# Overview of recent LHC results

CAVEAT: this is a impossible task, so I had to make a lot of personal choices and selected only few results
Apologies for all those omitted. I am sure next speakers will give them justice!

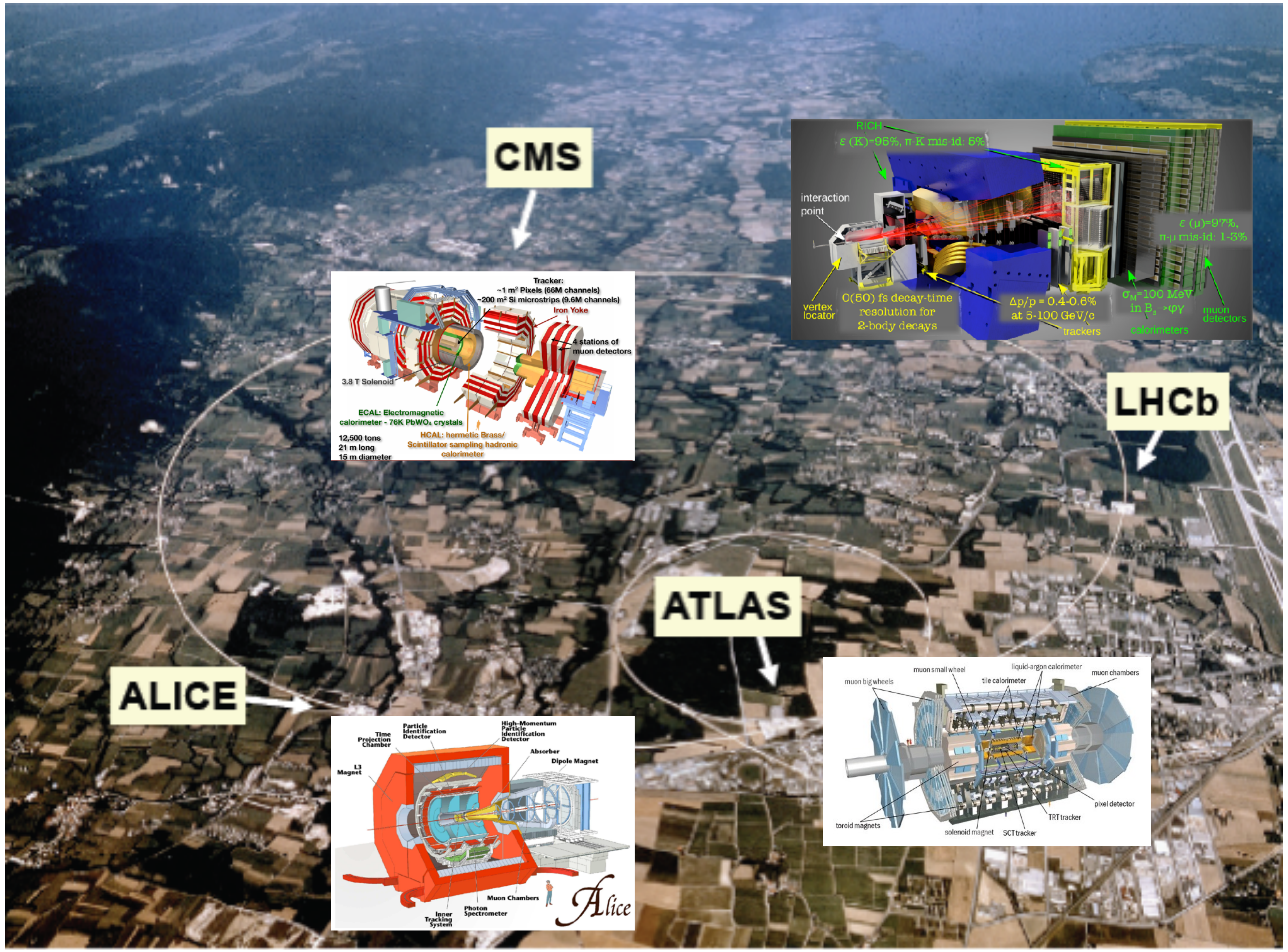
**Luca Malgeri**

**30 September 2024 - LHC Days in Split**

# Credits and more info

- CERN web pages: https://timeline.web.cern.ch/origins
- CERN 70 years: https://cern70.cern/
- LEP EW Working group http://doc.cern.ch/archive/electronic/cern/preprints/phep/phep-2005-041.pdf
- 10th year Higgs celebrations https://indico.cern.ch/event/1135177/timetable/
- LHCP 2024:
  - ALICE: https://indico.cern.ch/event/1253590/contributions/5814443/attachments/2869212/5025926/20240603_ALICE_highlights_LHCP.pdf
  - LHCb: https://indico.cern.ch/event/1253590/contributions/5814444/attachments/2868729/5021987/LHCbArtusoLHCP24f.pdf
  - CMS: https://indico.cern.ch/event/1253590/contributions/5814450/attachments/2869480/5023453/LHCP2024-CMS-wa.pdf
  - ATLAS: https://indico.cern.ch/event/1253590/contributions/5814445/attachments/2869555/5023791/LHCP_atlas_hgray.pdf
- ICHEP 2024:
  - ALICE: https://indico.cern.ch/event/1291157/contributions/5958022/attachments/2901068/5087468/nj_ICHEP24_ALICE_Highlights.pdf
  - LHCb: https://indico.cern.ch/event/1291157/contributions/5958029/attachments/2901092/5096981/ICHEP2024-YasmineAmhis.pdf
  - CMS: https://indico.cern.ch/event/1291157/contributions/5958001/attachments/2901064/5087563/CMSHighlights.pdf
  - ATLAS: https://indico.cern.ch/event/1291157/contributions/5957999/attachments/2901060/5087458/2024_07_22_ICHEP.pdf
- CMS W mass seminar: https://indico.cern.ch/event/1441575/

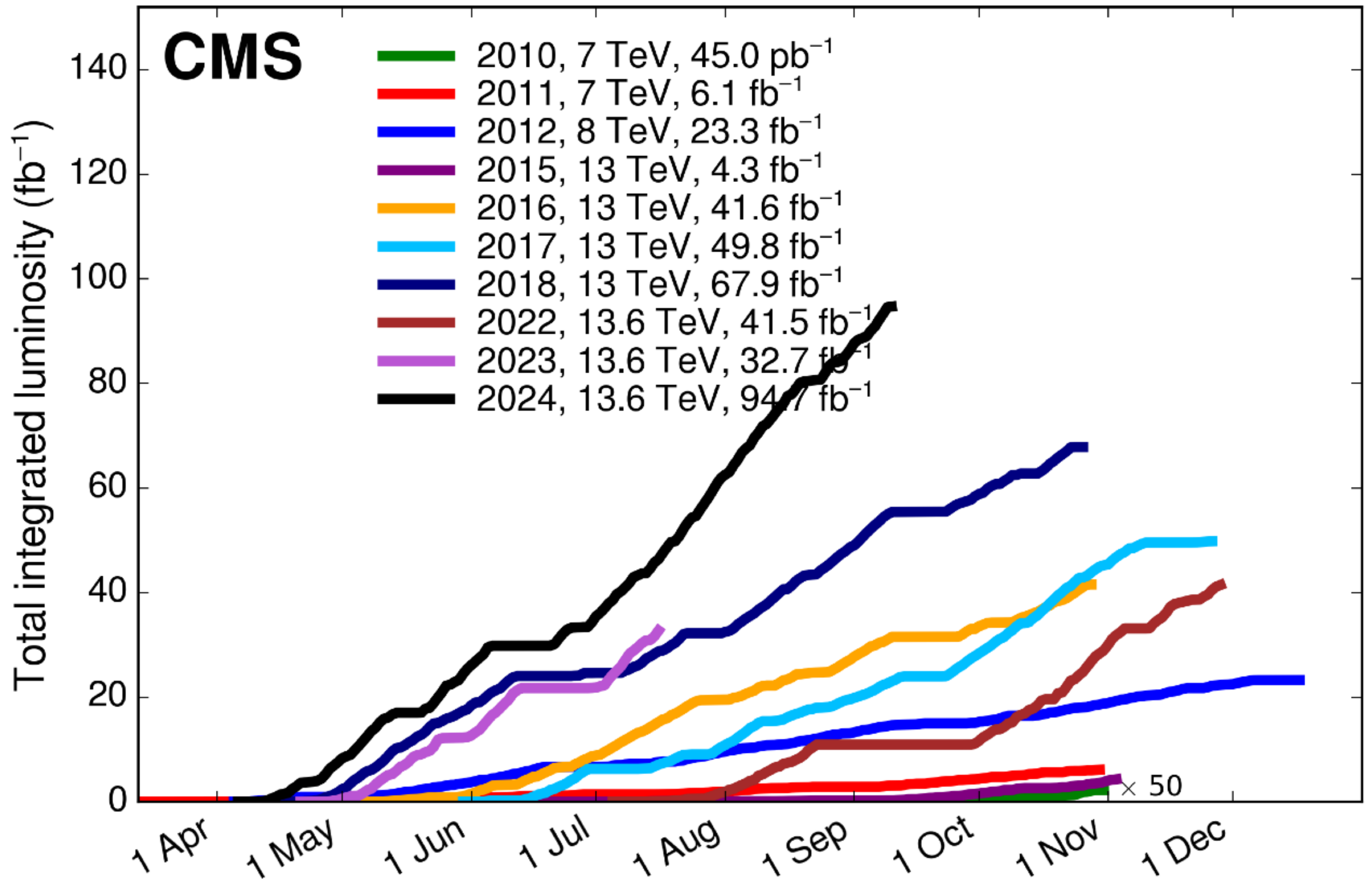
# The current LHC detectors

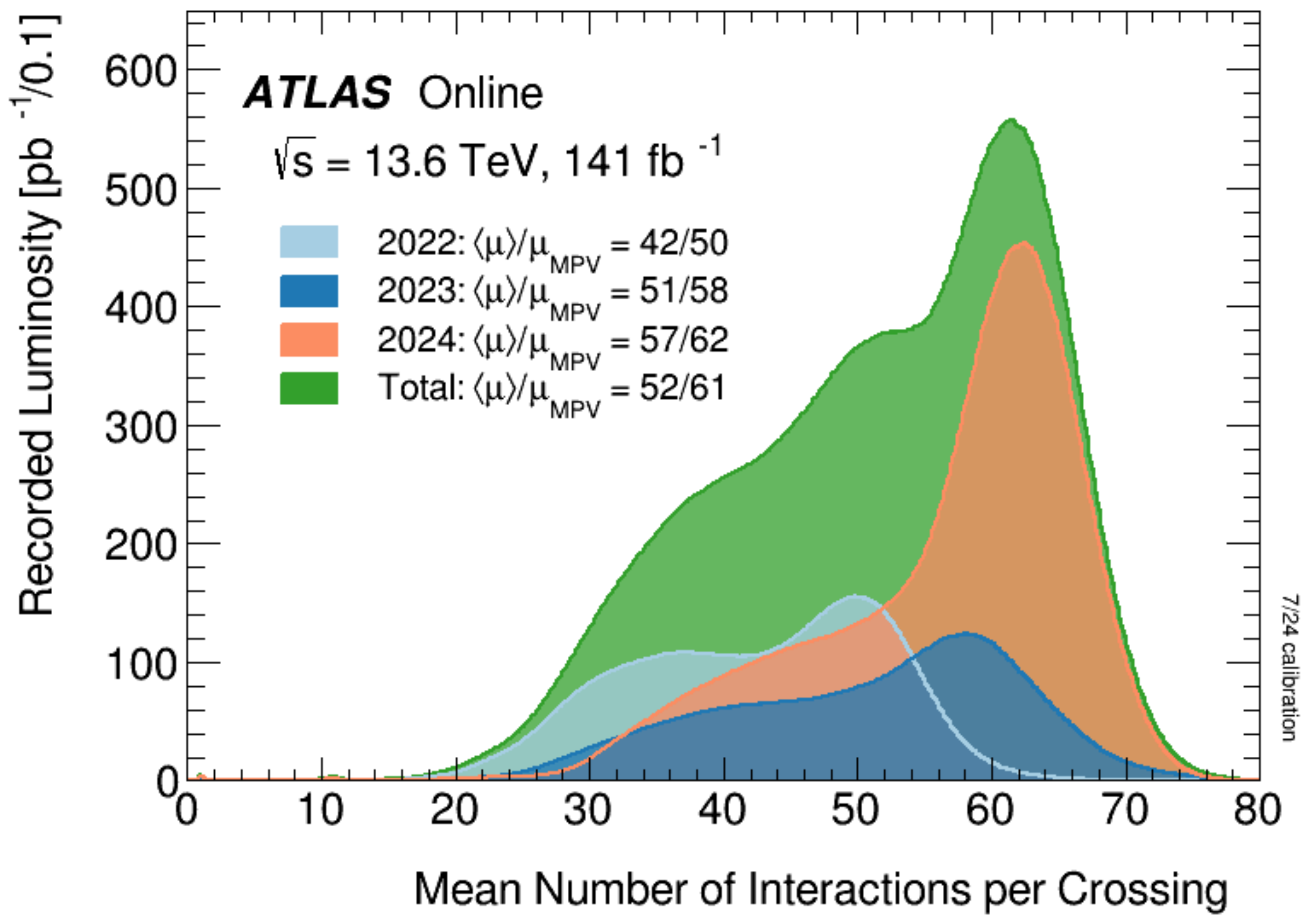



**LHC experiments:**

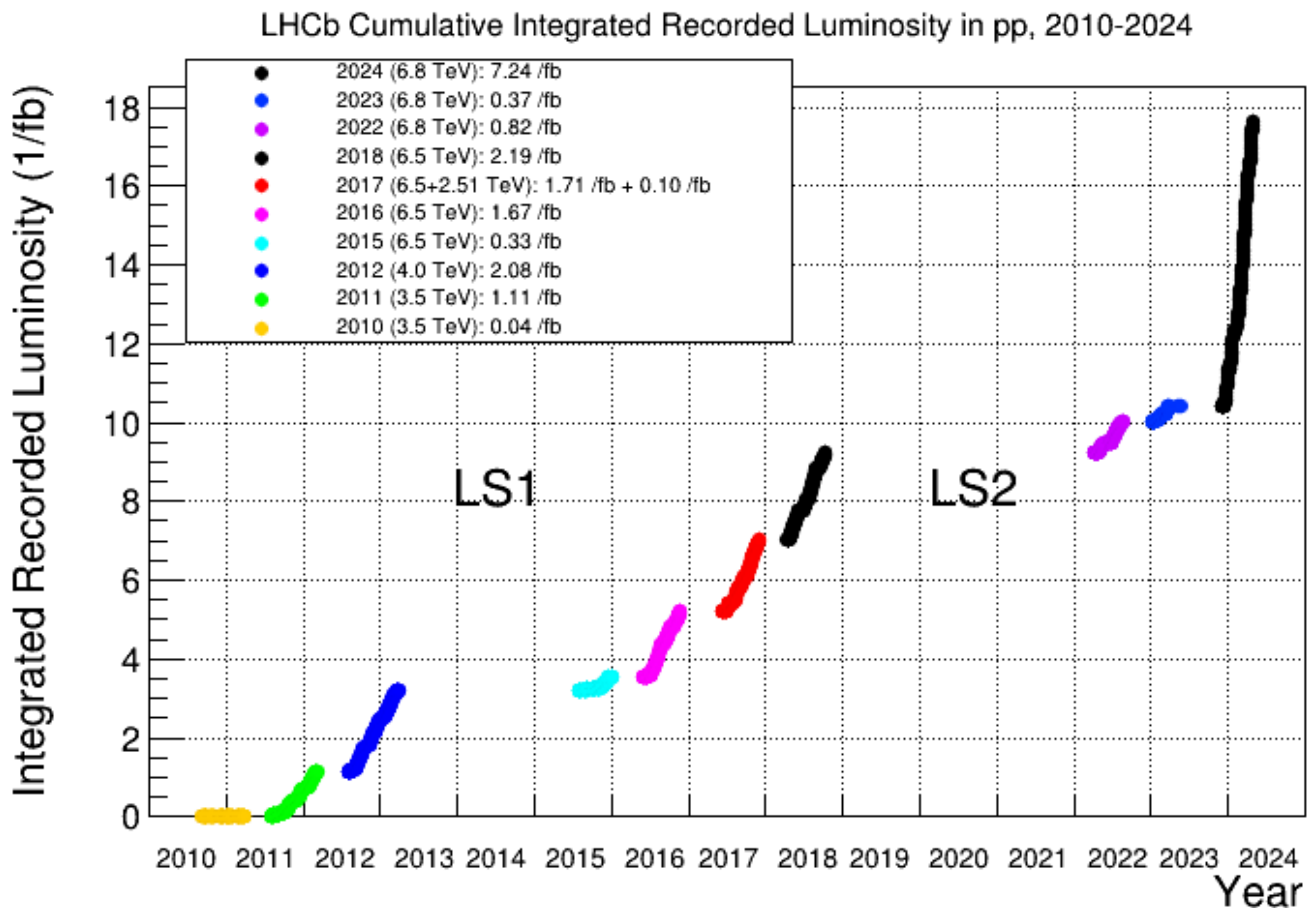
- **2 multipurpose detectors**:
  - **ATLAS** and **CMS** with accurate silicon trackers, strong magnetic field, almost full coverage electromagnetic and hadronic calorimeters and muon chambers surrounding them
- **2 dedicated detectors**:
  - **LHCb** for b quark physics: accurate forward tracking to tag long lived particle
  - **ALICE**: designed for heavy ions collisions with accurate particle identification enabled by a large time projection chamber

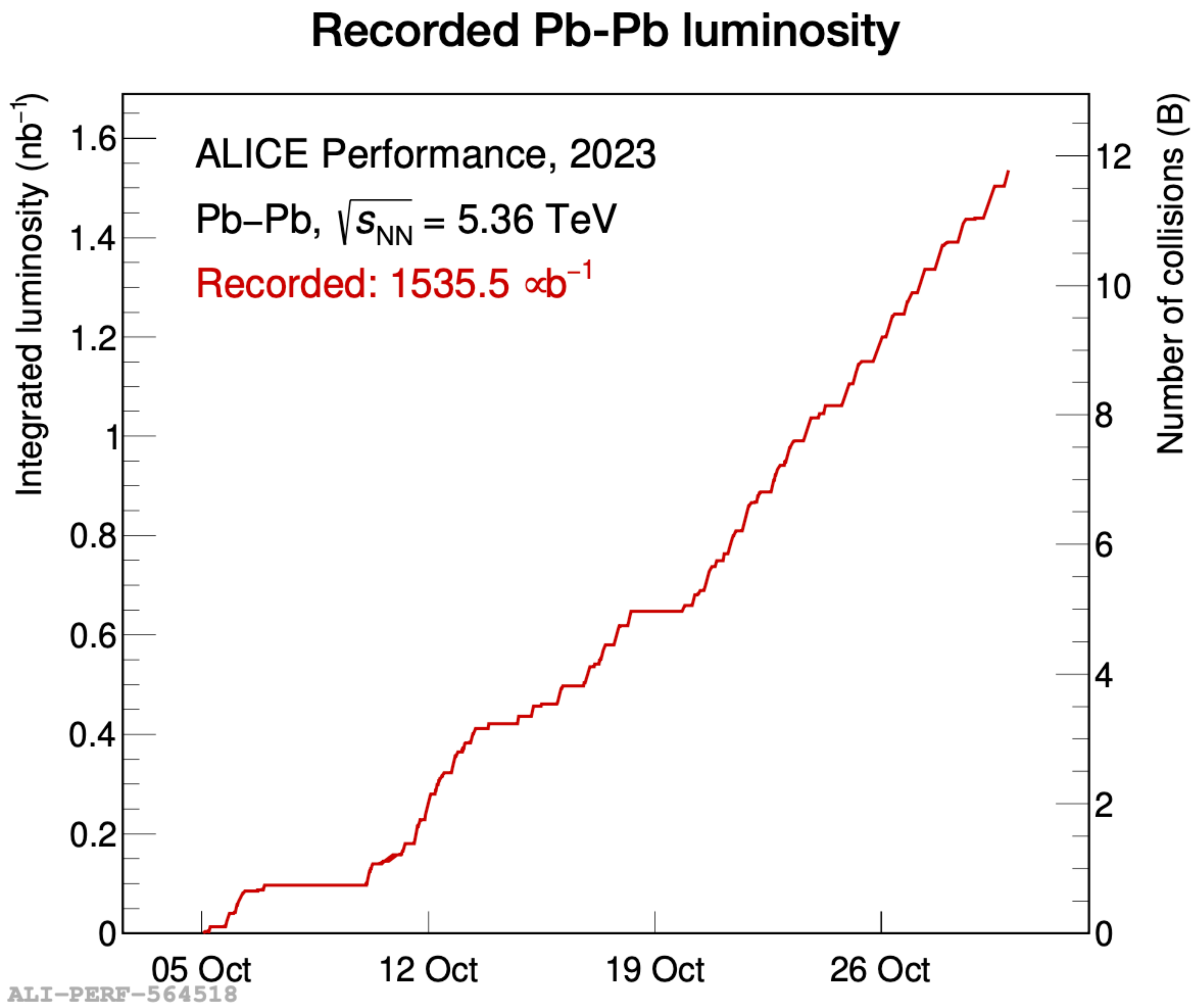
# LHC performance so far (Run1-3)

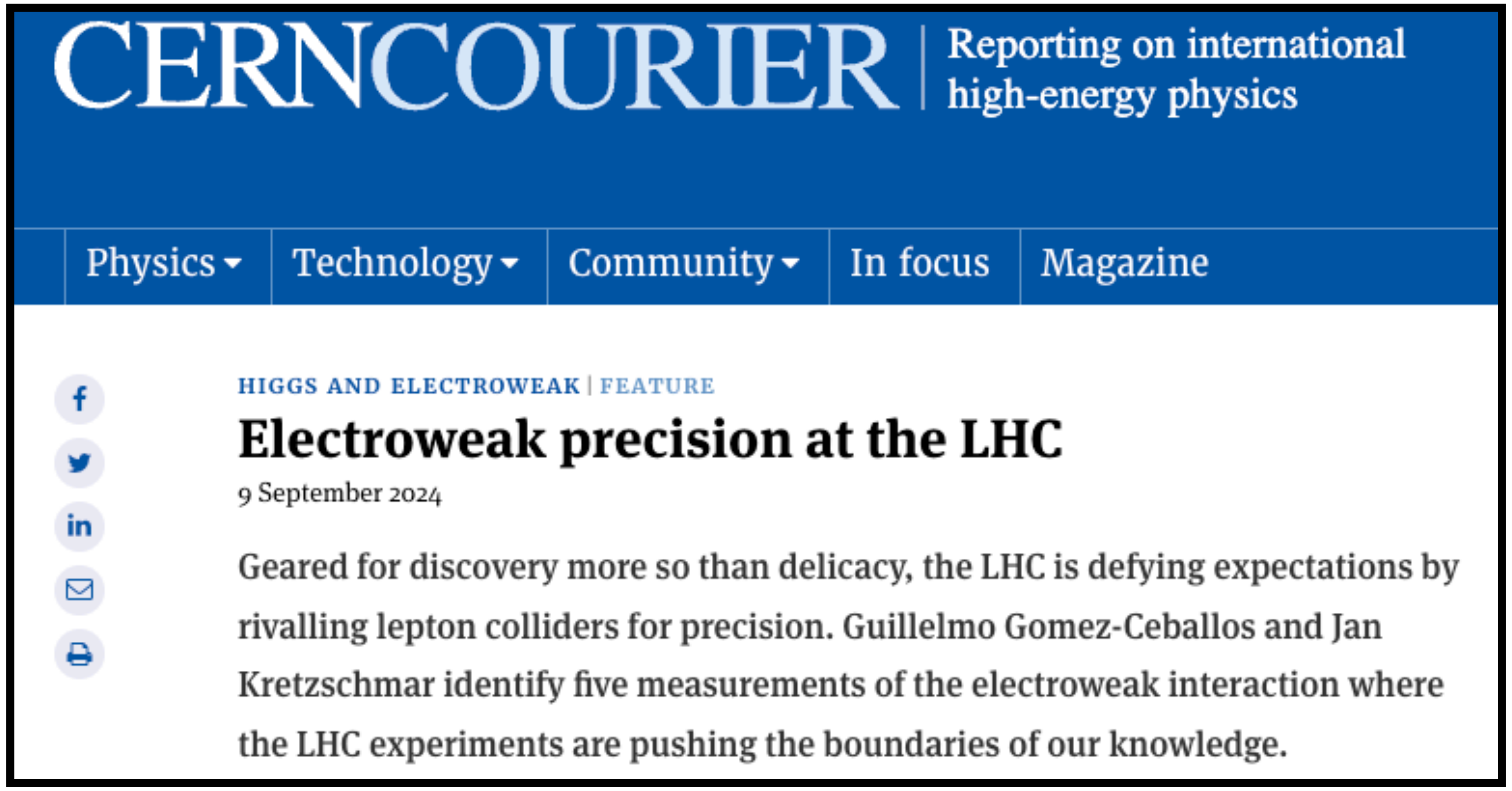



- Delivered lumi: ~350 $fb^{-1}$ (ATLAS/CMS)
- Pile-Up: up to 60 (average) 70 (max) (ATLAS/CMS)





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Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

HIGGS AND ELECTROWEAK | FEATURE

**Electroweak precision at the LHC**

9 September 2024

Geared for discovery more so than delicacy, the LHC is defying expectations by rivalling lepton colliders for precision. Guillelmo Gomez-Ceballos and Jan Kretzschmar identify five measurements of the electroweak interaction where the LHC experiments are pushing the boundaries of our knowledge.

# SM Precision Physics

## Please check the recent CERN Courier article for more details!

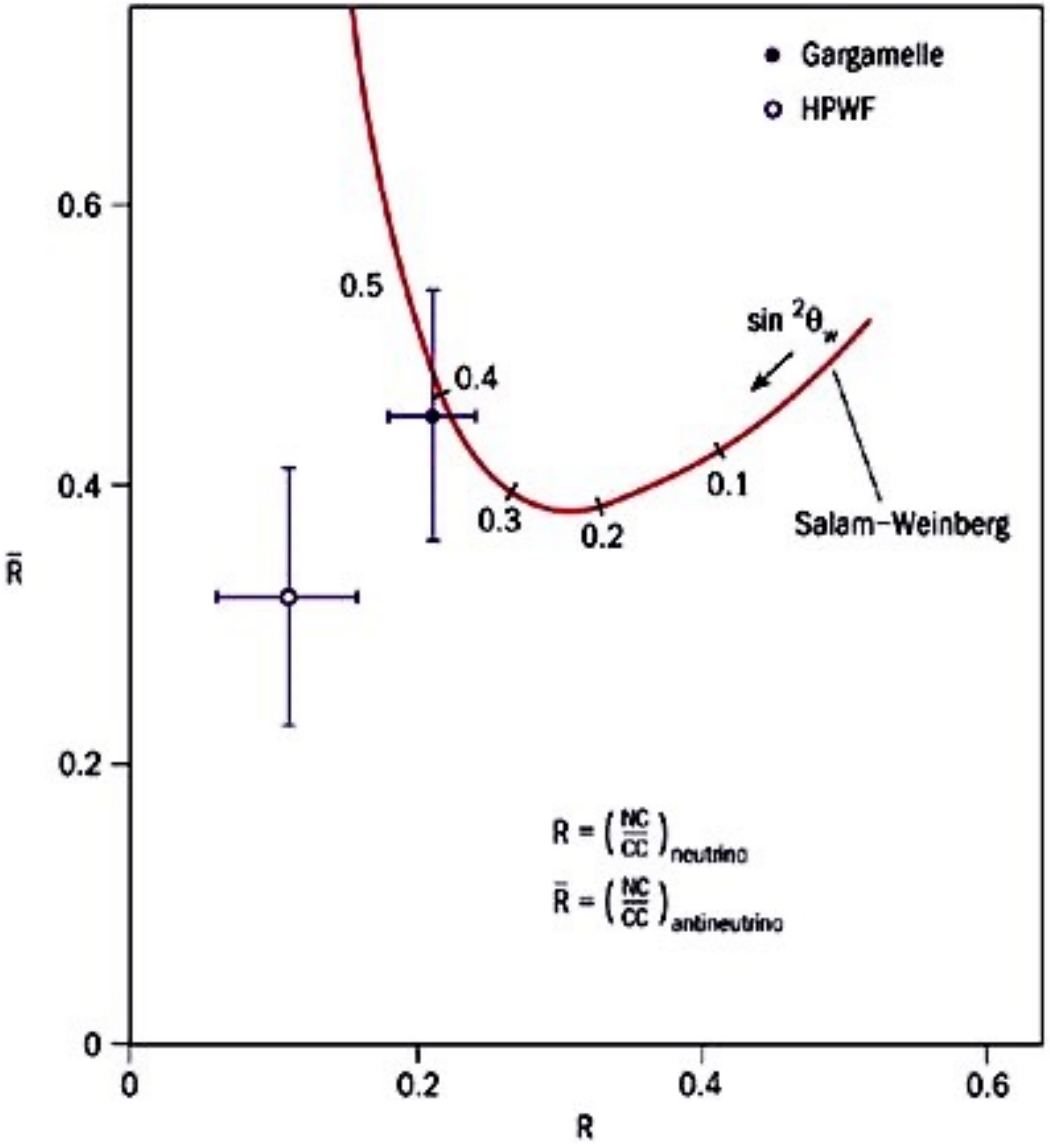
# The journey started long ago

**The combined measurements of rates of neutral current and charge current events for neutrino and anti-neutrino beams in SM:**

**first indirect indication of the existence of W and Z boson as well as of their mass:**

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G}}\frac{1}{\sin\,\theta_W} = \frac{37\ \text{GeV}}{\sin\,\theta_W} \approx 70\ \text{GeV}$$

**This happened much before the direct discovery of W and Z bosons and guided the CERN future accelerator path.**



# Today's measurements of the weak mixing angle

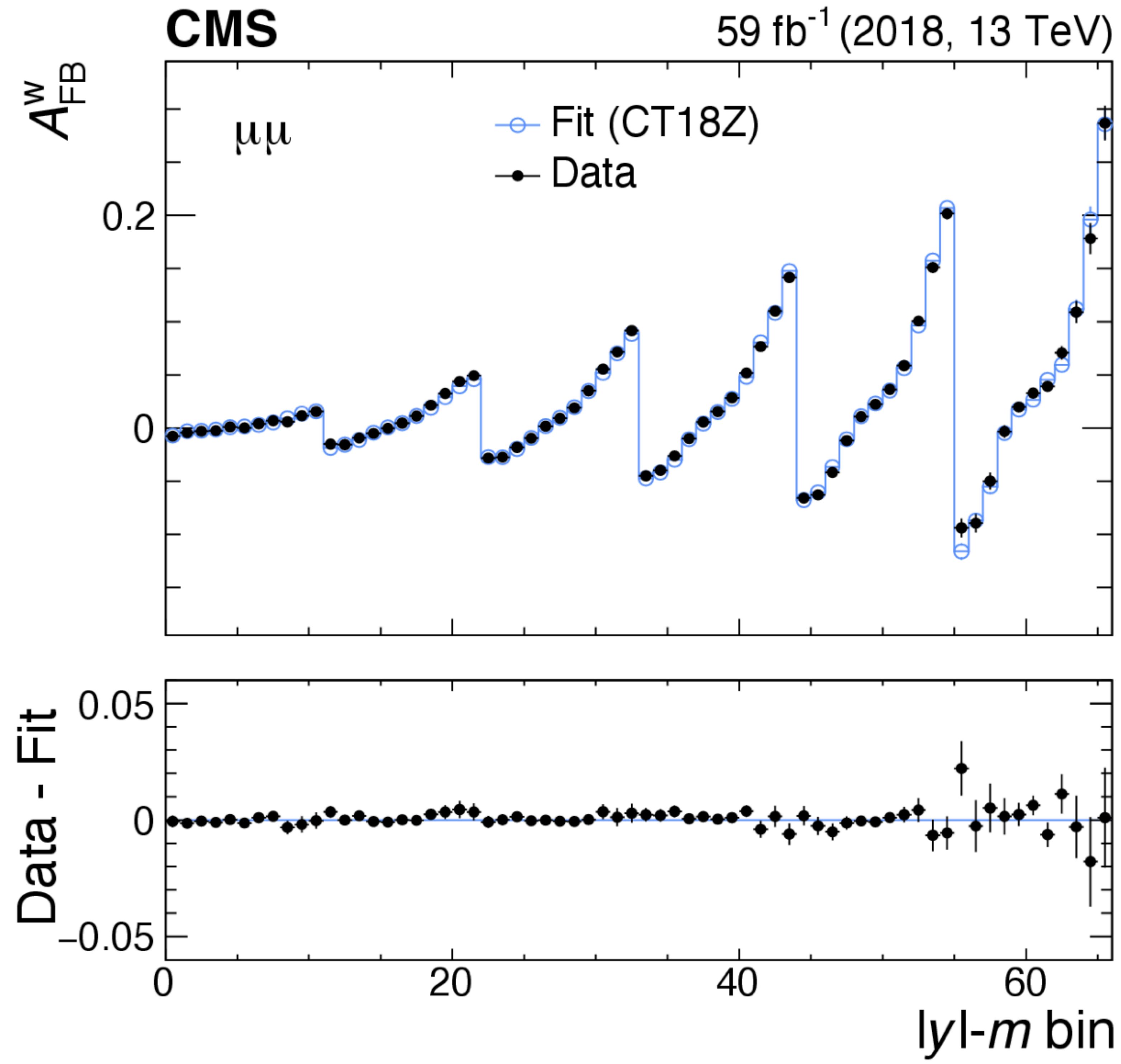
- Using forward-backward asymmetry AFB of DY (leptons) using the full 13 TeV data
- $\sin^2\theta$ extraction by fitting mass and rapidity dependence of AFB, strong dependence on mass because of the axial–vector interference
- Most precise measurement of $\sin^2\theta$ at hadron colliders (similar to LEP)
- Allows also to constrain PDFs

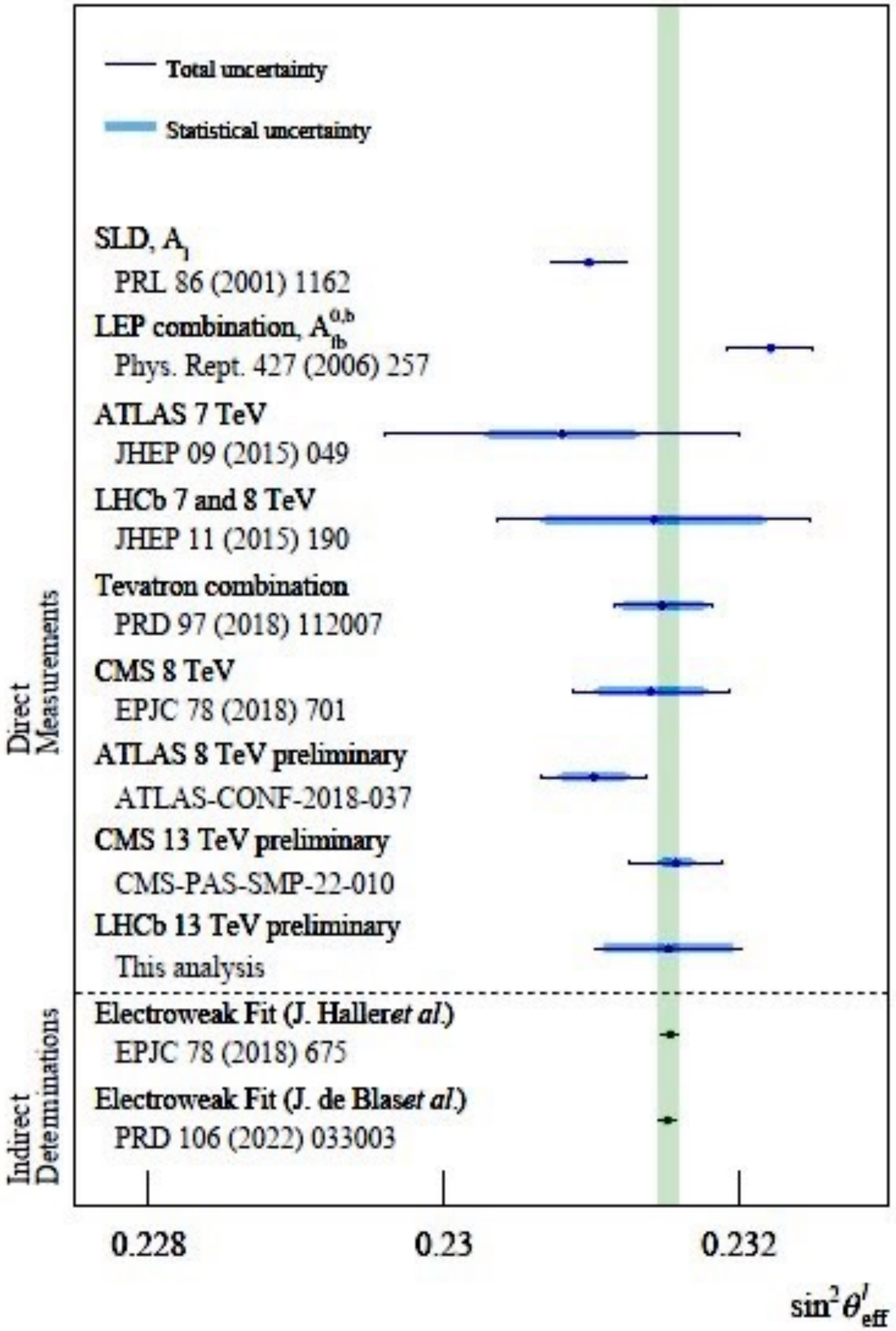
$$\frac{M_W}{M_Z} = \cos\theta_W \qquad \frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}\mathcal{A}(1+\cos^2\theta) + \mathcal{B}\cos\theta\right]$$

$$\mathcal{A} = Q_l^2 Q_q^2 + 2Q_l Q_q g_V^q g_V^l \,\mathrm{Re}(\chi(s)) + \left((g_V^l)^2 + (g_A^l)^2\right)\left((g_V^q)^2 + (g_A^q)^2\right)|\chi(s)|^2$$

$$\mathcal{B} = \frac{3}{2} g_A^q g_A^l \left(Q_l Q_q \,\mathrm{Re}(\chi(s)) + 2 g_V^q g_V^l |\chi(s)|^2\right)$$

$$\chi(s) = \frac{1}{\sin^2\theta_W \cos^2\theta_W}\,\frac{s}{s - m_Z^2 + \imath\Gamma_Z m_Z}$$



# W-mass:
# Hadron colliders taking the baton

## A key parameter of the SM!

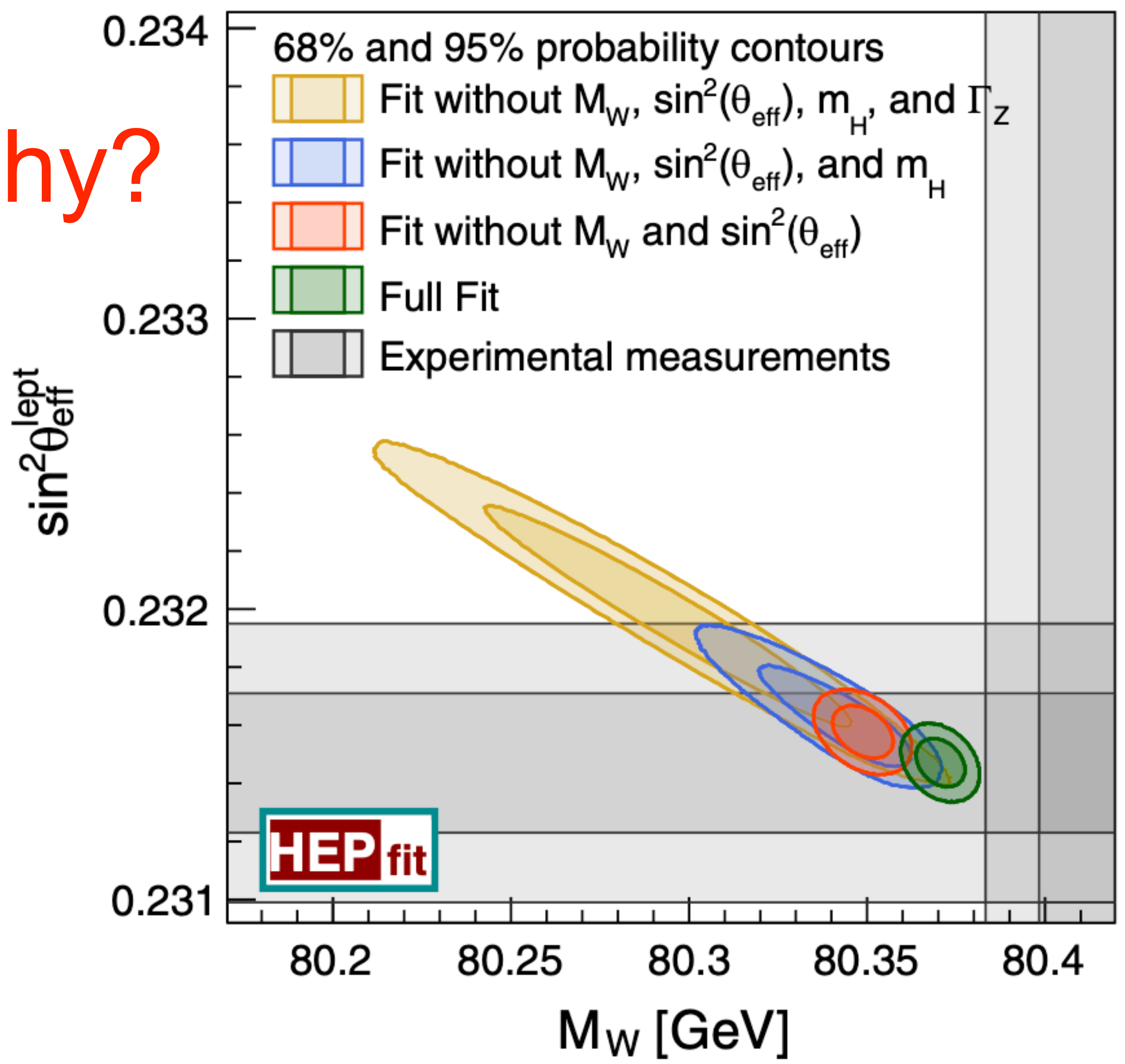
**Once LEP crossed the di-boson production threshold, it had the cleanest environment for its measurement.**

**Hadron colliders deemed unsuited for such a precise measurement given the theoretical and experimental uncertainties.**

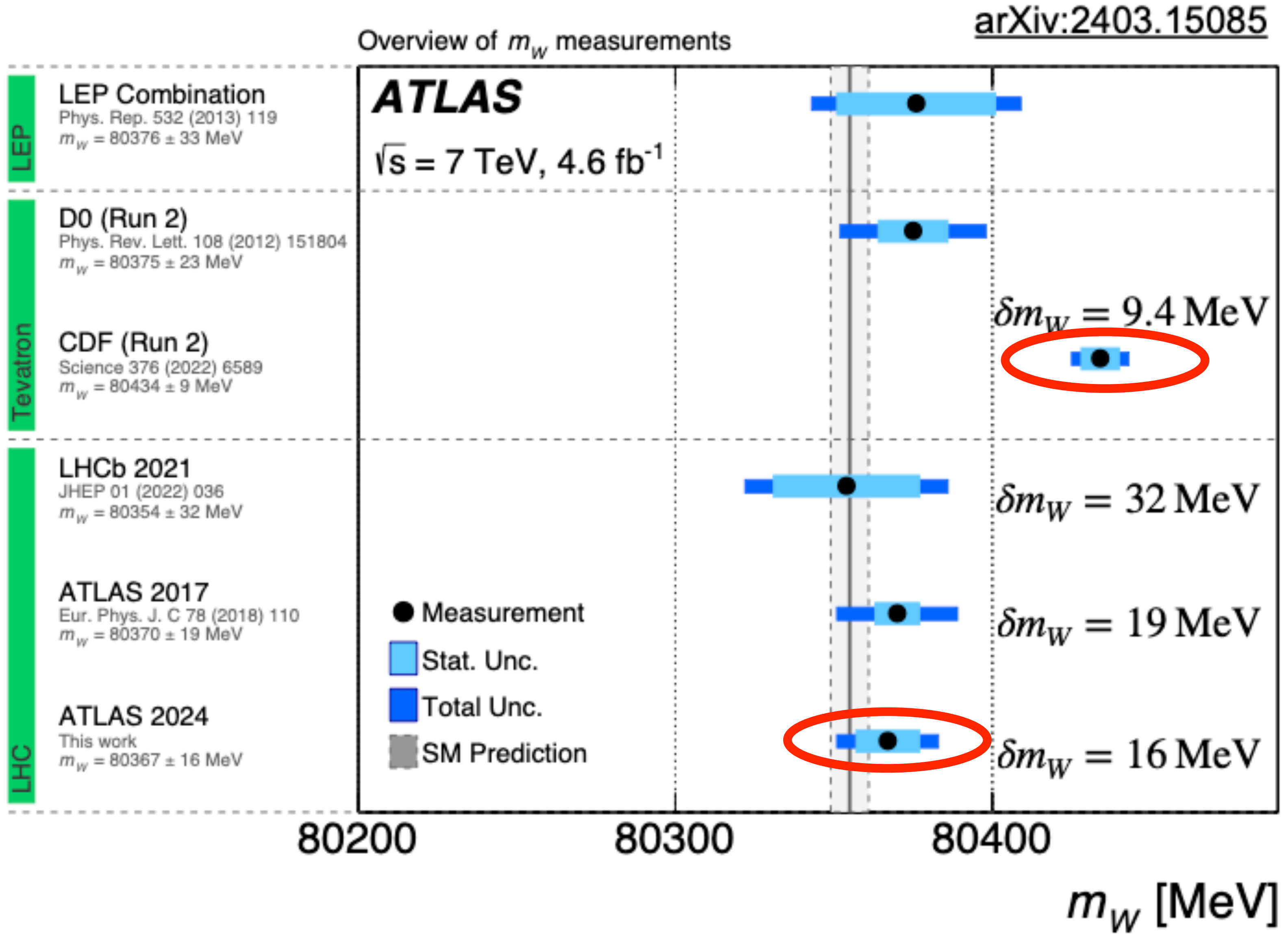
**First Tevatron and later LHC proved this statement wrong!**

**A striking tension between CDF and LHC+EW constraint has fuelled many BSM interpretations.**

Why?



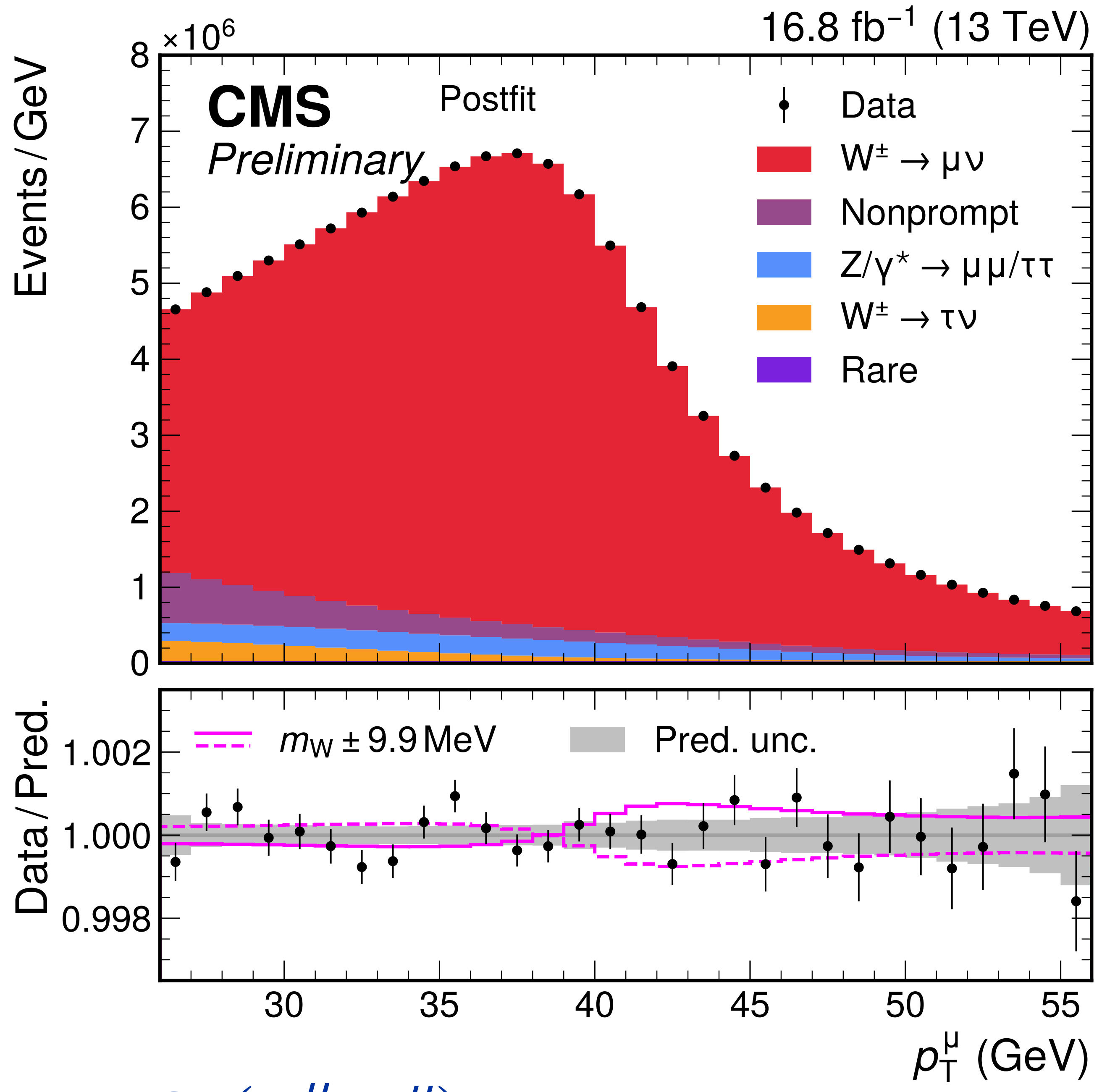

arXiv:2403.15085



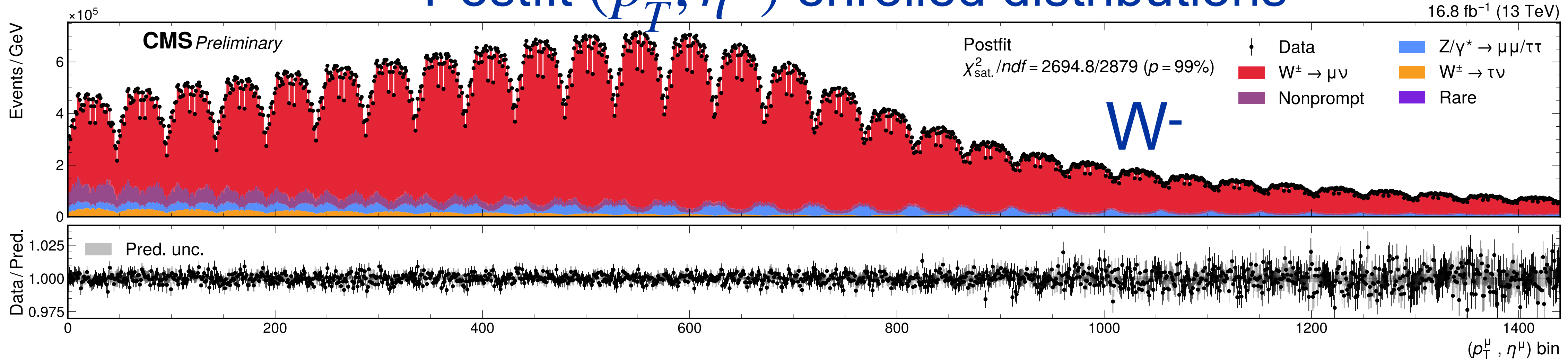
# W-mass: Hadron colliders taking the baton

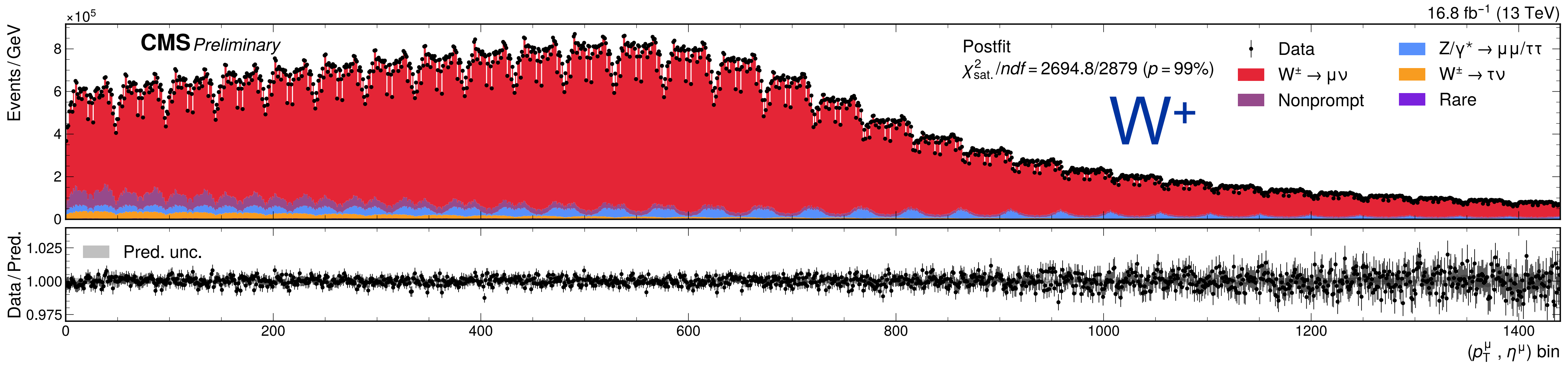
**After a decade-long analysis recently CMS produced a new result (actually two) with the most precise measurements at the LHC:**

- Nominal theory-dependent fit
  - Exploit state-of-the-art improvements in theoretical QCD and EW calculations and uncertainty modelling, and in-situ constraints from data
- Helicity cross section fit: trading reduced theory unc. in for larger stat. unc.
  - Standard theoretical uncertainties parametrised in terms of helicity cross section terms and corresponding variations binned in momentum and rapidity



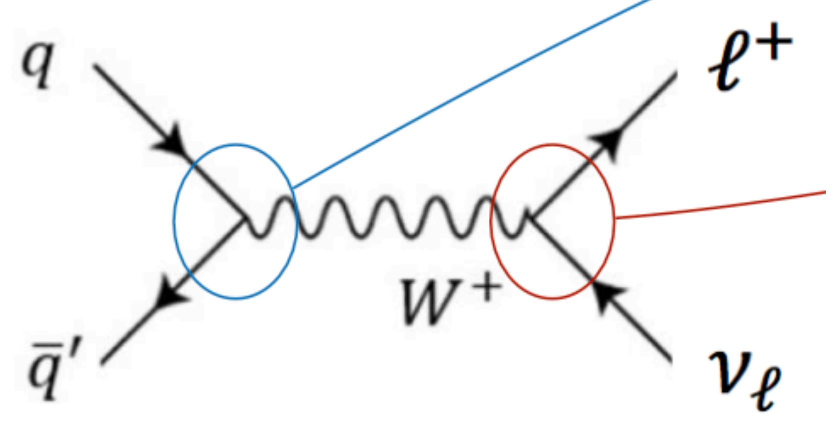

Postfit $(p_T^\mu, \eta^\mu)$ enrolled distributions




**Decomposition for d⁵σ valid at any order in QCD**

$$\frac{d^5\sigma}{dp_T^2\, dY\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma}{dp_T^2\, dY\, dm} \times \Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$



# W-mass:
# Hadron colliders taking the baton

## Systematics:

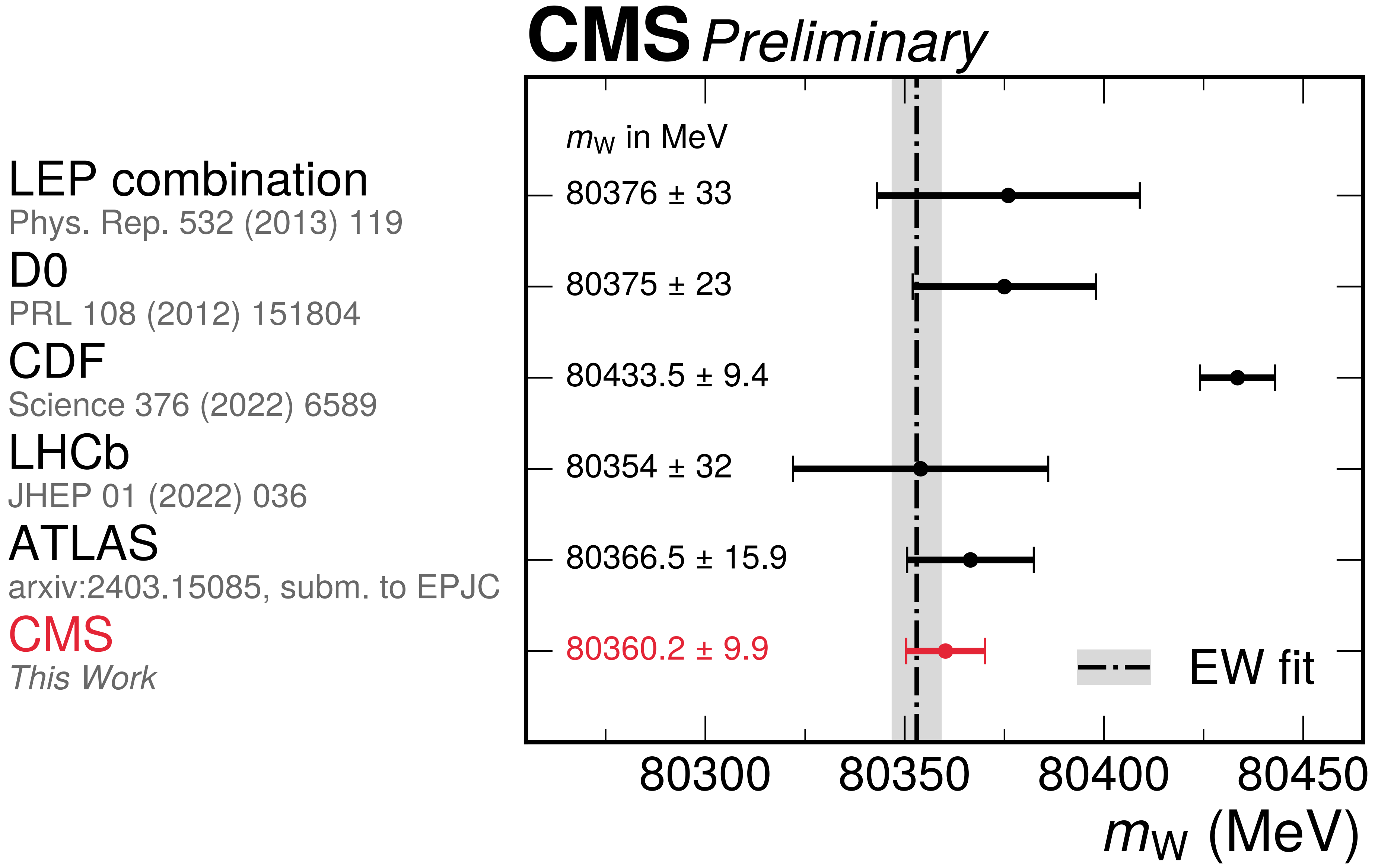
**“Global”:**

**a rearrangement of uncertainties that tries to separate the stat. component of the systematic unc.**

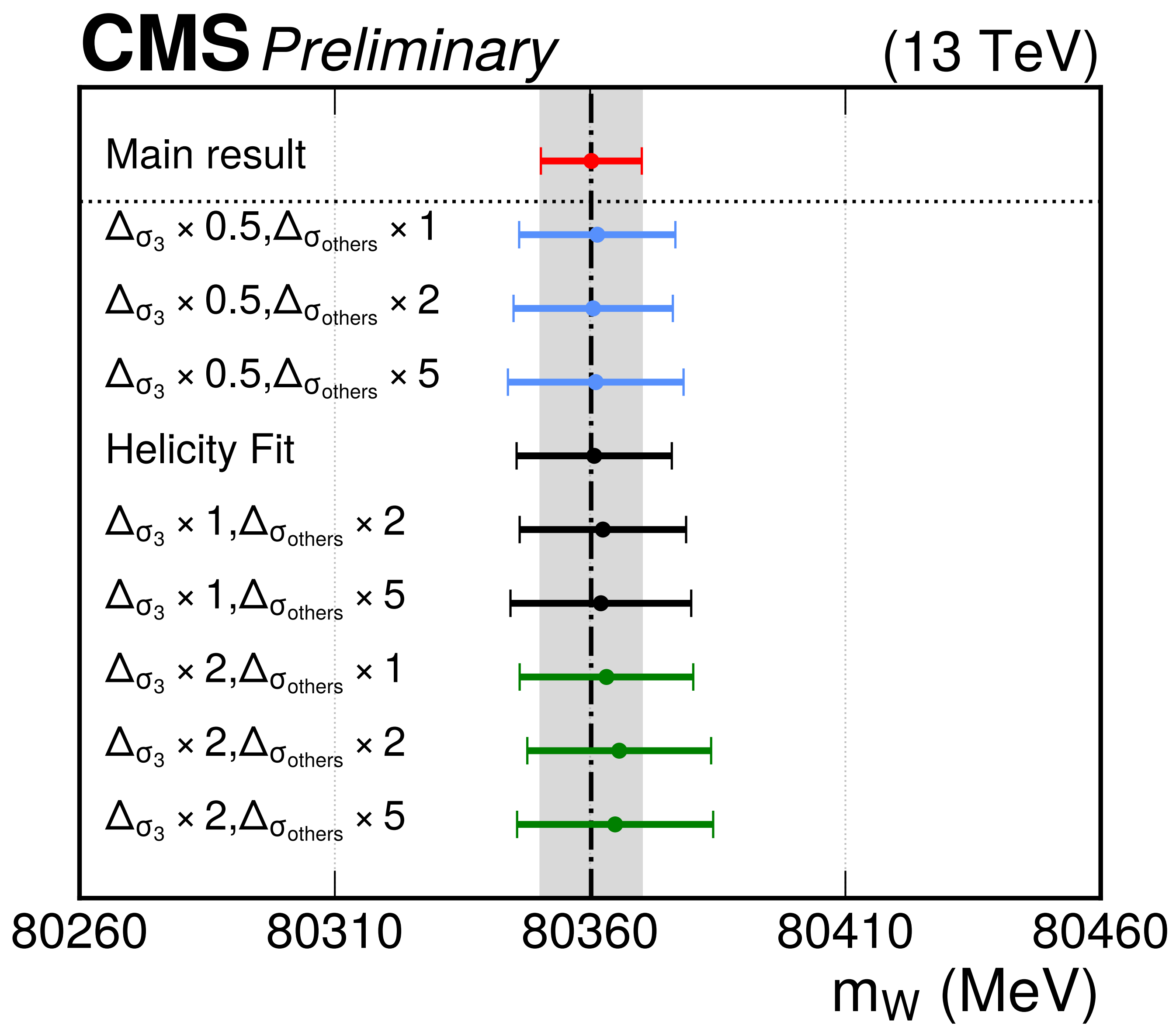
| Source of uncertainty | Impact (MeV) Nominal in $m_Z$ | Nominal in $m_W$ | Global in $m_Z$ | Global in $m_W$ |
|---|---|---|---|---|
| Muon momentum scale | 5.6 | 4.8 | 5.3 | 4.4 |
| Muon reco. efficiency | 3.8 | 3.0 | 3.0 | 2.3 |
| W and Z angular coeffs. | 4.9 | 3.3 | 4.5 | 3.0 |
| Higher-order EW | 2.2 | 2.0 | 2.2 | 1.9 |
| $p_T^V$ modeling | 1.7 | 2.0 | 1.0 | 0.8 |
| PDF | 2.4 | 4.4 | 1.9 | 2.8 |
| Nonprompt background | – | 3.2 | – | 1.7 |
| Integrated luminosity | 0.3 | 0.1 | 0.2 | 0.1 |
| MC sample size | 2.5 | 1.5 | 3.6 | 3.8 |
| Data sample size | 6.9 | 2.4 | 10.1 | 6.0 |
| Total uncertainty | 13.5 | 9.9 | 13.5 | 9.9 |

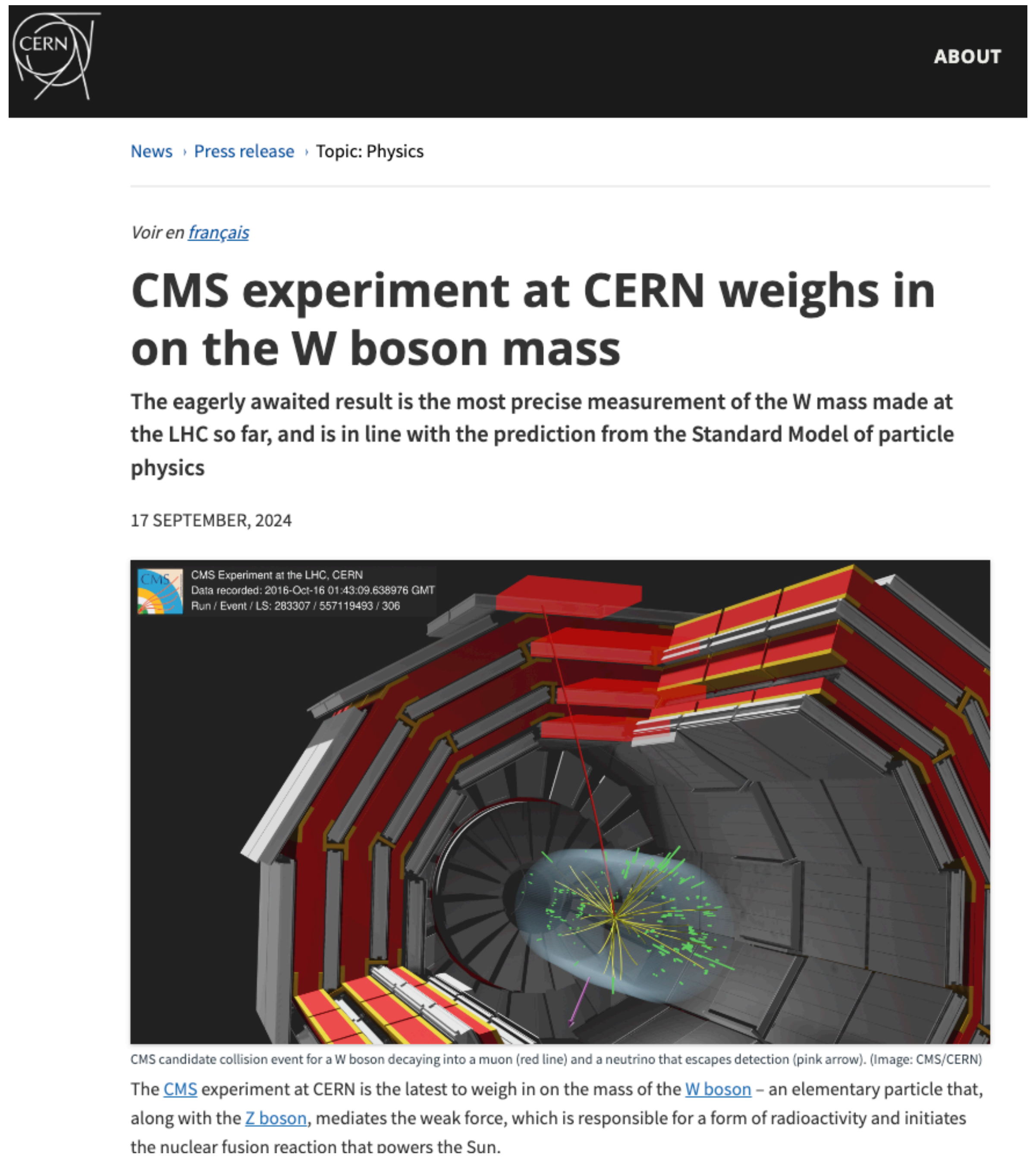
## Results: nominal

$$m_W = (80360.2 \pm 9.9)\ MeV$$




## Helicity fit



ABOUT

News › Press release › Topic: Physics

*Voir en français*

**CMS experiment at CERN weighs in on the W boson mass**

**The eagerly awaited result is the most precise measurement of the W mass made at the LHC so far, and is in line with the prediction from the Standard Model of particle physics**

17 SEPTEMBER, 2024

CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-16 01:43:09.638976 GMT
Run / Event / LS: 283307 / 557119493 / 306

CMS candidate collision event for a W boson decaying into a muon (red line) and a neutrino that escapes detection (pink arrow). (Image: CMS/CERN)

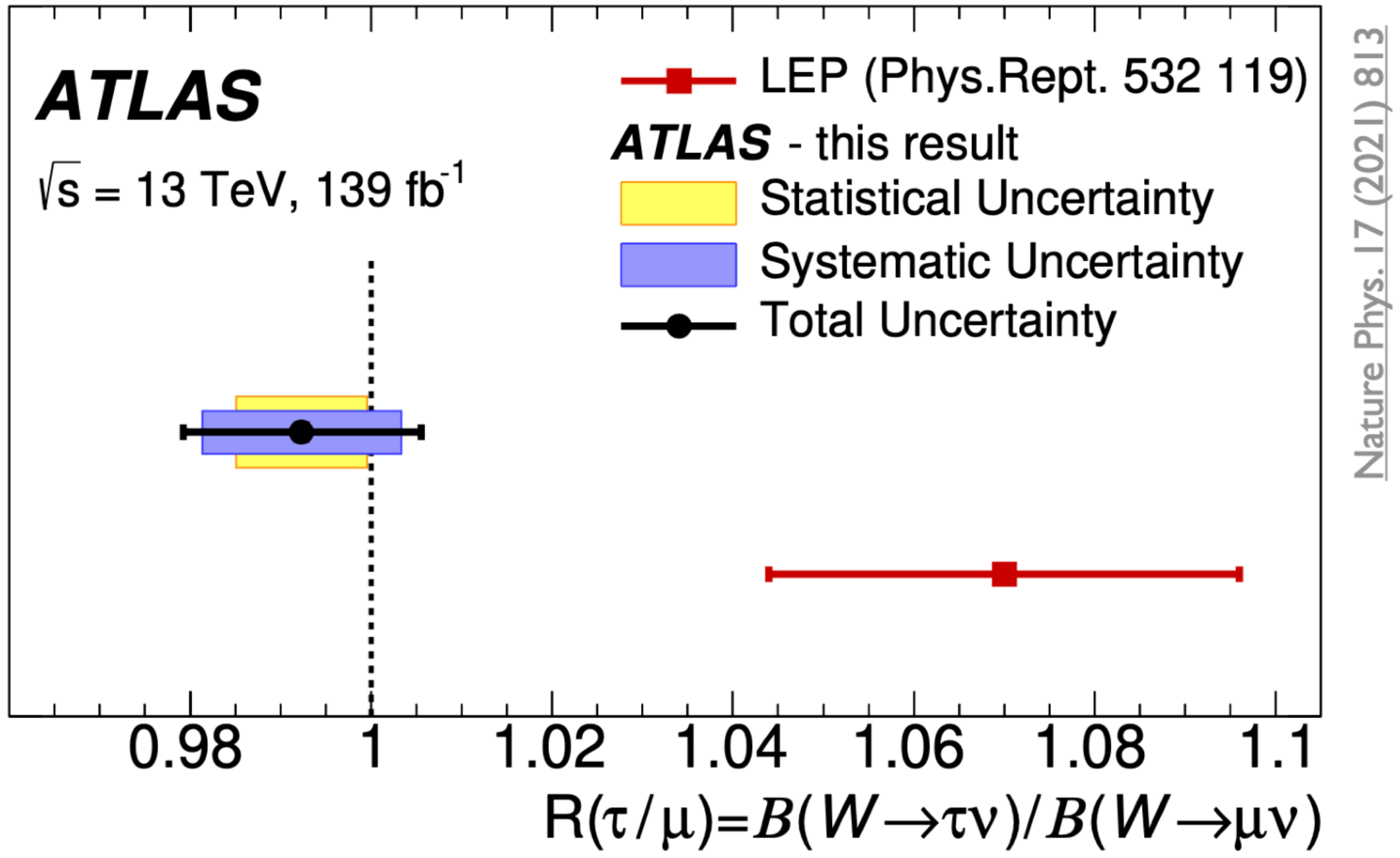
The CMS experiment at CERN is the latest to weigh in on the mass of the W boson – an elementary particle that, along with the Z boson, mediates the weak force, which is responsible for a form of radioactivity and initiates the nuclear fusion reaction that powers the Sun.

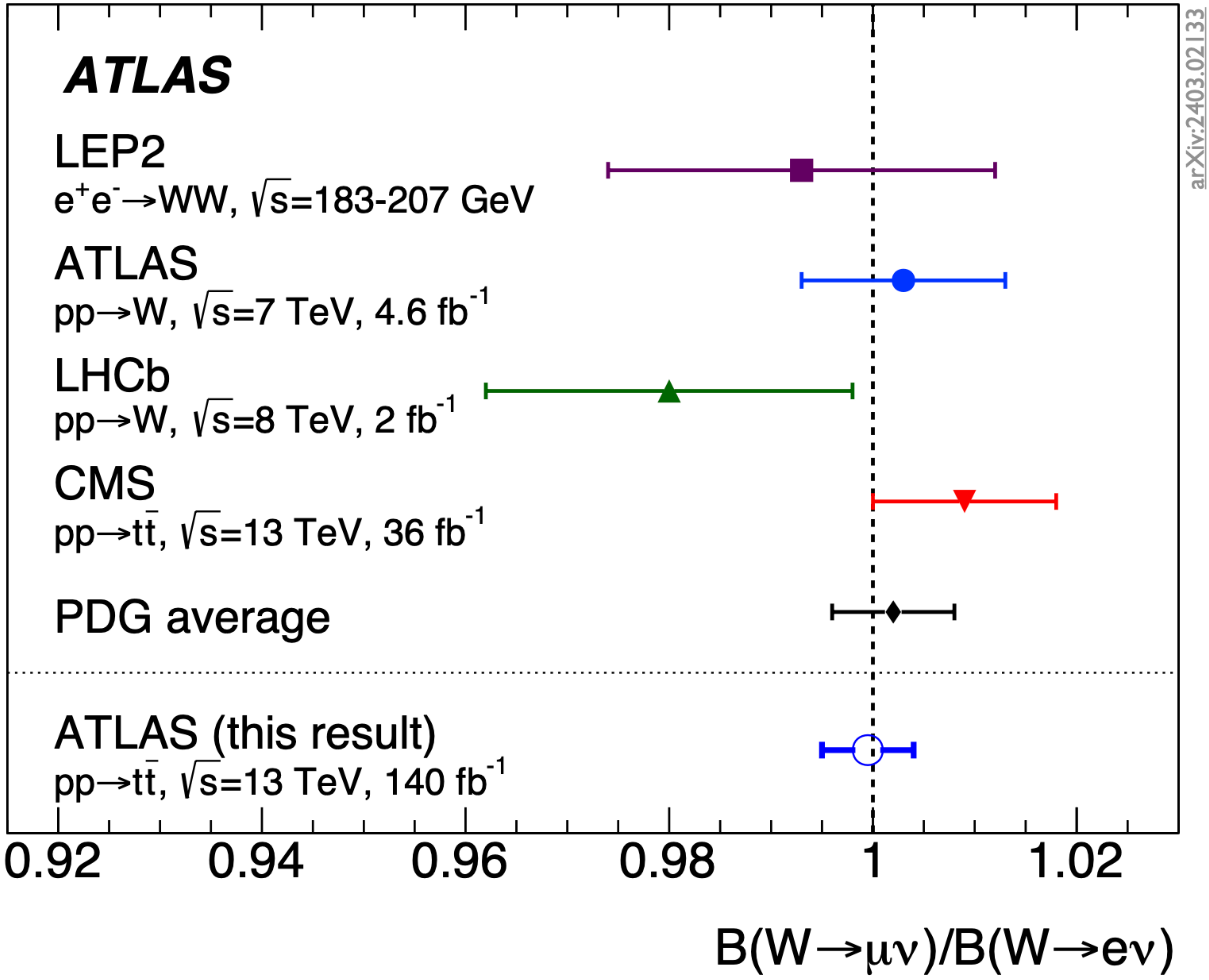
# Lepton Universality in W decays at the LHC

## Recent result from ATLAS: W decays to electrons and muons from top-pair events

- **2x improvement on single-experiment precision**

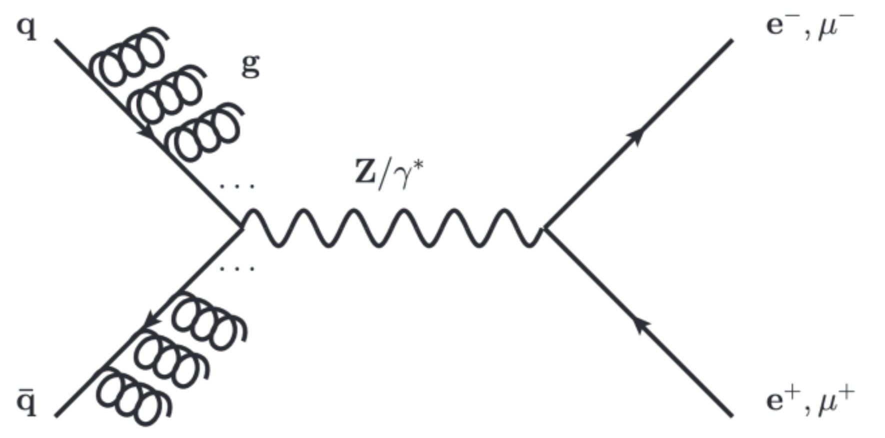
[Nature Phys. 17 (2021) 813]



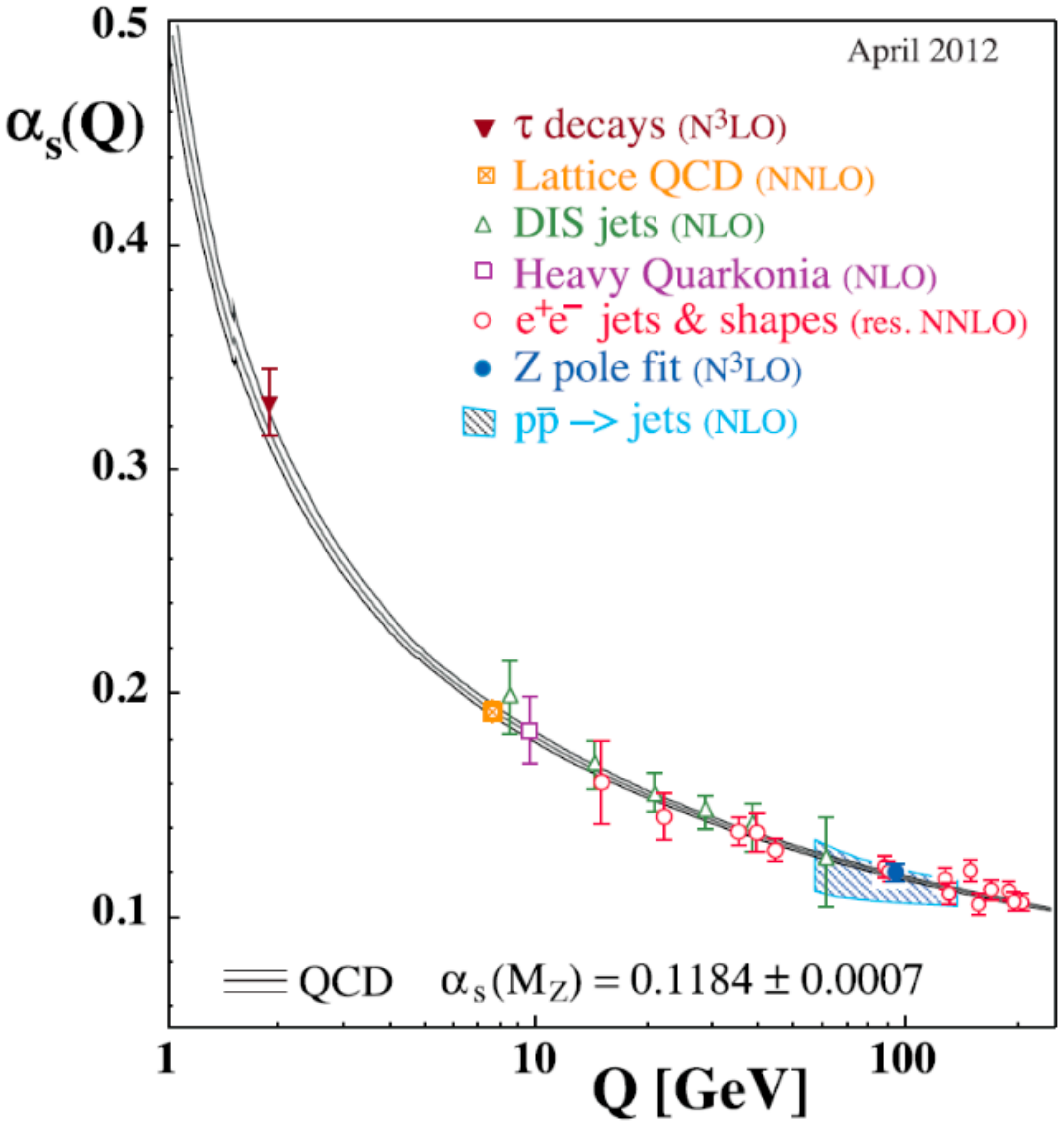
# LHC and the measurement of the strong force

**Several techniques used: jets production, ttbar and W/Z cross sections and asymmetries in Transverse Energy-Energy Correlations**

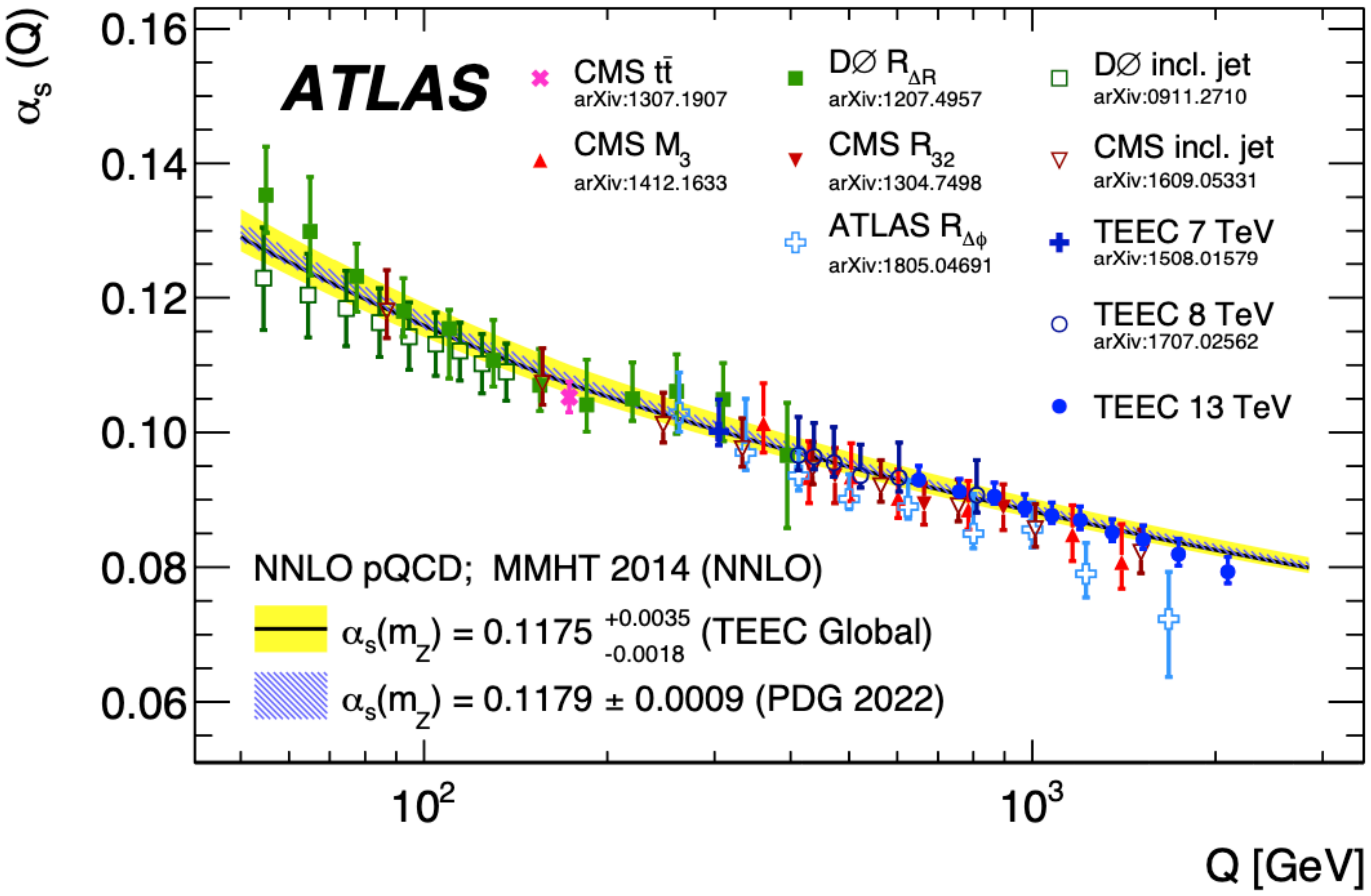



$$\text{TEEC}= \frac{1}{\sigma'}\frac{d\Sigma'}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\frac{1}{\Delta\cos\phi}\sum_{\substack{a,b=1 \\ \text{pairs in } \Delta\cos\phi}}^{N_{jets}}\frac{2E^A_{T_a}E^A_{T_b}}{(E^A_T)^2}$$

Before LHC




At the LHC



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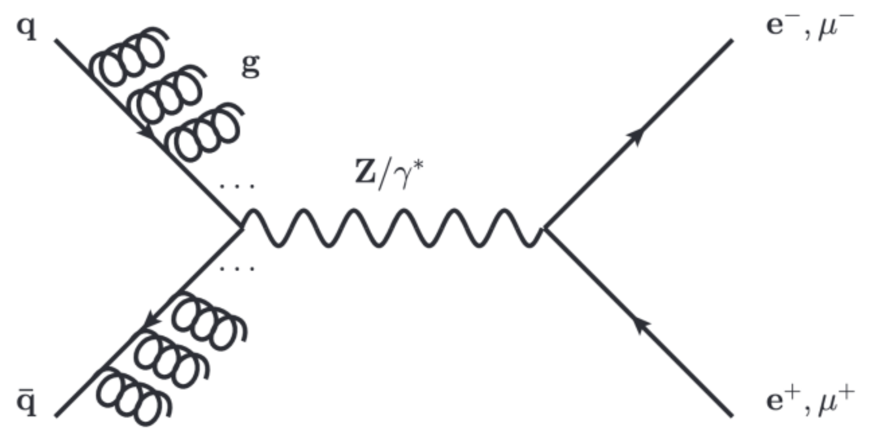
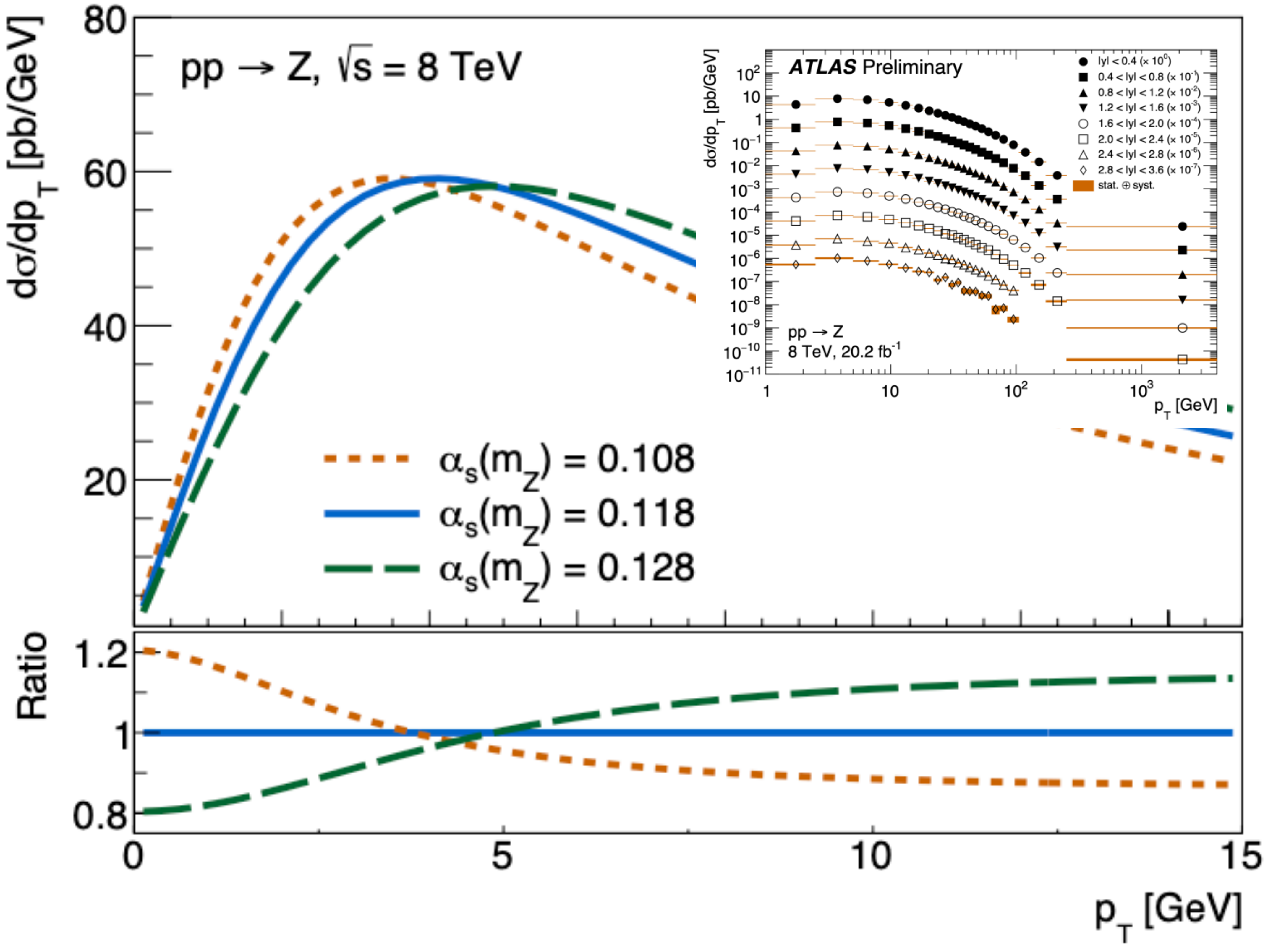
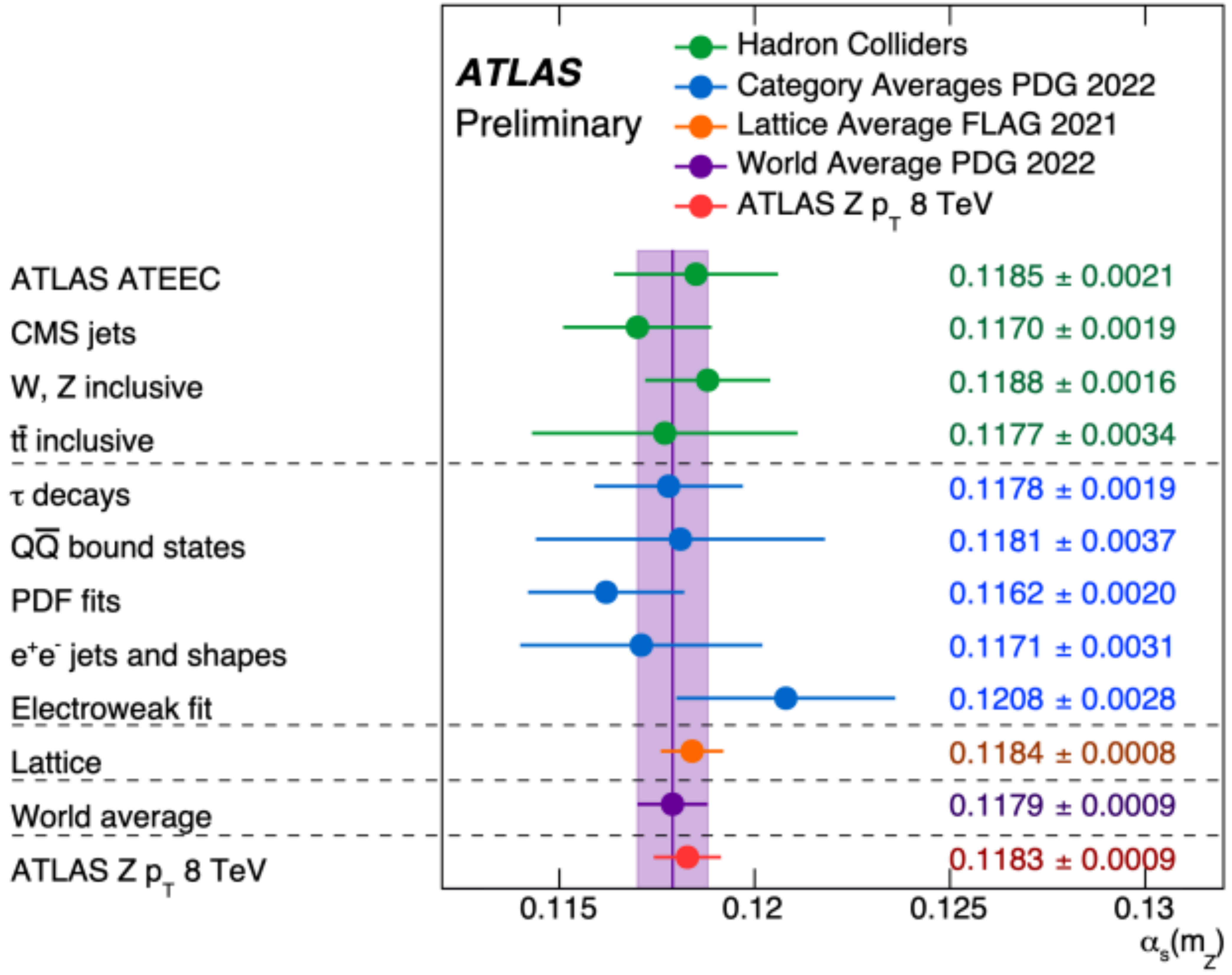



Less than one year ago, ATLAS made public the most precise determination from a single experiment: **better than 1%.** It rests on the foundation of the Z pT studies needed for W mass.

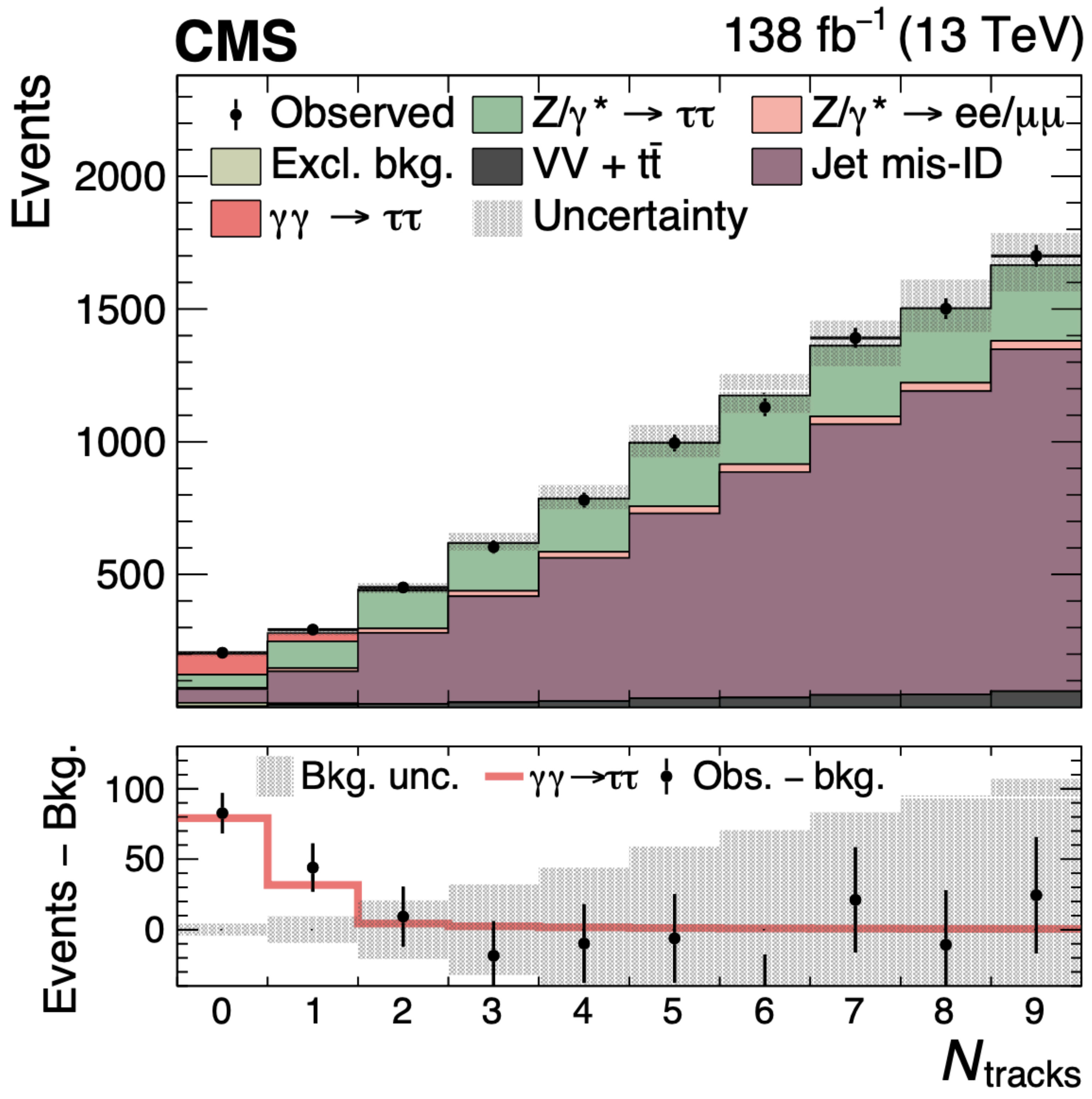


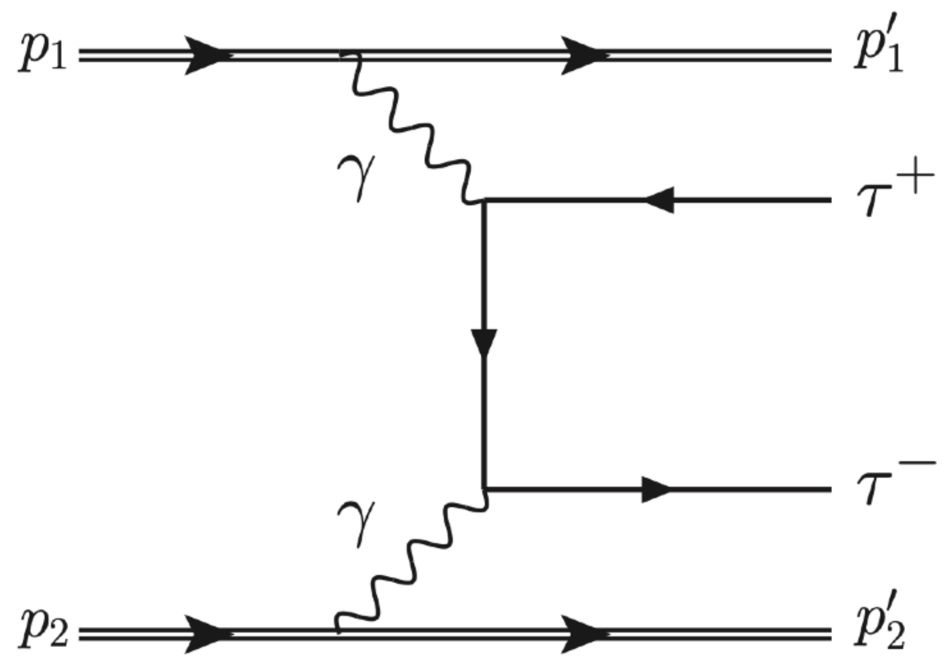



# Bonus SM results (if time allows)

# The LHC as a photon collider

## First observation of γγ→ττ in pp collisions:
**5.3σ obs (6.5σ exp.)**

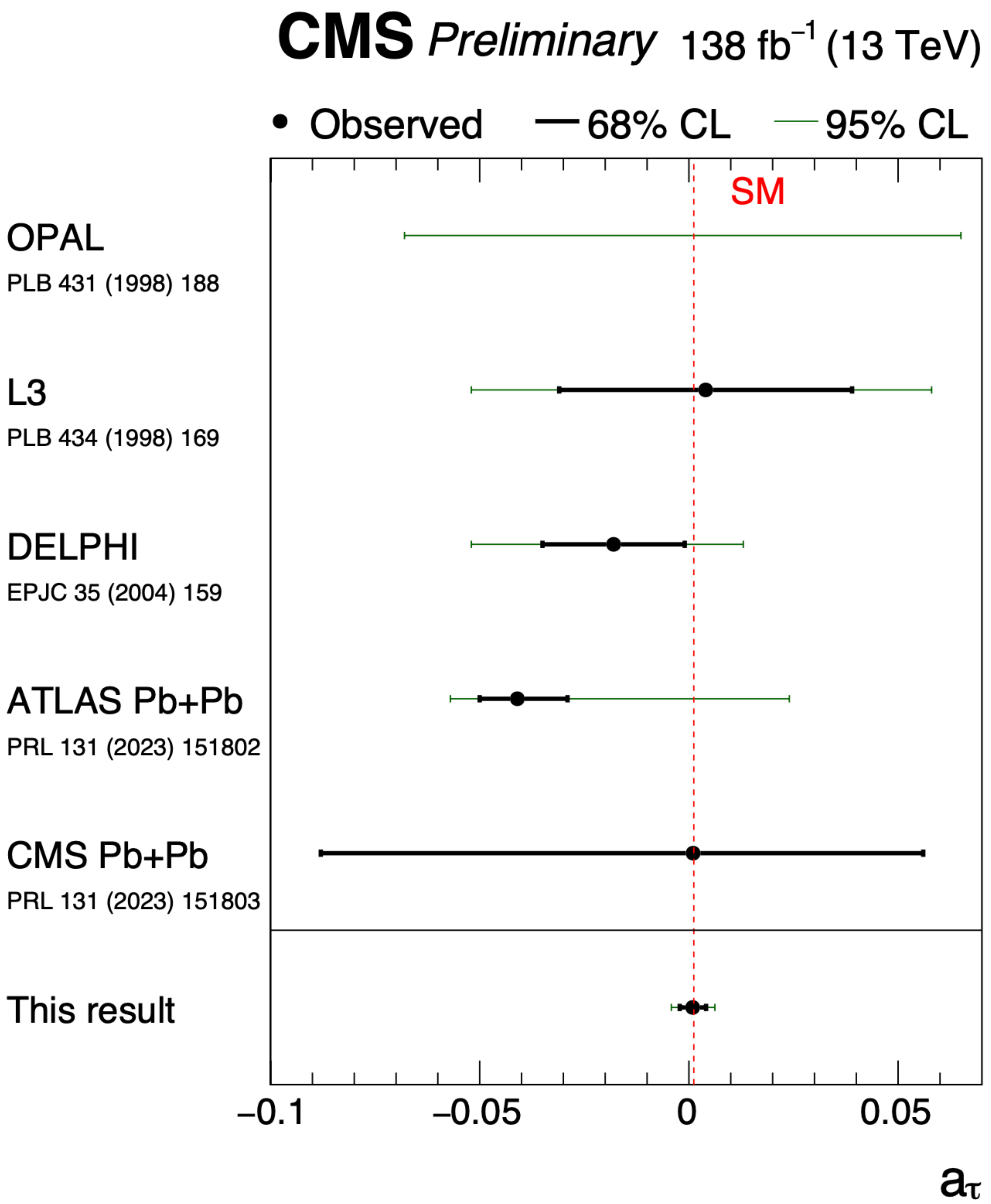



**Constraint on anomalous magnetic moment of the τ lepton:**

$$a_\tau = 0.0009^{+0.0032}_{-0.0031}$$

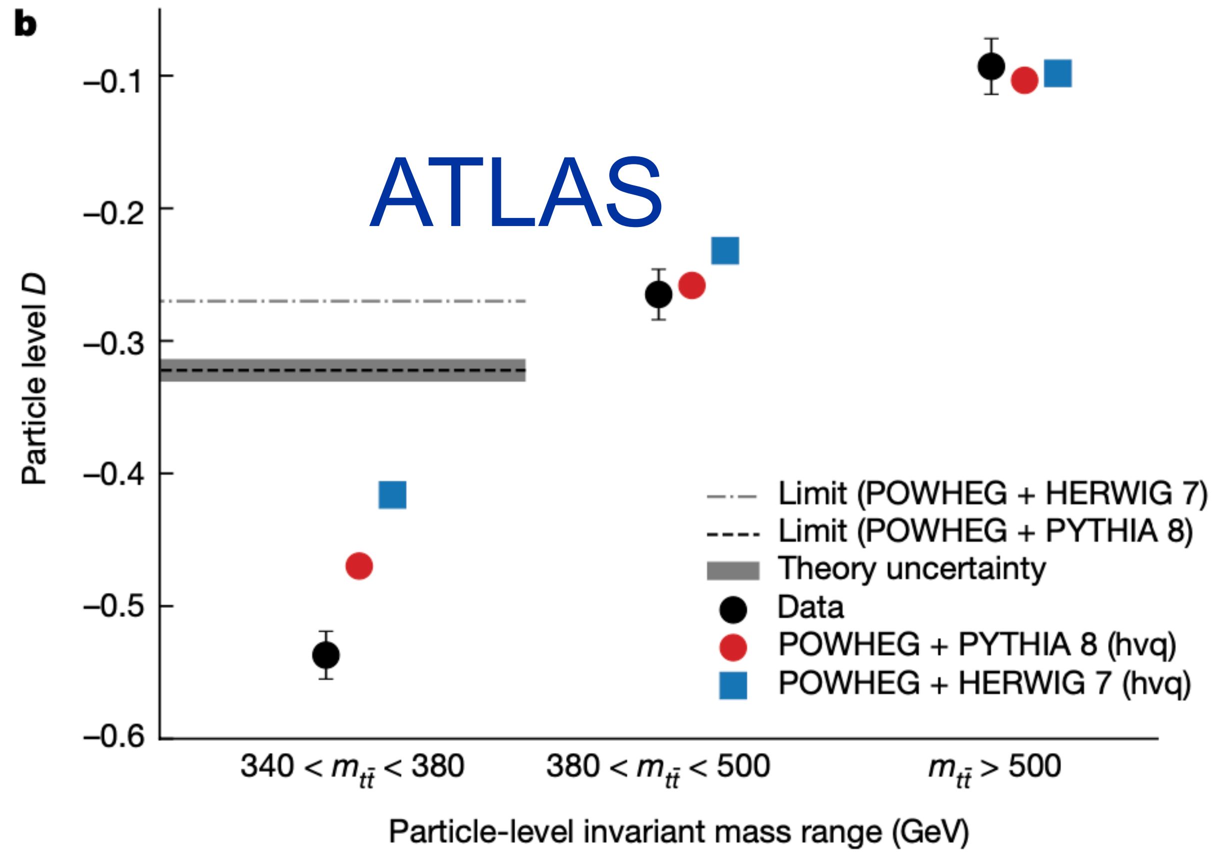
**(x5 better than LEP)**

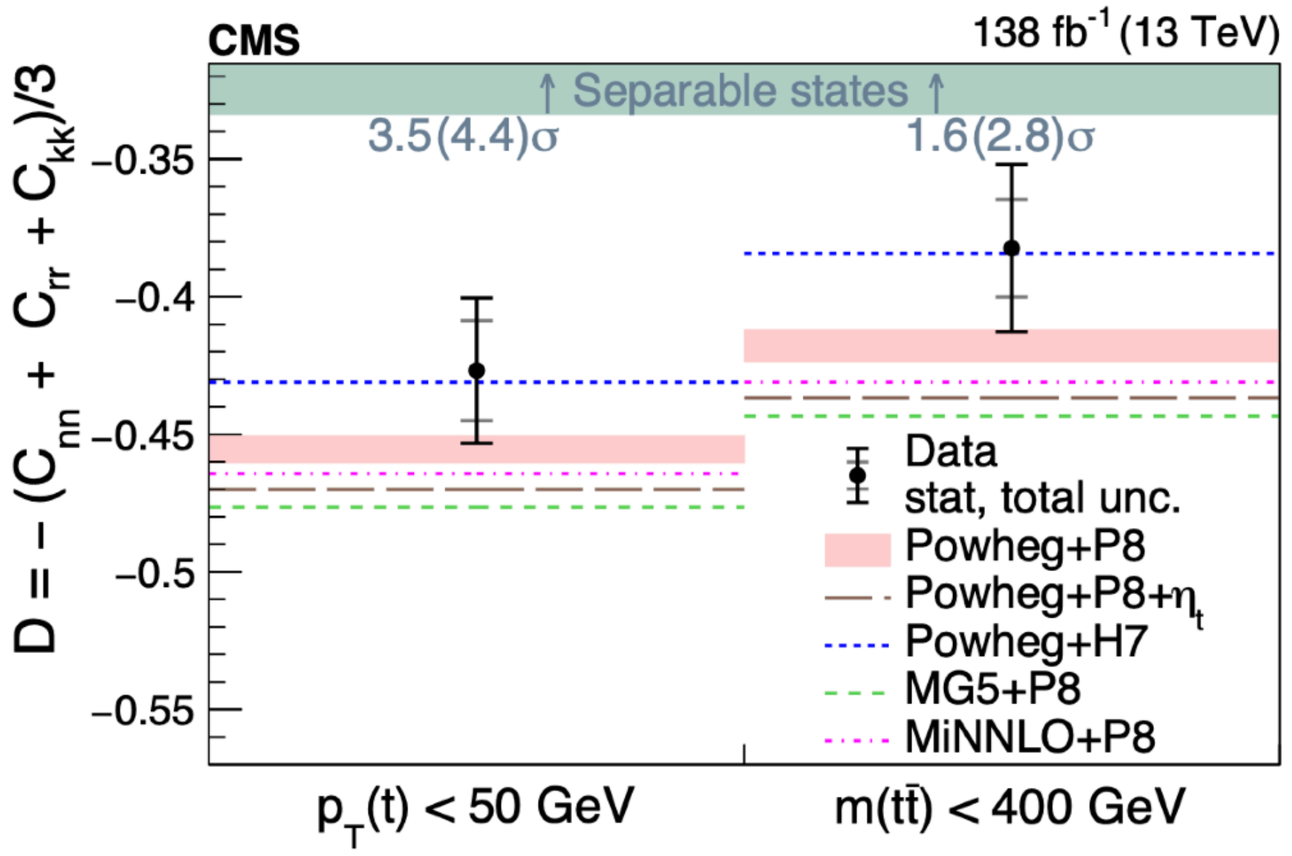


# TOP as a quantum lab: entanglement

ATLAS: Nature 633, 542–547 (2024)
CMS: arxiv:2409.11067

**The study of polarization and spin correlations in ttbar events is used to detect QM entanglement at high energy. A world first!**
**Spin entanglement is inferred from the observable D (based on decay leptons angle). The entanglement is expected to be significant around the ttbar threshold.**
**The limit of separable states is D~-1/3.**



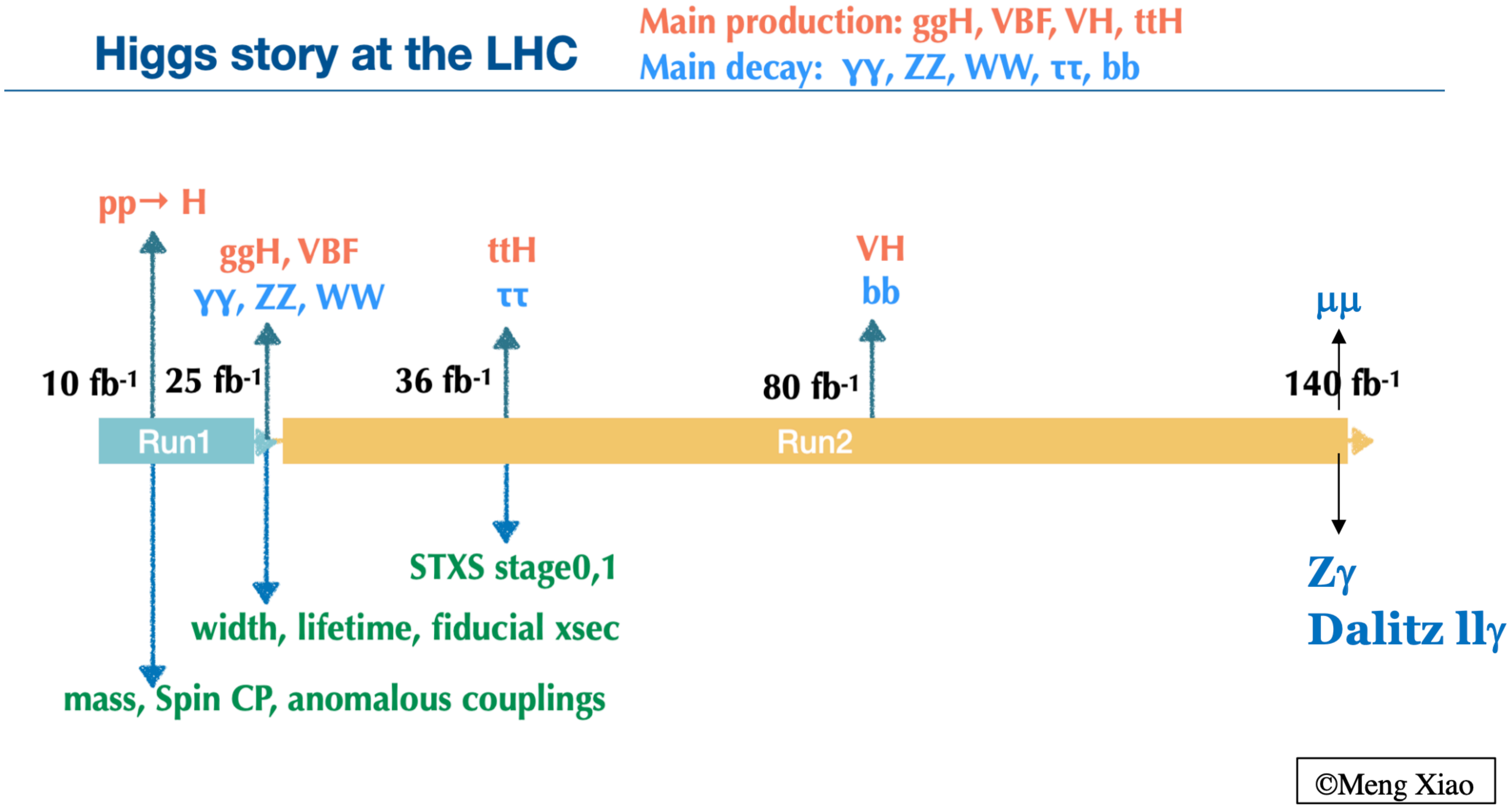

## LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024

# Higgs


10 years
of Higgs Research
at CERN
4th July 2022


Higgs story at the LHC
Main production: ggH, VBF, VH, ttH
Main decay: γγ, ZZ, WW, ττ, bb
pp→ H
ggH, VBF
γγ, ZZ, WW
ttH
ττ
VH
bb
μμ
10 fb-1
25 fb-1
36 fb-1
80 fb-1
140 fb-1
Run1
Run2
STXS stage0,1
width, lifetime, fiducial xsec
mass, Spin CP, anomalous couplings
Zγ
Dalitz llγ
©Meng Xiao

# Higgs: status and questions

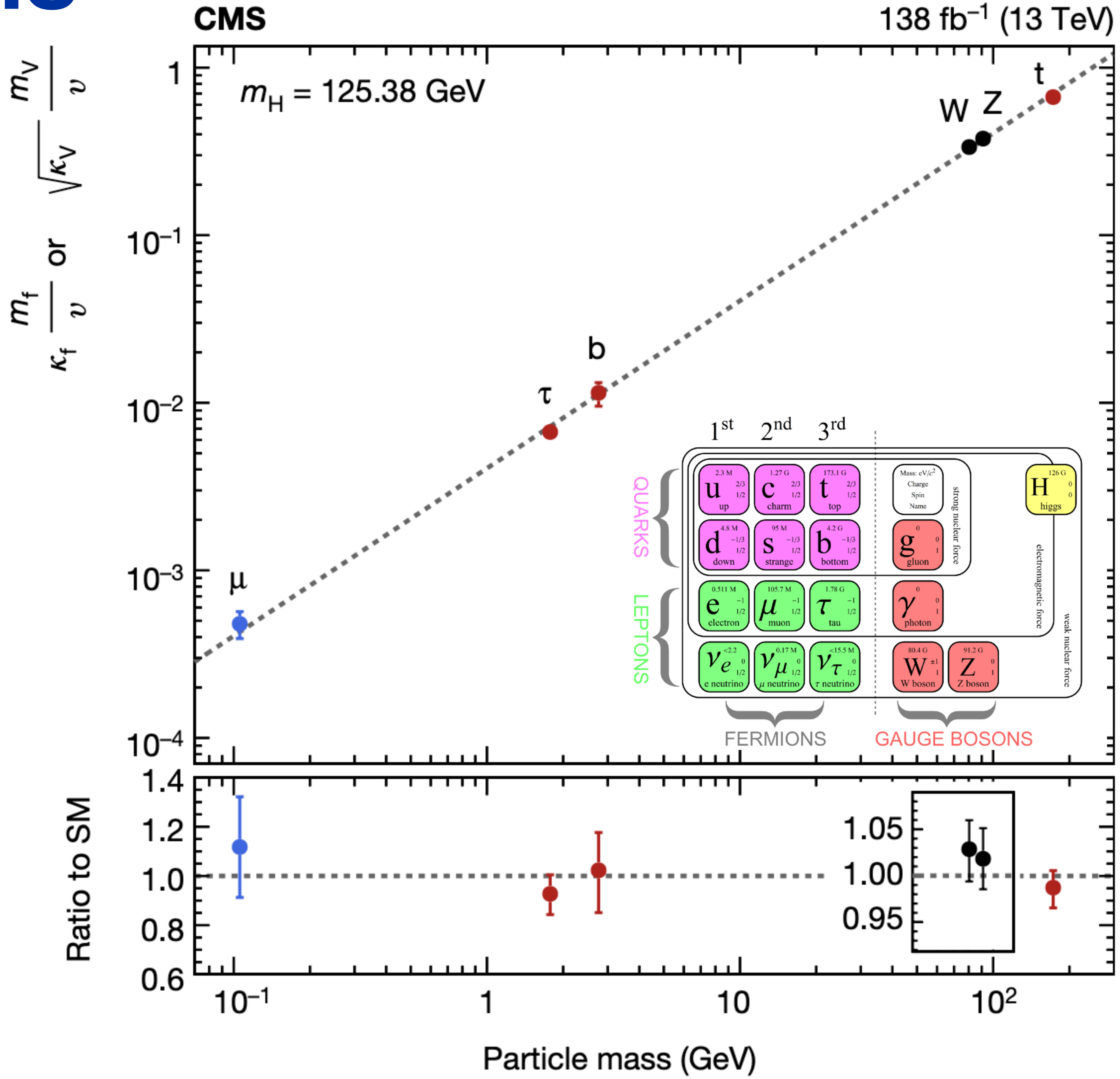
**The discovery of the Higgs boson was a gigantic milestone.**

**It completes the Standard Model parameter set.**

**It is the ONLY fundamental scalar (i.e. with no intrinsic spin) that we know of.**

**It is ESSENTIAL to measure all properties of the Higgs boson up to the ultimate precision:**

- **does it "couple" as expected? (the strength of the coupling is what gives particles their mass!)**

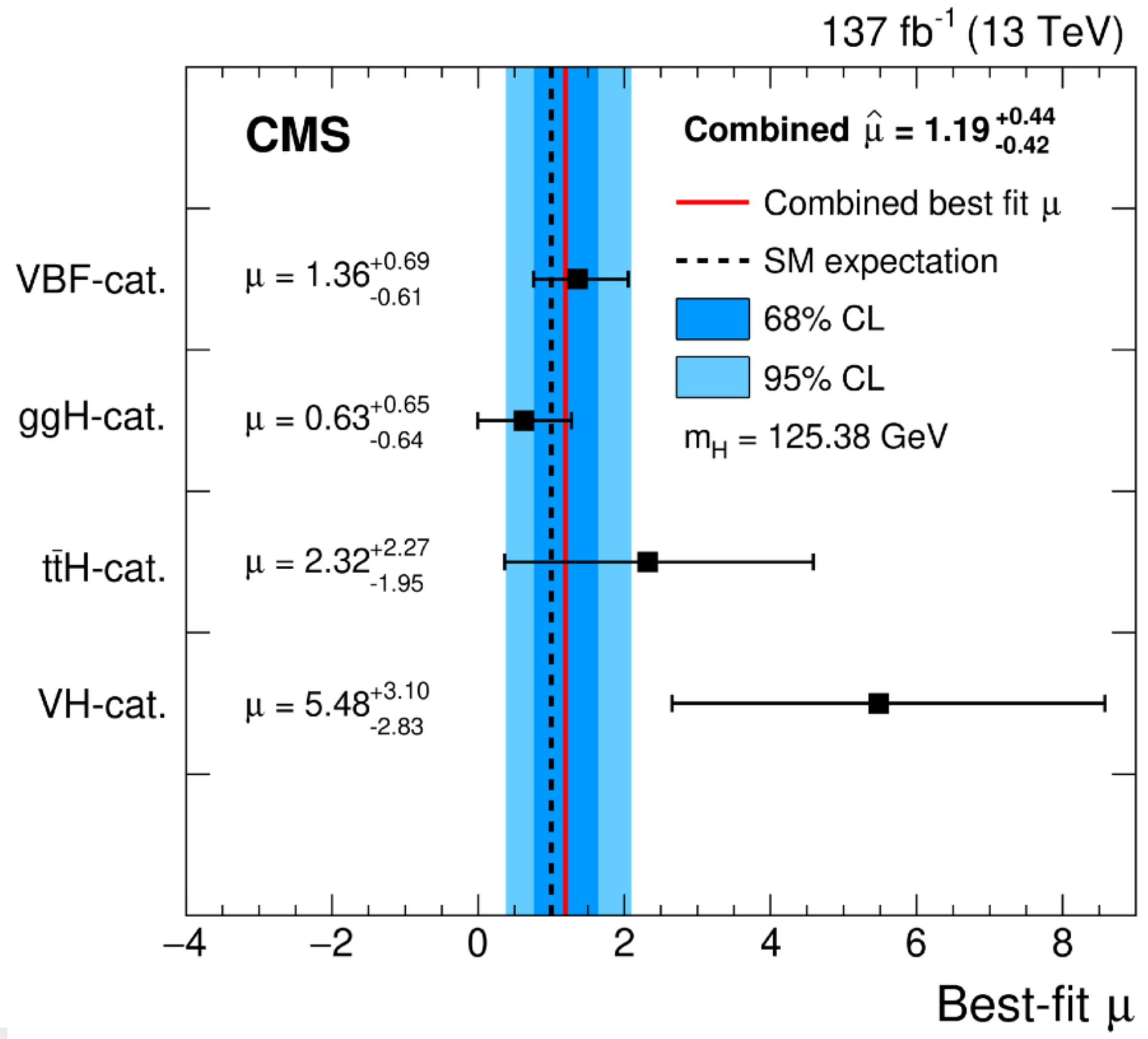


# Higgs: two "recent" highlights

## 1) second generation couplings

[CMS-HIG-21-008](#)
*Phys. Rev. Lett. 131 (2023) 061801*

### Search for H->$\mu\mu$ in VBF category

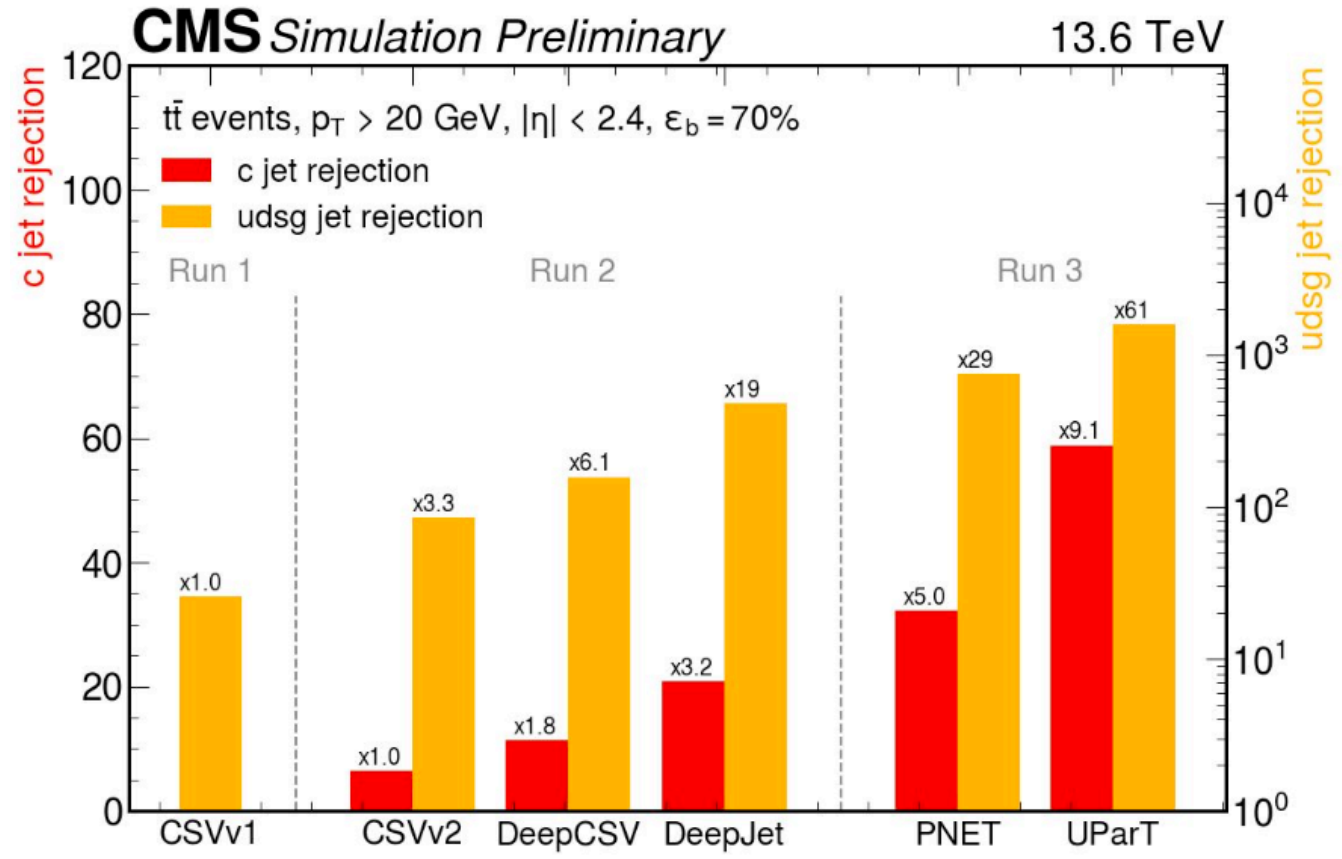



[CMS-HIG-19-006](#)
*JHEP 01 (2021) 148*

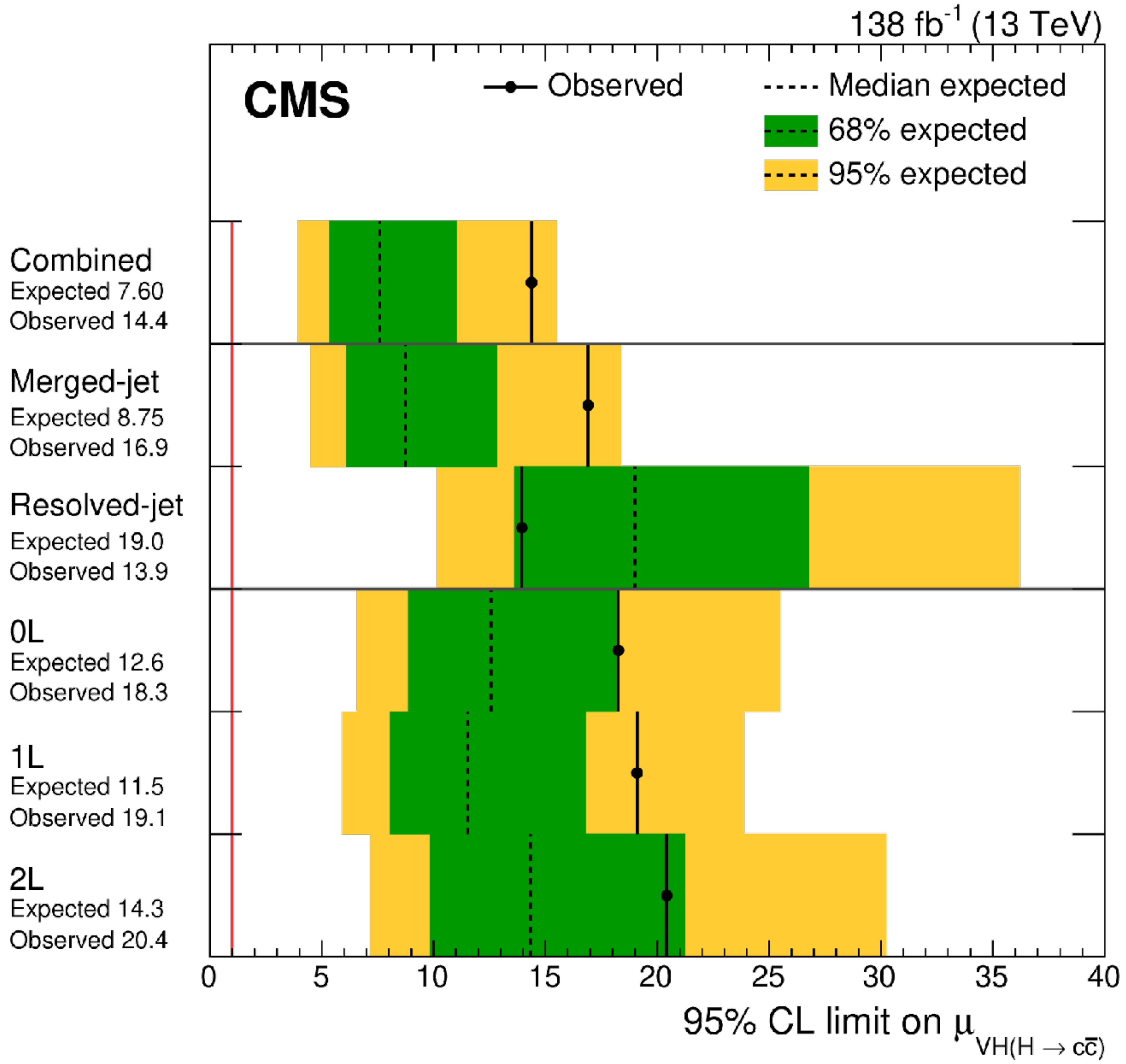
$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$$

Obs. (exp.) significance: 3.0 (2.5) σ

Use **advanced machine learning techniques**.
Sensitivity to H→cc < 10× SM.




### Search for H->cc in VH events



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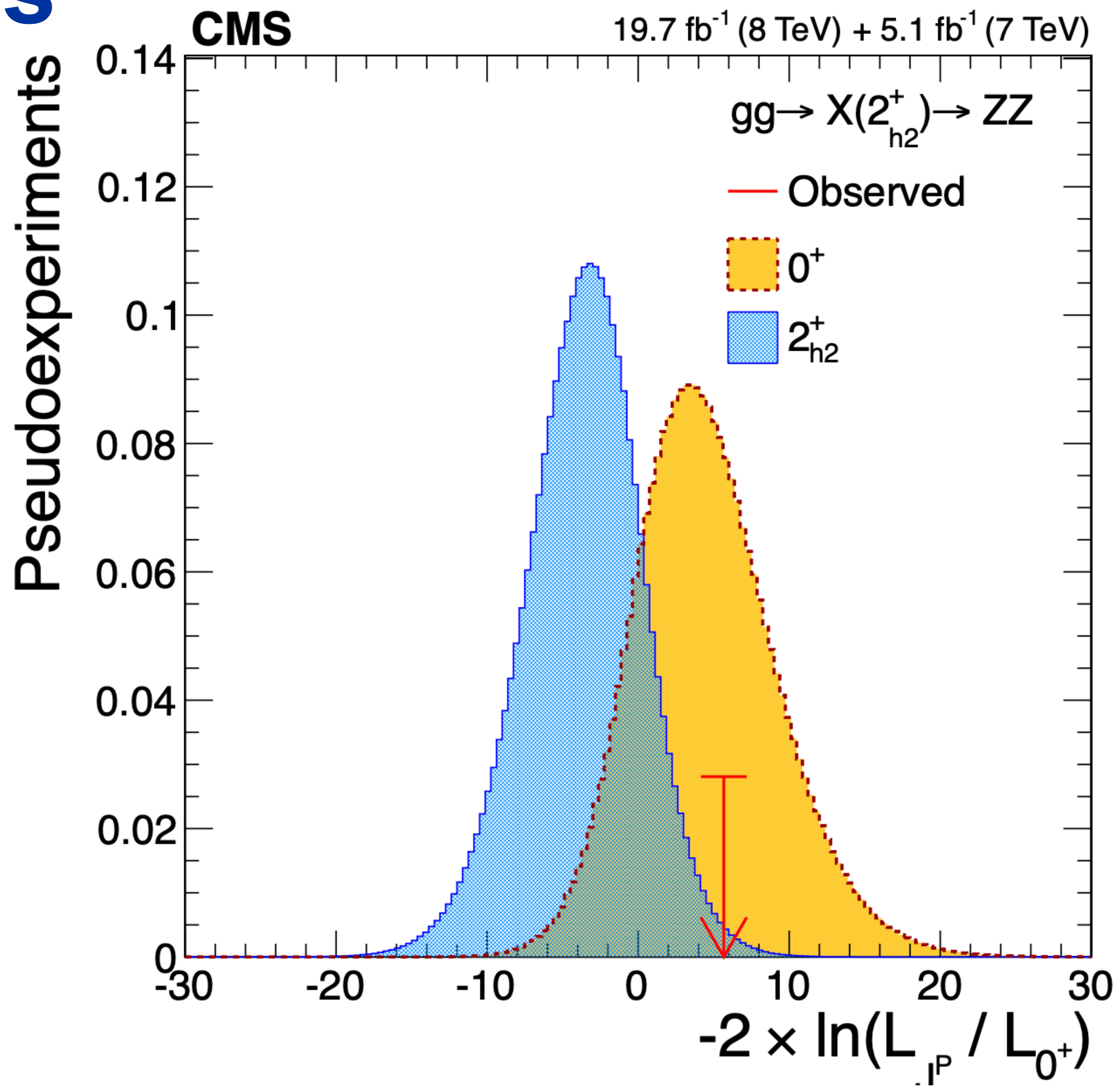
- **is it really a scalar?**



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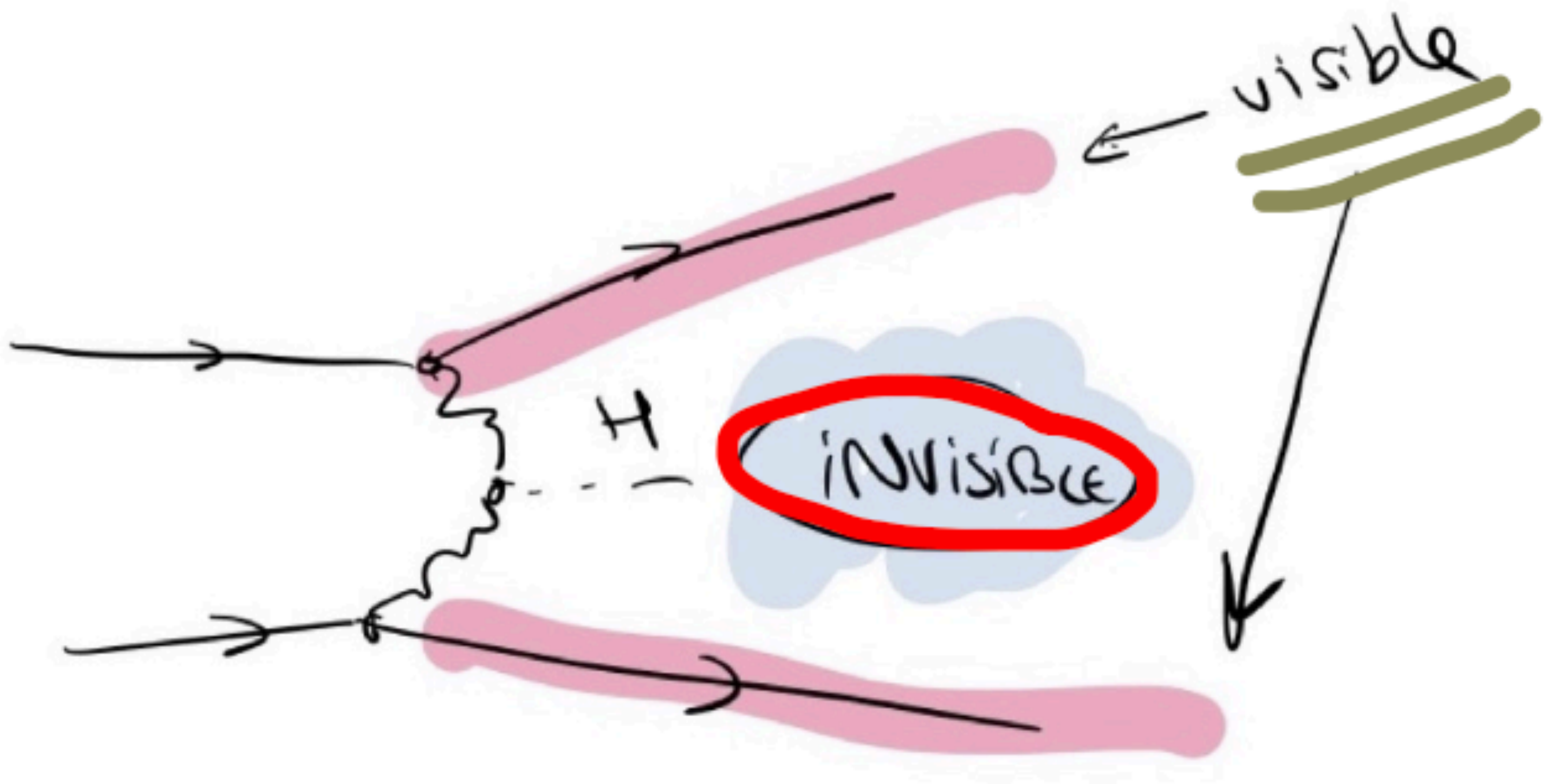


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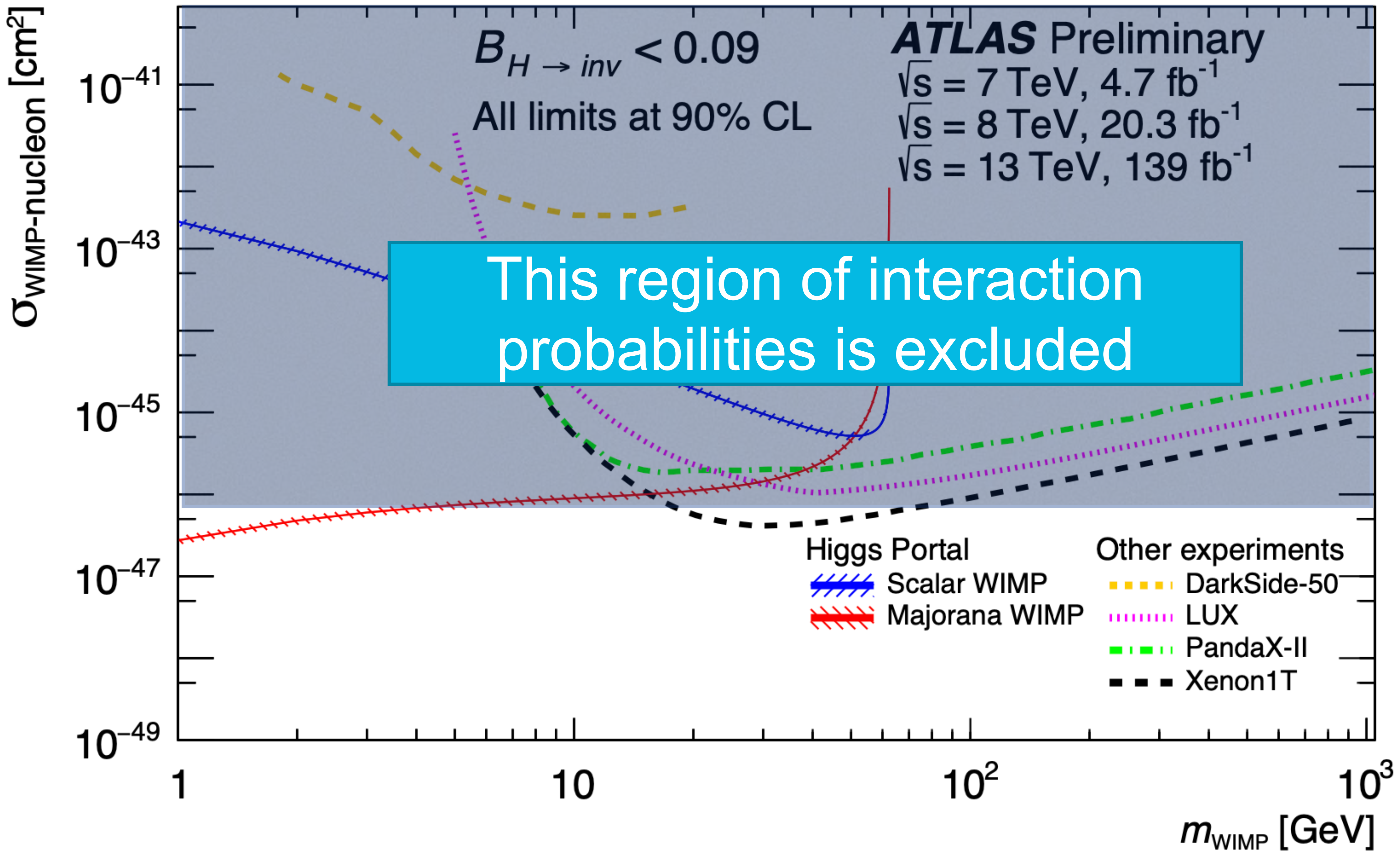

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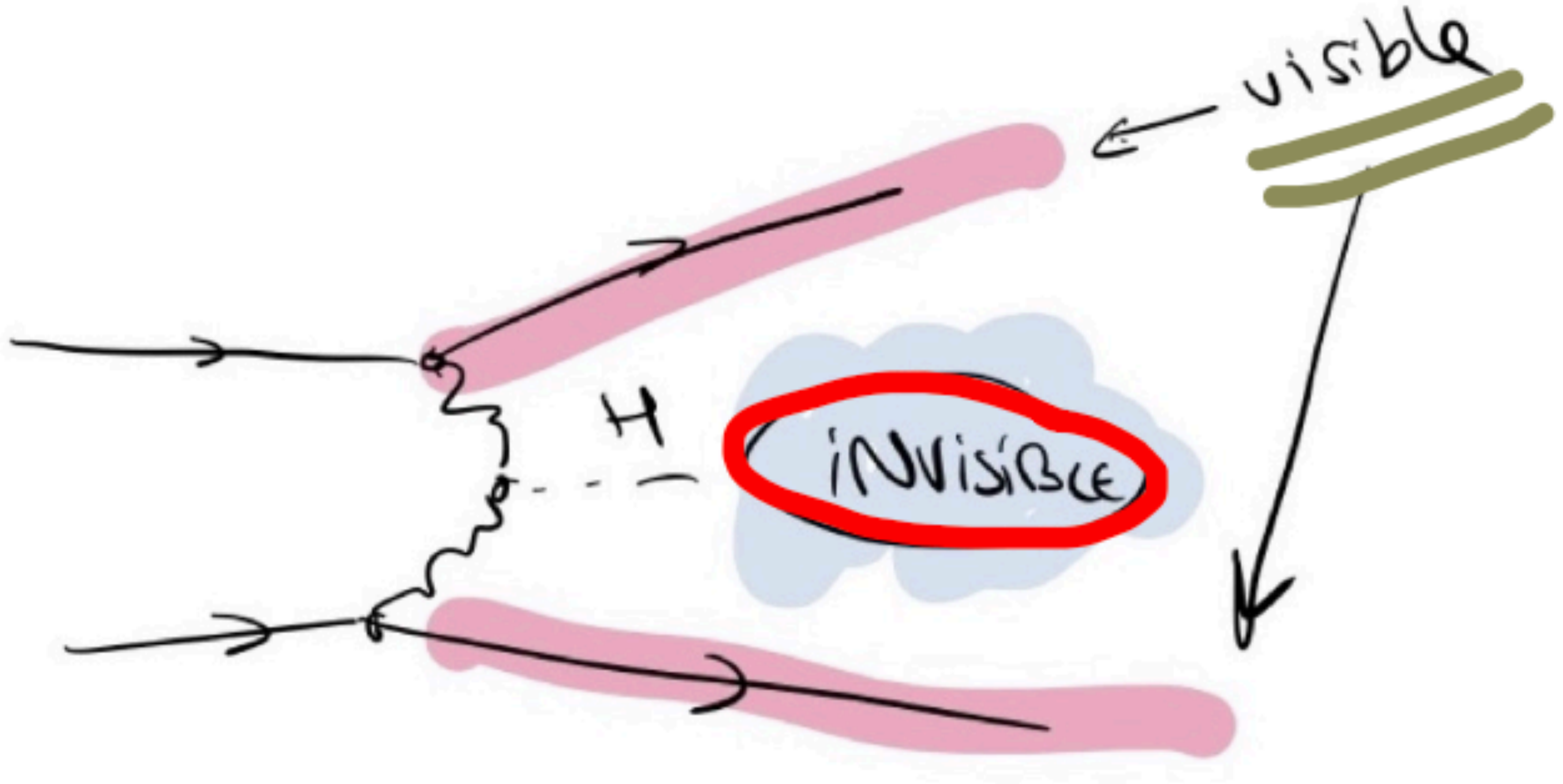


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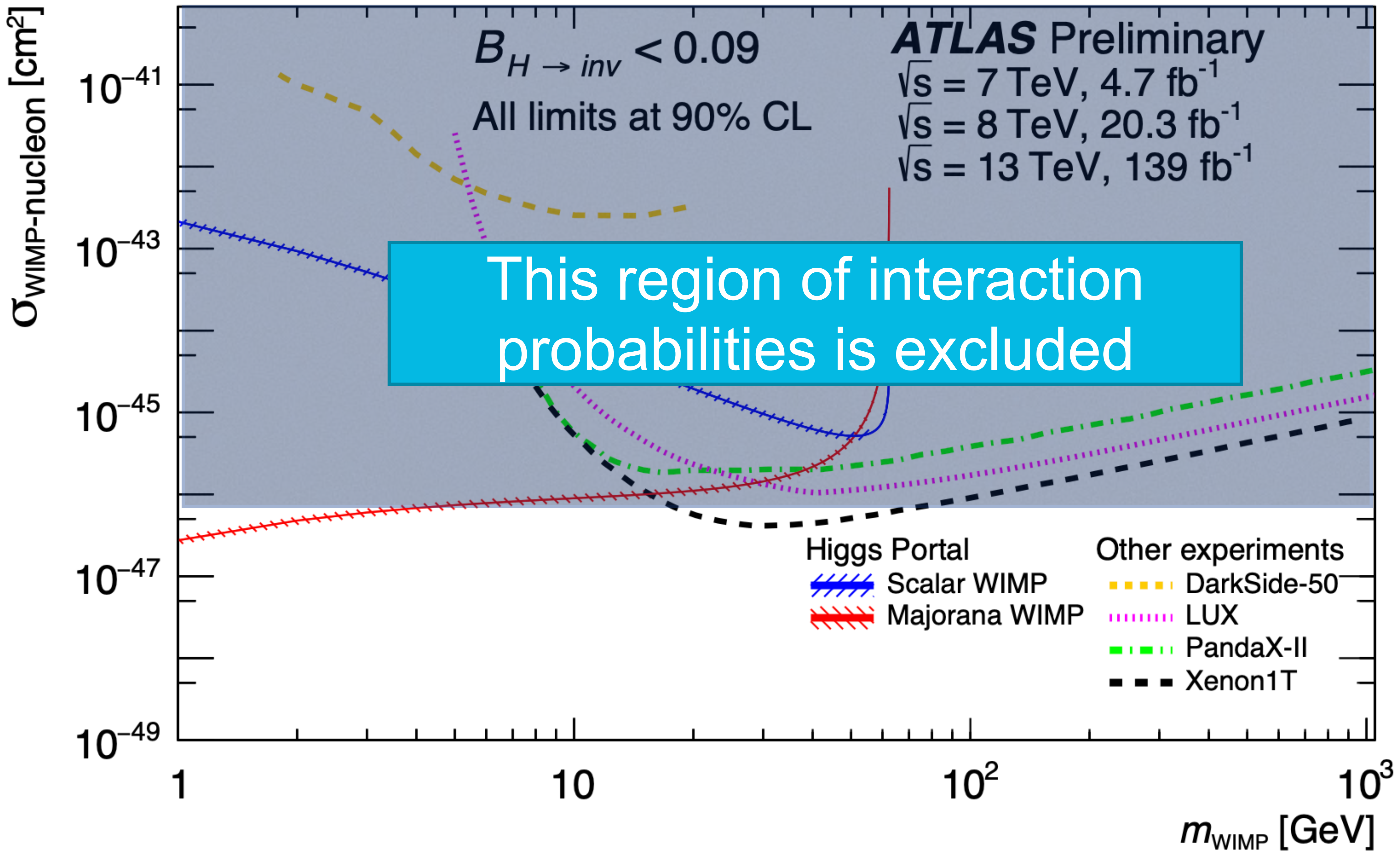
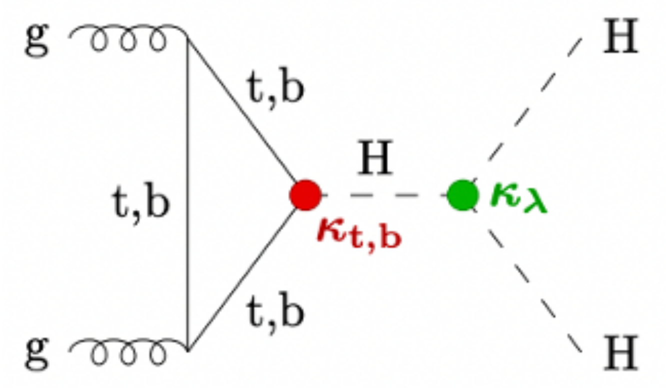
- **is it really a scalar?**
- **does it decay in invisible particles (dark matter)?**
- **does it couple to itself as foreseen?**



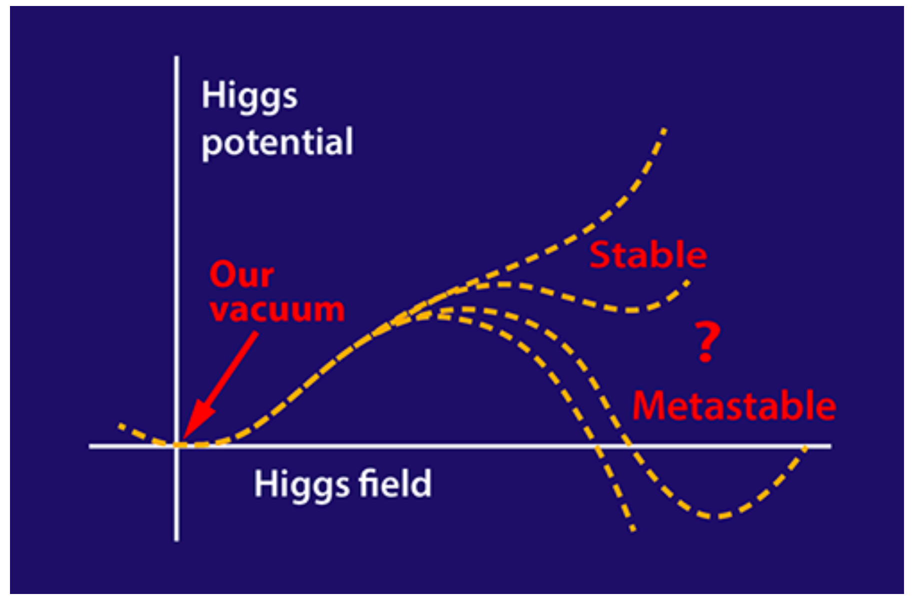
# Higgs: two "recent" highlights

## 2) Di-Higgs (self interaction)

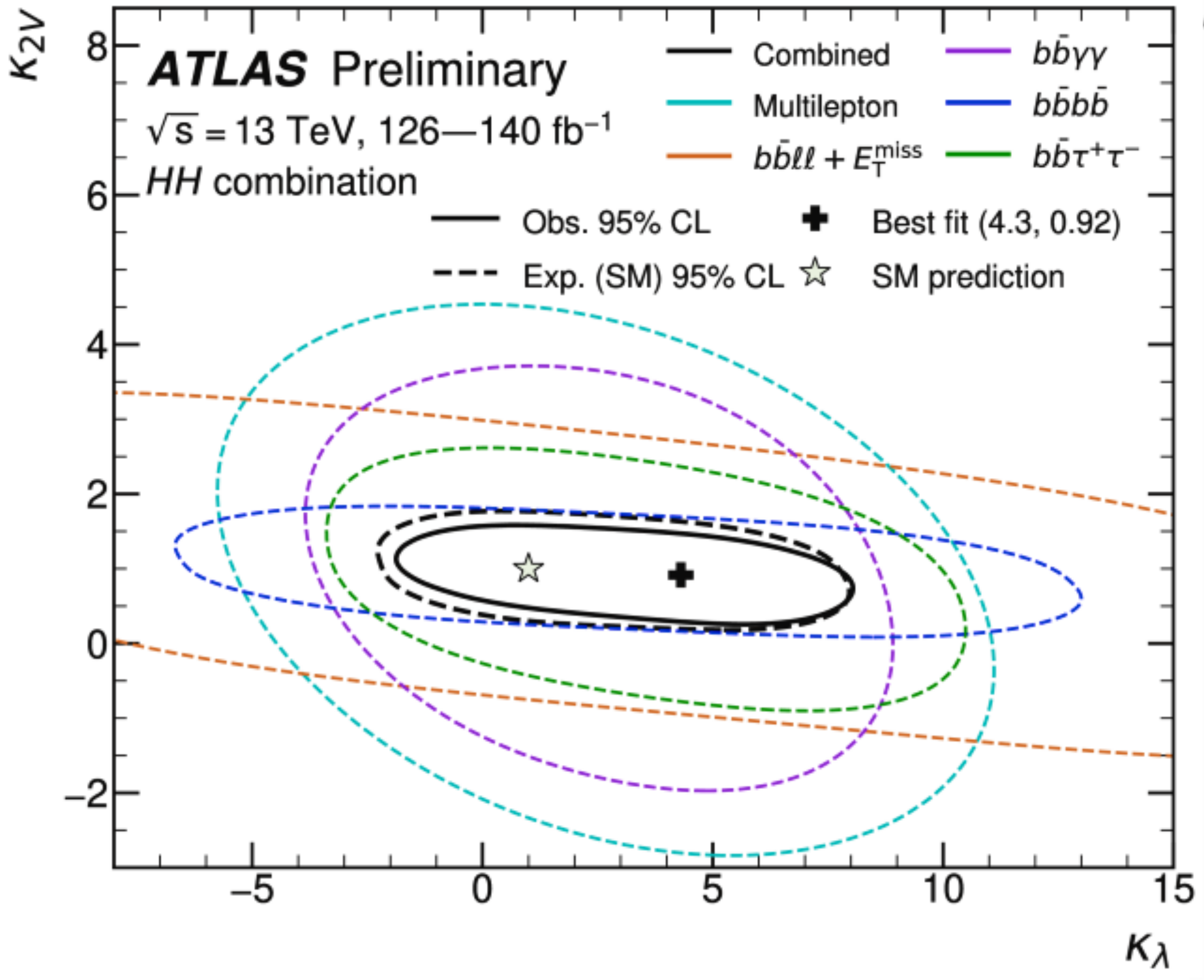


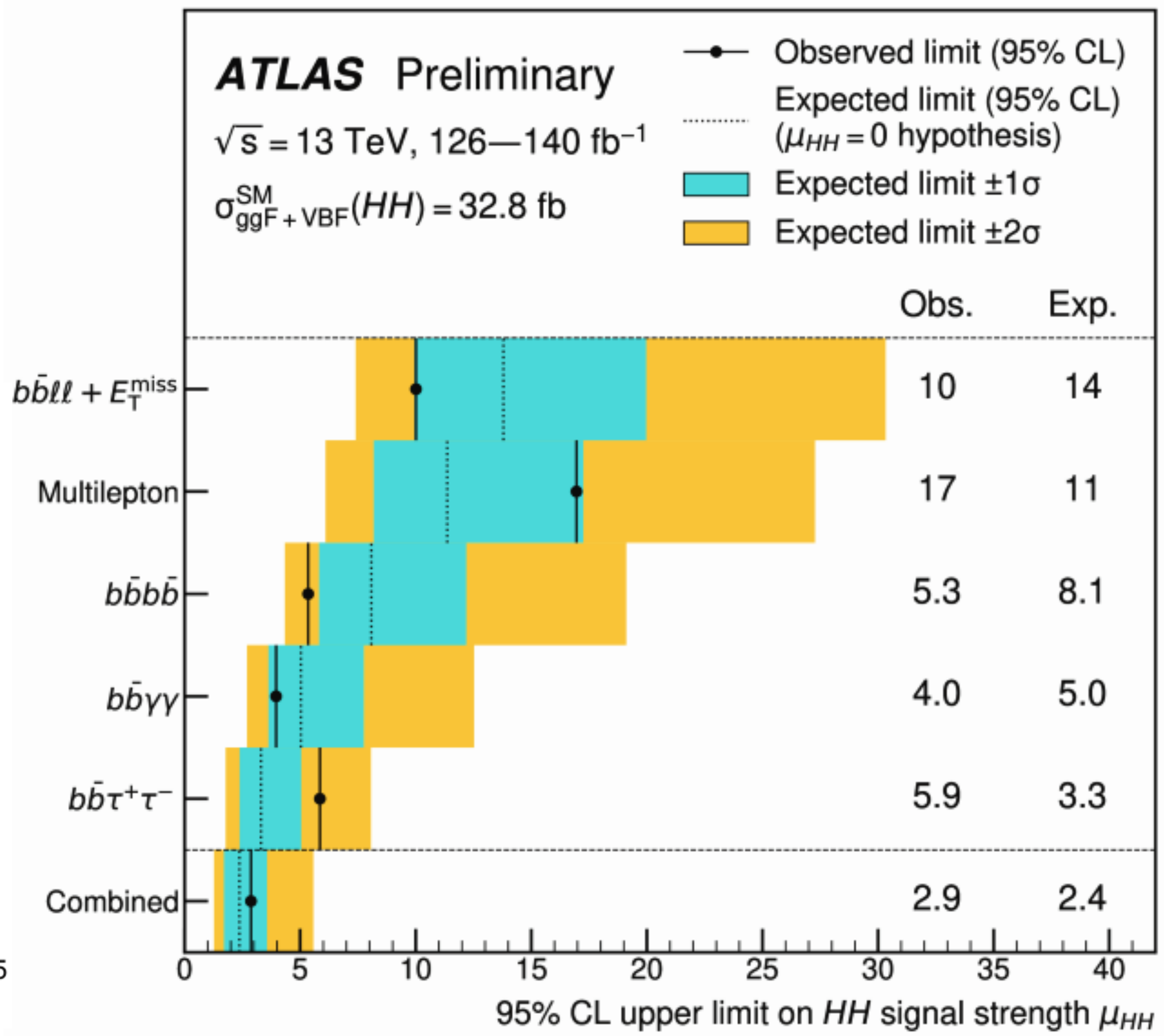

fundamental component of the SM

$$V(\phi) = \frac{1}{2}m_H^2\phi^2 + \sqrt{\lambda/2}m_H\phi^3 + \frac{1}{4}\lambda\phi^4$$




**Recent new combination from ATLAS includes all improvements to classical channels plus the multi-lepton and bbℓℓ + ETmiss decay channels.**
**It is the most stringent limit to date.**
**Similar results also from CMS.**




**Inclusive**
$\sigma/\sigma_{SM}$ < 2.9 (2.4) at 95% CL

# Higgs: two "recent" highlights

## 2) Di-Higgs (self interaction)

fundamental component of the SM

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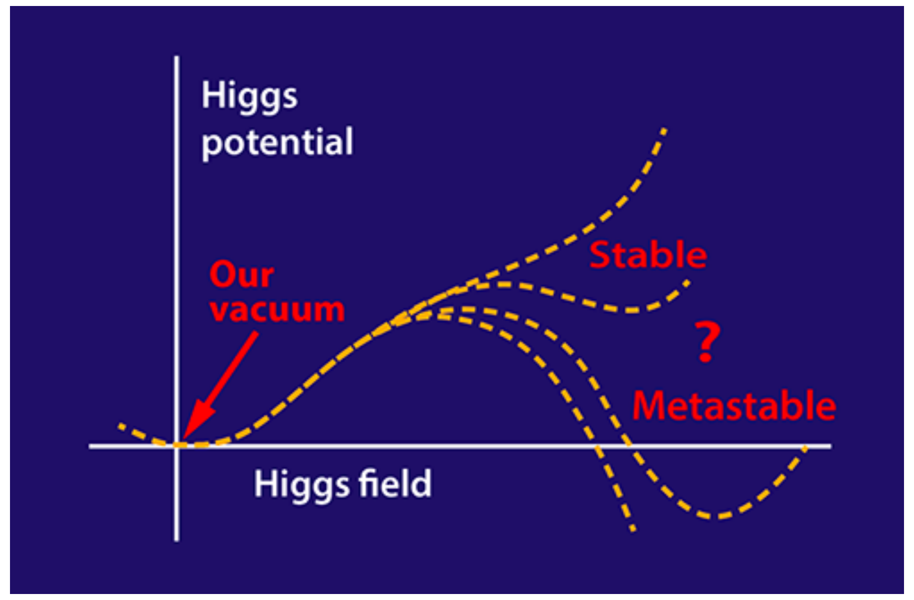


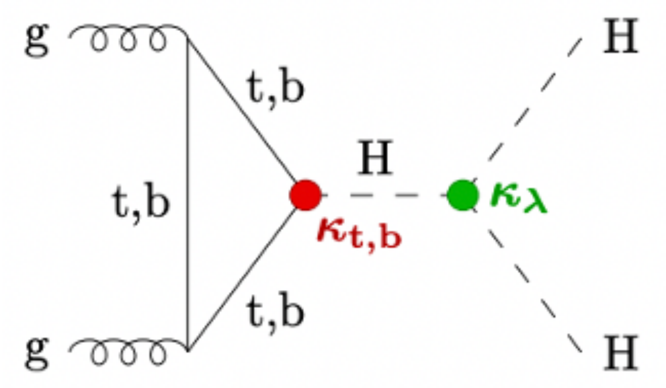


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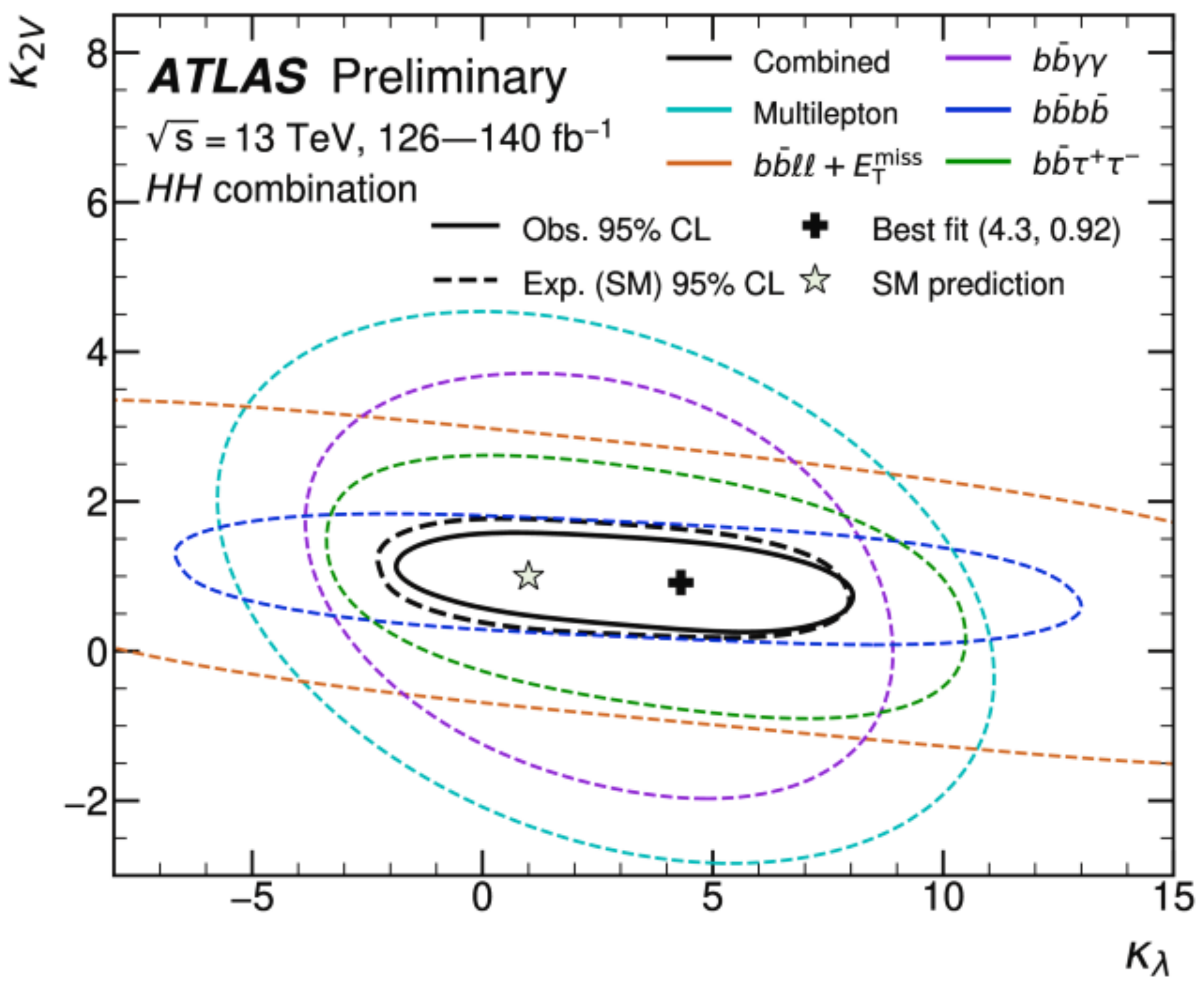
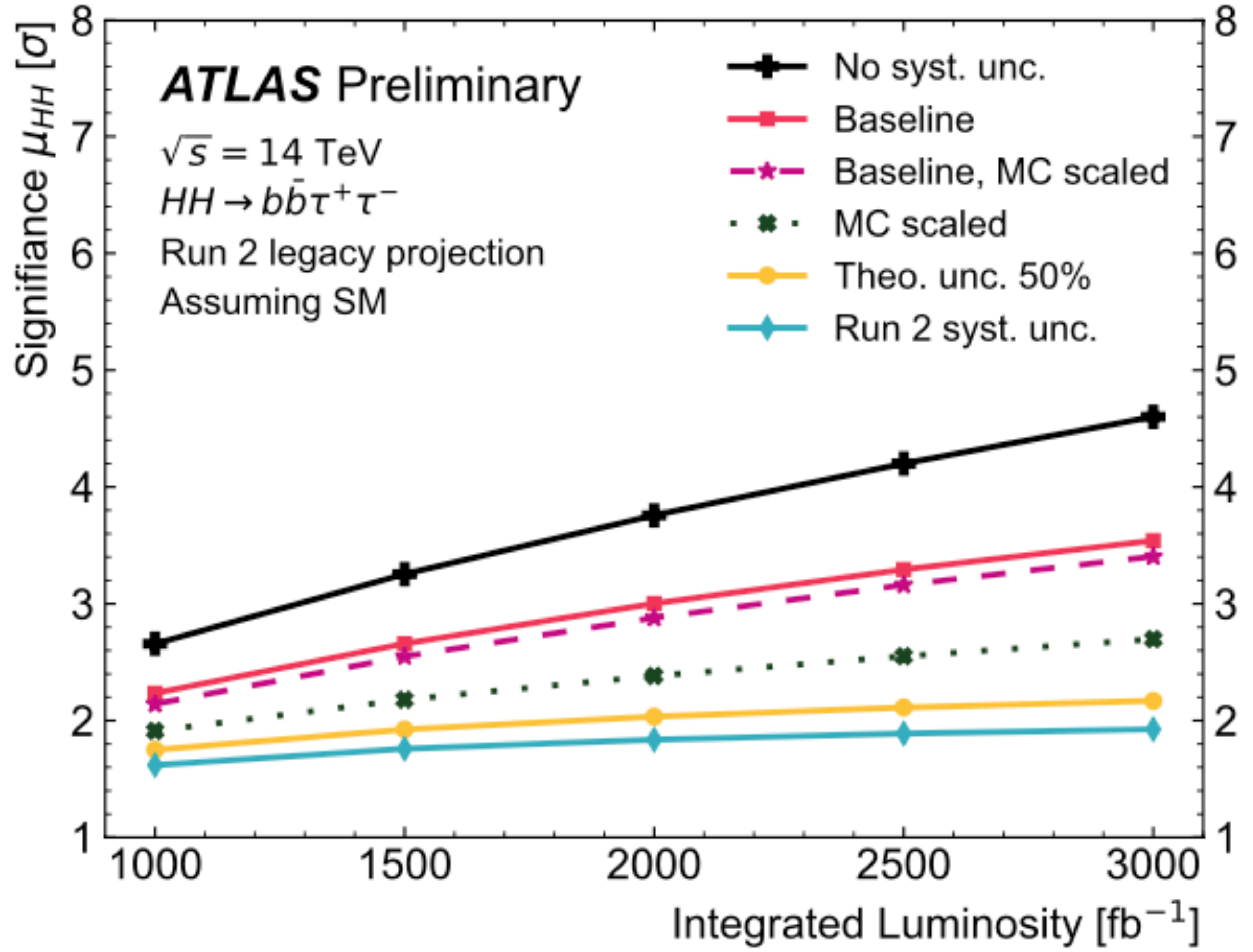



Triggering updated projections for HL-LHC

ATL-PHYS-PUB-2024-016



# A walk into history:
# only few years ago the projected estimations where much worse!

It’s 2.5σ with half lumi now.

It’s 3.5σ with current projections.

## Rare decays: $H\to\mu^+\mu^-$ and $H\to J/\psi\gamma$

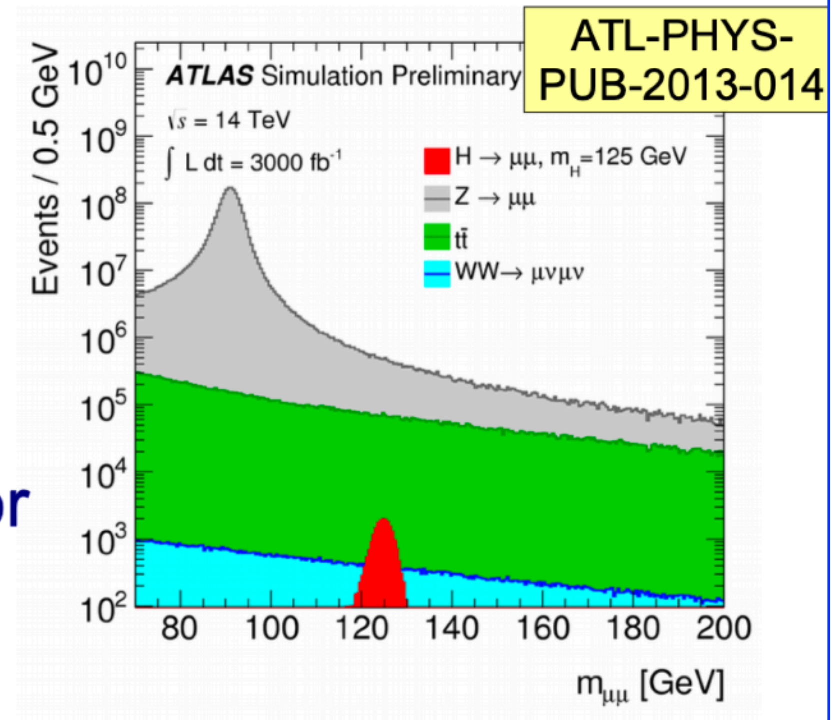
37

Probes Higgs coupling to 2nd generation quarks/leptons

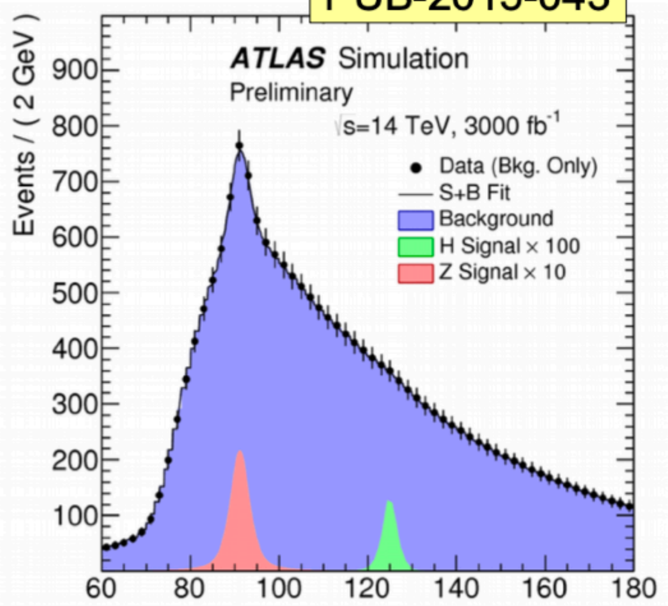
### $H\to\mu^+\mu^-$

- $BR(H\to\mu^+\mu^-)=2.2\times10^{-4}$ in SM
  - Combined Run-1 and Run-2 limit is 2.8xSM
- Expect significance of ~2σ with 300 $fb^{-1}$ and ~7σ with 3000 $fb^{-1}$ in inclusive channel
  - Improved tracker resolution not accounted for (~30% improvement on mass resolution)
  - Also specific channels like ttH, $H\to\mu^+\mu^-$

ATL-PHYS-PUB-2013-014




ATL-PHYS-PUB-2015-043




### $H\to J/\psi\gamma$ (coupling to charm quark)

- $BR(H\to J/\psi\gamma)=2.9\times10^{-6}$ in SM
  - ATLAS Run-1 limit at 95% CL: $BR(H\to J/\psi\gamma)<1.5\times10^{-3}$
- Multivariate analysis for HL-LHC projection
  - With 3000 $fb^{-1}$ will have just 3 signal events and 1700 background events
  - Expected limit at 95% CL: $BR(H\to J/\psi\gamma)<(44^{+19}_{-12})\times10^{-6}$

## Higgs Self Coupling Projections

40

### CMS extrapolations from Run-2 analyses:

CMS-PAS-FTR-16-002

| Channel | Median expected limit in $\mu_r$ ECFA16 S2 | Stat. Only | Z-value ECFA16 S2 | Stat. Only | Uncertainty as fraction of $\mu_r = 1$ ECFA16 S2 | Stat. Only |
|---|---|---|---|---|---|---|
| $gg\to HH\to\gamma\gamma bb$ (S2+) | 1.44 | 1.37 | 1.43 | 1.47 | 0.72 | 0.71 |
| $gg\to HH\to\tau\tau bb$ | 5.2 | 3.9 | 0.39 | 0.53 | 2.6 | 1.9 |
| $gg\to HH\to VVbb$ | 4.8 | 4.6 | 0.45 | 0.47 | 2.4 | 2.3 |
| $gg\to HH\to bbbb$ | 7.0 | 2.9 | 0.39 | 0.67 | 2.5 | 1.5 |

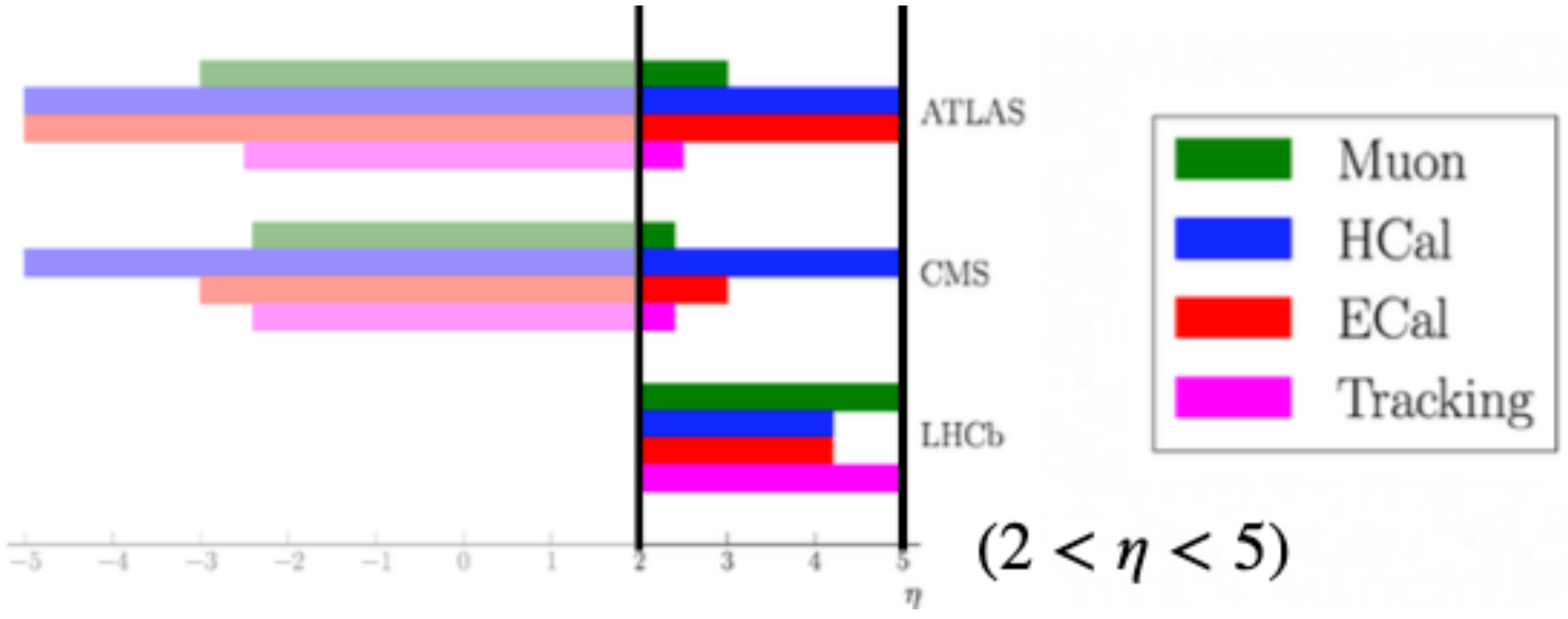
### ATLAS simulations (HH→bbbb is Run-2 extrapolation):

| Channel | Expected limit in μ: Full Syst. | Expected limit in μ: Stat. only | Significance: Full Syst. | Significance: Stat. only | Limits on $\lambda/\lambda_{SM}$ at 95% CL: Full Syst. | Limits on $\lambda/\lambda_{SM}$ at 95% CL: Stat. only |
|---|---|---|---|---|---|---|
| $gg\to HH\to\gamma\gamma bb$ (ATL-PHYS-PUB-2017-001) | | | 1.05σ | | | $-0.8<\lambda/\lambda_{SM}<7.7$ |
| $gg\to HH\to\tau\tau bb$ (ATL-PHYS-PUB-2015-046) | 4.3 | | 0.6σ | | $-4<\lambda/\lambda_{SM}<12$ | |
| $gg\to HH\to bbbb$ (ATL-PHYS-PUB-2016-024) | 5.2 | 1.5 | | | $-3.5<\lambda/\lambda_{SM}<11$ | $0.2<\lambda/\lambda_{SM}<7$ |
| $ttHH\to t_{had}t_{lep}bbbb$ (ATL-PHYS-PUB-2016-023) | | | | 0.35σ | | |

**Typical presentation in 2017**

# Higgs studies where nobody expected to happen (LHCb)

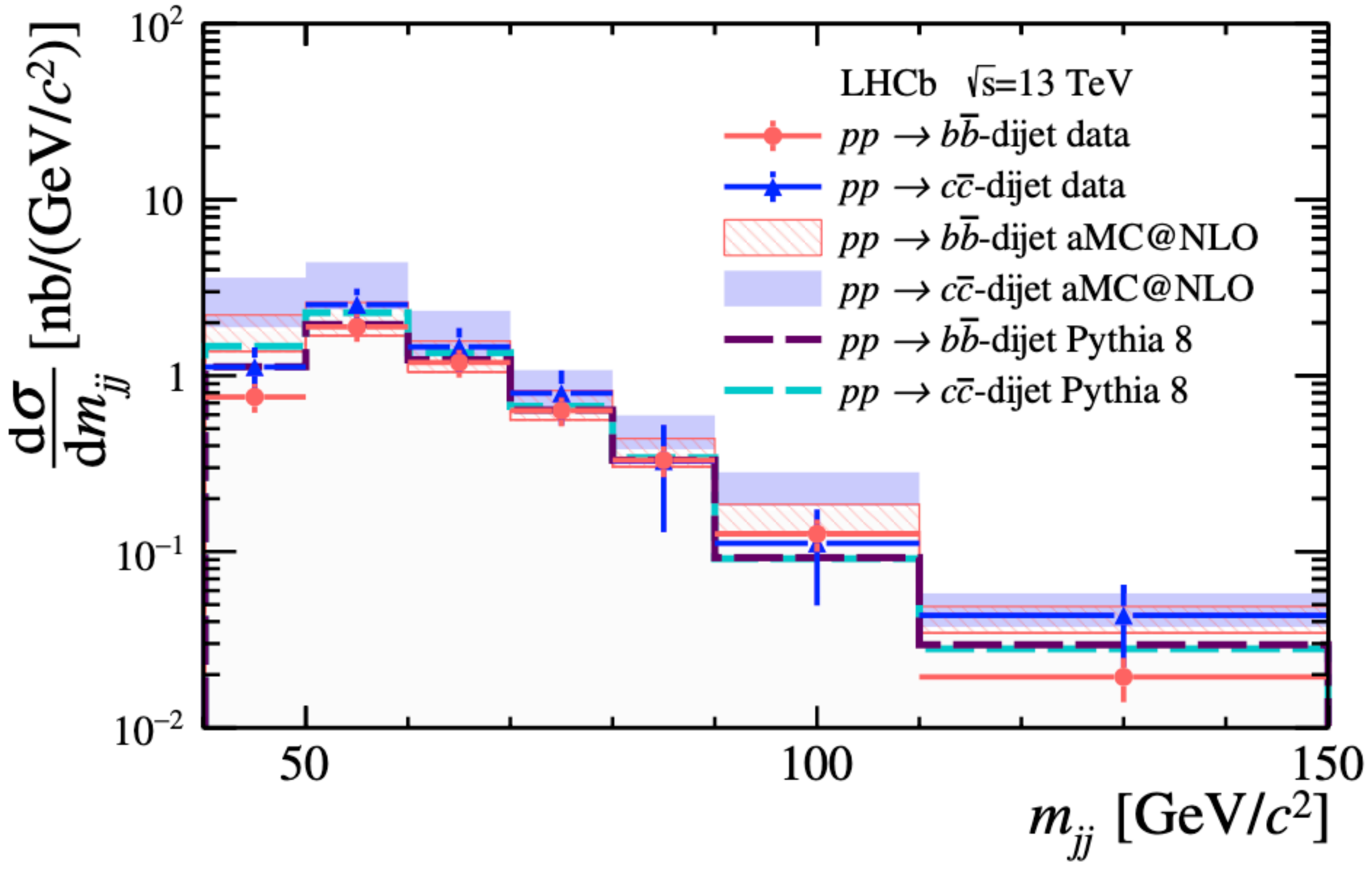
## Complementary phase space, completing the SM picture

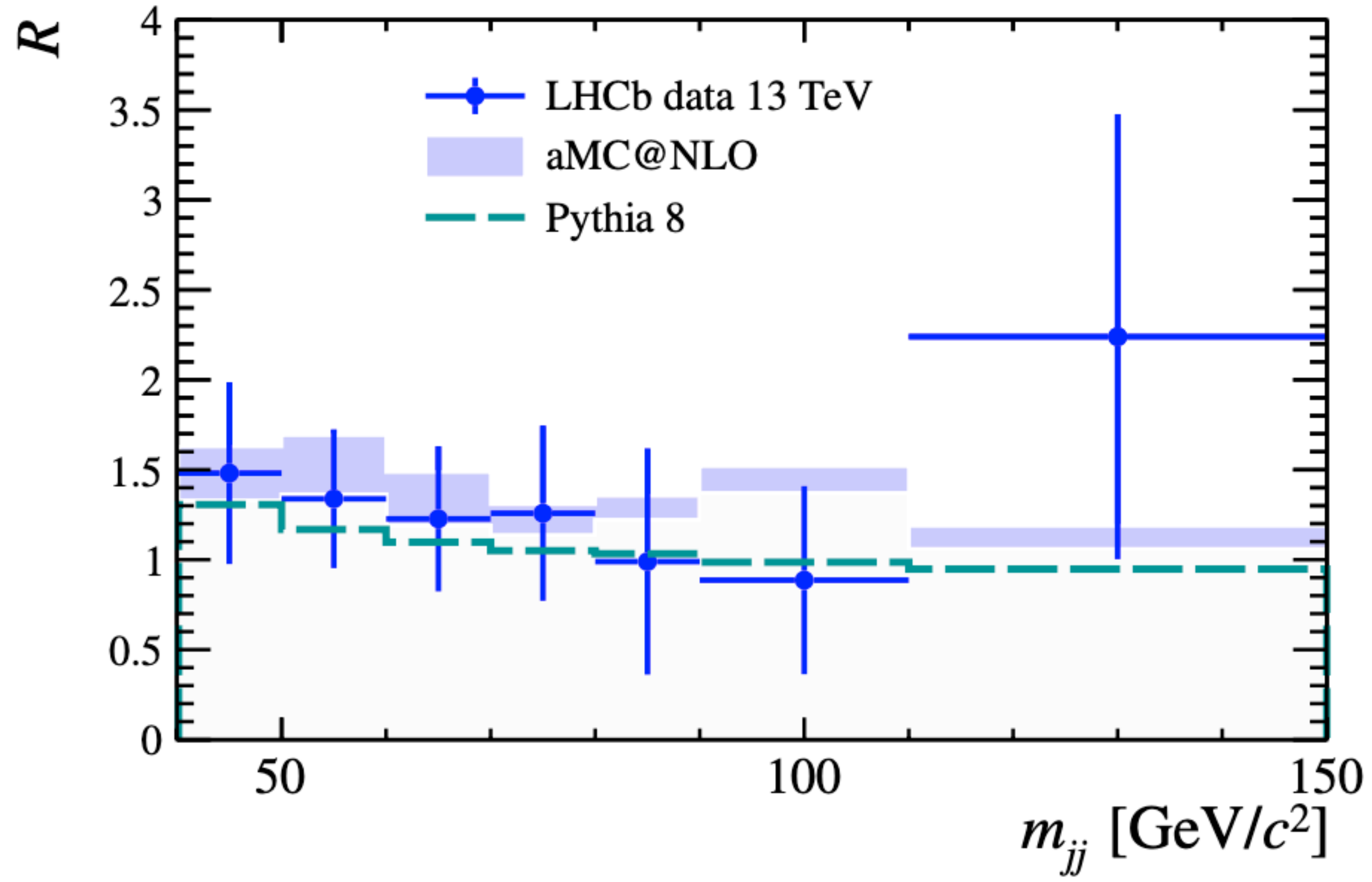


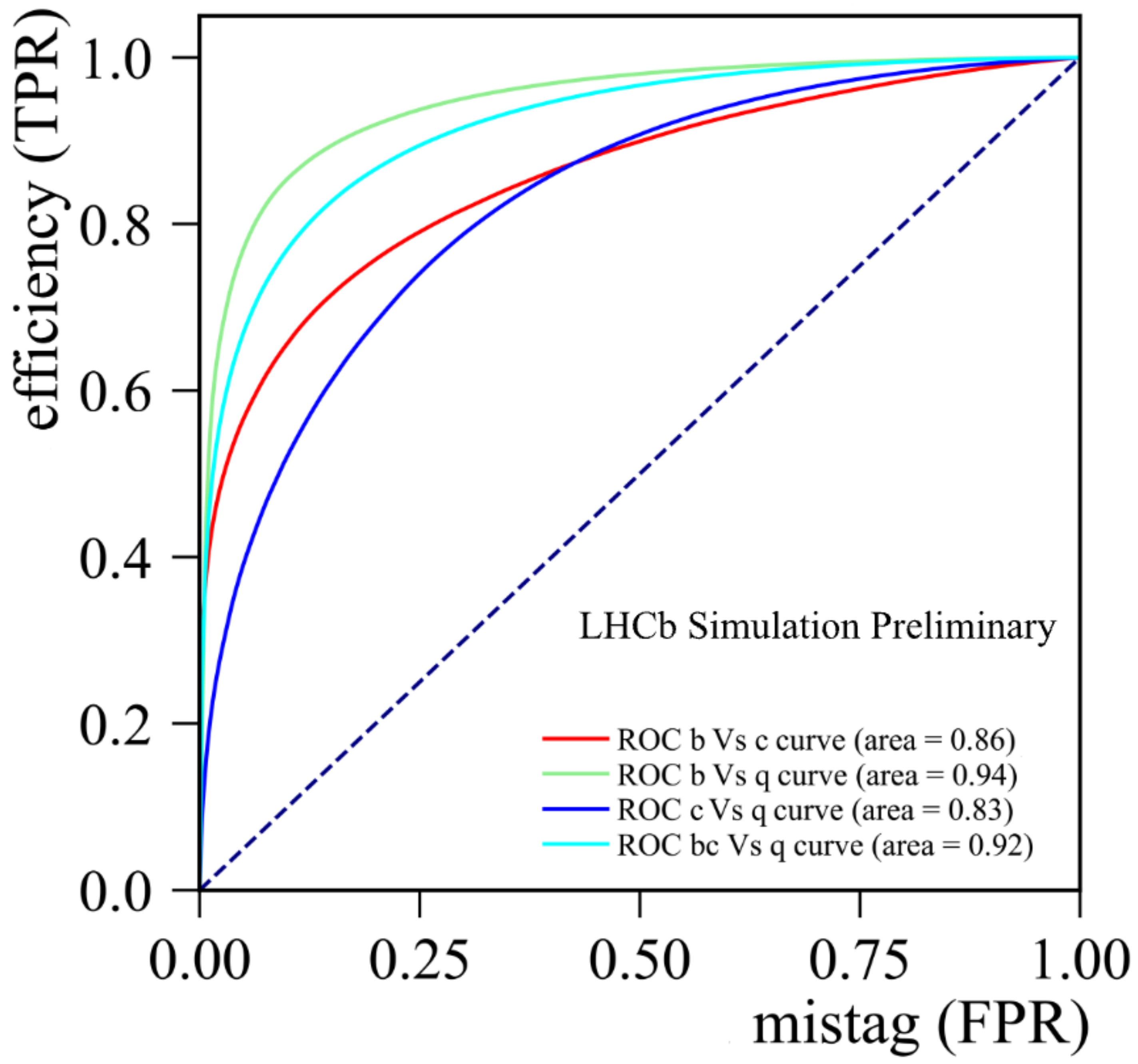

**Final (ambitious!) goal: search for bb,cc Higgs decays in di-jet events.**

- step 1: first measurement of cc di-jet differential cross section at a hadron collider (JHEP 02 (2021) 023)
- step 2: improve b- and c-tag efficiency and regression using modern techniques (inspired by CMS DNNs)

**Stay tuned!**



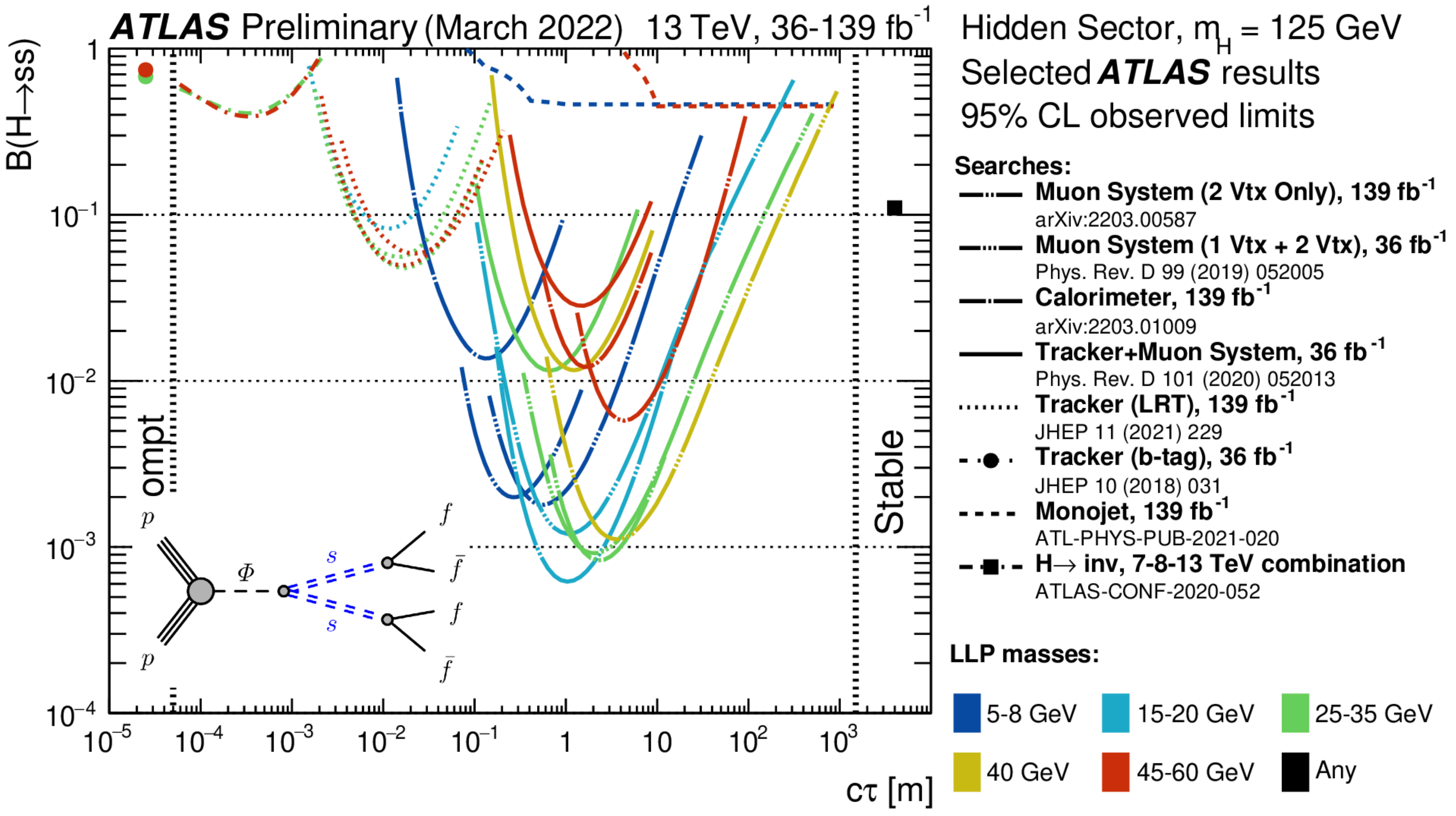



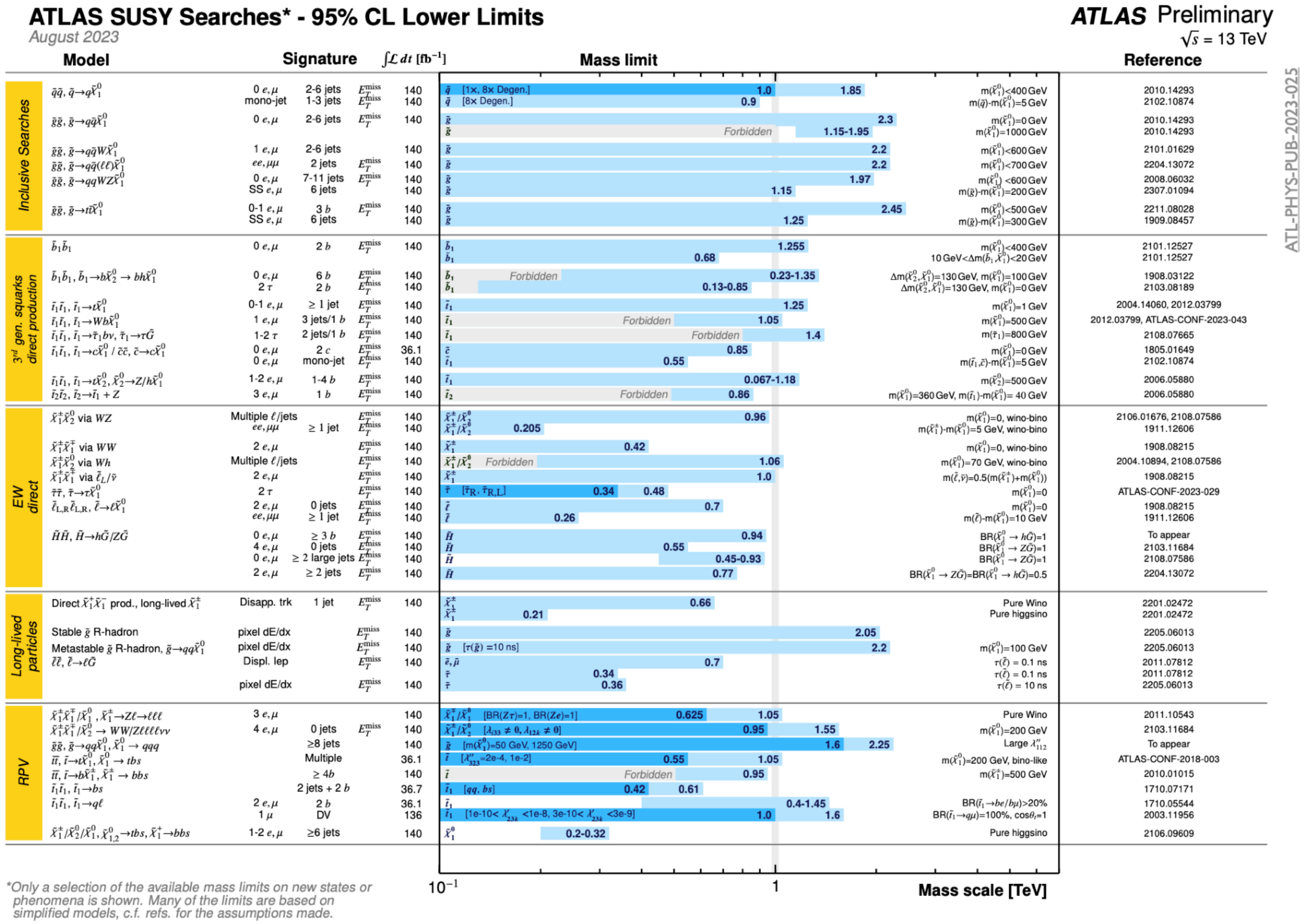
# Searches for new physics

# More and more models being tested

Extending phase space to hidden sectors, usually producing long-lived particles:

- unprecedented challenges on the reconstruction algorithm:
- Higgs used as a portal
- SuSy searches (including EW and Strong production) are now excluding NP below the 1 TeV scale



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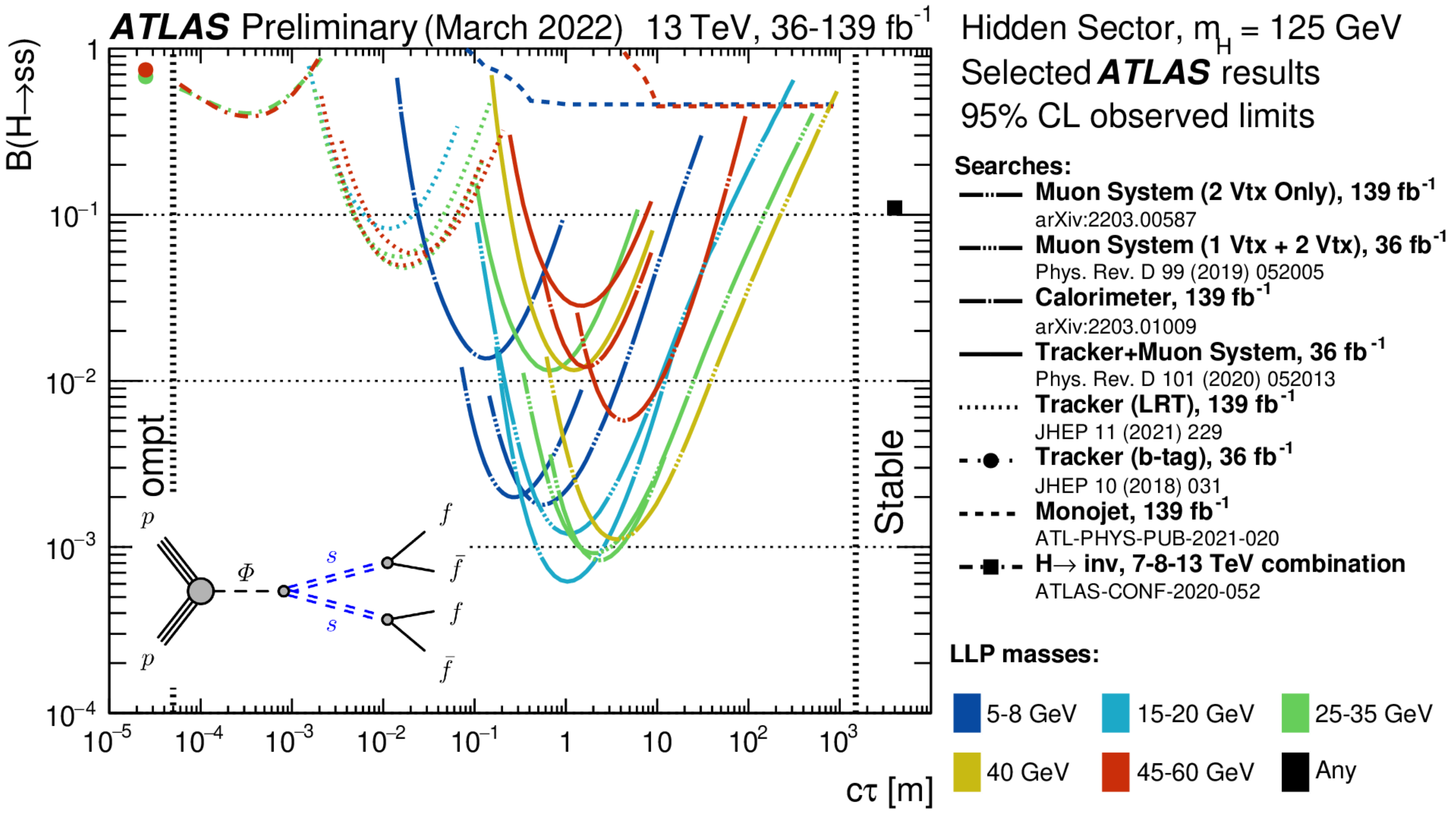
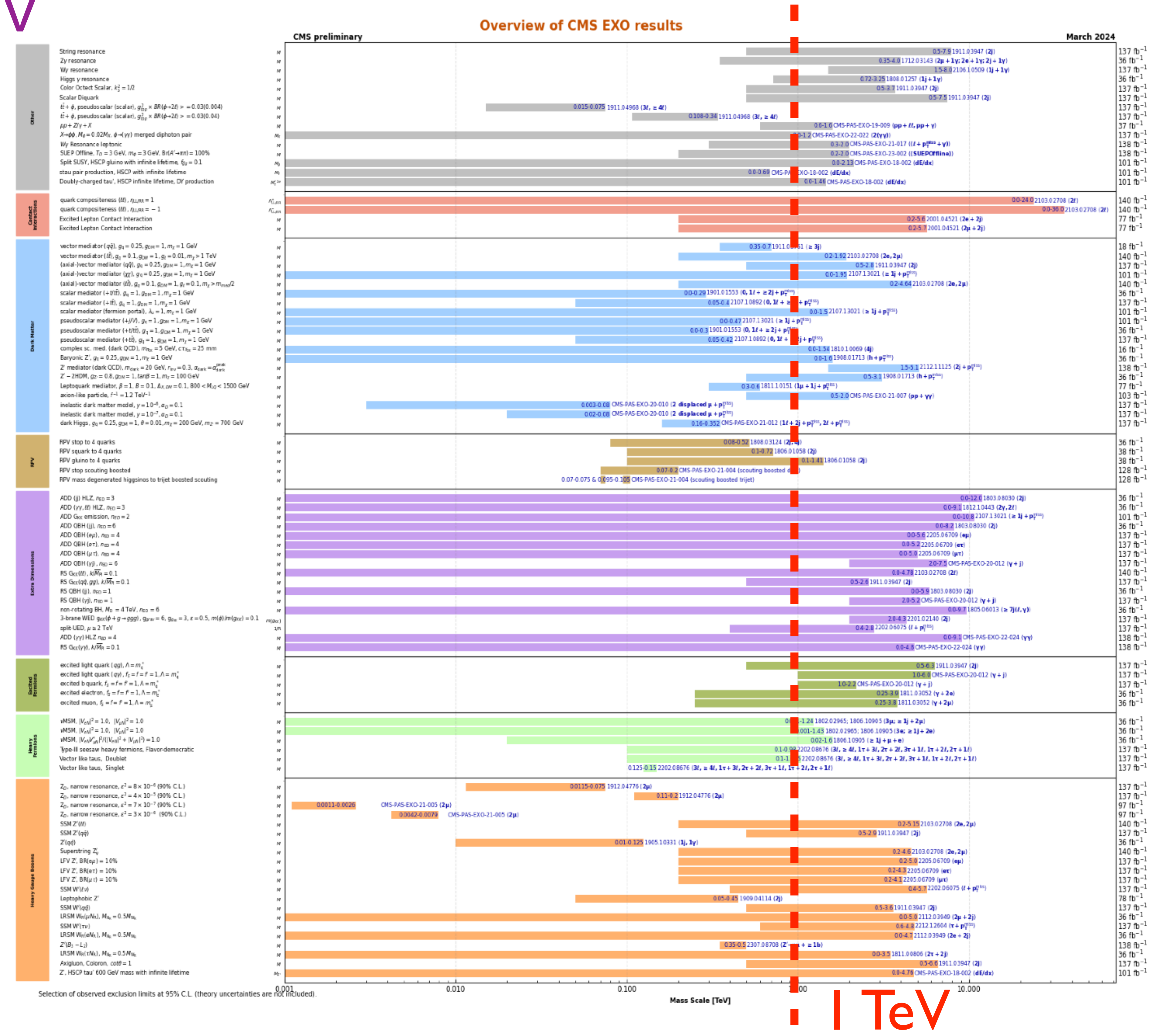
Extending phase space to hidden sectors, usually producing long-lived particles:

- unprecedented challenges on the reconstruction algorithm:
- Higgs used as a portal
- SuSy searches (including EW and Strong production) are now excluding NP below the 1 TeV scale
- Exotica high mass scalars and vectors limits well above 1 TeV



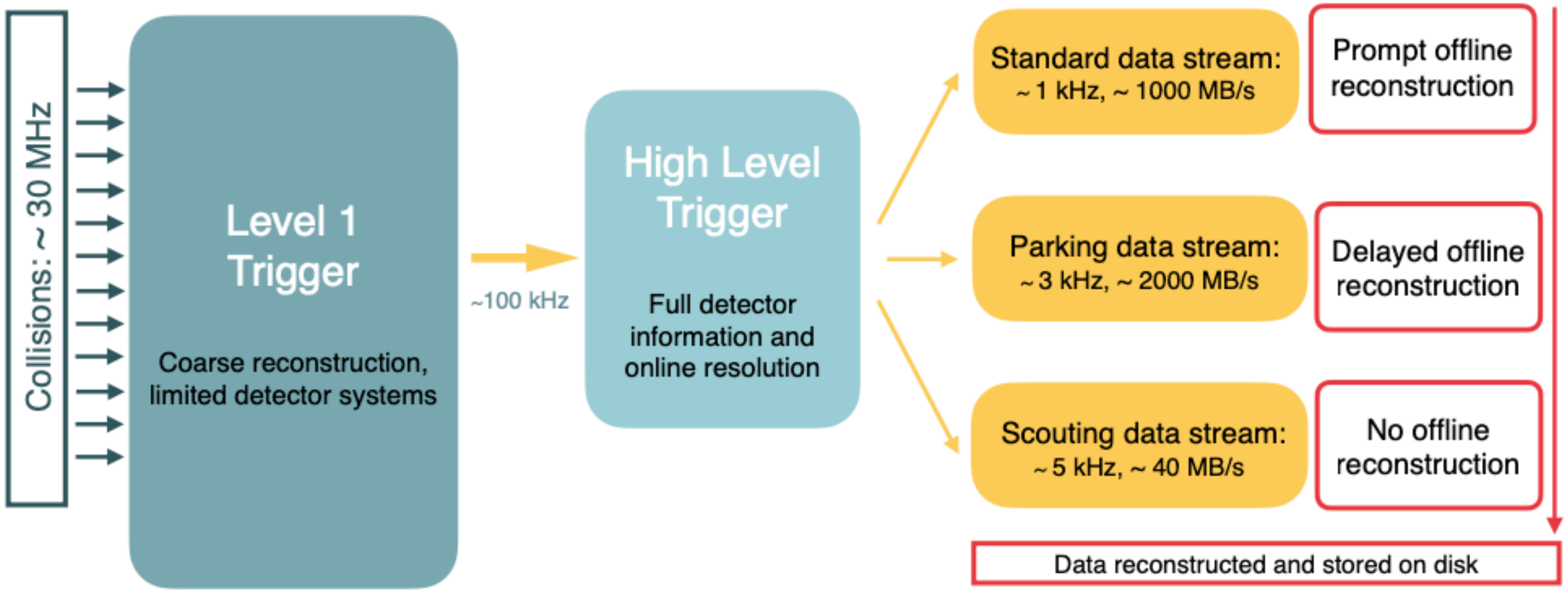



# A single highlight on searches: new strategies!

Since Run2 of the LHC, new data taking strategies have been employed to optimize data taking and explore region of phase space (intensity frontier) deemed inaccessible in a typical tiered trigger system.

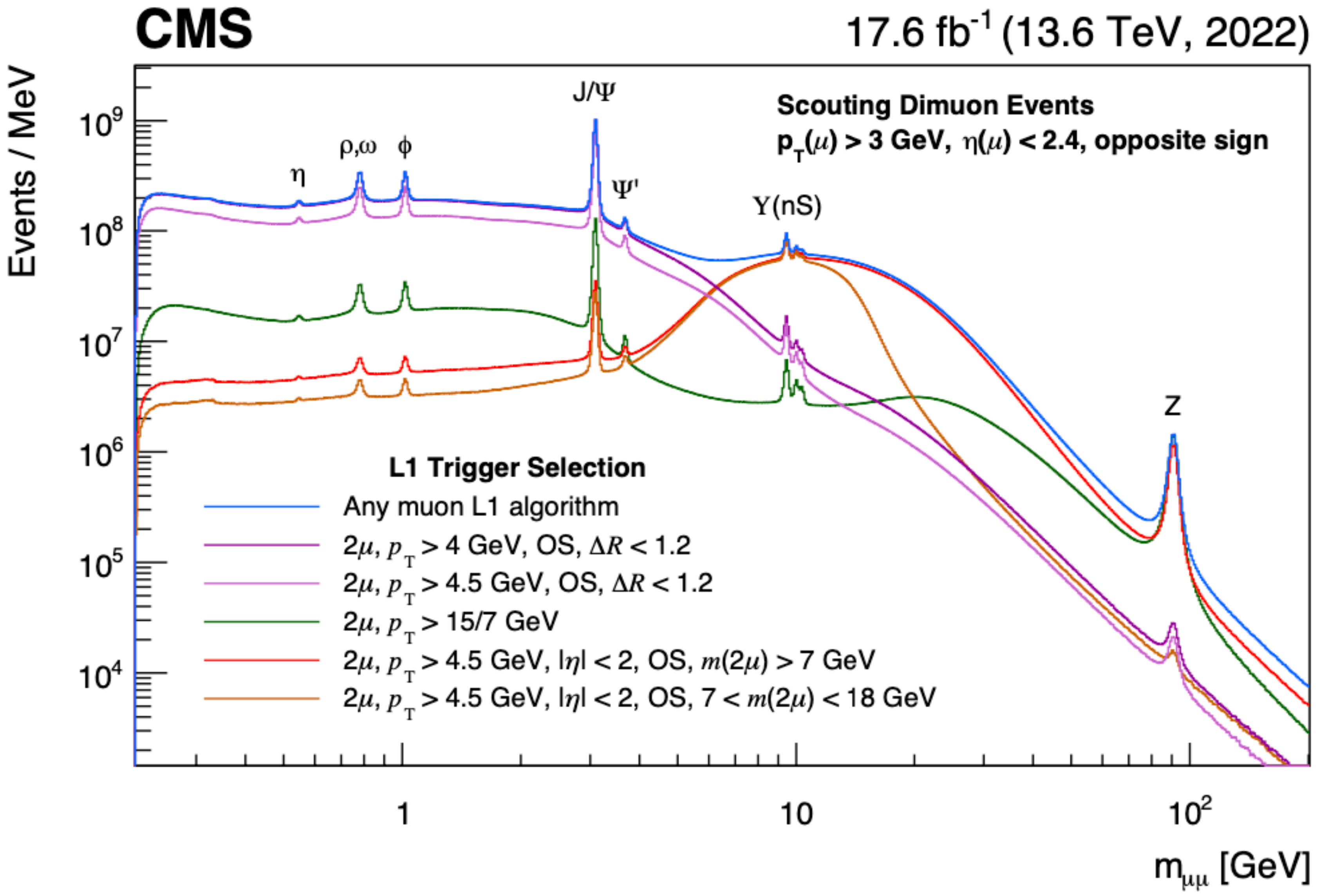
Example here taken from CMS but techniques used, mutatis mutandis, by other Collaborations:


Data flow for a typical 2018 data-taking scenario

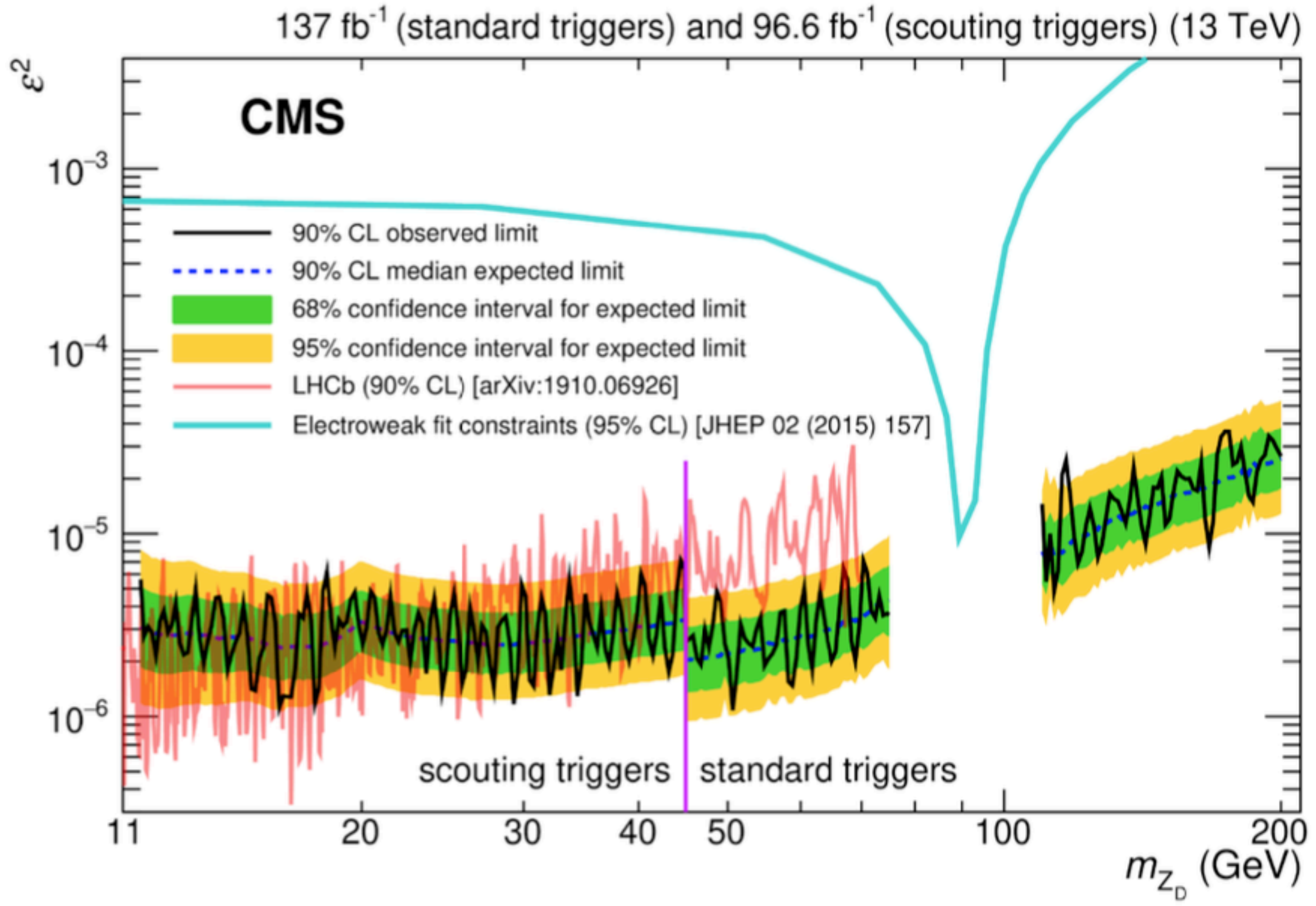


# A single highlight on searches: new strategies!

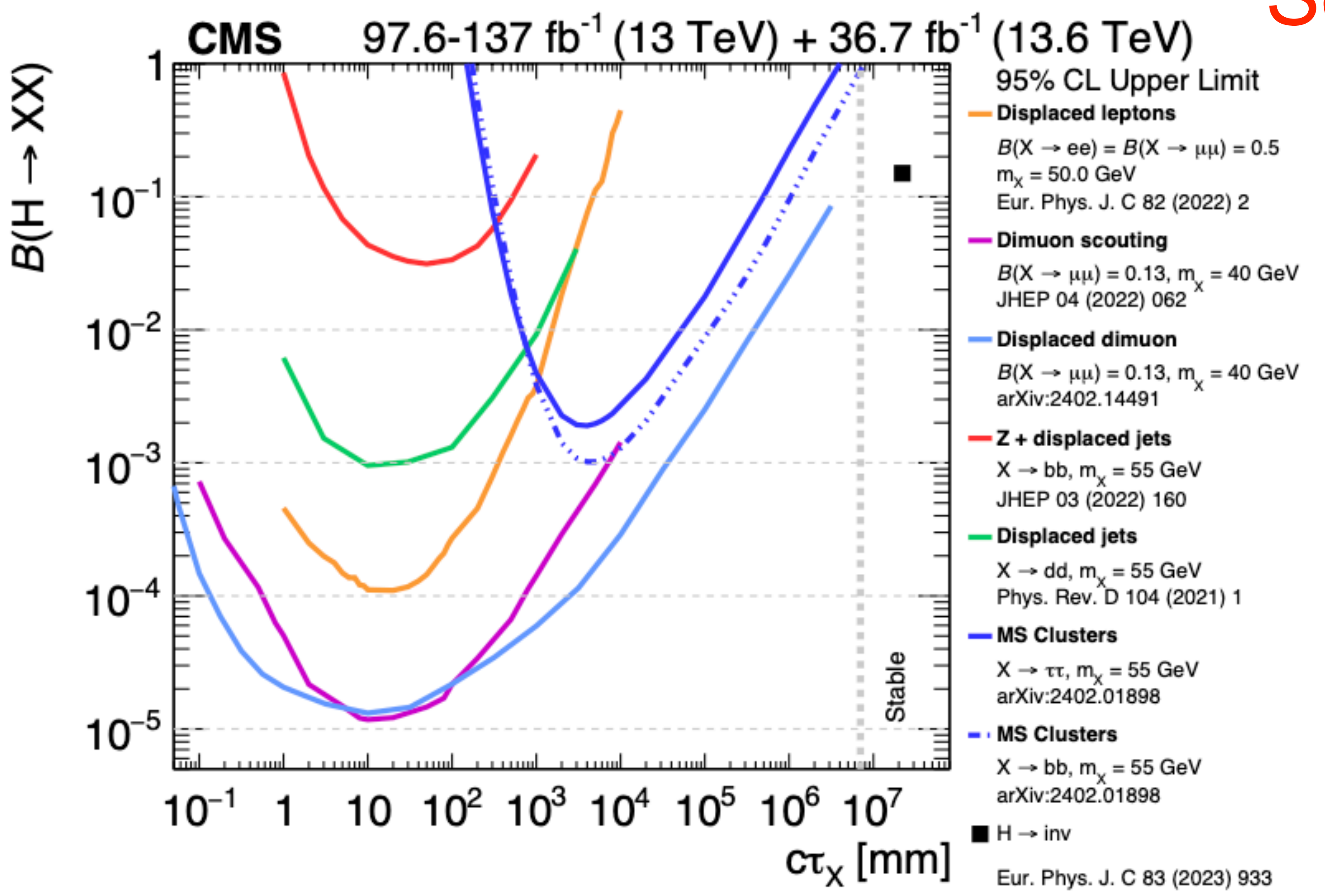

(a.k.a. Trigger Level Analysis): use bandwidth to store very low thresholds reconstructed information (dimuon, di-jet) and drop raw data. Increases acceptance rate and extends search window towards low masses.



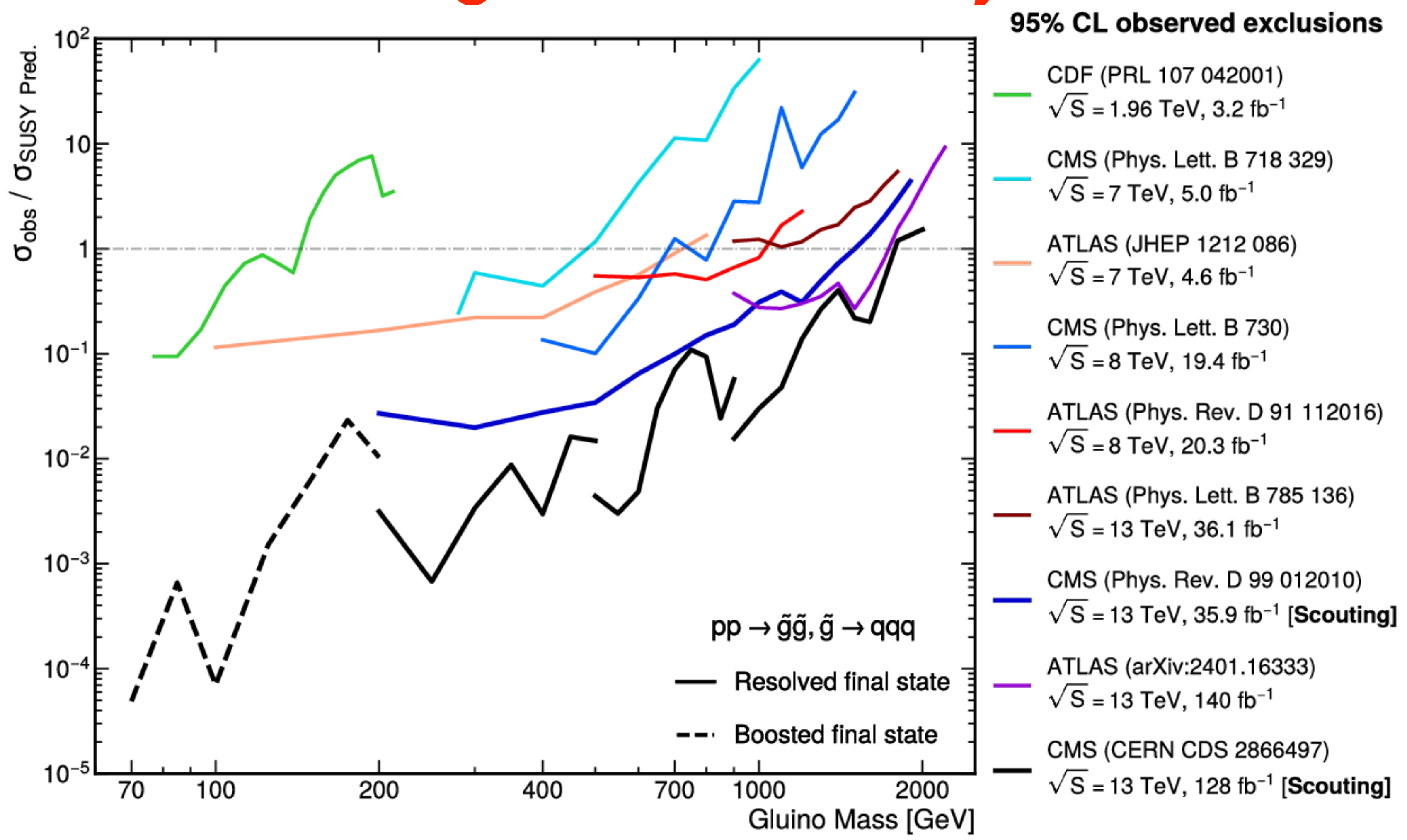

Search for low mass dimuon resonances




Search for long lived particles decaying in two muons

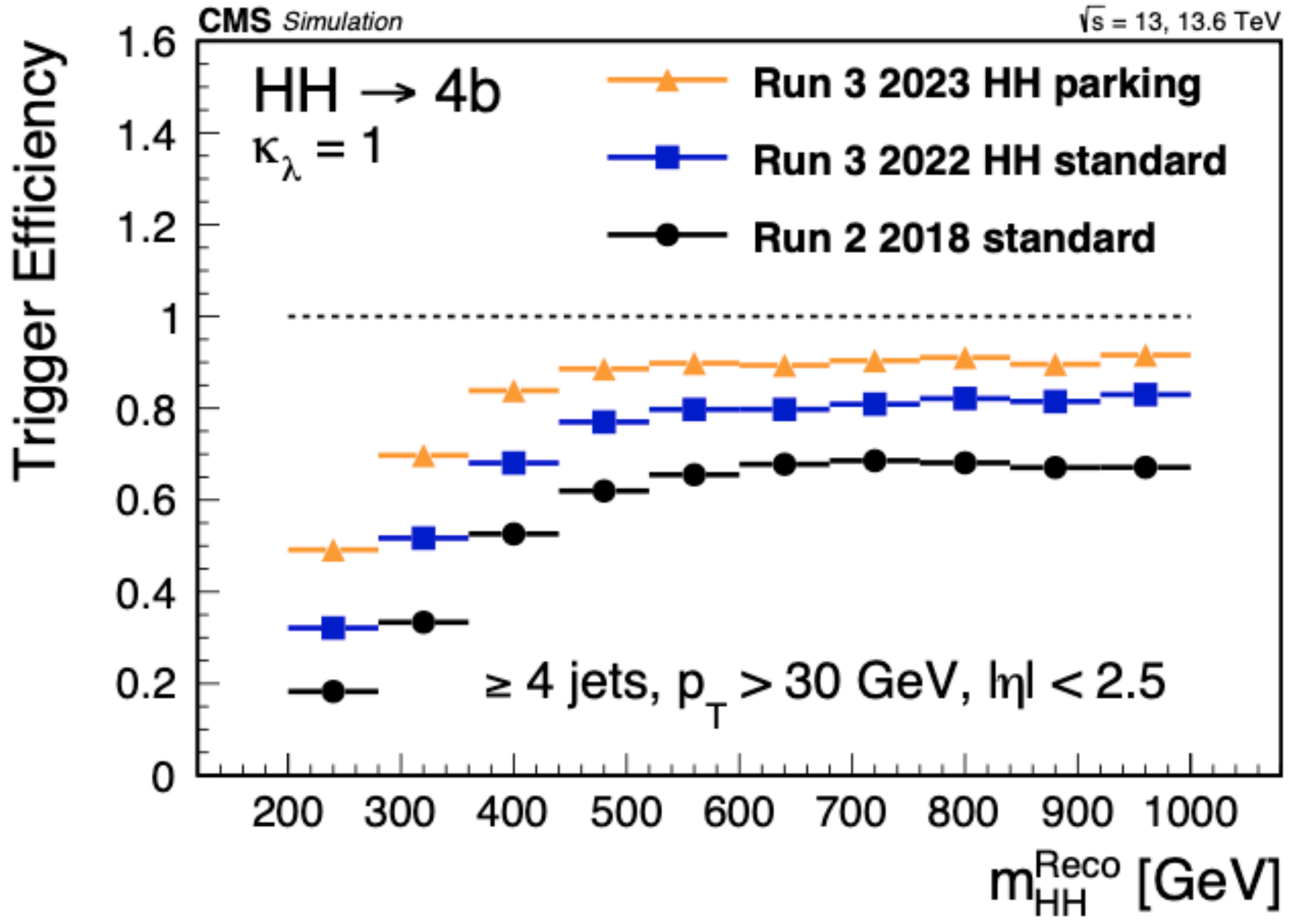


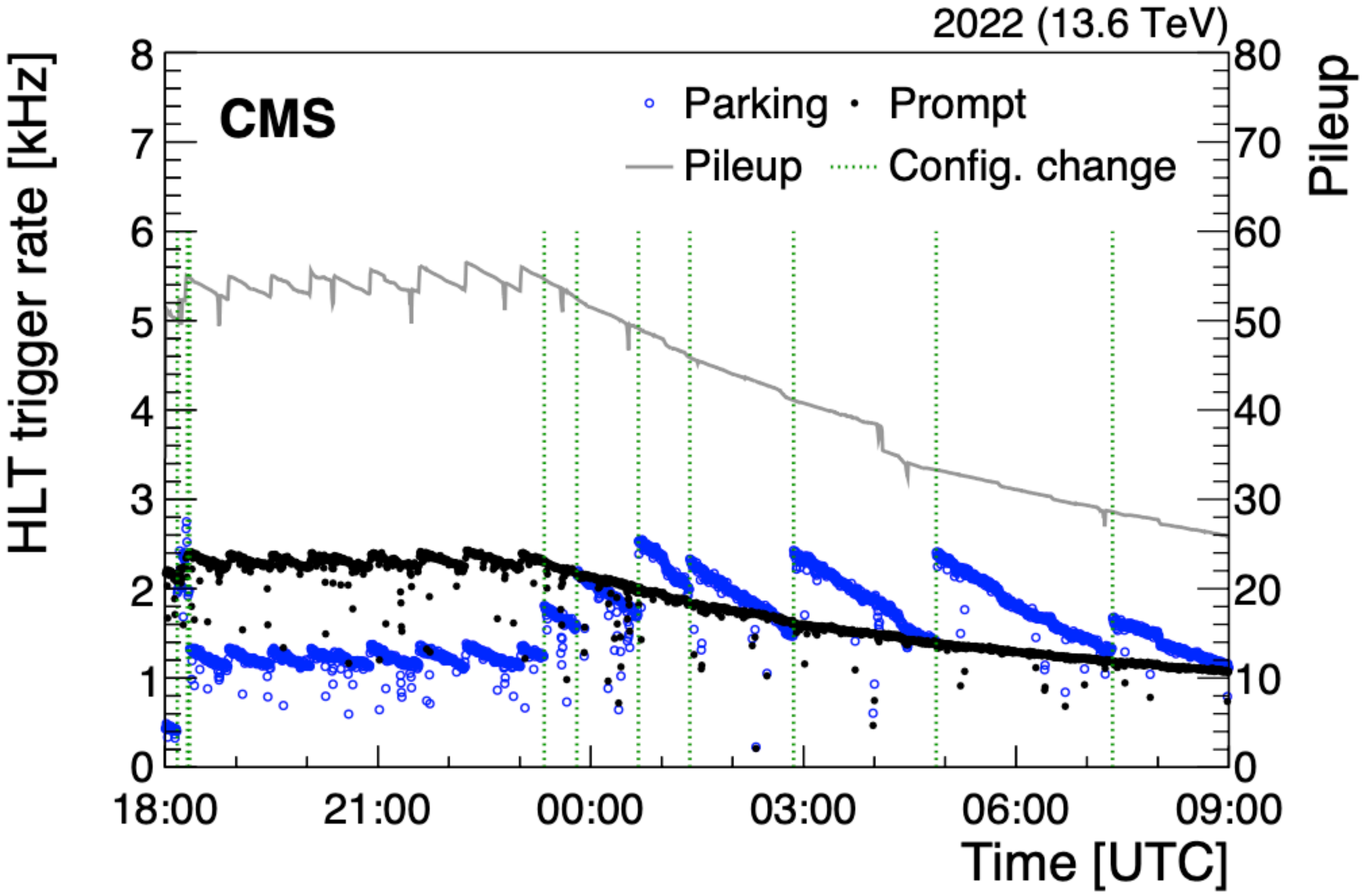

Search for RPV gluinos in multijet final states



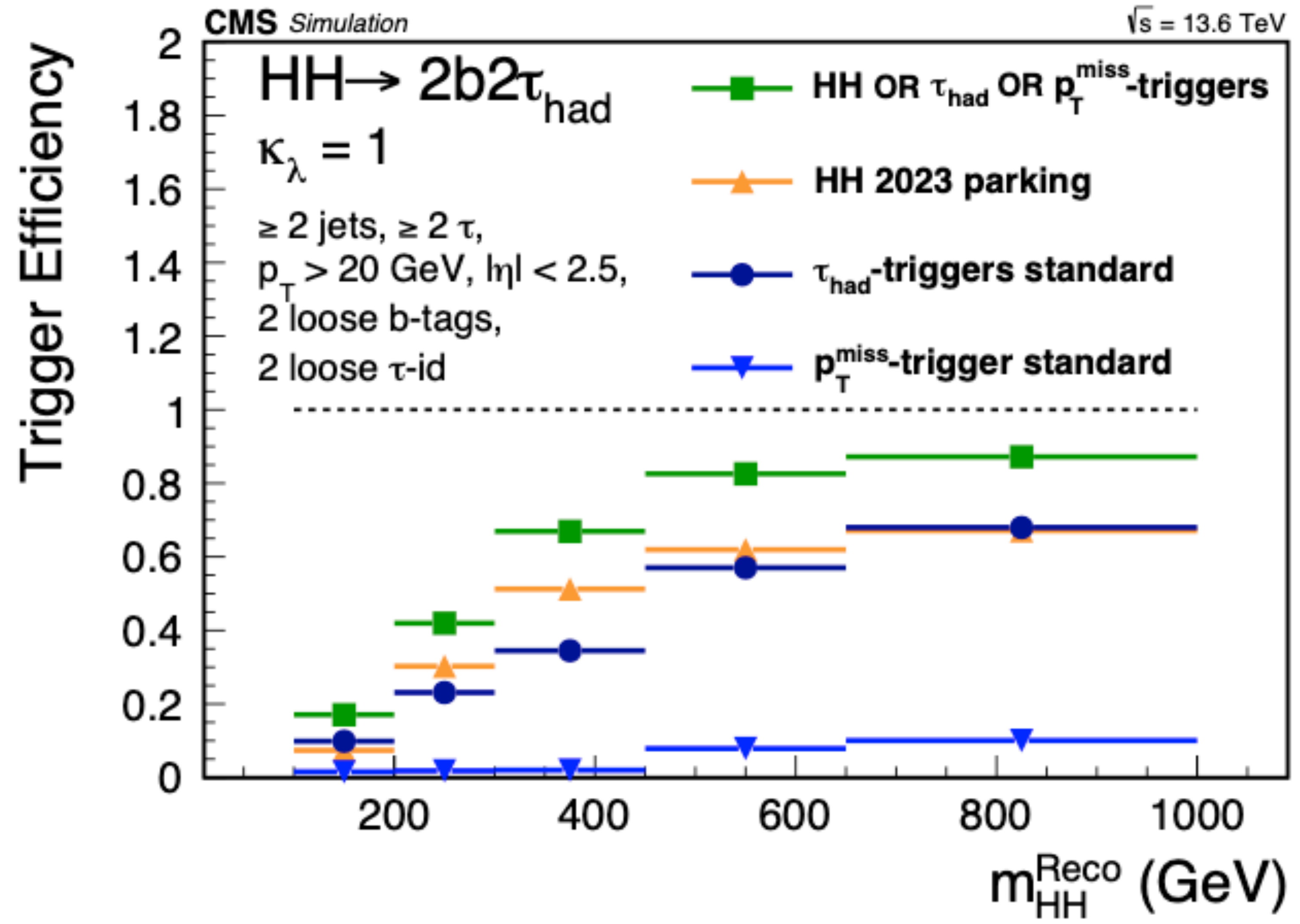
# A single highlight on searches: new strategies!


a.k.a. delayed reconstruction: store raw/low-level reco at high rate to be reconstructed during shutdowns/ opportunistically.




Initiated for flavor physics studies, now used to extend physics reach also in high pT physics (di-Higgs as example)

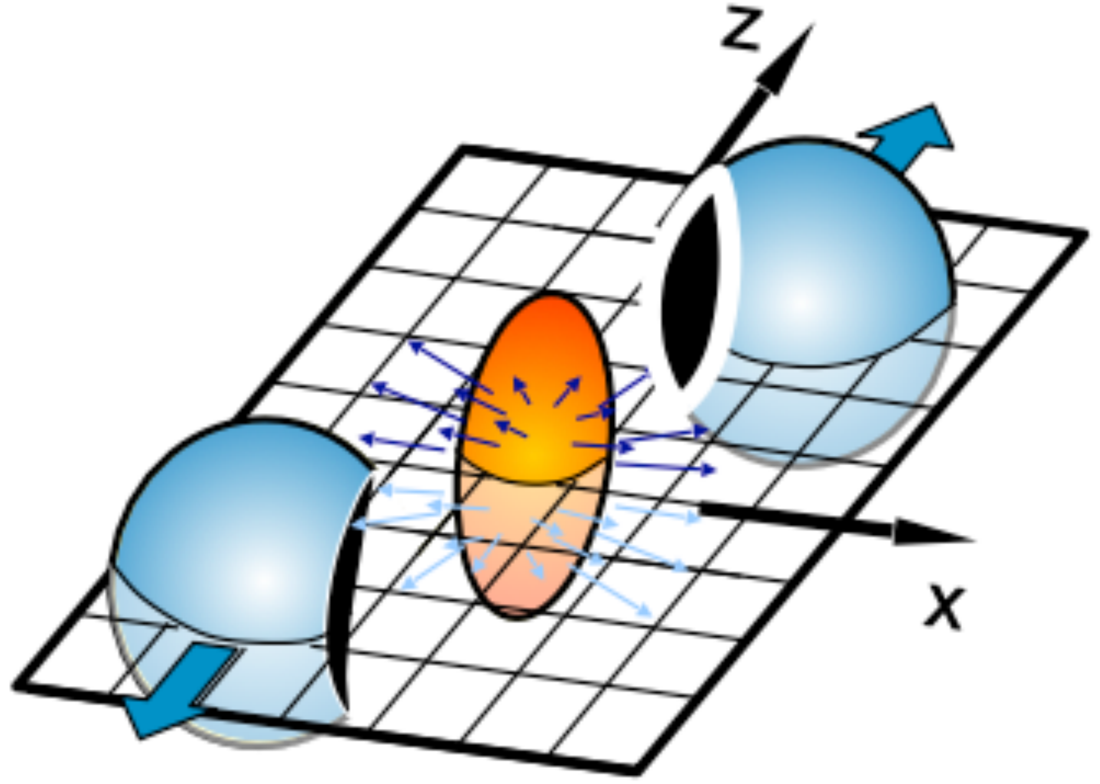


# Heavy Ions recent result(s)

# LHC as QuarkGluonPlasma lab

**The flow studies through multi-particle correlations can tell us something about the “fluid”:**

- **Is it a perfect liquid ?**
- **Collective flow driven or initial state?**
- **Does it behave differently depending on particle type?**



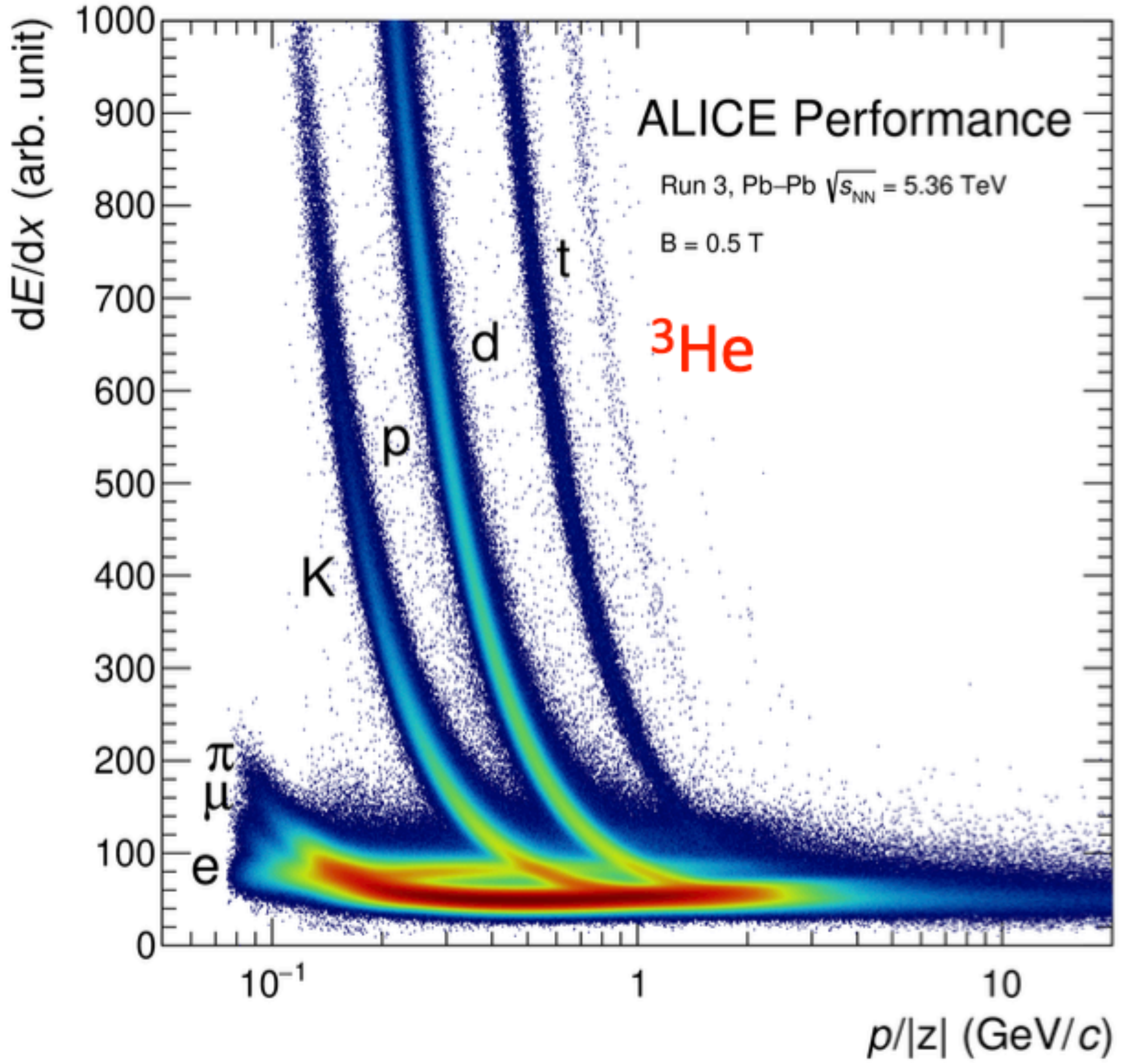

$$v_2 = \langle \cos 2\phi \rangle$$

$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

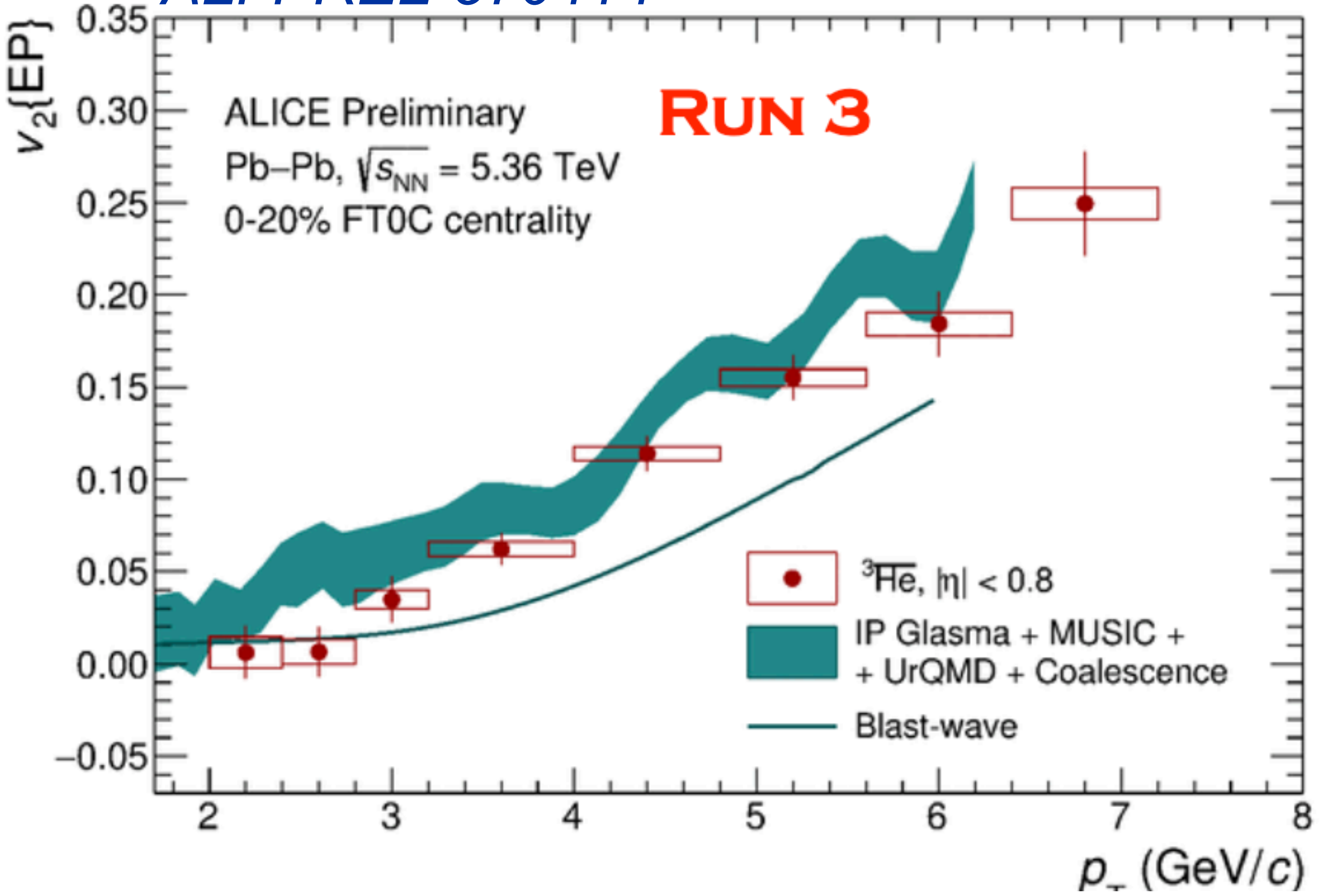
**off-central heavy-ion collisions**

**The upgraded ALICE detector now allows to measure with precision the elliptic flow of rare particles like anti-3He:**

- **are they formed directly at the freeze-out of the deconfined partons and inherit the flow directly from them (Blast-wave model)?**
- **or are they formed at a later stage by coalescence from anti-protons and anti-neutrons and they inherit the flow from the these particles (coalescence model)?**




ALI-PREL-570414

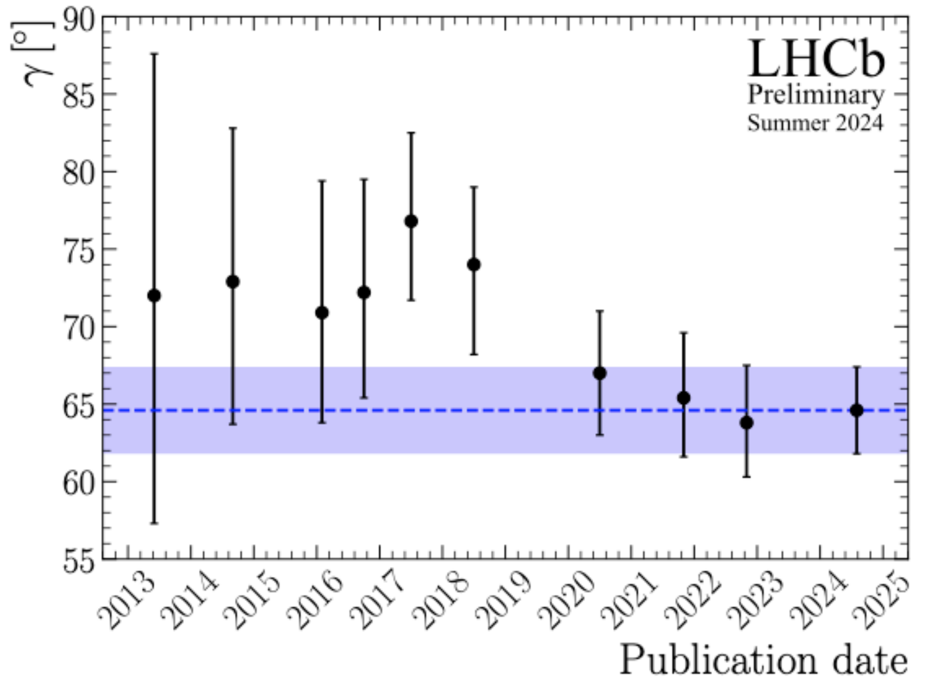


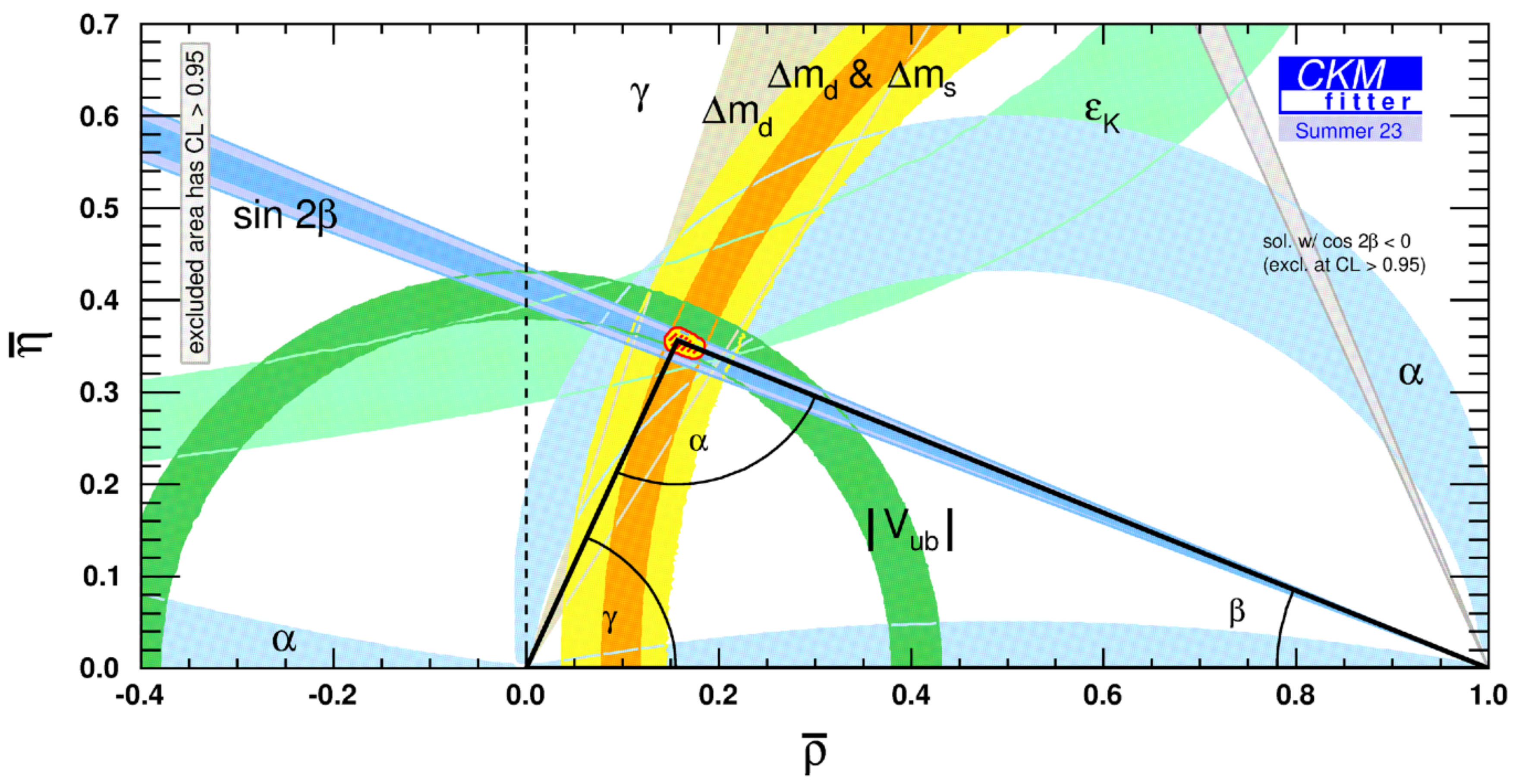
# Flavour Physics: a couple of highlights

# LHCb leads the precision rally of the CKM matrix!

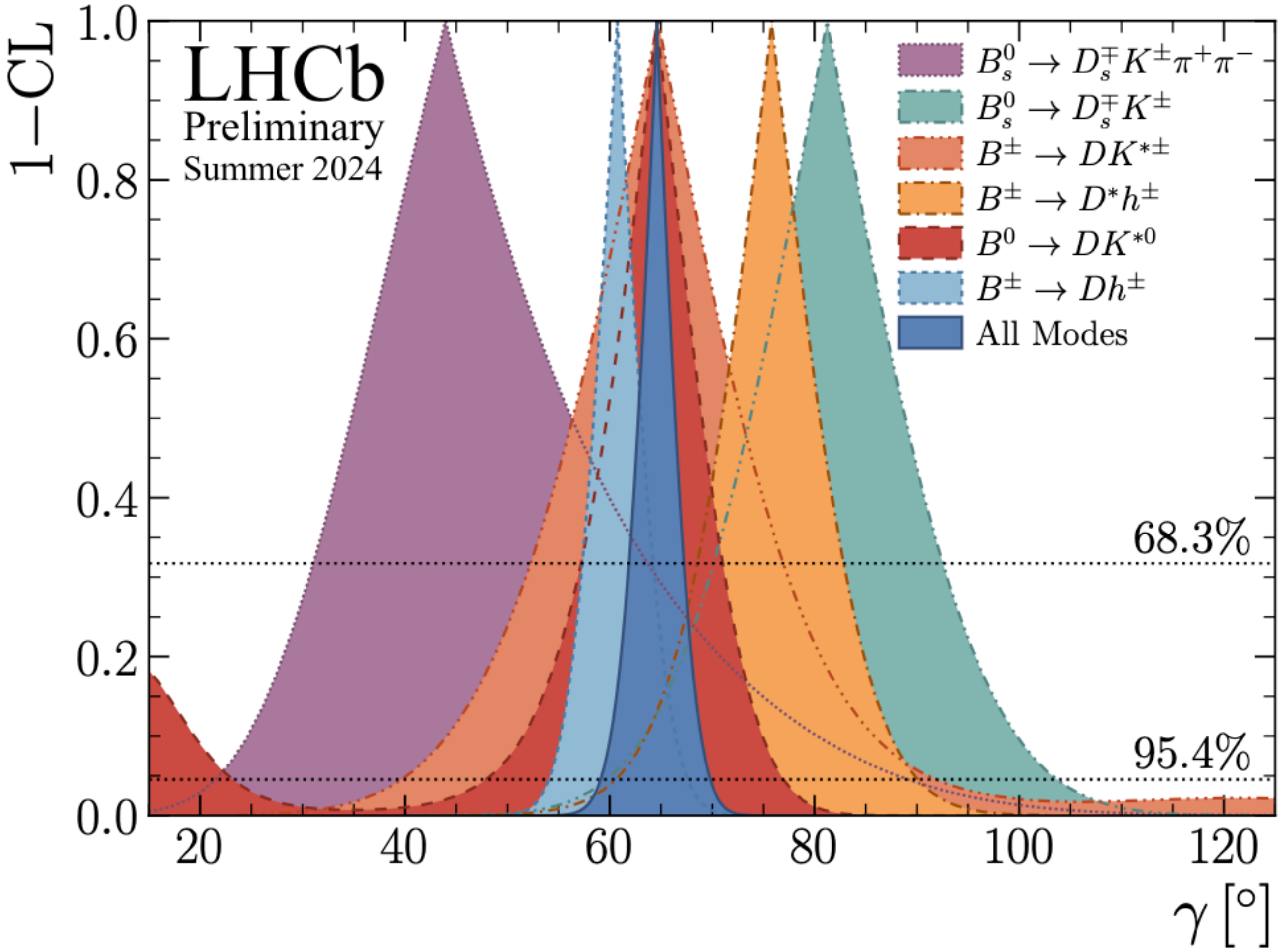
- Unitarity matrix: triangles in the complex plane
- Use multiple measurement to constrain them in the hope of a SM crack:
  - CKMfitter 2023 (indirect) WA: $\gamma = (66.3^{+0.7}_{-1.9})^\circ$
  - HFLAV 2024 (direct) WA: $\gamma = (66.4^{+2.8}_{-3.0})^\circ$

$$V_{\text{CKM}} \sim \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$




*LHCB-CONF-2024-004*




LHCb recently presented new results and a new combination based on B decays with a precision in par to the WA:

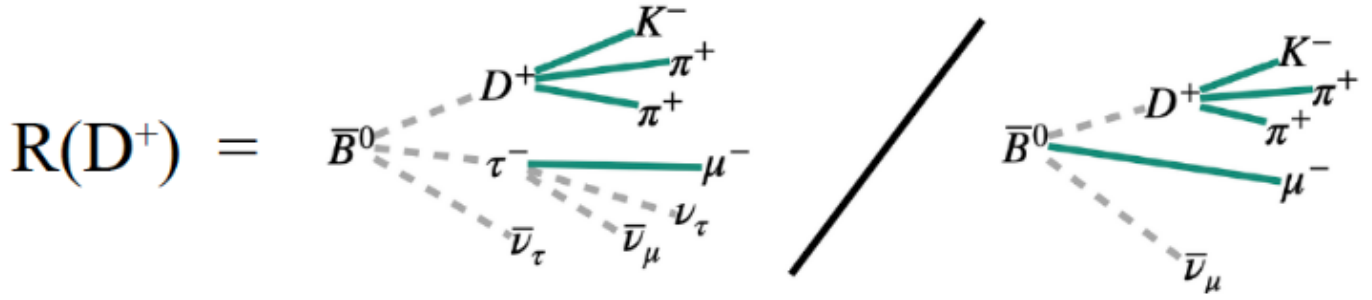
$$\gamma = (64.6 \pm 2.8)^\circ$$

# … but LHCb also keeps the hope for NP alive …

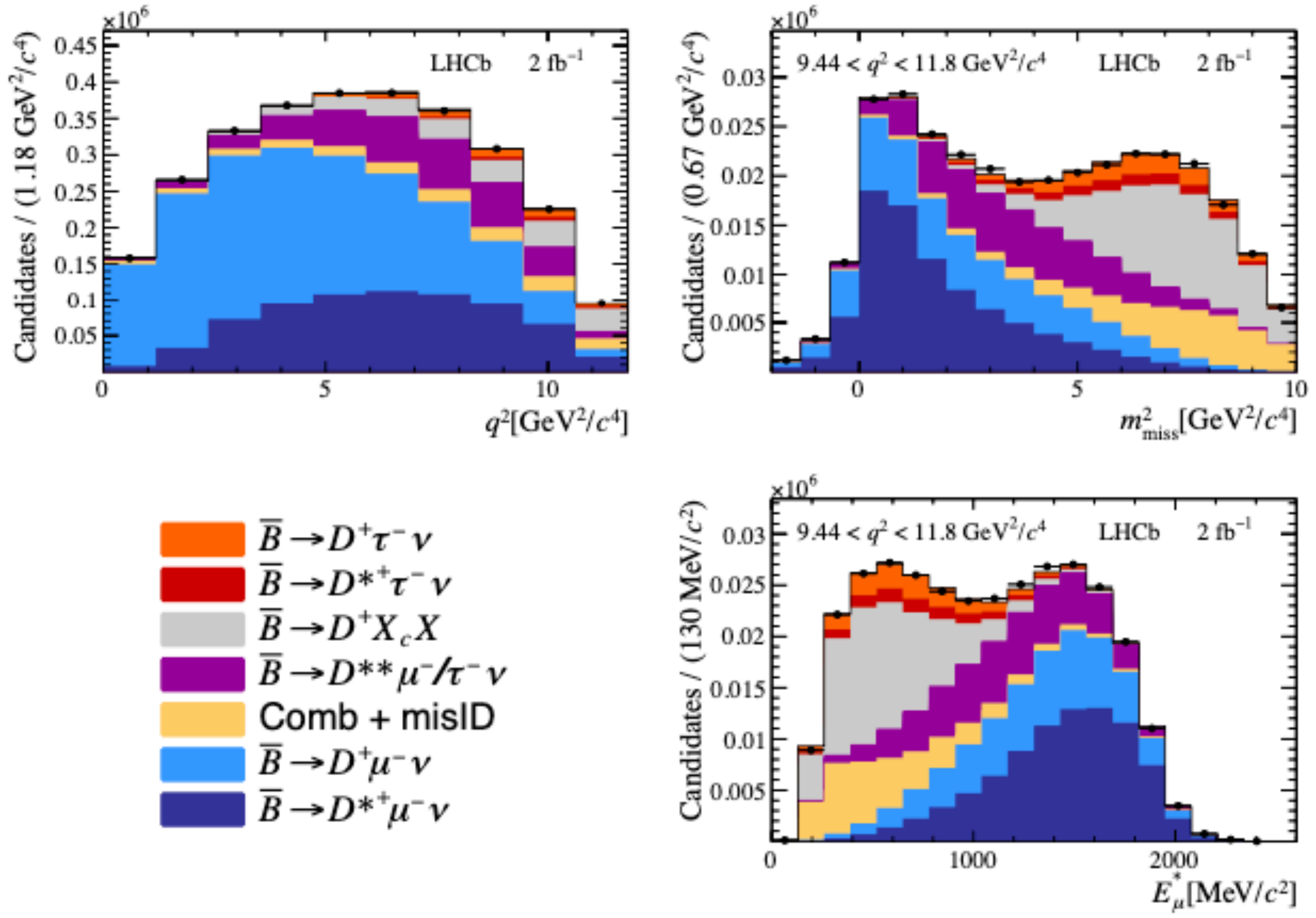
$$R_{D^*} = \frac{\Gamma(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\Gamma(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

In the recent years LHCb (and others) kept the ezcitement up with a series of puzzling measurements:

- B→K*$\mu\mu$ angular modeling (a.k.a. $P_5$')
- LFV anomalies (B→K*$\mu\mu$/B→K*ee, B→D*τν/B→D*$\mu$ν)
- some of them faded with time but the R(D) puzzle remains strong
- a recent result on R($D^+$) and R($D^{*+}$) by fitting simultaneously $q^2$, $m^2_{miss}$ and $E^*_l$ in $B^0$ decays:




*LHCB-PAPER-2024-007*

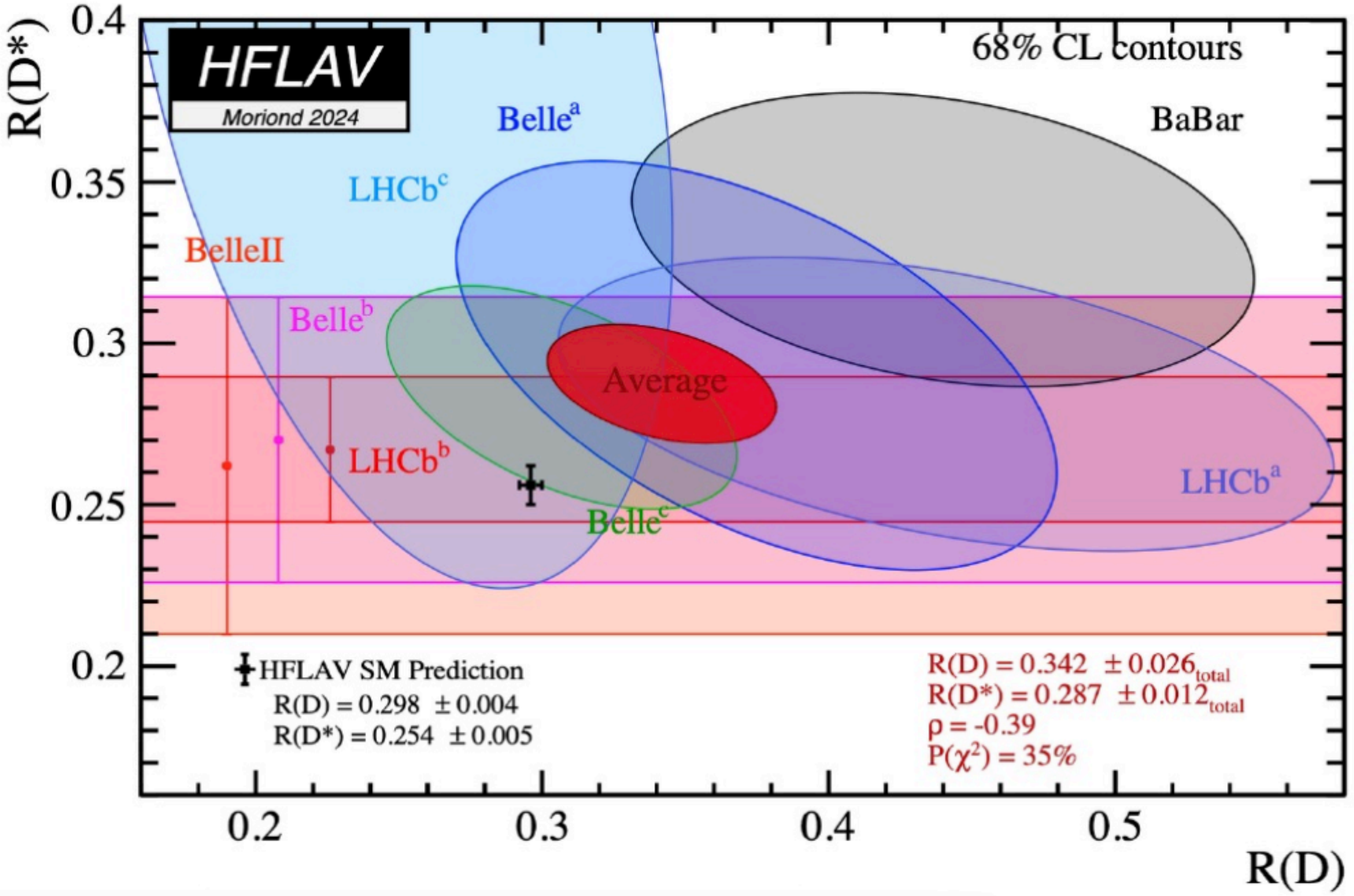



$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$

using isospin symmetry:

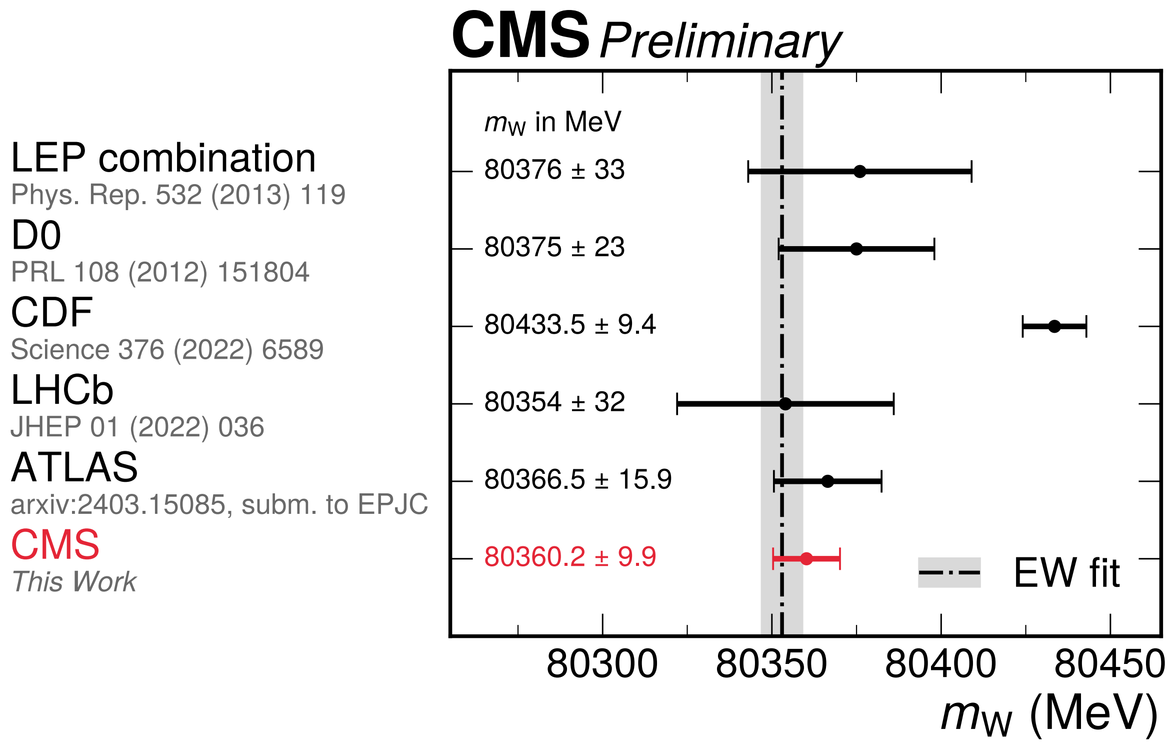
$$R(D) = 0.335 \pm 0.052$$
$$R(D^*) = 0.279 \pm 0.019$$

Compatible with SM but also with previous measurements, so the 3.3σ tensions remains!



# Conclusions

- The LHC is a discovery machine that does unexpectedly well on precision physics (rivalling lepton colliders):
  - top mass, W mass, Z mass (in future), $\sin^2\theta$, Higgs, strong coupling constant, etc.

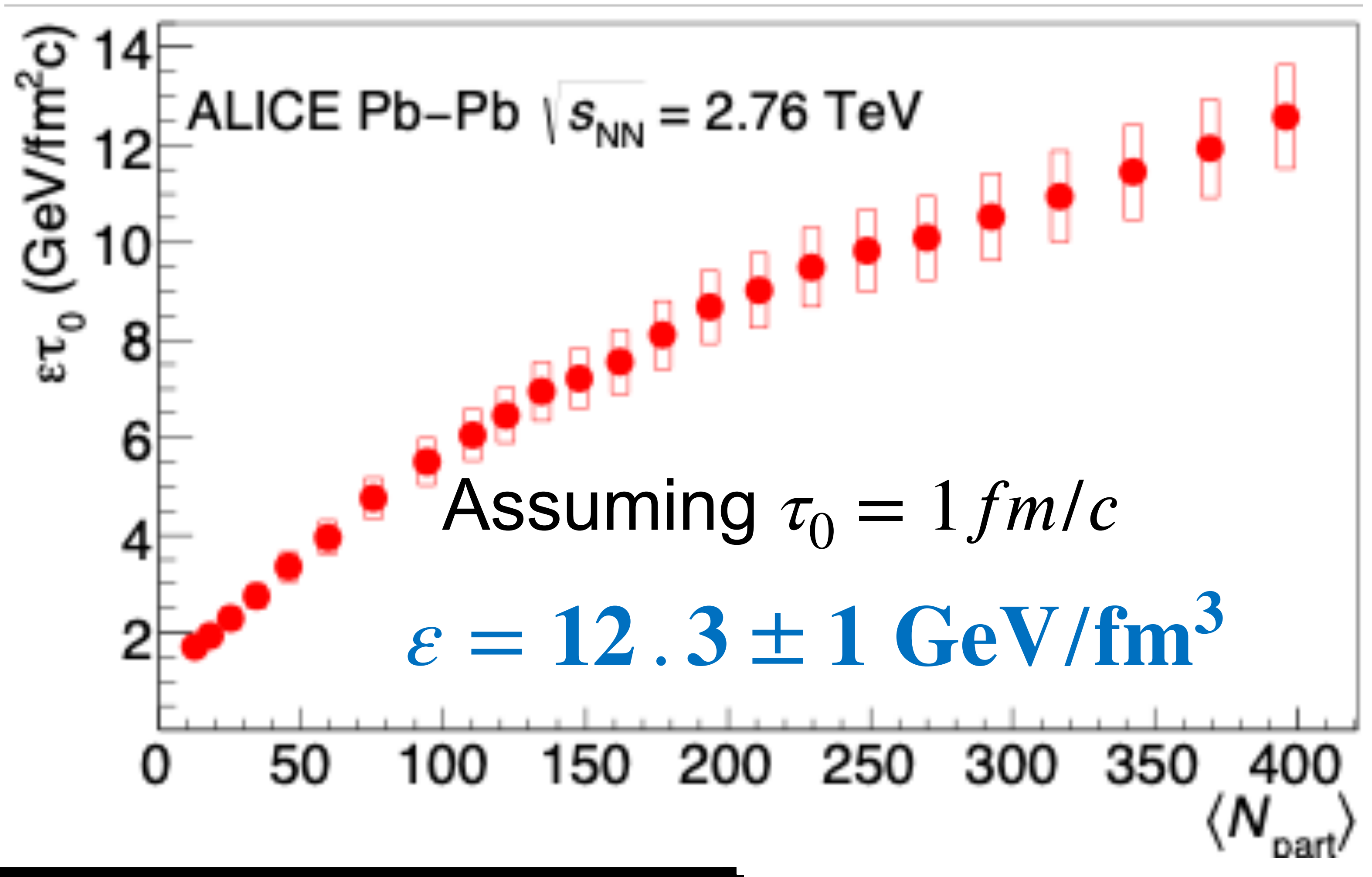



- After the Higgs discovery and in absence of observed new physics, the overconstrained SM is our most powerful tool to get hints of where to look next.
  - hard but worth it!

- Compared to Physics TDR (2007) and Upgrades TDR (2015) we have results that are at least a factor two and up to a factor 10 better than expectations (and some that where not even expected!):
  when planning for the future we need to take the brain factor into account:
  - improved calibration techniques
  - optimization from machine learning and AI
  - smart data taking modes

# BACKUP

# LHC as QuarkGluonPlasma lab




## LHC was designed to also collide heavy ions (Pb+Pb, Xe-Xe and p+Pb) at high energy.

**The density of the colliding "material" is so high to replicate the situation just after the big-bang when an exotic state of matter was created: the quark-gluon plasma (QGP) (CERN announcement in 2000!)**

**Energy and temperature conditions for the formation of QGP:**

$$\varepsilon_c = (0.42 \pm 0.06)\ GeV/fm^3$$ critical energy

$$T_c = (156.5 \pm 1.5)\ MeV$$ critical temperature

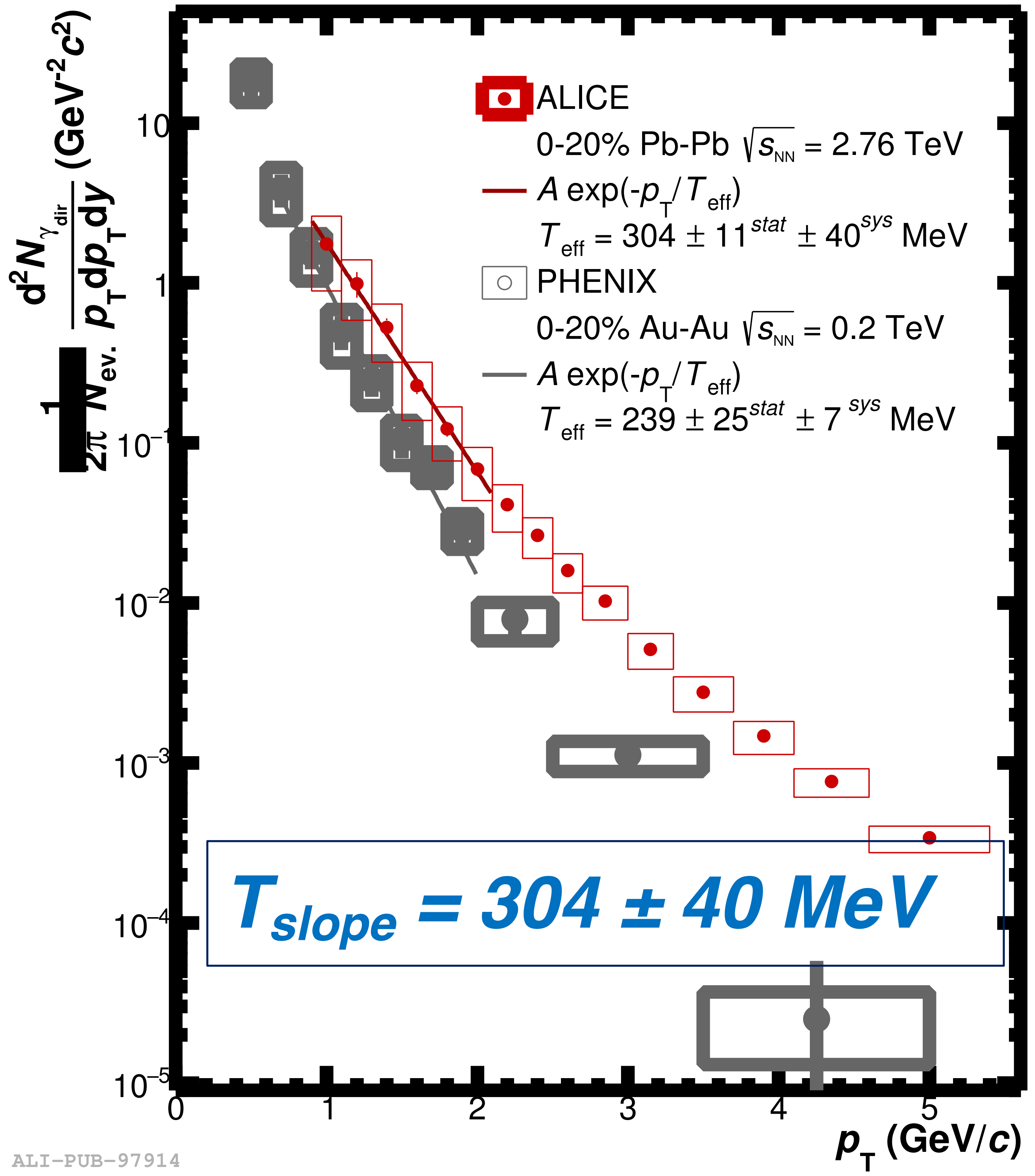
**For comparison**

T=156 MeV ≙ 1.8·10$^{12}$ K

Sun core: 1.5 · 10$^7$ K

Sun surface: 5778 K

**Old but fundamental result**



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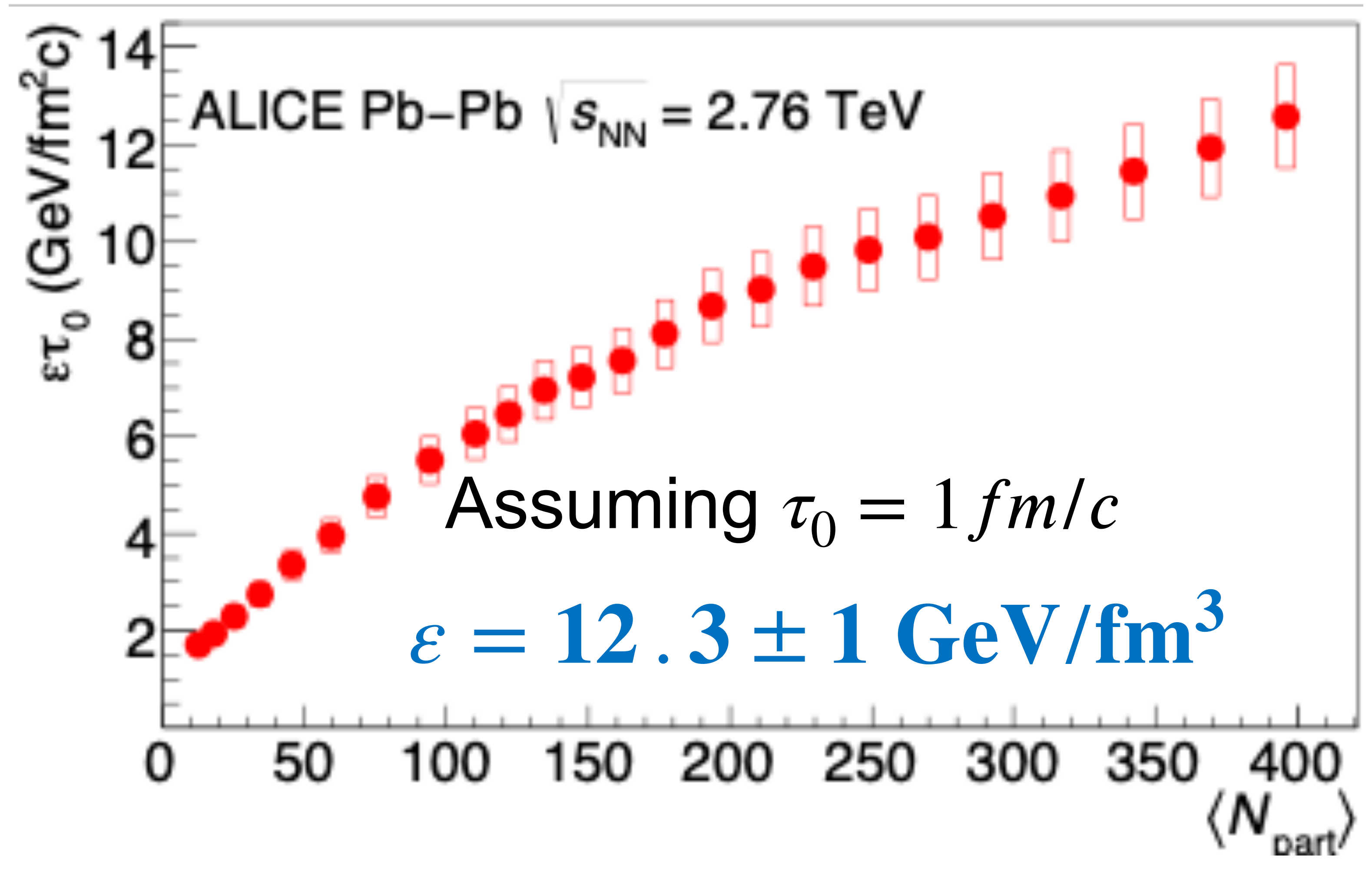


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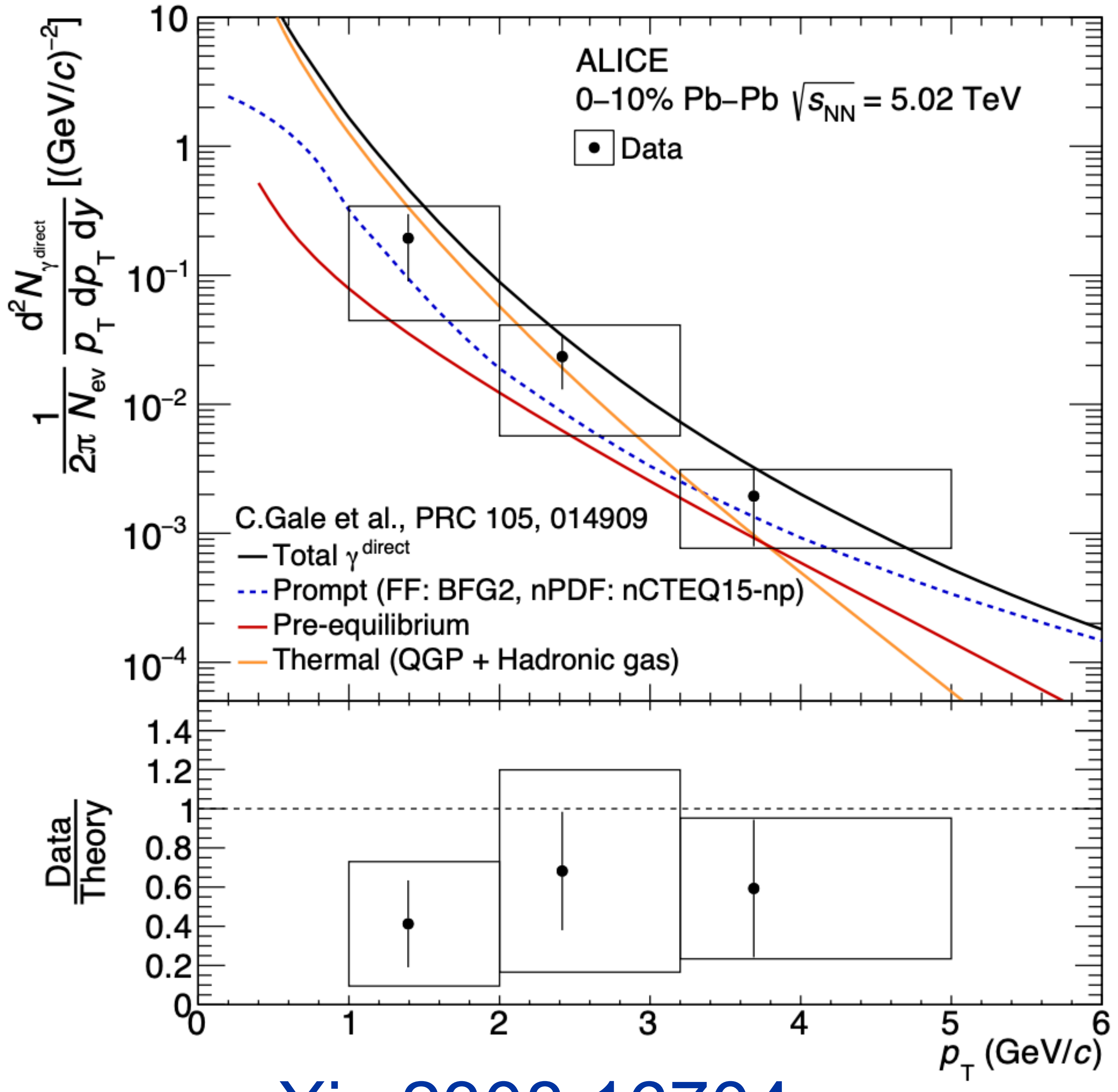
**Recent result**




arXiv:2308.16704

# Massive bosons: where are they?

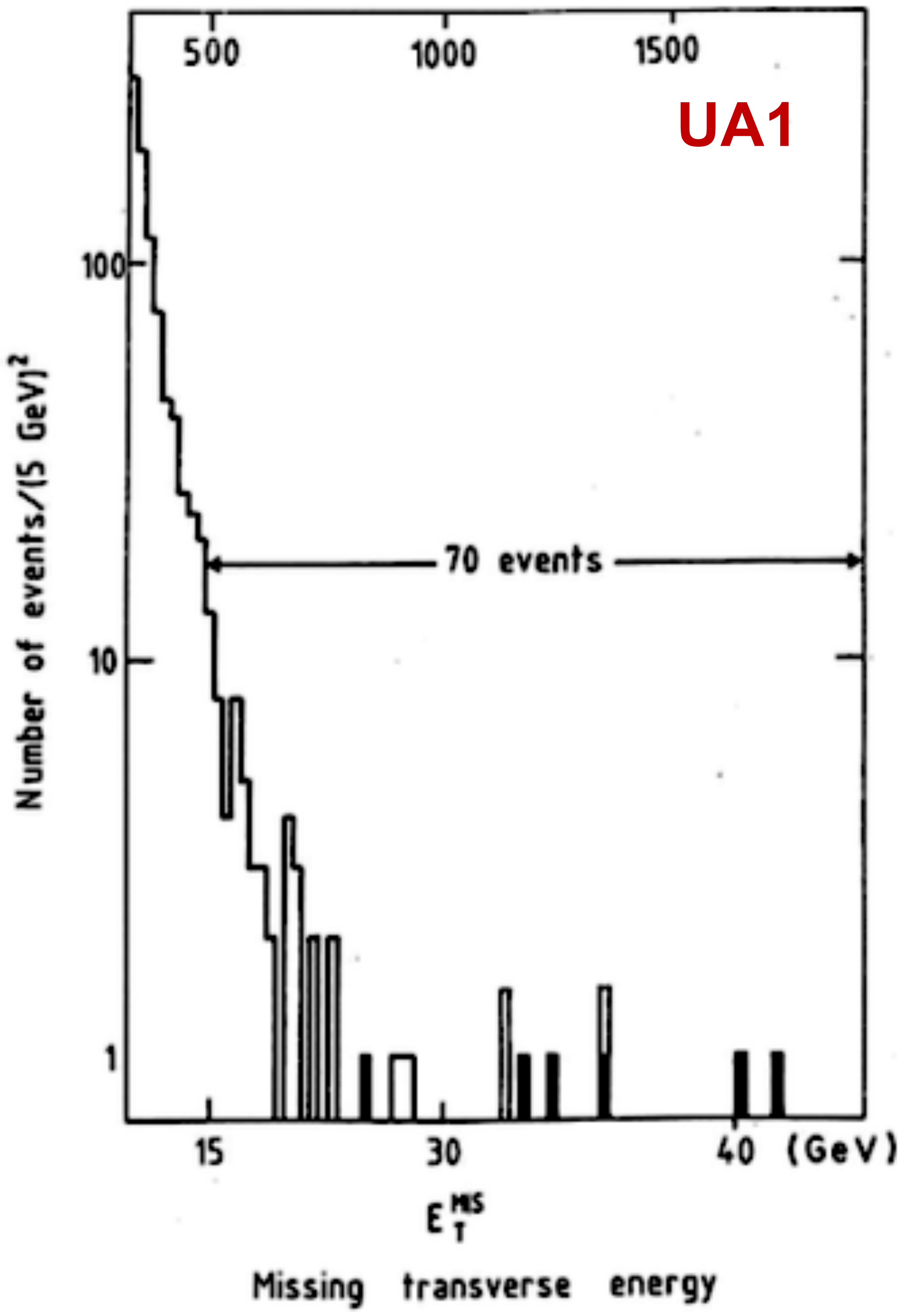
**UA1 and UA2 presented the first results in two separate seminars at CERN on 20 and 21 January 1983.**

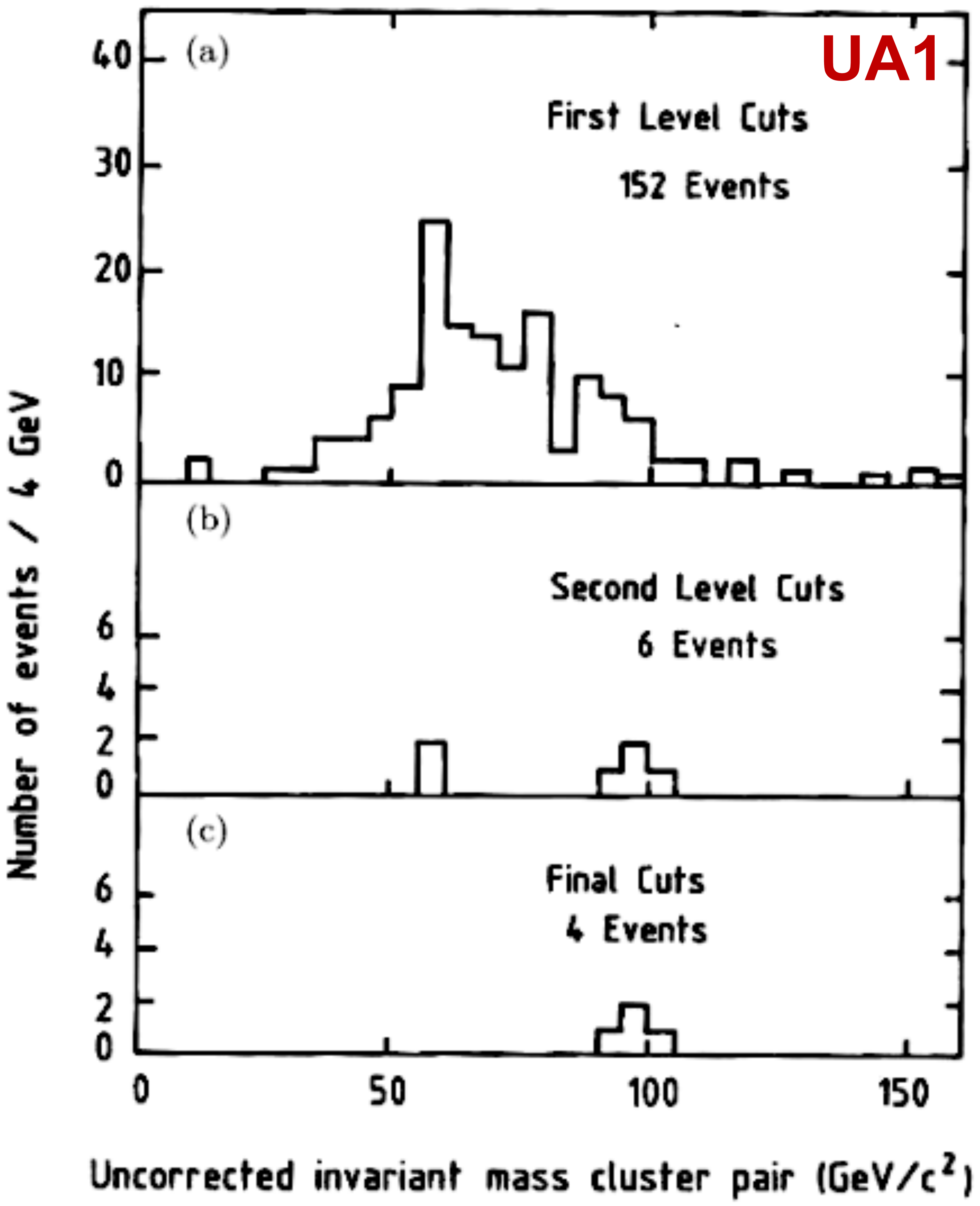
**6 candidates for both experiments with high energy electrons and high missing energy (i.e. neutrinos).**

**The quest for the W boson was over!**

**In July of the same year, clear evidence of the Z boson was also presented.**

**Carlo Rubbia and Simon van der Meer shared the 1984 Nobel prize.**

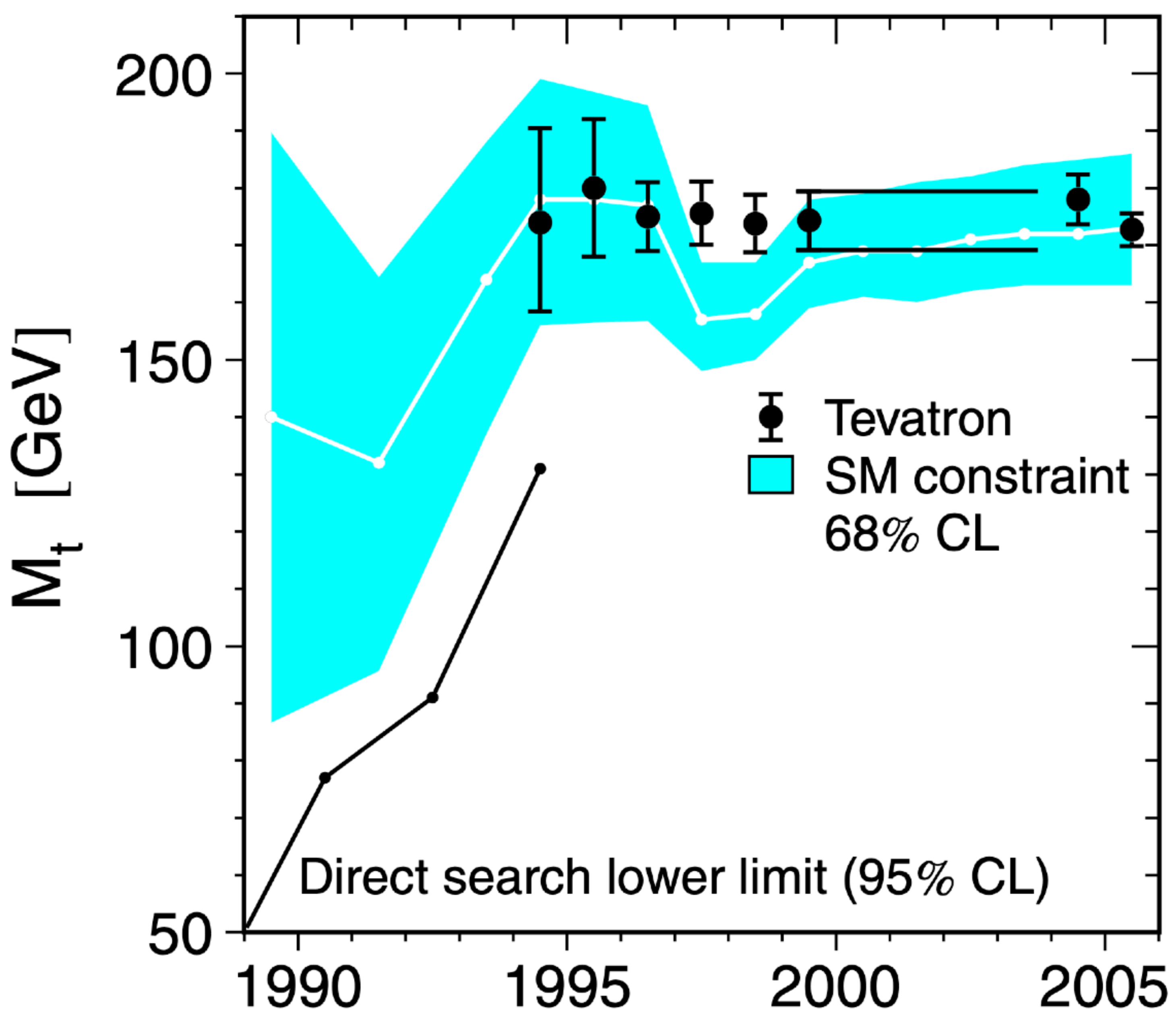


# LEP went far beyond its energy range

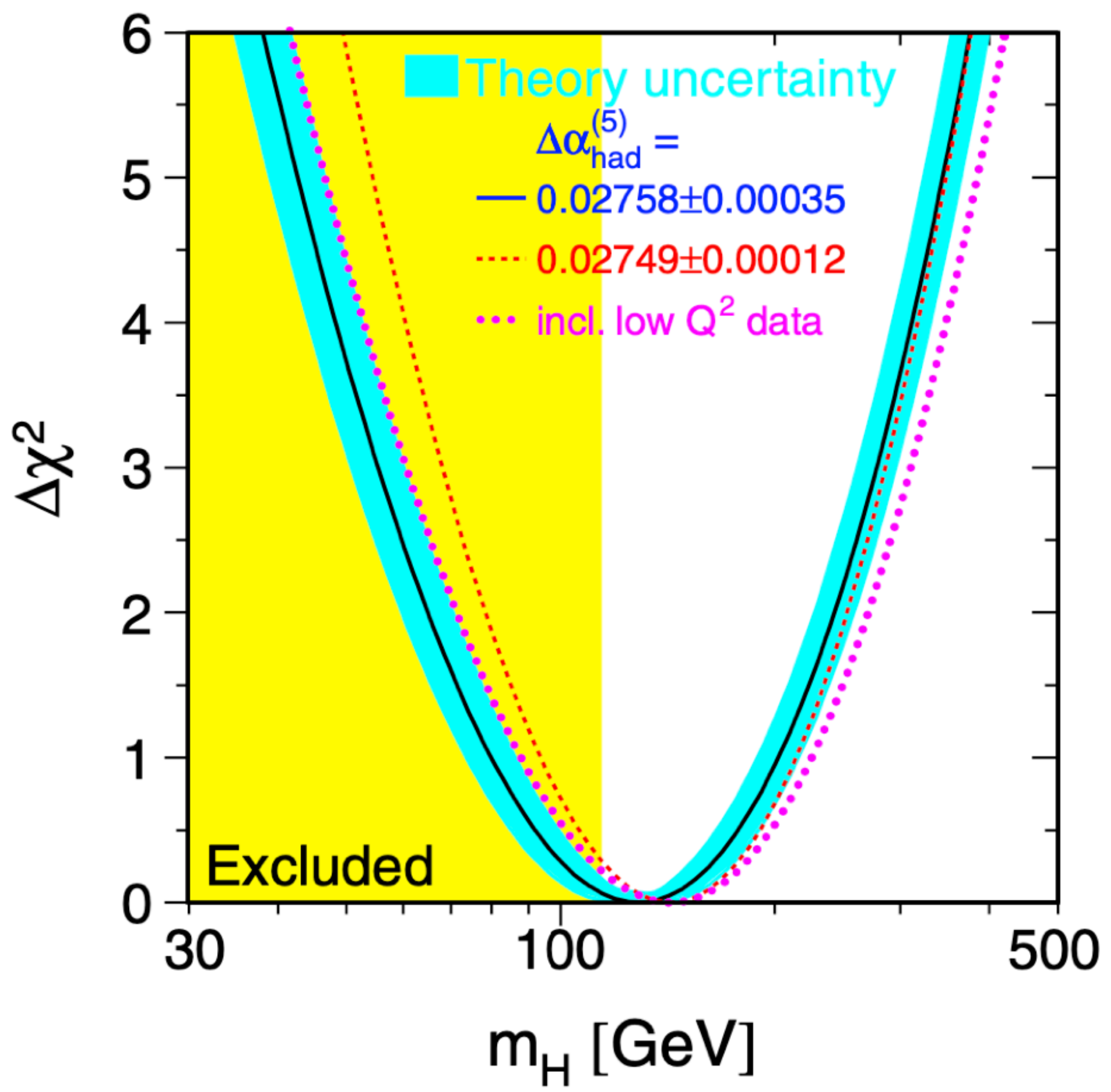
**LEP was the perfect complement to the Standard Model theory.**

**Nailing down most of its parameters it predicted what it was inaccessible and indicated the road to the future:**



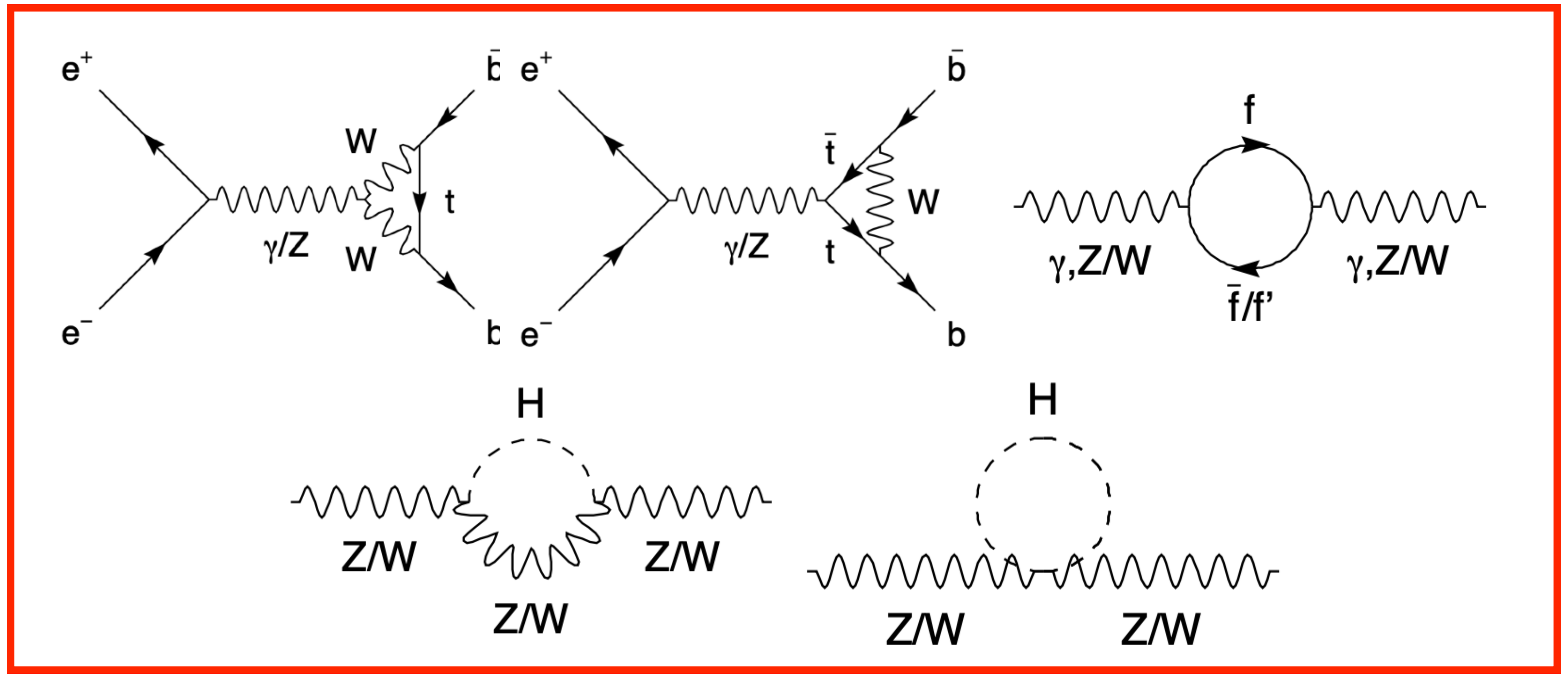

Top quark mass prediction from LEP:
$172.6^{+13.2}_{-10.2}\ GeV$

TEVATRON (discovery)+LHC:
$172.69 \pm 0.30\ GeV$




Higgs mass prediction from LEP:
$128 \pm^{74}_{49}\ GeV$

LHC:
$125.11 \pm 0.11\ GeV$



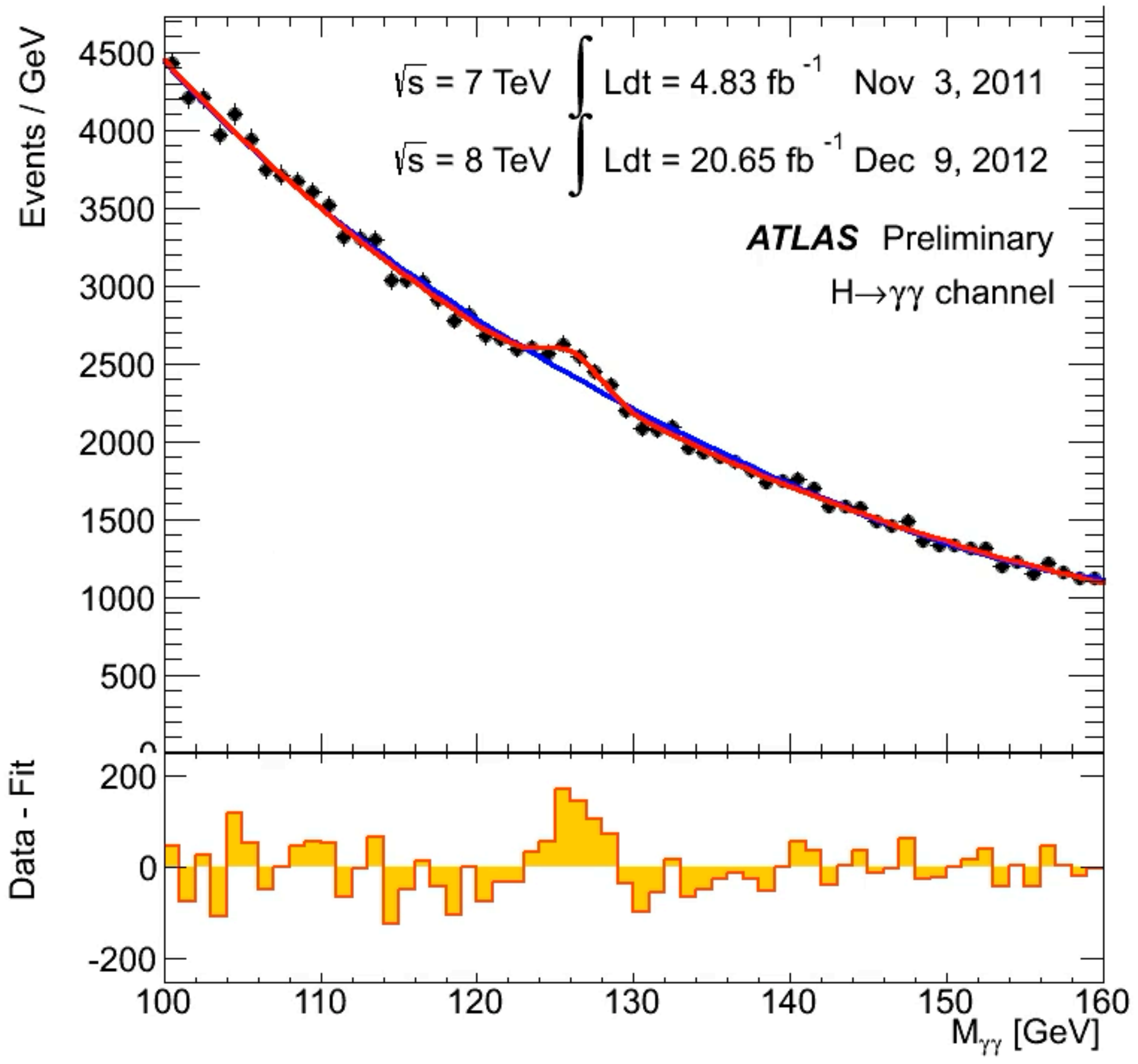
# Higgs: history of a discovery….

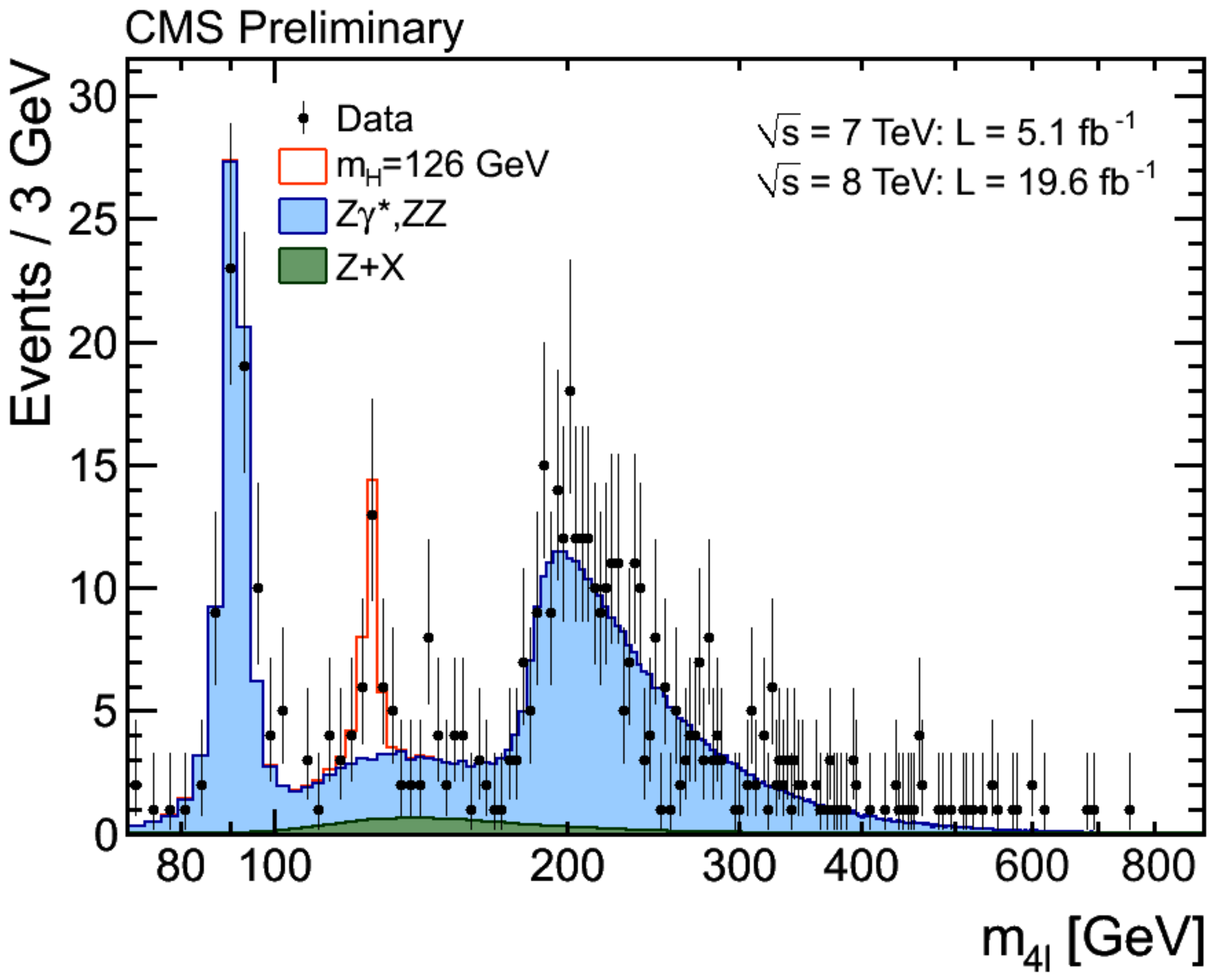
**Summer 2011: drops in the bucket**

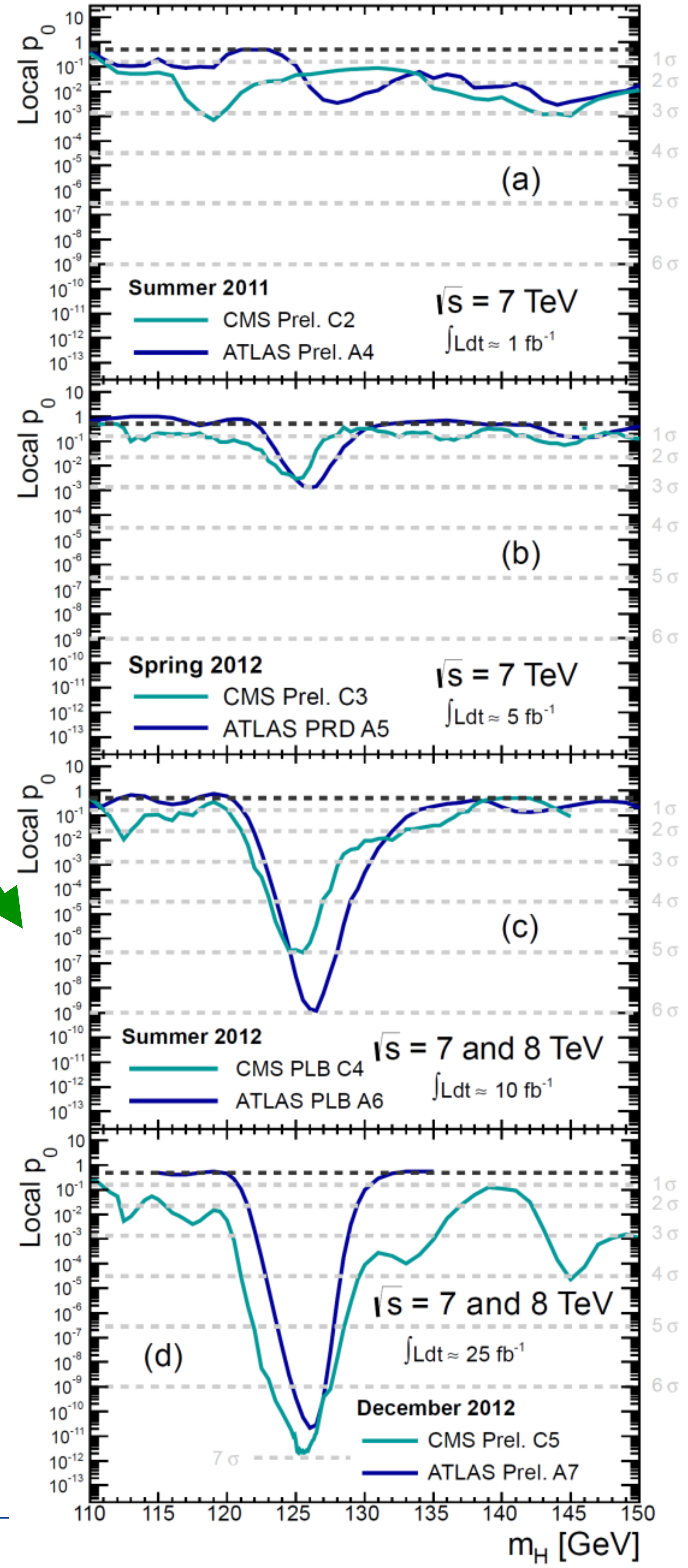
**End of 2011: tantalizing hint, the trail begins**

**Summer 2012: discovery! 5σ from both experiments**

**End of 2012: confirmation! Measurement era begins**



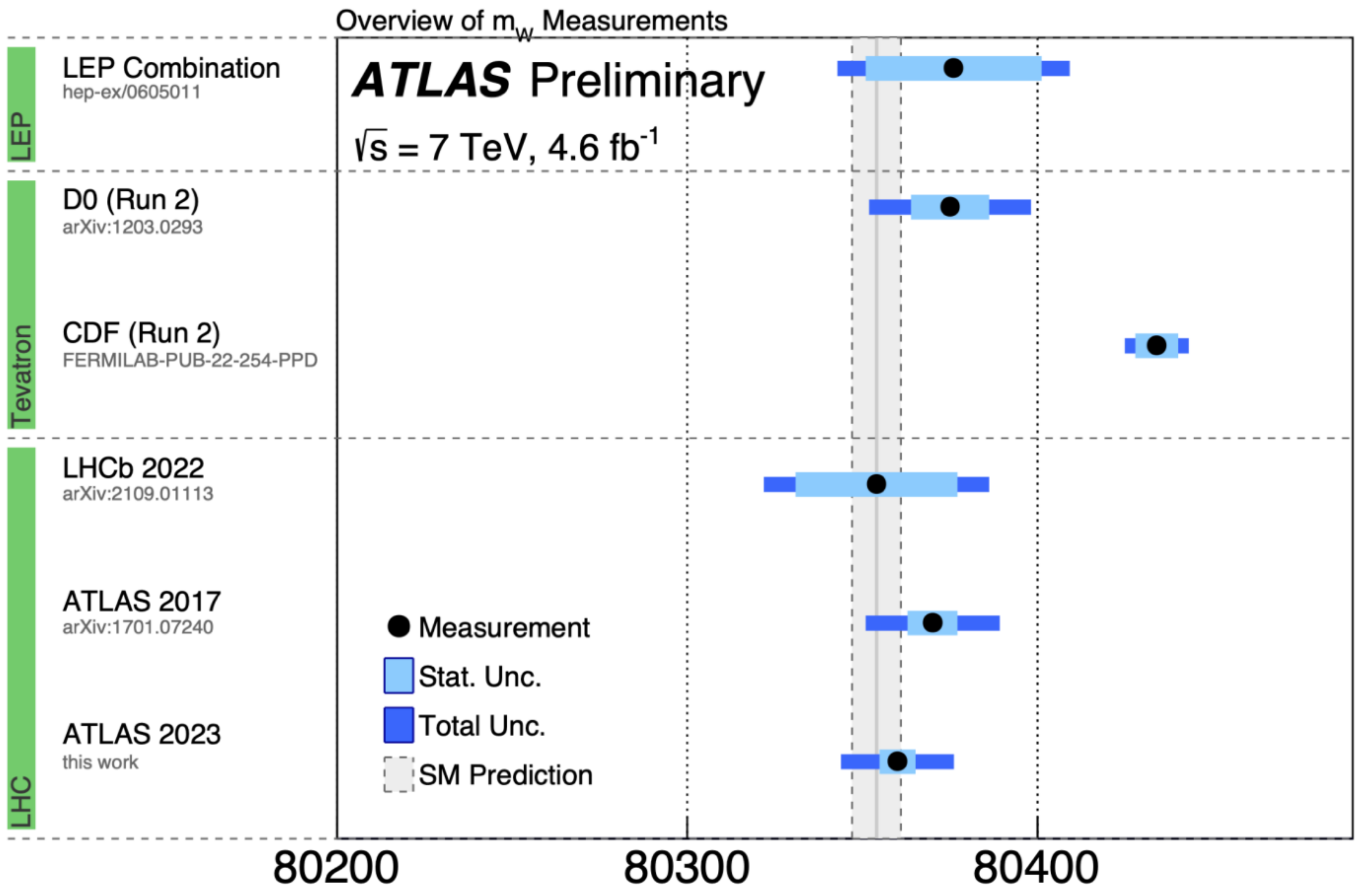



# LHC taking the baton from LEP as SM precision tester!

The LHC was intended as a discovery machine, targeting the Higgs as first goal.

It turned out that it is becoming a precision measurement machine challenging LEP on its own territory.



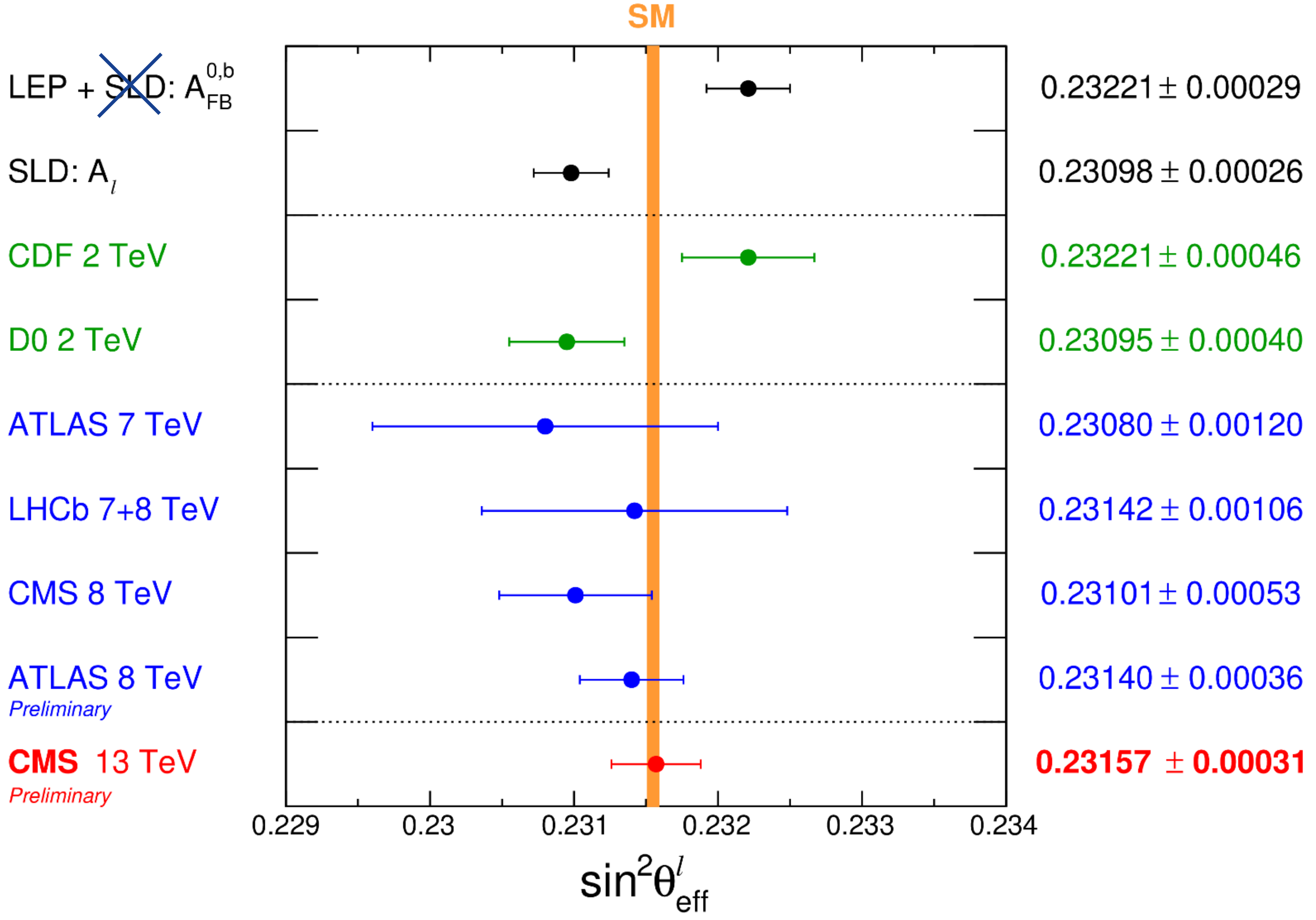

**Few examples here:**

**measurement of the W mass:**
**LEP ~0.04%, LHC ~0.02%**

**measurement of $\sin^2\theta^\ell_{eff}$:**
**LEP ~0.12%, LHC ~0.13%**

Recap: $\sin^2\theta^\ell_{eff} \sim 1 - \frac{m_W^2}{m_Z^2}$

**And, as bonus, top quark mass:**
**Tevatron ~0.37%, LHC ~0.19%**



# What's next?

## Short term: High Lumi LHC

**A 10-fold increase in luminosity (statistics) of the accelerator with a vigorous upgrade of all detectors to cope with the new challenges and extend the physics reach. It will run until 2040-2042**

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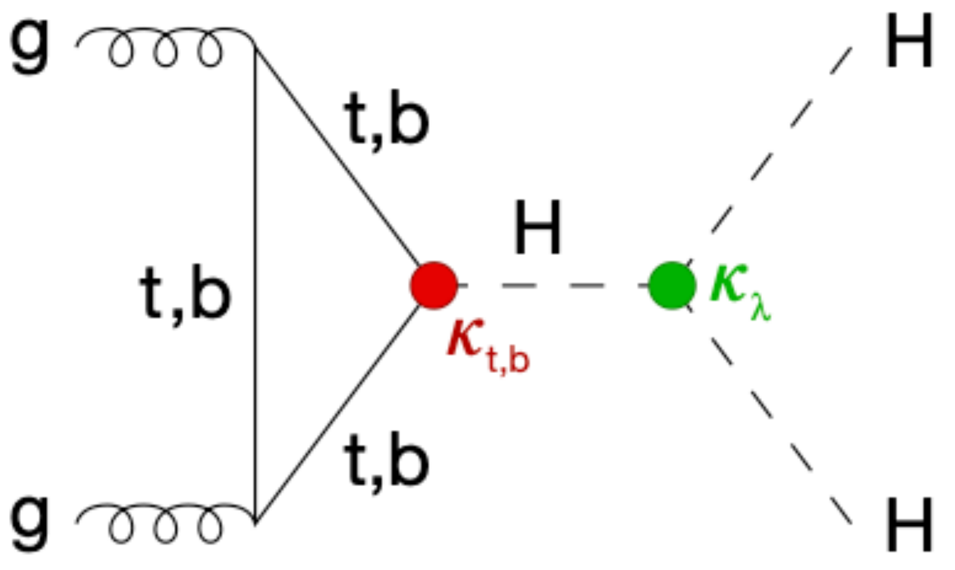
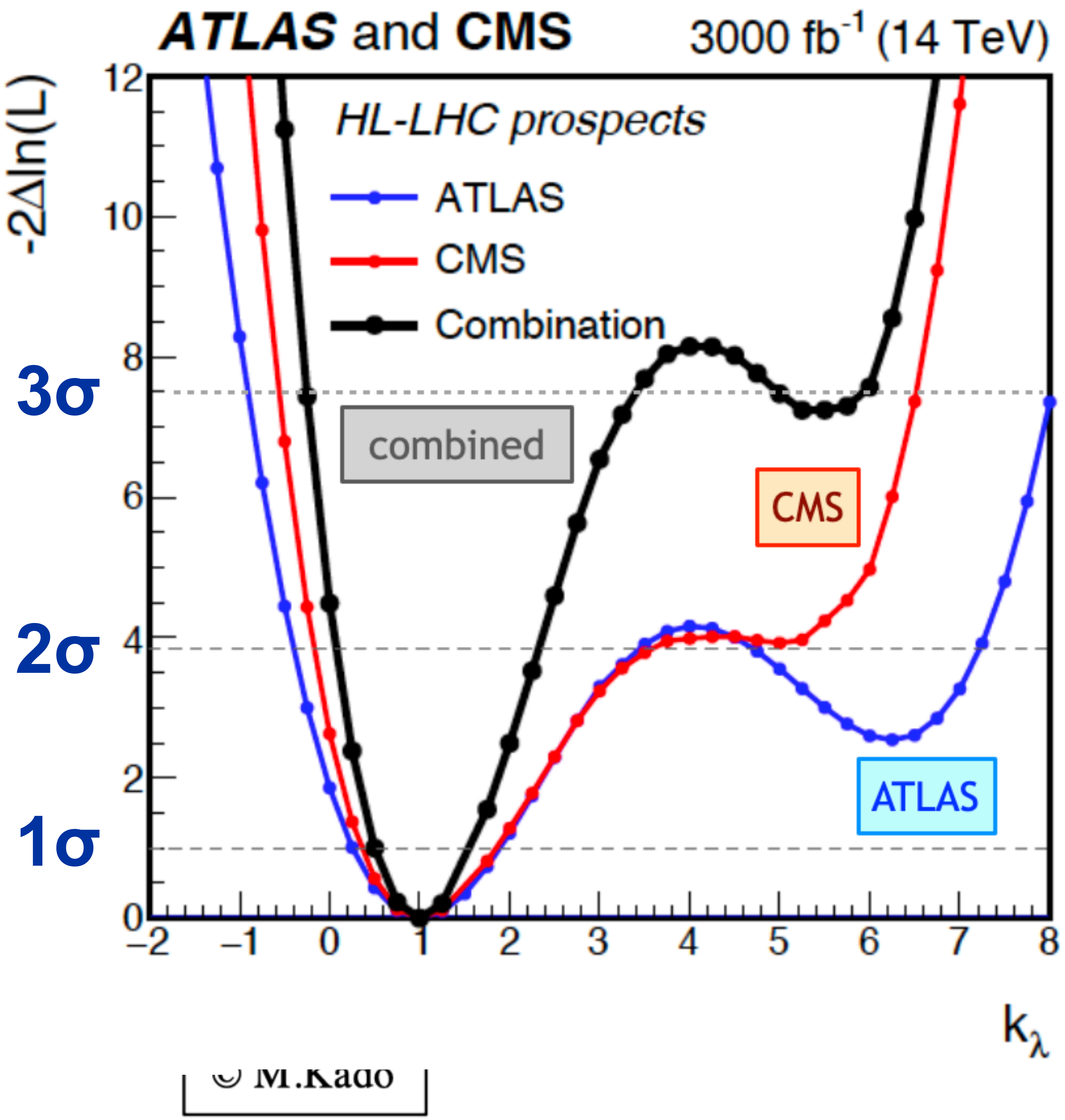
**The Higgs self-coupling, key parameter of the Standard Model and not accessible with current statistics, will be measured.**

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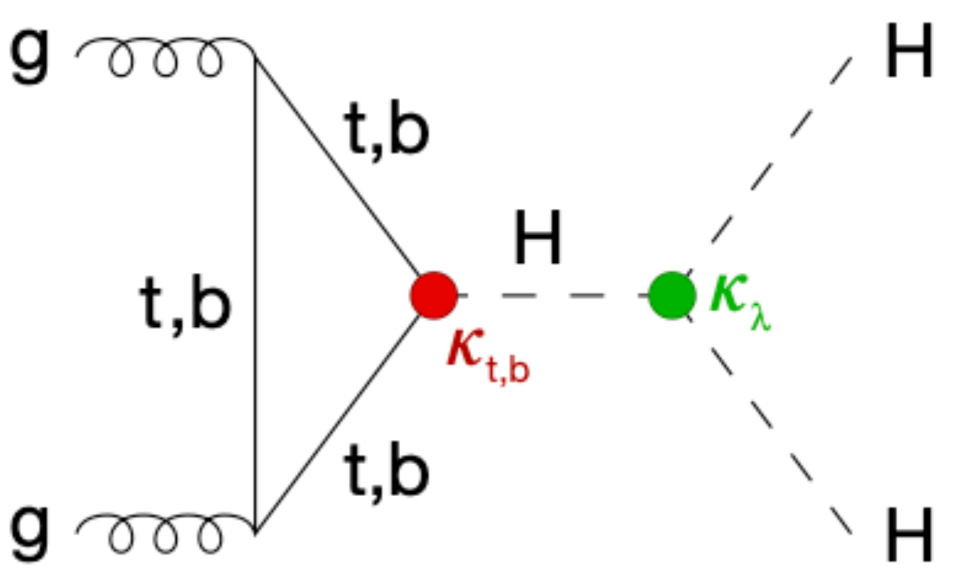


**Search for new particles/physics in the high mass regime will be extended by 20-200% percent**

| | ATLAS - CMS Run 1 combination | Current precision | HL-LHC |
|---|---|---|---|
| $\kappa_\gamma$ | 13% | 6% | 1.8% |
| $\kappa_W$ | 11% | 6% | 1.7% |
| $\kappa_Z$ | 11% | 6% | 1.5% |
| $\kappa_g$ | 14% | 7% | 2.5% |
| $\kappa_t$ | 30% | 11% | 3.4% |
| $\kappa_b$ | 26% | 11% | 3.7% |
| $\kappa_\tau$ | 15% | 8% | 1.9% |
| $\kappa_\mu$ | - | 20% | 4.3% |
| $\kappa_{Z\gamma}$ | - | 30% | 9.8% |
| $B_{inv}$ | | 11% | 2.5% |

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