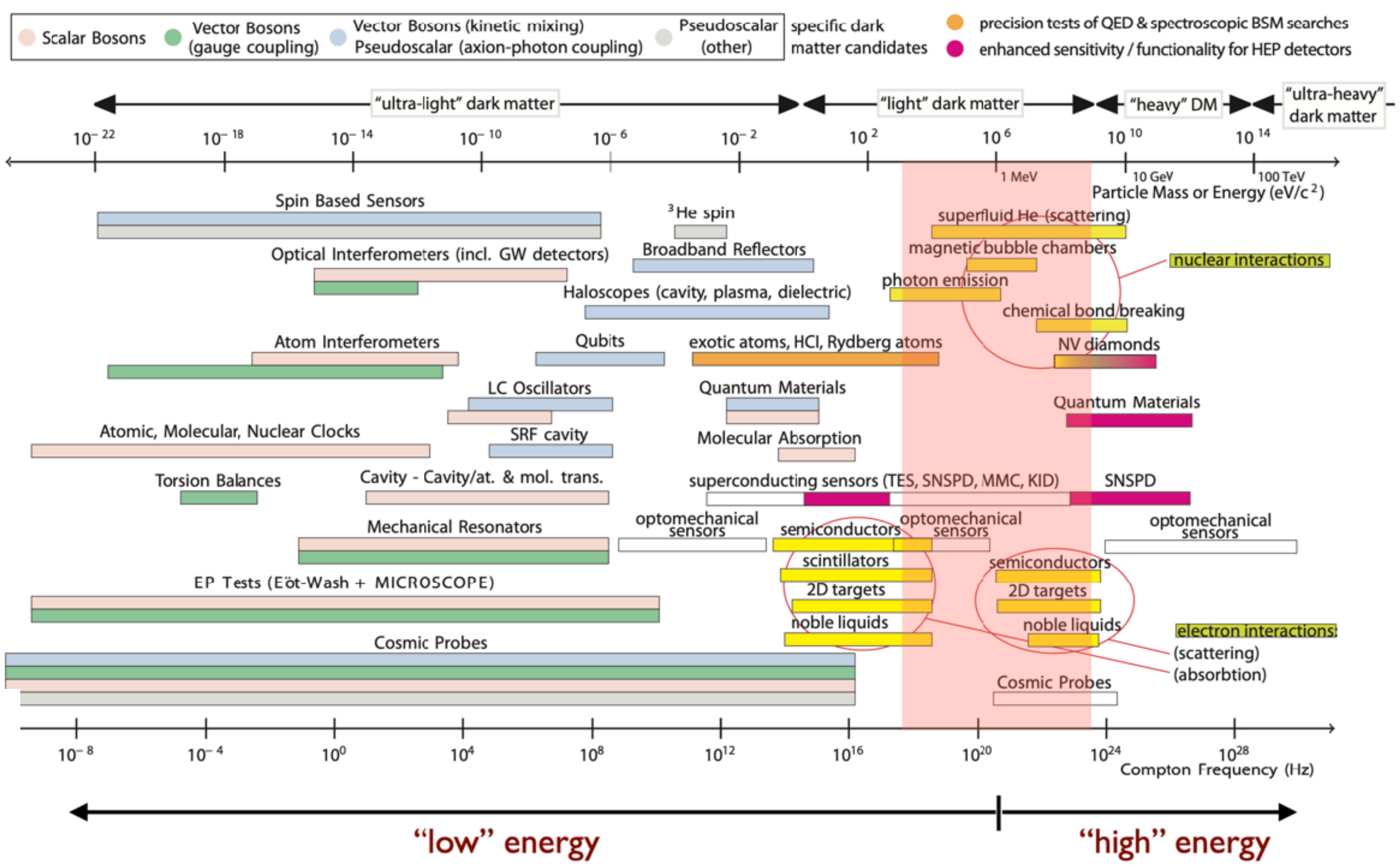
Daniel Baxter I IDM 2024   Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

$\Delta E \sim 1$ eV
e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

$\Delta E \sim 10-100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

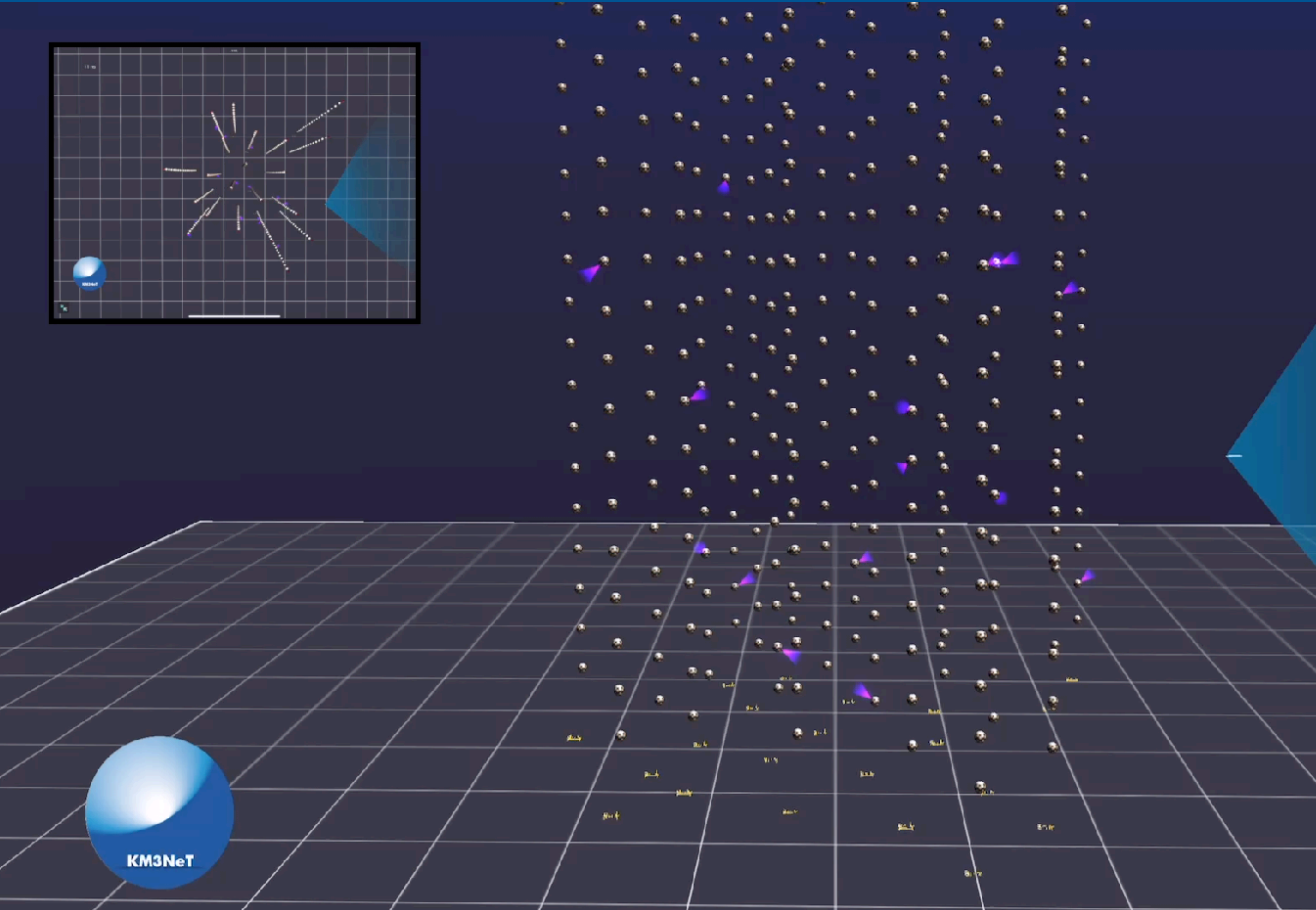
$\Delta E \sim 1$ meV
e.g. superfluids, superconductors

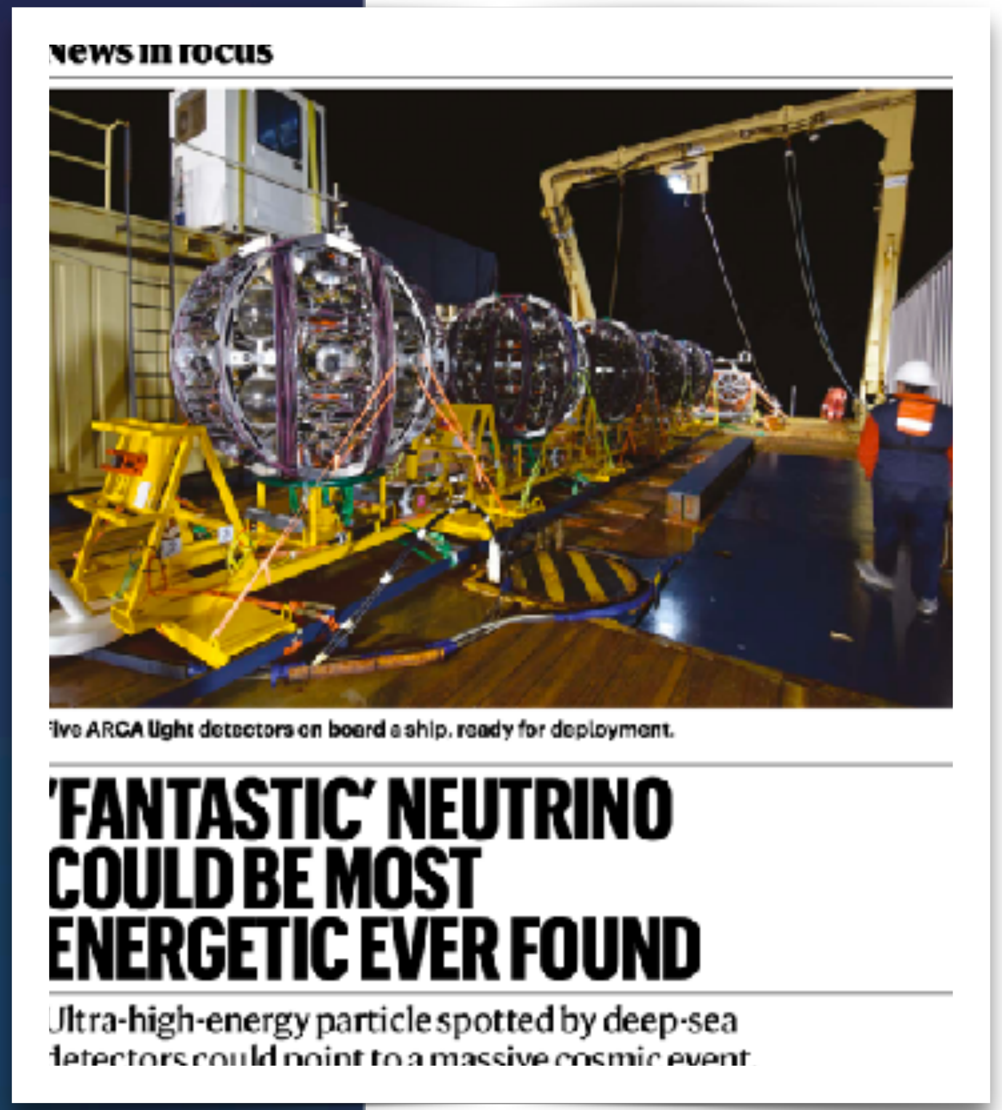
Ranges of applicability of different quantum sensor techniques to searches for BSM physics



Multi-Messenger Astrophysics

Paschal Coyle, Vitor de Souza, Lu Lu

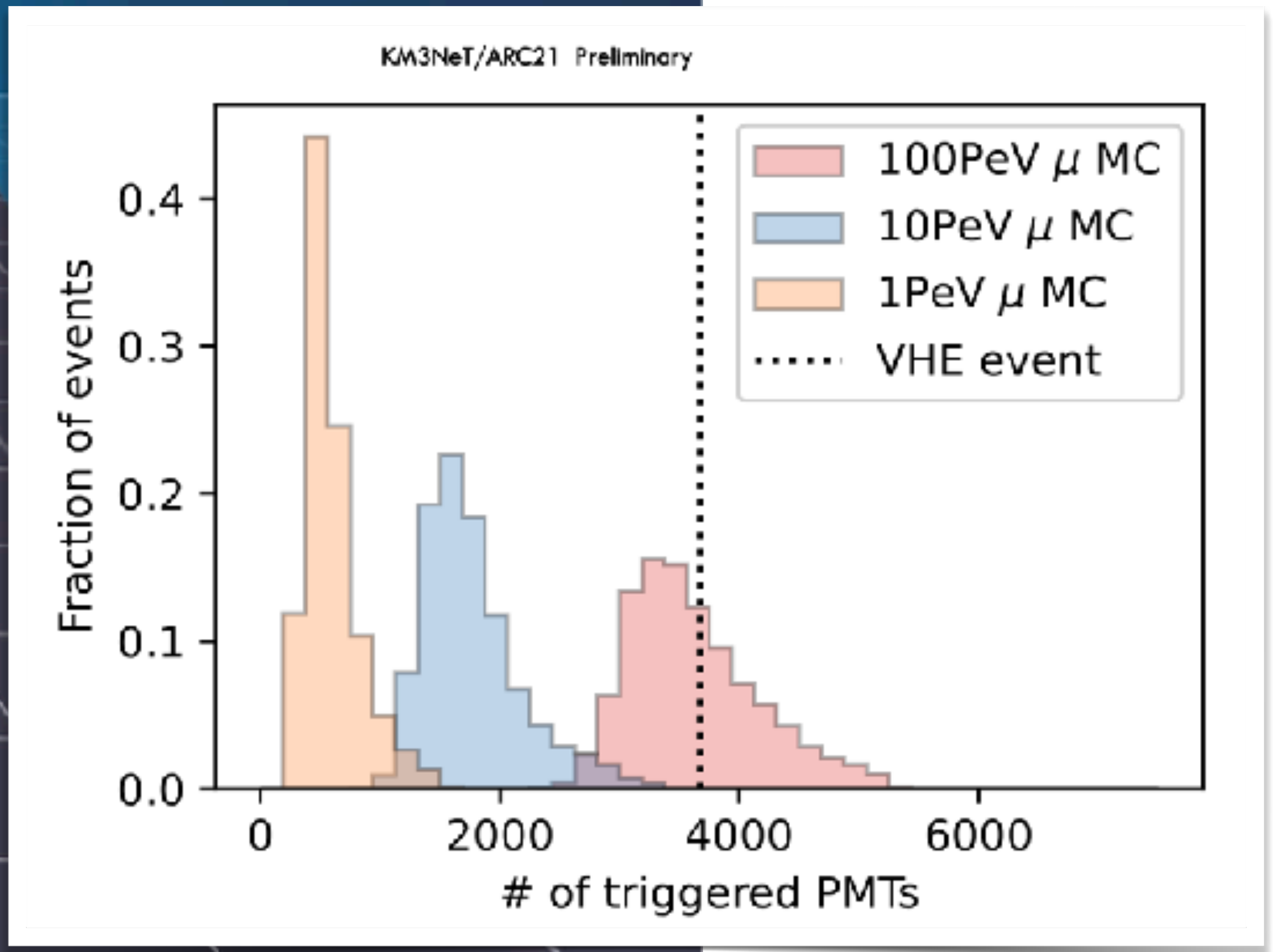



News in focus

ive ARCA light detectors on board a ship, ready for deployment.

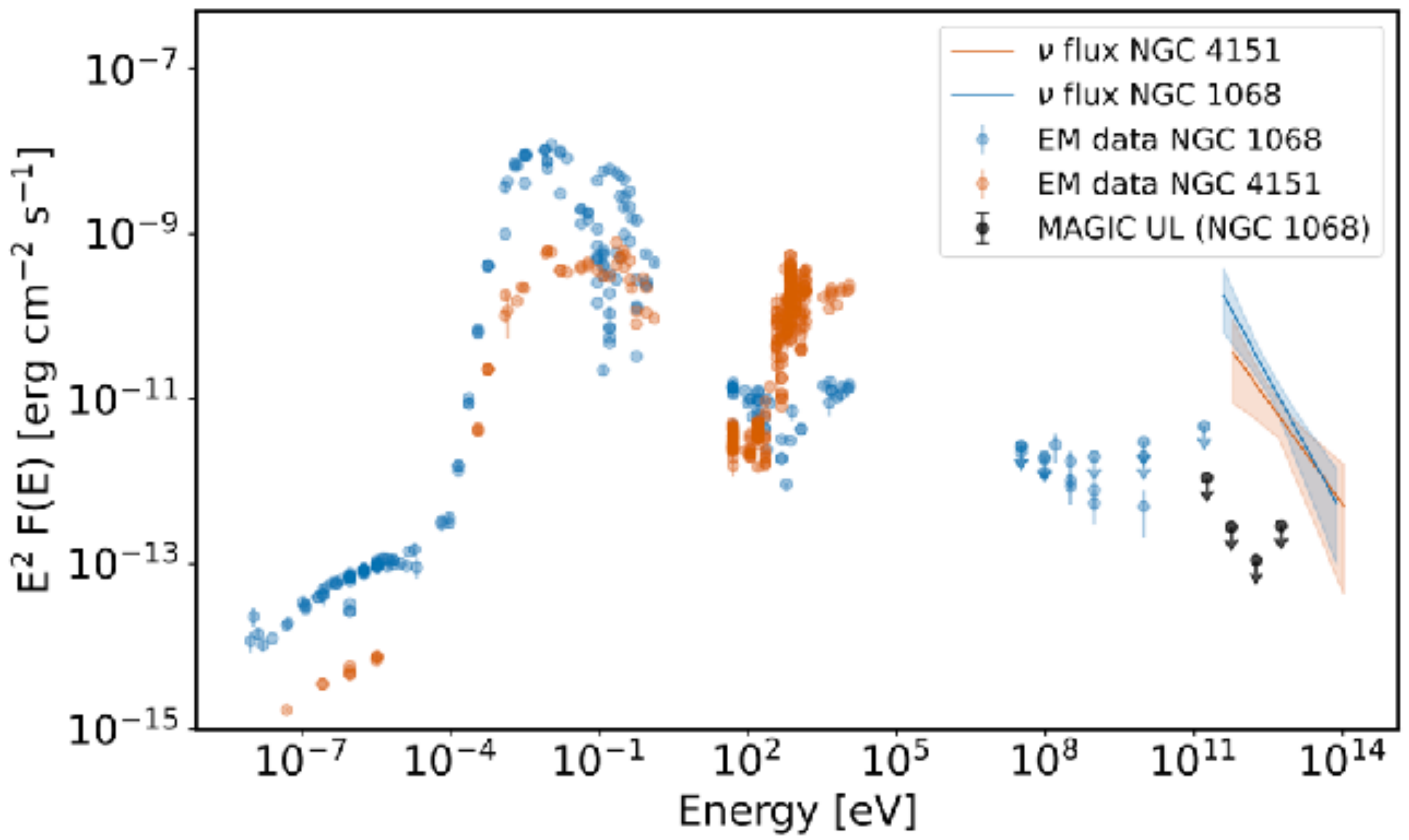
'FANTASTIC' NEUTRINO COULD BE MOST ENERGETIC EVER FOUND

Ultra-high-energy particle spotted by deep-sea detectors could point to a massive cosmic event



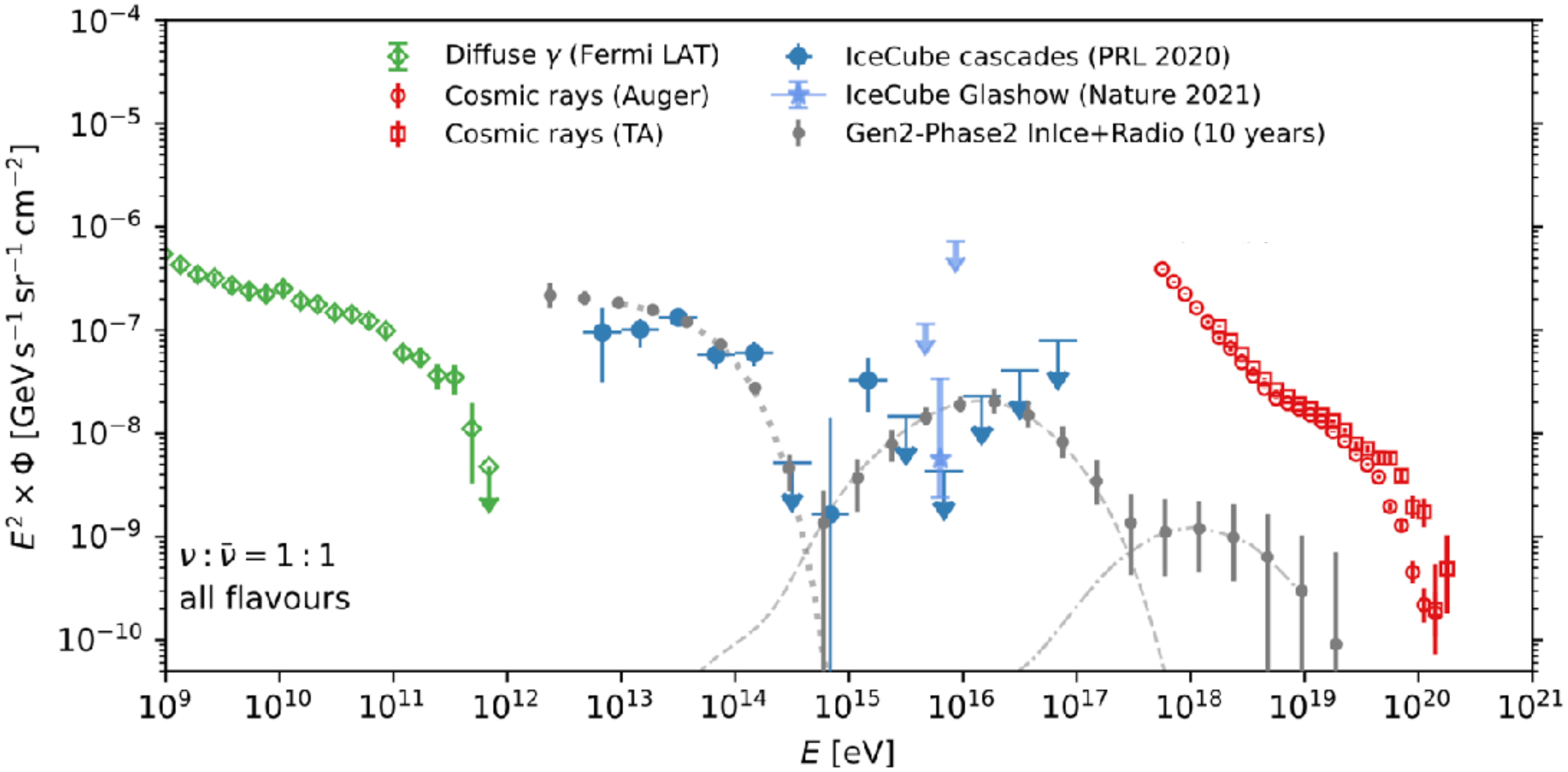
Multi-Messenger Astrophysics

Observation by IceCube of NGC1068!



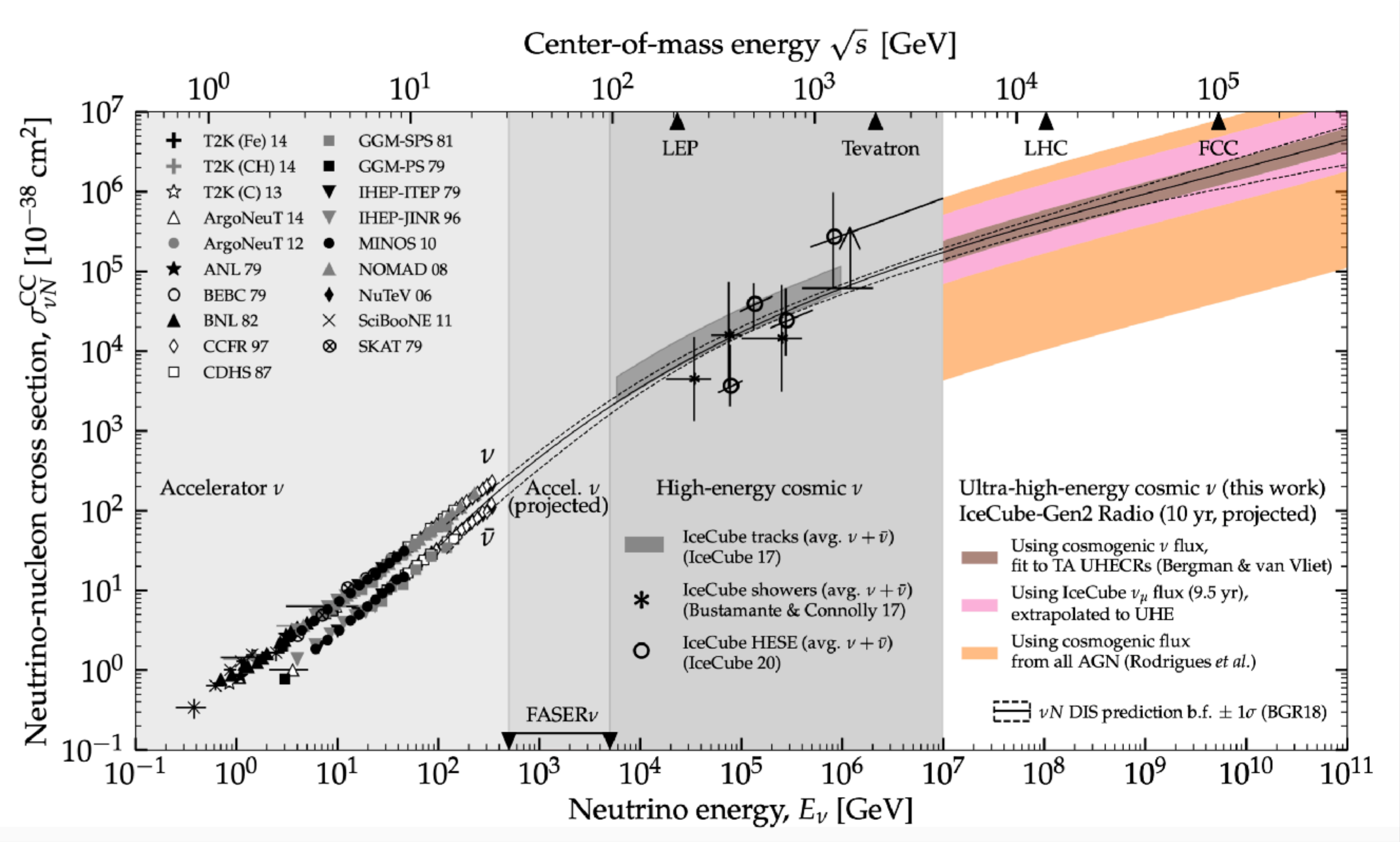
In 2022 ESO found a cloud of cosmic dust (obscuring/attenuting γ rays) at the centre of NGC1068 hiding a supermassive black hole.

Evidence for diffuse astrophysical neutrinos: "10 PeV Neutrinos a gateway to 10^{20} eV cosmic rays!"



IceCube Gen2 in the race towards Ultra High Energy neutrinos with ARA, Trinity 18, GRAND, and POEMMA projects!

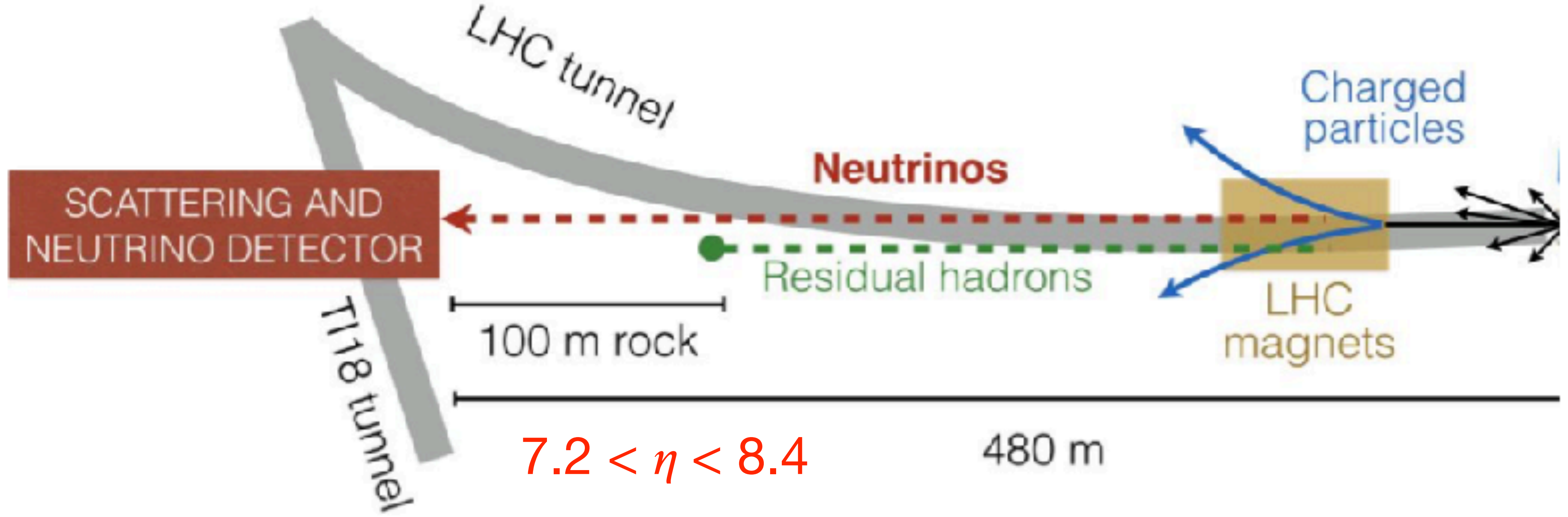
The birth of Collider Neutrinos (at the LHC)

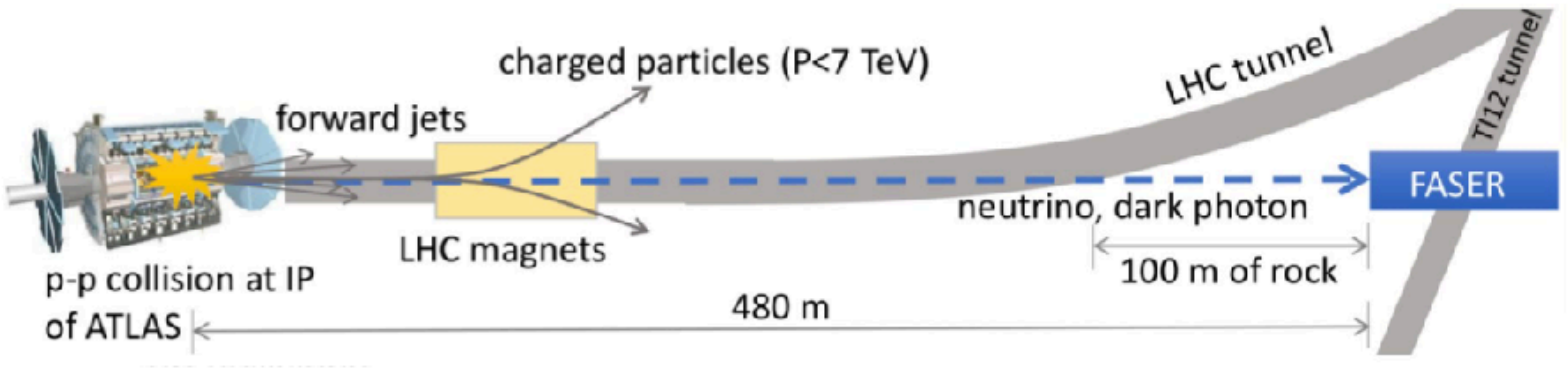


Accelerator neutrinos, up to O(100 GeV)

Cosmic neutrinos

The birth of Collider Neutrinos (at the LHC)

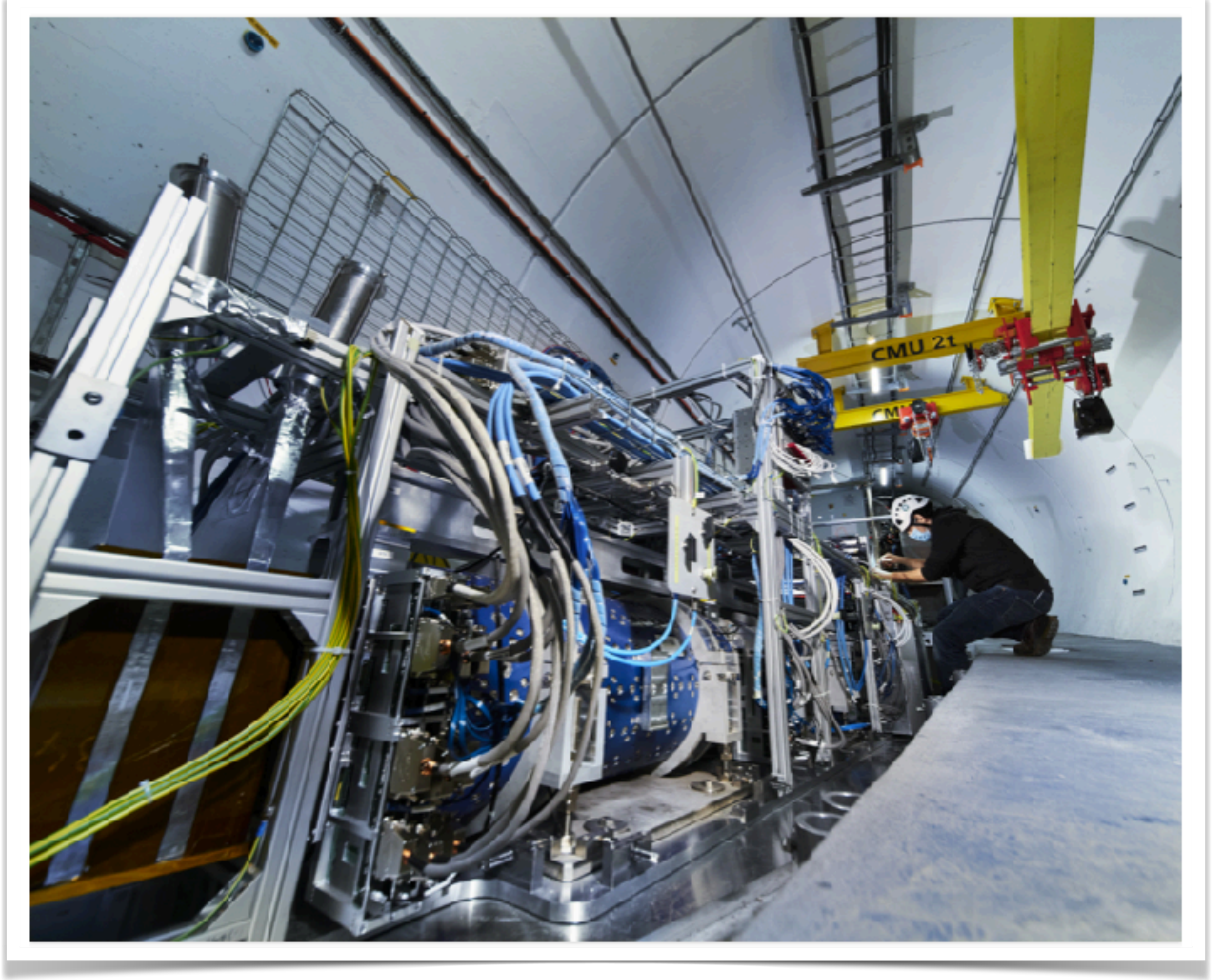




On axis

SND

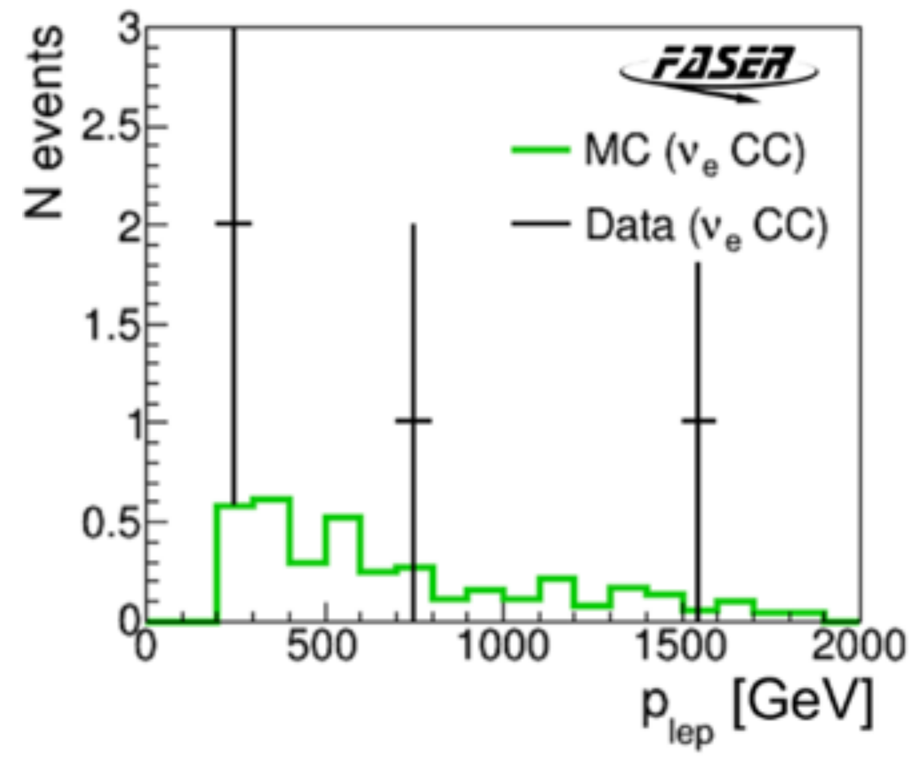
Faser-ν

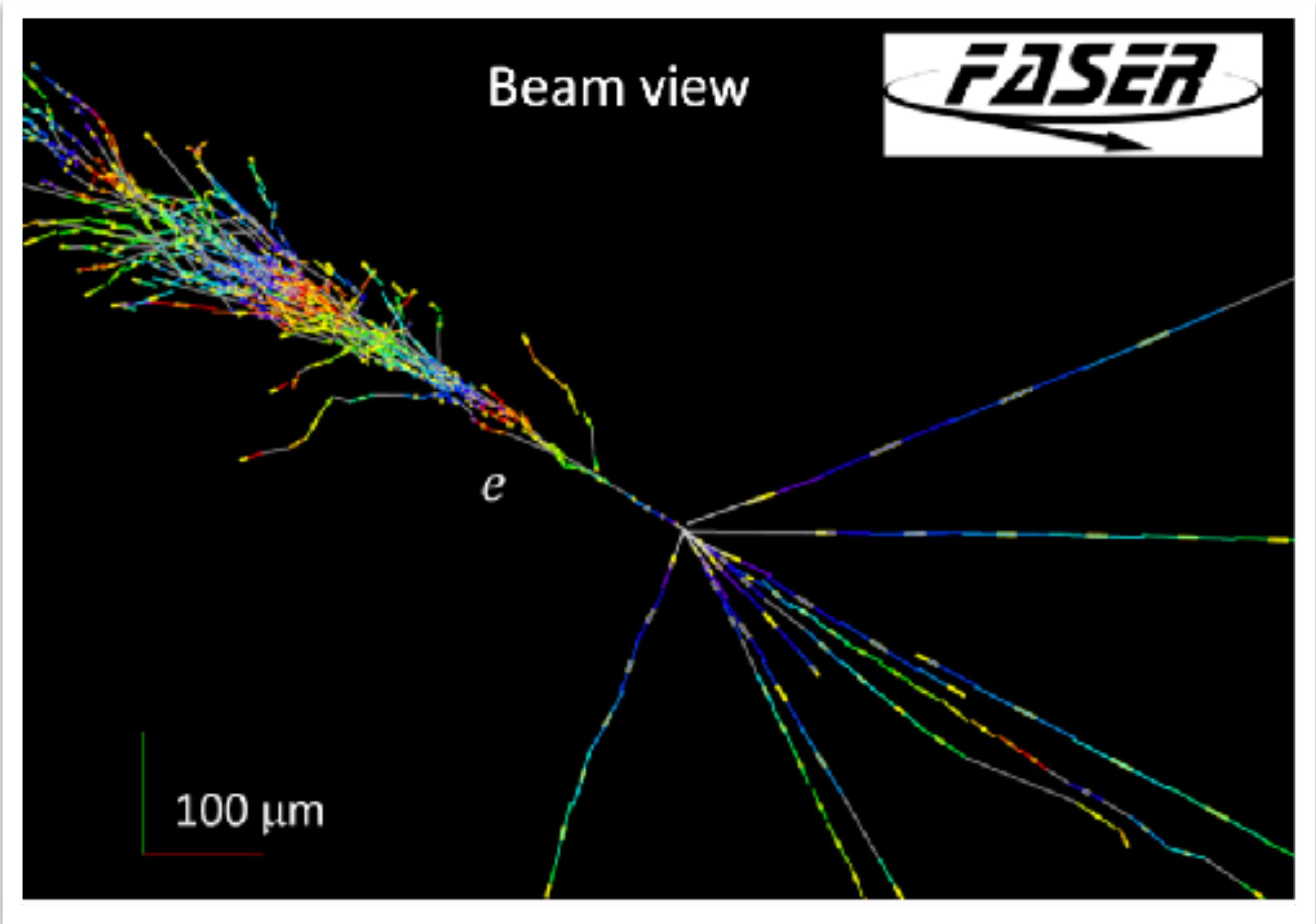


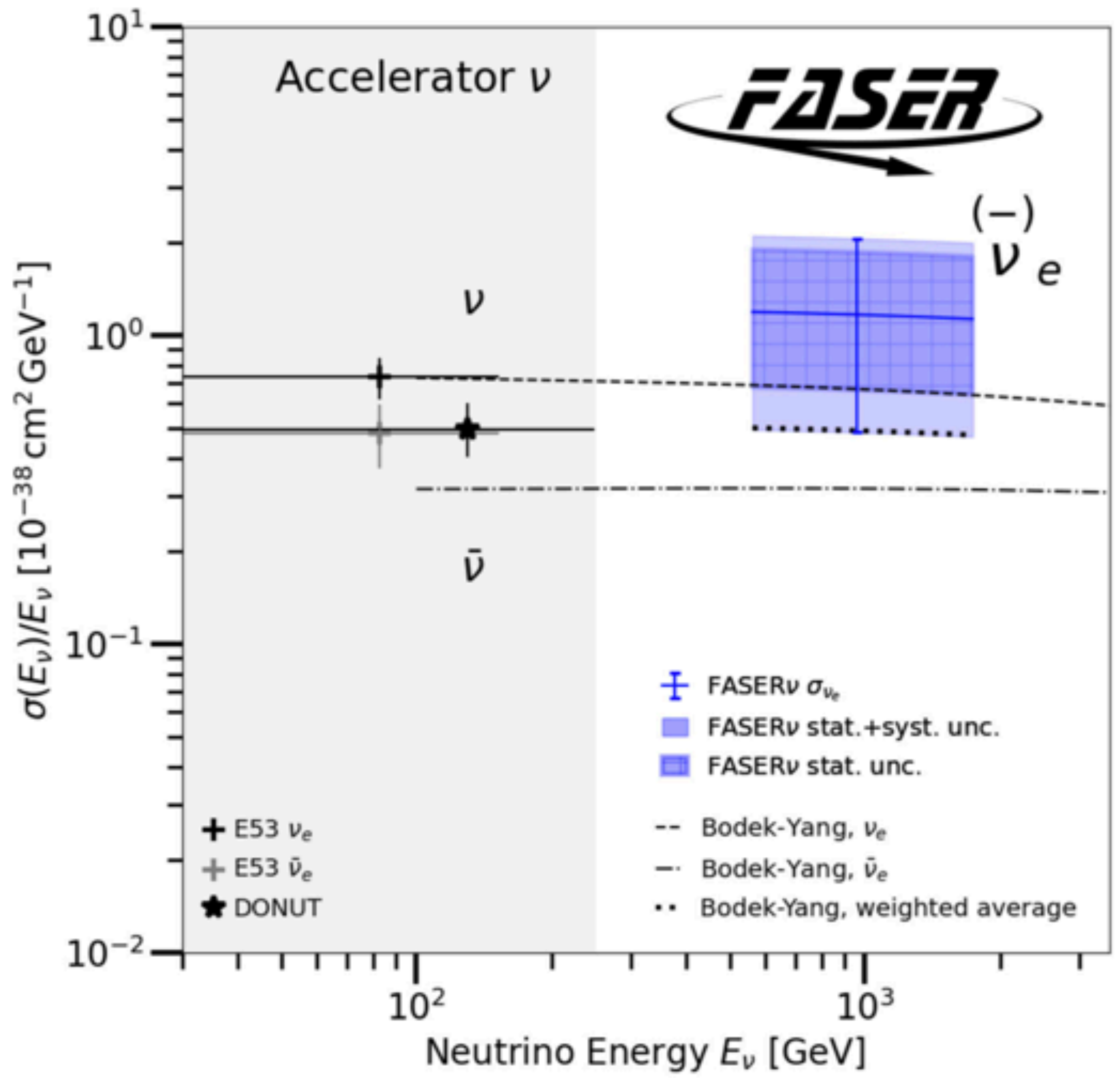
Faser-v

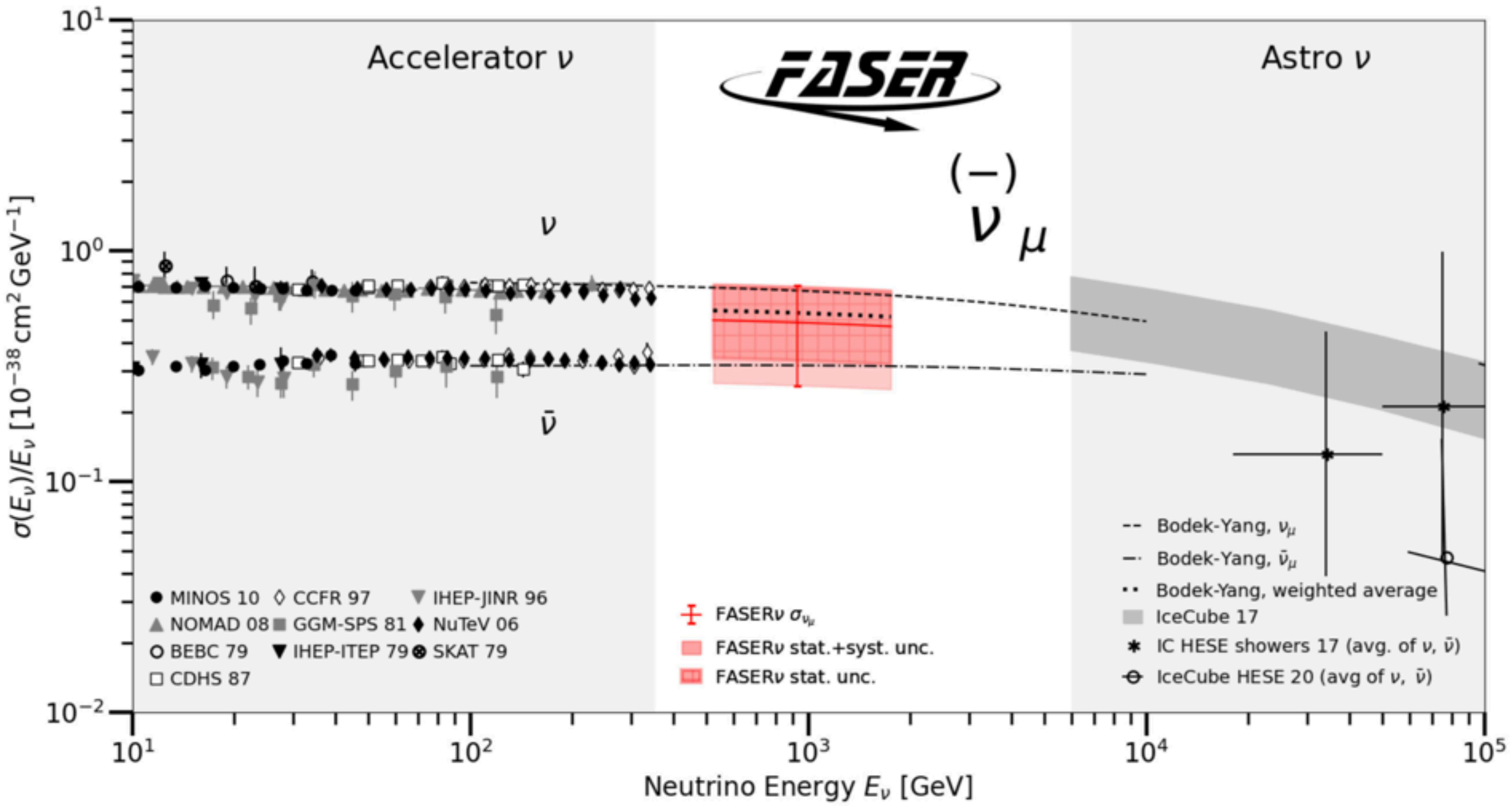
Results with emulsions (produced in Japan, sent to CERN and processed again in Japan)!

Results with emulsions (produced in Japan, sent to CERN and processed again in Japan)!



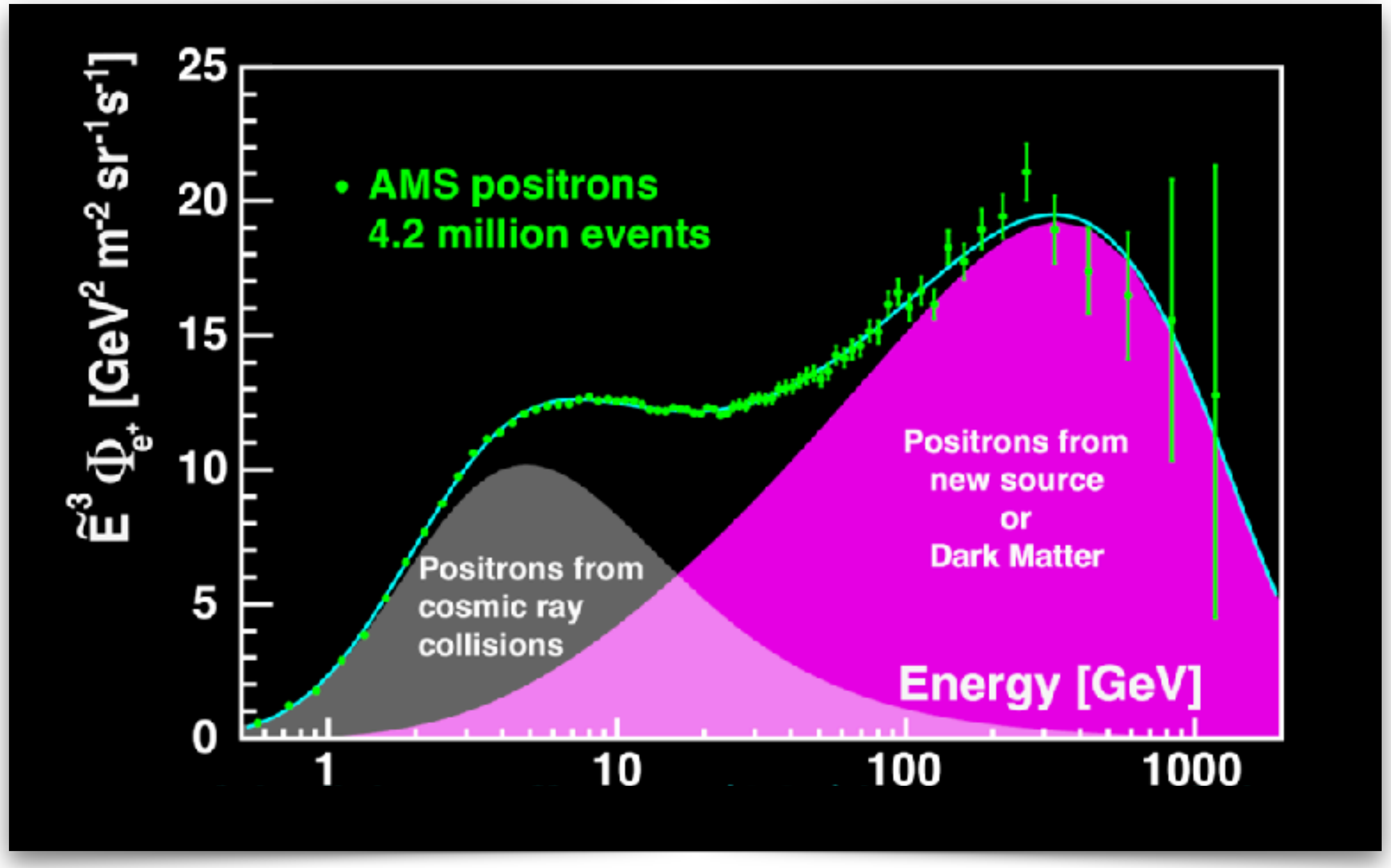






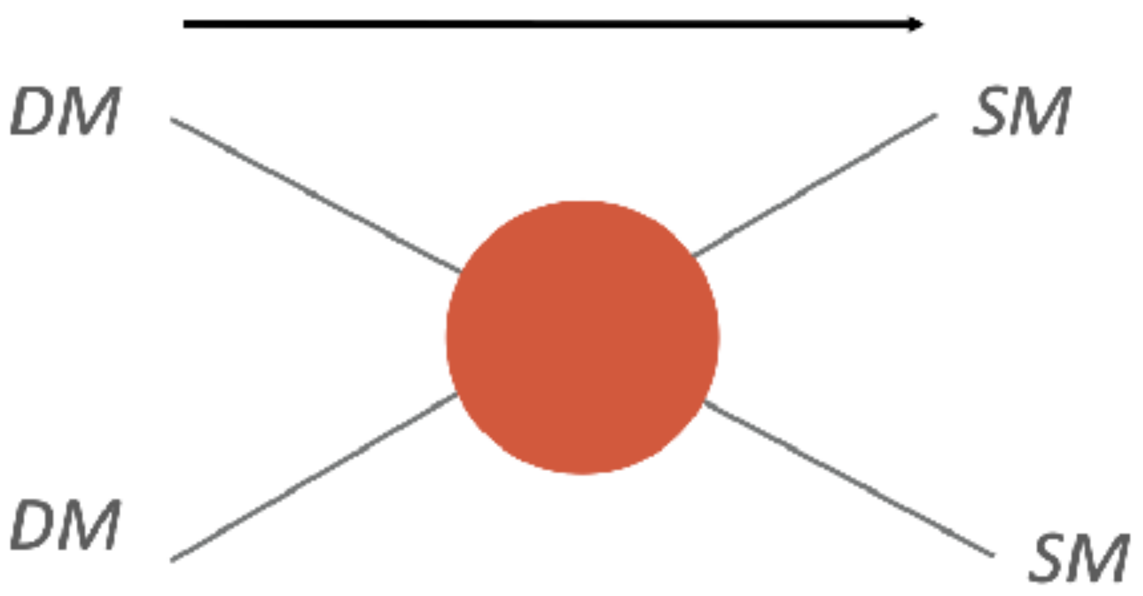
AMS Positron Data

Latest data with complete dataset 2 times larger than previous release!



Interesting to note that there is a rather **sharp cut-off** indicative of mass range for DM candidate mass (in the DM annihilation hypothesis)

Relic abundance, indirect detection

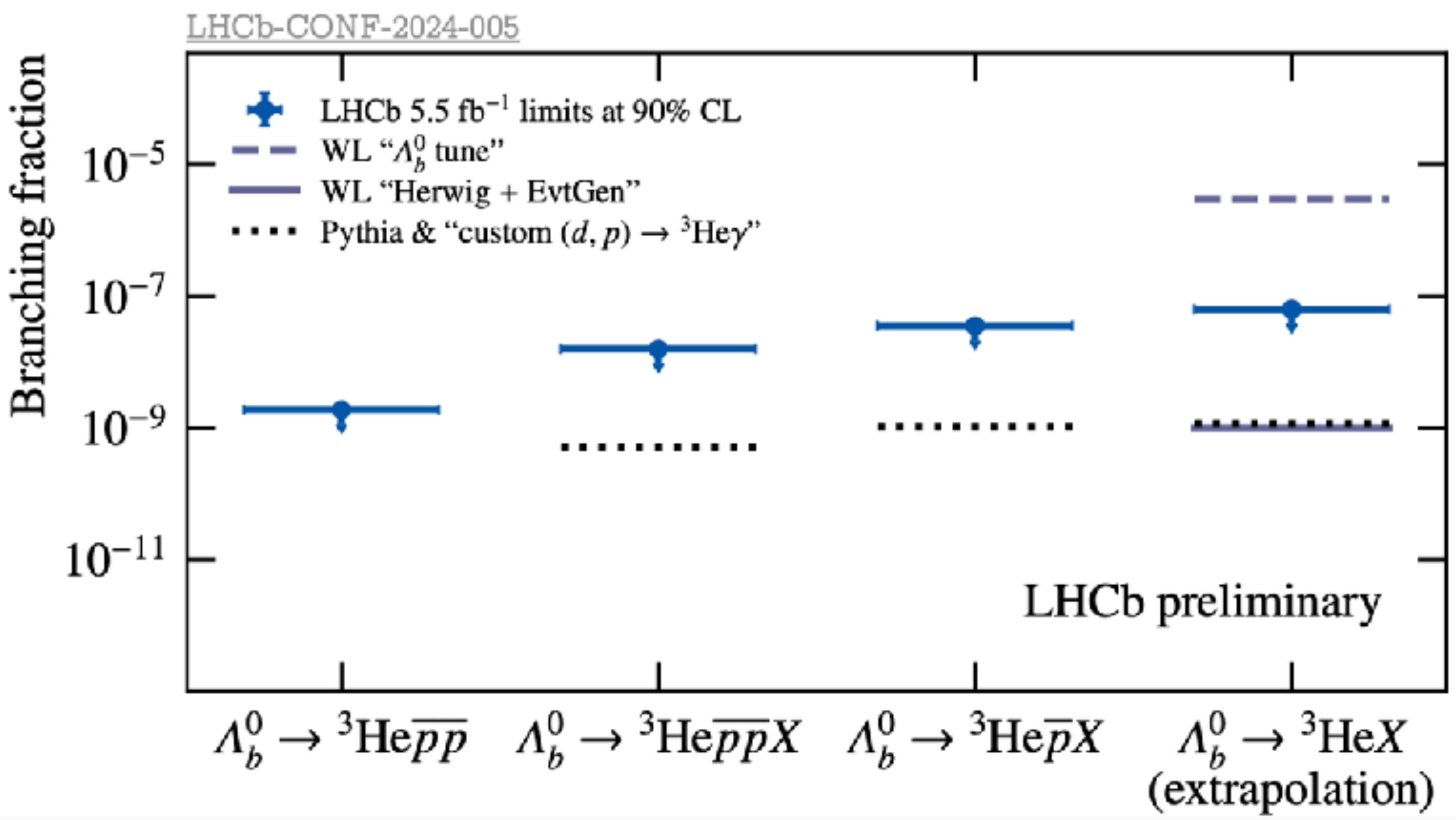


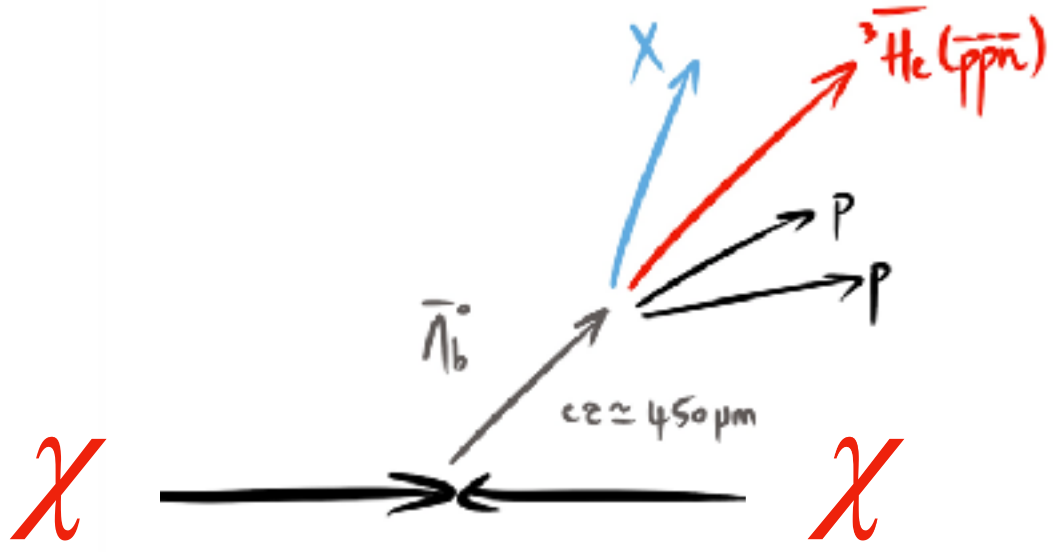
LHCb on $^3\overline{He}$ production in Λ_b decays

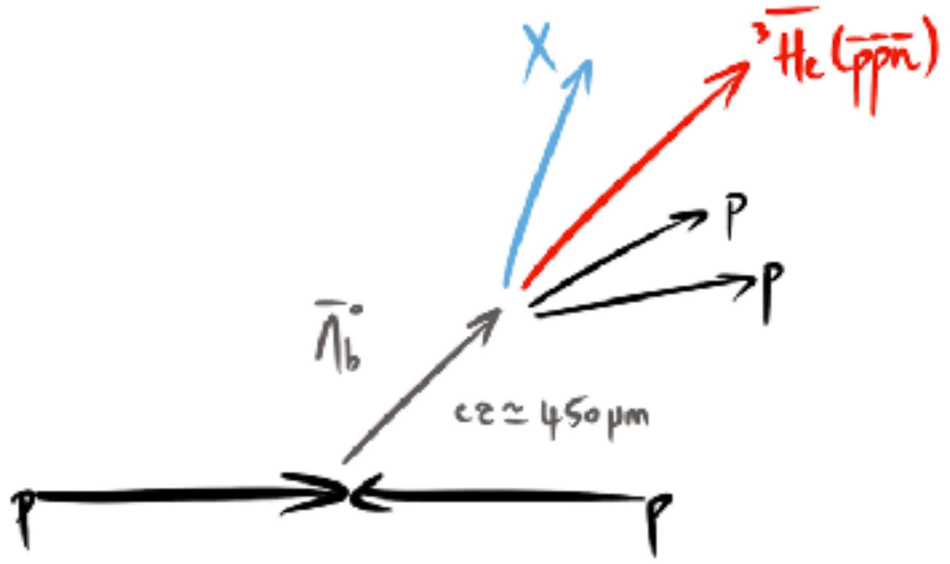
Anti-helium in Cosmic Rays could be a signature of physics beyond the standard model (e.g. **DM annihilation**)!

Interesting scenario where anti-Λb are produced in Dark Matter scenario annihilation.

He3 identified with correlated measurements of charge between VELO and Silicon Strips Tracker

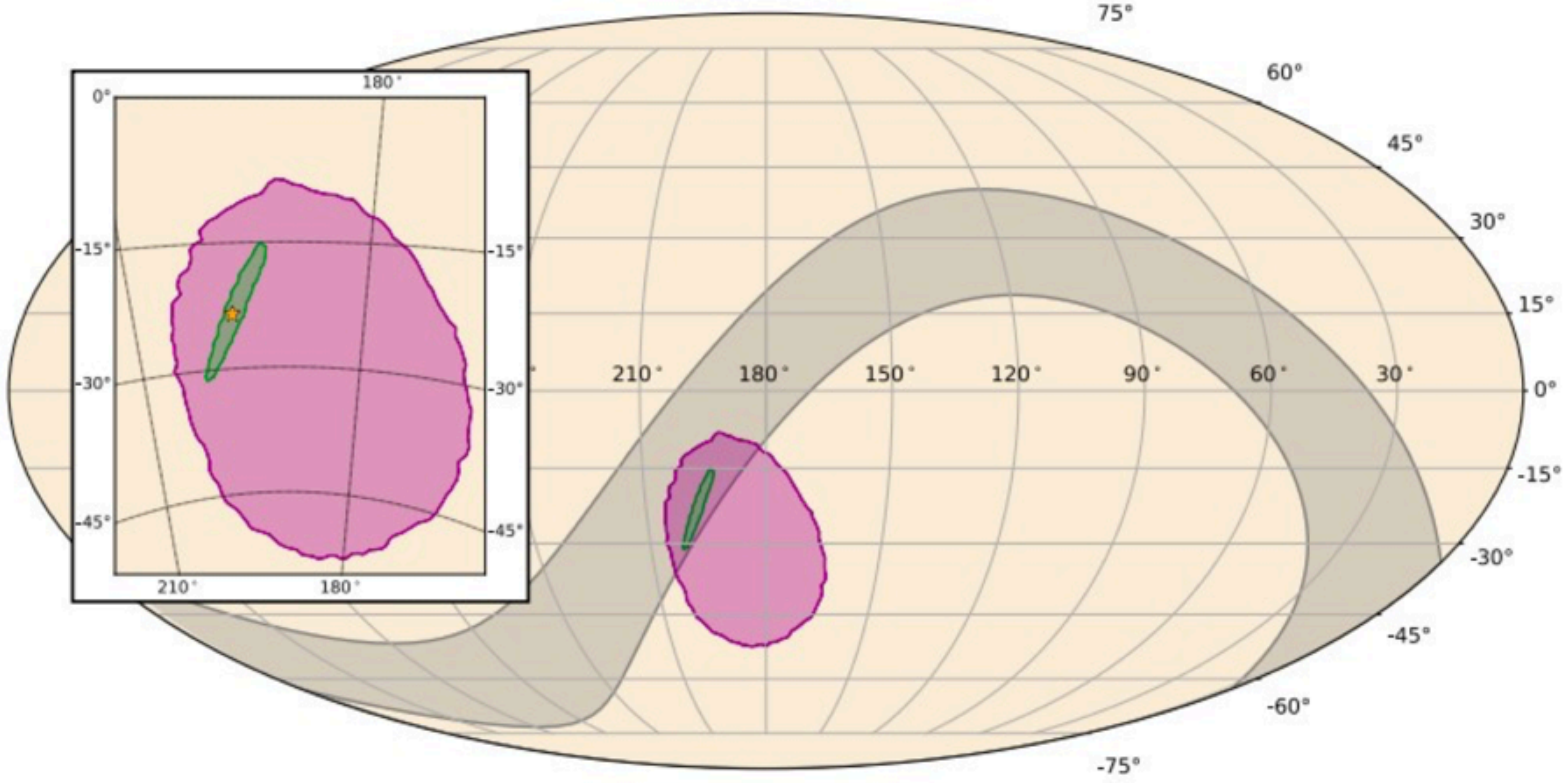






Important to understand the production of $\Lambda_b, {}^3\overline{He}$ in cosmic rays

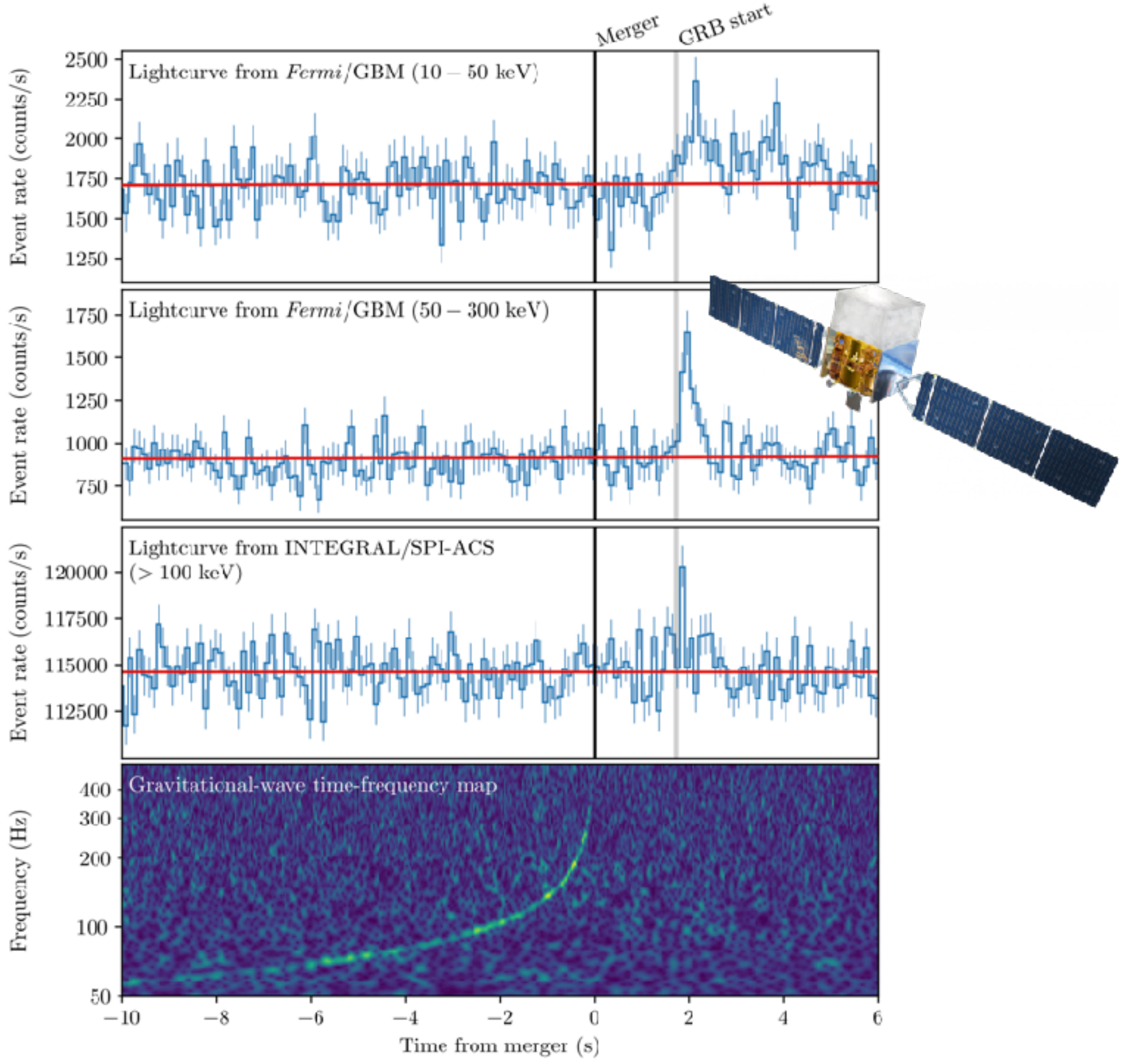
Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A



Signal from LIGO-Hanford, LIGO- Livingston data, Fermi Gam. Ray Burst monitor (NASA) and INTEGRAL (ESA)

Test of speed of gravity and light and equivalence principle

$$-3 \times 10^{-15} \leq \frac{v_{gw}}{v_{em}} - 1 \leq 7 \times 10^{-16}$$

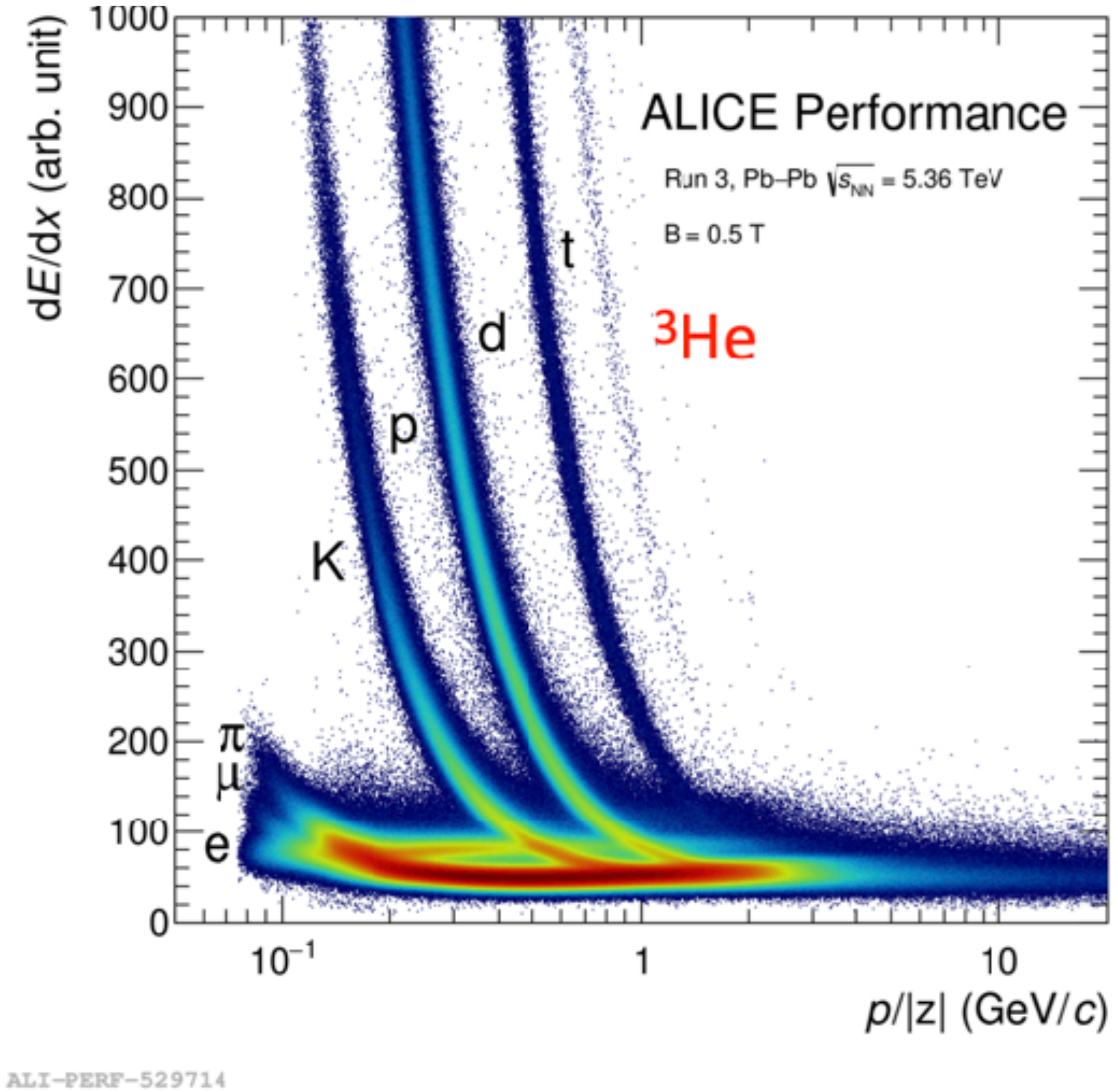


Signal from LIGO-Hanford, LIGO- Livingston data, Fermi (NASA) and INTEGRAL (ESA)

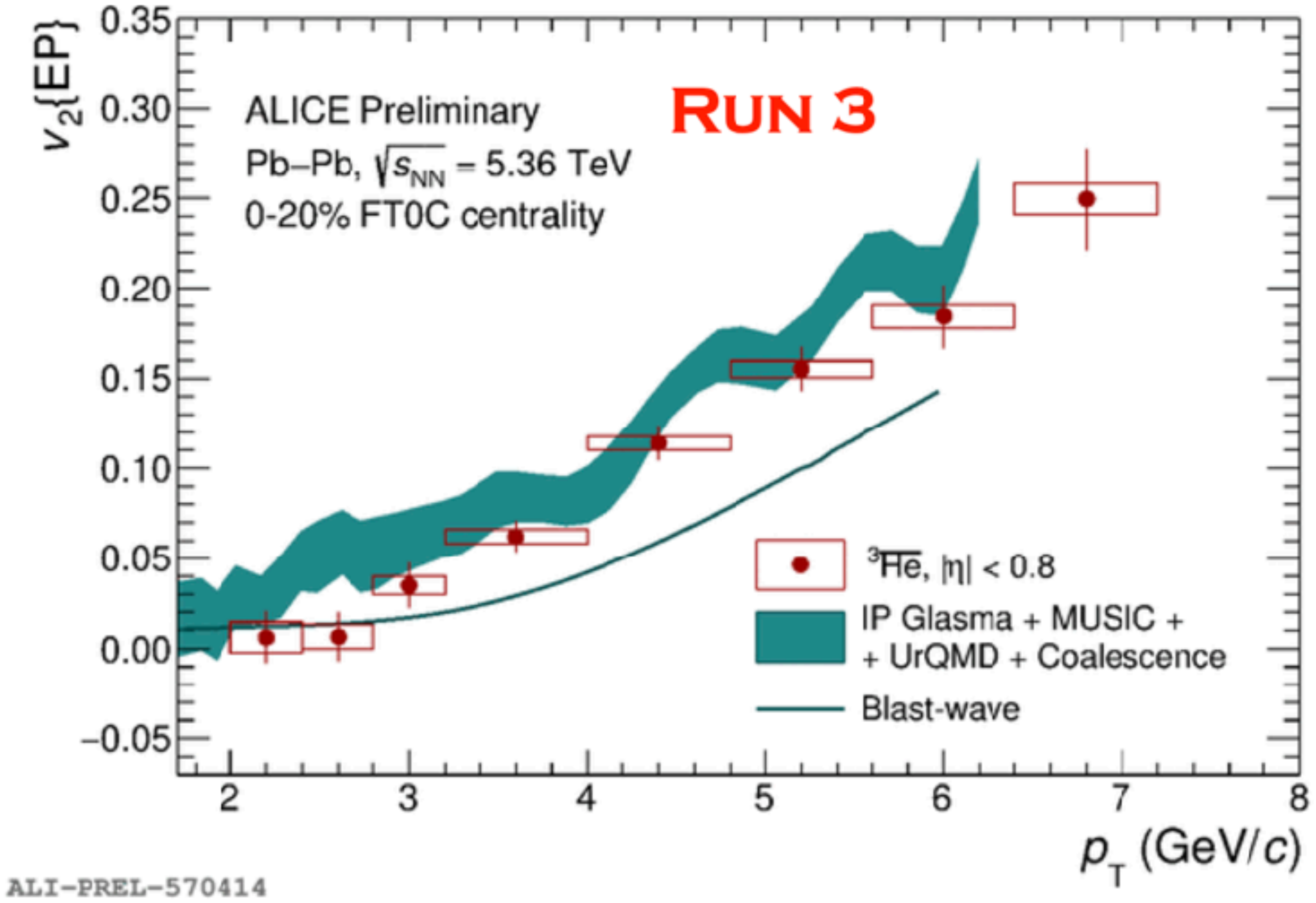
Also allows to constrain neutron star Equation of State!

Heavy Ion Physics

Anti-Helium 3 production in heavy ion collisions, can give an interesting measure of the medium viscosity!



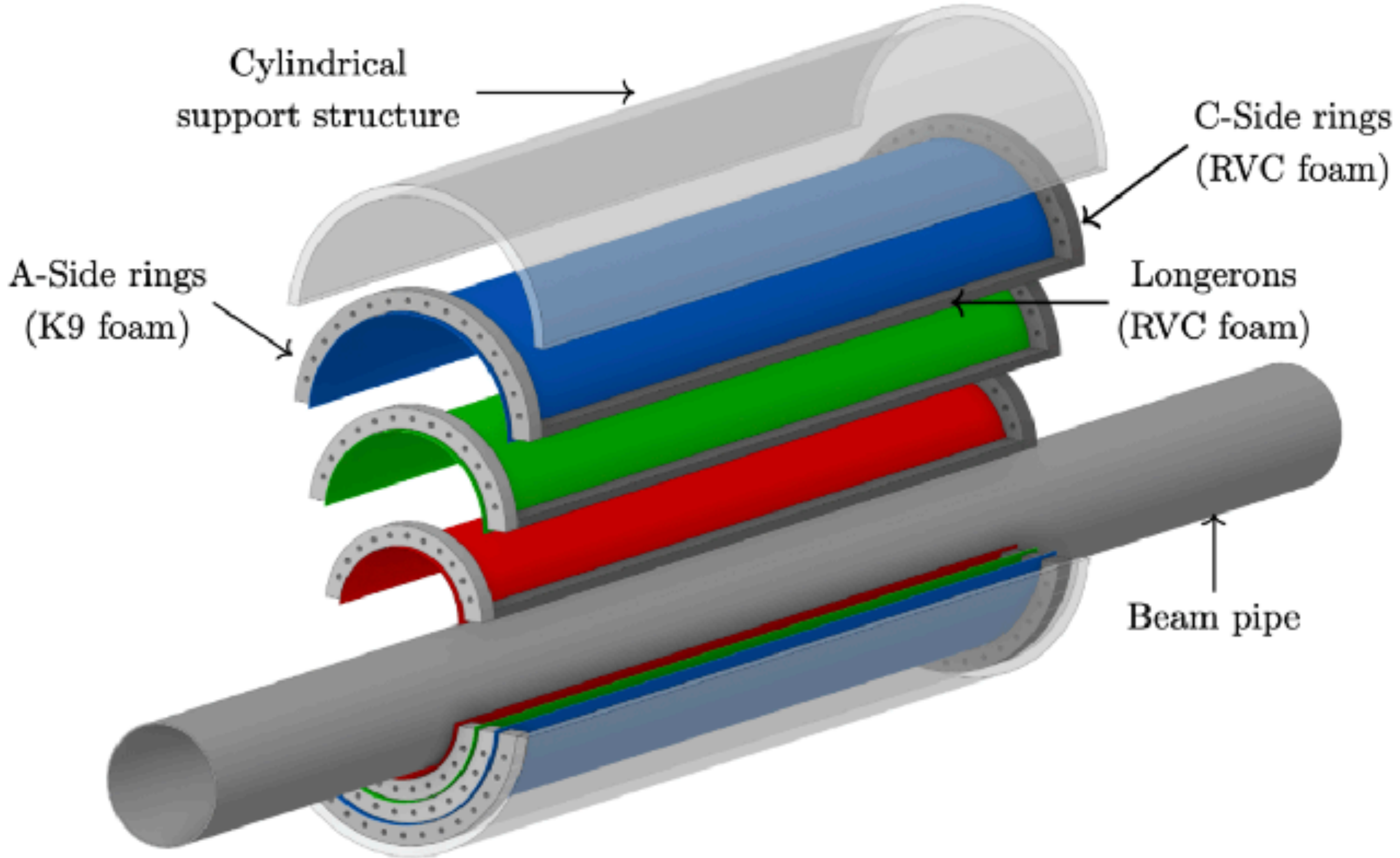
Helium nucleus (Z = 2), clean PID, rare probe

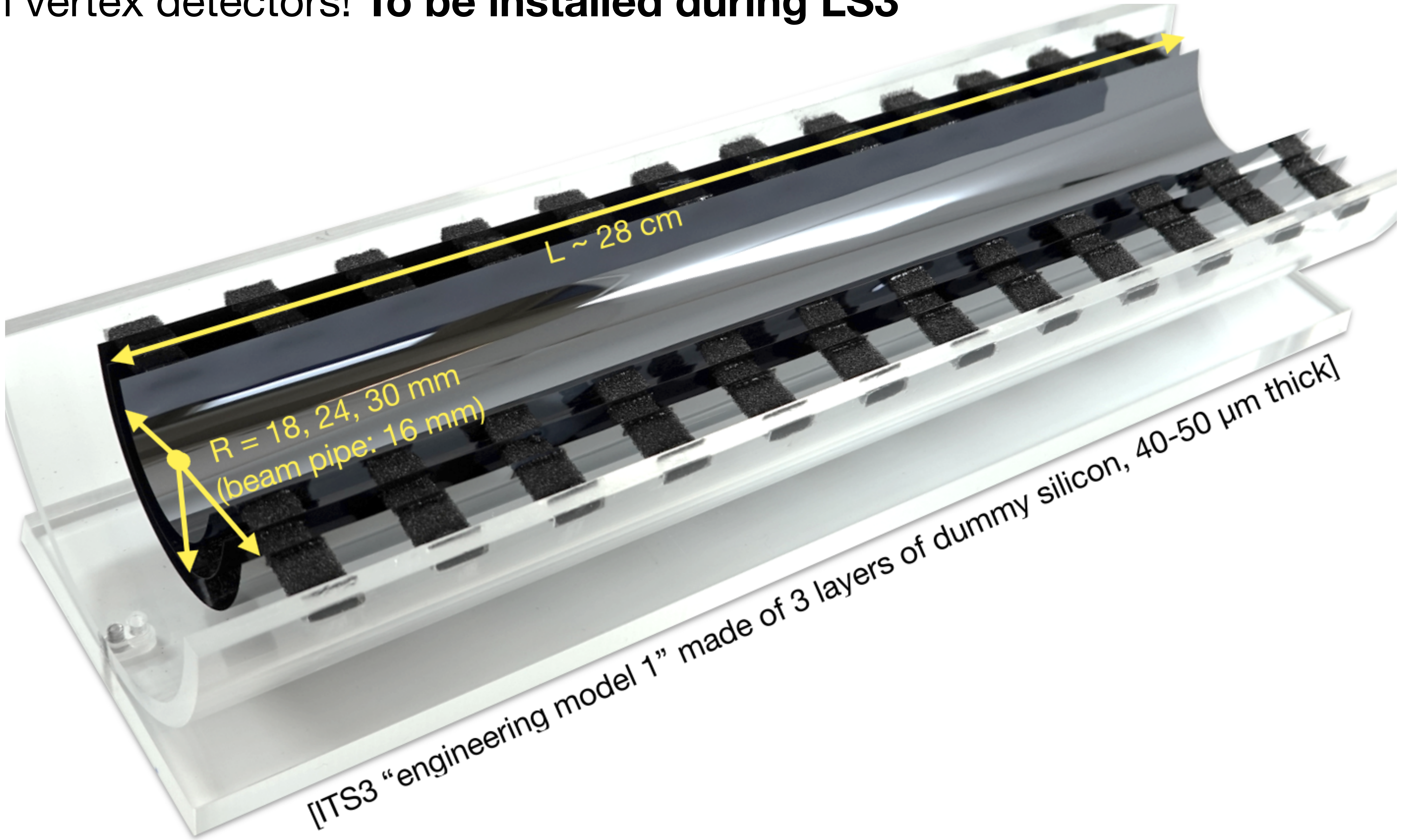


Problem of **collective expansion microscopic models**

Featuring ITS3 Upgrade for ALICE

Monolithic CMOS (MAPS - Monolithic Active Pixel Sensors) technology for the ITS3 upgrade of ALICE - Key technology also for future electron-positron vertex detectors! **To be installed during LS3**





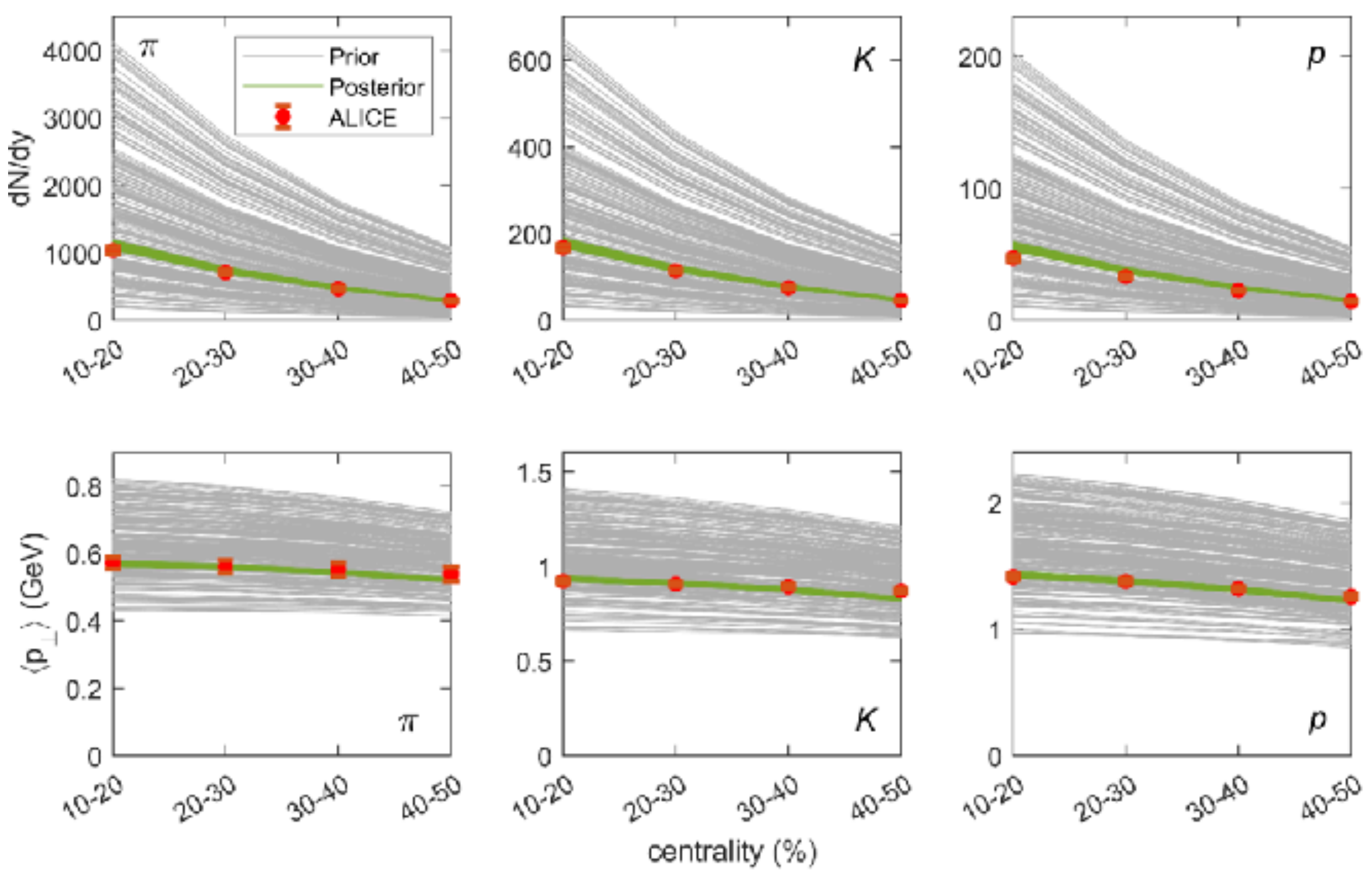
[ITS3 "engineering model 1" made of 3 layers of dummy silicon, 40-50 μm thick]

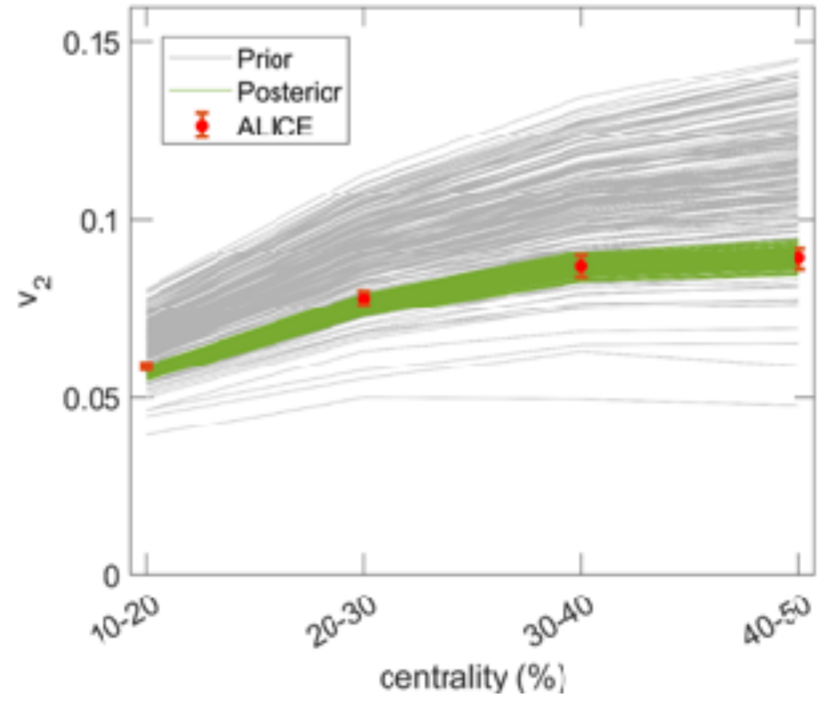
The design of the new vertex detector aims to reduce the material budget of the **first detection layer to an unprecedented minimum of 0.05% X0**, and to **get closer to the interaction point at a radial distance of 18 mm**.

Requires having in the active area only the thin MAPS silicon sensor (<50μm)

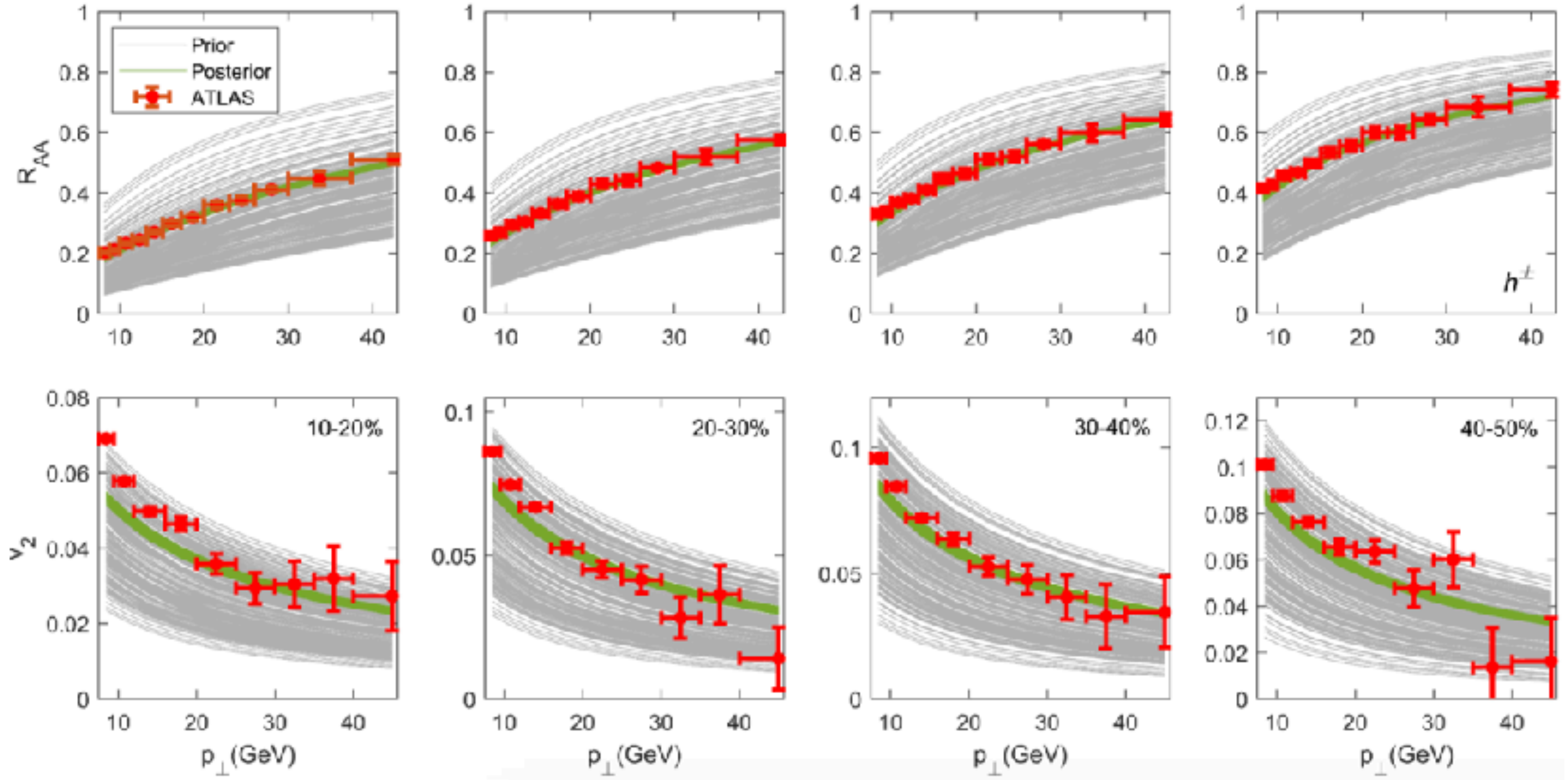
Heavy Ion Physics

Development of a global framework to constrain QGP properties through both high-pT (Nuclear modification factors RAAs) and low pT (flows) observables - DREENA!

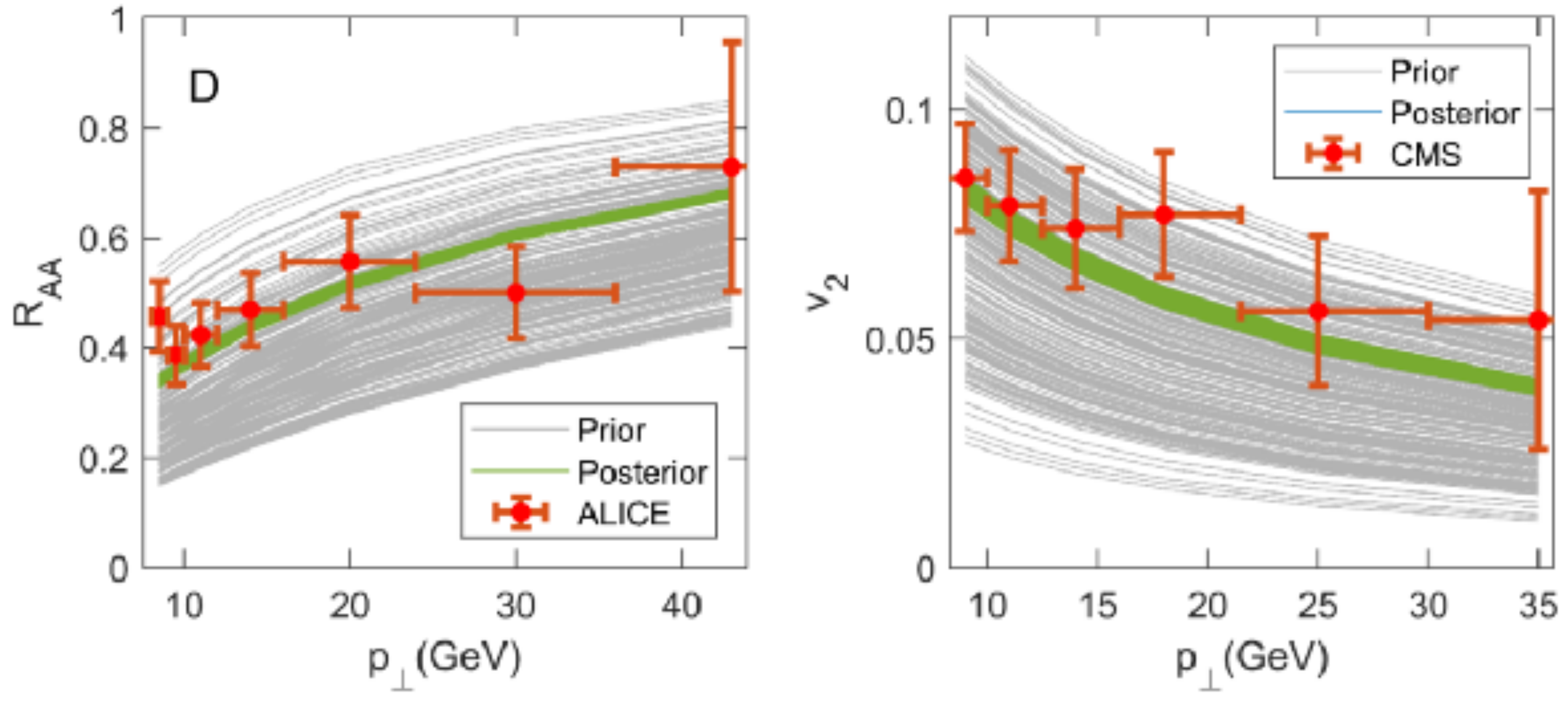




Low-pT observables



High-pT observables



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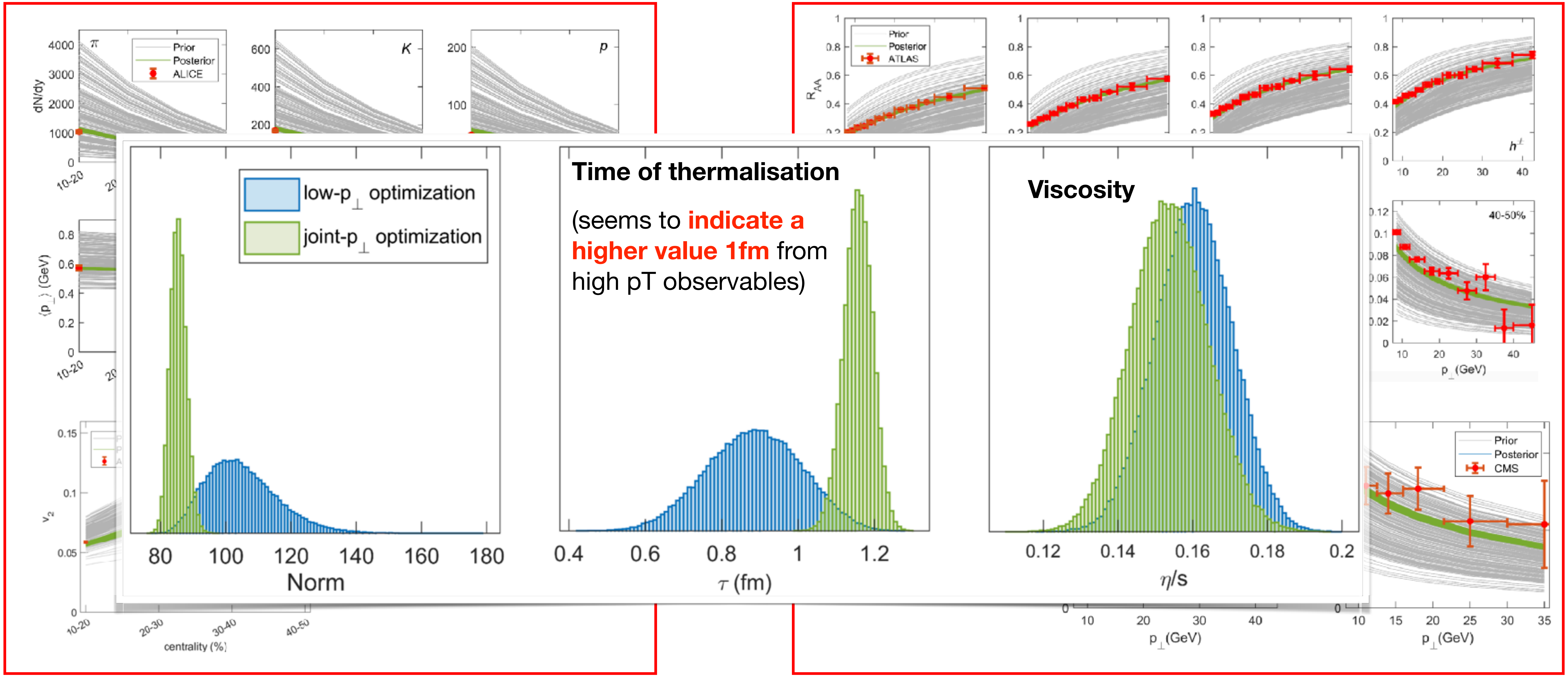
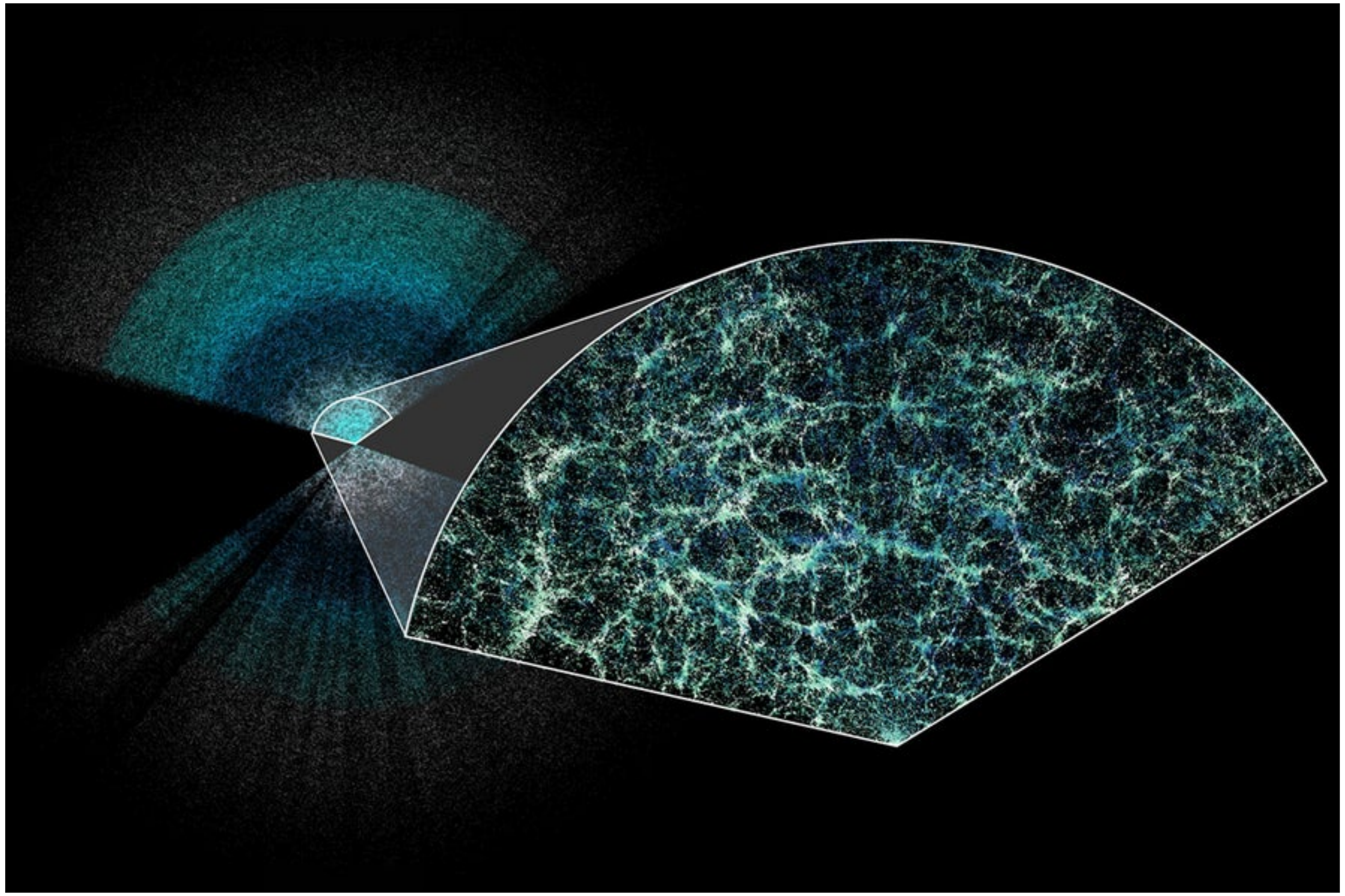


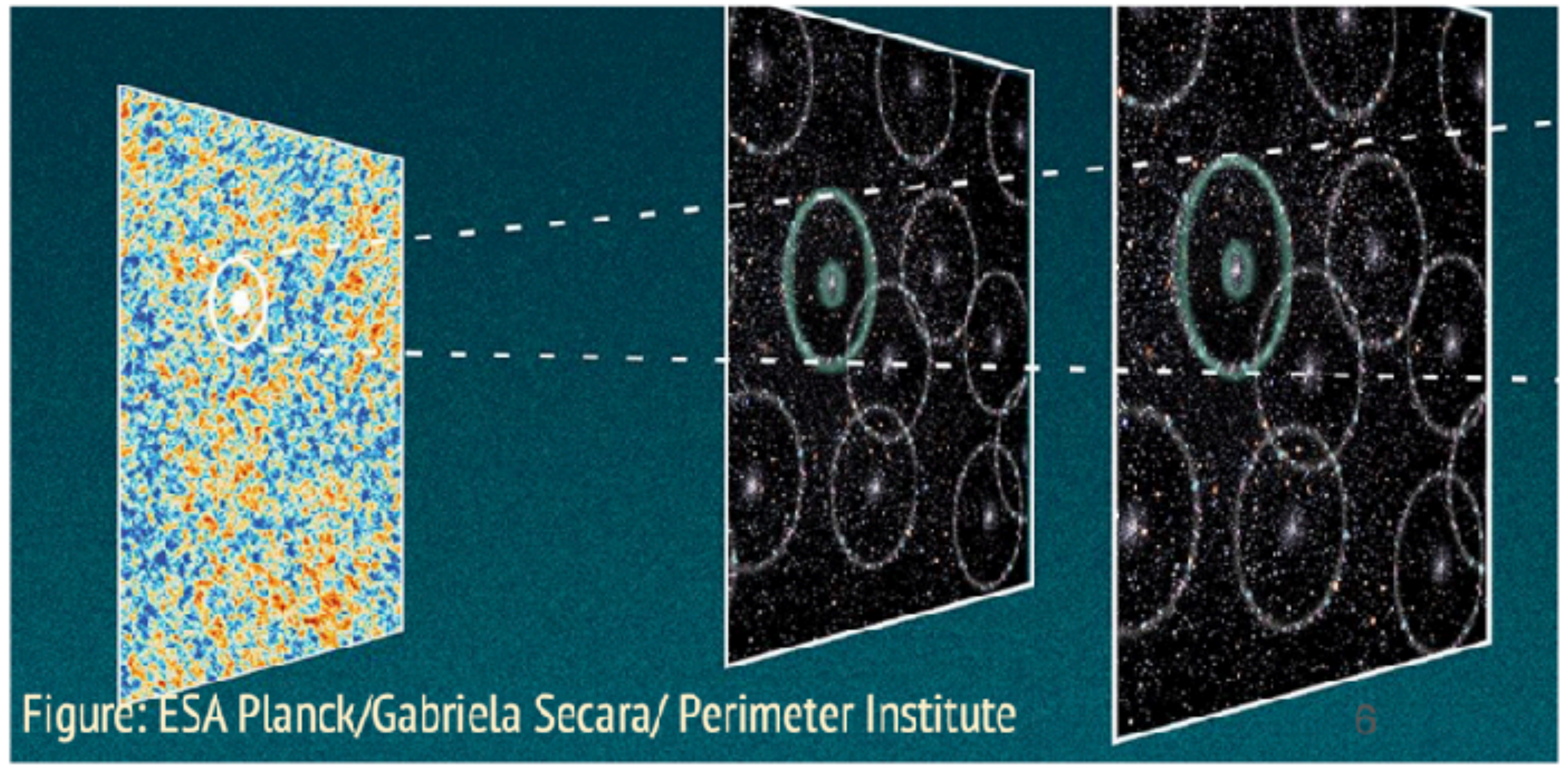
Cosmology

DESI - Dark Energy Spectroscopic Instrument in operations since 2021 and first publication of Year 1 Results!

In one year more specific data than all previous experiments!

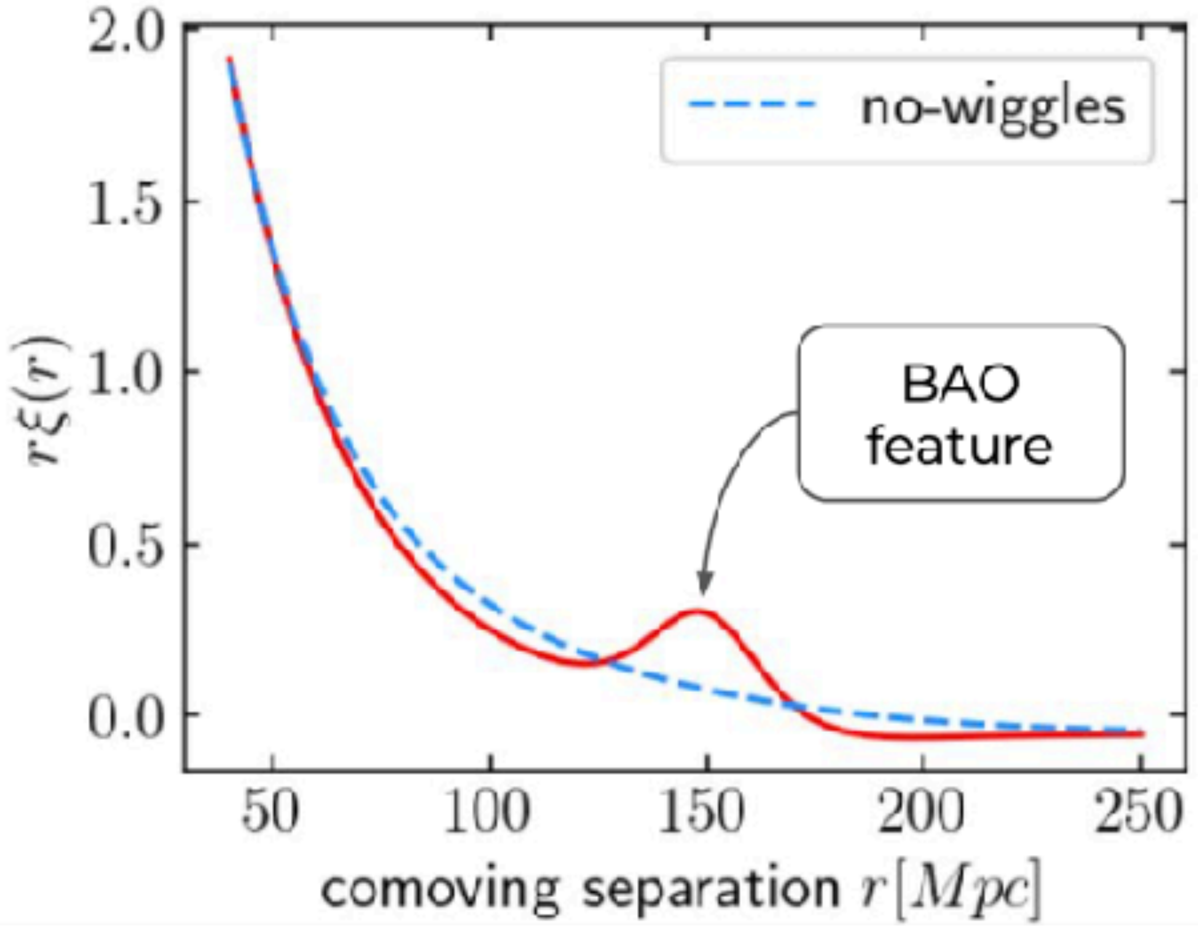


DESI 3D map of our universe to date.



Baryon acoustic oscillations

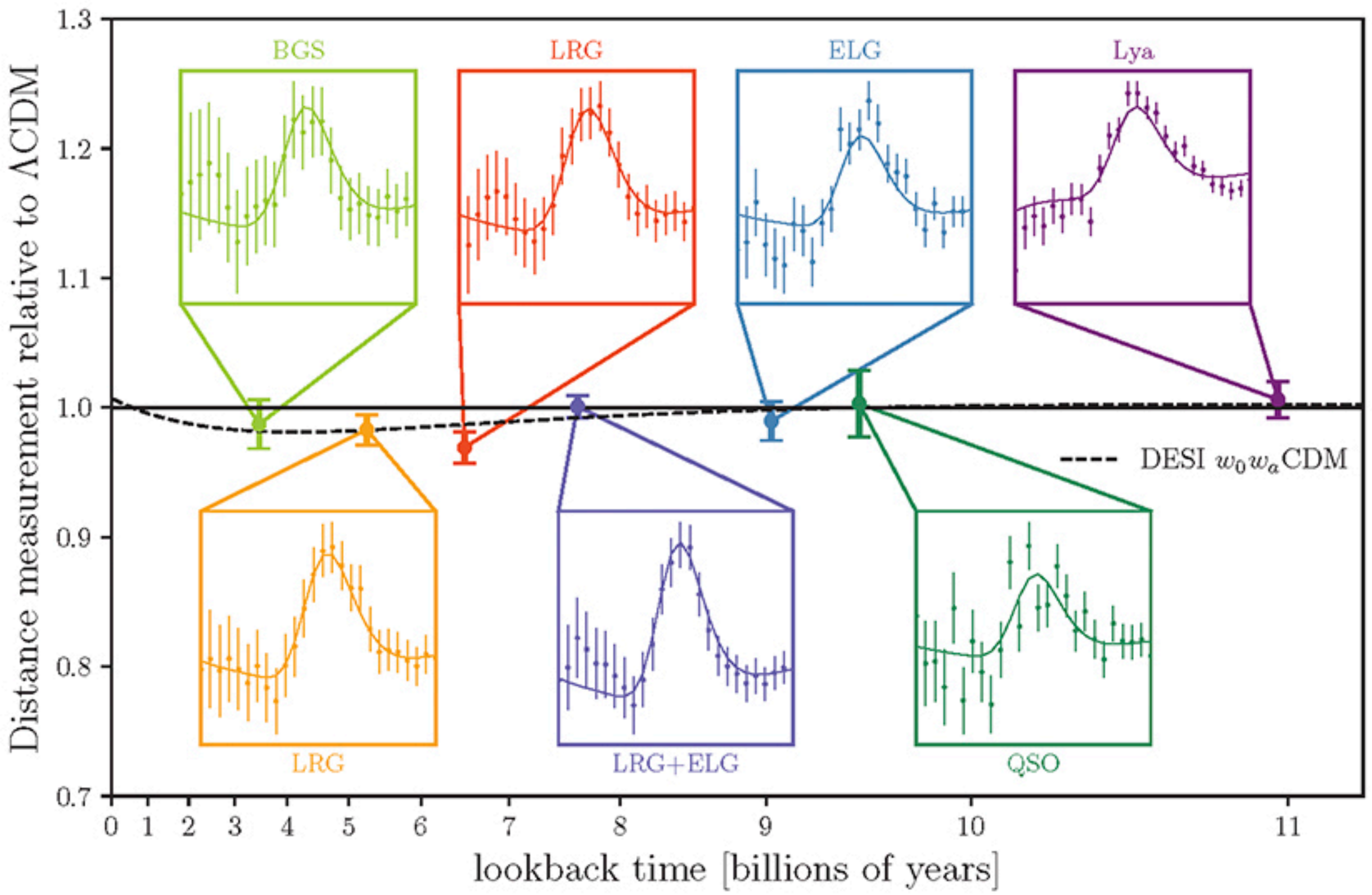
Early universe over-densities leave imprints (frozen when baryons and radiation decouple ~400,000y) in the distribution of galaxies.



Cosmology

- 6 million spectra grouped in 7 different redshifts [0.4<z<4.2] (LGR, BGS, QSO, Lya)

- Fully exploits the capabilities of DESI and increases sensitivity!



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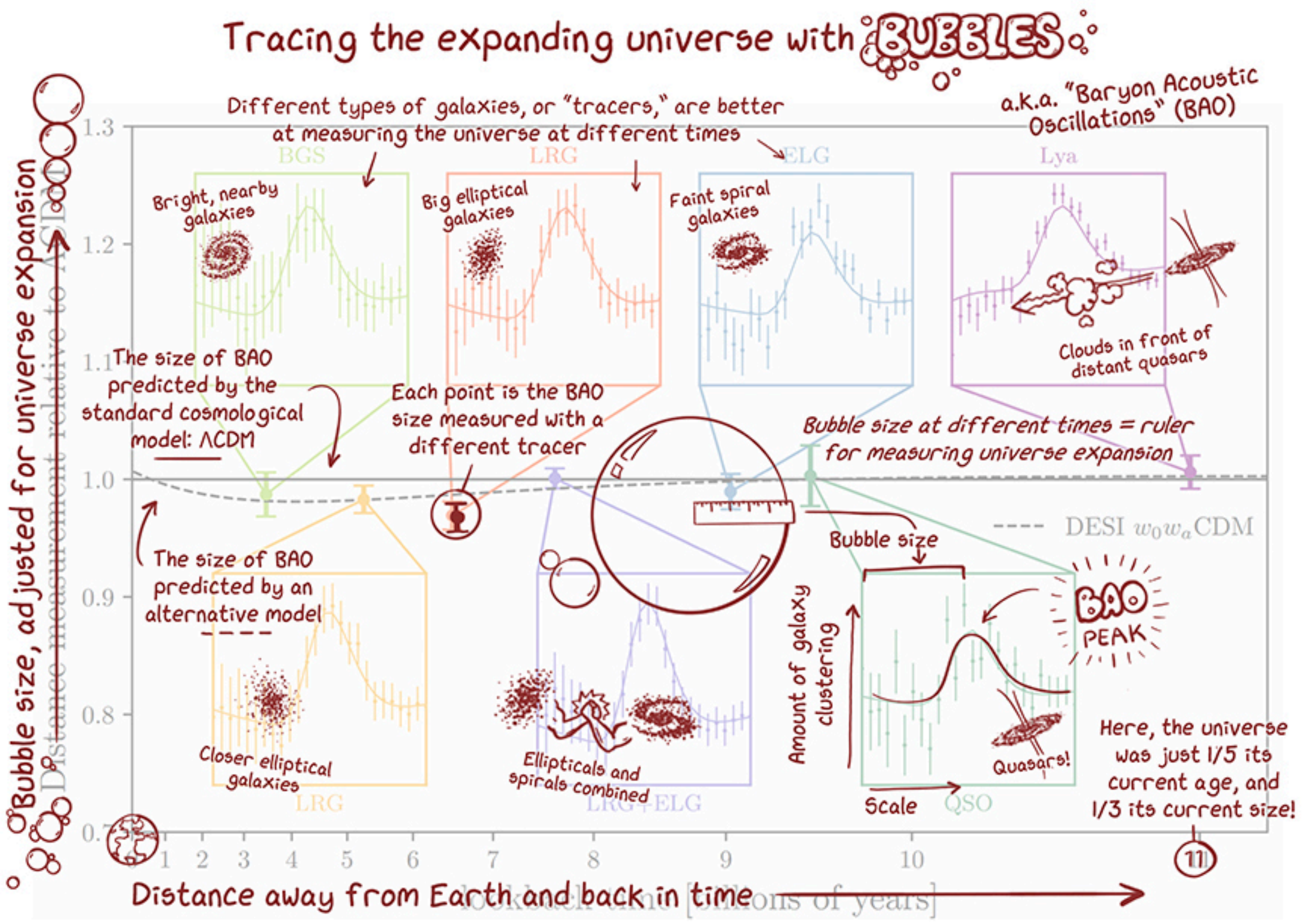
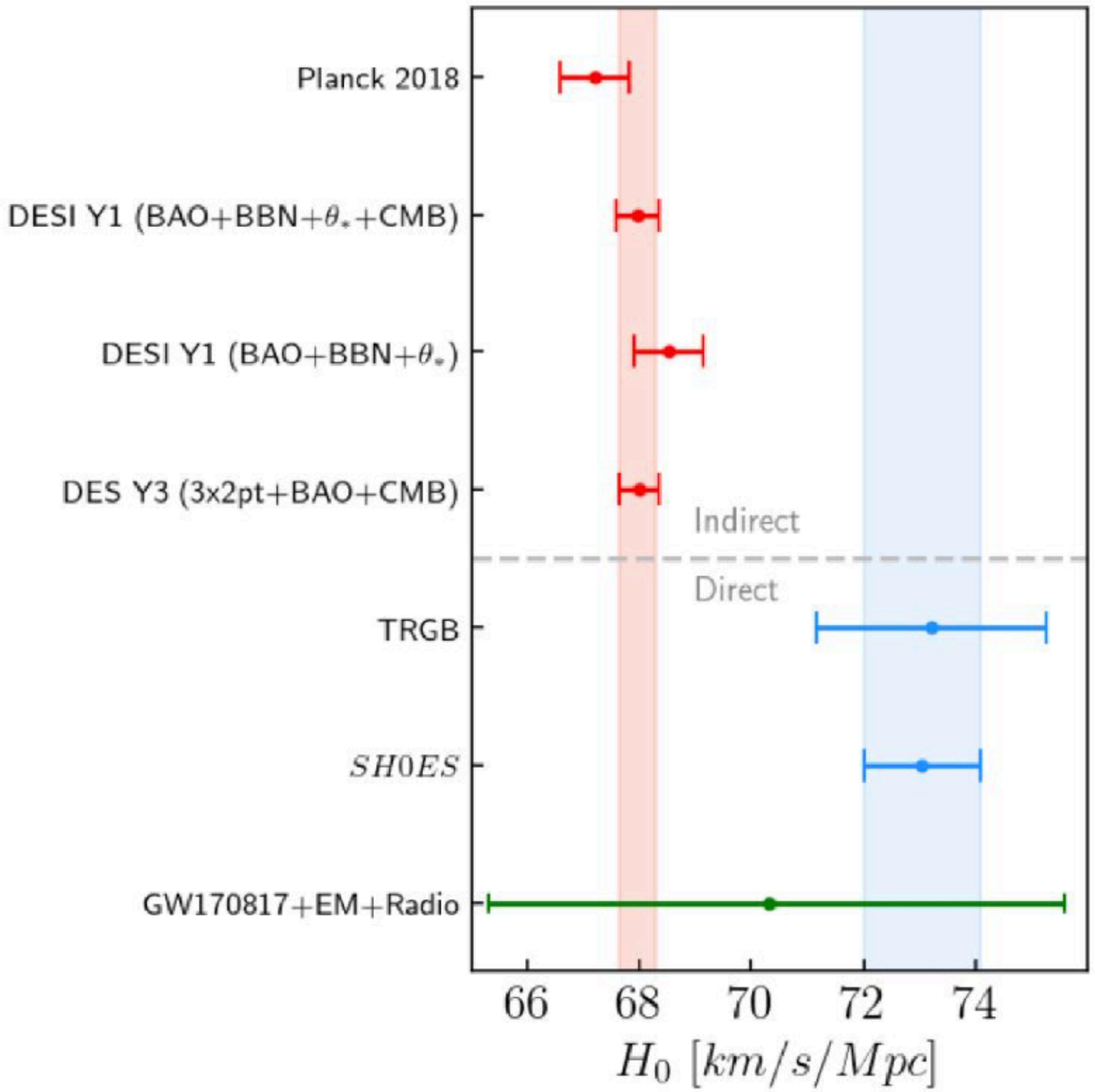


The Hubble tension does not significantly change with much improved Cosmological BAO measurements!



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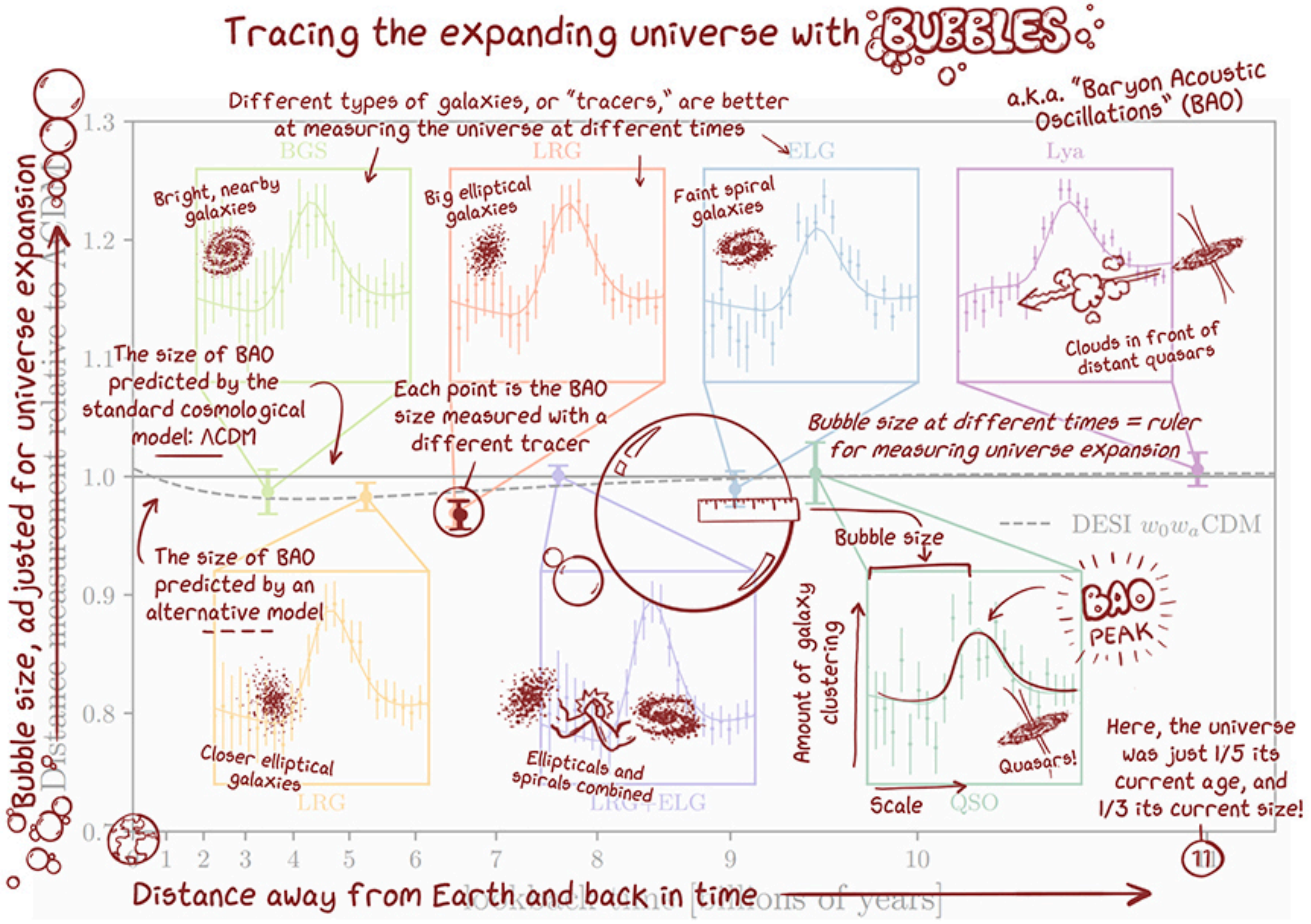
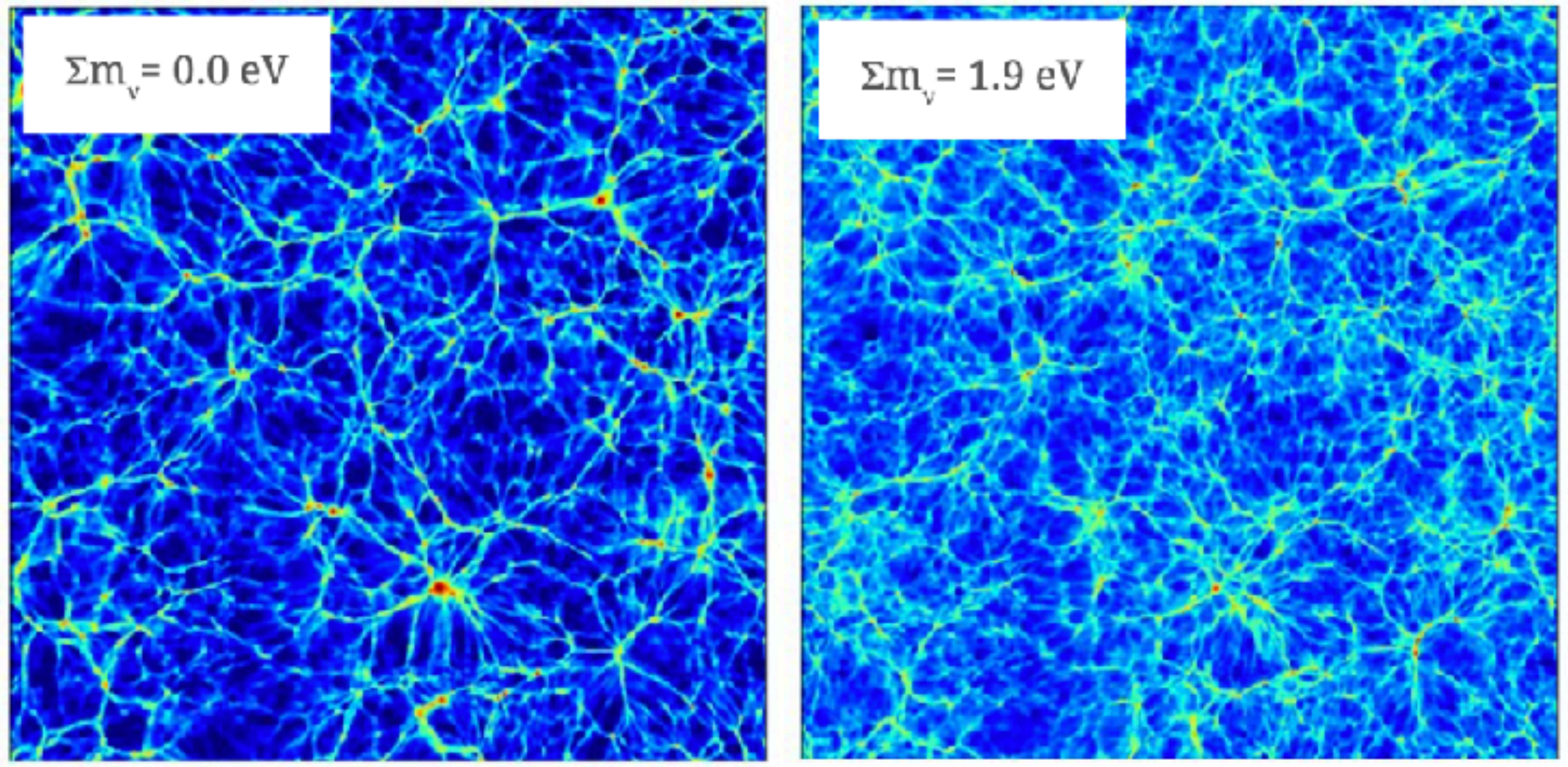
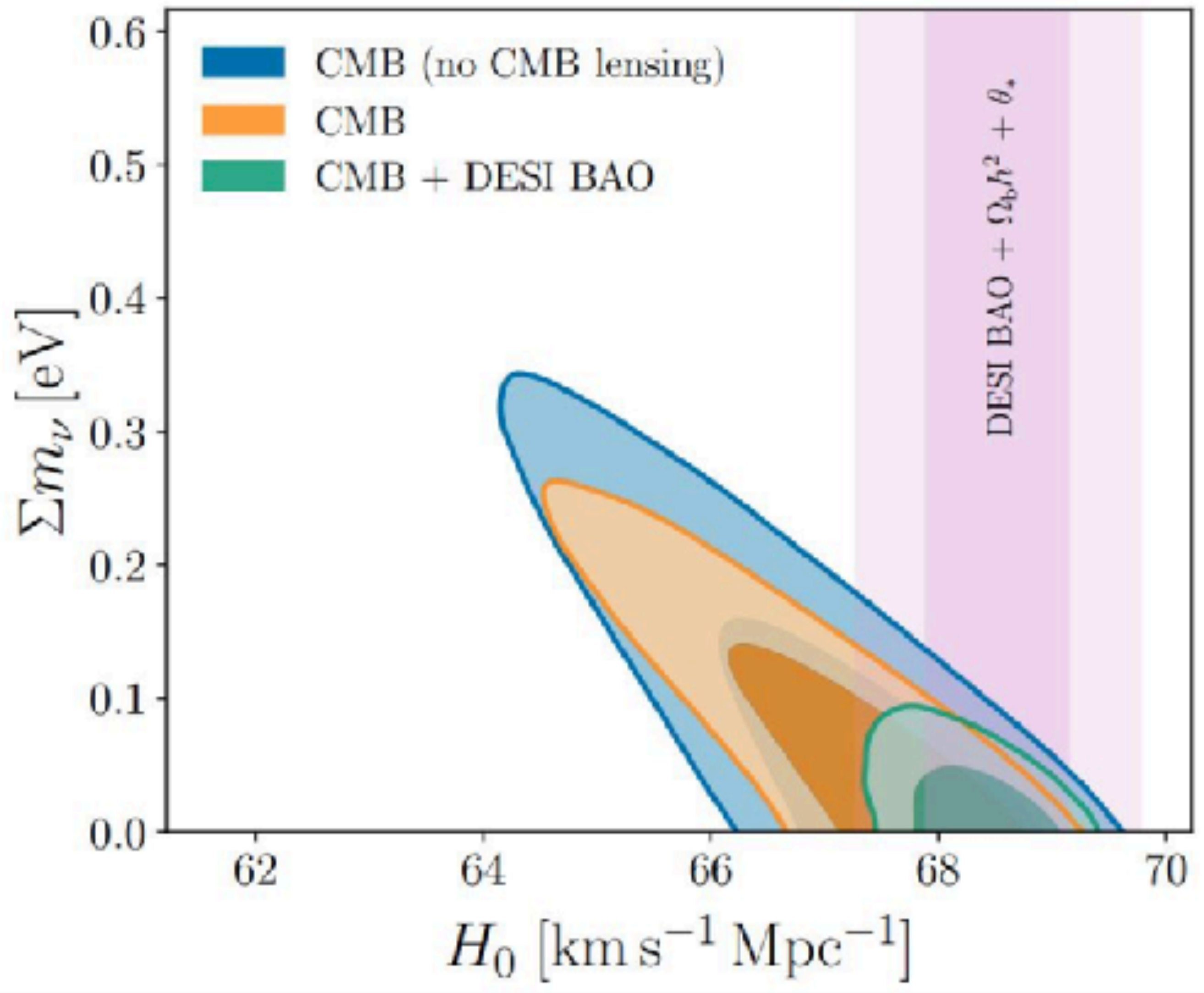


The sum of neutrino masses affect how matter is clustering in the Universe



Argawal & Feldman, MNRAS 2011



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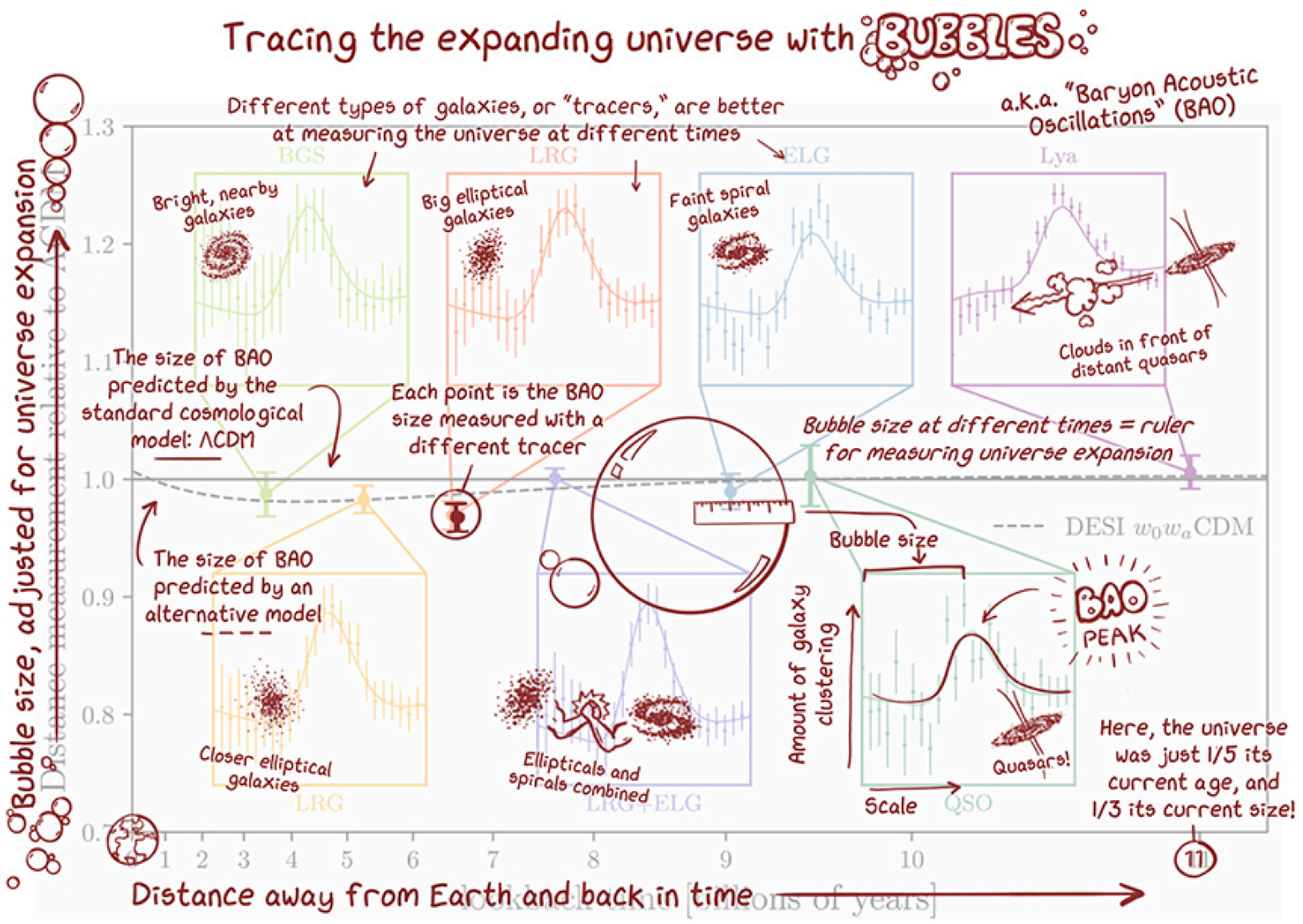
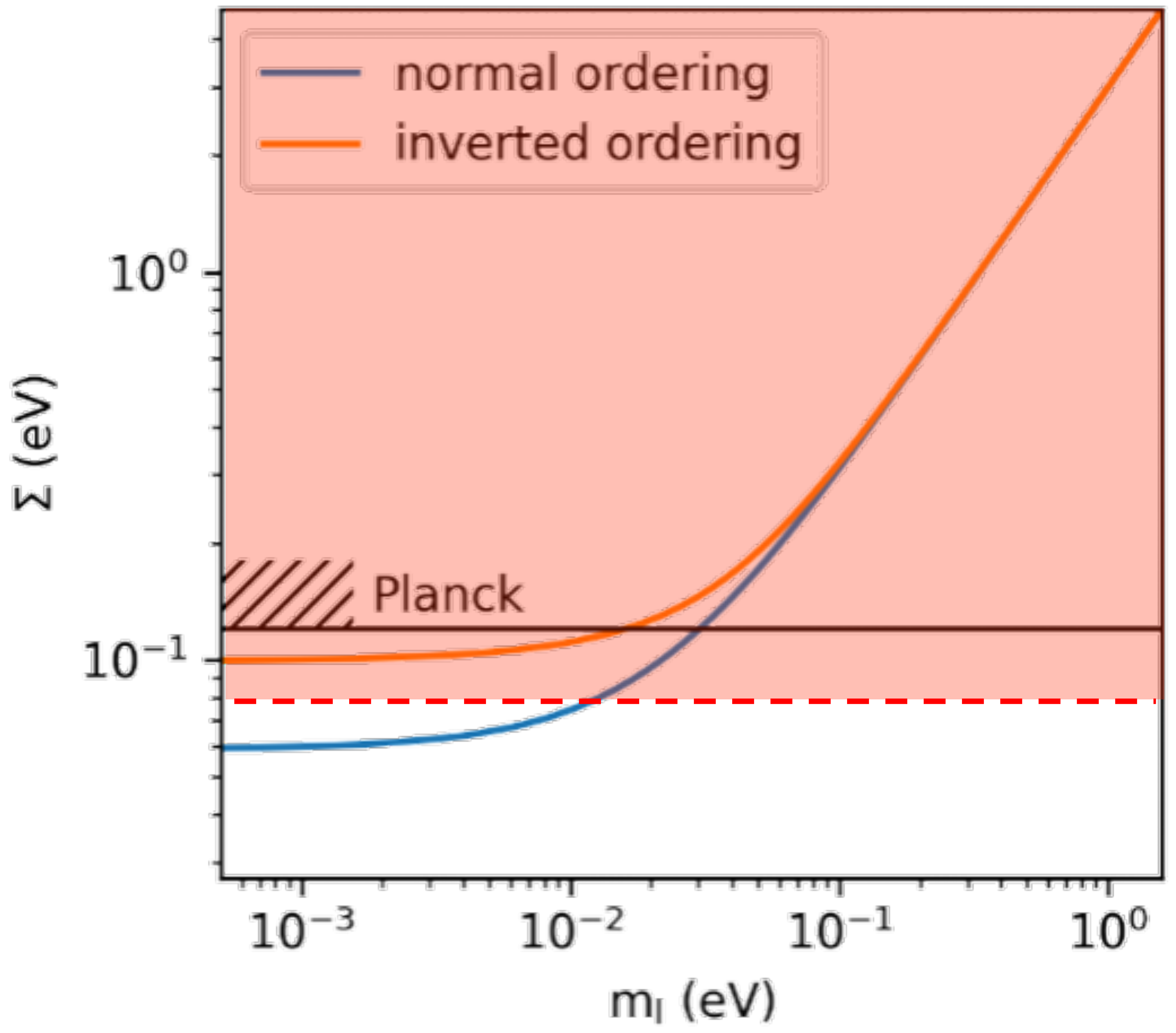


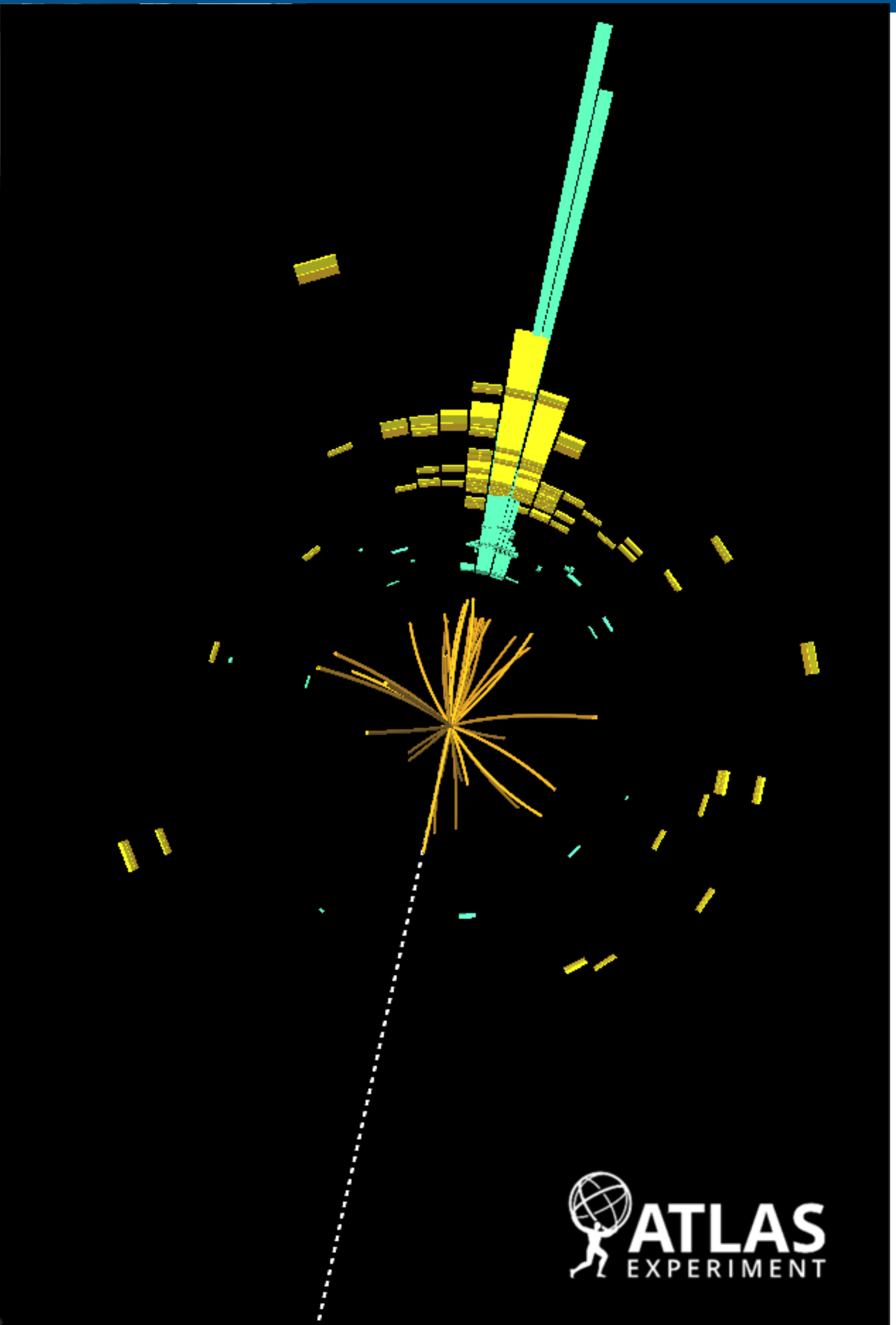


CMB + DESI (BAO) sets a imit at $\Sigma m_\nu < 0.072$ eV

NO seems to be favoured, but this result **is** dependent on the cosmological model and priors adopted

Direct Searches for new Physics at the LHC

Livia Soffi



Livia presented more than 20 new searches for new physics in extend higgs sectors, Dark sector, SUSY, Heavy fermions, and EFT. Impressive harvest of searches for new physics mostly at Run 2!

Leaving no stones unturned!

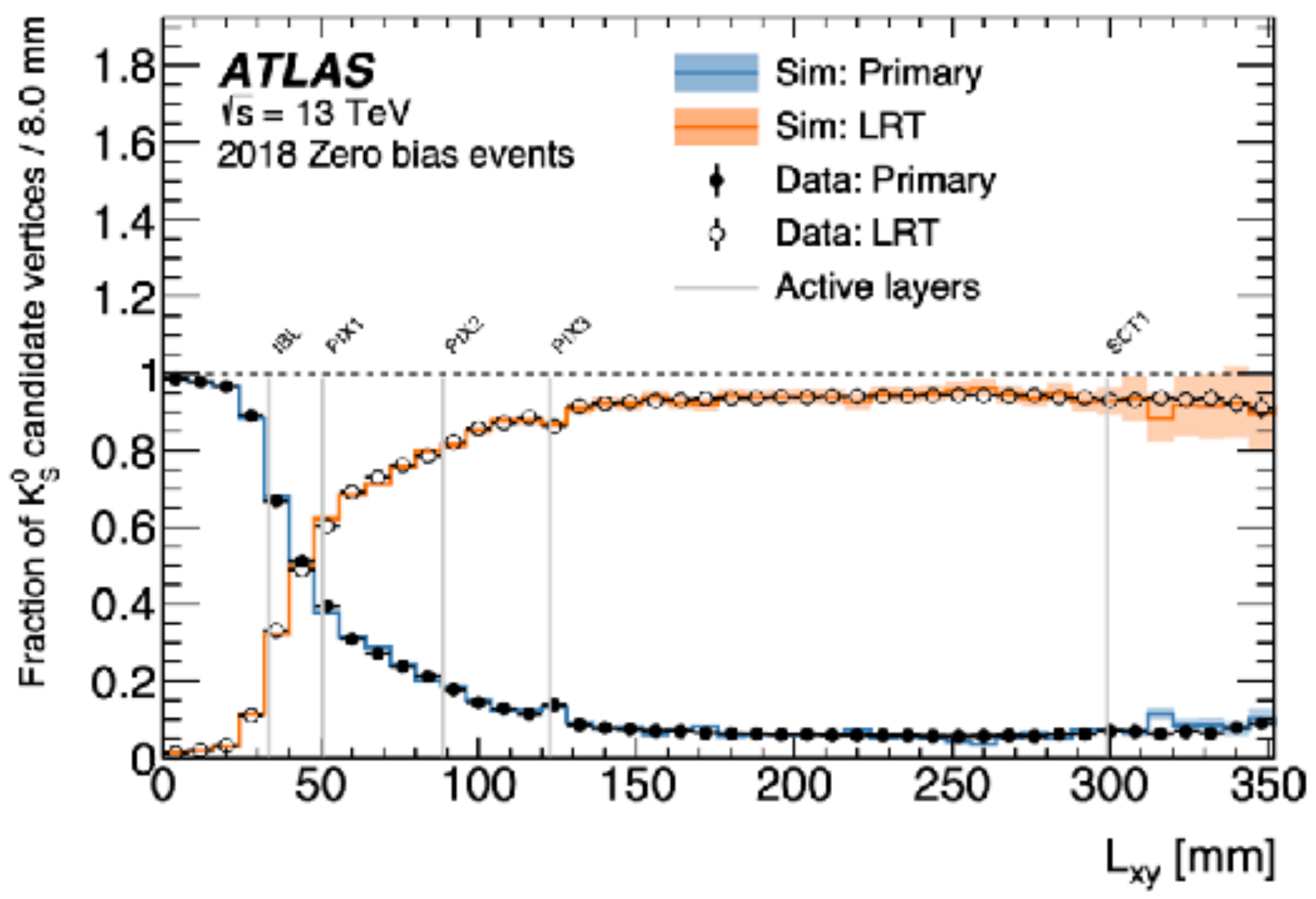
Reference	Topic	Experiment	Model	Explored energy range (0 – 3000 GeV)
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector	
HDBS-2020-11	$H^{\pm} \to cs$	ATLAS		
HDBS-2023-19	Combination of charged H	ATLAS		
HIG-24-002	$H \to ZZ \to 4l$	CMS		
HIG-22-004	$A \to Zh(\tau\tau)$	CMS		
SUS-24-001	$\phi \to b\bar{b}$	CMS		
EXOT-2018-55	Prompt Leptonjets	ATLAS	Dark Sector +ALPs	
EXOT-2022-04	Neutral LLP into displaced jets	ATLAS		- displaced
SUS-23-004	mono$-t$	CMS		dark matter
SUS-23-012	mono$-h(\tau\tau)$	CMS		dark matter
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS		
SUS-24-004	pMSSM	CMS	Supersymmetry	
SUS-23-003	Compressed SUSY w/ RJR	CMS		
ATLAS-2024- 011	Run3 displaced leptons	ATLAS		- displaced
ATLAS-2024-008	VLL $\to \tau b$	ATLAS	Heavy Fermions	
EXO-23-015	VLL $\to \tau a(\gamma\gamma)$	CMS		- displaced
B2G-22-005	$t^* \to tg$	CMS		
EXO-23-010	$ll +$ b $-$ jets, non $-$ resonant	CMS	EFT	
EXO-24-007	Low mass dijet+ISR	CMS	Z' Mediator	
EXO-22-006	$Z' \to \mu\mu +$ b $-$ jets, resonant	CMS		

Direct Searches at Colliders

Livia Soffi

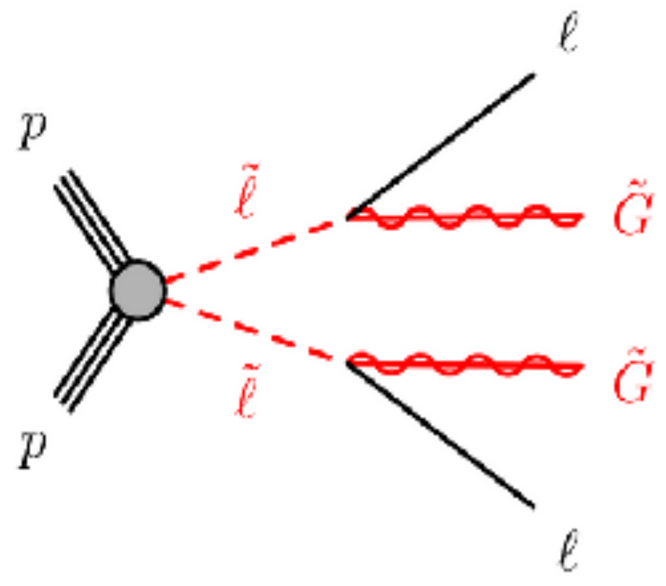
Run 3 search!

Improving reconstruction techniques e.g. ATLAS Large Radius Tracking at Run 3 and reprocessed Run 2!

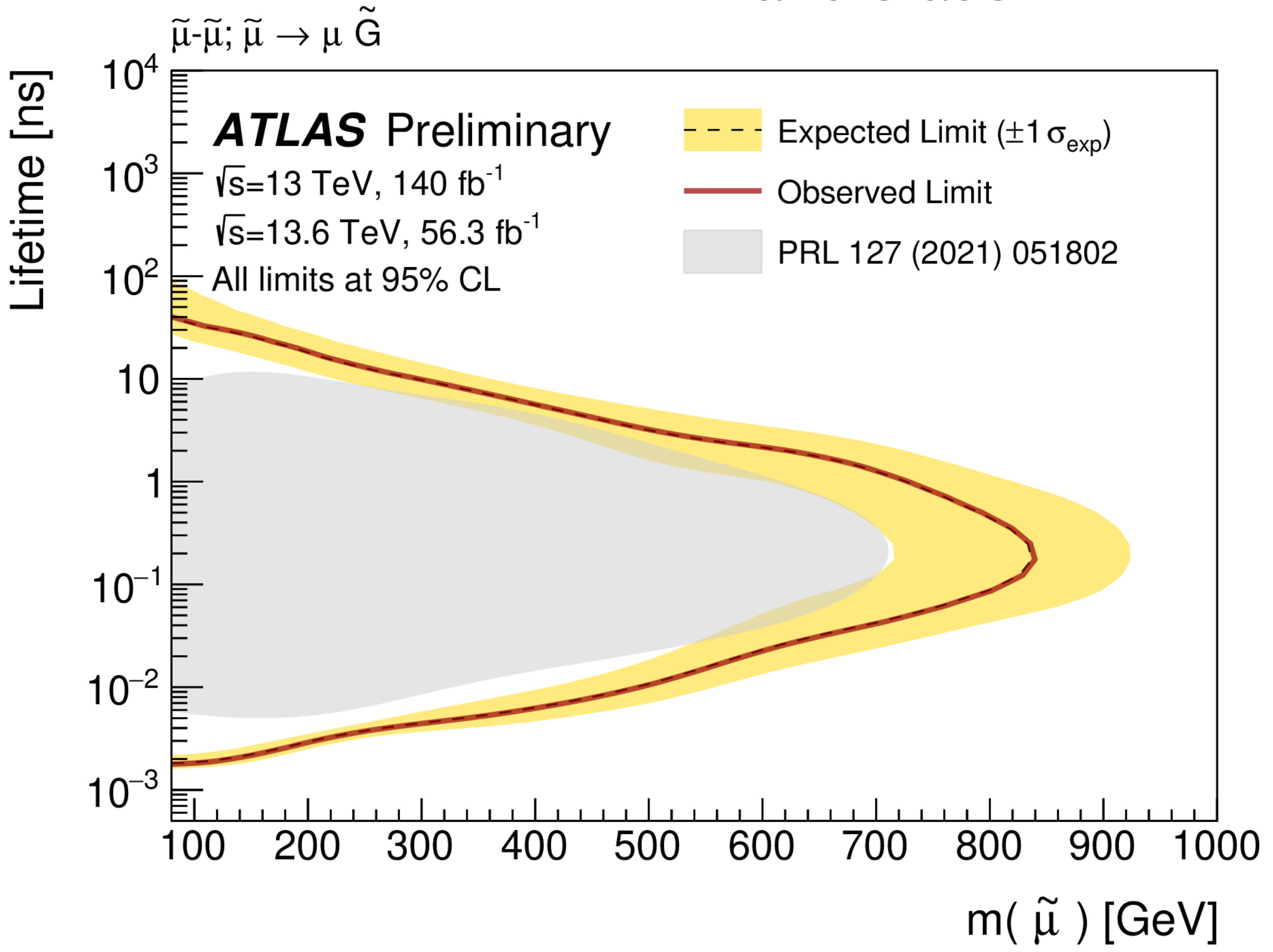


LRT performance tested with Ks reconstruction (Paper)

Search done for smuons, selectron and staus.

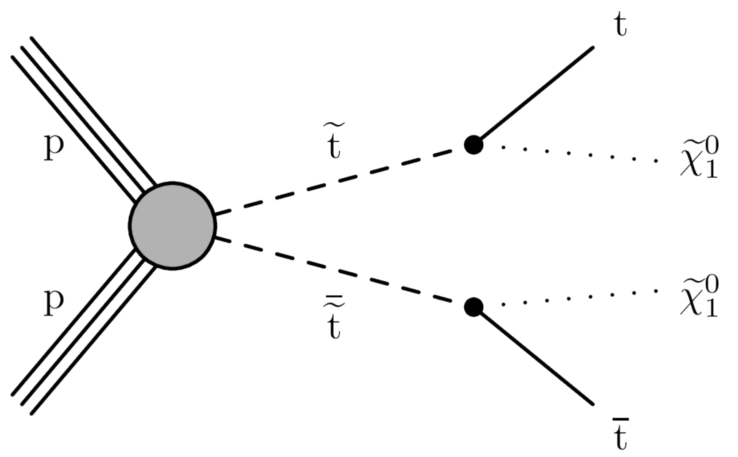


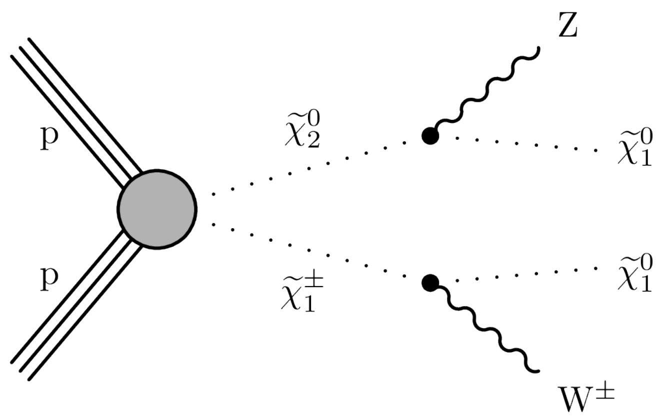
Long lifetime due to the small coupling to the low mass gravitino!

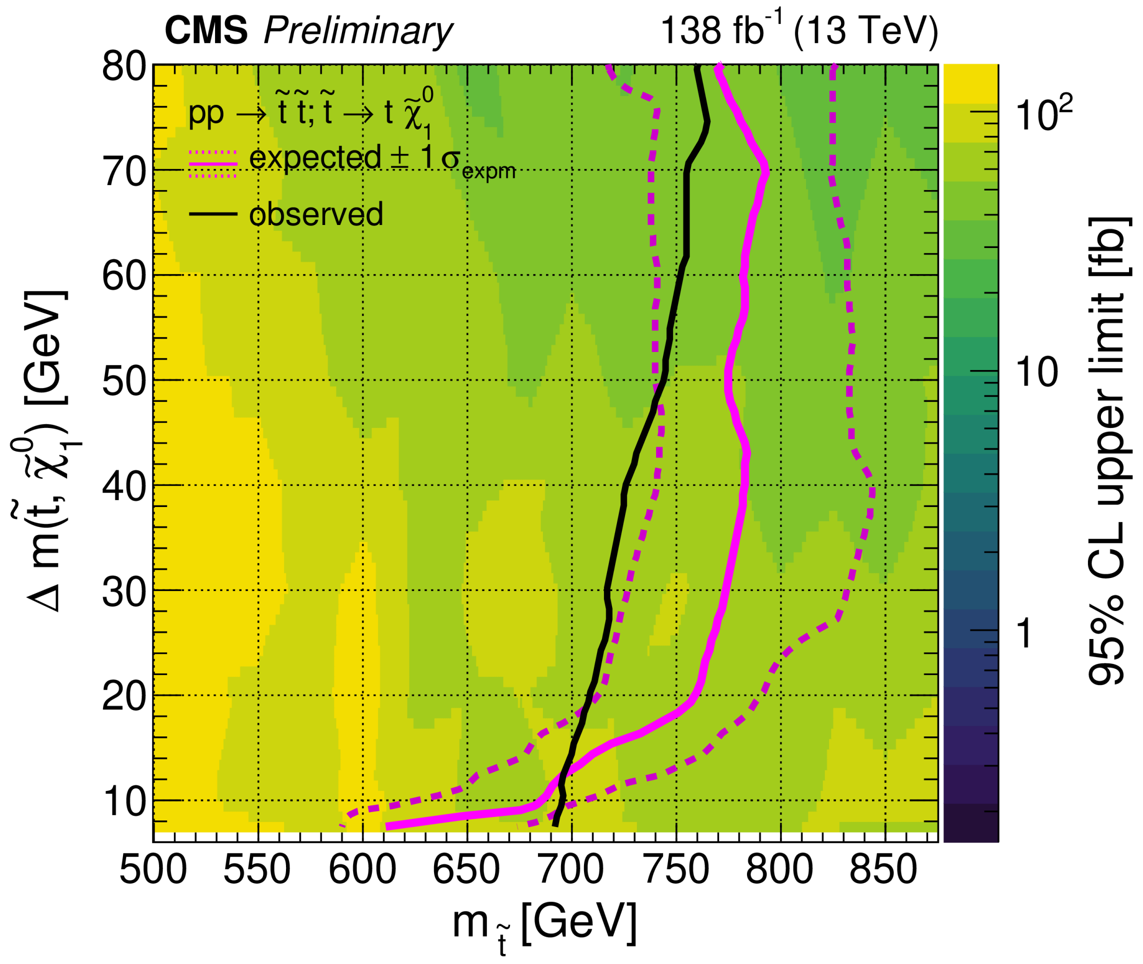


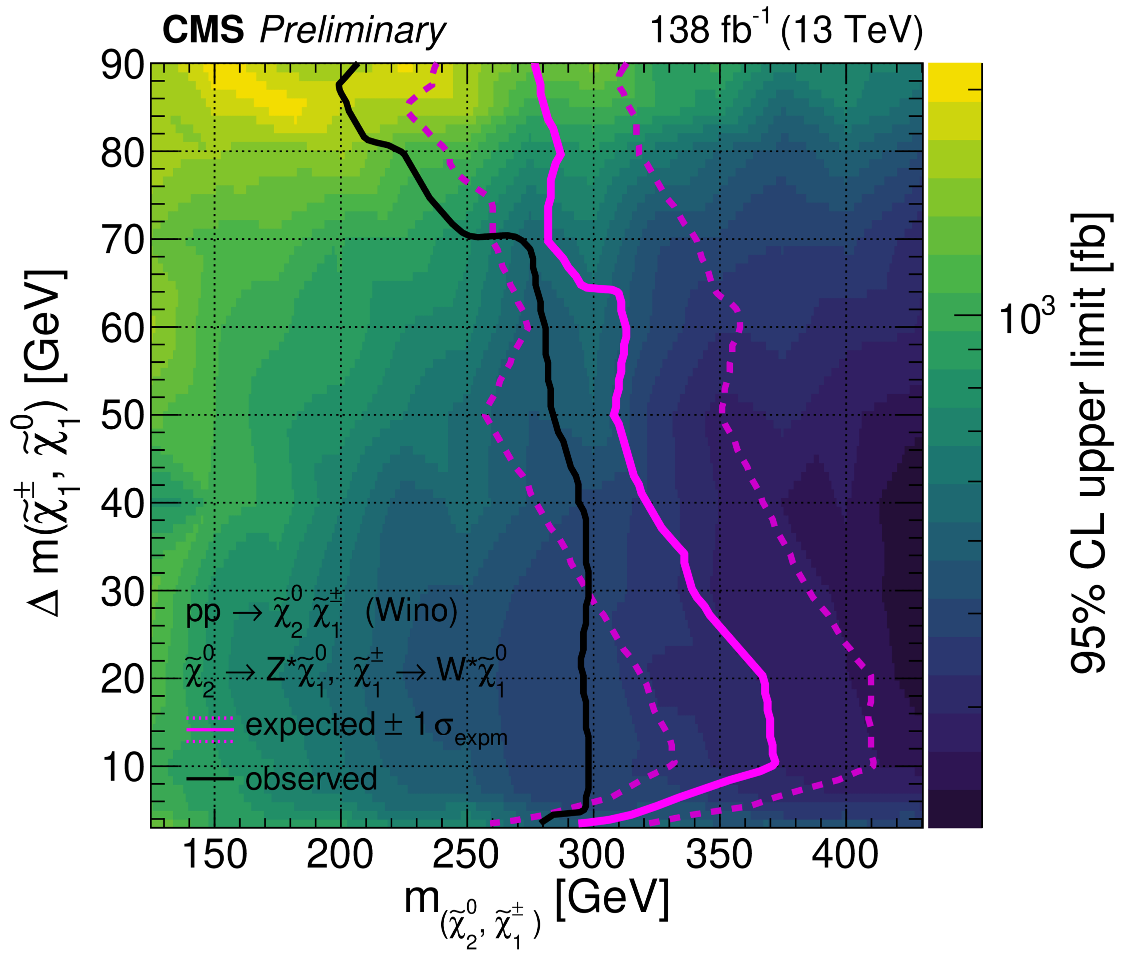
Searches for EWK production SUSY compressed scenarios

Wide range of signatures targeting electroweakinos, sleptons, and top squarks with focus on events with a high transverse momentum system from initial-state-radiation jets and significant missing transverse momentum.





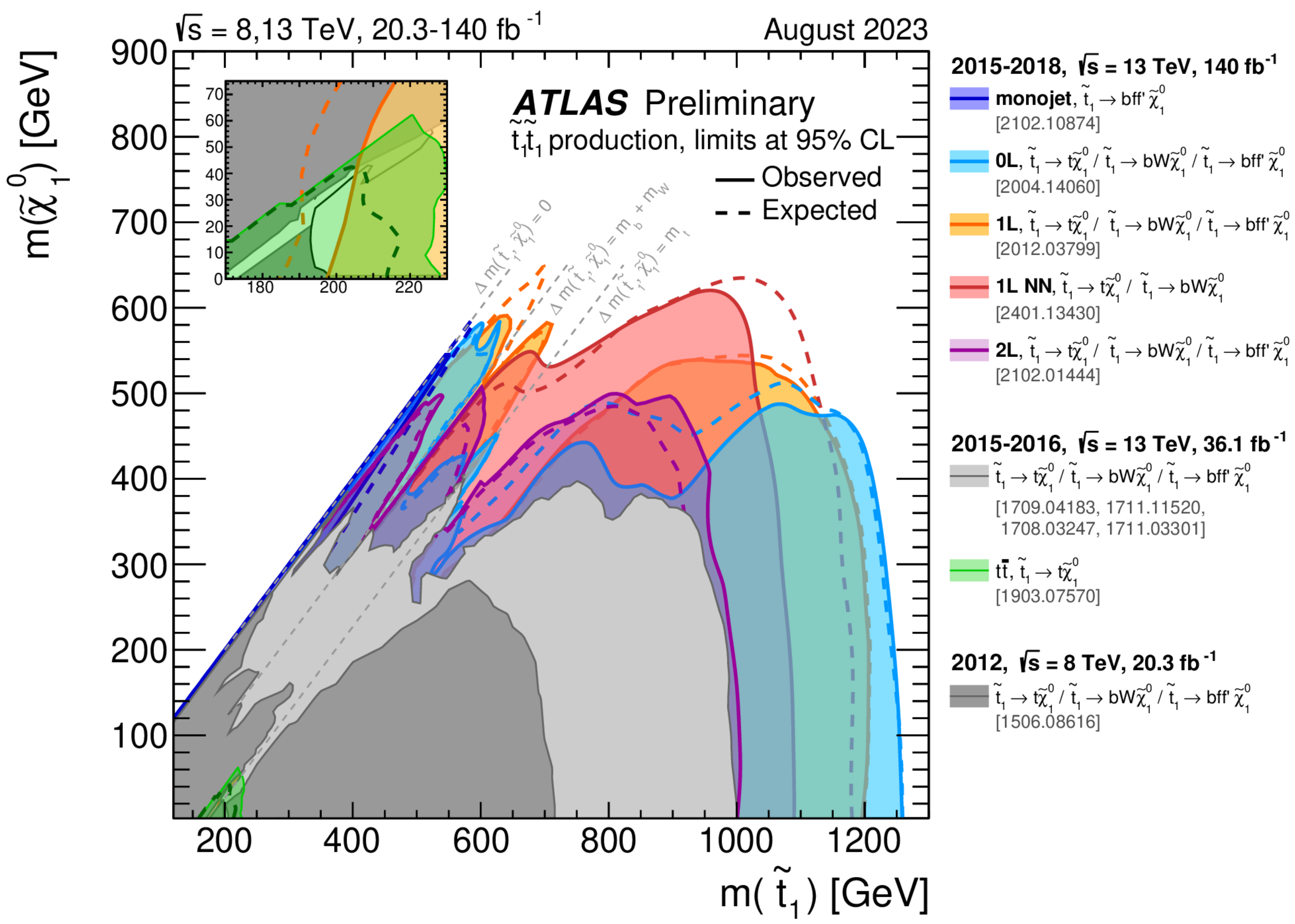




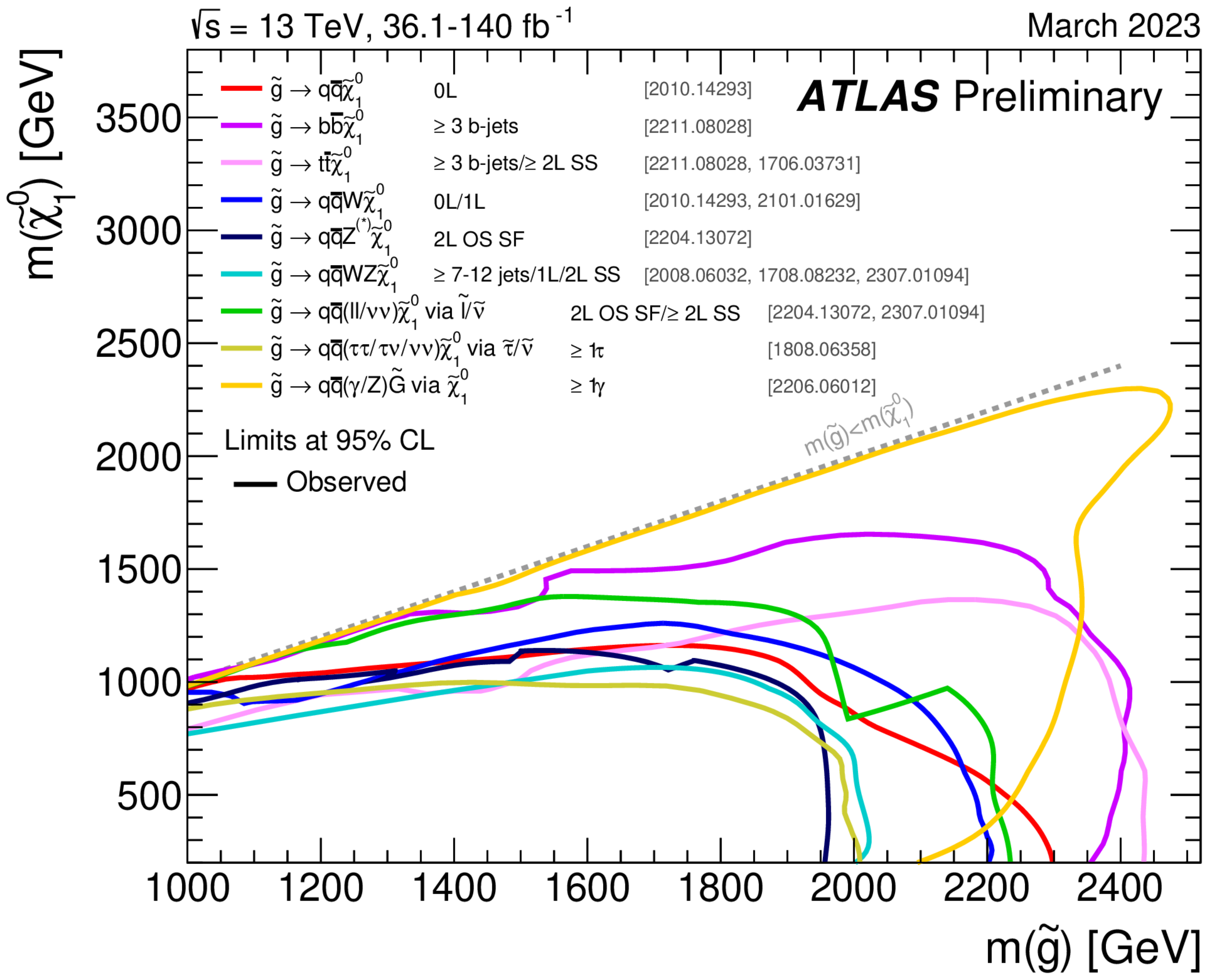
Constraining Naturalness (SUSY) Scenarios

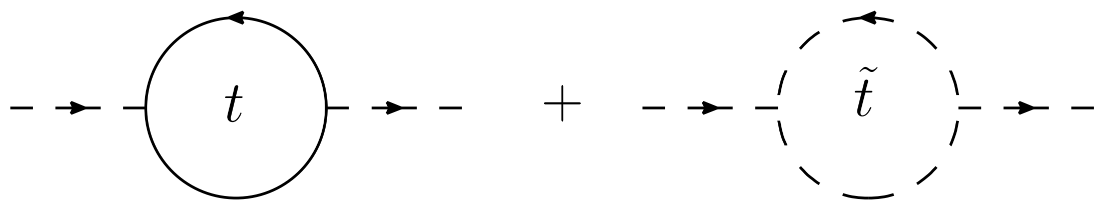
Livia Soffi

Stop searches



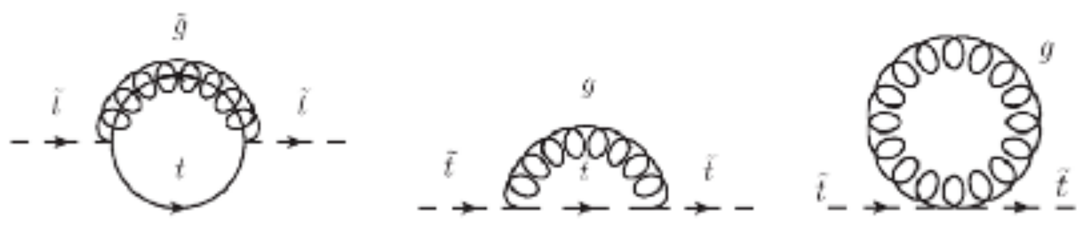
Gluino searches





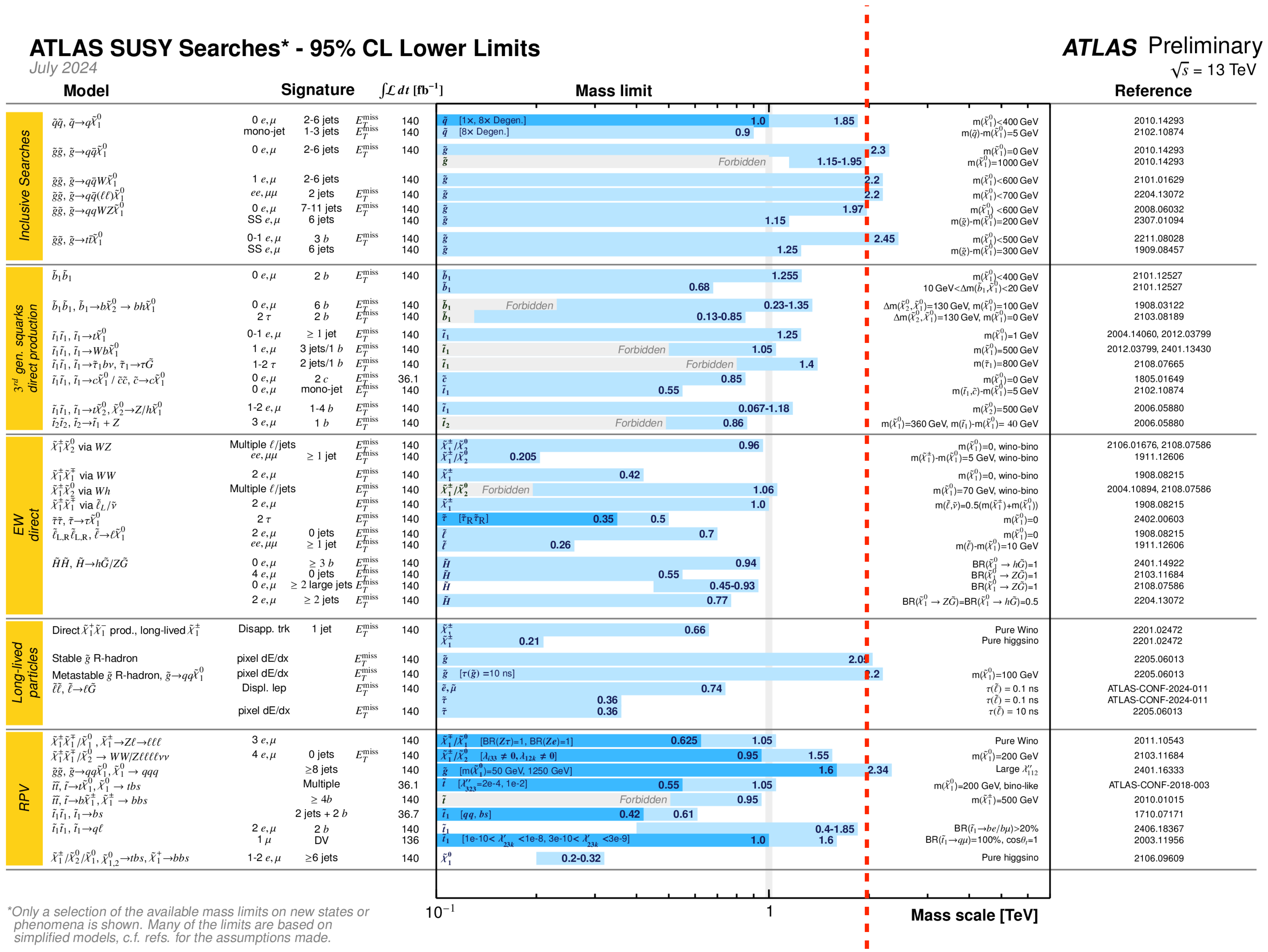
Not so natural SUSY: Stops > 1.2 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.

Stop also a scalar requires light gluinos to be light enough: for gluinos > 2.4 TeV ~tuning of Factor of **30**



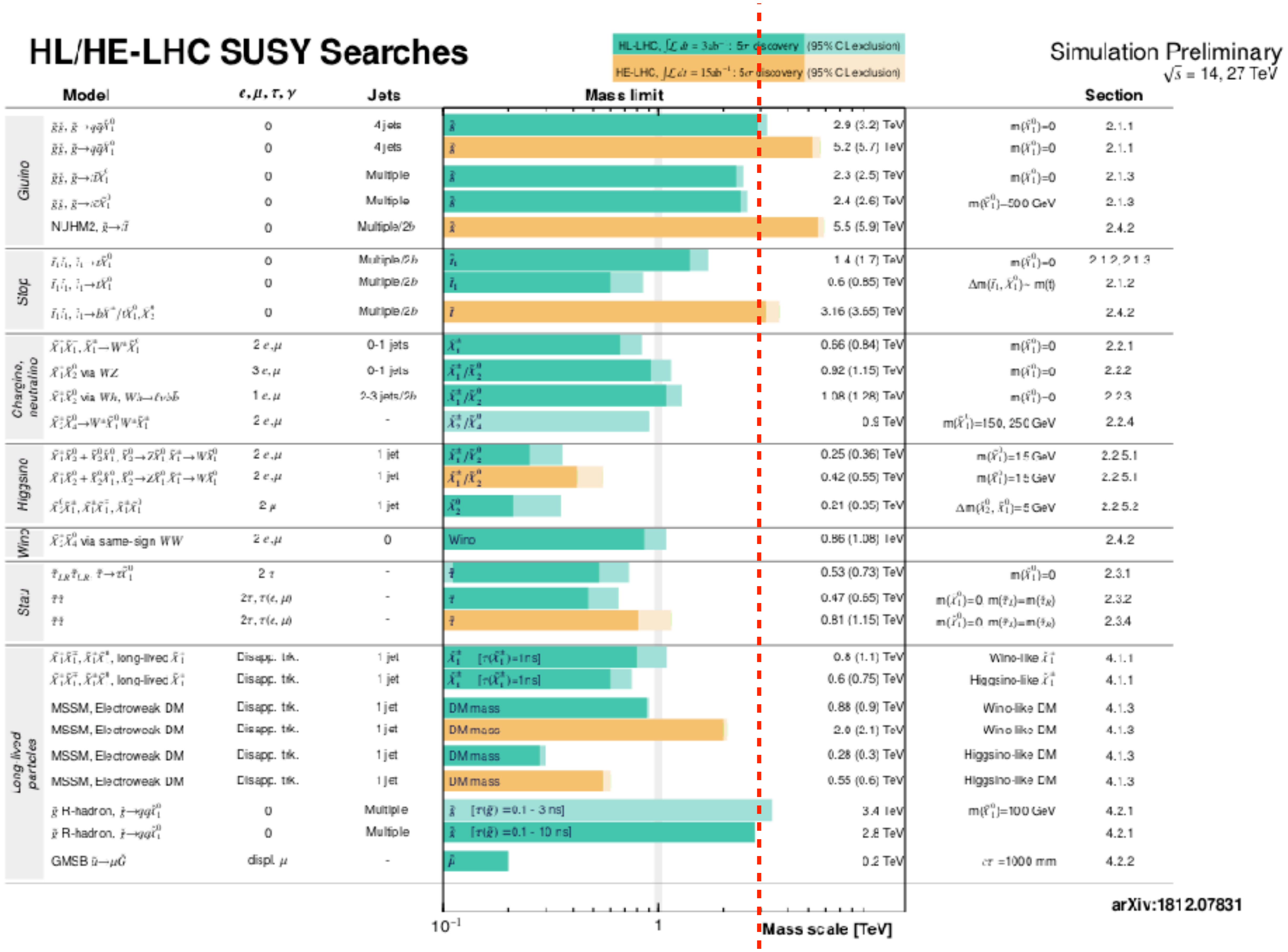
Very Large Number of SUSY Searches

(in large variety of topologies and models)



2 TeV

Example from ATLAS (similar for CMS)



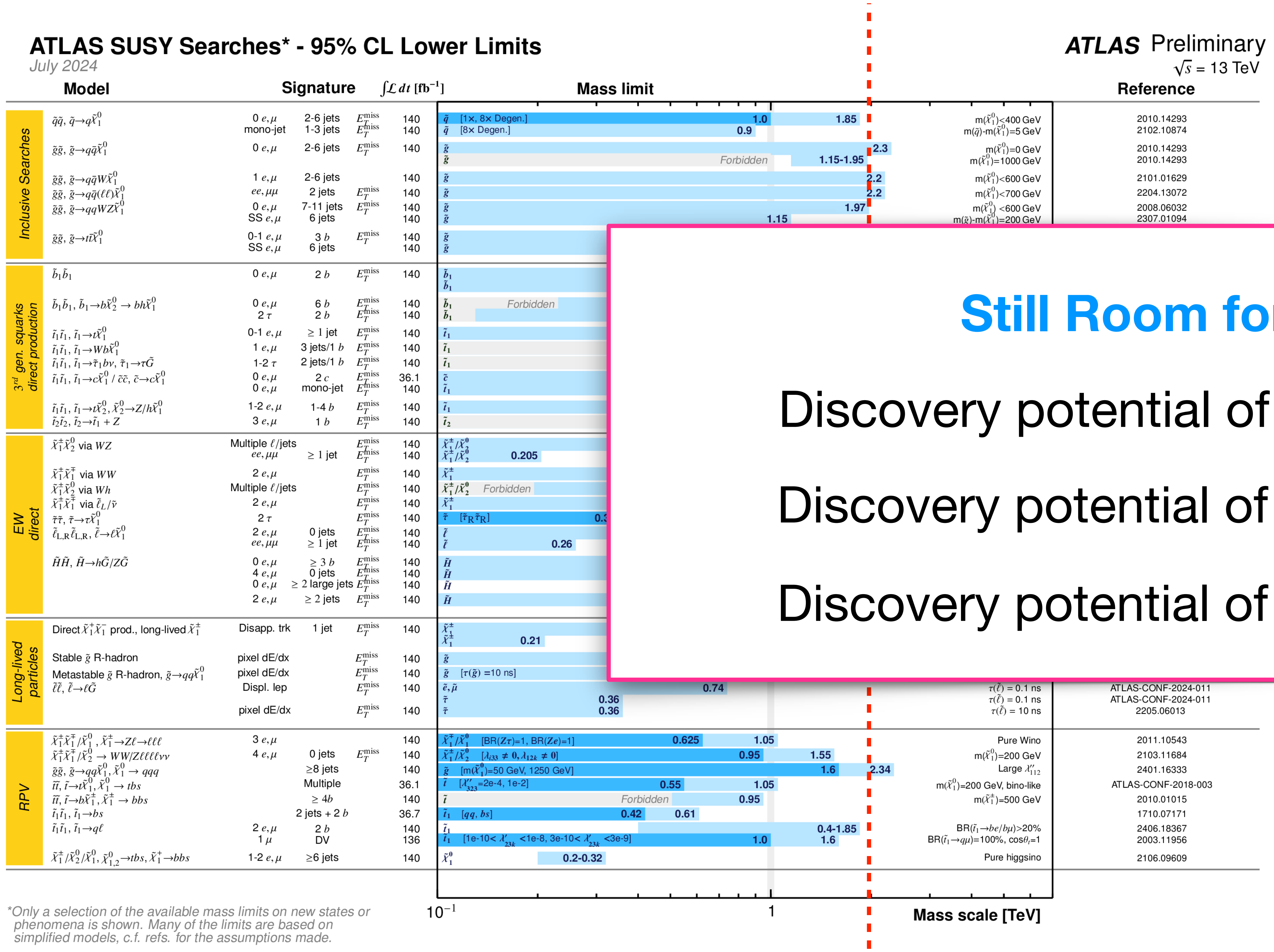
3 TeV

HL-LHC YR
1812.07831

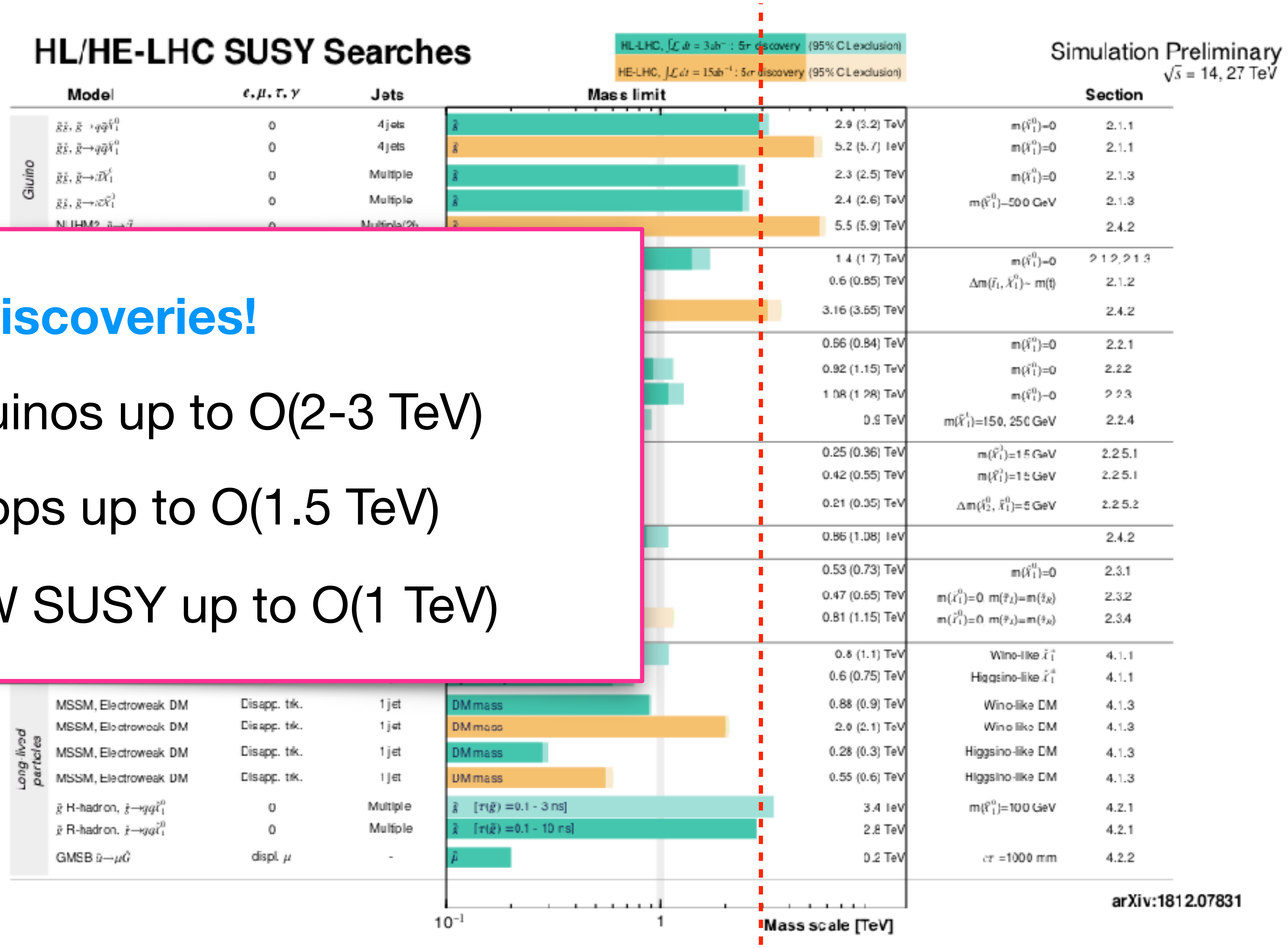
Very Large Number of SUSY Searches

(in large variety of topologies and models)

Livia Soffi



2 TeV



3 TeV

Still Room for Discoveries!

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)

Example from ATLAS (similar for CMS)

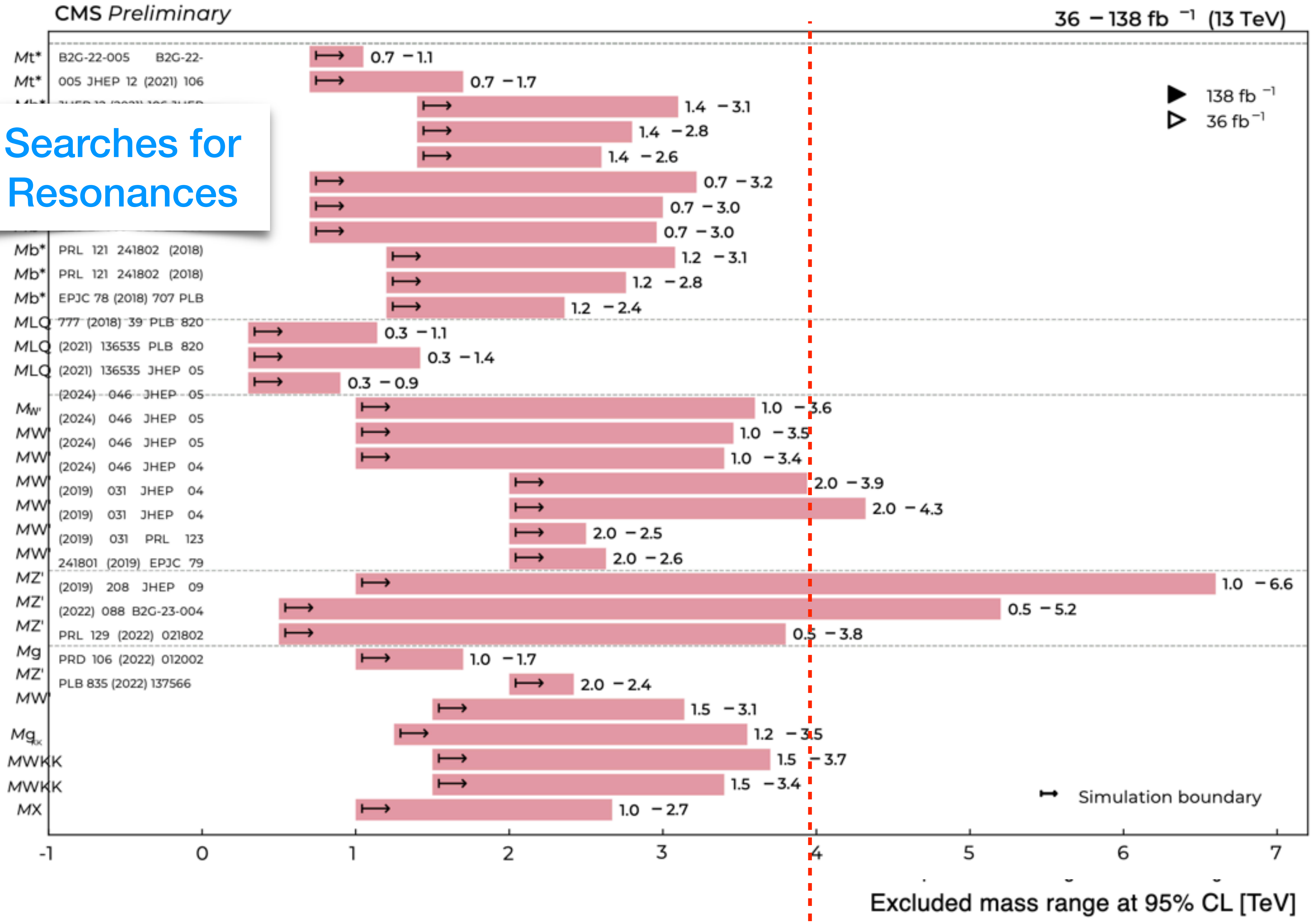
HL-LHC YR 1812.07831

Very Large Number of Searches

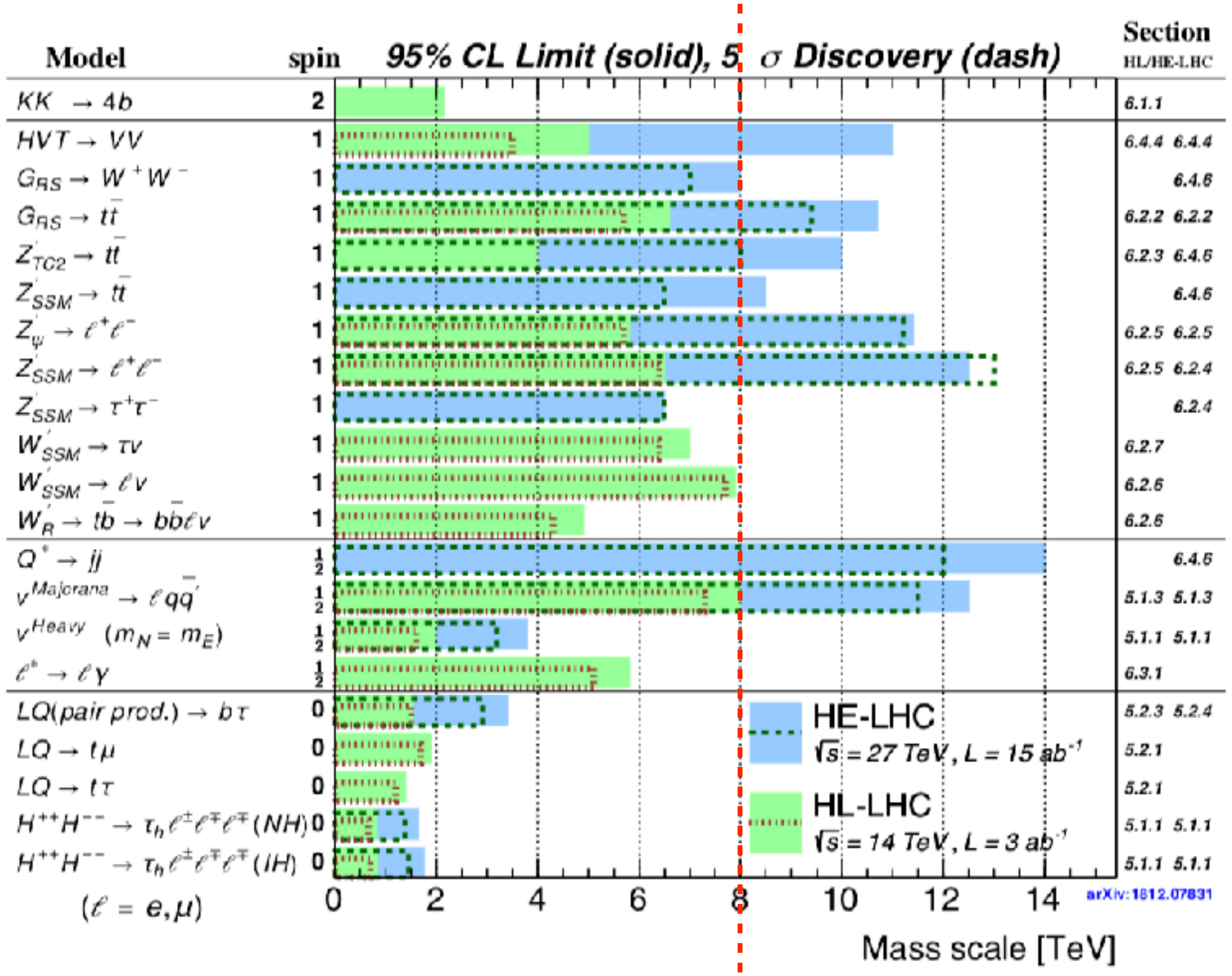
(in large variety of topologies and models)

Livia Soffi

Searches for Resonances



4 TeV



8 TeV

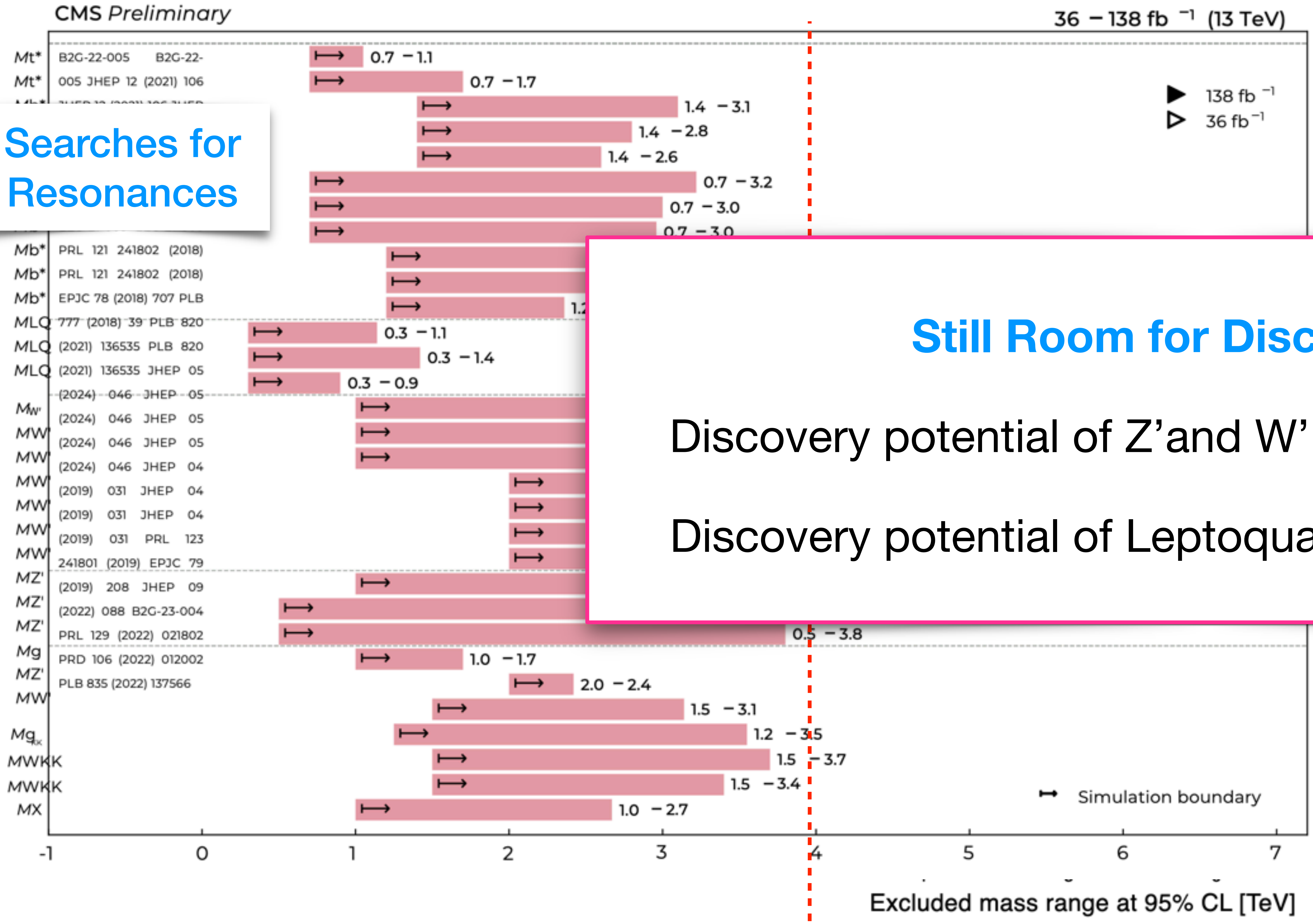
Example from CMS (similar for ATLAS) - latest plot in the backup!

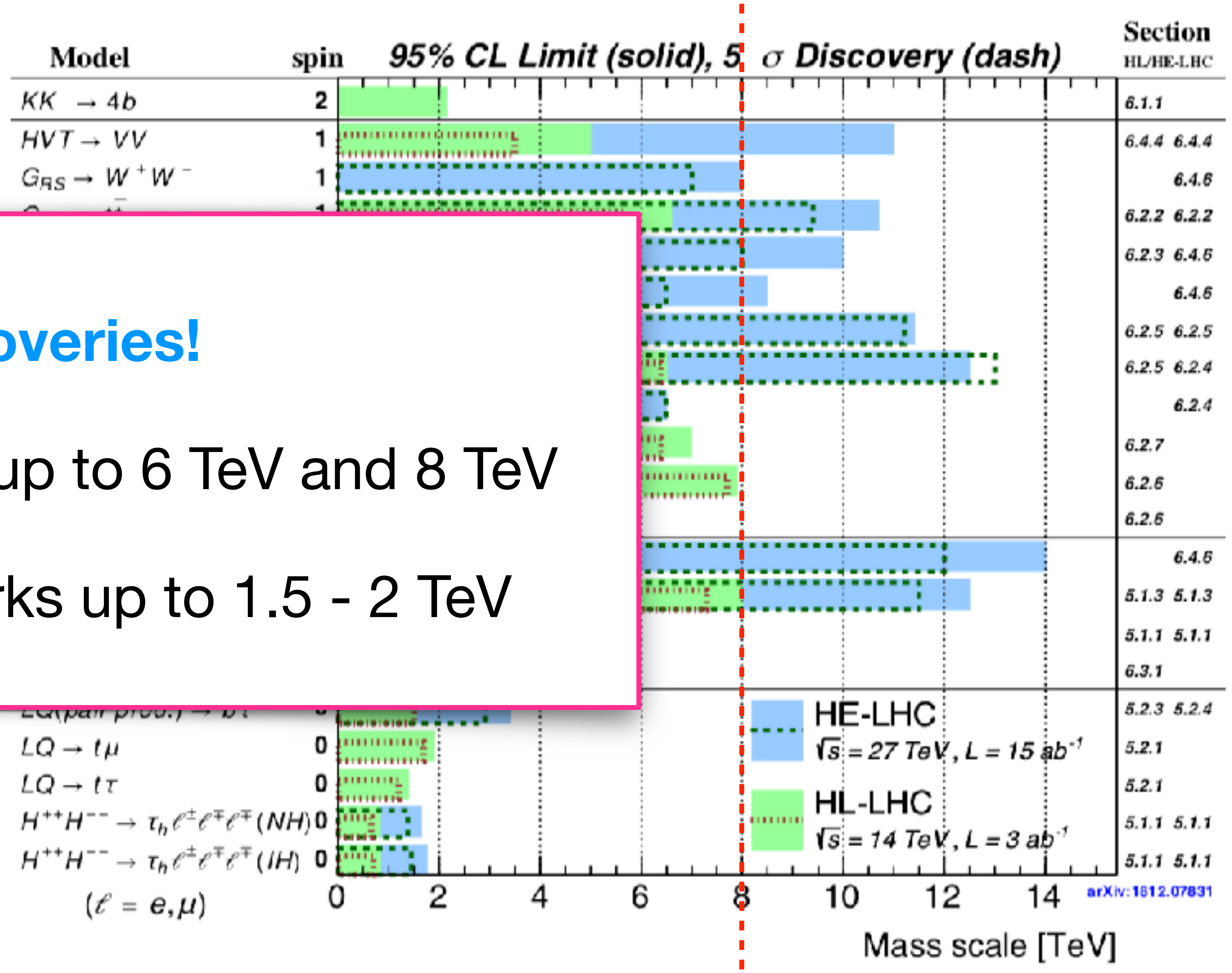
HL-LHC YR 1812.07831

Very Large Number of Searches

(in large variety of topologies and models)

Searches for Resonances





Still Room for Discoveries!

Discovery potential of Z'and W' up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

4 TeV

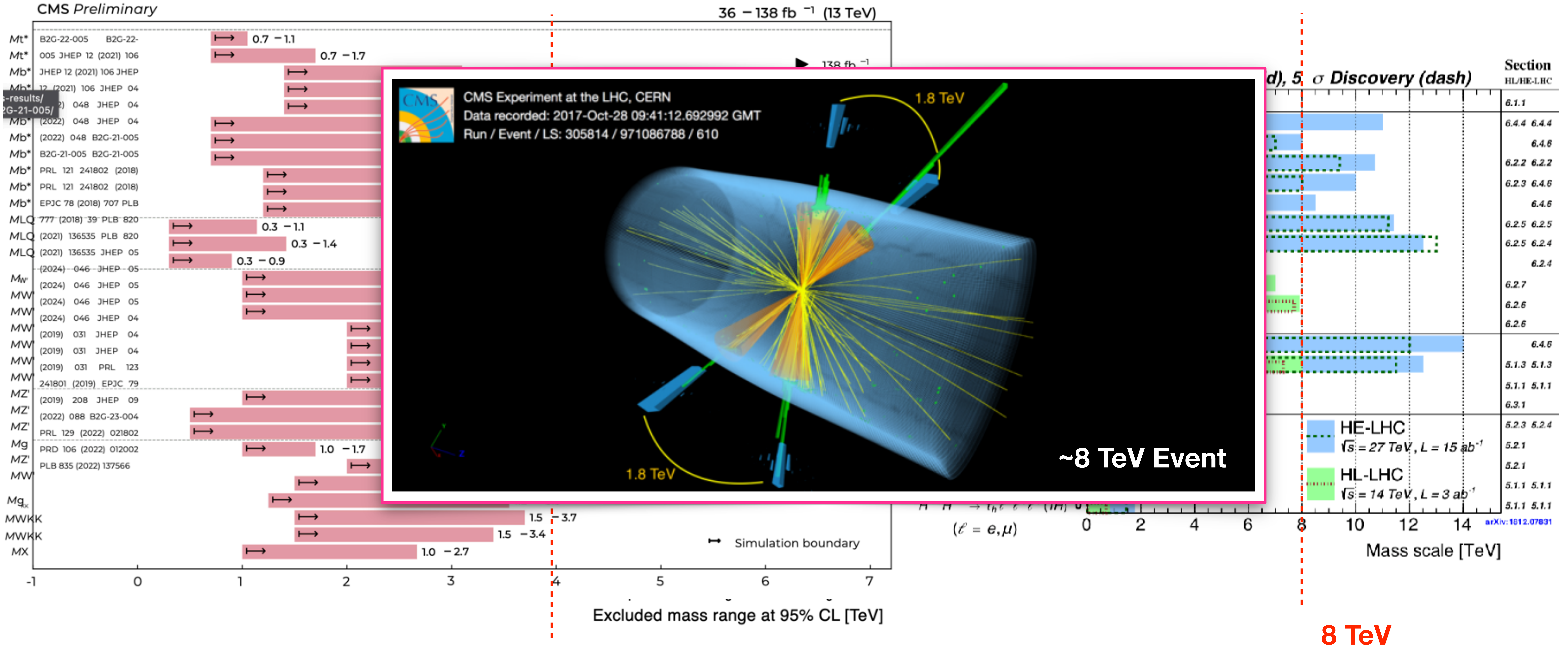
8 TeV

Example from CMS (similar for ATLAS) - latest plot in the backup!

HL-LHC YR
1812.07831

Very Large Number of Searches

(in large variety of topologies and models)



HL-LHC YR
1812.07831

Example from CMS (similar for ATLAS) - latest plot in the backup!

A Scientific Mission for the 21st Century

Rende Steerenberg

Future Large Collider Projects

Hitoshi Murayama

The field is facing a defining moment in its history!

P5 - Reveal the secrets of the Higgs boson and much more… ultimate EW precision factory!

"We would not consider the theory of electromagnetism established if we had only verified the strength of electromagnetic forces to within 10% accuracy." (Salam, Wang, Zanderighi, Nature)

P5 - A realistic path to a 10 TeV parton center-of-momentum (pCM) collider.

Closing quotes from the panel discussion (video)

Yifang Wang: "In the Future, not very far from now there will be a Higgs factory!"

Lia Merging: "Need to continue to be bold and ambitious and dream big!"

Fabiola Gianotti: "As we have seen at this conference the field is extremely vibrant and exciting!"

Conference Summary and Highlights

Many thanks to all participants for the excellent discussions and great atmosphere!

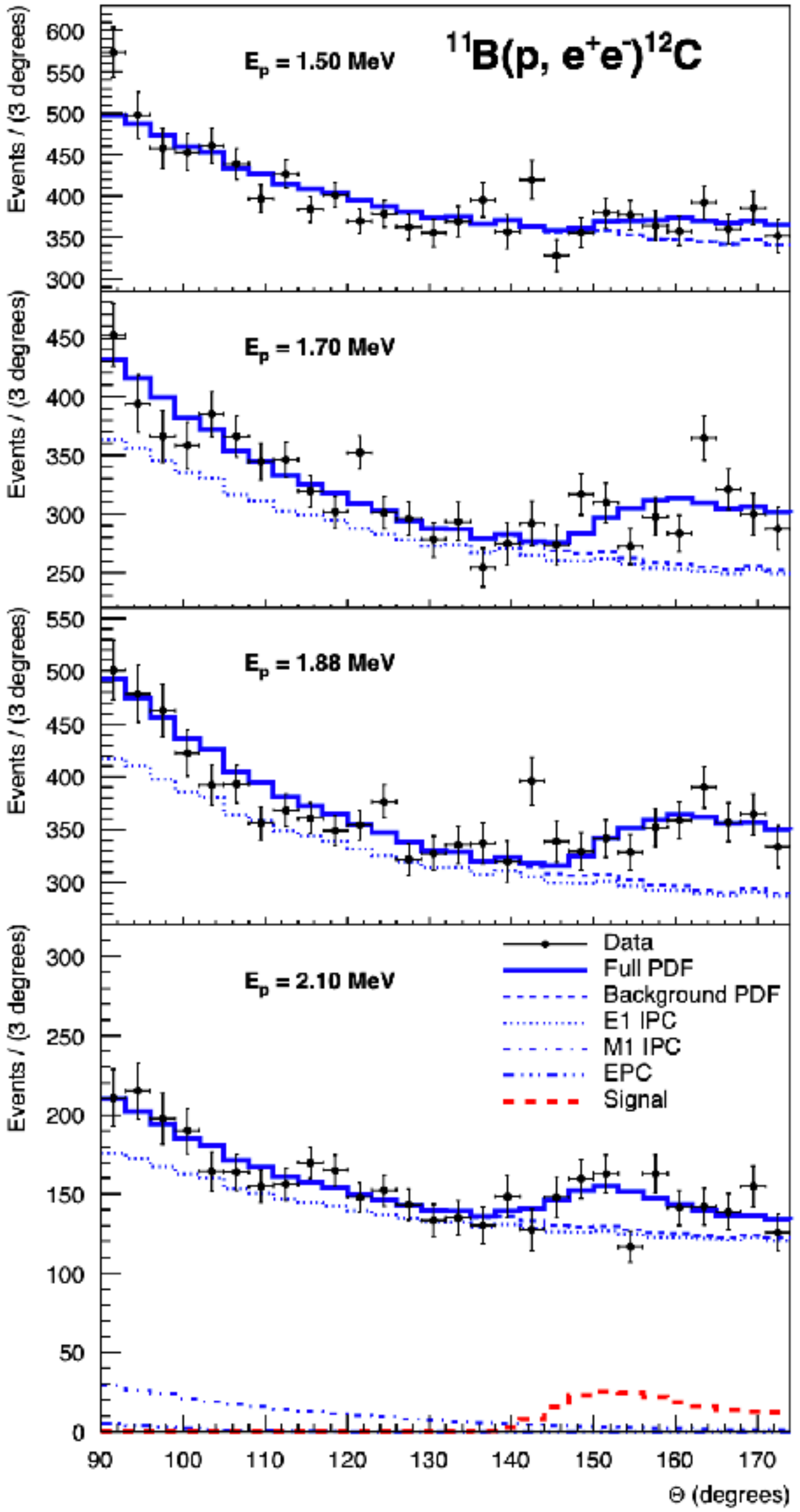
Many thanks and congratulations to all the speakers and collaborators for the splendid talks and results!

Many thanks to the organisers for the amazing conference in this amazing place! The organisation was perfect!

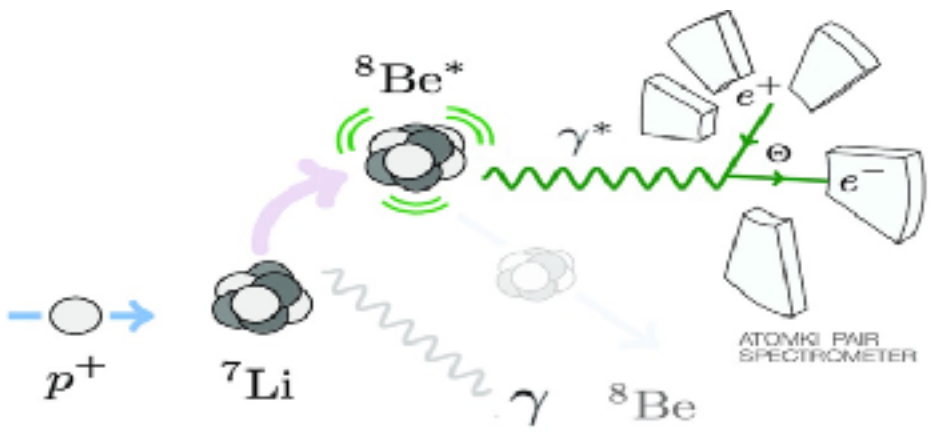
Backup

^8Be Anomaly and PADME

Venelin Kozhuharov

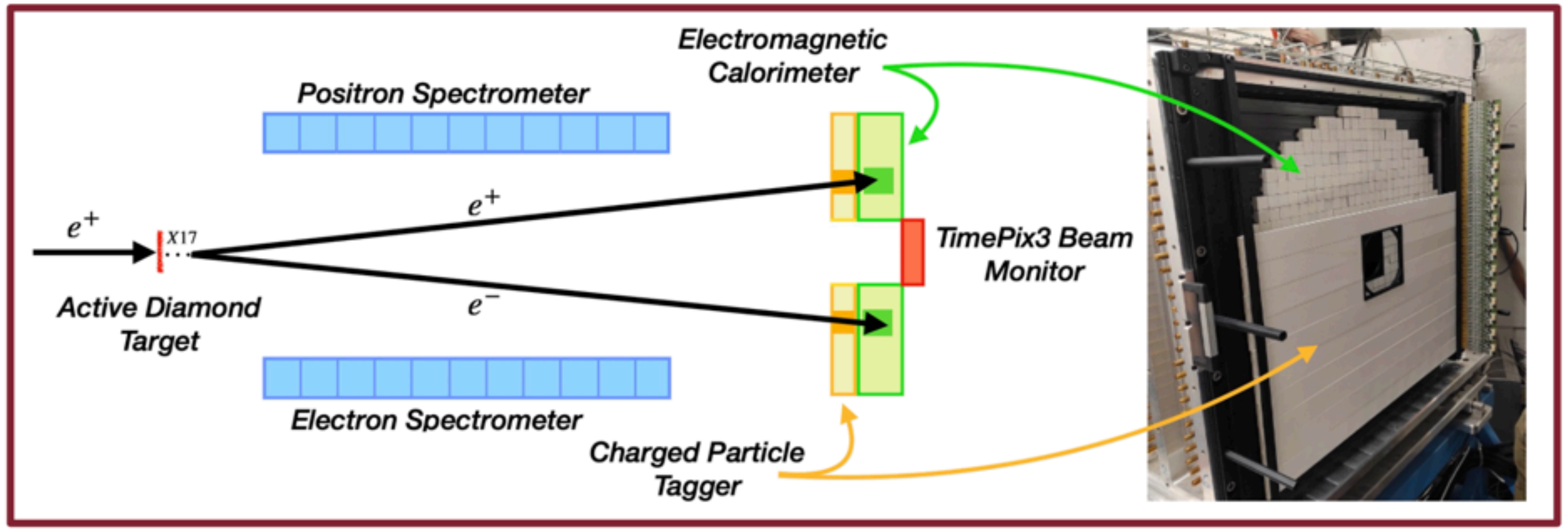


The ATOMKI institute observes the long standing ^8Be anomaly, observed also in ^4He and ^{12}C, i.e. a significant excess compatible with new particle of 17 MeV mass.



DAΦNE Beam Test Facility is the only facility in the world with a positron beam at 282 MeV (yielding 17 MeV centre-of-mass collisions with fixed target electron!)

PADME experiment (**P**ositron **A**nnihilation into **D**ark **M**atter **E**xperiment)



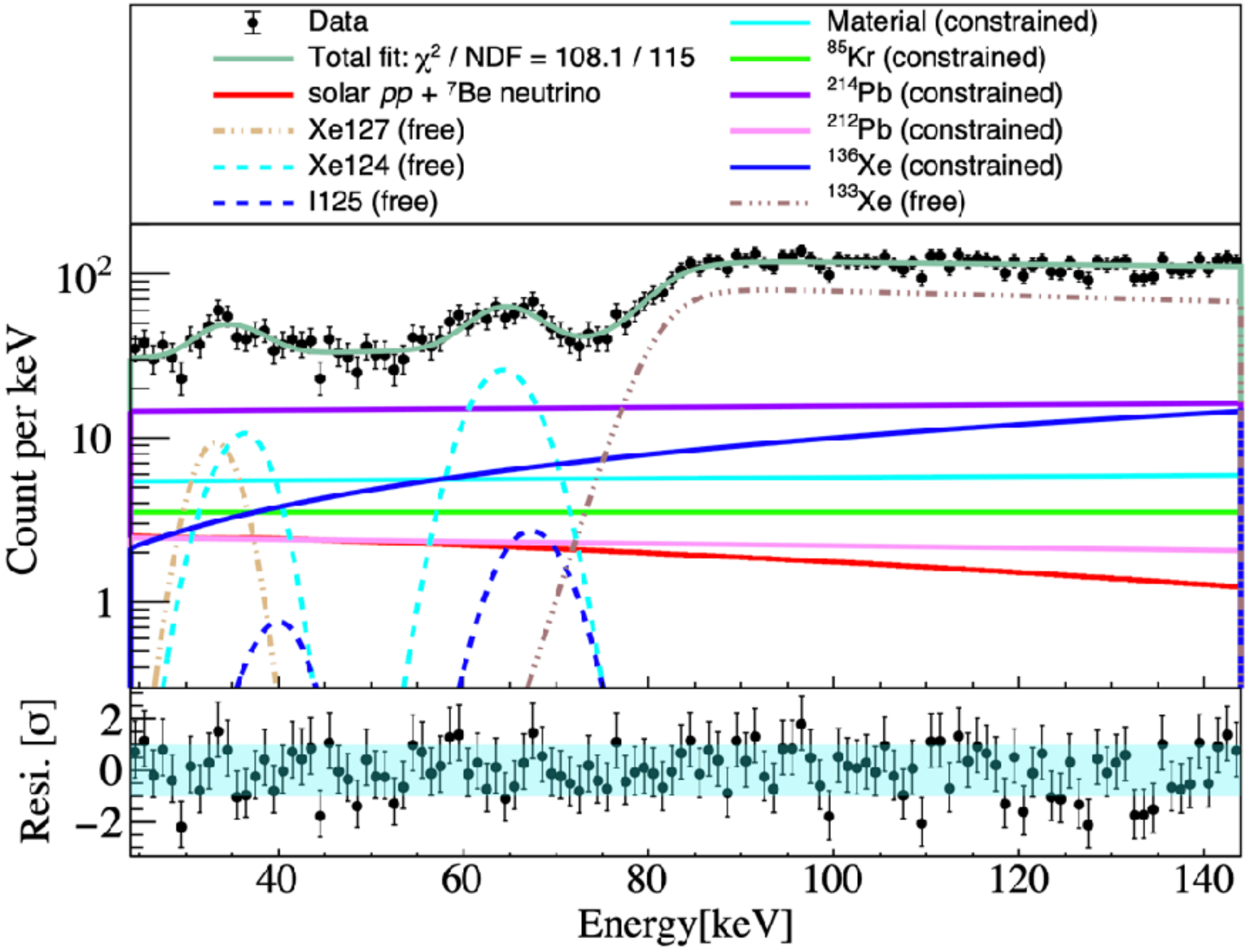
Run has finished and data analysis is ongoing, hoping to shine light on ^8Be

Data not unblinded yet!

Solar Neutrinos in the Electron Recoils

Challenge #2: Search for WIMPs to the Neutrino Background in Direct Detection

Constraints on the $pp + {}^7Be$ neutrino flux from PandaX-4T

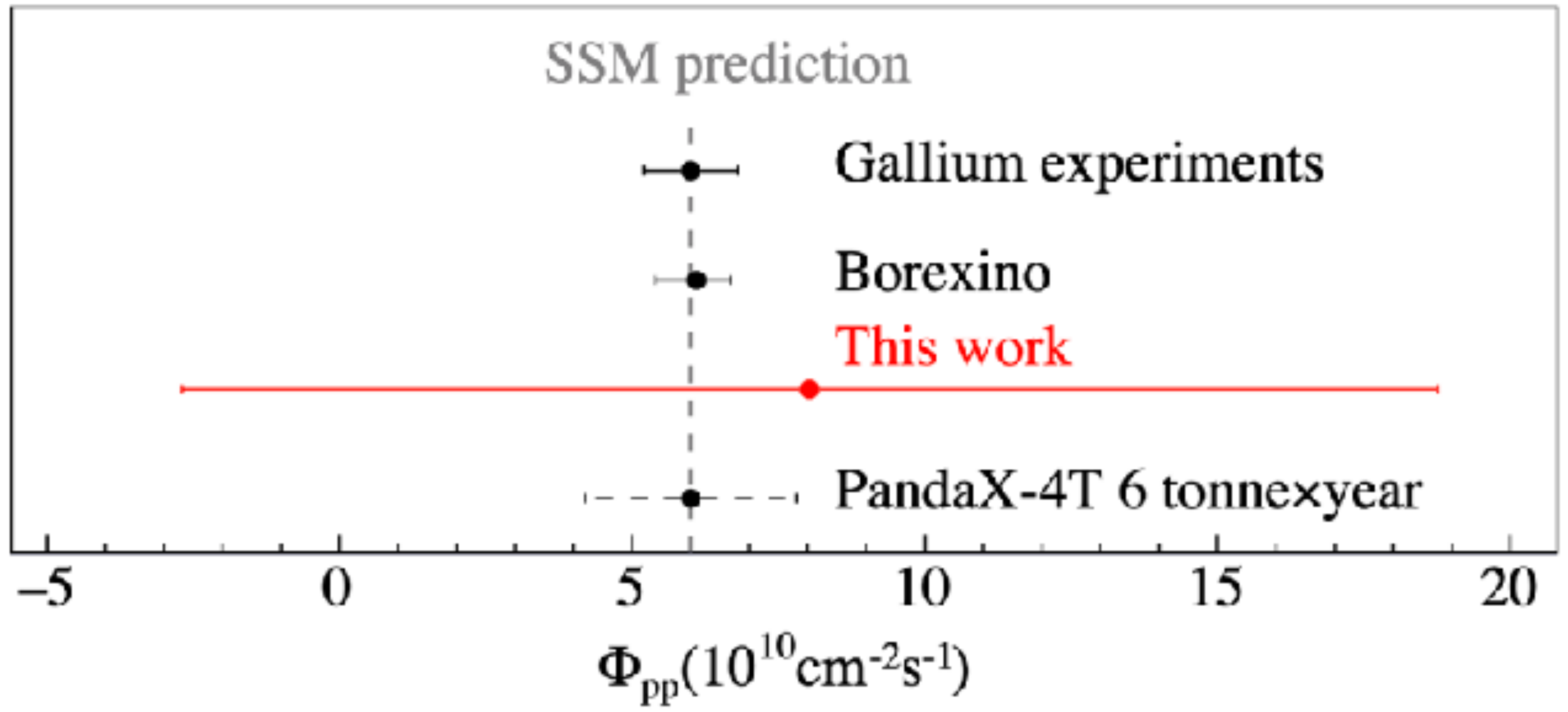


$$\nu_x + e^- \to \nu_x + e^-$$

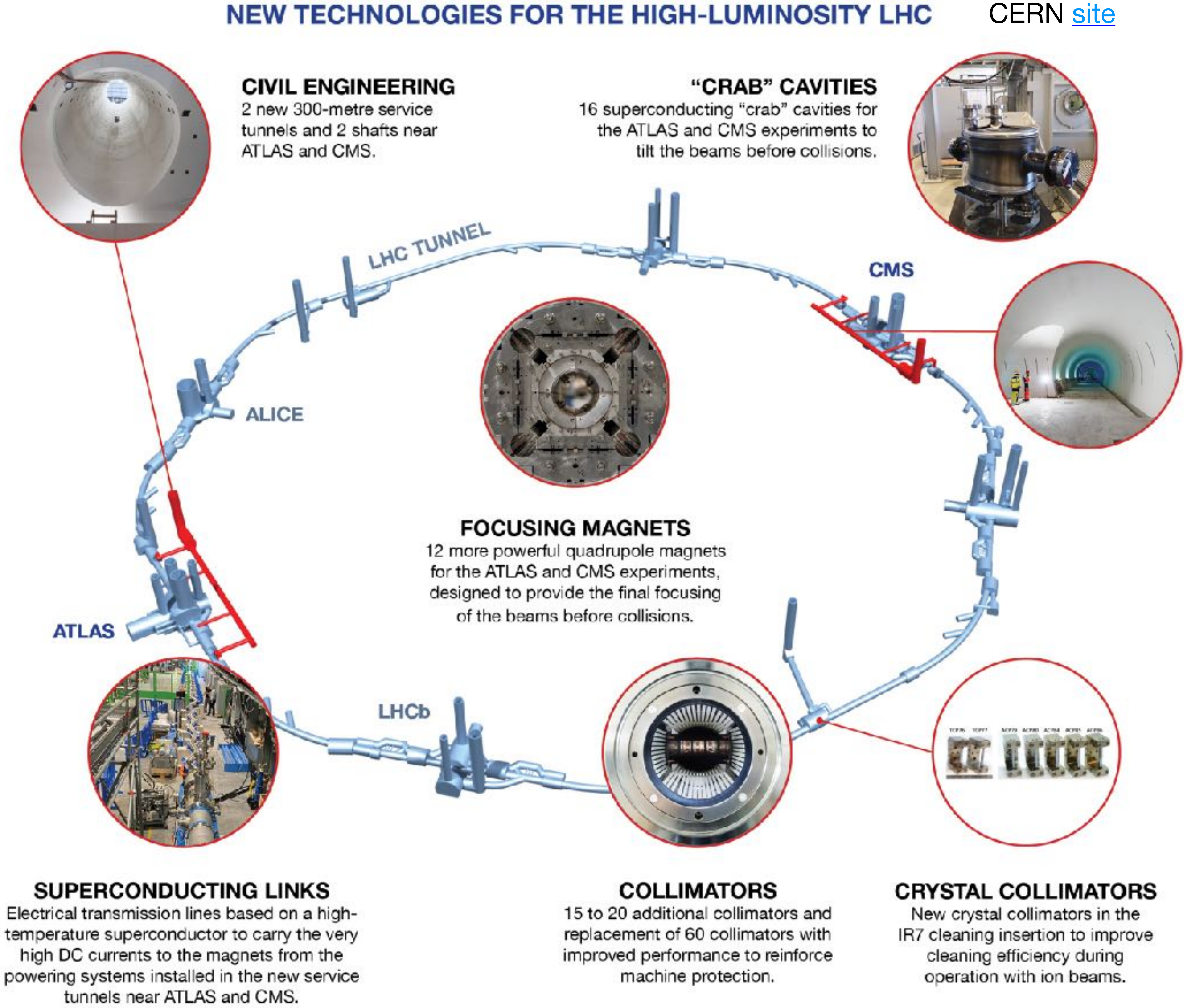
PandaX-4T is a dual phase liquid Xe TPC

$pp + {}^7Be$ neutrinos ar a sub-dominant background in the electron recoil!

No evidence yet for solar neutrinos - **Yet**!



LHC Machine Towards Major LS3 Upgrades



CERN site

Front page of the CERN Courier says it all!

LS3 installation fully on track!

Nb_3Sn series magnets manufactured at Fermilab arrived at CERN! See CERN News.

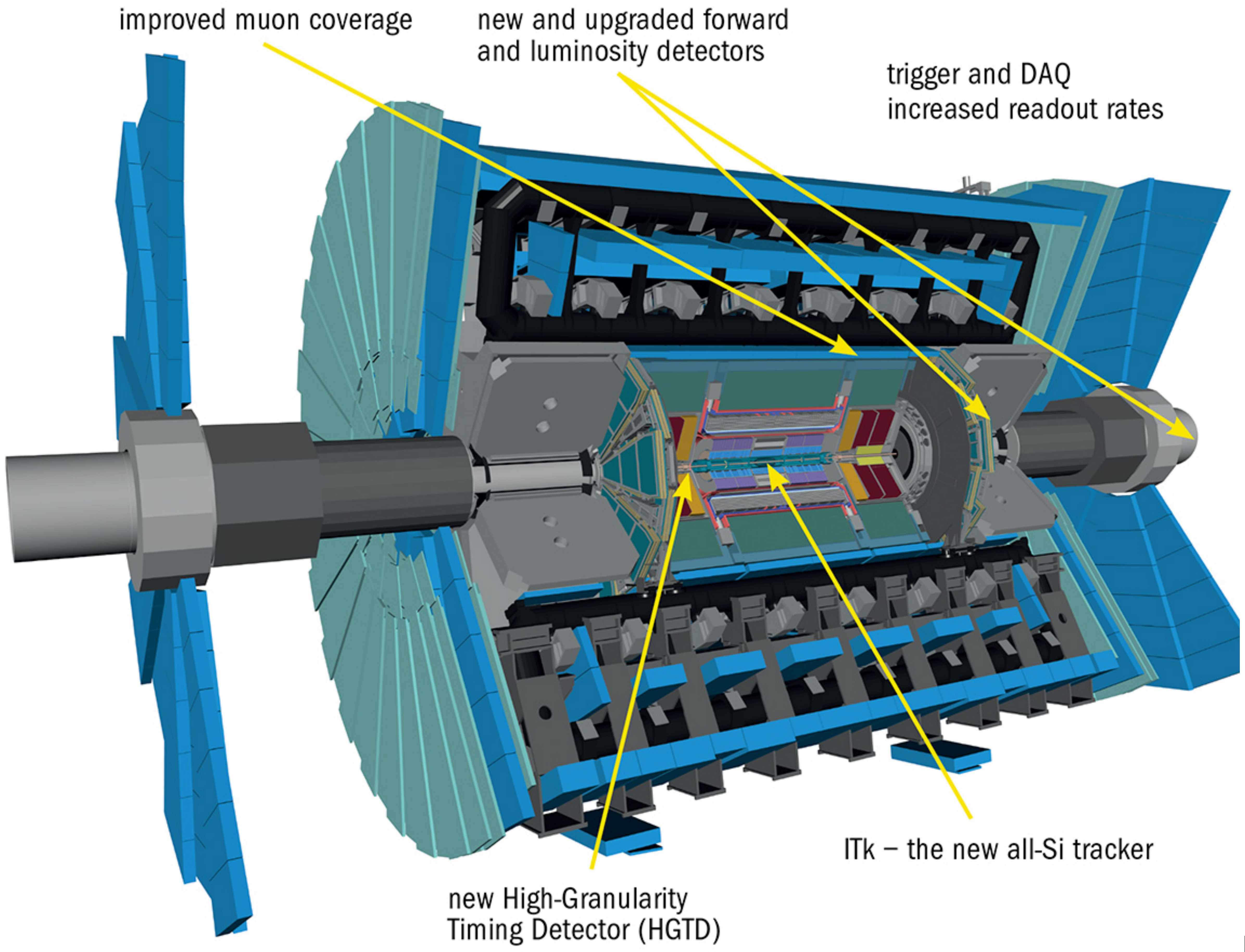
ATLAS and CMS Towards Major LS3 Upgrades

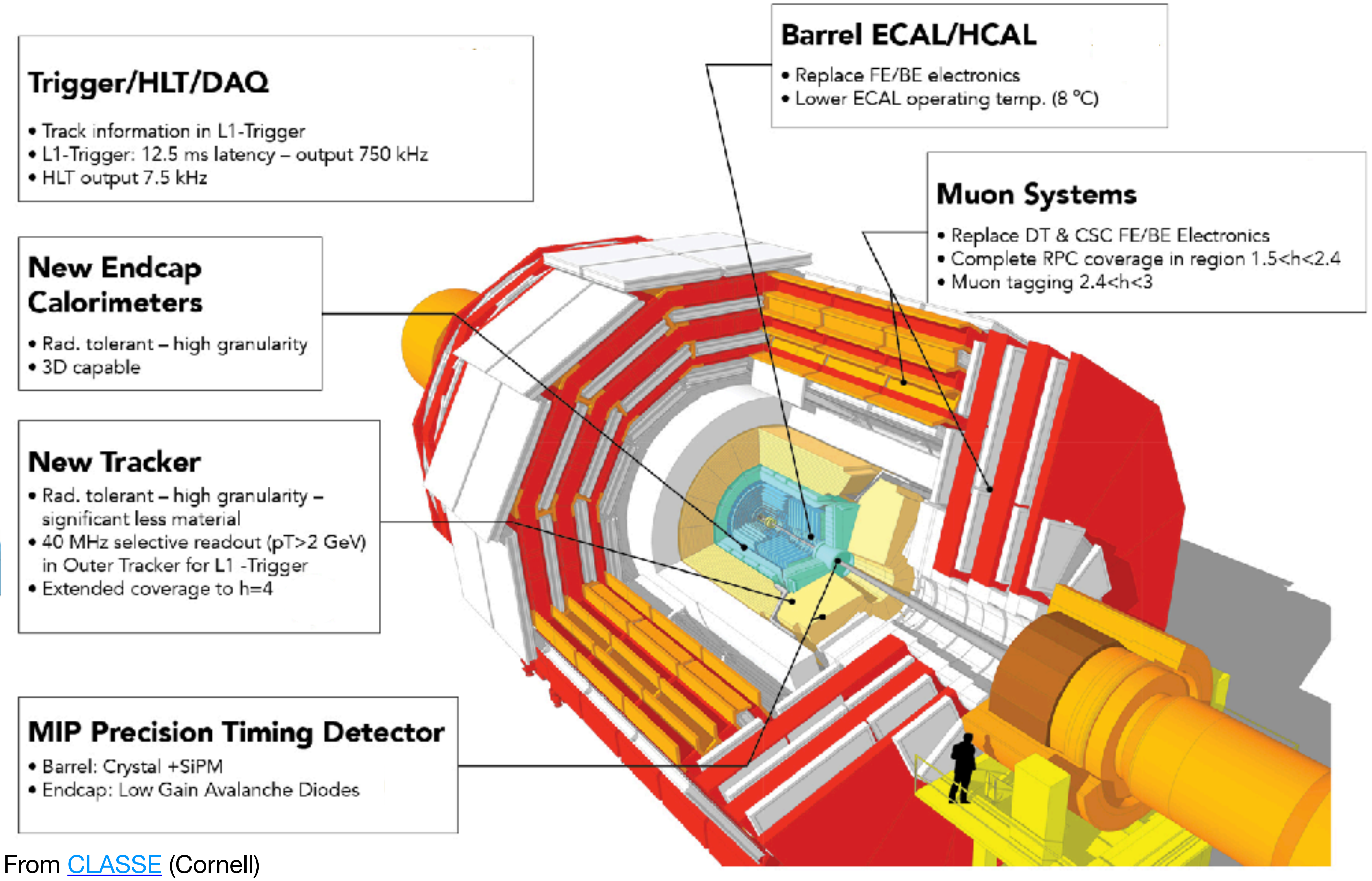
A new ATLAS for the high-luminosity era
18 January 2023 | By Stefan Guindon, Christian Ohm, Caterina Vernieri

Feature link

ACCELERATORS | FEATURE
CMS prepares for Phase II
9 January 2023

CERN Courier article link





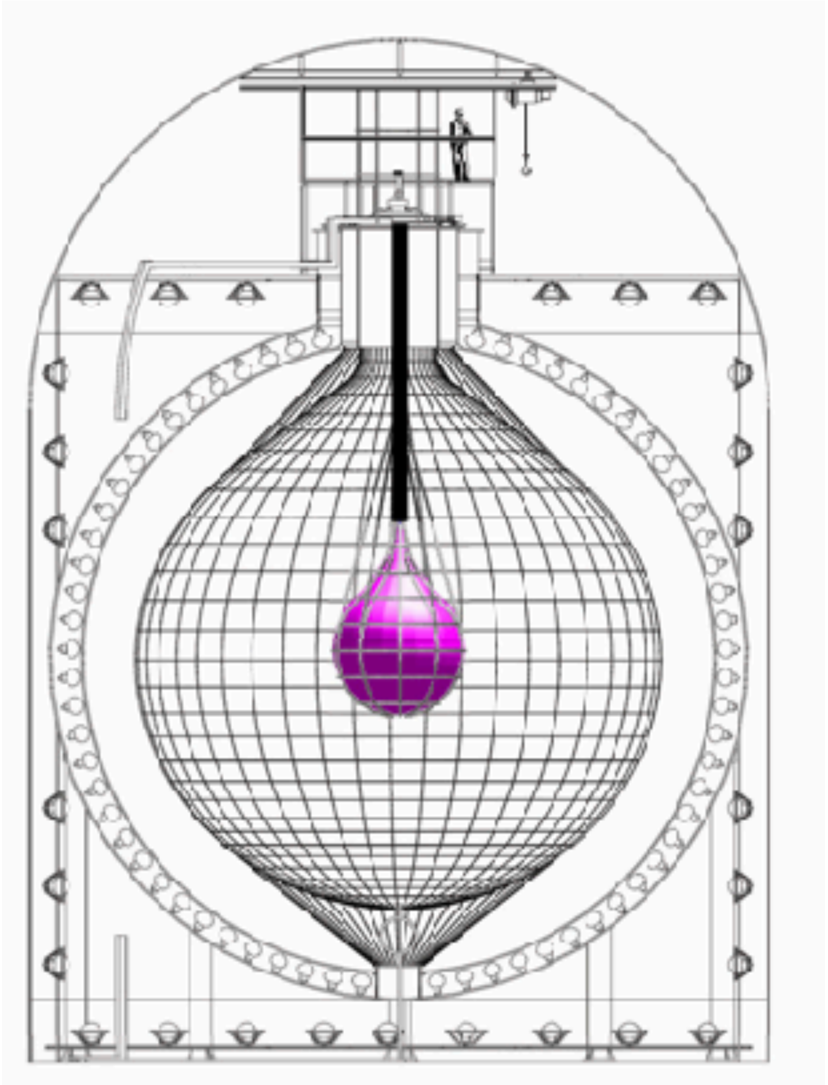
From CLASSE (Cornell)

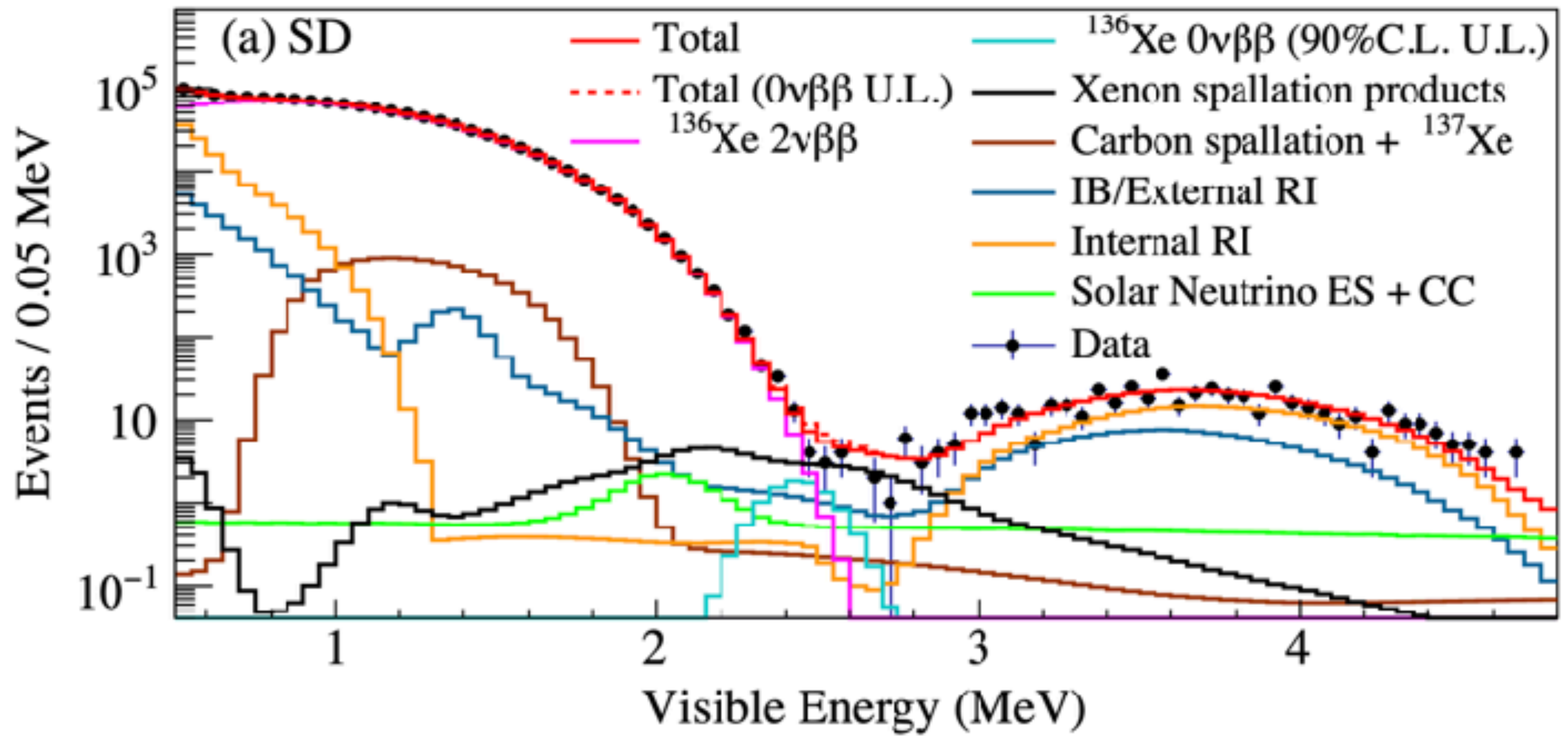
Neutrinoless double beta decay

KamLandZen

Mini-balloon Radius = 1.90 m
Xenon mass = 750 kg
Data taking started in 2019

The largest number of ββ nuclei. Low BG by distillation and filtration of both Liquid Scintillator and Xenon.



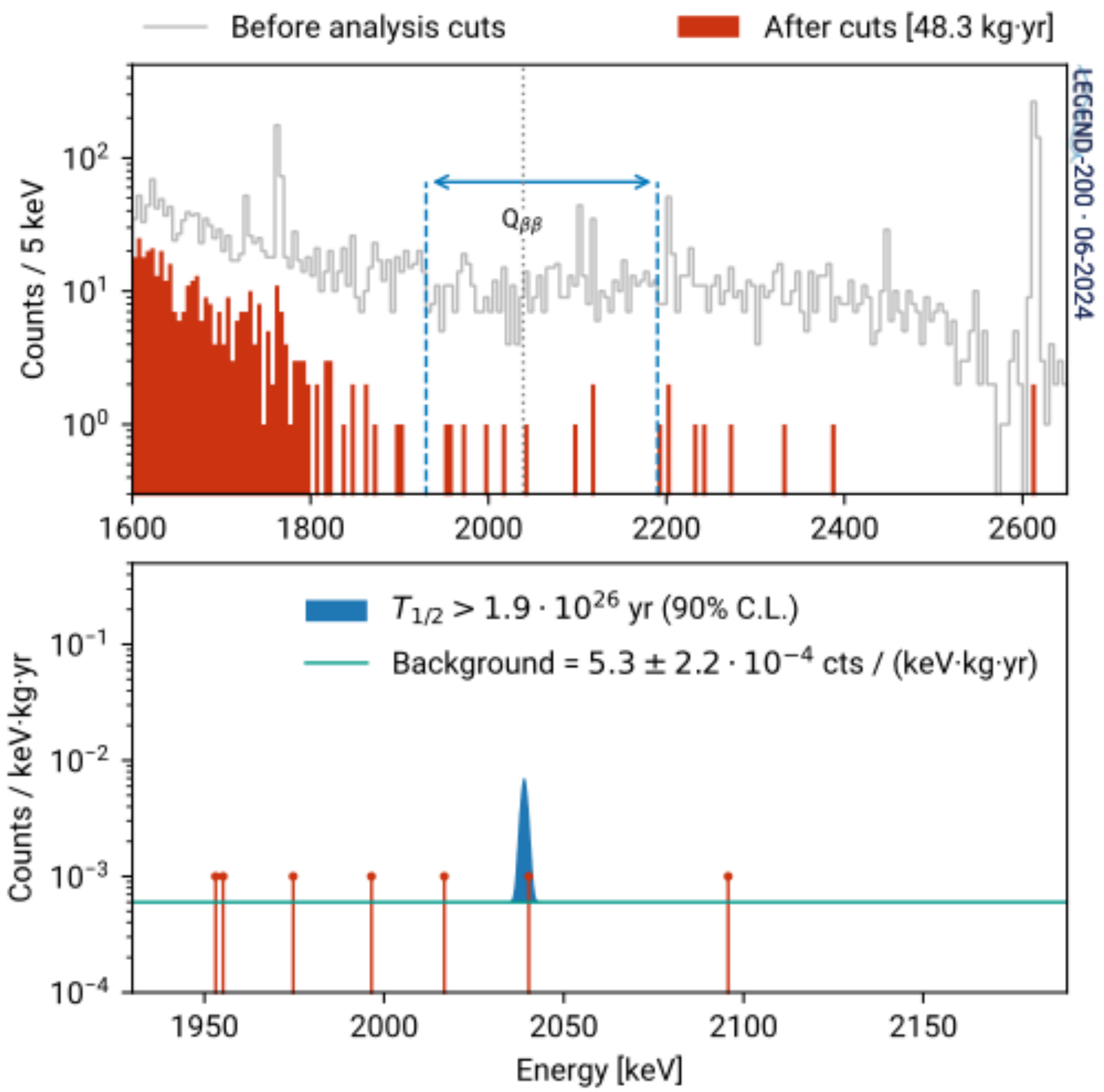


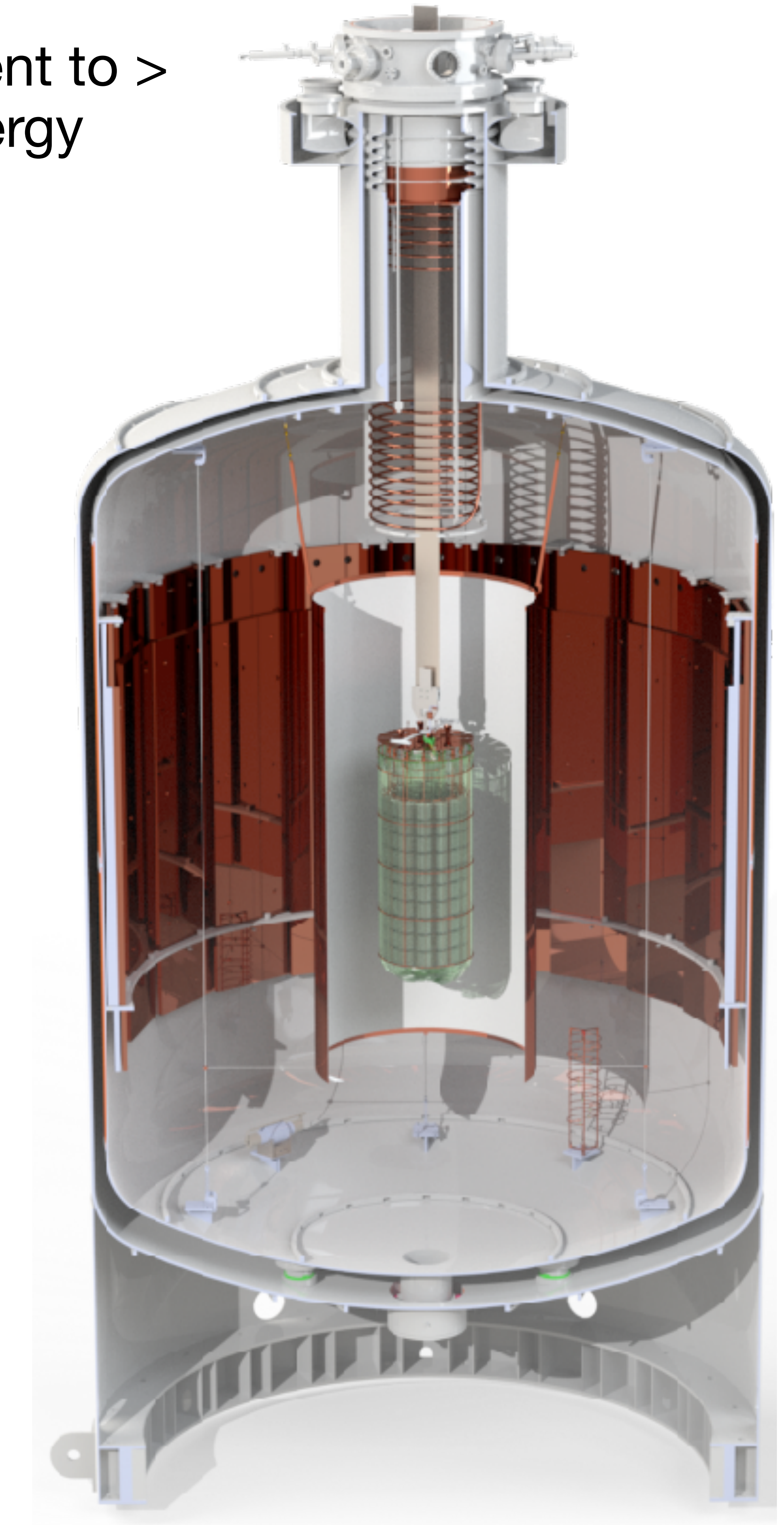
$\langle m_{\beta\beta} \rangle < 28 - 122$ meV

KamLAND-ZEN-1T: $\langle m_{\beta\beta} \rangle <$ ~20 meV

Legend-200

Germanium Semiconductor, with enrichment to > 90% in ^{76}Ge ($Q_{\beta\beta}$=2039 keV). Excellent energy resolution (0.1 % FWHM @ $Q_{\beta\beta}$)





$\langle m_{\beta\beta} \rangle < 75 - 178$ meV

Legend 1000 $\langle m_{\beta\beta} \rangle <$ ~20 meV