PRECISION PHYSICS IN THE ERA OF (HL)LHC

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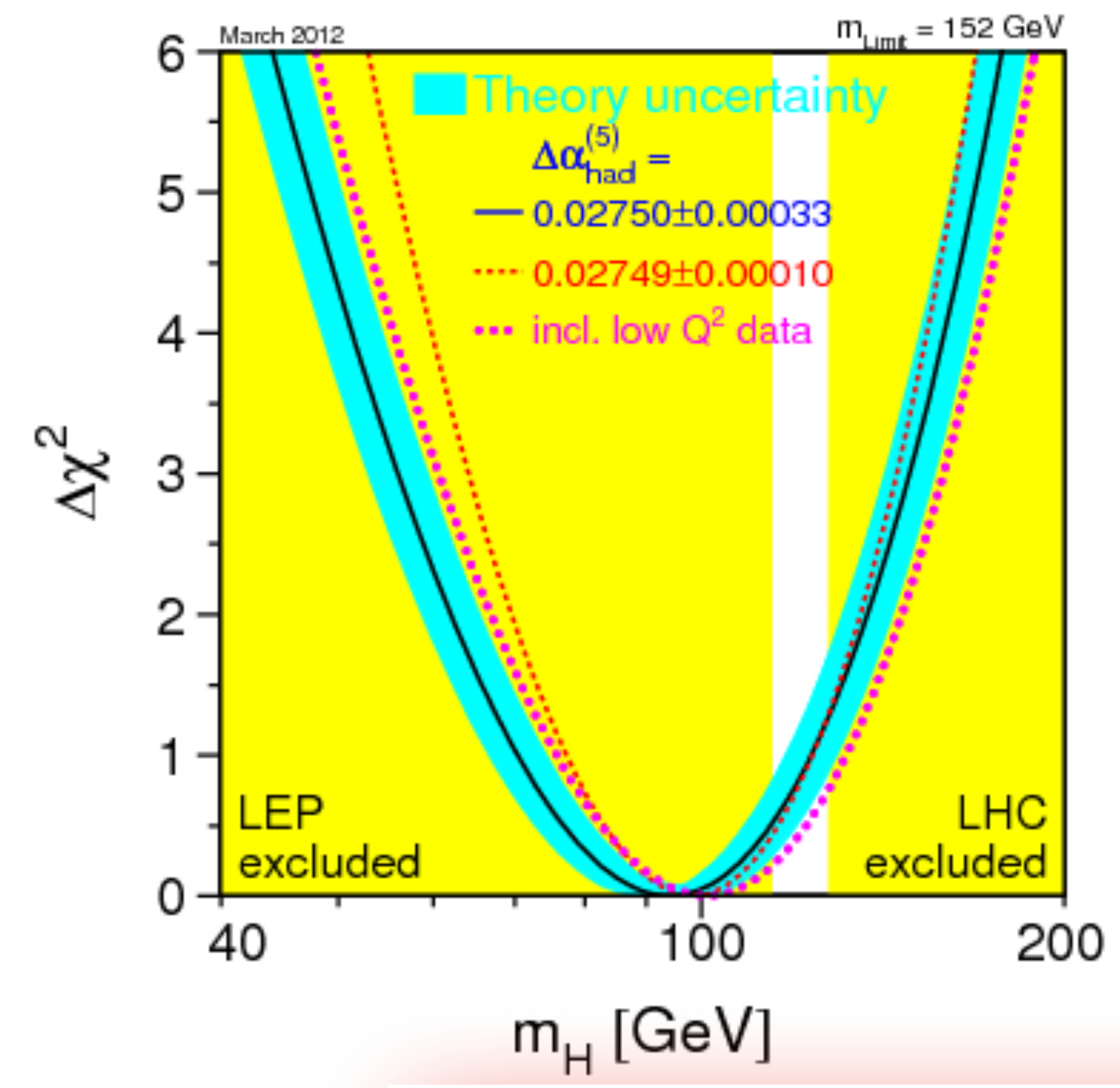
CERN

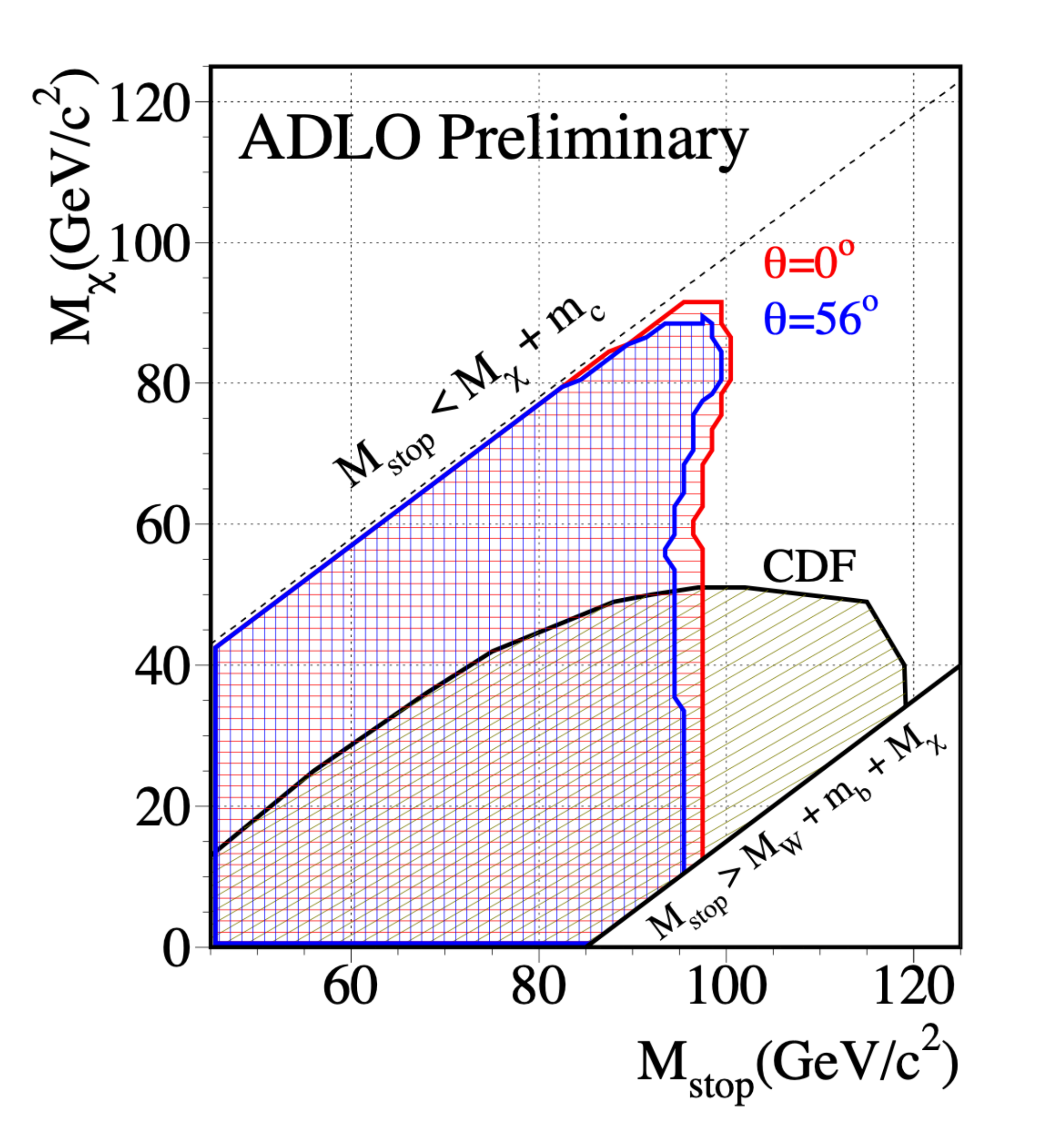
Particle Physics before the LHC

- Our understanding of particle physics was standing on two big assumptions:
  - The Higgs mechanism
  - EW-scale SUSY to stabilize the Higgs VEV
- Experimental physics was active on two fronts:
  - Indirect search of new physics via precision measurements at e^+e^- colliders
  - Direct search for new physics at hadron colliders

with few notable exceptions, among which

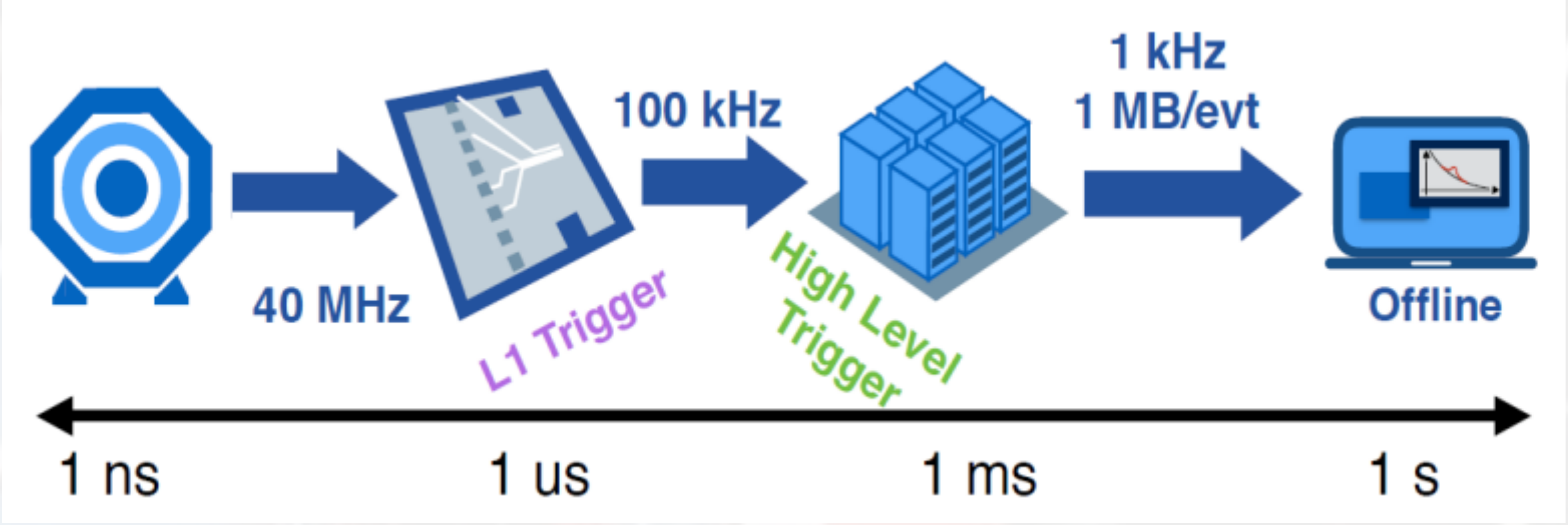
  - Search for EW SUSY at LEP
  - W mass measurement at Tevatron

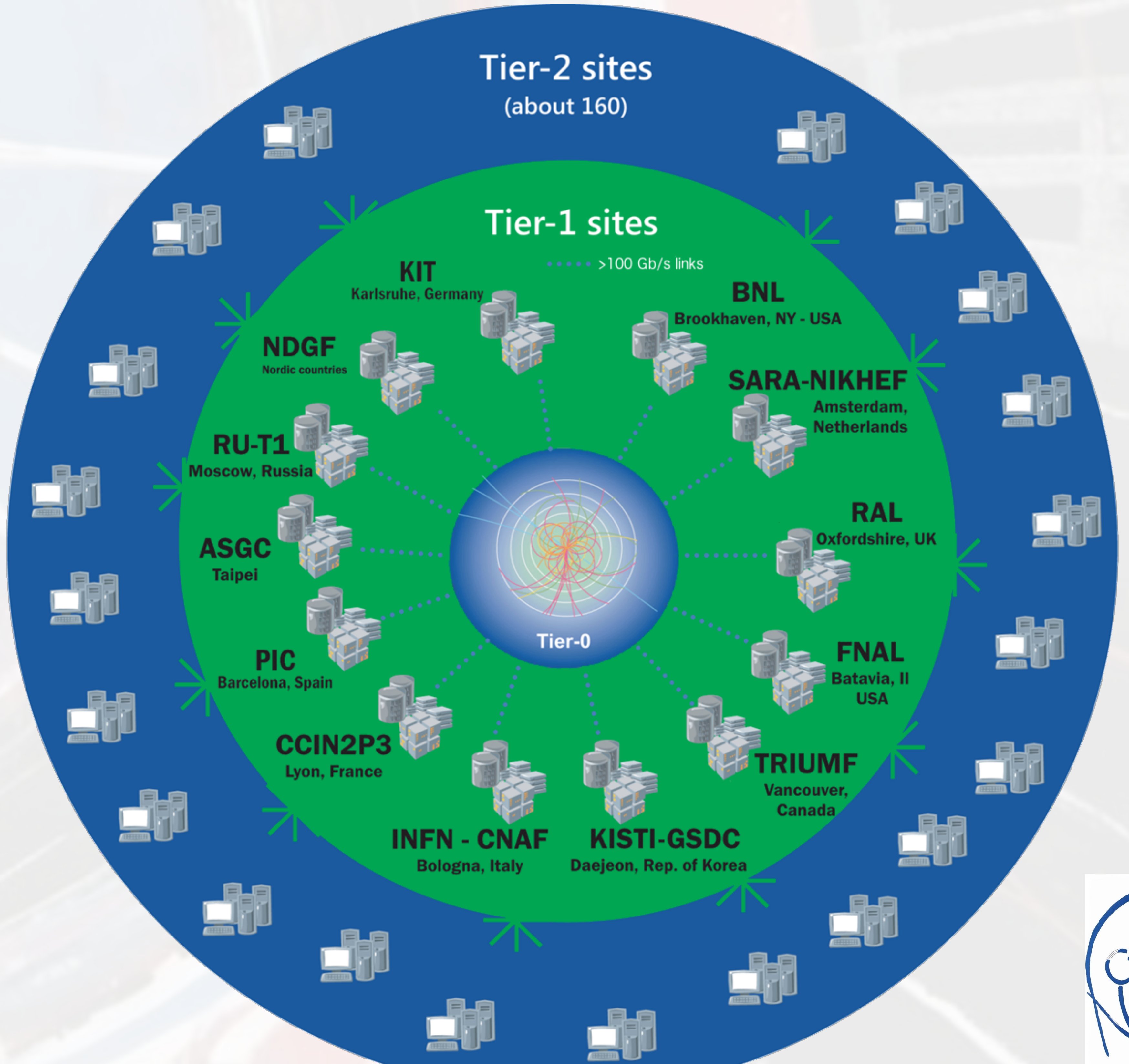




The initial mission

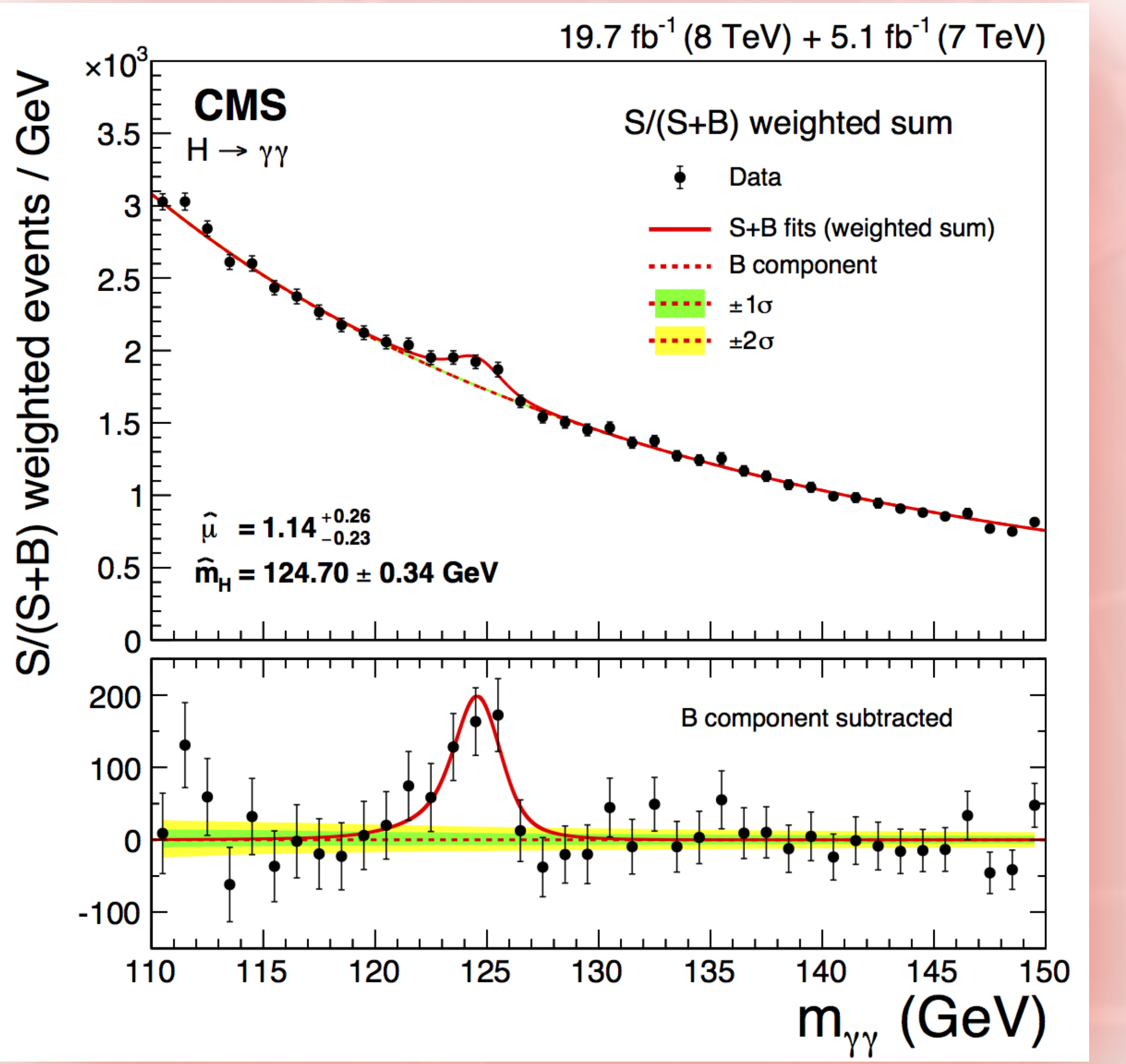
- LHC was built as the ultimate discovery machine and its initial mission reflected that
  - Find the Higgs boson or exclude the entire allowed mass range
  - Find SUSY at the EW scale (or any other SUSY alternative, e.g., extra dimensions)
- The main strength was supposed to be the large dataset
  - Which came with computing challenges, addressed by the HLT paradigm and the LHC Computing Grid
- The price to pay was the harsh environment
  - High particle multiplicity at collision
  - Pileup
- Most of these challenges are now "business as usual" thanks to unforeseen progress we made

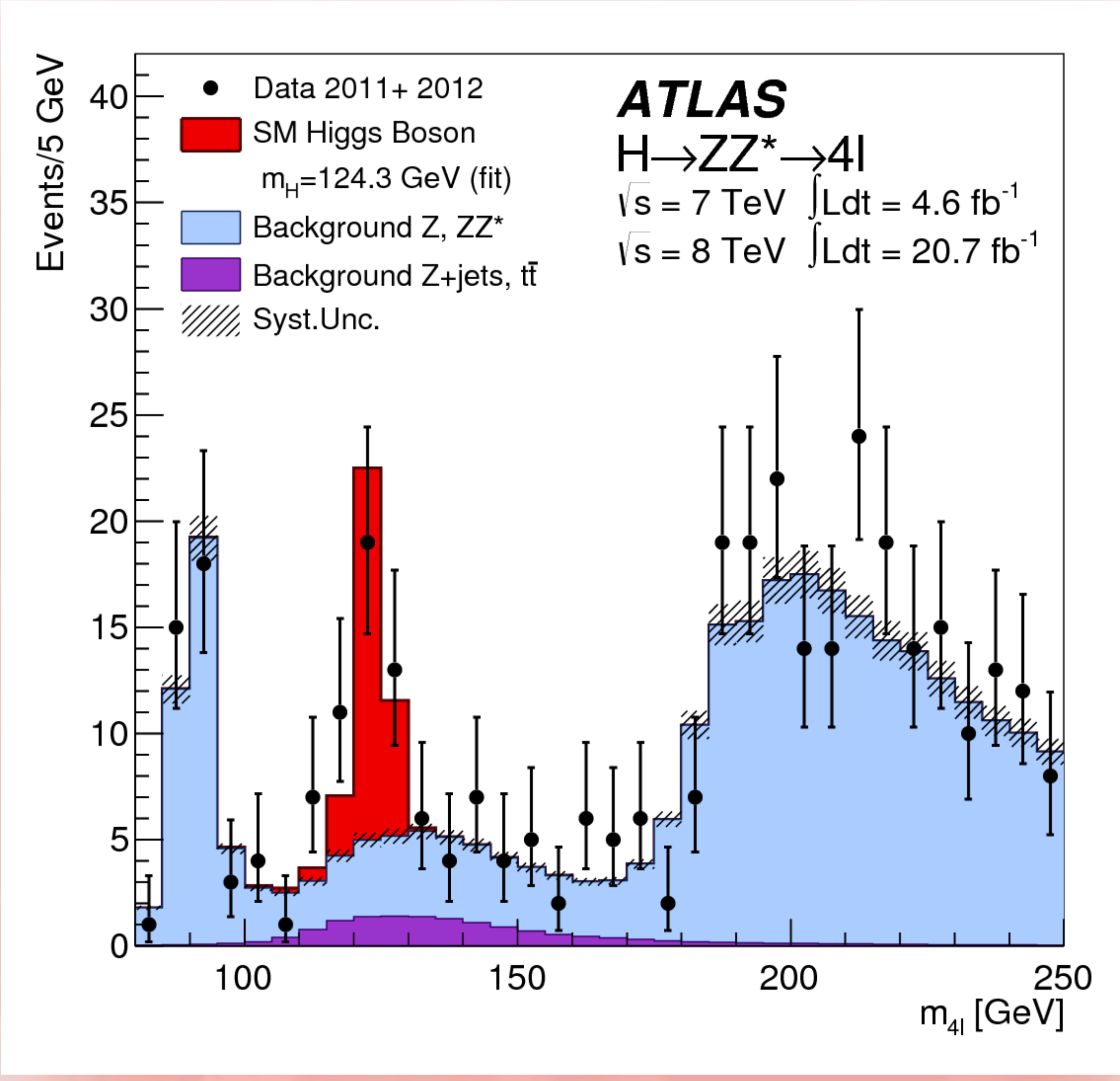


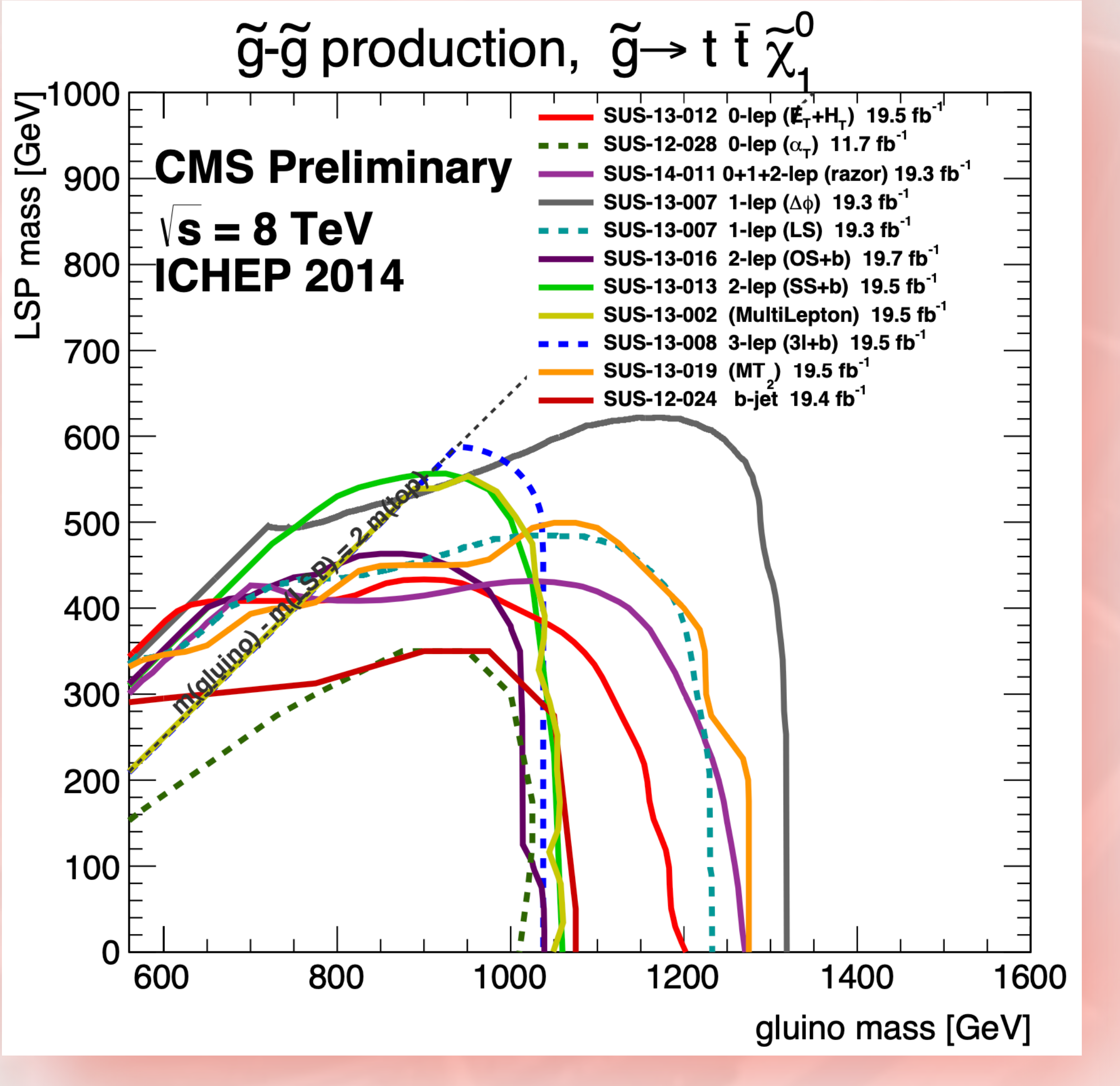


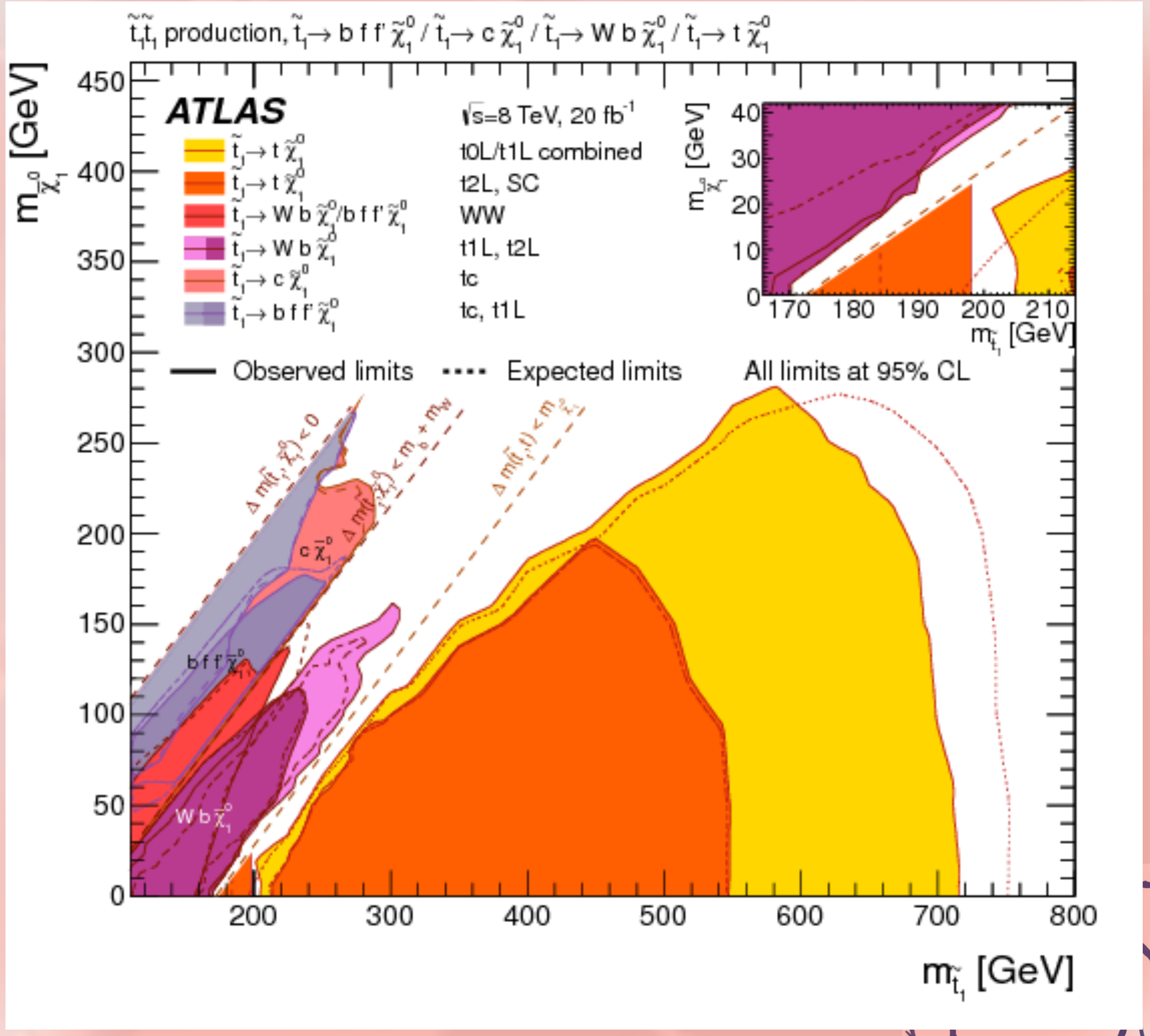
Mission (sort of) Accomplished

- We discovered the Higgs boson
  - Earlier than anticipated, with 1/2 the energy and way less data
- We excluded **most** of EW-scale Natural SUSY parameter space (*)
  - gluon searches kill any model in which the gluino is accessible at the LHC
  - if gluon decouples, majority of the parameter space is in any case excluded





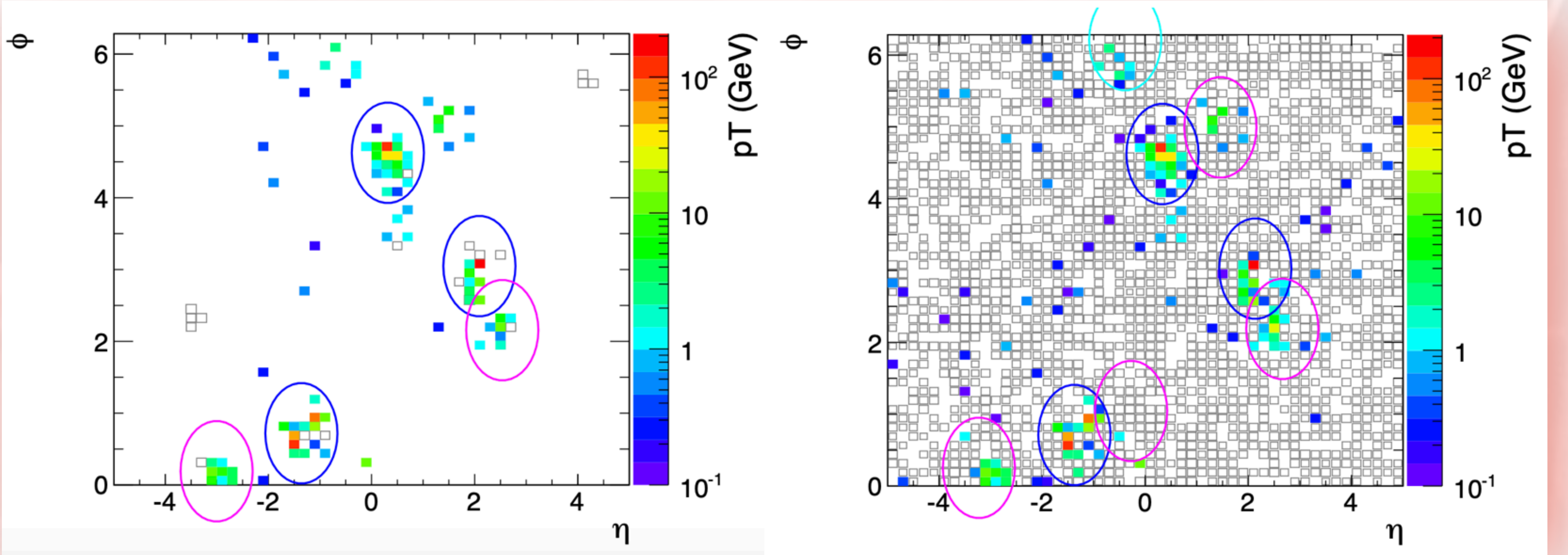


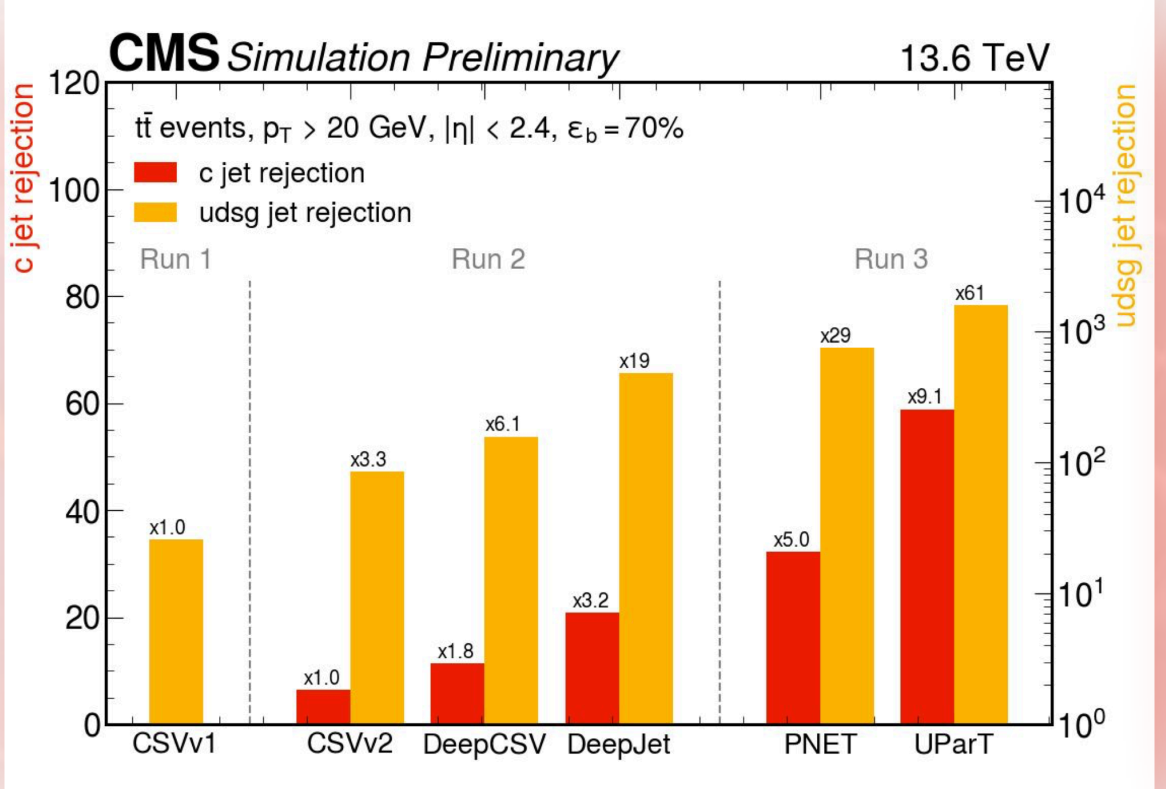


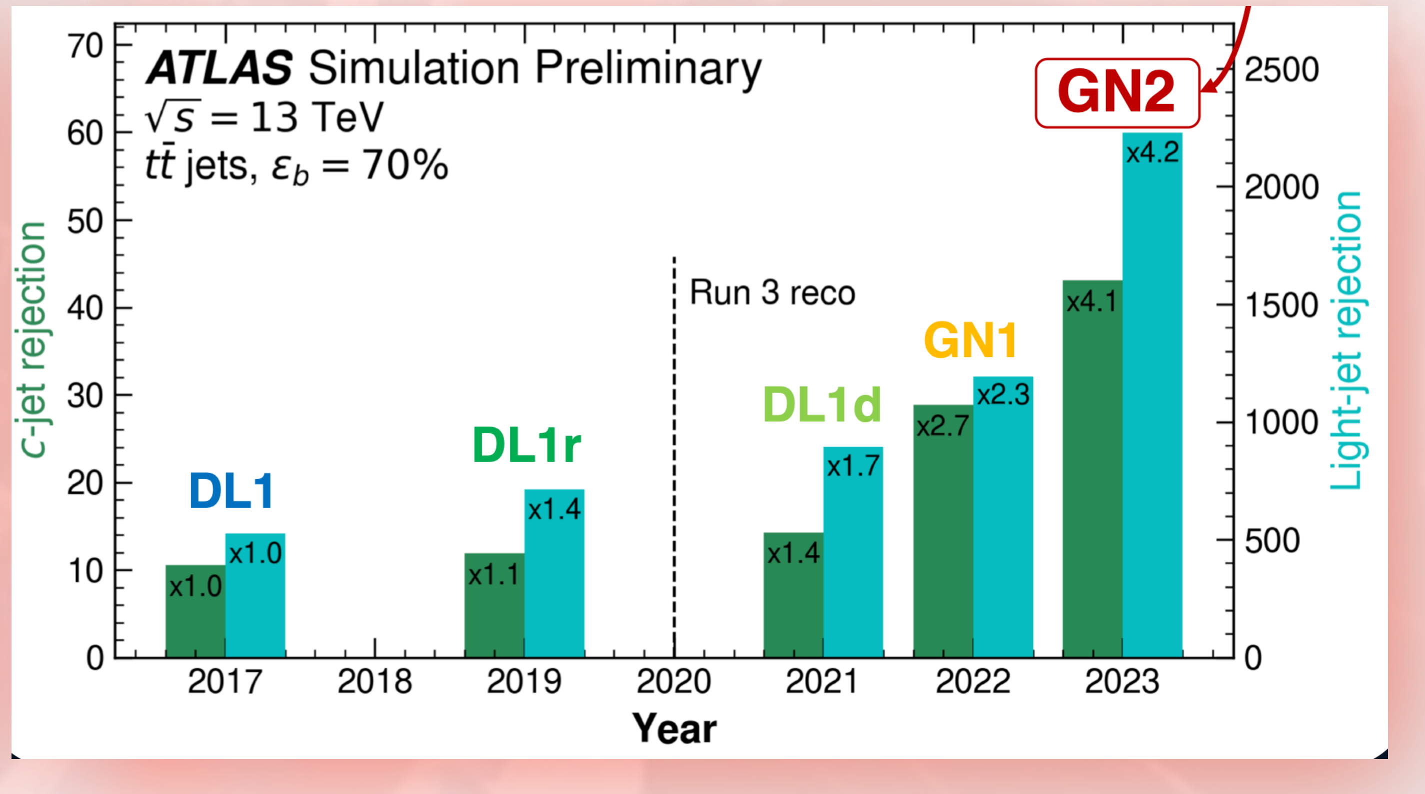
(*) With R-parity conservation, etc. etc.

Rise in Precision: Better Data

- The quest to accomplish these goals and the following exploitation of Run3 produced several experimental milestones
  - Advanced event processing, e.g., pileup subtraction schemes
  - Improved reconstruction algorithms, e.g., jet tagging
  - …
- Since ~ 2015, these improvements have been boosted by the use of Deep Learning algorithms
- The result of this process is a much more accurate event reconstruction, enabling the exploitation of LHC data for precision physics

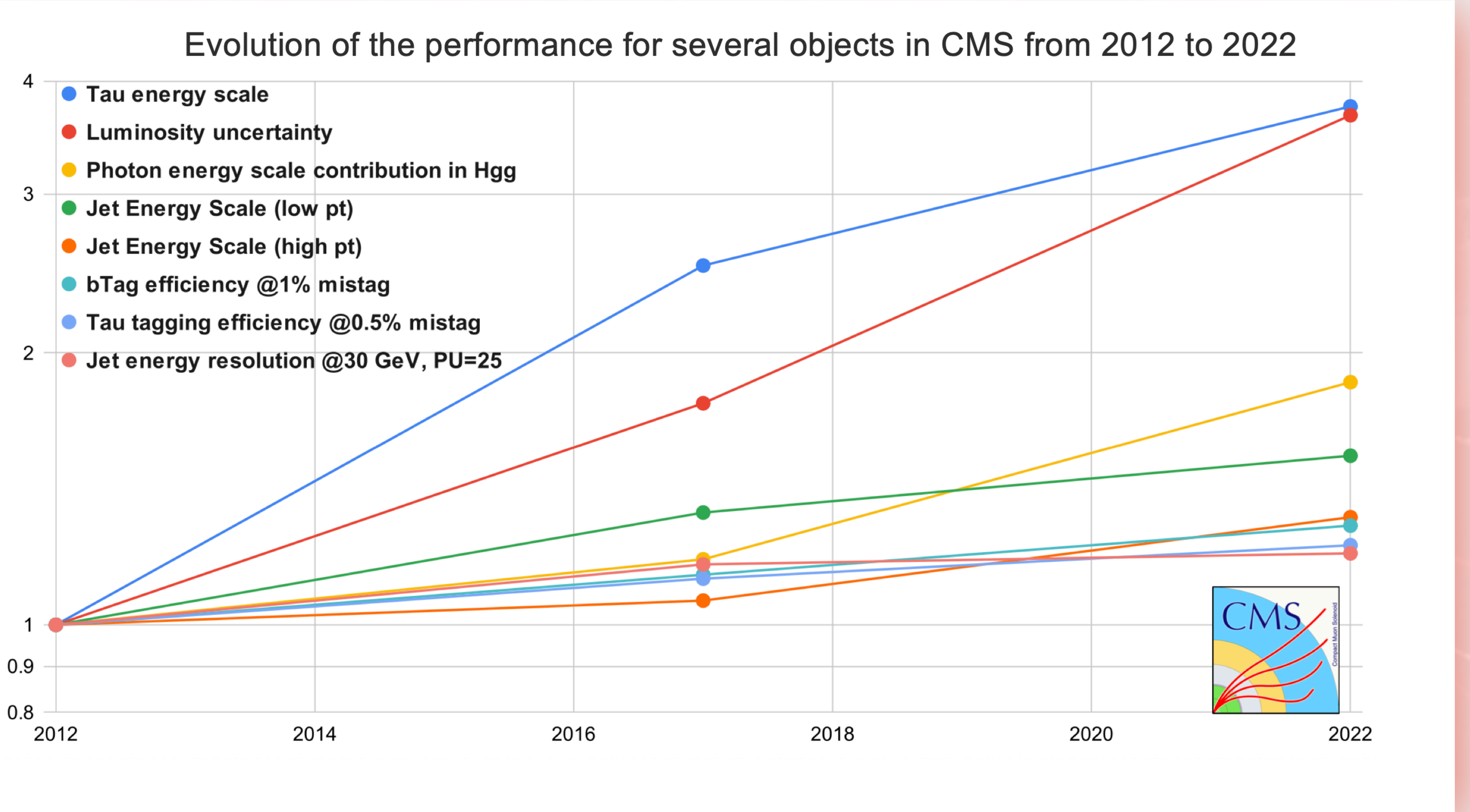






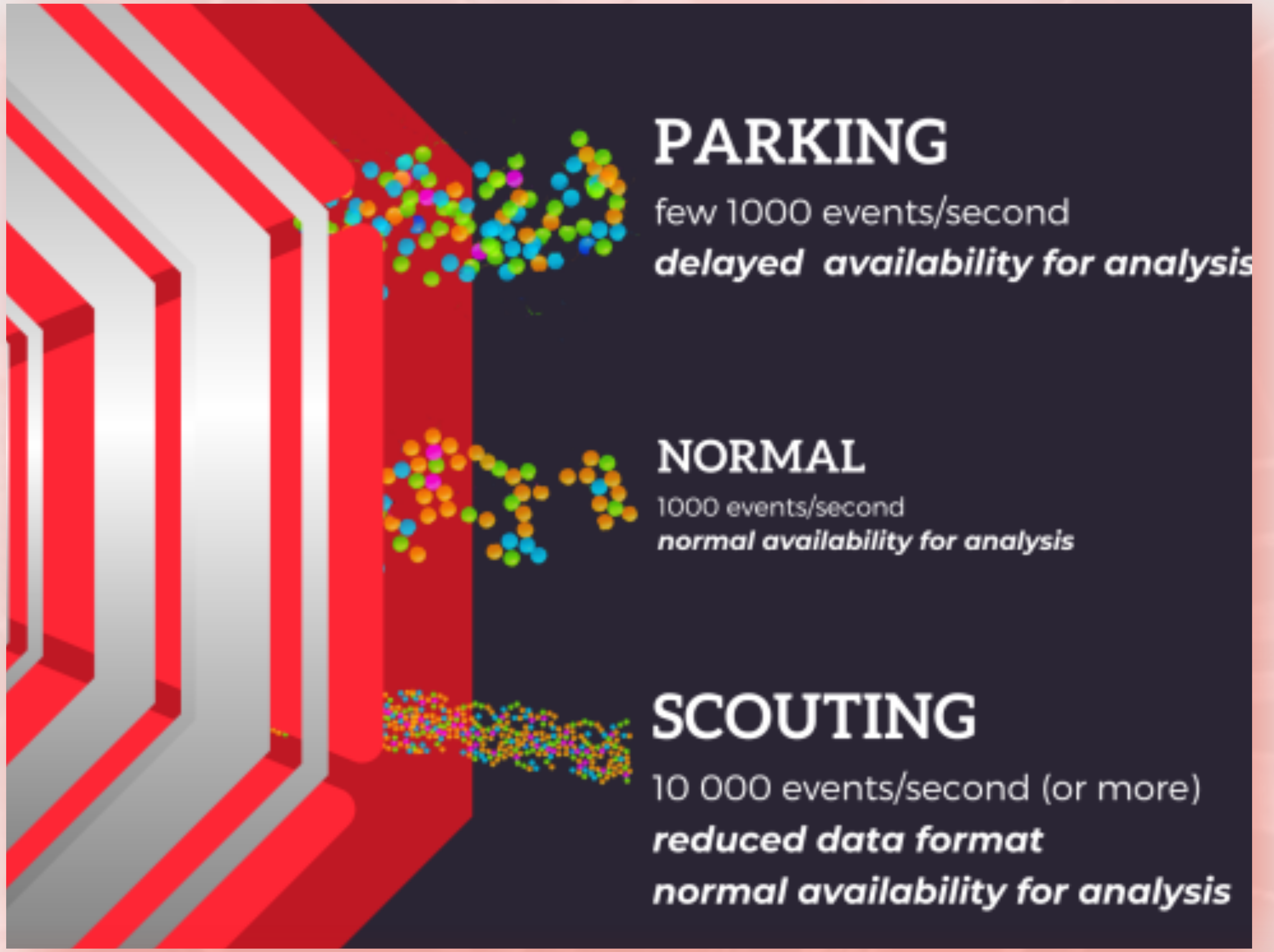
Rise in Precision: Better Data

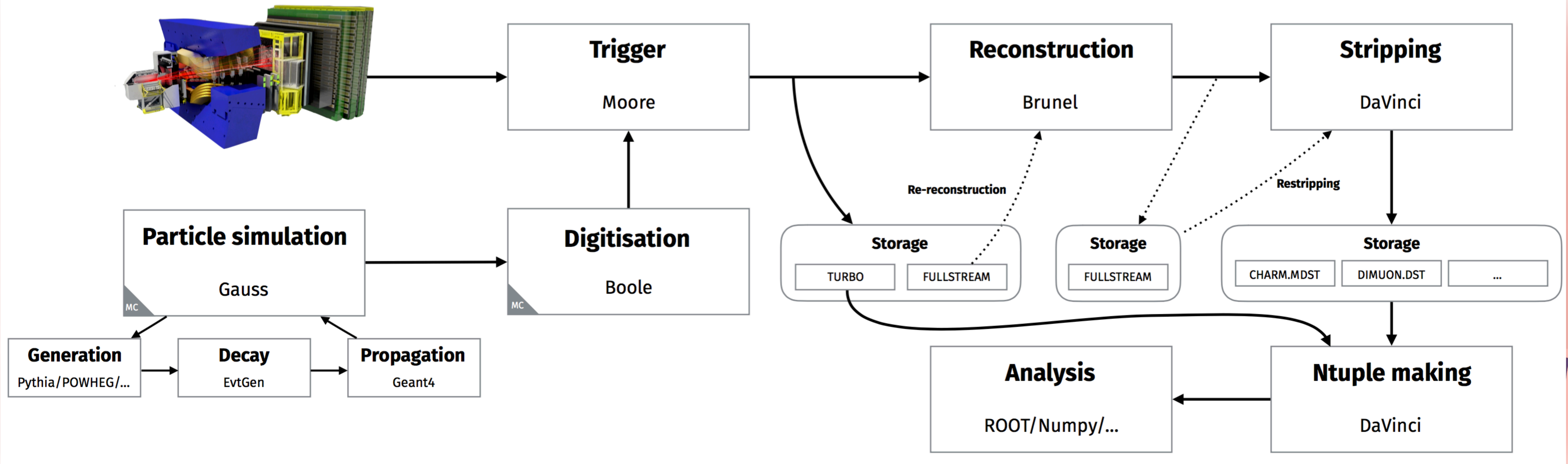
F. Gianotti's talk at ICHEP 2022



Rise in Precision: More Data

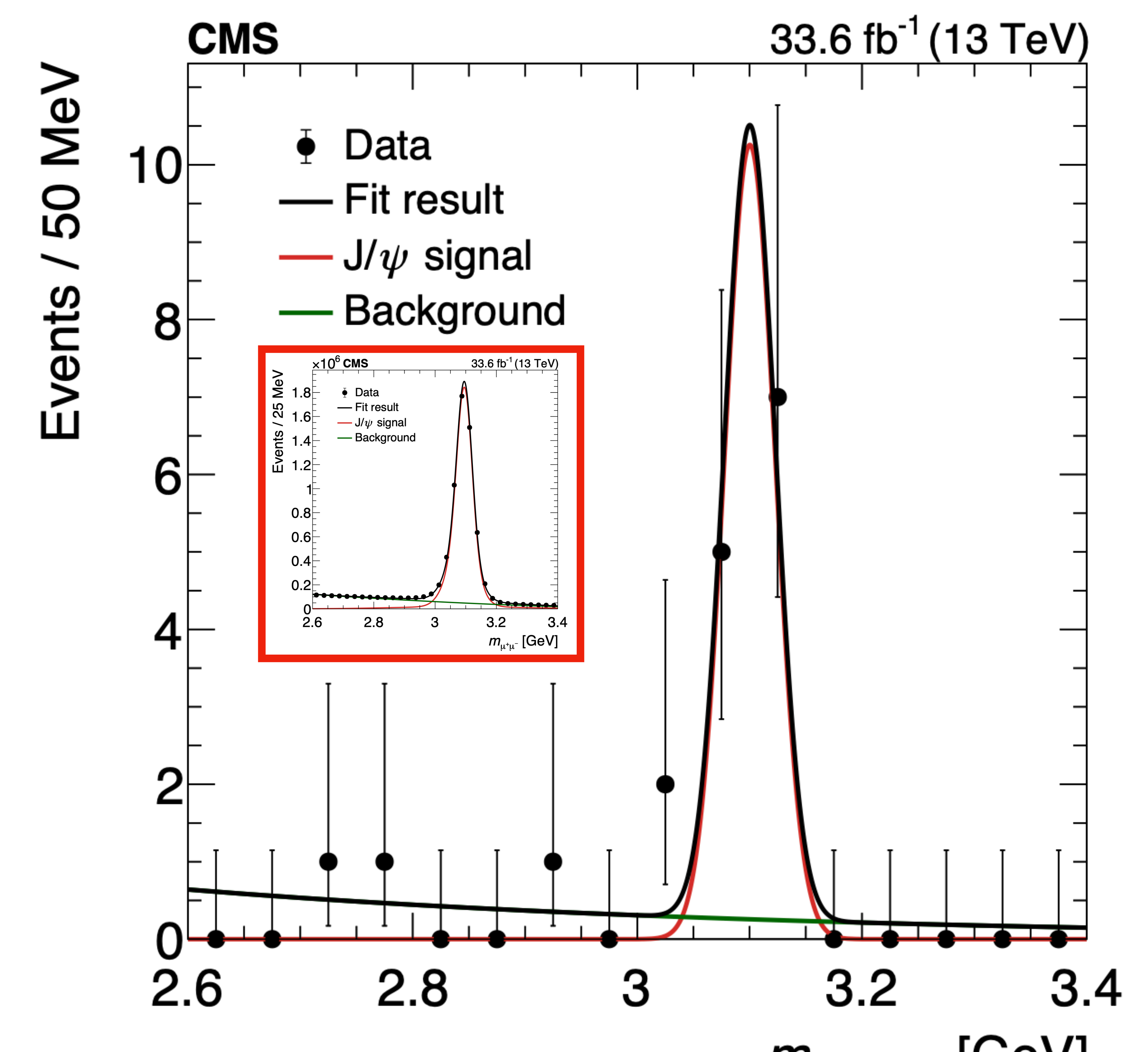
- The LHC delivers more collision than what the experiments can take
  - Experiments designed to take only "interesting events" up to some budget
- Since Run1, experiments worked to break this paradigm
  - With parking / delayed reconstruction: take more data than what can be processed promptly. Store them on tape. Process them when CPU available (e.g., during shutdowns)
  - With scouting / turbo stream / Trigger-level analysis: exploit the trigger reconstruction to do analysis, as opposed to use it just to accept/reject the event



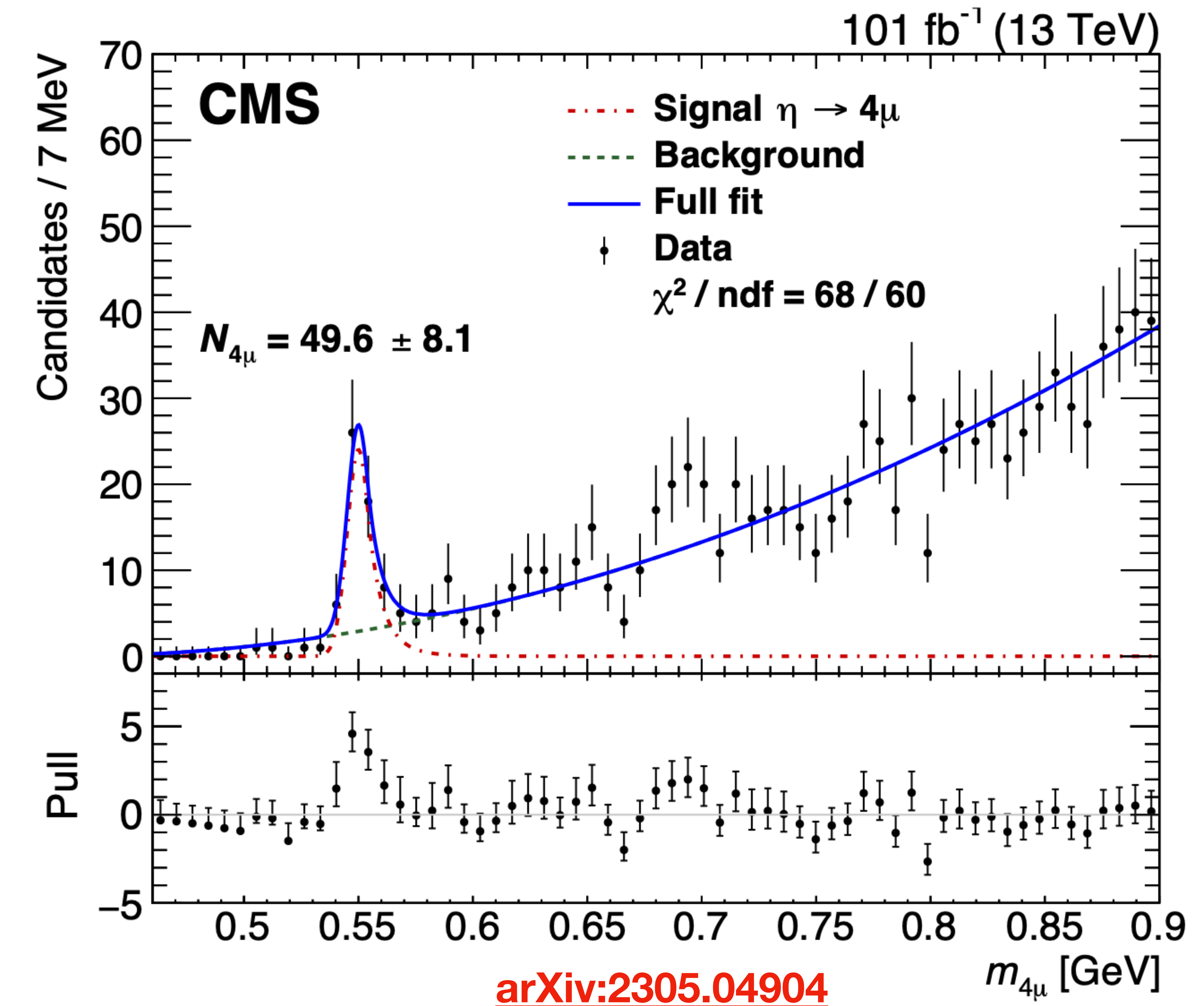


Rise in Precision: More Data

- A detector built to look for resonances decaying to muons at O(100) GeV and above can now be used in a completely different regime

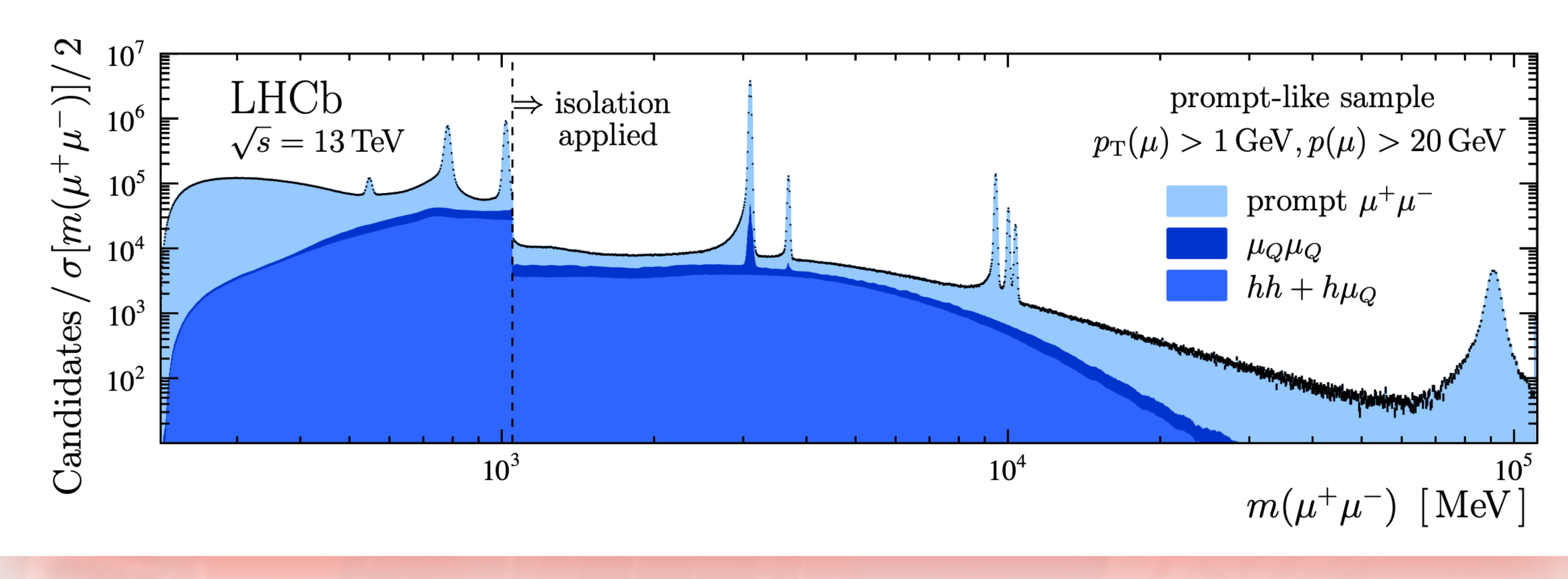


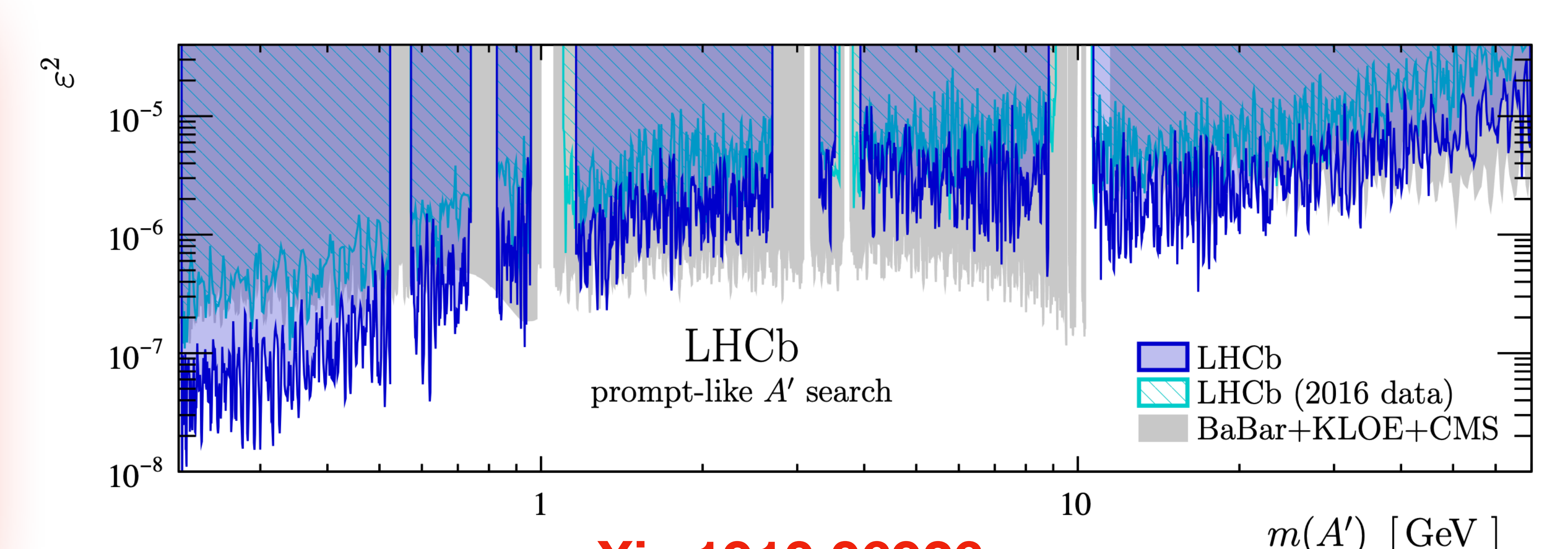
arXiv:2403.11352



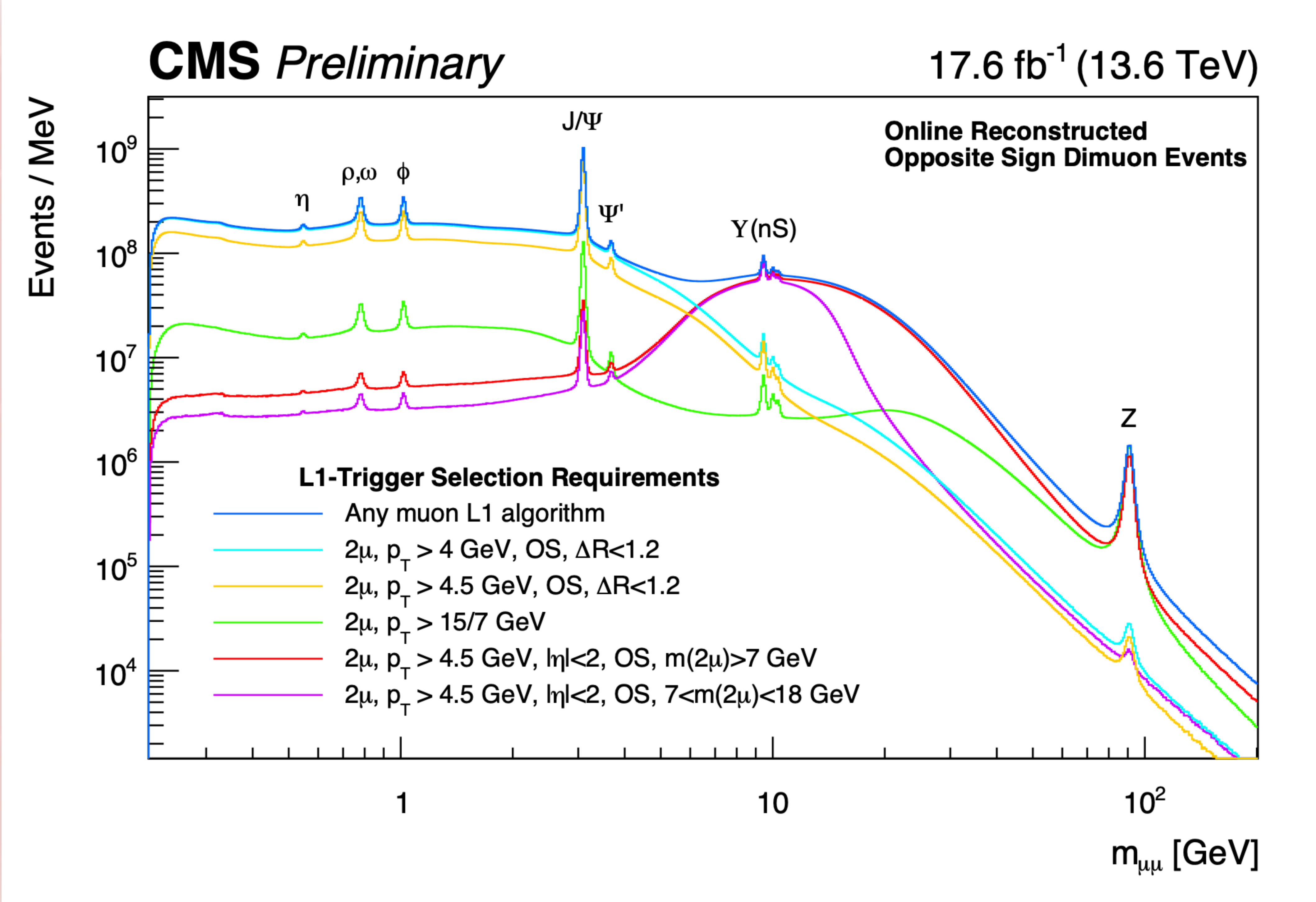
arXiv:2305.04904

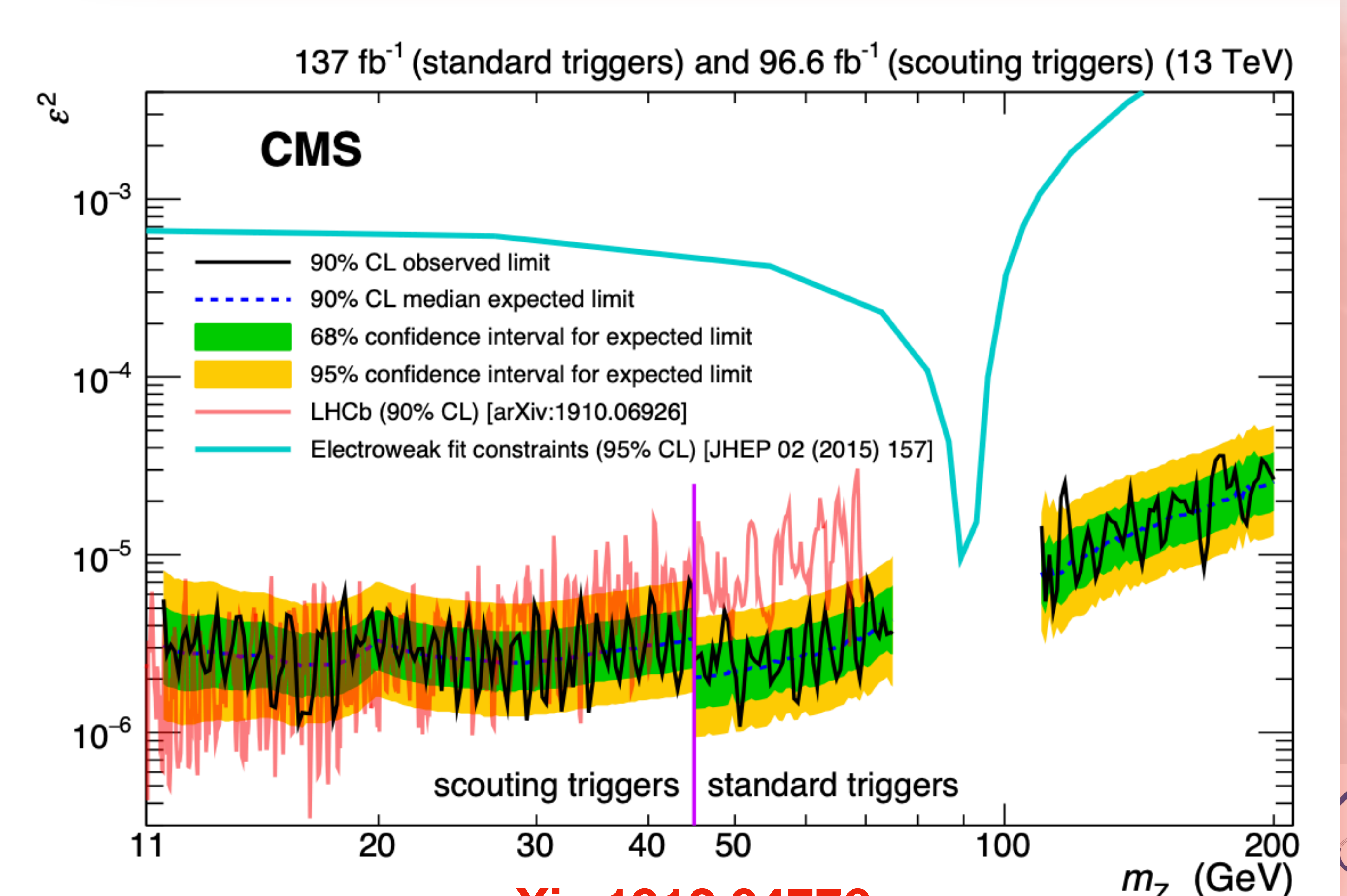
From the candle calibration to the search





arXiv:1910.06926

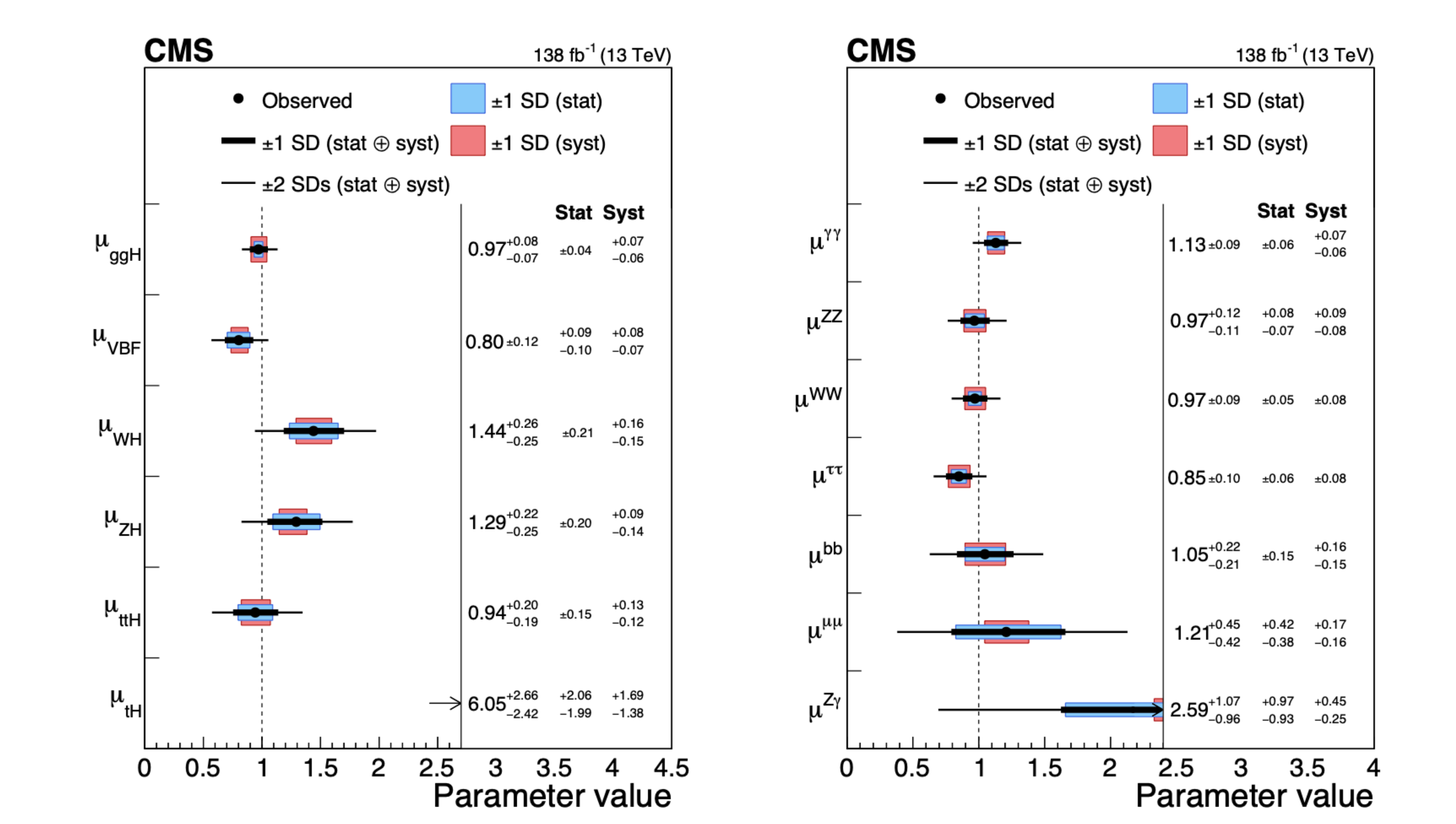


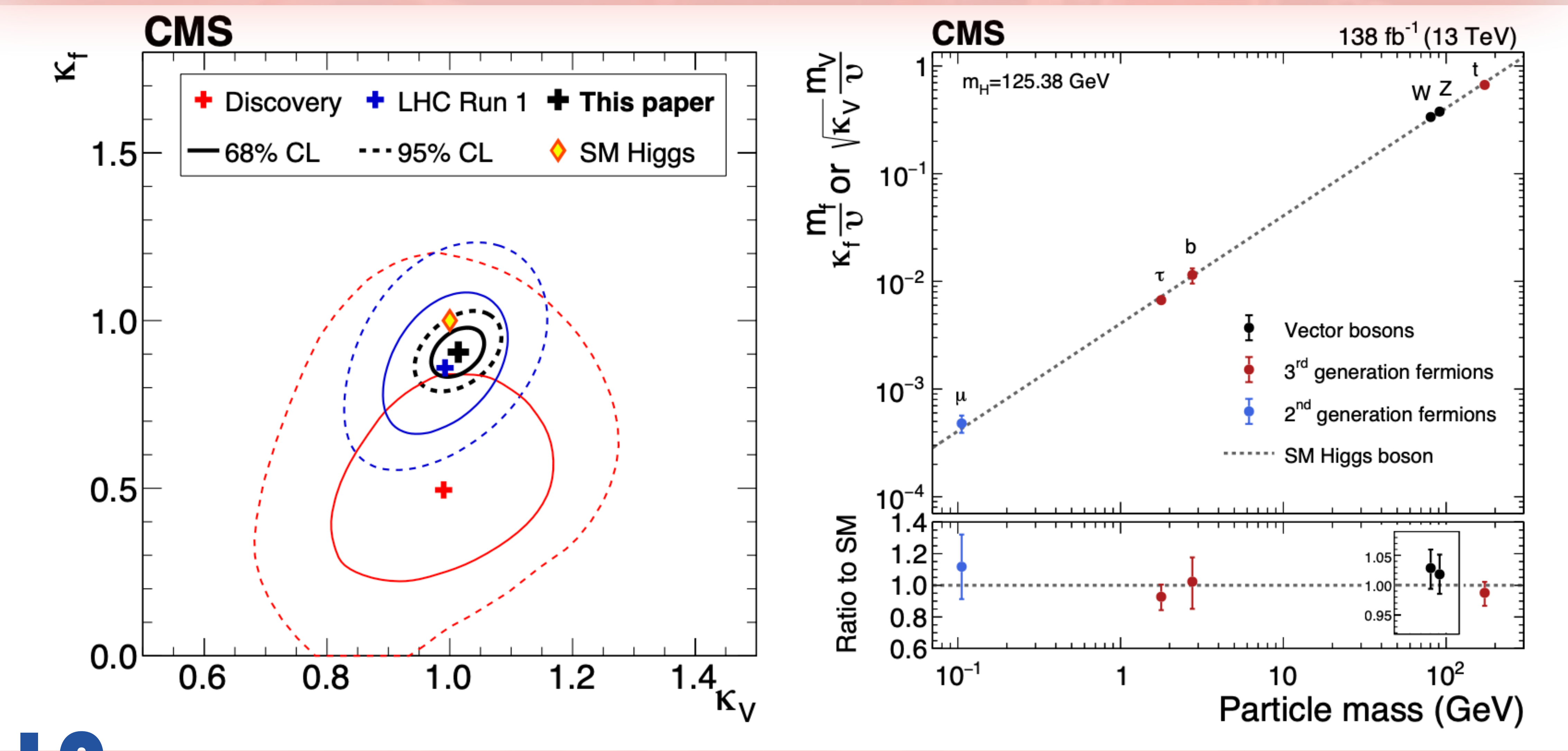


arXiv:1912.04776

Precision H Physics

- Pushing precision already <10% for most of the couplings
  - Exploiting ~5% of the total (expected) HL-LHC dataset
- Extended sensitivity beyond expectations
  - We can probe the 2nd generation with $H \to \mu\mu$ and $H \to cc$ via novel deep-learning based c-jet taggers

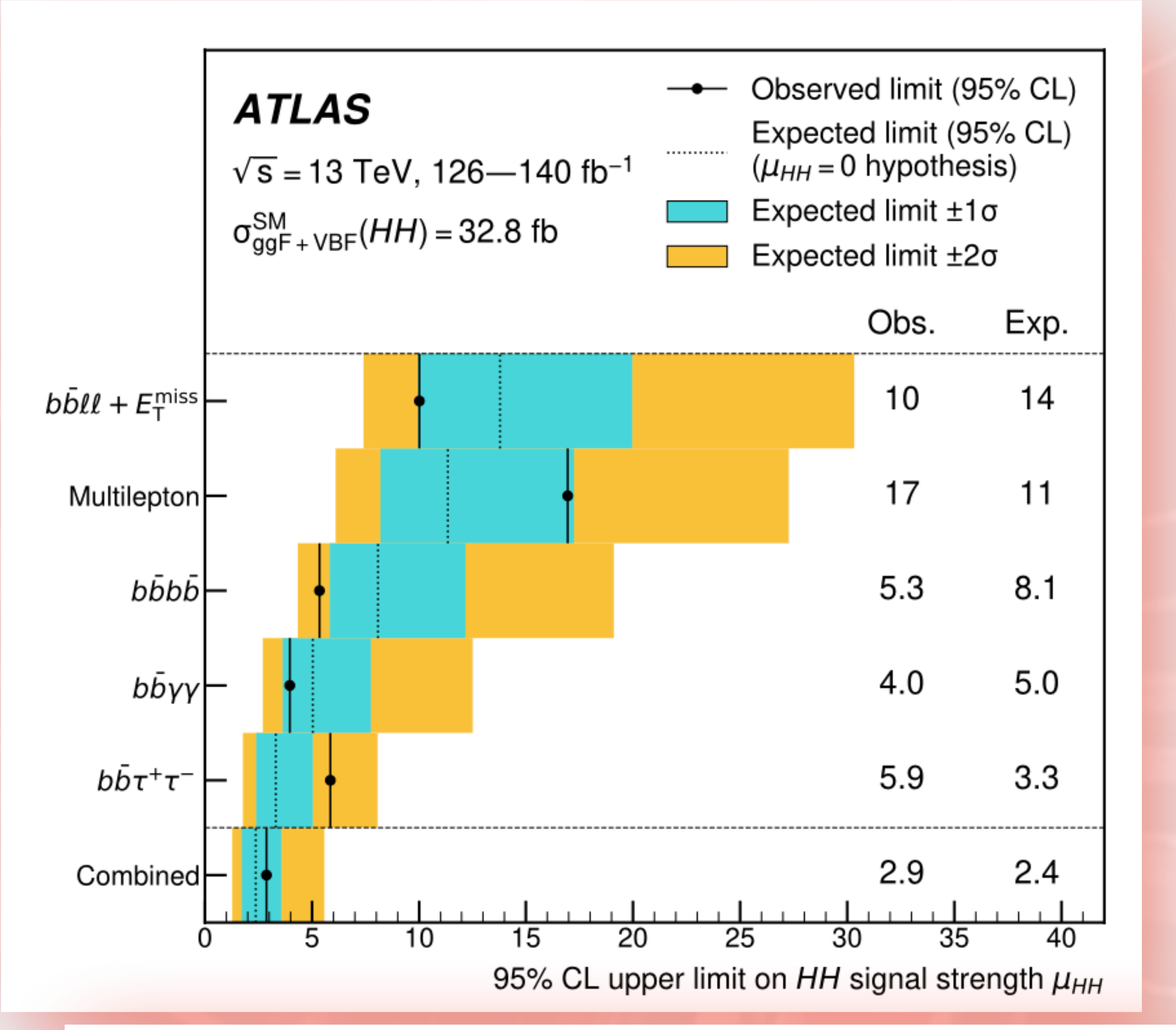


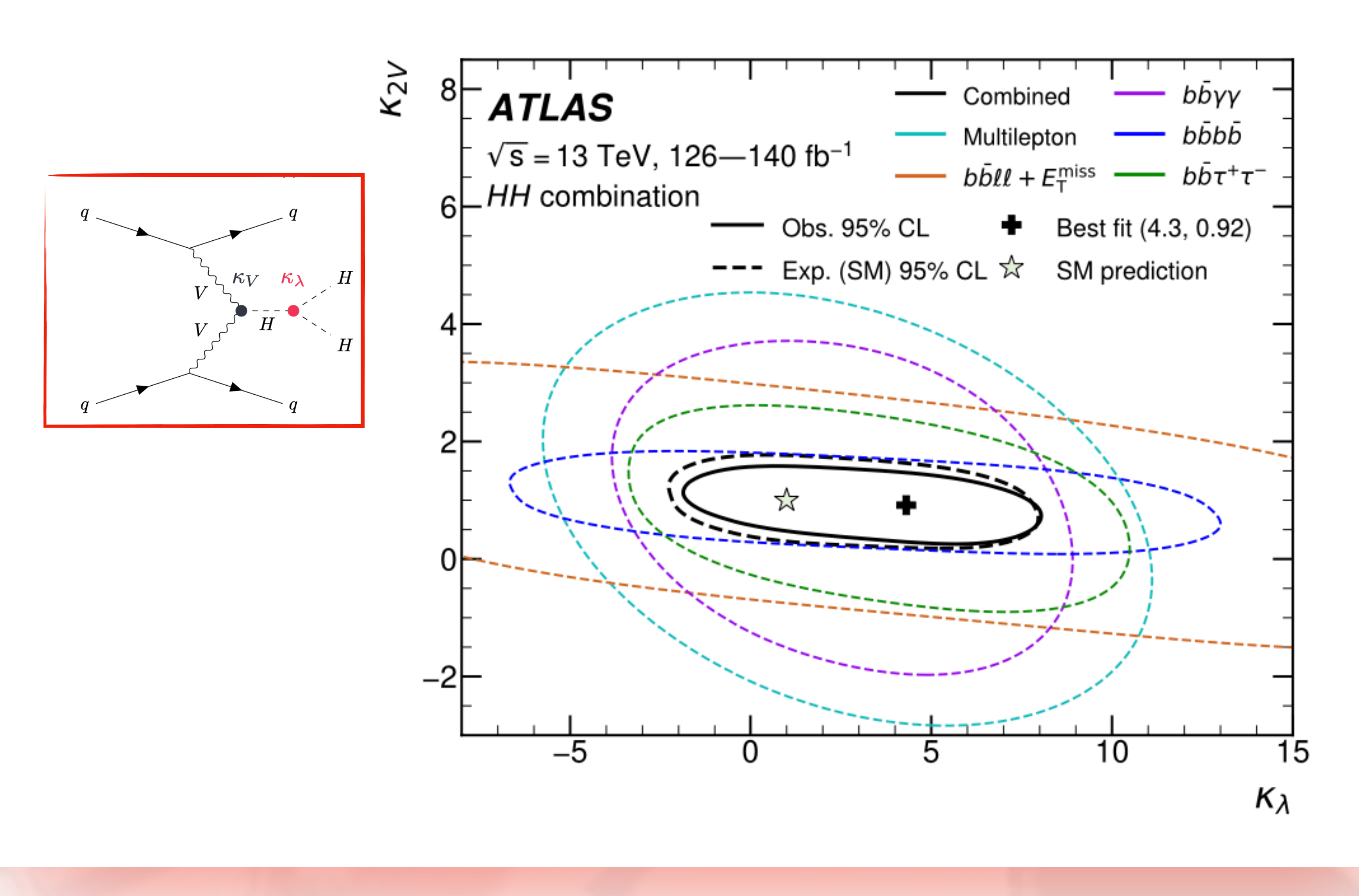


arXiv:2207.00043

Towards Precision HH Physics

- Made incredible progress on HH since the first round of analyses
  - Added boosted topologies, thanks to novel taggers (e.g., Hbb)
  - Improved resolved topologies, thanks to better b-jet and hadronic tau identification
- At the end of Run2, we reached the precision that HL-LHC studies predicted for 1000 fb^{-1} statistics



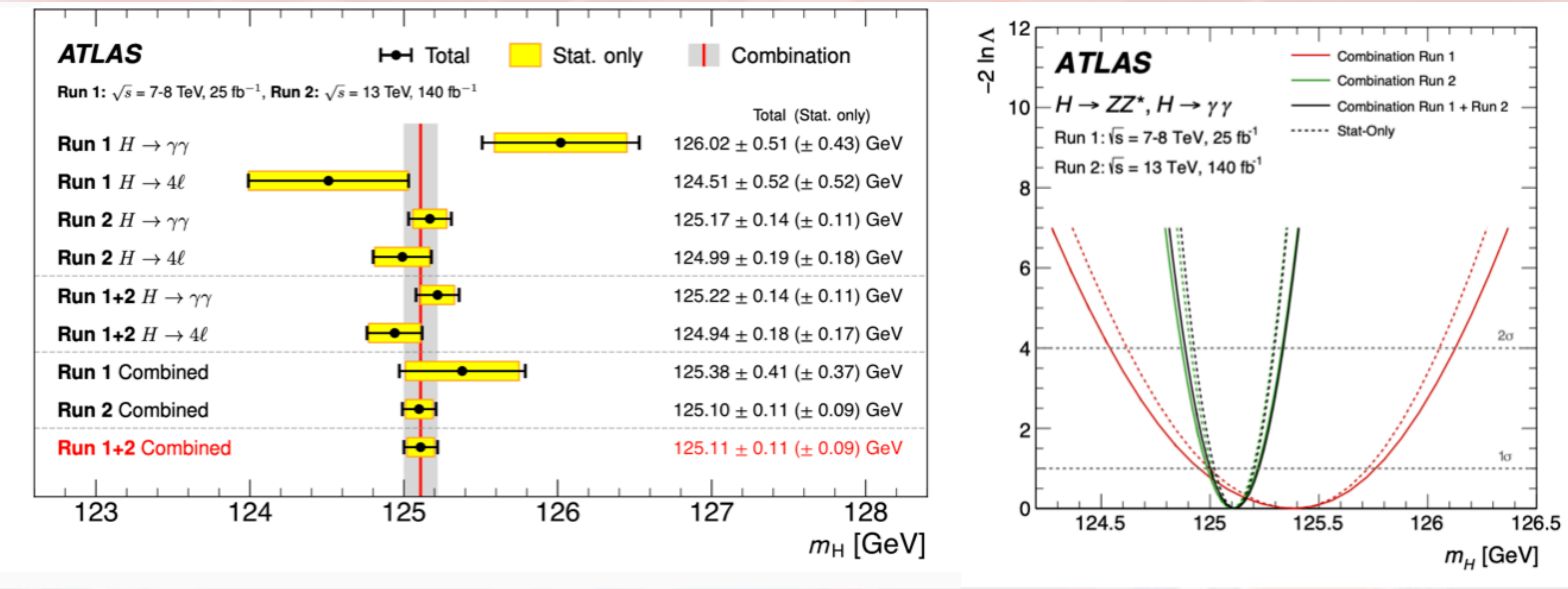


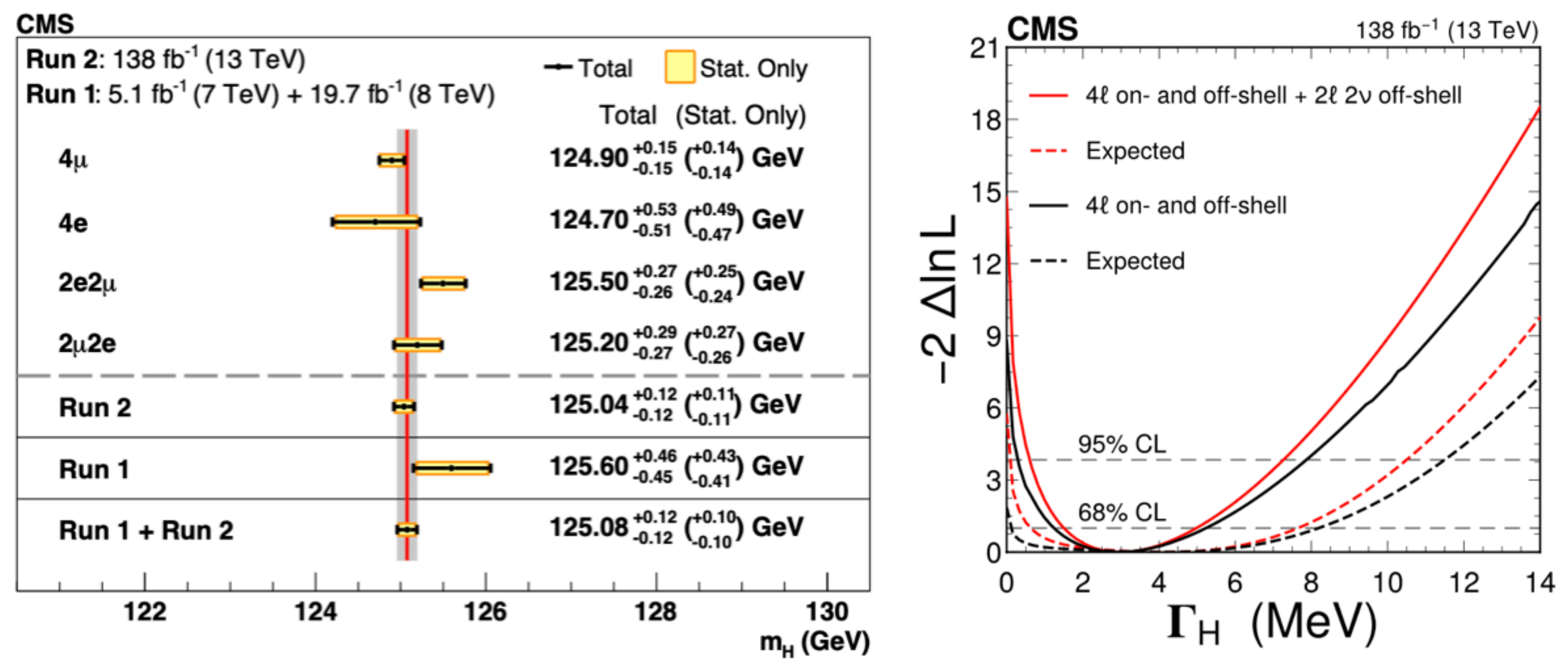
arXiv:2406.09971

Measurement of the H mass

$m_H = 125.11 \pm 0.11$ GeV

- At the LHC, Higgs mass measured by the two golden channels
  - $H \to \gamma\gamma$ exploiting calorimeter resolution
  - $H \to 4\ell$ exploiting tracking resolution
- Reached 0.09% precision (ATLAS only)
  - Further improvement expected with legacy Run2 combination

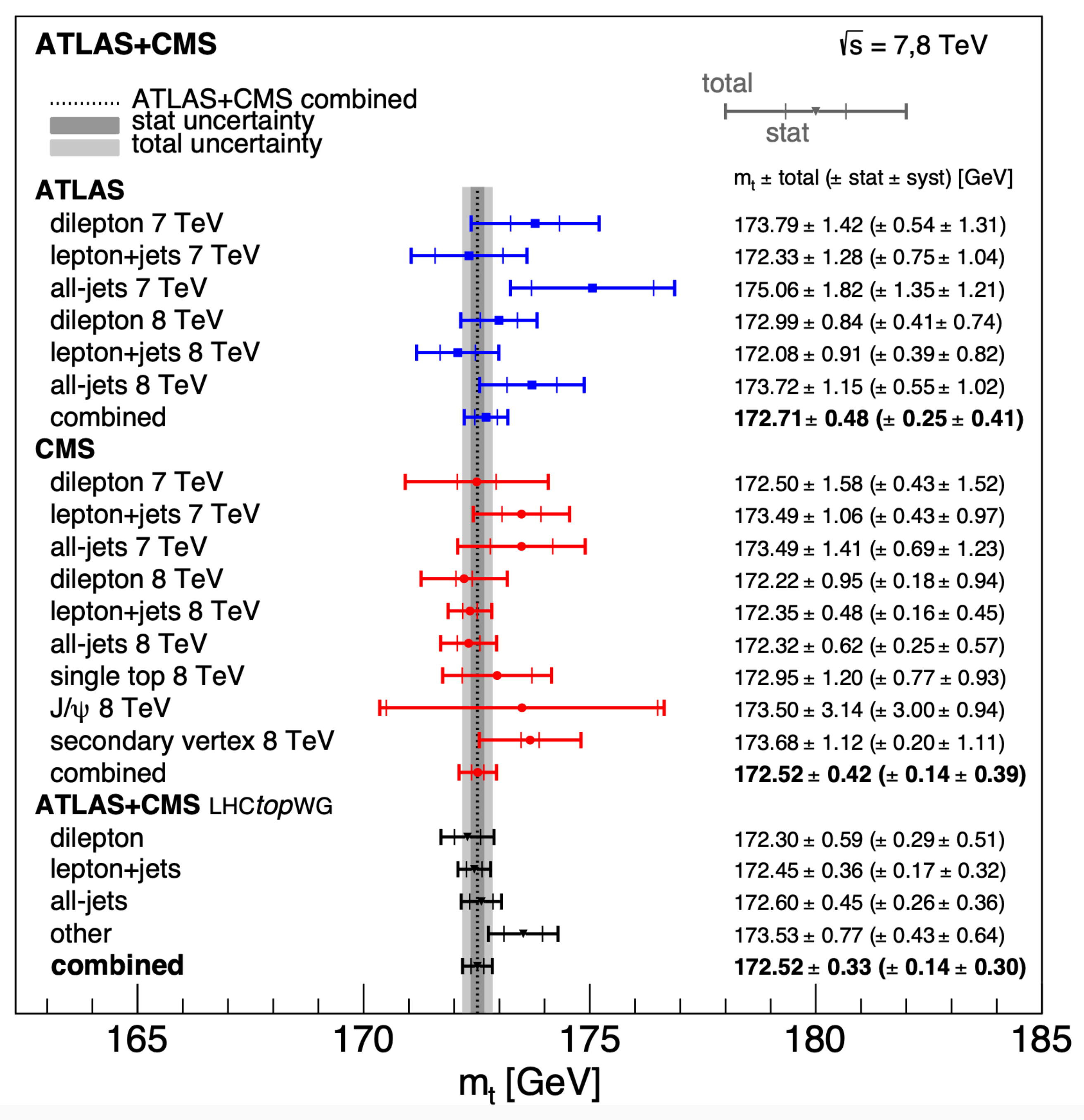


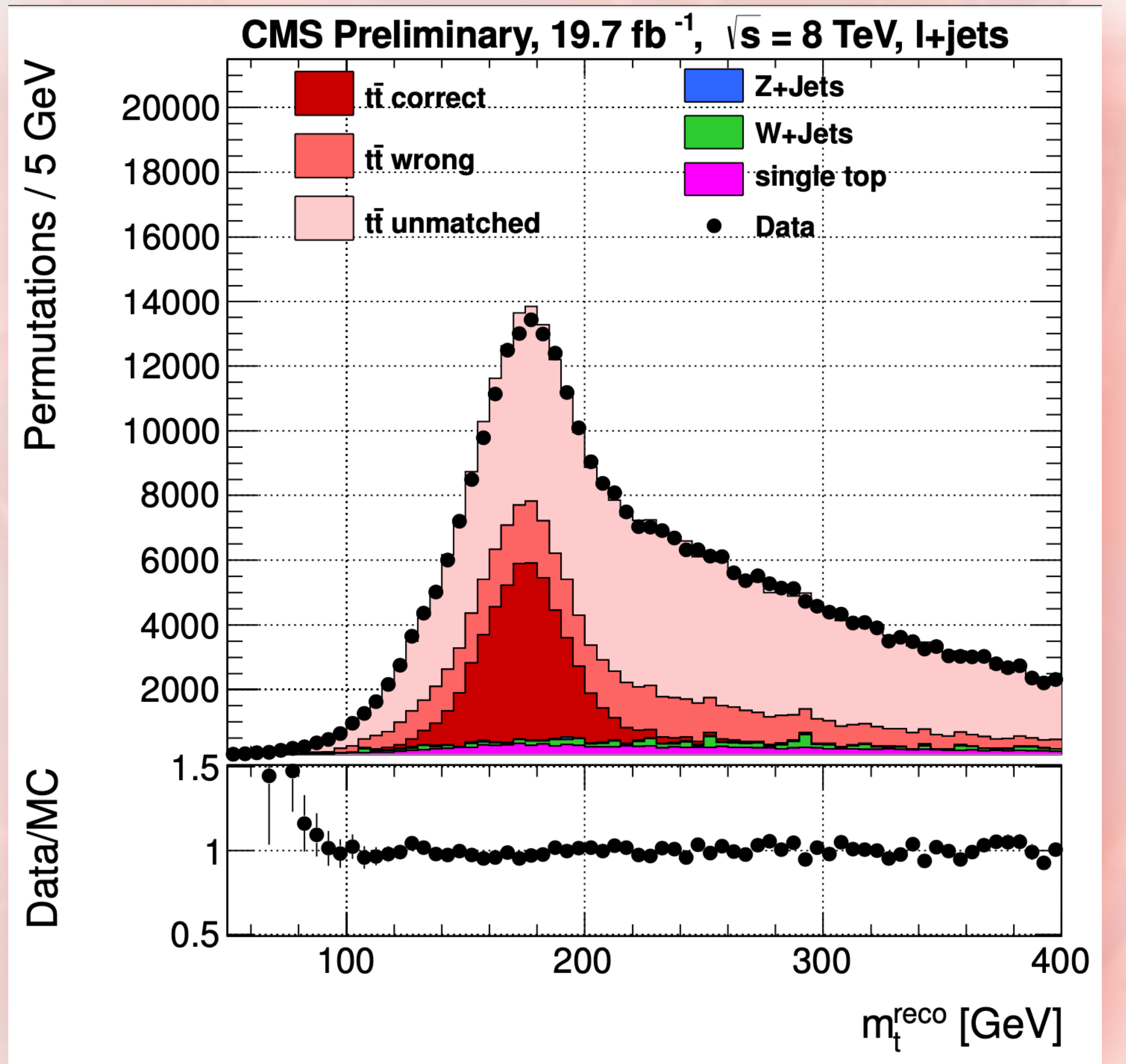


CMS-HIG-21-019-003

Measurement of the top mass

- Extensive program to measure the top mass
  - Multiple techniques probing various final states (with and without leptons), processes (cross section vs kinematic variables) and topologies (resolved vs boosted top decays)
- Recent Run 1 ATLAS+CMS combination provided most precise determination $m_t = 172.52 \pm 0.33$ GeV
- In Run 2, the use of modern statistical methods (e.g., systematic profiling as in Higgs discovery) allowed to reach similar precision on individual measurement $m_t = 171.77 \pm 0.37$ GeV





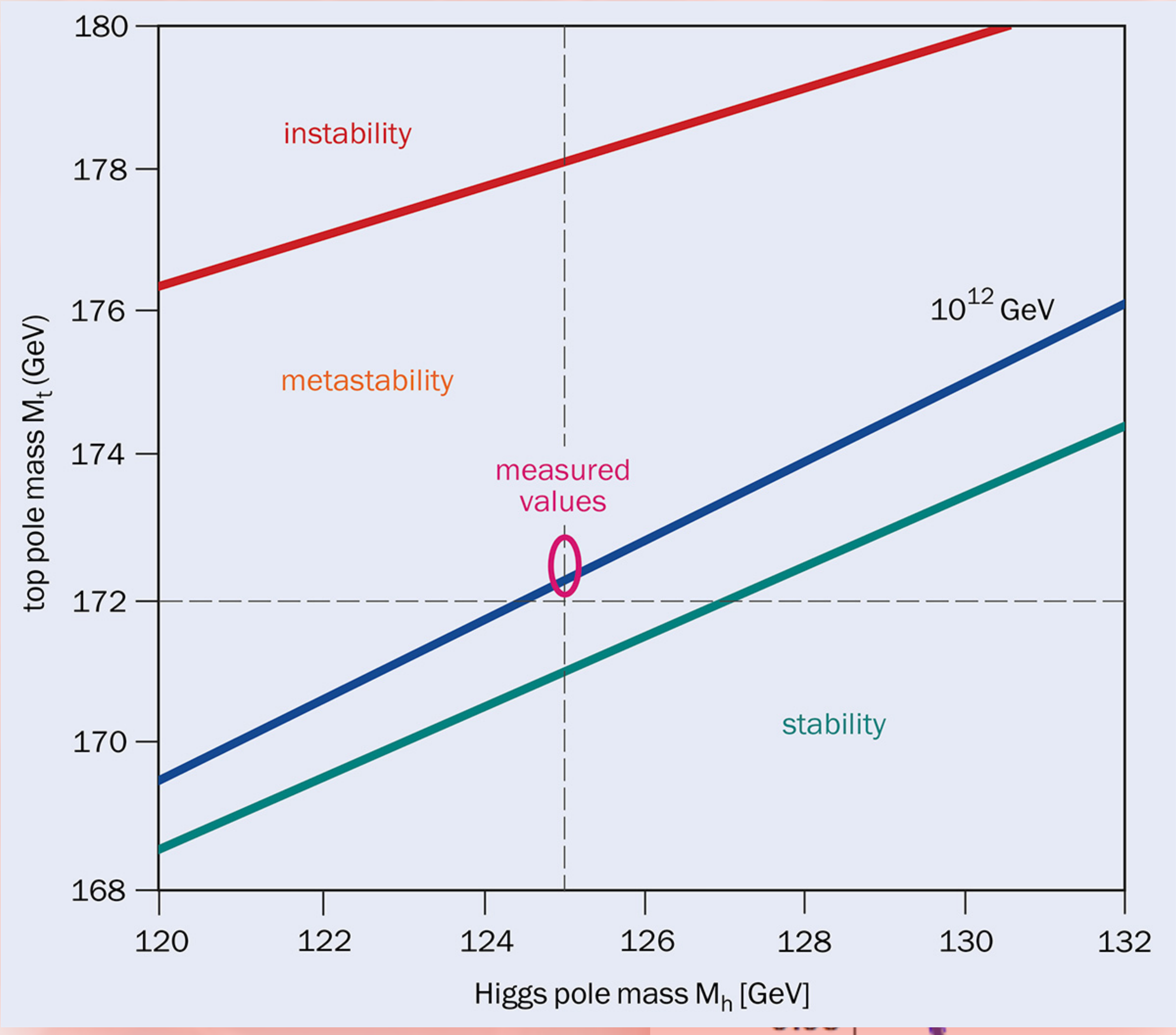
arXiv:2402.08713

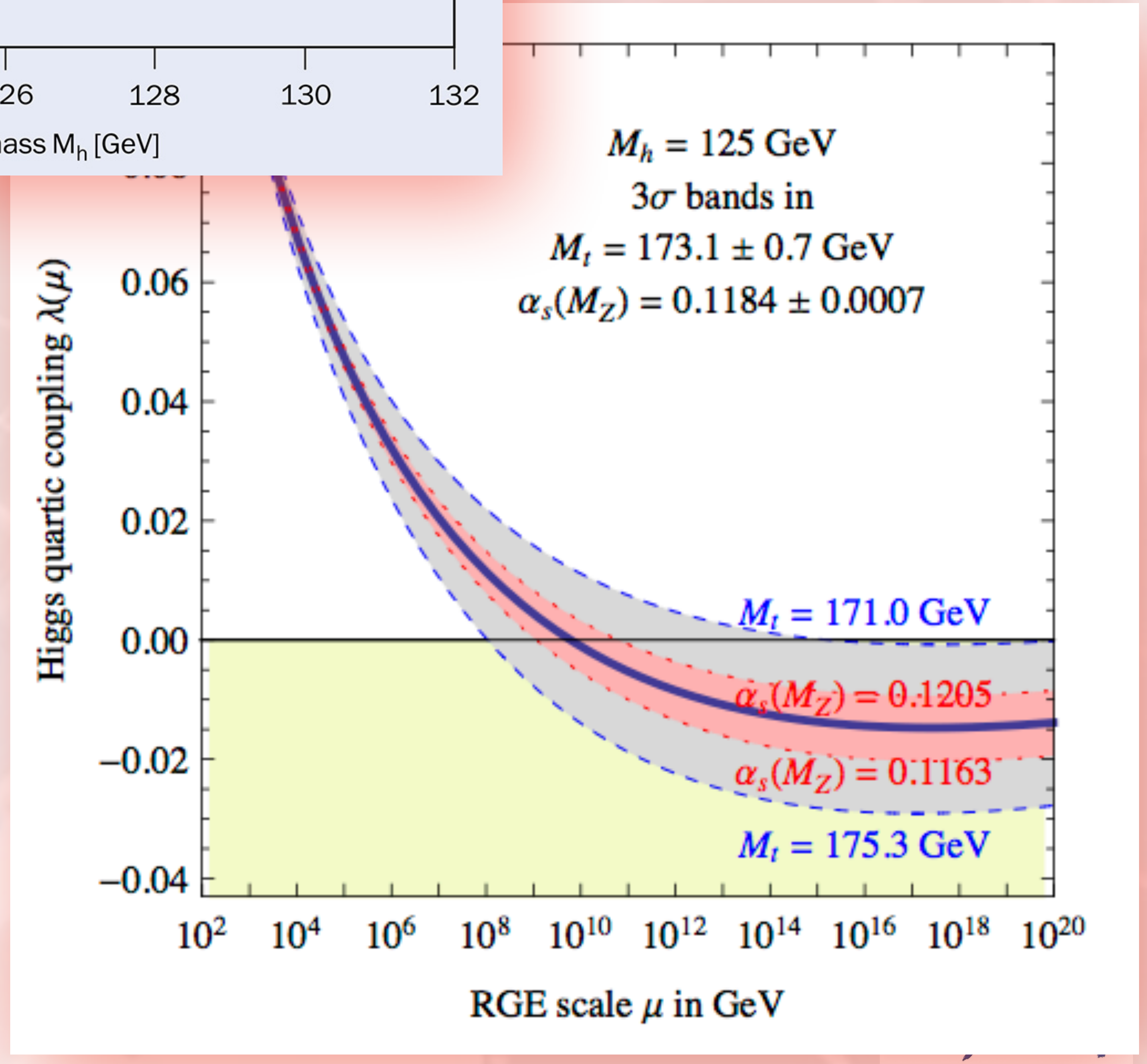
arXiv:2302.01967

From precision physics to the big picture

- Assuming validity of the SM up to Planck scale, mH and mt are key inputs to determine the nature of the Higgs vacuum
    - Current best-fit at the boundary between stable and metastable
    - Jump in precision needed for a conclusive statement
- The RGE evolution affected by knowledge of α_S
    - With improvement on mH and mt, one has to measure α_S accordingly

Measurements from 2022 PDG

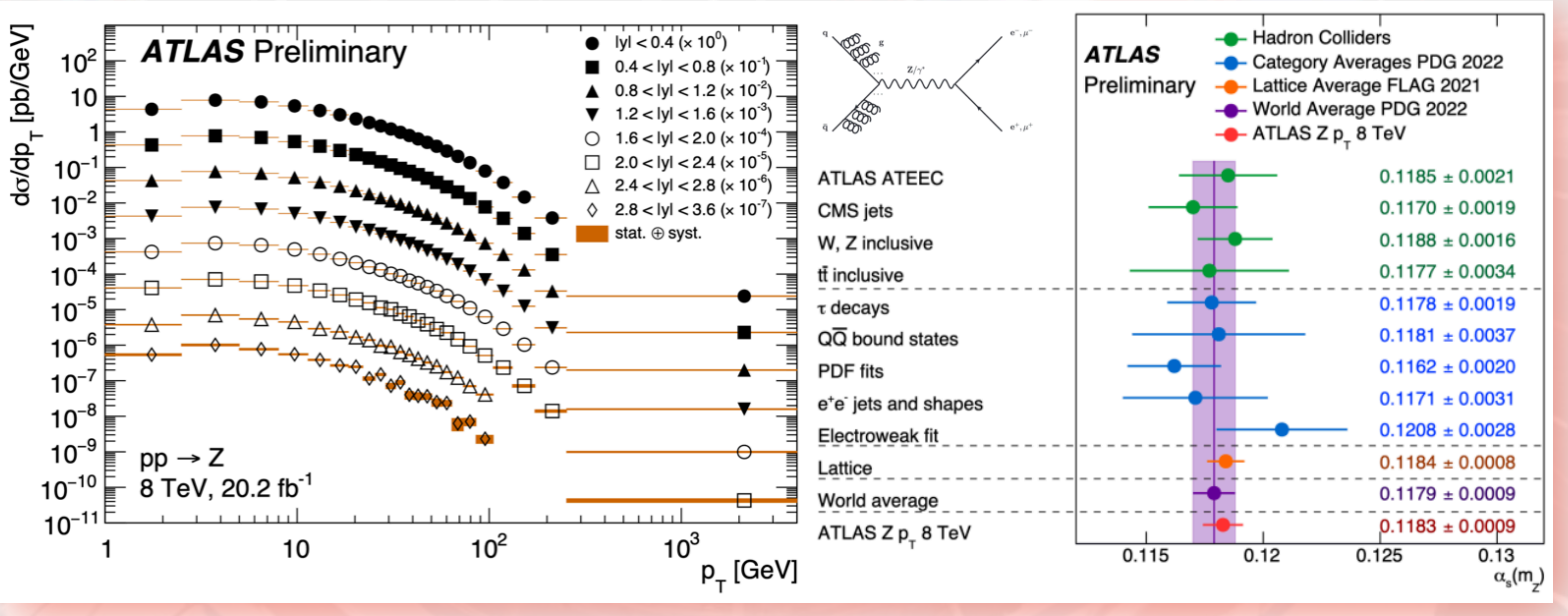




Precision Measurement of α_s

- ATLAS released most precise determination of α_S using the dependence of the Z p_T distribution $\alpha_S(M_Z) = 0.1183 \pm 0.0009$
  - Discussion ongoing on the NNLO nature of the measurement
  - Regardless, unquestionable jump in precision

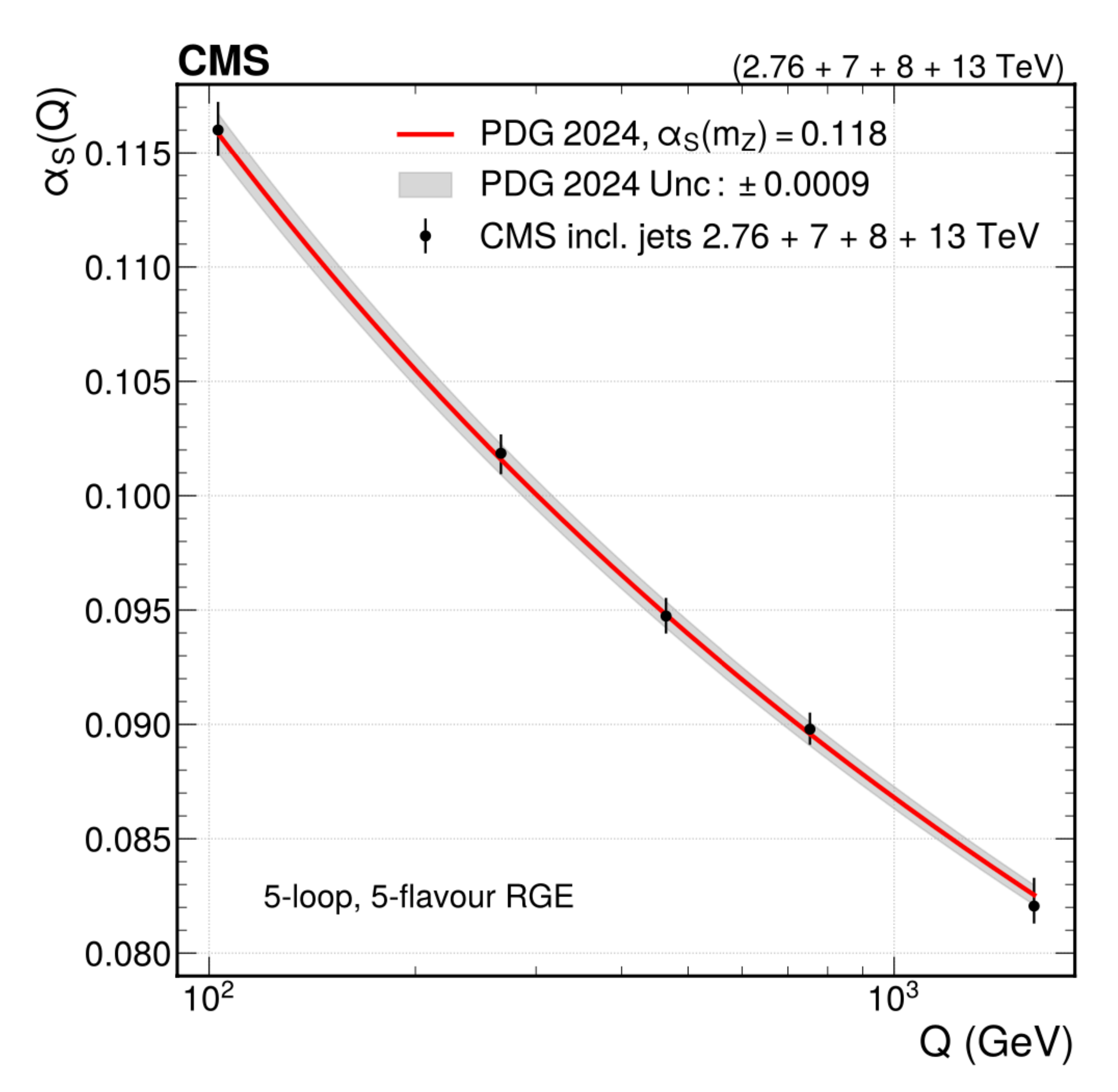
arXiv:2309.12986

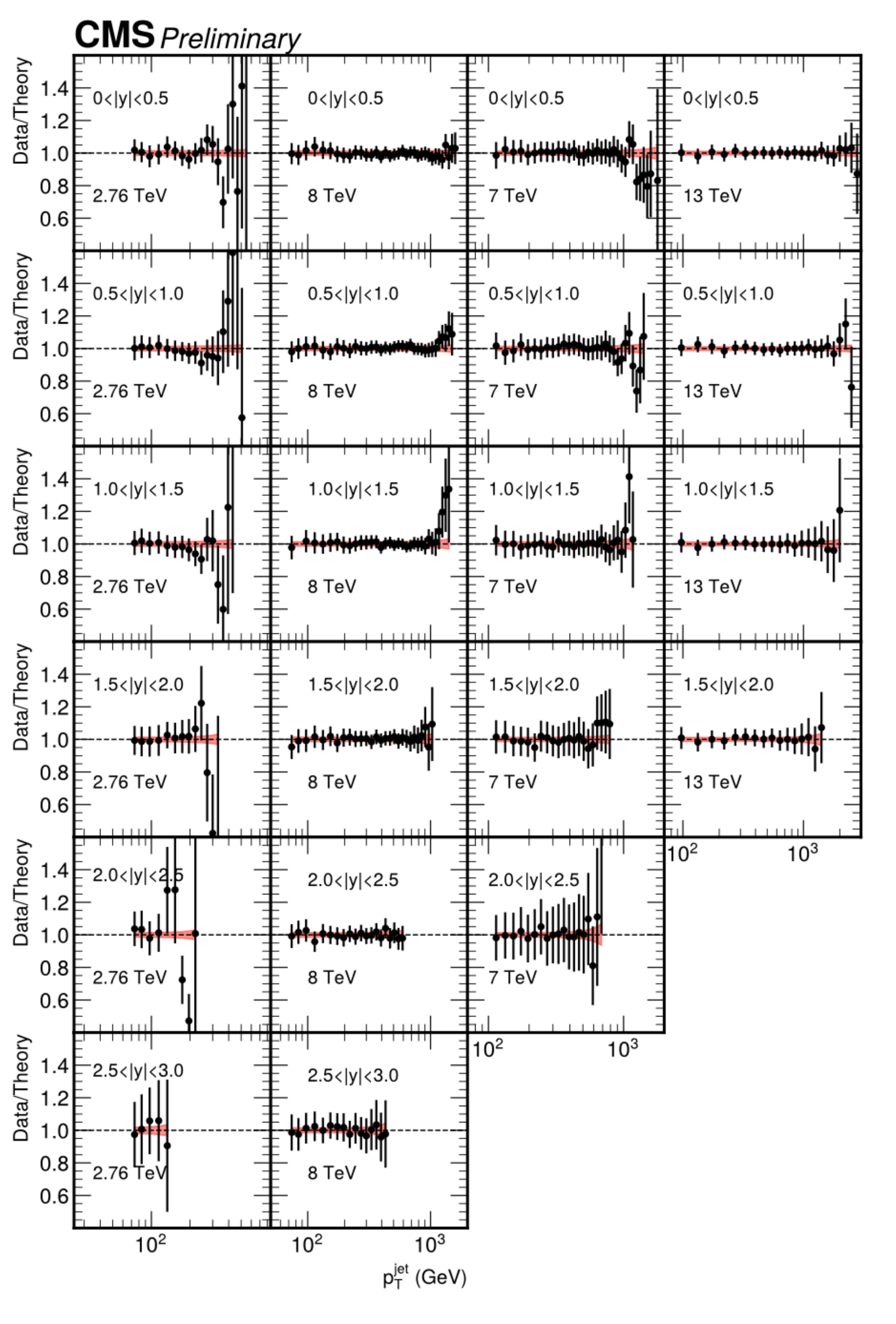


Precision Measurement of α_s

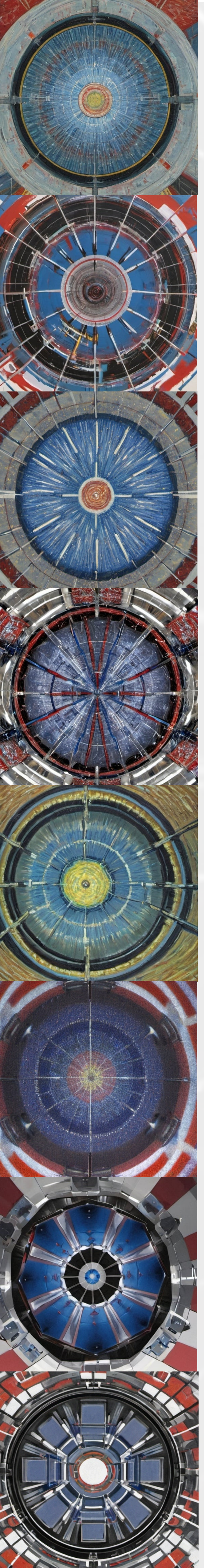
CMS-SMP-24-007

- CMS analyses jet production at 2.76, 7, 8, and 13 TeV data in a combined fit
  - used to measure $\alpha_S(M_Z) = 0.1176^{+0.0014}_{-0.0016}$ at NNLO simultaneously to an in-situ constraint on the parton density functions
    - The most precise determination of aS in jet events
    - Still not as precise at the measurement from Z pT

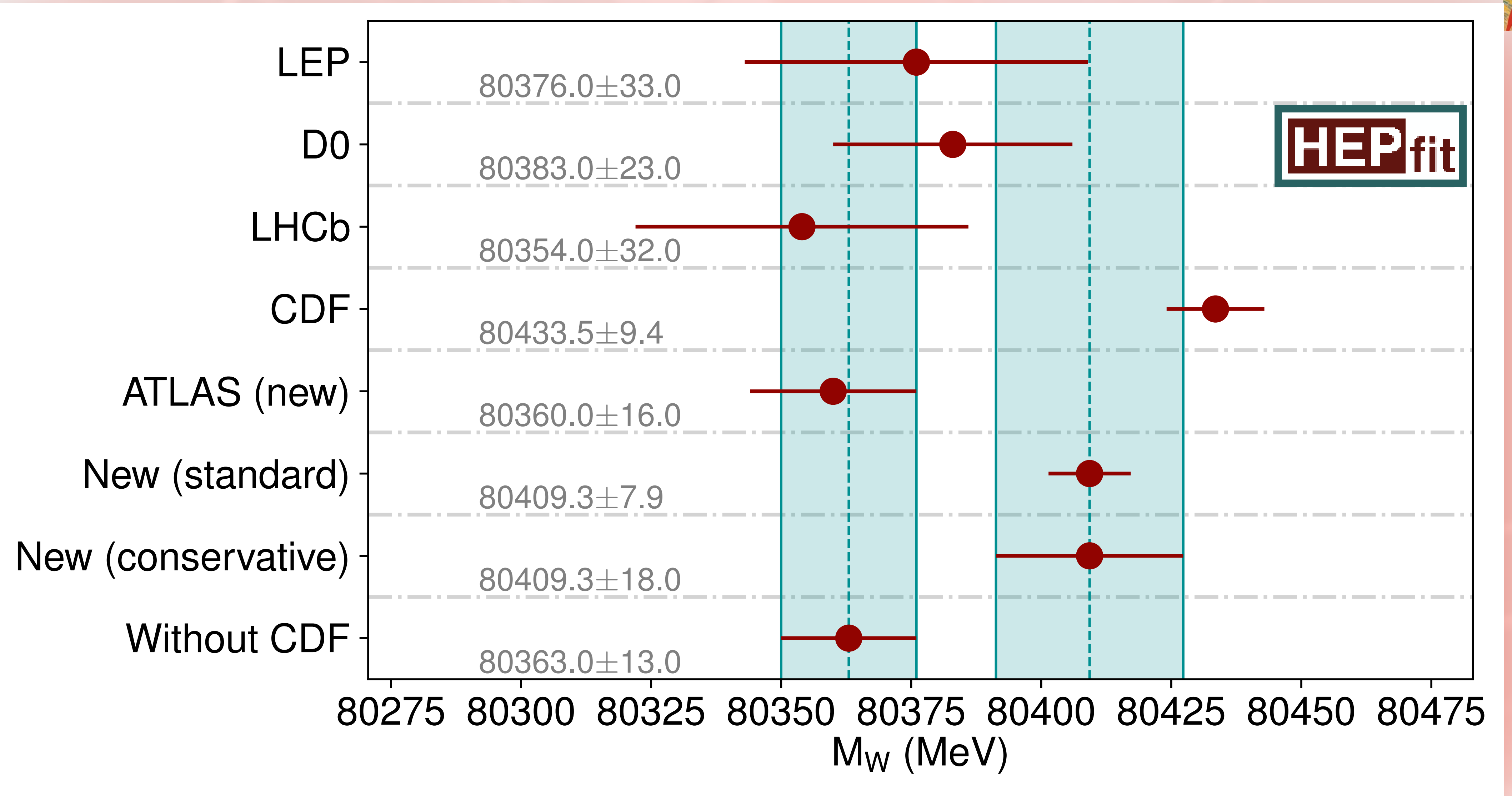


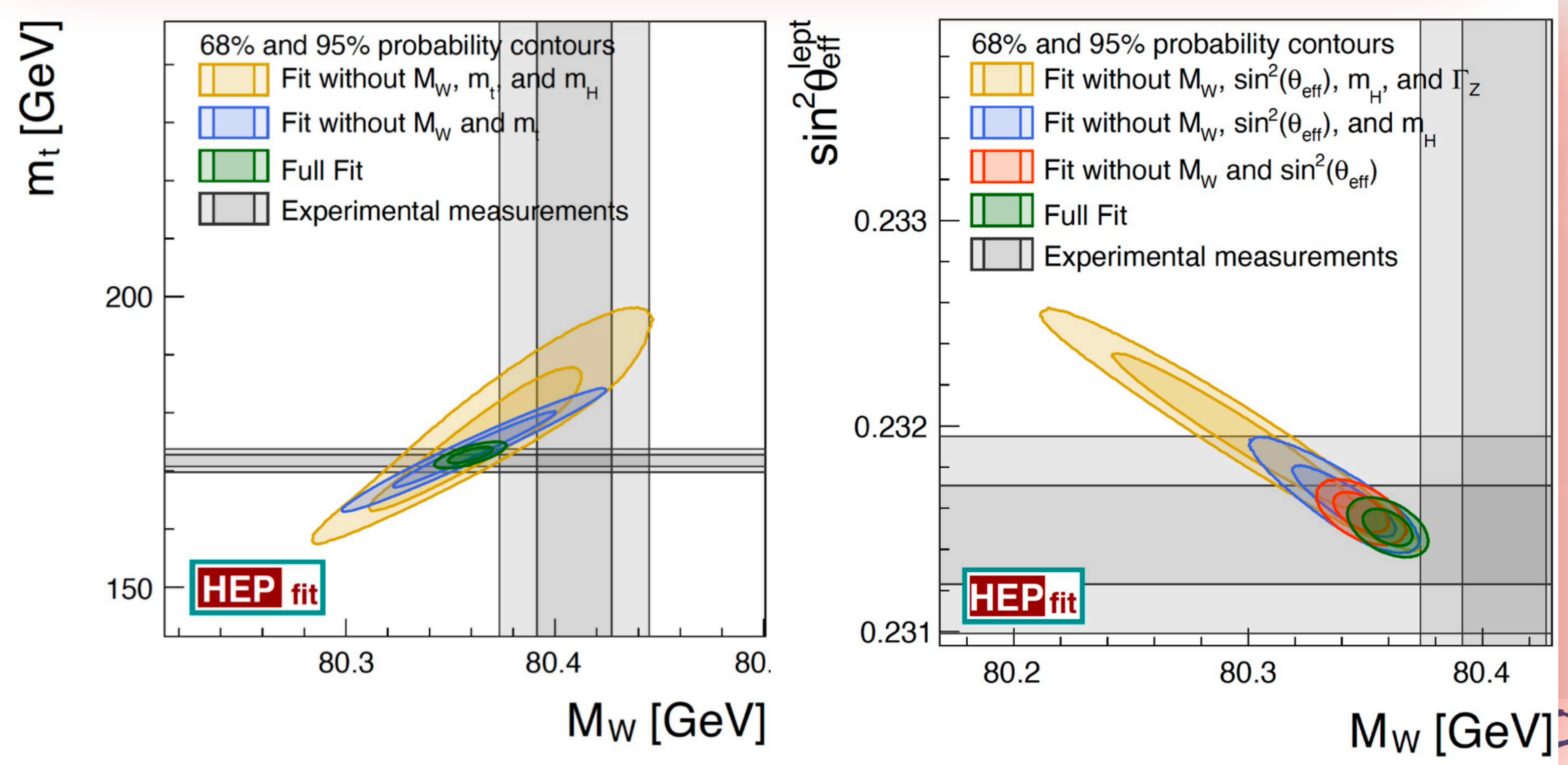


EW Precision at Hadron Collider



- Status of the EW fit in 2023
  - Driven by EWPO at e^+e^- colliders
  - Hadron colliders contribute mostly with mH, mW, and mt
  - and with a lot of confusion
    - Tension on mt Tevatron vs LHC
    - Tension on mW CDF vs the rest of the planet
- A lot happened since then
  - mt ATLAS+CMS combination (see above)
  - Precise aS by ATLAS (see above)
  - New W mass and width by ATLAS
  - Precision step up on mW at LHC by CMS
  - A_{FB}^{ℓ} by CMS pass LEP precision
  - CMS W BRs measurements improve over LEP

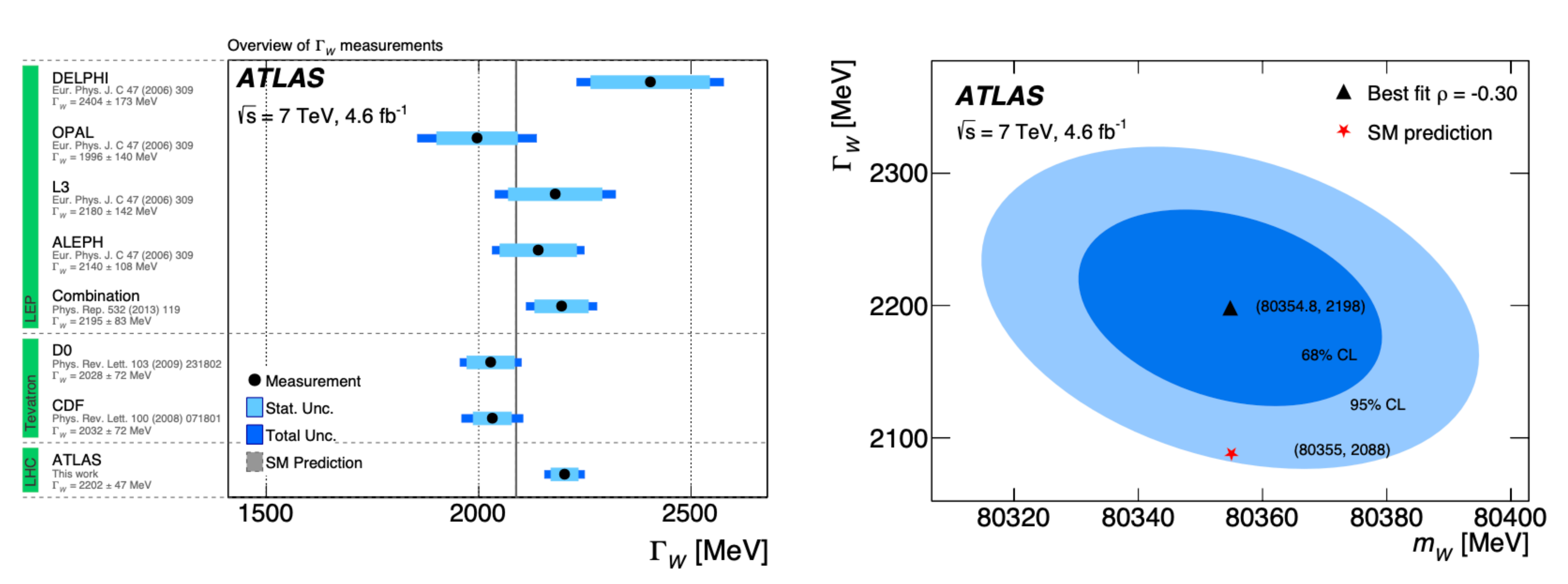




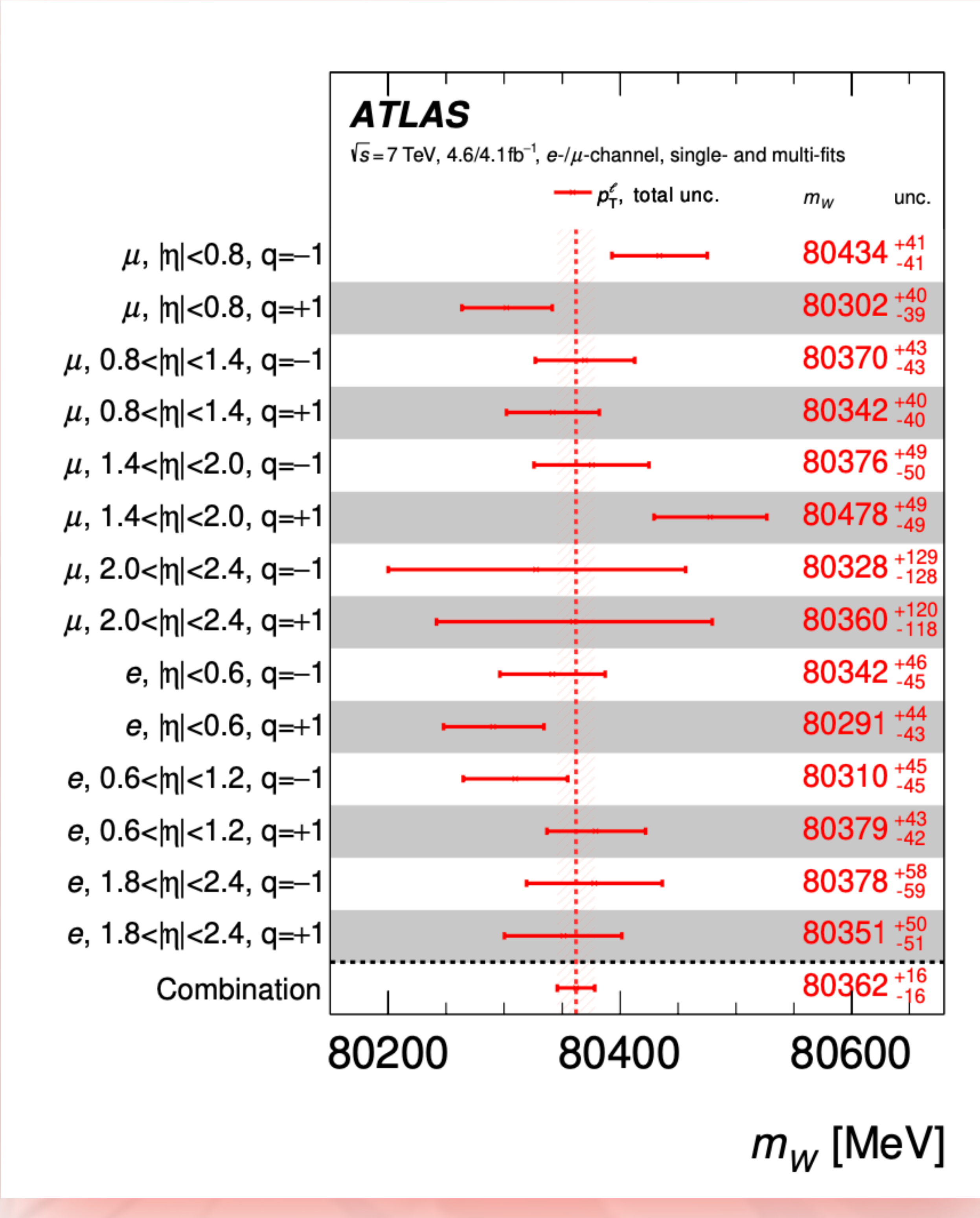
arXiv:2204.04204

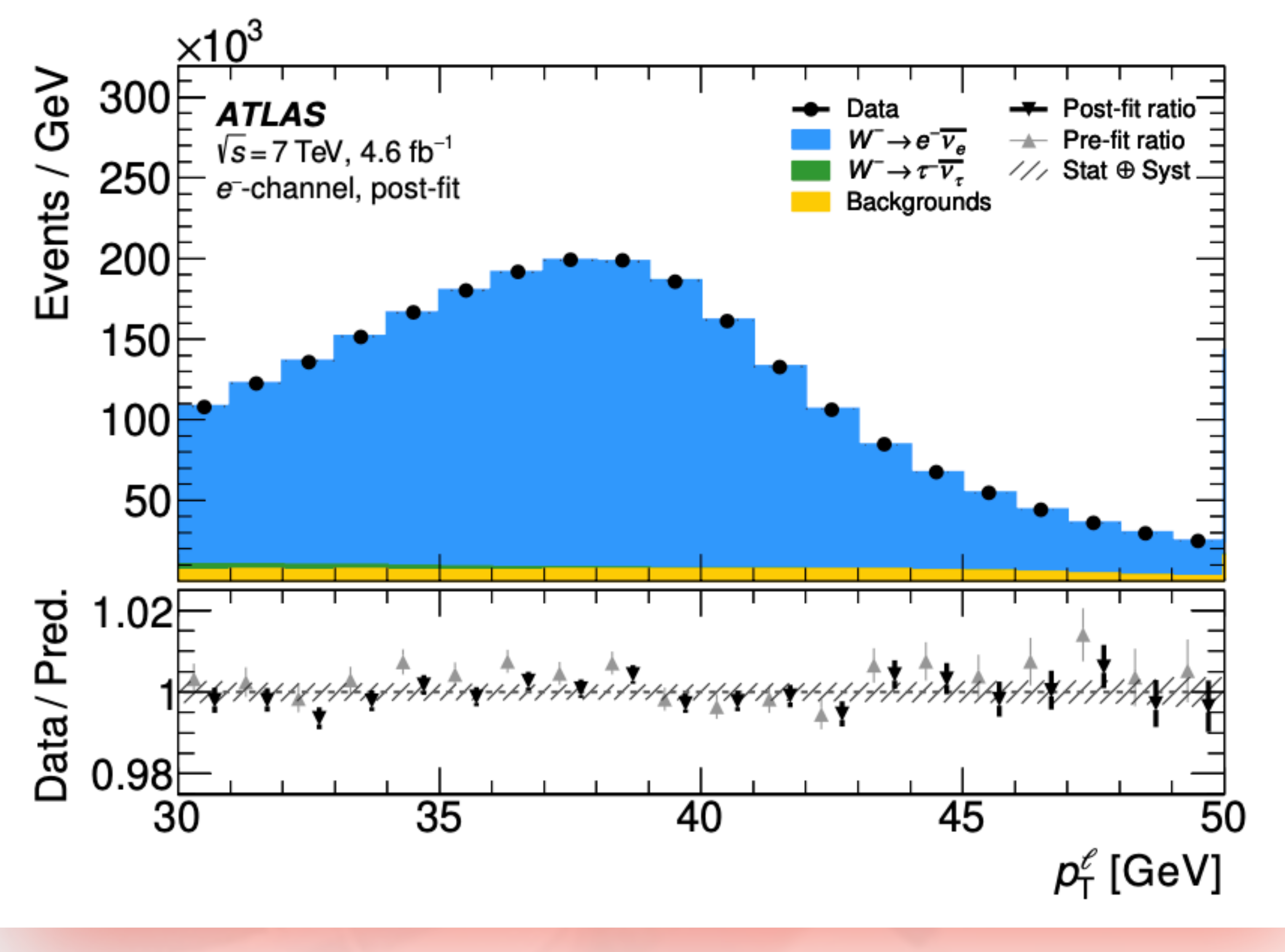
W mass and width by ATLAS

- ATLAS exploited low-pileup 2011 data to measure the W mass and width
  - Use both muon and electron decays
  - exploit both p_T and M_T distribution



$$M_W = 80366.5 \pm 15.9 \text{ MeV} \quad \Gamma_W = 2202 \pm 47 \text{ MeV}$$



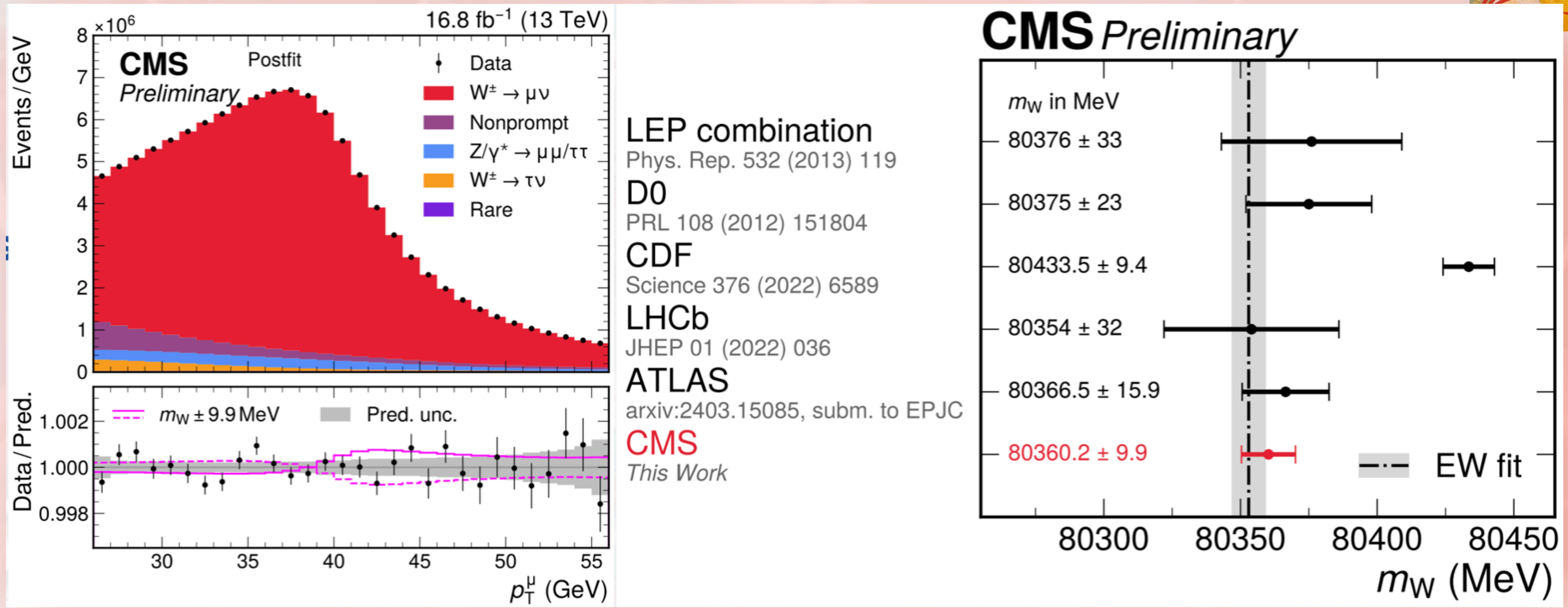


arXiv:2403.15085

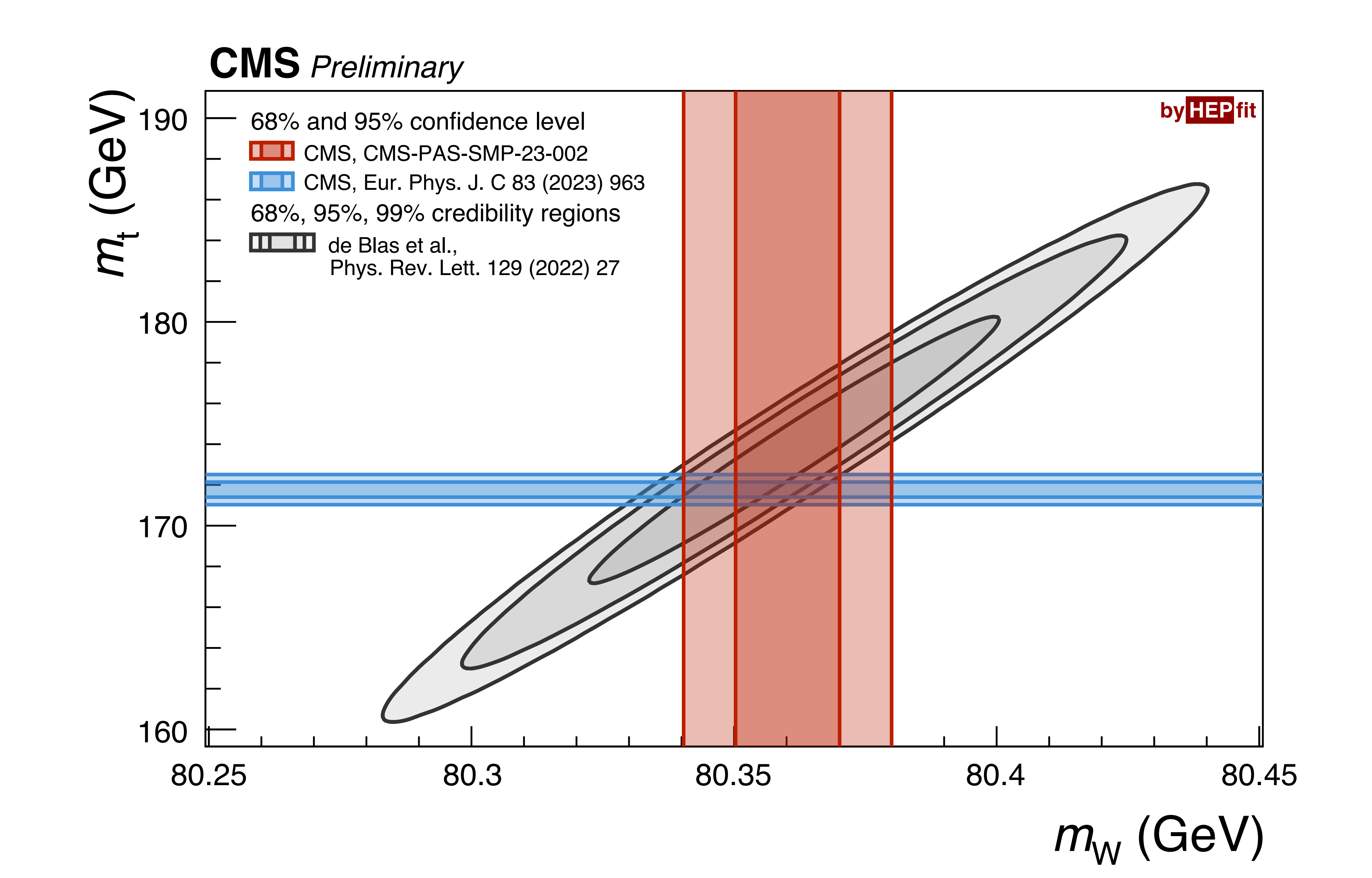
CMS W Mass in the era of pileup

CMS-PAS-CMP-23-002

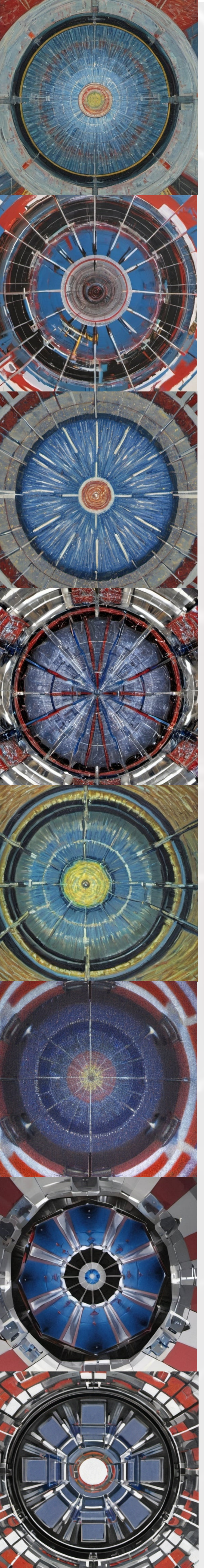
- CMS just released the most precise M_W determination at LHC
  - Exploited 1/2 of 2016 dataset
  - Only used muons and p_T vs η distribution (robustness vs pileup)
  - Second alternative measurement with relaxed theory assumptions gave consistent result
- Result in agreement with other LHC measurements and SM prediction



$$M_W = 80360.2 \pm 9.9 \text{ MeV}$$



CMS W Mass in the era of pileup



SEPTEMBER 19, 2024 | 4 MIN READ

Ultra-Precise Particle Measurement Narrows Pathway to 'New Physics'

A long-awaited calculation of the W boson's mass agrees with theory, contradicting a previous anomaly that had raised the possibility of new physics beyond the Standard Model

BY ELIZABETH GIBNEY & NATURE MAGAZINE

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NEWS | 17 September 2024

'The standard model is not dead': ultra-precise particle measurement thrills physicists

CERN's calculation of the *W* boson's mass agrees with theory, contradicting a previous anomaly that had raised the possibility of new physics.

By Elizabeth Gibney

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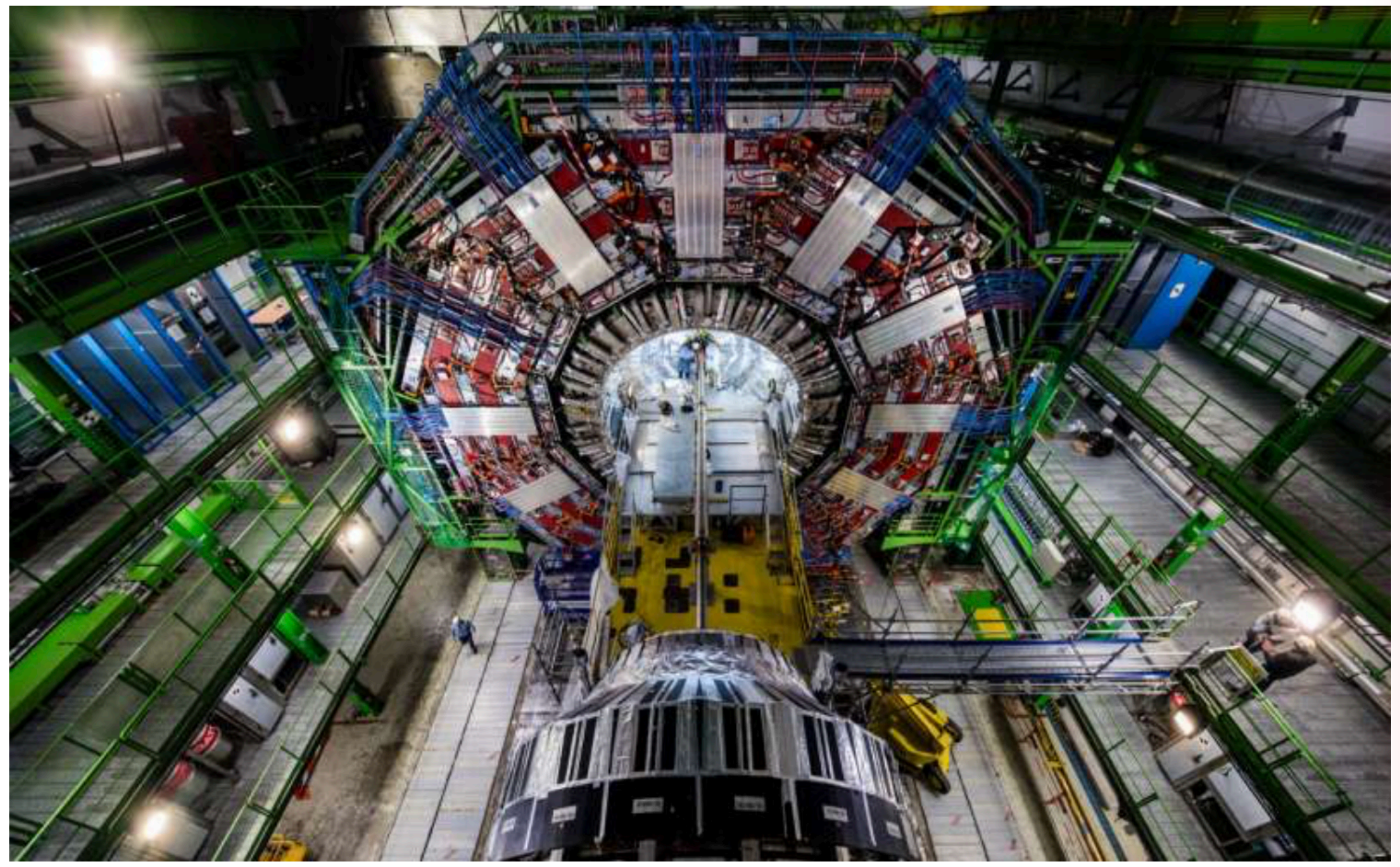
SEPTEMBER 22, 2024 | Editors' notes

New results from the CMS experiment put W boson mass mystery to rest

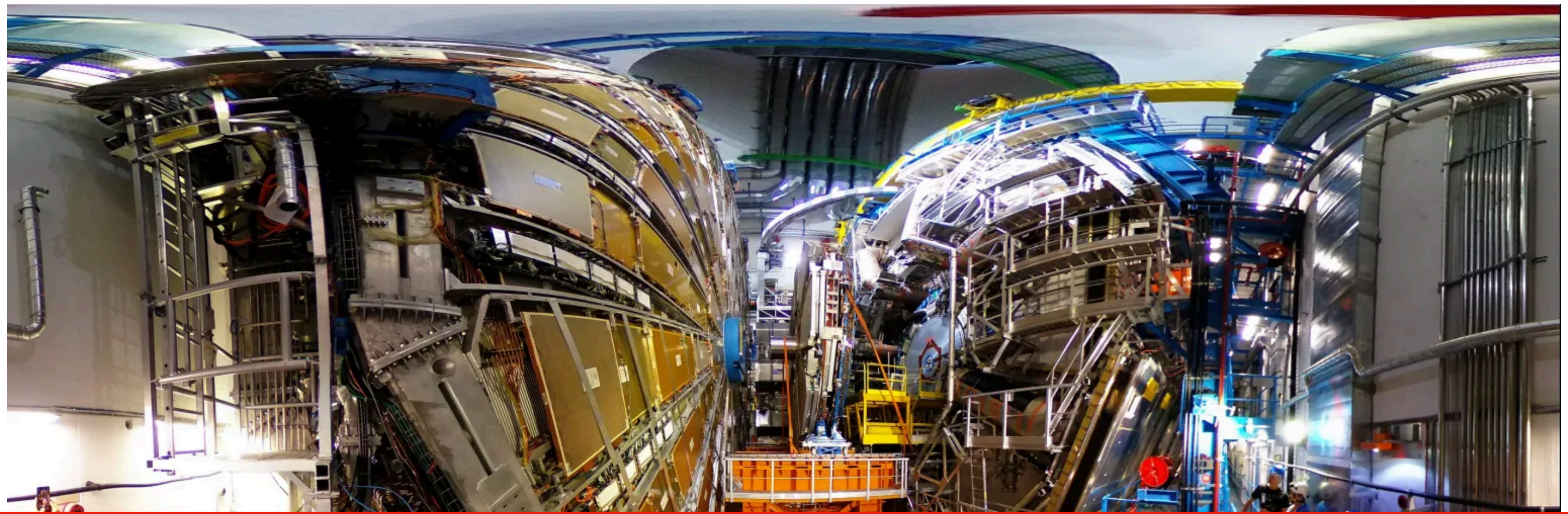
by Tracy Marc, Fermi National Accelerator Laboratory



STARTS WITH A BANG — MAY 15, 2024

New LHC results refute Fermilab's "hole" in the Standard Model

With new W-boson, top quark, and Higgs boson measurements, the LHC contradicts earlier Fermilab results. The Standard Model still holds.



CMS W Mass in the era of pileup

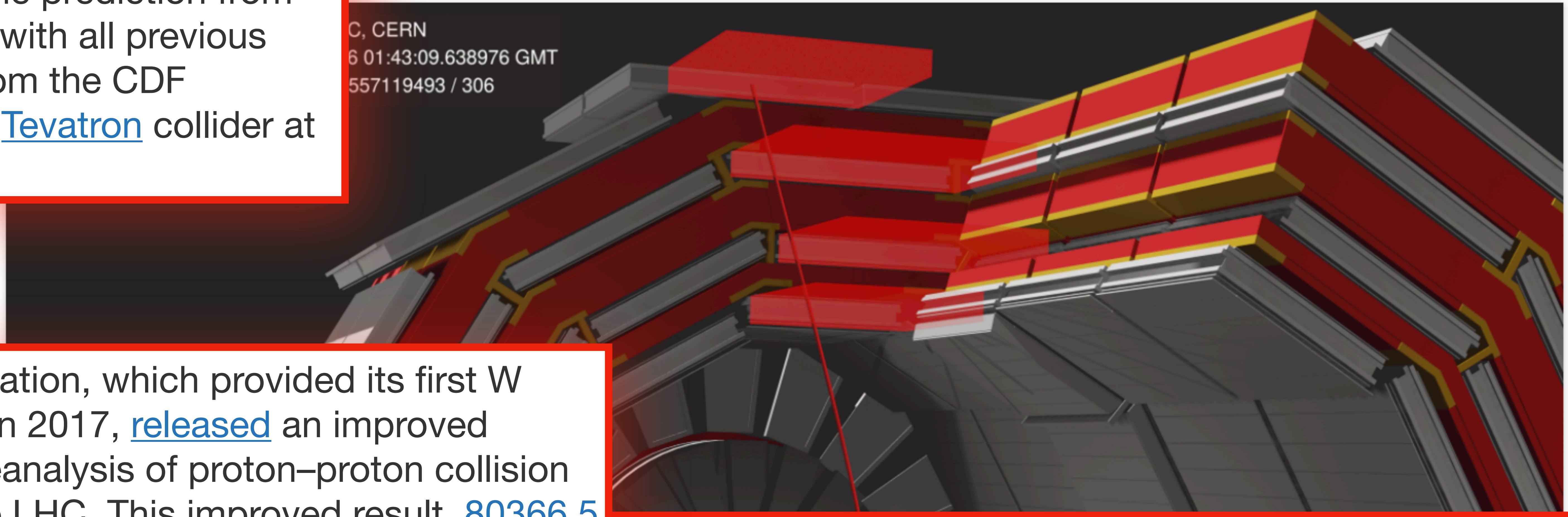
https://cds.cern.ch/record/2910372

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

The CMS experiment at CERN is the latest to weigh in on the mass of the W boson

The result is the most precise measurement of the W mass made so far at the LHC, and is in line with the prediction from the Standard Model of particle physics and with all previous measurements, except the measurement from the CDF experiment at the former proton–antiproton Tevatron collider at Fermilab.



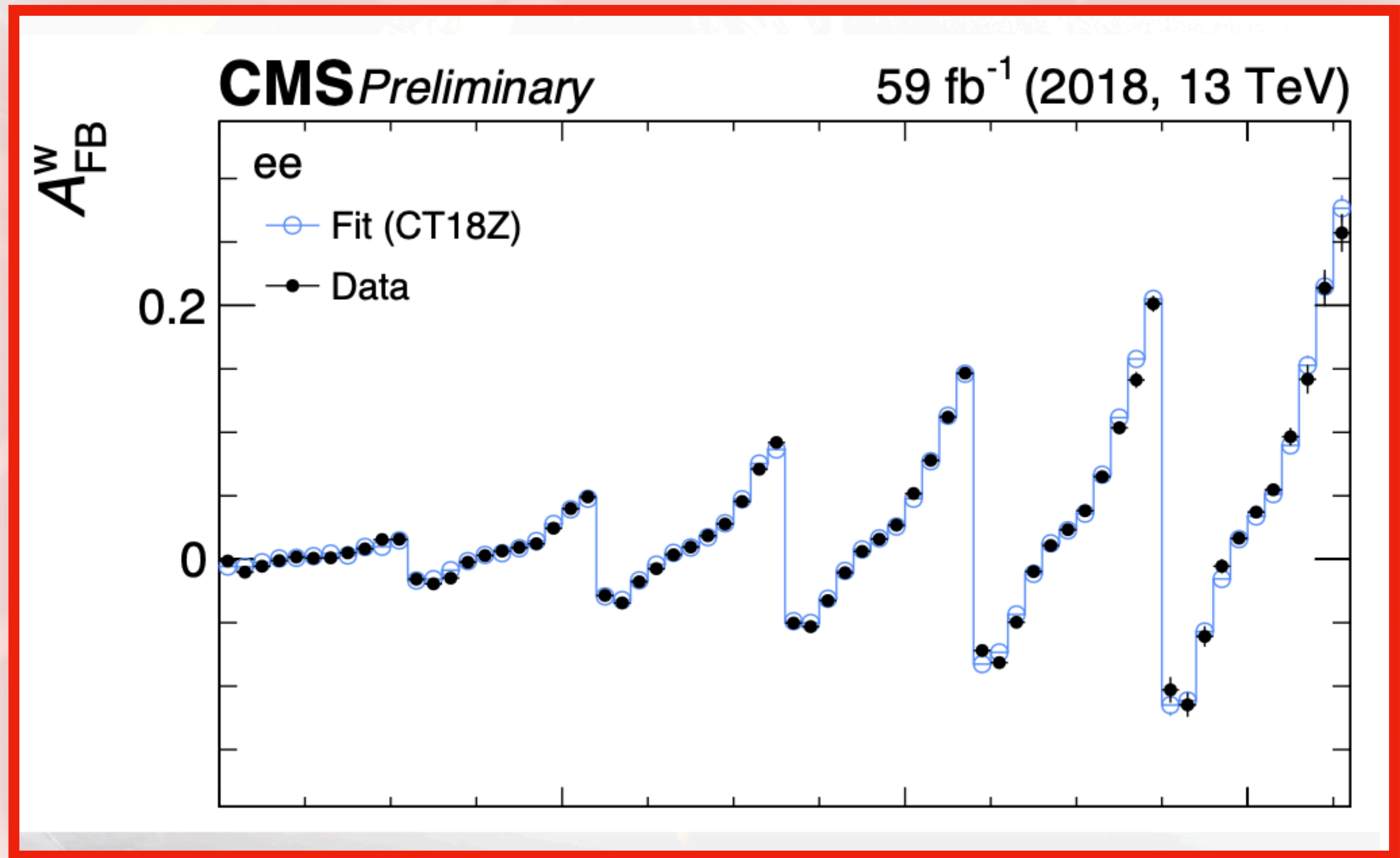
In 2023, the ATLAS collaboration, which provided its first W boson mass measurement in 2017, released an improved measurement based on a reanalysis of proton–proton collision data from the first run of the LHC. This improved result, 80366.5 MeV with an uncertainty of 15.9 MeV, lined up with all previous measurements except the CDF measurement, which remains the most precise to date, with a precision of 0.01%.

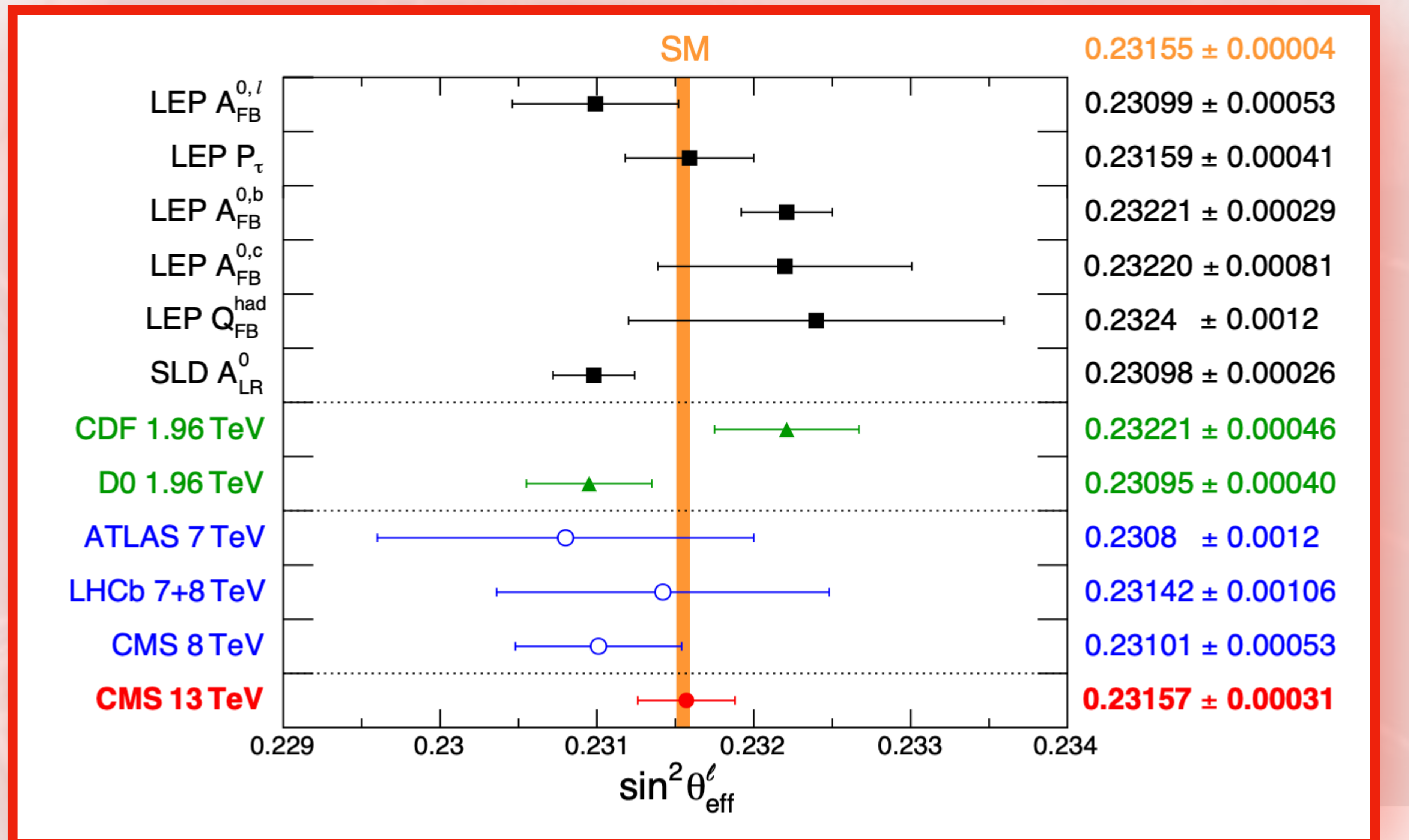
If CERN was in 2024 Italy...

The Weak Mixing Angle

- Recently released a full-Run2 $\sin^2\theta_W$ measurement using A_{FB} in $pp \to \ell\ell$ events
  - More precise than LEP combination on equivalent quantity
  - Precision comparable to LEP A^b_{FB} and SLD A_{LR} determination
  - Sits in between the two, in perfect agreement with SM prediction
    - adds to understanding of a long-standing tension
- Extracted value of $\sin^2\theta_{eff}$

$$\sin^2\theta_{eff} = 0.23157 \pm 0.00010\ \text{(stat)}\ \pm 0.00015\ \text{(syst.)}\ \pm 0.00009\ \text{(theory)}\ \pm 0.00027\ \text{(PDF)}$$





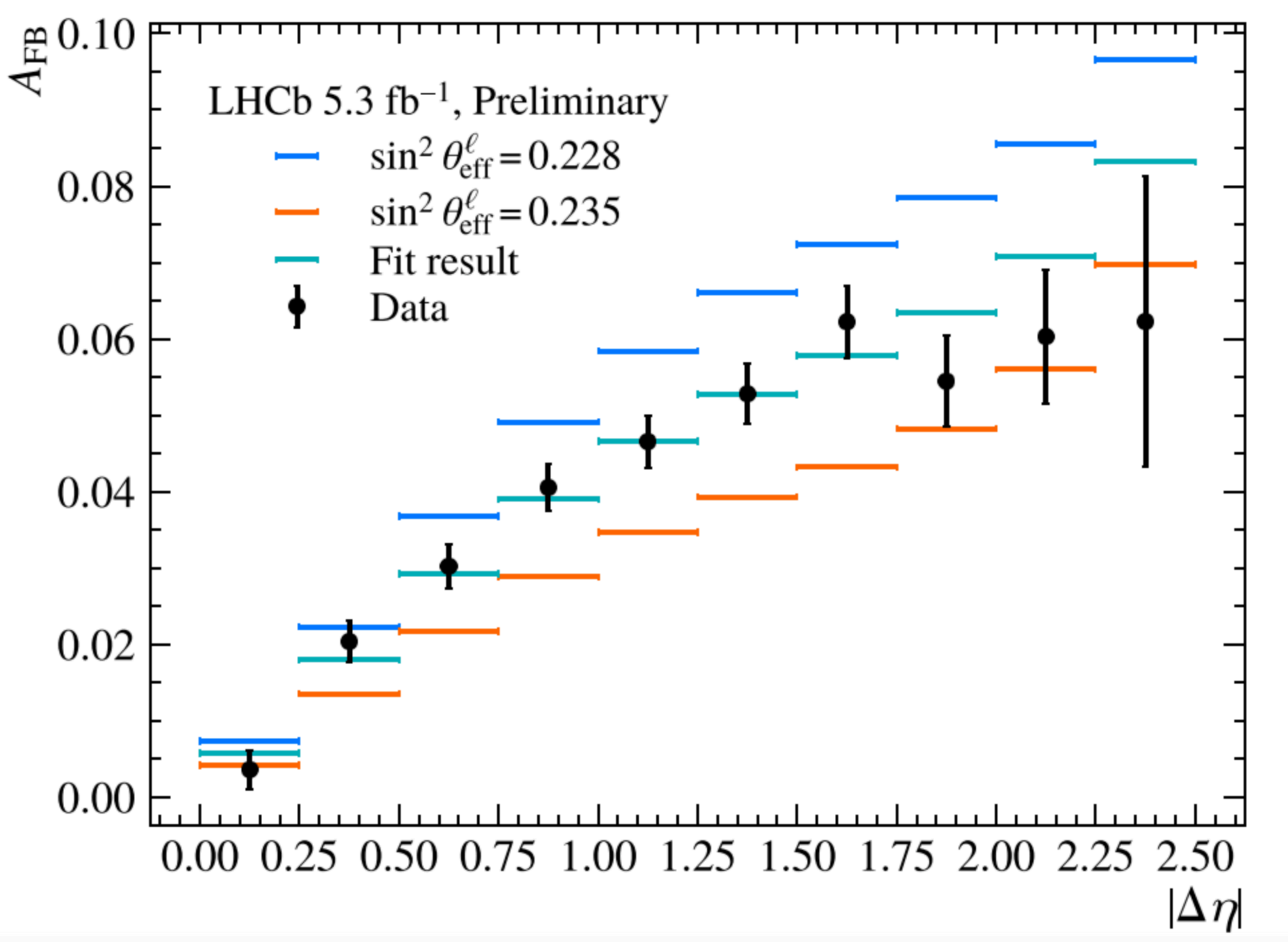
arXiv:2408.07622

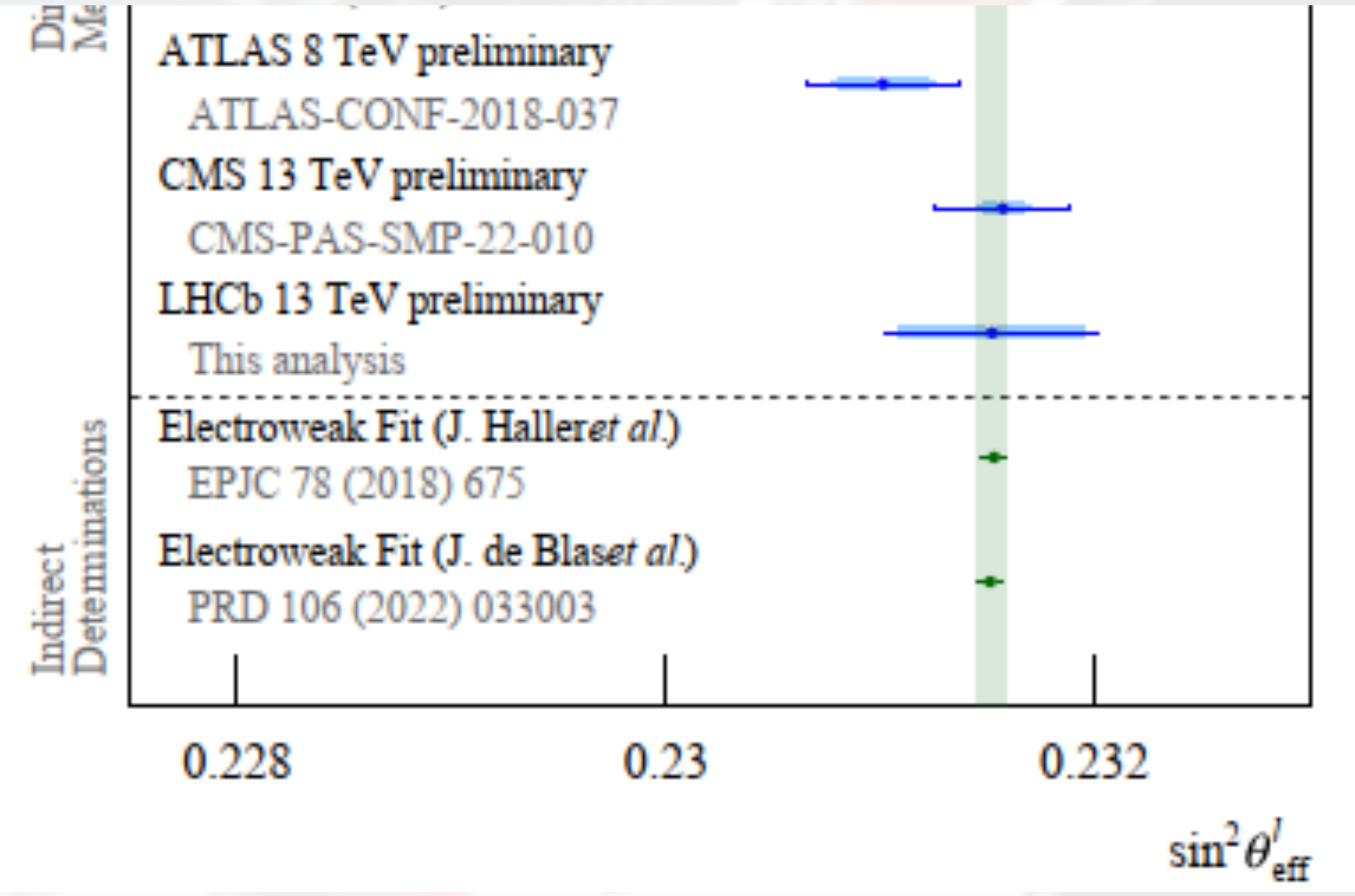
The Weak Mixing Angle

- Last Summer, LHCb released their precise measurement of A_{FB}
  - This is then translate to a very competitive measurement of $sin^2\theta_{eff}$

$$\sin^2\theta_{eff} = 0.23152 \pm 0.00044\ \text{(stat)}\ \pm 0.00005$$
$$\pm 0.00005\ \text{(syst.)}\ \pm 0.00022\ \text{(theory)}$$

  - The interesting aspect is the completely different error breakdown
    - Large statistical error (LHCb has less data, due to beam separation)
    - Much smaller theory systematic uncertainty (e.g., from PDFs), thanks to the different phase space (measurement in a fwd detector)





https://cds.cern.ch/record/2905291

W hadronic BRs

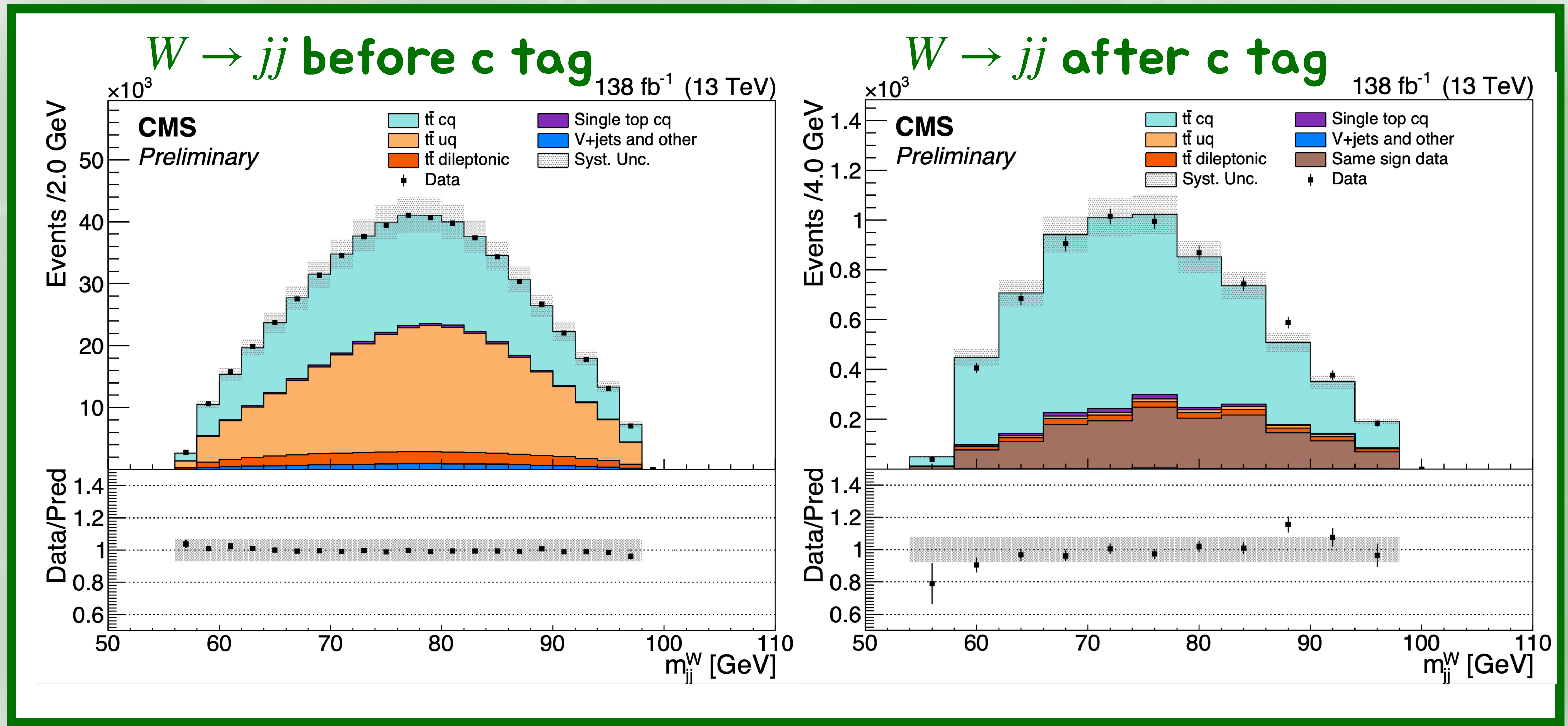
- Improved over LEP measurement of $W \to q\bar{q}'$ branching ratios
- Used $t\bar{t}$ events exploiting exclusive $c \to X\mu\nu$ tagging

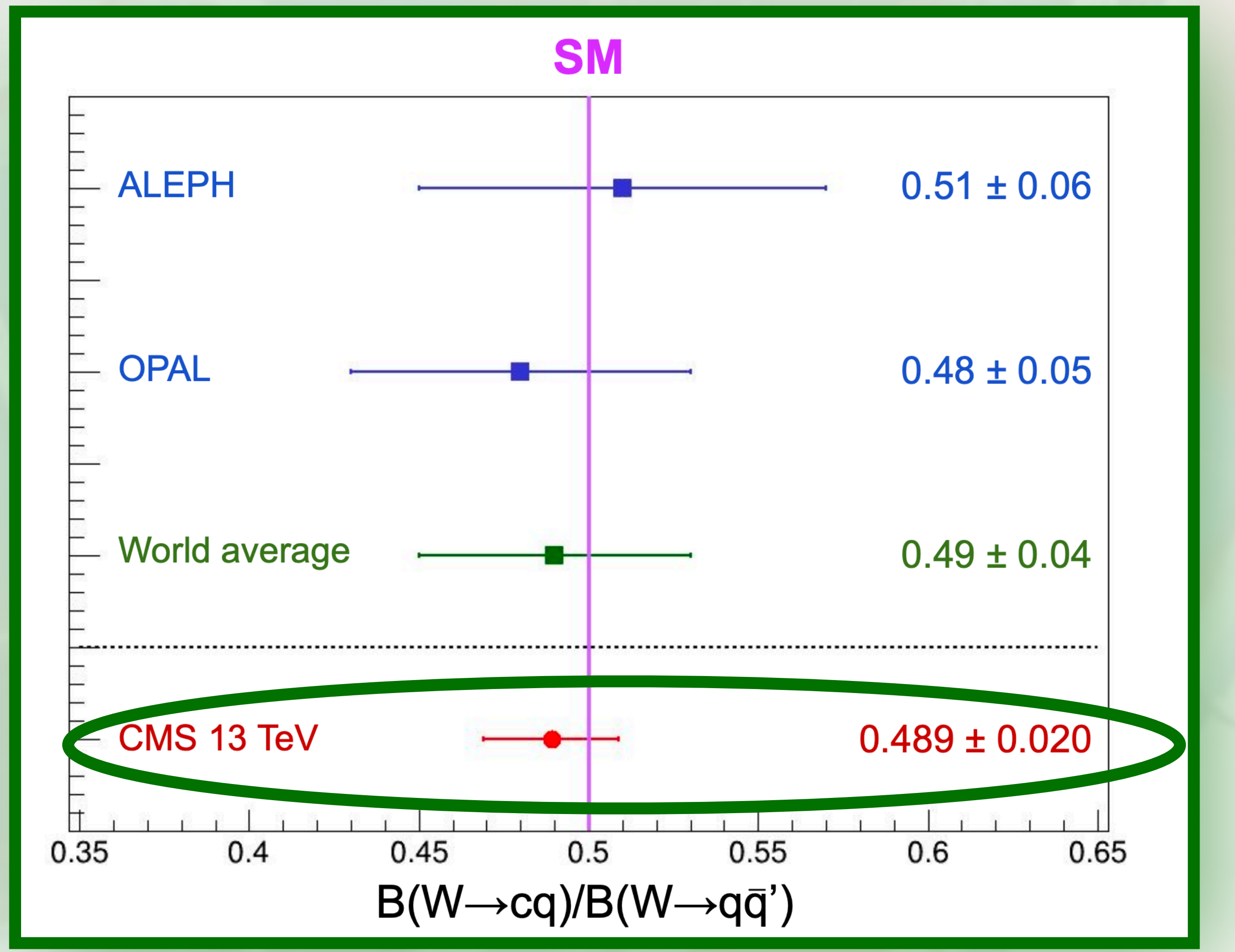
CMS-PAS-SMP-24-009

$$R_c^W = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2} = 0.498 \pm 0.005(\text{stat}) \pm 0.019(\text{sys})$$

From R_c^W and previous indirect determination of the denominator (from W leptonic BR) we can test CKM unitarity on second row

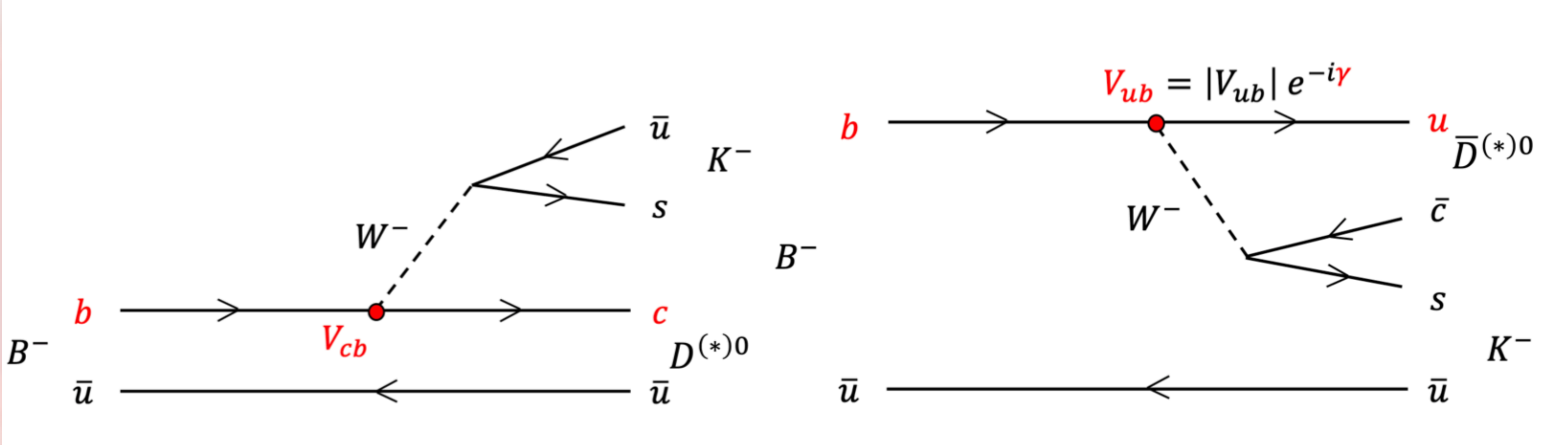
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.970 \pm 0.041$$

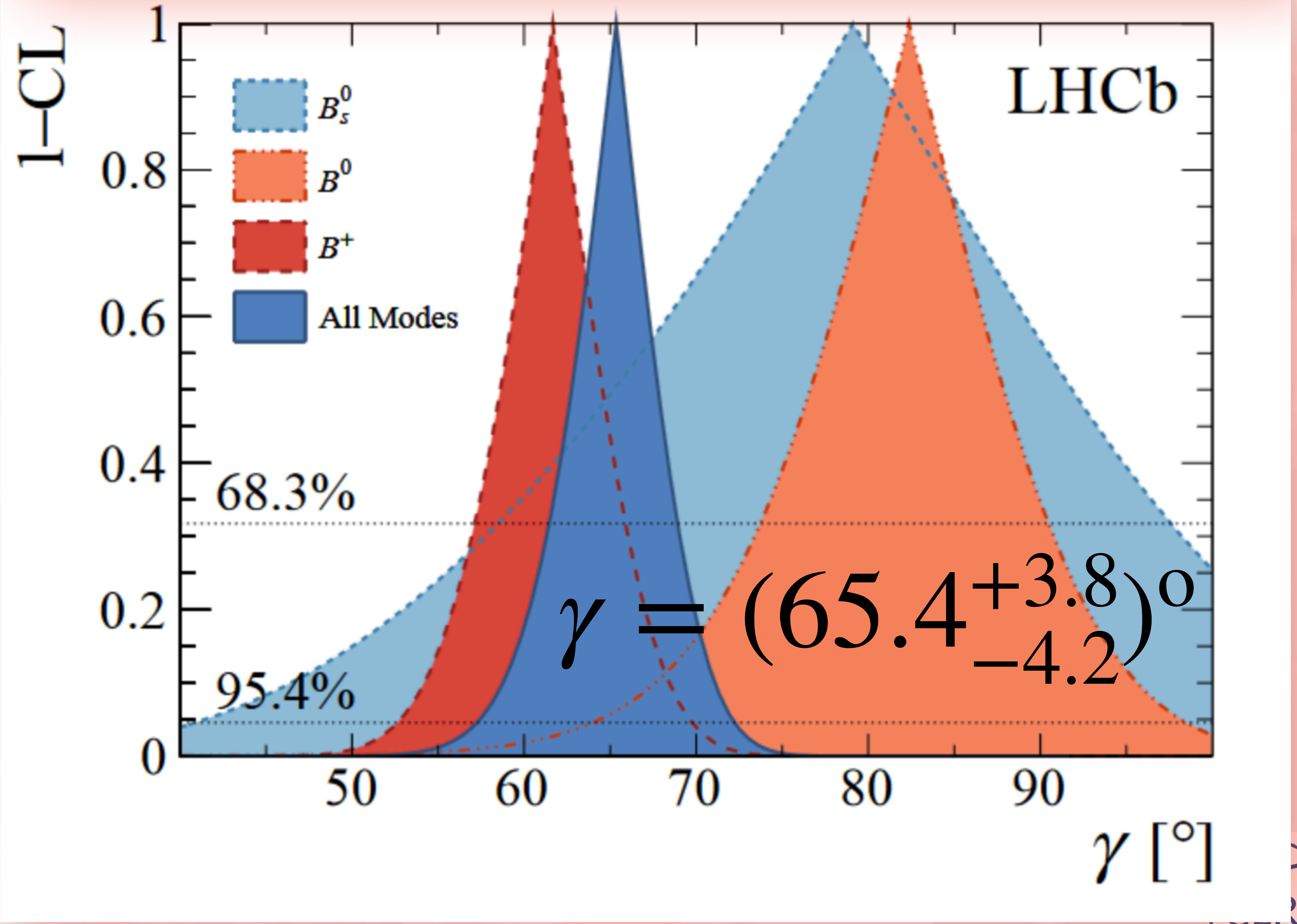




Precision Flavor Physics

- One of the most remarkable results of LHCb is the precision step up in the determination of γ
  - Used to be the UT angle known with worst precision
  - Now it is determined with a few degrees error
- This has remarkable consequences on the determination of the CKM matrix
  - Tree-level measurement, so robust vs. New physics contributions. It sets the SM baseline to BSM analyses



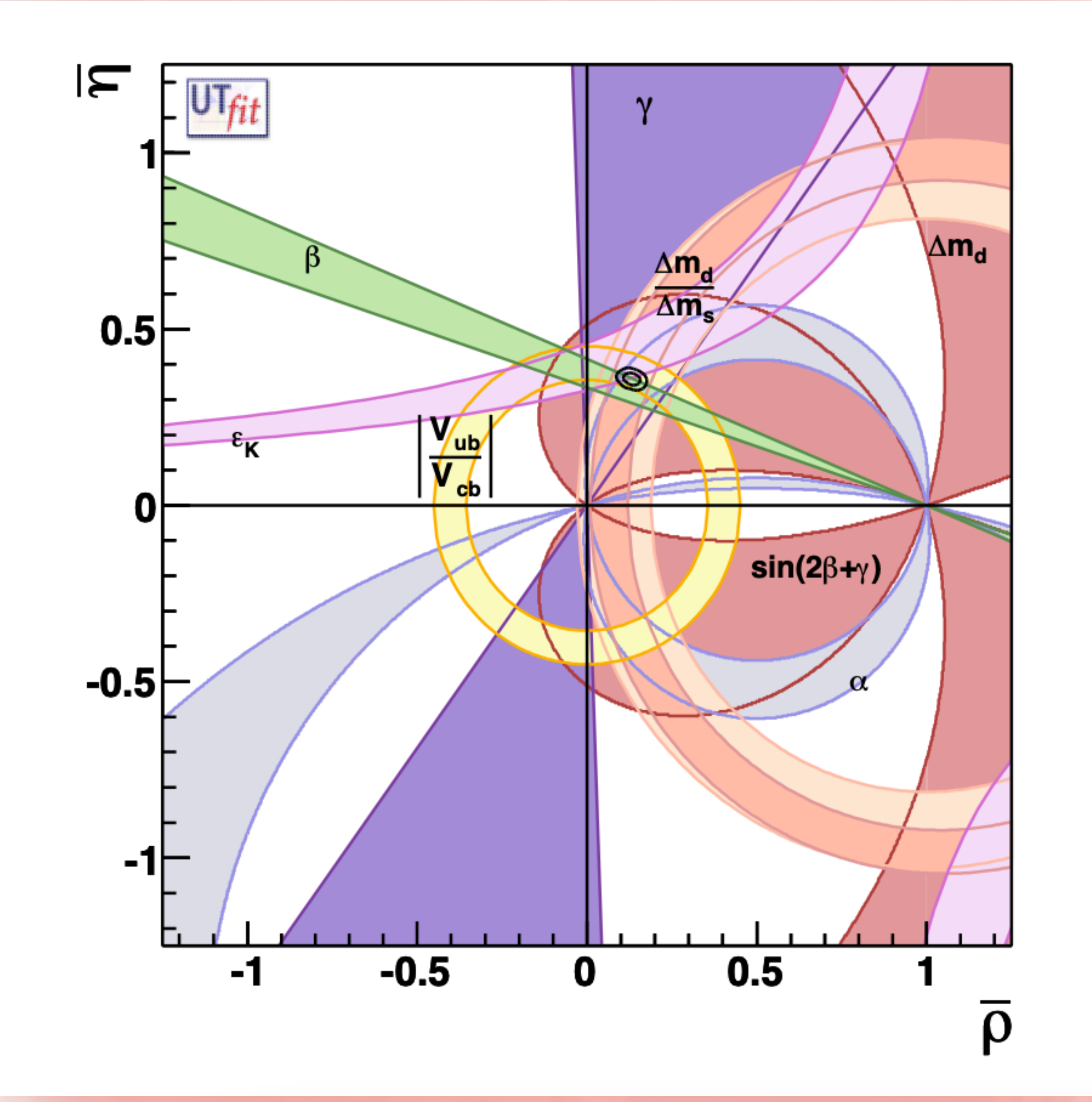


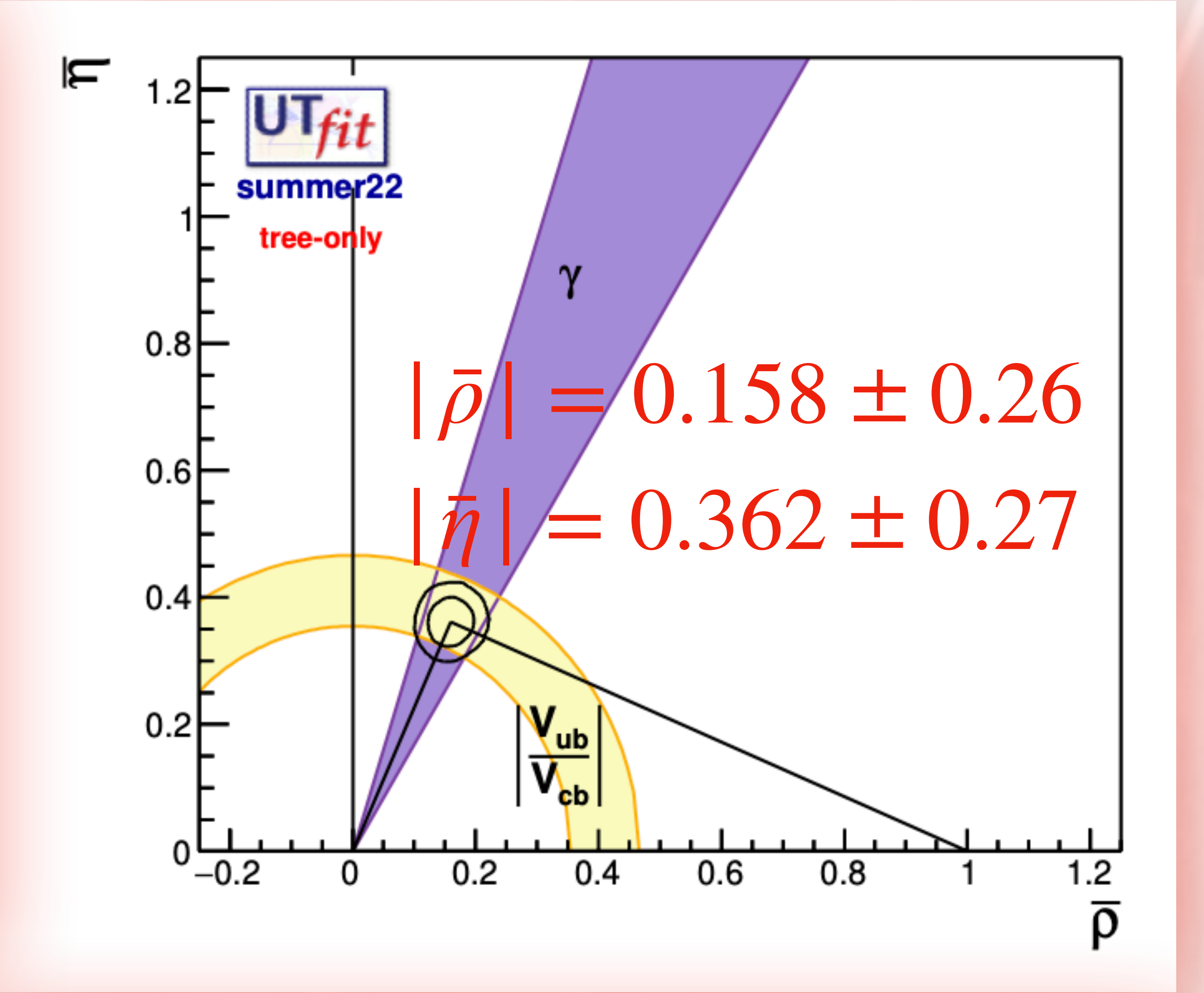
arXiv:2110.02350

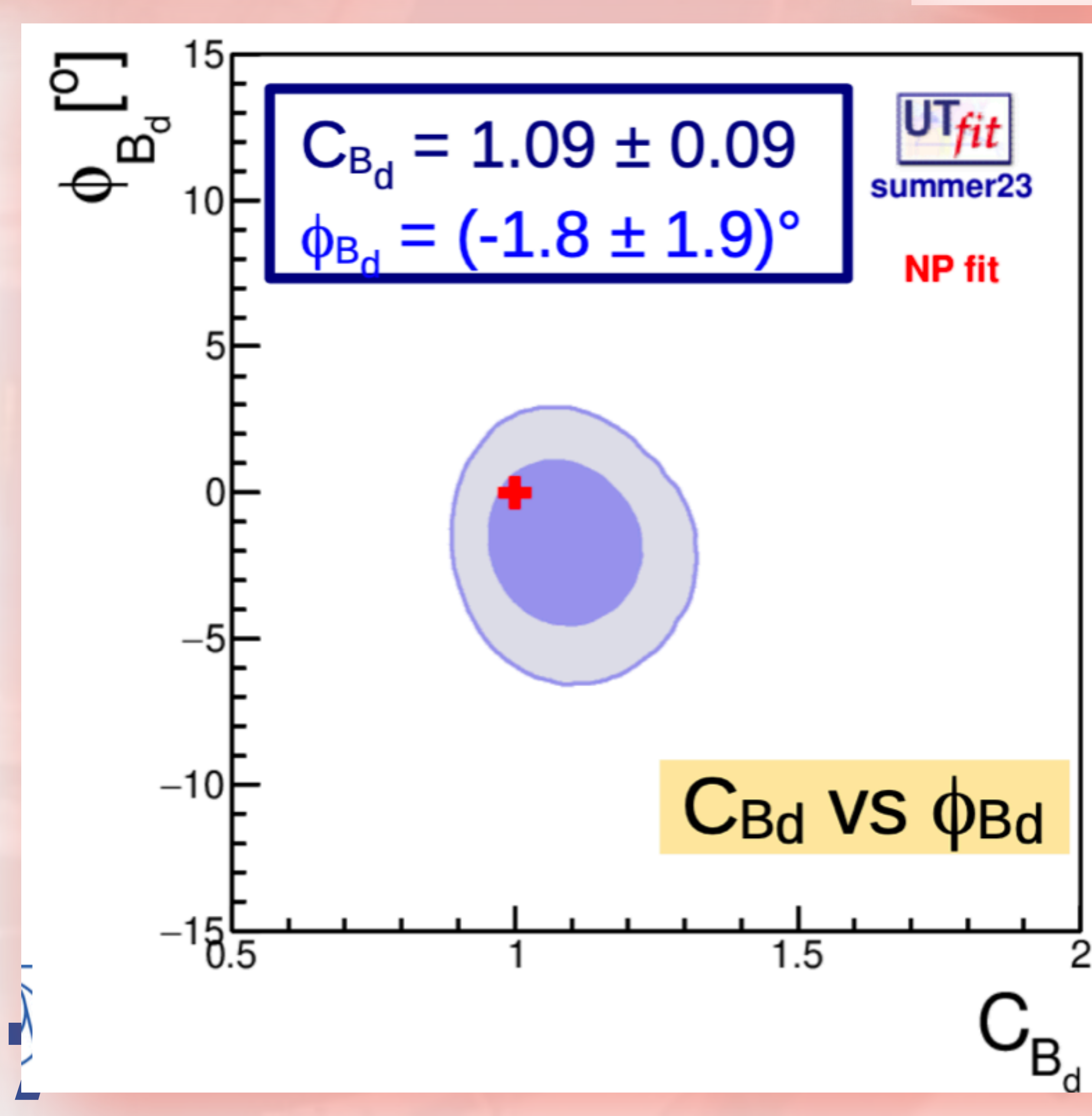
And what it tells us about the SM

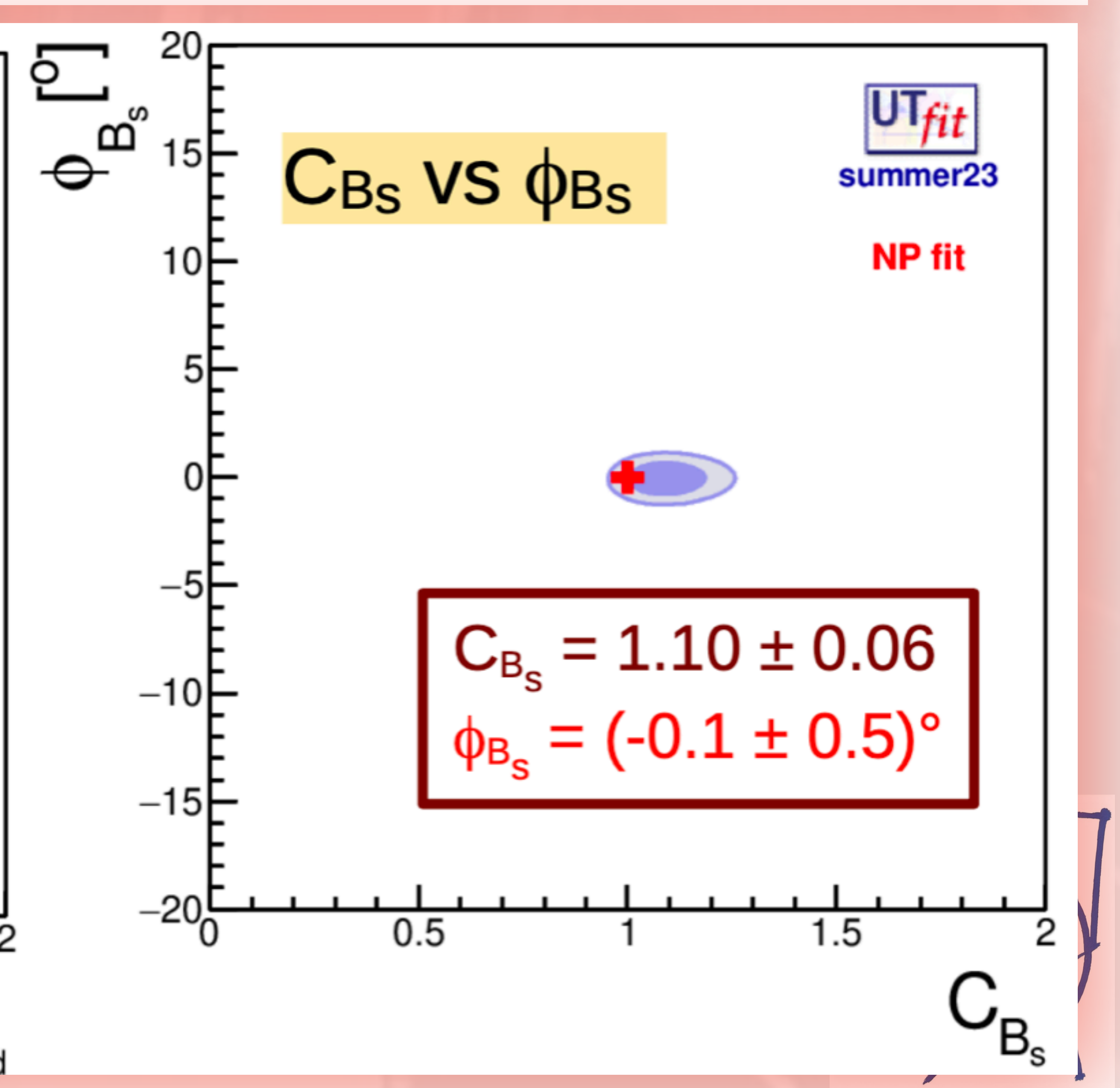
$$|\bar{\rho}| = 0.132 \pm 0.20$$
$$|\bar{\eta}| = 0.358 \pm 0.12$$

- Thanks to this improvement step up, the tree-level analysis has now a precision comparable to the full pre-LHCb analysis
- One can establish the CKM parameters from tree-level quantities
- Further measurements (e.g., CP violation in mixing) bounds New Physics amplitude in $|\Delta F| = 2$ processes



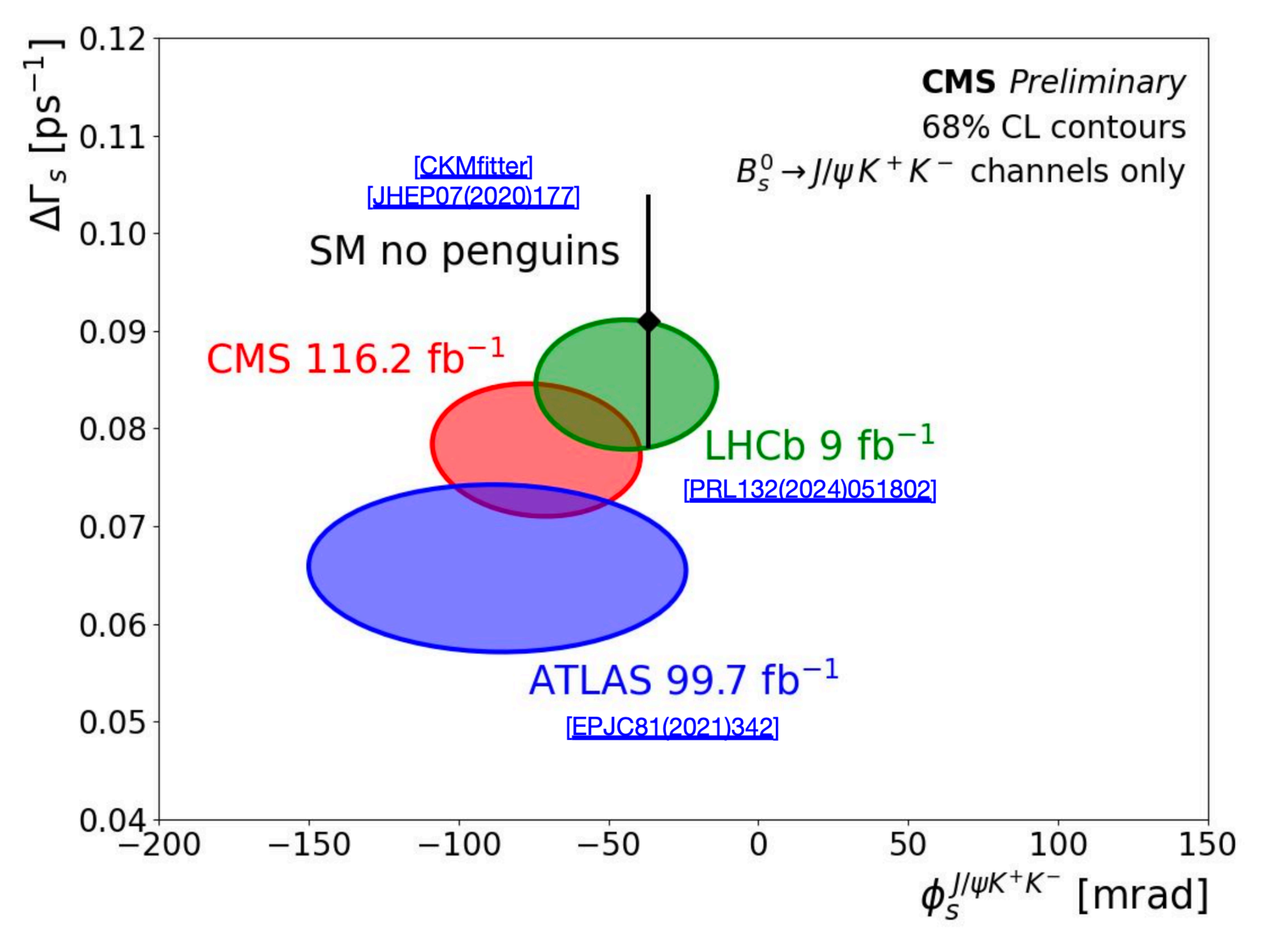






Precision Flavor Physics

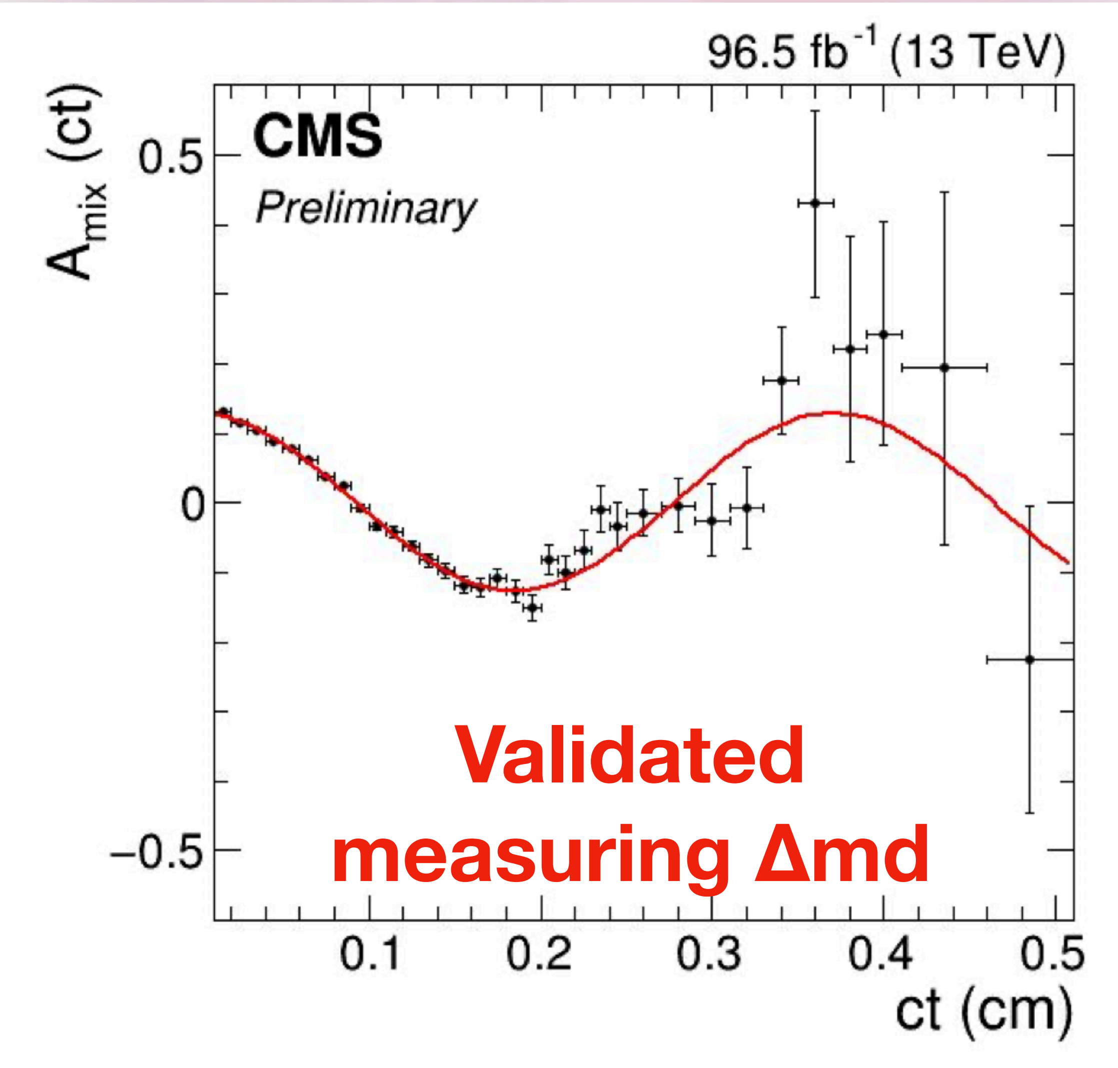
- CP Violation measurements in mixing reached astonishing precision
- Remarkably, contributions with three experiments are on equal precision level
  - reached ~10 mad precison
  - Evidence of CP Violation
  - Some tension in the values of $\Delta\Gamma$

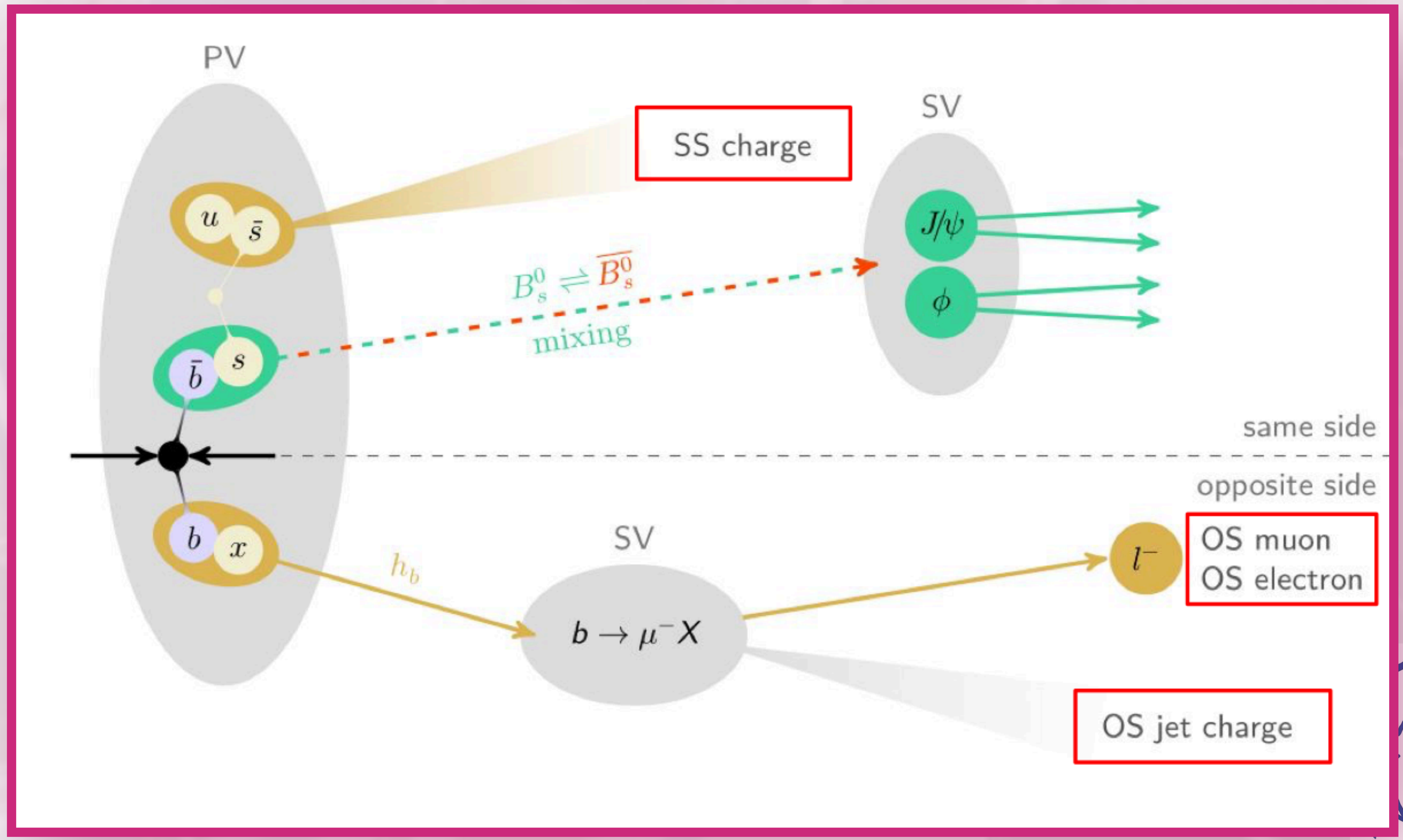


Performance Boost from Machine Learning

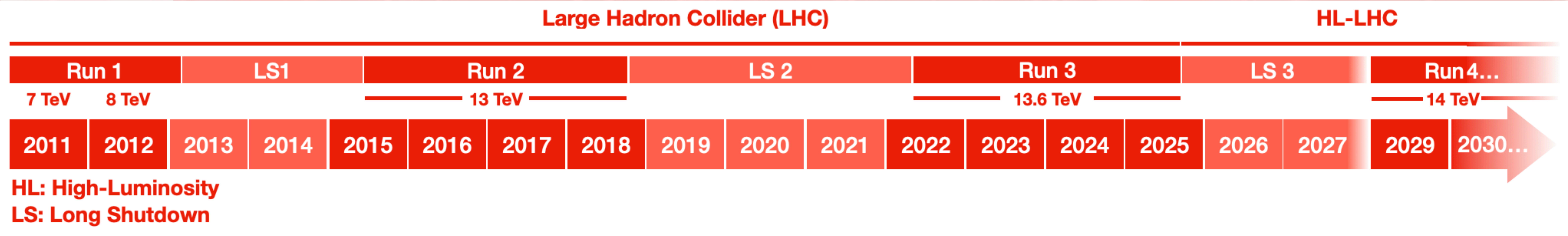
CMS-PAS-BPH-23-004

- CM managed to compensate the lack of a PID system with cutting-edge deep learning
  - 5.6% tagging power (x4 better than before)
  - Exploit both same-side and opposite-side triggers
  - First evidence of CP violation in Bs oscillations, thanks to novel AI-powered b flavor tagger (using DeepSets)
  - Further improvements expected in Run 3 with Parking





What to expect for the future



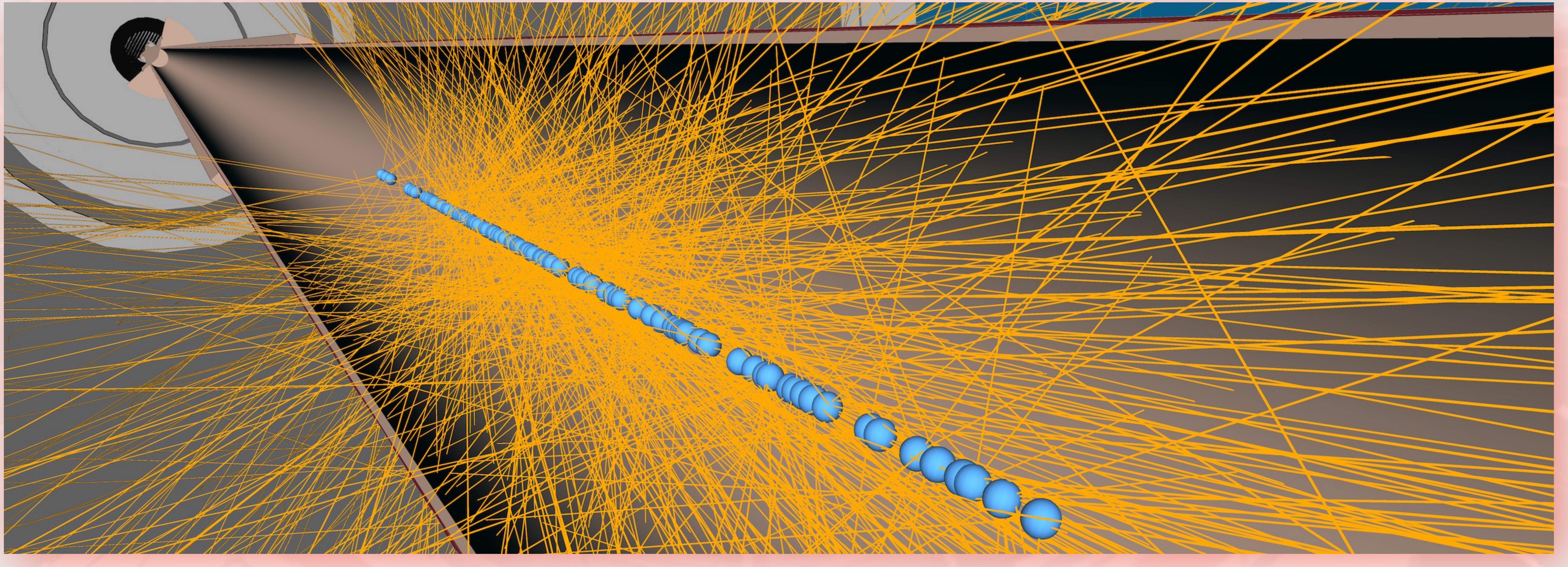
- First phase of LHC program to be completed soon
  - ATLAS and CMS aimed at >300 fb^{-1} (Run2+Run3) by the end of 2025. Should get there this year
- Working on upgrading the detector for the High-Luminosity phase
  - The target is 3000 fb^{-1} by 2041

The Future is NOW

- Meanwhile, we are pushing the detectors beyond their limits. The CMS example
  - Recording up to 63 simultaneous collisions/event (2.5x CMS design, 45% of HL-LHC)
  - Collecting data @7 kHz (70% of HL-LHC, 7x Run2 normal operations)

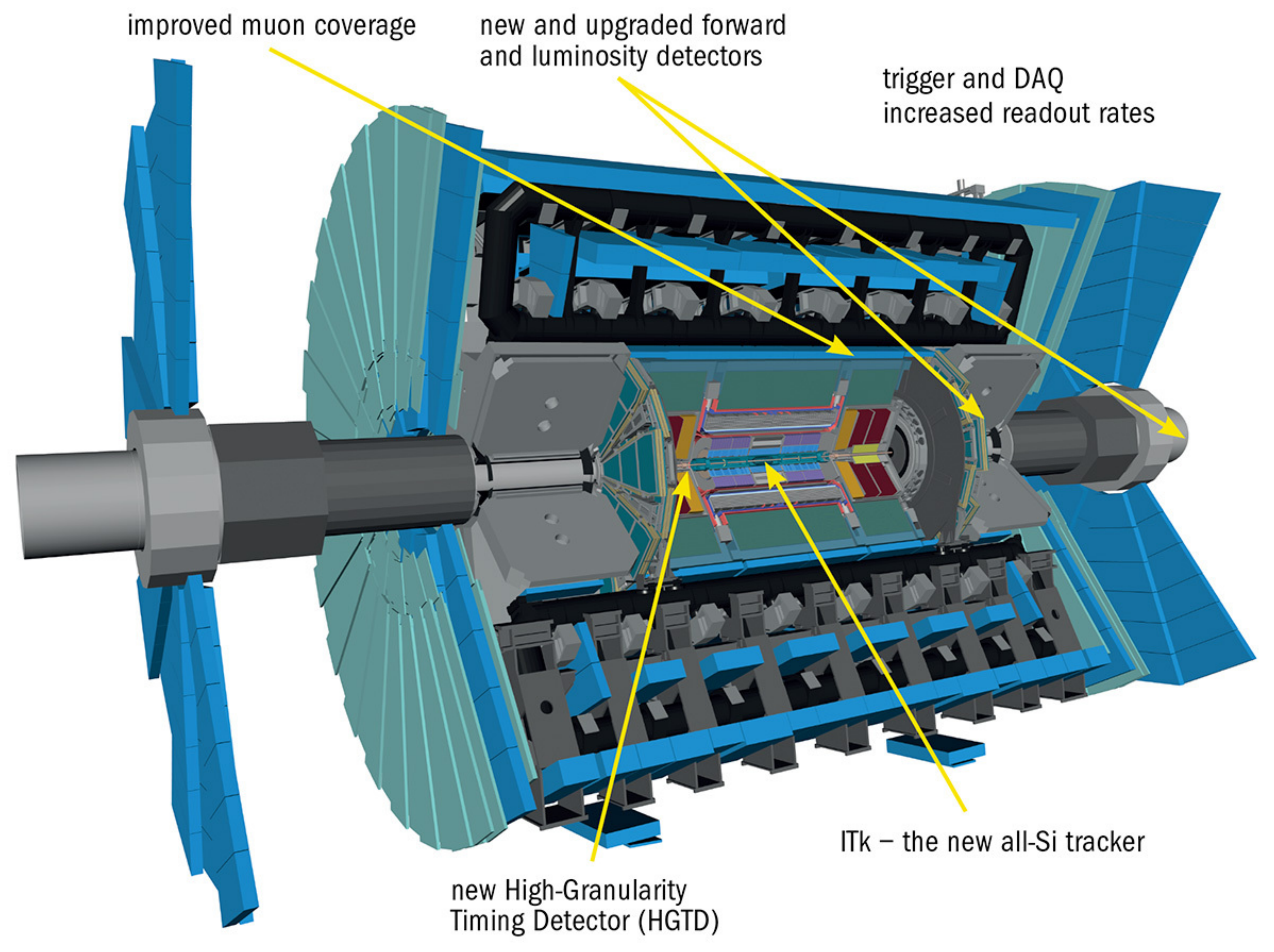
Harsher Experimental Environment

- To increase the amount of recorded data, we will have to deal with the large pileup (140 simultaneous collisions, to be compared to the design tolerance of ~20)
- But we learned how to do that (CMS and ATLAS take data at pileup ~ 62)
- And we will be equipped with better detectors



New Experimental Tools

- Larger angular coverage (e.g., for tracker devices)
  - Extended information (e.g., particle-flow reconstruction) in the forward region
- Track Trigger
  - Tracking capability in the hardware-based trigger
- Higher granularity
  - Pileup suppression
  - Better particle reconstruction inside jets
- Timing readout
  - Pileup suppression
  - Time of flight
  - PID



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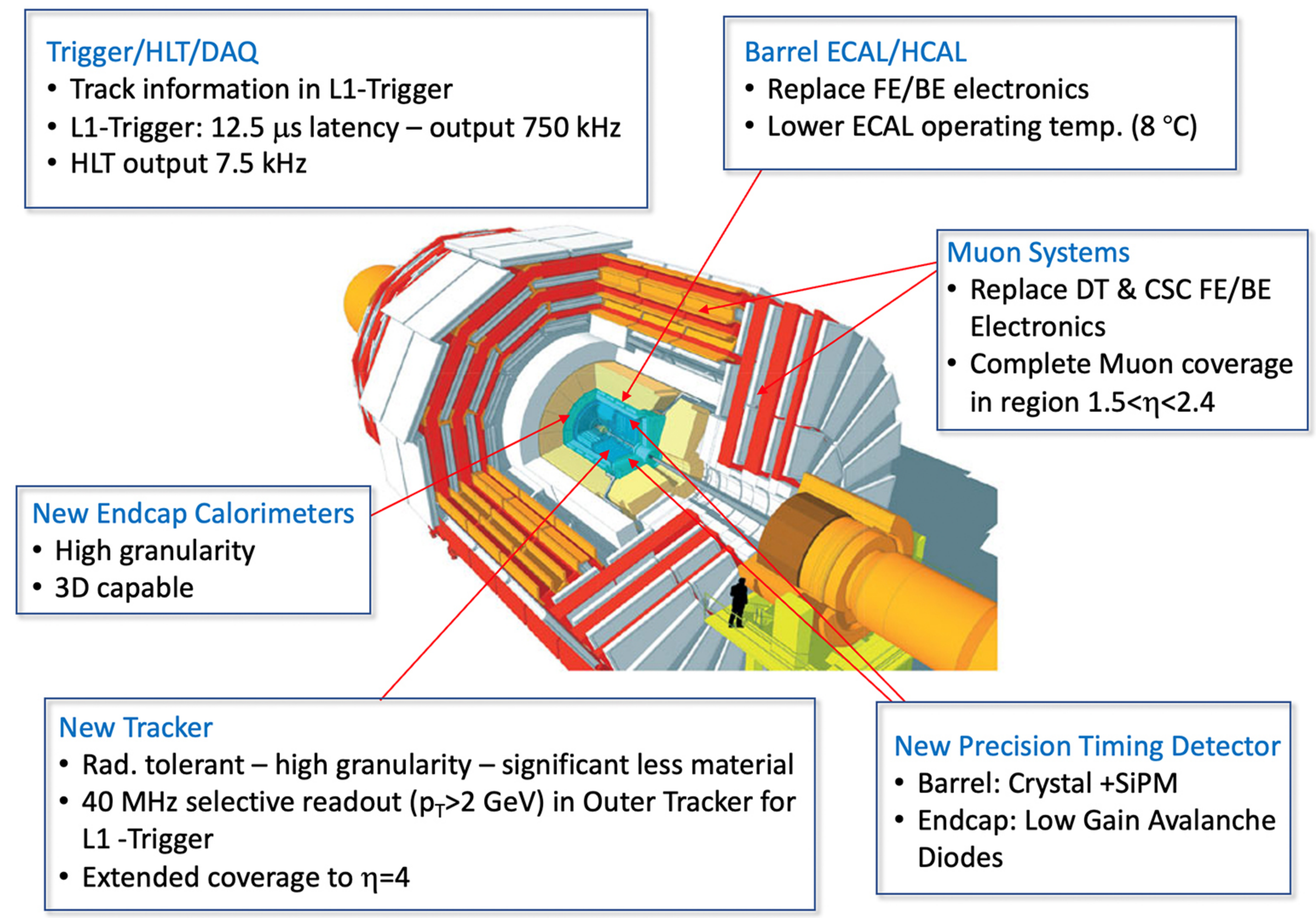
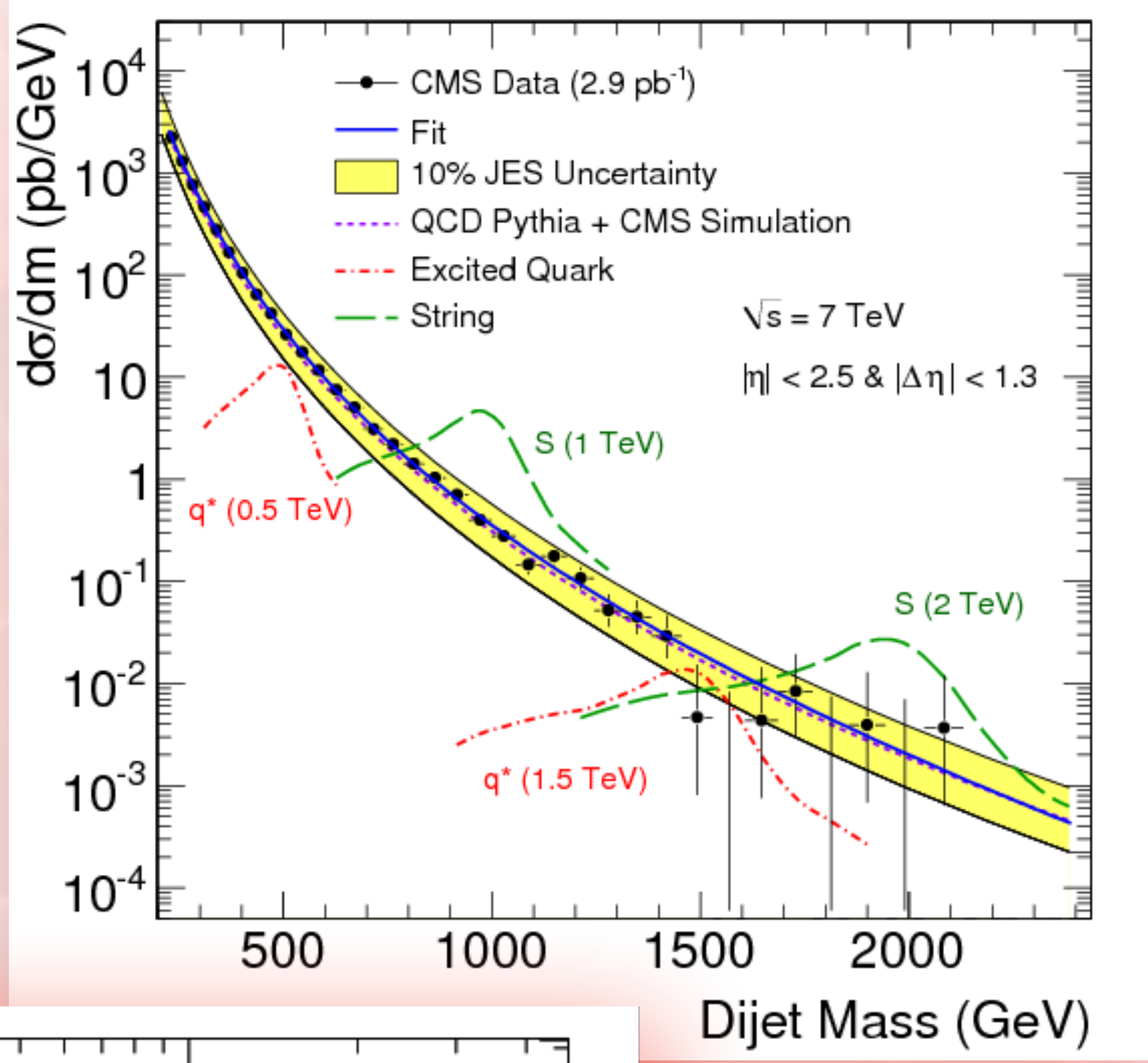
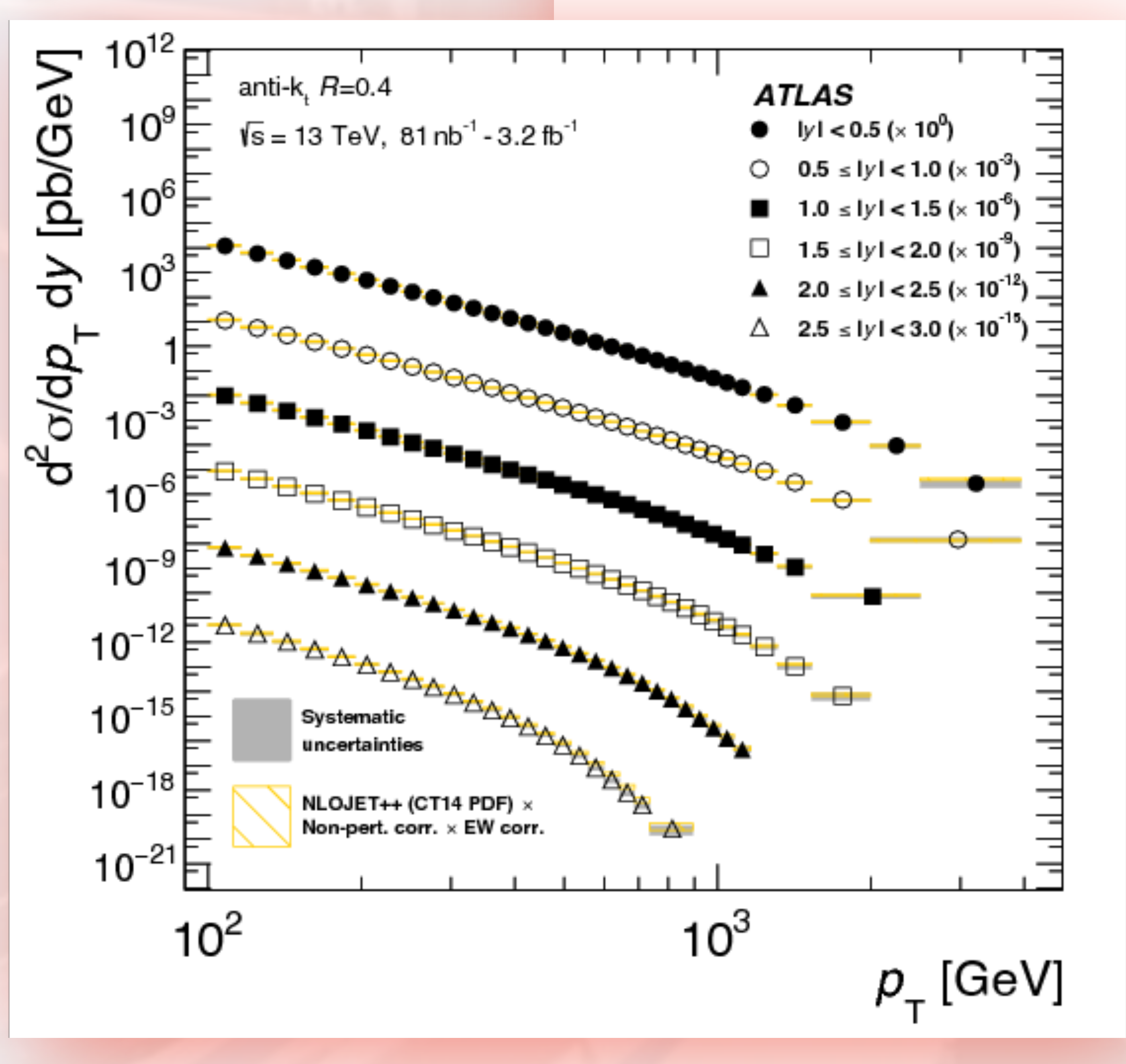


Searches vs Precision Measurements

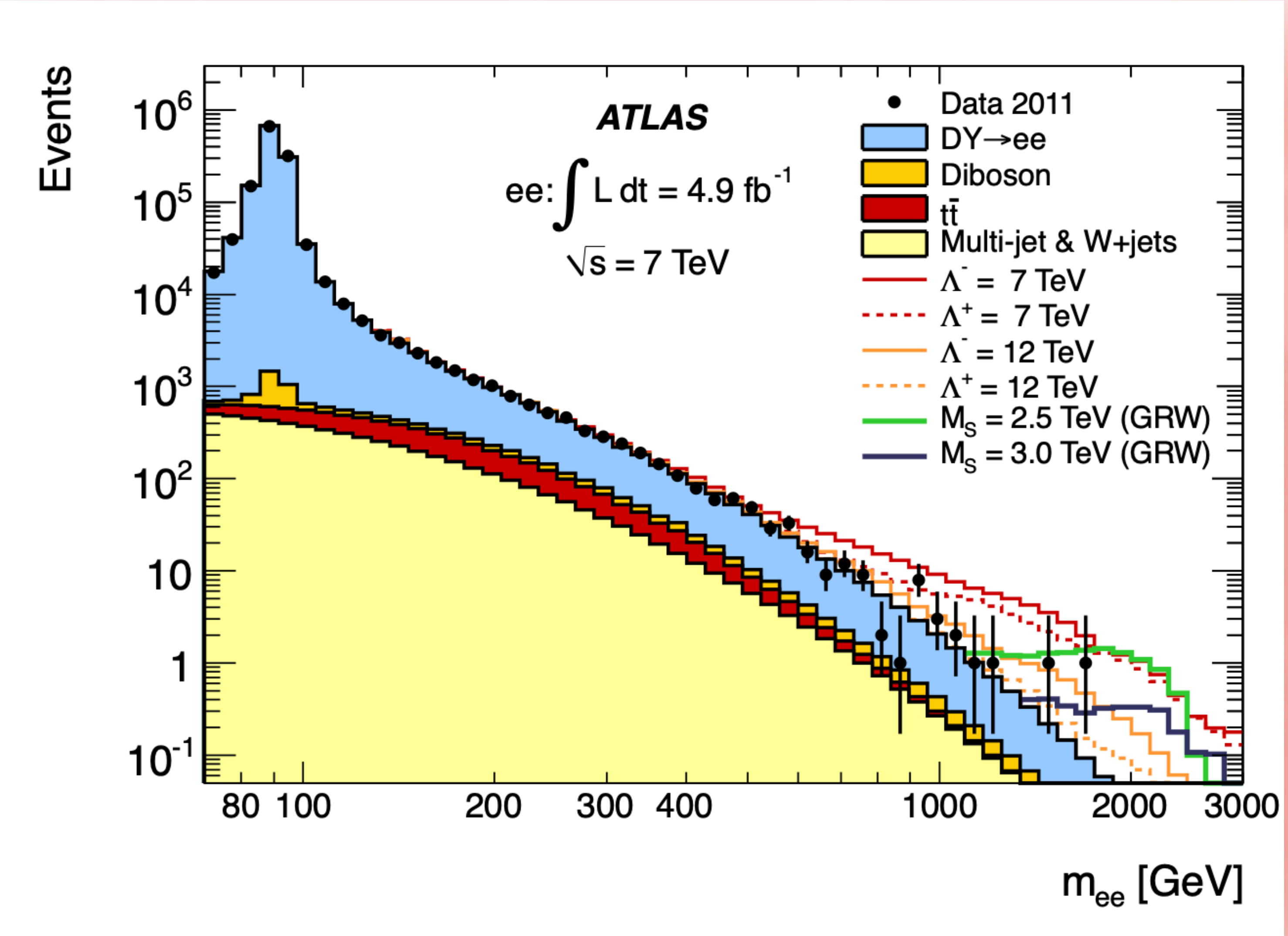
- Today, ATLAS and CMS work on two independent fronts to look for new physics
  - **DIRECT SEARCHES** for new physics: assume some new physics model and search for it as a hypothesis test
    - Use data driven models of the background, e.g., template fits in bump hunting
  - **INDIRECT BOUNDS FROM MEASUREMENTS:** measure absolute and differential cross sections of specific Standard Model processes and compare that to the theory
    - Big emphasis to constraining systematic uncertainties, in particular from theory, to reach high precision



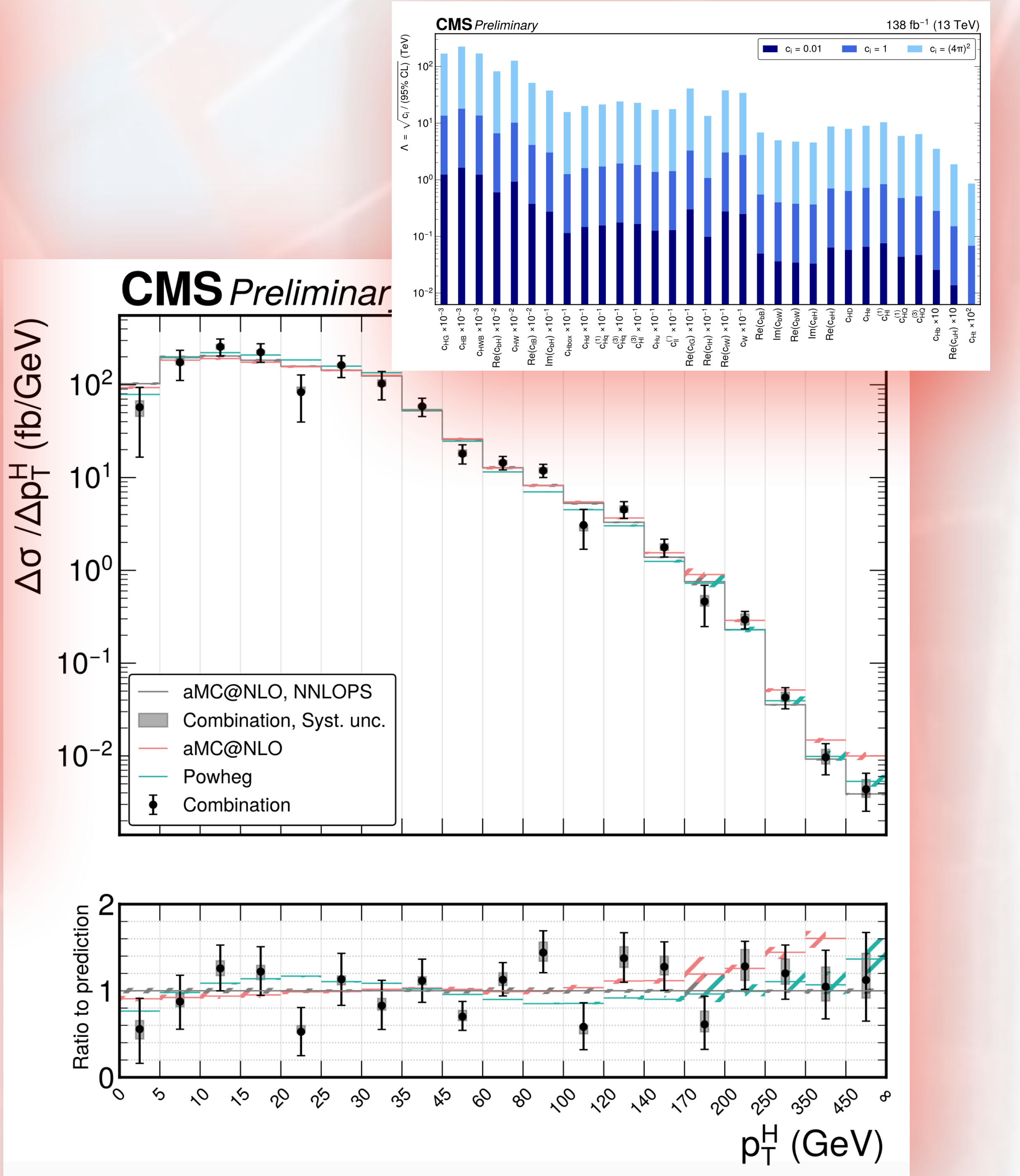


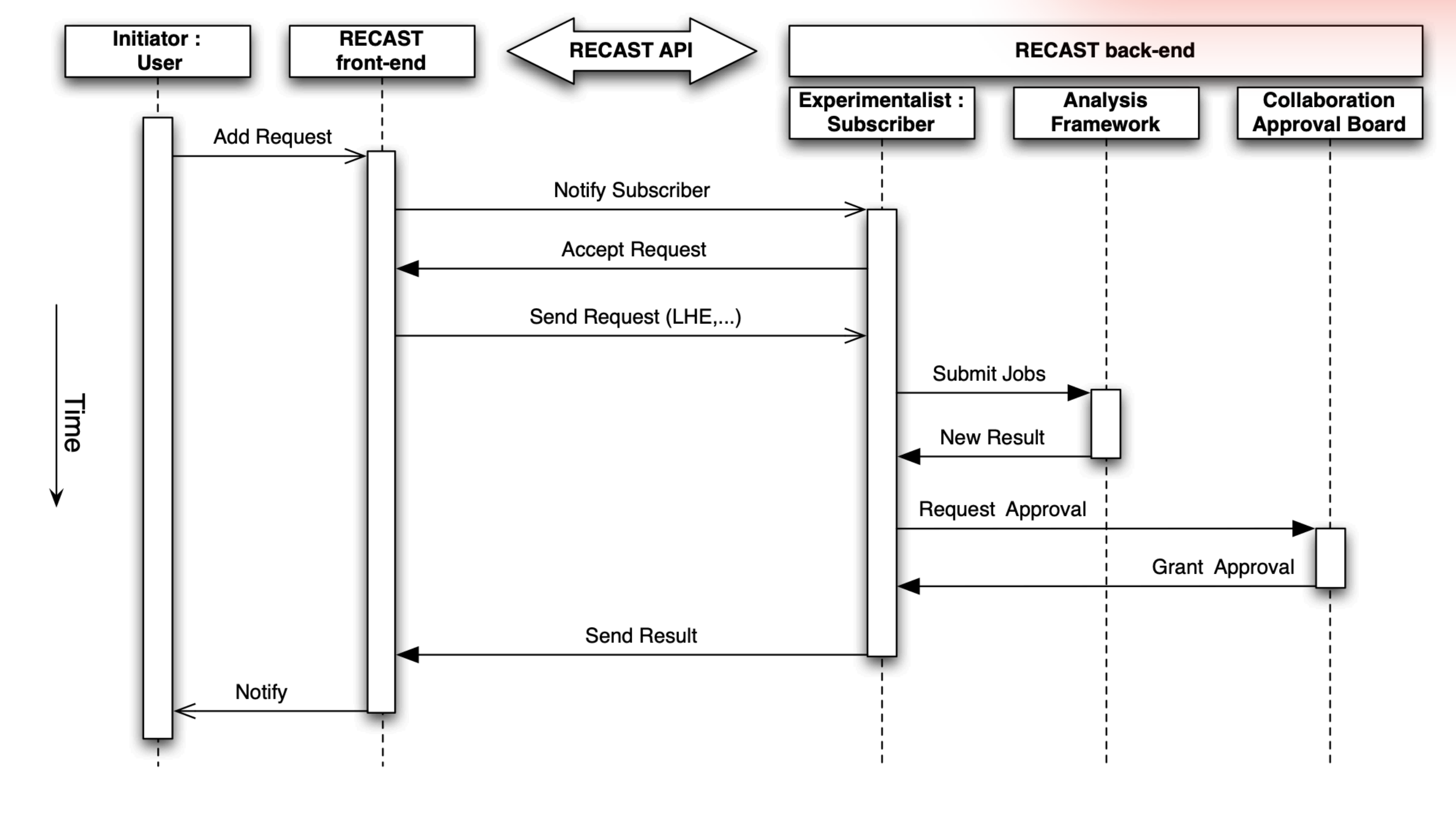
Searches ~~vs~~ with Precision Measurements

- The (re)growing interest in Effective Field Theory will build the bridge between these two fronts
  - EFT analyses are searches in which the model is specified higher-order operators in matrix-element approach
  - EFT is a precision measurement of some differential cross section
- There is little difference in searching for a deviation of the data from the SM precision on a tail and certain models of new physics
  - large extra dimensions
  - broad resonances
- On HL-LHC time scale, the two fronts will mostly merge
  - Recasting studies from one scenario to another will be essential



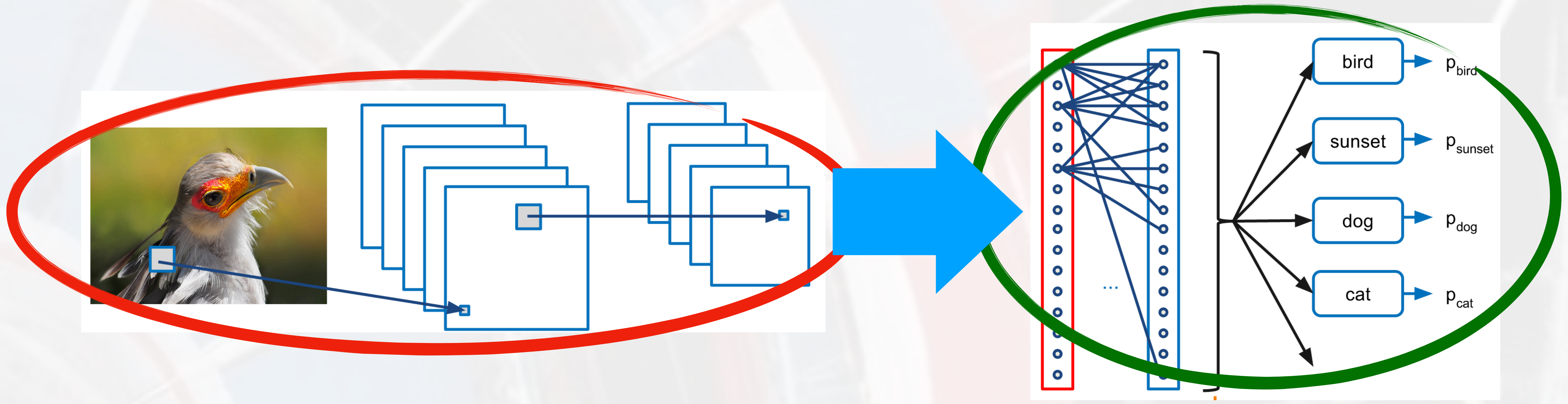
arXiv:1010.2506

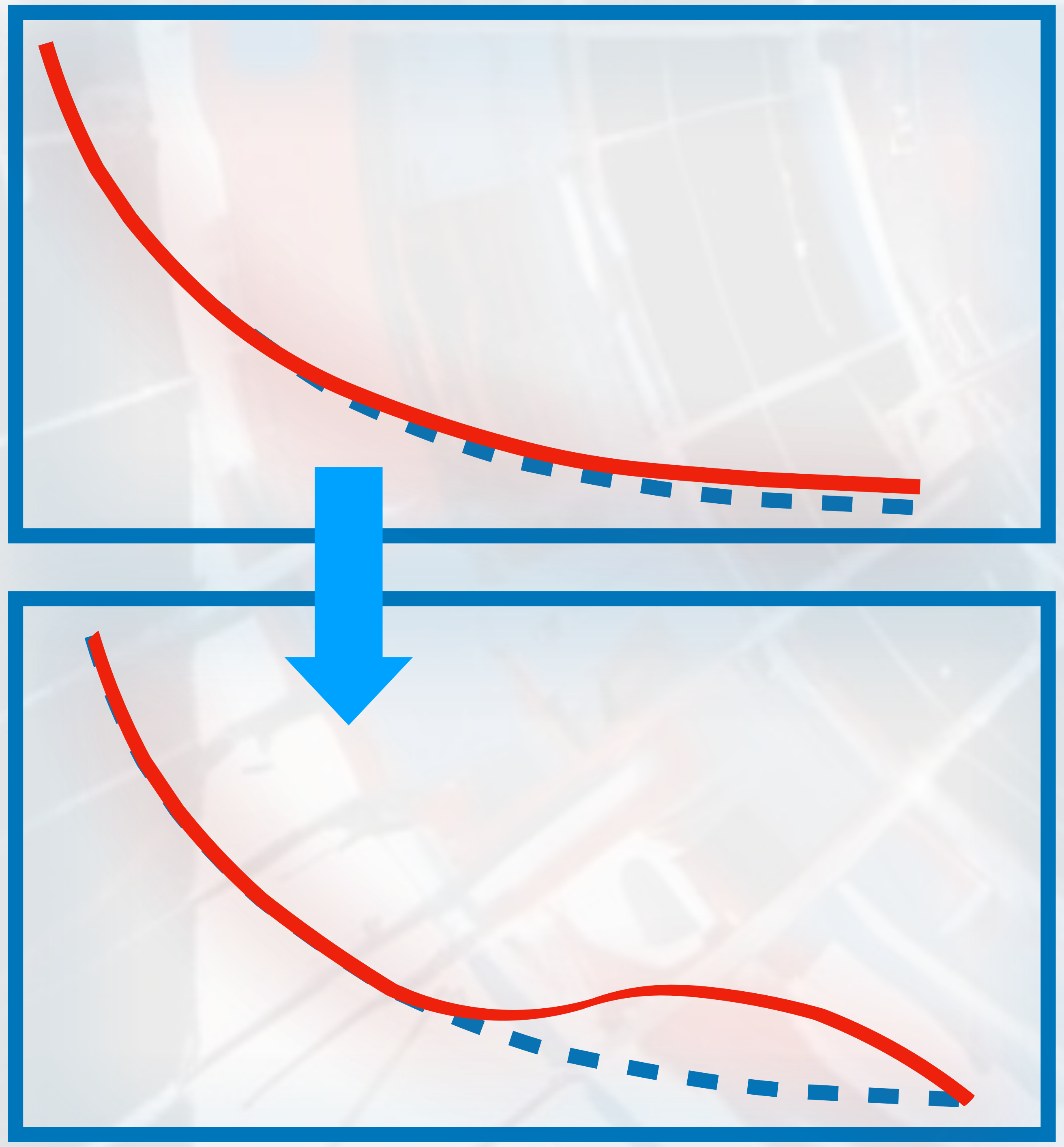


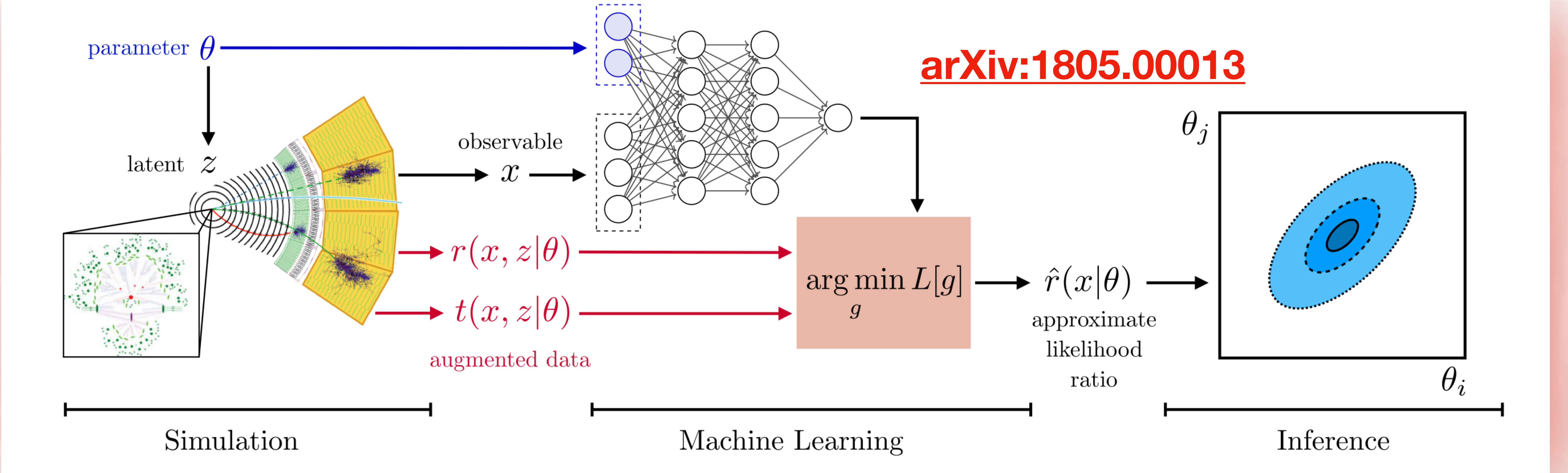


The Role of Deep Learning

- Deep Neural Network are fantastic in processing raw data and building discriminating quantities
  - Used to be the job of clever PhD students in experiments
- In an EFT program development, DNNs could be the ideal tool to define new quantities X to maximise signal visibility in a differential x-sec measurement

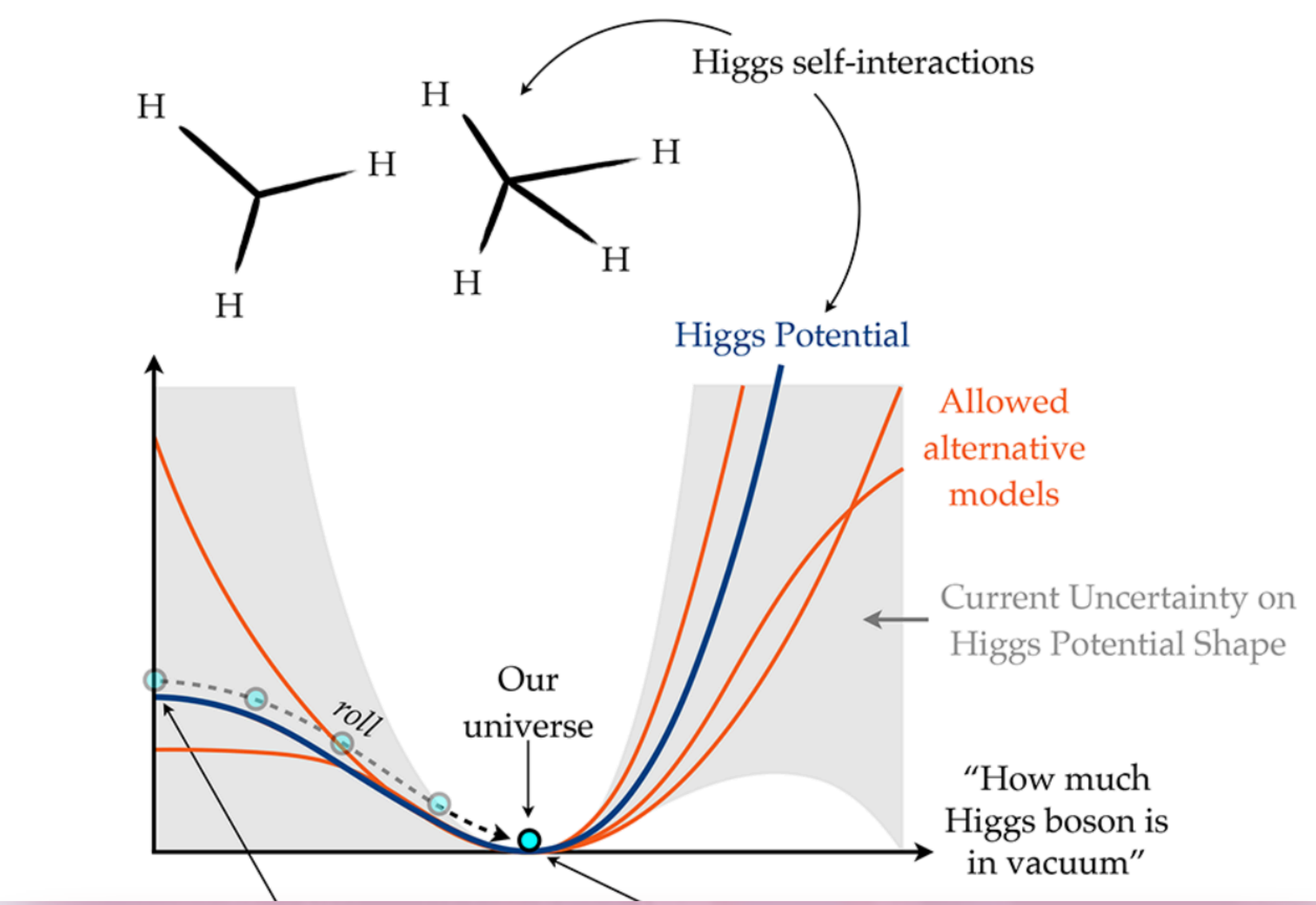


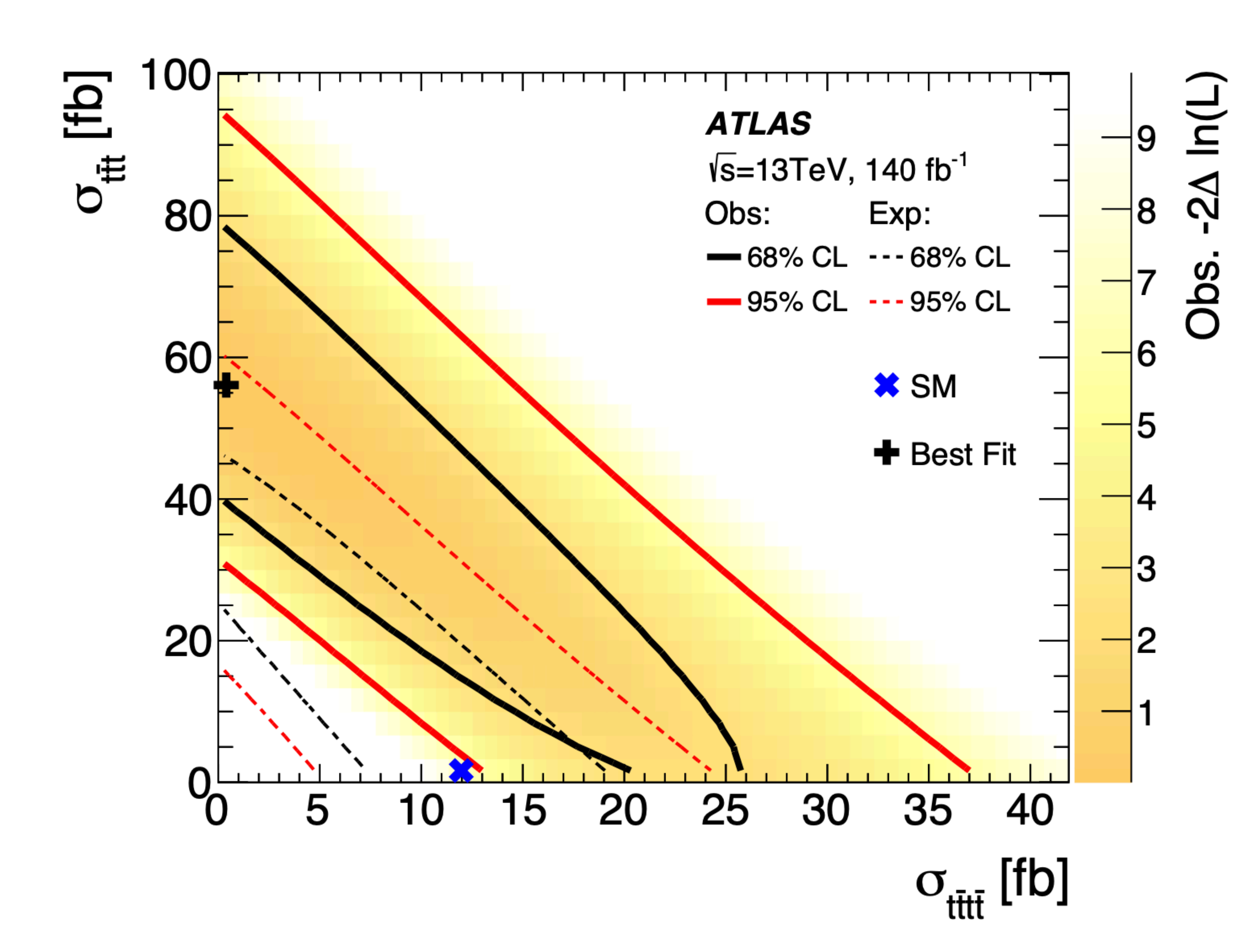




The HL-LHC physics legacy

- Assuming no other hadron collider before 2070 (if any), the LHC has unique access to key aspects of Standard Model physics
  - Rare Higgs decays, loop mediated, could be sensitive to high-mass new particles via virtual effects
  - HH production and the shape of the Higgs potential
    - Probing scenarios of new physics modifying the couplings
  - The Yukawa coupling of the top, probed in multiple ways
    - Higgs production (ttH) and decay ($H \to \gamma\gamma$)
    - Multitop production
  - Vector Boson scattering via VBF events





HL-LHC is a Higgs Factory

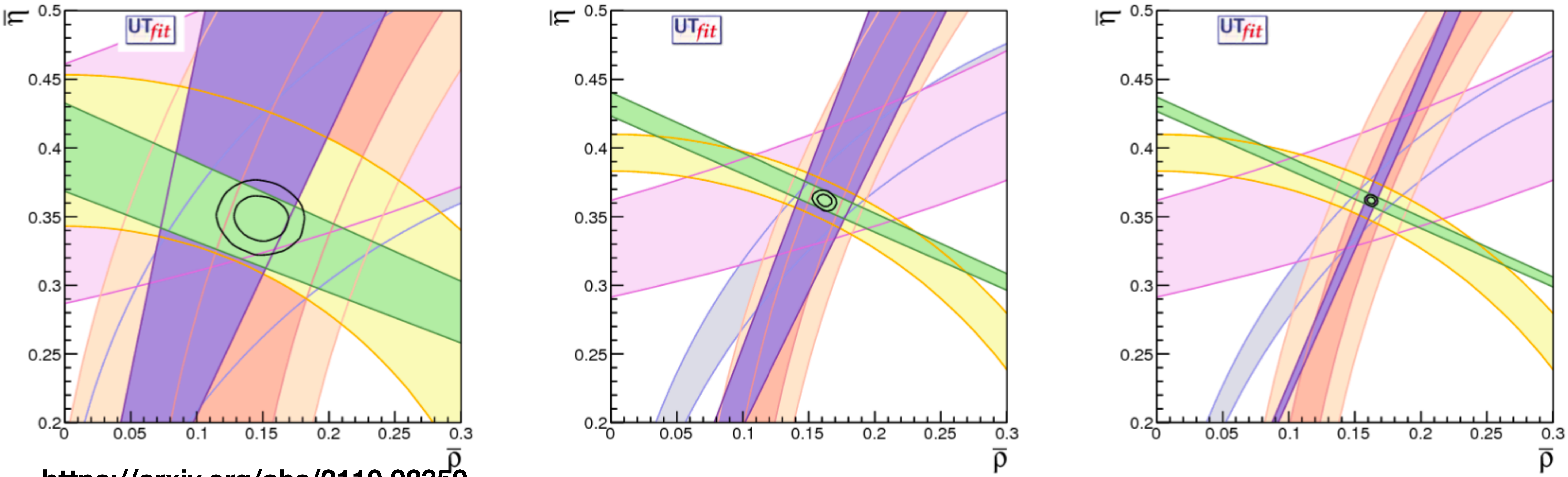
- The LHC will deliver precise coupling measurements before a Higgs factory
  - Most within a few %
- The Higgs factory will improve by a factor x2-3 on couplings to W, Z, g and mostly 3rd generation quark
- The Higgs factory will not produce enough H to improve LHC determinations for any rare decay
  - These are mostly loop-mediated, and they are valuable indirect probes on new physics
- Back in the days, when NP is small, we used to look for it in processes with small SM amplitudes

Ch.	HL-LHC	+ 240 GeV	+ 240+365 GeV	+ FCC-hh
κ_W	0.99	**0.88**	**0.41**	0.19
κ_Z	0.99	**0.20**	**0.17**	0.16
κ_g	2.00	**1.20**	**0.90**	0.5
κ_γ	1.60	1.3	1.3	0.31
$\kappa_{Z\gamma}$	10.0	10.0	10.0	0.7
κ_c	–	**1.50**	**1.30**	0.96
κ_t	3.20	3.10	3.10	0.96
κ_b	2.50	**1.00**	**0.64**	0.48
κ_μ	4.40	4.00	3.90	0.43
κ_τ	1.60	**0.94**	**0.66**	0.46
Inv.	1.9	**0.22**	**0.19**	0.024

HL-LHC impact on Flavor

- With HL-LHC, the UT analysis will reach <1% precision thanks to LHCb precision step up, setting a milestone for the SM and providing strong bounds for BSM model building
- Further push by CMS? Long-term implications of new strategy still under assessment

NOW | End of Run 3 | HL-LHC



https://arxiv.org/abs/2110.02350

Summary

- The LHC started as a discovery machine
  - Higgs discovery
  - SUSY (and SUSY alternatives) search
- With improved detector understanding and novel algorithms, LHC precision era started
  - Improved over LEP/Tevatron on many fronts
  - Big push from novel Deep Learning techniques
  - Reach enhanced by novel data taking paradigms (scouting & parking)
- With HL-LHC, new detector capabilities will further improve precision
  - On many fronts, LHC experiments will remain unchallenged until the next big high-energy collider
  - Legagy on fundamental questions (Higgs potential, vacuum stability, etc.)