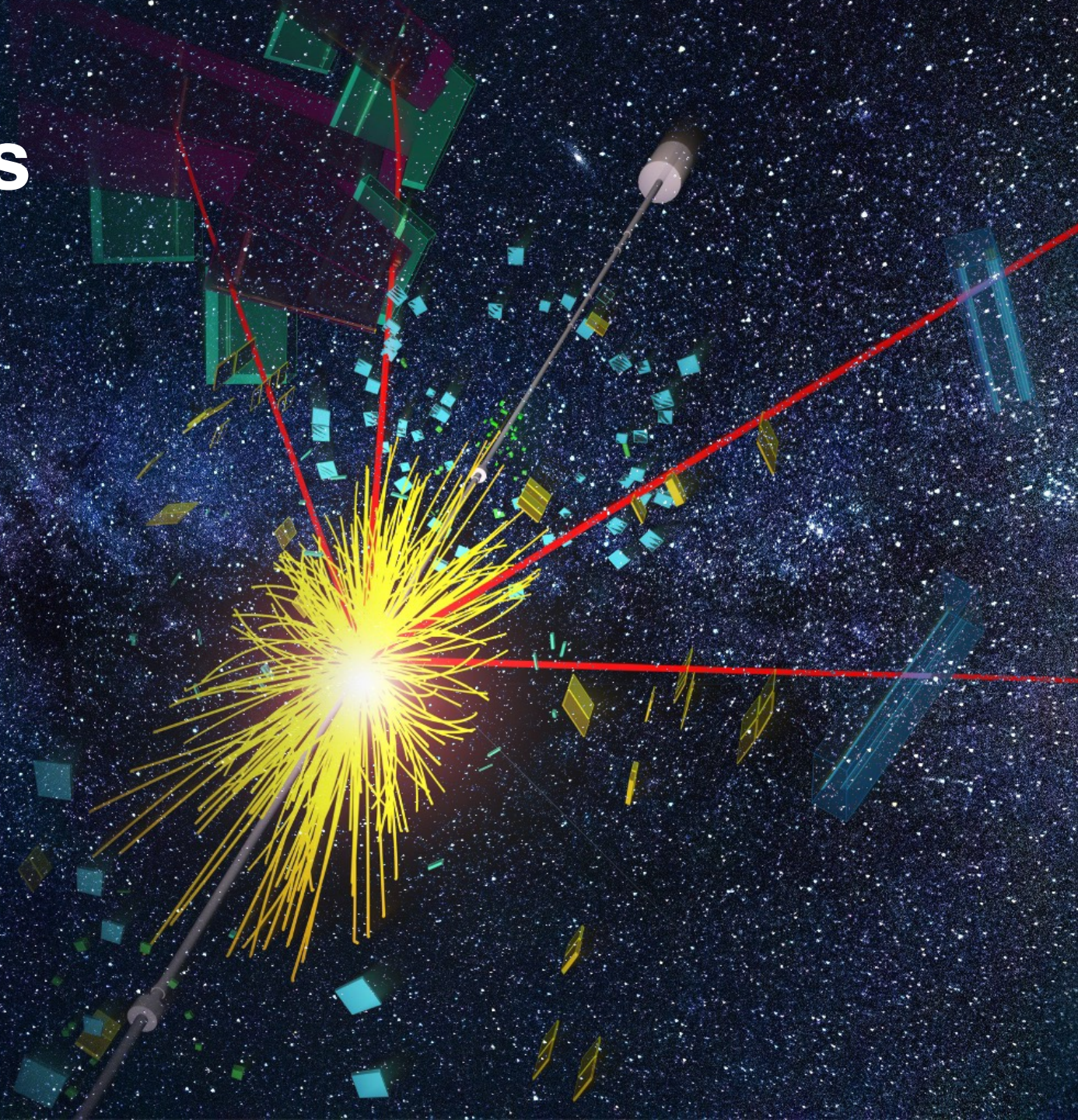


Experimental Physics at the LHC (3)

Andreas Hoecker (CERN)

57. Herbstschule HEP

1–11 September 2026, Bad Honnef, Germany

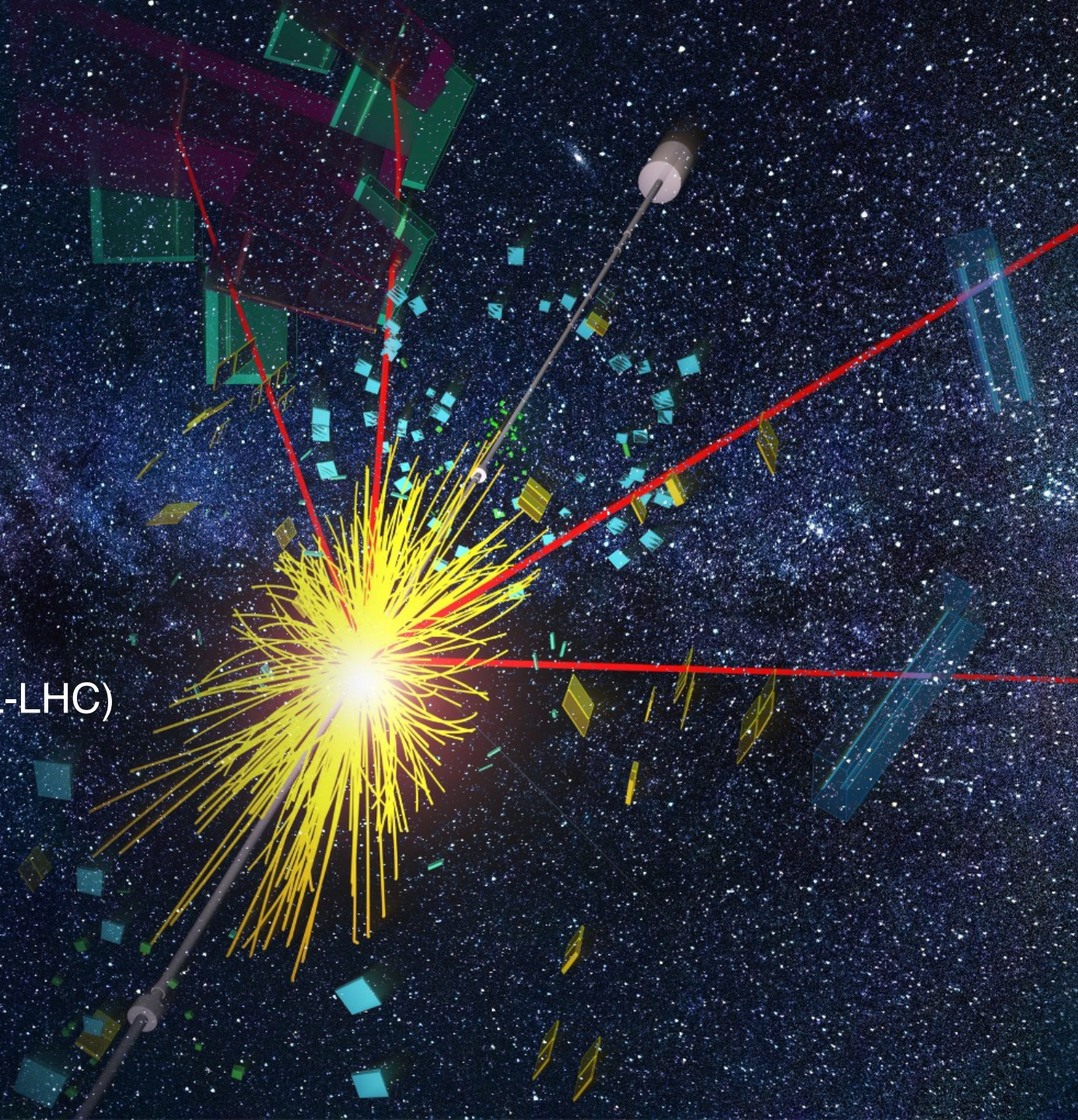


Today's lecture:

- Selected physics topics

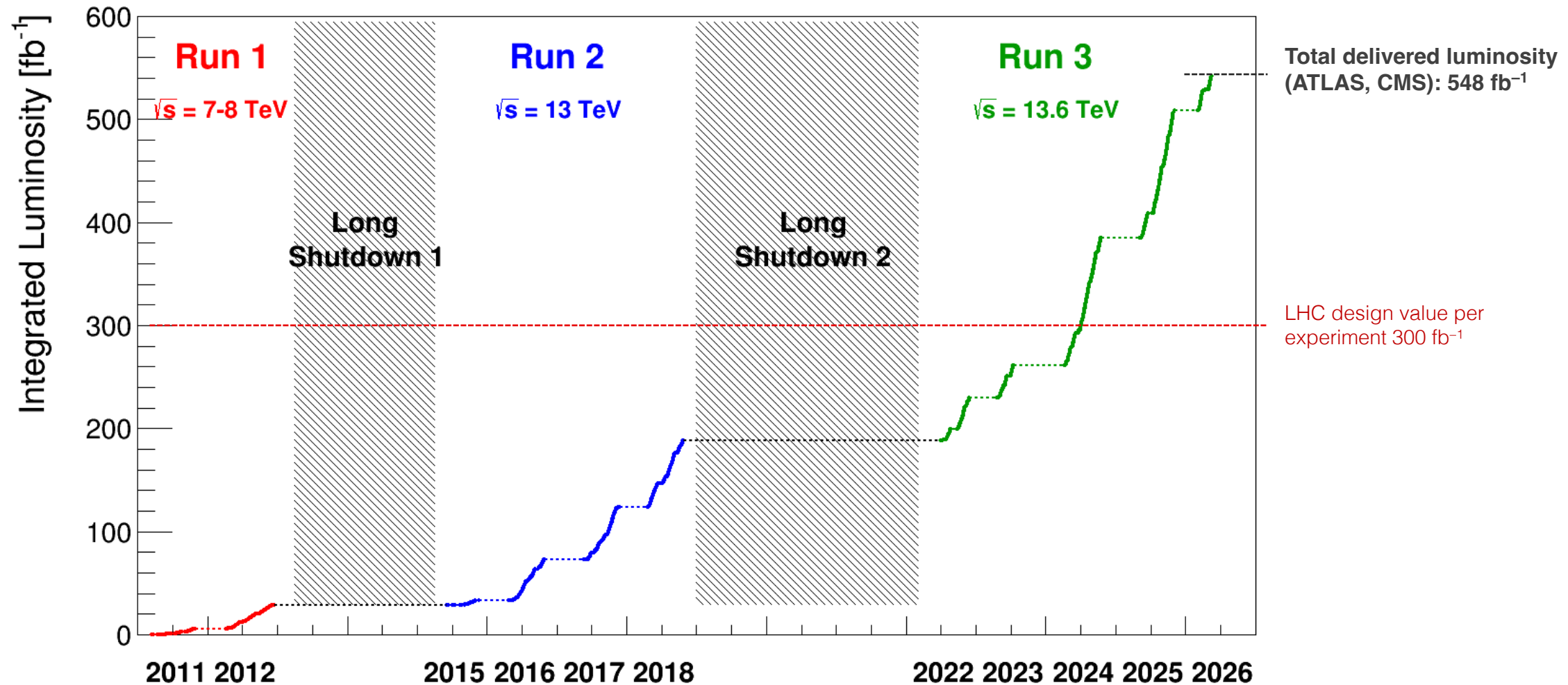
Next lectures:

- Upgrade to the High-Luminosity LHC (HL-LHC)
- New physics opportunities



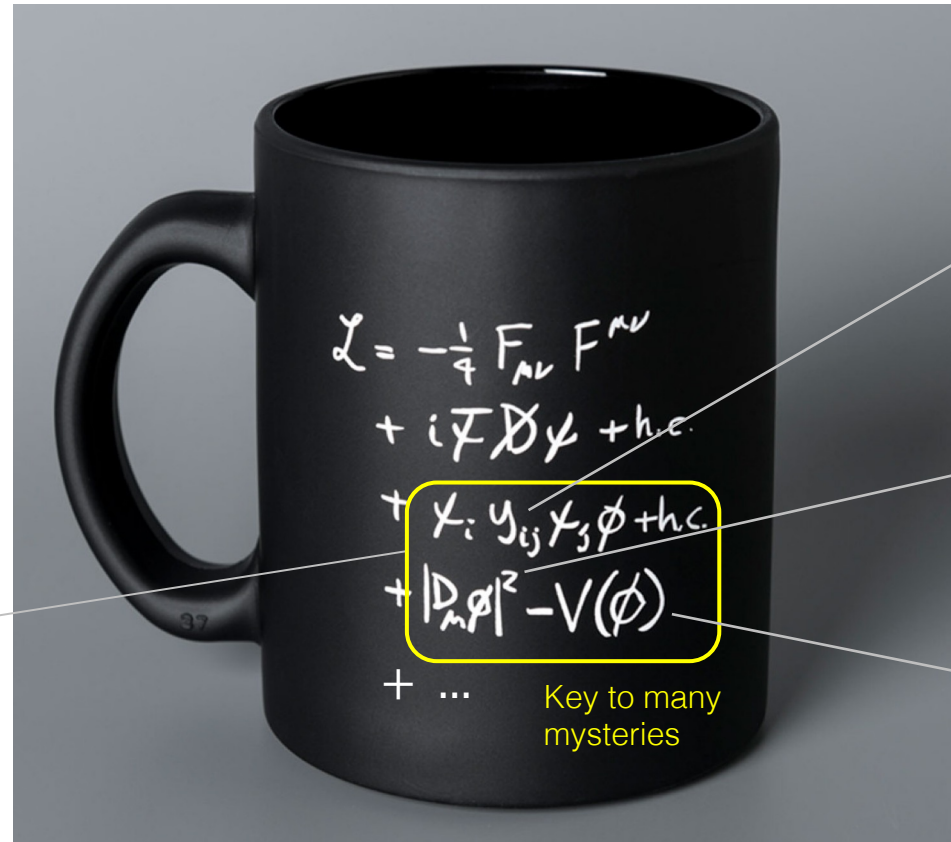
Delivered luminosity

Superb LHC performance in 2024 through 2026 — Run 2+3 > 3 × Run 2; > 450 fb⁻¹ good physics data at 13 & 13.6 TeV



Higgs physics

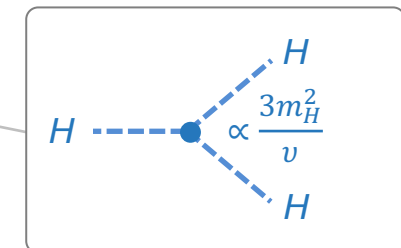
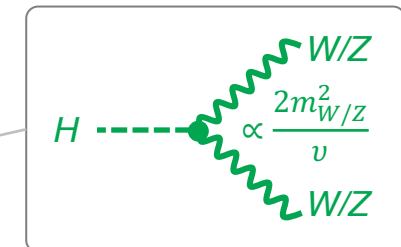
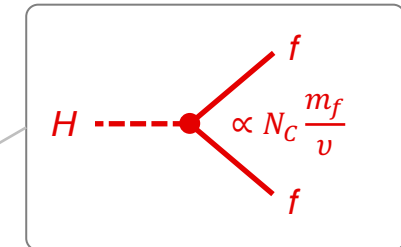
Sensitive tests of the SM by measuring the Higgs to boson and fermion couplings, and its self-coupling



This term is related to the **Higgs sector**

Unpleasant: not governed by symmetries, 23 free parameters*, large hierarchy among masses

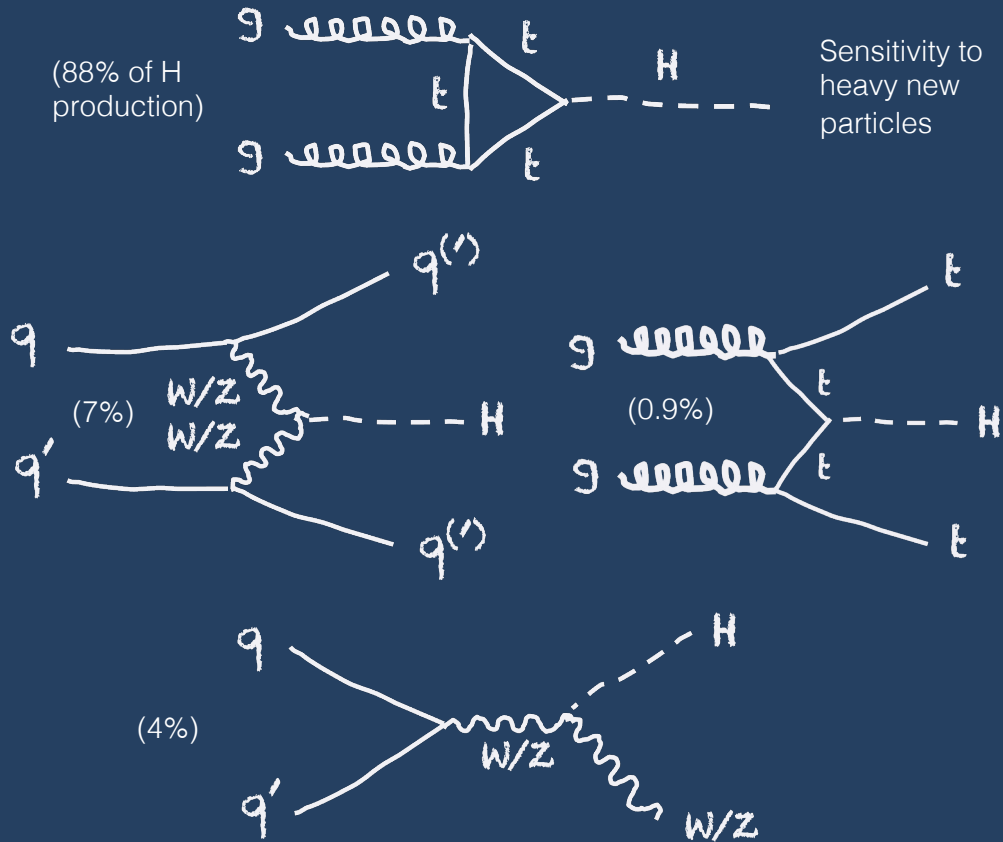
Key to many mysteries



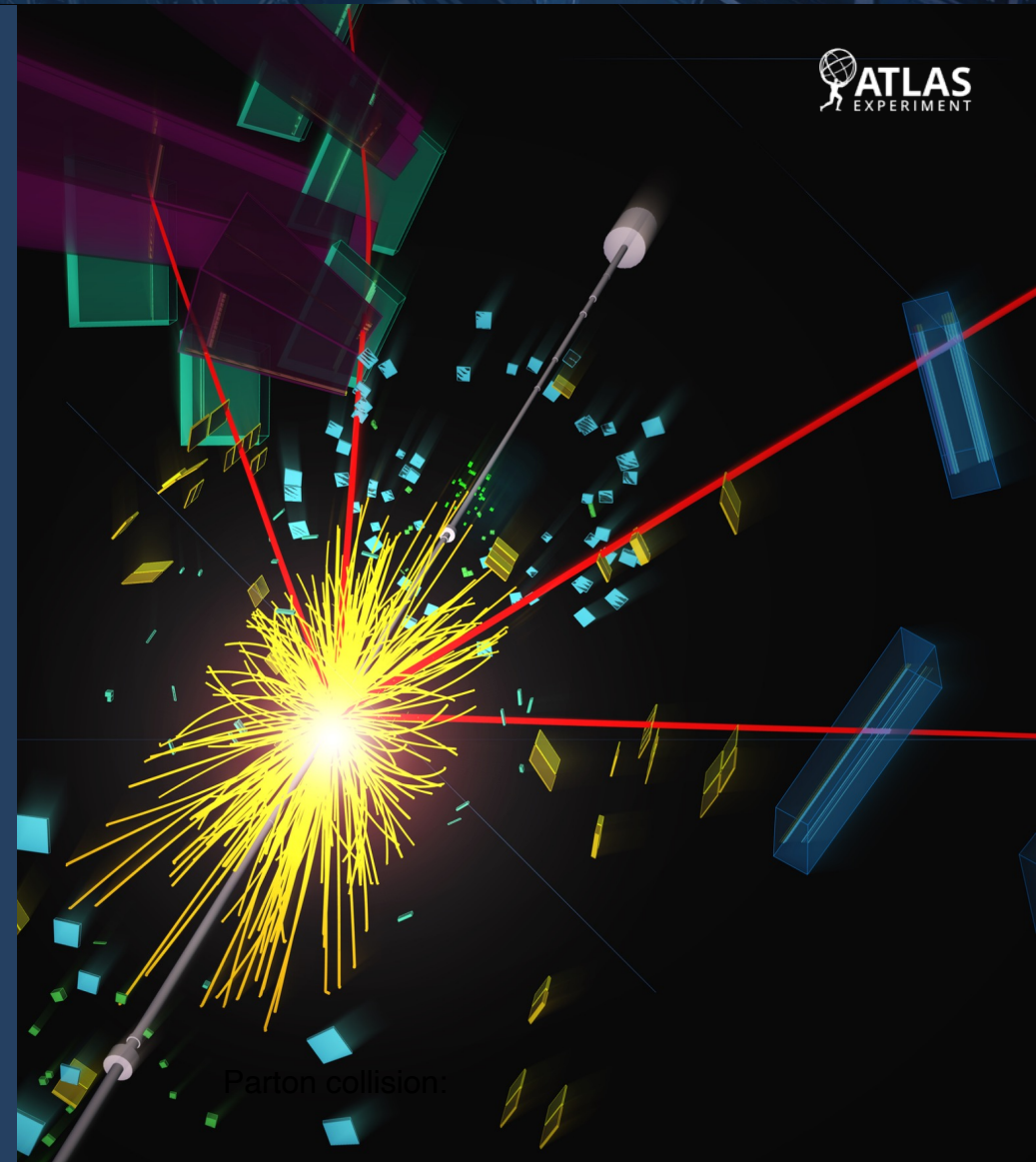
*Assuming neutrinos are Majorana particles (total of 9 neutrino related parameters)

Higgs boson production at the LHC

About one Higgs boson per second, about 28 million produced so far in each ATLAS and CMS

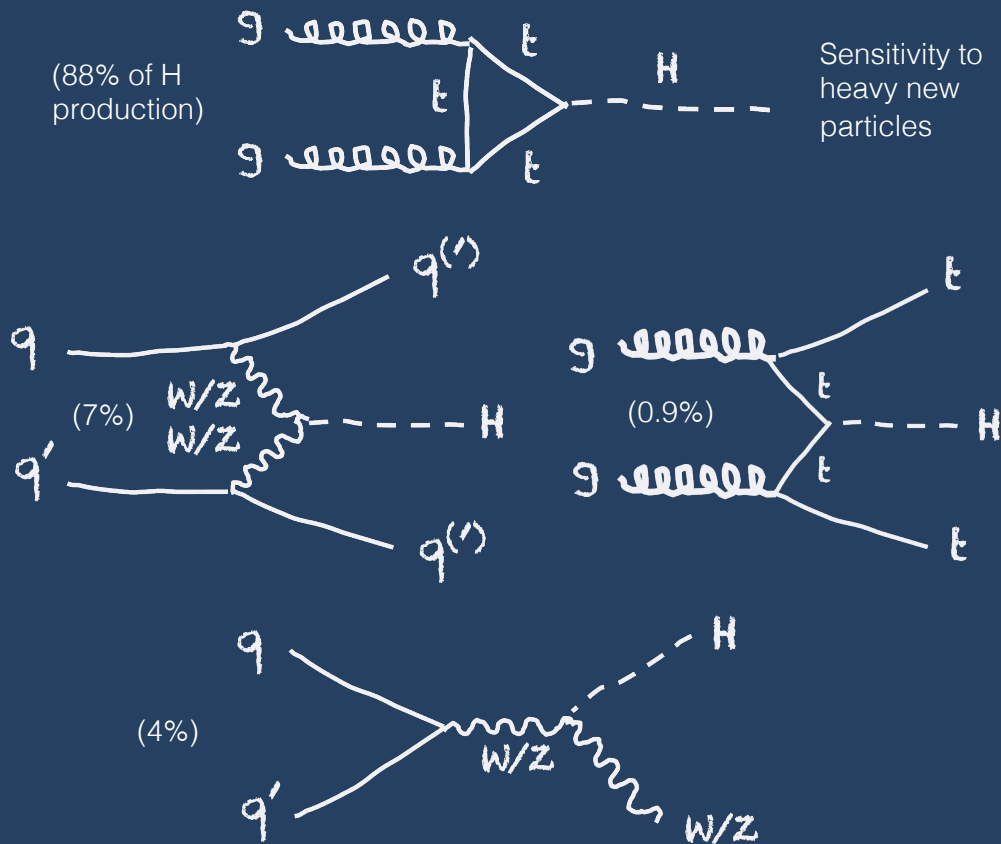


Total $pp \rightarrow H$ cross section: 55.7 pb (13 TeV), 59.9 pb (13.6 TeV)



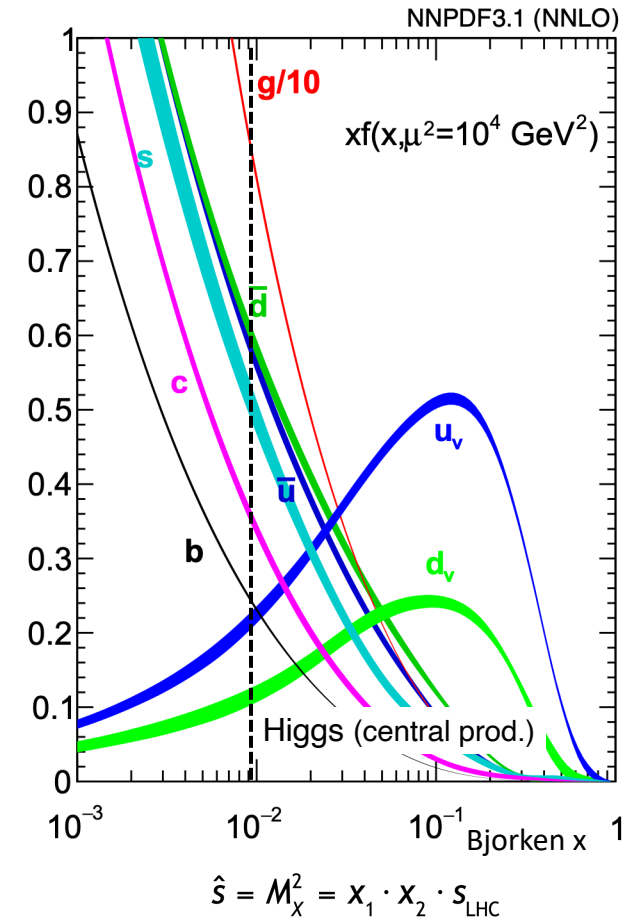
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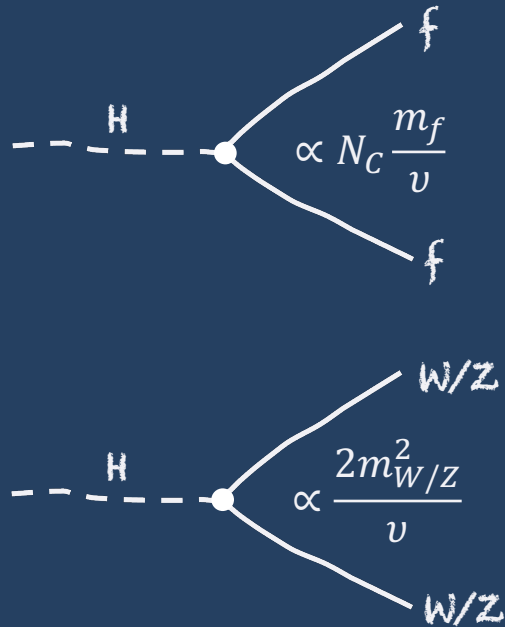
Parton distribution functions



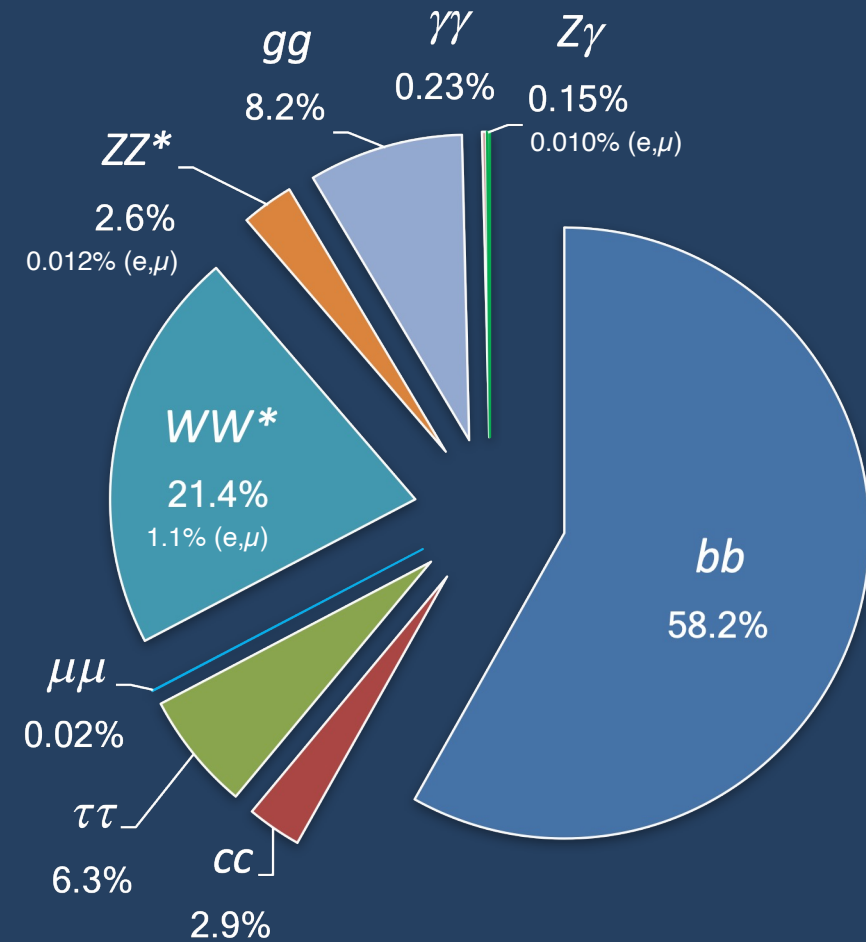
Higgs boson production at the LHC

About one Higgs boson per second, about 28 million produced so far in each ATLAS and CMS

It decays within 10^{-22} s



$H \rightarrow \gamma\gamma, Z\gamma$ occur through virtual top or W loops
(no direct Higgs coupling to massless particles)

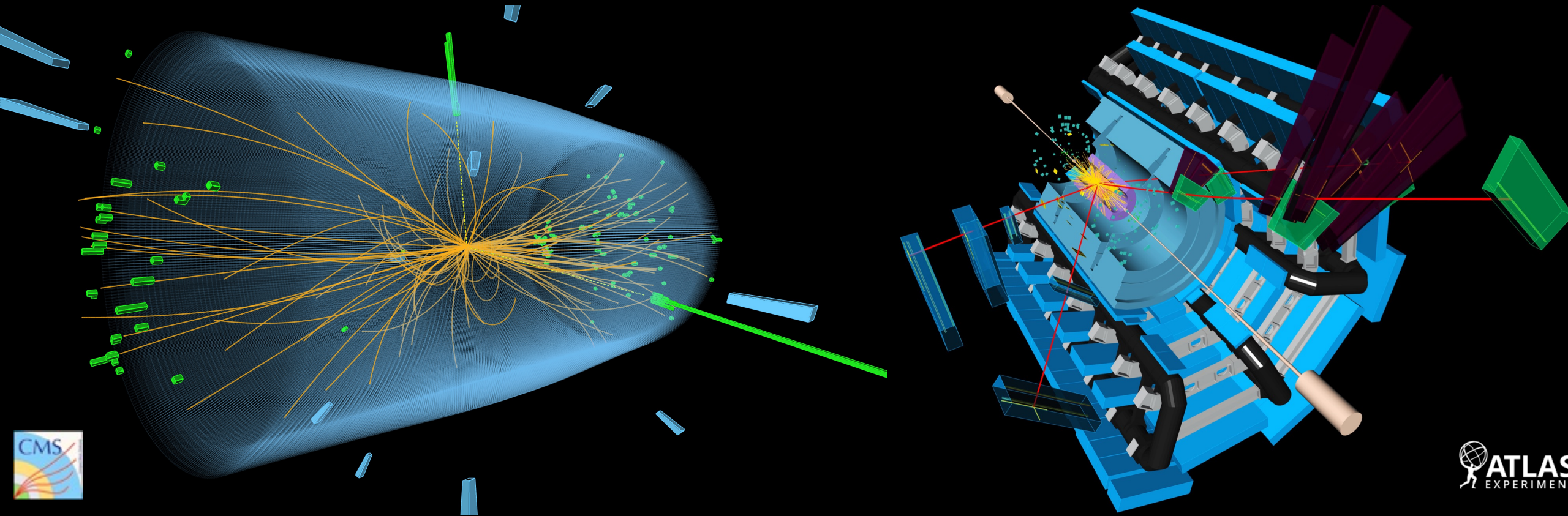


The Higgs boson discovery



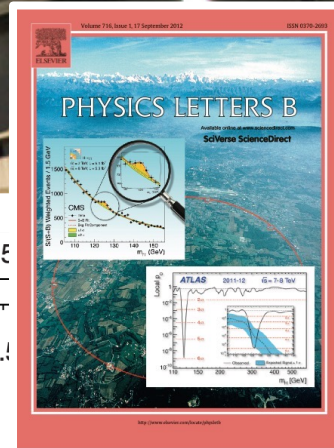
Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

The Higgs boson discovery



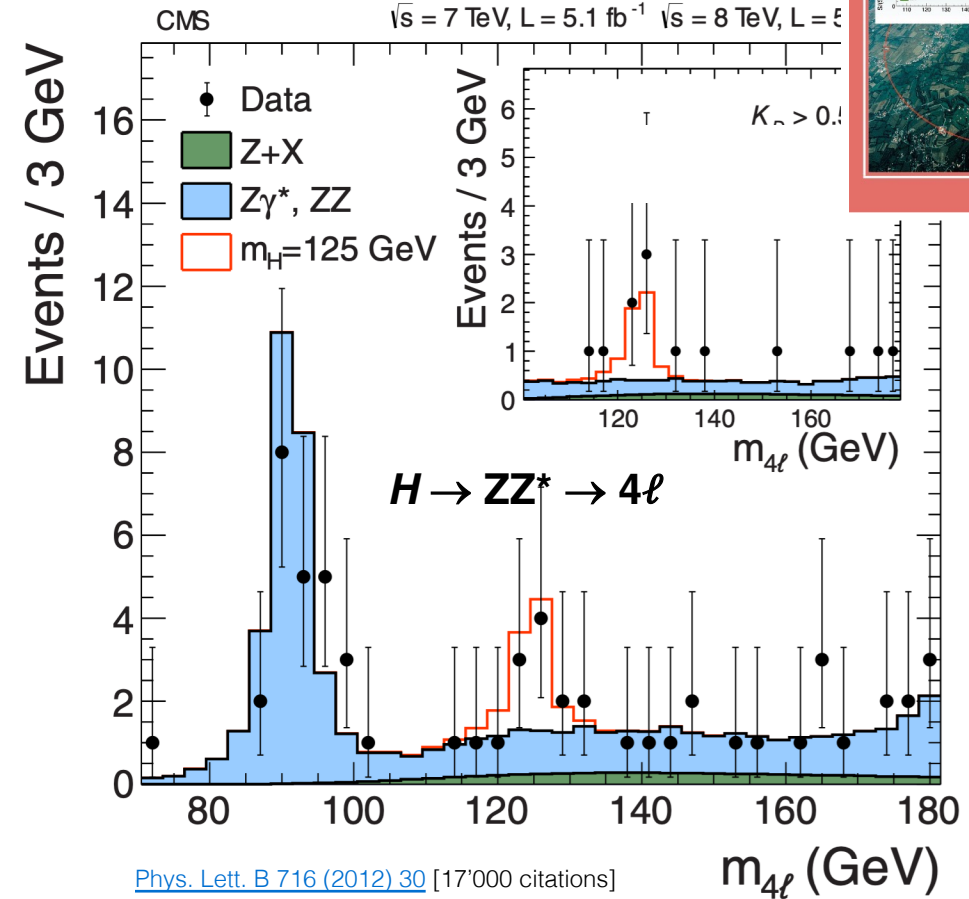
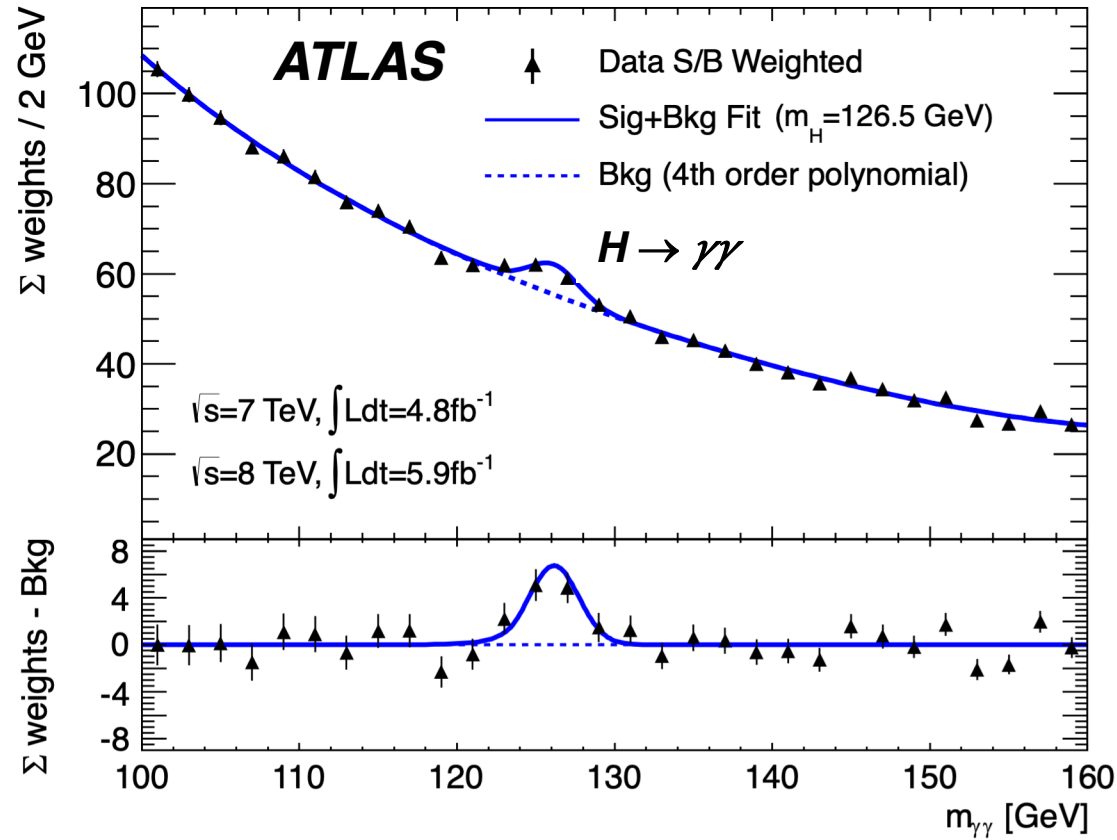
Presentation of Higgs boson discovery by ATLAS and CMS at CERN on 4 July 2012

The Higgs boson discovery



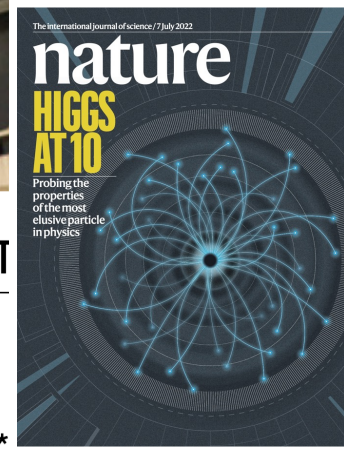
2012

[Phys. Lett. B 716 \(2012\) 1-29](#) [17'600 citations]



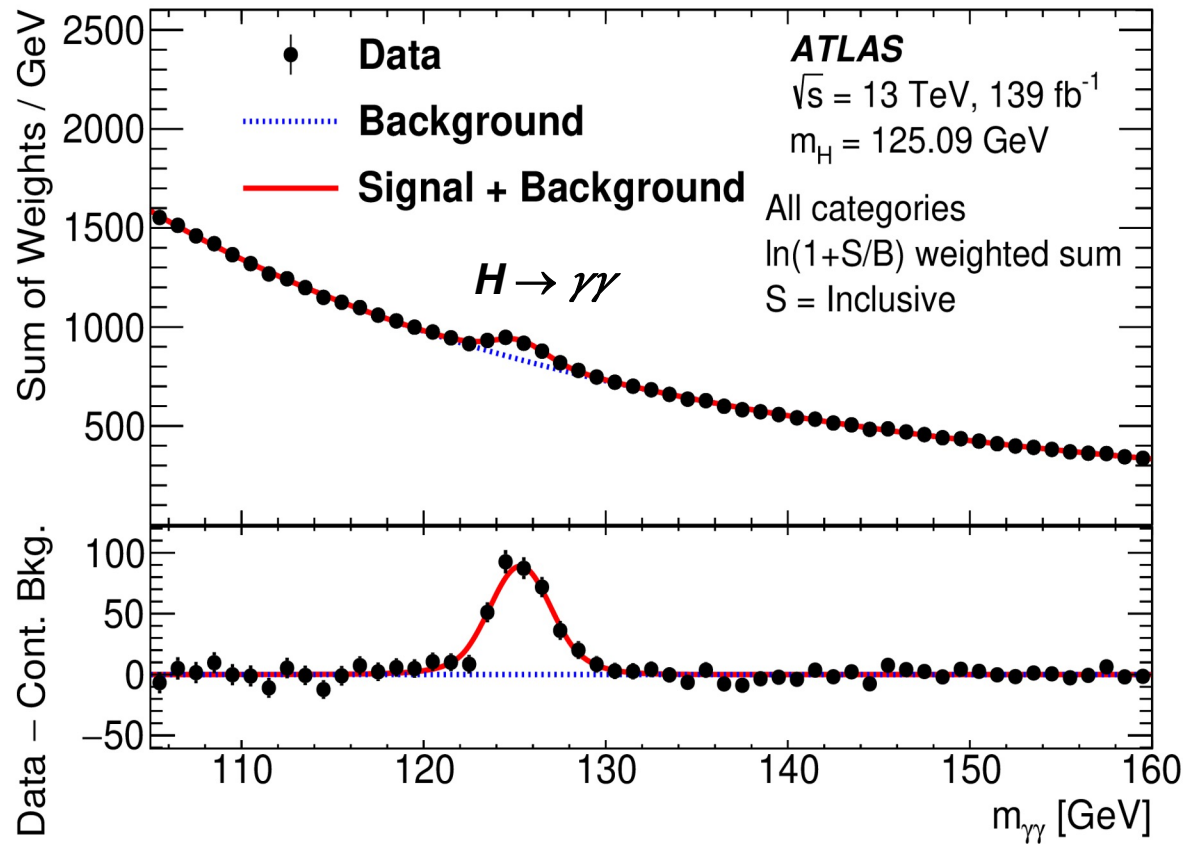
[Phys. Lett. B 716 \(2012\) 30](#) [17'000 citations]

The Higgs boson after Run 2



2020

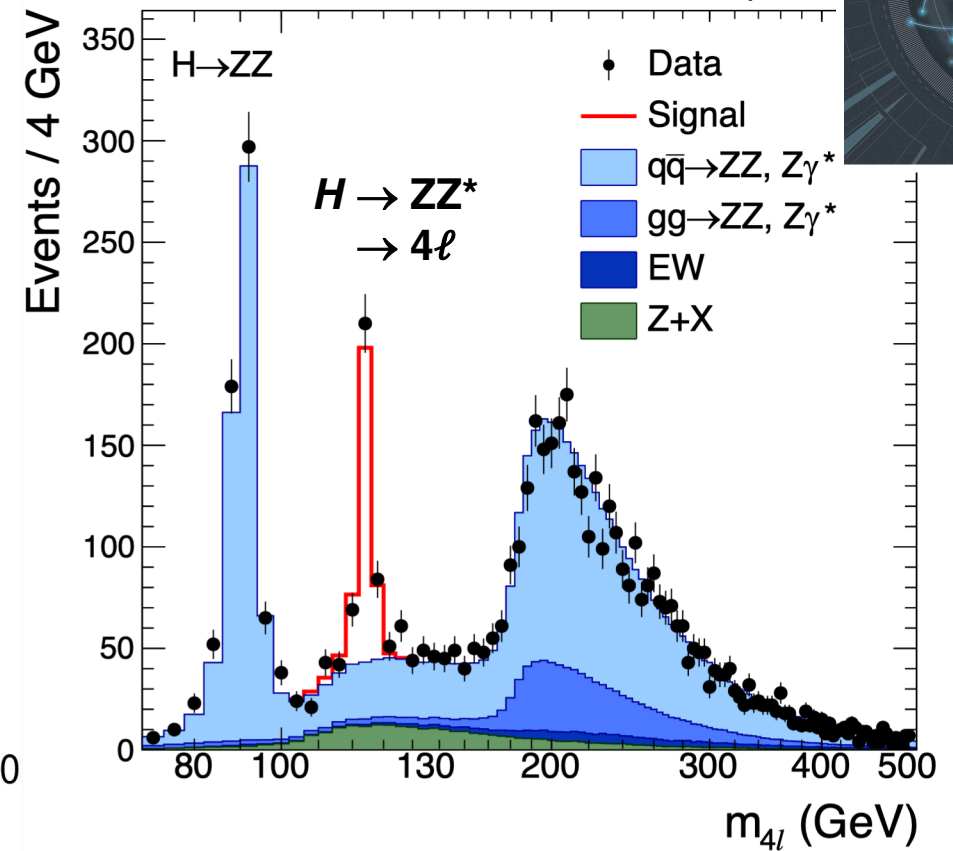
[JHEP 07 \(2023\) 088](#)



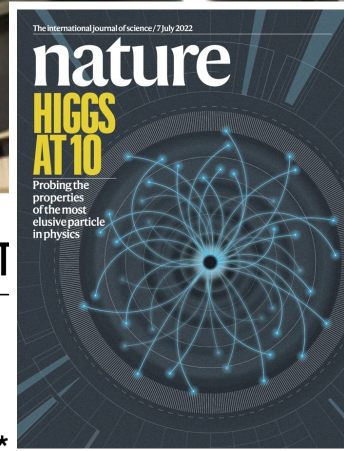
CMS

[Nature 607 \(2022\) 60-68](#)

138 fb⁻¹ (13 T)

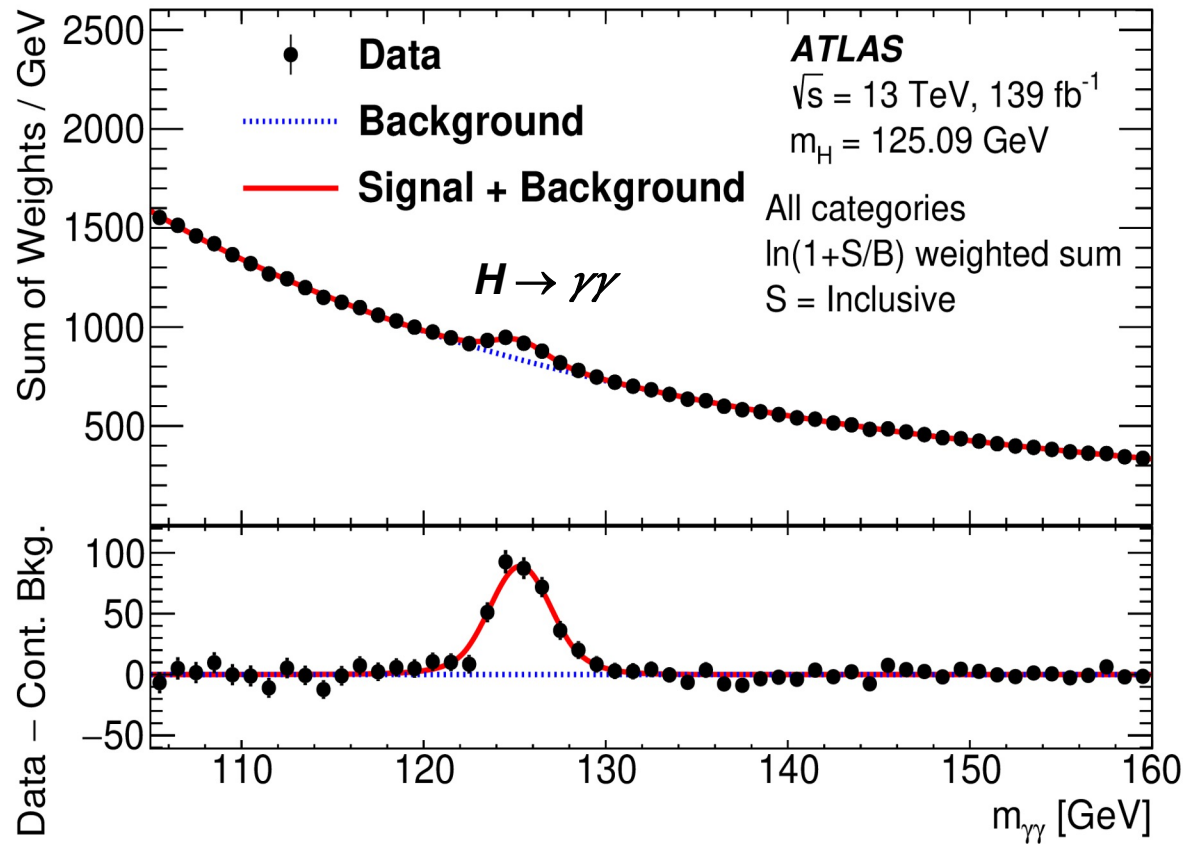


The Higgs boson after Run 2



2020

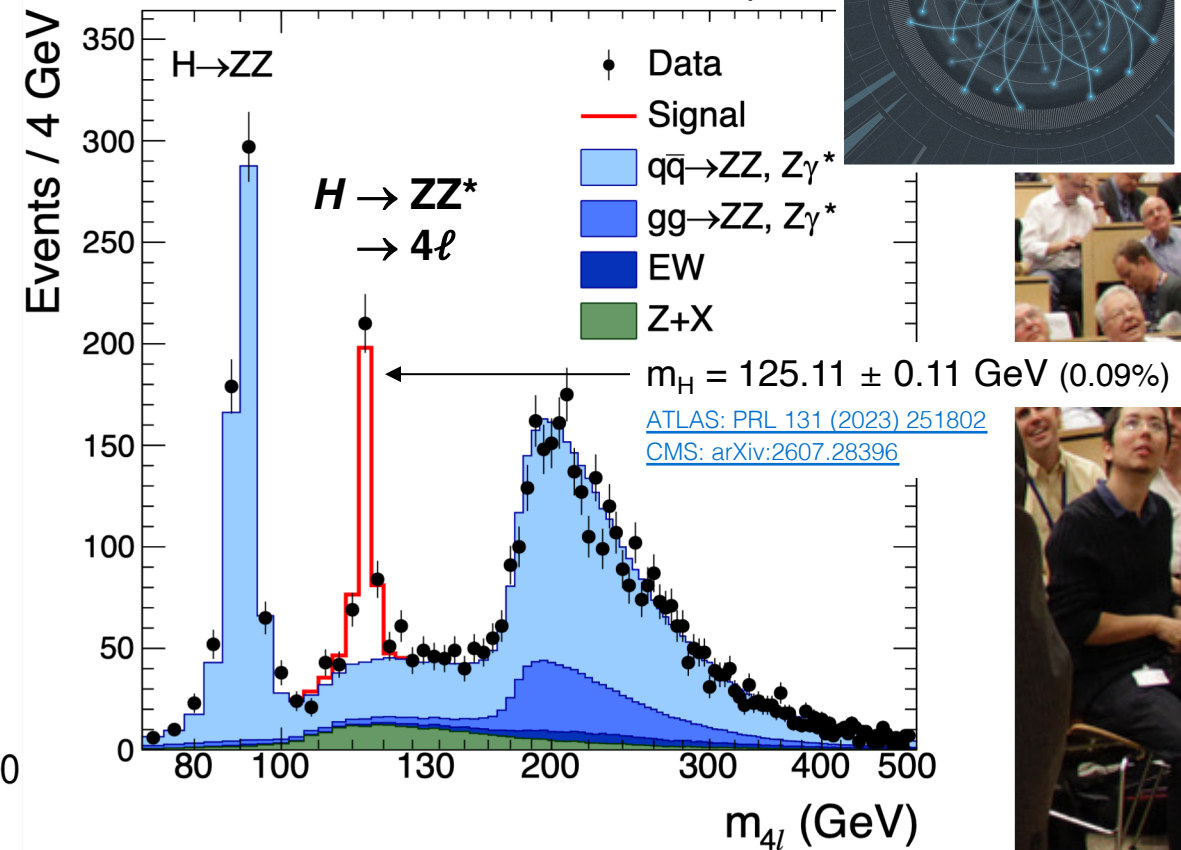
[JHEP 07 \(2023\) 088](#)



CMS

[Nature 607 \(2022\) 60-68](#)

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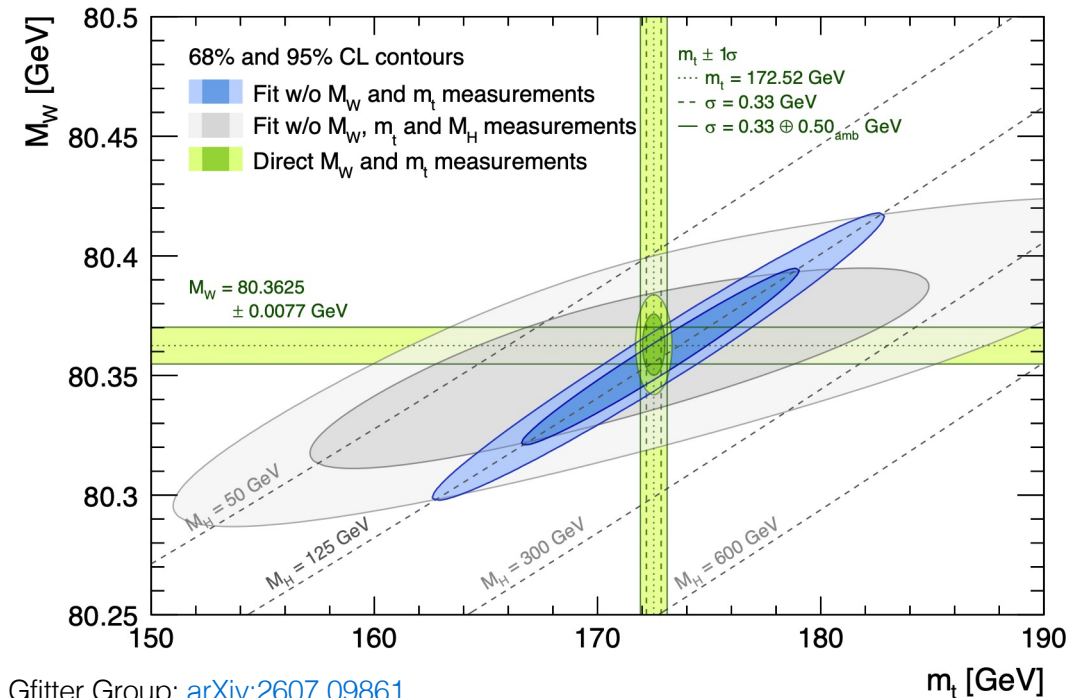
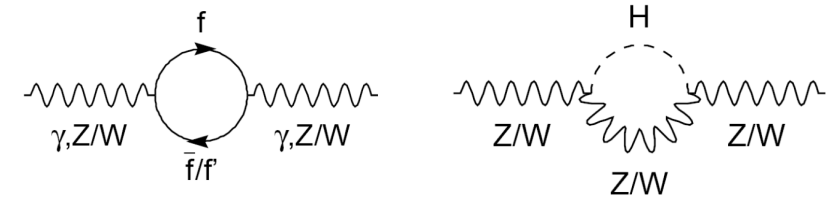


Higgs boson mass

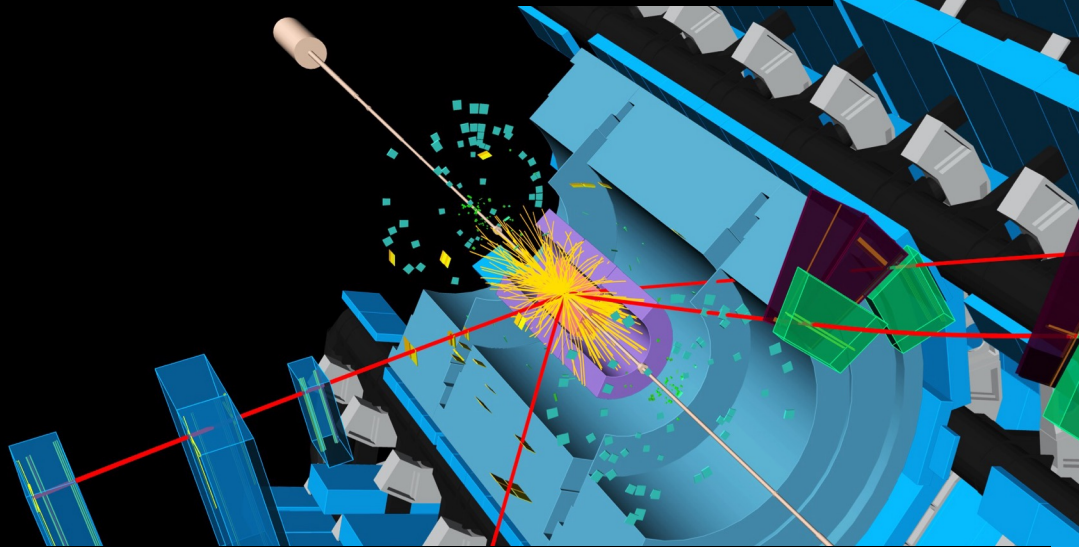
The Higgs mass is peculiar

- It is consistent with the global electroweak fit

Radiative corrections sensitive to heavy particles in loop



Higgs boson mass



The Higgs mass is peculiar

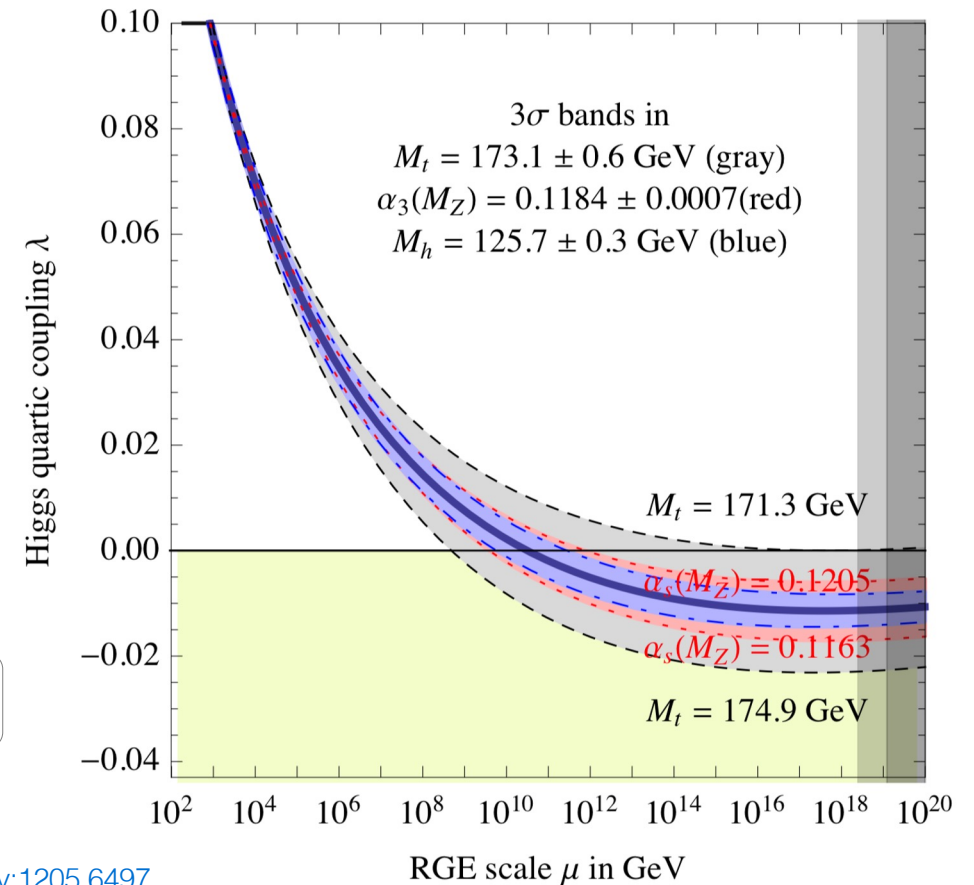
- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable

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

$$\frac{d\lambda}{d \ln \mu} \approx -\frac{3y_t^4}{8\pi^2} \approx -\frac{3}{2\pi^2} \left(\frac{m_t}{v}\right)^4 \left[1 - \frac{16\alpha_s}{3\pi}\right]$$

- Larger m_t increases y_t driving λ downwards more strongly
- Larger α_s reduces y_t thus stabilising λ

Evolution of the Higgs quartic coupling, assuming SM (only)



[arXiv:1205.6497](https://arxiv.org/abs/1205.6497)

Higgs boson mass

M. Veltman, Acta Phys. Pol. B 12, 437 (1981)

The scalar mass term (μ) in Higgs potential is not protected by any symmetry, so, in case of high-scale (Λ) new physics, eg, a particle of mass M coupling to the Higgs with strength κ :

$$\mu^2 = \mu_{\text{bare}}^2 + \delta\mu^2$$

$$\delta\mu^2 = \frac{3\Lambda^2}{16\pi^2 v^2} (m_H^2 + m_Z^2 + 2m_W^2 - 4m_t^2) \sim \frac{\kappa}{16\pi^2} M^2$$

This is the **hierarchy problem**: low-energy physics depends on high-energy physics. Maintaining $\mu^2 \ll M^2$ requires finetuned cancellations unless a symmetry or dynamical mechanism suppresses the heavy-scale threshold corrections

- Proposed mechanisms include supersymmetry, composite Higgs, neutral naturalness, extra space dimensions; alternatives accept tuning or invoke environmental selection in a landscape (anthropic principle)

The Higgs mass is peculiar

- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable
- And in case of new high-scale physics, the Higgs mass appears to be highly fine-tuned

Higgs boson mass

M. Veltman, Acta Phys. Pol. B 12, 437 (1981)

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[Riccardo Rattazzi at EPS-HEP, 2025](#)

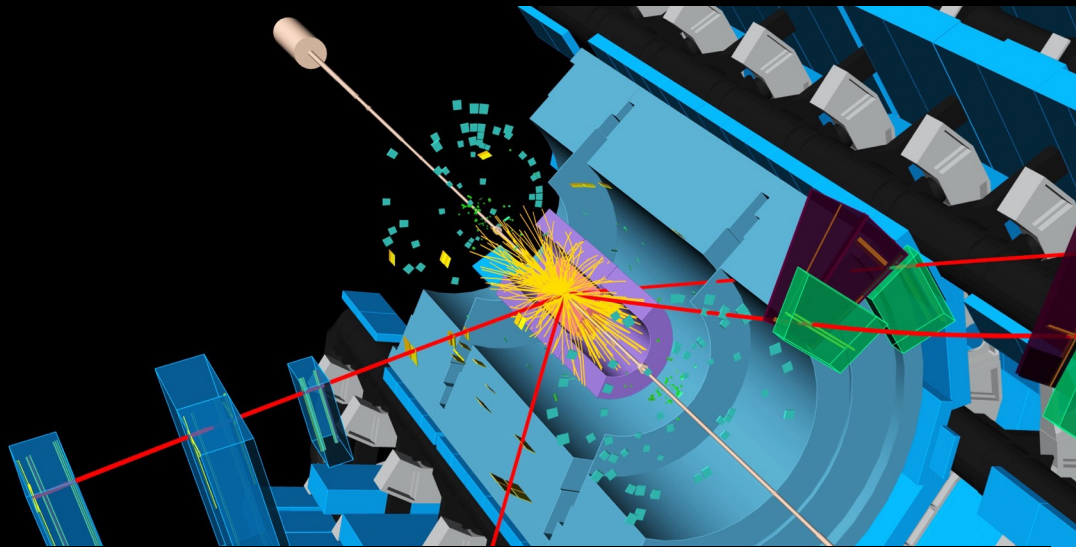
Physics relies on separation of scales, but not possible with scalars

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

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

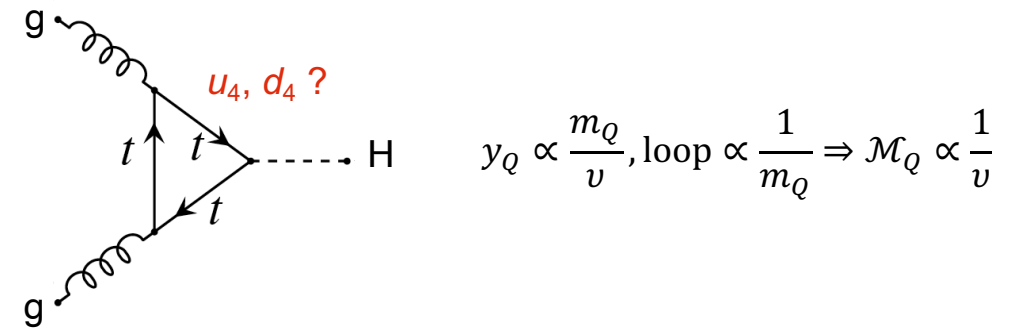
Clash between simplicity and naturalness

Higgs boson cross section



Powerful constraint on SM-like (chiral) 4th generation

Gluon fusion production of Higgs boson, heavy quarks do not decouple if u_4, d_4 obtain their masses from Higgs VEV



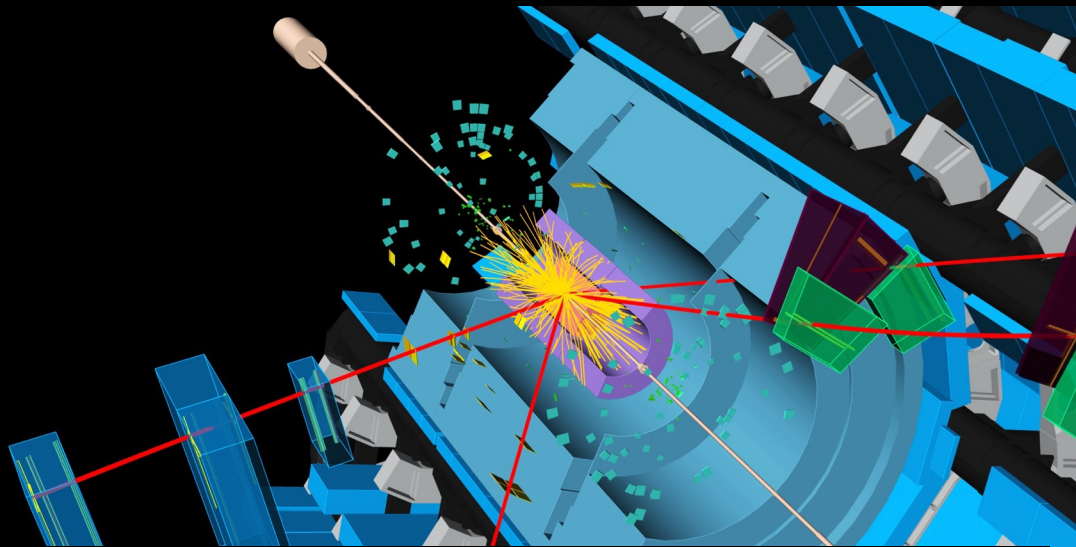
$$\sigma(gg \rightarrow H) \propto \frac{\alpha_s^2}{v^2} \left| \sum_q A_{1/2}(\tau_q) \right|^2, \text{ where } \tau_q = \frac{4m_q^2}{m_H^2}$$

Heavy quarks dominate: $A_{1/2}(\tau_q) \rightarrow 1$ for $m_q \gg m_H/2$

$$\frac{\sigma_{\text{SM4}}(gg \rightarrow H)}{\sigma_{\text{SM}}(gg \rightarrow H)} \simeq \frac{|1_{(t)} + 1_{(u_4)} + 1_{(d_4)}|^2}{|1_{(t)}|^2} = 3^2 = 9$$

SM-like Higgs cross section measurement excludes a chiral fourth generation

Testing the Brout-Englert-Higgs mechanism



The Higgs boson couplings to the SM particles are experimentally determined by measuring cross-sections of all accessible Higgs boson production and decay modes, and by performing a combined fit to all measurements

Careful detector and reconstruction calibration, and Machine Learning have led to substantial improvements

Huge experimental programme, some channels suffer from large backgrounds, big improvements from smart analysis techniques and machine learning

Channel categories		BR	ggF	VBF	VH	ttH
Cross Section (13 TeV)			48.6 pb	3.8 pb	2.3 pb	0.5 pb
$\gamma\gamma$	0.2 %	✓	✓	✓	✓	
ZZ	2.6%	✓	✓	✓	✓	
WW	21%	✓	✓	✓	✓	
$\tau\tau$	6.3 %	✓	✓	✓	✓	
bb	58%	✓	✓	✓	✓	
Z γ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	
$\mu\mu$	0.02 %	✓	✓	✓	✓	

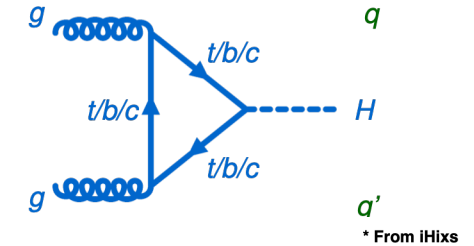
In grey: evidence for decays, but not observed yet

Theory predictions

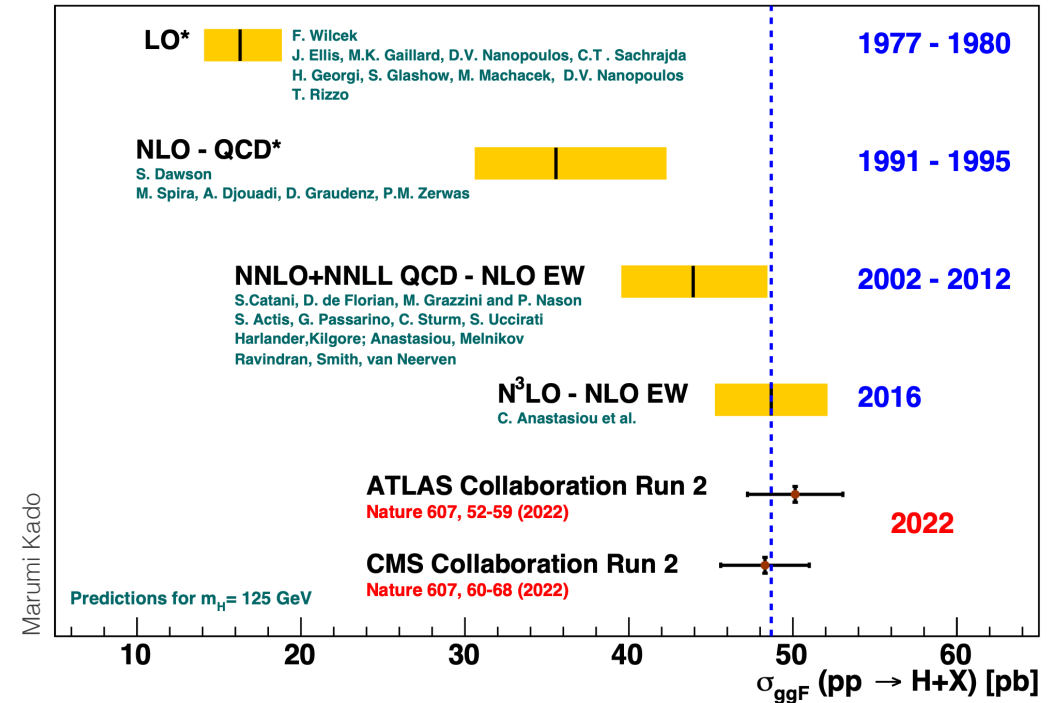
Predictions at hadron colliders are extremely complex and require several levels of modelling and calculations (higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc...)

The interpretability of our results relies on our ability to compute accurate and precise predictions

Calculations of Higgs boson production via gluon fusion versus time

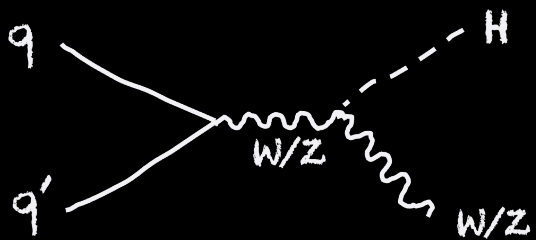
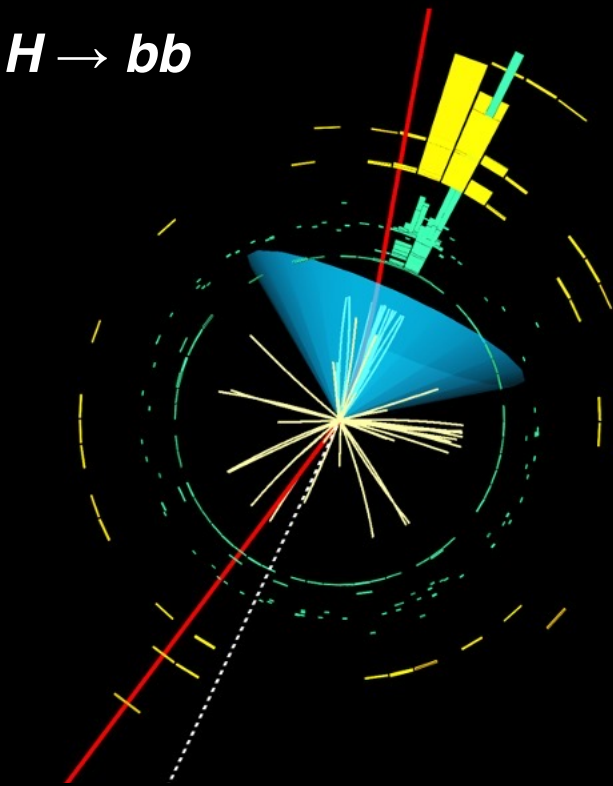


$\sqrt{s} = 13 \text{ TeV}$



Marumi Kado

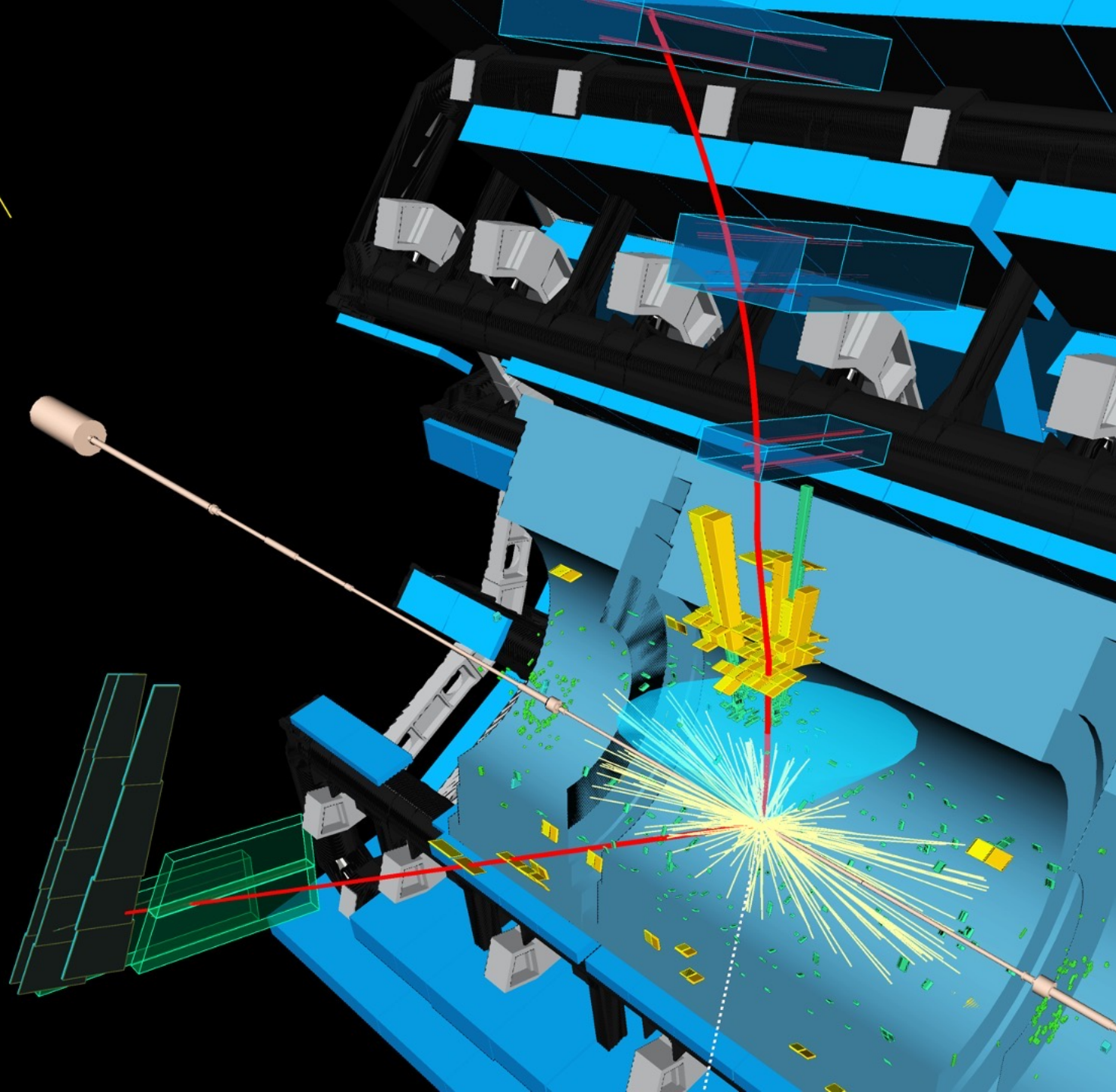
$H \rightarrow bb$



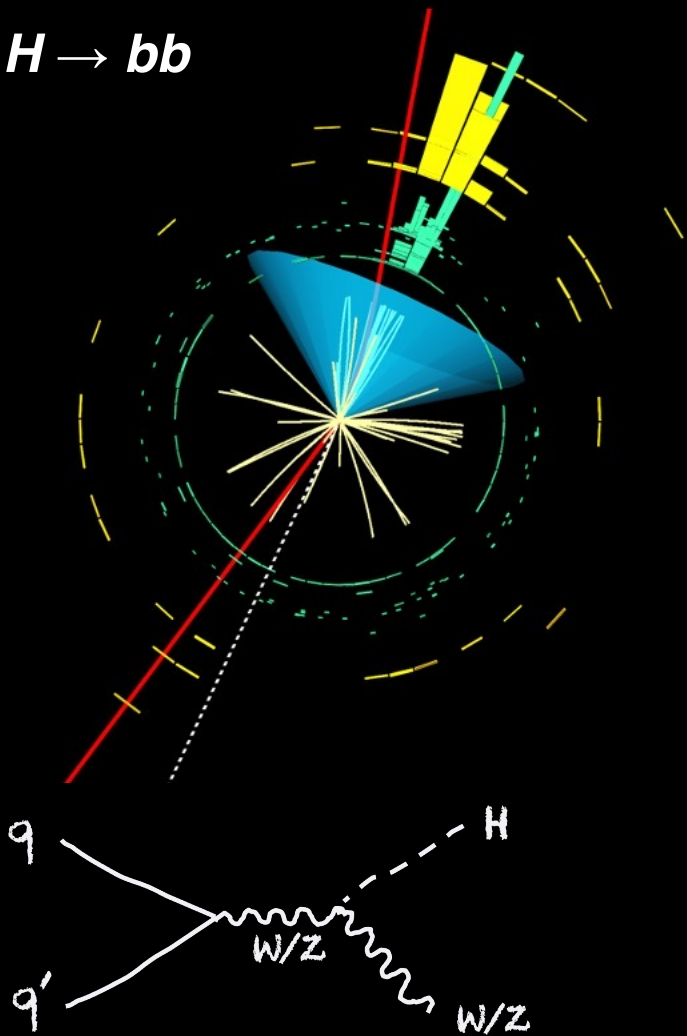
Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST



$H \rightarrow bb$

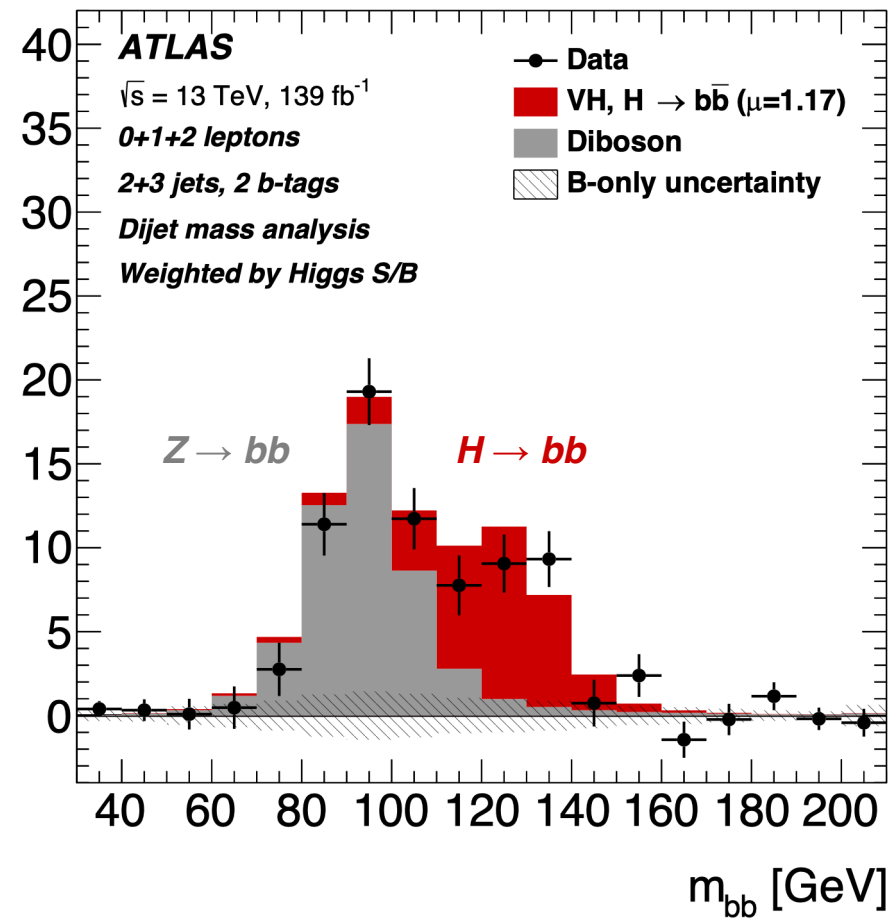


Run: 338349

Event: 616525246

2017-10-16 20:24:46 CEST

Events / 10 GeV (Weighted, B-subtracted)

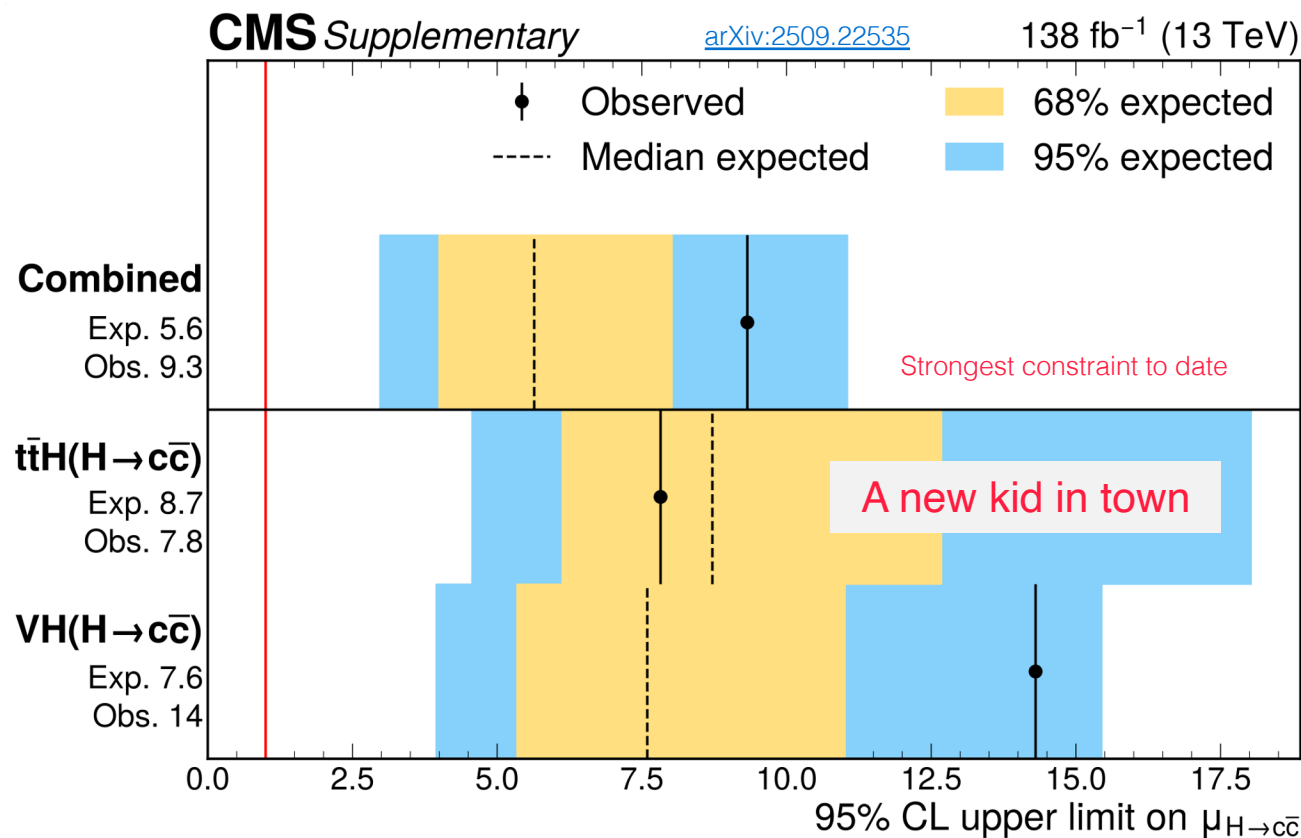


$H \rightarrow cc$

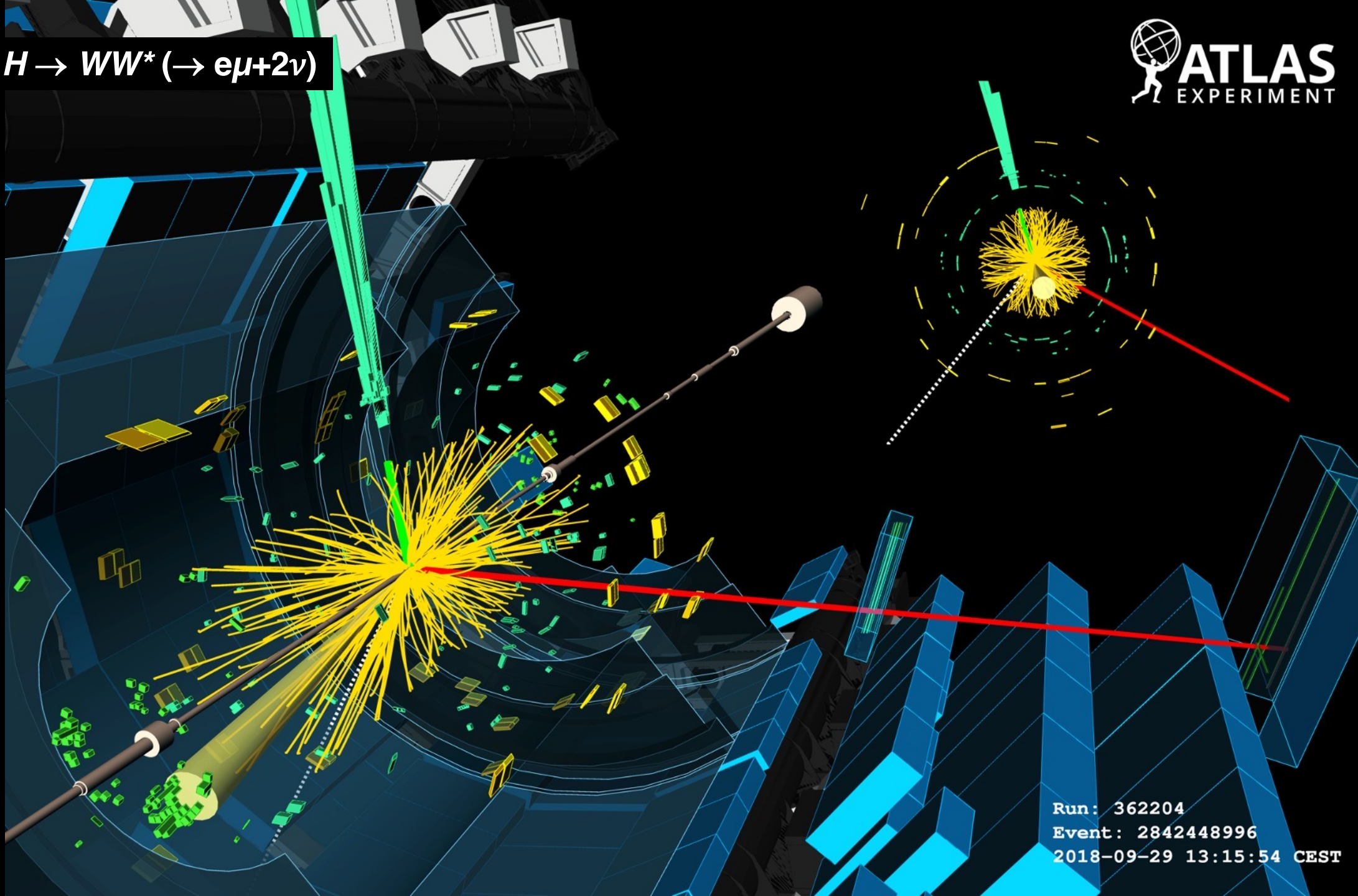
Rate of $H \rightarrow cc$ is 20 × smaller than $H \rightarrow bb$ due to lighter charm quark, challenging to isolate experimentally

Best constraints so far from $VH(\rightarrow cc)$ production: $\mu_{VH \times H \rightarrow cc} < 11.5_{\text{obs}} (10.6_{\text{exp}}) / 14_{\text{obs}} (7.6_{\text{exp}})$ (ATLAS / CMS) [[JHEP 04 \(2025\) 075](#) / [JHEP 03 \(2020\) 131](#)]

Strong recent result from CMS using $t\bar{t}H$ production and simultaneously measuring $H \rightarrow bb, cc$ (as also done in VH)



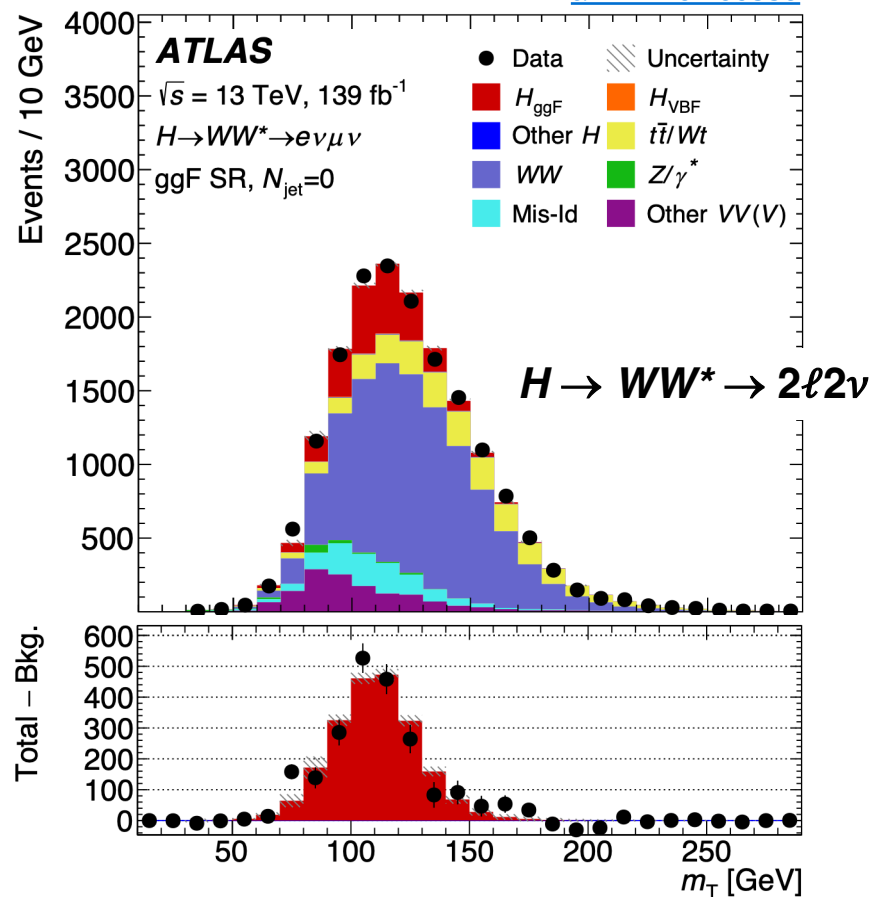
$H \rightarrow WW^* (\rightarrow e\mu + 2\nu)$



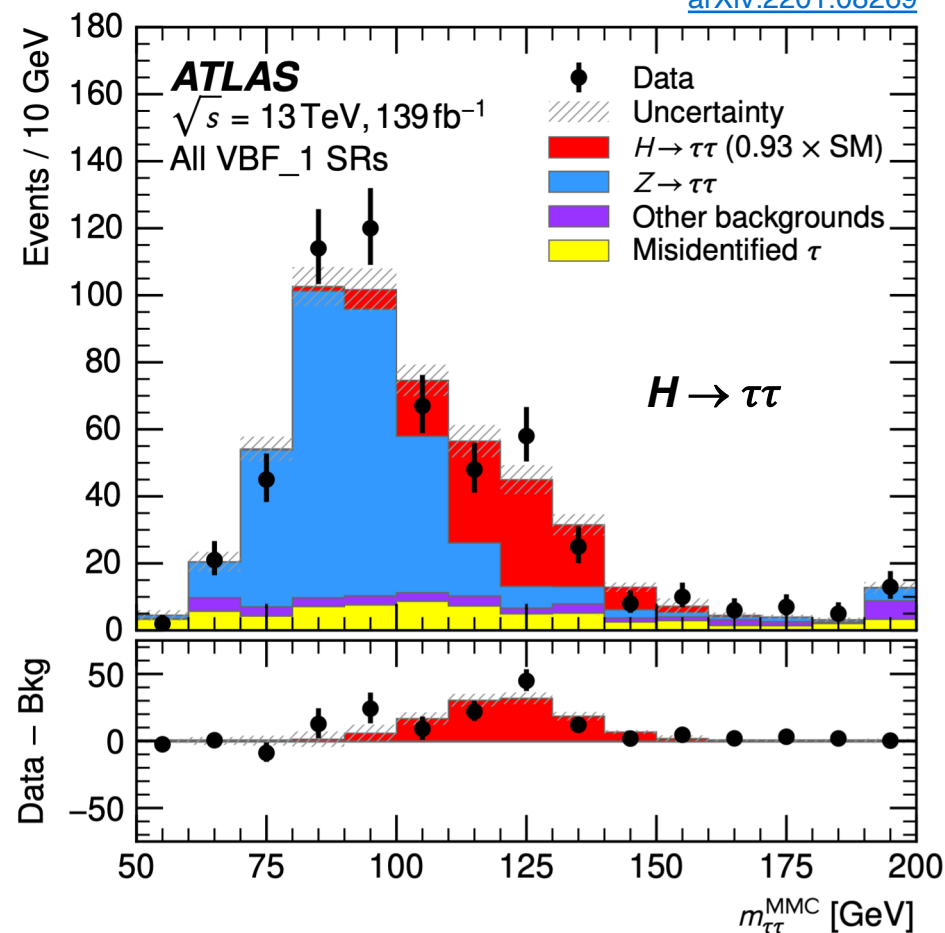
Run: 362204
Event: 2842448996
2018-09-29 13:15:54 CEST

$H \rightarrow WW^* (\rightarrow e\mu + 2\nu)$

[arXiv:2207.00338](https://arxiv.org/abs/2207.00338)



[arXiv:2201.08269](https://arxiv.org/abs/2201.08269)

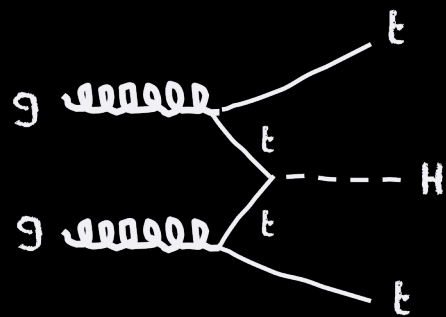


$t\bar{t}H$ production

Run: 303079

Event: 197351611

2016-07-01 05:01:26 CEST

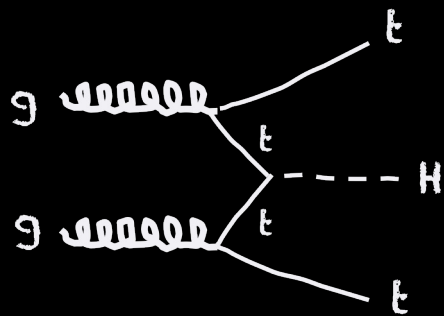
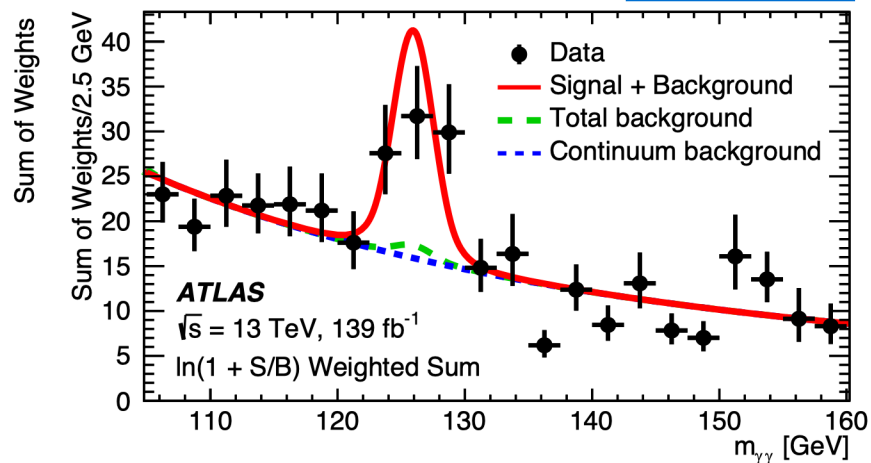


A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

$t\bar{t}H$ production

$t\bar{t}H$ production features rich events,
 $H \rightarrow \gamma\gamma$ channel most powerful

[arXiv:2004.04545](https://arxiv.org/abs/2004.04545)



A $t\bar{t}H \rightarrow 6 \text{ jets} + \gamma\gamma$ candidate event

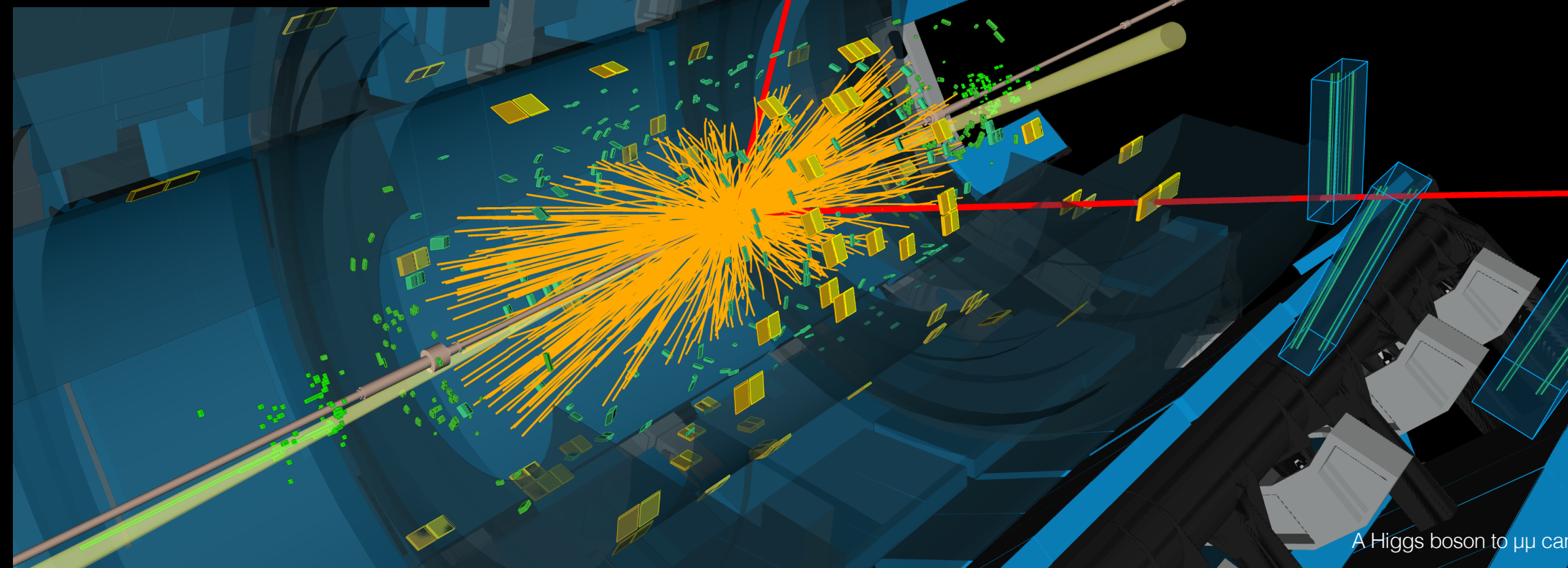
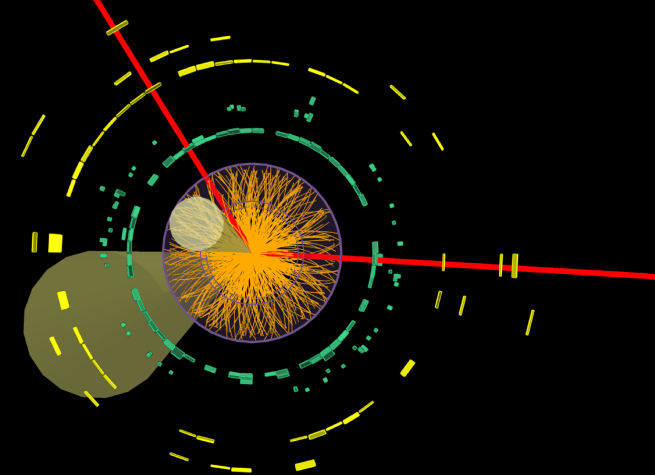


Run: 484466

Event: 3913031636

2024-09-13 05:46:24 CEST

Rare Higgs boson decays



A Higgs boson to $\mu\mu$ candidate event

Run: 484466

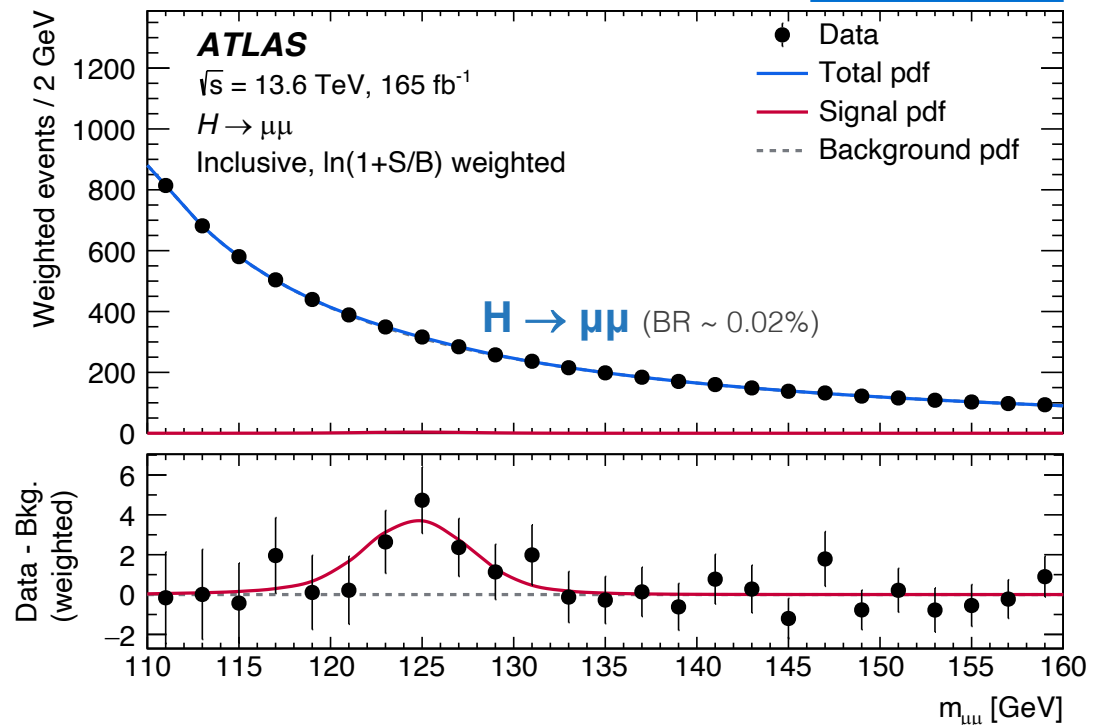
Event: 3913031636

2024-09-13 05:46:24 CEST

Rare Higgs boson decays

Using 305 fb⁻¹ of Run-2 + 3 (2022–2024) data, ATLAS reported evidence for rare 2nd generation $H \rightarrow \mu\mu$ (first seen by CMS)

[PRL 135 \(2025\) 231802](#)

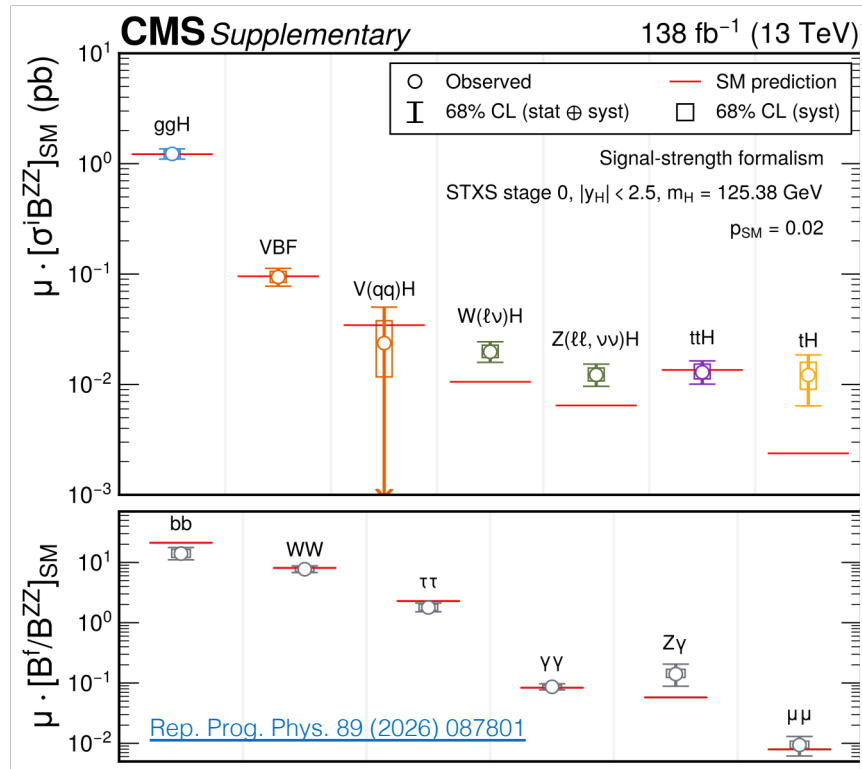


Significance: 3.4σ (2.5σ exp), $\sigma_{\text{exp}} / \sigma_{\text{SM}} = 1.4 \pm 0.4$

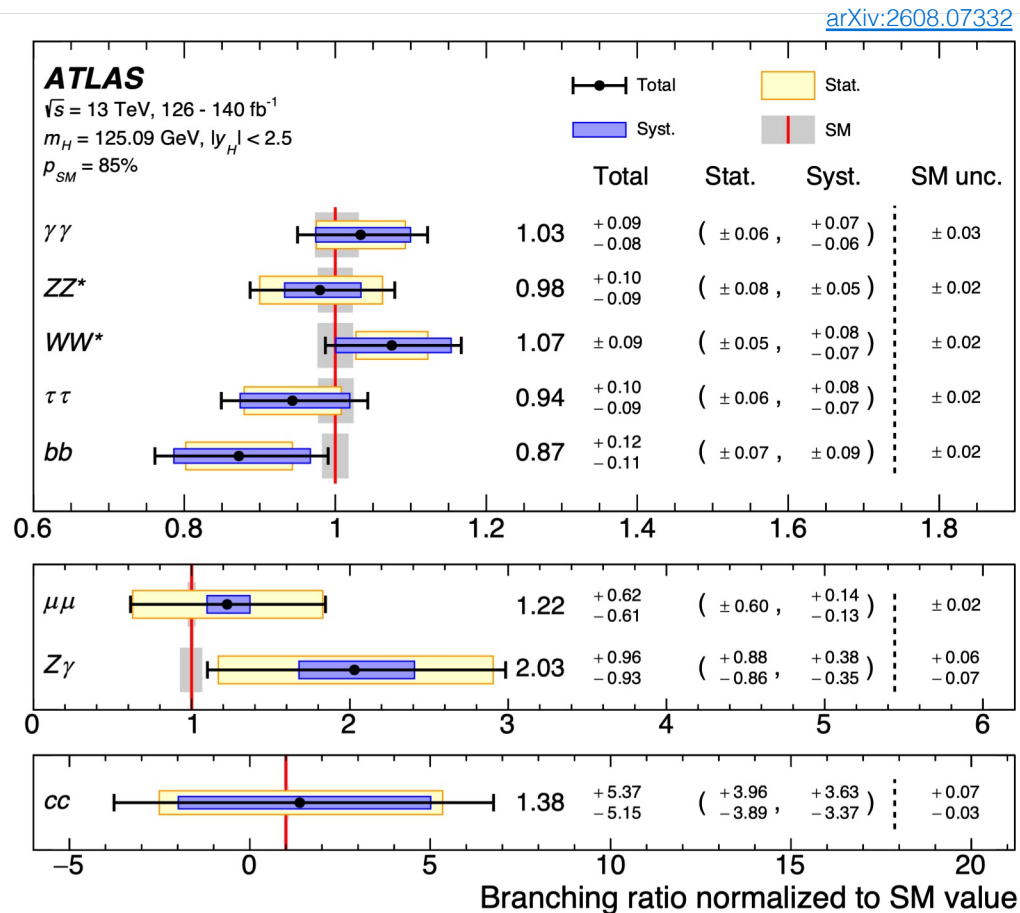
CMS (Run 2): $\mu = 1.19 \pm 0.43$ (3.0σ) [[JHEP 01 \(2021\) 148](#)]

Higgs cross sections and branching fractions

Combination of Higgs production and decay measurements using Run-2 13 TeV pp data



Cross section measurements assume SM Higgs branching fractions and vice versa



Among the many results:

- Detailed fiducial and differential cross section measurements
- Overall agreement with SM
Combined production & decay mode p-values: ATLAS / CMS = 0.85 / 0.006 (all categories)

- Up to O(100) cross sections measured simultaneously in ~1k categories, O(10k) parameters, including background “nuisance” parameters
- tH comes out high, see also recent ATLAS tH(bb) result; $\mu_{tH} = 8.1 \pm 3.3$ [[JHEP 10 \(2025\) 093](https://arxiv.org/abs/2508.093)]

Higgs couplings — “kappa framework”

Extraction of Higgs boson coupling strengths modifiers from signal-strength measurements

In the **Higgs coupling-modifier κ framework**, each Higgs coupling is rescaled relative to its SM value:

$$\kappa_i \equiv \frac{g_{Hi}}{g_{Hi}^{\text{SM}}}$$

For example: $\kappa_f = \frac{y_f}{y_f^{\text{SM}}}, \quad \kappa_W = \frac{g_{HWW}}{g_{HWW}^{\text{SM}}}, \quad \kappa_Z = \frac{g_{HZZ}}{g_{HZZ}^{\text{SM}}}, \quad \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{\text{SM}}}$

Assuming unchanged interaction structures: $\frac{\sigma_i}{\sigma_i^{\text{SM}}} \simeq \kappa_i^2, \quad \frac{\mathcal{B}(H \rightarrow f)}{\mathcal{B}^{\text{SM}}(H \rightarrow f)} = \frac{\kappa_f^2}{\kappa_H^2}, \quad \kappa_H^2 \equiv \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \sum_j \kappa_j^2 \mathcal{B}^{\text{SM}}(H \rightarrow j)$

If no non-SM Higgs decays!

The **signal strength** for production mode i and decay f is therefore: $\mu_i^f \equiv \frac{\sigma_i \mathcal{B}_f}{\sigma_i^{\text{SM}} \mathcal{B}_f^{\text{SM}}} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$

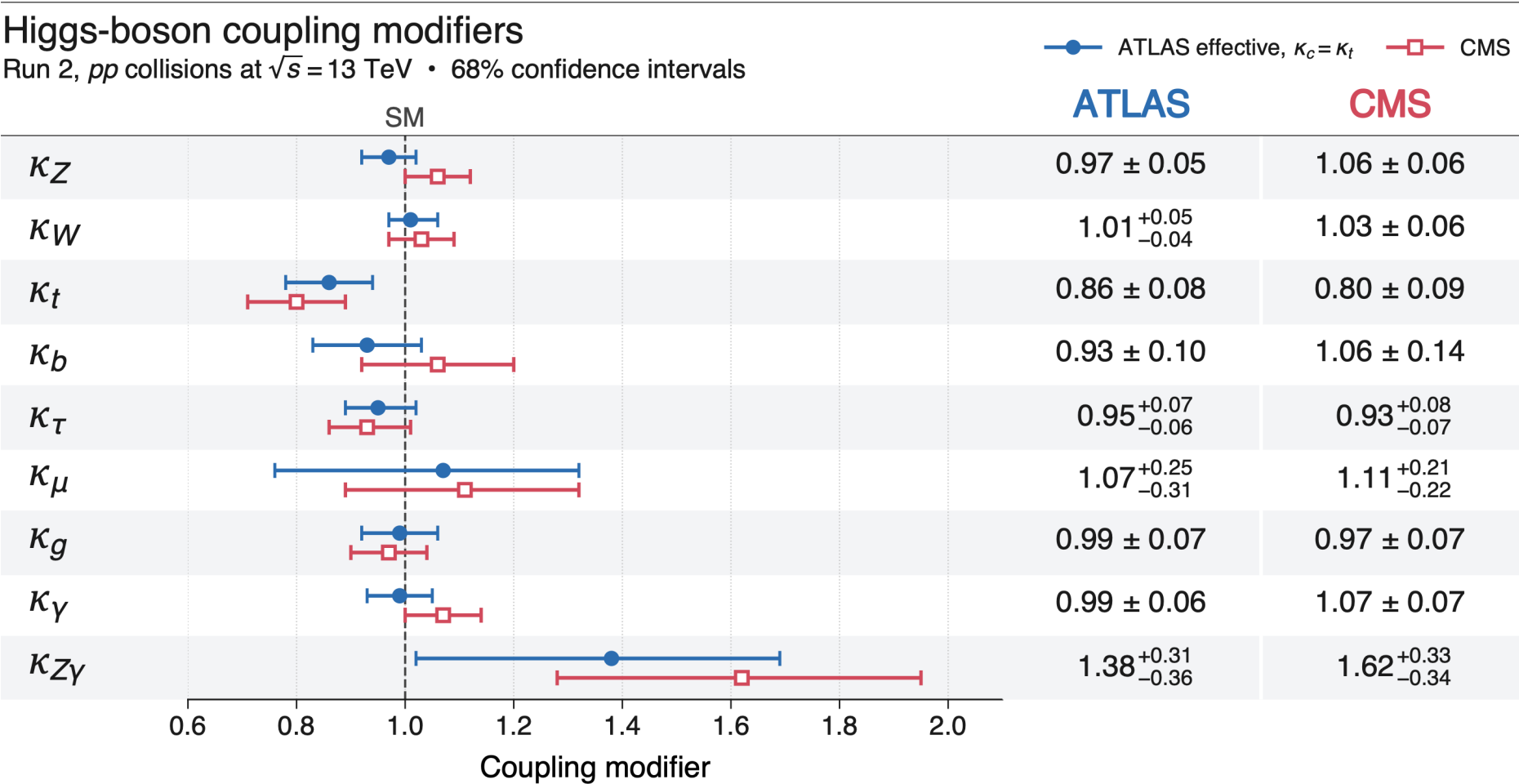
For loop-induced interactions (eg, $gg \rightarrow H, H \rightarrow \gamma\gamma$), one can either resolve the loop assuming SM, or define **effective** modifiers: $\kappa_g^2 \equiv \frac{\Gamma(H \rightarrow gg)}{\Gamma^{\text{SM}}(H \rightarrow gg)}, \quad \kappa_\gamma^2 \equiv \frac{\Gamma(H \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(H \rightarrow \gamma\gamma)}$

The “kappa framework” assumes one narrow Higgs with SM Lorentz structures and constant coupling rescalings. It is a useful phenomenologically, but not a general gauge-invariant Effective Field Theory (EFT)

Higgs couplings

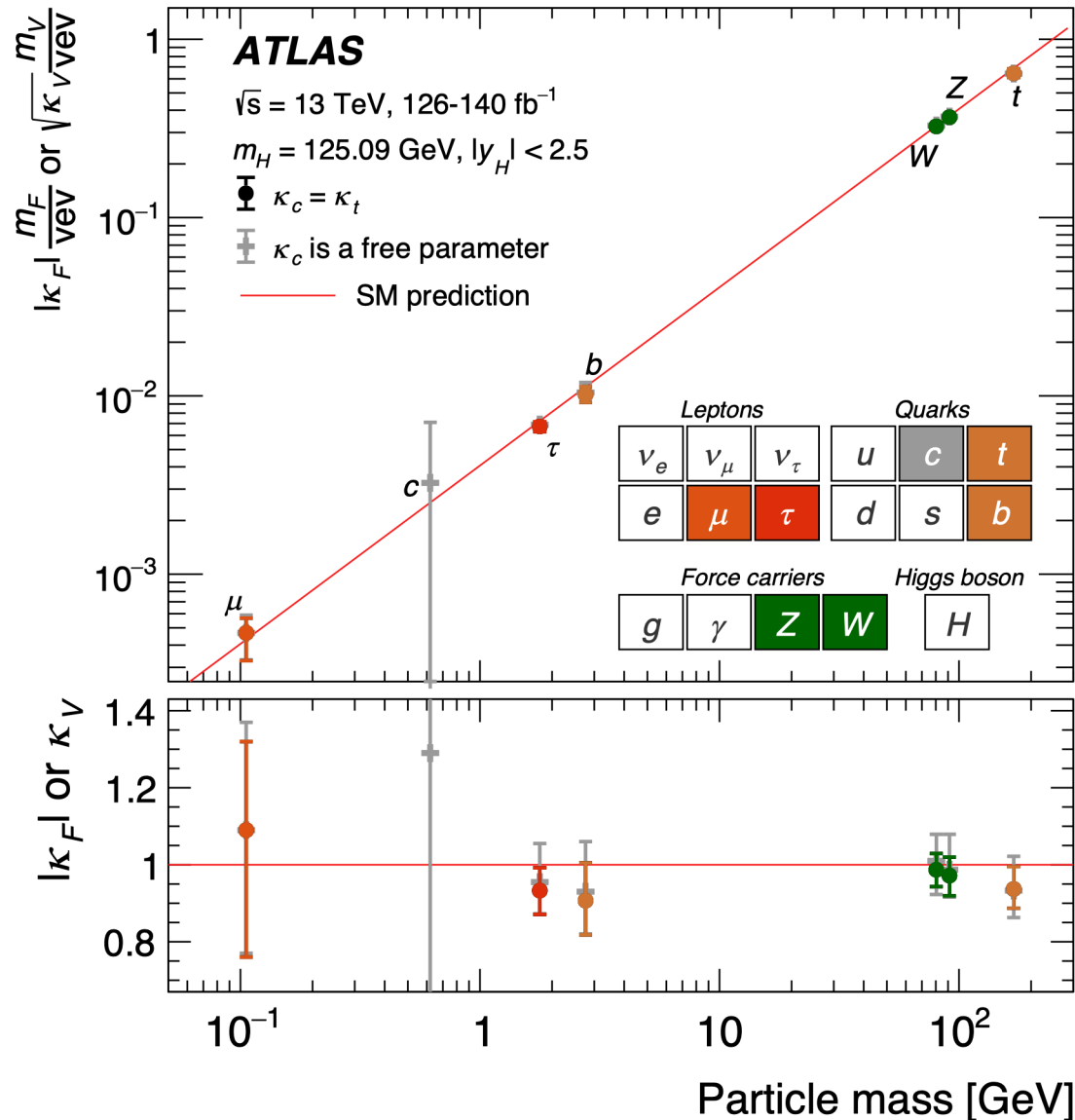
Extraction of Higgs boson coupling strengths modifiers from Run-2 signal-strength combination

Fit assume: $\Gamma_{H\rightarrow\text{inv/und}} = 0$, $\kappa_c = \kappa_t$, and *effective* parametrisation



Higgs couplings

ATLAS: [arXiv:2608.07332](https://arxiv.org/abs/2608.07332), CMS: [Rep. Prog. Phys. 89 \(2026\) 087801](https://arxiv.org/abs/2608.07332)

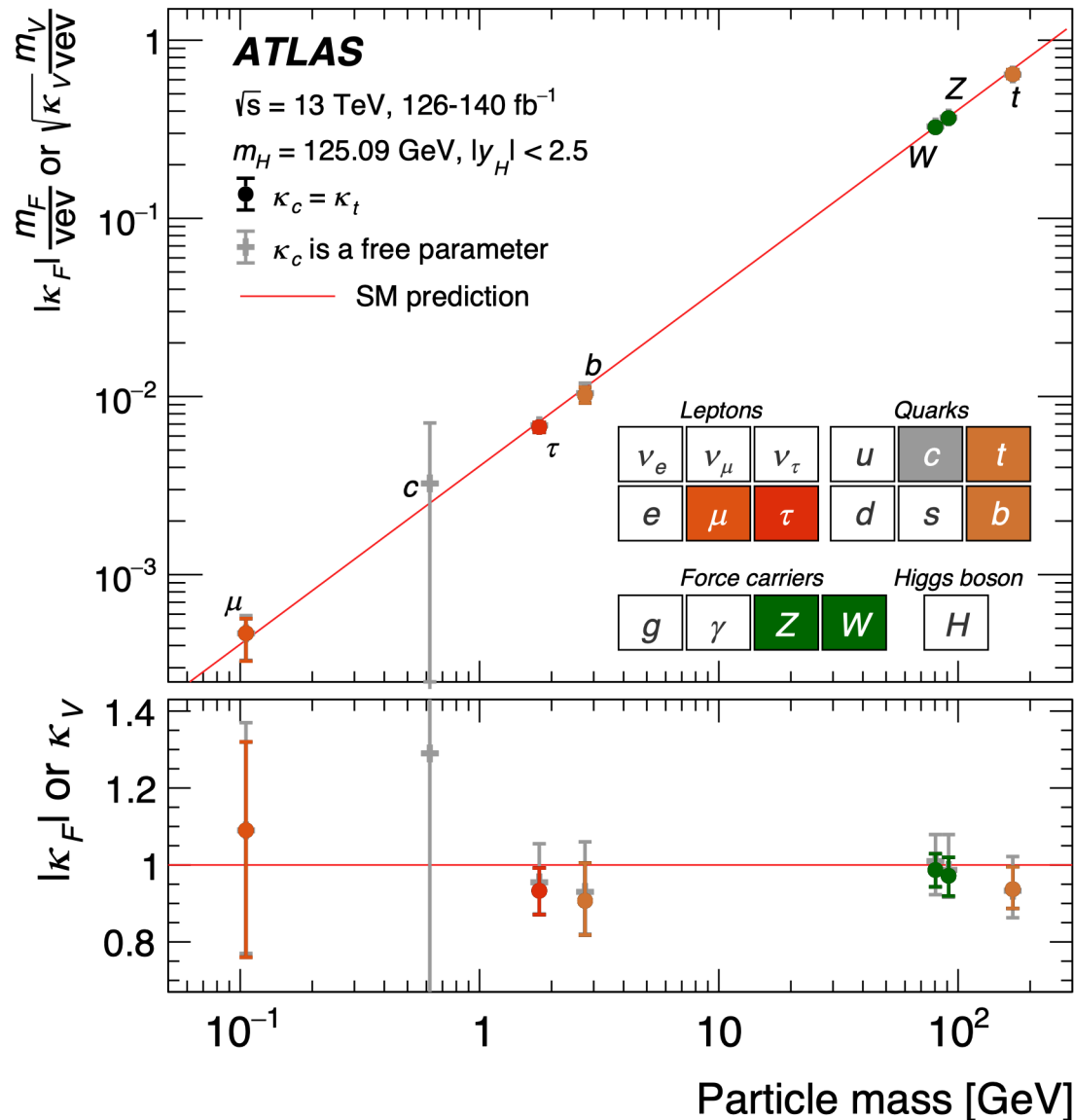


The Brout-Englert-Higgs mechanism is real

The measurements by ATLAS and CMS have confirmed the non-universal, mass-dependent coupling strengths of the Higgs boson to the SM particles

Higgs couplings

ATLAS: [arXiv:2608.07332](https://arxiv.org/abs/2608.07332), CMS: [Rep. Prog. Phys. 89 \(2026\) 087801](https://arxiv.org/abs/2608.07332)



The Higgs boson relates to many open questions in particle physics and cosmology

- Why is the Higgs boson so light?
- Is the Higgs boson elementary or composite ?
- Do Higgs interactions violate CP symmetry?
- Is the Higgs boson unique?
- Does the Higgs boson couple to dark matter?
- What is the origin of the large mass hierarchy of the fermions in the Standard Model?
- Is the vacuum metastable?
- Is the Higgs field connected with cosmic inflation?
- Why is the dark energy in the universe so much smaller than the Higgs vacuum energy?

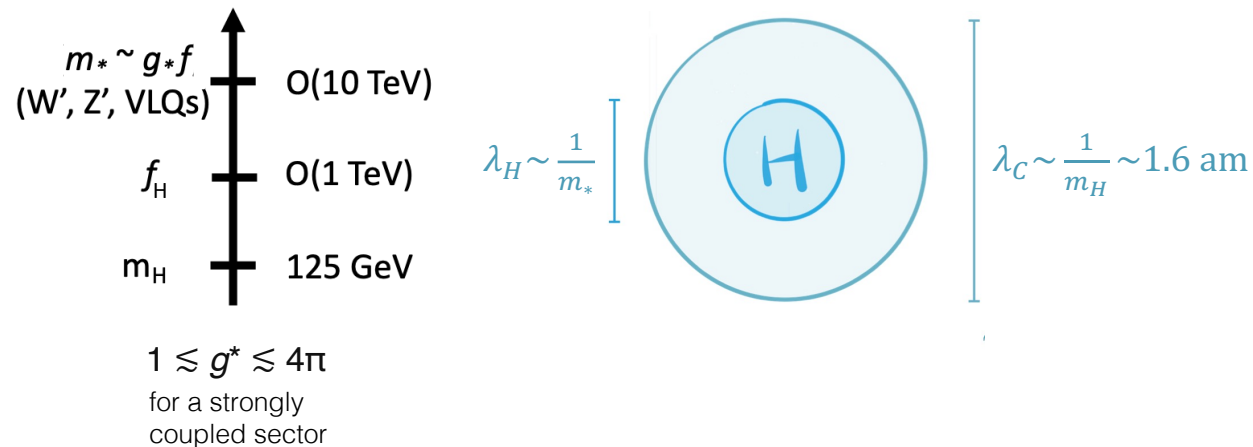
Higgs couplings — probing composite Higgs doublet

[JHEP 0706:045 \(2007\)](#), [arXiv:1412.6356](#)

The Higgs doublet may not be elementary but a composite pNGB multiplet of a new strong sector, with global symmetry broken at f_H and resonances at $m_* \sim g_* f_H$, with coupling $1 \lesssim g_* \lesssim 4\pi$. SM gauge and top-sector couplings explicitly break this symmetry, generating the Higgs potential and Higgs mass through loops

Analogously, QCD chiral symmetry breaks at f_π , producing pions as pNGBs and resonances at $m_\rho \sim g_\rho f_\pi$. Quark masses explicitly break the symmetry and generate m_π

Composite-Higgs scales



The pNGB nature of the Higgs modifies its interactions by terms of order $\xi \equiv v^2/f_H^2$

In minimal composite-Higgs models, the couplings to W and Z bosons are universally suppressed:

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \sqrt{1 - \xi} \simeq 1 - \frac{\xi}{2} \quad (V = W, Z)$$

Fermion coupling also shift by $O(\xi)$, but model-dependently. Precision Higgs-coupling measurements therefore probe the compositeness scale

5.0 (0.1)% precision on κ_i probes $f_H \sim 0.8$ (5.5) TeV

The **best measured coupling** probes Higgs compositeness best

Higgs width

The Higgs boson is a narrow resonance: $\Gamma_H(\text{SM}) = 4.1 \text{ MeV}$

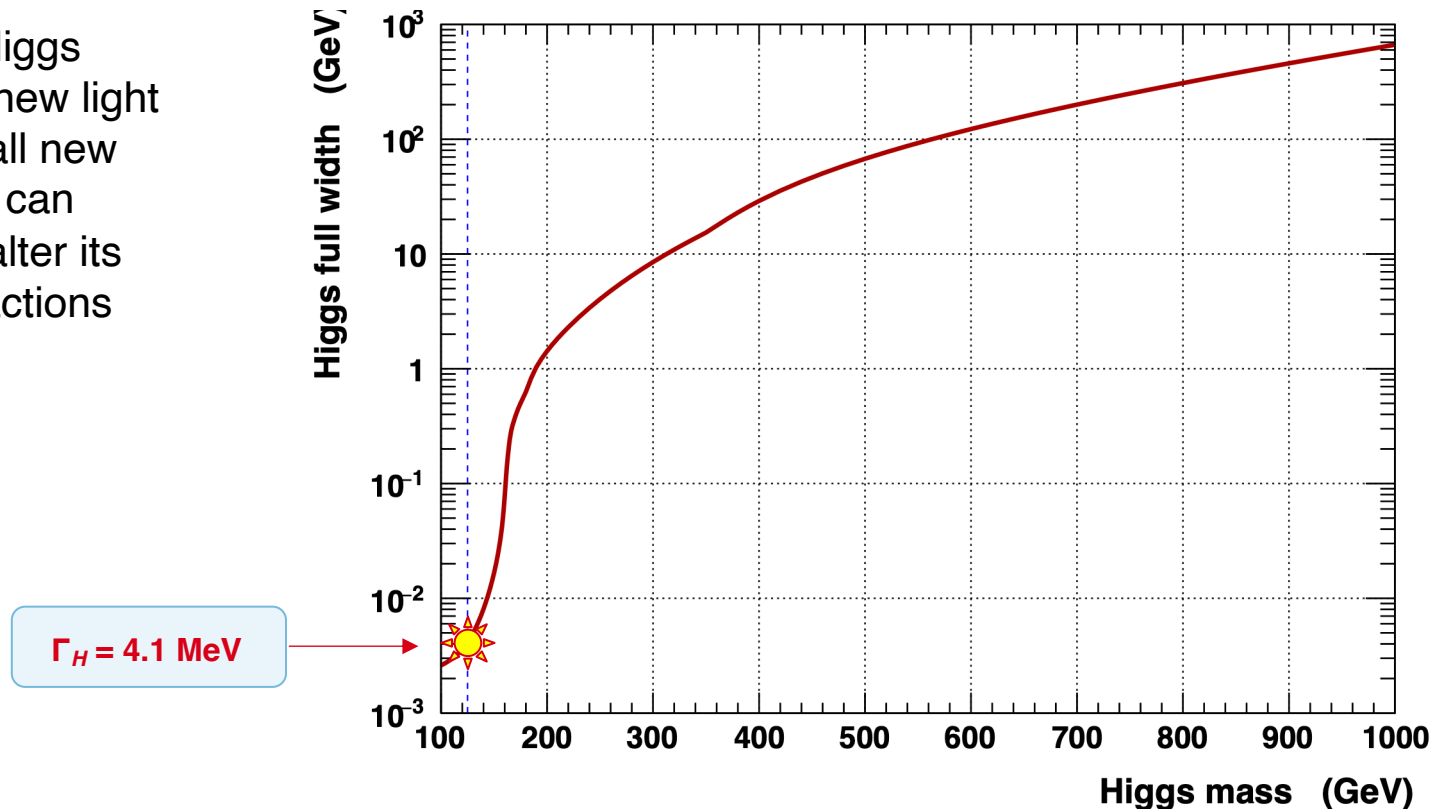
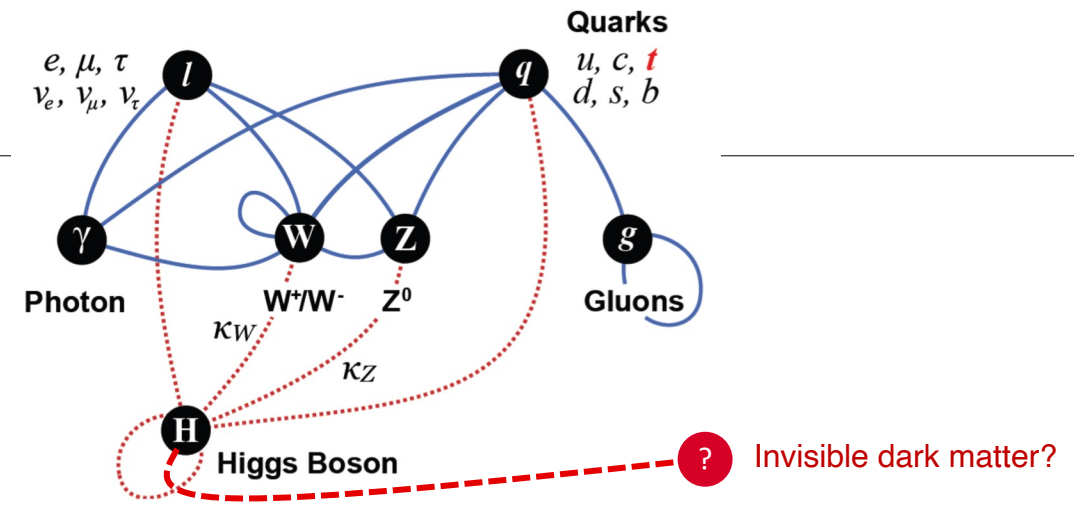
For comparison:

$$\Gamma_W = 2.1 \text{ GeV}$$

$$\Gamma_Z = 2.5 \text{ GeV}$$

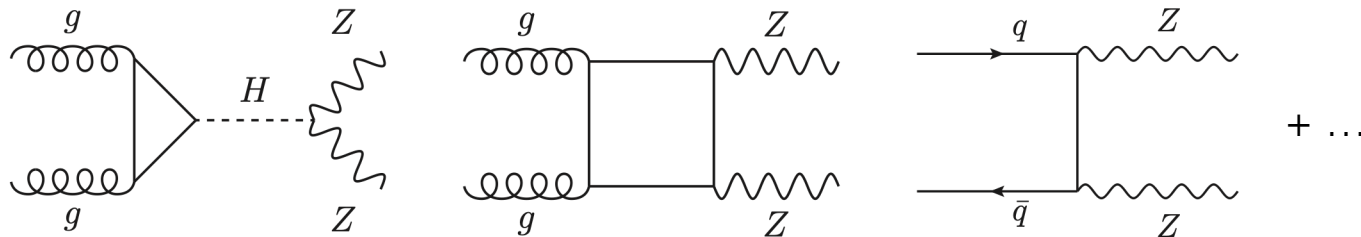
$$\Gamma_{\text{top}} = 1.3 \text{ GeV}$$

Even small Higgs couplings to new light states (a small new partial width) can measurably alter its branching fractions



Higgs width

Access to the Higgs boson decay width by comparing the high-mass off-shell Higgs production rate of $H^* \rightarrow ZZ, WW$ (insensitive to Γ_H) to the on-shell (125 GeV) one (dependent on Γ_H)



$gg \rightarrow H$ matrix element: $\mathcal{M}_H(gg \rightarrow H^* \rightarrow VV) = \mathcal{M}_{g g H} D_H(\hat{s}) \mathcal{M}_{H V V}$

so that $\hat{\sigma}_H(\hat{s}) \propto g_{g g H}^2 g_{H V V}^2 |D_H(\hat{s})|^2$ with $|D_H(\hat{s})|^2 = \frac{1}{(\hat{s} - m_H^2)^2 + m_H^2 \Gamma_H^2}$

For the full $gg \rightarrow VV$ process: $|\mathcal{M}|^2 = |\mathcal{M}_H|^2 + |\mathcal{M}_{\text{box}}|^2 + 2 \text{Re}(\mathcal{M}_H \mathcal{M}_{\text{box}}^*)$

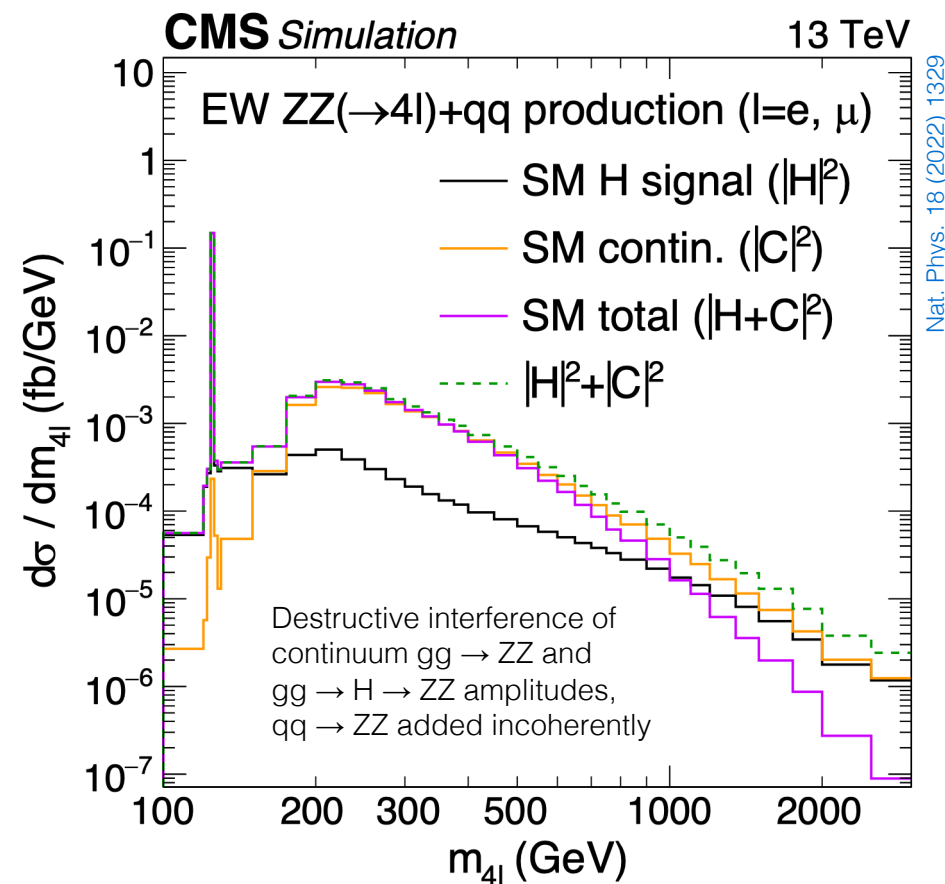
On-shell: $\mu_{\text{on}} = \frac{\kappa_i^2 \kappa_f^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$

Negative far off-shell: Higgs sector preserves consistency of longitudinal weak-boson scattering amplitudes!

Far off-shell: $\mu_{\text{off}}(\hat{s}) \simeq \kappa_i^2(\hat{s}) \kappa_f^2(\hat{s})$

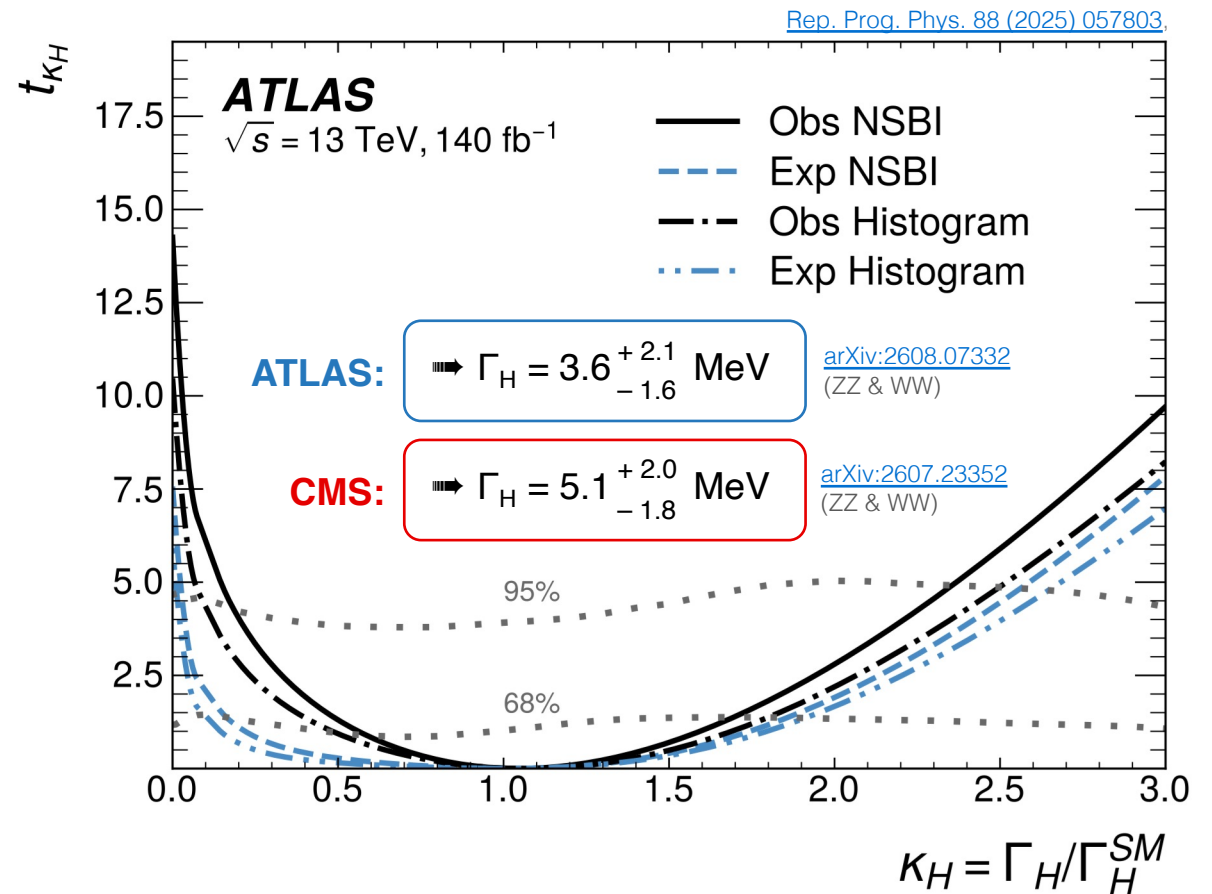
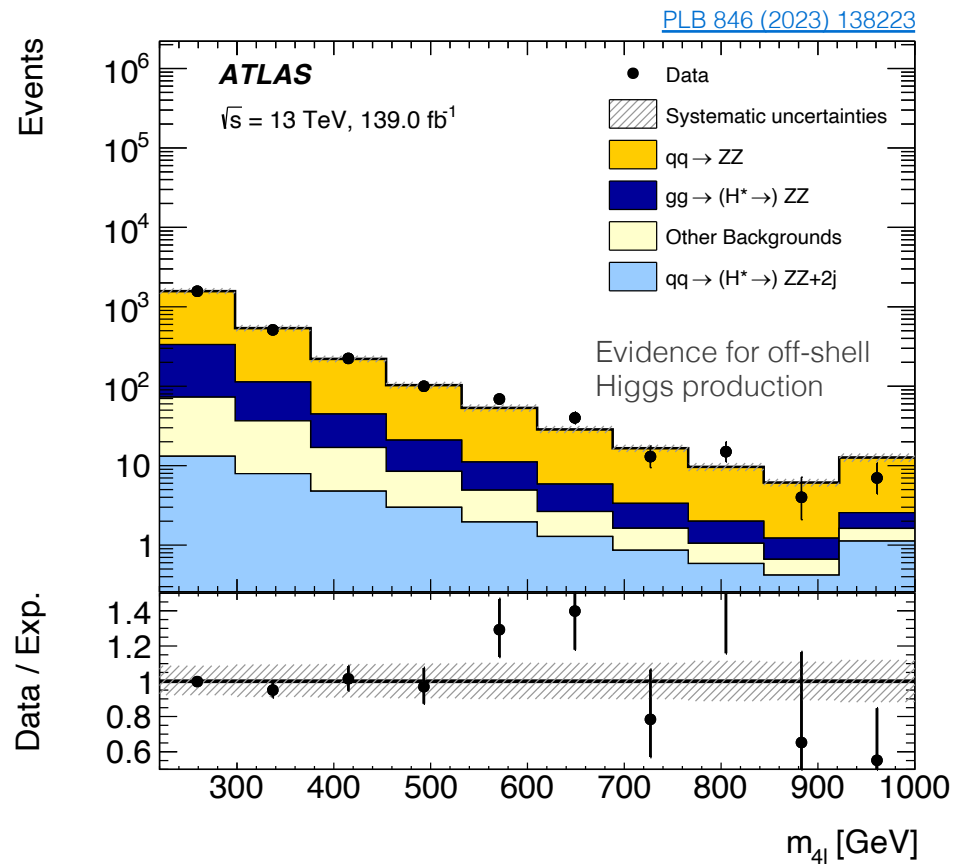
So that under the assumption $\kappa_{i,f}^{\text{off}} = \kappa_{i,f}^{\text{on}}$:

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\mu_{\text{off}}}{\mu_{\text{on}}}$$



Higgs width

Access to the Higgs boson decay width by comparing the high-mass off-shell Higgs production rate of $H^* \rightarrow ZZ, WW$ (insensitive to Γ_H) to the on-shell (125 GeV) one (dependent on Γ_H)

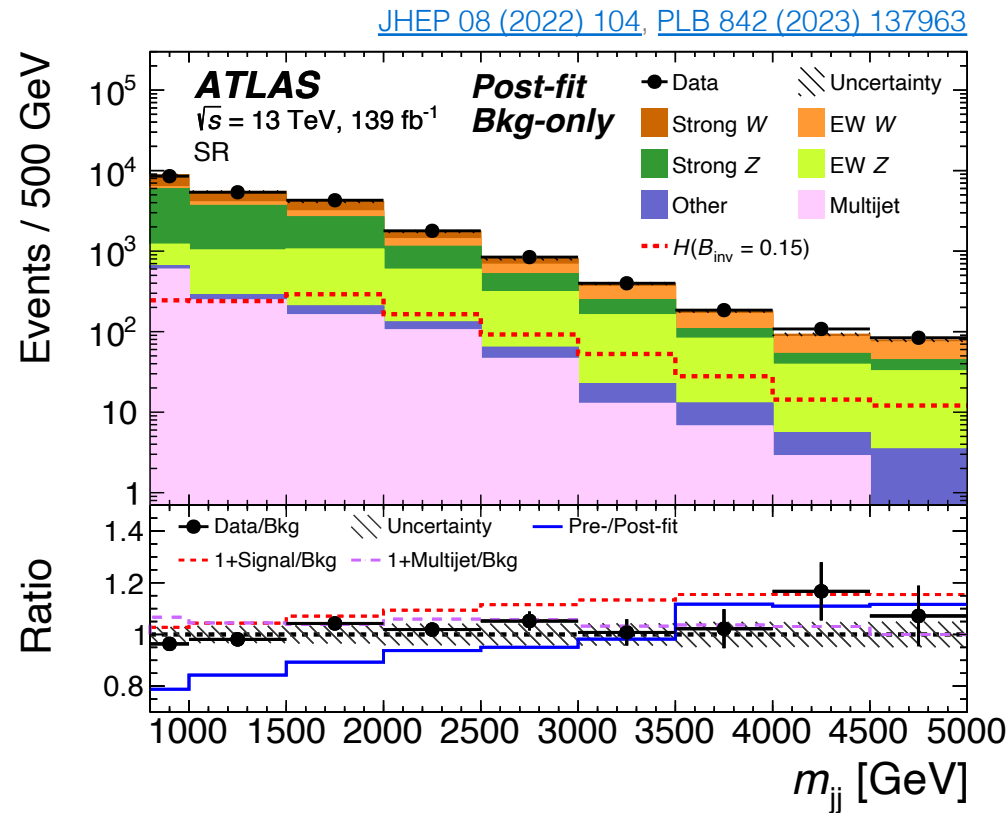
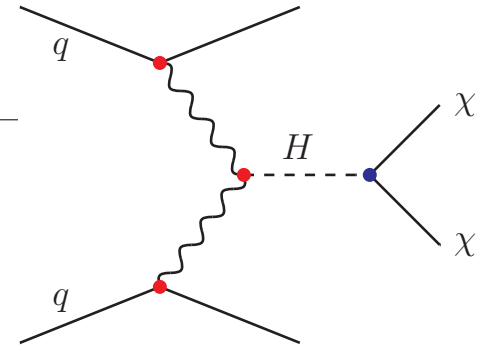


First use of neural simulation-based inference technique at LHC [\[Link\]](#) to exploit the complete multidimensional event kinematics (similar to Matrix Element method, but simulation based)

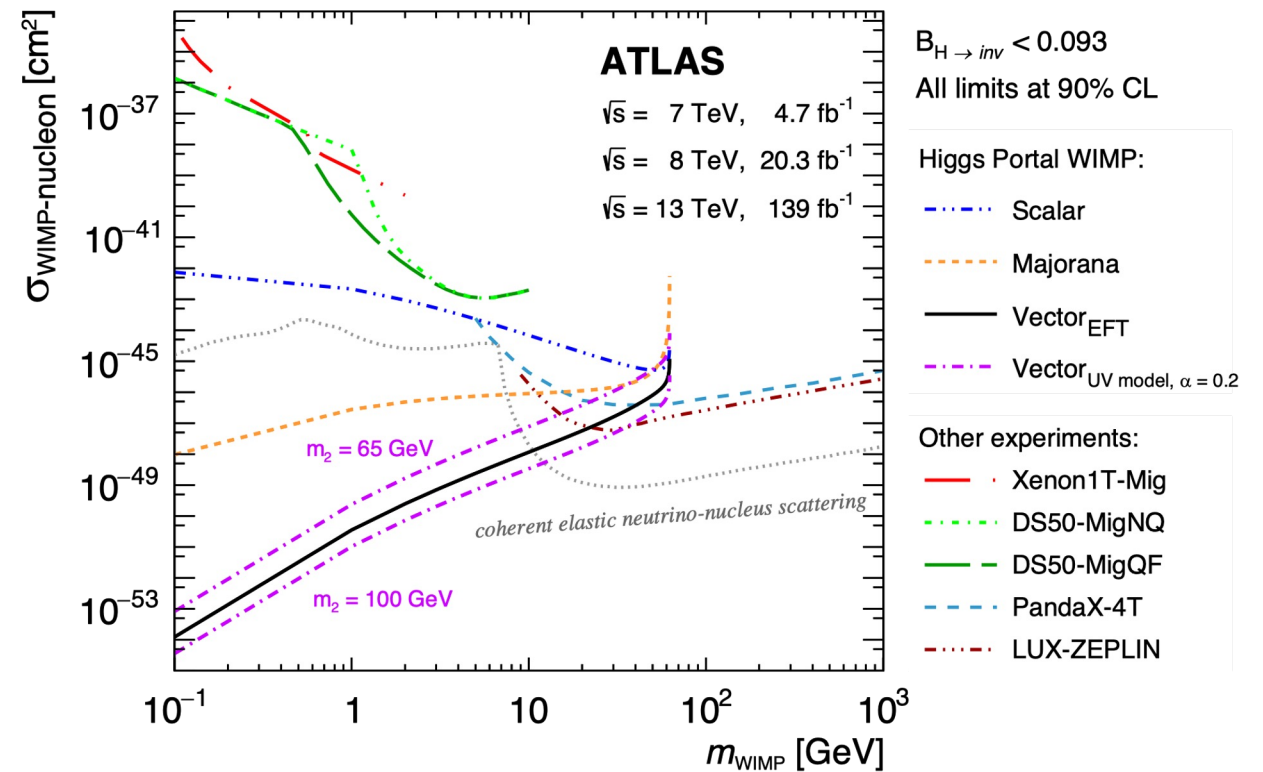
Invisible Higgs decays

The Higgs boson may invisibly decay to dark matter, if kinematically allowed

Detect through missing E_T generated by recoil against visible particles, e.g, in weak boson fusion



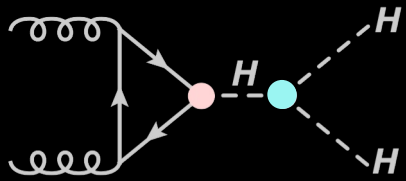
⇒ $\text{BR}(H \rightarrow \text{invisible}) < 0.107 \text{ (0.077) at 95\% CL}$



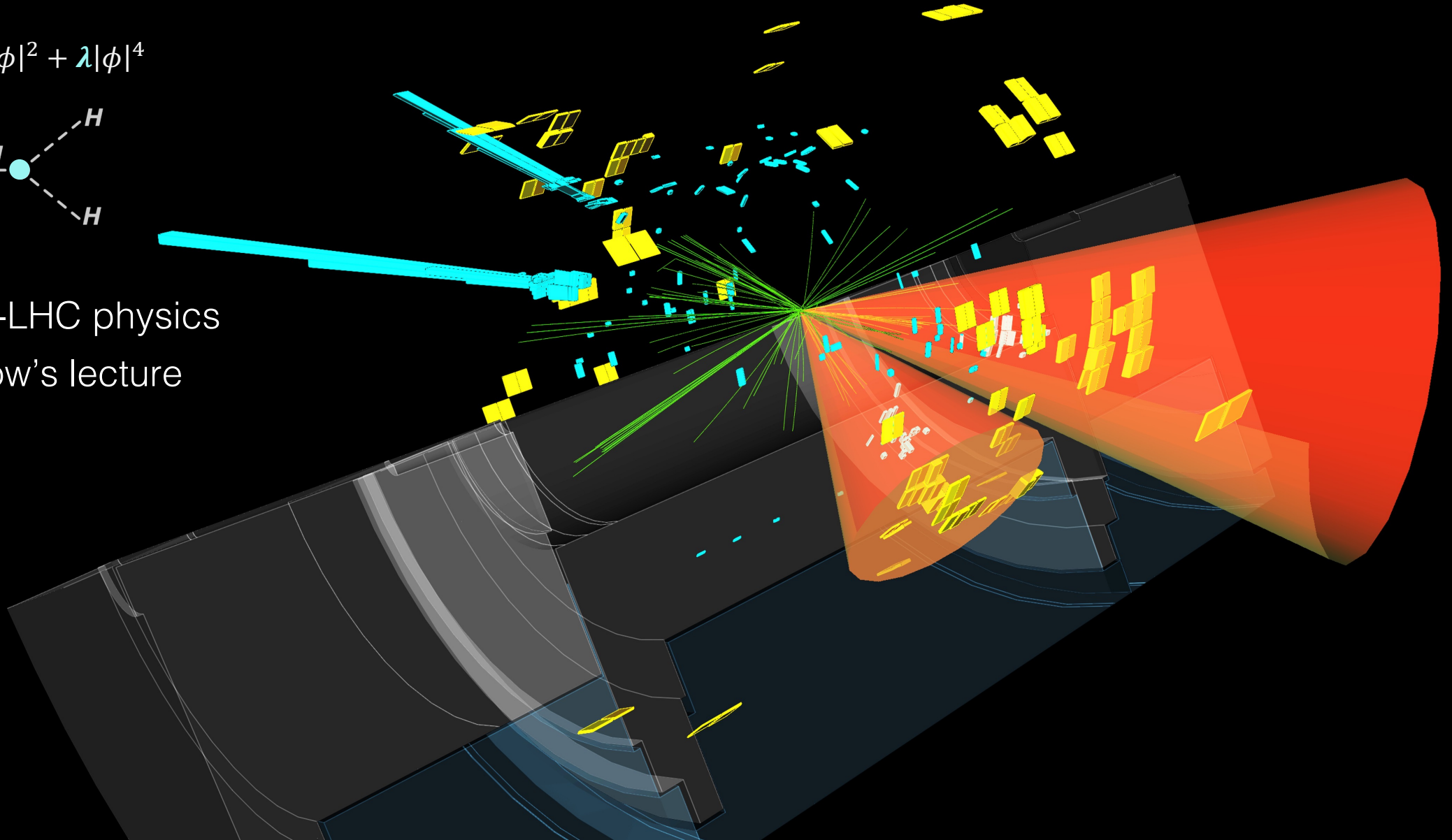
Minimal Higgs-portal interpretation: $m_\chi < m_H/2$, $\mathcal{B}_{\text{inv}} = \mathcal{B}(H \rightarrow \chi\chi)$, pure scalar SM Higgs exchange and scalar-nucleon form factor $f_N = 0.308 \pm 0.018$ ($g_{HNN} = f_N m_N/v$) (Vector limits are UV-model dependent)

Higgs self-coupling via Higgs pair production

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



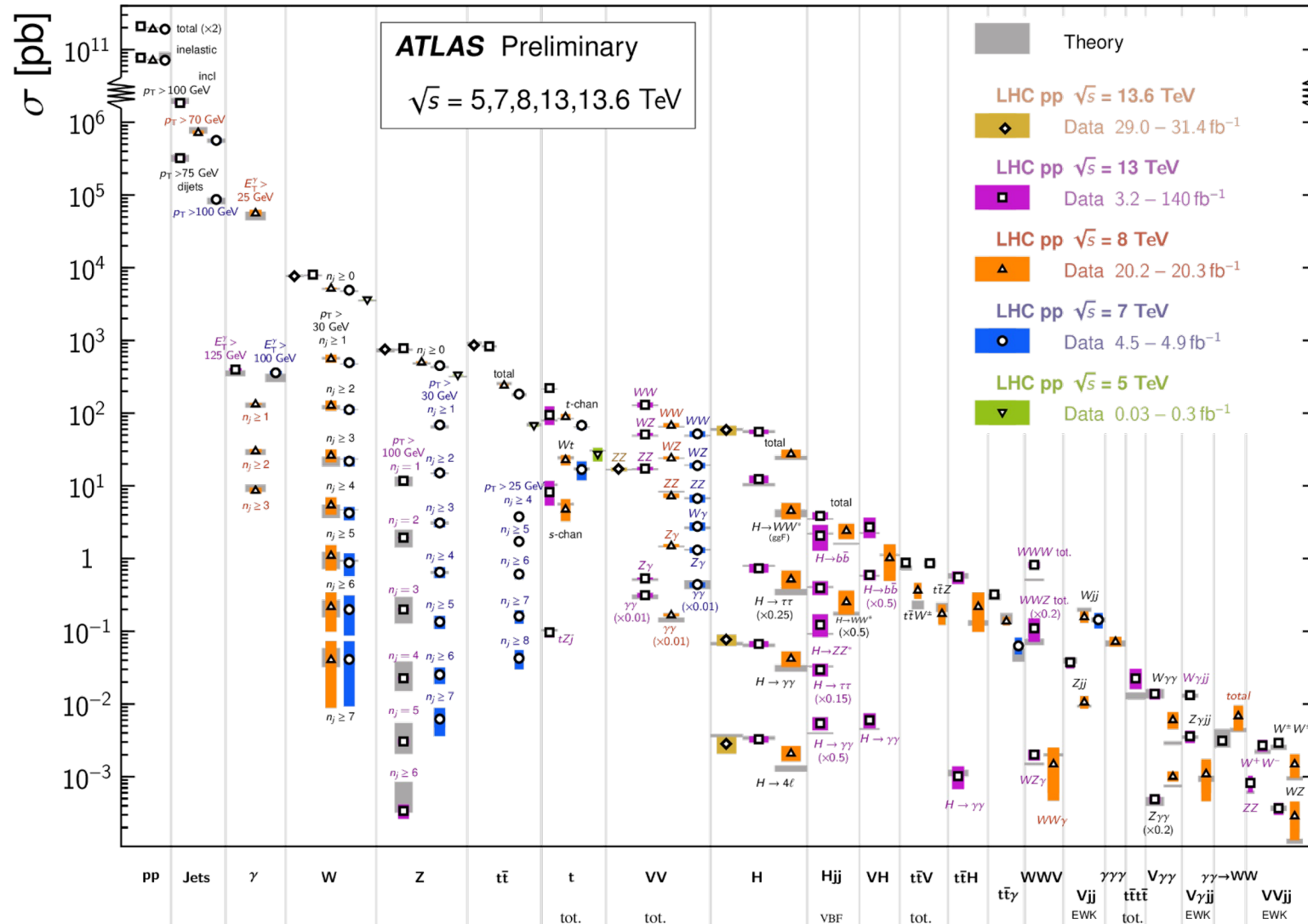
Mainly HL-LHC physics
→ tomorrow's lecture



LHC physics is incredibly rich

Standard Model Production Cross Section Measurements

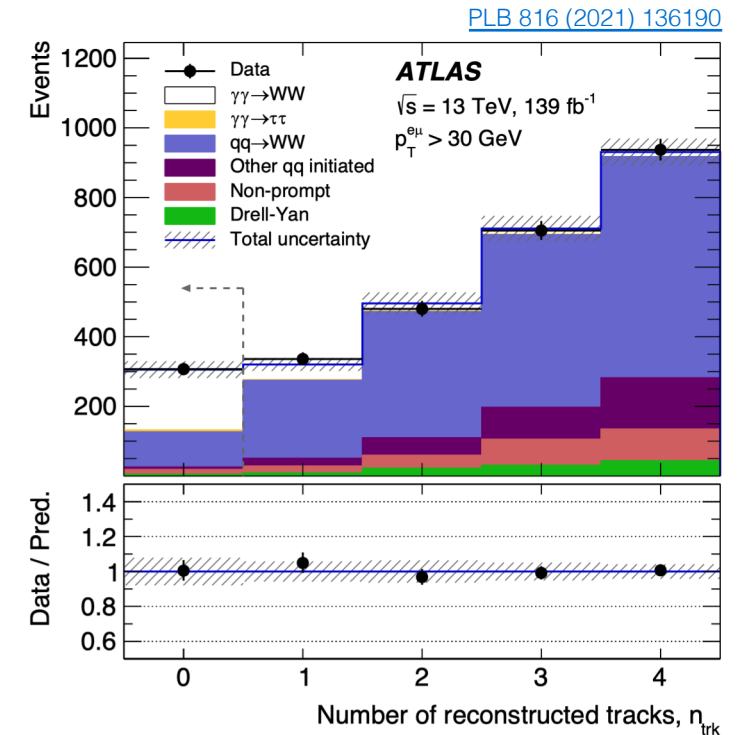
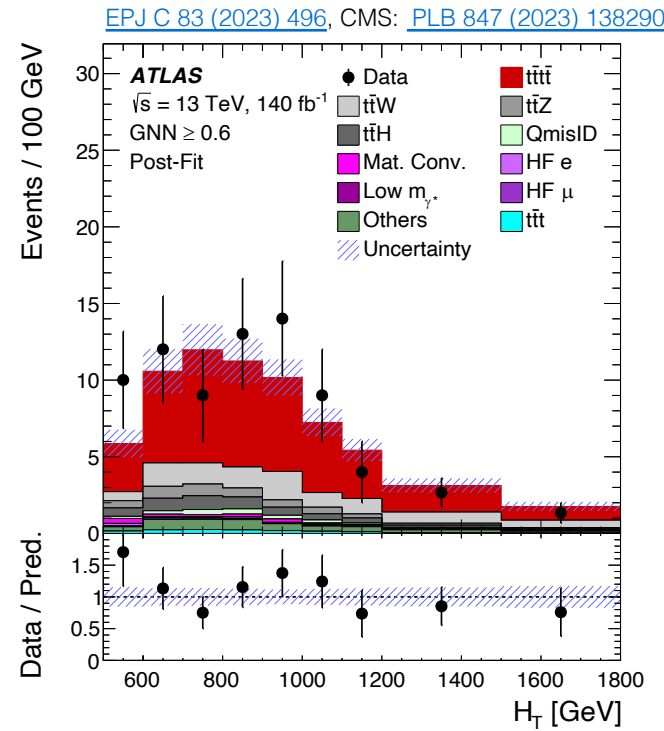
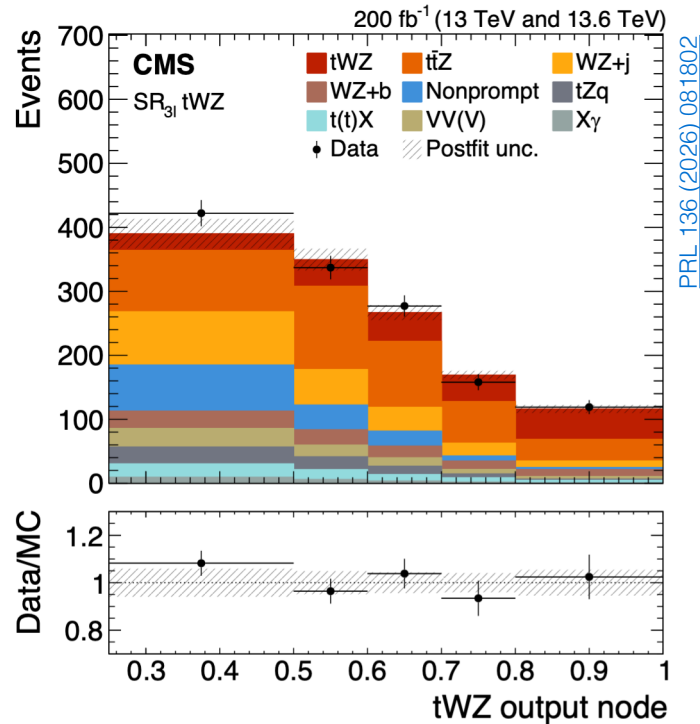
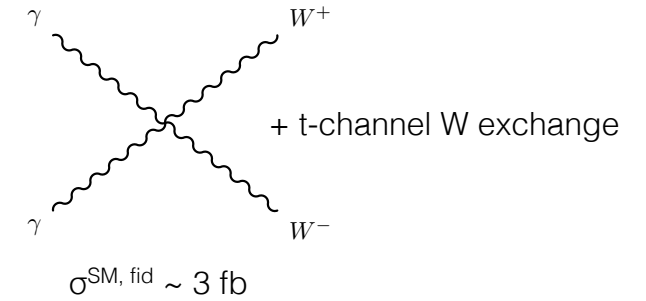
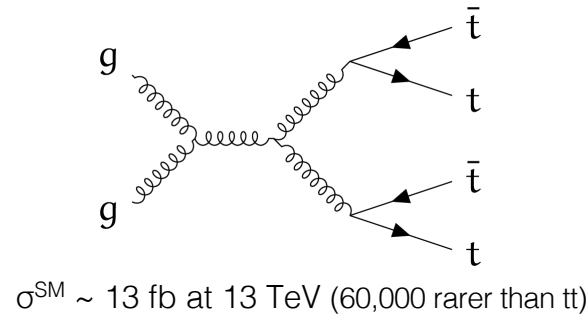
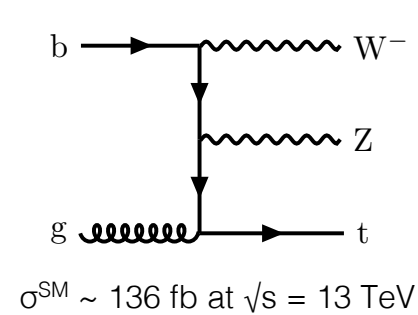
Status: June 2024



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

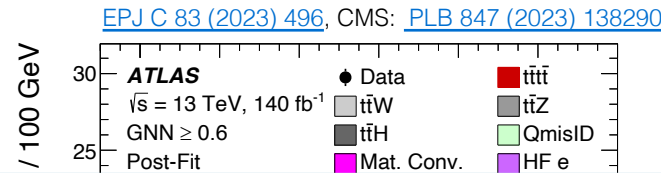
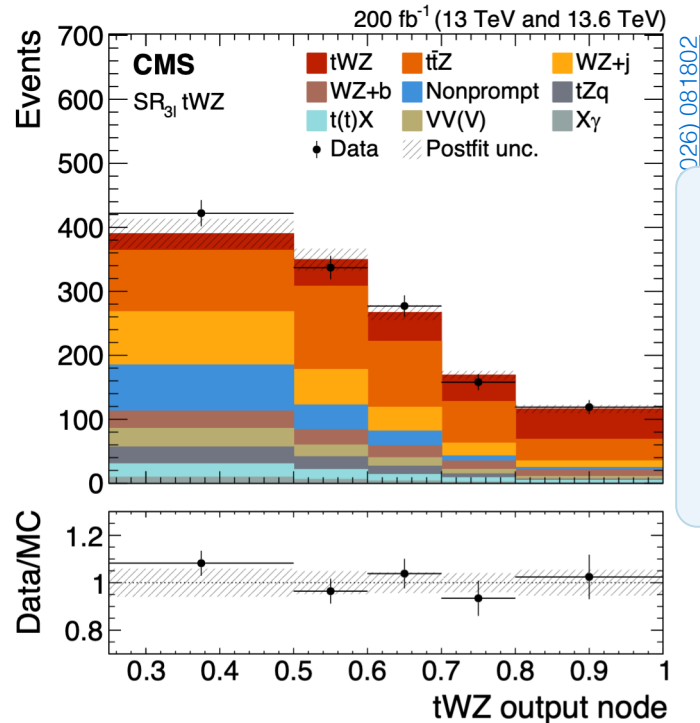
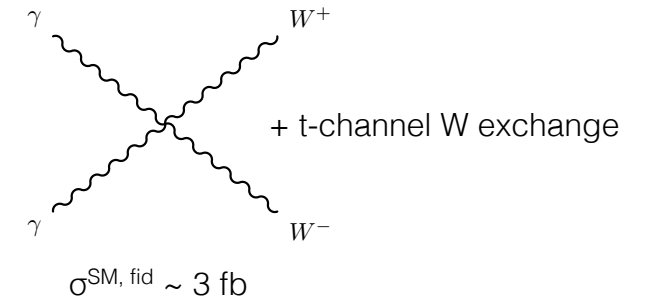
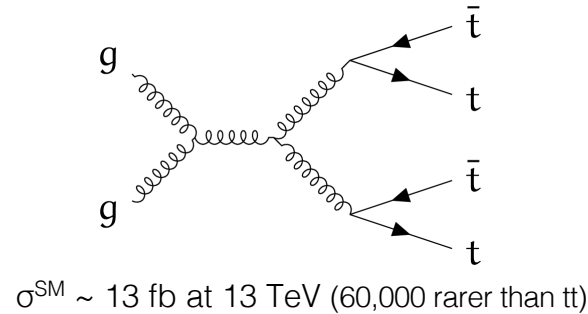
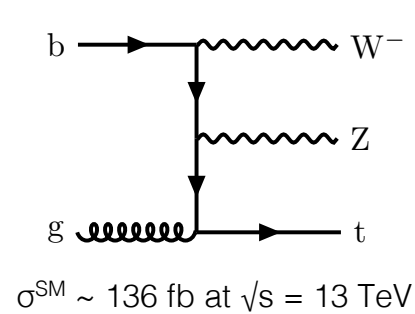
Observing rare processes

Rare high-energy processes expose interaction vertices that do not occur in abundant reactions — examples



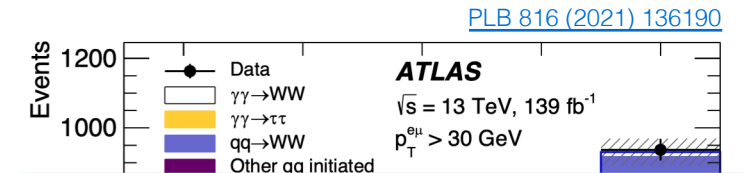
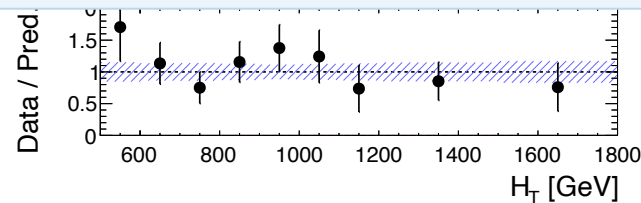
Observing rare processes

Rare high-energy processes expose interaction vertices that do not occur in abundant reactions — examples

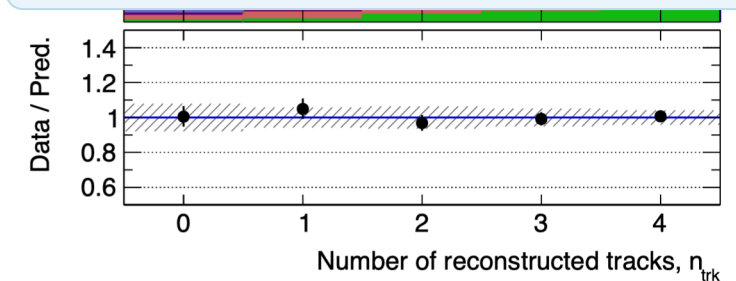


Directly probes four-top-quark $D = 6$ contact operators such as $(\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R)$, which otherwise only enter through loops / indirectly

Four-top production is effectively a top-top scattering experiment embedded inside a proton collision



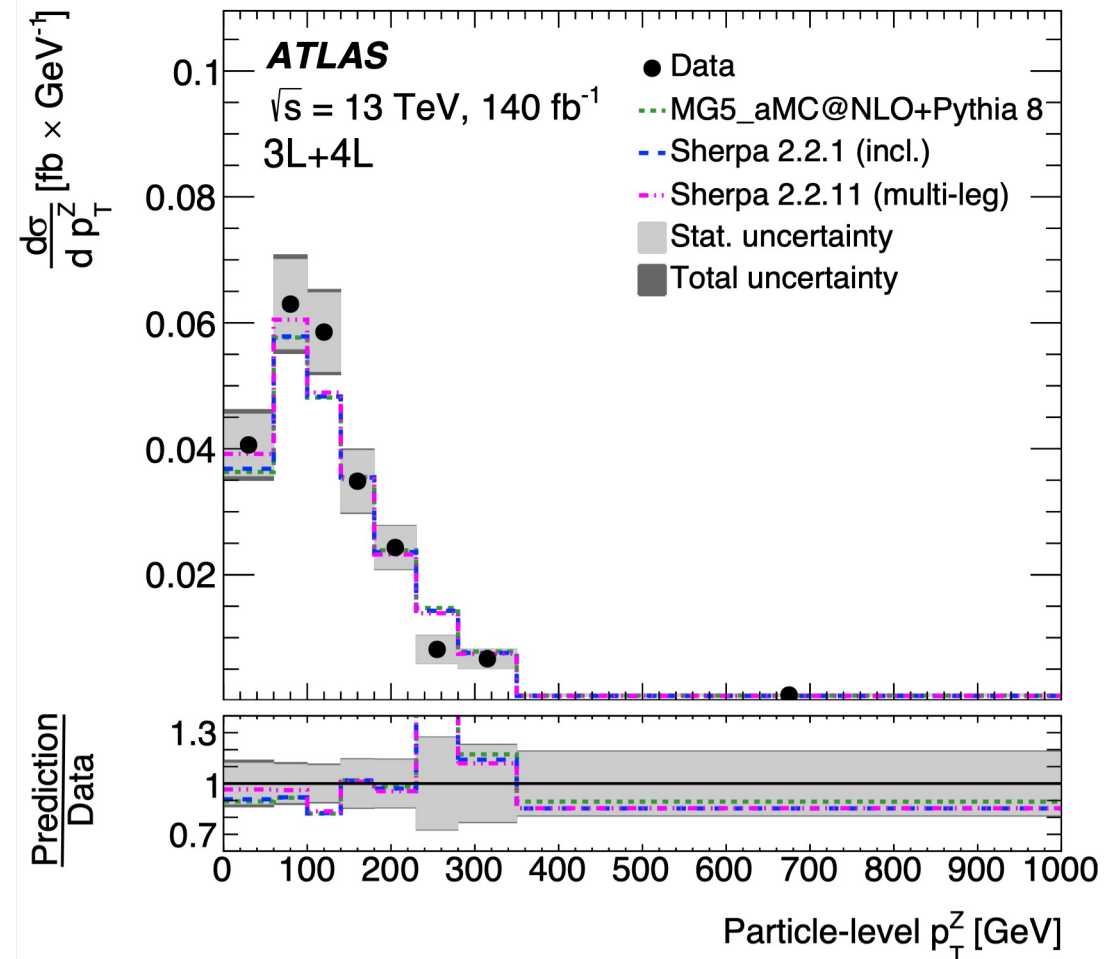
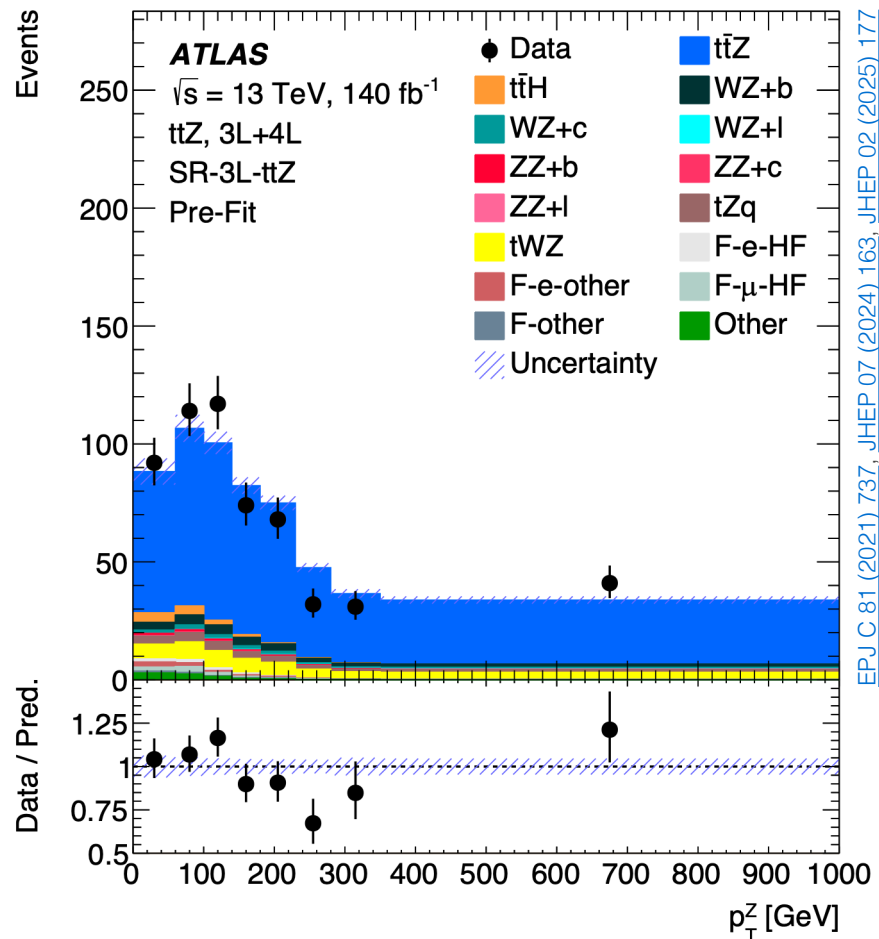
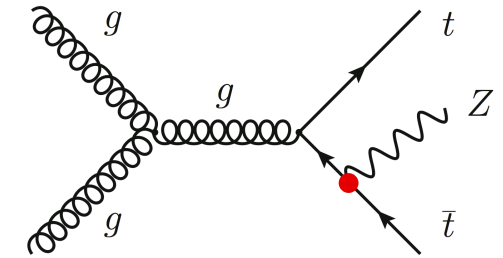
Directly probes $D = 8$ anomalous quartic gauge couplings (QGCs), which can change QGCs without modifying triple-gauge couplings (TGCs), so ordinary diboson production may be insensitive



Probing the top-Z coupling

Measurement of the rare $t\bar{t}Z$ process provides clean access to the top-Z coupling. The large luminosity of Runs 2 and 3 allow detailed studies of this process for the first time

Clean multi-lepton signature, inclusive cross section: $\sigma(t\bar{t}Z) = 0.86 \pm 0.04 \pm 0.04$ pb (SM: 0.86 ± 0.08 pb)



Longitudinal vector boson scattering

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

At $E \gg m_W$, longitudinal W and Z bosons behave like the Goldstone modes absorbed during symmetry breaking

Goldstone boson equivalence theorem: at $E \gg m_V$, amplitude of $V_L V_L \rightarrow V_L V_L \sim GG \rightarrow GG$

Unitarity: $W_L W_L$ scattering violates unitarity for gauge diagrams, quartic (WWWW) interaction plus γZ exchange

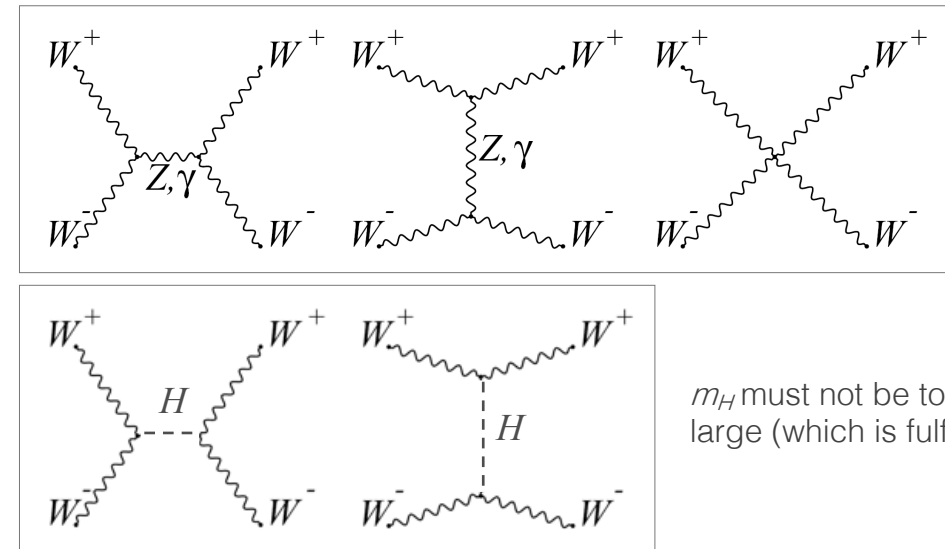
$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson exchange restores unitarity of total amplitude:

$$A_{\text{tot}}(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$

Why this is an exceptional probe?

- The longitudinal modes are the physical imprint of the symmetry-breaking field
- Their high-energy scattering tests the Higgs–vector coupling and gauge self-interactions in the same amplitude
- A failed cancellation could reveal extra scalars, TeV-scale resonances or higher-dimensional interactions

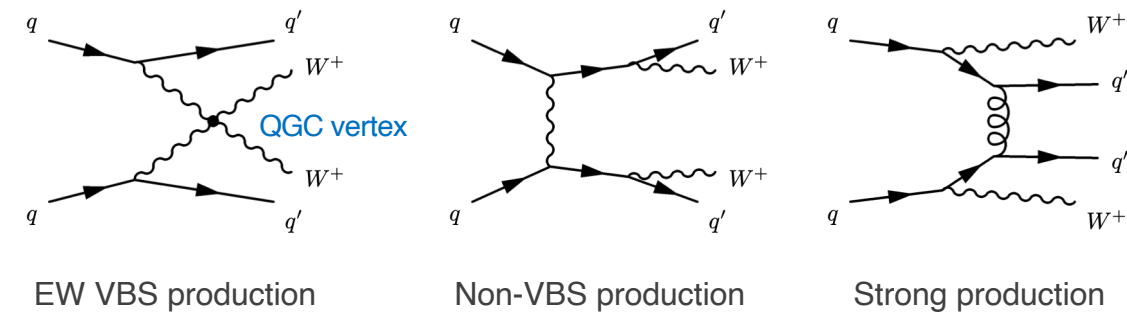
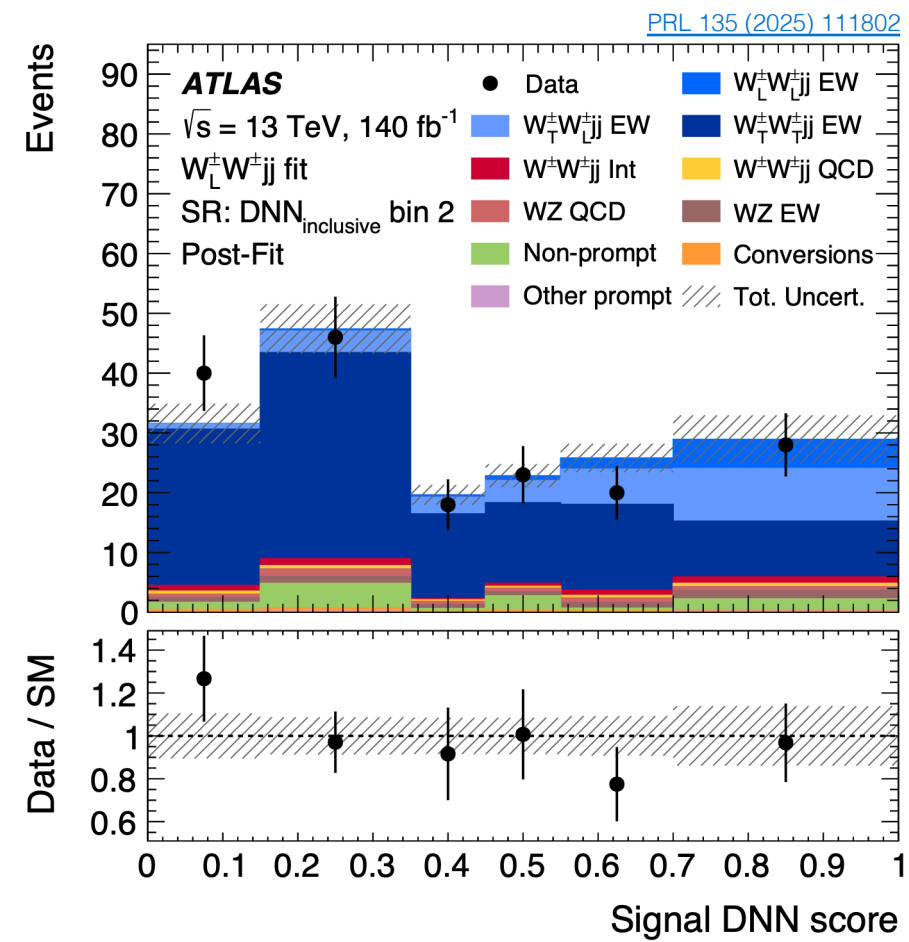


m_H must not be too large (which is fulfilled)

Longitudinal VV scattering tests whether the observed Higgs boson really completes the electroweak theory

Longitudinal vector boson scattering

Look for VBS scattering in high dijet invariant mass distributions — extremely rare processes requiring extraction of longitudinal polarisation



ATLAS recently reported first ensemble evidence for at least one longitudinally polarised W boson in $W^\pm W^\pm \rightarrow W^\pm W^\pm$ VBS

Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)
$W_L^\pm W_L^\pm jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)
$W_T^\pm W_T^\pm jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)
$W_L^\pm W_T^\pm jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)
$W_T^\pm W_L^\pm jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)

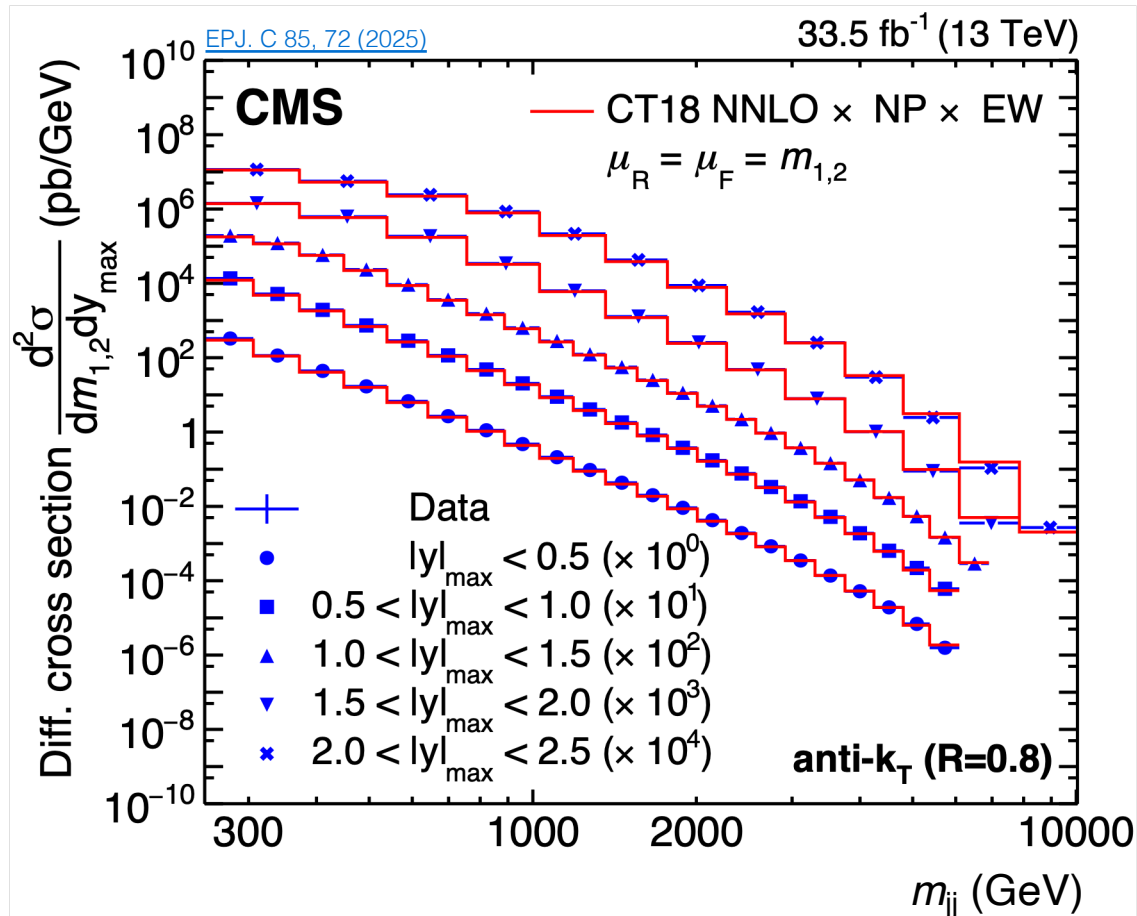
[3.3 σ_{obs} (4.0 σ_{exp})]

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!

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

Testing QCD to large scales

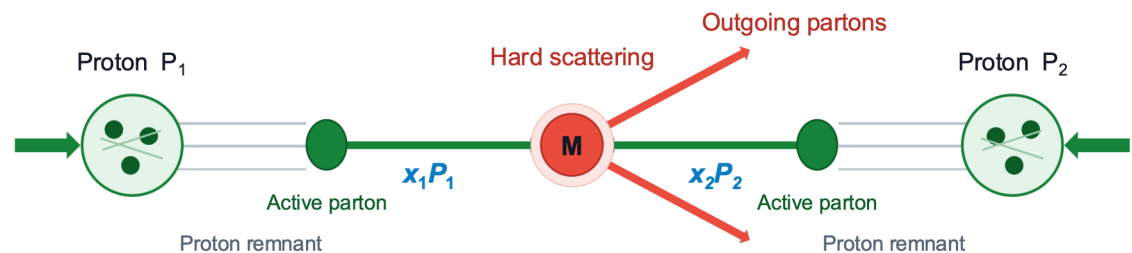
By measuring inclusive jet p_T or dijet mass spectra (or ...), the LHC tests perturbative QCD across an enormous energy range, constrains the proton's parton structure and α_S , and probes new physics in the highest-energy tail



$x - Q^2$ phase space covered by collider and fixed target experiments

$$m_{jj}^2 = x_1 x_2 s$$

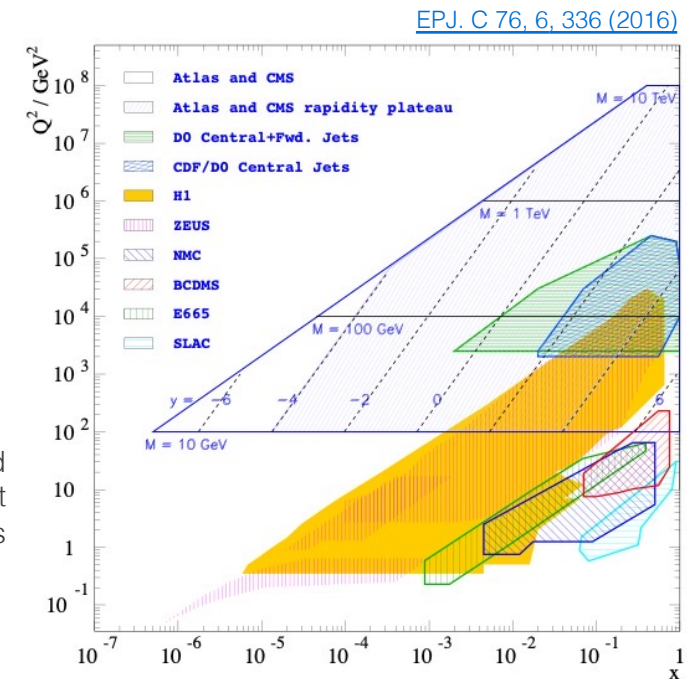
$$x_{1,2} = \frac{m_{jj}}{\sqrt{s}} \exp\left(\pm \frac{|y_1 + y_2|}{2}\right)$$



Combined fit of m_{jj} differential dijet cross section data to NNLO QCD and HERA deep-inelastic ep cross section data allows simultaneous extraction of PDFs and the strong coupling strength:

$$\alpha_S(m_Z) = 0.1179 \pm 0.0019$$

[Fit uncertainty: 0.0015, scale: 0.0008, PDF model: 0.0008]

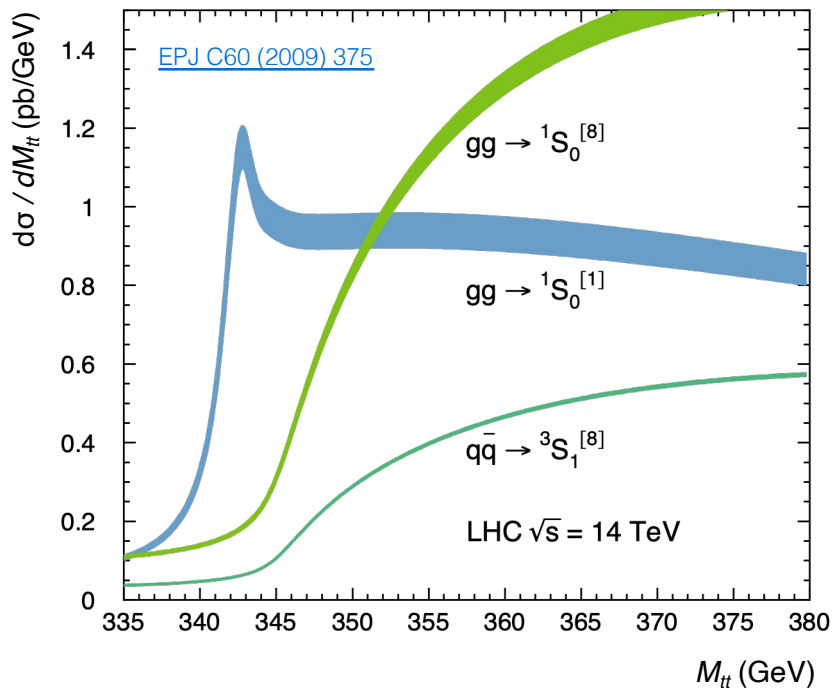


Top–antitop production at threshold

Near production threshold, repeated gluon exchange attracts a colour-singlet top–antitop pair through the Coulombic potential $V^{[1]}(r) \simeq -C_F\alpha_s/r$ ($C_F = 4/3$ colour factor), producing a quarkonium-like correlation with $\Gamma_{tt} \approx 2\Gamma_t \approx 2.8$ GeV

Unlike ordinary quarkonium, toponium decays through its constituent tops ($\tau_t \approx 5 \cdot 10^{-25}$ s), allowing only a brief correlation

Finite top width smears the would-be 1S pole into a broad quasi-bound threshold enhancement

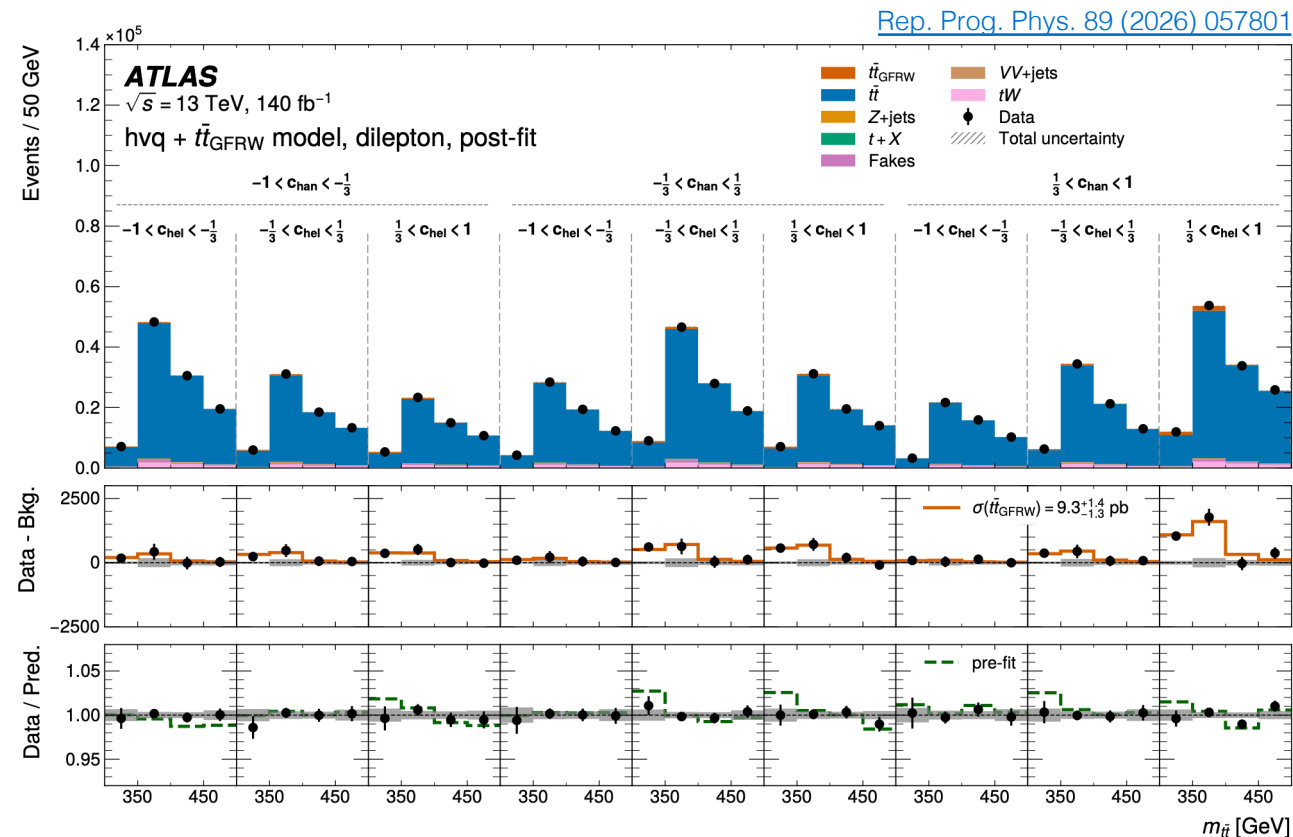
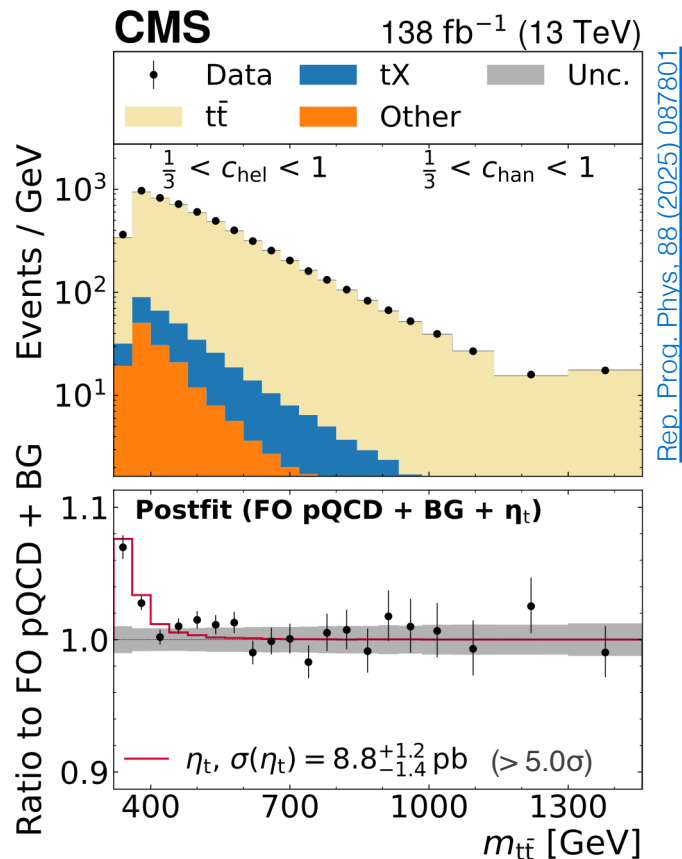


At LHC, toponium is dominantly pseudoscalar: $\eta_t = 1S_0^{[1]}$ (where: $2S+1L_J^{[\text{colour}]}$)

- Spin singlet: $S = 0$ (antiparallel tt spins); S wave: $L = 0 \rightarrow J = 0$, colour singlet: $[1]$
- For neutral quark–antiquark state: $P = (-1)^{L+1}$, $C = (-1)^{L+S} \rightarrow J^{PC} = 0^{-+}$
- Gluon-fusion at LHC favours the attractive $1S_0^{[1]}$ state: $3S_0^{[1]}$ via gluons is forbidden, P-waves are velocity-suppressed, and the colour-octet $gg \rightarrow 3S_0^{[8]}$ and $qq \rightarrow 3S_1^{[8]}$ channels feel the repulsive $V^{[8]}(r) \simeq +\alpha_s/(6r)$
- Non-relativistic QCD (NRQCD) exploits $v \simeq \sqrt{|E|/m_t} \ll 1$ near threshold, factorising hard tt production from non-relativistic evolution, and resumming enhanced terms $(\alpha_s/v)^n$ from repeated gluon exchange using colour-dependent QCD potentials

Top–antitop production at threshold

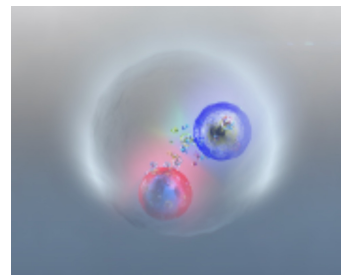
Toponium was thought not to be resolvable at the LHC, but with smart analysis using dilepton tt decays CMS reported the observation of a pseudoscalar “toponium” enhancement near production threshold — observation confirmed by ATLAS



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

Observed significance $> 8\sigma$ for a cross section of $9.3 \pm 1.4 \text{ pb}$

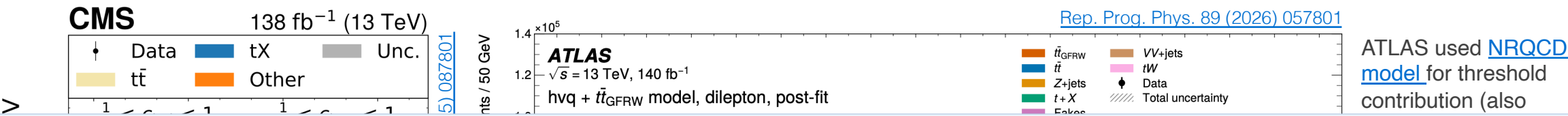
(With CMS signal model ATLAS finds: $13.2 \pm 1.8 \text{ pb}$)



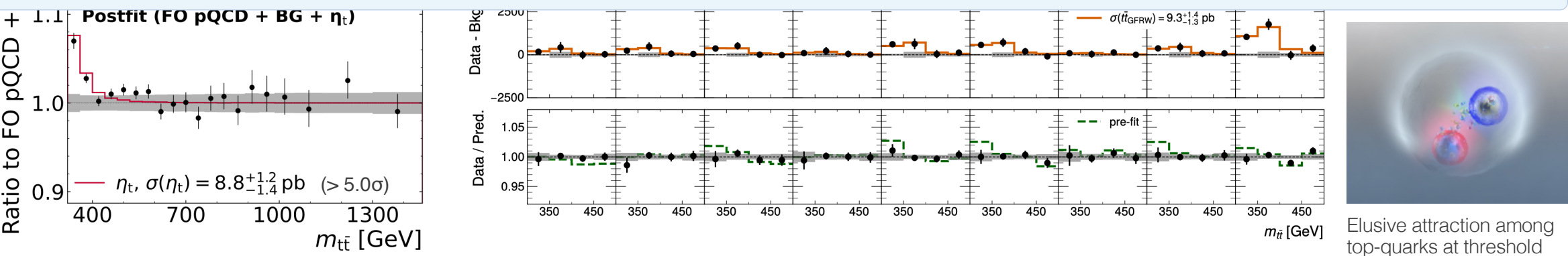
Elusive attraction among top-quarks at threshold

Top–antitop production at threshold

Toponium was thought not to be resolvable at the LHC, but with smart analysis using dilepton $t\bar{t}$ decays CMS reported the observation of a pseudoscalar “toponium” enhancement near production threshold — observation confirmed by ATLAS



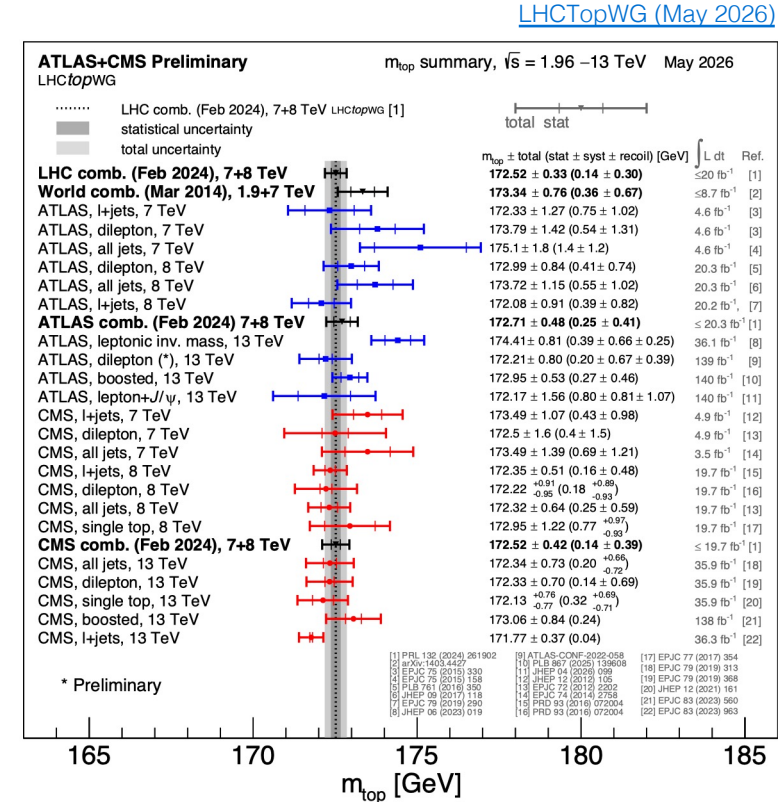
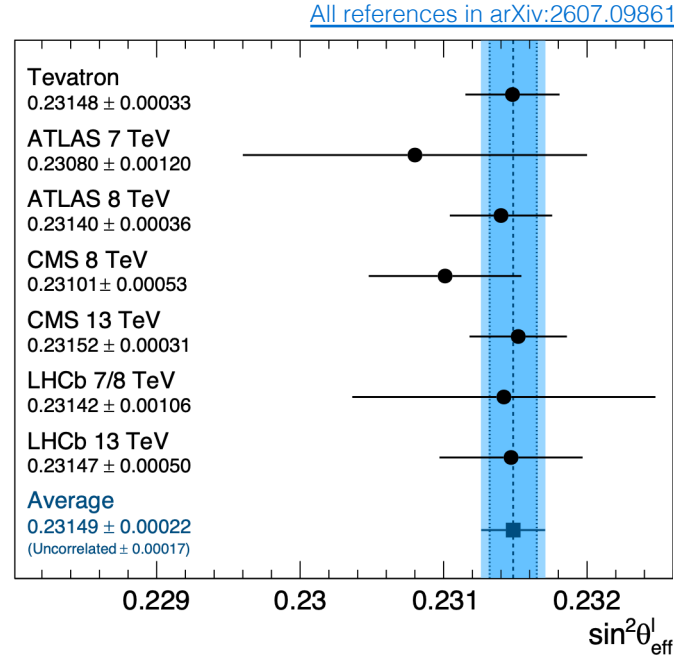
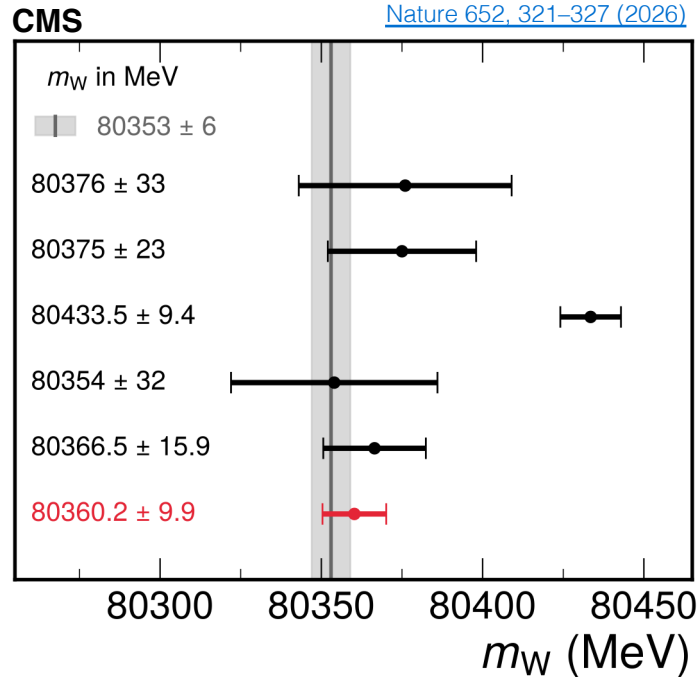
Extremely challenging measurement of a subtle signal in a difficult modelling environment.
This observation will spur further theoretical and experimental progress at the $t\bar{t}$ threshold



High-precision measurements of fundamental SM parameters

The LHC is both a high-E+Lumi discovery machine and a facility for extraordinarily precise measurements

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
DO
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work



World / LHC+Tevatron averages:

LEP & SLD: 0.23153 $\pm$ 0.00016

$$m_W|_{\text{excl. CDF}} = 80.3625 \pm 0.0077 \text{ GeV}$$

$$\sin^2 \theta_{\text{eff}}^l|_{\text{Had Coll}} = 0.23149 \pm 0.00021$$

$$m_{\text{top}} = 172.52 \pm 0.33 \text{ GeV}$$

SM (global EW fit): 80.3558 $\pm$ 0.0061 GeV

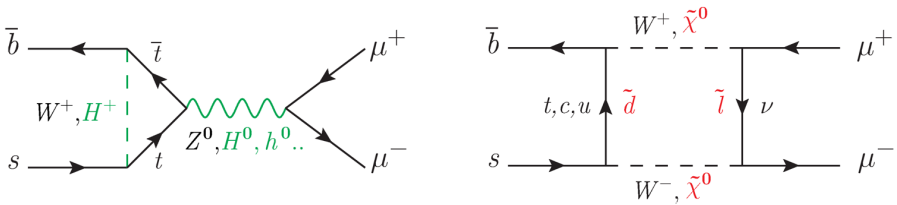
0.23149 $\pm$ 0.00006

173.6 $\pm$ 1.5 GeV

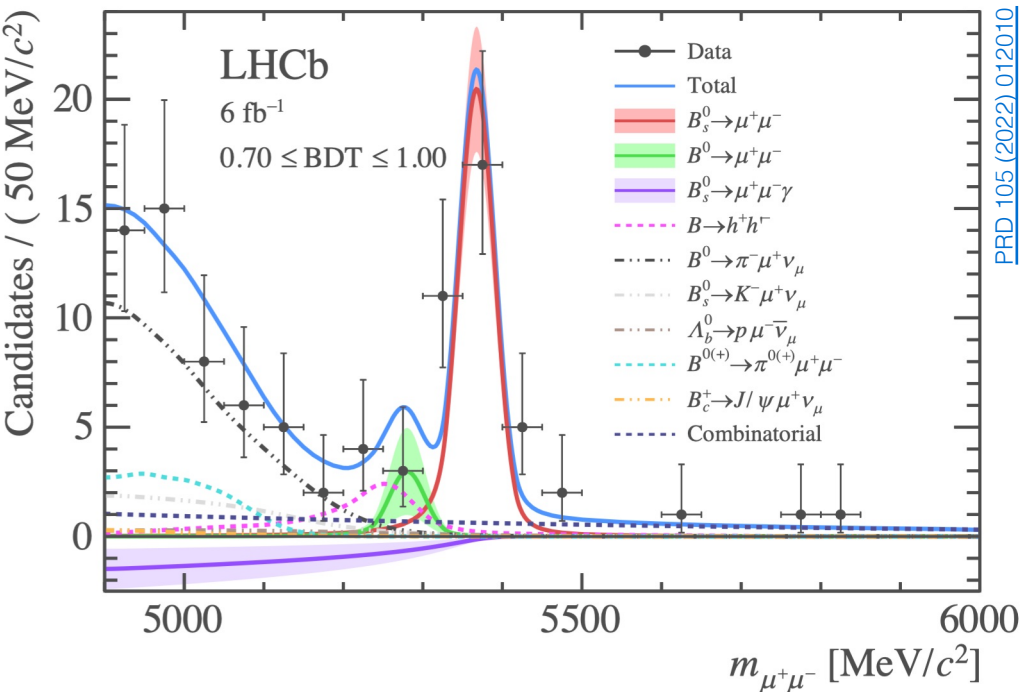
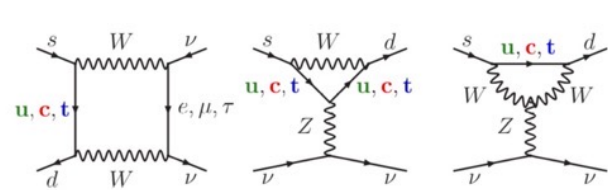
Flavour physics — dedicated lecture, so only a few highlights here

Extremely rare channels such as $B_s \rightarrow \mu\mu$ (left) and $K^+ \rightarrow \pi^+\nu\nu$ (right) occur as predicted

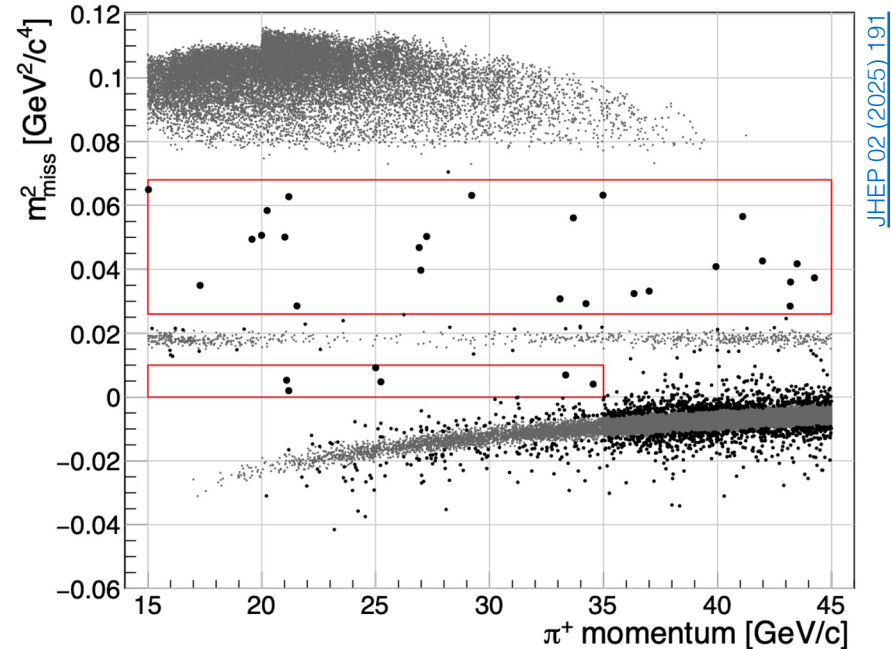
Possible new physics contributions to $B_s \rightarrow \mu\mu$



SM contributions to $K^+ \rightarrow \pi^+\nu\nu$



$B(B_s \rightarrow \mu\mu) = 3.1 \pm 0.5 \cdot 10^{-9}$
SM: $3.6 \pm 0.1 \cdot 10^{-9}$
Similar precision by CMS
[PLB 842 (2023) 137955, 140 fb⁻¹]

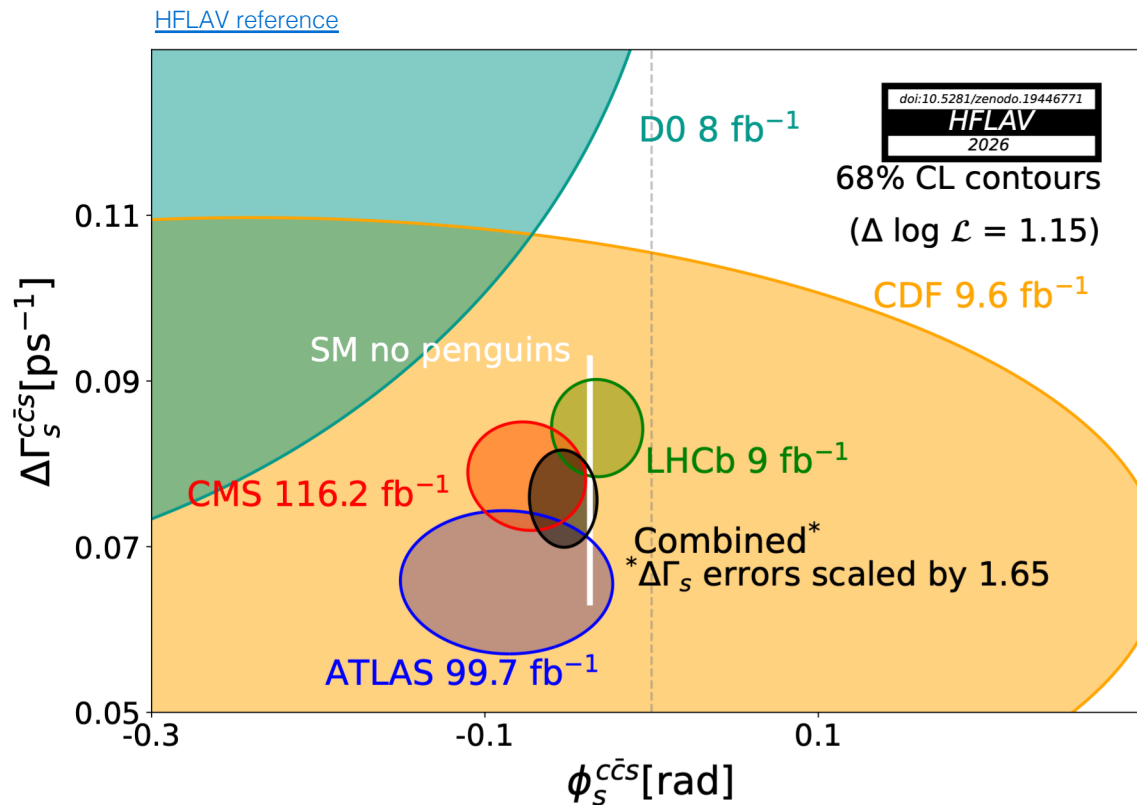


$B(K^+ \rightarrow \pi^+\nu\nu) = 13.0^{+3.3}_{-3.0} \cdot 10^{-11}$
SM: $8.4 \pm 1.0 \cdot 10^{-11}$

Flavour physics — CP violation

High-precision CKM angle measurements overconstrain CKM matrix and probe new physics

Mixing-induced time-dependent CP violation measurements in $J/\psi\phi$
(and similar)



$$\phi_a^{c\bar{c}s} = -2\beta_s = -0.052 \pm 0.013 \text{ rad}, \text{ with } \beta_s \equiv \arg \left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right]$$

SM: $-0.0376 \pm 0.0006 \text{ rad}$

LHCb:

$$\gamma = 64.6 \pm 2.8 \text{ deg}$$

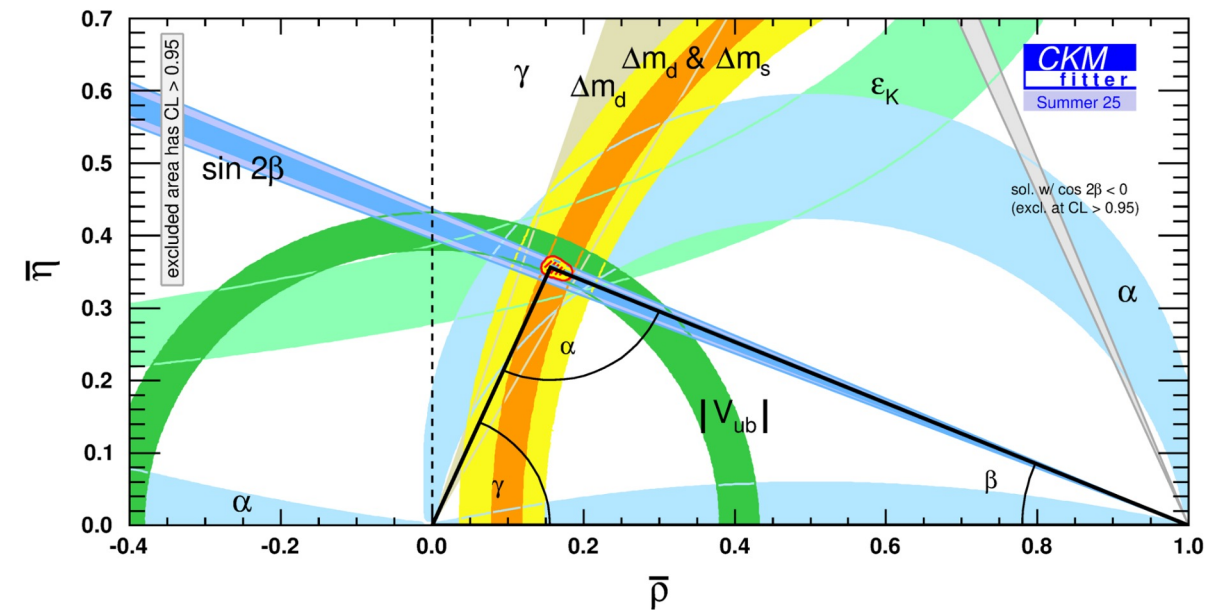
[LHCb-CONF-2024-004](#)

$$\sin 2\beta = 0.717 \pm 0.015$$

[PRL 132 \(2024\) 021801](#)

(more precise than B-factory combination)

in agreement with CKM fit

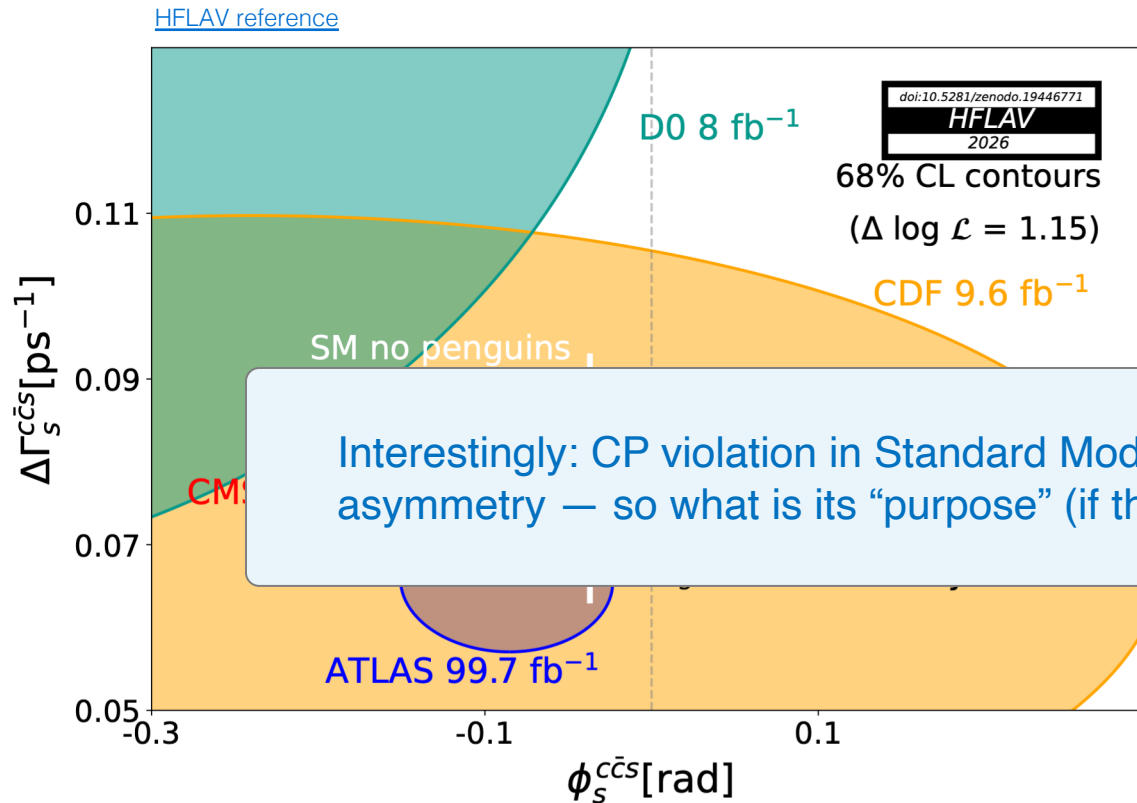


$$\beta \equiv \arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right], \quad \gamma \equiv \arg \left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$$

Flavour physics — CP violation

High-precision CKM angle measurements overconstrain CKM matrix and probe new physics

Mixing-induced time-dependent CP violation measurements in $J/\psi\phi$
(and similar)



$$\phi_a^{c\bar{c}s} = -2\beta_s = -0.052 \pm 0.013 \text{ rad}, \text{ with } \beta_s \equiv \arg \left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right]$$

SM: $-0.0376 \pm 0.0006 \text{ rad}$

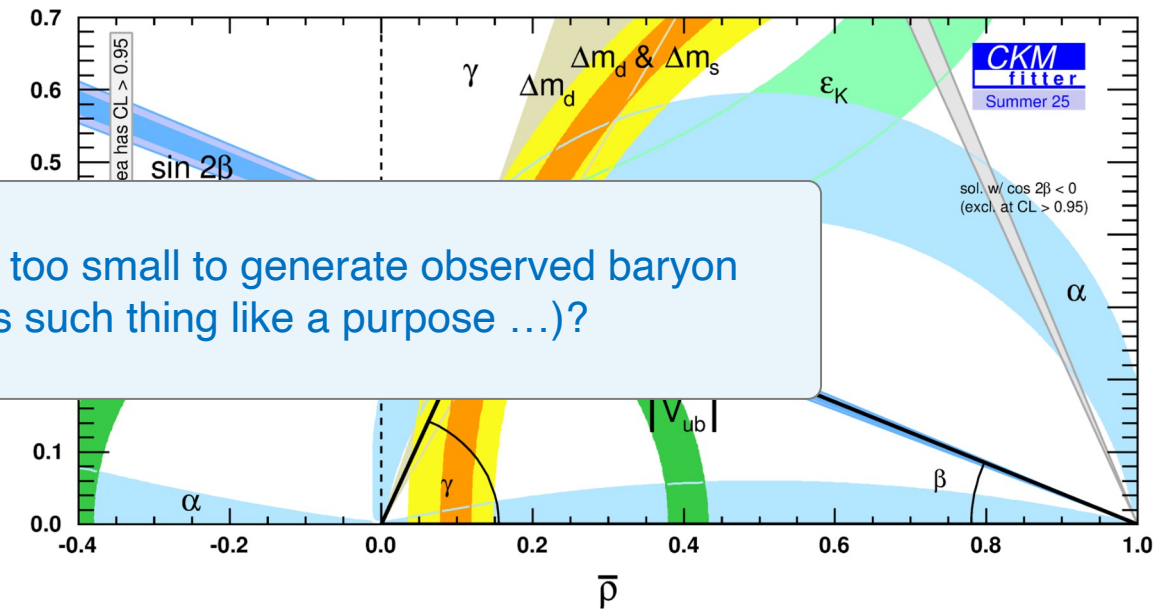
LHCb:

$$\gamma = 64.6 \pm 2.8 \text{ deg} \quad \text{LHCb-CONF-2024-004}$$

$$\sin 2\beta = 0.717 \pm 0.015 \quad \text{PRL 132 (2024) 021801}$$

(more precise than B-factory combination)

in agreement with CKM fit

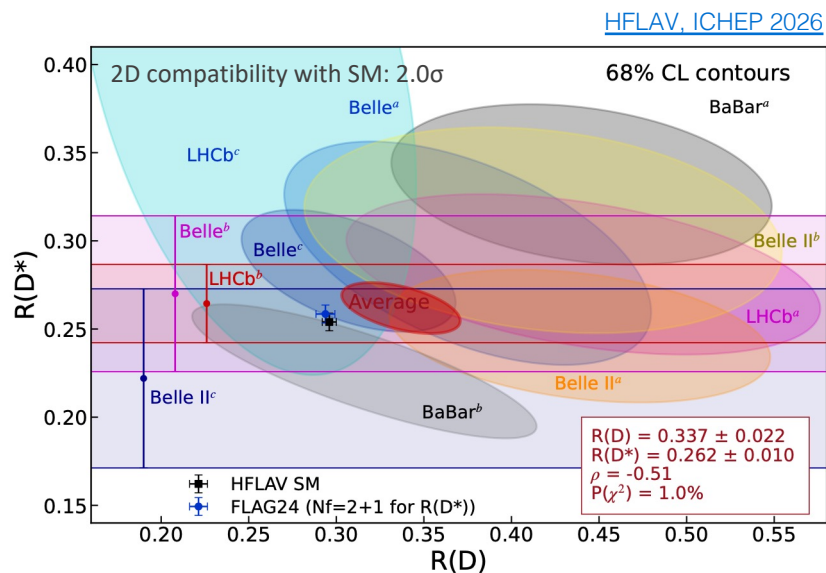


$$\beta \equiv \arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right], \quad \gamma \equiv \arg \left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$$

Flavour physics — Anomalies?

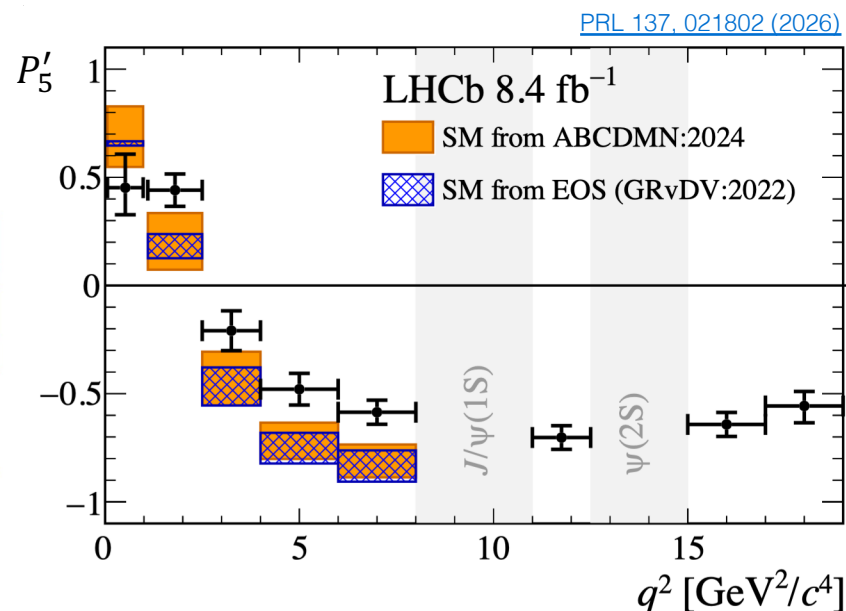
Flavour physics probes Yukawa sector of the Standard Model with high sensitivity to new physics — explaining the considerable attention given to even statistically not-yet-significant deviations

Among the remaining “anomalies”

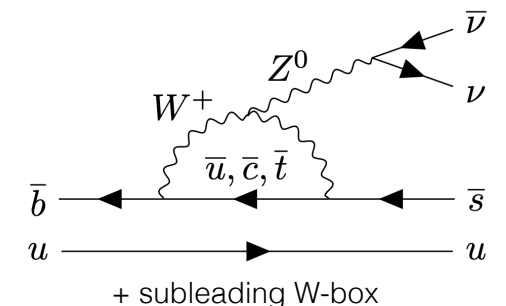
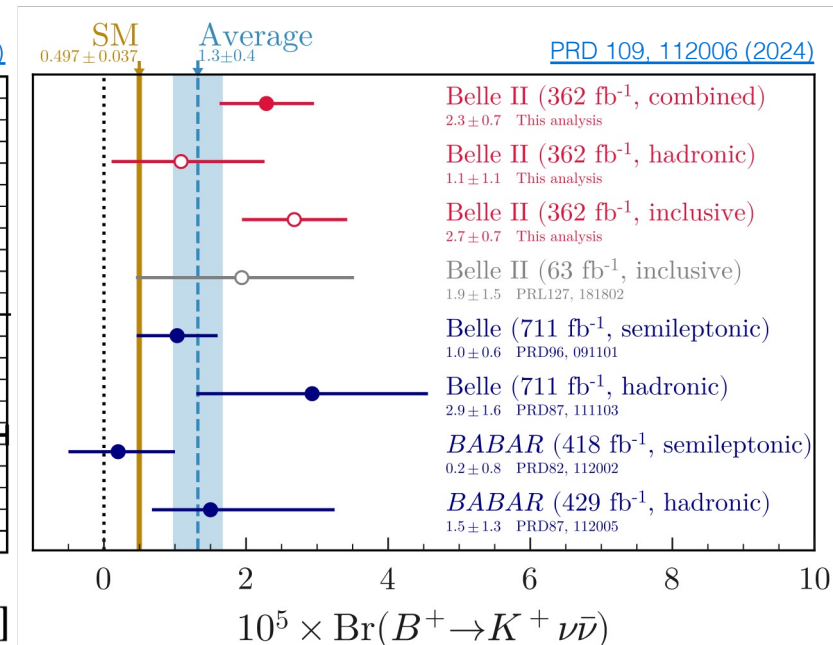


$$R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)} \tau \nu)}{B(B \rightarrow D^{(*)} \ell \nu)}$$

probing the charged current transition: $b \rightarrow c \ell \nu$

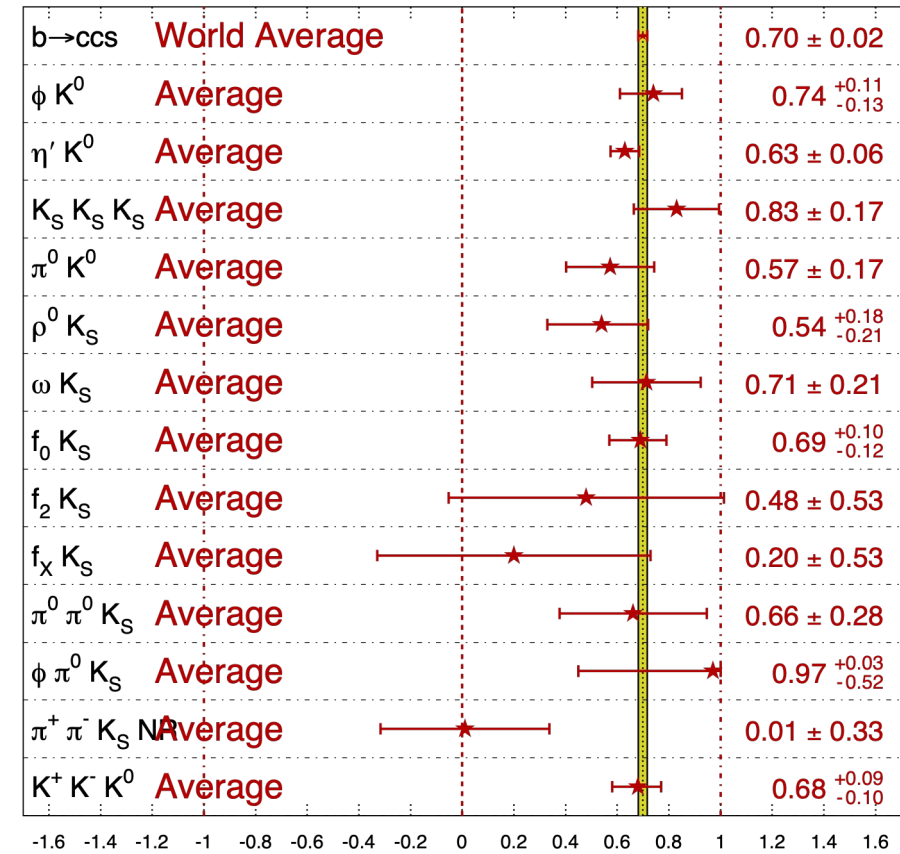
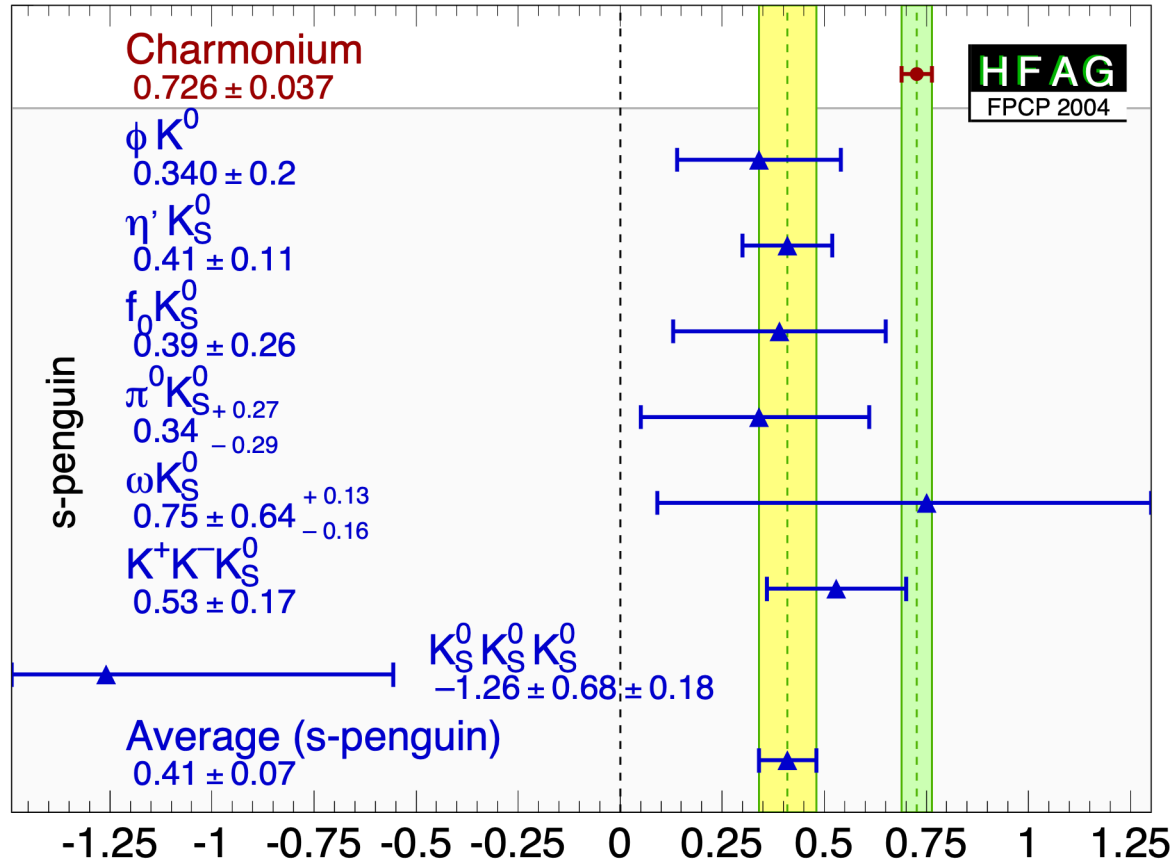
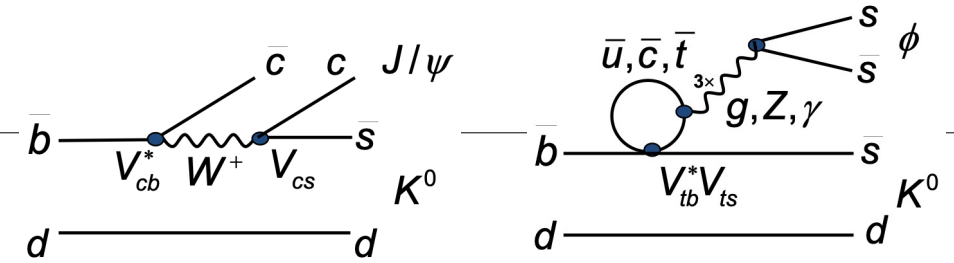


P'_5 is an angular observable in $B^0 \rightarrow K^* \mu \mu$ ($q^2 = m_{\mu\mu}^2$), which probes the underlying short-distance $b \rightarrow s \ell \ell$ interaction with reduced form-factor uncertainties



Flavour physics — Anomalies?

A lesson from penguins...



HFLAV
Moriond 2021
PRELIMINARY

4.0 σ discrepancy between penguin and charmonium averages in 2004 – new physics?

Searches for new phenomena

Run: 329716

Event: 857582452

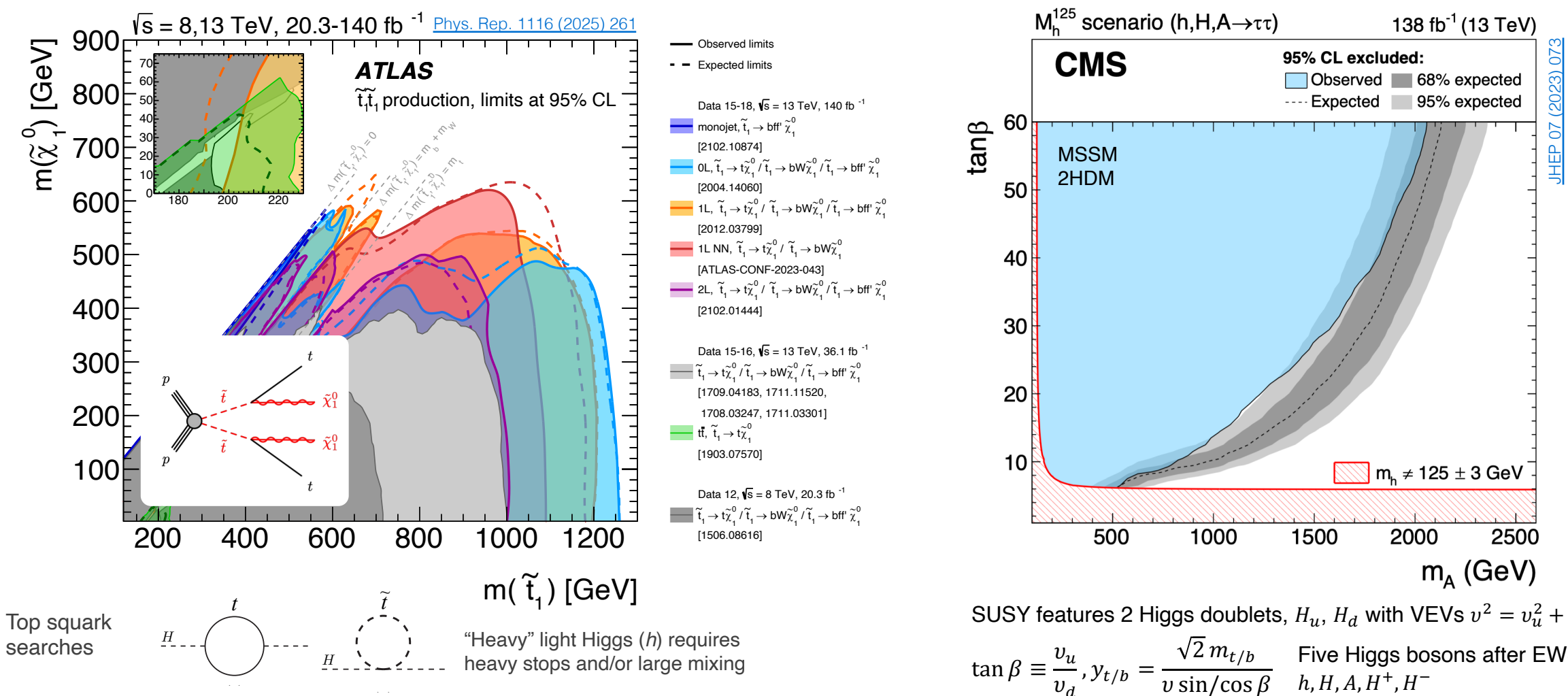
2017-07-14 10:48:51 CEST



ATLAS
EXPERIMENT

Searches for physics beyond the Standard Model

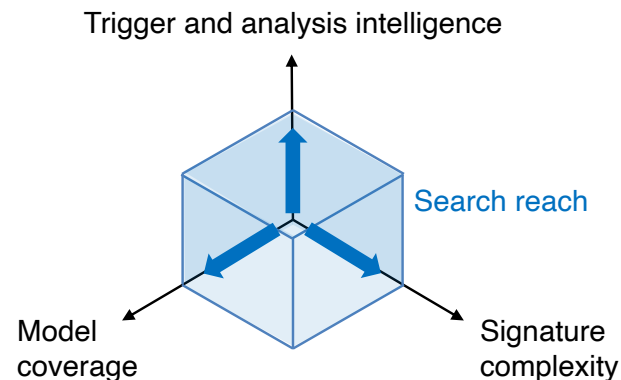
Direct searches have not yet revealed signs of high- or low-scale new physics, dark matter, or an extended scalar or flavour sector; no signs of Supersymmetry yet (neither in sparticle no extended Higgs searches)



The evolution of BSM searches at the LHC

A few general BSM search tendencies since the start of the LHC and into the future

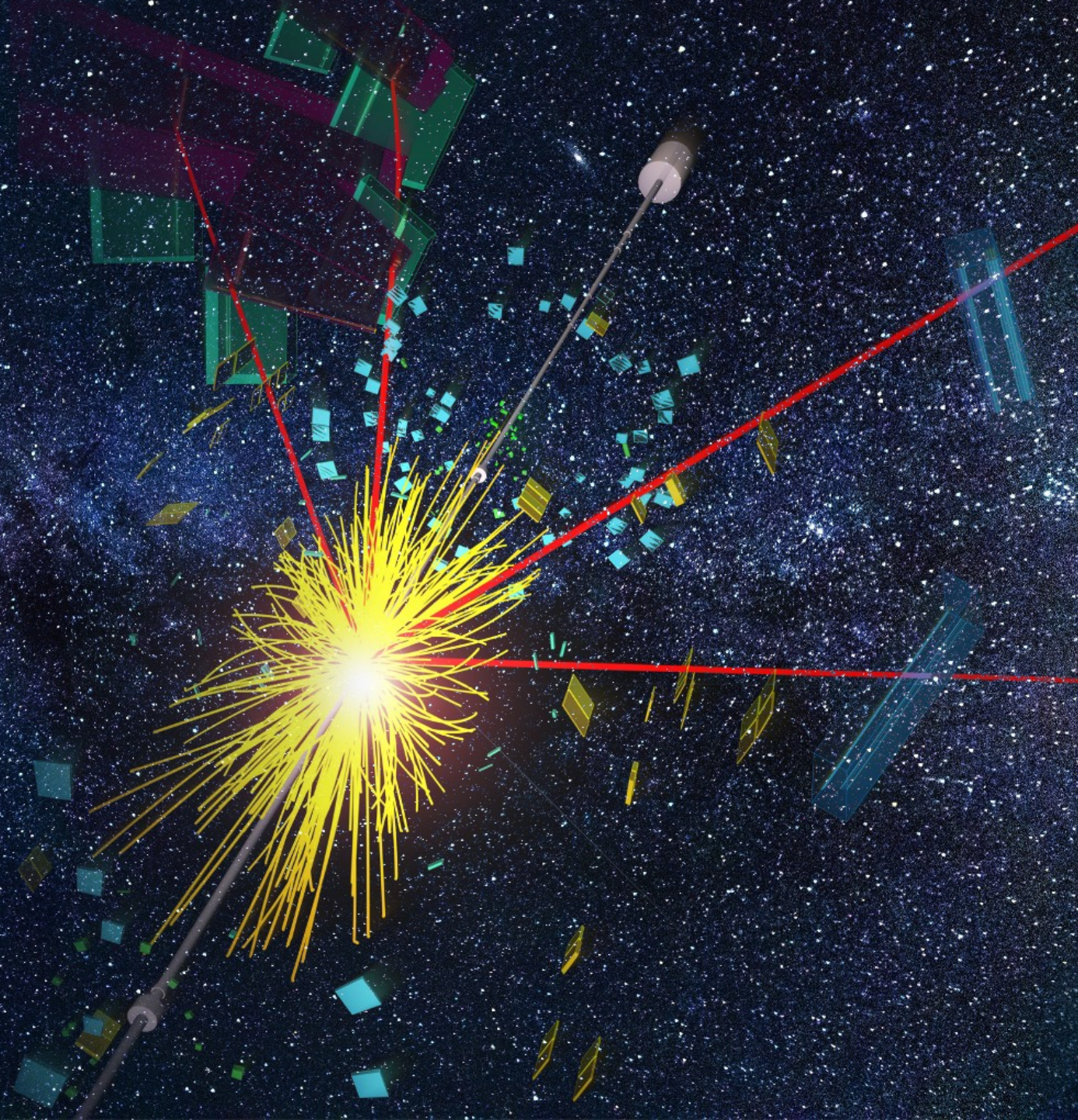
Search paradigm	Targeted, model-specific	→	Broader scenarios (eg, dark sectors, hidden phenomena, FIPs, ...), more model-agnostic, diffuse, data-driven (anomaly detection, ...)
Search reach	Direct production at accessible mass scales	→	Addition of indirect sensitivity via precision, rare processes, EFT
Kinematic range	Focus on high mass and momenta	→	All regions, incl. very low masses and soft particles, small couplings
Object topology	Clean, prompt, isolated leptons/jets	→	Complex, boosted, merged, displaced, non-pointing
Trigger approach	Rigid thresholds, fixed menus	→	Real-time ML, scouting/TLA/PEB, use of turn-ons and prescaled triggers, dedicated per-analysis triggers
Analysis approach	Cut-based, simple ML	→	Advanced ML: GNNs, transformers, unsupervised learning



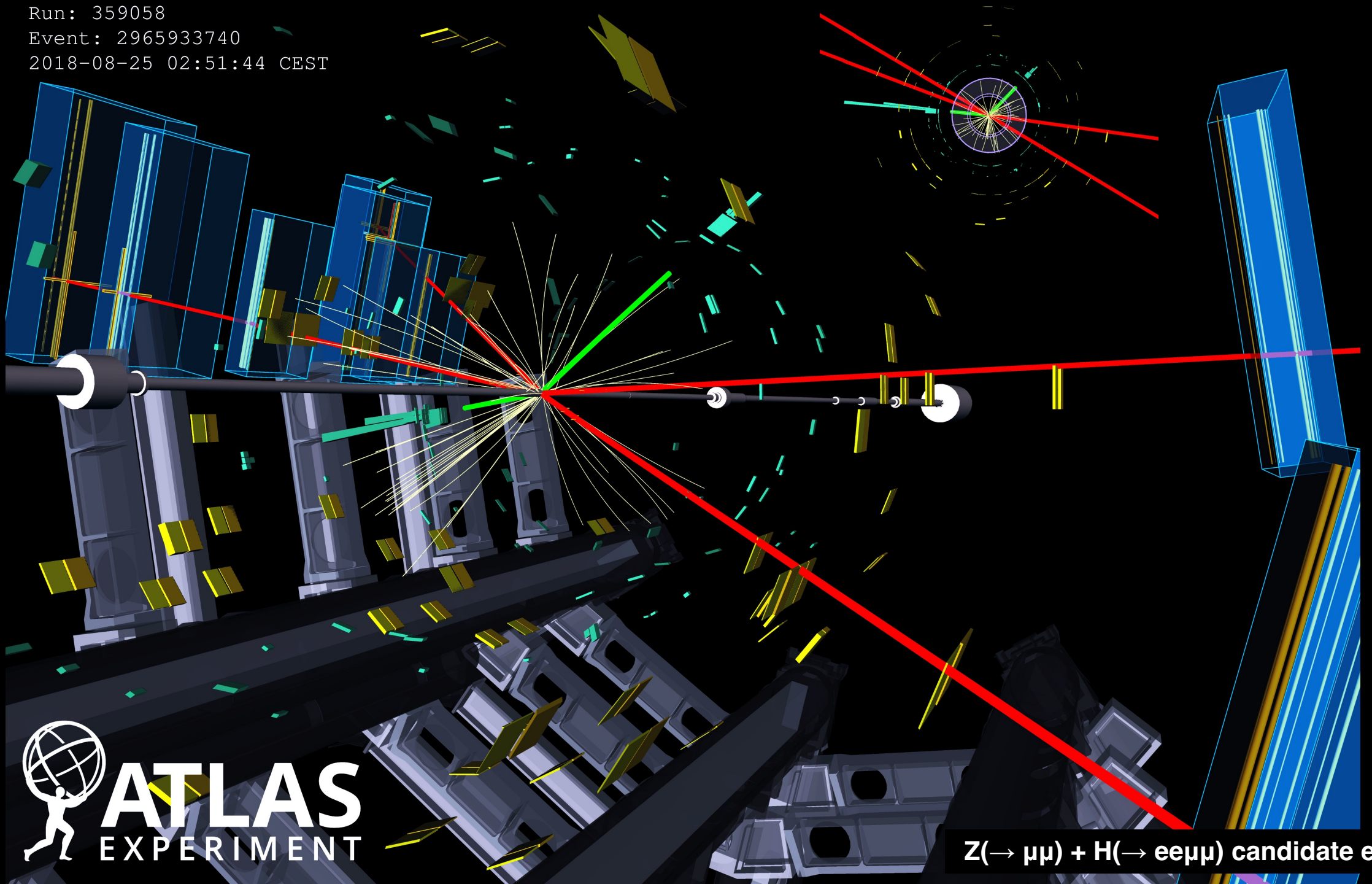
Summary of today's lecture

- The Higgs mechanism is real
- The LHC allows for the first time to directly probe interactions of the Higgs boson with the other particles, thereby deeply probing the SM
- Rare Higgs boson couplings and Higgs self coupling are relatively unexplored yet
- The study of rare electroweak processes provides qualitatively new information
- The LHC performs precision QCD and top-quark physics across unprecedented scales, observing new phenomena
- Precision electroweak and flavour measurements have made huge progress, and reveal no decisive inconsistency yet
- No direct new-physics signal has yet emerged, but the search programme has expanded dramatically

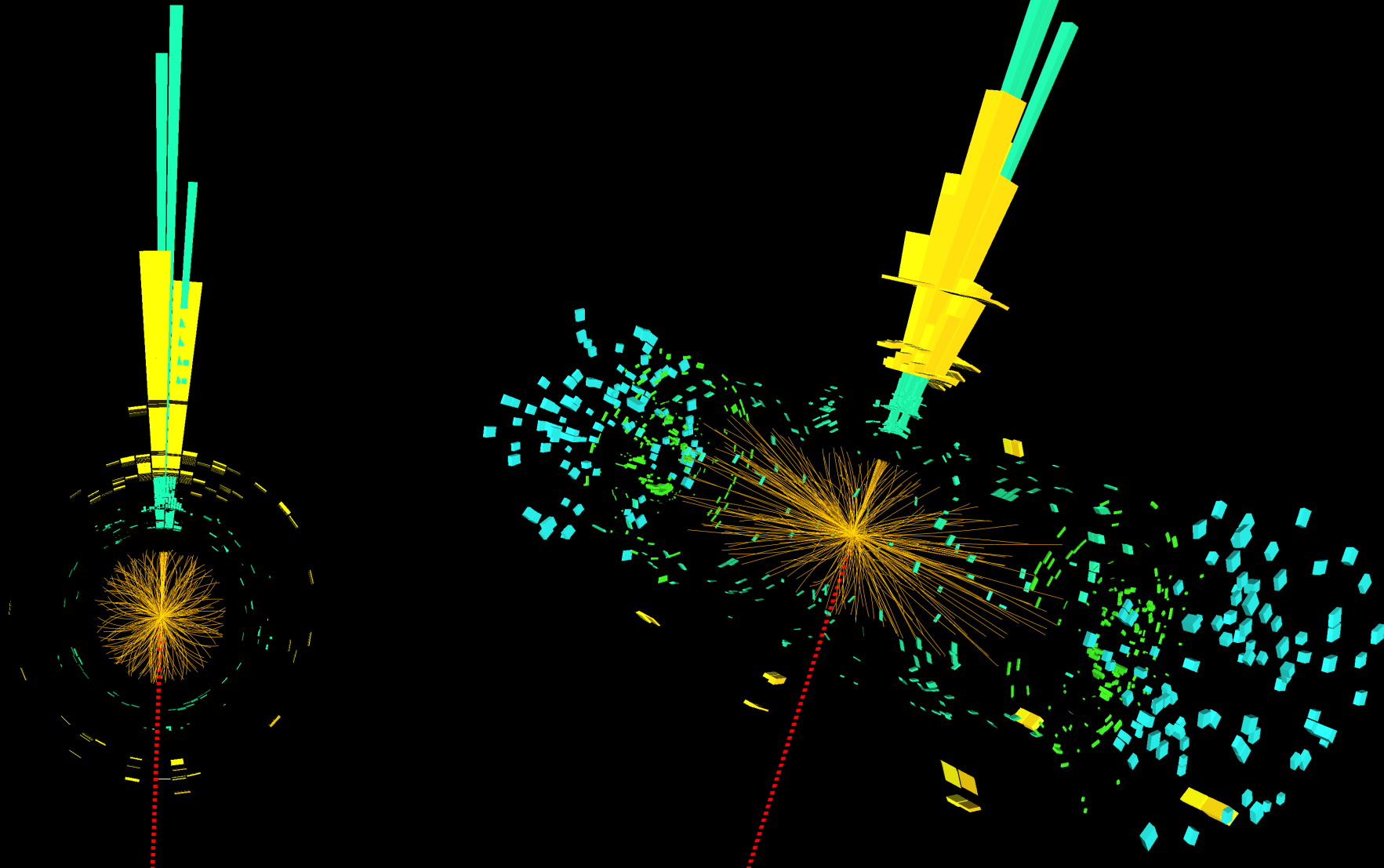
Extra slides



Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST



Searches for Dark Matter



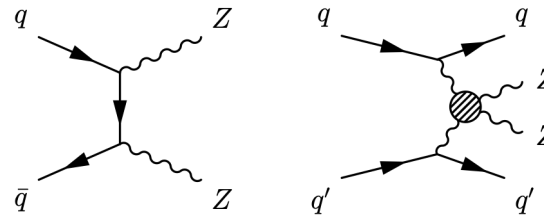
Observation of $Z_L Z_L$ production

ATLAS: [arXiv:2607.12879](https://arxiv.org/abs/2607.12879)

The existence of longitudinally polarised weak bosons is a consequence of the BEH mechanism (it requires the weak bosons to be massive)

Inclusive production is dominated by: $q\bar{q} \rightarrow Z_L Z_L$

Small EW $Z_L Z_L jj$ contribution included but not isolated (ie, not a measurement of $Z_L Z_L \rightarrow Z_L Z_L$). Gluon fusion $gg \rightarrow ZZ$ is subtracted

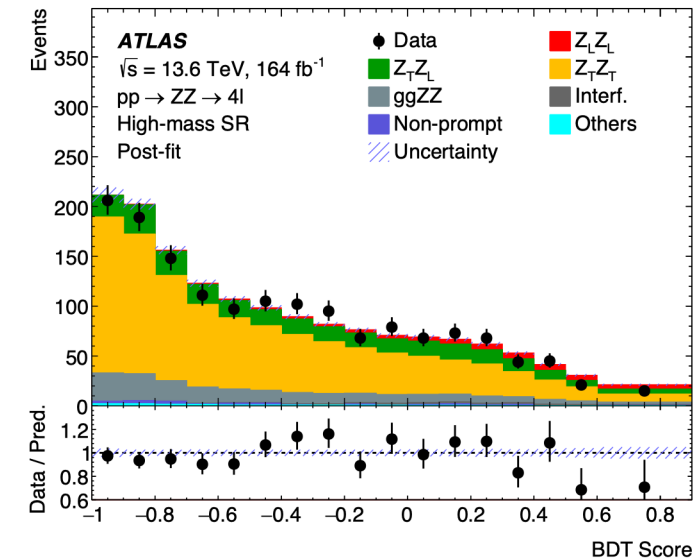
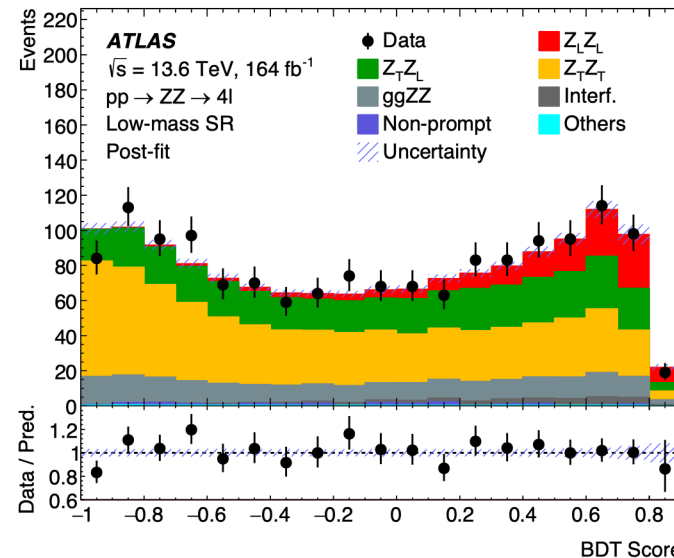


Connection through EWSB: at high energy

$$\mathcal{M}(q\bar{q} \rightarrow Z_L Z_L) \simeq \mathcal{M}(q\bar{q} \rightarrow G^0 G^0) + \mathcal{O}\left(\frac{m_Z}{E}\right)$$

- Ordinary t/u-channel quark-exchange Zqq contributions are gauge suppressed $\propto m_Z/E_Z$
- G^0 is neutral Goldstone boson

Tiny G^0 -light quark Yukawa couplings suppress high-energy $Z_L Z_L$ production, so f_{LL} falls with m_{ZZ} , a prediction of EWSB



Observation of $Z_L Z_L$ production with 6.5σ

$$f_{LL} = 0.080 \pm 0.017 \quad (f_{LL}^{\text{SM}} = 0.061 \pm 0.002)$$

q^2 -dependnet results (consistent with SM predictions):

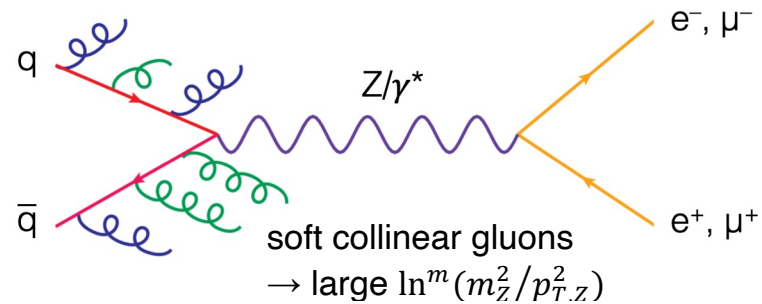
$$f_{LL}(180 < m_{4\ell} < 240 \text{ GeV}) = 0.108 \pm 0.028$$

$$f_{LL}(m_{4\ell} > 240 \text{ GeV}) = 0.011 \pm 0.017$$

High precision α_s measurement using Drell-Yan data

EPJ C 84 (2024) 315, [arXiv:2309.12986](https://arxiv.org/abs/2309.12986)

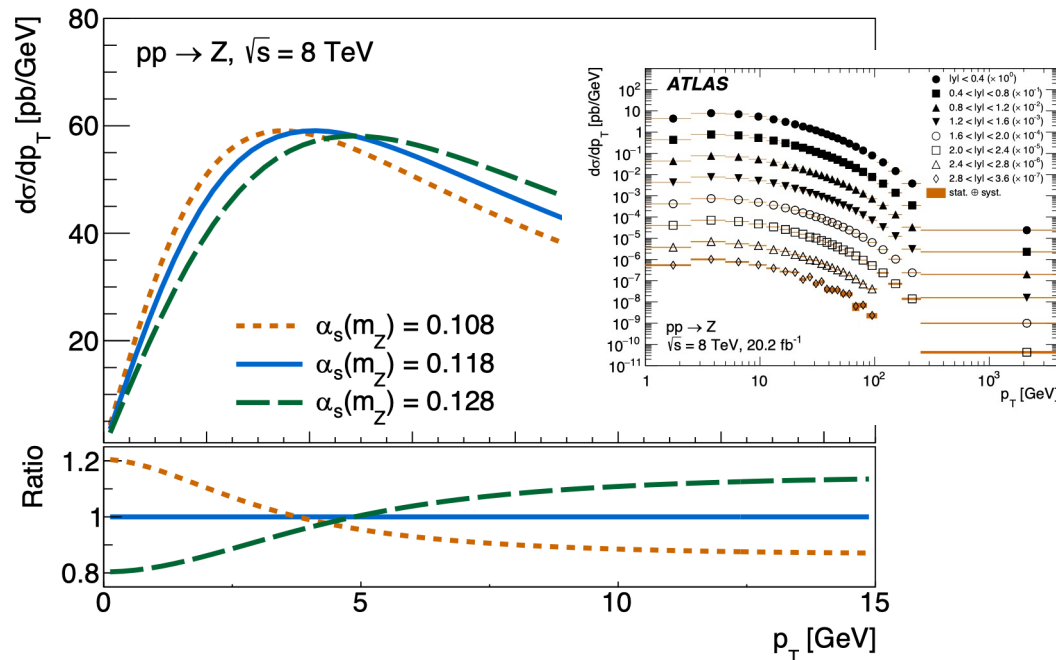
The low $p_{T,Z}$ Drell-Yan spectrum is shaped by soft and collinear QCD radiation and is therefore highly sensitive to α_s . N³LO predictions matched to resummation of large logarithms at approximate N⁴LL accuracy, enable a sub-percent determination of the strong coupling



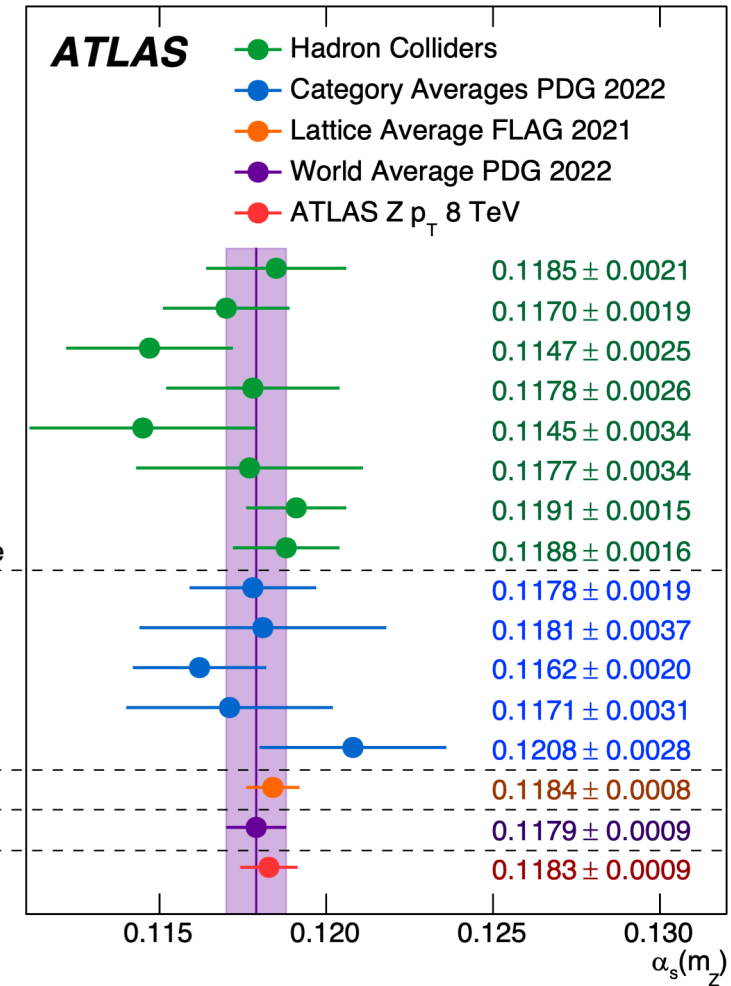
Precise extraction (incl. PDF profiling):

$$\alpha_s(m_Z) = 0.1183 \pm 0.0009$$

[Dominated by PDF and QCD scale uncertainties]



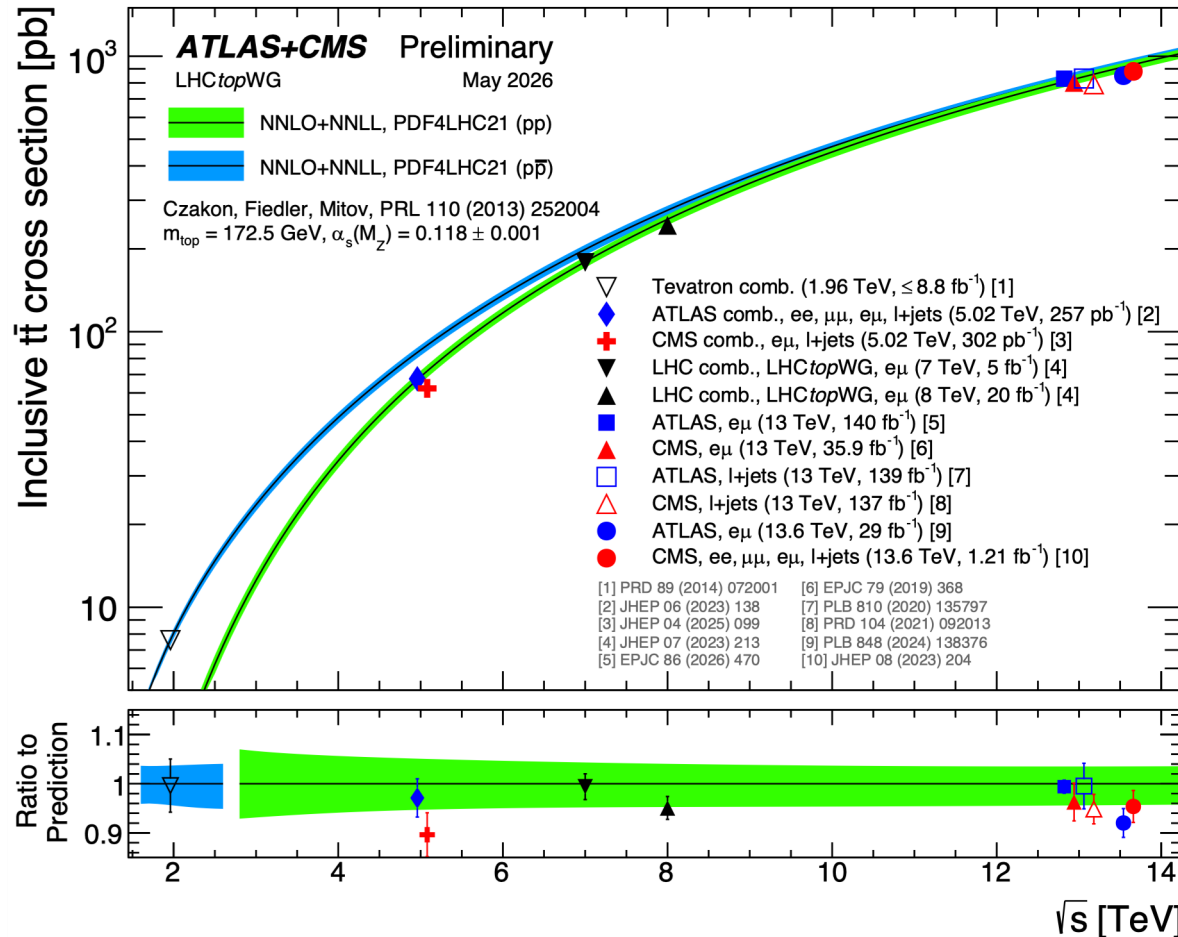
ATLAS ATEEC
CMS jets
H1 jets
HERA jets
CMS $t\bar{t}$ inclusive
Tevatron+LHC $t\bar{t}$ inclusive
CDF $Z p_T$
Tevatron+LHC W, Z inclusive
 τ decays and low Q^2
 $Q\bar{Q}$ bound states
PDF fits
 e^+e^- jets and shapes
Electroweak fit
Lattice
World average
ATLAS $Z p_T$ 8 TeV



Understanding top–antitop production – LHC as a top factory

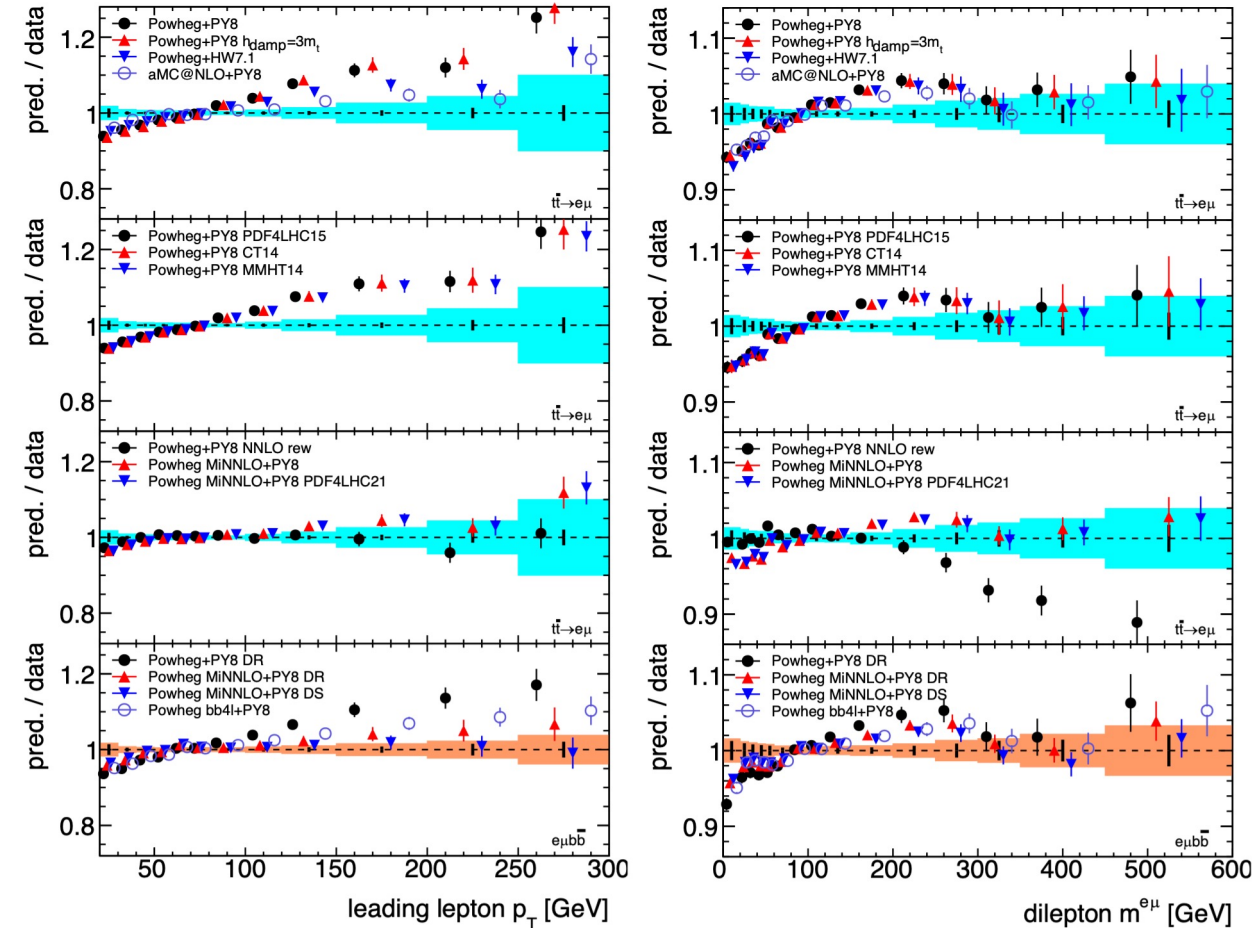
Good description of inclusive cross sections, but precise modelling of differential distributions remains challenging

Measured top–antitop cross section versus pp energy compared to NNLO QCD calculation complemented with NNLL resummation



[LHCtopWG \(May 2026\)](#)

High-precision top–antitop diff. cross section measurement in the $e\text{--}\mu$ channel
Powheg+MiNNLO: differential NNLO+PS ($t\bar{t} + 1 \text{ jet}$ NLO) accuracy + small- q_T resummation

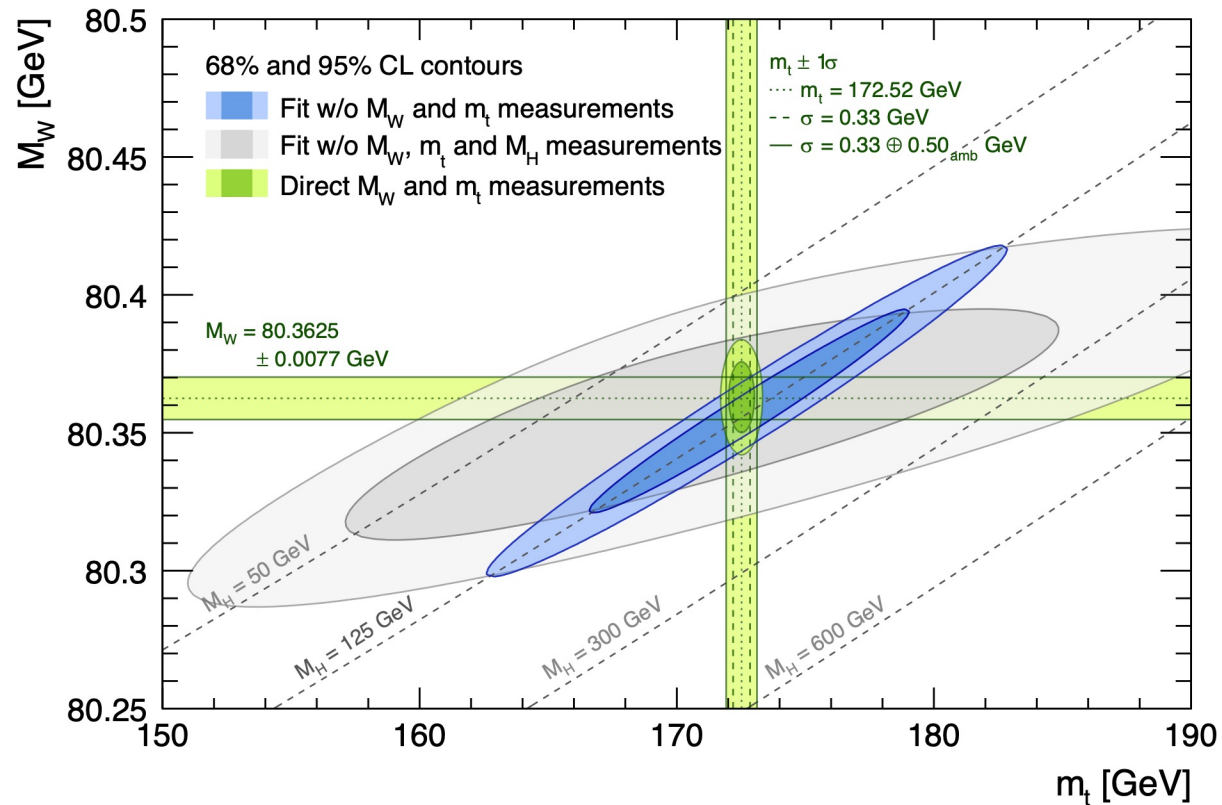


[arXiv:2509.15066](#)

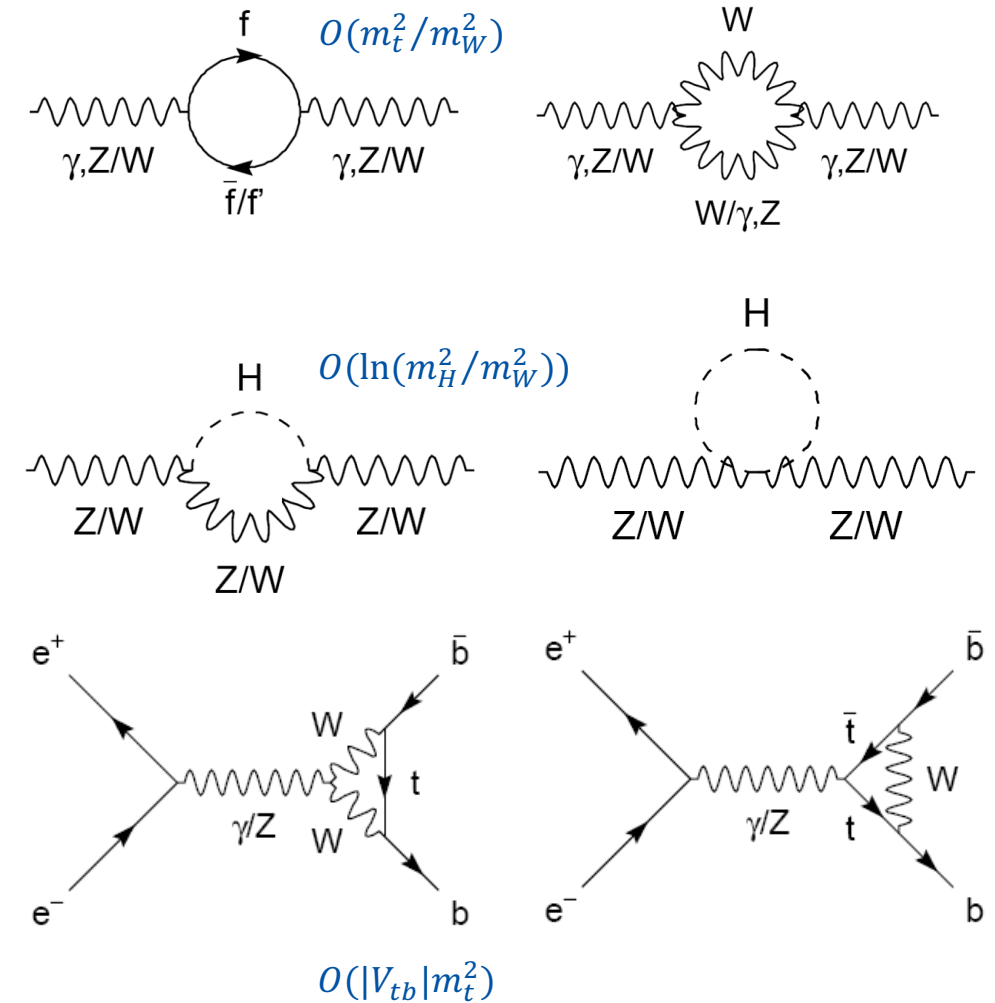
Deep test of Electroweak Standard Model

Gfitter, 2607.09861

Confronting Z-pole observables, W, top, and Higgs masses with SM predictions probes quantum-loop effects



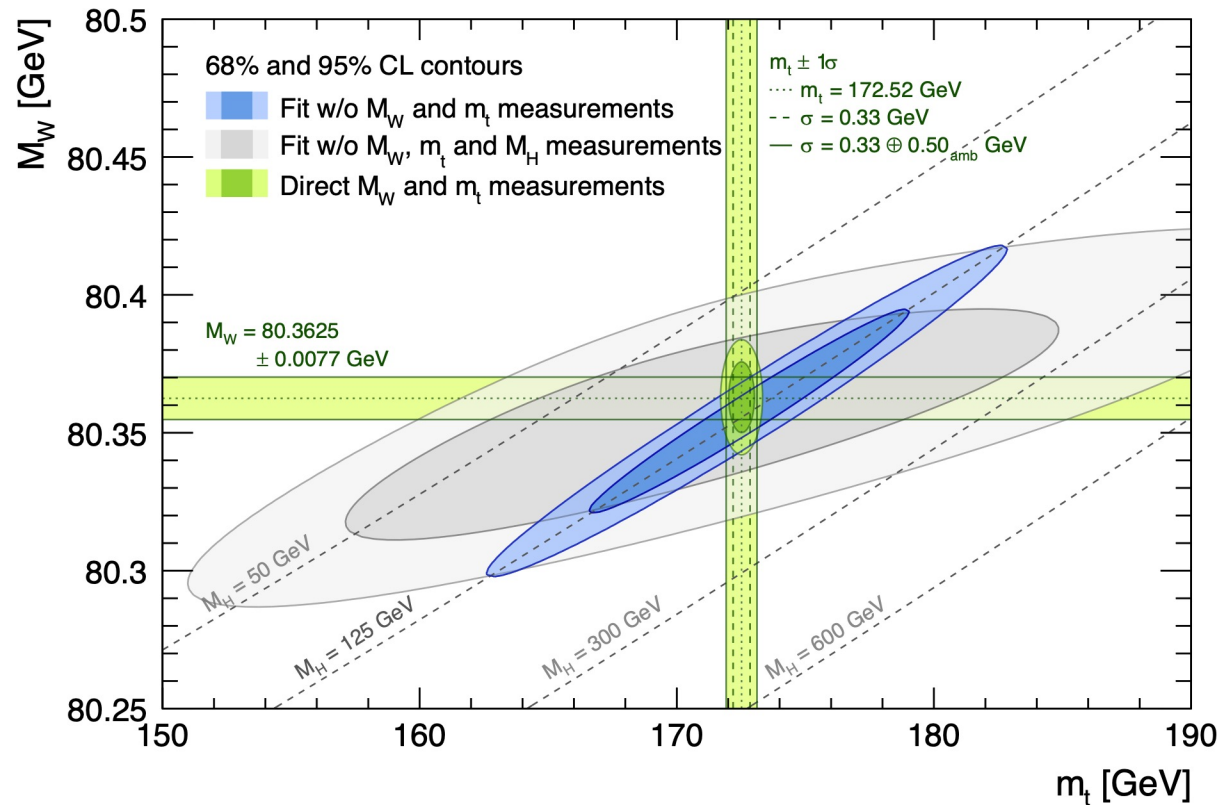
Excellent consistency of measurements with electroweak Standard Model



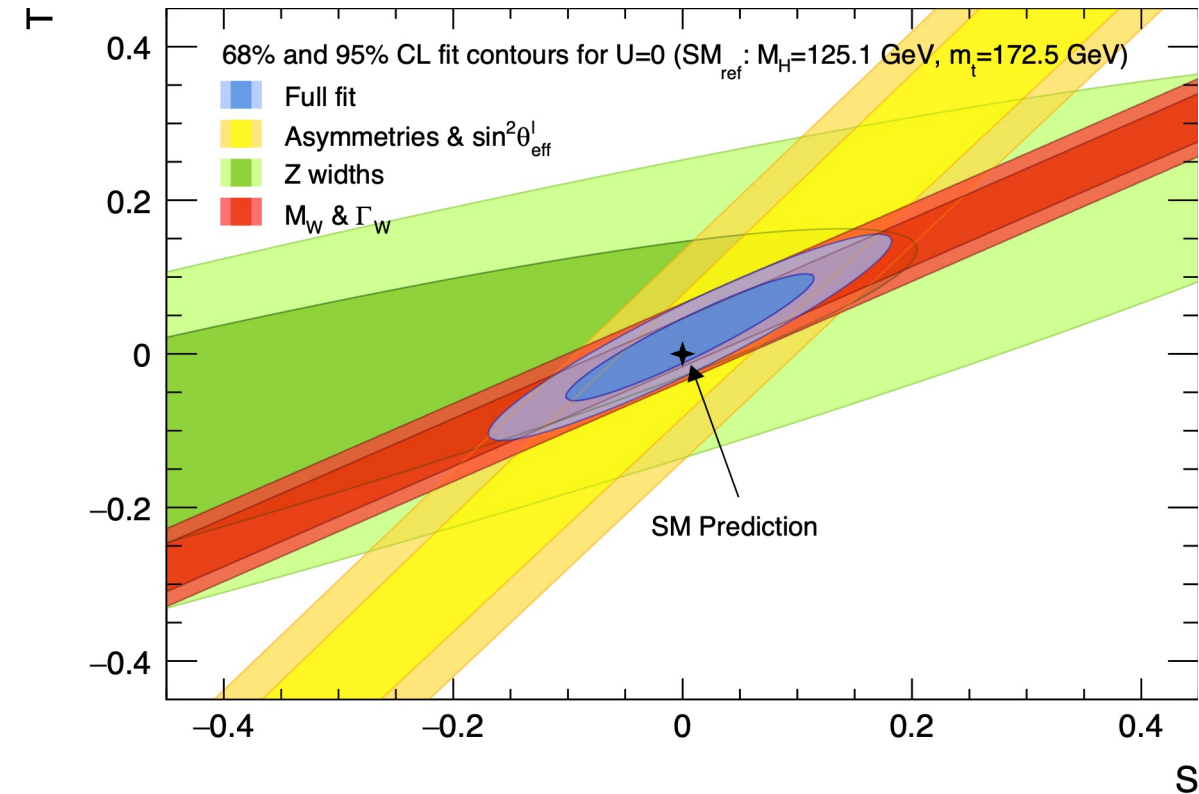
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Gfitter, 2607.09861

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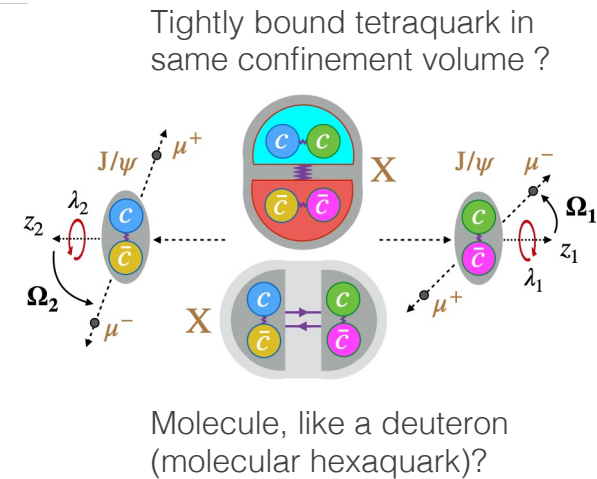
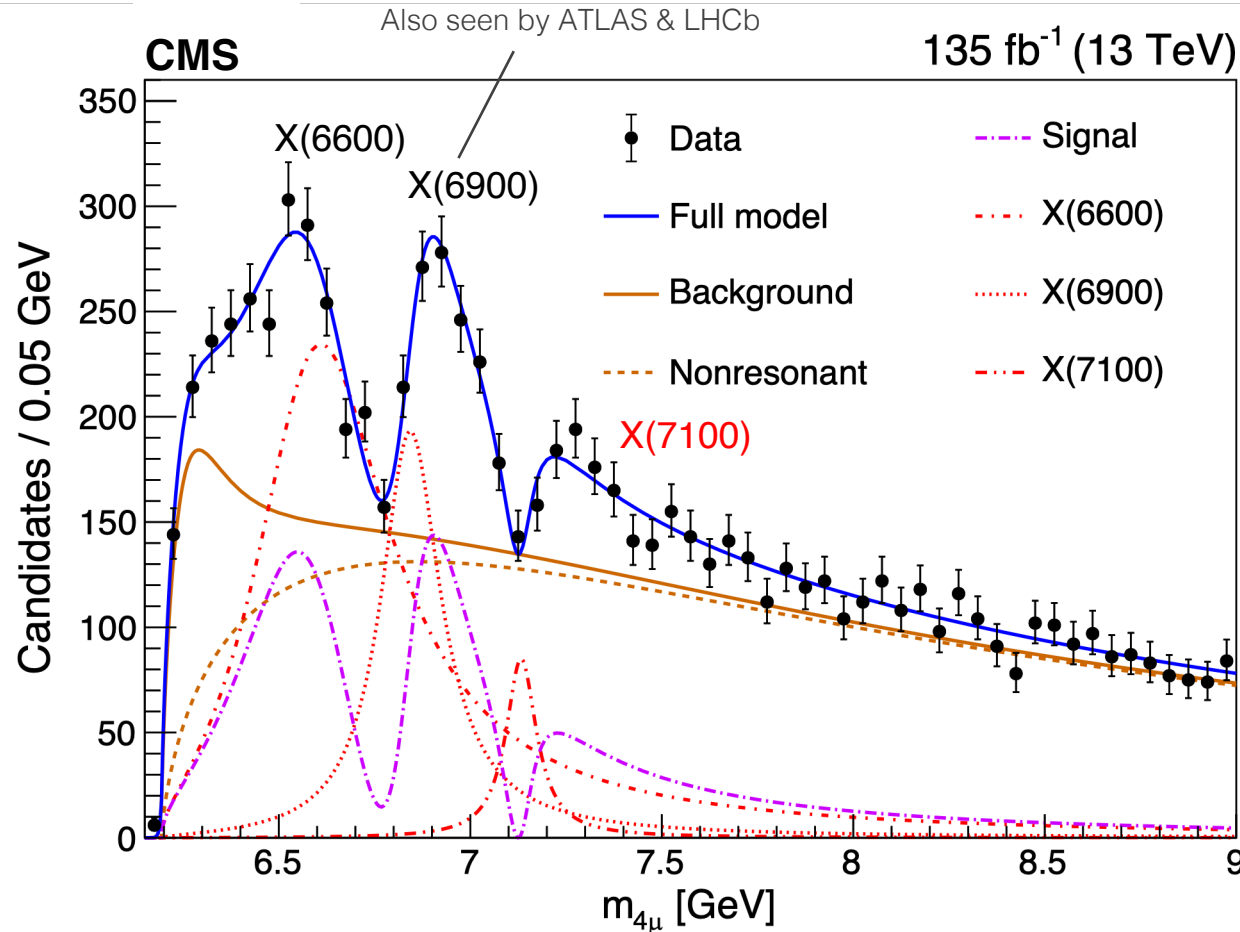


Probe BSM physics in loops (“oblique (= indirect) parameters”)

- **S**: momentum dependence of neutral-current self-energies
- **T**: custodial-symmetry breaking between neutral and charged current self-energies

Hadron spectroscopy

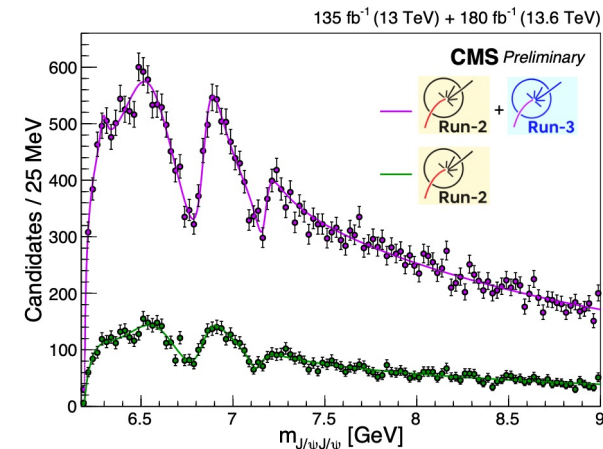
CMS revealed family of 3 all-charm X resonances in $J/\psi J/\psi \rightarrow 4\mu$ mass spectrum [Nature 648 (2025) 58]



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)

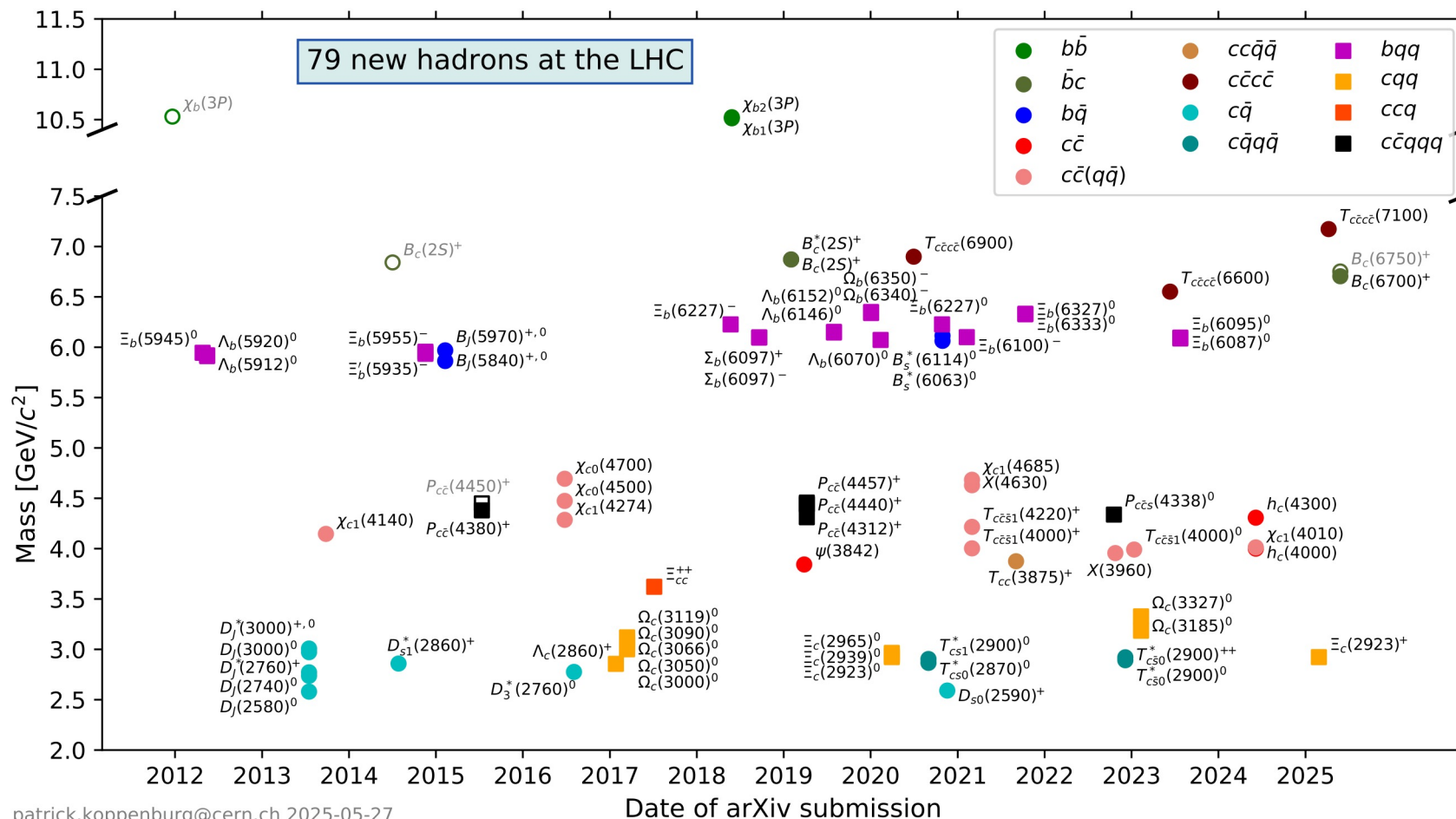


Run-3 provides much larger sample thanks to improved triggers and parking stream

Hadron spectroscopy

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



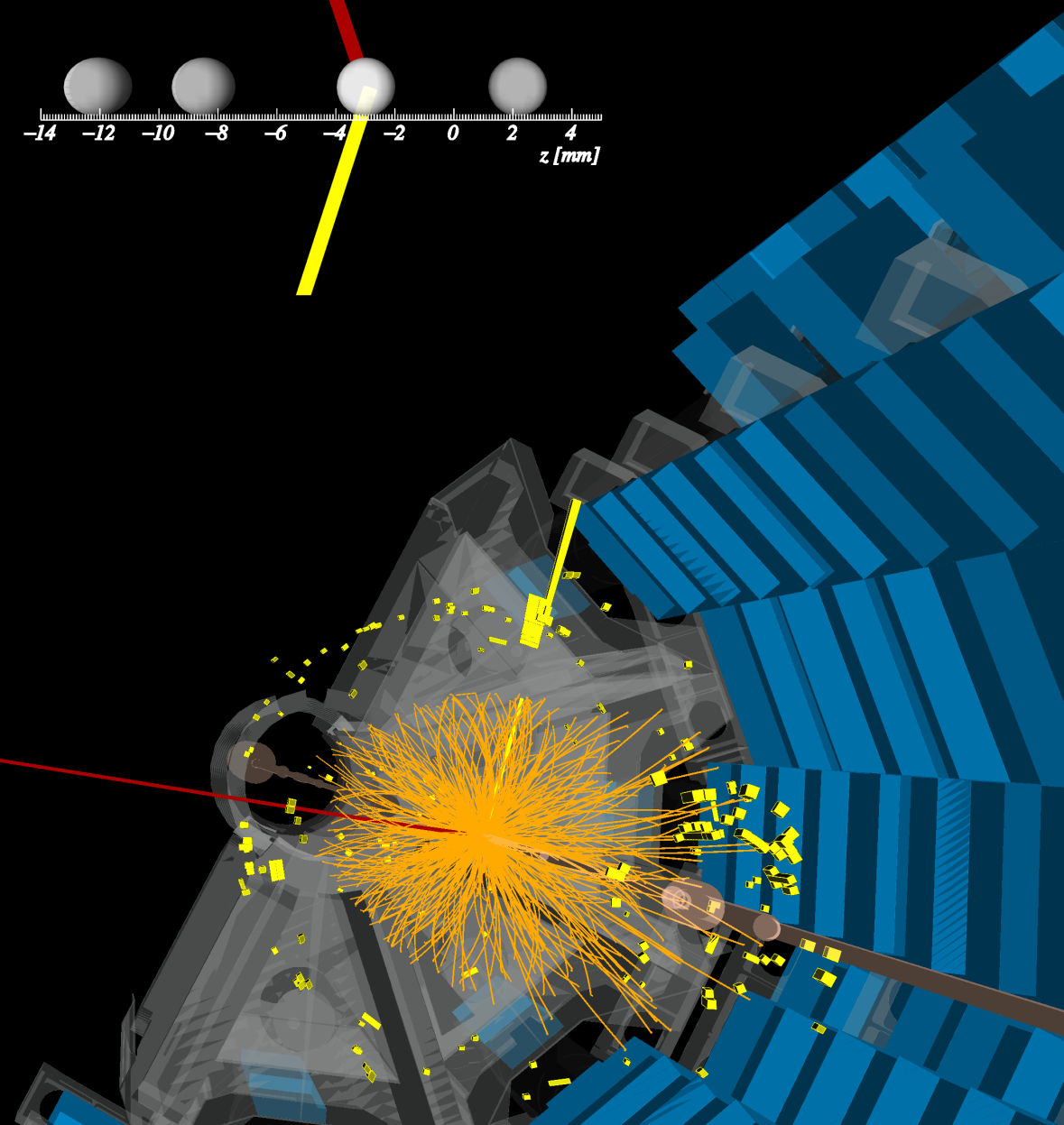
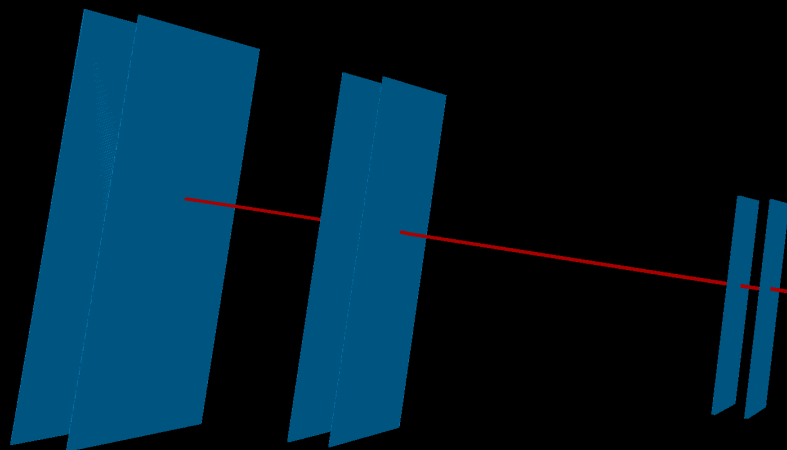
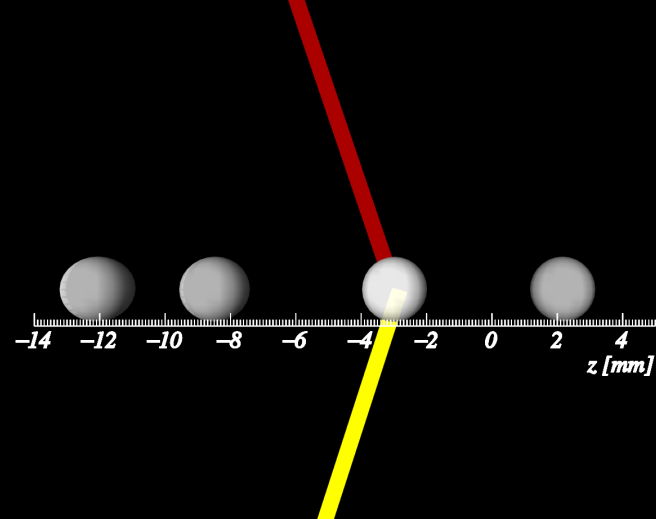
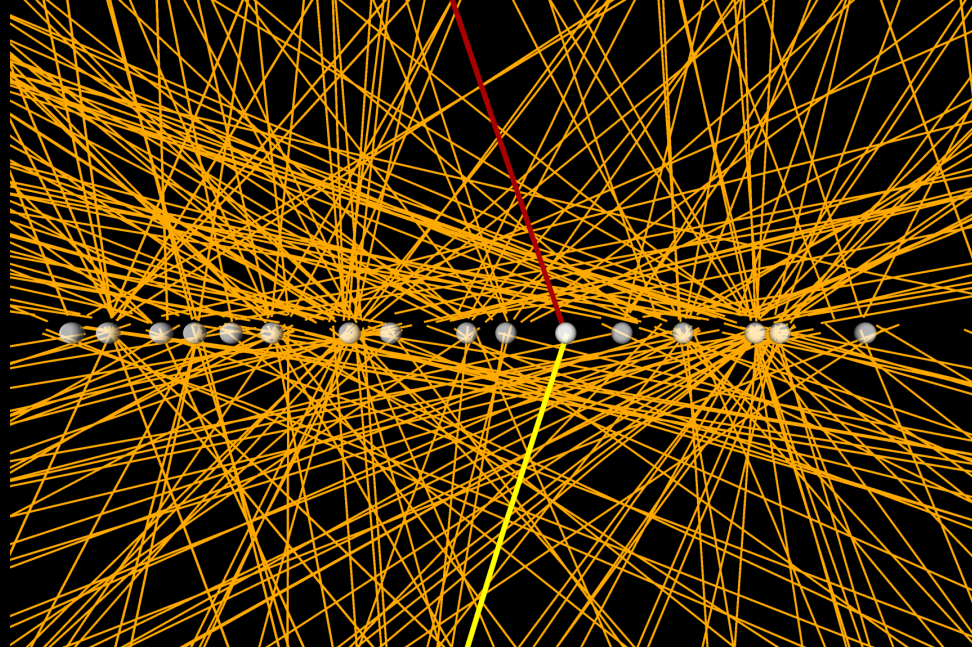
Who finds the T_{bb} ($bb\bar{u}\bar{d}$) first ?

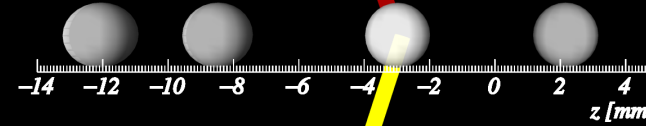
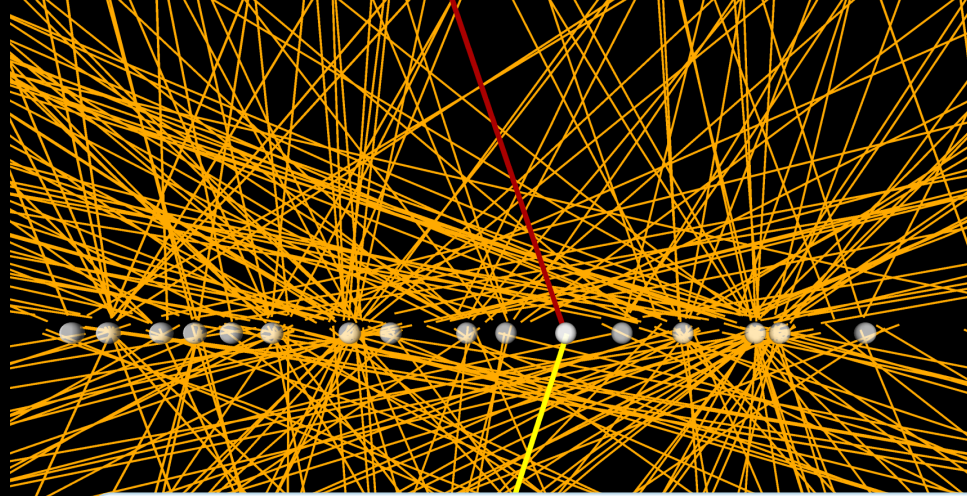
Attraction between two heavy quarks $\propto \alpha_s^2 m_q \rightarrow$ large negative binding energy, so expected to have mass below BB threshold and thus weakly decaying (contrary to $T_{cc}(3875)^+$, which has less binding energy and decays strongly)

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 $Z_b(10610)^+$ $cc/bb\bar{u}\bar{d}$ states discovered by Belle

A $\gamma\gamma \rightarrow WW \rightarrow e\mu + 2\nu$ candidate event





Rare processes are not automatically more sensitive to new physics merely because they are rare. The strength of these processes comes from a particularly favourable combination of

Small amplitude + High energy + Unique external particles

A new contribution can therefore be a large fraction of the SM rate, and some interactions can only contribute directly when the rare final state is present



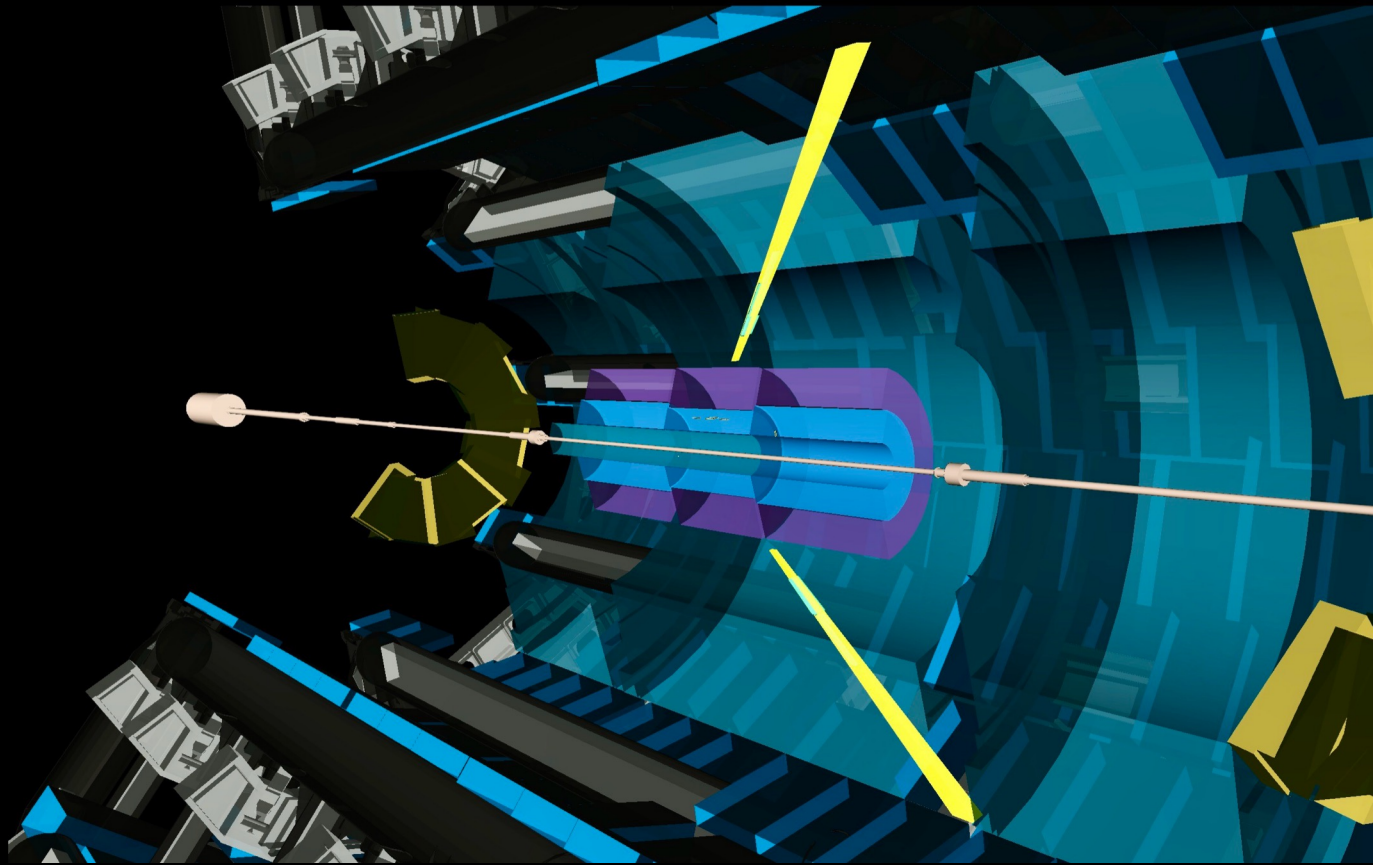
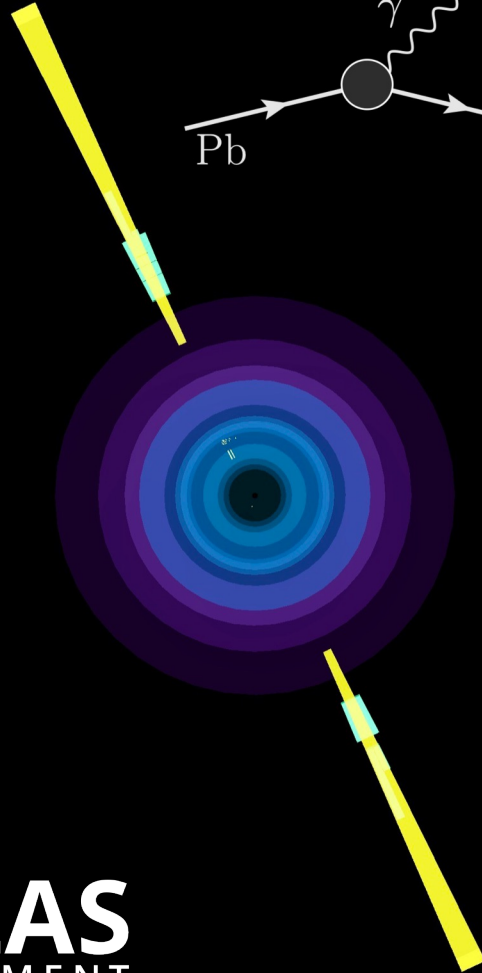
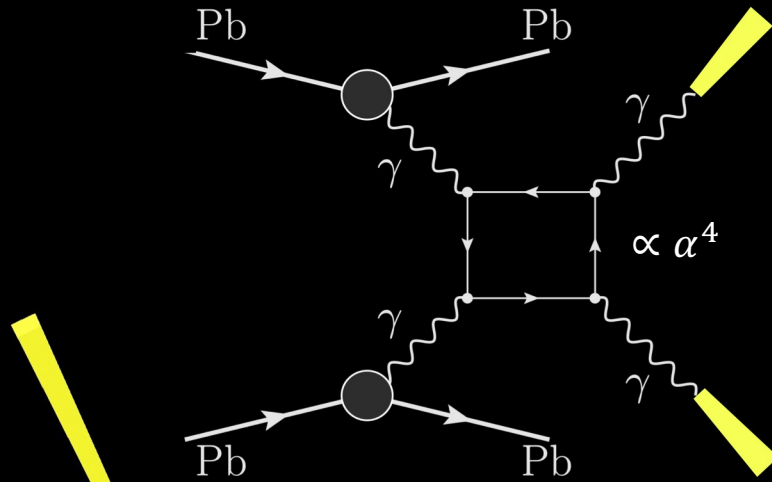
ATLAS
EXPERIMENT

Run: 357620

Event: 653219636

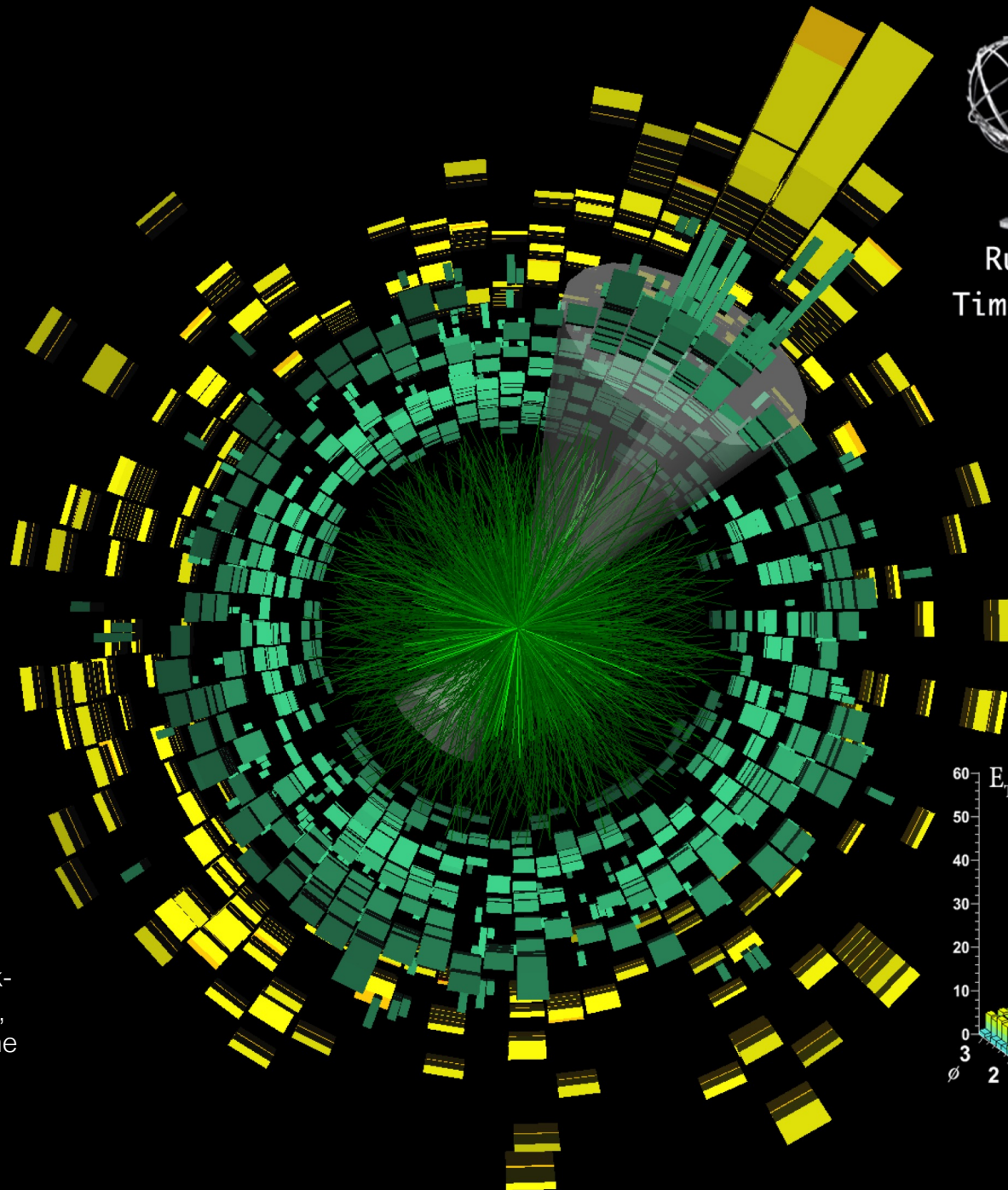
2018-08-06 01:08:33 CEST

Studies of physics in extreme electromagnetic fields



And a detailed mapping of the properties of the quark-gluon plasma with soft and hard probes

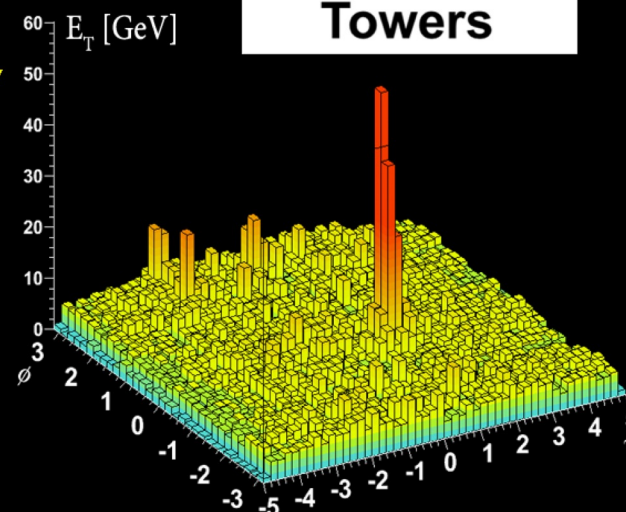
In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun



ATLAS EXPERIMENT

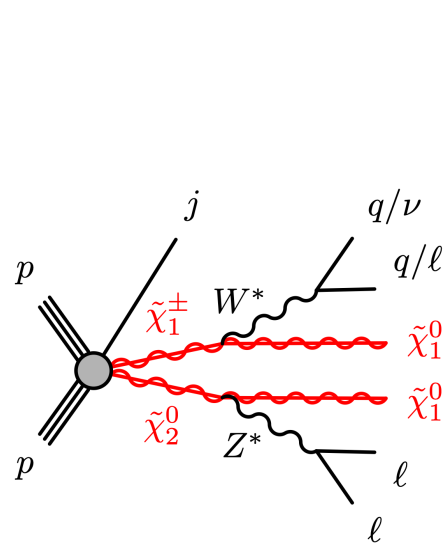
Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET

**Calorimeter
Towers**

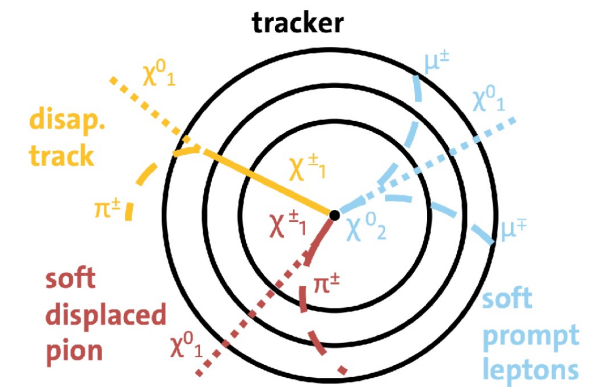
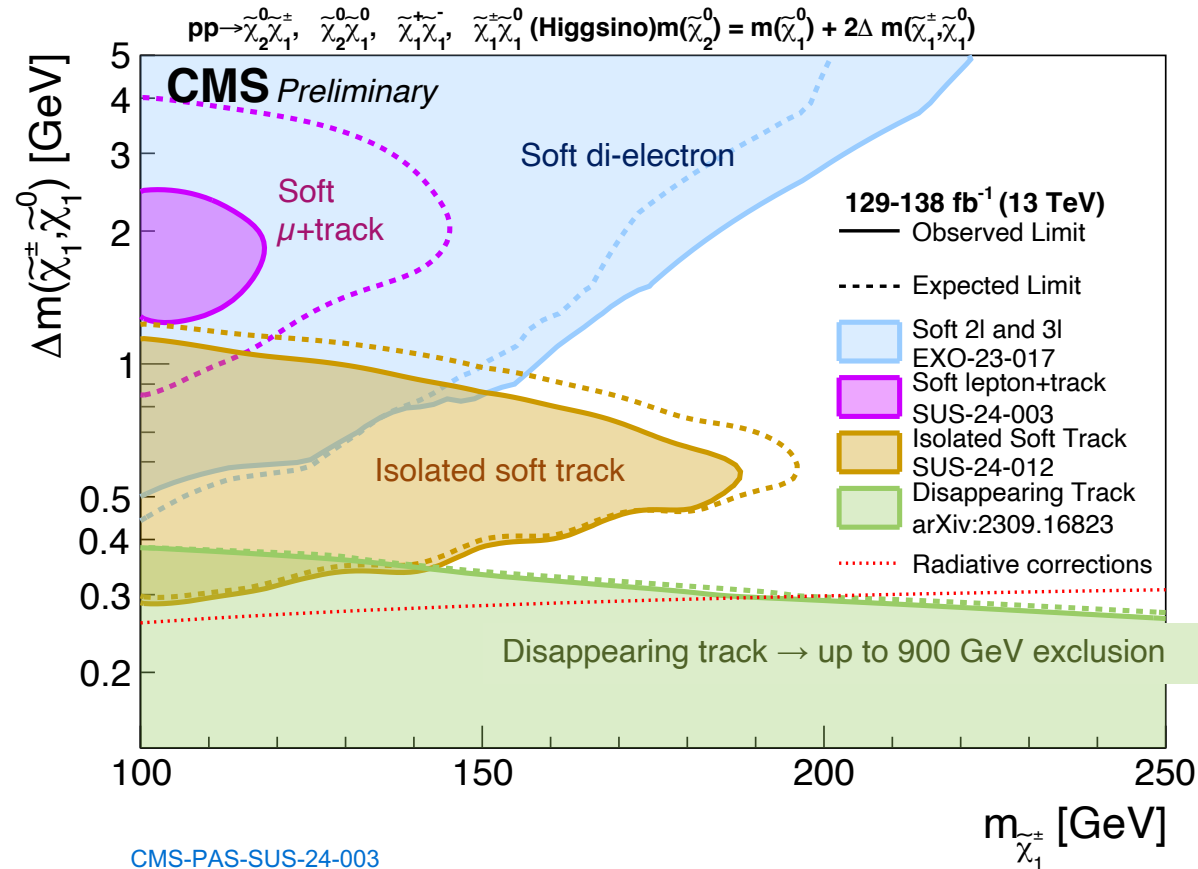


Searches for physics beyond the Standard Model

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



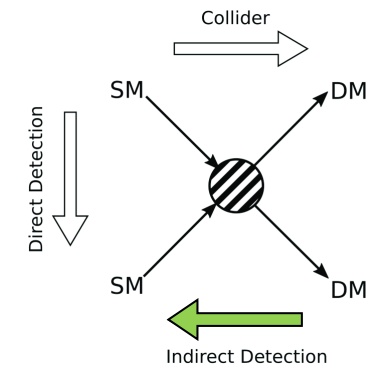
Comprehensive set of analyses targeting ultra-compressed spectra



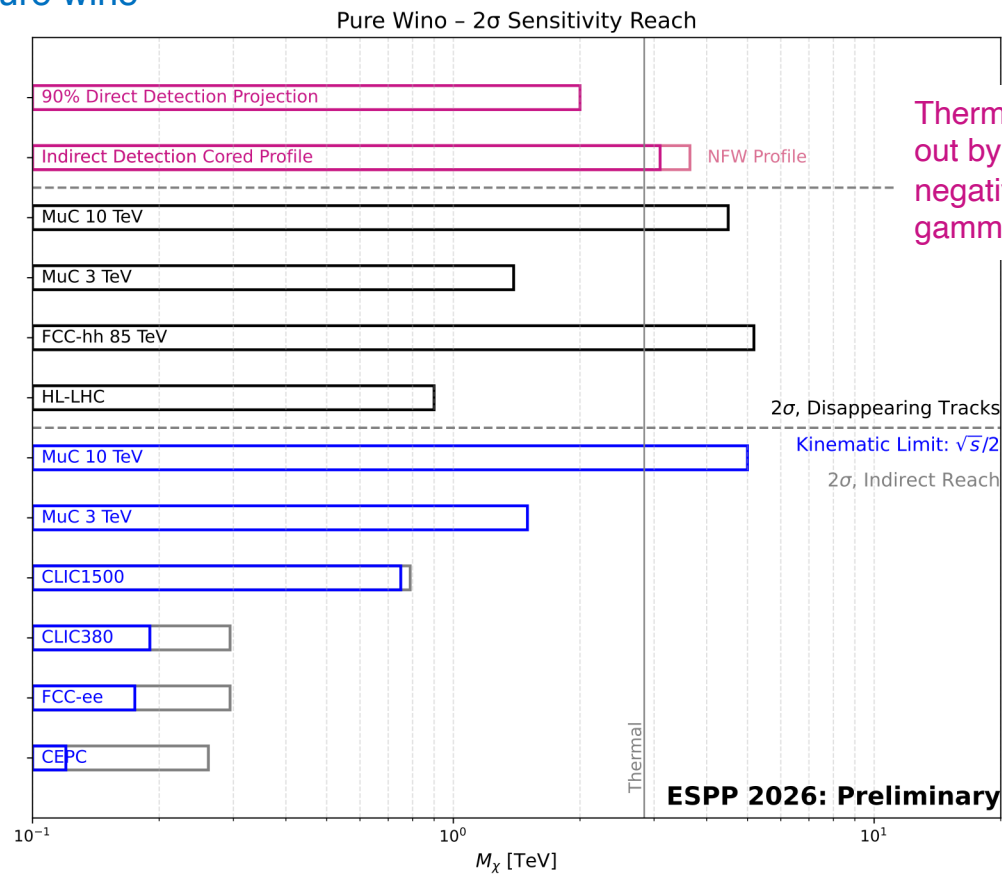
Low-momentum isolated tracks, electrons calibrated down to 1 GeV!

Indirect detection — thermal wino / higgsino

Space observations can also provide hints for new physics (as is the case for Dark Matter!)
— and set competitive constraints on dark matter models [\[arXiv:2511.03883\]](https://arxiv.org/annals/202511.03883)

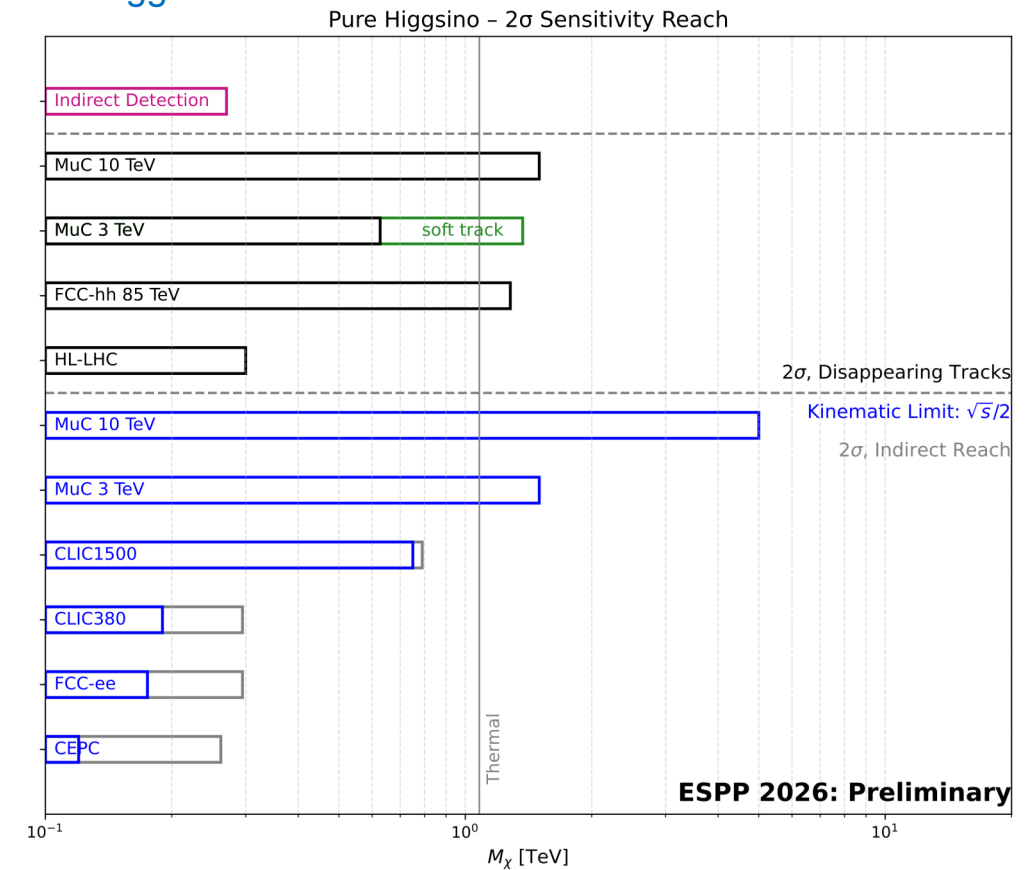


Pure wino*



*Majorana fermion triplet

Pure higgsino*



*Dirac fermion doublet