EPS-HEP 2025 — Conference Highlights

Focus on new / recent results shown this week

Andreas Hoecker (CERN)

Marseille, France, 11 July 2025

Amazing science week that featured

- 102 posters
- 526 parallel talks
- 38 plenary talks
- 7 prizes

EPS-HEP 2025 — Conference Highlights

Focus on new / recent results shown this week

Andreas Hoecker (CERN)
Marseille, France, 11 July 2025

Update of the European Strategy for Particle Physics

Scientific mission for the 21st century

These are crucial times for **High-Energy Physics**

In a data-driven field with critical theoretical guidance and support, we are exploring together how to best achieve the next big leap at the high precision and energy frontiers

While we continue to exploit the powerful tools we have in our hands, and successfully complete those under construction*

*A *sine qua non* for the next-generation collider project!

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

EPS HEP

Kyle Cranmer citing David Donoho [Link]

Involved research communities are progressing much faster

Galileo Galilei

Measure what can be measured, and make measurable what cannot be measured

This week has showcased the remarkable creativity and innovation in experiment and theory in advancing our understanding of fundamental physics at **all scales**

The deep ties between particle, nuclear, astroparticle physics, and cosmology are increasingly evident

Progress critically relies on our capability to design, build and operate the appropriate instruments pushing the boundaries of technology

EUROPEAN PHYSICAL SOCIETY

EPS HEP2025 MARSEILLE

EPS HEP

Chris Parkes

2021 ECFA Cross-Community Detector Roadmap and implementation of Detector R&D (DRD) Collaborations

(Need to ensure solid funding structure)

DRD 1–8

Gas	Liquid	Solid State	Photon & PID	Quantum	Calorimetry	Electronics Processing	Mechanics & Cooling

Also HEP Software Foundation initiatives for SW & C

Simulation	Generators	Analysis	Triggers & Tracking	GRID

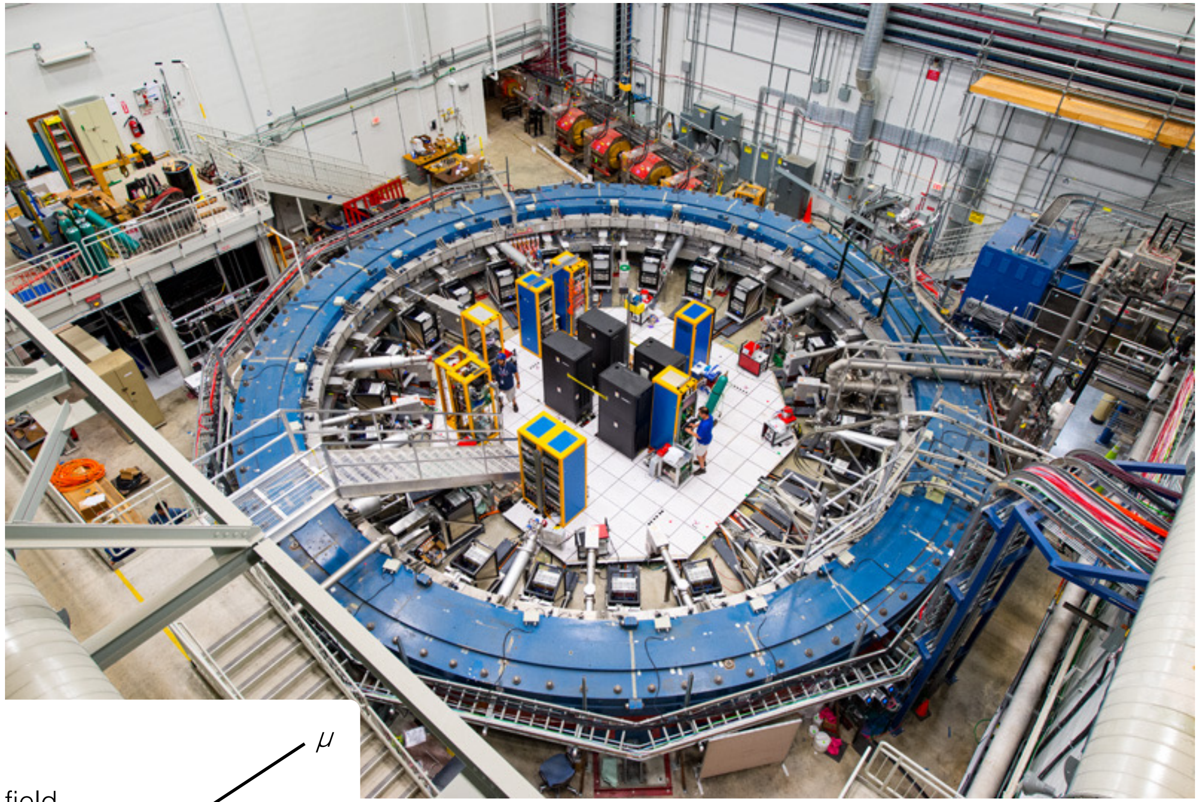
Experimentation requires long-term investment at all levels: funding agencies, universities, labs, and in our community **to support the careers and recognition of talent and leadership in detectors, software and computing**. This includes support for construction, commissioning & operation, training, as well as for strategic and basic R&D

Physics is the science of precision

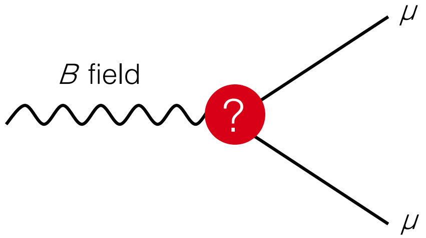
Ultimate precision — C o n g r a t u l a t i o n s !

Elia Bottalico, Saskia Charity, Alberto Lusiani, Graziano Venanzoni, Estifa'a Zaid

Final result from Fermilab Muon g–2 experiment, after analysis of 2020–2023 data (Runs 4–6)



Muon g–2 Experiment at Fermilab

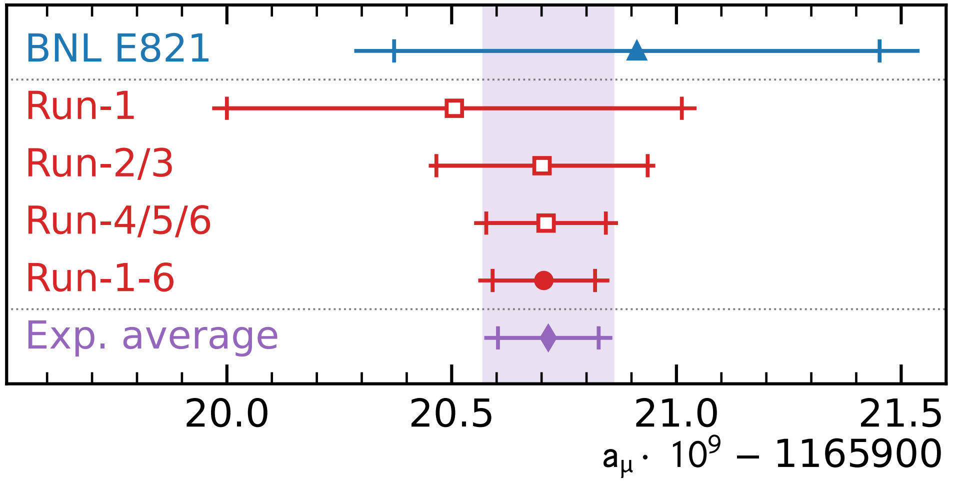


New world average (dominated by Fermilab experiment)

$$a_\mu \equiv \frac{g_\mu - 2}{2} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_B} \frac{m_\mu}{m_e}$$

$$= 116\,592\,072(15) \cdot 10^{-11}$$ (0.12 ppm !)

arXiv:2506.03069

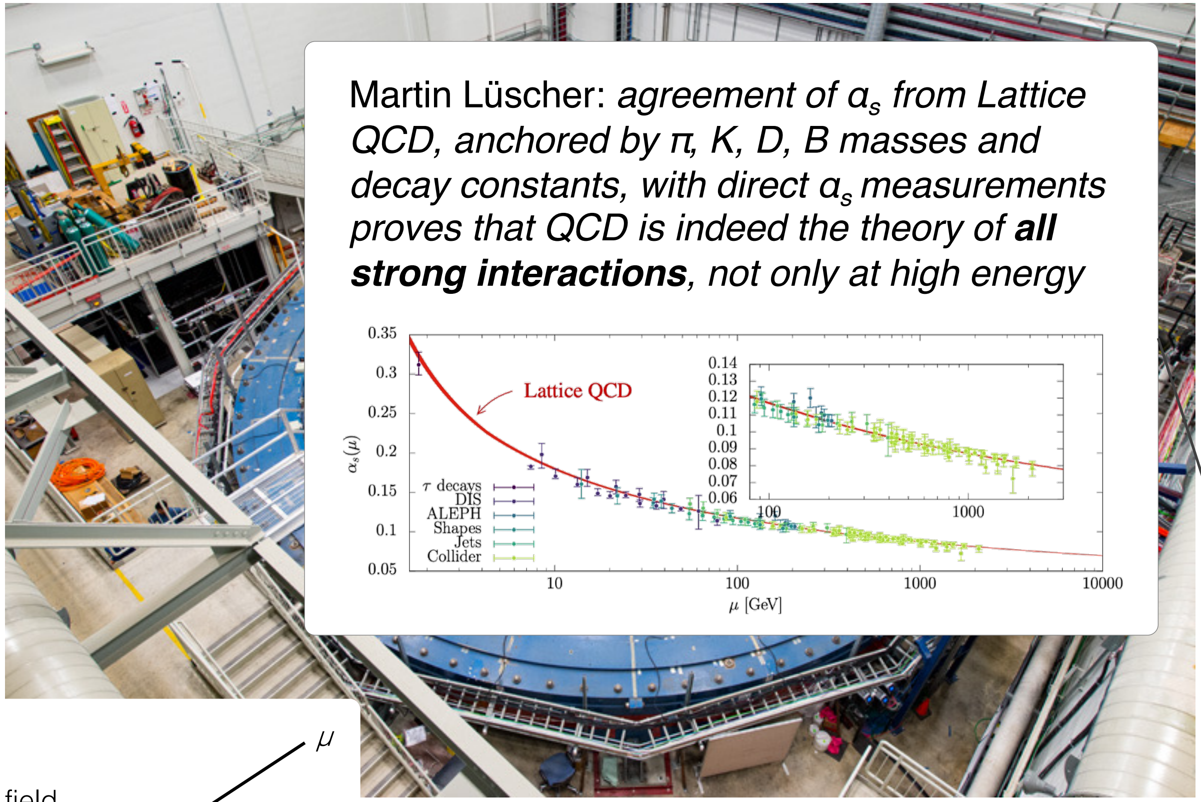


Within 1σ of 4× less precise SM prediction based on Lattice QCD for LO-HVP (traditional data-driven HVP suffers from large discrepancies in low-energy cross-section data) → **more to come (exp, Japan & theory)!**

Ultimate precision — C o n g r a t u l a t i o n s !

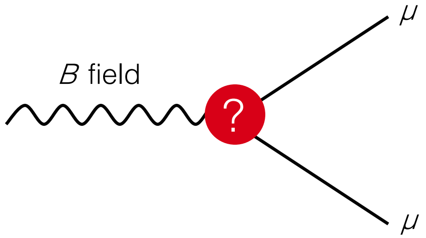
Elia Bottalico, Saskia Charity, Alberto Lusiani, Graziano Venanzoni, Estifa'a Zaid

Final result from Fermilab Muon g–2 experiment, after analysis of 2020–2023 data (Runs 4–6)



Martin Lüscher: *agreement of α_s from Lattice QCD, anchored by π, K, D, B masses and decay constants, with direct α_s measurements proves that QCD is indeed the theory of **all strong interactions**, not only at high energy*

Muon g–2 Experiment at Fermilab

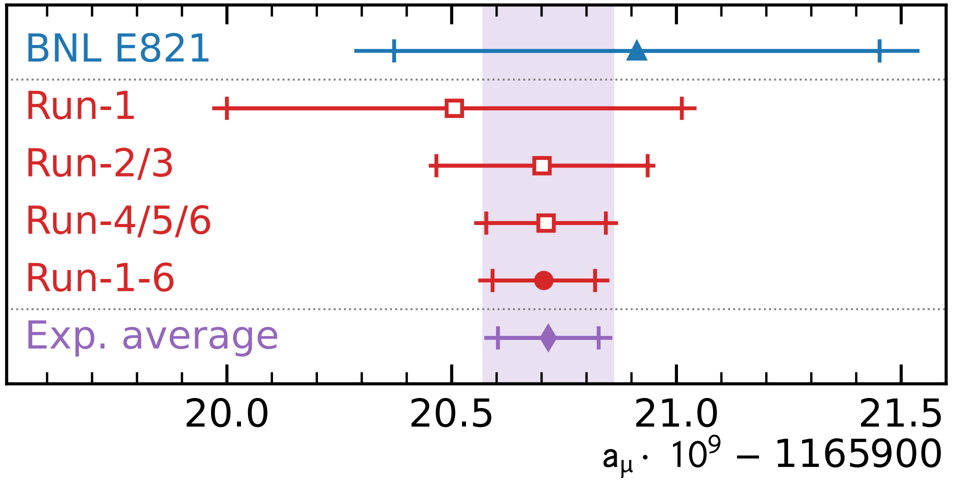


New world average (dominated by Fermilab experiment)

$$a_\mu \equiv \frac{g_\mu - 2}{2} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_B} \frac{m_\mu}{m_e}$$

$$= 116\,592\,072(15) \cdot 10^{-11}$$ (0.12 ppm !)

arXiv:2506.03069



Within 1σ of 4× less precise SM prediction based on **Lattice QCD** for LO-HVP (traditional data-driven HVP suffers from large discrepancies in low-energy cross-section data) → **more to come (exp, Japan & theory)!**

Ultimate precision — C o n g r a t u l a t i o n s !

Elia Bottalico, Saskia Charity, Alberto Lusiani, Graziano Venanzoni, Estifa'a Zaid

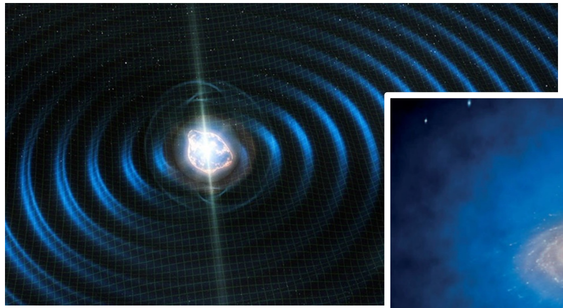
Final result from Fermilab Muon g–2 experiment, after analysis of 2020–2023 data (Runs 4–6)

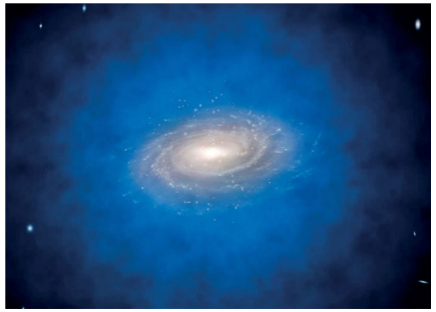
New world average (dominated by Fermilab experiment)

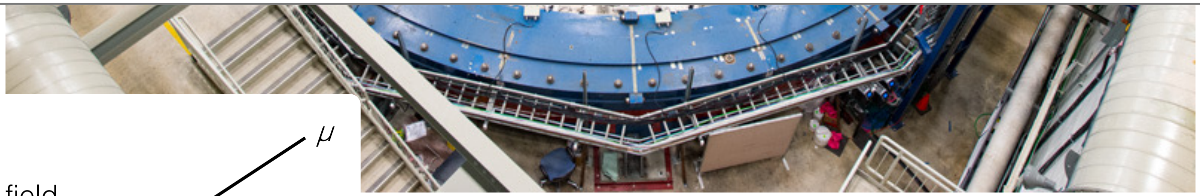
$$a_\mu \equiv \frac{g_\mu - 2}{2} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_B} \frac{m_\mu}{m_e}$$

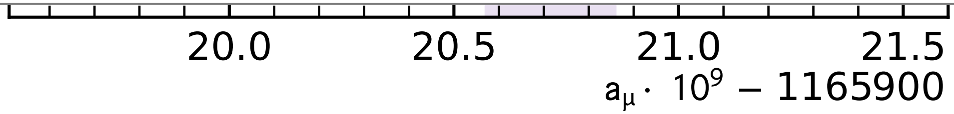
Clara Murgui, Antoine Petiteau

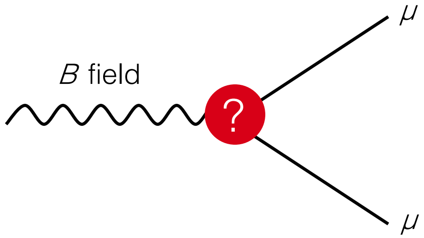
In July 2024, a JILA team unveiled a strontium-87 optical lattice clock with 8.1×10^{-19} precision, half a second over the universe's age. Such clocks may soon test general relativity and, harnessed with atom interferometry, detect gravitational waves and probe dark matter









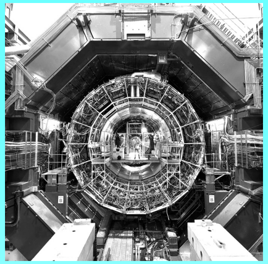


Muon g–2 Experiment at Fermilab

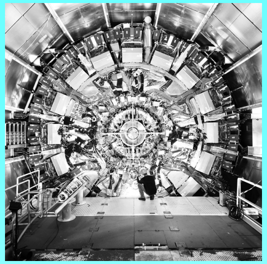
Within 1σ of 4× less precise [SM prediction](#) based on Lattice QCD for LO-HVP (traditional data-driven HVP suffers from large discrepancies in low-energy cross-section data) → **more to come (exp, Japan & theory)!**

2025 Breakthrough Prize in Fundamental Physics awarded to the **ALICE, ATLAS, CMS, LHCb collaborations** for results from LHC Run 2

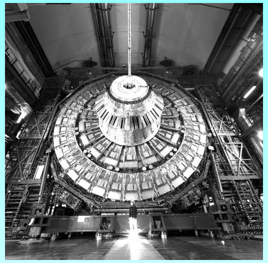
For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.



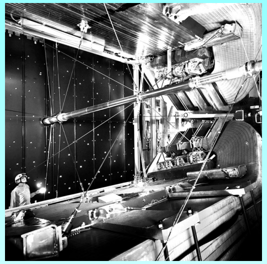
ALICE



ATLAS



CMS



LHCb

Energy frontier

Extremely successful LHC Run-2 physics programme with groundbreaking results by all LHC experiments

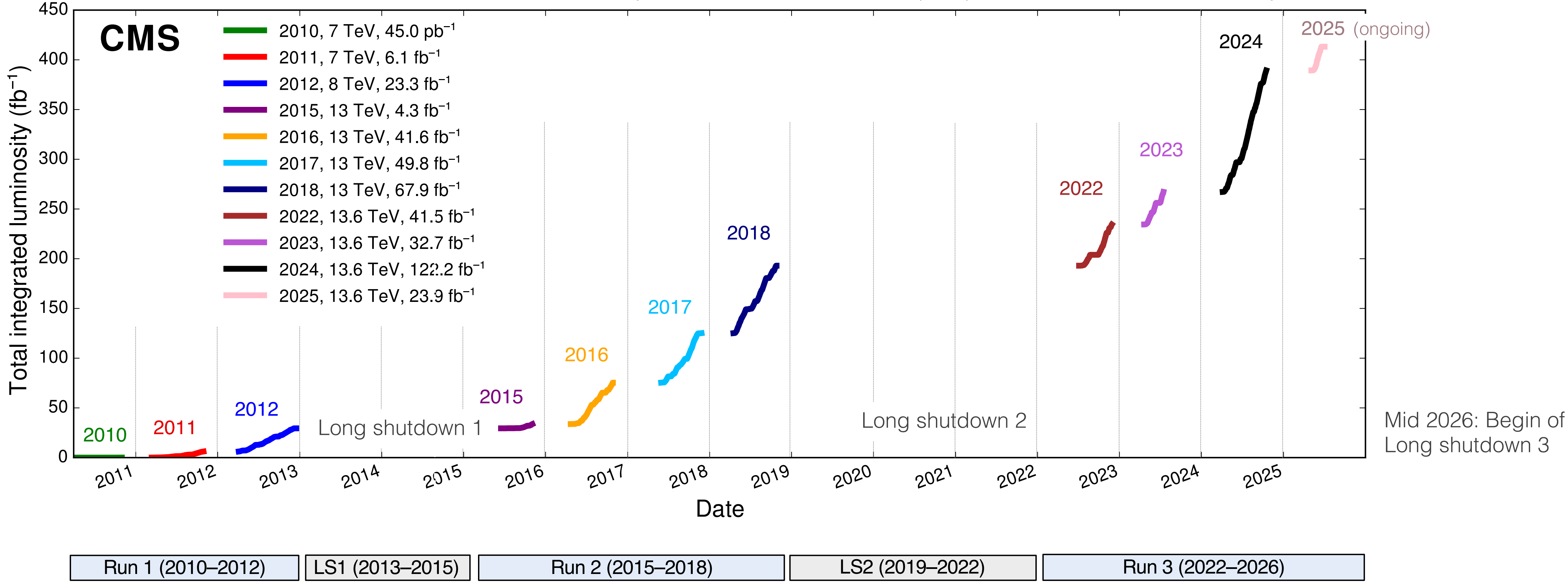
Run 3 data taking has now surpassed Run 2 and results are pouring in

Energy-frontier physics relies on the LHC

Helga Timko

Superb LHC performance in 2024 — on track for a strong Run-3 finish

Peak luminosity in 2024: 2.1×10^{34} $cm^{-2}s^{-1}$, pileup of 63, total delivered luminosity: 403 fb^{-1}



Treasure trove: ATLAS & CMS can each expect > 450 fb^{-1} of good-for-physics data from LHC Runs 2 + 3

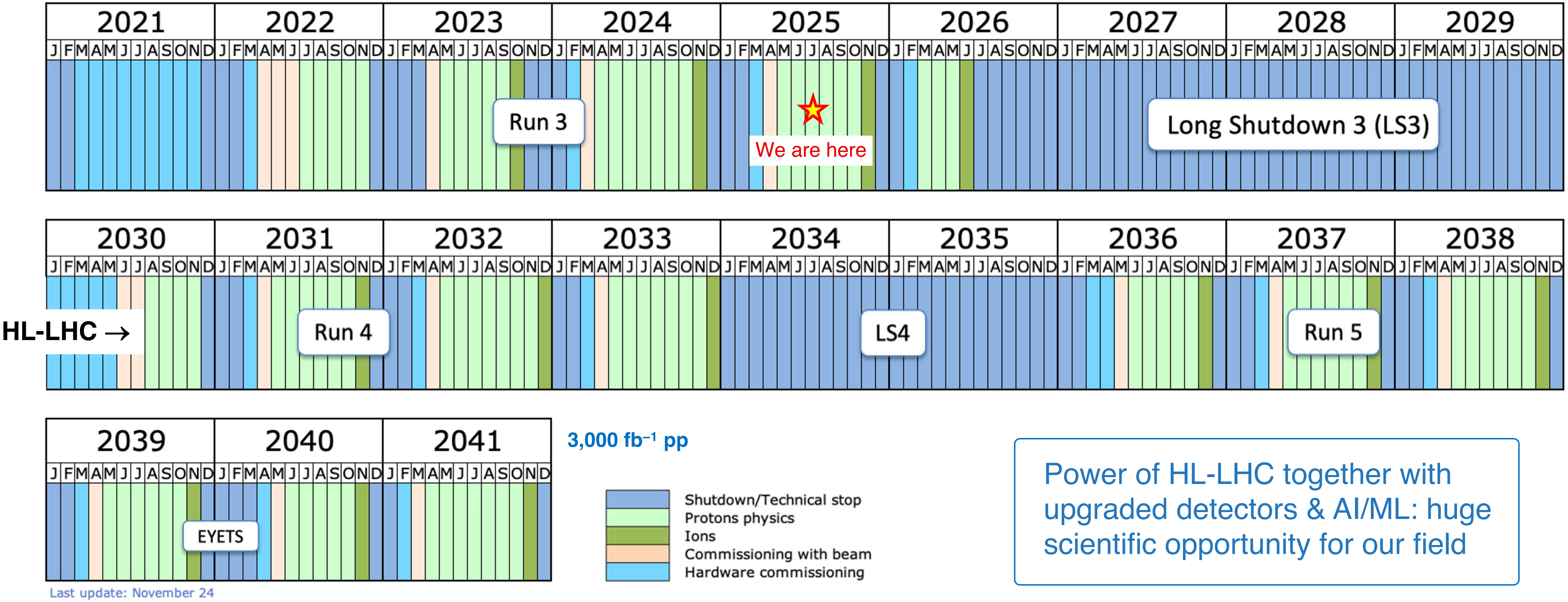
Energy-frontier physics relies on the LHC

Igor Altsybeev, Fabio Cerutti, Vladimir Gligorov,
Roberto Salerno, Helga Timko

Huge effort ongoing to construct High-Luminosity LHC (HL-LHC) and experiment upgrades – a bright future

World's flagship collider project during the next decade — 10 times current dataset (360M H, 240k HH ($\gg 5\sigma$, $< 30\%$ on λ_{HHH}), 13B top, …)

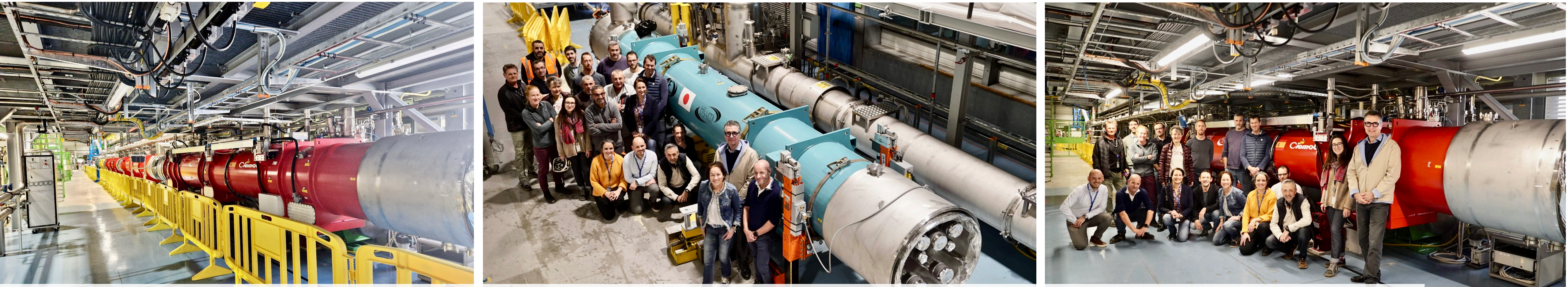
Large-scale ATLAS & CMS upgrades under construction, ALICE & LHCb plan significant upgrades for Run 5



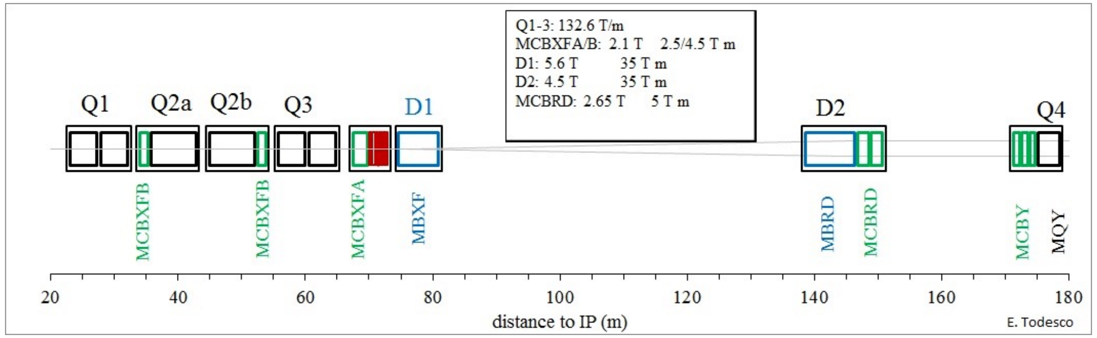
Power of HL-LHC together with upgraded detectors & AI/ML: huge scientific opportunity for our field

HL-LHC & detector upgrades are technology drivers

Helga Timko



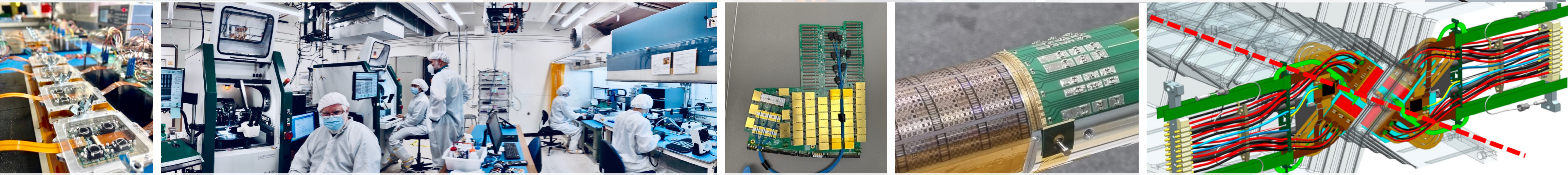
Fully realistic inner triplet string test facility at CERN, from left to right: installation of superconducting link, installation of D1 and Q2a cryo-assemblies, tests to start in Oct 2025



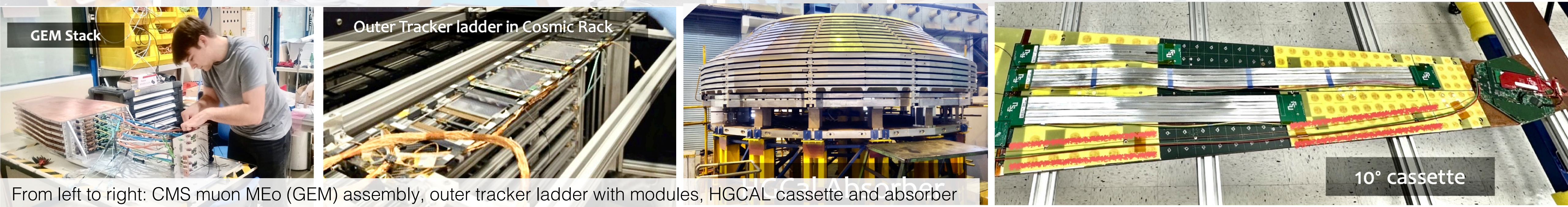
Nb_3Sn technology for high-field superconducting magnets successfully demonstrated for HL-LHC!

HL-LHC & detector upgrades are technology drivers

Fully realistic inner triplet string test facility at CERN, from left to right: installation of superconducting link, installation of D1 and Q2a cryo-assemblies, tests to start in Oct 2025



From left to right: ATLAS ITk Pixel modules, Strip module production cleanroom, HGTD front-end board, ALICE ITS3 prototype, Design of VELO modules with timing for LHCb Upgrade II)



From left to right: CMS muon MEo (GEM) assembly, outer tracker ladder with modules, HGCAL cassette and absorber

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

Progress in Higgs physics

Chiral gauge structure of weak interaction forbids bare masses; they arise only via the Higgs mechanism $m_i \propto g_i v$ — making SM particles naturally light (they “survive down to the EW scale”)

Since the Higgs has a bare mass, why isn’t it super heavy like, possibly, other left-right symmetric (eg, vector-like) particles?

This is the core conceptual challenge of the SM, calling for in-depth study of the scalar sector and potential TeV-scale extensions

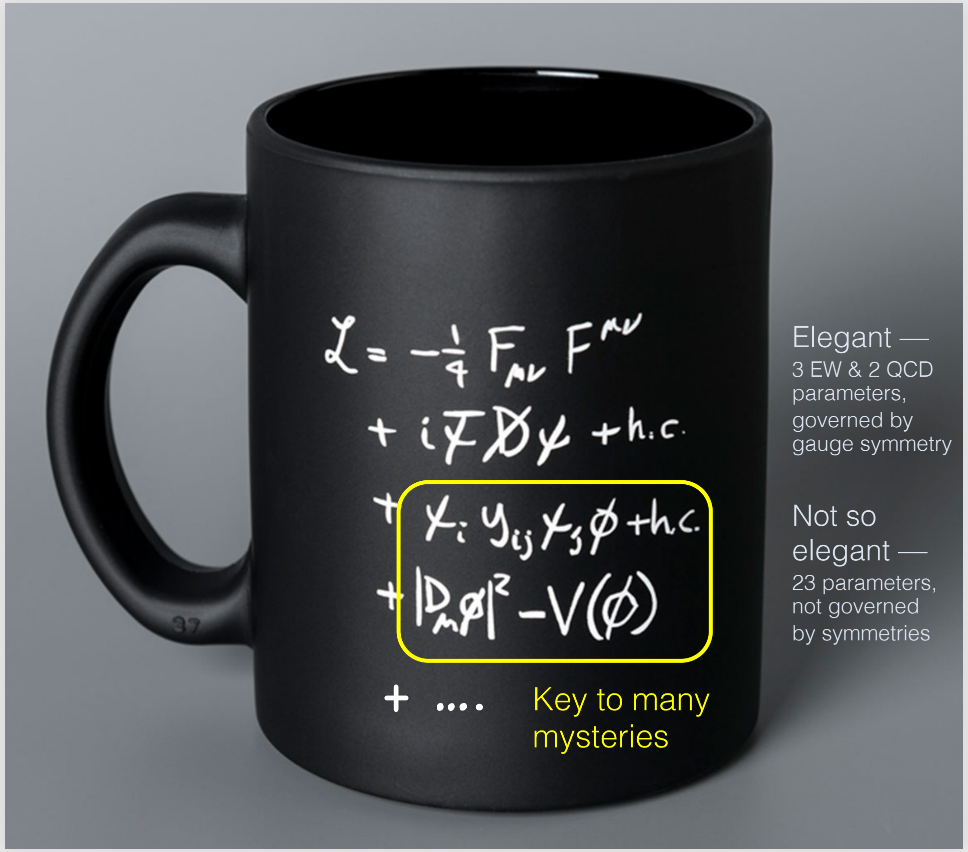
Riccardo Rattazzi

Physics relies on separation of scales, but not possible with scalers

“Hierarchy Paradox”: $\mathcal{L} = \mathcal{L}^{d\leq 4} + \frac{1}{m_*}\mathcal{L}^{d=5} + \frac{1}{m_*^2}\mathcal{L}^{d=6} + \ldots$

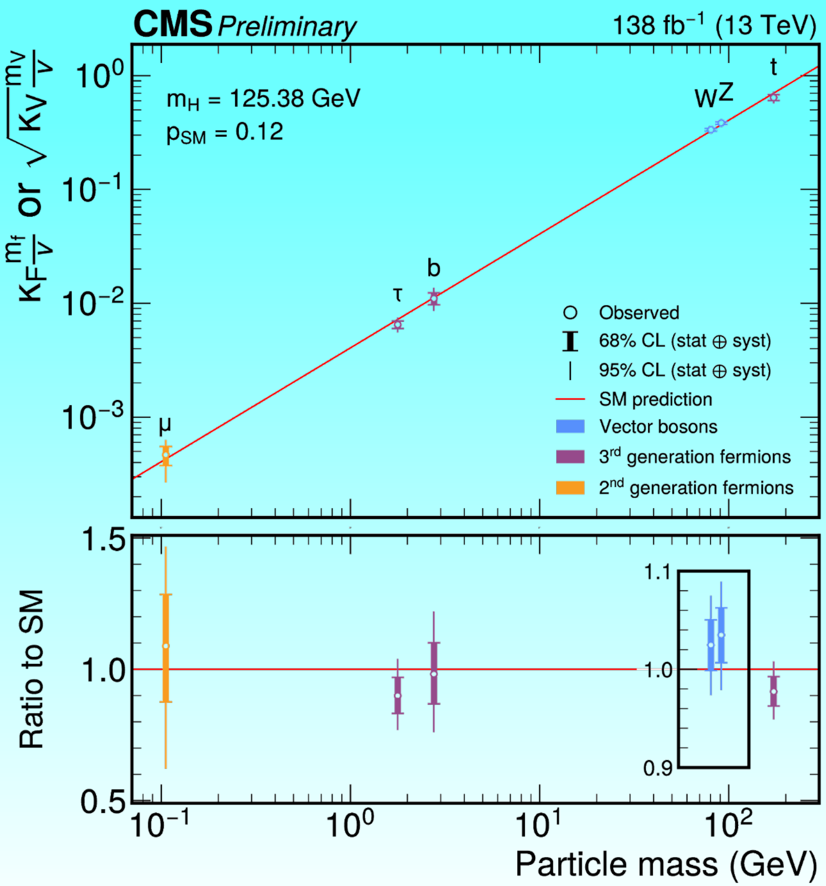
- $m_* \gg m_{\rm weak}$: accidental symmetries (B, L, GIM) respected, but m_H^2 unnatural
- $m_* \approx m_{\rm weak}$: m_H^2 natural, but B, L, GIM difficult to maintain

Clash between simplicity and naturalness

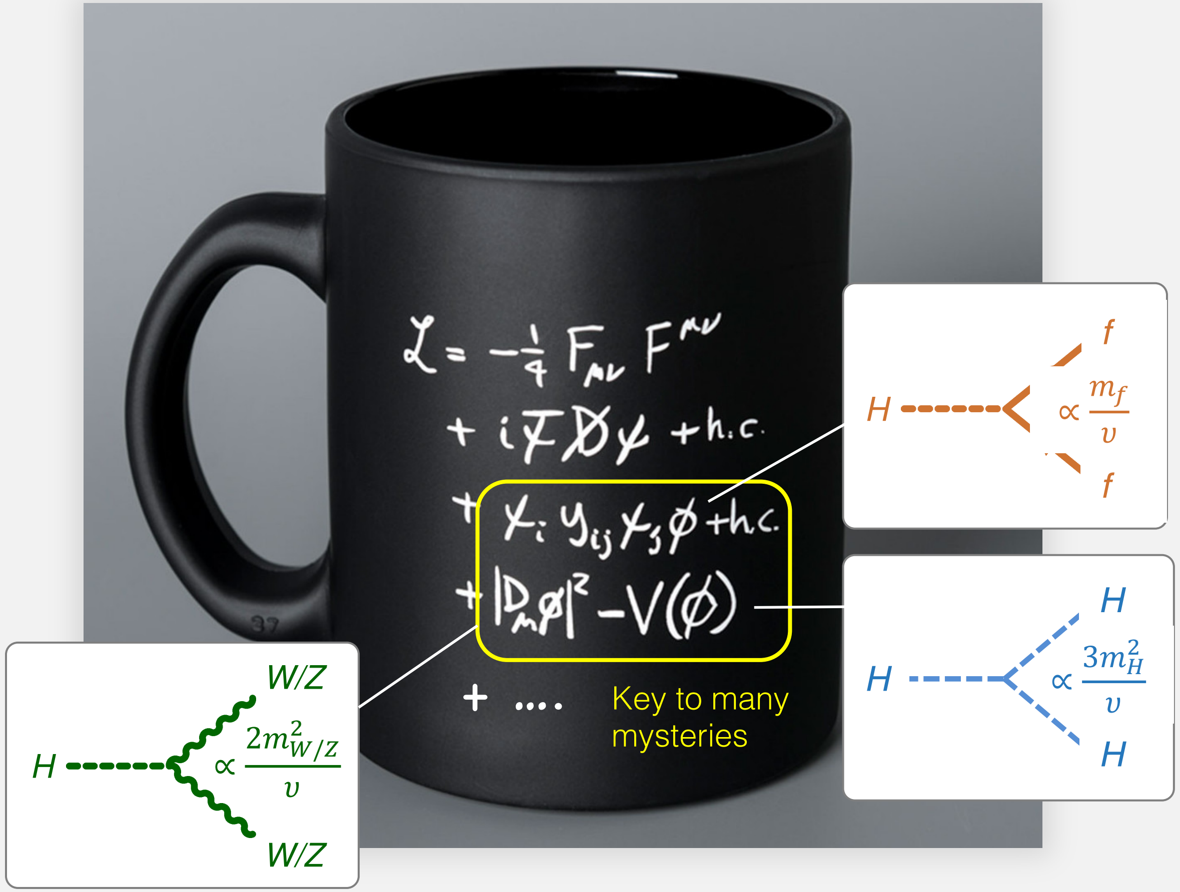


Progress in Higgs physics

The Brout-Englert-Higgs mechanism is real!



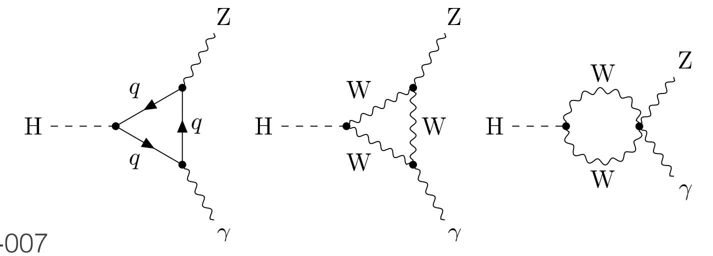
ATLAS & CMS 2022



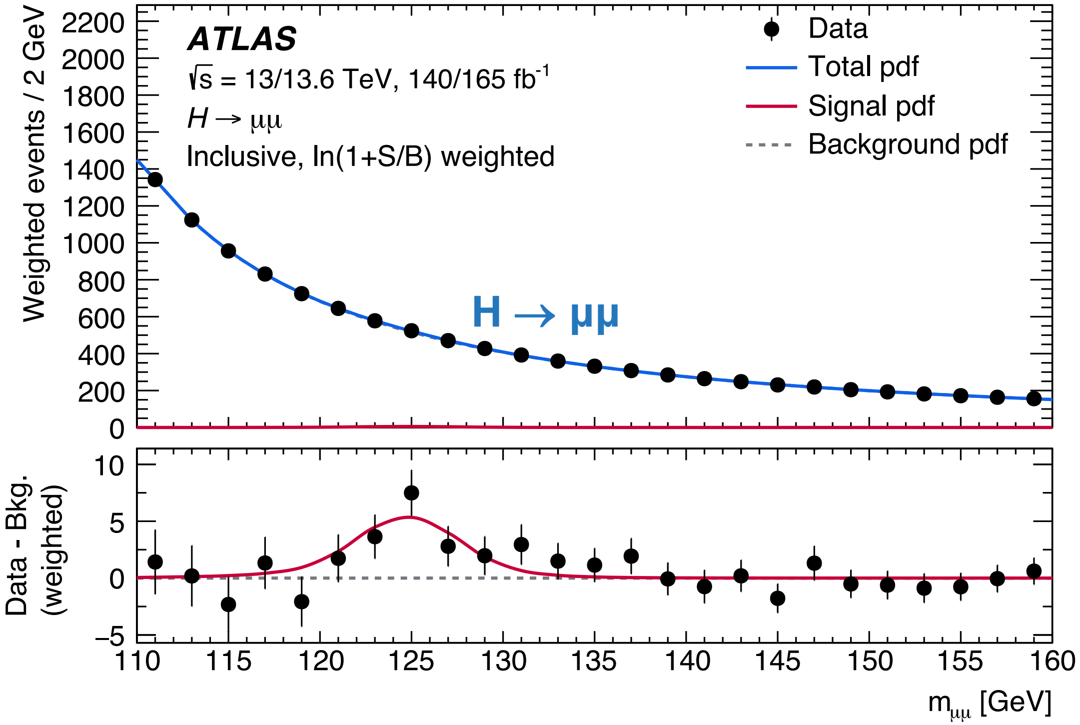
Run 3 data flowing in and being analysed

Fabio Cerutti , Emanuele Di Marco,
Tamar Zakareishvili, Alberto Zucchetta

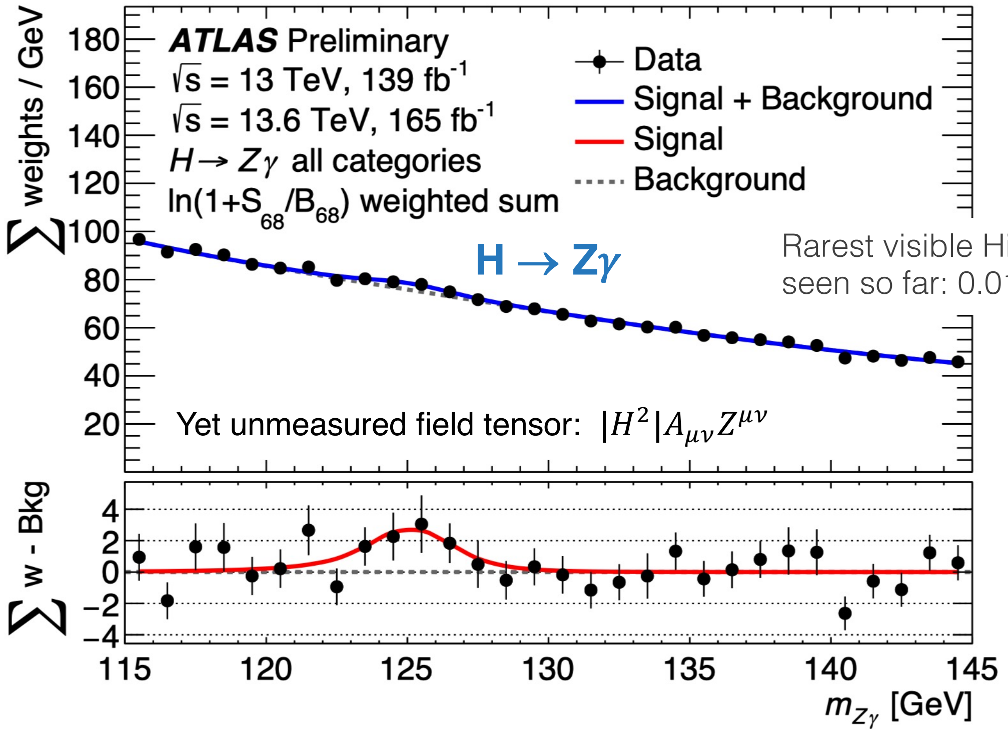
Using 305 fb^{-1} of Run-2 + 3 data, ATLAS reports evidence for rare 2nd generation H → μμ, and released new result on loop decay H → Zγ



arXiv:2507.03595



ATLAS-CONF-2025-007



Rarest visible Higgs decay seen so far: 0.010%

Significance: 3.4σ (2.5σ exp), μ = 1.4 ± 0.4

Reminder: CMS (Run 2): μ = 1.19 ± 0.43 (3.0σ) [arXiv:2009.04363]

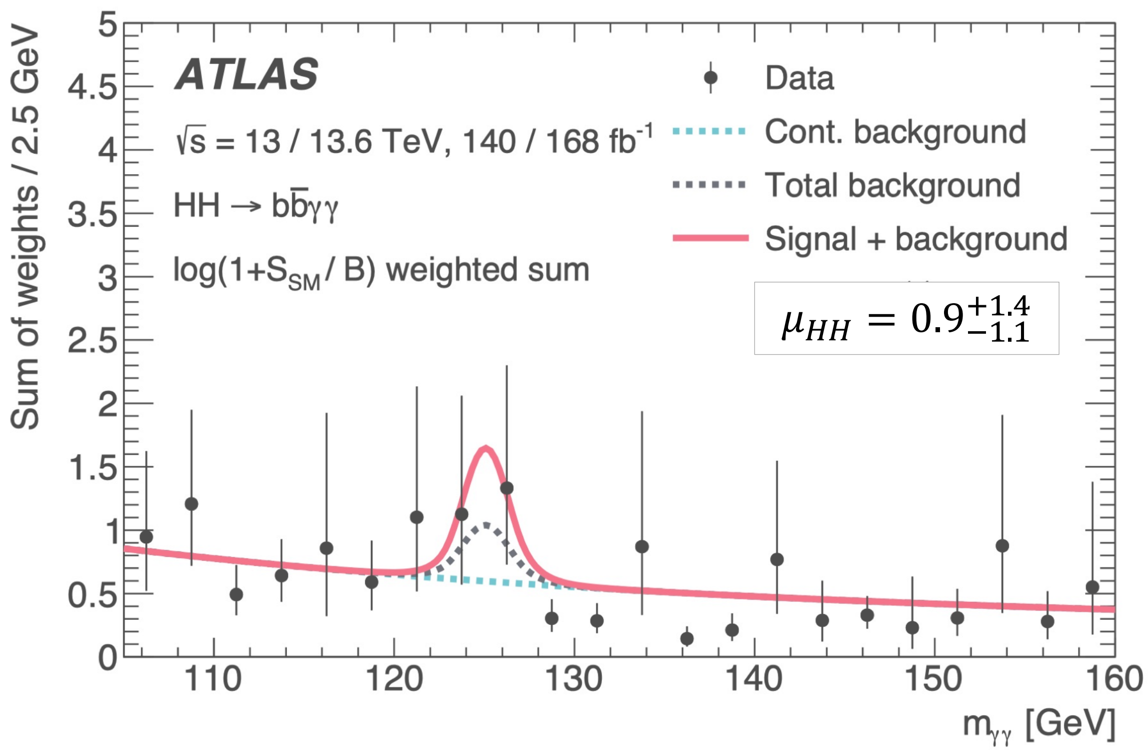
Significance: 2.5σ (1.9σ exp), μ = 1.3 $^{+0.6}_{-0.5}$

Reminder: ATLAS & CMS (Run 2): μ = 2.2 ± 0.7 (3.4σ) [arXiv:2309.03501]

Run 3 data flowing in and being analysed

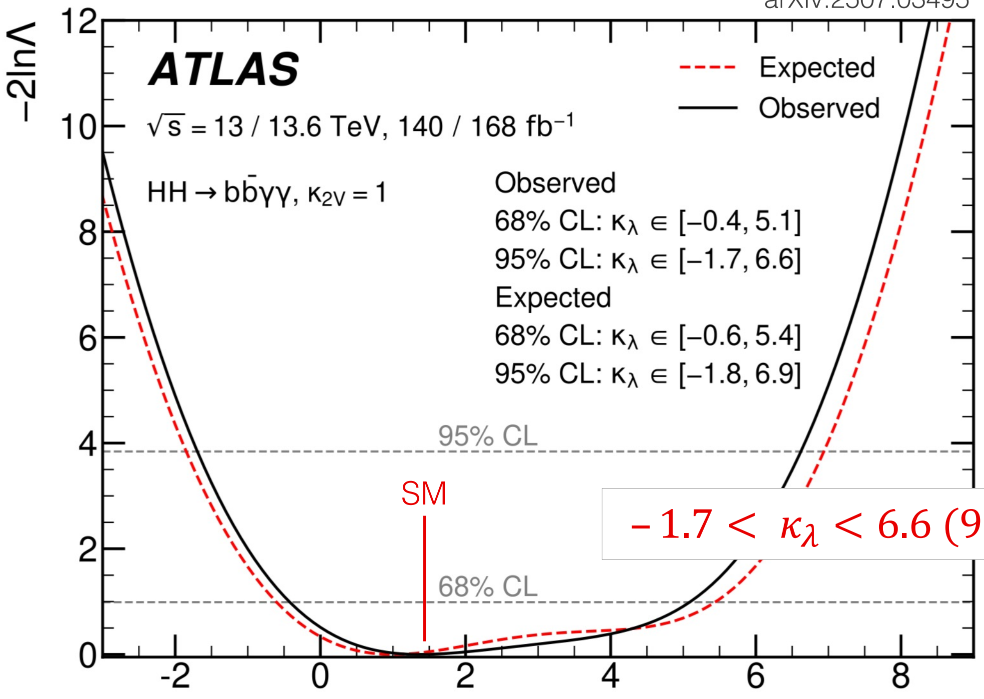
Fabio Cerutti, Emanuele Di Marco,
Oleksii Kurdysh

New ATLAS result on $HH \to bb\gamma\gamma$ with 308 fb^{-1} Improvements: more data (50%), better b-tagging (20%), analysis optimisation (10%), m_{bb} kin. fit (5%)



$\mu_{HH} = 0.9^{+1.4}_{-1.1}$

arXiv:2507.03495

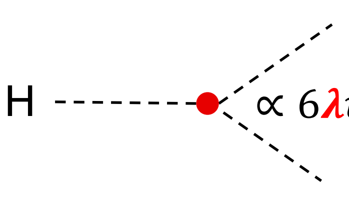


$-1.7 < \kappa_\lambda < 6.6\ (95\%\ CL)$

$\kappa_\lambda = \lambda/\lambda_{SM}$

$\lambda_{SM} \sim 0.13$

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



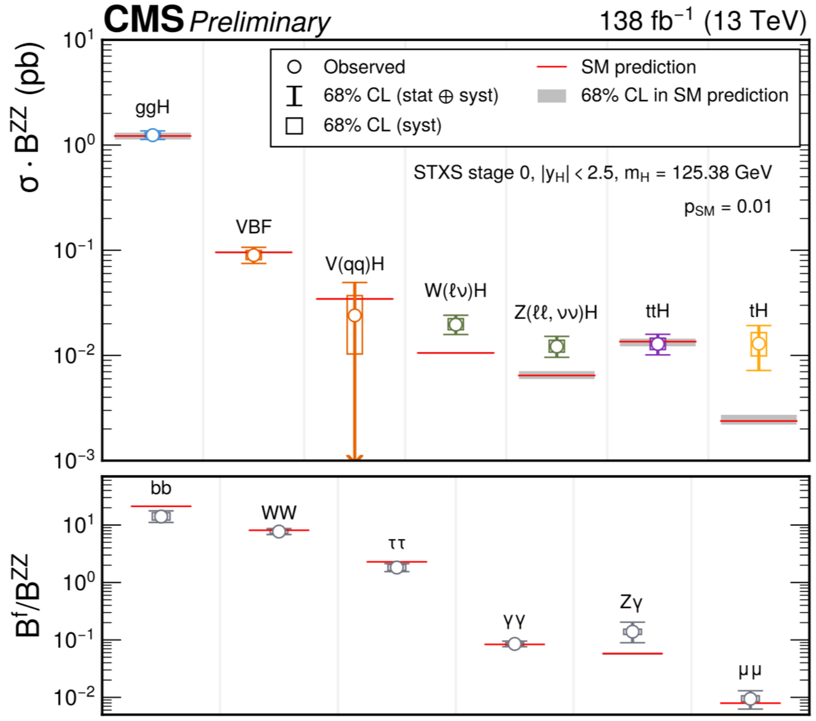
$\propto 6\lambda v = \frac{3m_H^2}{v}$

Did the universe boil as it transitioned from the symmetric to the broken phase?

ATLAS and CMS released new Run-2 combinations

Fabio Cerutti, Malgorzata Kazana, Emanuele Di Marco, Roberto Salerno, Zef Wolffs

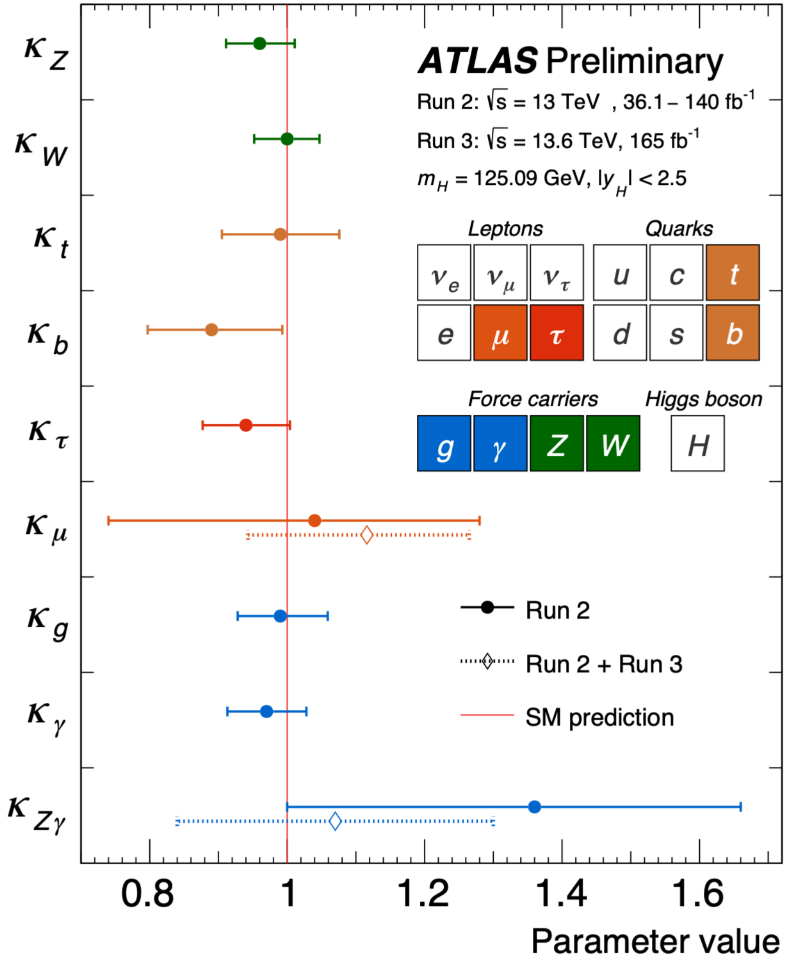
Comprehensive combinations of Higgs production and decay measurements using Run-2 data



CMS-PAS-HIG-21-018

- Up to O(100) cross sections measured simultaneously in ~1k categories
- O(10k) parameters, including non-Higgs "nuisance" parameters

ATLAS-CONF-2025-006



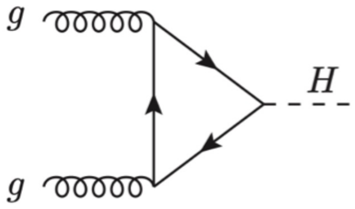
Among the many results:

- Effective Higgs couplings to W: 4%, Z: 5%, γ: 7%, Zγ: 31%, gluon: 7%, top: 9%, bottom: 12%, τ: 7%, μ: 21% (all assuming $B_{BSM} = 0$, $\kappa_c = \kappa_t$)
- Overall agreement with SM. Combined production & decay mode p-values: ATLAS / CMS = 0.85 / 0.006 (all categories)
- Comparable sensitivity to λ_{HHH} as HH

Testing the SM requires precise theory predictions

Ramona Gröber, Gregory Soyez

Cross section and coupling measurements are compared to theory — whose uncertainties will dominate at the HL-LHC



Current baseline prediction of ggF cross section [CERN-2017-002-M]

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF+}\alpha_s)\,.$$

Recent advances include finite quark mass effects at NNLO and t+b interference

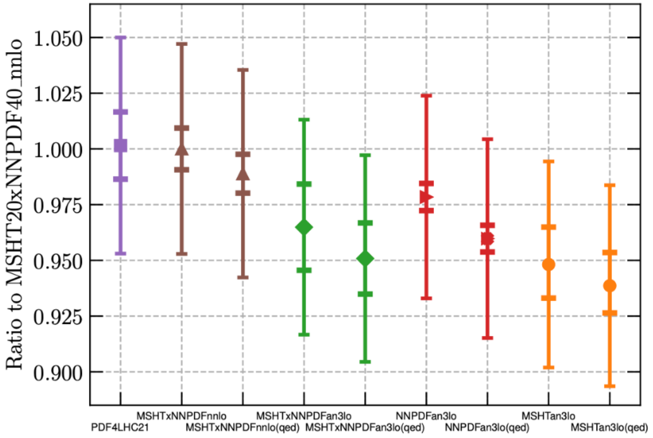
$$\sigma_{ggH} = 48.81(1)^{+0.65}_{-2.02}(\text{N}^3\text{LO HEFT}) - 0.16^{+0.13}_{-0.03}(\text{NNLO } t) - 1.74(2)^{+0.13}_{-0.03}(\text{NNLO } t \times b)\ \text{pb.}$$

[arXiv:2407.12413]

Also: approximate N³LO PDF sets are becoming available

Cross section shrinks

Very active development area, first steps towards N⁴LO, matching to PS



Kyle Cranmer — AI for amplitudes

Use generative AI to help compute multi-loop scattering amplitudes. Is there an opportunity ahead for these challenging QCD calculations?

NB: HEFT is directly inspired by Chiral Perturbation Theory (EPS-HEP prize winners Jürg Gasser, Heinrich Leutwyler): Goldstones from electroweak symmetry breaking in HEFT (longitudinal W and Z) behave like the pions in ChPT (HEFT is sometimes referred to as the *electroweak chiral Lagrangian*)

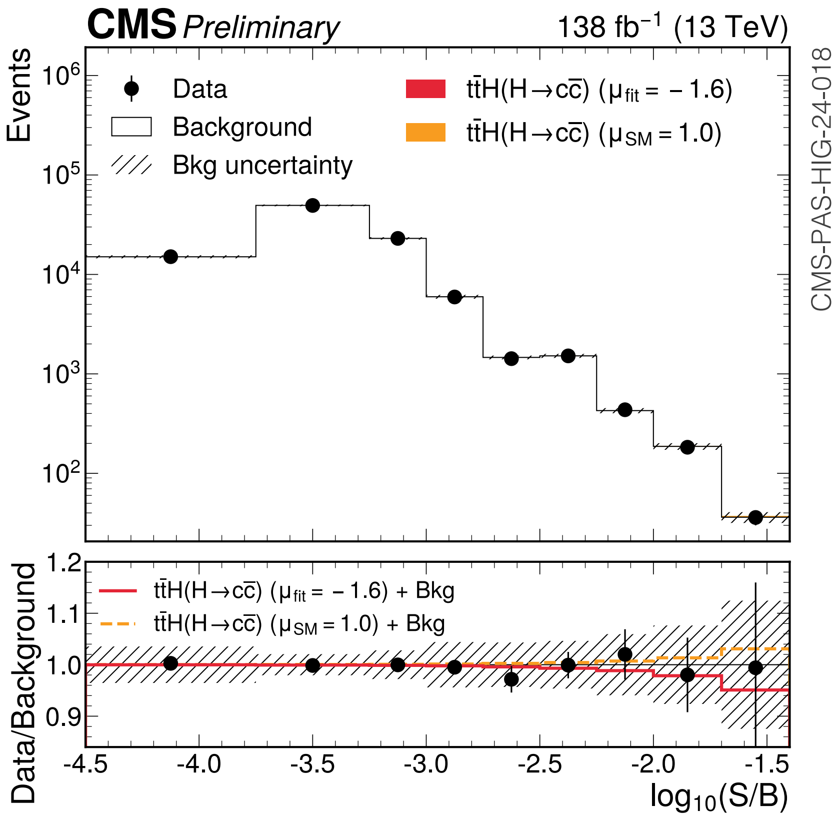
Higgs coupling to charm quarks

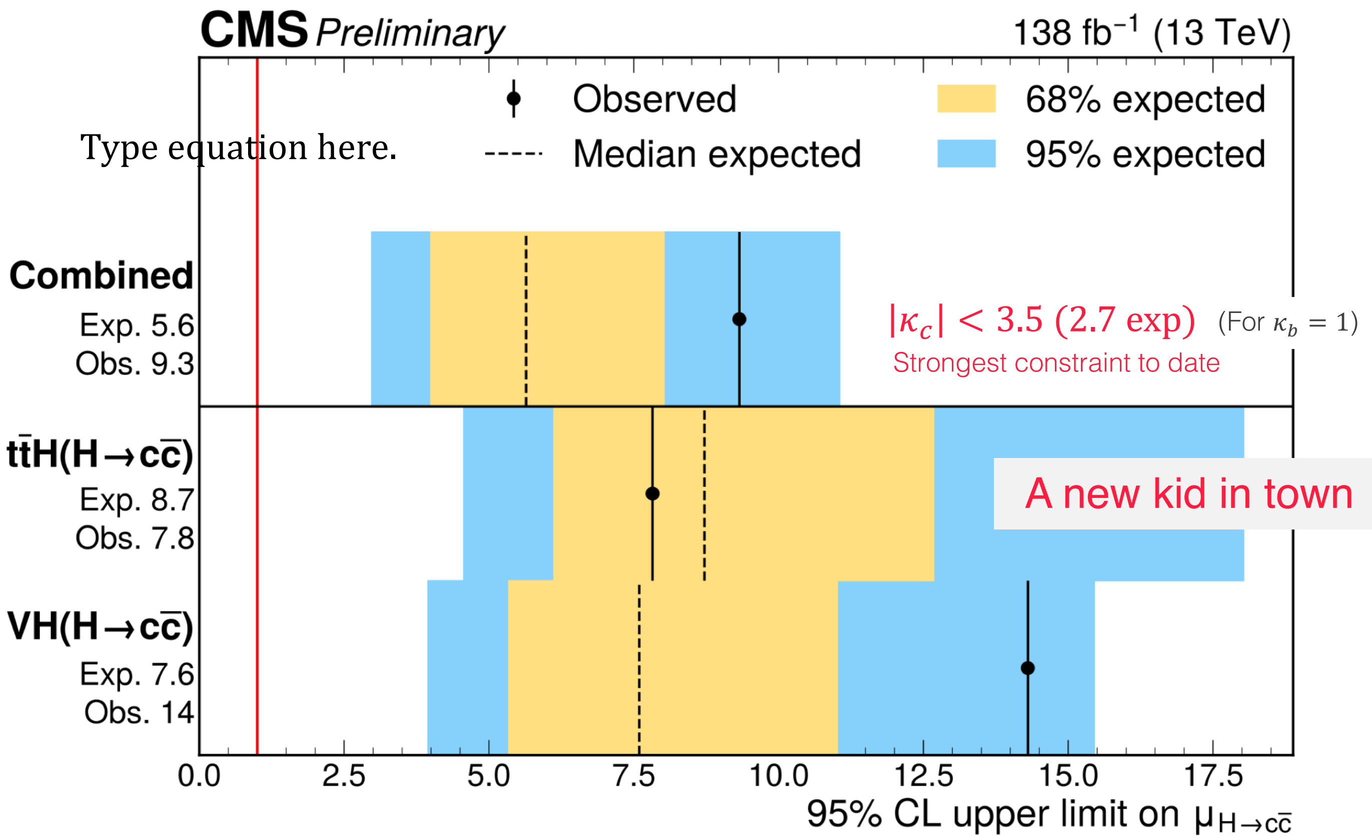
Felix Heyen, Daina Leyva Pernia,
Emanuele Di Marco, Roberto Salerno

BR(H → cc) 20 × smaller than H → bb due to lighter charm quark, challenging to isolate experimentally

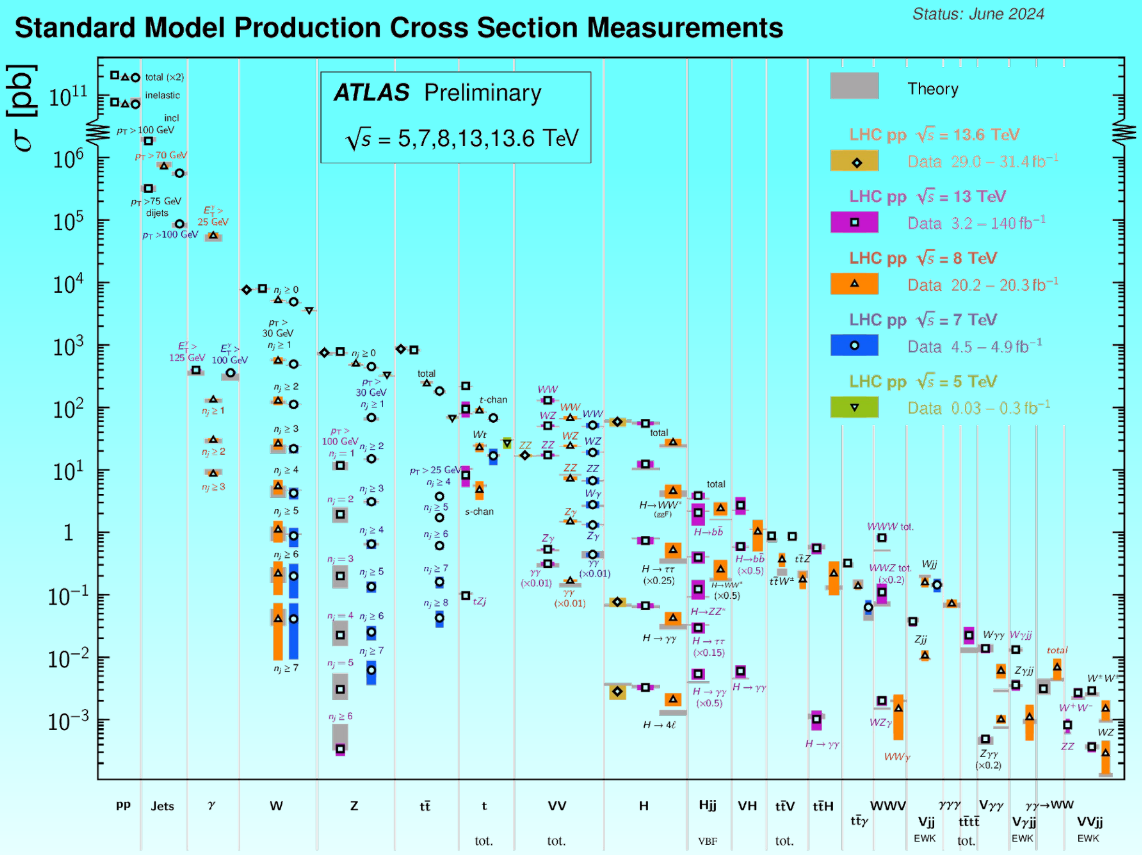
Best constraints so far from VH production: $\mu_{VH \times H \to cc} < 11.5_{obs}$ (10.6_{exp}) / 14_{obs} (7.6_{exp}) (ATLAS / CMS) [arXiv:2410.19611 / 1912.01662]

Strong new result from CMS using ttH production and simultaneously measuring H → bb / cc (as also done in VH)





EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE



Electroweak, top, QCD at the LHC

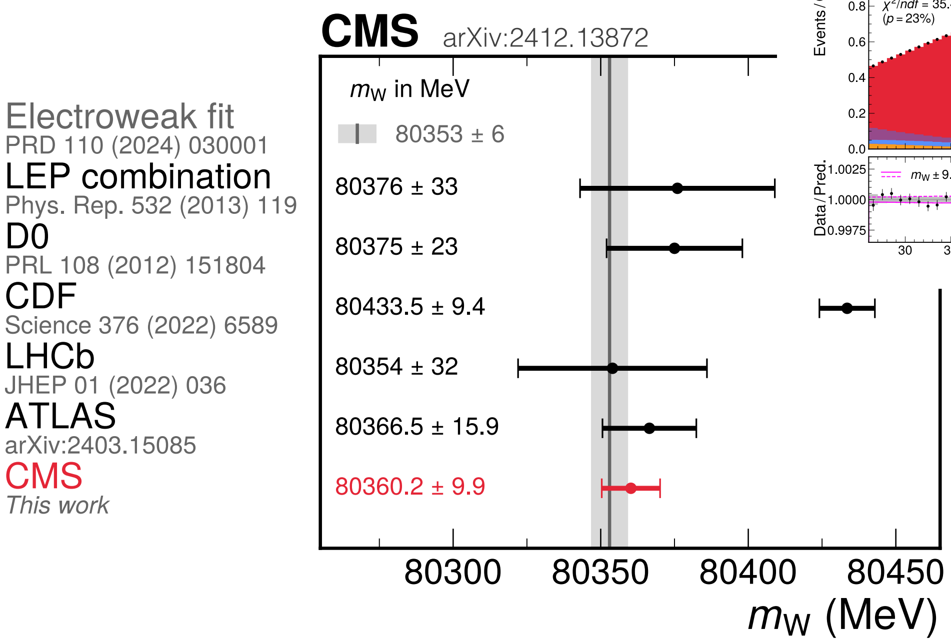
Huge harvest of results delivering (i) high precision measurements of fundamental SM parameters, (ii) improving our understanding of process dynamics, and (iii) looking for ripple effects from new physics

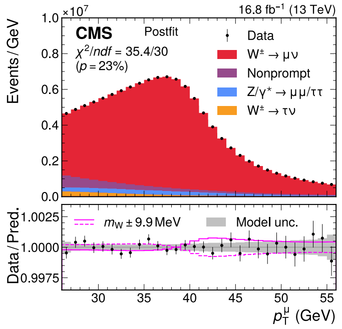
Measuring fundamental SM parameters

Josh Bendavid, Kenneth Long, Menglin Xu

Several new high-precision measurements from CMS and LHCb during 2024 / 2025

W mass a particular *tour de force*



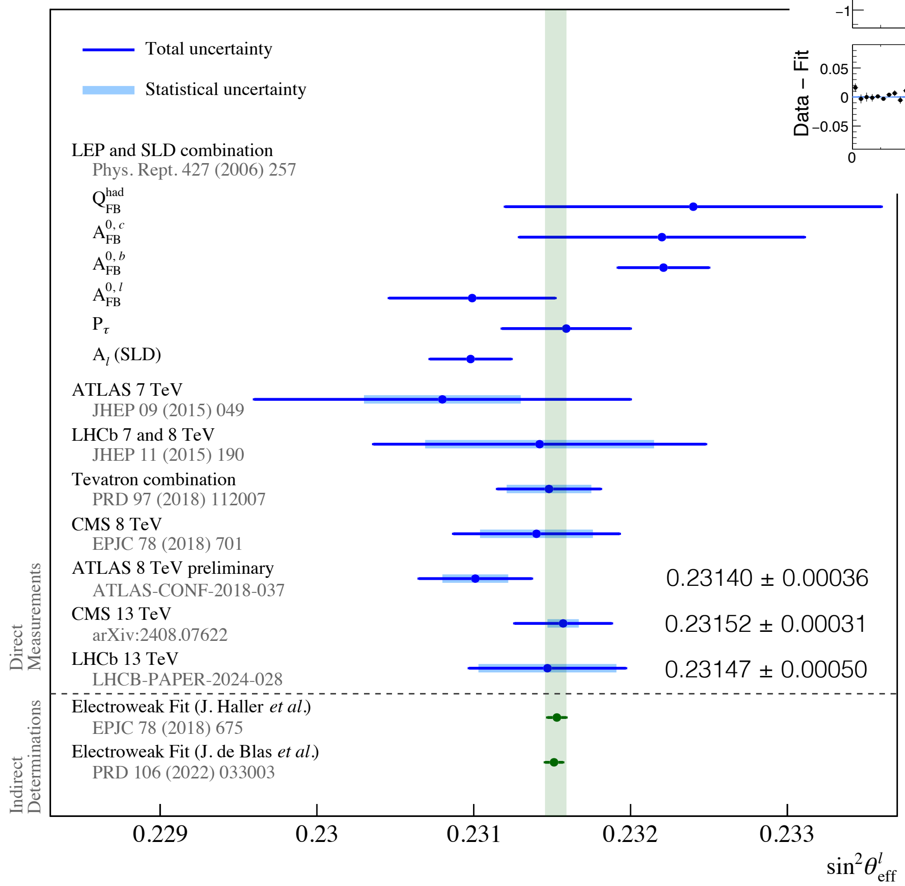


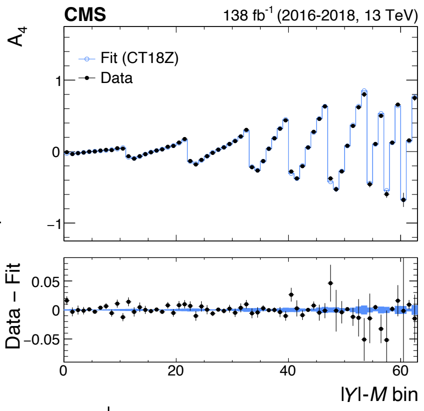
SM predictions (Δm_W = 7 MeV, $\Delta \sin^2\theta^\ell_{eff}$ = 6×10^{-5})

$$M_W = 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \pm 0.0024_{\Delta\alpha_{\rm had}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \mathrm{GeV}$$

$$\sin^2\theta^\ell_{\rm eff} = 0.231532 \pm 0.000011_{m_t} \pm 0.000016_{\delta_{\rm theo} m_t} \pm 0.000012_{M_Z} \pm 0.000021_{\alpha_S} \pm 0.000035_{\Delta\alpha_{\rm had}} \pm 0.000001_{M_H} \pm 0.000040_{\delta_{\rm theo}\sin^2\theta^\ell_{\rm eff}}$$

arXiv:2408.07622 (CMS), arXiv:2410.02502 (LHCb)





LHCb also realised a first LHC Z-mass measurement with 9.3 MeV precision consistent with LEP (σ = 2.1 MeV)

[arXiv:2505.15582]

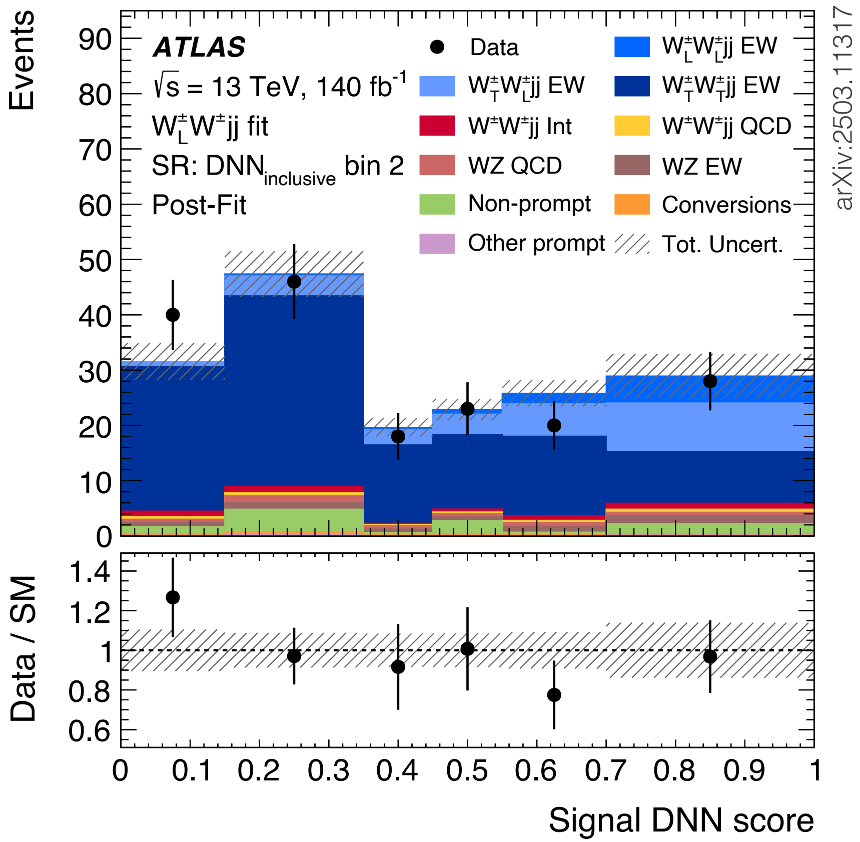
Longitudinal vector boson scattering

Josh Bendavid, Fabio Cerutti, Vadim Kostyukhin

Higgs boson restores unitarity of longitudinal vector boson scattering (VBS) at high energy

Goldstone boson equivalence theorem*: at E ≫ m_V, amplitude of $V_LV_L \to V_LV_L \sim GG \to GG \propto -m_H^2/v^2$, a process directly determined by EWSB

ATLAS reported first evidence for one longitudinally polarised W boson in $W^\pm W^\pm \to W^\pm W^\pm$ VBS



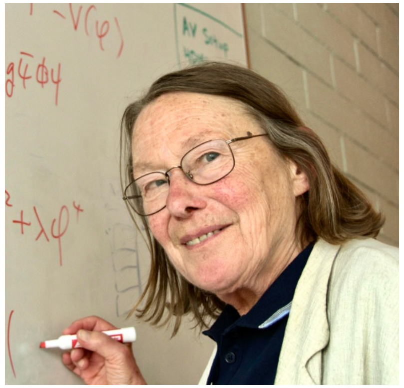
Measurement
$\sigma\left(W_L^\pm W^\pm jj\right) = 0.88 \pm 0.30$ fb

SM prediction
$\sigma\left(W_L^\pm W^\pm jj\right) = 1.18 \pm 0.29$ fb

Significance for at least one W_L: 3.4σ_{obs} (4.0σ_{obs})

Light Higgs and $W^\pm W^\pm$ VBS consistent with SM suggests weakly coupled Higgs dynamics

But strongly coupled resonances may still appear in the TeV regime!



Mary K. Gaillard (1939 – 2025)

*M.S. Chanowitz, M.K. Gaillard (LBL), NP B 261, 379 (1985) [Link]

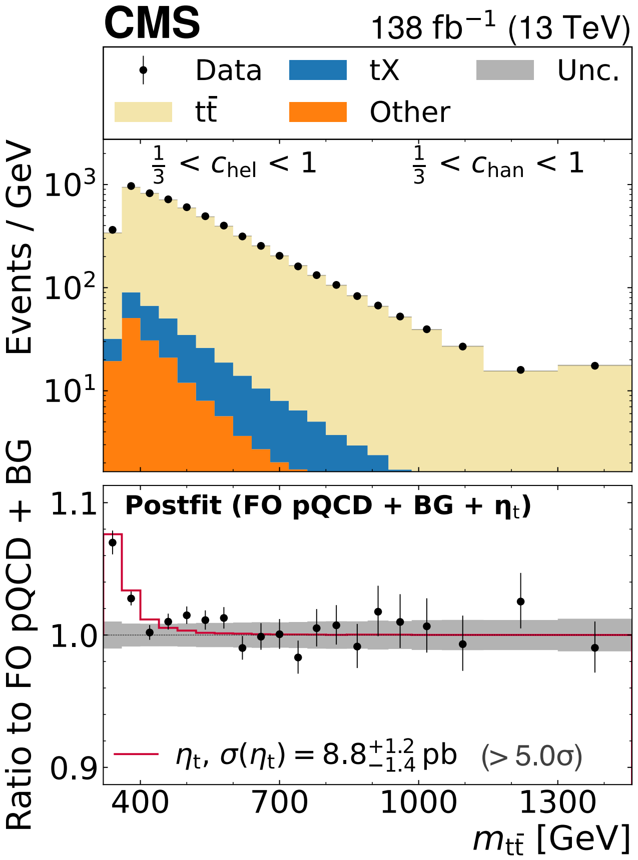
Top–antitop production at threshold

Josh Bendavid, Fabio Cerutti, Haifeng Li,
Roberto Salerno, Christian Schwanenberger

CMS observed enhancement near $t\bar{t}$ production threshold — observation confirmed by ATLAS at EPS

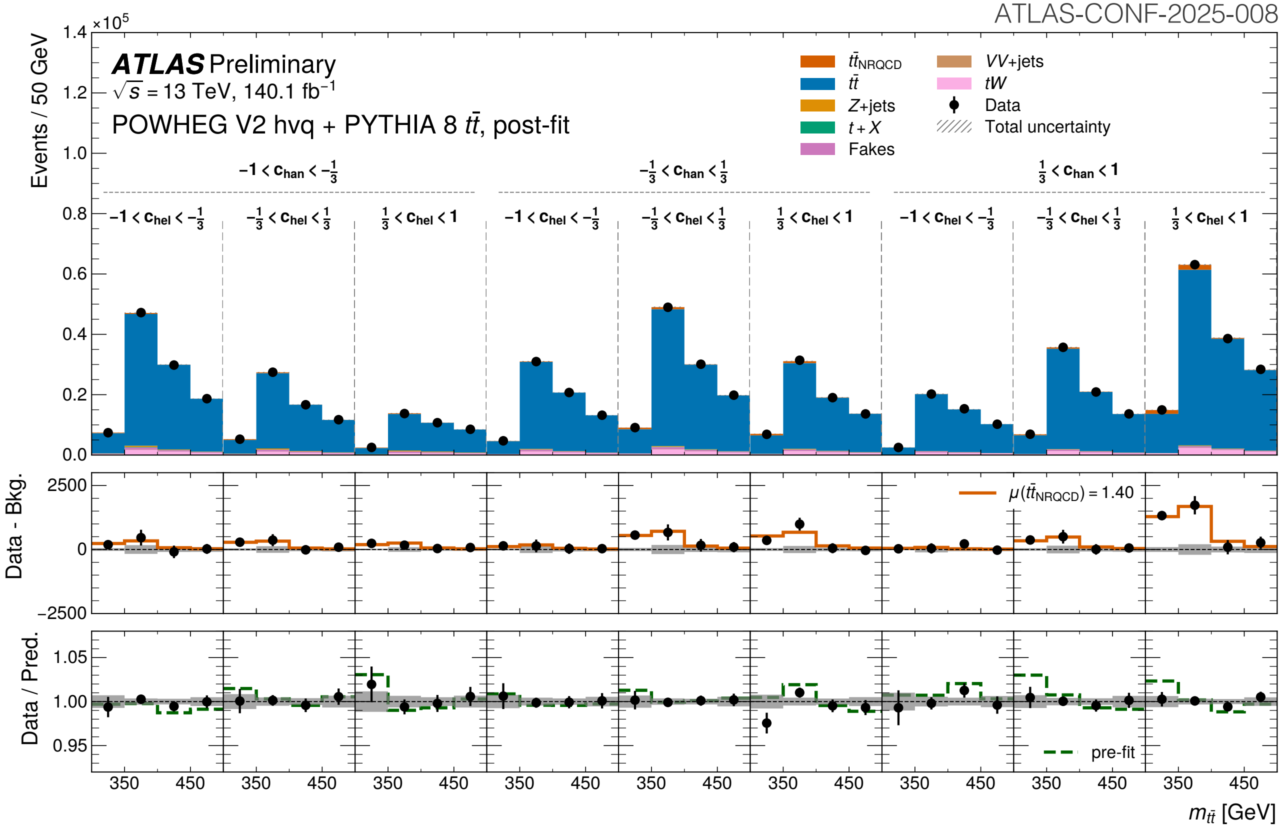
Strong interaction predicts colour-singlet quasi-bound $t\bar{t}$ states (there is no self-annihilation, top decays before)

The effect can be computed in non-relativistic QCD (NRQCD); it behaves like a pseudoscalar, but is *not* an s-channel resonance



arXiv:2503.22382

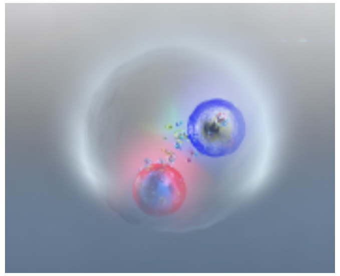
ATLAS-CONF-2025-008



ATLAS used [NRQCD model](#) for threshold contribution (also alternative models studied)

Observed significance of 7.7σ for a cross section of 9.0 ±1.3 pb

(With CMS signal model ATLAS finds: 13.4 ±1.9 pb)



Elusive attraction among top-quark pairs

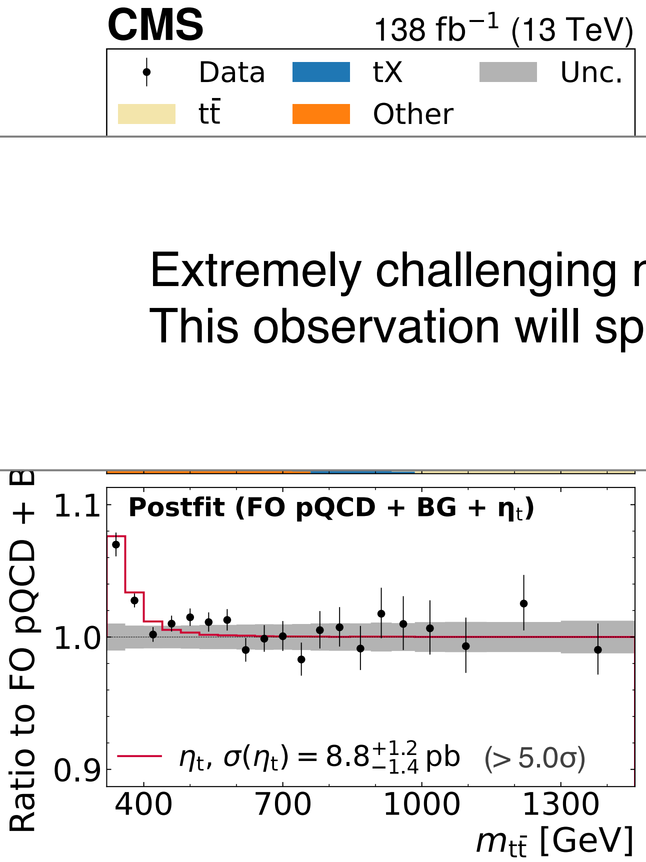
Top–antitop production at threshold

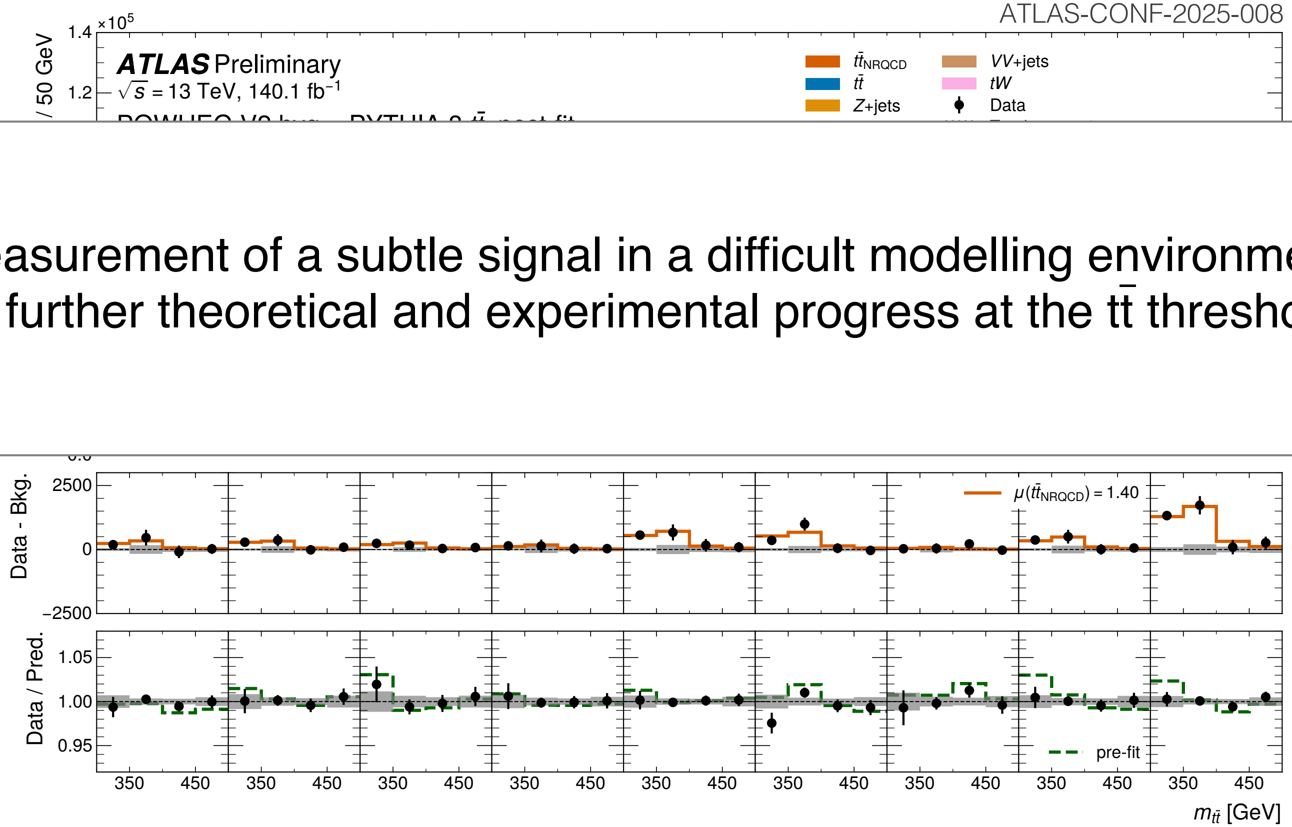
Josh Bendavid, Fabio Cerutti, Haifeng Li,
Roberto Salerno, Christian Schwanenberger

CMS observed enhancement near $t\bar{t}$ production threshold — observation confirmed by ATLAS at EPS

Strong interaction predicts colour-singlet quasi-bound $t\bar{t}$ states (there is no self-annihilation, top decays before)

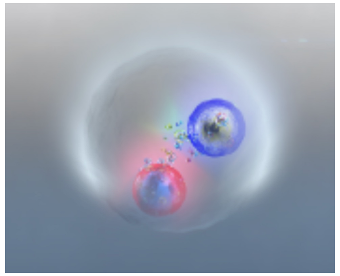
The effect can be computed in non-relativistic QCD (NRQCD); it behaves like a pseudoscalar, but is *not* an s-channel resonance





ATLAS used NRQCD model for threshold

Extremely challenging measurement of a subtle signal in a difficult modelling environment.
This observation will spur further theoretical and experimental progress at the $t\bar{t}$ threshold



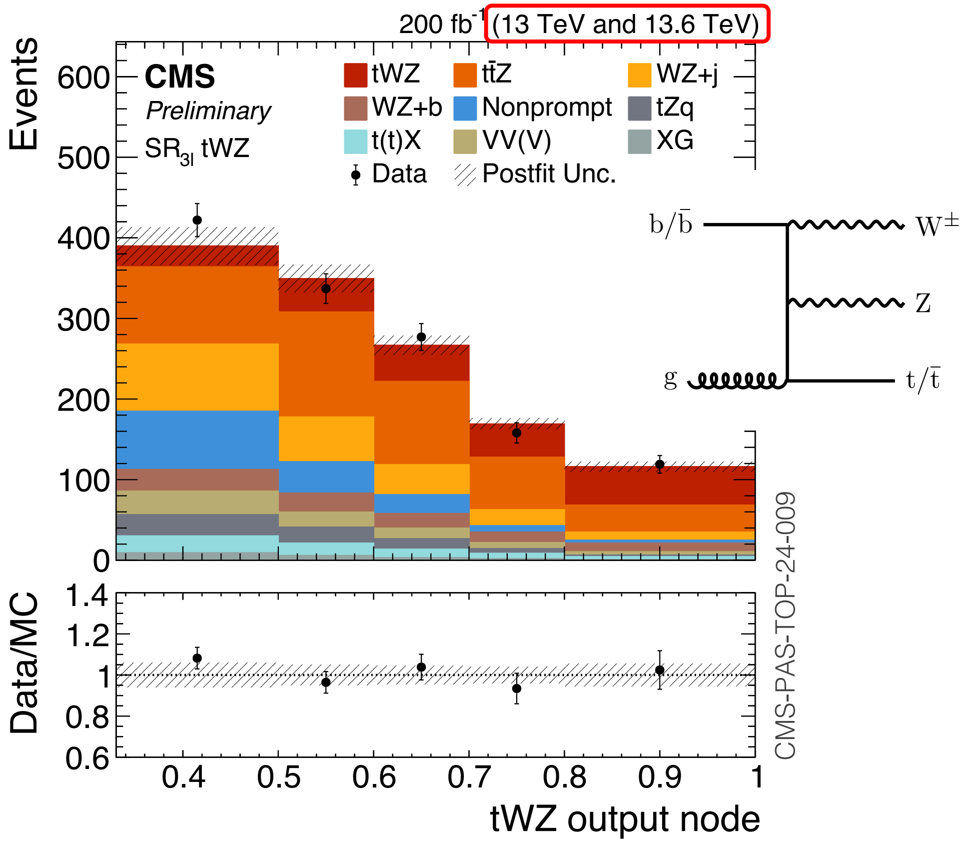
Elusive attraction among top-quark pairs

Rare processes

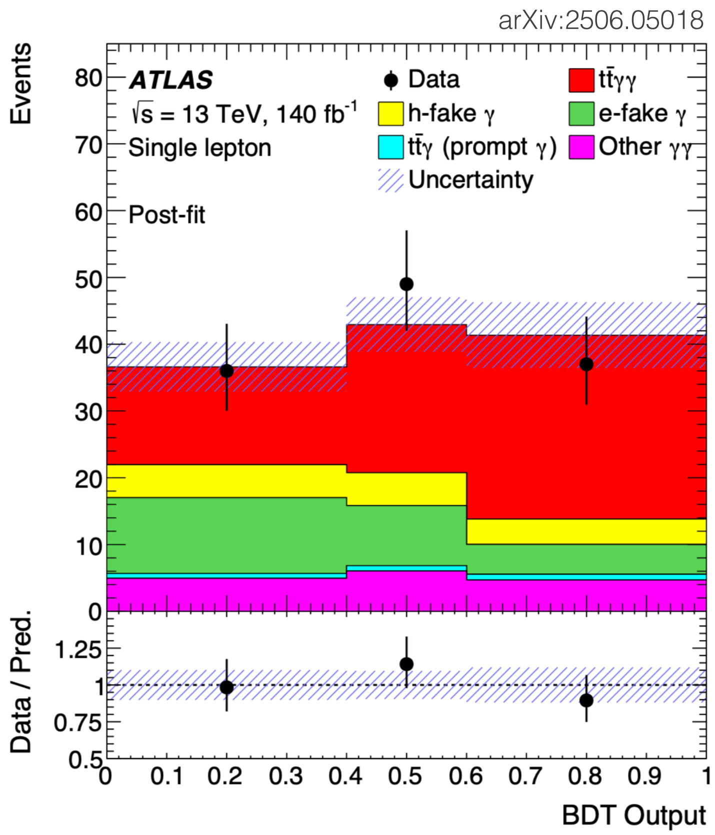
Alberto Belvedere, Josh Bendavid,
Jose Enrique Palencia Cortezon, Amartya Rej

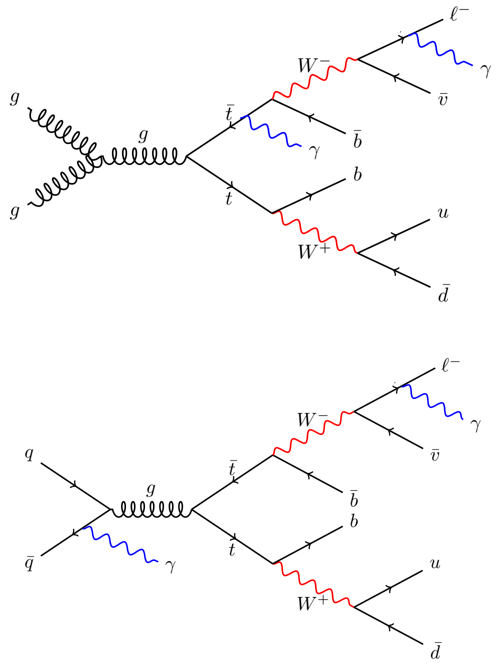
LHC experiments push intensity frontier to ever rarer processes — with help from machine learning

Each of them probes new, often deep facets of the SM. Here: first observation of tWZ (left) and tt$\gamma\gamma$ (right)



σ(tWZ) = 248 ± 52 fb (5.8σ significance)





σ_{fid}(tt$\gamma\gamma$) = 2.4 ± 0.5 fb (5.2σ significance)

New annual conference dedicated to direct new physics searches.
First edition Oct 20–24, 2024 at CERN [Link]

Searches

Tamara Vazquez Schröder

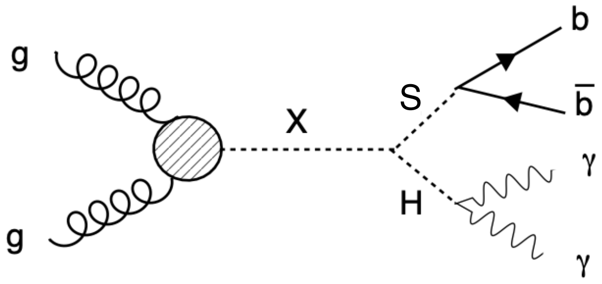
No BSM physics seen at the LHC yet, crucial to pursue broad and deep searches during Run 3 and beyond

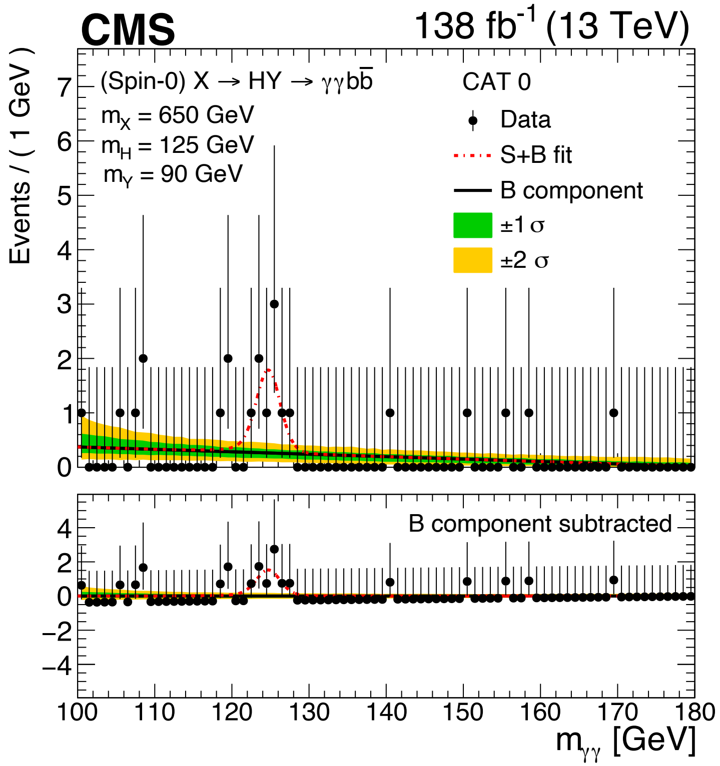
- Follow-up on excesses from Run-2 searches
- Benefit from new triggers, reconstruction, and analysis techniques in Run 3
- Systematically tackle missed opportunities, benefitting from > doubled data sample

Follow-up on Run-2 excesses

Yanlin Liu, Tamara Vazquez Schröder

Several (non-significant) excesses seen in Run-2 data, for example in this search:

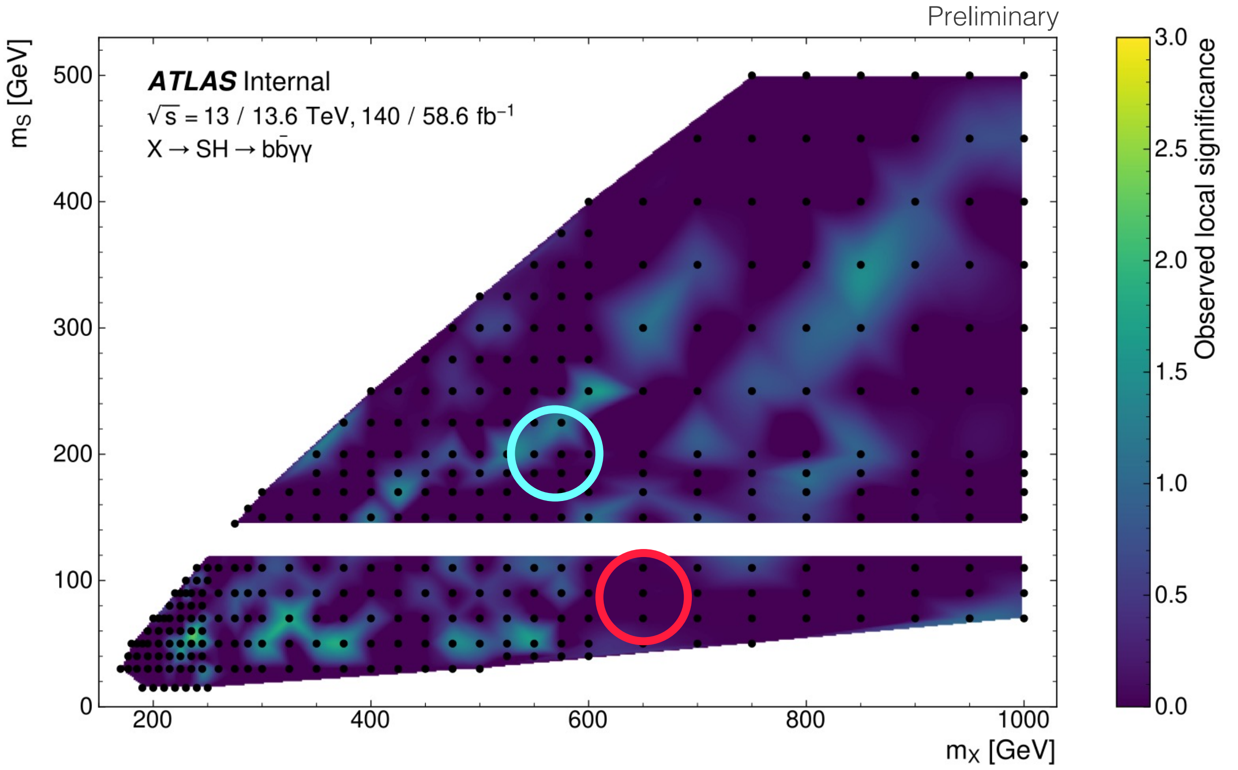




CMS saw global (local) 2.8σ (3.8σ) excess at
m_X = 650 GeV
m_Y = 90 GeV
[arXiv:2310.01643]

Not seen by ATLAS in Run 2
[arXiv:2404.12915]

New ATLAS result using Run-2 (140 fb^{-1}) and 59 fb^{-1} of Run-3 data

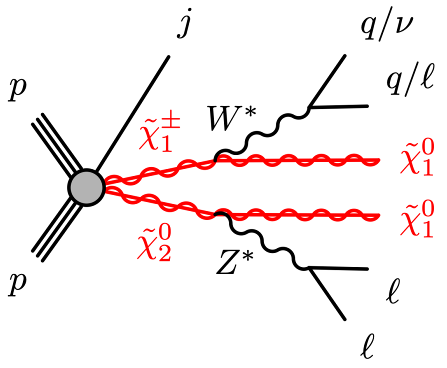


CMS excess not confirmed in this search, nor a previous ATLAS excess at (m_X, m_S) = (575, 200) GeV

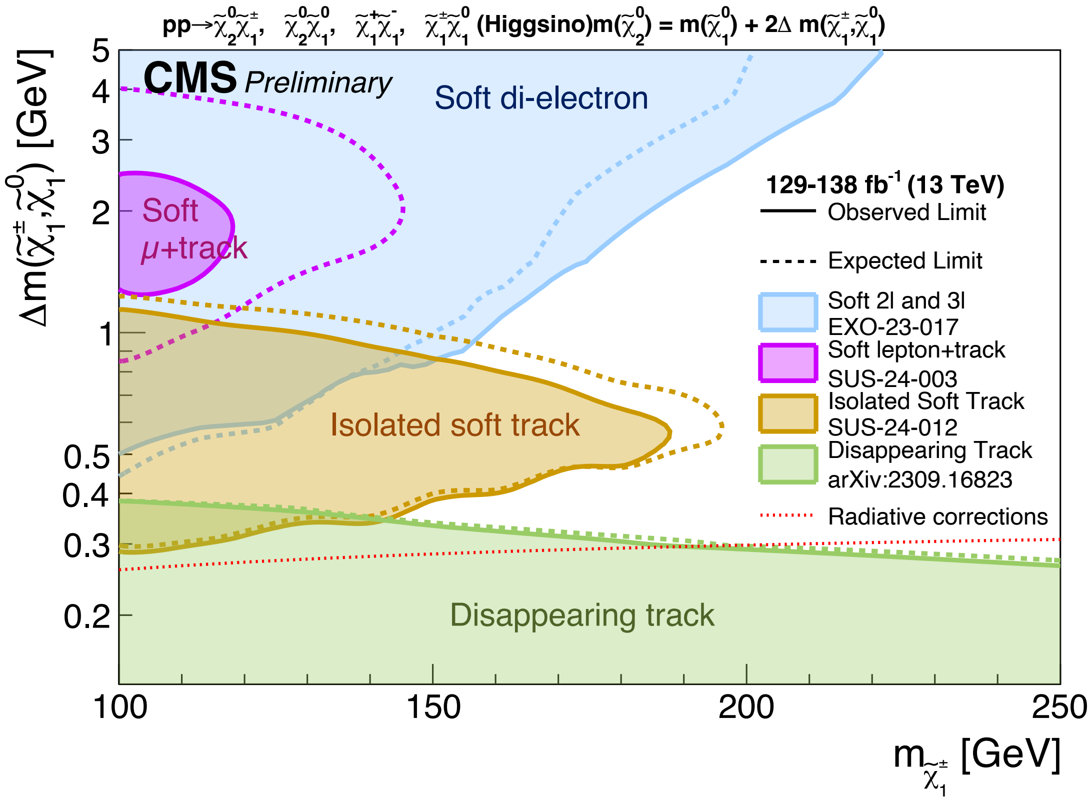
Exploiting new techniques

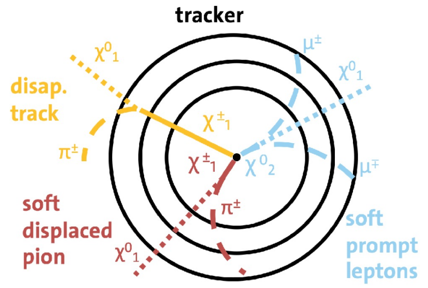
Samuel Bein, Pantelis Kontaxakis,
Tamara Vazquez Schröder

Compressed electroweak SUSY spectrum featuring degenerate neutralinos / charginos (higgsinos) — hard to tackle, experiments pushing the limits of their reconstruction



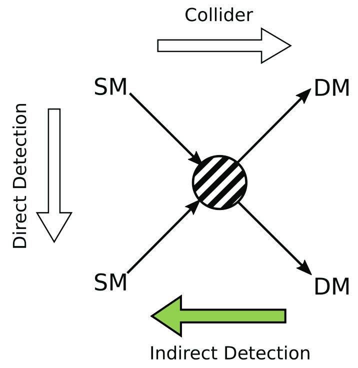
Comprehensive set of analyses targeting ultra-compressed spectra





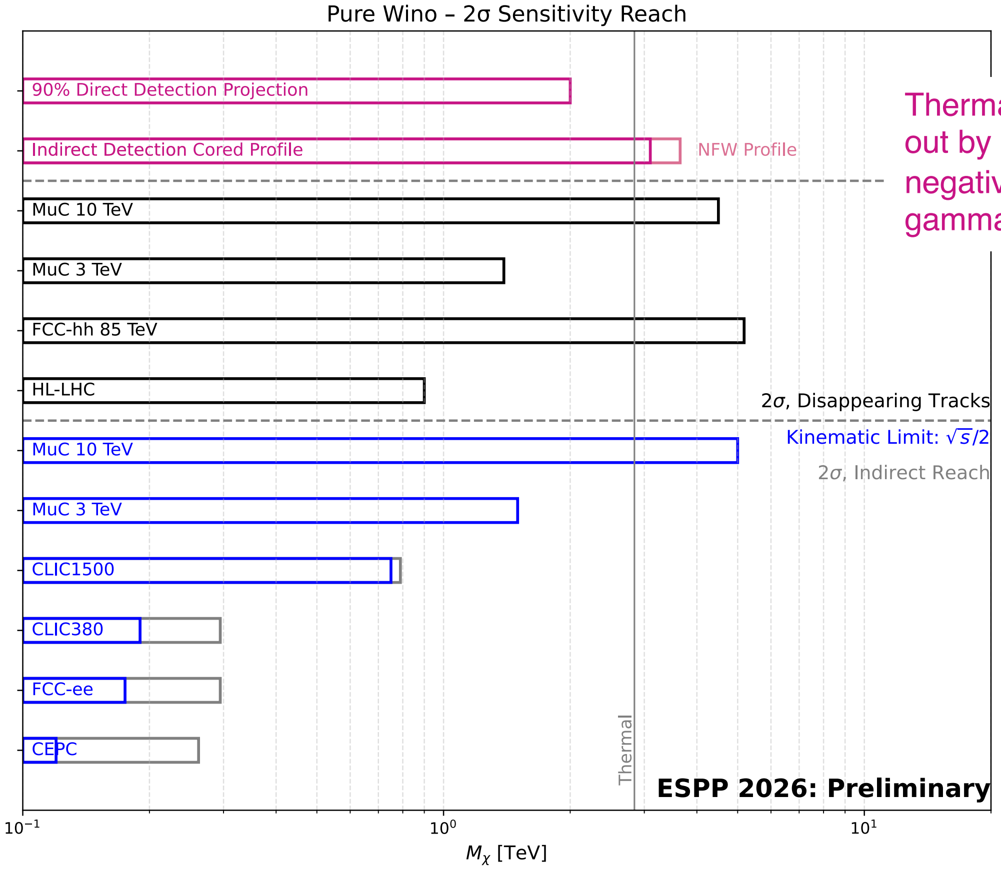
Low-momentum isolated tracks

Indirect detection — thermal wino / higgsino



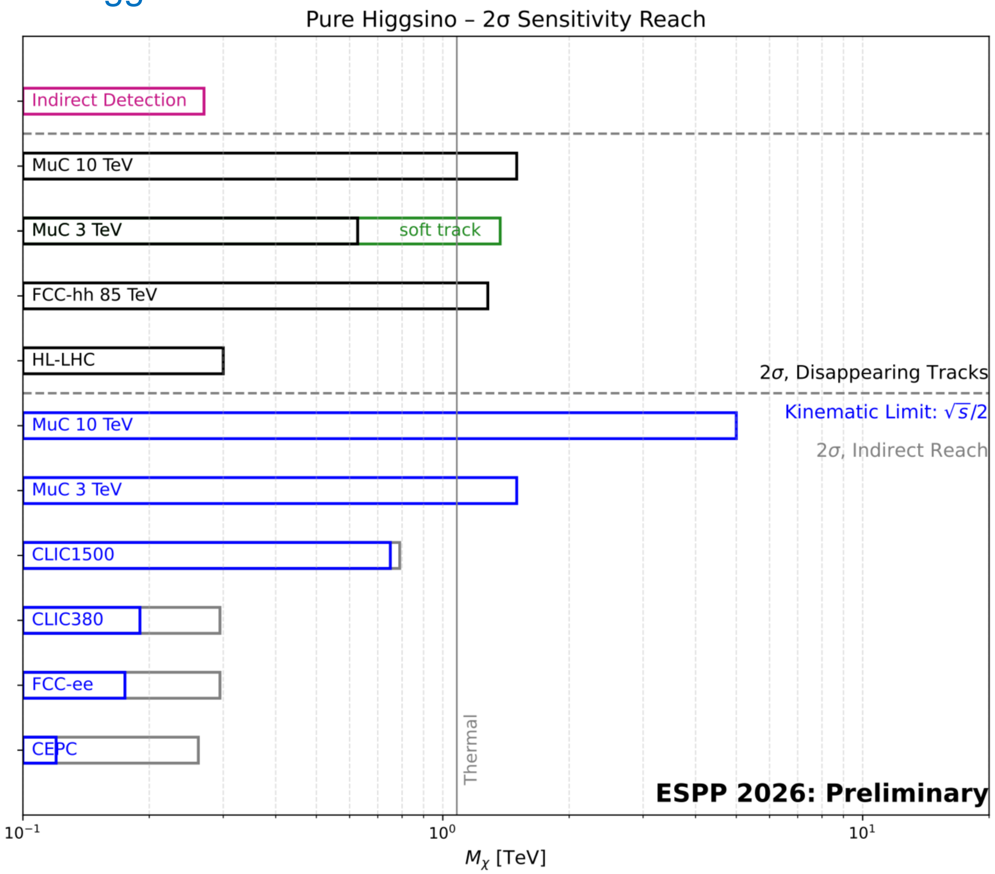
At Venice symposium, we heard about the following preliminary plots on indirect DM detection limits compared to future collider facilities [Link to slides by Tim Cohen]

Pure wino*



Thermal wino ruled out by HESS and negative Ferm-LATi gamma-ray data

Pure higgsino*



*Majorana fermion triplet

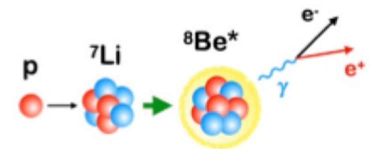
*Dirac fermion doublet

X17

Paolo Valente, Cecilia Voena

Puzzle from measurements of internal pair conversion process ^{7}Li + p → ^{8}Be*(18.1) → ^{8}Be + γ*(→ e⁺e⁻)

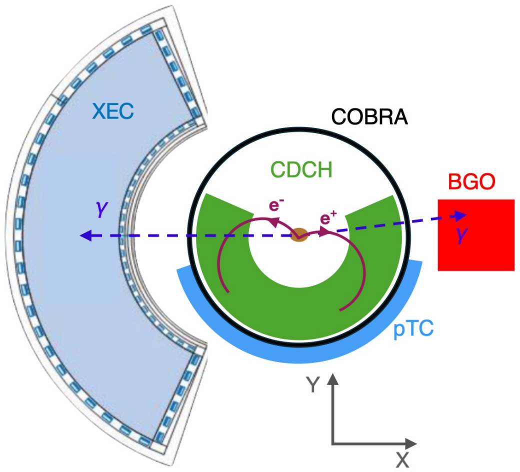
Since 2016, ATOMKI data show a persistent excess in e⁺e⁻ angular distributions consistent with a ~17 MeV particle at rate vs. γ of ~ 6×10⁻⁶ (challenging measurement due to low energy of emerging e⁺ / e⁻). Follow-up studies with refined analyses and other nuclei confirm the anomaly. No SM explanation exists for such a phenomenon.

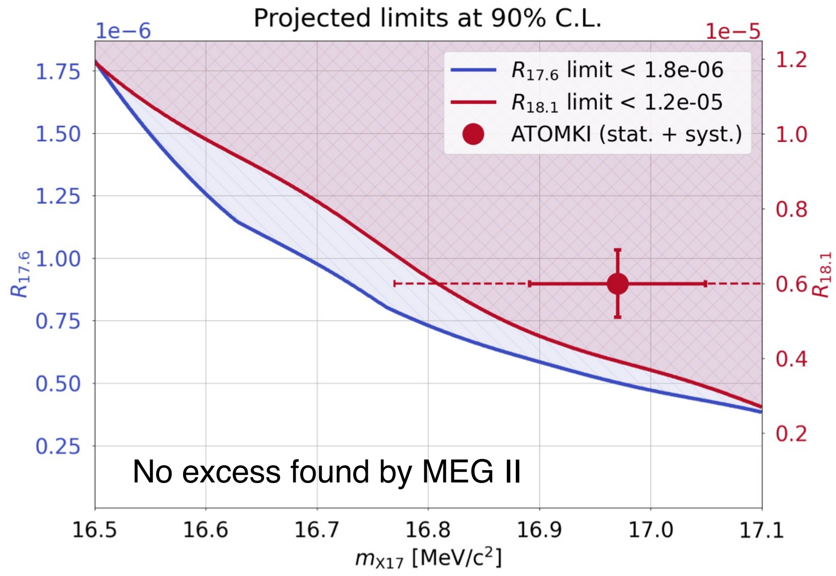


Many groups looking at this anomaly. Two reports this week:

MEG II (PSI) [arXiv:2411.07994]

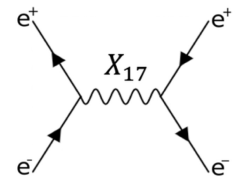
Dedicated 4-week run in Feb 2023 with 1.08 MeV proton on Li target, measuring outgoing ^{8}Be* de-excitation photons and e⁺, e⁻

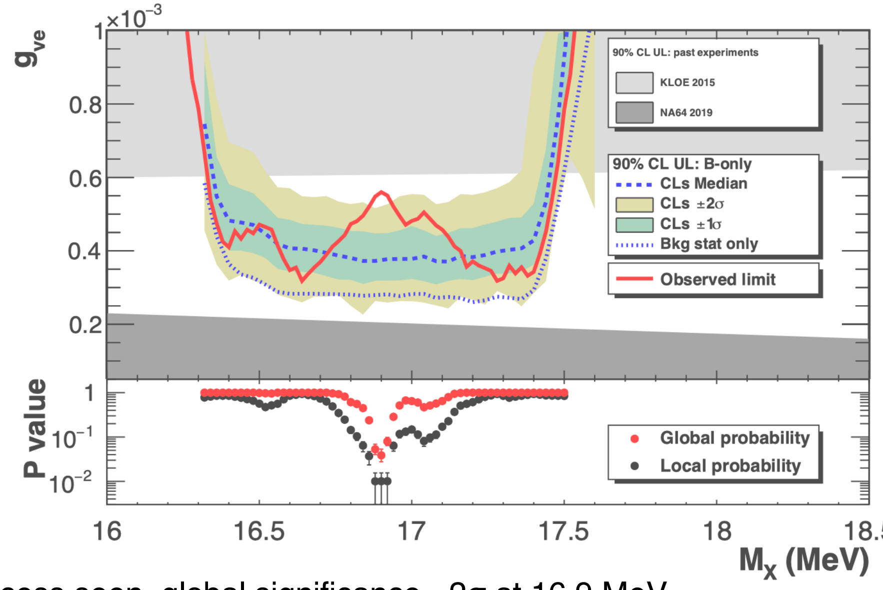




PADME (Frascati) [arXiv:2505.24797]

Try to directly produce X17 by hitting thin (0.1 mm) diamond target with 283 MeV e⁺ beam and measure outgoing e⁺, e⁻





Small excess seen, global significance ~2σ at 16.9 MeV

Lepton flavour violation

Paolo Valente, Cecilia Voena

Puzzle from measurements of Internal pair conversion process $^7Li + p \rightarrow {}^8Be^* \rightarrow {}^8Be + \gamma^*(\rightarrow e^+e^-)$

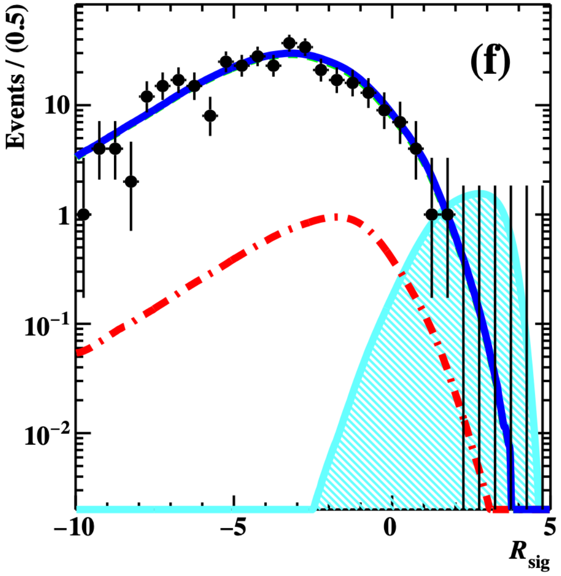
Since 2016, ATOMKI data show a persistent excess in e^+e^- angular distributions consistent with a ~17 MeV particle at rate vs. γ of ~ 6×10^{-6} (challenging measurement due to low energy of emerging e^+ / e^-). Follow-up studies with refined analyses and other nuclei confirm the anomaly. No SM explanation exists for such a phenomenon.

Tim Gershon, Atsushi Oya

Main program of **MEG II**: search for charged-lepton-flavour violating decay $\mu^+ \rightarrow e^+\gamma$

Look for monoenergetic & back-to-back $e\gamma$ coincidence peak; main background from accidental coincidence

New result using data from 2021 & 2022 (analysis of 2023 and 2024 data ongoing)



New limit [arXiv:2504.15711]

$B(\mu^+ \rightarrow e^+\gamma) < 1.5\times10^{-13}$ (90% CL)

Small excess seen, global significance ~2σ at 16.9 MeV

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

La Cité Radieuse (1952) – Le Corbusier

Hadrons & Flavour

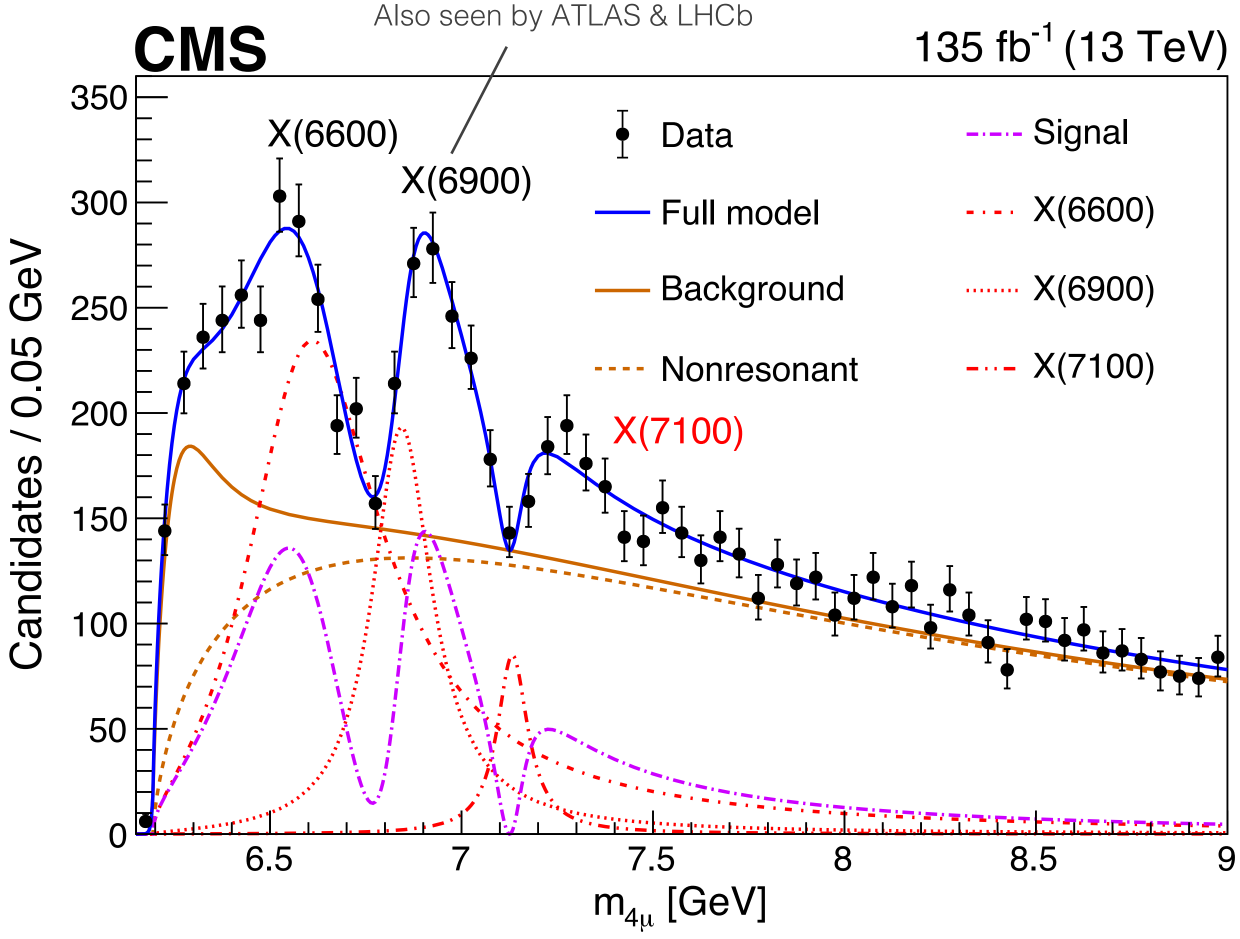
Hadron spectroscopy became a renrewed field since the first observation of the exotic X(3872) by Belle in 2003, and was revolutionised at the LHC, mainly (but not only) by LHCb

Flavour physics remains key in our comprehensive programme testing the SM and beyond

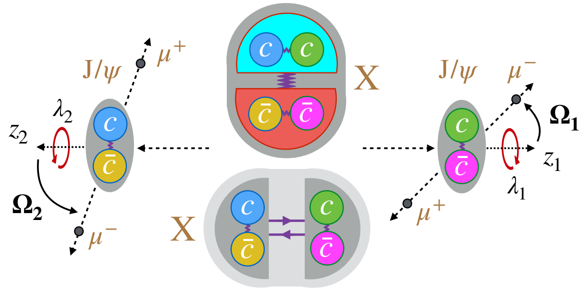
Hadron spectroscopy

Roberto Salerno

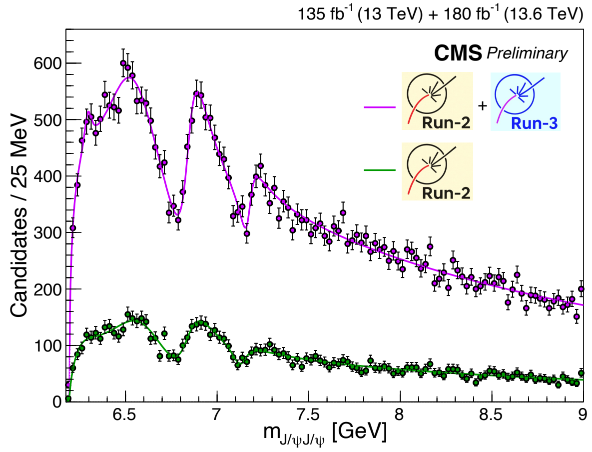
CMS revealed family of 3 all-charm X resonances in J/ψJ/ψ → 4μ mass spectrum [arXiv:2506.07944]



Tightly bound tetraquark in same confinement volume ?



Molecule, like a deuteron (molecular hexaquark)?



Since J/ψ does not couple to light quarks, X unlikely hadronic molecules bound by light meson exchange, but too heavy to be cccc ground state

Angular analysis prefers $J^{PC} = 2^{++}$, suggesting tightly bound tetraquarks

(On the contrary, narrow-width P_{cc} appear to be $\Sigma_c D^{(*)}$ or $\Xi_c D$ molecule)

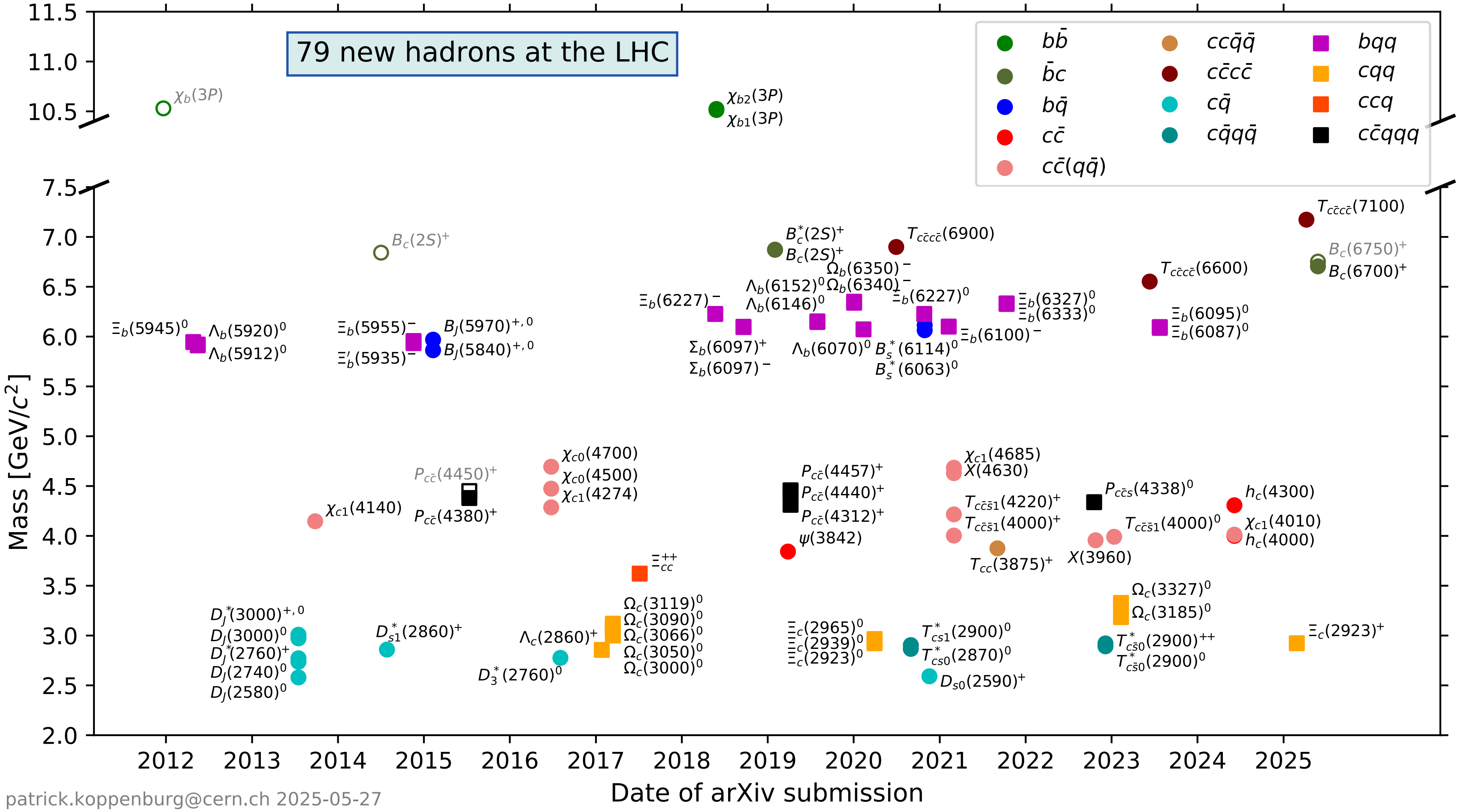
Run-3 provides much larger sample thanks to improved triggers and parking stream

Hadron spectroscopy

Tim Gershon, Vladimir Gligorov

Several 4- and 5-valence quark states found, majority by LHCb, and certainly not the end of the story…

Resonances with heavy quarks reduce the amount of open decay channels and thus have smaller width
→ easier to discover if enough energy, luminosity, and momentum resolution



Who finds the T_{bb} ($bb\bar{u}\bar{d}$) first ?

Attraction between two heavy quarks $\propto \alpha_s^2 m_q$ → large negative binding energy, so expected to have mass below BB threshold and thus weakly decaying (contrary to $T_{cc}(3875)^+$, which has less binding energy and decays strongly)

See this instructive CERN Courier article by Marek Karliner and Jonathan Rosner (Jonathan sadly passed away just recently)

Several other states discovered in e^+e^- collisions (not included in figure), e.g., $Z_c(3900)^+$ and $Z_b(10610)^+$ cc/bbud states discovered by Belle

CP violation in charm

Tim Gershon, Vladimir Gligorov, Ludovico Massaccesi, Giovanni Punzi

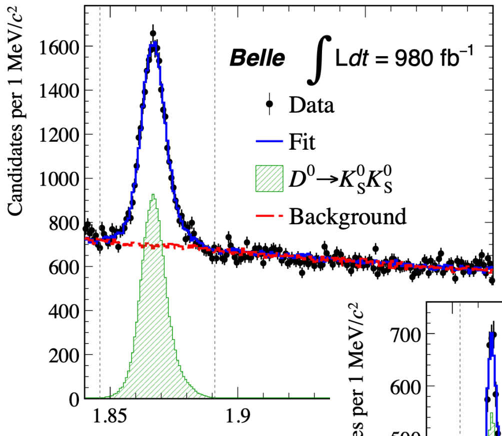
CP violation in charm sector (up-type quarks) is mostly expected to be very small (< O(10^{-3}) in SM

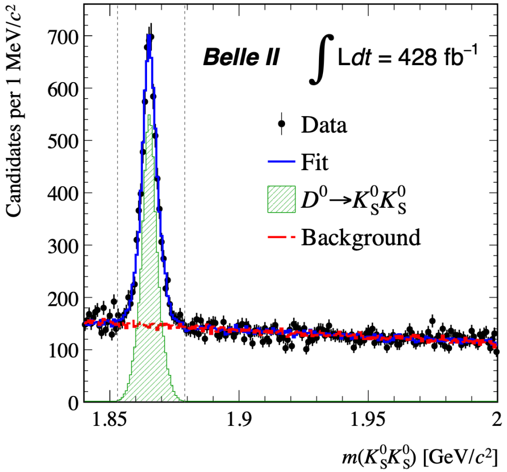
First observation by LHCb in 2019 from ΔA_{CP} between $D^0 \to K^+K^-$ and $D^0 \to \pi^-\pi^+$ decays = $(-15.4 \pm 2.9)\times10^{-4}$ [arXiv:1903.08726]
which is about six times larger than theoretical bounds (but difficult calculations)

New measurements by Belle II and LHCb

$$\mathcal{A}^{CP}(K^0_S K^0_S) \equiv \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}$$

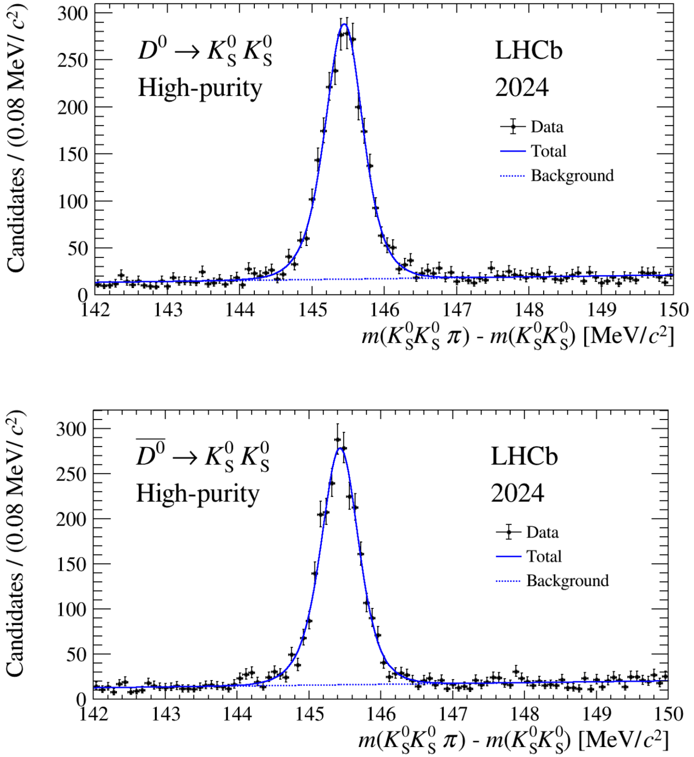
Echange & loop diagrams only,
may enhance CPV to ~1% [Link]

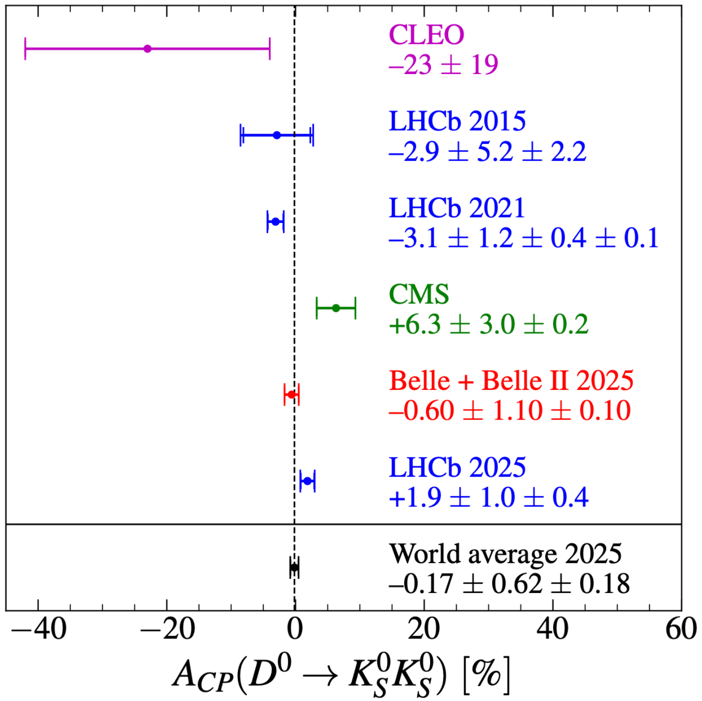




Combination of Belle and Belle II data

LHCb 2024 dataset →





CP violation in baryons

Tim Gershon, Xueting Yang

First observation of CP violation in baryon decay by LHCb

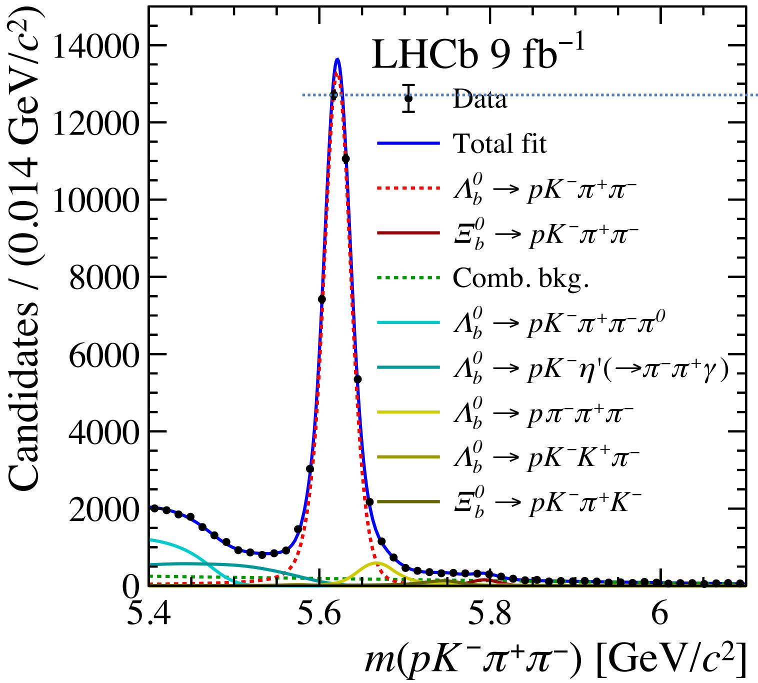
Direct CPV requires interference of diagrams with non-zero differences of weak *and* strong phases

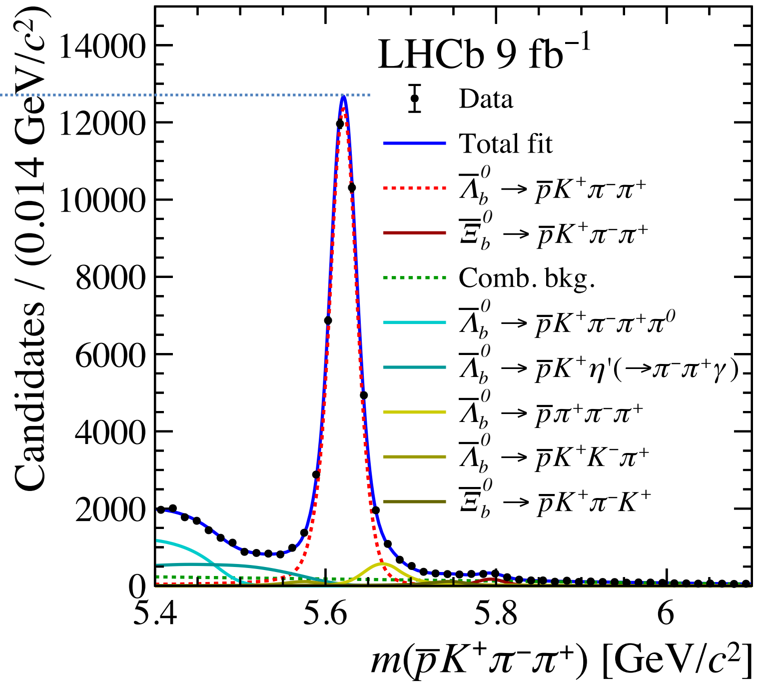
$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)} = (2.45 \pm 0.46 \pm 0.10)\%$$

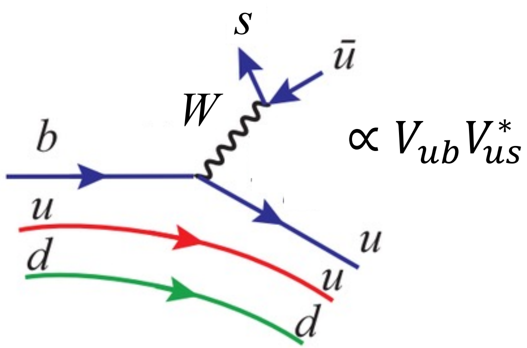
Decay proceeds mostly through intermediate resonances (showing different amount of A_{CP})

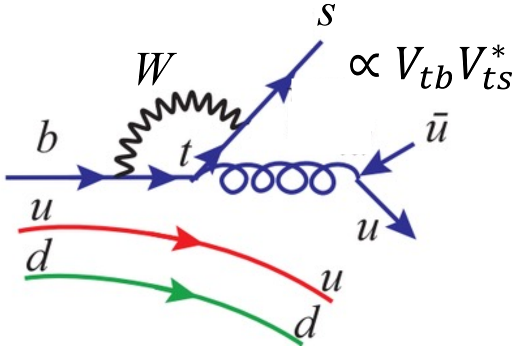
Derived from uncorrected yield difference: $A_N = 3.71 \pm 0.39$ %

arXiv:2503.16954









CP violation due to interference between tree and penguin diagrams

Precise amount of CPV very hard to predict, but interestingly smaller in baryon than similar meson systems

Note that baryogenesis requires proton decay and CPV, but not necessarily in the baryon sector

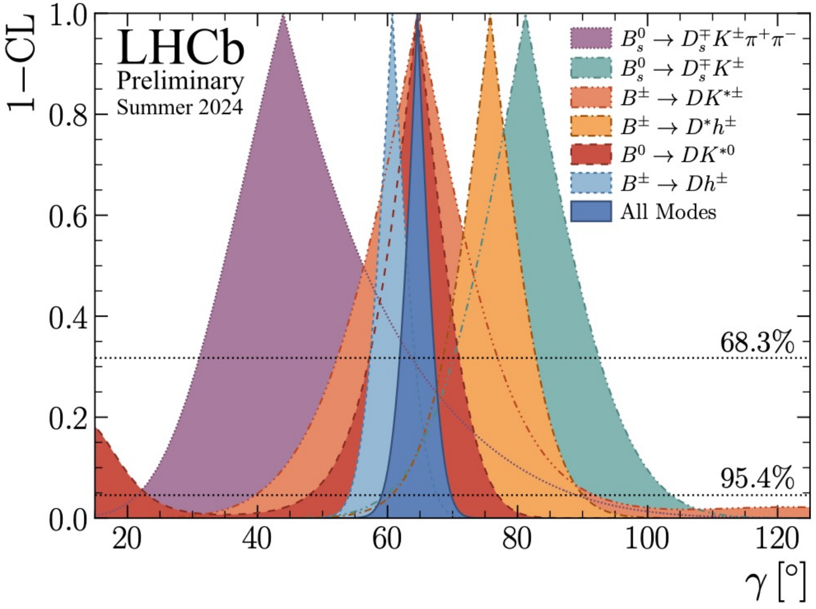
CKM unitarity

Tim Gershon, Vladimir Gligorov

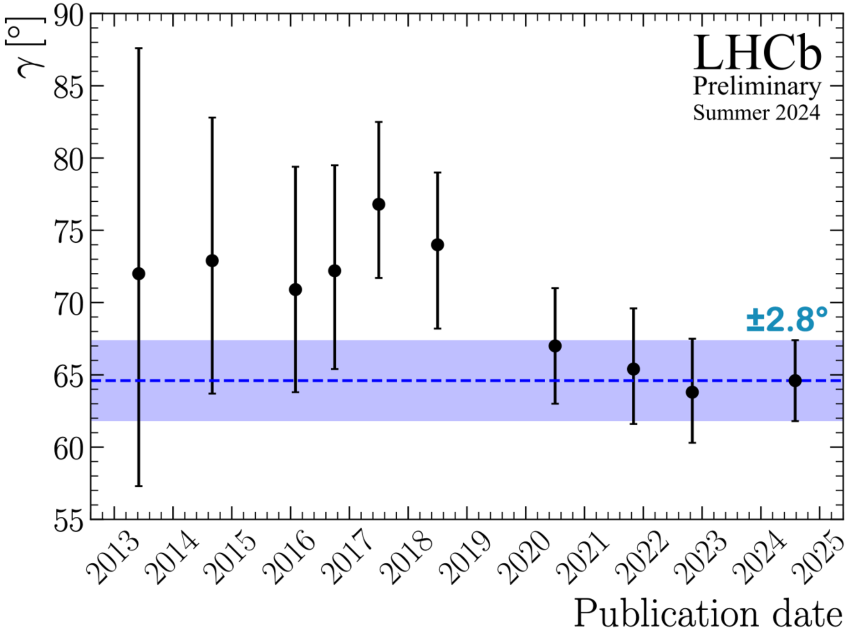
A tribute to the monumental work by LHCb on improving the apex measurements of the CKM unitarity triangle

Leading measurements of γ, currently also world's most precise measurement of sin2β

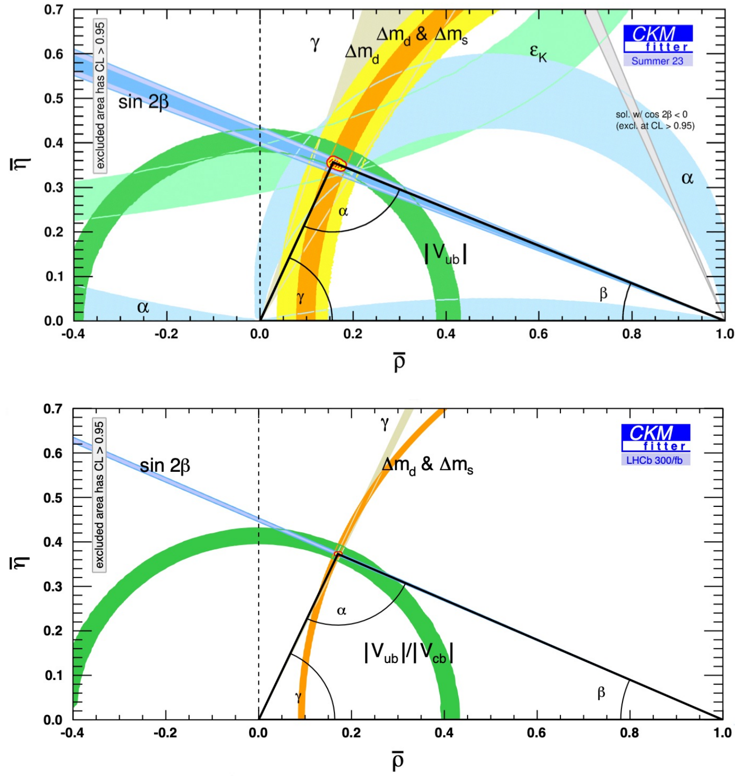
Constraints from various B → DK analyses



Constraint versus time



And much more to expect from LHCb Upgrade II



LHCb Upgrade II Scoping Document

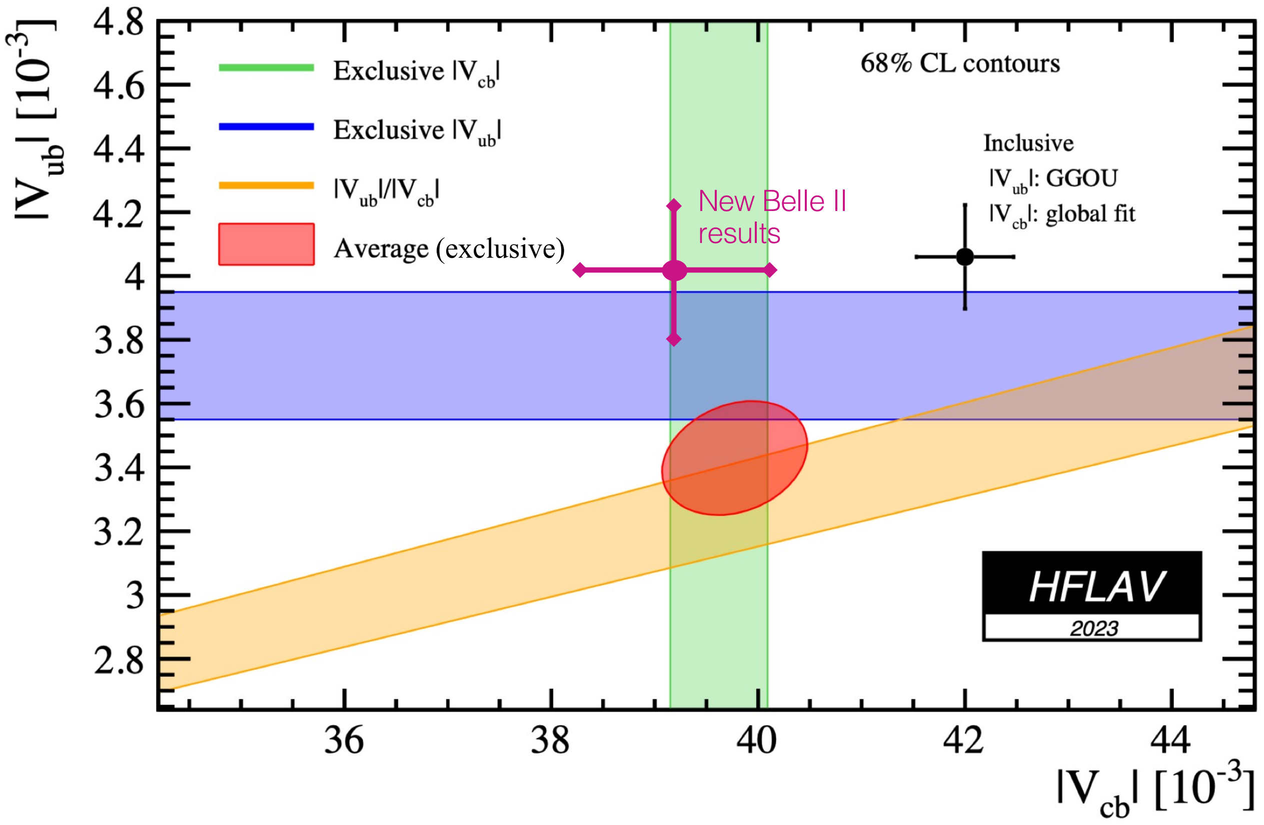
$|V_{cb}|$ and $|V_{ub}|$ (puzzle)

Tim Gershon, Karim Trabelsi

New measurements of inclusive $|V_{ub}|$ from $B \to X_u \ell \nu$ (first!) **and exclusive $|V_{cb}|$ from $B \to D \ell \nu$ by Belle II**

arXiv:2506.15256 and preliminary

Competitive precision, results confirm (but do not yet resolve) current puzzle between inclusive and exclusive measurements

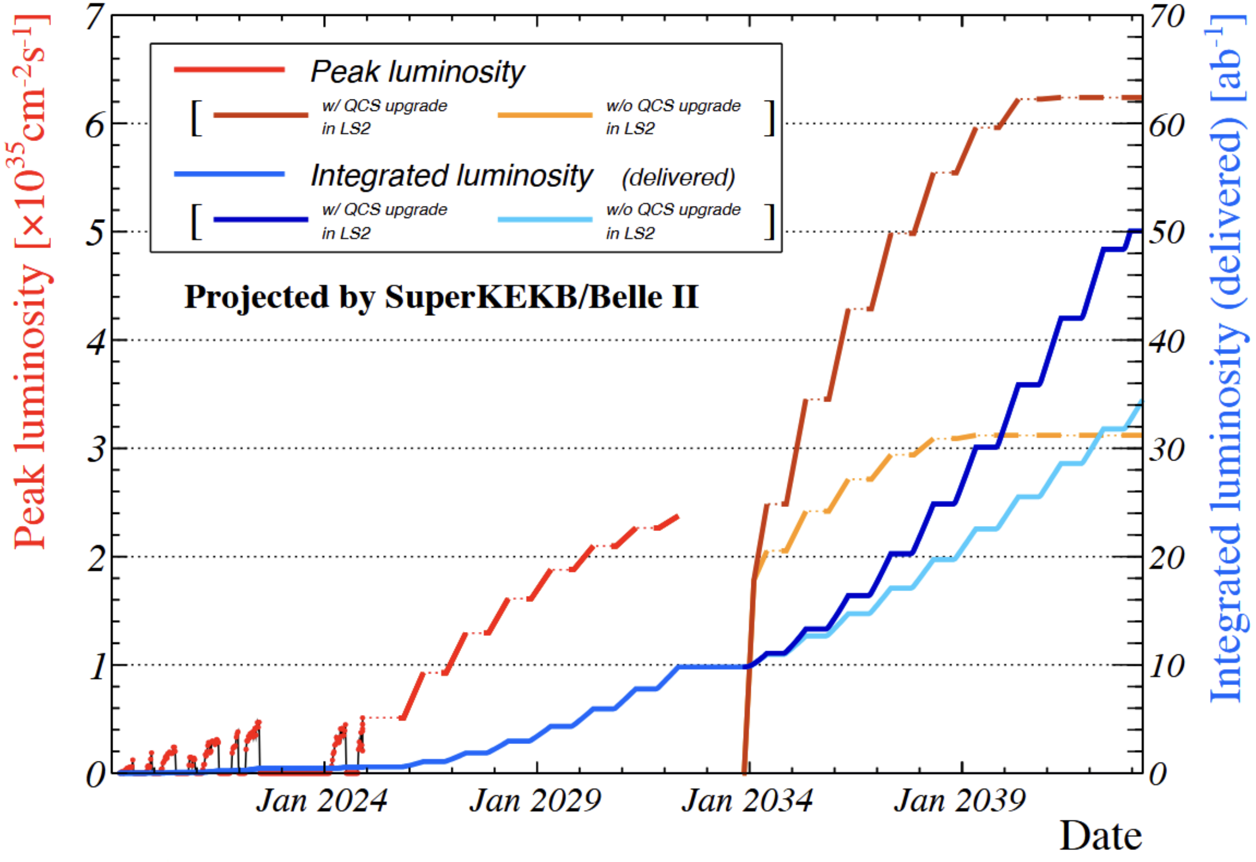


Roadmap for SuperKEKB / Belle II

Karim Trabelsi

Luminosity frontier (nano beams, powerful injector linac) **— production so far behind expectation due to machine problems** (sudden beam losses, low injection efficiency and reduced beam squeezing due to beam-beam interactions)

Hope to fix SBL problem with improved vacuum seals. Aim: > 10^{35} cm^{-2}s^{-1} in 2025 with further increases up to 2.4×10^{35} cm^{-2}s^{-1}
Plan to upgrade superconducting final focusing magnet system (QCS) in ~2032 with stronger field (Nb_3Sn) closer to IP (not approved yet)



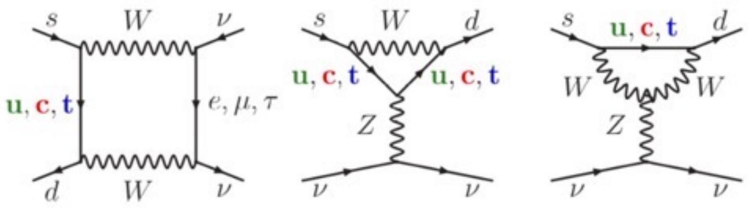
Long-term roadmap, distinguishing two cases depending on the QCS upgrade scenario

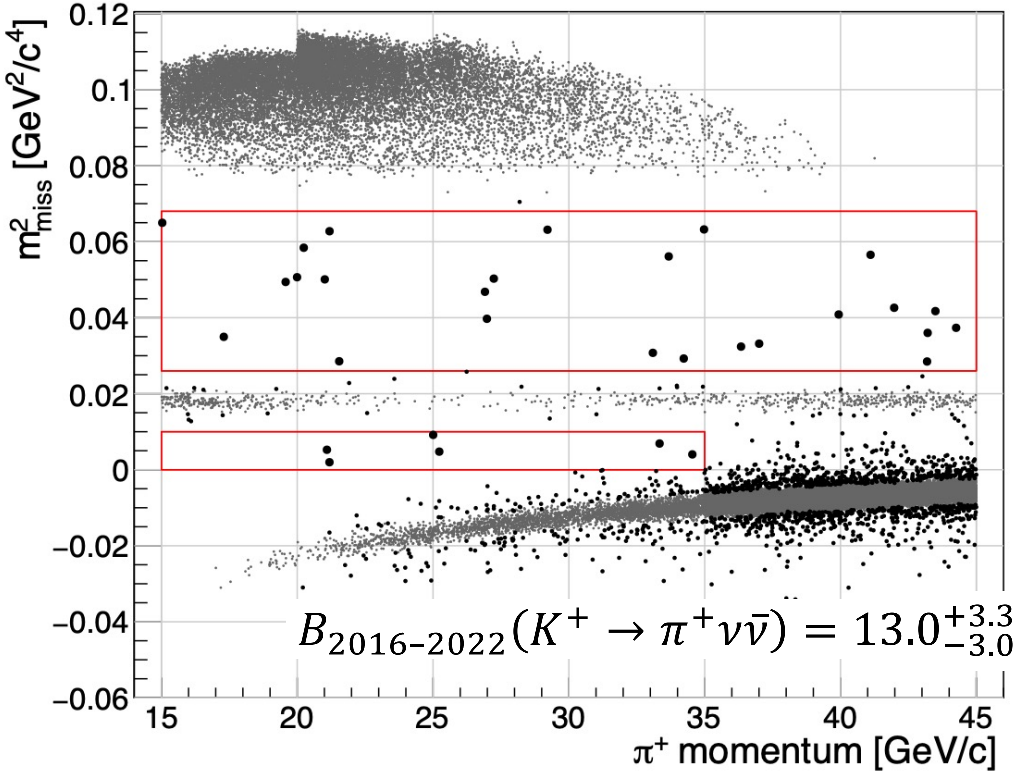
Ultra rare kaon decays

Tim Gershon, Sophie Renner, Angela Romano

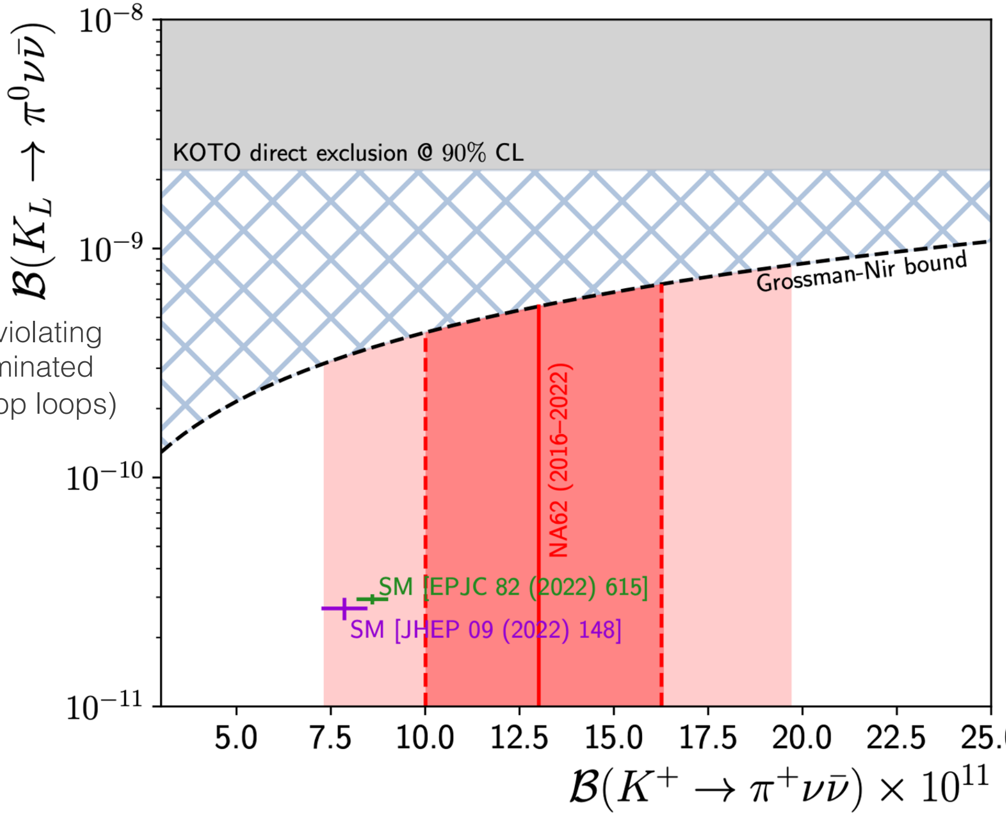
NA62 at CERN's SPS observed $K^+ \to \pi^+ \nu\bar{\nu}$ (2016–18, 2021–22 data) [arXiv:2412.12015]

GIM and CKM suppressed, dominated by Z penguin and contributions from box diagram:
$B_{SM} \sim 8 \times 10^{-11}$ (compare: $B_s \to \mu\mu \sim 4 \times 10^{-9}$)





$B_{2016\text{–}2022}(K^+ \to \pi^+\nu\bar{\nu}) = 13.0^{+3.3}_{-3.0} \times 10^{-11}$



CP-violating (dominated by top loops)

CP-conserving (contributions from top and charm loops)

Total of 51 events observed for 18^{+3}_{-2} background events expected > 5σ

More to come: NA62 continues running until 2026 (when the rare kaon physics programme ends at CERN)

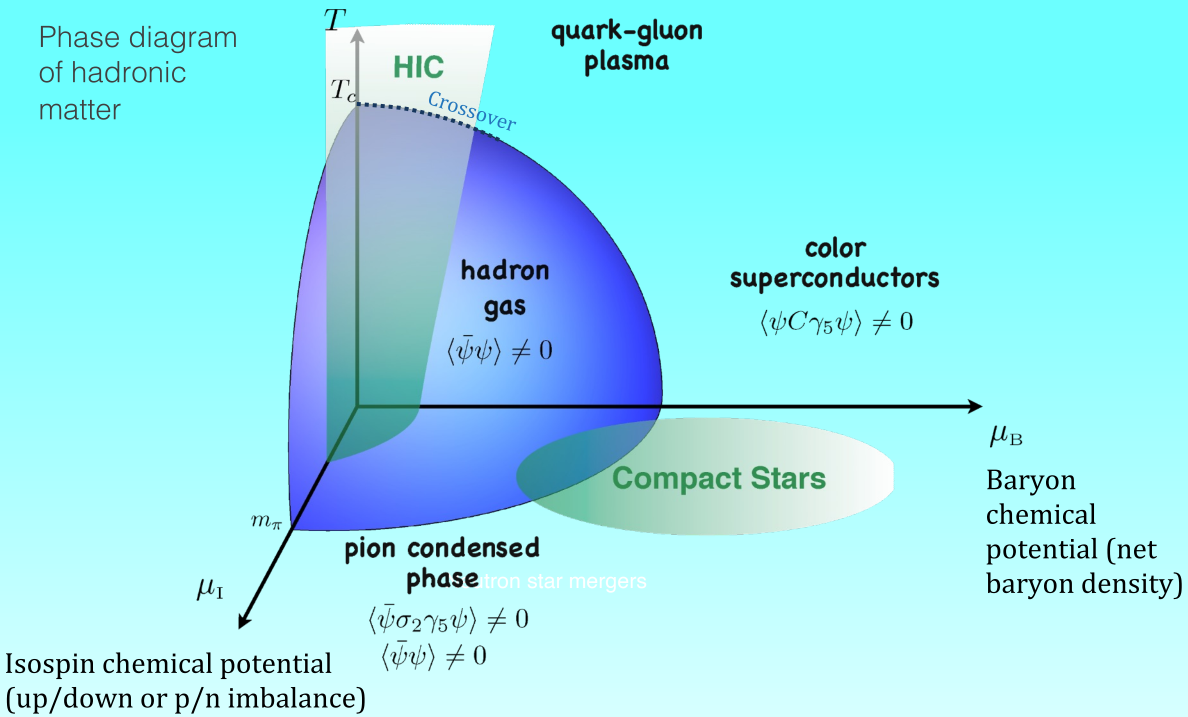
Quark matter

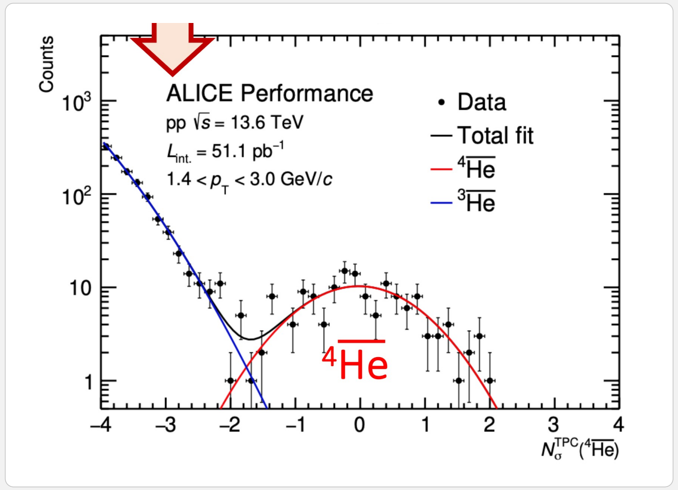
At LHC, QGP shows > 10 GeV/fm³ energy density, deconfinement, jet quenching, near-perfect fluidity, thermal hadronisation, and collective effects even in small systems

Urs Wiedemann

HI collisions cannot be explained by the superposition of nucleon–nucleon collisions → strong collective phenomena

Phase diagram of hadronic matter





Observation of $^4\overline{He}$ in pp collisions

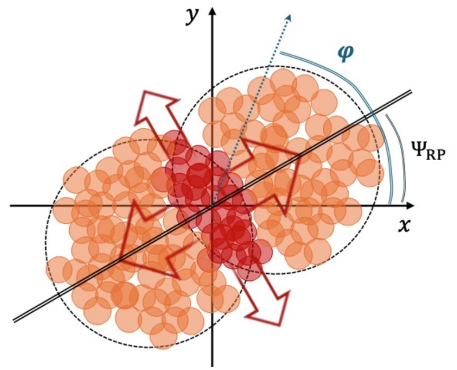
Anisotropic flow

Igor Altsybeev, Francesco Prino, Urs Wiedemann

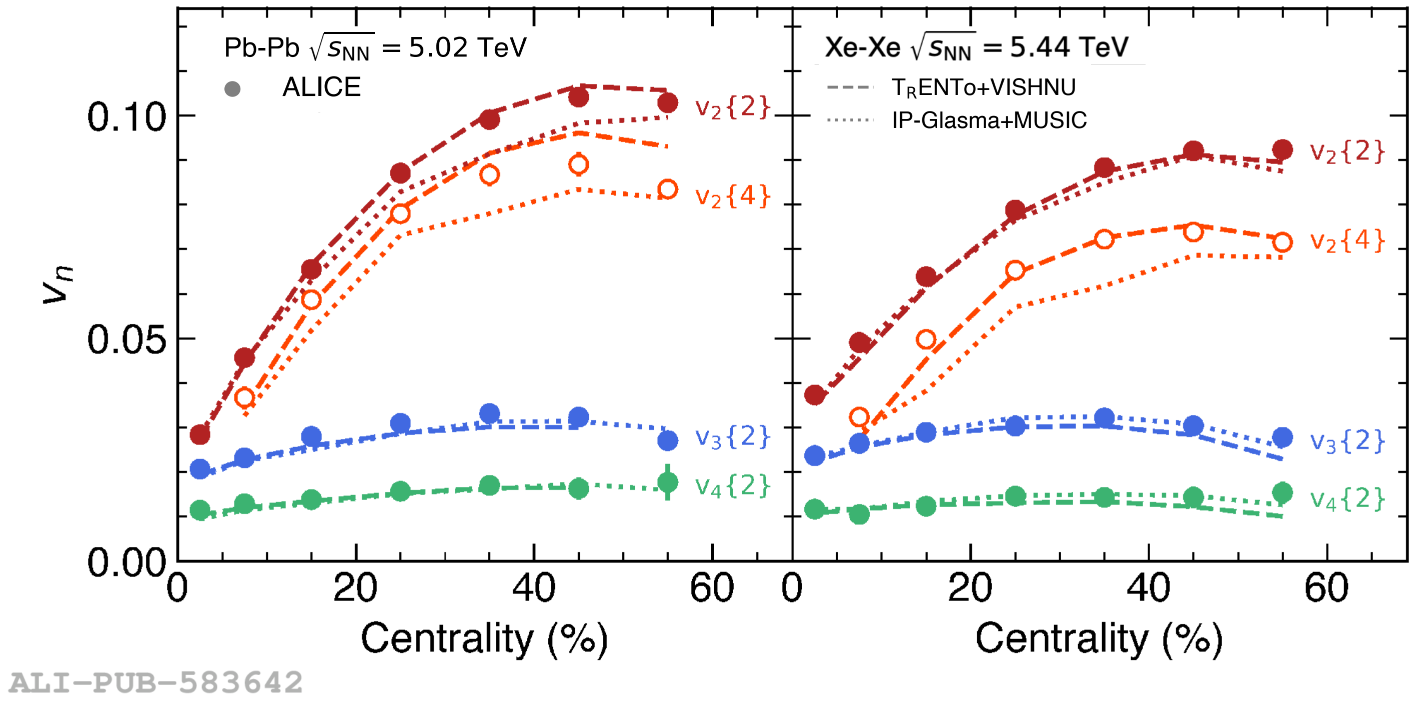
Transverse energy density profile in PbPb collisions at LHC has characteristic spatial fluctuations ("flow") quantified by Fourier harmonics v_n of particle distributions

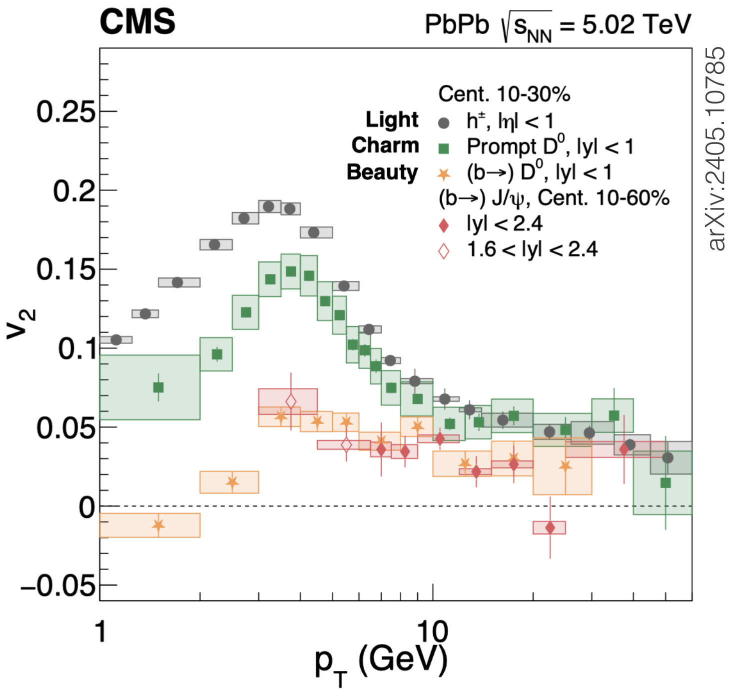
Collective dynamics translates spatial into momentum anisotropy, which is well reproduced by hydrodynamic models for light hadrons: quarks and gluons form a collective medium that flows as a relativistic fluid with exceptionally low viscosity-to-entropy ratio (10 times less than any other known form of matter)

Collective response (v_2) smaller for c and b-hadrons → heavy quarks participate less in flow of fluid
(longer thermalisation time of heavy quarks)



arXiv:2211.04384





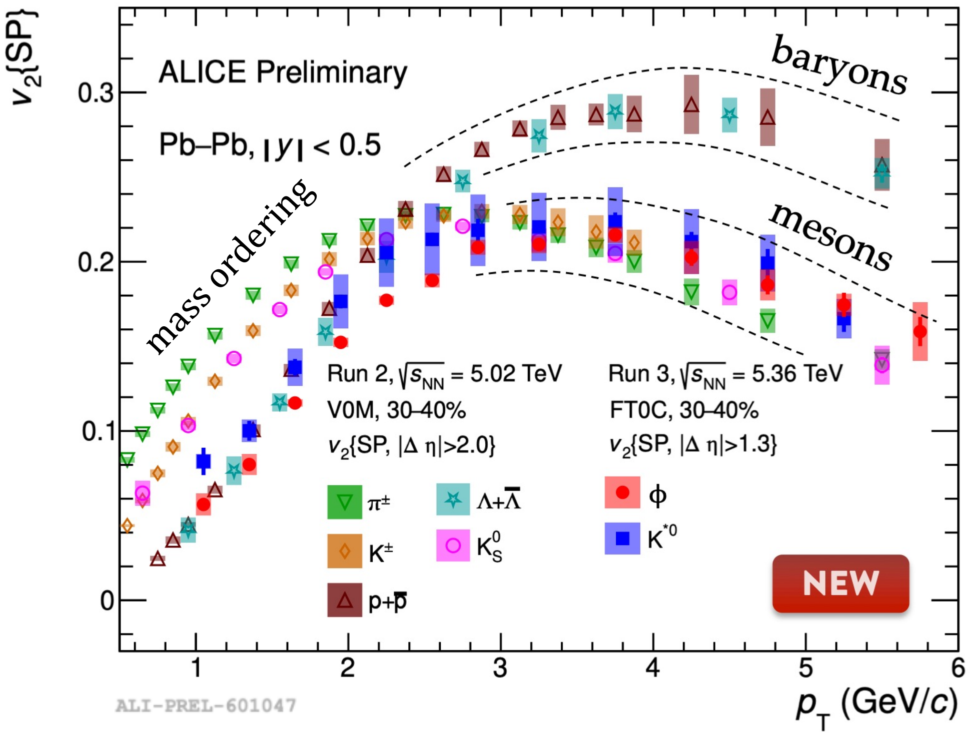
Anisotropic flow

Igor Altsybeev, Marcello Di Costanzo, Francesco Prino, Urs Wiedemann

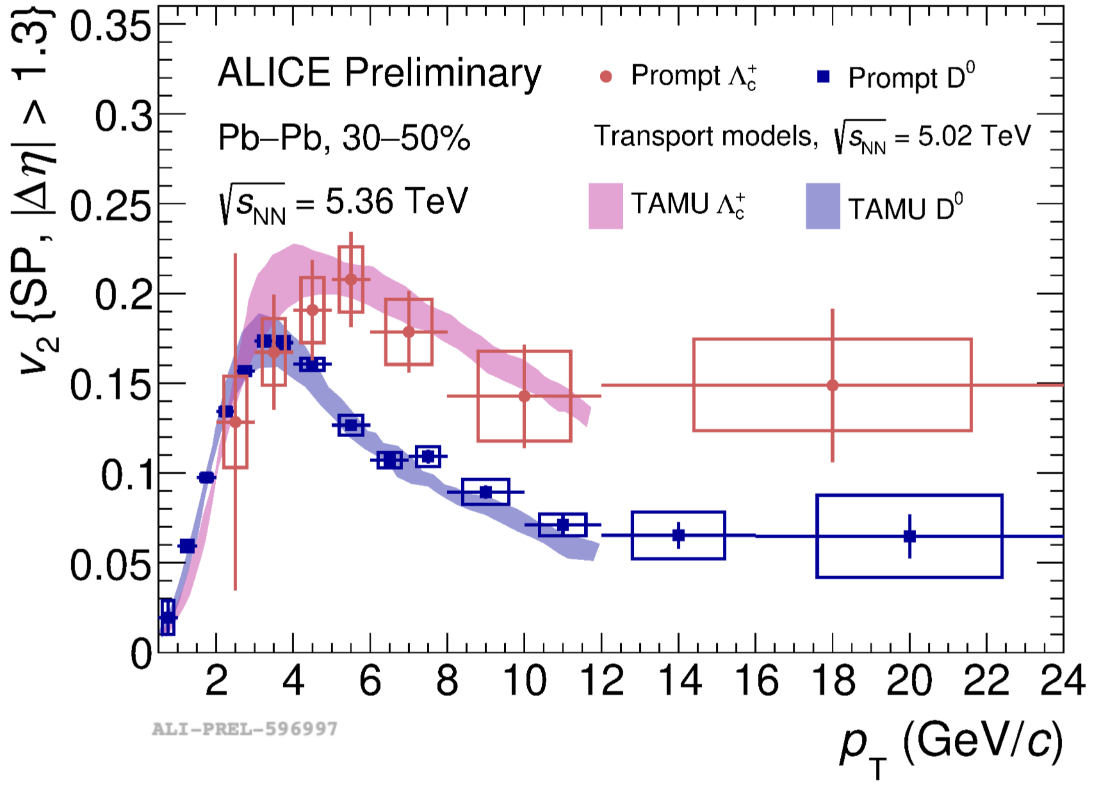
Transverse energy density profile in PbPb collisions at LHC has characteristic spatial fluctuations (“flow”) quantified by Fourier harmonics v_n of particle distributions

Understanding of underlying thermalization process would benefit from low-p_T (< 1 GeV) data: well measured for light flavour hadrons, but not yet for heavy flavour hadrons and baryons

First prompt charm-baryon v_2 measurement in heavy-ion collisions by ALICE



Low p_T: mass ordering, described by hydrodynamic models
High p_T: baryon/meson grouping (flow mostly driven by quark content (quark coalescence), not mass)



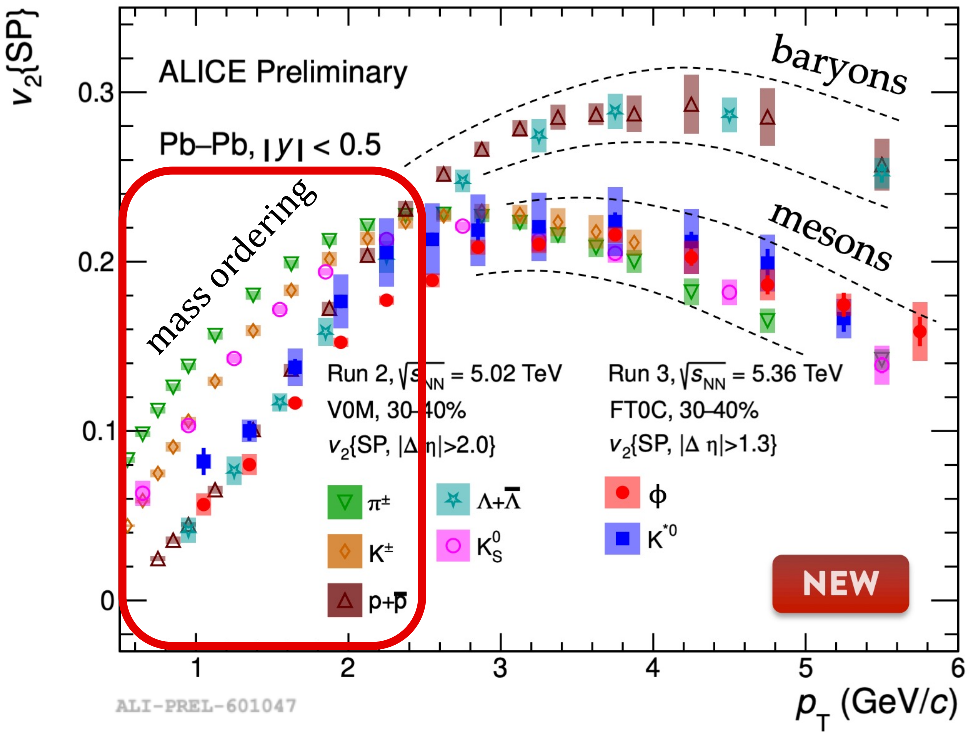
First evidence for charm baryon/meson splitting at high p_T
TAMU model with quark coalescence describes the trend

Anisotropic flow

Igor Altsybeev, Marcello Di Costanzo, Antonin Maire, Francesco Prino

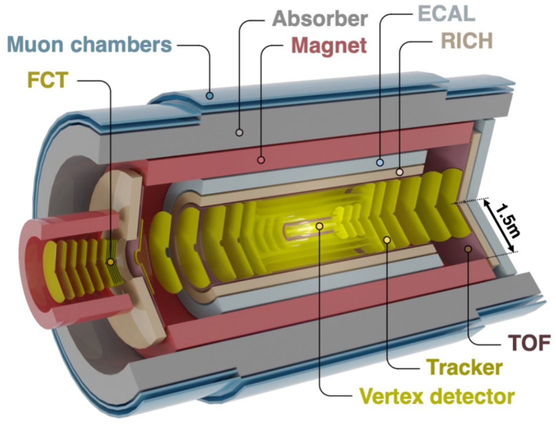
Transverse energy density profile in PbPb collisions at LHC has characteristic spatial fluctuations ("flow") quantified by Fourier harmonics v_n of particle distributions

Understanding of underlying thermalization process would benefit from low-p_T (< 1 GeV) data: well measured for light flavour hadrons, **but not yet for heavy flavour hadrons and baryons**

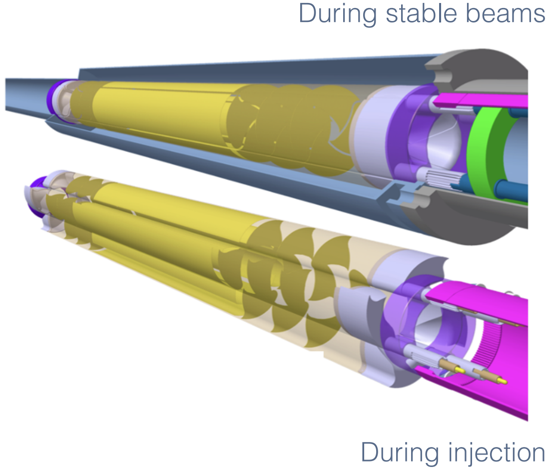


Low p_T: mass ordering, described by hydrodynamic models
High p_T: baryon/meson grouping (flow mostly driven by quark content (quark coalescence), not mass)

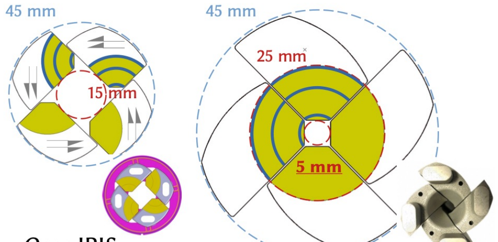
→ **ALICE3 upgrade**



ALICE3 detector model



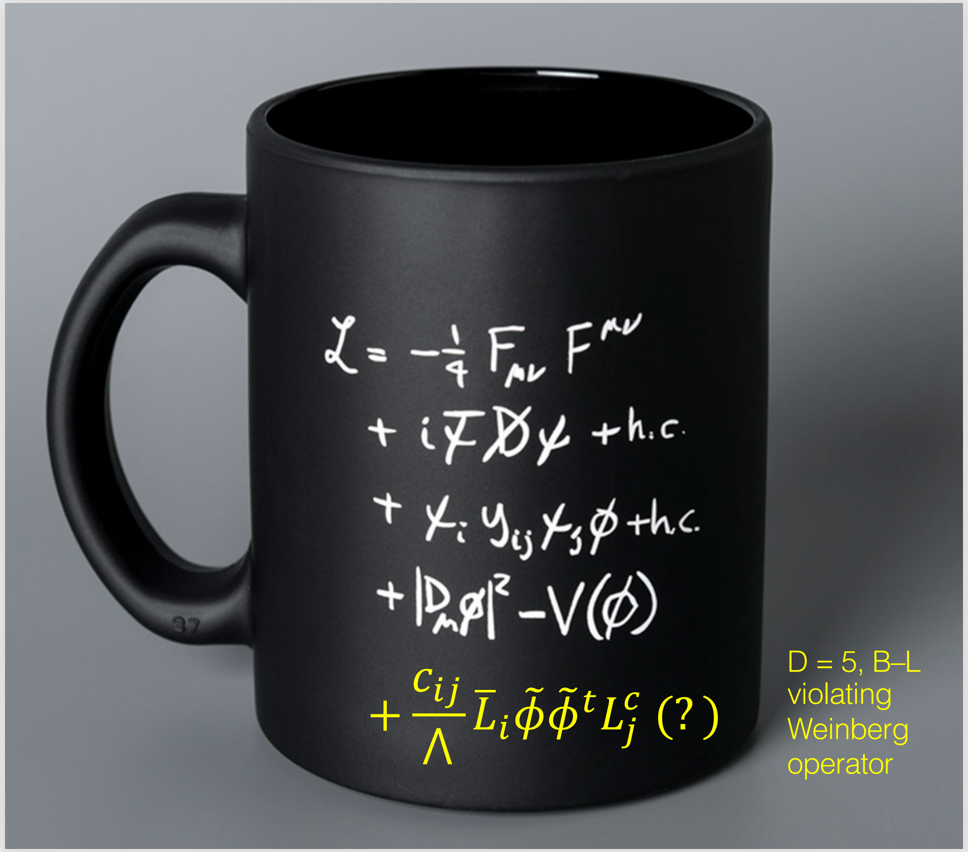
Retractable silicon vertex detector at 5 mm (15 mm during injection) from beam, giving < 10 μm pointing resolution for p_T > 200 MeV in high-multiplicity environment at ALICE3



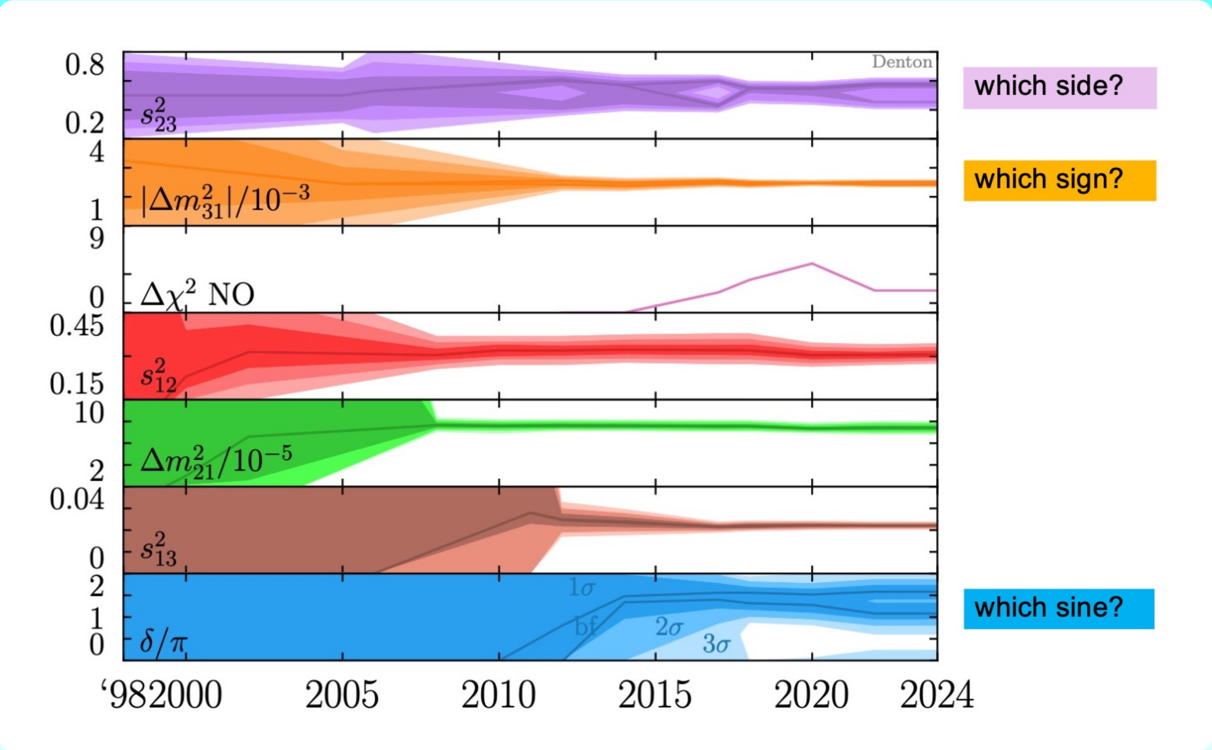
Open IRIS (injection)   *Closed* IRIS (stable beams)

Neutrinos


Kamioka, Japan


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
$+ \frac{c_{ij}}{\Lambda} \bar{L}_i \tilde{\phi} \tilde{\phi}^t L_j^c$ (?)
D = 5, B–L violating Weinberg operator

Neutrinos



Peter Denton, CIPANP 2025

Huge progress during the last 25 years since the discovery of neutrino oscillation — precise measurements of PMNS matrix elements (2.1 / 3.1 / 1.3% for $\theta_{12\,/\,13\,/\,23}$) and mass-squared differences (2.5 / 0.8% for $\Delta m^2_{21/3\ell}$)

The big remaining questions:

- Are neutrinos their own anti-particles (Majorana, lepton-number violating)?
- What is the neutrino mass ordering (normal or inverted)?
- What is the neutrino mass scale?
- How do neutrinos get their mass?
- Is there CP violation in neutrino sector?
- What can we learn about the N_R sector?
- What is the role of neutrinos in the early universe?

Neutrinos are also probes for astrophysical and cosmological phenomena, and for new physics (eg, neutrino portal)

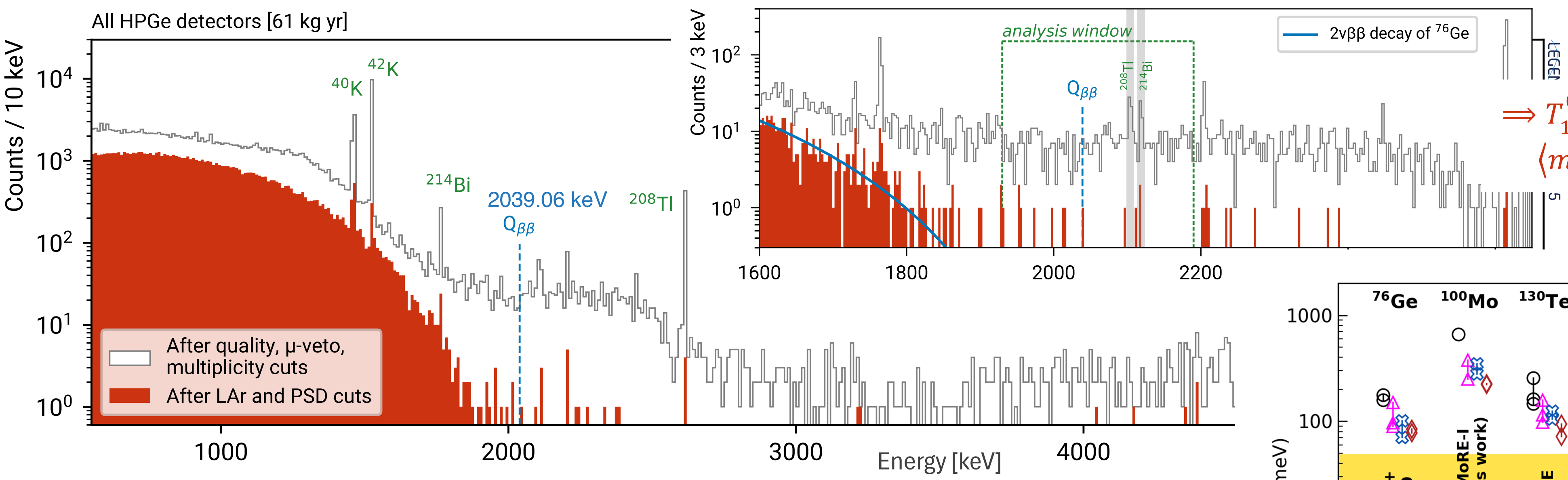
Mass nature of neutrinos

Enrique Fernández-Martínez, Giovanna Saleh, Kate Scholberg

Neutrinoless double β decay (ΔL = 2) — non-zero Majorana mass term and constraint on neutrino mass scale

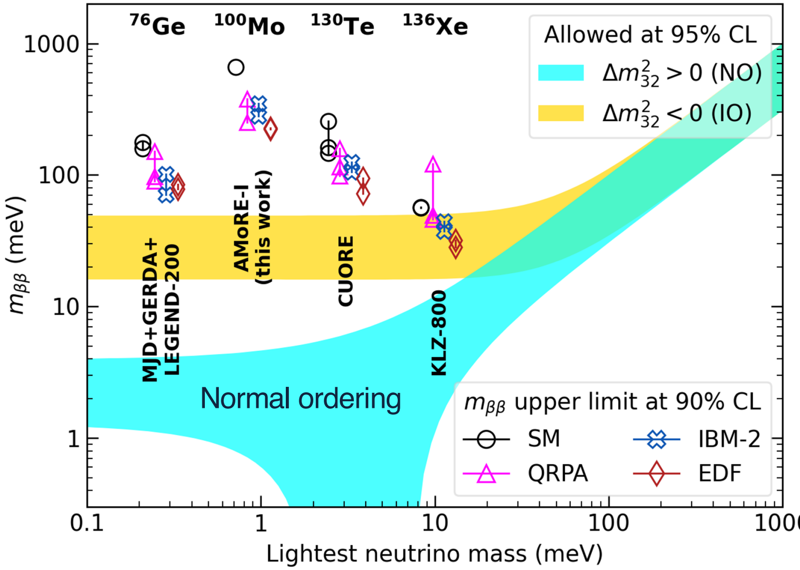
Use naturally occurring isotopes with energetically forbidden $\nu\beta$ but allowed $2\nu\beta\beta$ decays: 35 known candidates (^{136}Xe, ^{130}Te, ^{100}Mo, ^{76}Ge, ^{82}Se, …)
Several new results, here the first from 61 kg yr LEGEND-200 data (LNGS) using ${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + 2e^- + (2\bar{\nu})$, building upon GERDA

arXiv:2505.10440



$\Longrightarrow T_{1/2}^{0\nu\beta\beta} > 1.9 \cdot 10^{26}$ years
$\langle m_{\beta\beta} \rangle < 75\text{–}200$ meV

PRL 134, 082501 (2025)



Robust experimental program with next-gen ton-scale detectors to cover the IO band

Critical to further improve nuclear matrix element calculations and uncertainties (better agreement among groups since inclusion of short-range contributions)

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta}(Q^5, Z) \cdot \left|\boldsymbol{M^{0\nu\beta\beta}}\right|^2 \cdot \left|\langle m_{\beta\beta}\rangle\right|^2 \quad \text{where: } \left|\langle m_{\beta\beta}\rangle\right| = \left|\sum_\nu U_{e\nu}^2 m_\nu\right|$$

Accelerator neutrinos: long baseline

Katarzyna Kowalik, Kate Scholberg

Oscillation probabilities of ν_μ disappearance and ν_e appearance in ν_μ & $\bar{\nu}_\mu$ beams at L/E_ν ~ 500 km/GeV sensitive to mixing parameters, mass ordering, and CP violation (Neutrino beam characterised by near detector)

Long-term program: MINOS, K2K, OPERA (past, 2000–2015) → **T2K, NOvA (present, 2015–2028)** → Hyper-K, DUNE (future, 2028+)

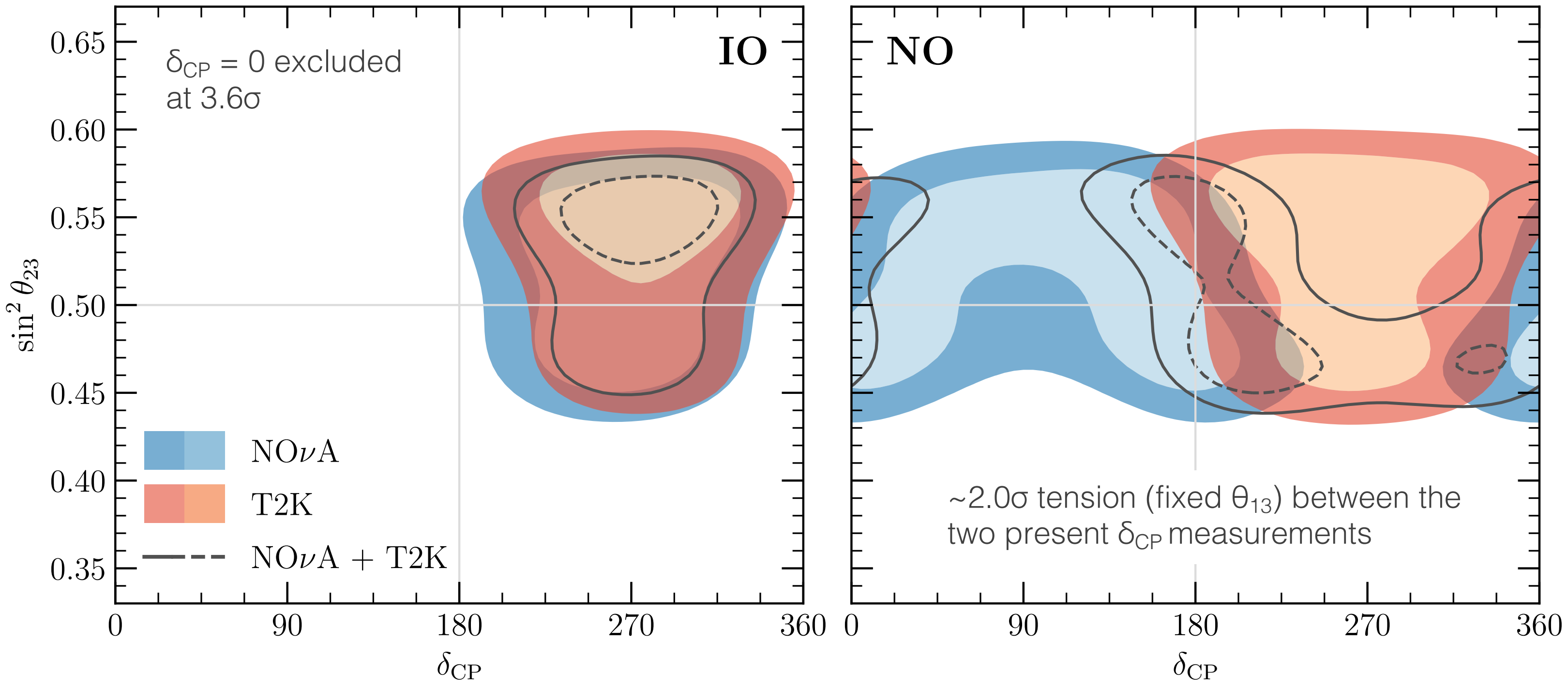
NOvA: 810 km / 2 GeV (0.8° off-axis NuMI beam, 1.0 MW in 2024), T2K: 295 km / 0.6 GeV (2.5° off-axis J-PARC beam, 0.76 MW), different matter & CP effects

NOvA and T2K released preliminary joint fit in 2024

Here, updated results from NuFit 6.0 (Oct 2024)

[arXiv:2410.05380]

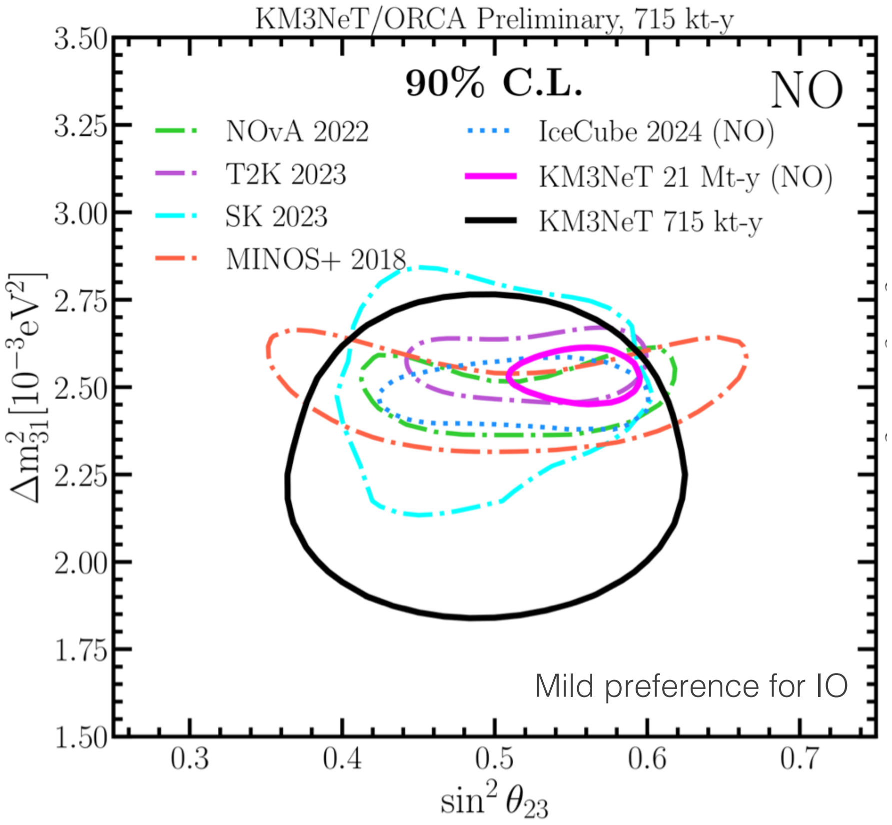
Both experiments have more data under analysis and continue running until end of 2026 (NOvA) and 2028 (T2K)



Atmospheric & high–E neutrinos

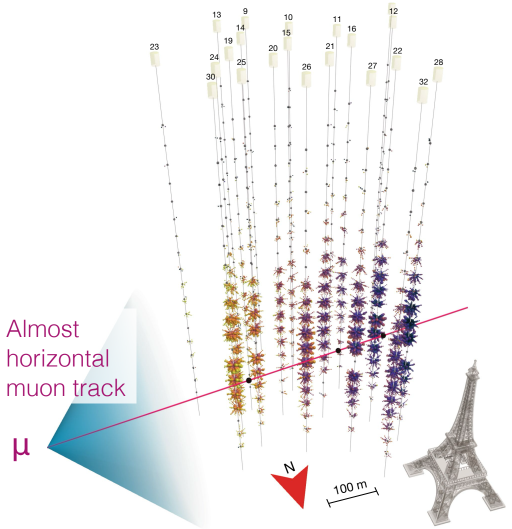
Victor Carretero, Annarita Margiotta, Kate Scholberg

KM3Net – ORCA (oscillation analysis): south of Toulon in Mediterranean sea. Status: 28 detection unit (DU) strings (25%), completion around 2028 (ORCA: 7 Mton seawater)



Collected 2.7 Mt-y of data in total, updated analysis expected soon

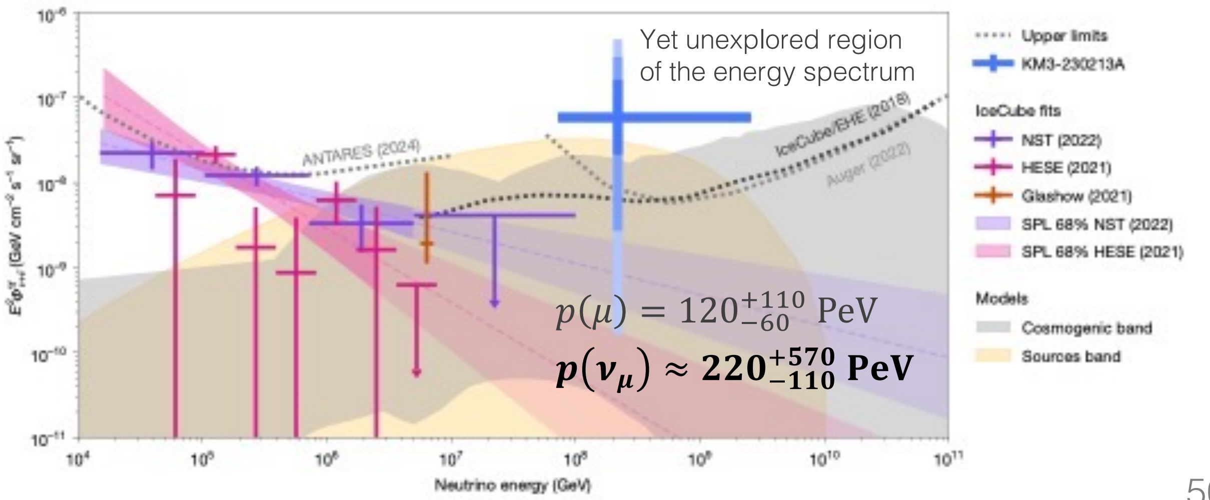
KM3Net – ARCA (high-E ν's): south-east of Sicily 3,450 m depth, 33 DUs (14%), big campaign to install ~20 additional DUs



Detected highest-energy neutrino ever measured

Hypotheses about origin:

- Galactic origin unlikely (no potential accelerators)
- Possibly Blazar (AGN with relativistic jets)
- Cosmogenic origin not excluded

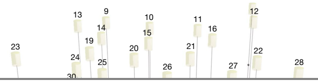


Atmospheric & high–E neutrinos

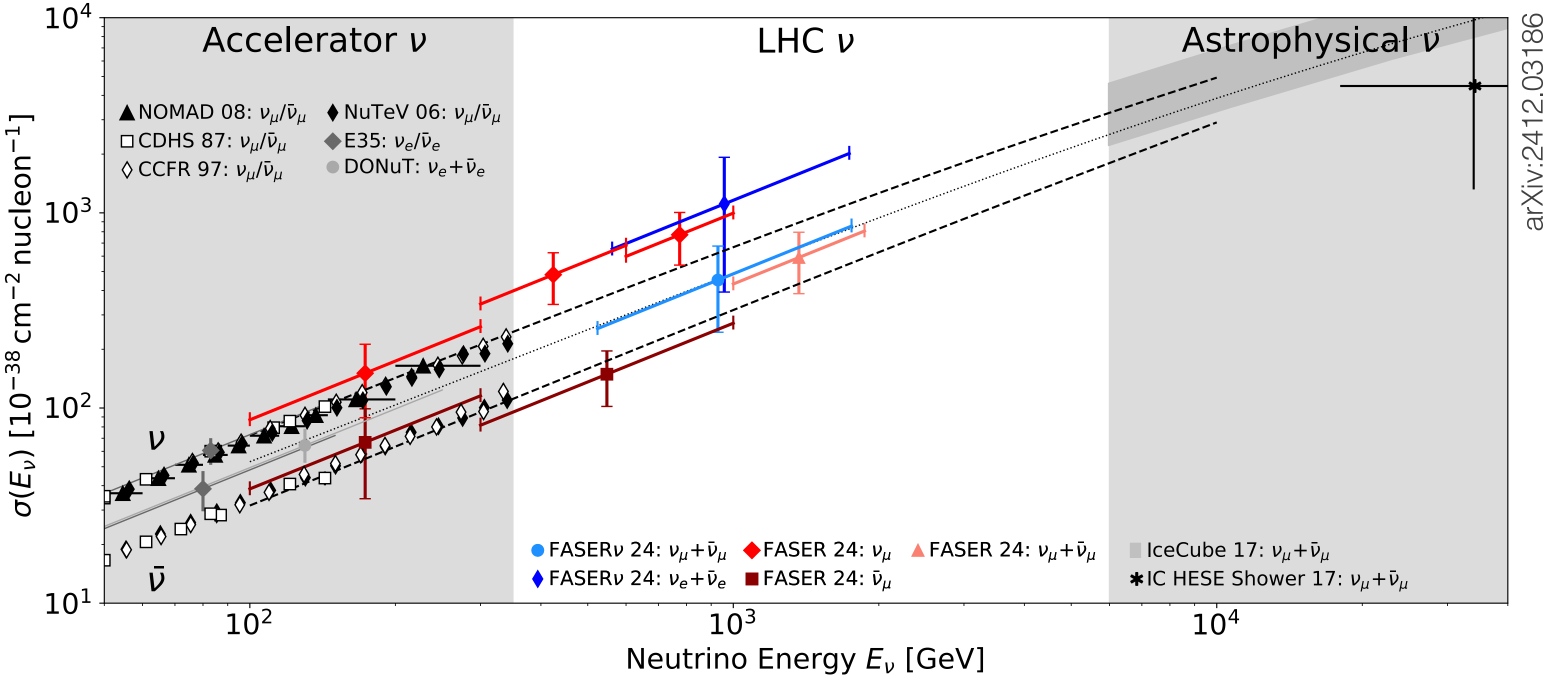
Victor Carretero, Annarita Margiotta, Kate Scholberg

KM3Net – ORCA (oscillation analysis): south of Toulon in Mediterranean sea. Status: 28 detection unit (DU) strings (25%), completion around 2028 (ORCA: 7 Mton seawater)

KM3Net – ARCA (high-E ν's): south-east of Sicily 3,450 m depth, 33 DUs (14%), big campaign to install ~20 additional DUs

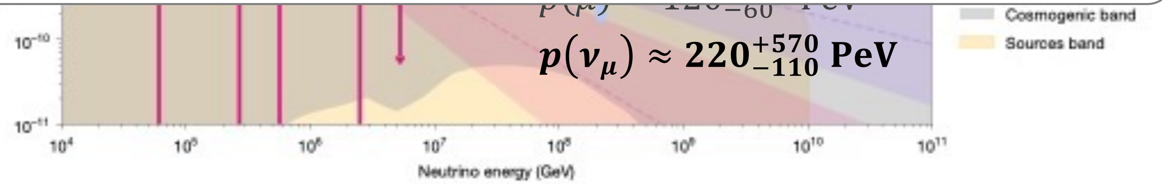


Above TeV energies, cosmic-ray neutrino backgrounds for astrophysical neutrino searches arise mainly from charm decays, whose flux and cross section can be measured at the LHC by FASER and SND



$\sin^2\theta_{23}$

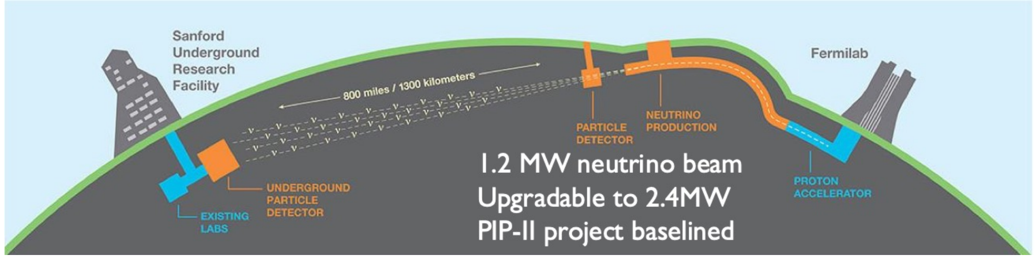
Collected 2.7 Mt-y of data in total, updated analysis expected soon



Upcoming large-scale experiments

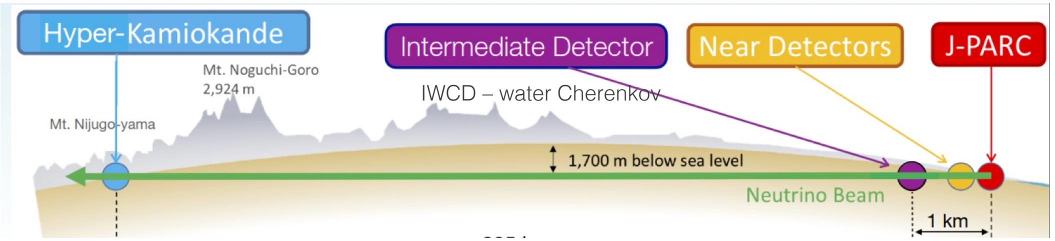
Justyna Łagoda, Laura Pérez Molina, Kate Scholberg, Runze Zhao

Long baseline accelerator and reactor experiments progressing with construction — amazing physics perspectives



LBNF/DUNE status (1,300 km baseline, 2–3 GeV ν energy beam, LAr-TPC)

- Excavation of far detector caverns at SURF completed April 2024
- Cryostat steel in South Dakota, vertical drift prototype operating at CERN
- Start beam in 2031 with staged approach

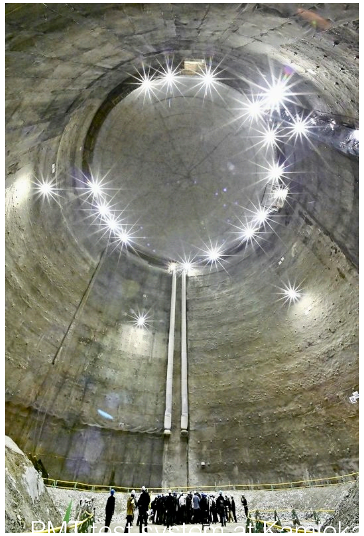


Hyper-Kamiokande status (295 km baseline, $\times$8 volume of Super-K, $\times$2.6 T2K beam power, new intermediate Water Cherenkov detector)

- Site excavation completed, > 10K of 20K PMTs delivered and tested
- 1.3 MW beam power by reducing cycle time, operation start in 2028

JUNO status (reactor ν detector)

- Medium baseline: 53 km from two reactors, mass ordering from precise measurement of fine $\overline{\nu}_e$ disappearance pattern
- 20-kton liquid scintillator (central detector) neutrino observatory located near Kaiping, southeast China
- Installation completing, commissioning ongoing, start of data taking end of 2025
- Challenge: control uniformity and response of gigantic detector



Upcoming large-scale experiments

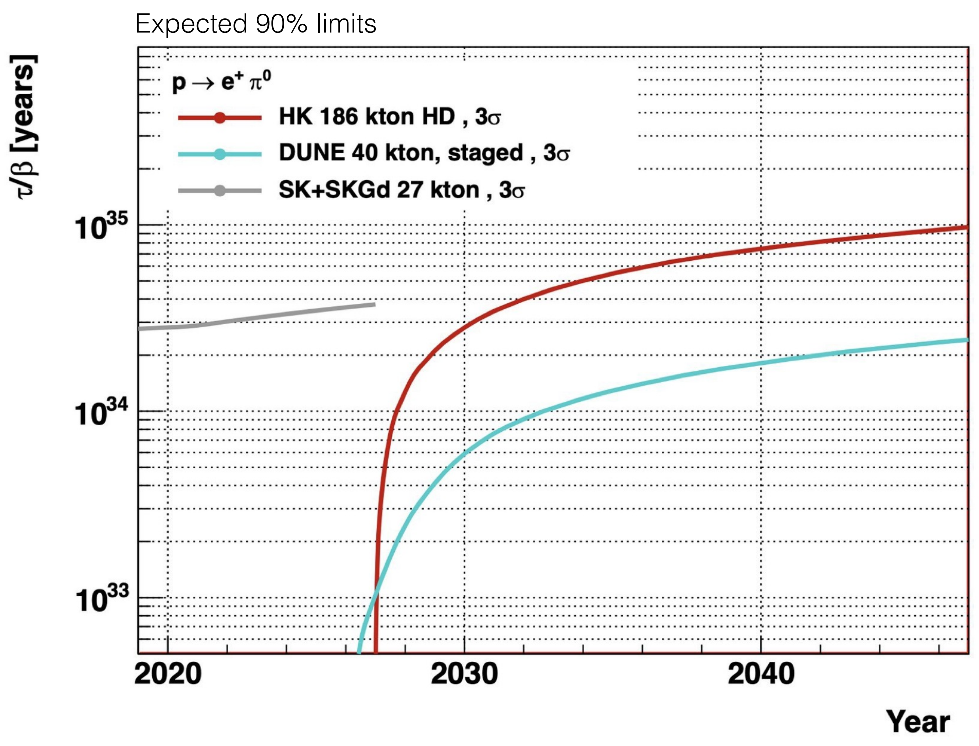
Justyna Łagoda, Laura Pérez Molina, Kate Scholberg, Runze Zhao

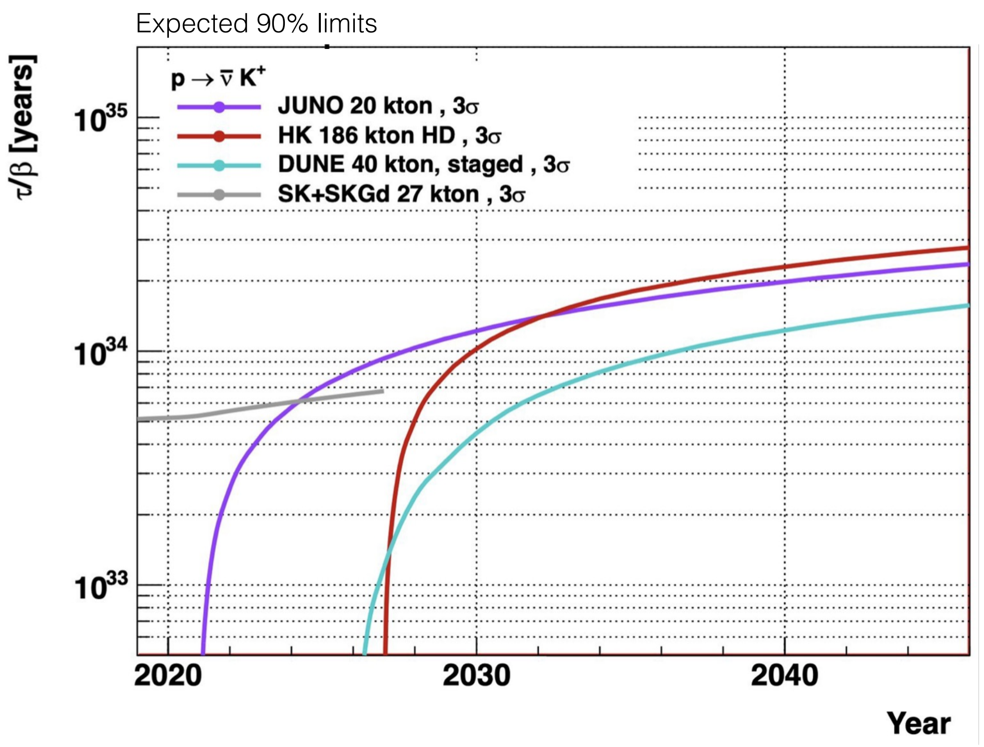
Large-scale long baseline accelerator and reactor experiments progressing with construction

Justyna Łagoda

These detectors will also have **significantly enhanced sensitivity to proton decay**

Hyper-K sensitivity to p → e+π^0 (3σ) decay in 20 years: 1×10^{35} yr (current SK limit: > 2.4×10^{34} yr)

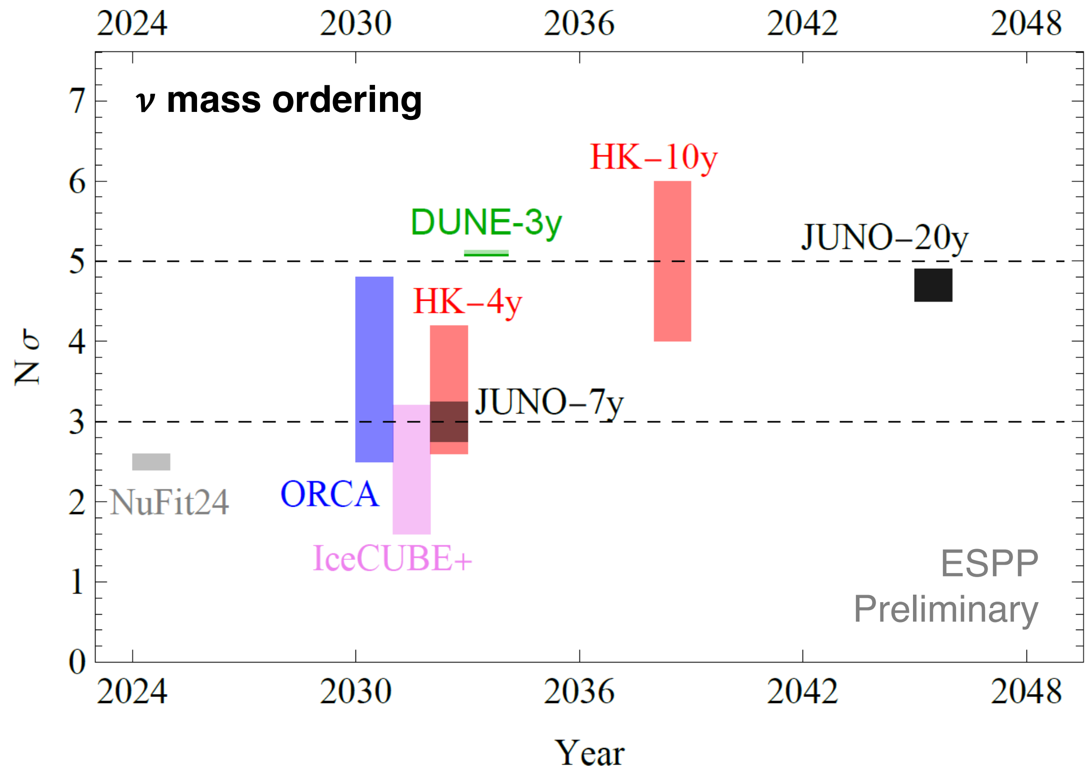


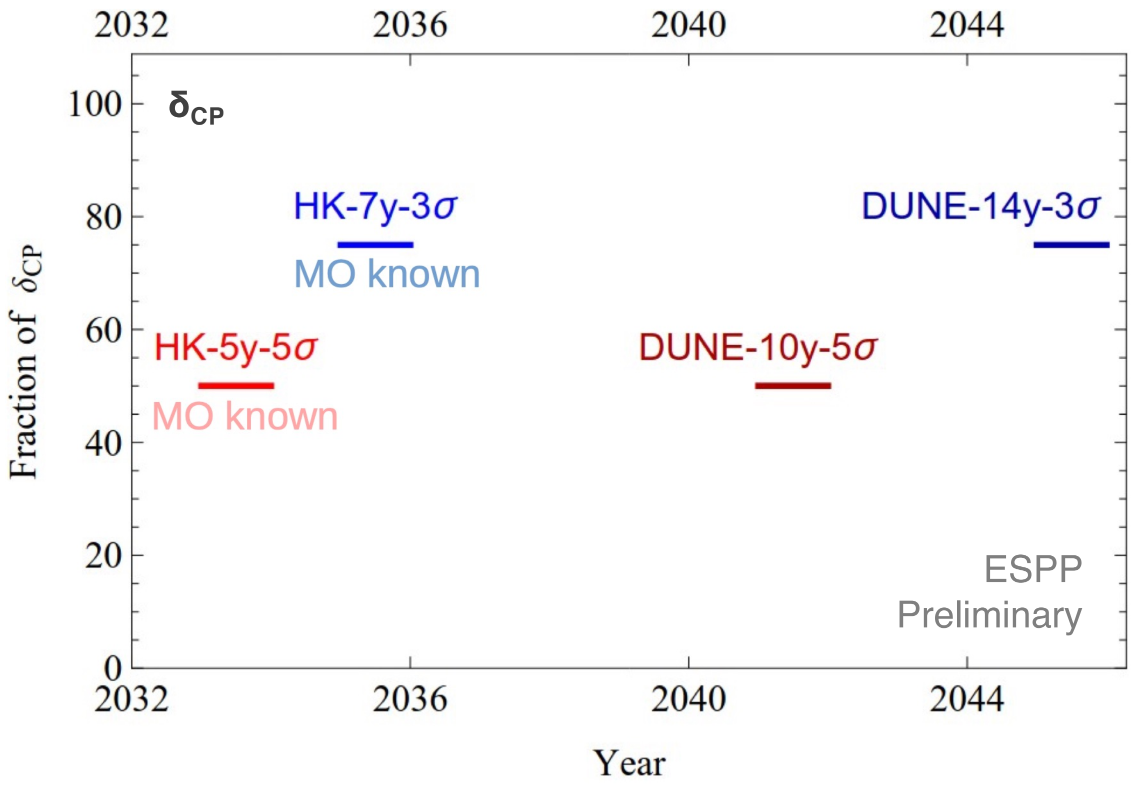


Neutrino mass ordering and CP violation

Pilar Hernandez

When will we know?





Vertical bar width due to uncertainty in PMNS elements, primarily θ_{23}

If CPV large, discovery in 2–4 years (starting 2030~2032) depending on systematics, but knowing MO is important in degenerate regions

If CPV small, systematics may be the ultimate limitation to discovery

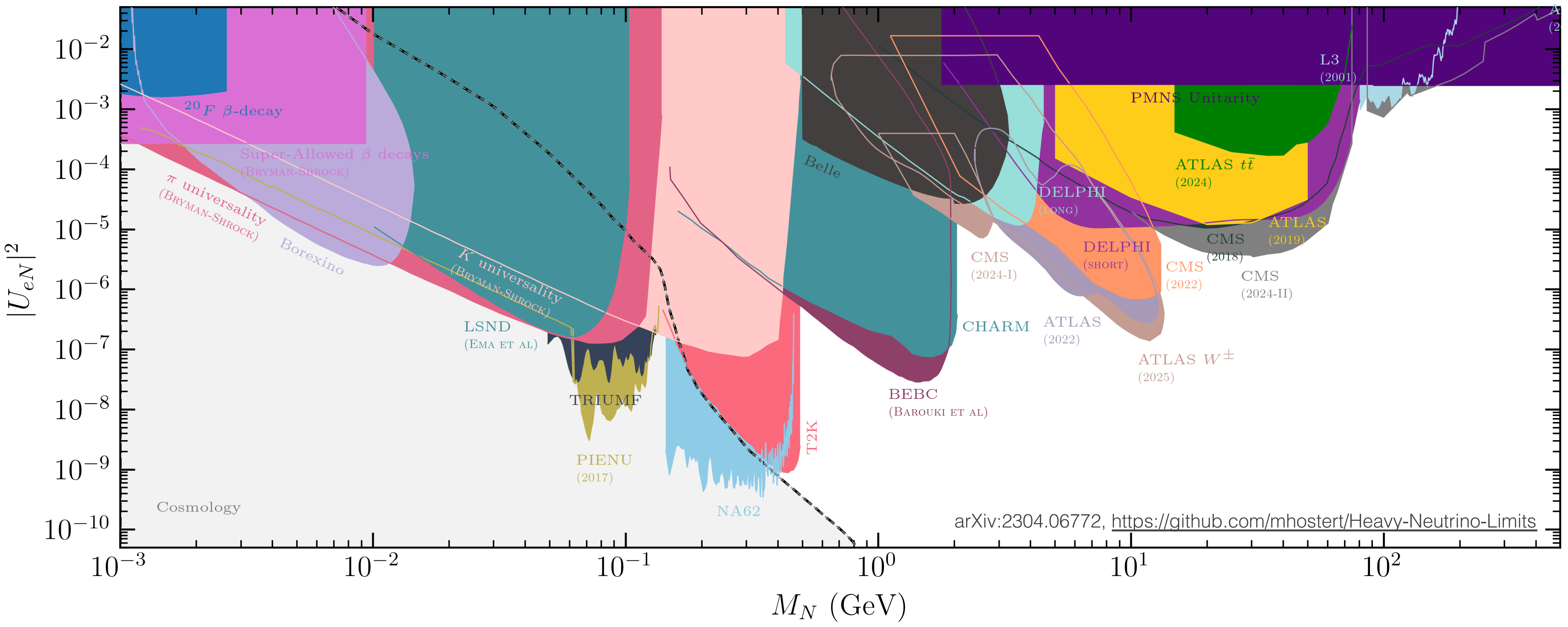
Right-handed neutrinos

Enrique Fernández Martínez

Simplest massive neutrino extension: add Majorana N_R to SM — basis of high-scale seesaw and leptogenesis scenarios

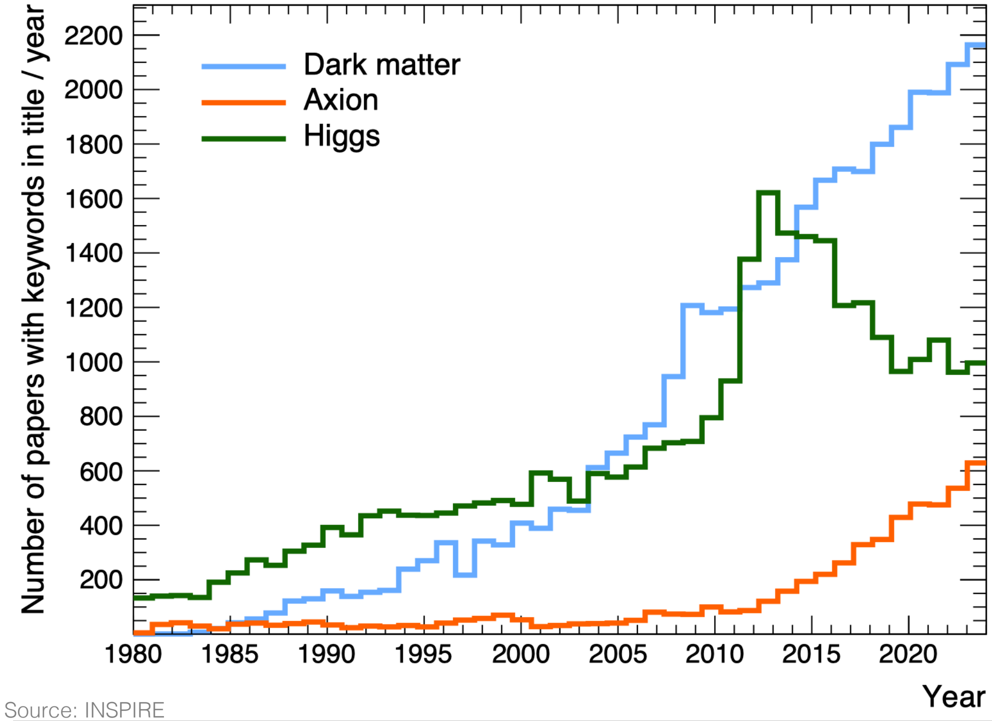
N_R do not need to be super heavy. With increasing mass, probed via direct searches (see below) and indirectly through PMNS unitarity, precision tests, flavour violation, as well as constrains from cosmology and 0νββ

← ν oscillation & kinks in β spectrum I meson decays peak searches I fixed target & collider searches I indirect probes →



Constraints on SM extension with single N_R that is SM singlet and mixes with ν_e

Dark matter & Axions



Source: INSPIRE

Overwhelming evidence of DM from gravitational observations at different times and scales
— *strong evidence for particle nature*

Huge range of possible forms across almost the entire mass scale (up to annihilation unitarity limit of ~100 TeV)

The DM sector may be complex!

“ DM is a fantastic particle physics problem with strong complementarity among the different experimental searches and phenomenological constraints, as well as the technological developments — it brings the communities together ”

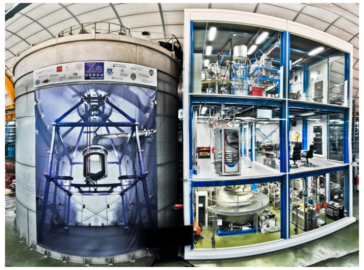
Dark matter halo — operating xenon experiments

Looking for nuclear recoil of target from elastic collision with dark matter particle

Paloma Cimental, Amy Cottle,
Clara Murgui Galvez

LUX-ZEPLIN (LZ) at SURF, South Dakota, USA , 7 t active mass

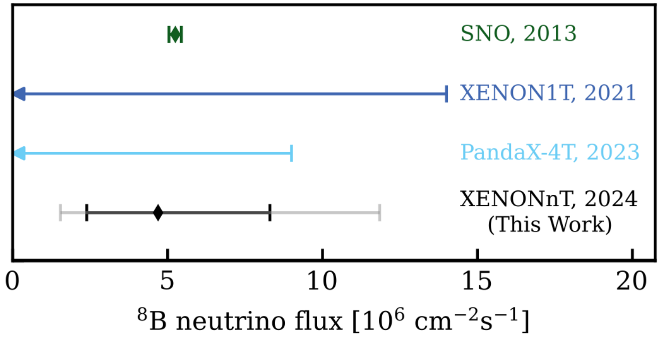
XENONnT at LNGS, Italy, 5.9 t active mass



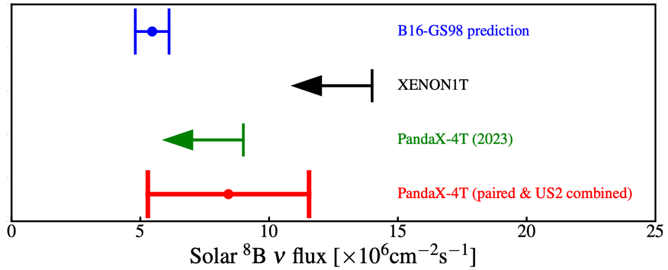
PandaX-4T at CJUL, China, 3.7 t active mass

XENONnT and PandaX-4T report first evidence of nuclear recoils from solar neutrinos (boron-8) with a dark matter detector

arXiv:2408.02877



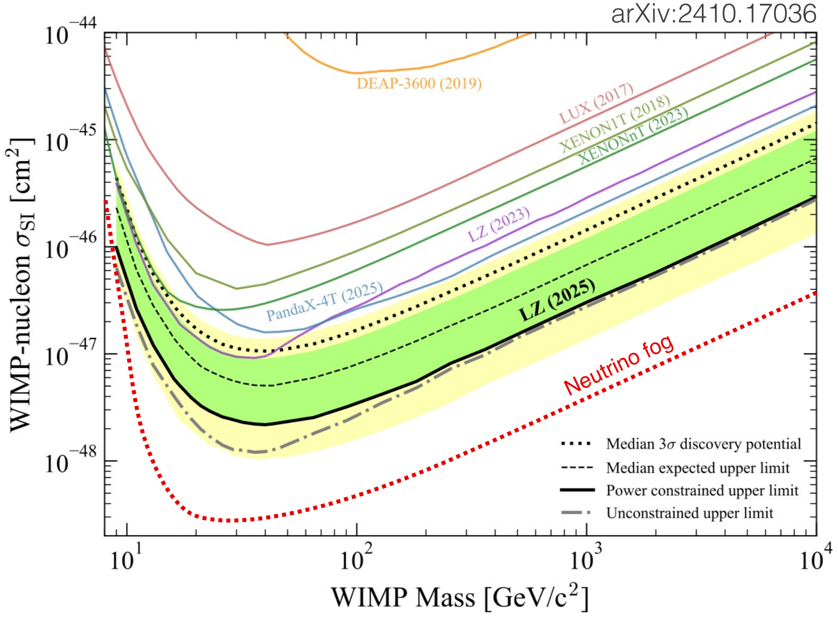
arXiv:2407.10892



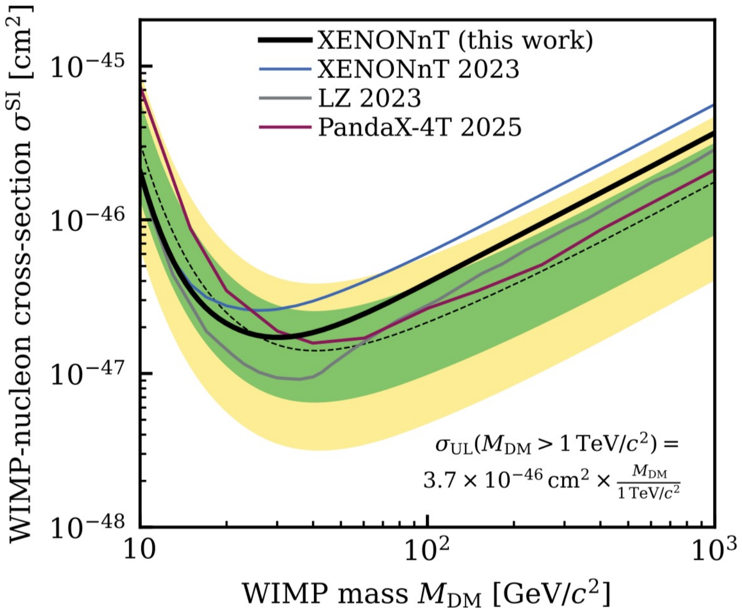
First detection of elastic NRs from astrophysical neutrinos, first measurement of the coherent elastic neutrino-nucleus scattering (CEνNS) process with Xe target, first step into the “neutrino fog” by DM experiment

Latest SI result with 4.2 t×yr exposure:
(LZ and XENONnT continue running until 2028)

arXiv:2410.17036



Latest SI result with 3.1 / 1.54 t×yr exposure for XENONnT [2502.18005] / PandaX-4T [2408.00664]:



Dark matter halo — future

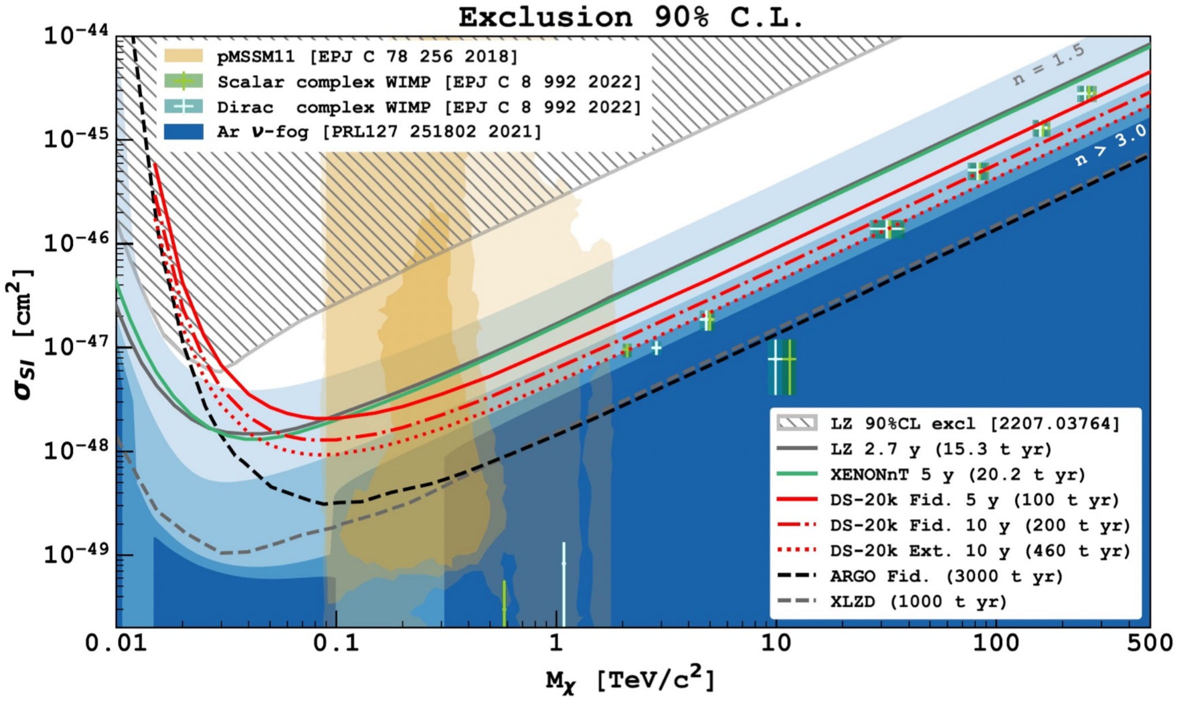
Zoe Balmforth, Clara Murgui Galvez

DarkSide-20k at LNGS, Italy, 50 (20) t active (fiducial) Ar mass, well advanced, begin data taking 2027/28

Global consortia projects

- **XLZD** (XENON, LZ, DARWIN), 60 t active Xe mass
- **ARGO** at SNPLAB (300 t fiducial)

These experiments will need to deal with neutrino fog



PandaX-xT at CJUL, China, staged growth of PandaX-T to 43 t fiducial Xe mass

All experiments include DM, $2\nu\beta\beta$, Supernovae alert, Sun ν, etc. in their physics programs

Axions

Clara Murgui Galvez, Fabrice Hubaut

QCD axion is primary target, but ALPs also possible; relic density suggests m_a ~ O(45 – 65) μeV ~ O(9 ~ 13) GHz

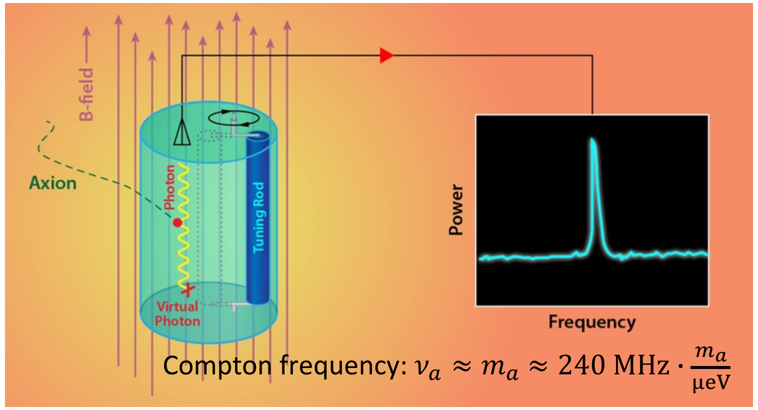
Large variety of operating and planned experiments!

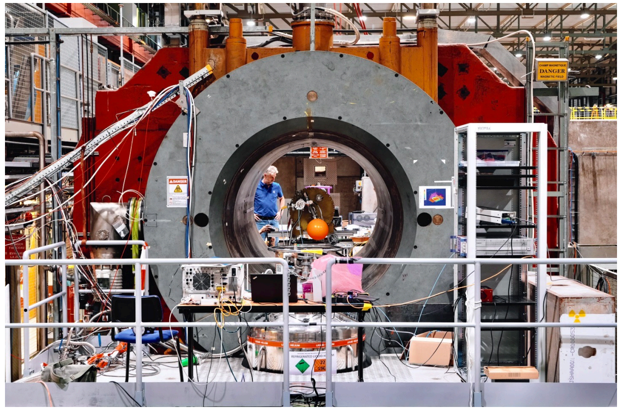
Haloscopes (relic axions)

Primakoff effect to resonantly convert axions to photons in a strong magnetic field

Signal power $\propto g_{a\gamma}^2 \cdot V \cdot B^2$

Cryoenic environment O(100 mK) to minimise thermal noise, ultra-low-noise amplifier, quantum sensing





MADMAX prototype at CERN

Helioscopes (solar axions)

IAXO (DESY, prototype BabyIAXO under construction): meV ~ eV mass range

Light shining through wall (lab axions)

ALPS, ALPS-II (DESY
OSQAR (CERN)
…

Tuneable high-Q microwave cavity resonator (challenge: high mass → small cavity)

ADMX (B = 7.6 T, Seattle) [new result: arXiv:2504.07279]
HAYSTAC (8 T, Yale) [new result: arXiv:2409.08998]
QUAX (8.1 T, Frascati)
CAST-CAPP (8.8 T, CERN)
RADES (11.7 T, CERN)
…

New concepts (future):

MADMAX (DESY, dielectric disks to boost axion signal)

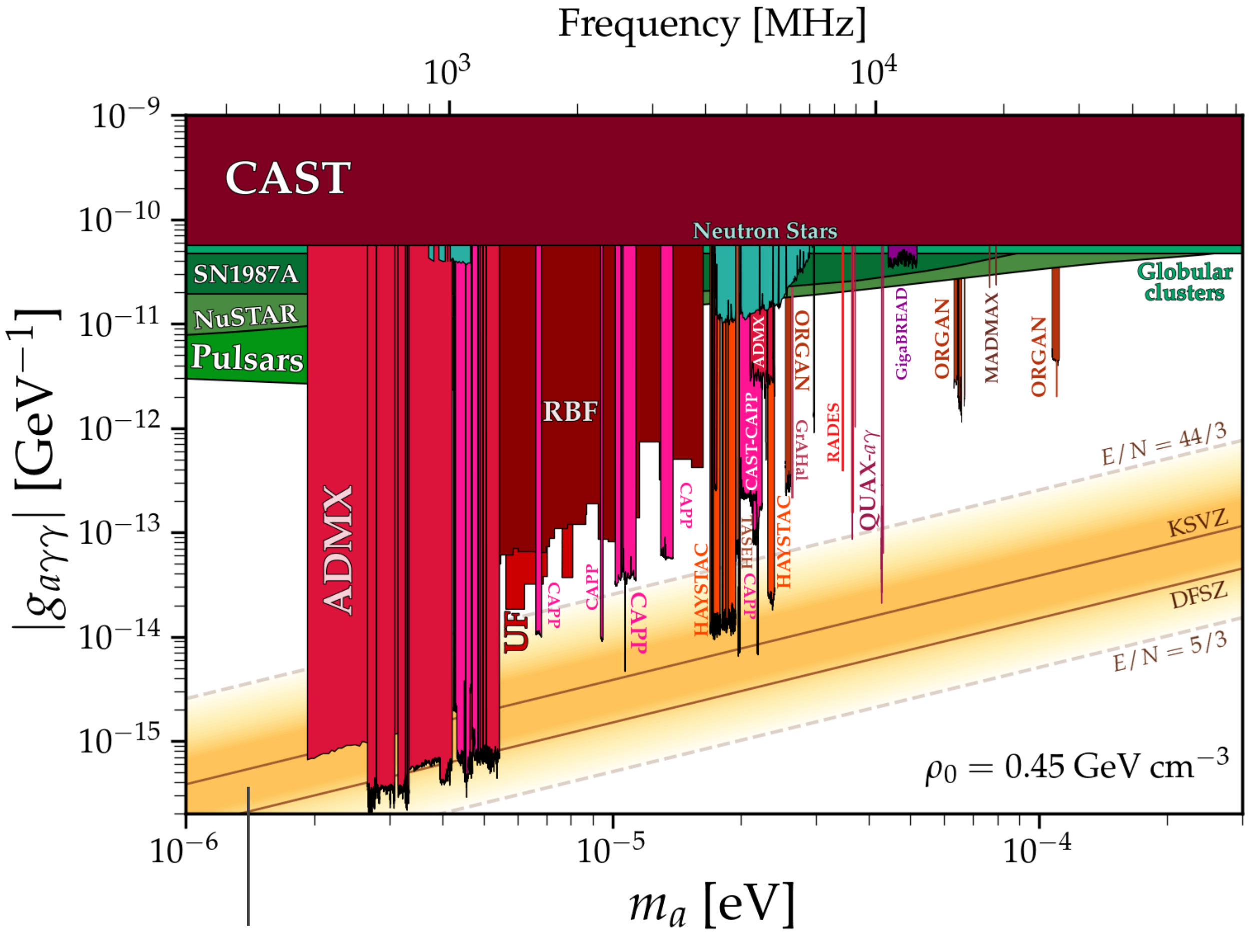
ALPHA (Yale, plasmonic resonance via multiple thin wires)

In both concepts, spacing of disks / wires determines resonance frequency

Axions

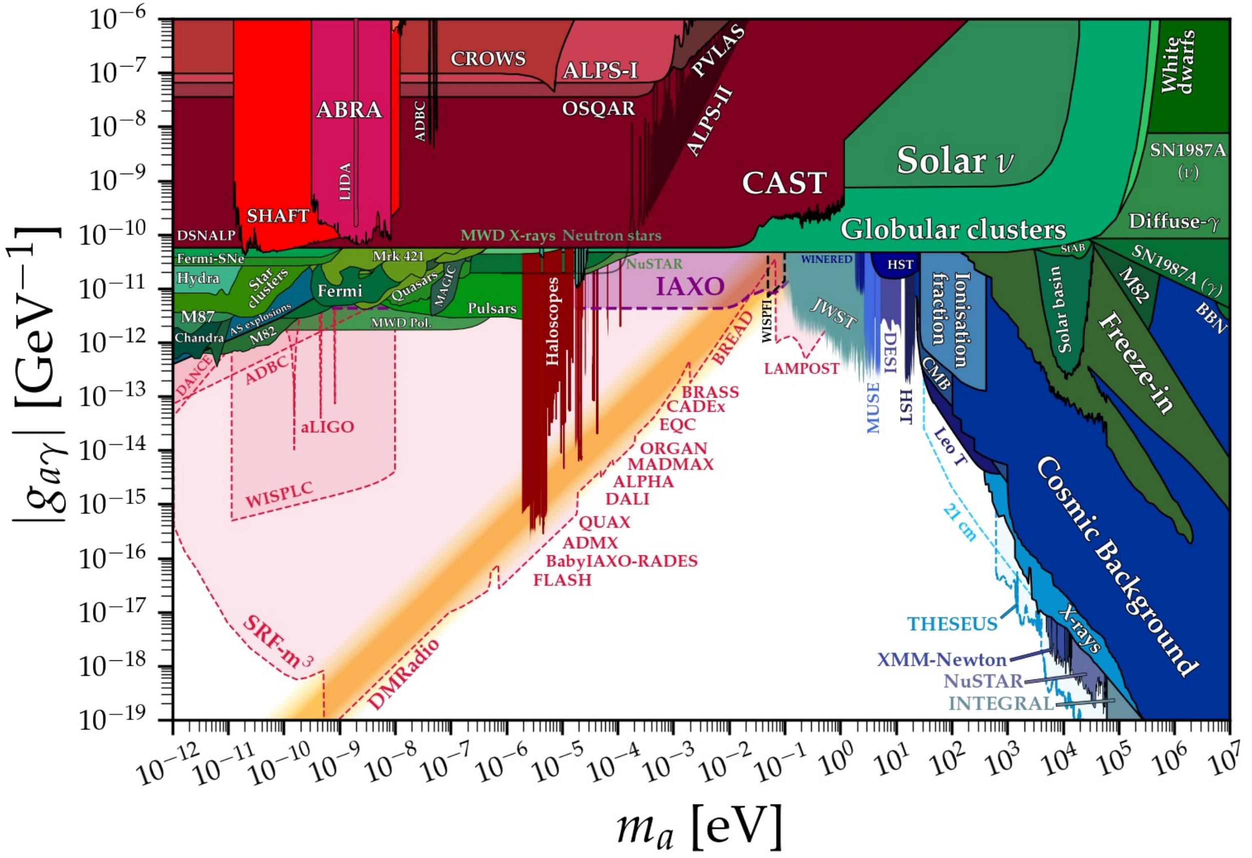
Clara Murgui Galvez

Current status (Helioscopes closeup) and future (full range) — very encouraging, but more work ahead!



$g_{a\gamma\gamma} \sim m_a/\Lambda^2_{QCD}$

Cioran O'Hare [Link to figures]

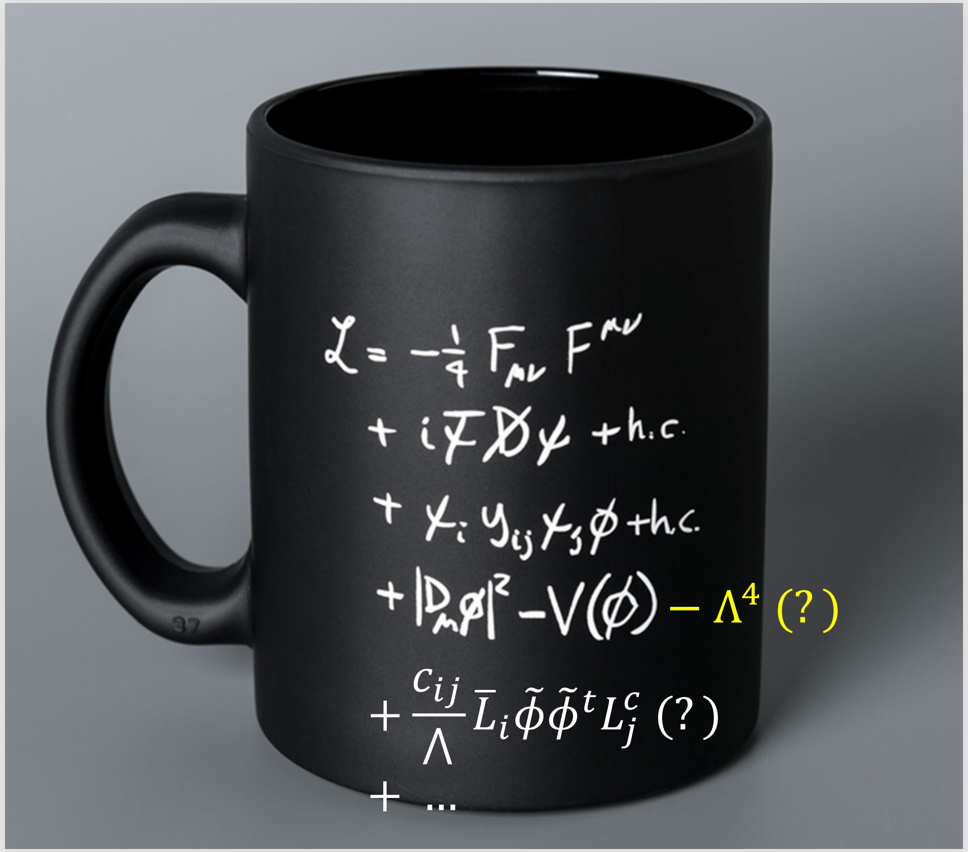


Gravitational Waves and Cosmology

ΛCDM is a remarkable six-parameter model describing 13.8 B years of cosmic evolution: from inflation over CMB anisotropies to large-scale structure formation, SN Ia observations, and today's energy density

It achieves this without a clue about the nature of DM and dark energy, and the mechanism for inflation. ΛCDM assumes a cosmological constant dark energy (Λ) with energy density that is constant in space and time

But there are some troubling signs…



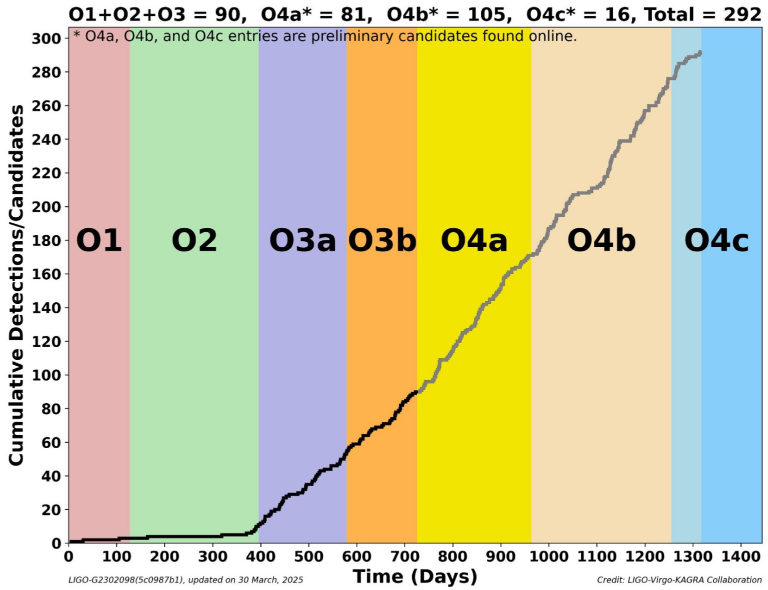
Gravitational waves (GW)

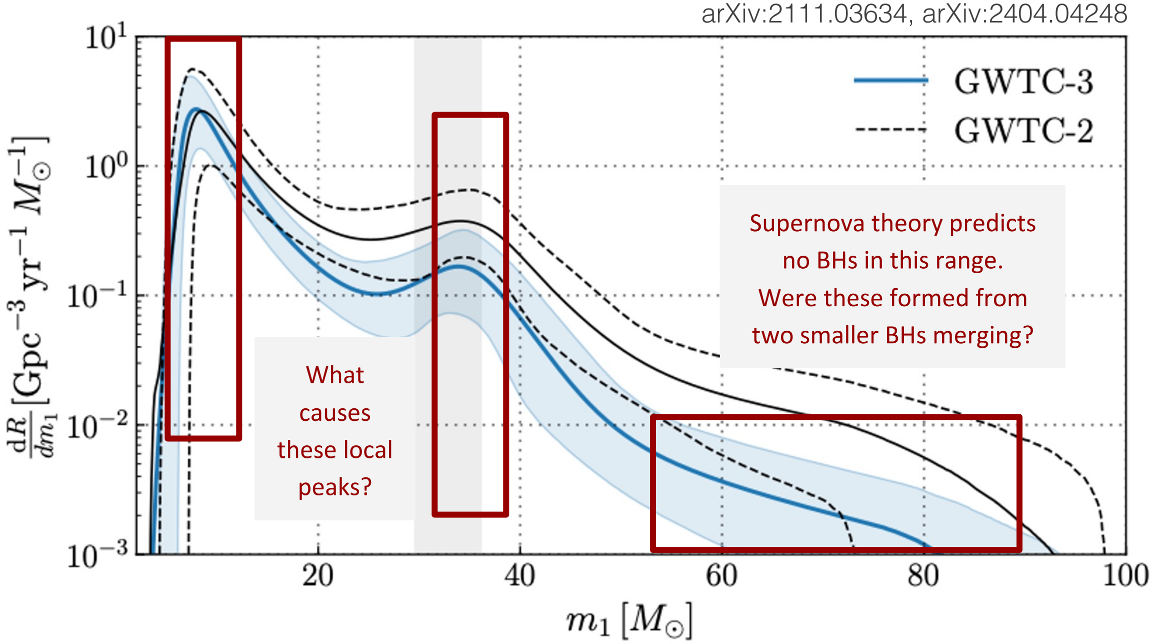
Antoine Petiteau, Aditya Vijaykumar

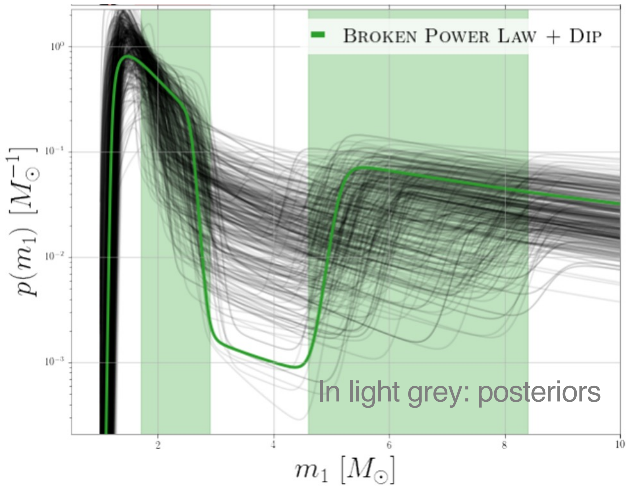
arXiv:2111.03634, arXiv:2404.04248

Total of 292 GW events detected (and continuing), GW science is becoming statistical

Basic distributions such as mass and mass differences of binary mergers under scrutiny





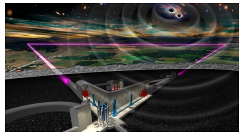


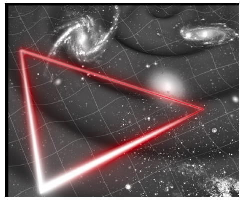
Top: Distributions deviate from smooth power law seen in stars more massive than the Sun

Left: Electromagnetically detected compact objects show "gap" (i.e. no objects) between ~2 Msun and ~5 Msun

With GWs, there is small but nonzero rate in this region (could be of exotic origin)

With **Einstein** and **Cosmic Explorer** expect to collect > 10^5 BH-BH, BH-NS, and NS-NS merger events





Extraordinary scientific potential also with **LISA** (3 spacecrafts on heliocentric orbits separated by 2.5 millions km) in the 0.02 mHz ~ 1 Hz range. Approved and under construction. Expected launch: 2035

Gravitational waves (GW)

Antoine Petiteau, Jishnu Suresh, Sonali Verma

Evidence for stochastic gravitational wave background in the nHz range
by four groups analysing radio astronomy pulsar (dense neutron stars) data (Pulsar Timing Array experiments)

Astro versus Cosmo

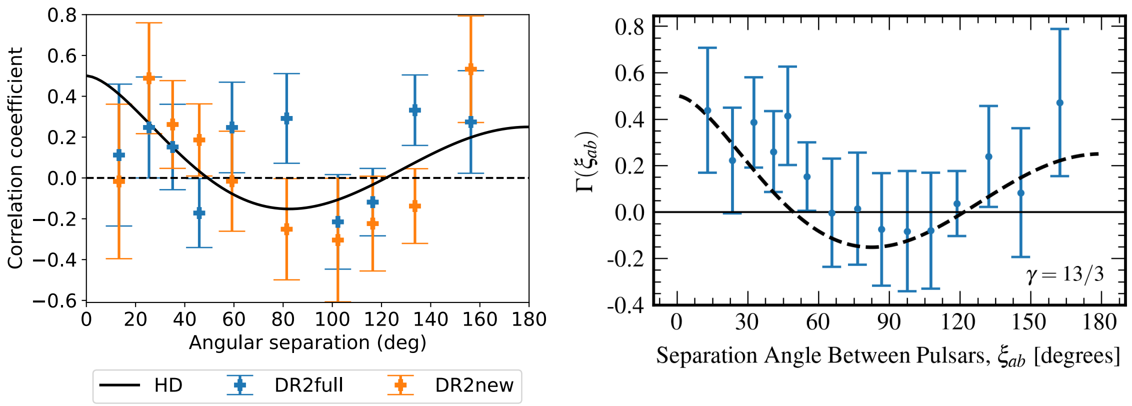
The stochastic background could be produced by many close-by (~ light-day) pairs of supermassive black holes orbiting each other due to earlier galaxy mergers in the hearts of distant galaxies [link]

It could also be stochastic background from cosmological origin: first order phase transition, cosmic strings, primordial black holes, …

Important to understand astrophysical stochastic background before probing the cosmological one

Illustration of gravitational waves caused by orbiting supermassive black hole pairs [found here]

For an isotropic GW background, characteristic spatial correlation (Hellings-Down curve) — tricky analysis



Angular-separation–binned inter-pulsar correlations, The dashed black line shows the Hellings–Downs correlation pattern [Left: arXiv:2306.16214, right: arXiv:2306.16213]

Both collaborations find ~3σ evidence, but significance is noise model dependent.
Important to analyse the combined data (IPTA) to better understand the signal

Articles: arXiv:2306.16213, 2306.16214, 2306.16215, 2306.13611, Nature news1, news2

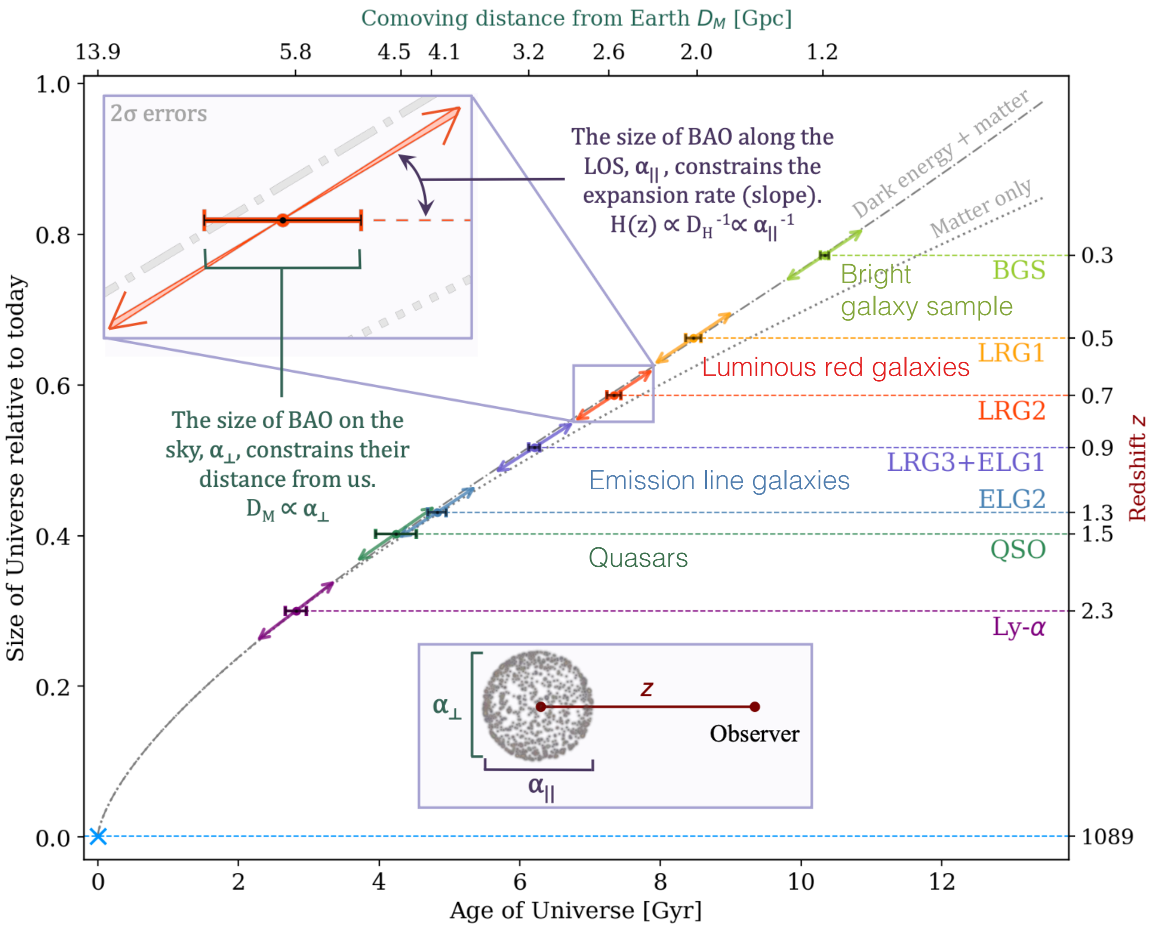
Is dark energy weakening?

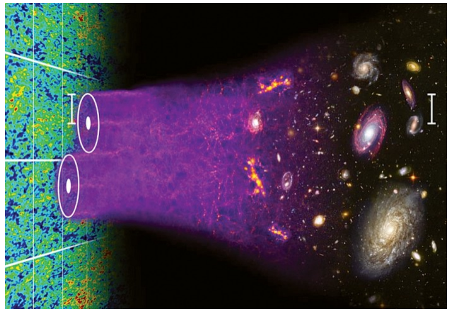
Julian Bautista, Camille Bonvin, Adrien La Posta

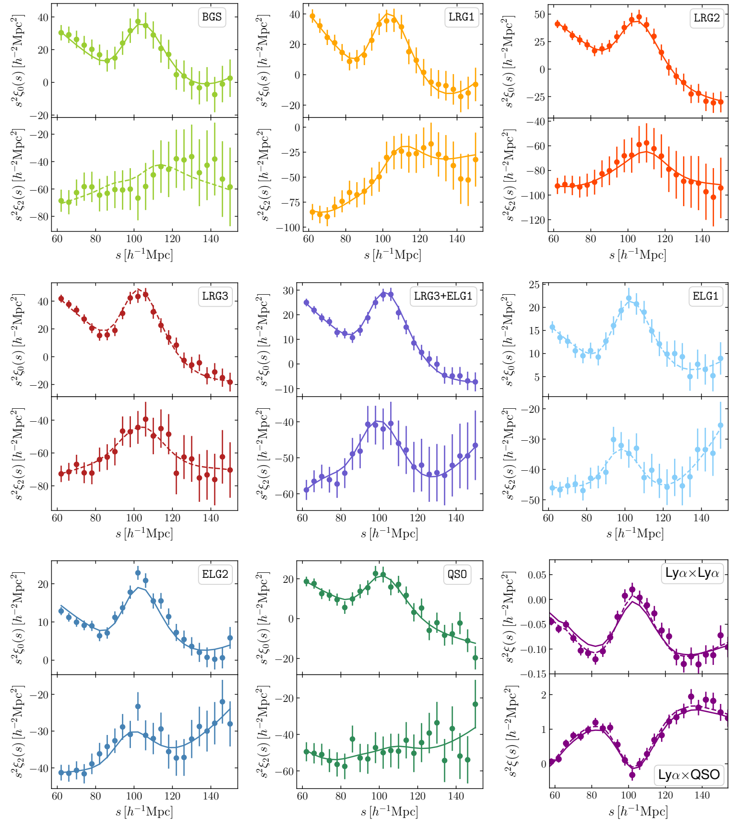
DESI DR2 (3 years) results on Baryon Acoustic Oscillation (BAO) — standard cosmological ruler (~ 150 Mpc today)

~14 million redshifts analysed (~40 million to come)

arXiv:2503.14738







Left: illustration how DESI BAO measurements constrain the expansion history of the Universe

Right: monopole (top) and quadrupole (bottom) moments of measured correlation functions of galaxies and quasars (last is autocorrelation of Lyα forest)

Is dark energy weakening?

Julian Bautista, Camille Bonvin, Adrien La Posta

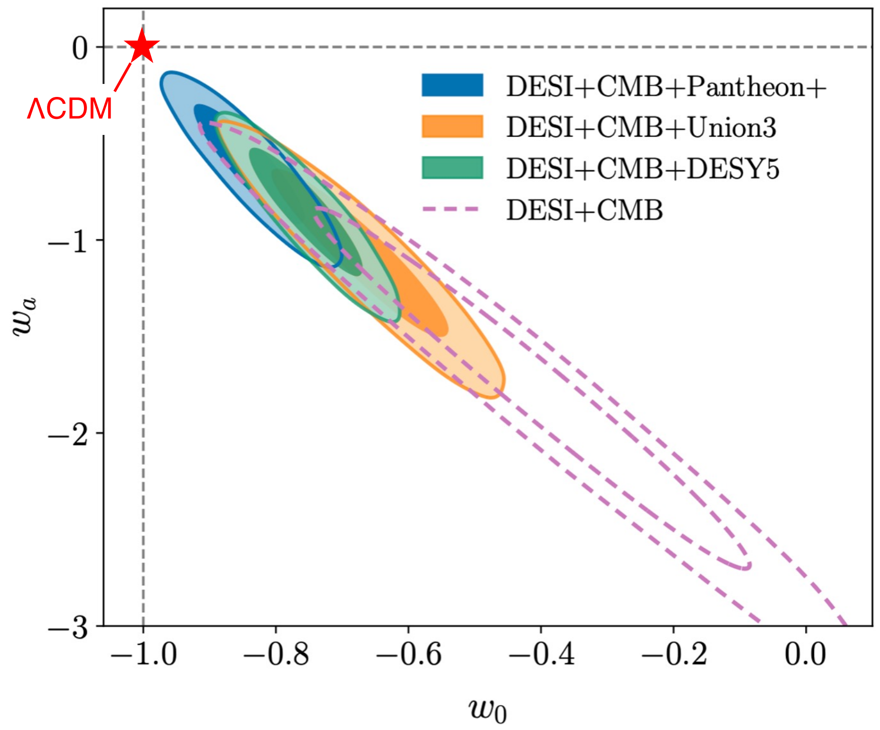
DESI DR2 (3 years) results on Baryon Acoustic Oscillation (BAO) — standard cosmological ruler (~ 150 Mpc today)

~14 million redshifts analysed (~40 million to come)

Evolving EOS model:
$\omega(a) = \omega_0 + \omega_a(1 - a)$

($p = \omega\rho$. ΛCDM (const. neg. press.) if $\omega_0 = -1$, $\omega_a = 0$, $a = (1+z)^{-1}$)

arXiv:2503.14738



Main conclusions from cosmological analysis:

- 2.3σ tension among ΛCDM fits of BAO and CMB data
- 3.1σ evidence for dynamical dark energy from DESI+CMB
- Adding SNe, discrepancy of 2.8–4.2σ, depending on data used
- All datasets favour $\omega_0 < -1$ and $\omega_a < 0$, indicating weakening dark energy today
- No indication of deviation from General Relativity

However:

- $\omega < -1$ hard to achieve with standard dark energy models; perhaps exotic dark energy or modification of gravity
- Models other than ΛCDM are strongly constrained
- CMB alone sees no deviation from ΛCDM (Planck, ACT)

Is dark energy weakening?

Julian Bautista, Camille Bonvin, Adrien La Posta

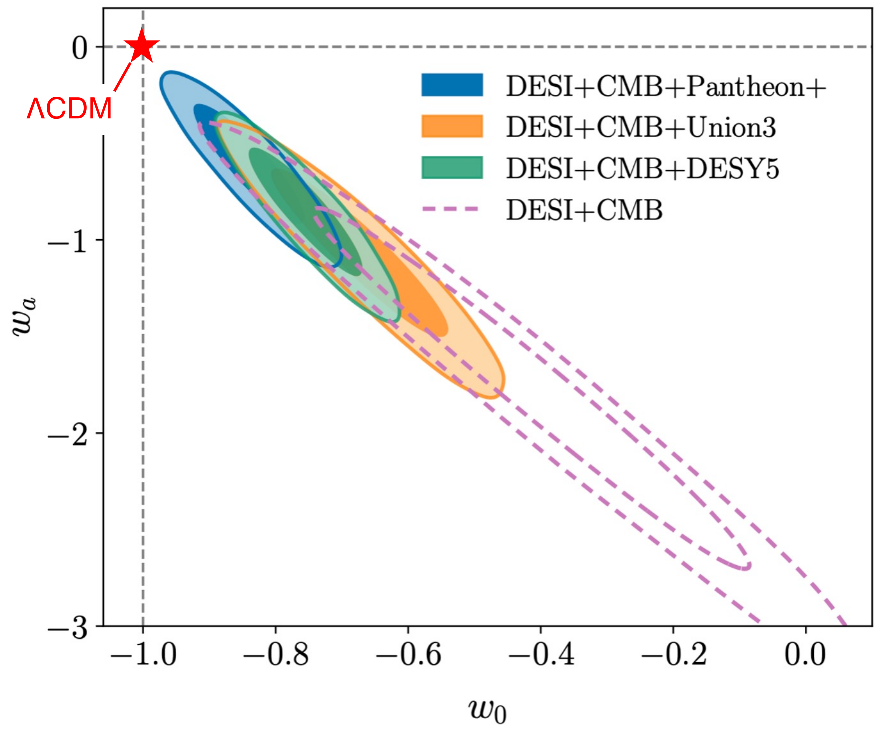
DESI DR2 (3 years) results on Baryon Acoustic Oscillation (BAO) — standard cosmological ruler (~ 150 Mpc today)

~14 million redshifts analysed (~40 million to come)

Evolving EOS model:
$\omega(a) = \omega_0 + \omega_a(1 - \mathrm{a})$

($p = \omega\rho$. ΛCDM (const. neg. press.) if $\omega_0 = -1$, $\omega_a = 0$, $a = (1-z)^{-1}$)

arXiv:2503.14738



Main conclusions from cosmological analysis:

- 2.3σ tension among ΛCDM fits of BAO and CMB data
- 3.1σ evidence for dynamical dark energy from DESI+CMB
- Adding SNe, discrepancy of 2.8–4.2σ, depending on data used
- All datasets favour $\omega_0 < -1$ and $\omega_a < 0$, indicating weakening dark energy today
- No indication of deviation from General Relativity

However:

- $\omega < -1$ hard to achieve with standard dark energy models; perhaps exotic dark energy or modification of gravity
- Models other than ΛCDM are strongly constrained
- CMB alone sees no deviation from ΛCDM (Planck, ACT)

Hubble tension:

Did new physics alter the sound horizon in the early universe (used to calibate both CMB and BAOs)?

H_0 = (68.50 ± 0.58) km s^{-1} Mpc^{-1} (DESI + BBN)

H_0 = (67.4 ± 0.5) km s^{-1} Mpc^{-1} (CMB)

H_0 = (73.17 ± 0.86) km s^{-1} Mpc^{-1} (SN Ia, SH0ES*)

} > 5σ tension

Very difficult analysis, not the final word

*SHoES: Hubble telescope measurement based on SN Ia's luminosity-calibrated against intermediate-distance cepheids, which are calibrated against 4 nearby "geometric anchors" whose distance is known

JWST with better resolution will provide further clues

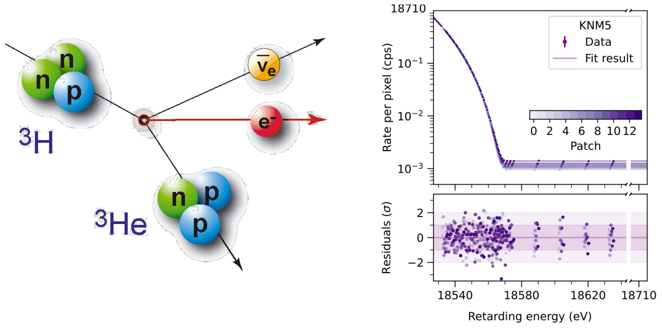
Absolute neutrino masses and mass ordering

Julian Bautista, Enrique Fernández Martínez, Adrien La Posta

Best current direct limit $m_{\nu_e} < 450$ meV (KATRIN 2024 at 90% CL, using high-activity tritium source and precision spectroscopy of β-decay close to kinematic endpoint)

Solid / model-independent

arXiv:2406.13516

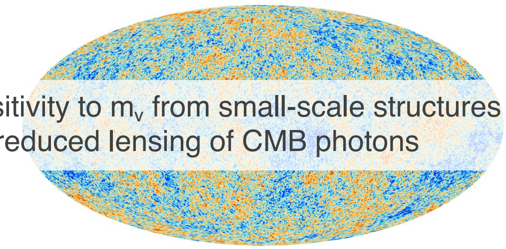


$0\nu\beta\beta$ limit: $|\sum_\nu U_{e\nu}^2 m_\nu| < 28\text{–}122$ meV (KamLAND-Zen at 90% CL, assuming mediation by light Majorana neutrinos)

Cosmological limits (95% CL):

$\sum_\nu m_\nu < 89_{\Lambda\mathrm{CDM}}$ meV (CMB (Planck, ACT))

$\sum_\nu m_\nu < 53_{\Lambda\mathrm{CDM}}$ $(< 177_{\omega_0\omega_a\mathrm{CDM}})$ meV (CMB & BAO (DESI DR2), mild tension strengthens limit)



Sensitivity to m_ν from small-scale structures and reduced lensing of CMB photons

Why never a hint on $m_{\nu_e} > 0$ from cosmology?
Planck 2018 (and WMAP) “increased lensing” anomaly pushes $m_{\nu_e} < 0$, effect reduced in subsequent analyses

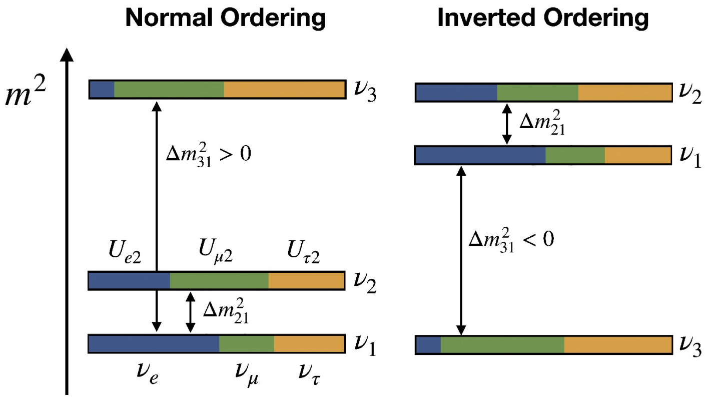
Lower limit from oscillation data:

$$\sum_\nu m_\nu > 58_{\mathrm{NO}}\ (98_{\mathrm{IO}})\ \mathrm{meV}$$ (NuFit-6.0)

Solid / model-independent

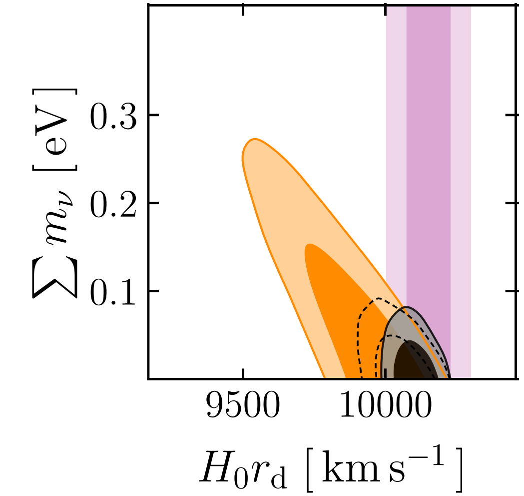
Inverted ordering under tension in ΛCDM, but too early to conclude (Kate Scholberg: *consider using lab ν results as input to cosmological analyses*)

(Note: various assumptions in all these constraints, well documented in corresponding literature; if a conflict occurs, this may be a hint for new physics!)



Very small (<2σ) preference for NO in global fit

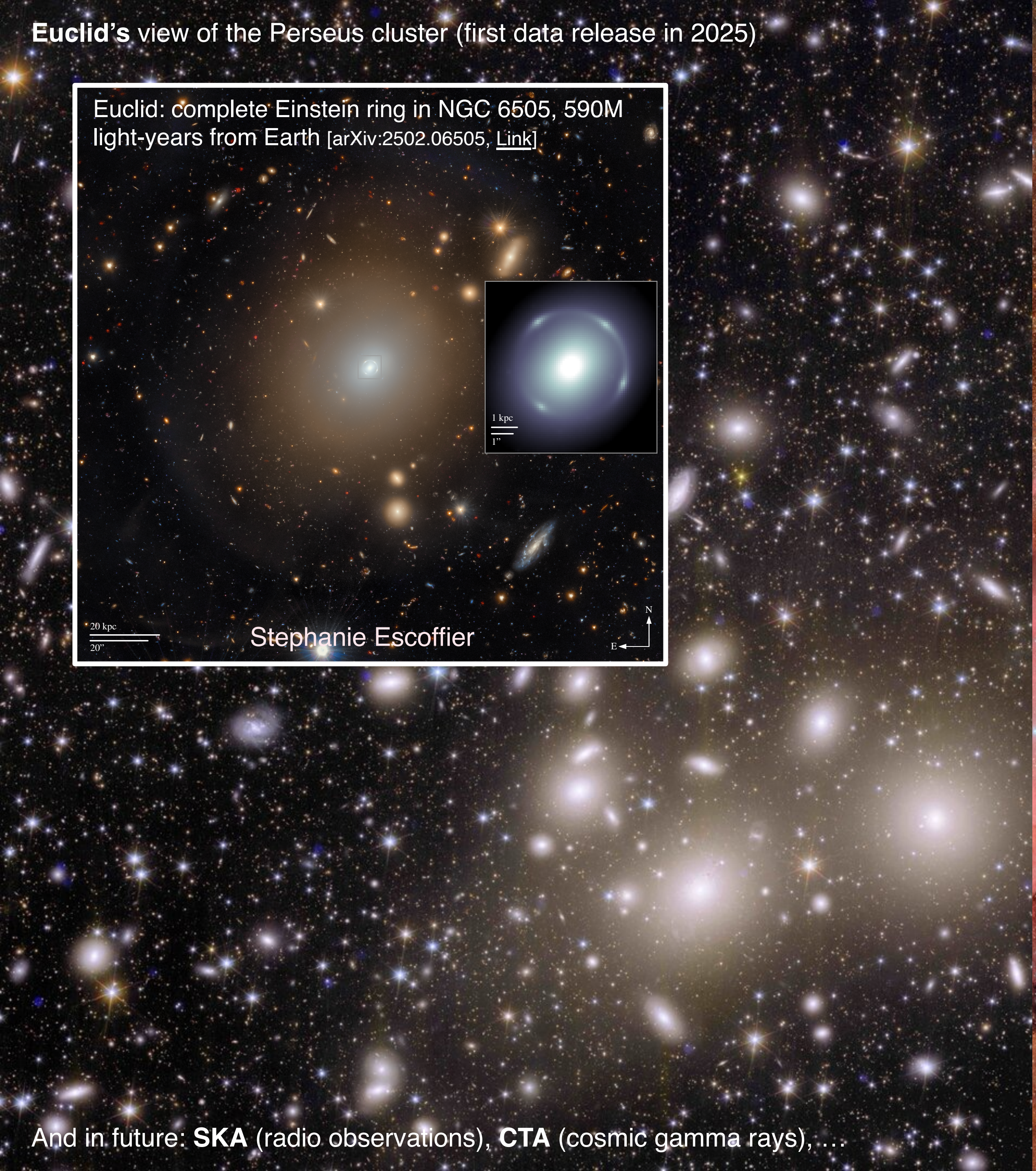
arXiv: 2503.14744




Euclid's view of the Perseus cluster (first data release in 2025)
And in future: **SKA** (radio observations), **CTA** (cosmic gamma rays), …


"First look" image composed of 678 images captured by the
Vera C. Rubin Observatory LSST
Stephanie Escoffier, Elizabeth Johana Gonzalez, Bruno Sanchez

Euclid's view of the Perseus cluster (first data release in 2025)



"First look" image composed of 678 images captured by the **Vera C. Rubin Observatory LSST**

And in future: **SKA** (radio observations), **CTA** (cosmic gamma rays), …


The future will be sharp


Thank you all for the amazing science,
inspiring talks, and a memorable
EPS-HEP 2025 conference in Marseille!