ОИЯИ
ОБЪЕДИНЁННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

CONFERENCE ON HIGH ENERGY PHYSICS
29 SEPTEMBER TO 3 OCTOBER 2025, YEREVAN, ARMENIA

‘25
September

Dmitry Kazakov

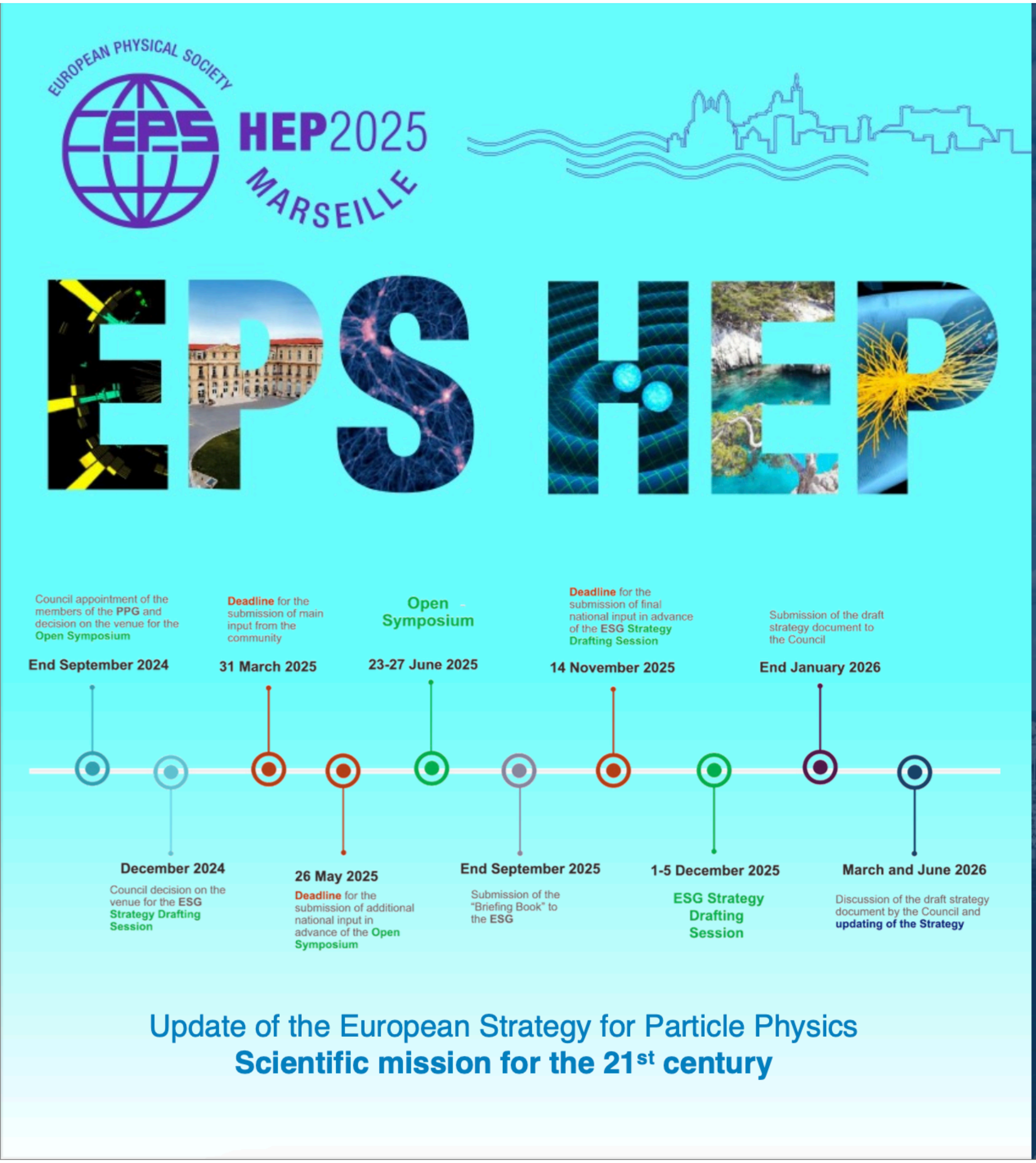
BLTP

Bogoliubov Laboratory of Theoretical Physics

В ожидании_е

The Standard Model: Autumn Landscape’25

Dubna



Andreas Hoecker (CERN)

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!

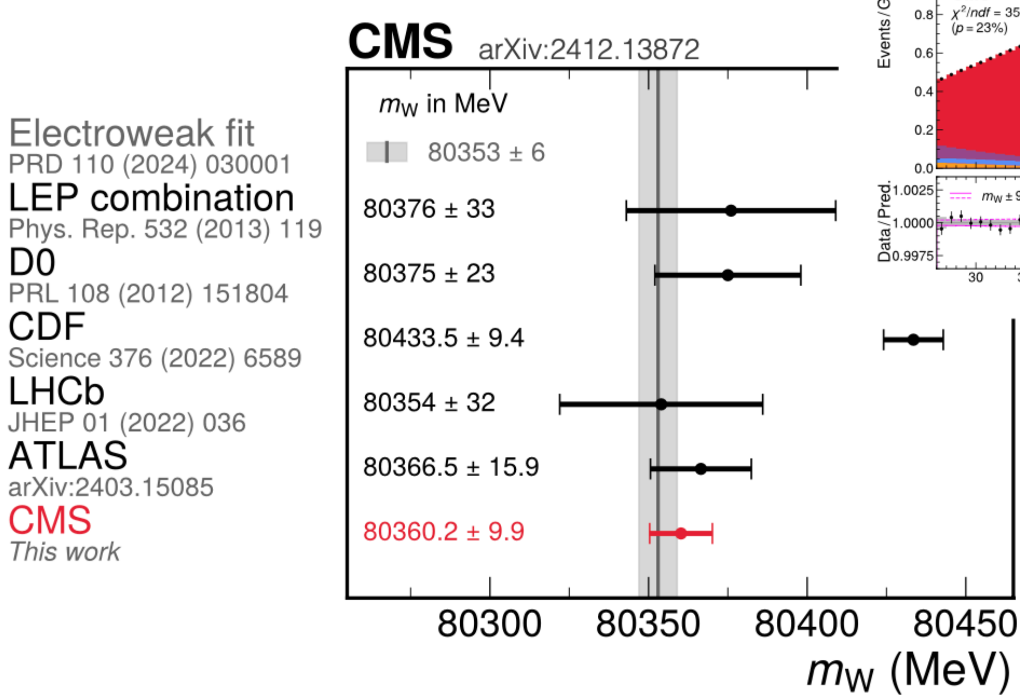
Colliders

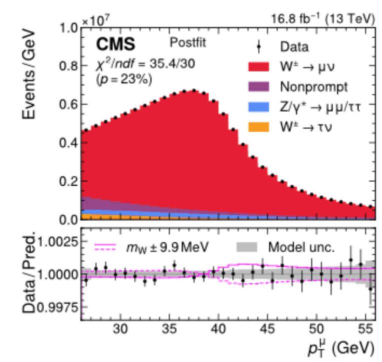
Measuring fundamental SM parameters

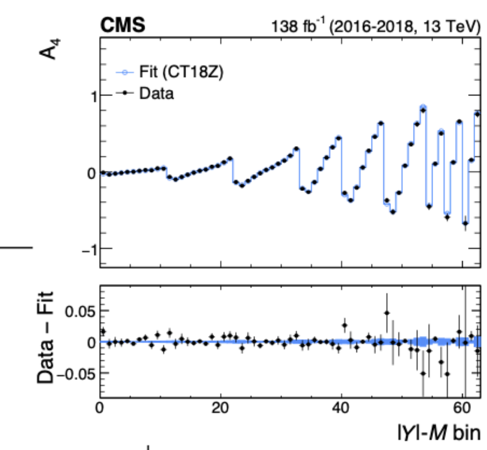
Josh Bendavid, Kenneth Long, Menglin Xu

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

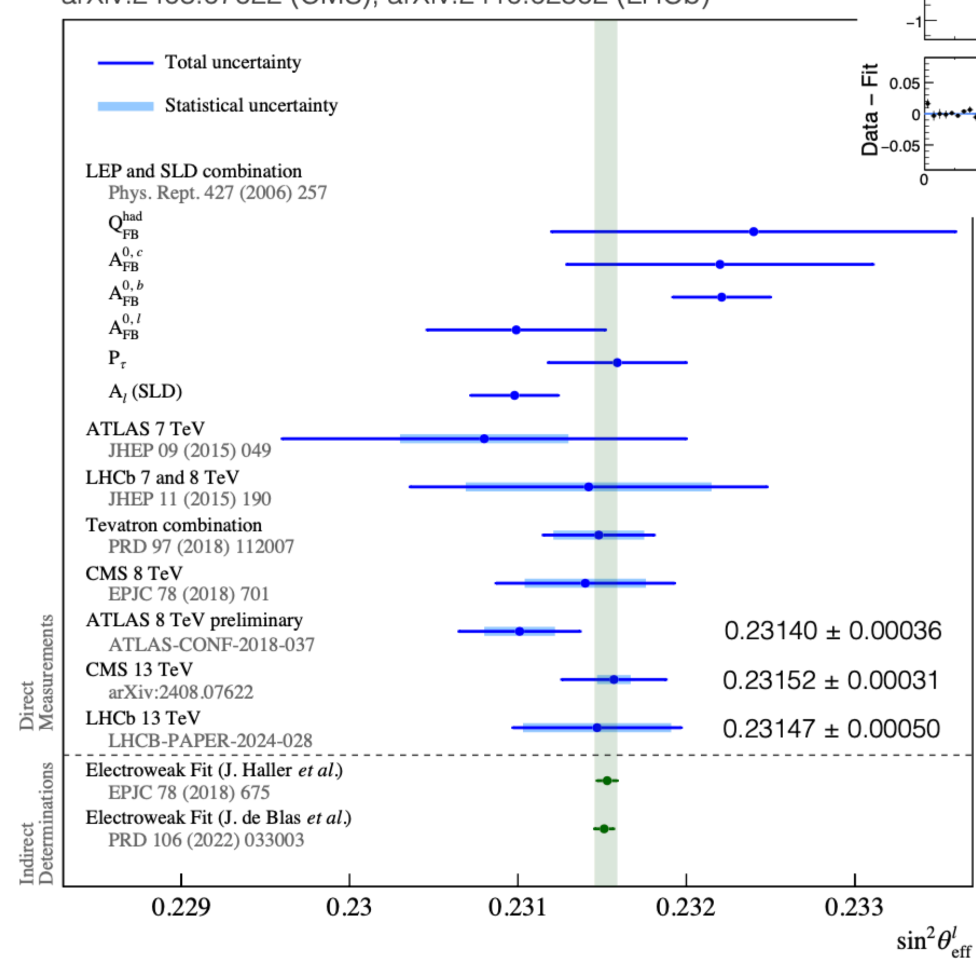
W mass a particular *tour de force*







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



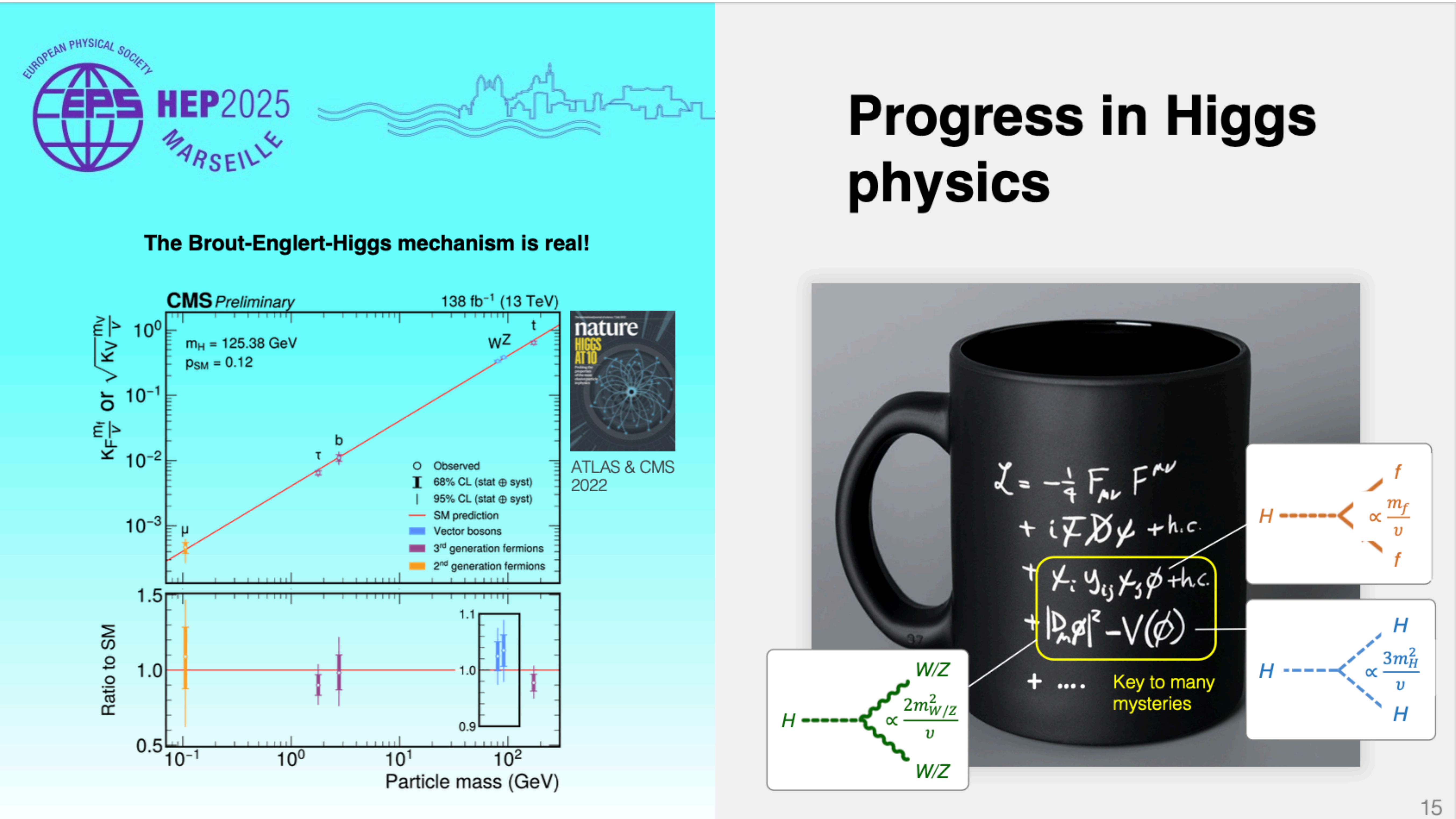
LHCb also realised a first LHC Z-mass measurement with 9.3 MeV precision consistent with LEP (σ = 2.1 MeV)

[arXiv:2505.15582]

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

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

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

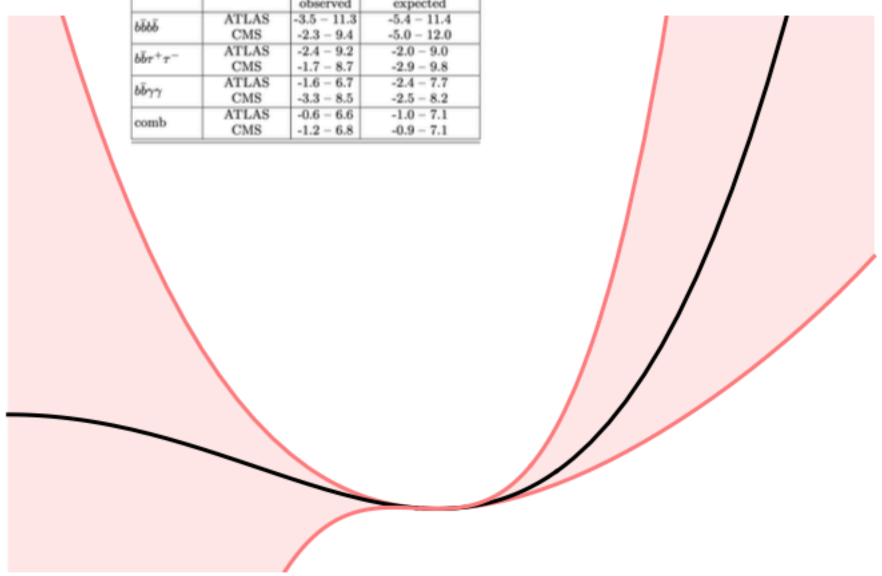

EUROPEAN PHYSICAL SOCIETY
EPS
HEP2025
MARSEILLE
The Brout-Englert-Higgs mechanism is real!
CMS Preliminary
138 fb⁻¹ (13 TeV)
m_H = 125.38 GeV
p_SM = 0.12
Observed
68% CL (stat ⊕ syst)
95% CL (stat ⊕ syst)
SM prediction
Vector bosons
3rd generation fermions
2nd generation fermions
μ
τ
b
W Z
t
Ratio to SM
Particle mass (GeV)
nature
HIGGS AT 10
ATLAS & CMS
2022
Progress in Higgs physics
Key to many mysteries
H
f
W/Z
15

Higgs self coupling [Meade]

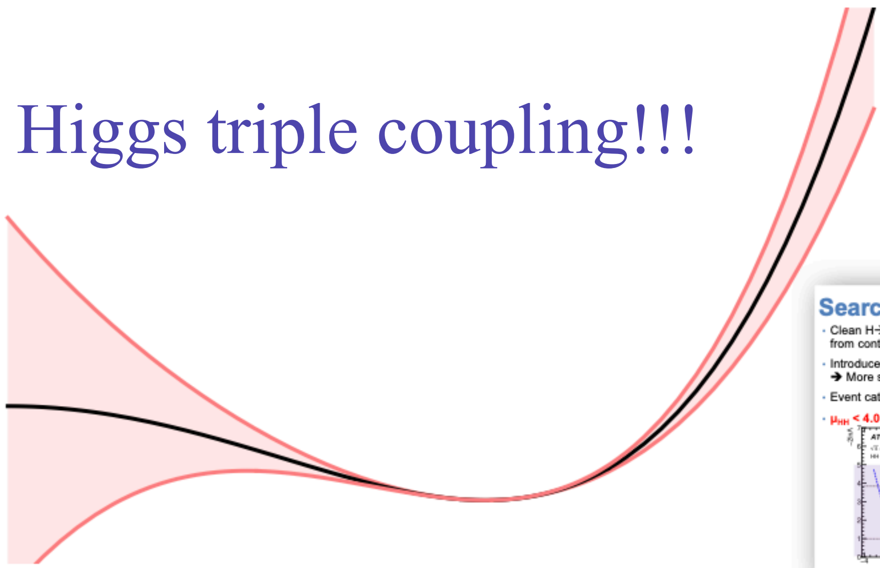
If the questions center on the Higgs, do we need to do more than sit back and wait for more data for more precision (or a Higgs factory)?

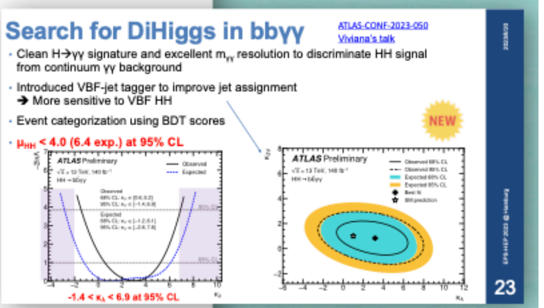
Snowmass EF Higgs Topical Report
2209.07510

Final state	Collaboration	allowed κ_λ interval at 95% CL observed	expected
$b\bar{b}b\bar{b}$	ATLAS	-3.5 – 11.3	-5.4 – 11.4
	CMS	-2.3 – 9.4	-5.0 – 12.0
$b\bar{b}\tau^+\tau^-$	ATLAS	-2.4 – 9.2	-2.0 – 9.0
	CMS	-1.7 – 8.7	-2.9 – 9.8
$b\bar{b}\gamma\gamma$	ATLAS	-1.6 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
comb	ATLAS	-0.6 – 6.6	-1.0 – 7.1
	CMS	-1.2 – 6.8	-0.9 – 7.1



Higgs triple coupling!!!





H/T N.Craig, R. Petrossian-Byrne

When do we *really* care about non-resonant di-Higgs (λ_3) for its own sake?

Interesting to think about in more general setups beyond singlet, e.g. composite Higgs

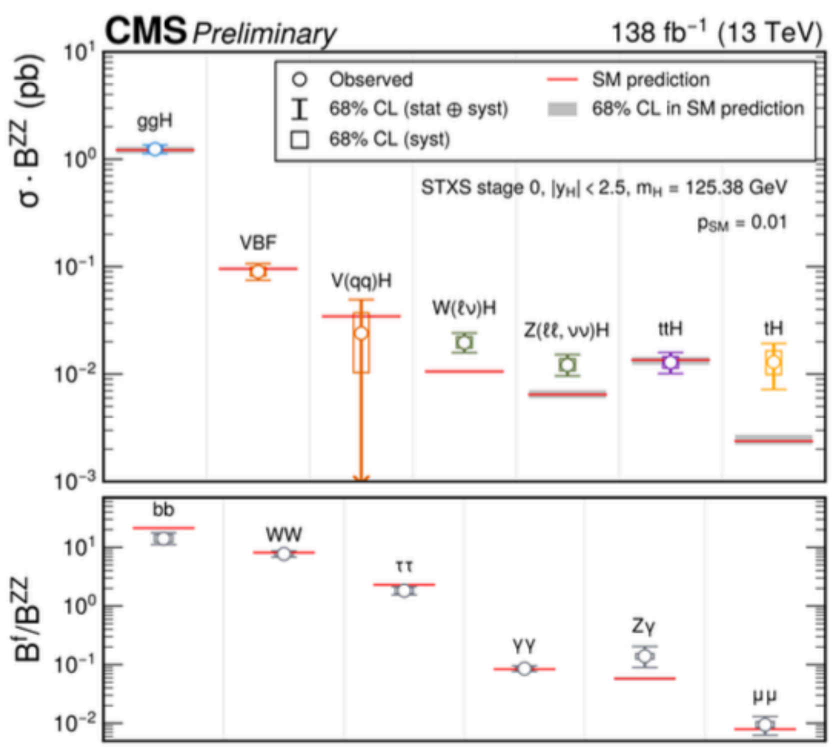
40

See G. Durieux et al, 2110.06941 for recent extensions

ATLAS and CMS released new Run-2 combinations

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

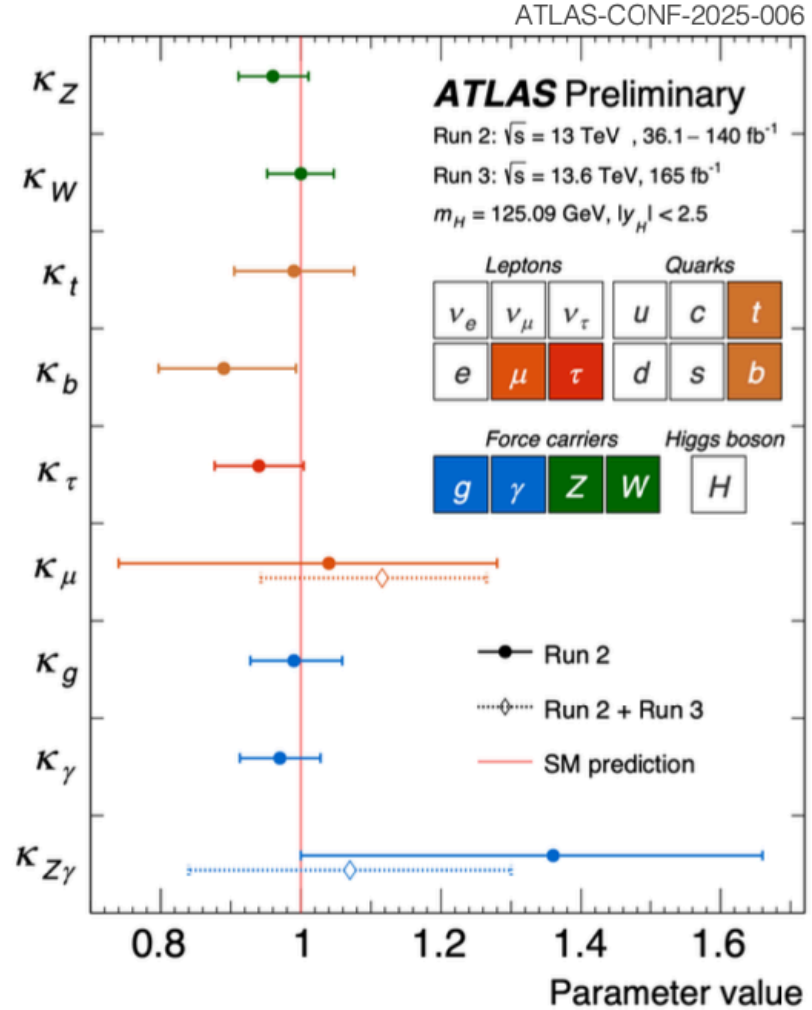
Comprehensive combinations of Higgs production and decay measurements using Run-2 data



CMS-PAS-HIG-21-018

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

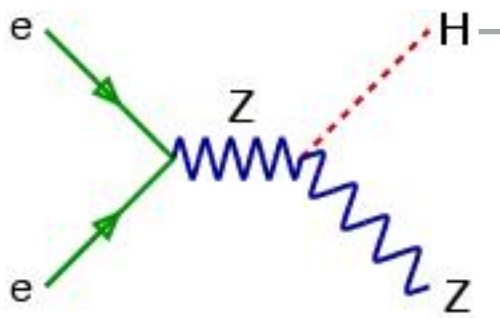
ATLAS-CONF-2025-006



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

PRECISION PHYSICS OF THE HIGGS BOSONS

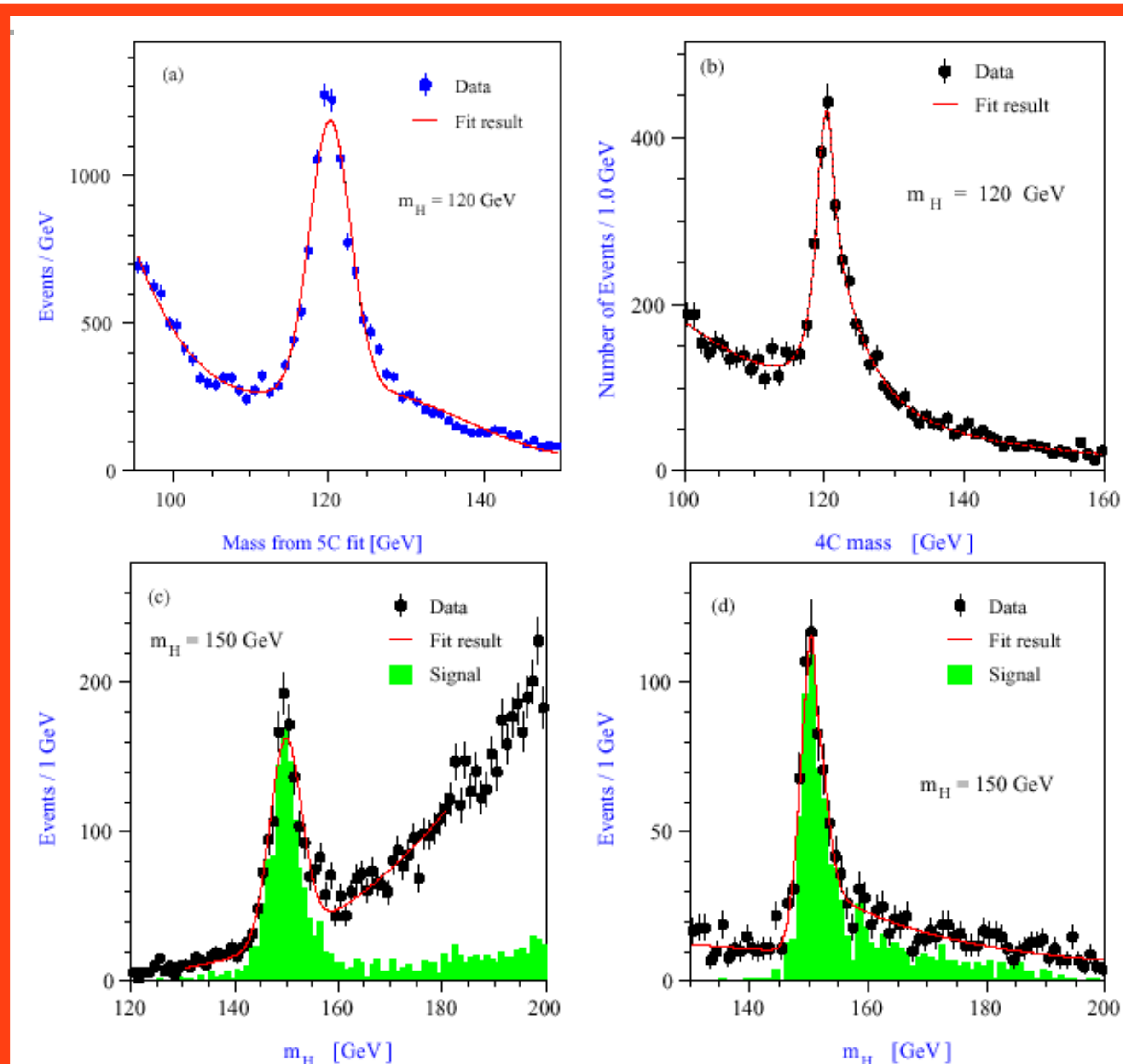


$\rightarrow b\bar{b}q\bar{q}$

ee -> HZ diff. decay channels

Int Linear Collider

$\rightarrow W^+W^-q\bar{q}$

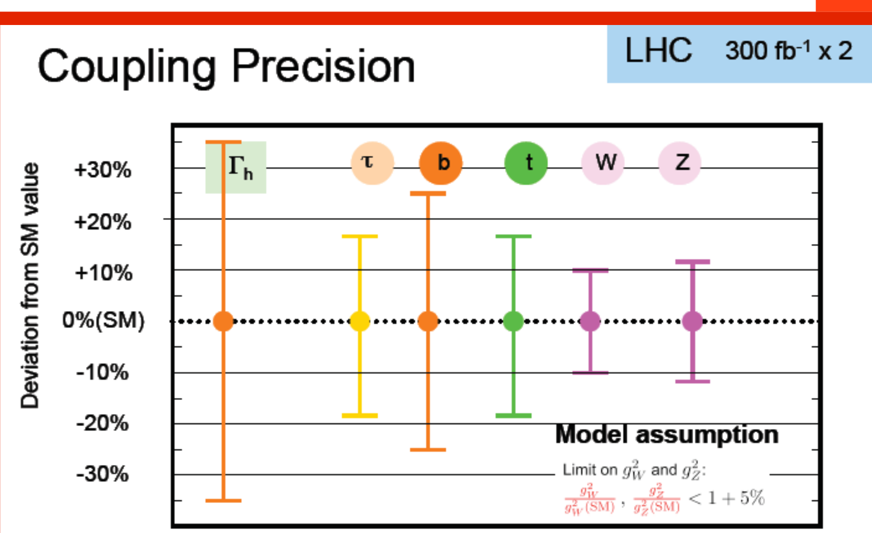


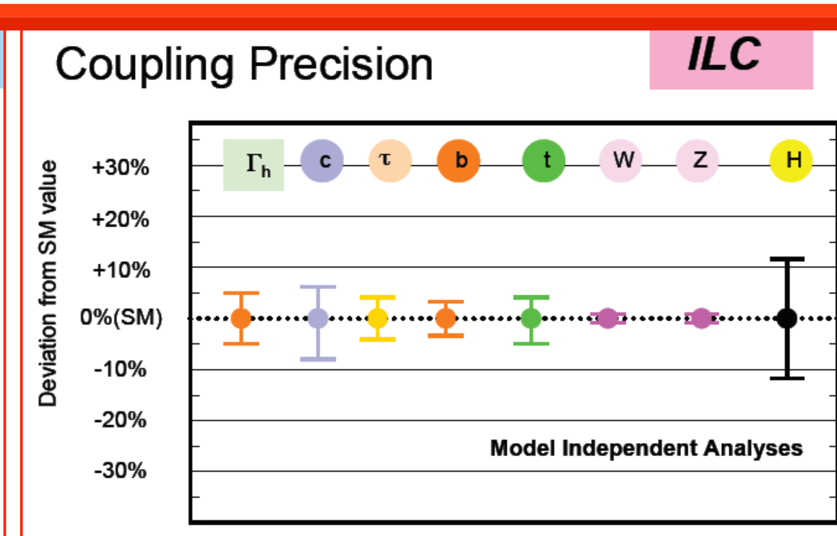
$\rightarrow q\bar{q}\ell^+\ell^-$

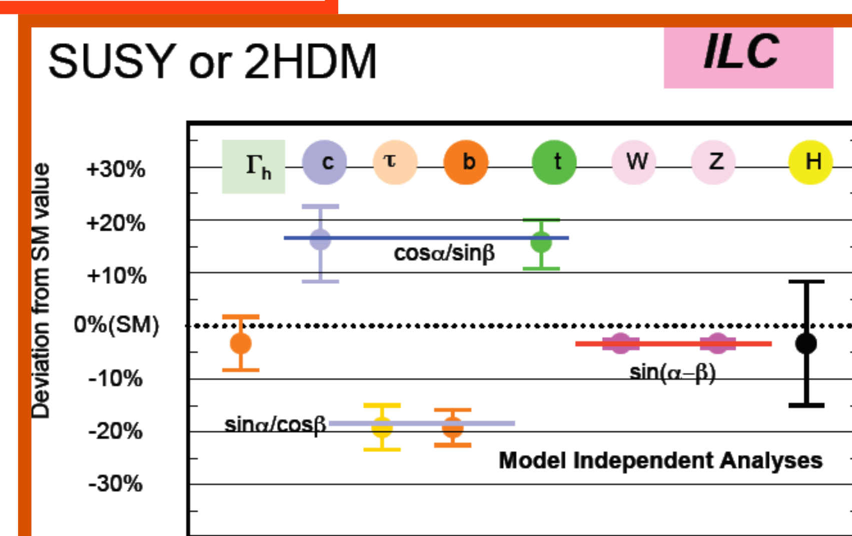
Δm_H = 40 MeV

$\rightarrow W^+W^-\ell^+\ell^-$

Δm_H = 70 MeV



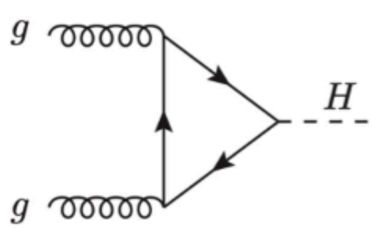




Testing the SM requires precise theory predictions

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]

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

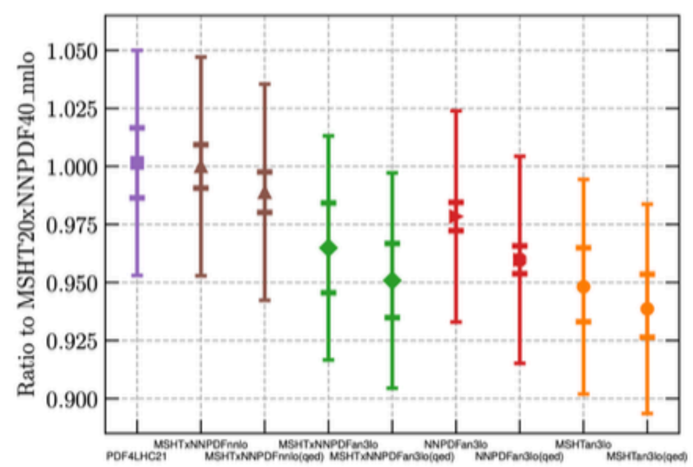
Recent advances include finite quark mass effects at NNLO and t+b interference

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

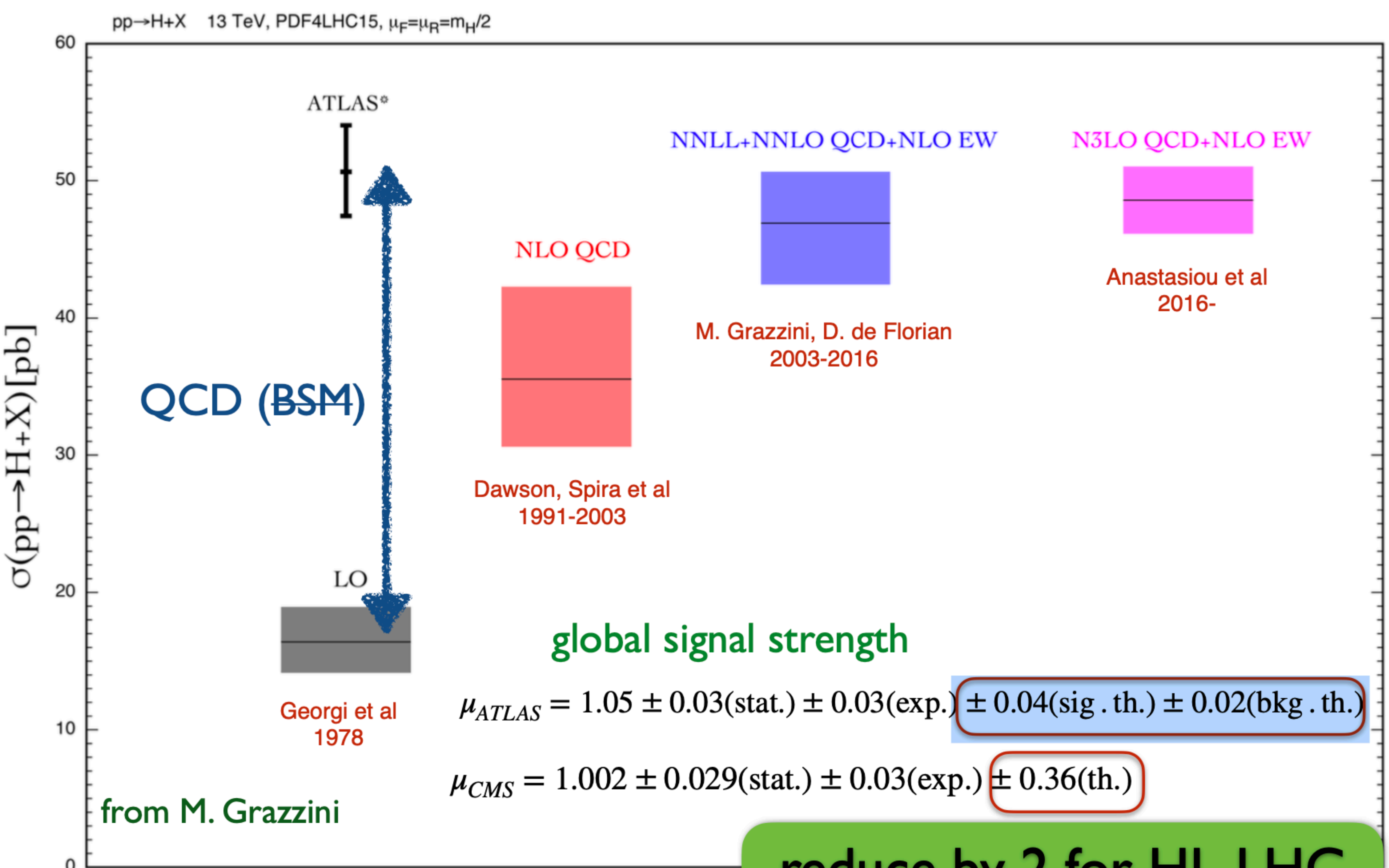


Kyle Cranmer — AI for amplitudes

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*)

Inclusive Higgs : an example of precision



global signal strength

$$\mu_{ATLAS} = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig . th.}) \pm 0.02(\text{bkg . th.})$$

$$\mu_{CMS} = 1.002 \pm 0.029(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.36(\text{th.})$$

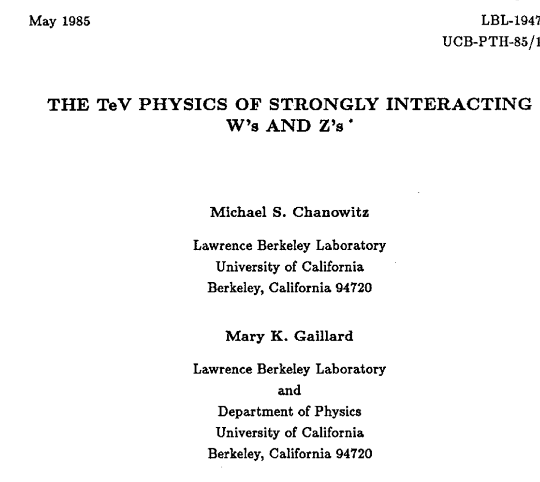
reduce by 2 for HL-LHC

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 $E \gg m_V$, amplitude of $V_L V_L \to V_L V_L \sim GG \to GG \propto -m_H^2/v^2$, a process directly determined by EWSB



May 1985

LBL-19470
UCB-PTH-85/19

THE TeV PHYSICS OF STRONGLY INTERACTING W's AND Z's*

Michael S. Chanowitz

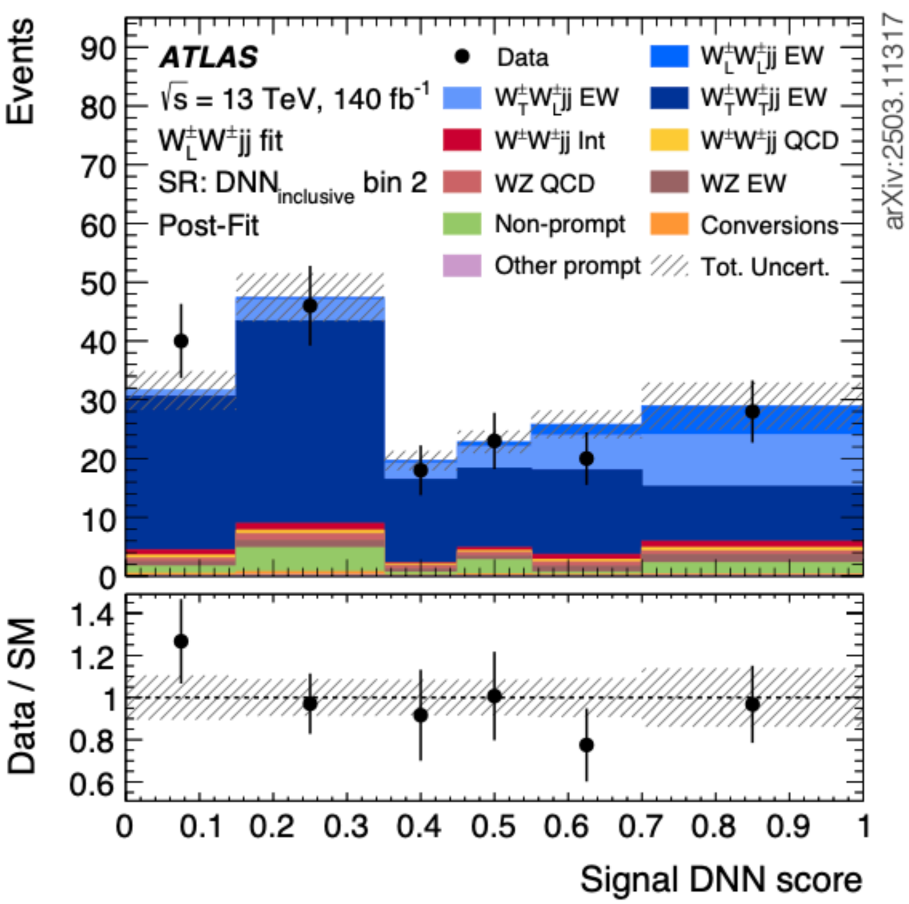
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Mary K. Gaillard

Lawrence Berkeley Laboratory
and
Department of Physics
University of California
Berkeley, California 94720

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

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



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

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

Significance for at least one W_L: $3.4\sigma_{obs}$ ($4.0\sigma_{obs}$)

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!

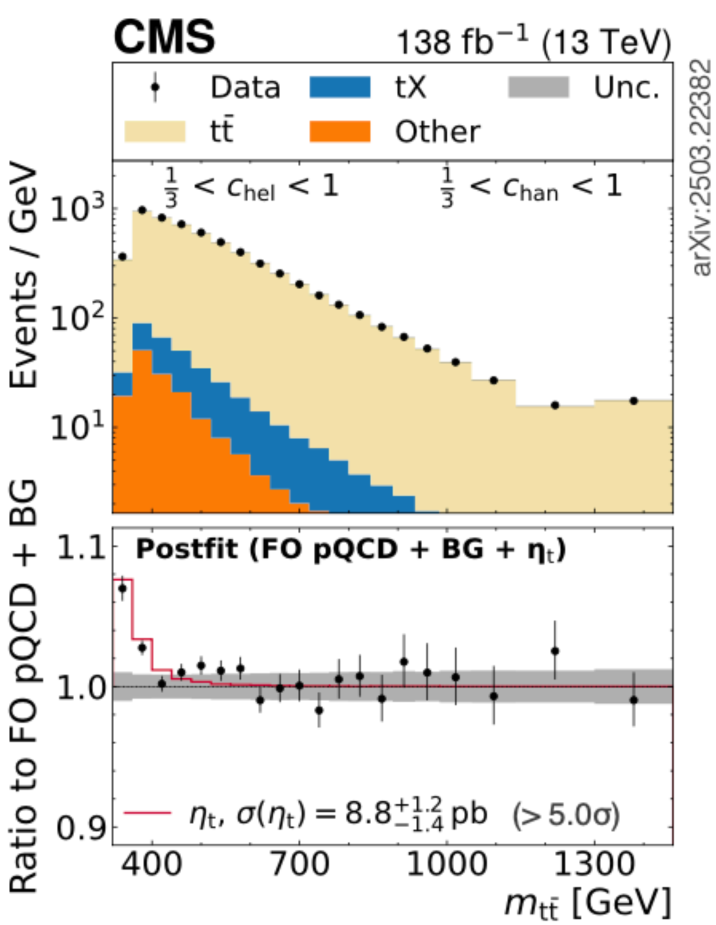
Top–antitop production at threshold

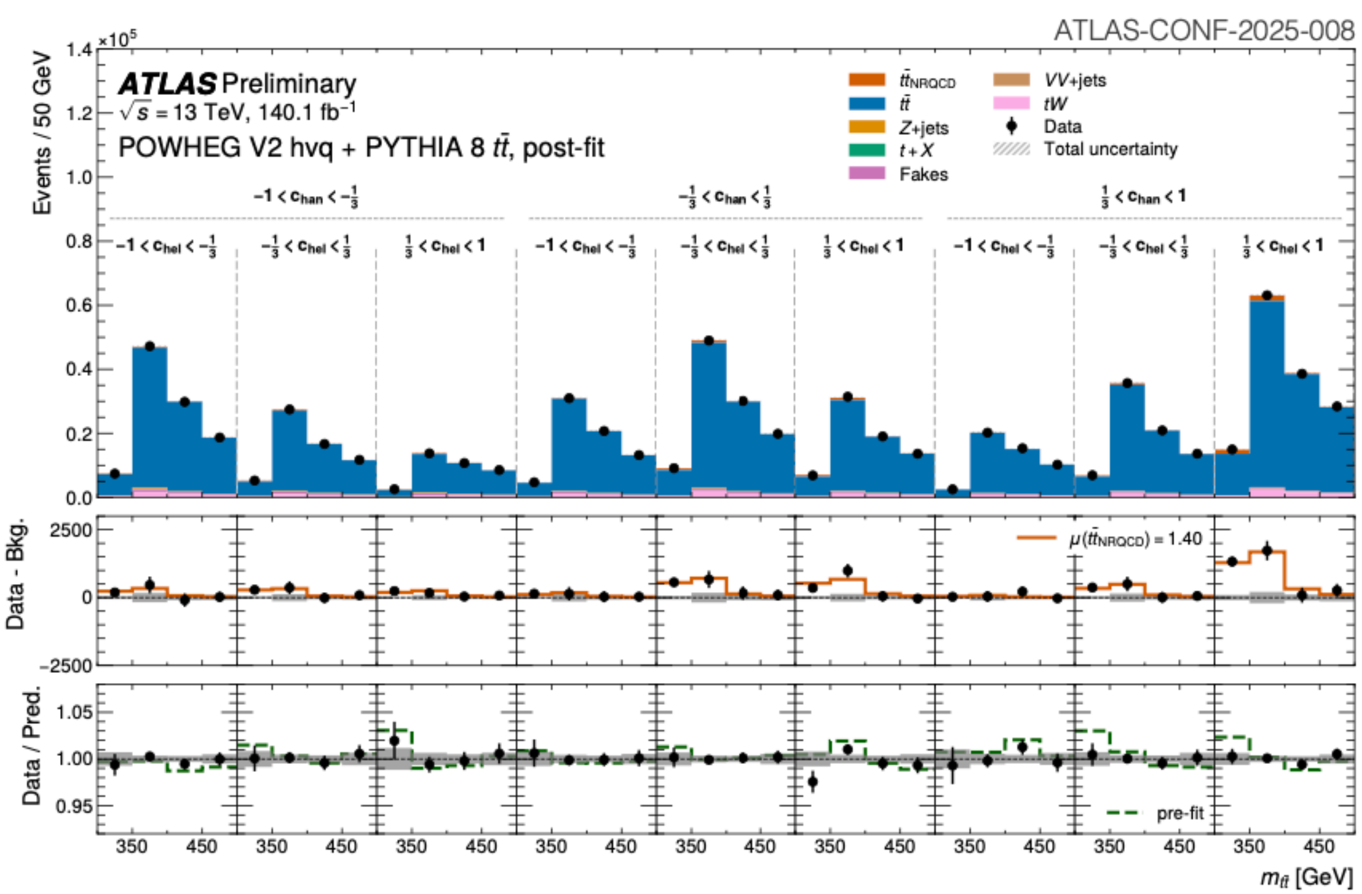
Josh Bendavid, Fabio Cerutti, Haifeng Li,
Roberto Salerno, Christian Schwanenberger

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

Strong interaction predicts highly compact, colour-singlet quasi-bound pseudoscalar $t\bar{t}$ states (negligible self-annihilation, top decays before)

The 'toponium' effect can be computed in non-relativistic QCD (NRQCD)

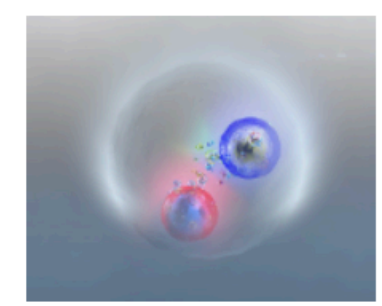




ATLAS used NRQCD model for threshold contribution (also alternative models studied)

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

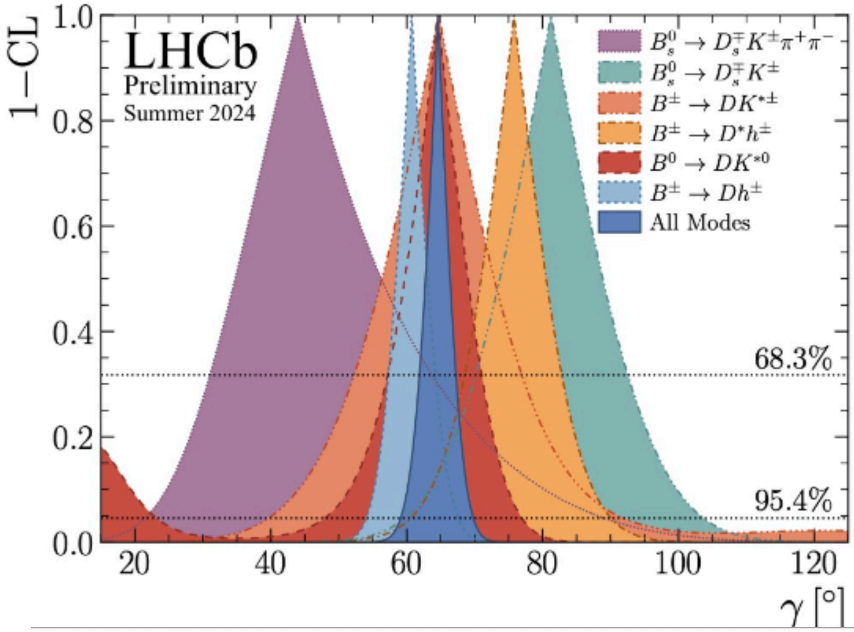
CKM unitarity

Tim Gershon, Vladimir Gligorov

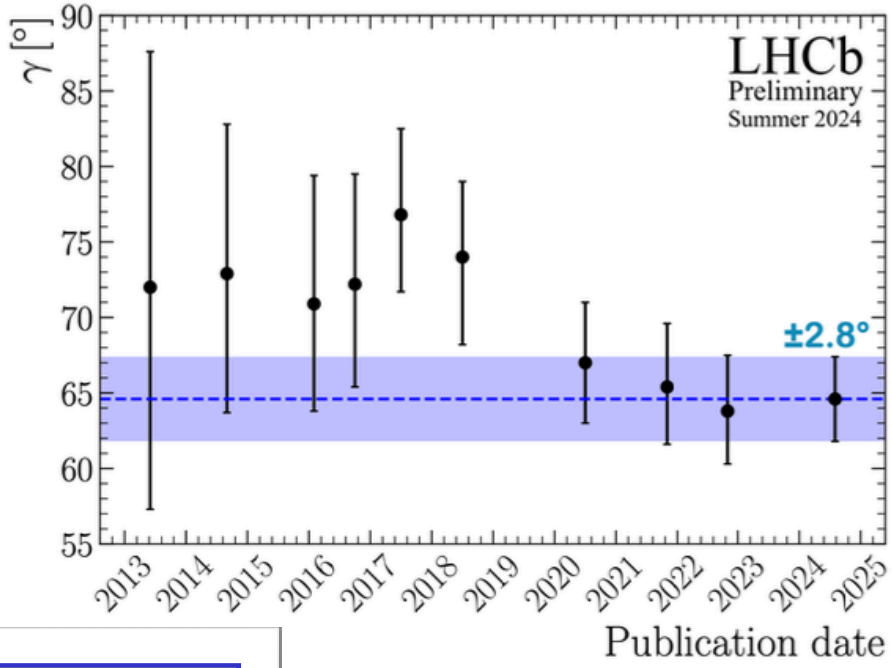
A tribute to the monumental work by LHCb on improving the apex measurements of the CKM unitarity triangle

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

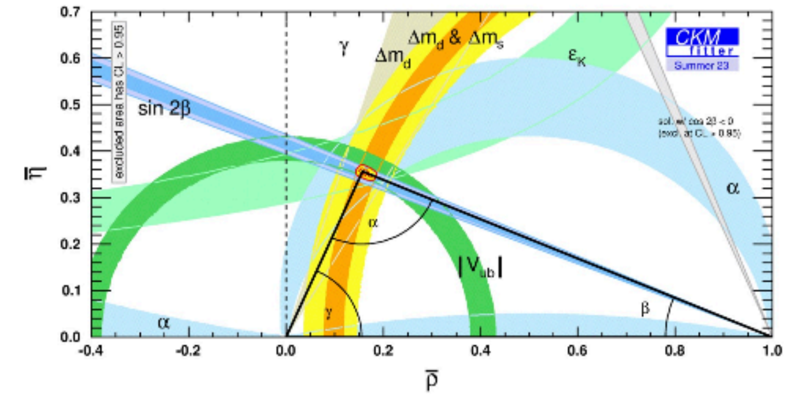
Constraints from various $B \to DK$ analyses

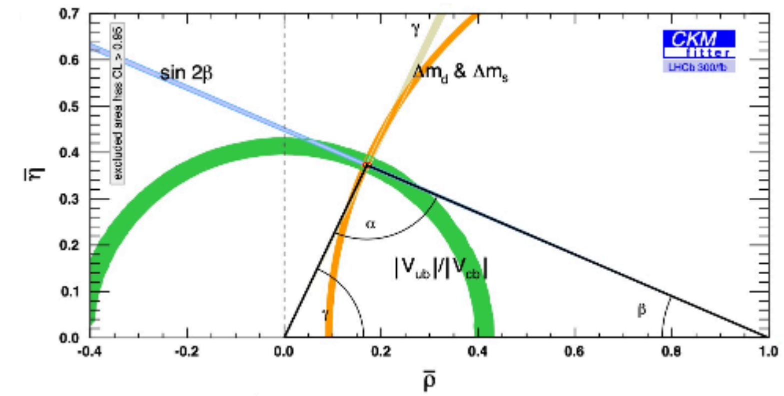


Constraint versus time

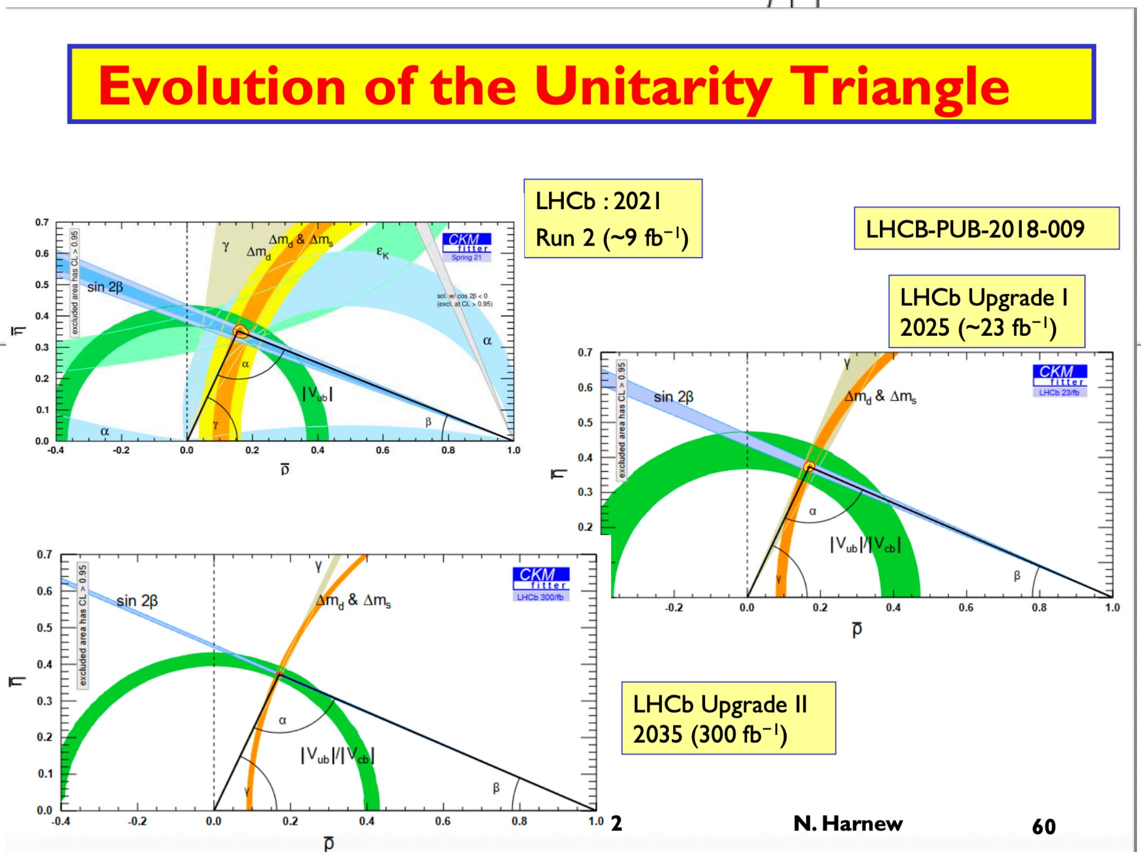


And much more to expect from LHCb Upgrade II





LHCb Upgrade II Scoping Document

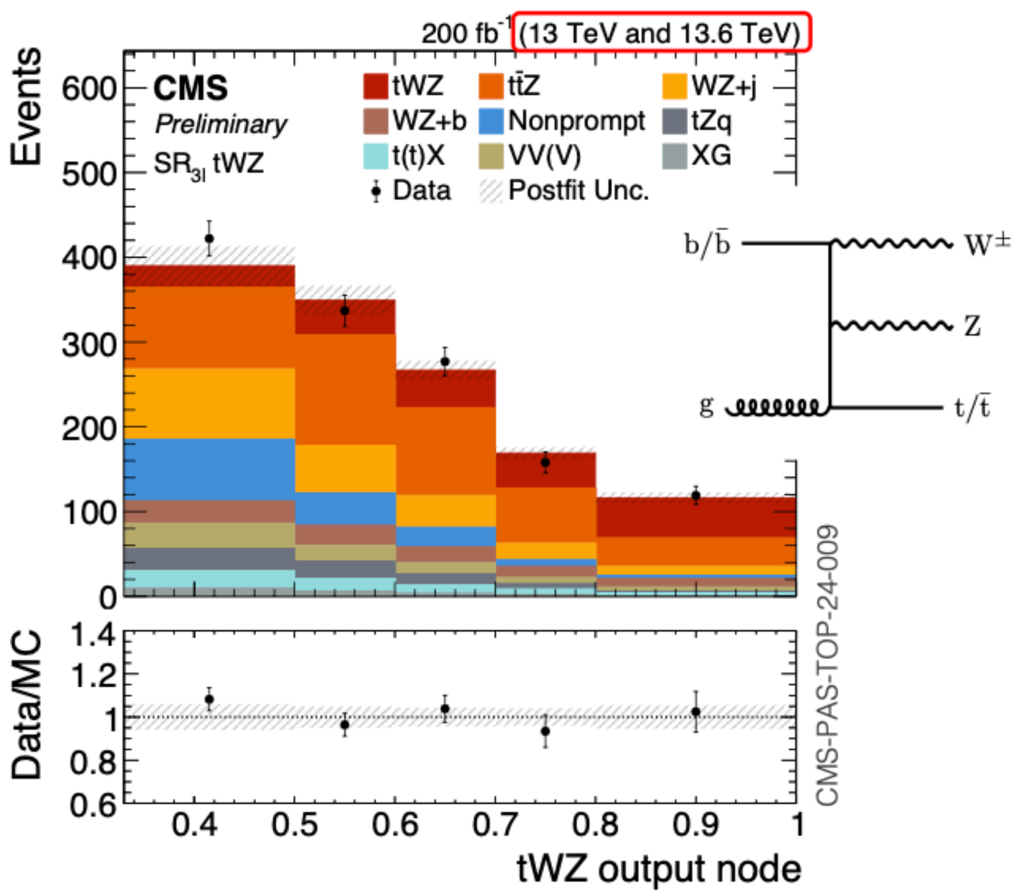


Rare processes

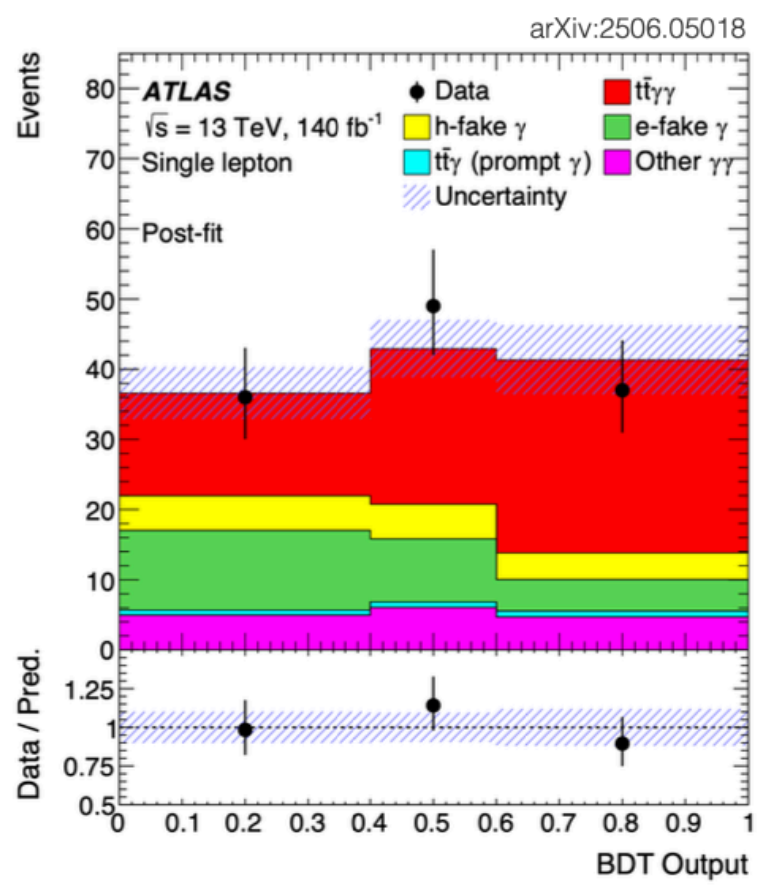
Alberto Belvedere, Josh Bendavid,
Jose Enrique Palencia Cortezon, Amartya Rej

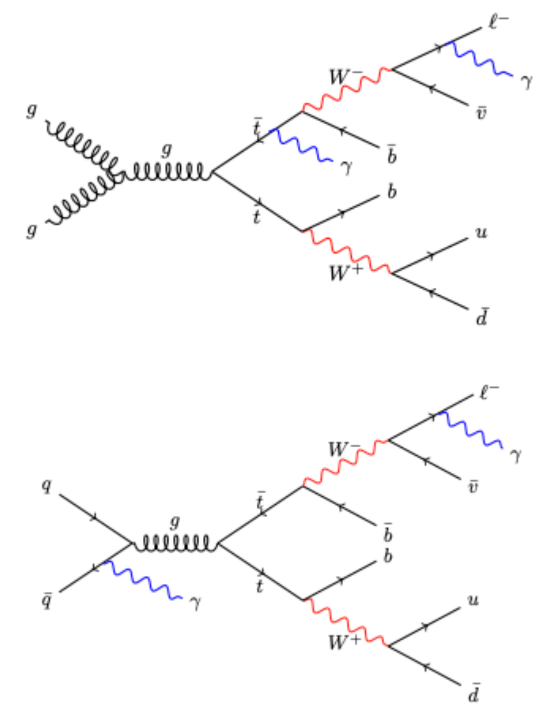
LHC experiments push intensity frontier to ever rarer processes — with help from machine learning

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



$\sigma(tWZ) = 248 \pm 52$ fb (5.8σ significance)





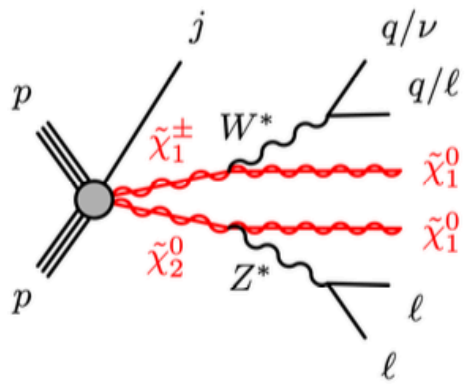
$\sigma_{fid}(tt\gamma\gamma) = 2.4 \pm 0.5$ fb (5.2σ significance)

SUSY Search

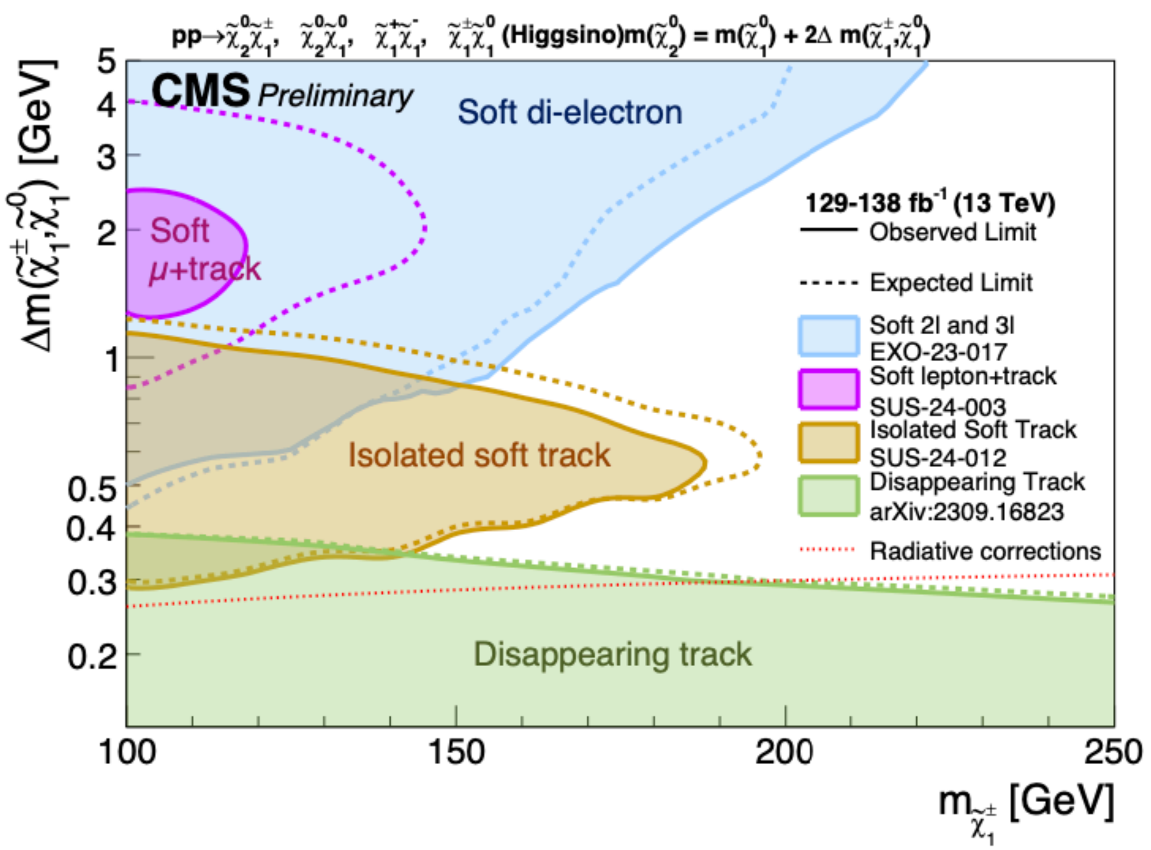
Exploiting new techniques

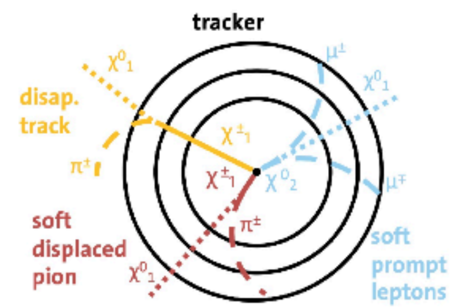
Samuel Bein, Pantelis Kontaxakis,
Tamara Vazquez Schröder

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

Degeneracy and Longlived particles

CP violation in baryons

Tim Gershon, Xueting Yang

First observation of CP violation in baryon decay by LHCb

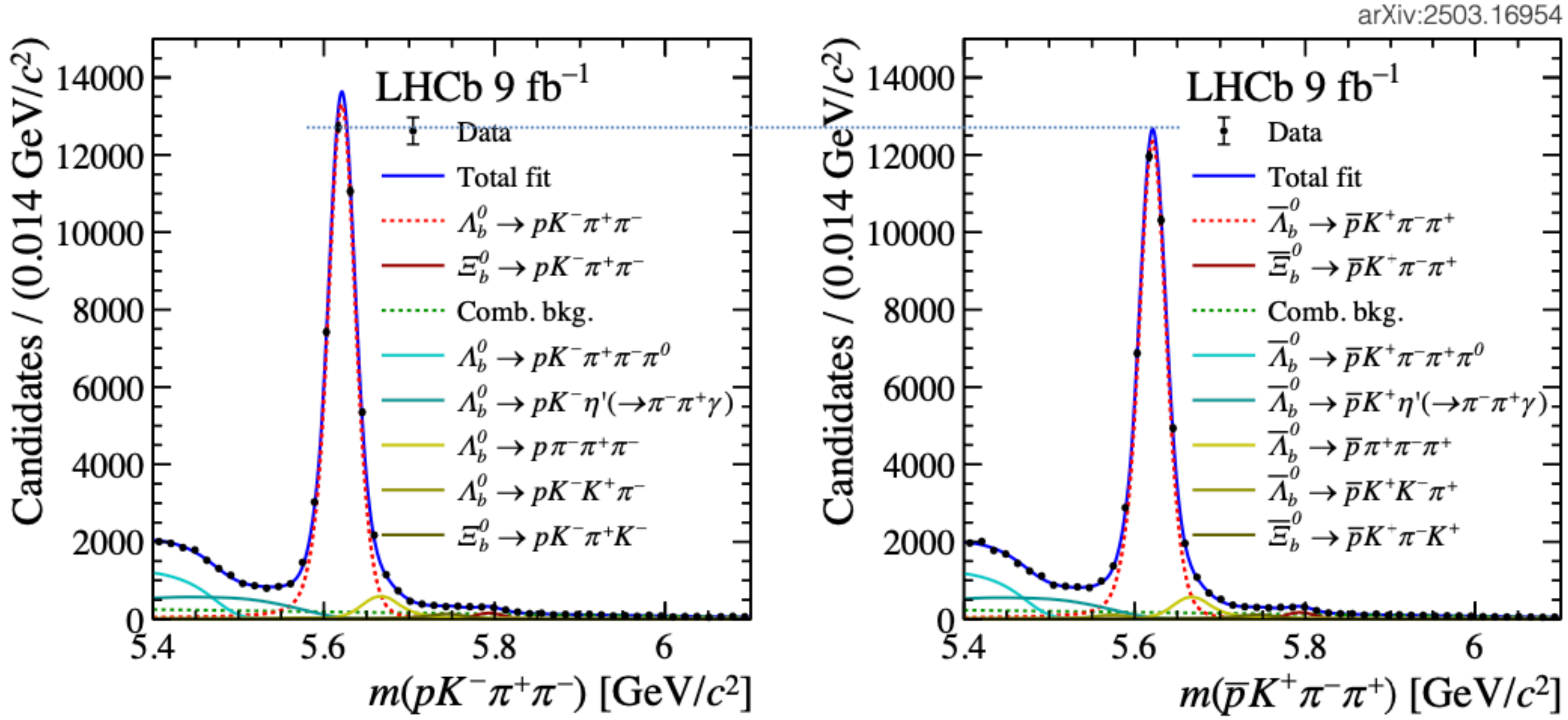
Direct CPV requires interference of diagrams with non-zero differences of weak *and* strong phases

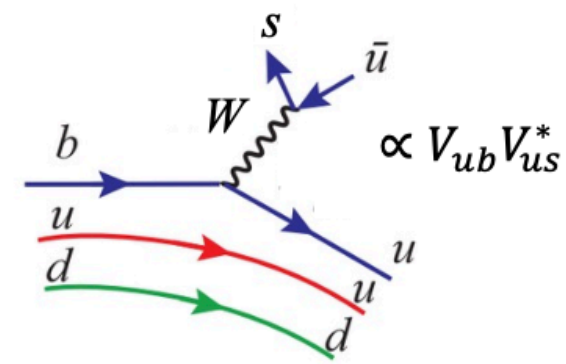
$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)} = (2.45 \pm 0.46 \pm 0.10)\%$$

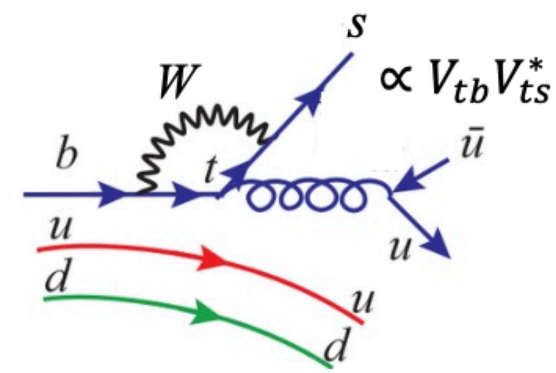
Decay proceeds mostly through intermediate resonances (showing different amount of A_{CP})

Derived from uncorrected yield difference: A_N = 3.71 ± 0.39 %

arXiv:2503.16954







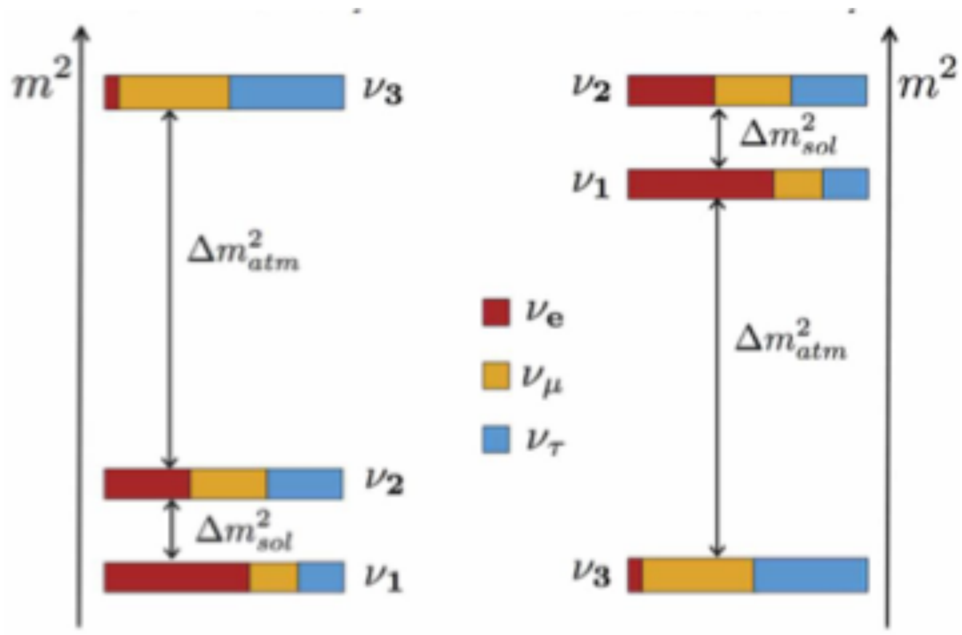
CP violation due to interference between tree and penguin diagrams

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

Neutrinos

Neutrino Physics



parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

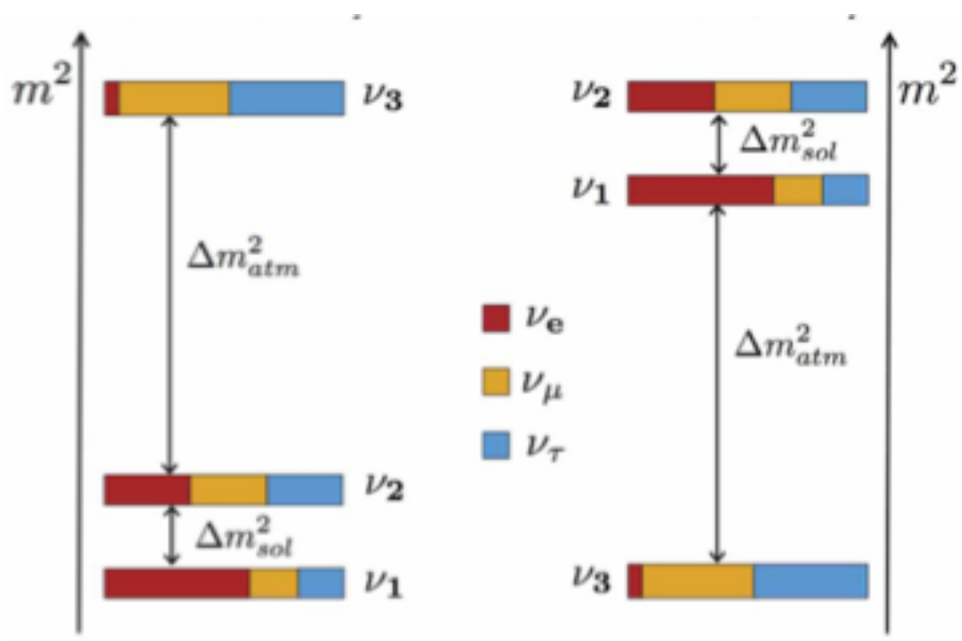
$$0.06\ eV < \sum m_\nu < 0.12\ eV$$

-osc CMB

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

Neutrino Physics



- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

$$0.06\ eV < \sum m_\nu < 0.12\ eV$$

ν-osc (lower bound) — CMB (upper bound)

parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

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)

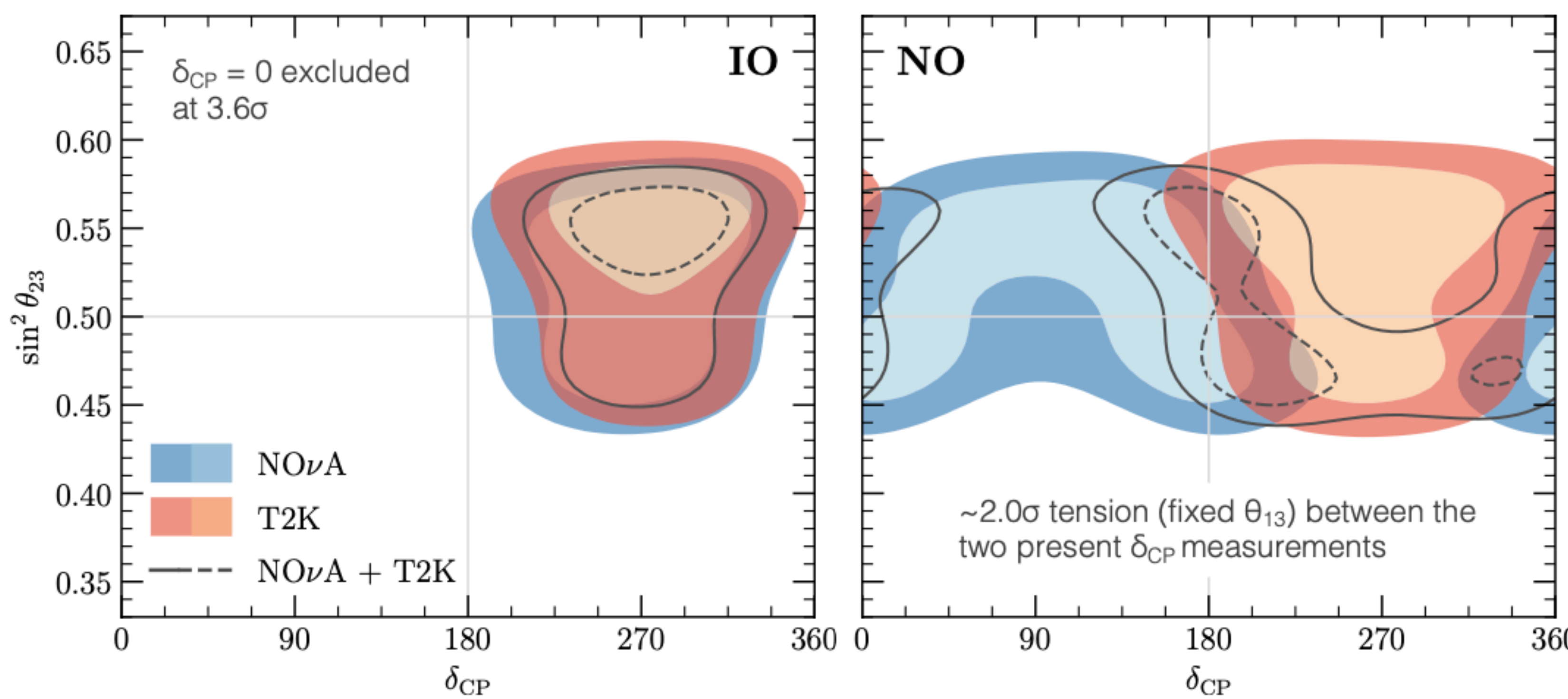
Long-term program: MINOS, K2K, OPERA (past, 2000–2015) → **T2K, NOvA (present, 2015–2028)** → Hyper-K, DUNE (future, 2028+)

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]

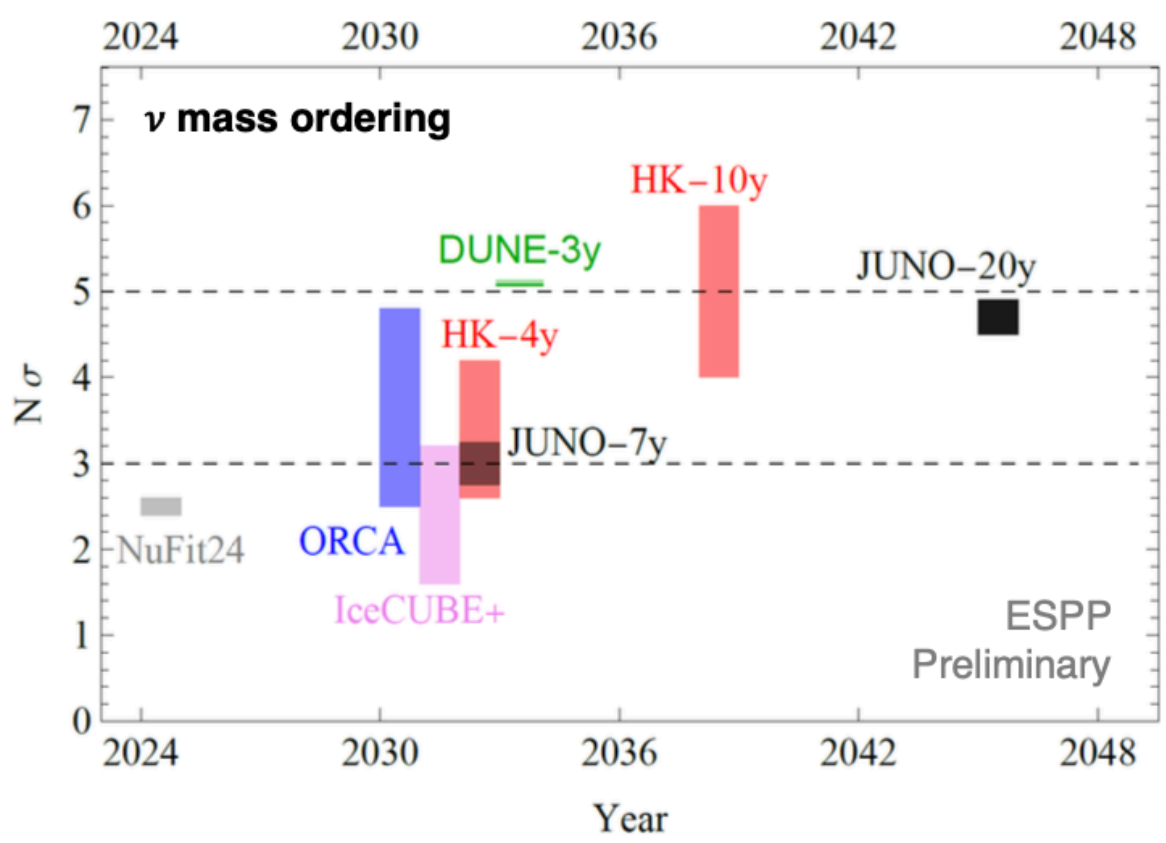
Both experiments have more data under analysis and continue running until end of 2026 (NOvA) and 2028 (T2K)

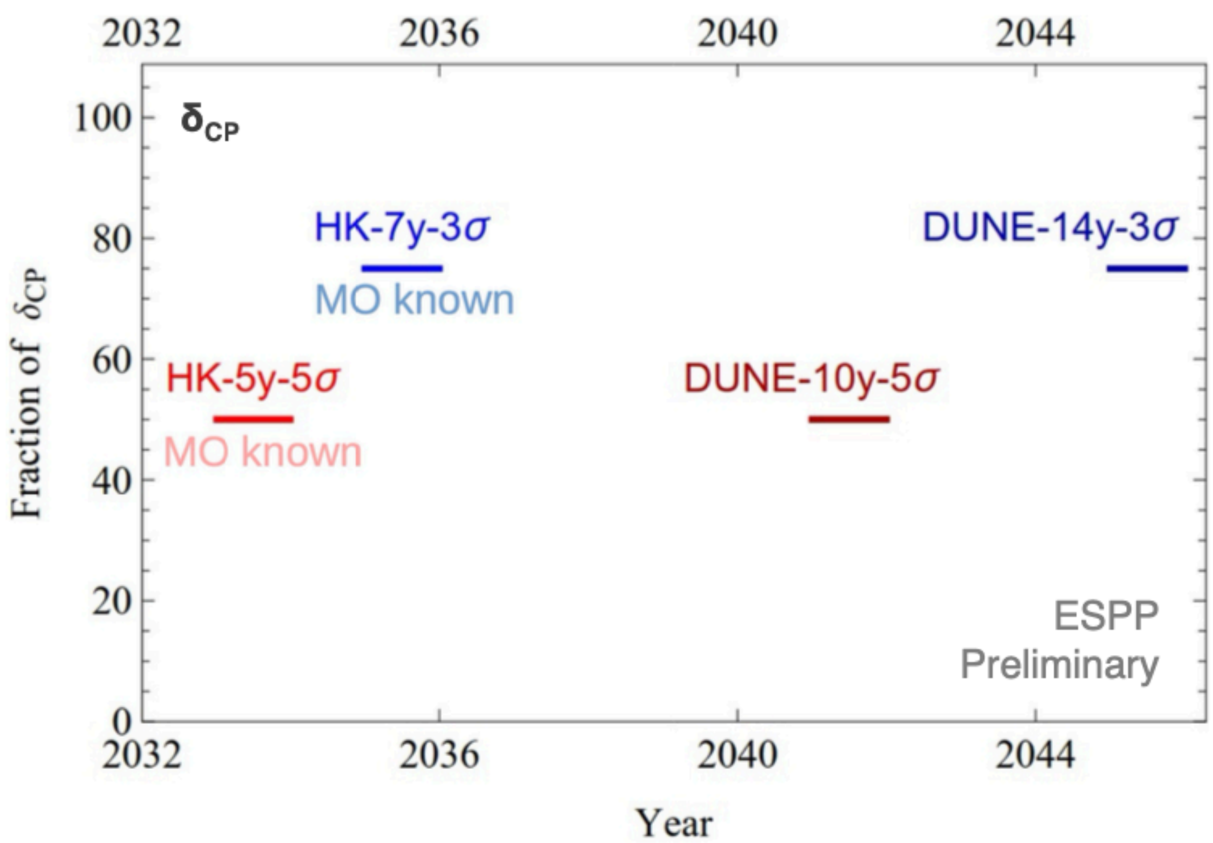


Neutrino mass ordering and CP violation

Pilar Hernandez

When will we know?





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

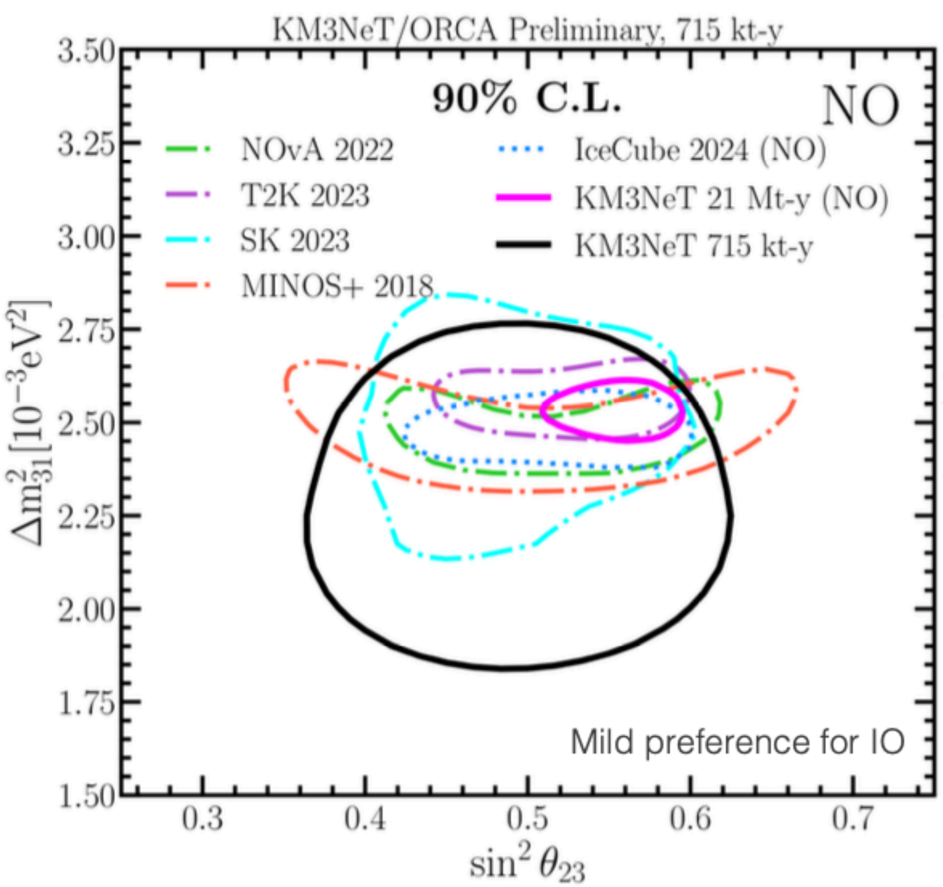
If CPV large, discovery in 2–4 years (starting 2030~2032) depending on systematics, but knowing MO is important in degenerate regions

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

Atmospheric & high–E neutrinos

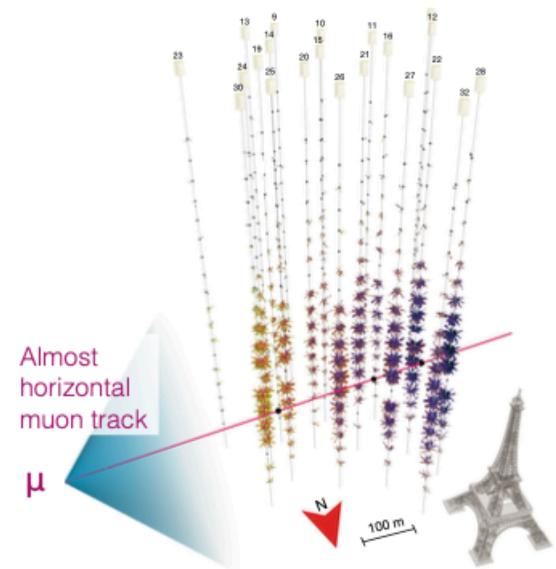
Victor Carretero, Annarita Margiotta, Kate Scholberg

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

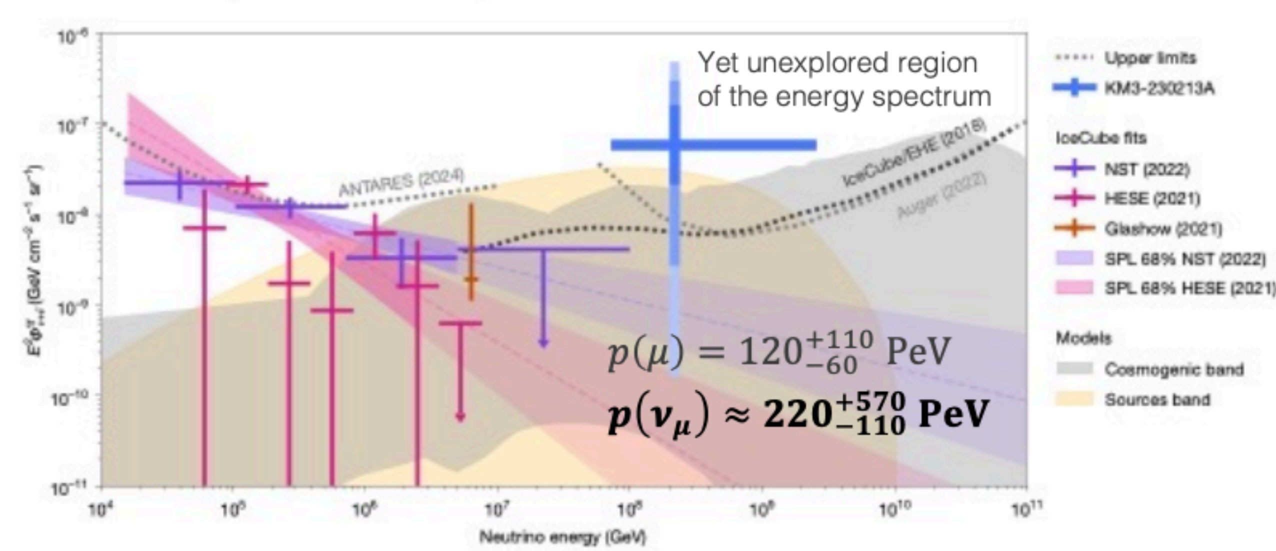
KM3Net – ARCA (high-E ν's): south-east of Sicily 3,450 m depth, 33 DUs (14%), big campaign to install ~20 additional DUs



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

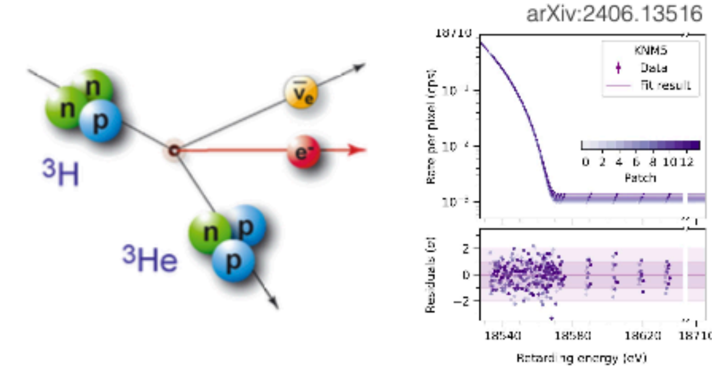


Absolute neutrino masses and mass ordering

Julian Bautista, Enrique Fernández Martínez, Adrien La Posta

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

Solid / model-independent

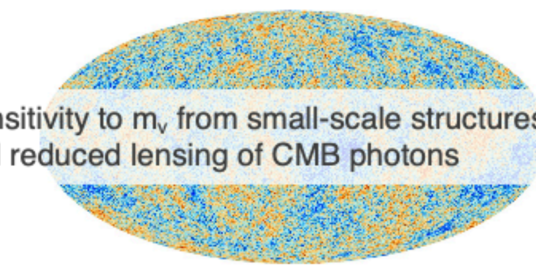


0νββ limit: $|\sum_\nu U_{e\nu}^2 m_\nu| < 28\text{–}122\ \mathrm{meV}$ (KamLAND-Zen at 90% CL, assuming mediation by light Majorana neutrinos)

Cosmological limits (95% CL):

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

$\sum_\nu m_\nu < 53_{\Lambda\mathrm{CDM}}\ (< 177_{\omega_0\omega_a\mathrm{CDM}})\ \mathrm{meV}$ (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

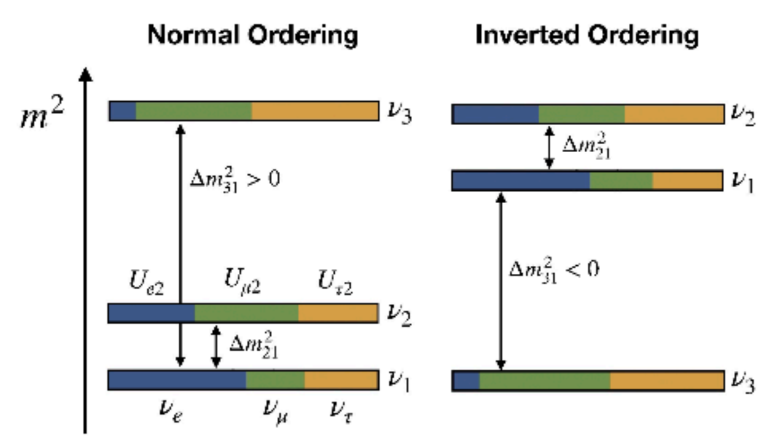
Lower limit from oscillation data:

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

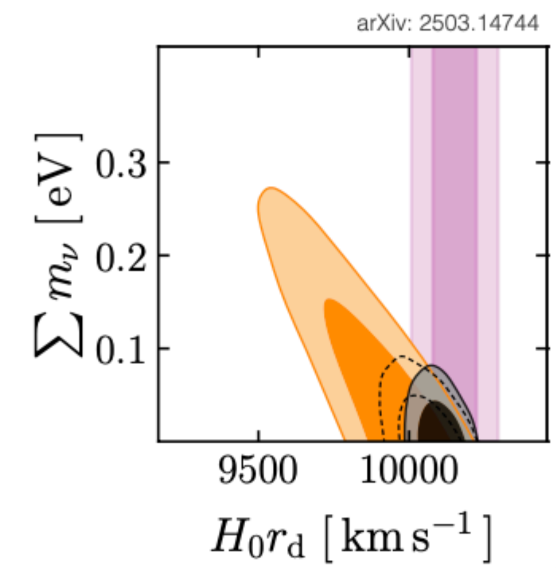
Solid / model-independent

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



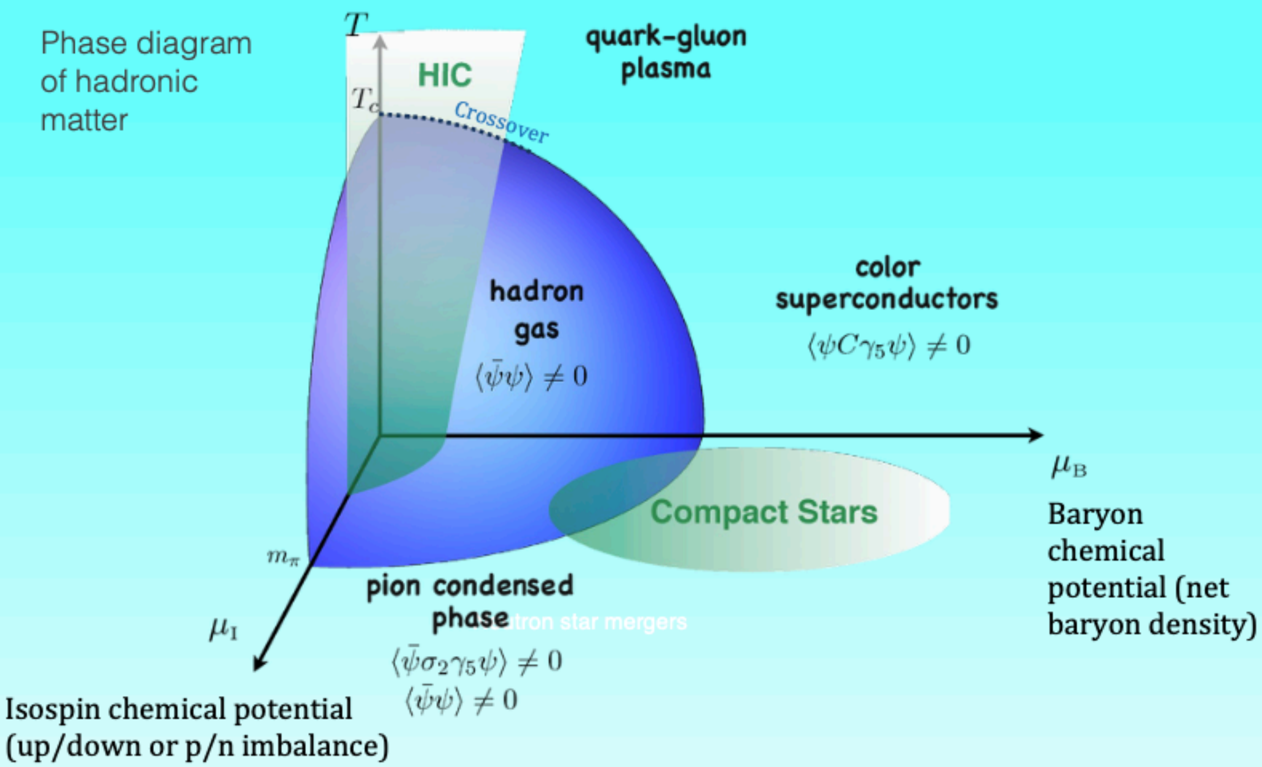
Quark matter

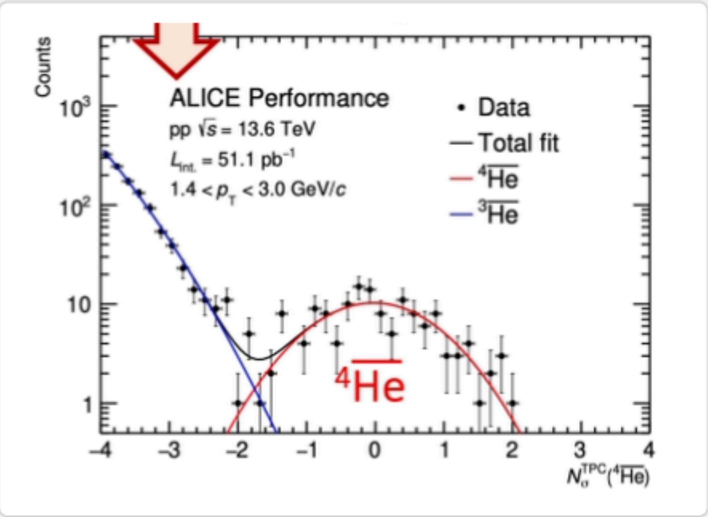
At LHC, QGP shows > 10 GeV/fm³ energy density, deconfinement, jet quenching, near-perfect fluidity, thermal hadronisation, and collective effects even in small systems

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

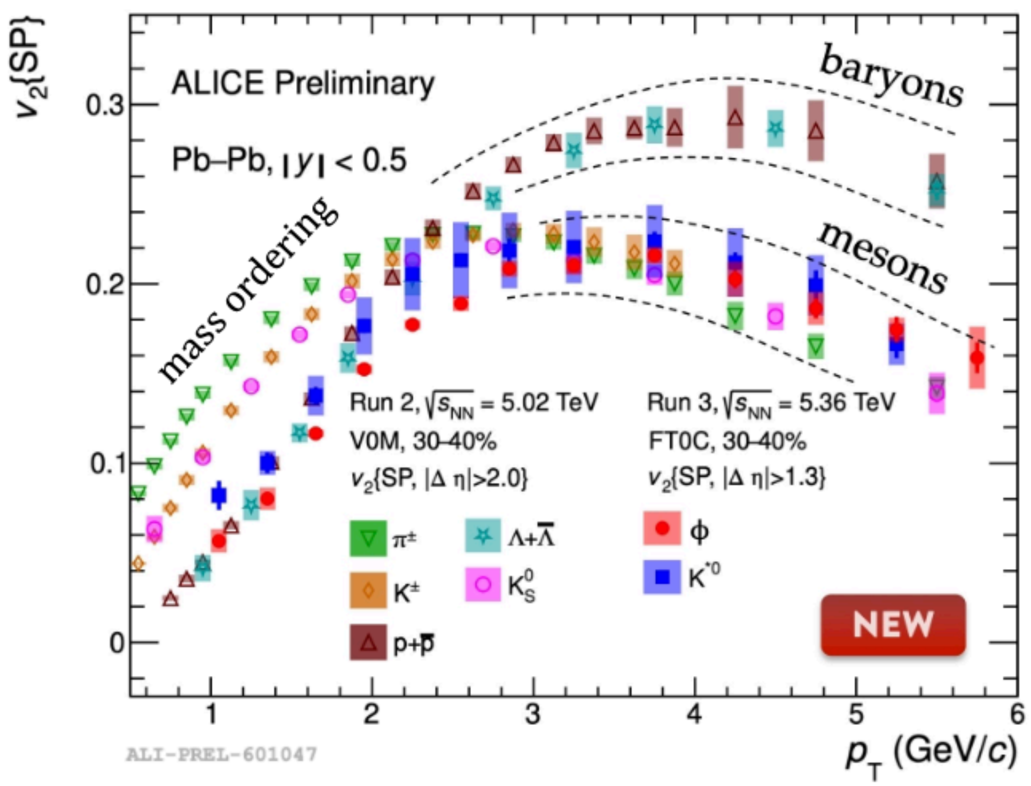
Anisotropic flow

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

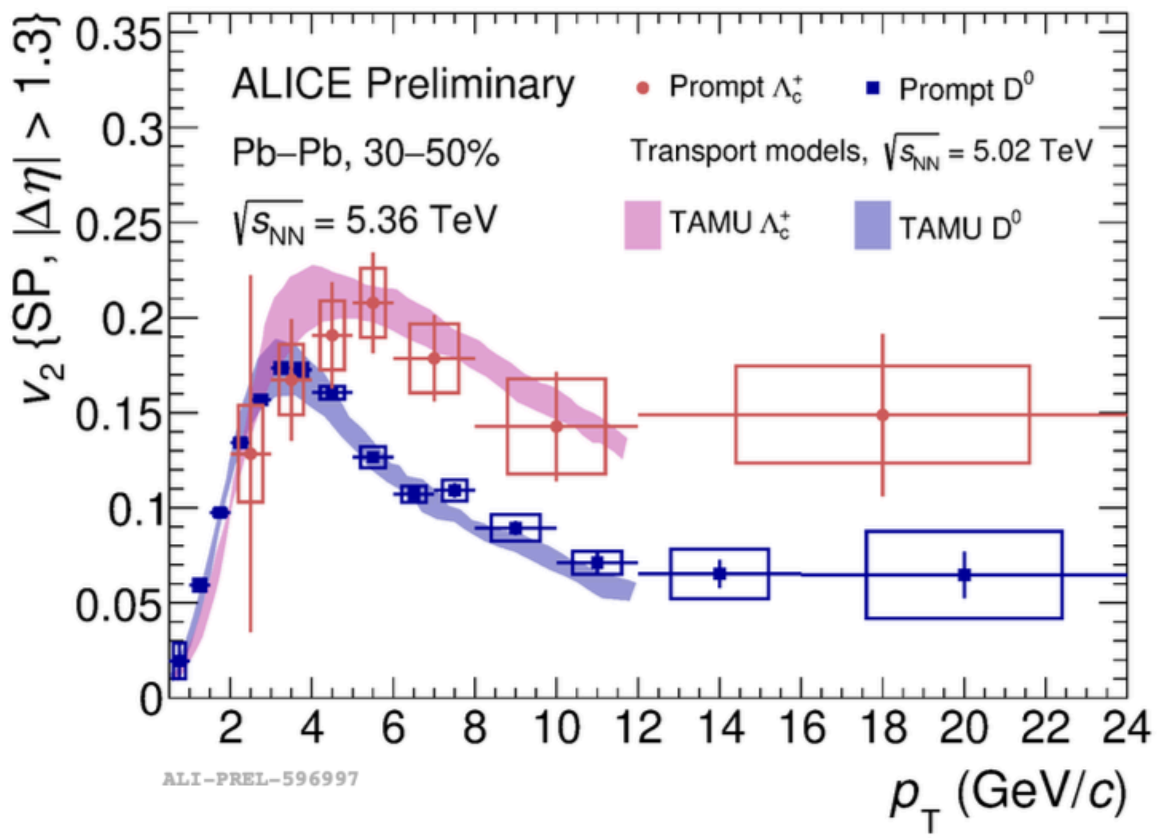
Transverse energy density profile in PbPb collisions at LHC has characteristic spatial fluctuations ("flow") quantified by Fourier harmonics v_n of particle distributions

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

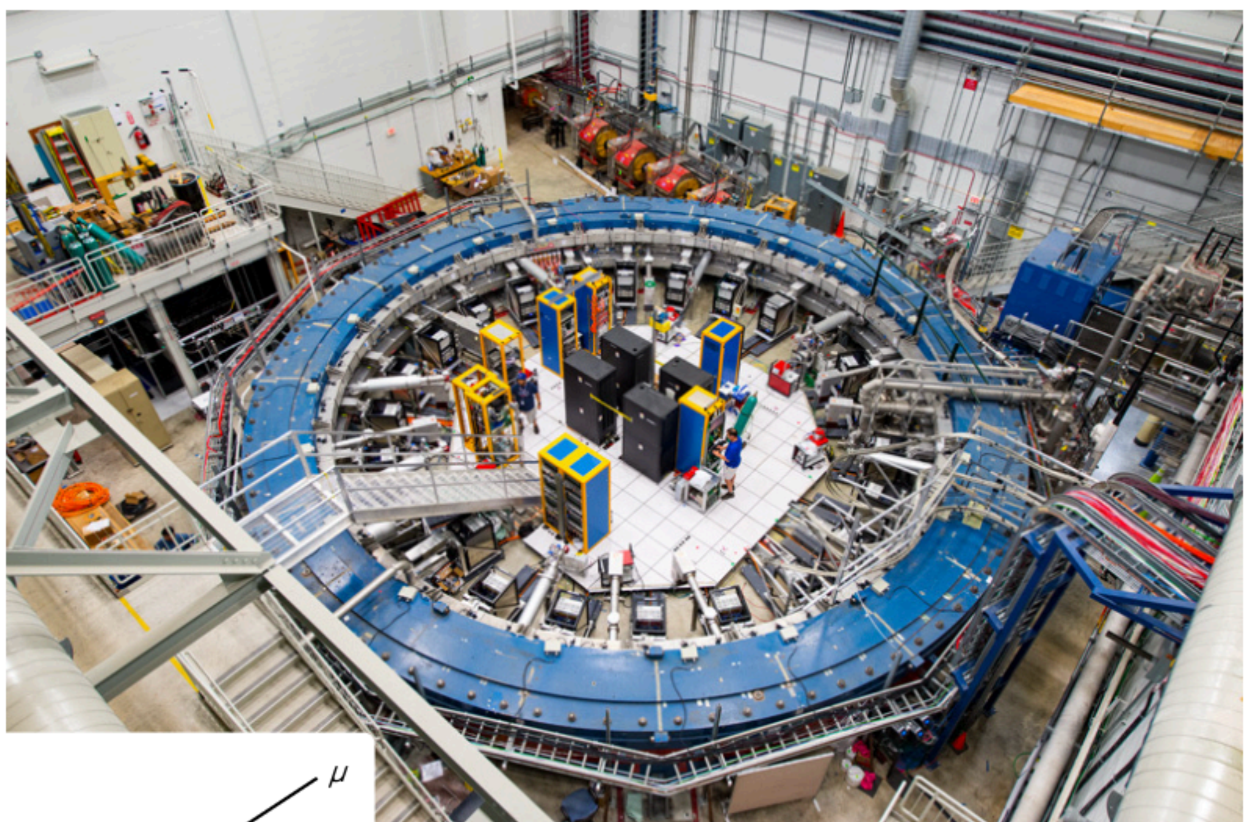
Anomalies

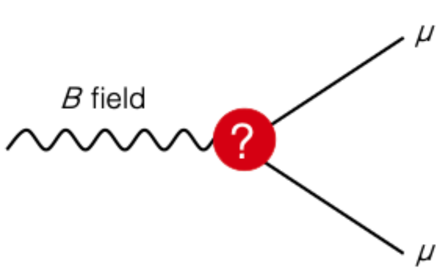
- The g-2 anomaly seems to go away

Ultimate precision — Congratulations!

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)





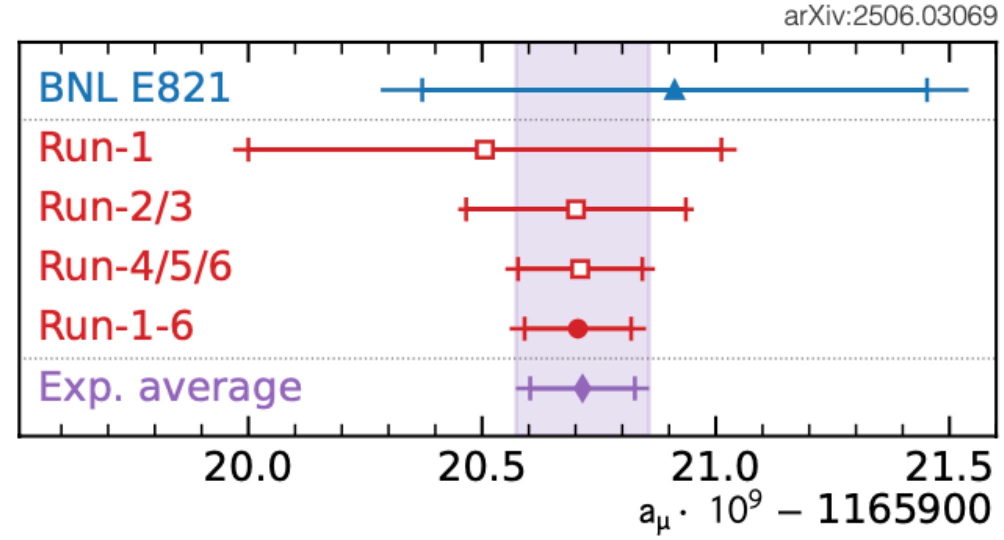
Muon g–2 Experiment at Fermilab

New world average (dominated by Fermilab experiment)

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

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

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)!**

THE STANDARD MODEL: THE STATUS AND OPEN QUESTIONS

- The W-mass anomaly seems to go away
- The lepton non-universality anomaly almost seems to go away

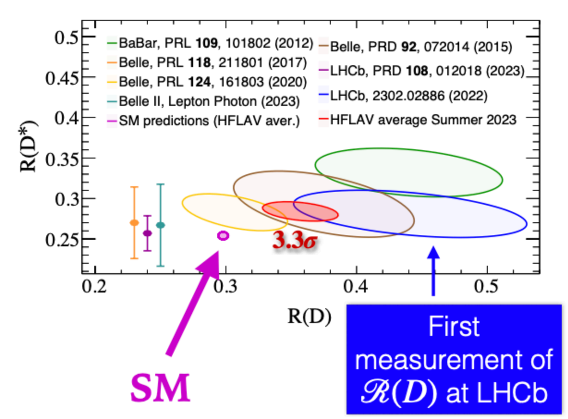
LHCb: $R(D^*) \equiv Br[B \to D^* \tau \nu_\tau] / Br[B \to D^* \ell \nu_\ell]$ [Franco Sevilla]

$\mathcal{R}(D^0)/\mathcal{R}(D^*)$ results

arXiv:2302.02886, submitted to *Phys. Rev. Lett.*

Contribution	Uncert. [%] $\mathcal{R}(D^*)$	$\mathcal{R}(D^0)$
Simulated sample size	5.3	10.2
DD bkg. shape	2.8	7.3
$\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ FFs	2.8	2.7
Signal/norm. FFs	2.5	4.8
Misidentified μ bkg.	2.5	2.7
Baryonic bkg.	2.5	2.7
DD bkg. model	2.1	1.6
$\overline{B} \to D_s^{**}\ell^-\overline{\nu}$ model	2.1	5.4
Total systematic	**8.5**	**15.0**
Total statistical	**6.4**	**13.6**
Total	**10.7**	**20.2**

Note that less than half of the systematic uncertainty is multiplicative, so the majority does not scale with central value



Manuel Franco Sevilla

Lepton flavour violation

Paolo Valente, Cecilia Voena

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

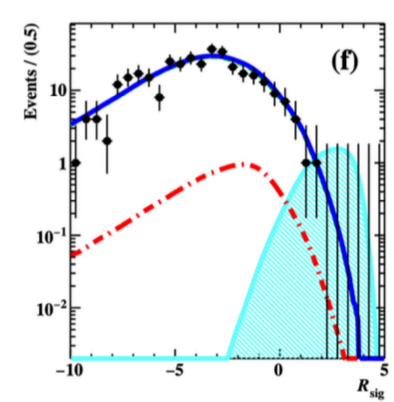
Since 2016, ATOMKI data show a persistent excess in e^+e^- angular distributions consistent with a ~17 MeV particle at rate vs. γ of ~ 6×10^{-6} (challenging measurement due to low energy of emerging e^+ / e^-). Follow-up studies with refined analyses and other nuclei confirm the anomaly. No SM explanation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

Tim Gershon, Atsushi Oya

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

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]

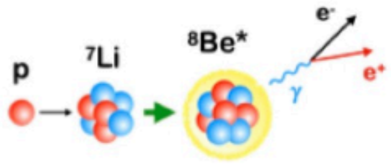
$B(\mu^+ \to e^+\gamma) < 1.5\times10^{-13}$ (90% CL)

X17 Seems to go away

Paolo Valente, Cecilia Voena

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

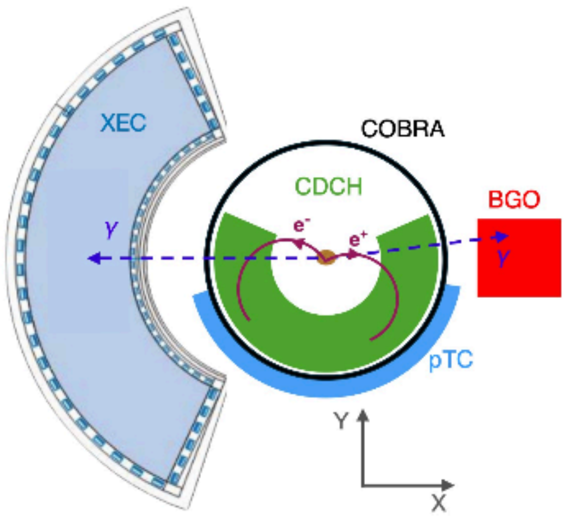
Since 2016, ATOMKI data show a persistent excess in e^+e^- angular distributions consistent with a ~17 MeV particle at rate vs. γ of ~ 6×10^{-6} (challenging measurement due to low energy of emerging e^+ / e^-). Follow-up studies with refined analyses and other nuclei confirm the anomaly. No SM explanation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

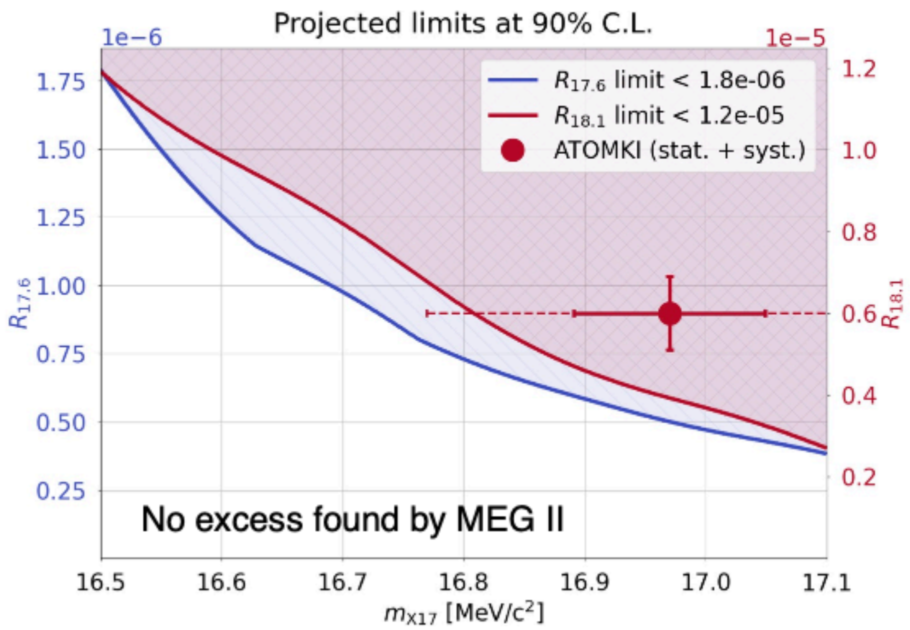


Many groups looking at this anomaly. Two reports this week:

MEG II (PSI) [arXiv:2411.07994]

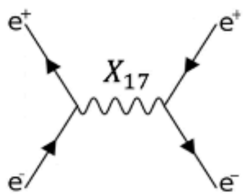
Dedicated 4-week run in Feb 2023 with 1.08 MeV proton on Li target, measuring outgoing ^{8}Be* de-excitation photons and e^+, e^-

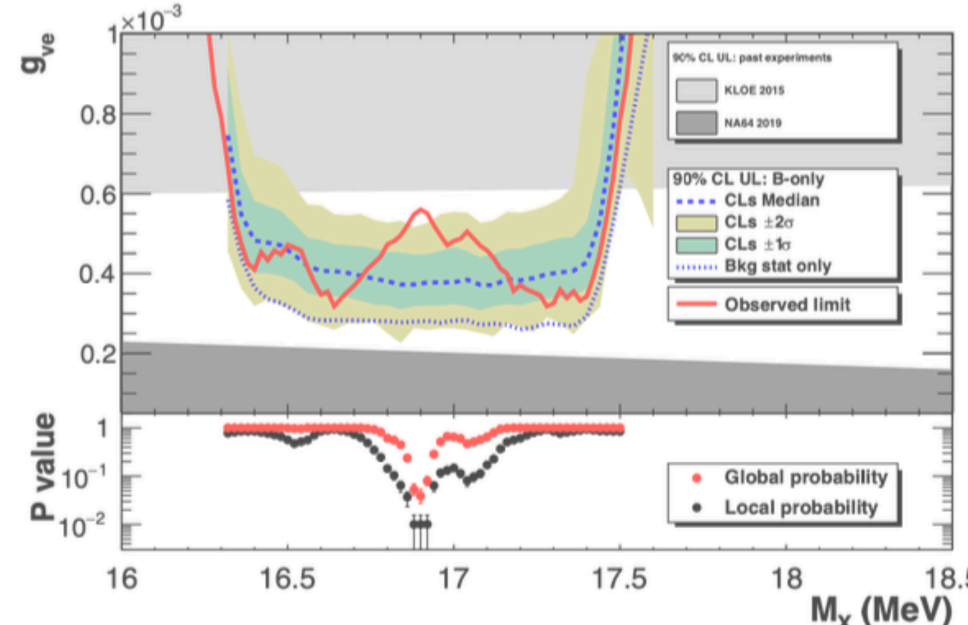




PADME (Frascati) [arXiv:2505.24797]

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

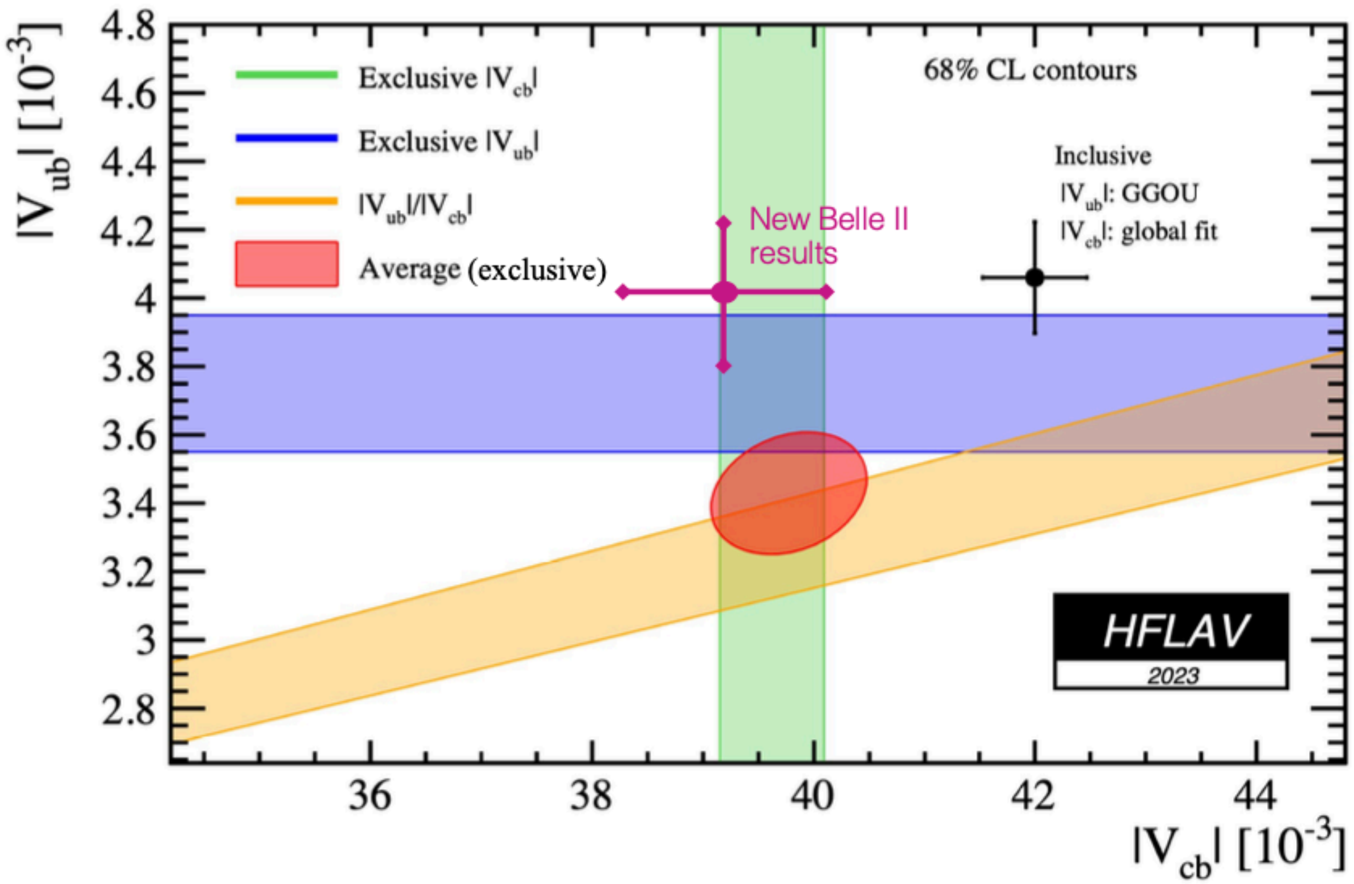
|V_{cb}| and |V_{ub}| (puzzle)

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

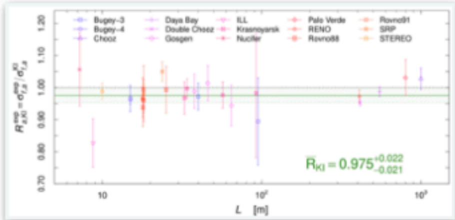
arXiv:2506.15256 and preliminary

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

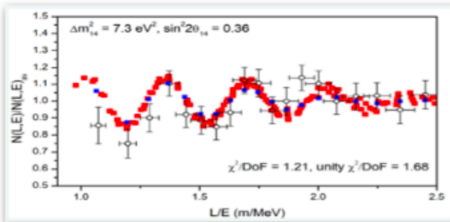


Neutrino Anomalies

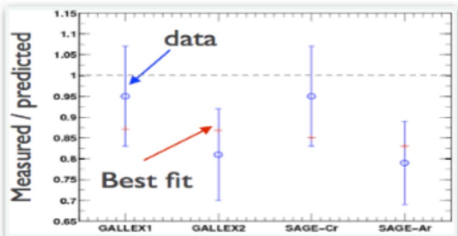
Albert De Roeck



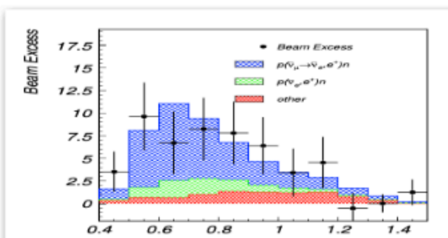
reactor flux anomaly
resolved with new input data
to flux calculation ✔



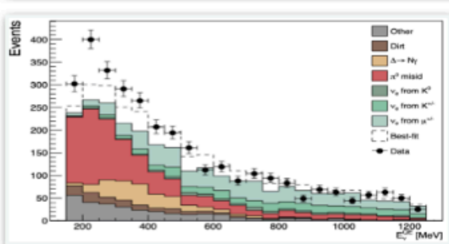
reactor spectra
is there really an anomaly? -> DANSS ?



gallium anomaly
unresolved, recently reinforced BEST ?



LSND
unresolved ?



MiniBooNE
unresolved µBooNe excluded some explanations
resolvable by next-gen. SBL experiments ?

More details in the backup

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides…
- Future: Reactor experiments continuing or new ones (eg JSNS^2) or new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

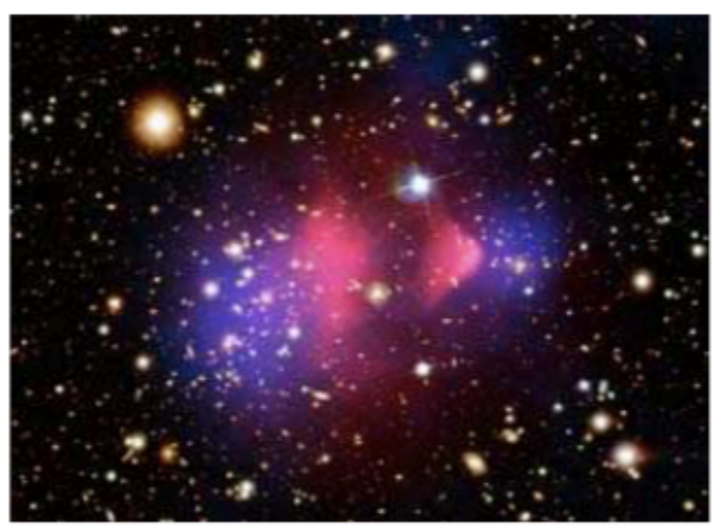
Dark matter

Major problem: 85% of matter is dark and remains invisible!

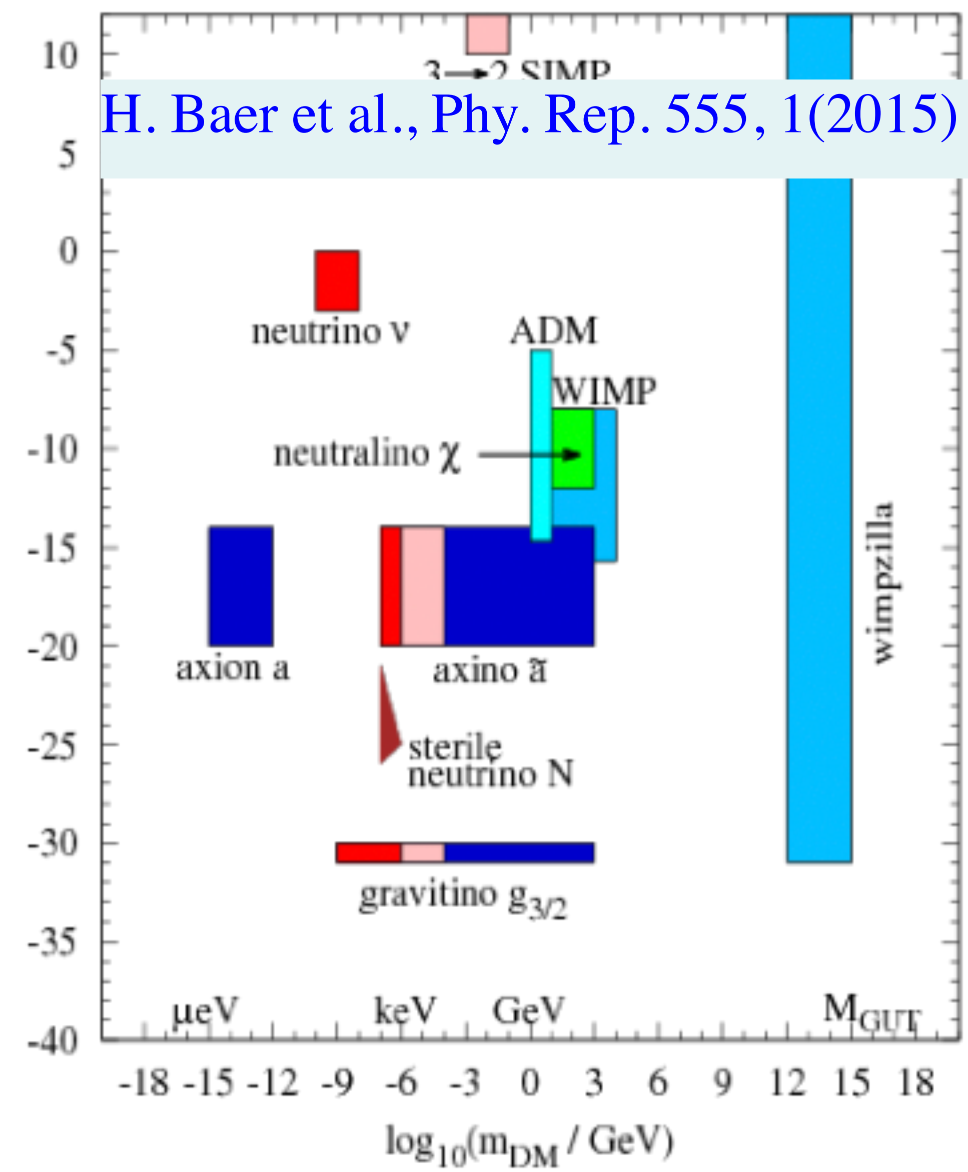
Is this compatible with the SM?

Does it requires modification of the SM or addition of gravity?

- **Many candidates in many orders of magnitude of mass:**
  - **MOND** (Problems: large scales, Bullet cluster)
  - **Primordial black holes** (LIGO, but constraints)
  - **Fuzzy** (very light bosons)
  - **Warm** (KeV sterile)
  - **WIMP**
  - **Axions/ALPs**
  - **Dark sector**
  - **Gravitinos**
  - **Moduli**
  - **Wimpzillas**



M. Drees



H. Baer et al., Phy. Rep. 555, 1(2015)

- **Direct, indirect, collider**

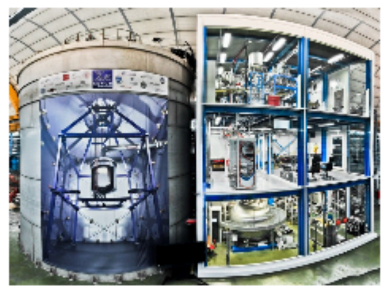
Dark matter halo — operating xenon experiments

Paloma Cimental, Amy Cottle,
Clara Murgui Galvez

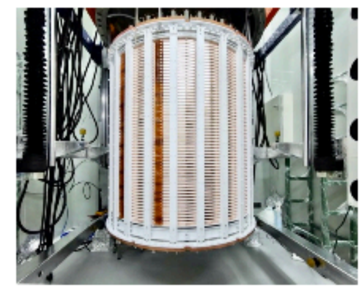
Looking for nuclear recoil of target from elastic collision with dark matter particle

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

XENONnT at LNGS, Italy, 5.9 t active mass

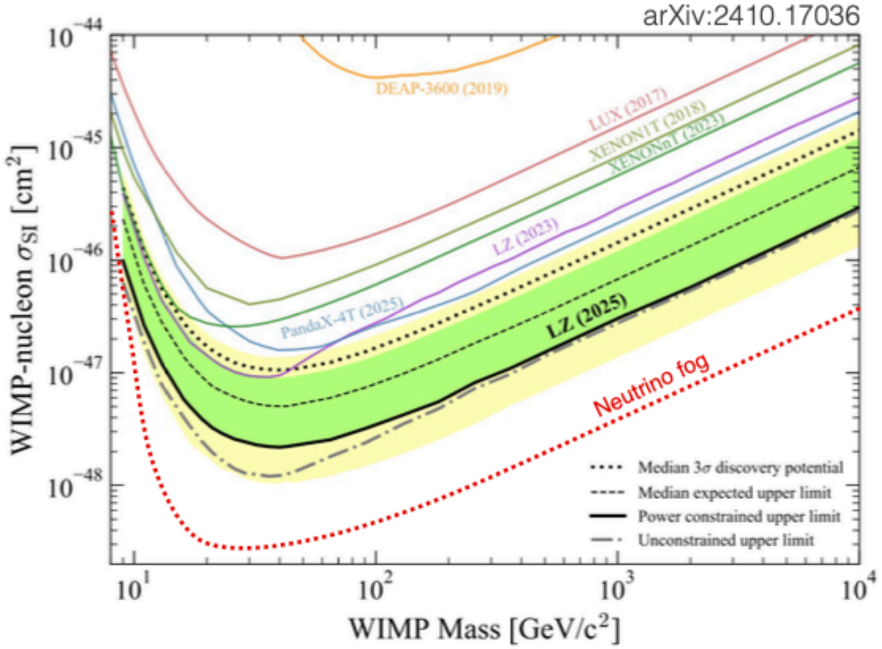


PandaX-4T at CJUL, China, 3.7 t active mass

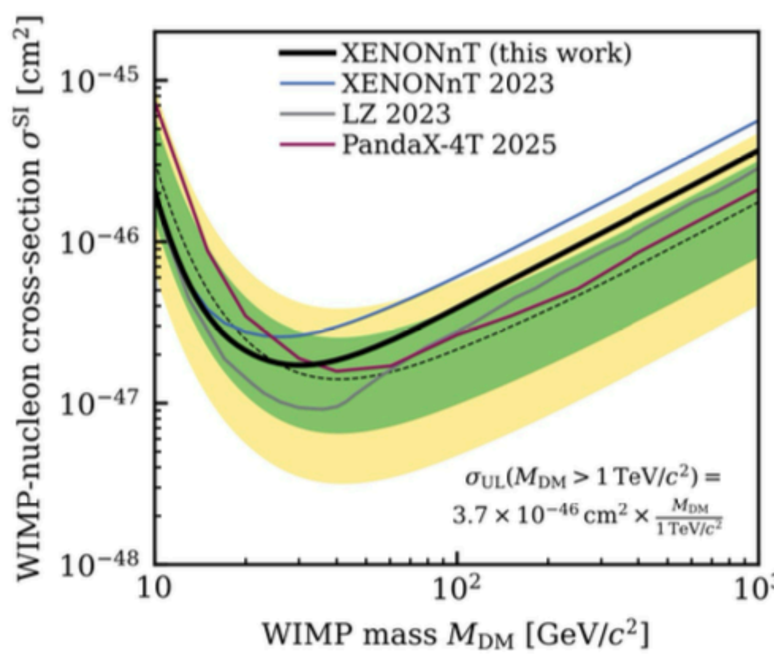


Latest SI result with 4.2 t×yr exposure:
(LZ and XENONnT continue running until 2028)

arXiv:2410.17036

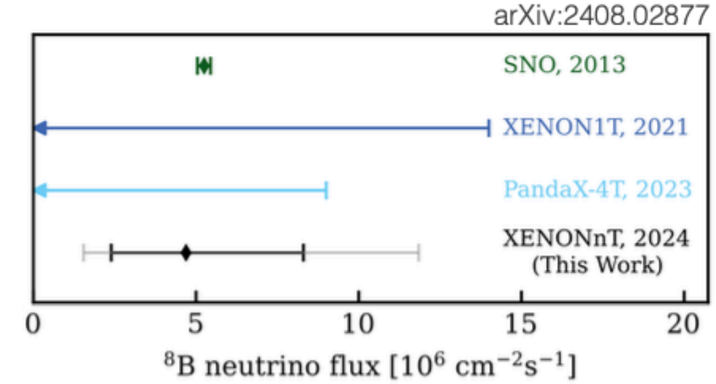


Latest SI result with 3.1 / 1.54 t×yr exposure for XENONnT [2502.18005] / PandaX-4T [2408.00664]:

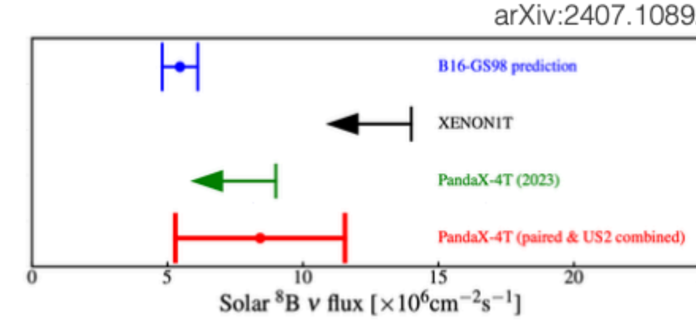


XENONnT and PandaX-4T report first evidence of nuclear recoils from solar neutrinos (boron-8) with a dark matter detector

arXiv:2408.02877



arXiv:2407.10892

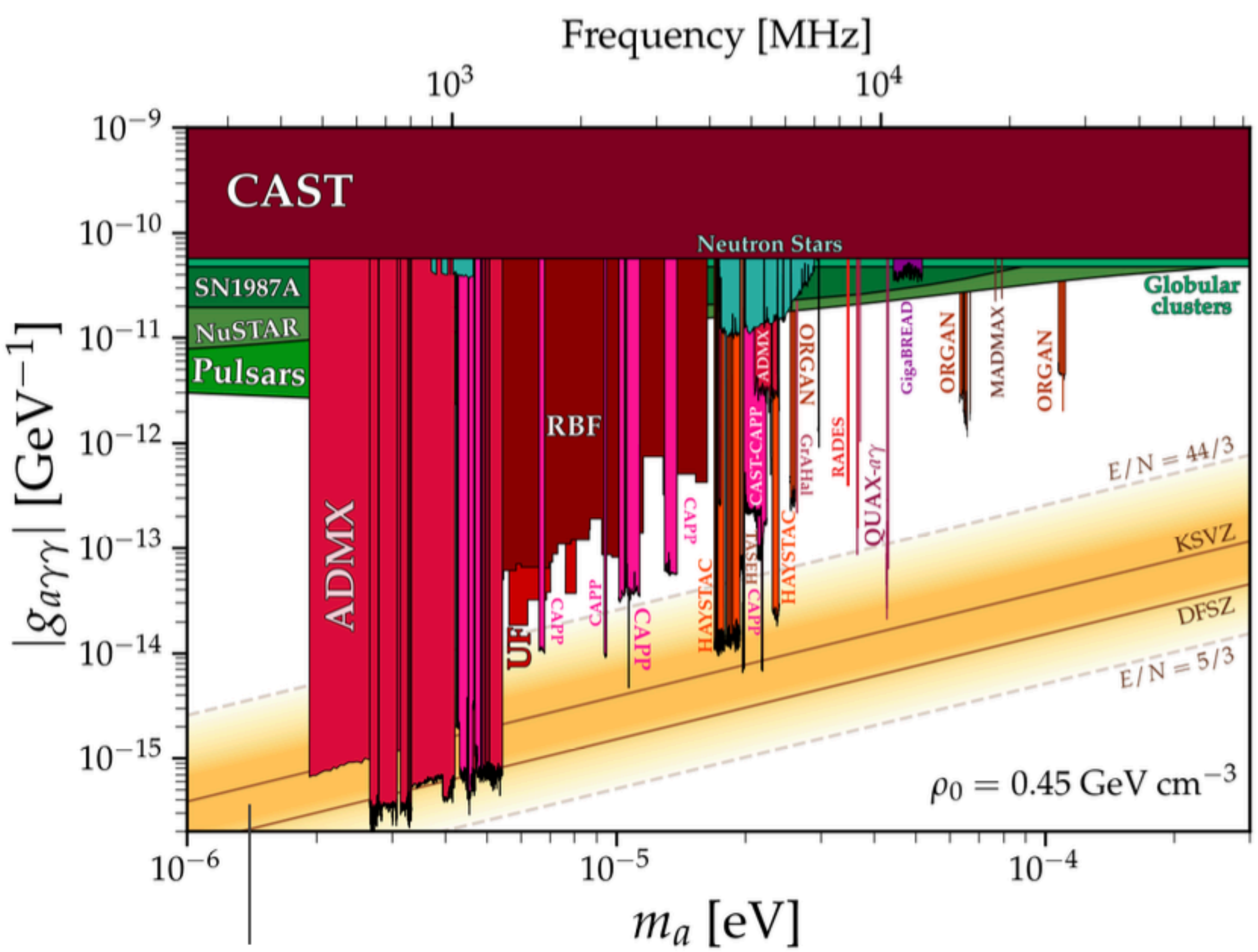


First detection of elastic NRs from astrophysical neutrinos, first measurement of the coherent elastic neutrino-nucleus scattering (CEνNS) process with Xe target, first step into the "neutrino fog" by DM experiment

Axions

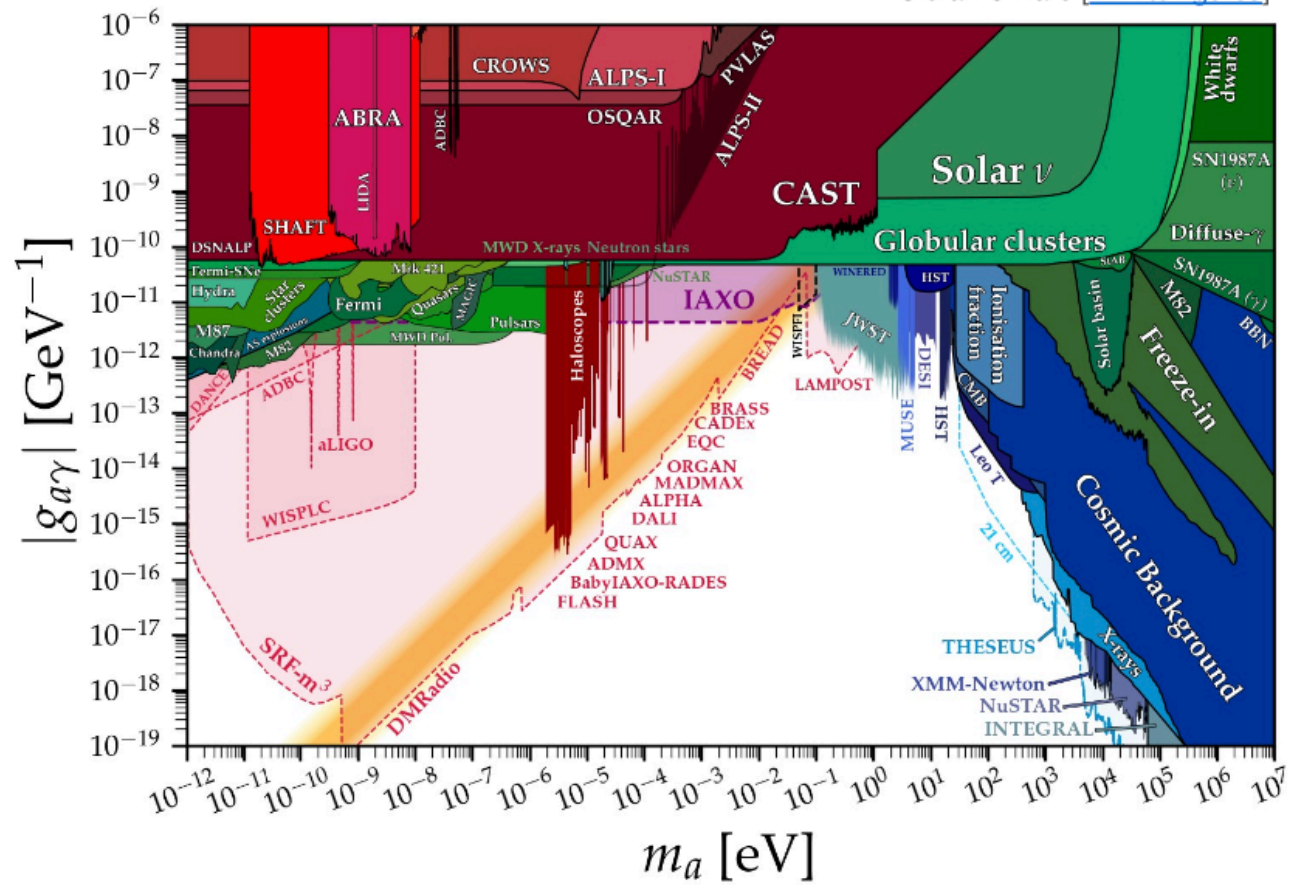
Clara Murgui Galvez

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



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

Cioran O'Hare [Link to figures]



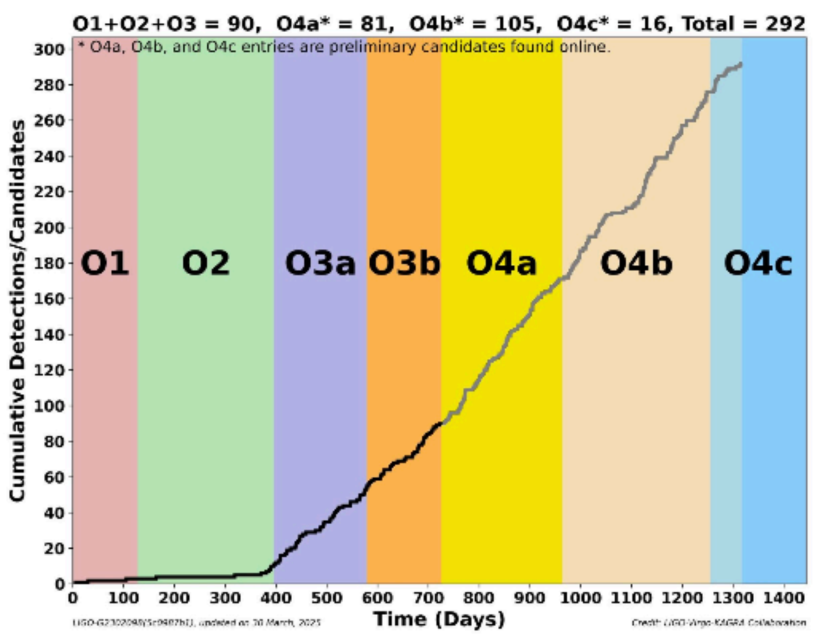
Gravitational waves

Gravitational waves (GW)

Antoine Petiteau, Aditya Vijaykumar

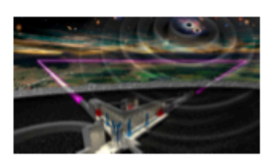
Total of 292 GW events detected (and continuing), GW science is becoming statistical

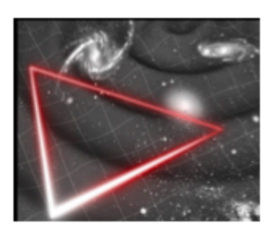
Basic distributions such as mass and mass differences of binary mergers under scrutiny



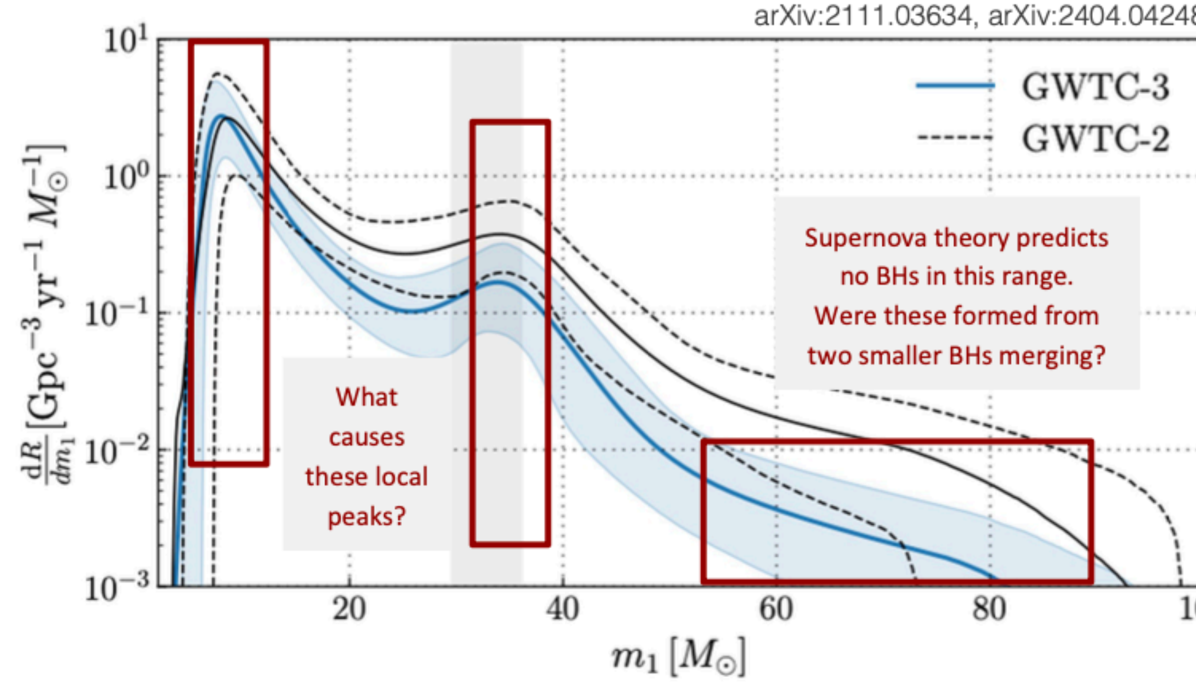
With **Einstein** and **Cosmic Explorer** expect to collect > 10^5 BH-BH, BH-NS, and NS-NS merger events

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

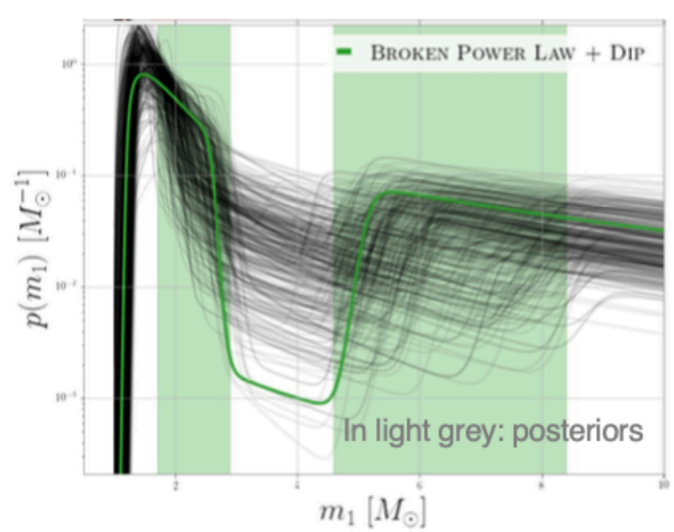




arXiv:2111.03634, arXiv:2404.04248



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)

Gravitational waves (GW)

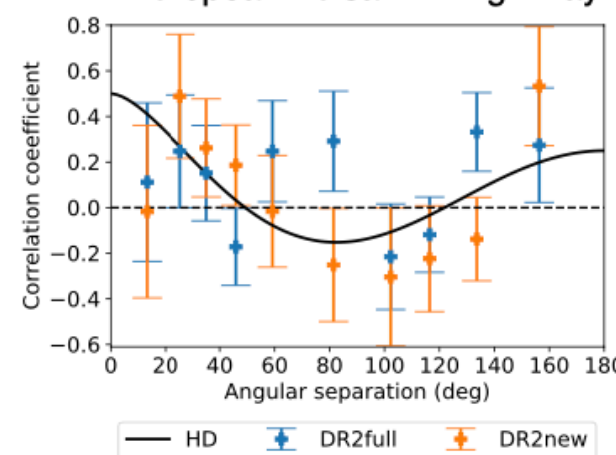
Antoine Petiteau, Jishnu Suresh, Sonali Verma

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)

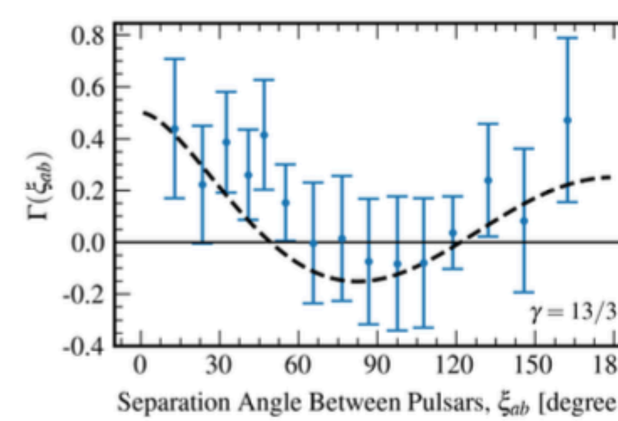
Illustration of gravitational waves caused by orbiting supermassive black hole pairs [found here]

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

European Pulsar Timing Array



NANOGrav



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

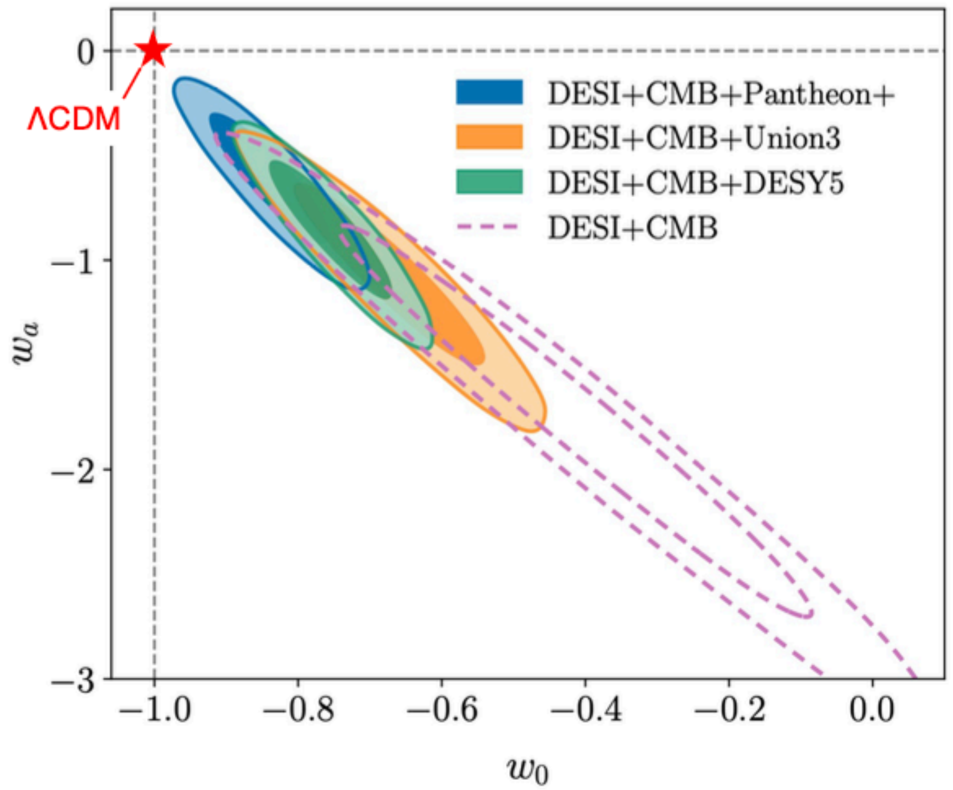
DESI DR2 (3 years) results on Baryon Acoustic Oscillation (BAO) — standard cosmological ruler (~ 150 Mpc today)

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

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)

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

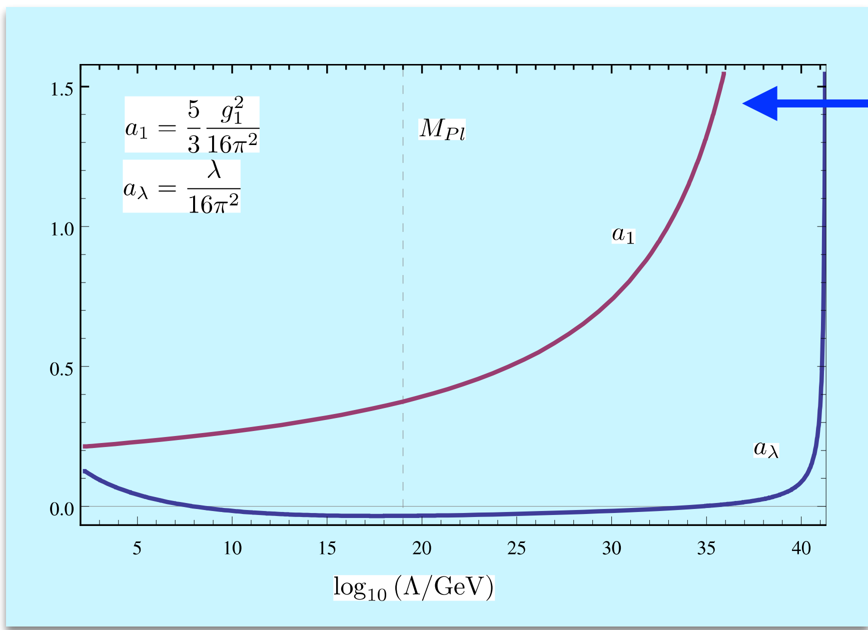
JWST with better resolution will provide further clues

The SM: open questions

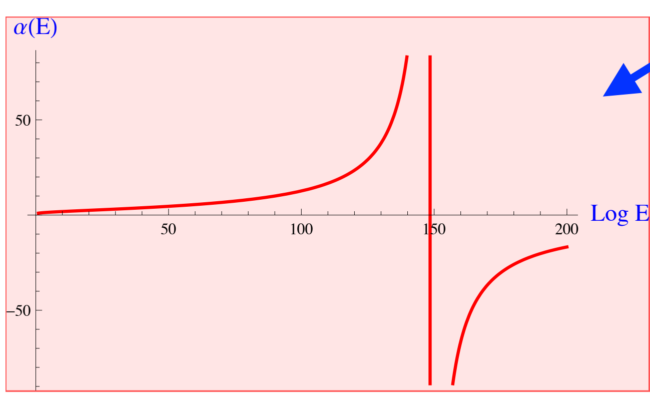
- Landau pole for the U(1) and Higgs couplings at subplankian energies
- Instability of the electroweak vacuum at the preGUT scale
- Hierarchy problem (unprotected Higgs mass with respect to radiative corrections)
- Problem of strong CP violation (absence of axion?)
- Possible new ingredients in neutrino sector (majorana neutrino)
- Inability to describe the Dark matter (unless it has pure gravitational nature)
- Baryon asymmetry of the Universe is a fundamental problem (Baryon and Lepton genesis might require new ingredients)
- Lack of understanding of flavour structure of the SM

Landau pole for the U(1) and Higgs couplings at subplankian energies

- The running couplings possess the Landau ghost poles at high energies



- The ghost pole exist for the U(1) coupling and for the Higgs coupling, but … beyond the Planck scale
- The Landau pole has a wrong sign residue that indicates the presence of unphysical ghost fields - intrinsic problem and inconsistency of a theory



This is the ghost pole

$$\alpha_1(Q^2) = \frac{\alpha_{10}}{1 - \frac{41}{10}\frac{\alpha_{10}}{4\pi}\log(Q^2/M_z^2)}$$

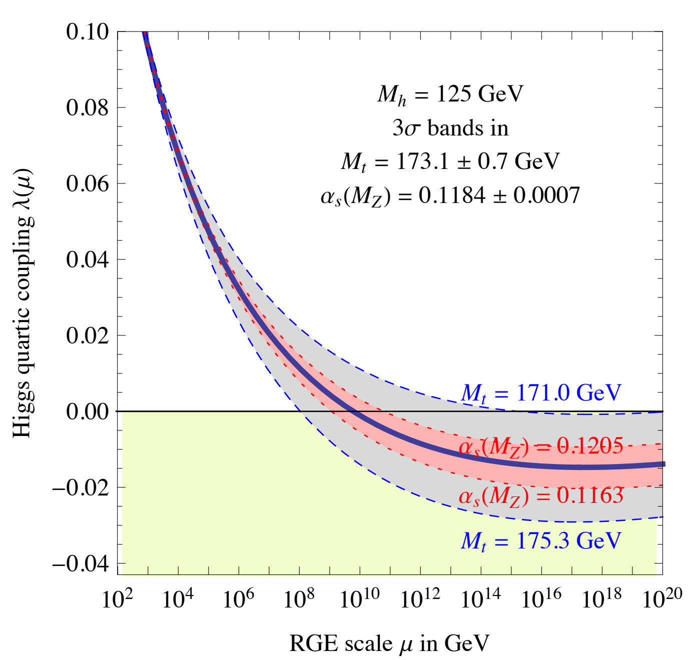
$$Q^* = M_Z e^{\frac{20\pi}{41\alpha_{10}}} \sim 10^{41}\ GeV$$

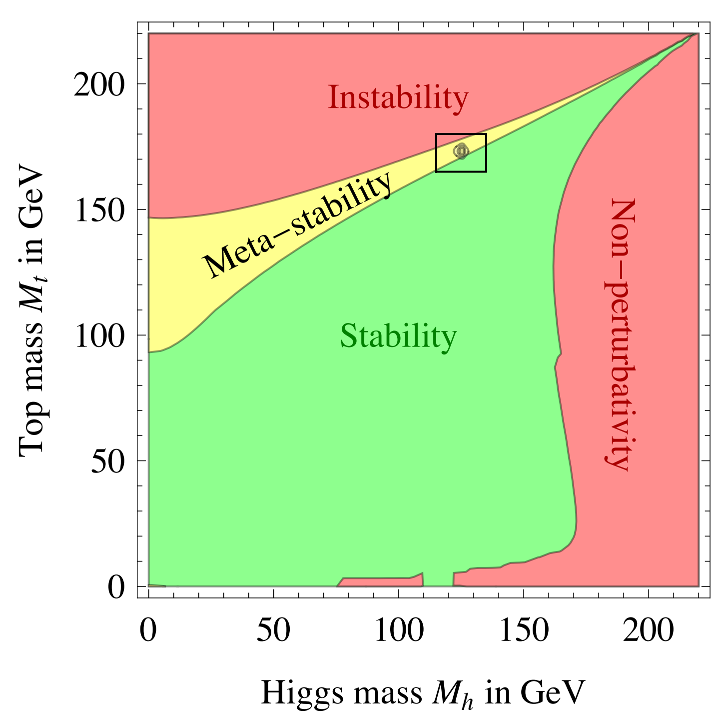
- The situation may change in GUTs due to new heavy fields @ the GUT scale
- requires modification of the SM at VERY high energies

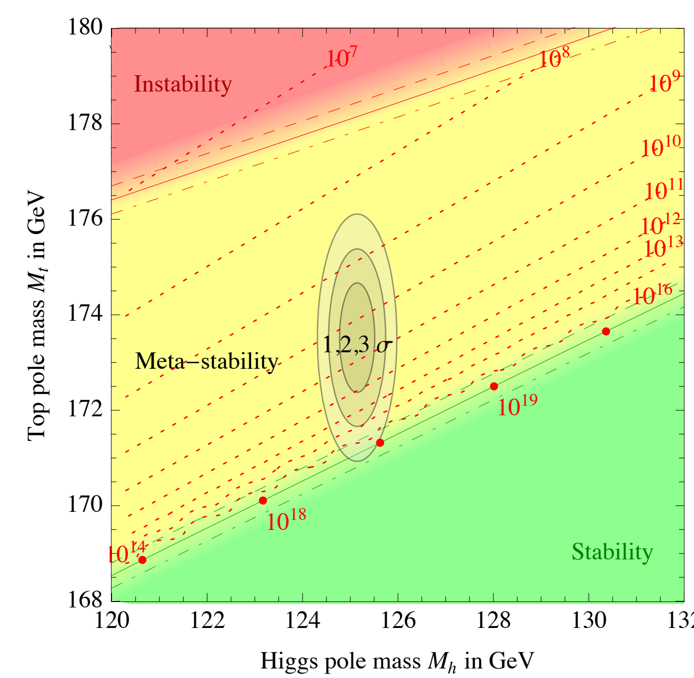
Instability of the electroweak vacuum at the preGUT scale

- Quantum corrections can make the vacuum unstable

- the whole construction of the SM may be in trouble being metastable or even unstable
- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and accuracy

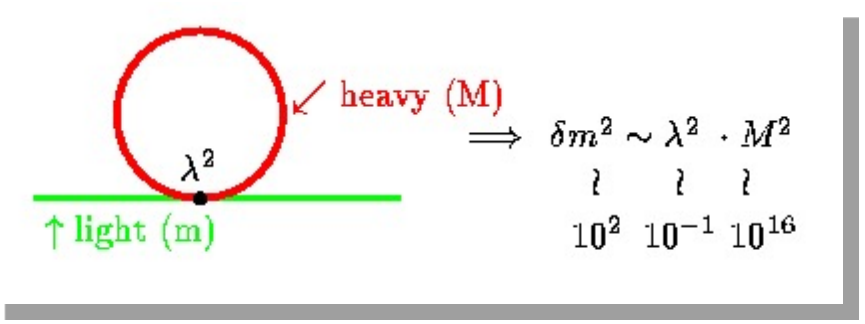






The way out might be the new physics at higher scale

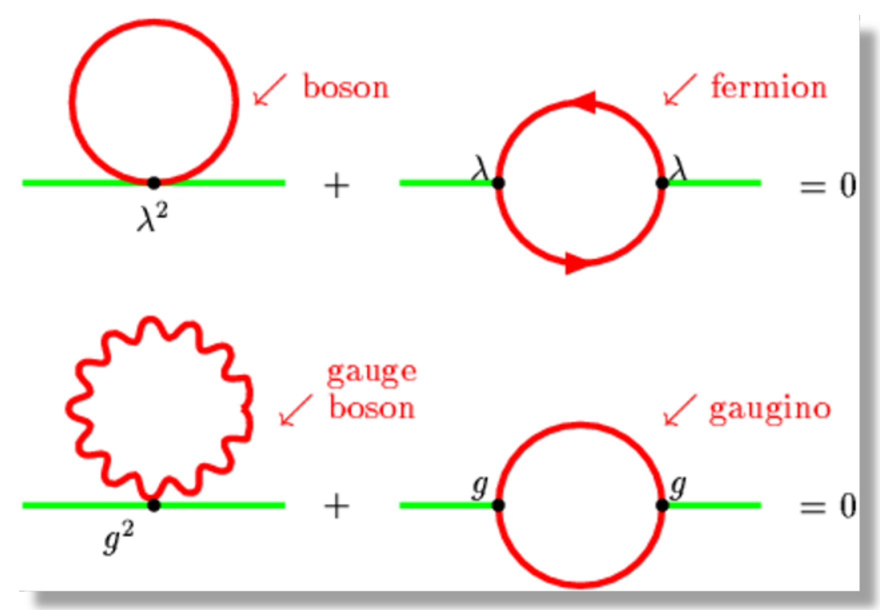
Hierarchy problem
(unprotected Higgs mass with respect to radiative corrections)



$$m_H \sim v \sim 10^2 \text{ GeV}$$
$$m_\Sigma \sim V \sim 10^{16} \text{ GeV}$$
$$\frac{m_H}{m_\Sigma} \sim 10^{-14} \ll 1$$

Destruction of the hierarchy by radiative corrections

Solution of the hierarchy problem in SUSY theories: cancellation due to fermions



Hierarchy problem is NOT the problem of the Standard Model!

It is the problem of high energy extensions of the SM.

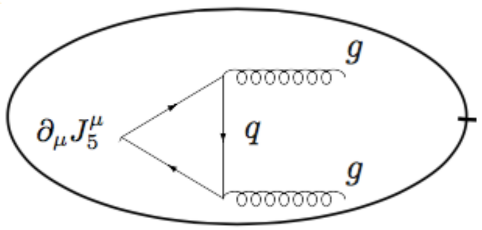
Problem of strong CP violation (absence of axion?)

Javier Redondo, EPS HEP 2017

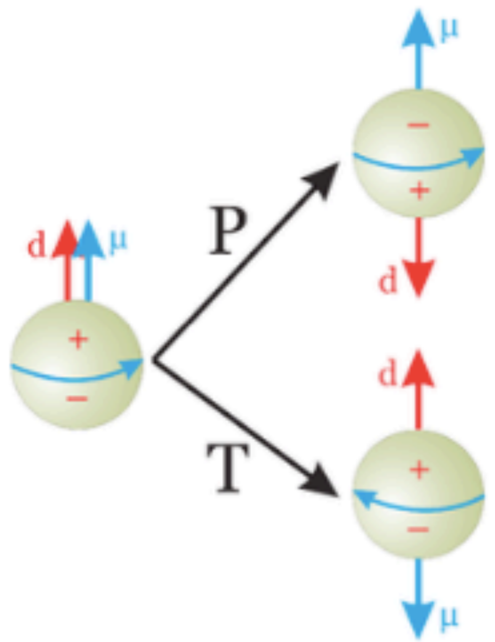
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f \delta$

$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\,\theta_{\rm QCD}$$

Axial anomaly



The θ-angle produces flavour-neutral CP violation like Electric Dipole Moments



- **Neutron EDM** (Guo 1502.02295)

$$d_n = -4 \times 10^{-3} \times \theta\,[\mathrm{e\,fm}]$$

- **Experimental upper limit** (Grenoble hep-ex/0602020)

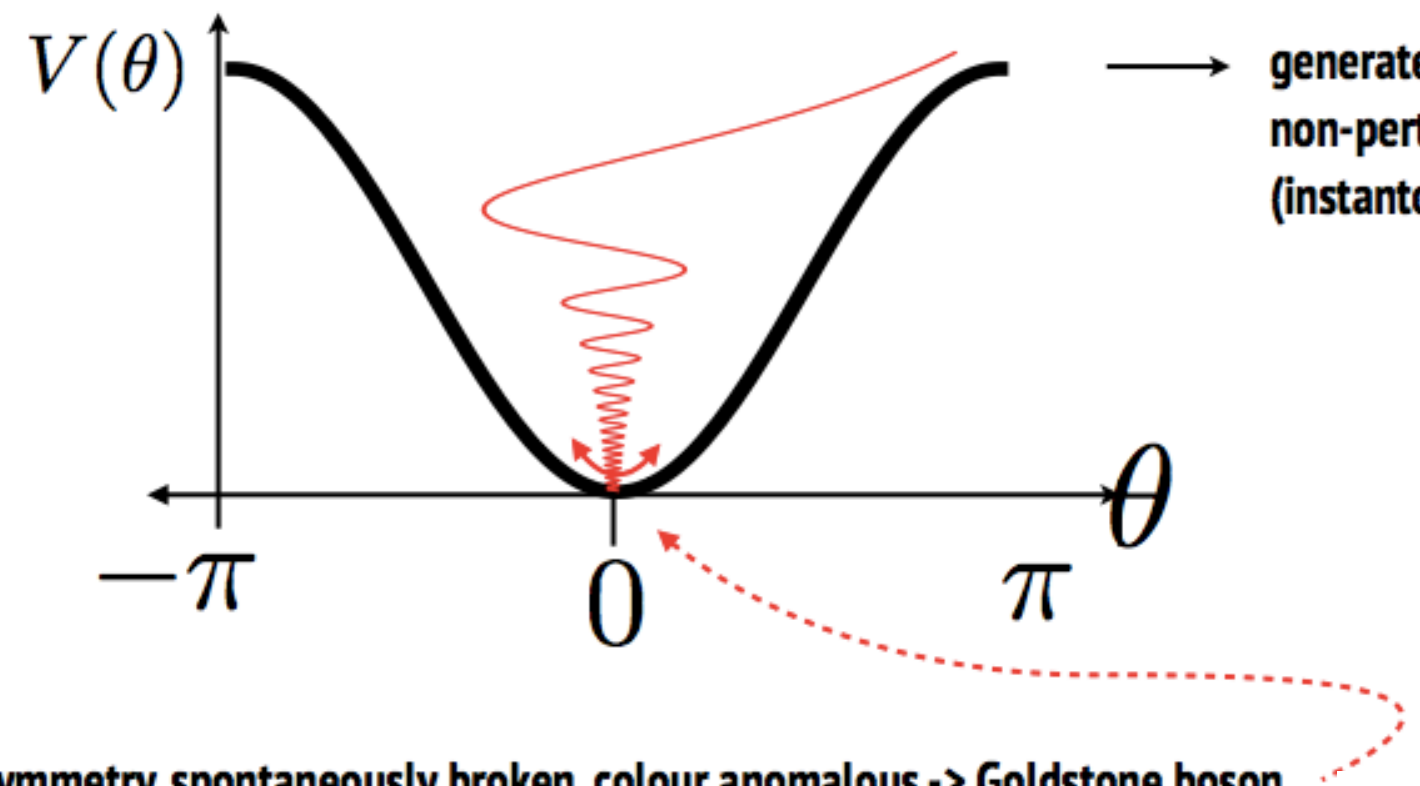
$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- **Why is $\theta < 10^{-10}$?**

PECCEI-QUINN MECHANISM - AXION

- Any theory promoting θ to a dynamical field, $\theta(t, \mathbf{x})$, will dynamically set $\theta \to 0$ after some time...

Potential energy density



generated by QCD non-perturbative dynamics (instantons)

- PQ Mechanism: Global U(1) axial symmetry, spontaneously broken, colour anomalous -> Goldstone boson

$$\mathcal{L}_\theta = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f_a^2 - \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta$$

New Spontaneous symmetry breaking [energy] scale f_a

Canonically normalised θ field is the QCD AXION! $a(x) = \theta(x) f_a$

WW Axion

NEUTRINO PUZZLE

One can often hear that:

- The Standard Model predicts zero neutrino mass
- The Standard Model does not describe neutrino oscillations

These are all false statements!

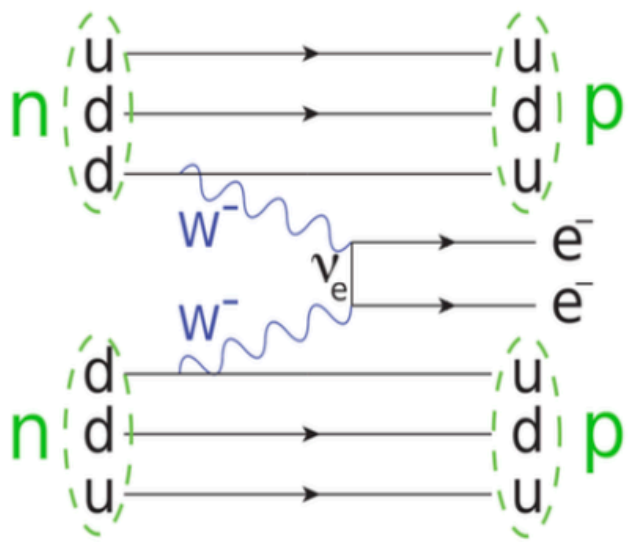
- One can always introduce interaction of neutrino with the Higgs field with arbitrary coupling and can introduce PMNS mixing martix just like in the quark sector.

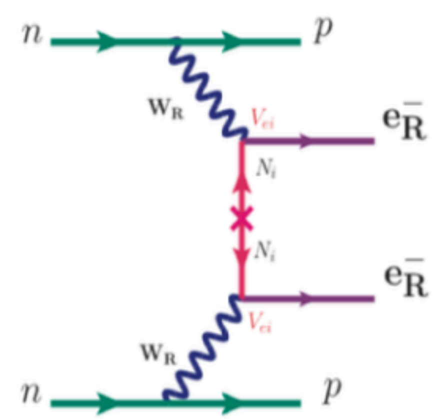
- If neutrinos are Majorana fields one can always add the Majorana mass term slightly extending the SM. Then one can also have additional phases in the mixing matrix.

Neutrinoless Double Beta Decay

The question is still unanswered:

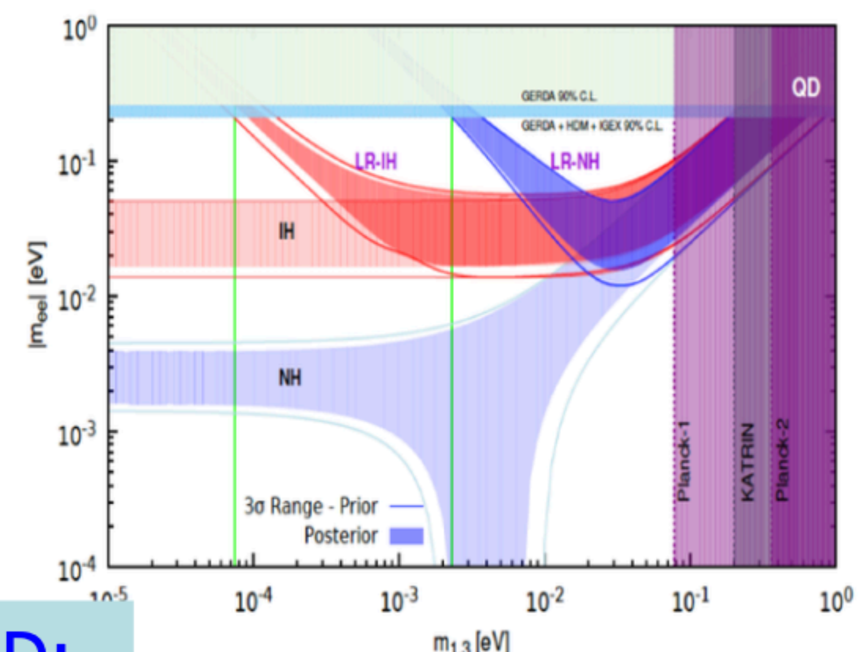
Are neutrinos their own antiparticles?





Left-Right Symmetric Model,
$M_{W_R} \sim 2$ TeV, $M_N = 1$ TeV,
$g_R \sim 2/3\, g_L$

JHEP 10 (2015) 077



Ton scale 0nuBB experiments will cover the inverted hierarchy by 2035

Many experiments operating, planned or in R&D:
LEGEND, SNO+, NEXT, CUPID, THEIA…

Looking for new physics we are looking for new Symmetry of Nature!

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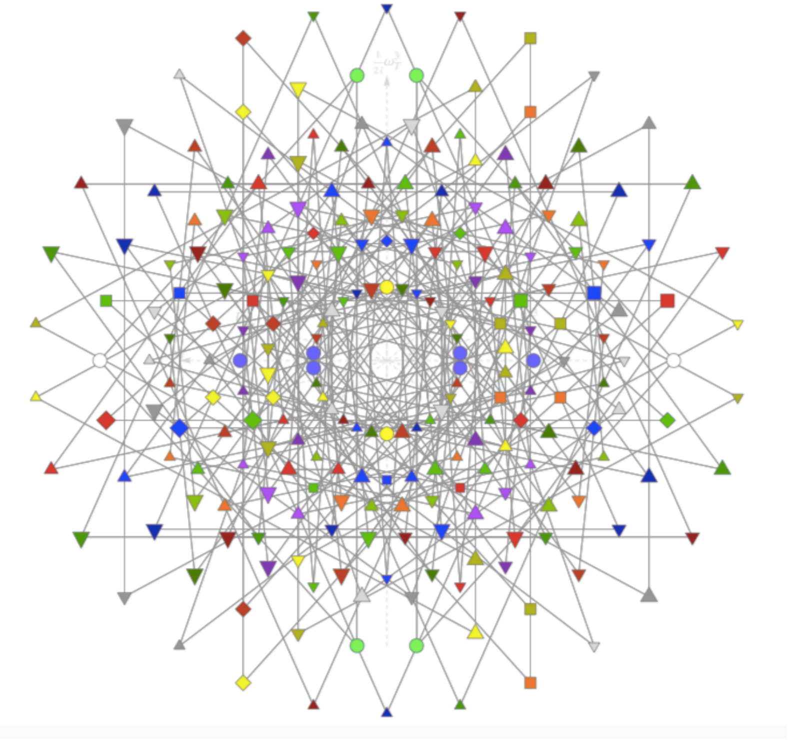
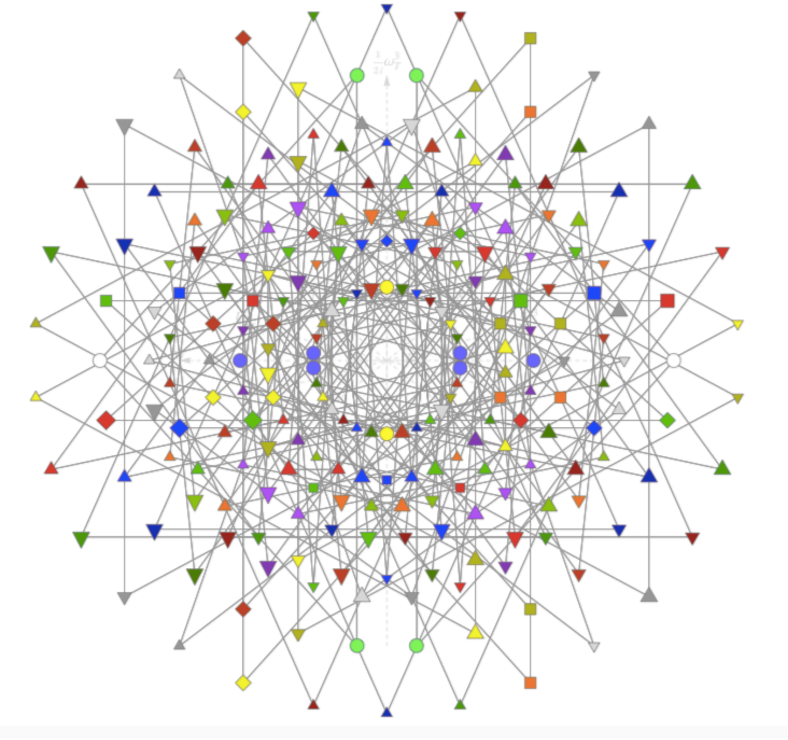


E8 roots

Looking for new physics we are looking for new Symmetry of Nature!



E8 roots

Symmetry might be tricky

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