Recent highlights from the CMS Experiment

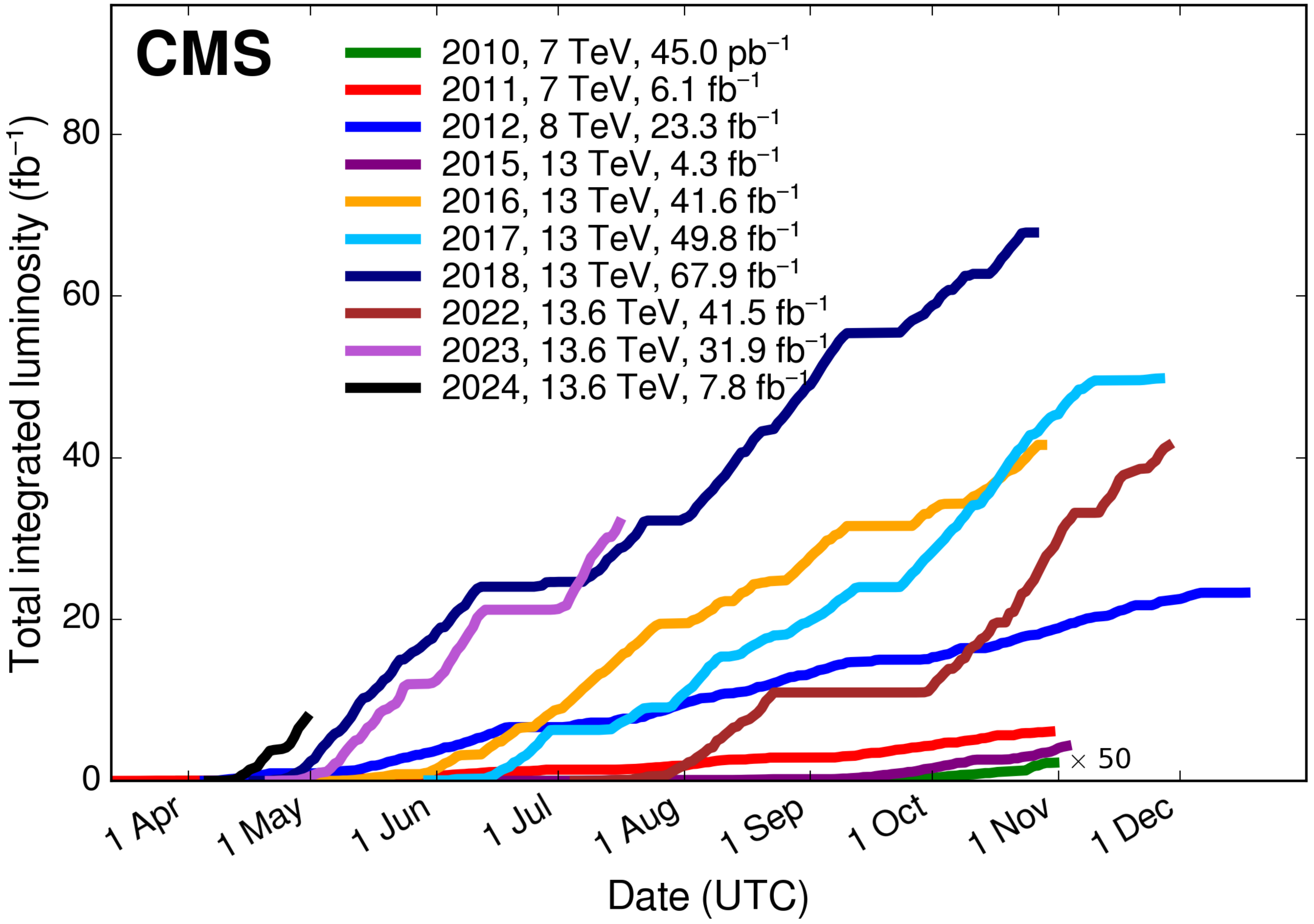
Focusing on results relevant to or dependent on precise calculations

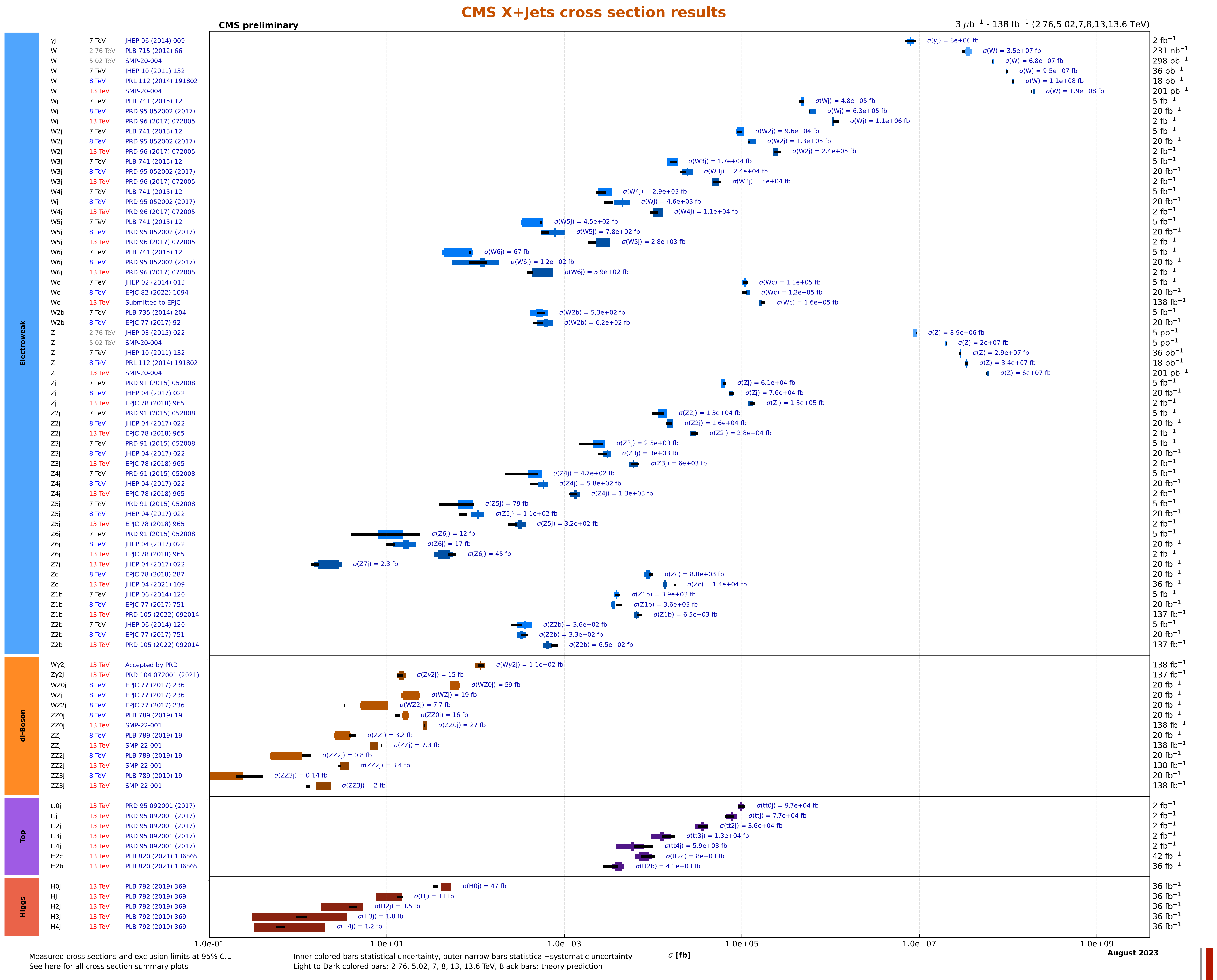
Kenneth Long (MIT)

Exploring the standard model with the LHC

- **Huge LHC data sets**: a good problem to have
  - How differential can you go?
  - How many bosons/jets/top quarks/Higgs…?

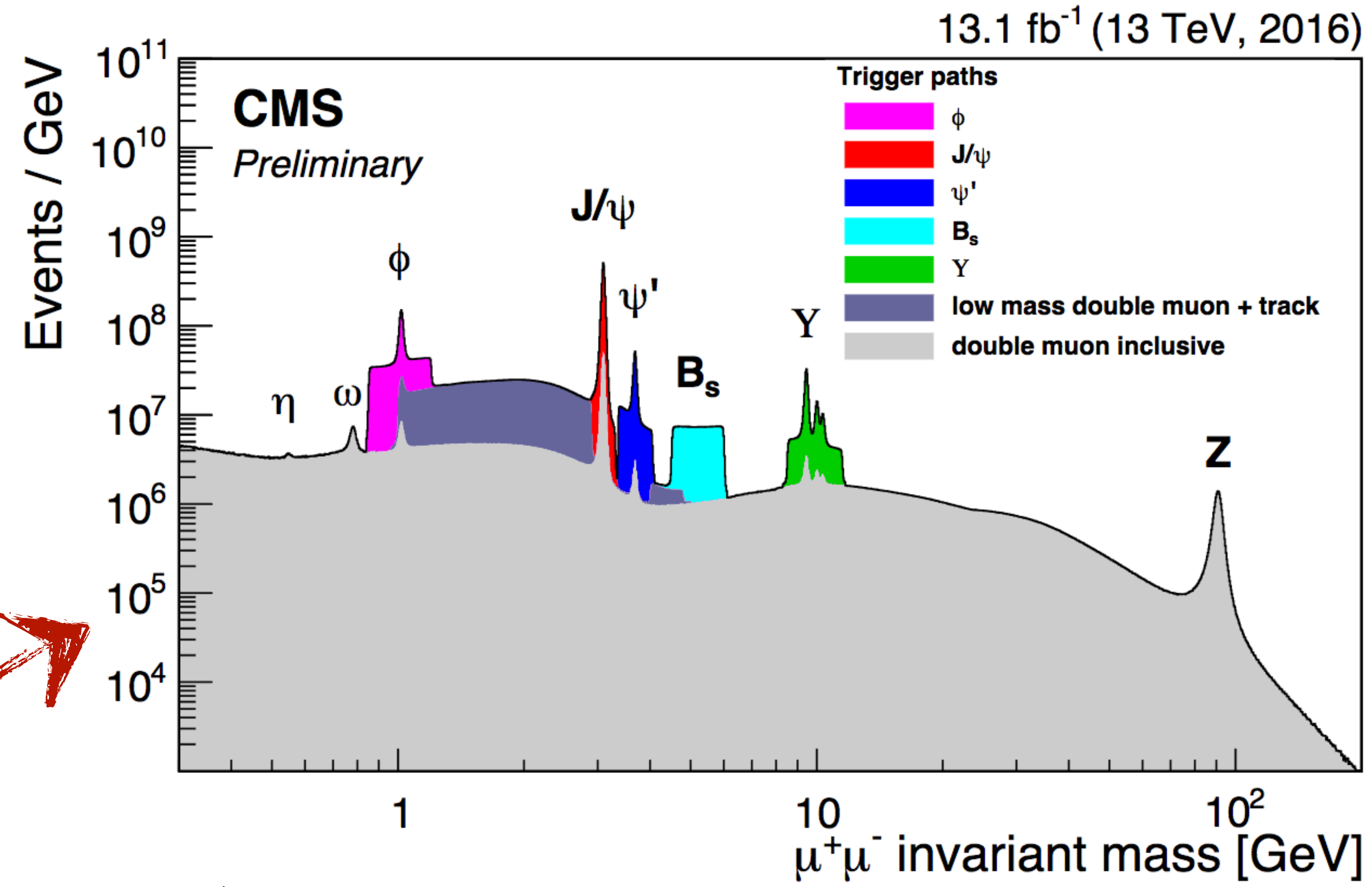
➡ (Any) measurement tests calculations





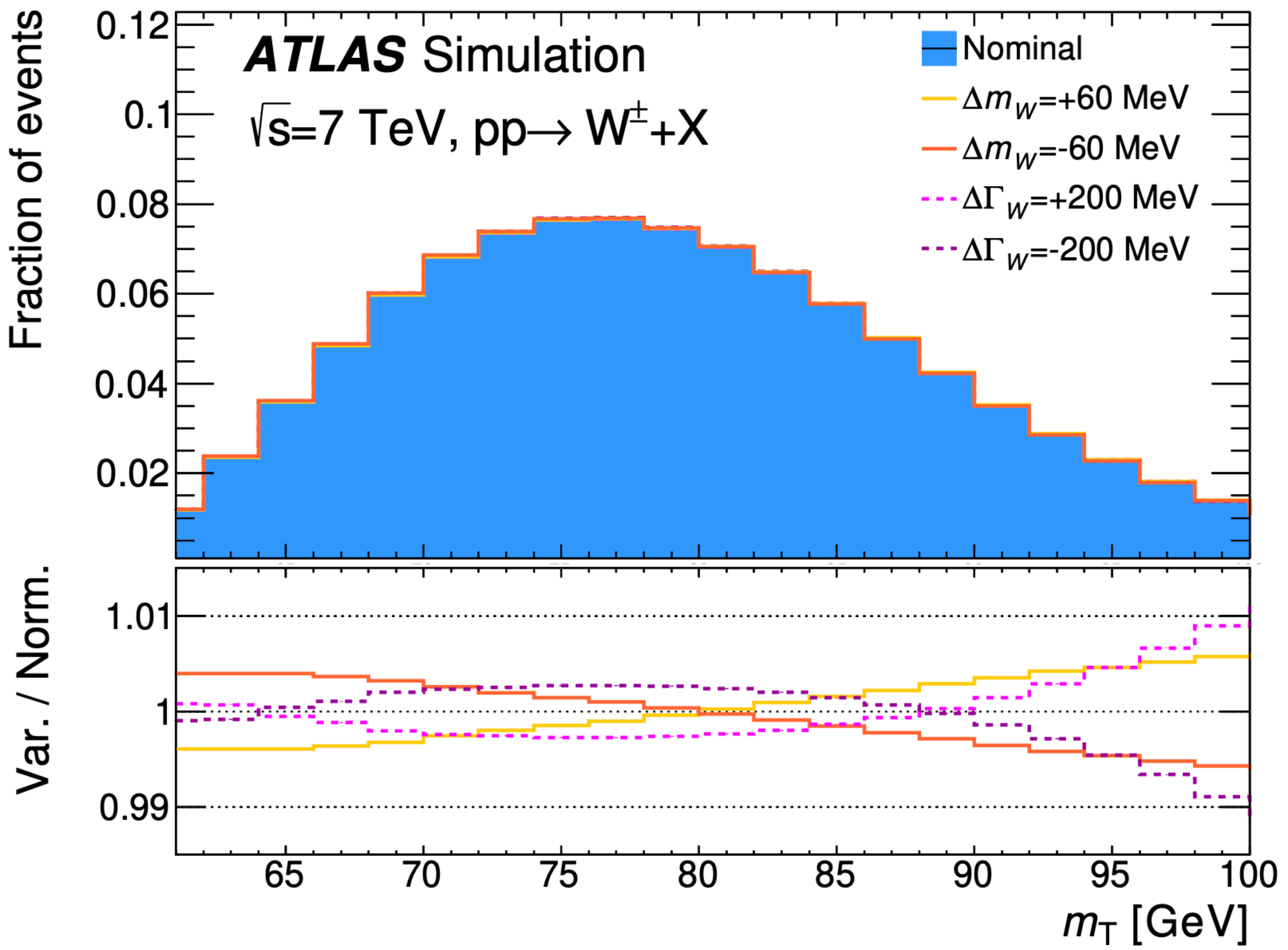
Interplay of theory and experiment in LHC measurements

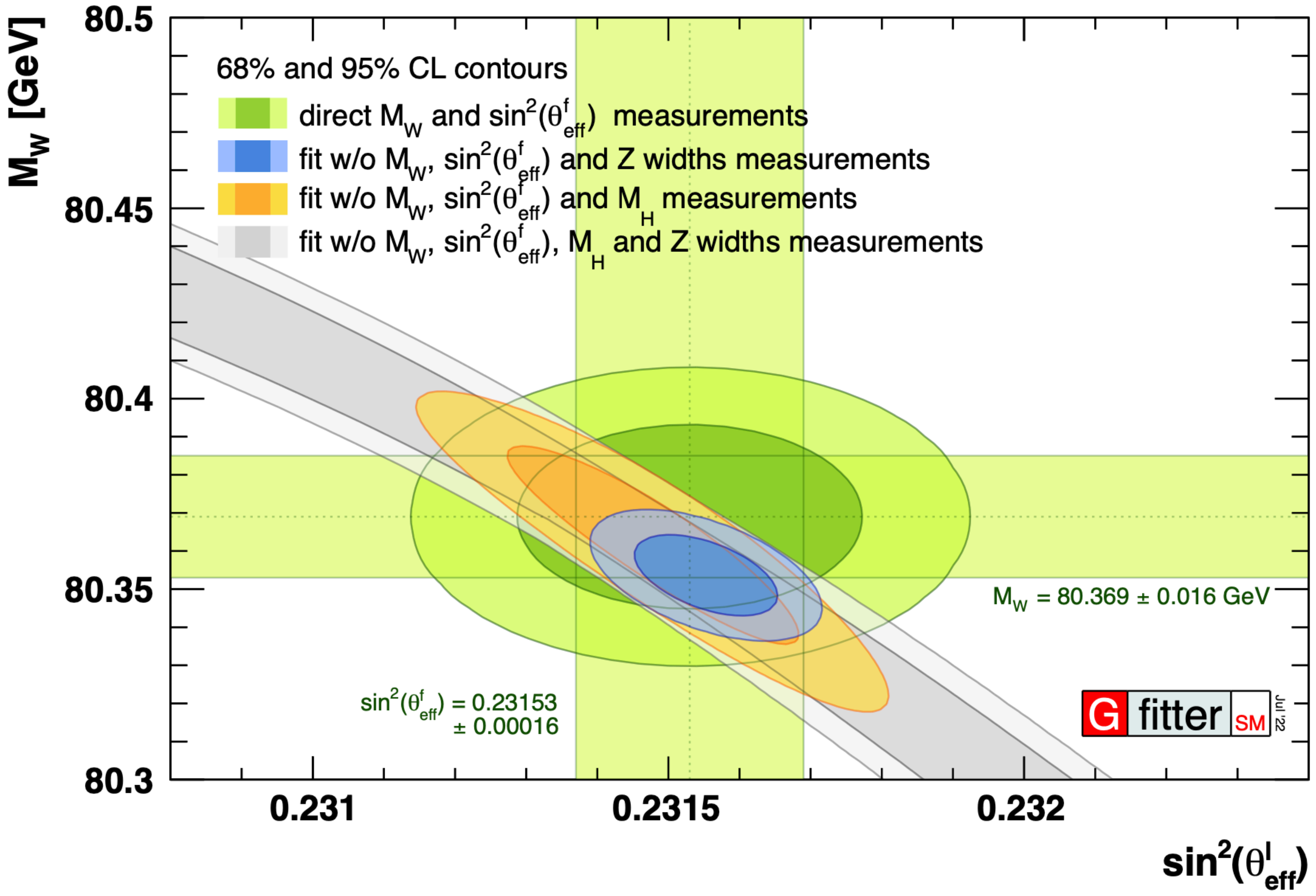
- Relationship between experimental and theoretical collider physics is multifaceted
  1. Completely **theory independent** measurements
     ➡ Theory guides interpretation
  2. Minimally **theory dependent**: e.g., estimation of backgrounds
  3. Theory-dependent conversion/extrapolation of/from direct observation to indirect observable



Measuring fundamental parameters of the SM

- SM **extremely successful** over vast scales
  - Some parameters are fundamentally experimental, but precise **relationships predicted by SM**
- Conversion of "what we observe" to fundamental parameters of the theory requires theoretical input
  - Direct interplay, neither can exist "on an island"



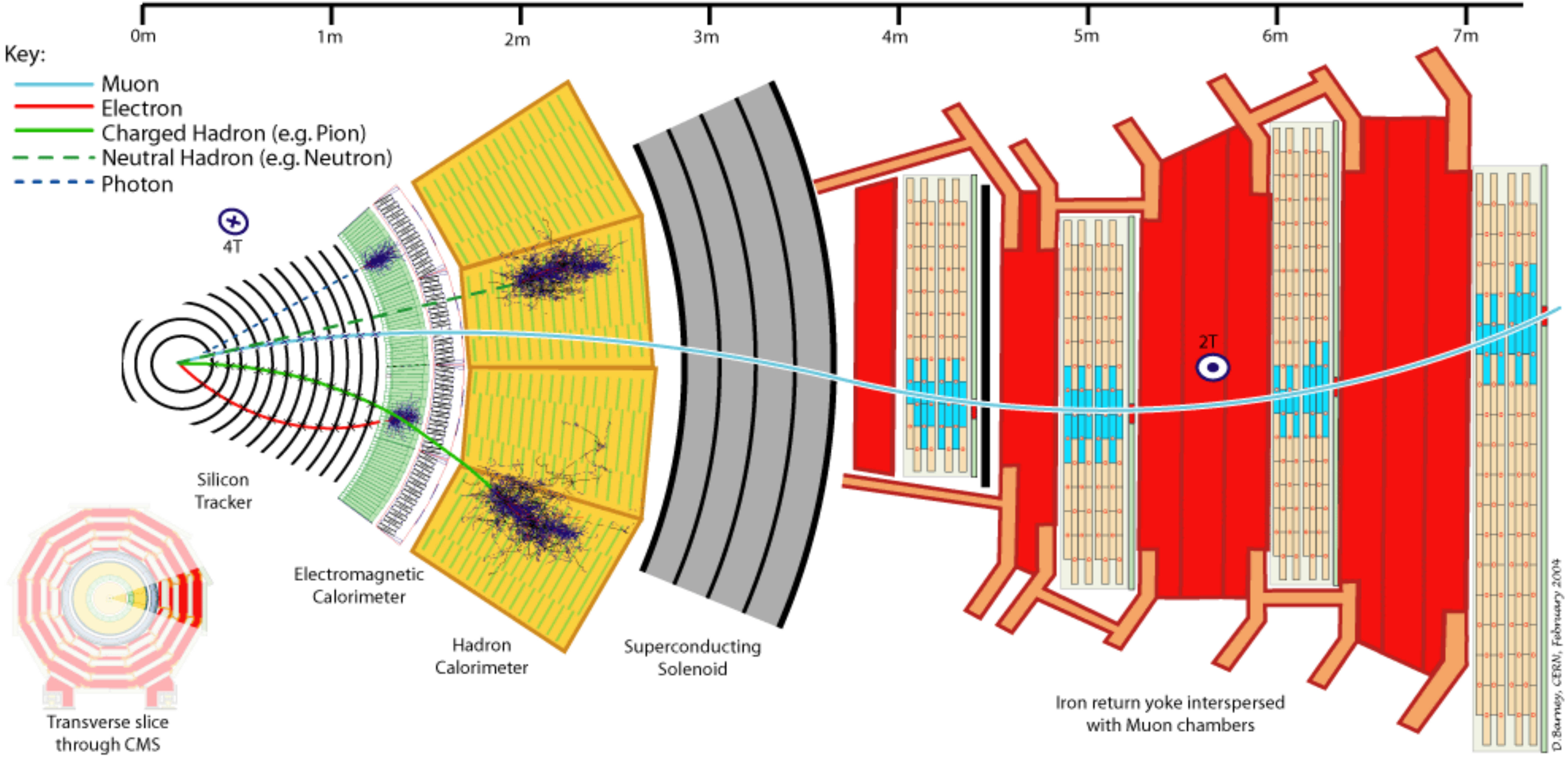


$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Higher-order corrections (Δr) depend on m_t, m_H, … m_{BSM}?

Kenneth Long

CMS event reconstruction: “particle flow”



- Exploit excellent silicon tracker and high B-field
  - Significantly improve jet resolution wrt calorimeter only
  - Powerful handle on pileup (e.g., PUPPI), substructure

Luminosity measurement and Z counting

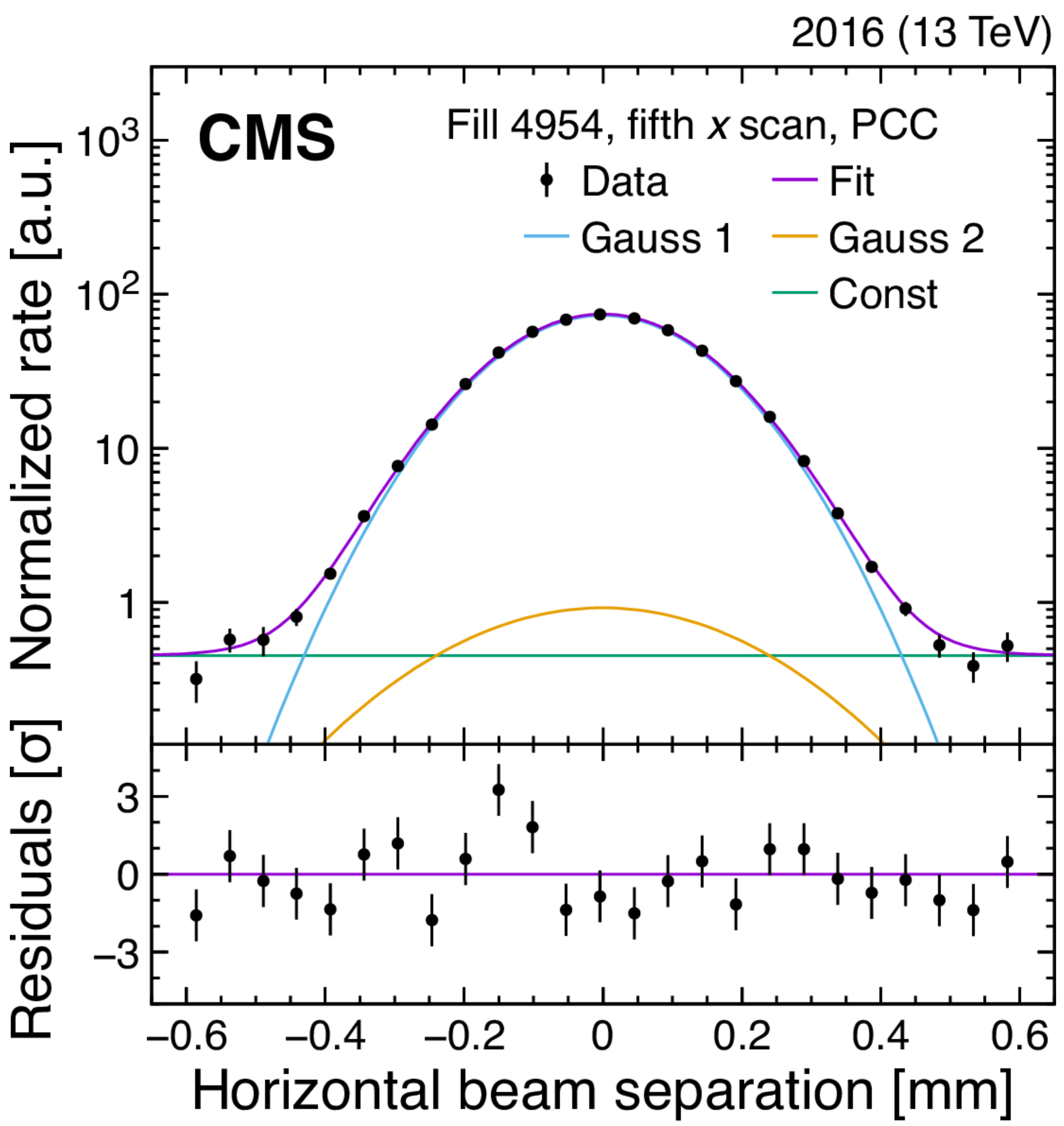
EPJC 81 (2021) 800

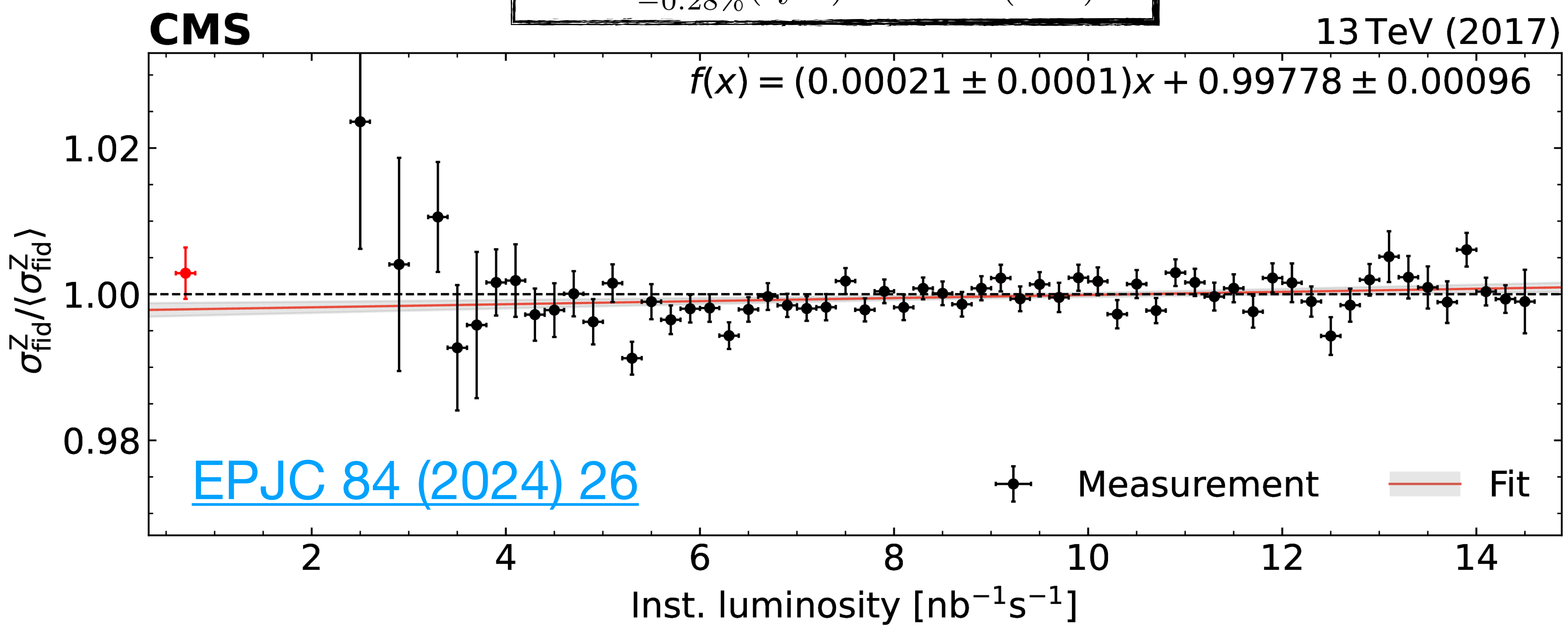
- Luminosity measurement is a **key ingredient to production rate measurements**
  - Uncertainty of 1.2 – 2.5%: sets the floor for precision
  - **Cancels in ratio measurements** (e.g., W/Z, differential ratios wrt total sec)
- Van der Meer scan measures the beam profile and sets reference
  - Extrapolate using rates measured in forward detectors
  - Stability/consistency major source of unc.
- **"Z counting"** now a sophisticated means to monitor luminosity
  - Very careful measurement of absolute reco. eff.

$$\mathcal{L} = \frac{N^{Z}}{\sigma^{Z}_{\text{fid}}\epsilon^{Z}}$$

➡ σ_{ref} from high precision measurement (or theory)

$$\delta r = \delta(N^{Z}_{\text{highPU}}/N^{Z}_{\text{lowPU}}) = ^{+0.47\%}_{-0.45\%}$$
$$= ^{+0.31\%}_{-0.28\%}(\text{syst}) \pm 0.35\%(\text{stat})$$





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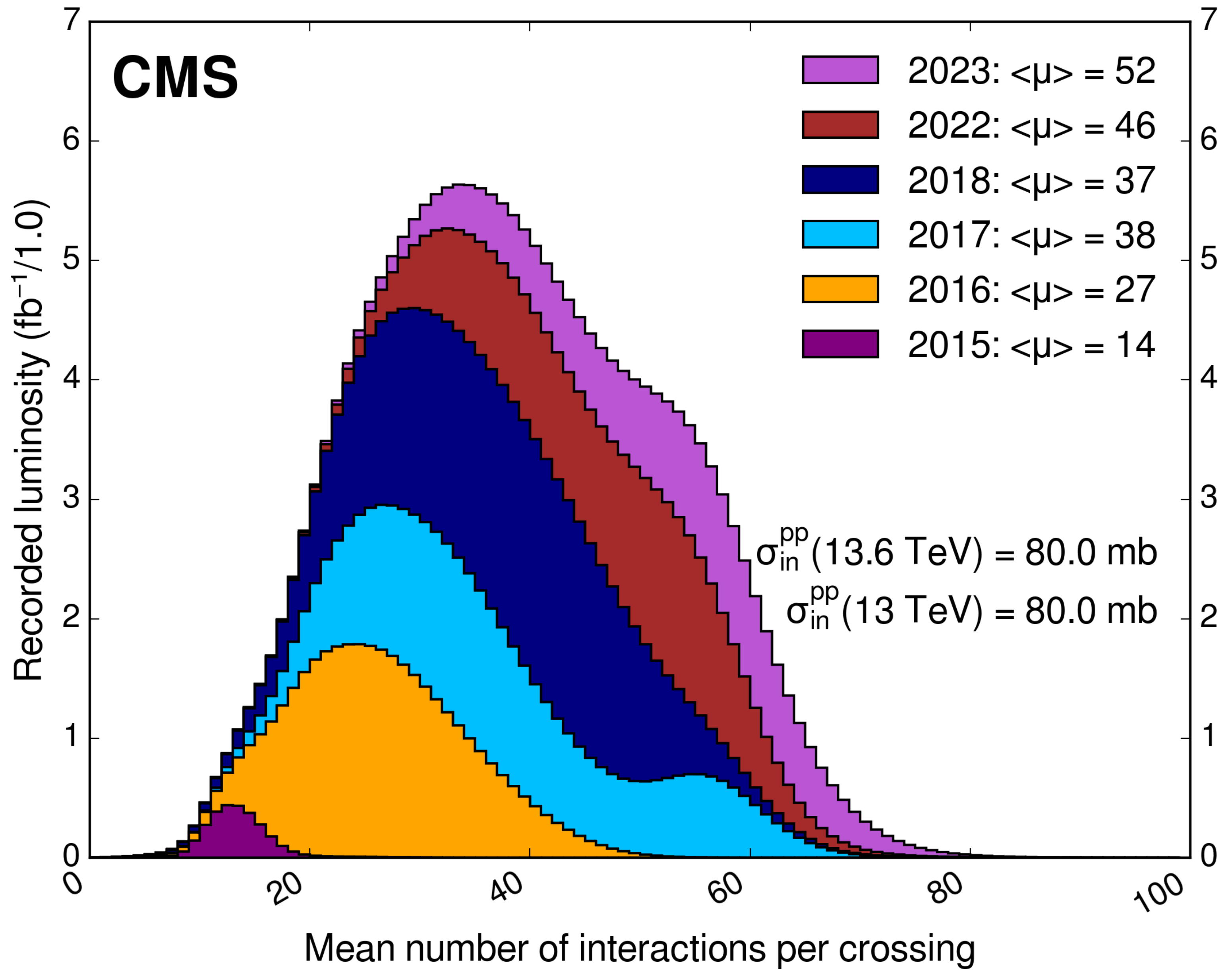
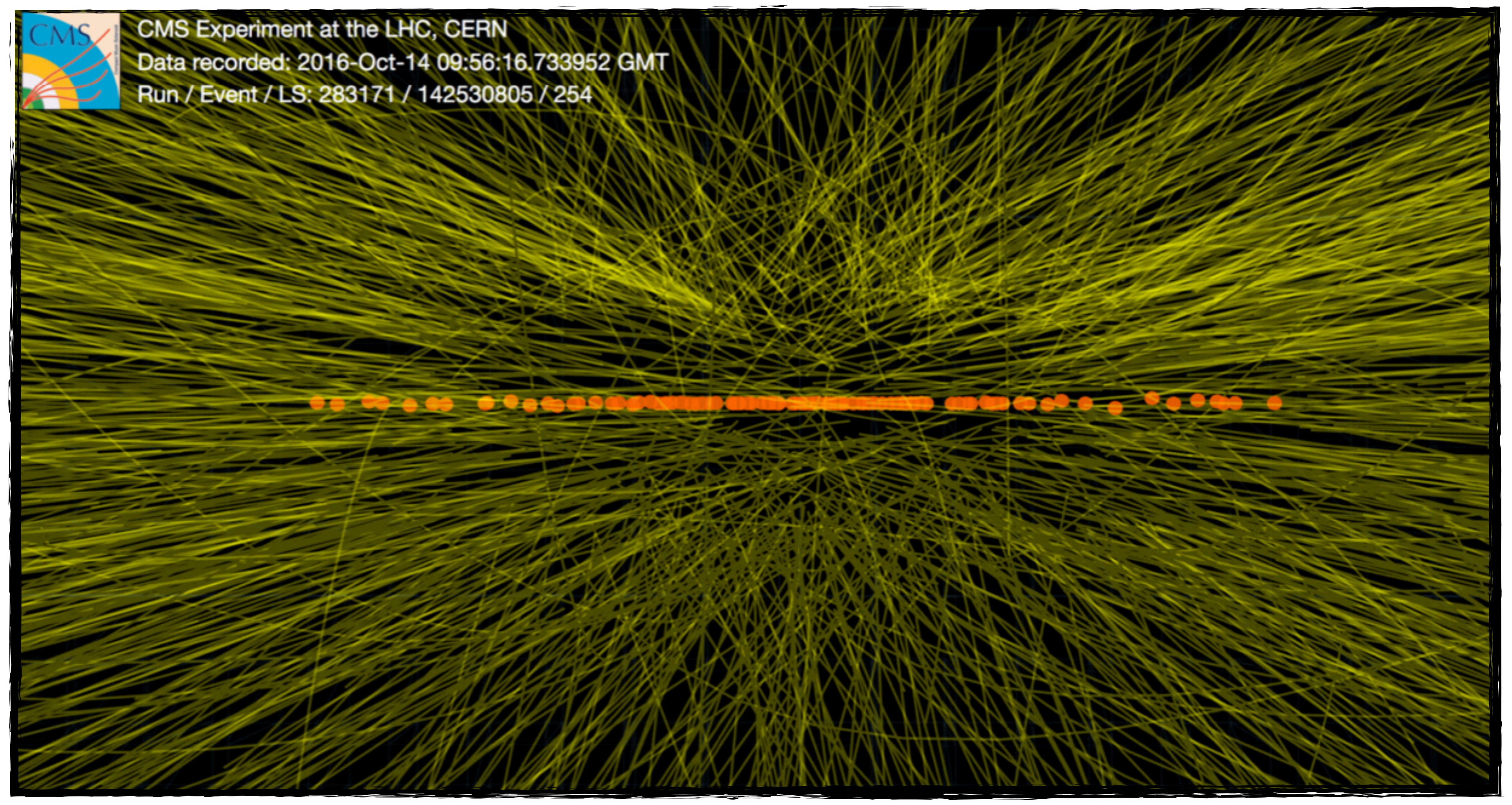
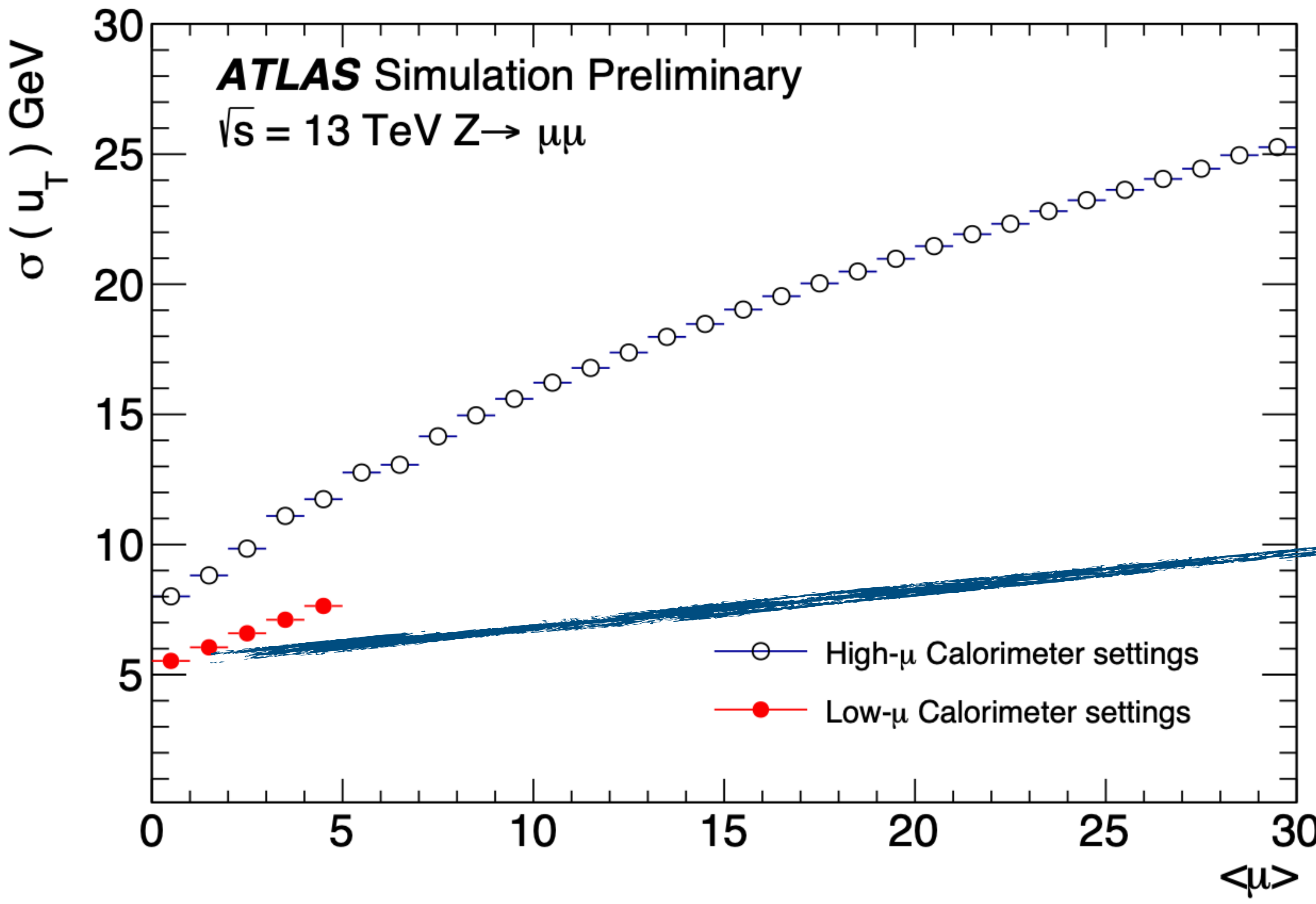
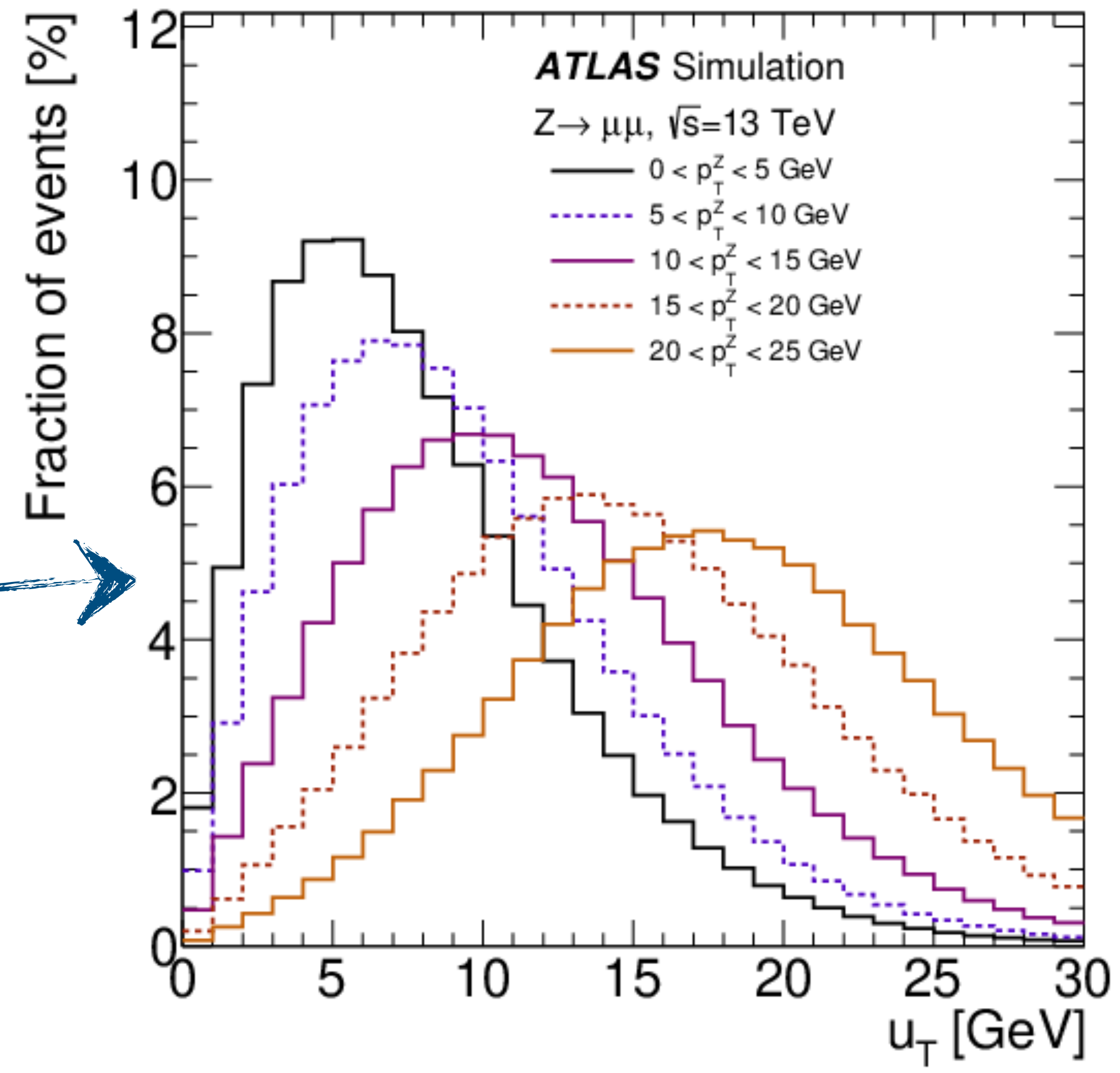
Pileup

- Critical to the LHC push to high luminosity, but doesn't come "for free"
- **"Is pileup really such a big deal?"** — Anonymous theory colleague
  - Most measurements: it's worth the hit
  - Precision measurements: it's a huge challenge!
- More stuff in the detector ⟹ more chances for confusion (e.g., tracks built from wrong hits), higher chance to mis-measure
  - Balancing act between lumi. and performance
  - **Dedicated low-pileup runs** offer unique opportunities





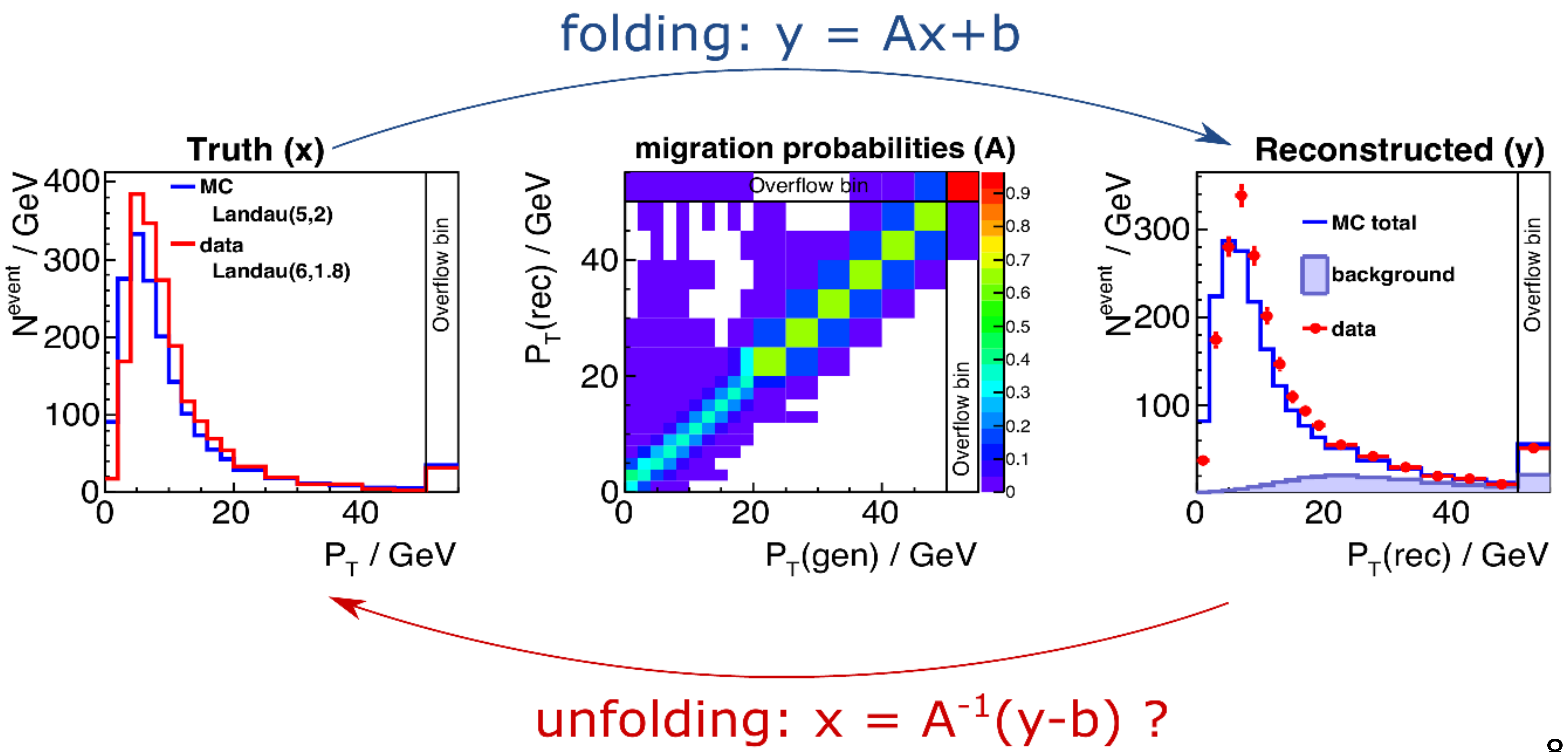




Fiducial cross sections and unfolding

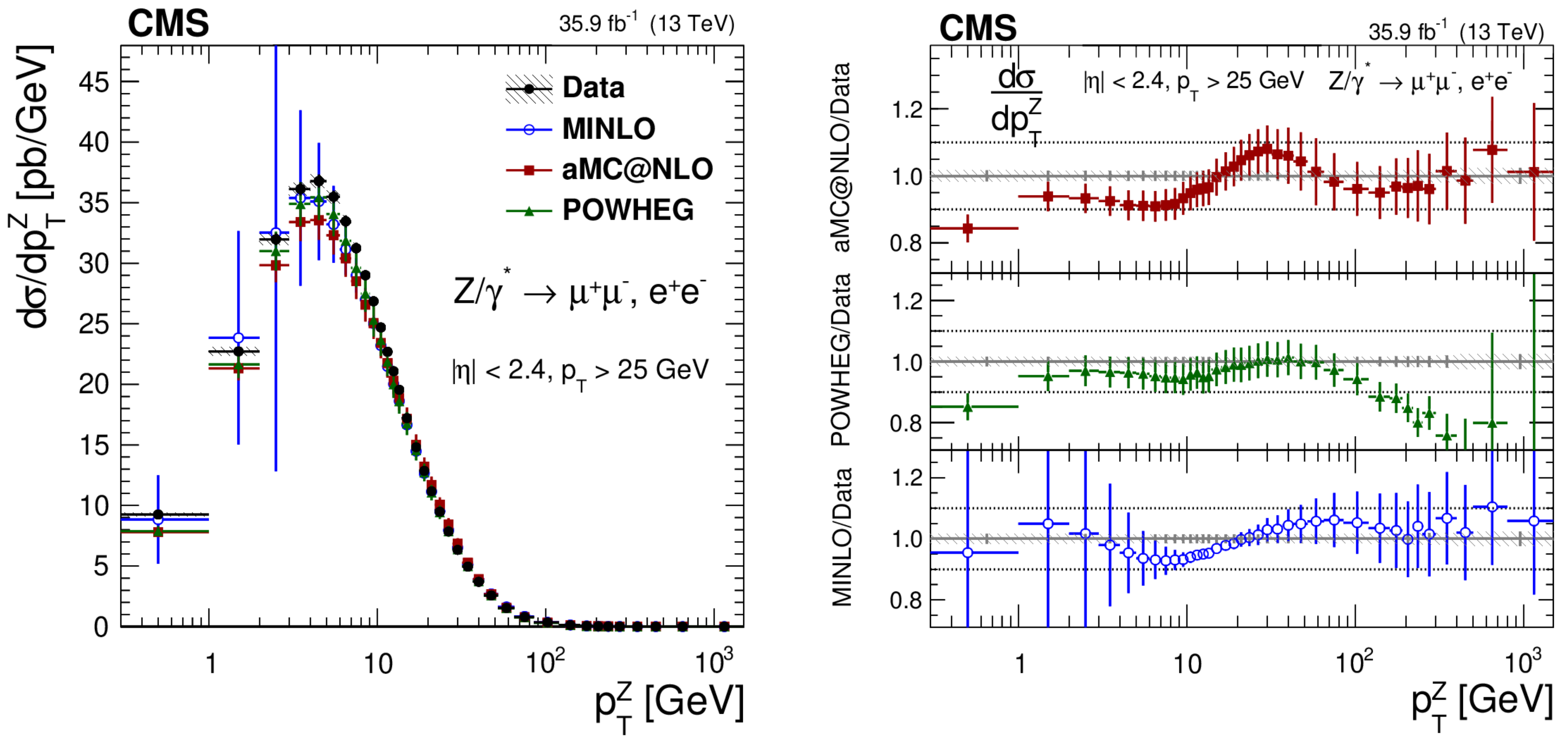
- Fiducial cross sections: **defined to minimise theoretical extrapolation**
- Generally post-FSR/shower/hadronization “particle level” observables
  - Bare muons, dressed electrons most reflective of measurement
    - But usually unified in results for convenience
- In practice, extrapolation is small, **but inconsistencies can cause headache**
  - Some small extrapolation may be worth it:
    - Common with ATLAS/CMS
    - Poorly measured observables (e.g., missing energy)

- **Remove detector effects via unfolding**
  - Iterative Baysian (TUNFOLD) with
  - Likehood based
    - Full covariance matrix needed for robust reinterpretation
- Both possible with/without regularisation, in practice usually used with former

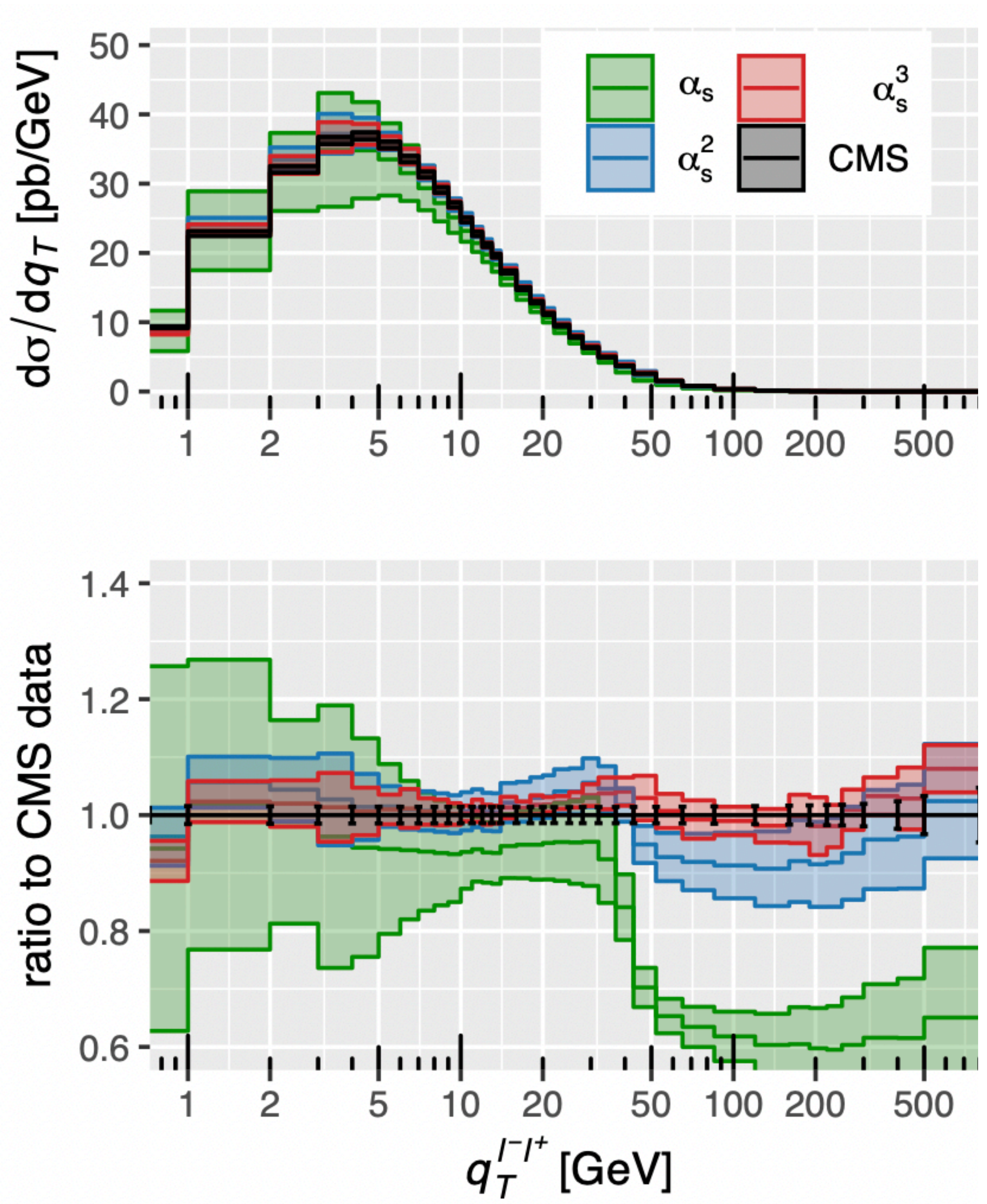


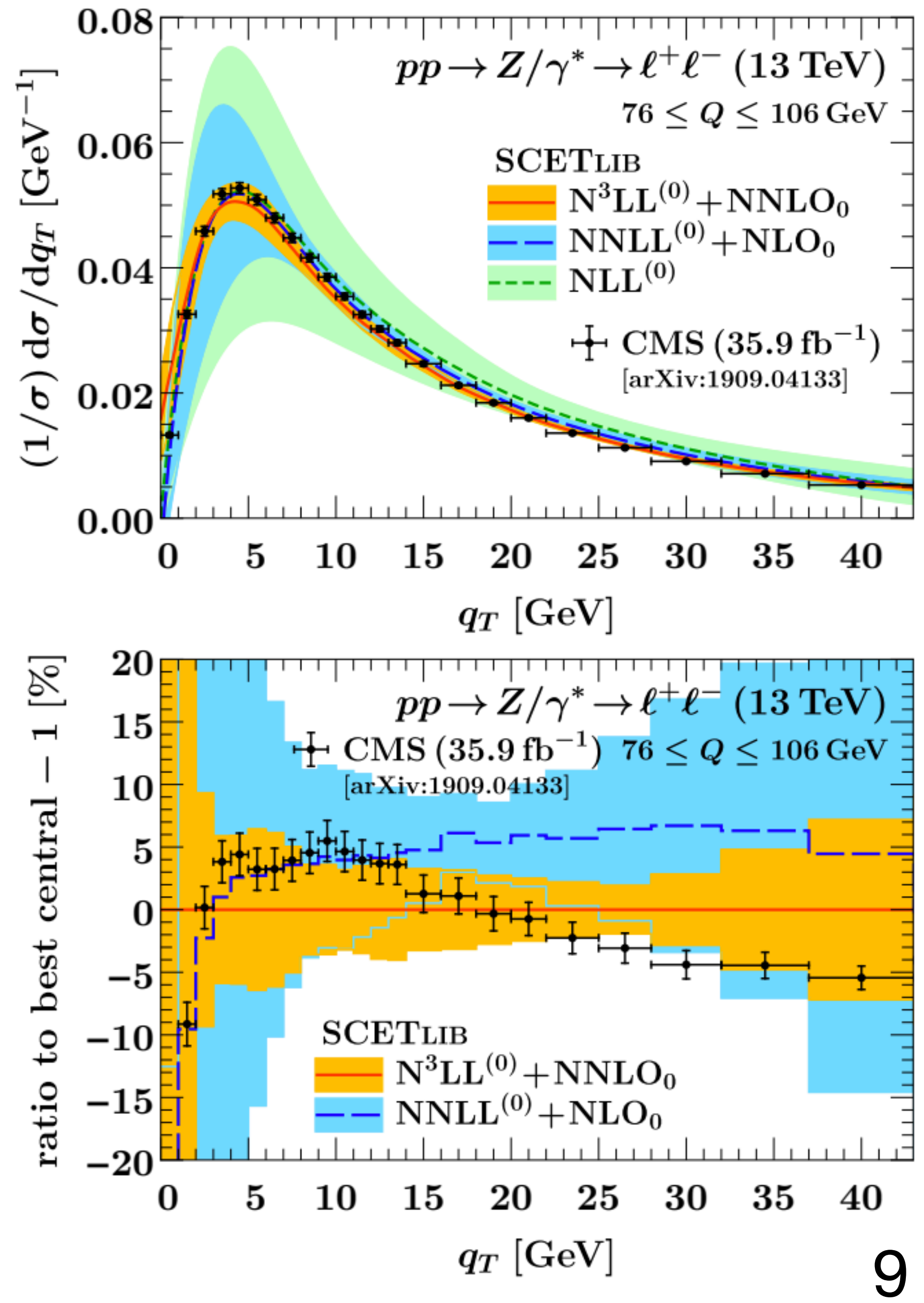
Theory vs. experiment for precision results

- Optimally, **publish new measurements published w/ comparisons to state-of-the-art predictions**. Practically…
  - Development cycle of new theoretical predictions may be faster than new precision measurements
  - Software may not be publicly available
  - Technical issues/resources/time constraints (or laziness) limit scope of comparisons in published paper
  - ➡HepData/Rivet essential for ease of comparison



- **"Wishlist"** for theorists
  - Public codes, **open access development** highly preferable
  - Better usability ⟹ more likely to be used by non-experts
    - In practice, author overlap at institute etc. can play a role
  - Example processes for validation, quick start instructions always useful
  - **Computationally performant**
    - Native multicore support
    - Easy scale out to batch/wide batch support

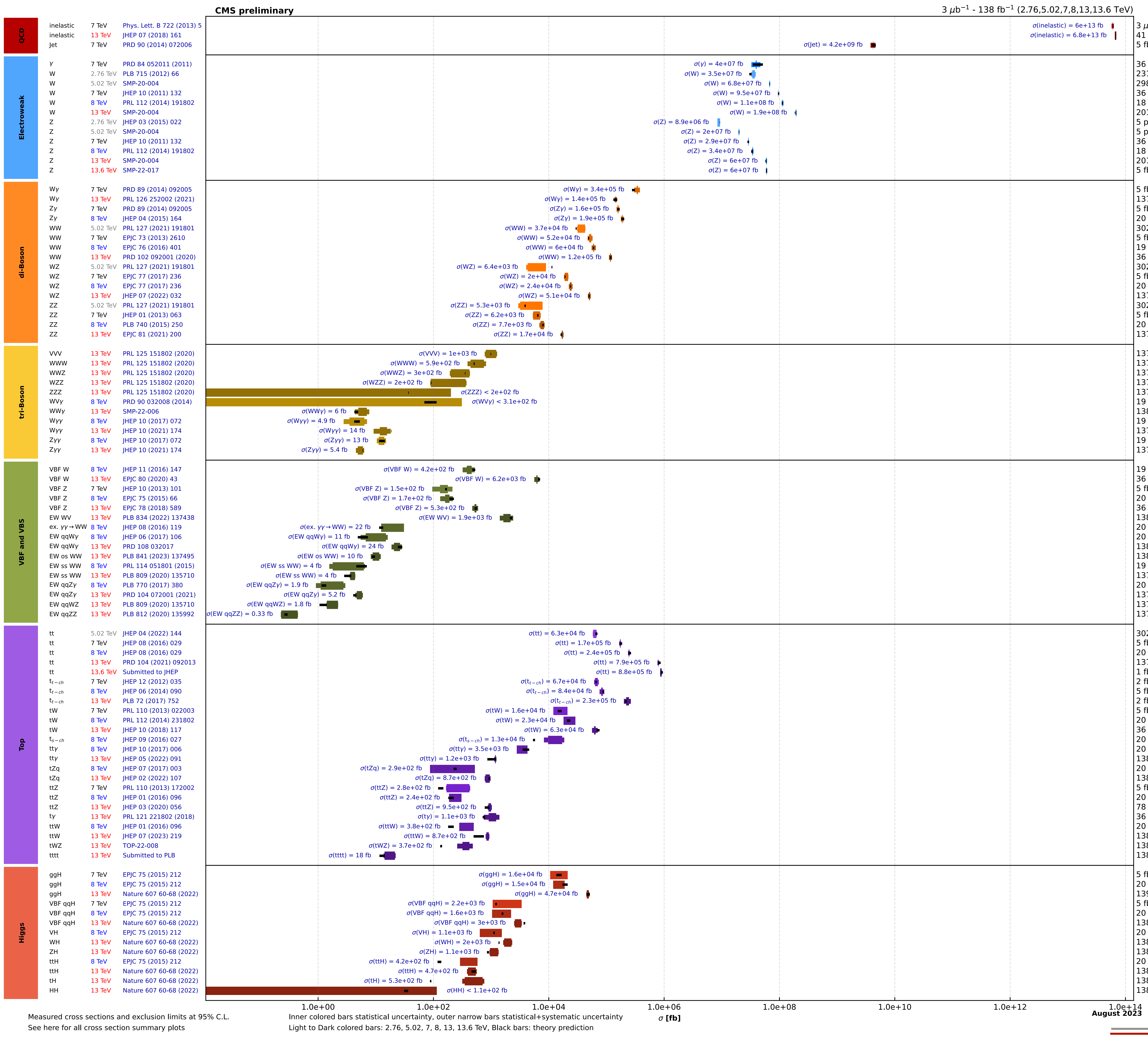




Outline

- Not complete! An assortment of new and interesting (to me) results
- Hadronic jet production
  - Dijet production and α_S
  - α_S with angular vars, substructure
- Single boson production
  - 13 and 13.6 TeV cross sections
  - $\sin\theta^{\ell}_{eff}$ measurement
- Diboson production
  - WW at 13.6 TeV
  - ZZ+jets and Z(4ℓ)
- Top measurements
  - 5, 13, 13.6 TeV cross sections
  - Entanglement
  - Mass combination
- Higgs measurements
  - ZZ(4ℓ) mass and width
  - VH(bb) production
- Diffractive $\tau\tau$ production

Overview of CMS cross section results

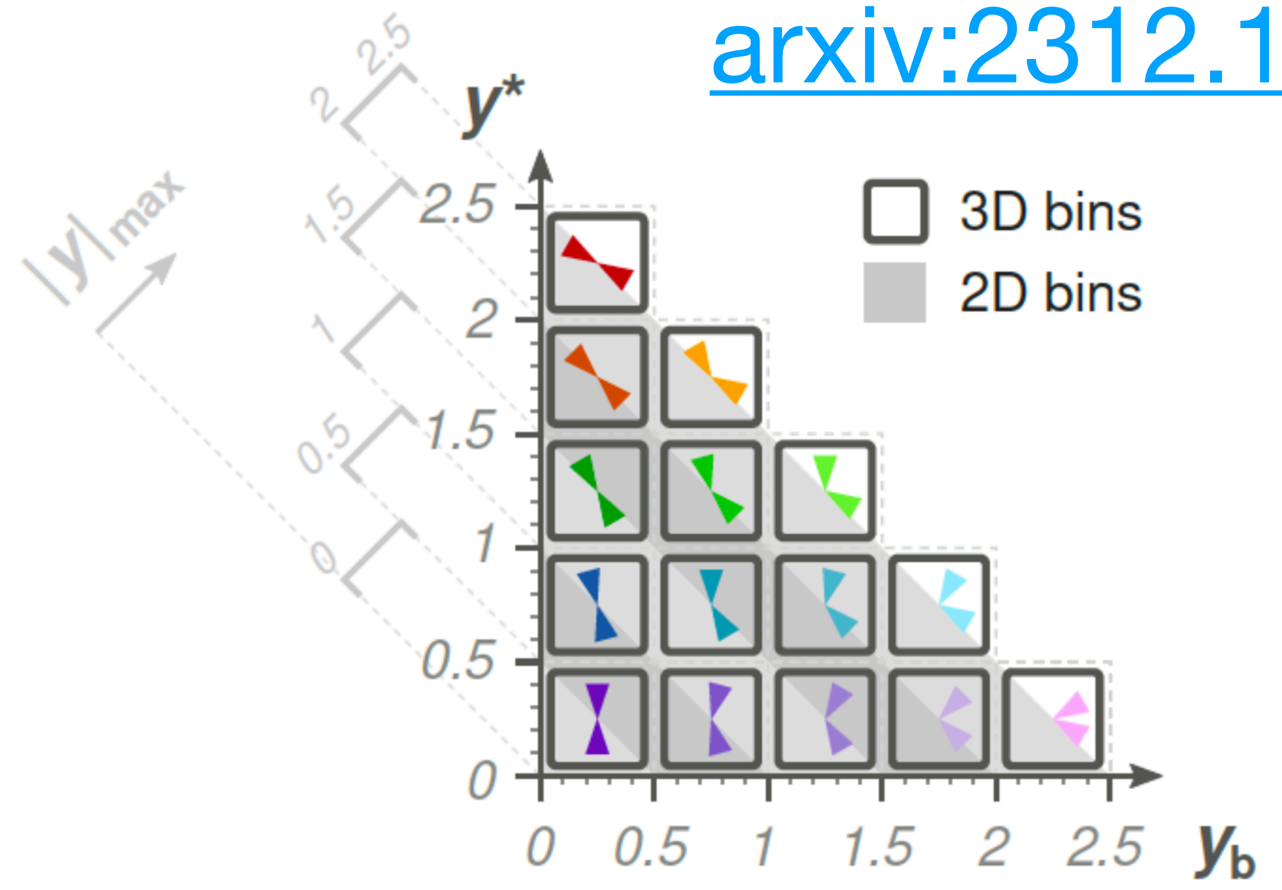


Hadronic jet production

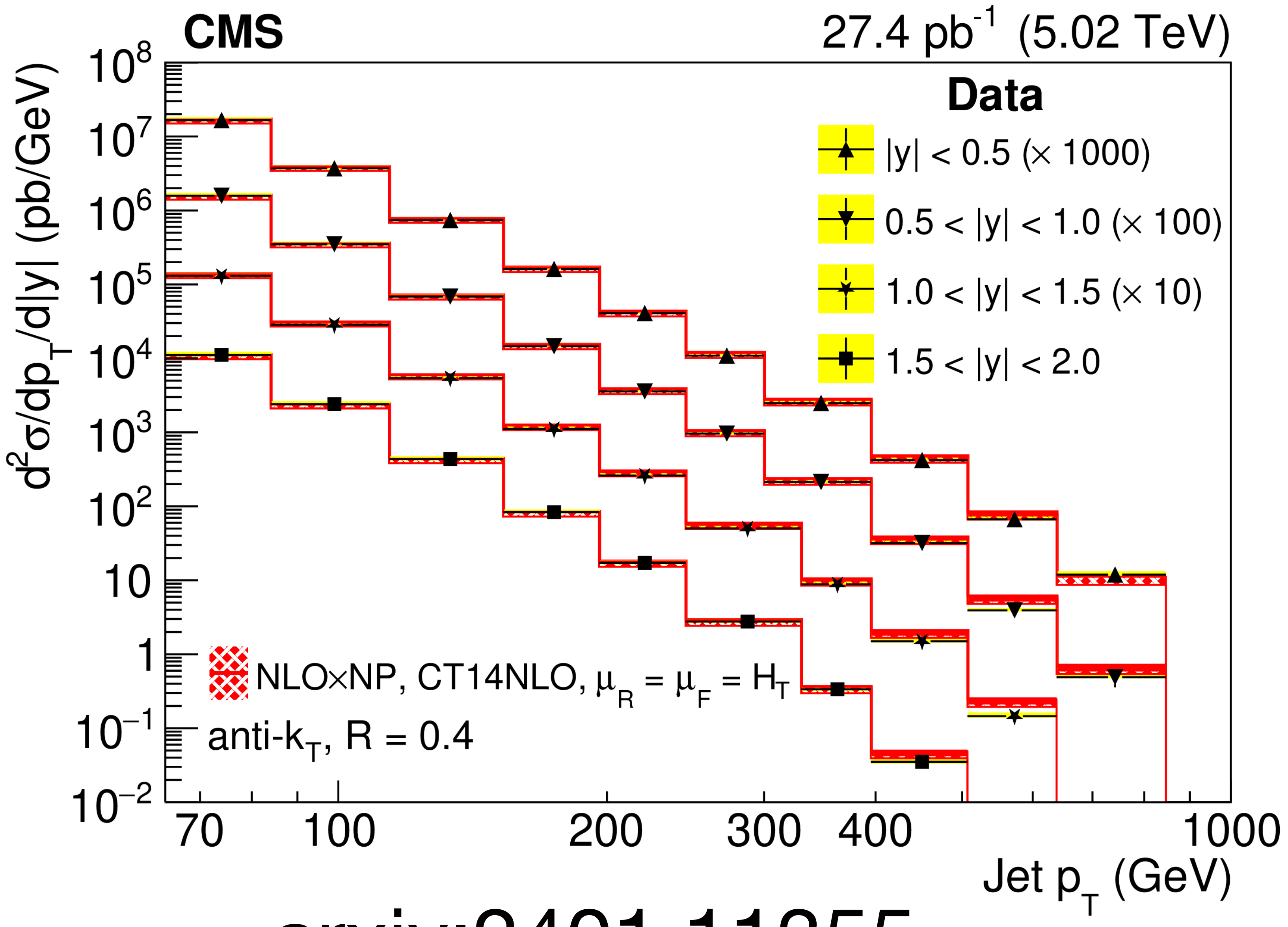
Dijet cross sections 5 and 13 TeV and α_S extraction

arxiv:2312.16669

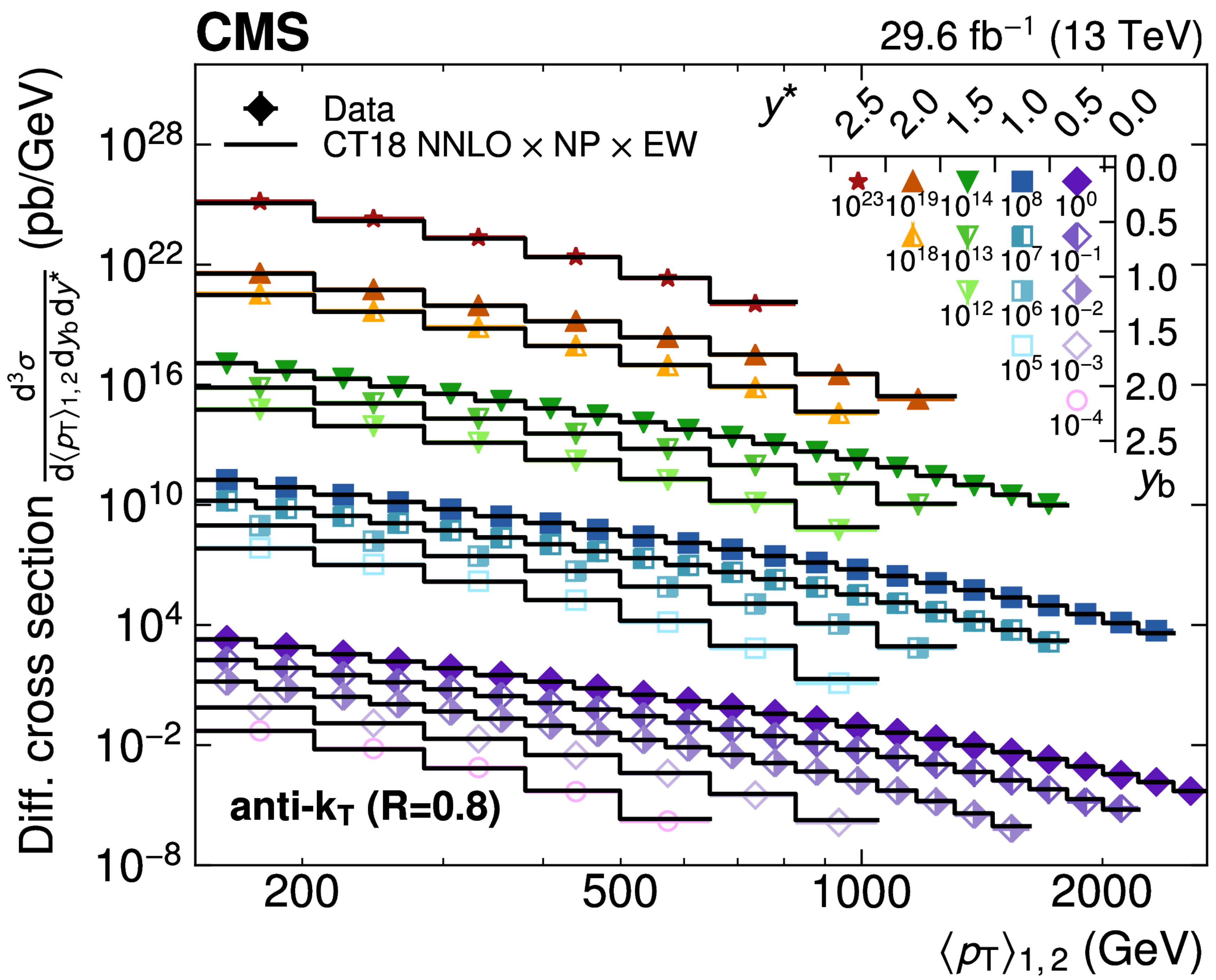
- Compiously produced at LHC, but still experimental and theoretical challenge
  - Reconstruction/measurement requires control of all objects
  - Direct test of QCD: Extraction of α_S due to excellent theory
- Extract α_S from PDF fit to CMS data + HERA DIS at 13 TeV
  - NNLOjet, NP corrections from Pythia vs. Herwig, EW corr

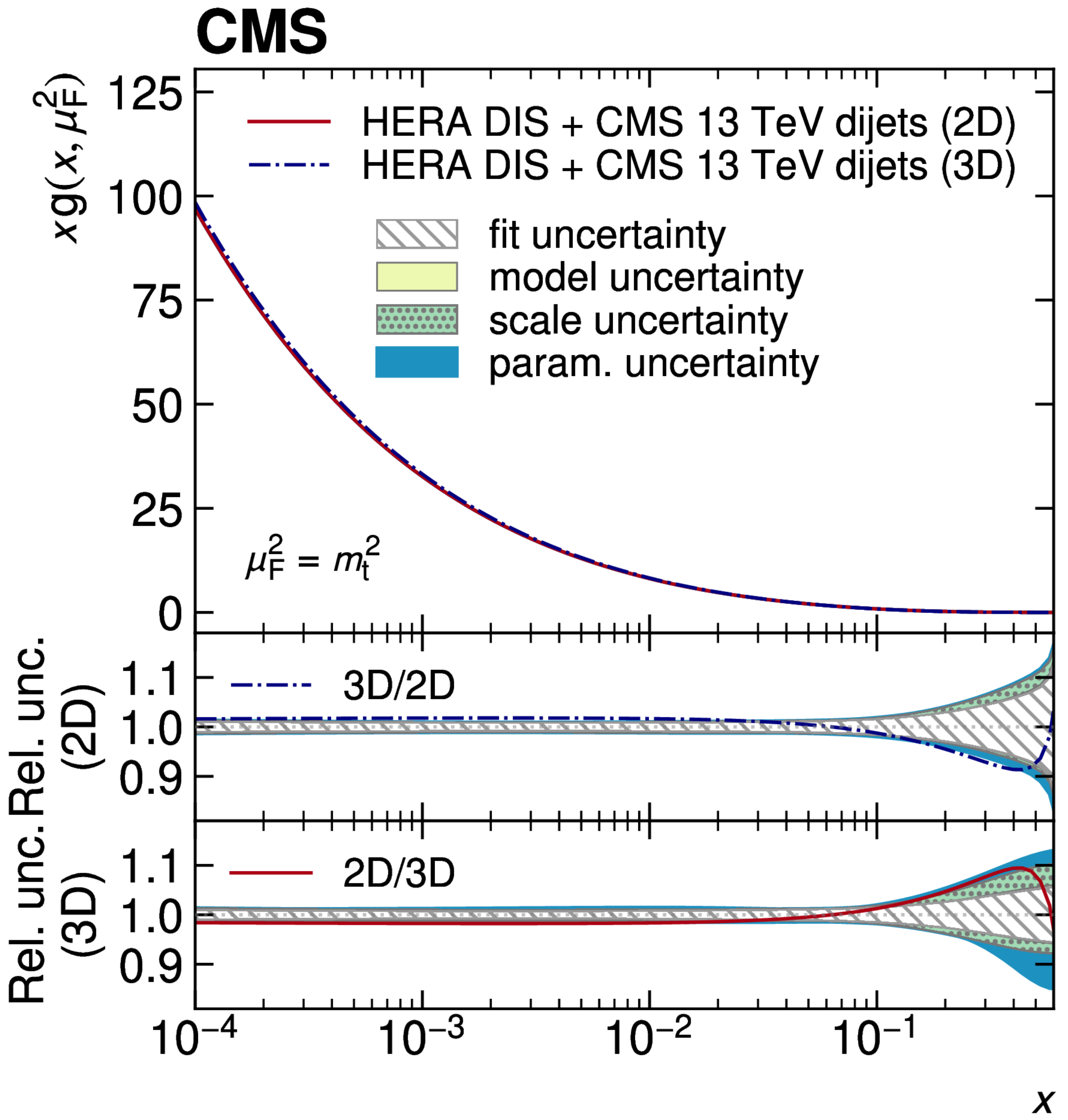


$$y^* = \frac{1}{2}|y_1 - y_2|, \quad y_b = \frac{1}{2}|y_1 + y_2|$$



arxiv:2401.11355





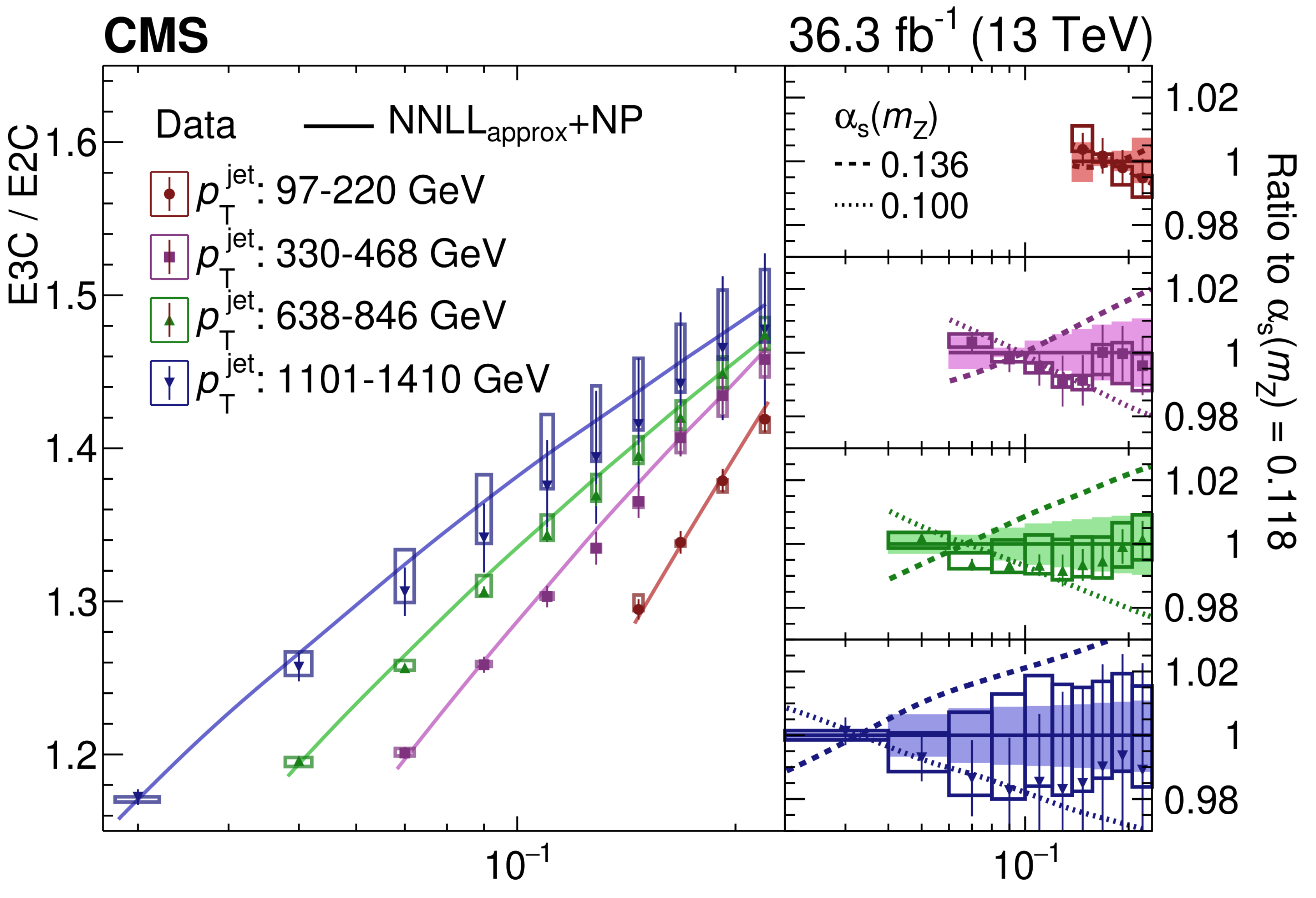
$$\alpha_S(m_Z)_{3D} = 0.1201 \pm 0.0010\,(\text{fit}) \pm 0.0005\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0006\,(\text{param.})$$

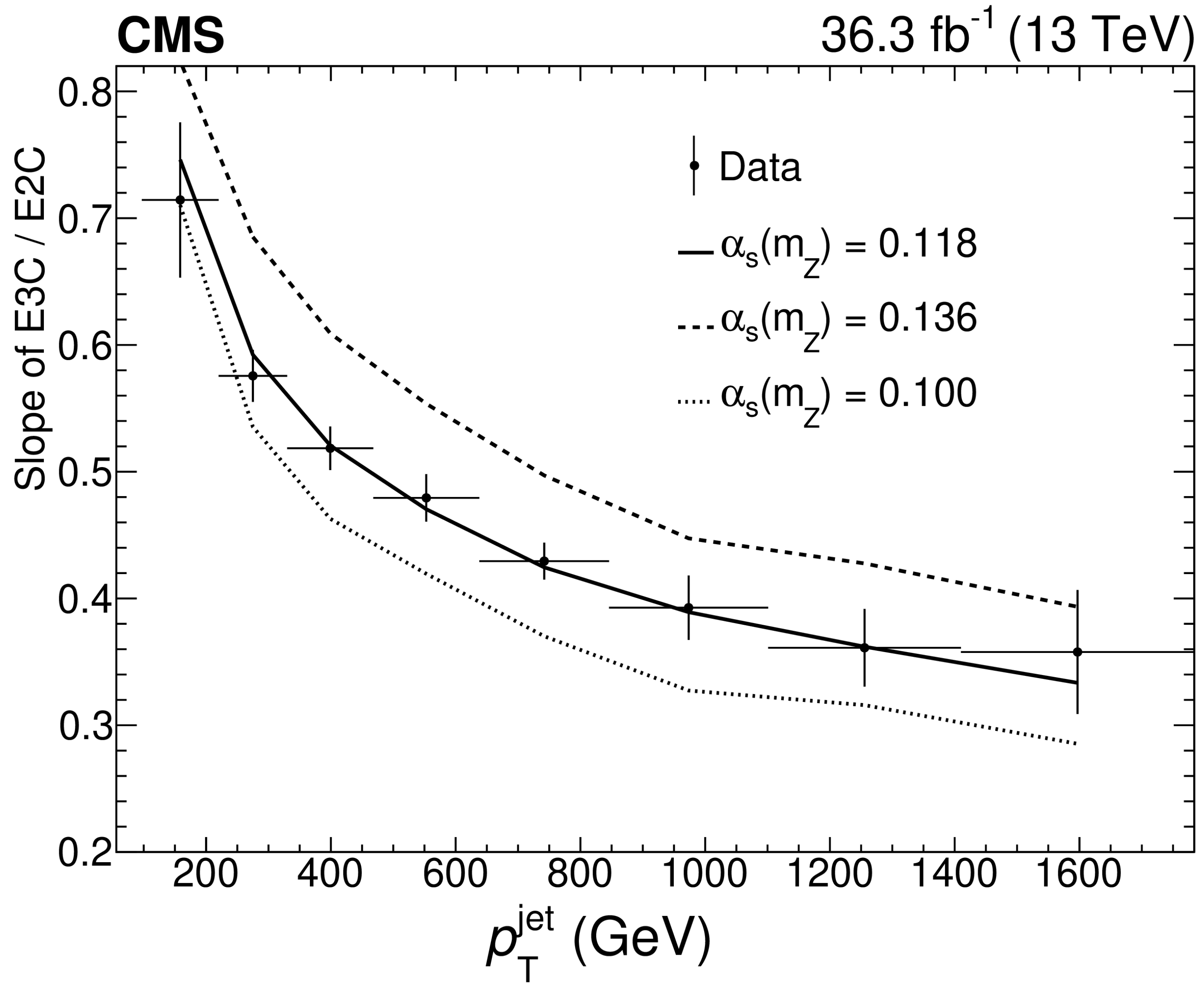
Extraction of α_S with other jet observables

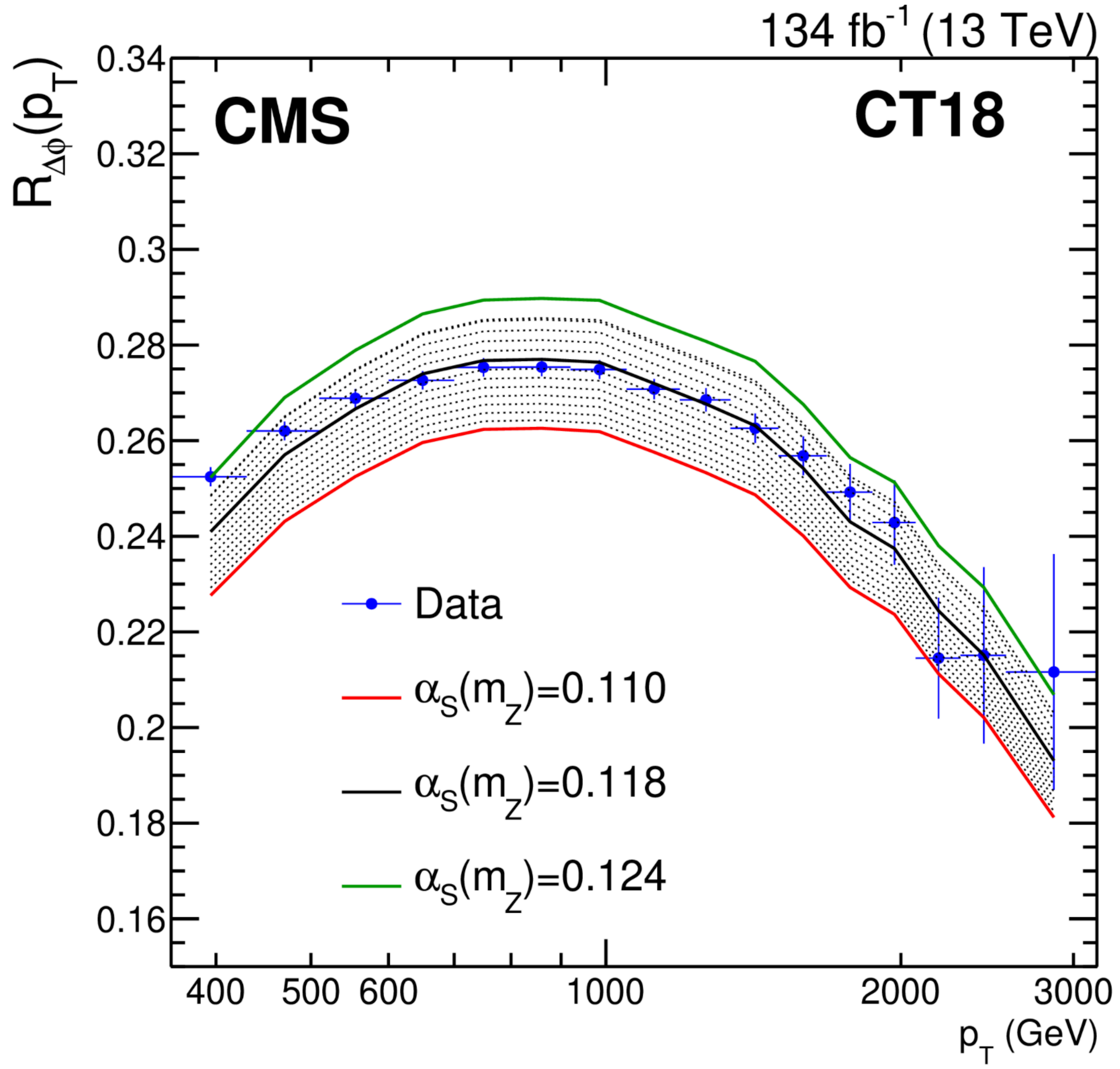
arXiv:2404.16082 arXiv:2402.13864

- Sensitivity to α_S also through multi-jet production, jet substructure
  - $R_{\Delta\varphi}$: Fraction of jets with a given p_T^{min} within $\Delta\varphi$
- **Ratio 2/3 energy correlators** (energies and angles of jet constituents)
- Extraction at NLO with NLOjet++ for $R_{\Delta\varphi}$, at aNNLL for EC

$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{jet}(p_T)} N_{nbr}^{(i)}(\Delta\phi, p_{Tmin}^{nbr})}{N_{jet}(p_T)}$$







$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

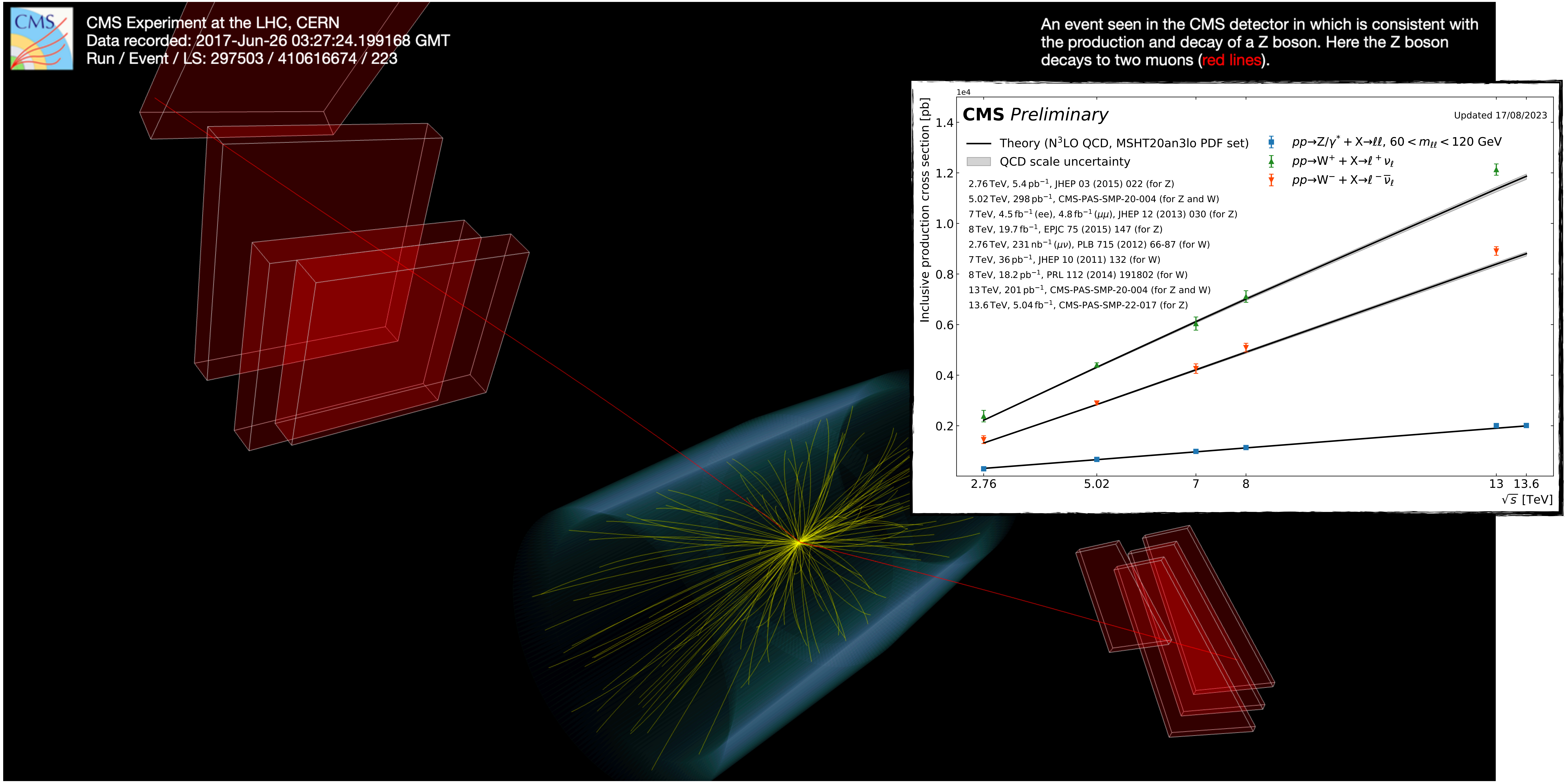
$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}\,(\text{exp})$$

EC Result

Results $R_{\Delta\varphi}$

NLO PDF set	$\alpha_S(m_Z)$	Exp.	NP	PDF	EW	Scale	χ^2/n_{dof}
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	$^{+0.0043}_{-0.0042}$	16/16
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$	17/16
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	$^{+0.0114}_{-0.0068}$	20/16

Single boson production

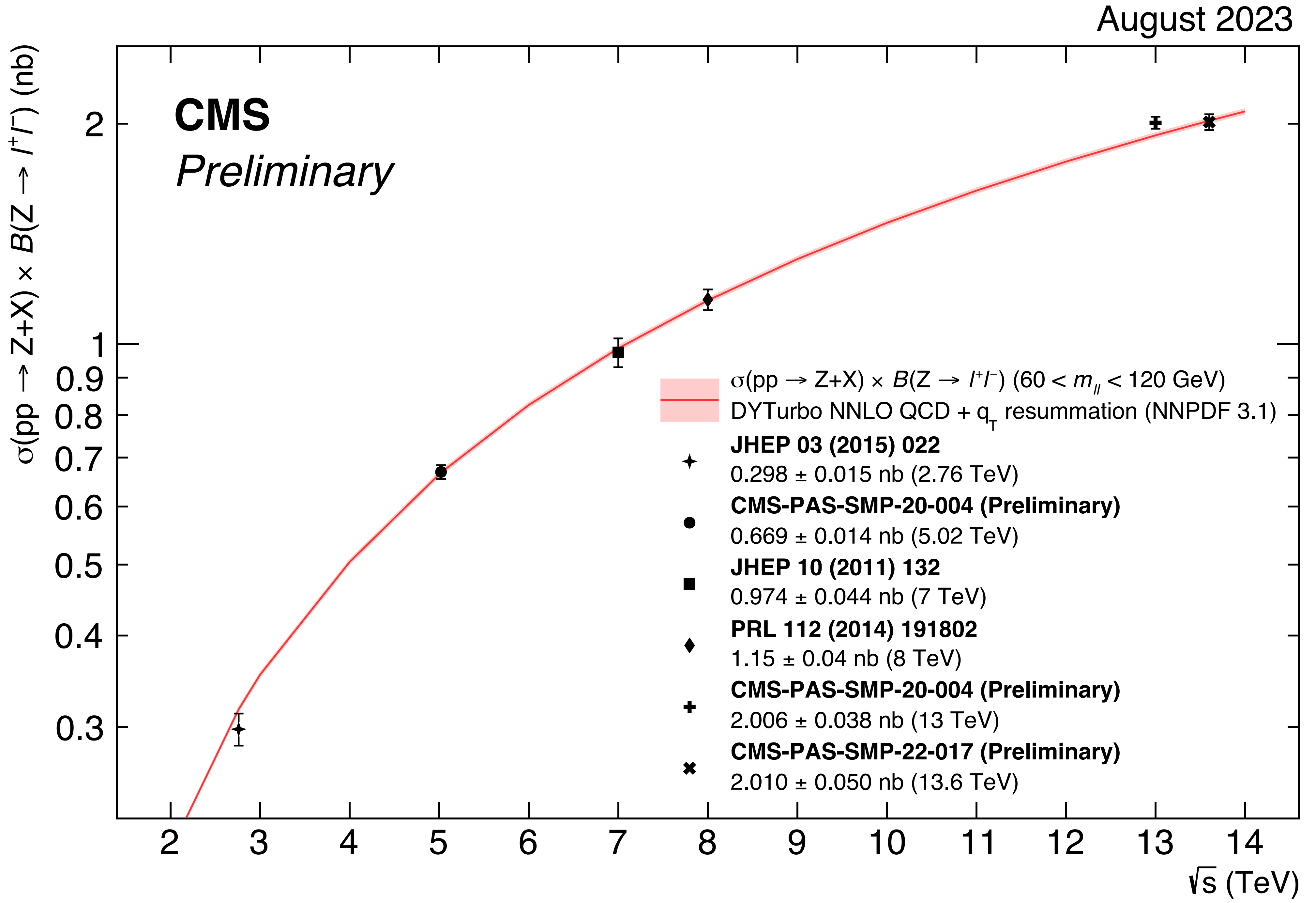


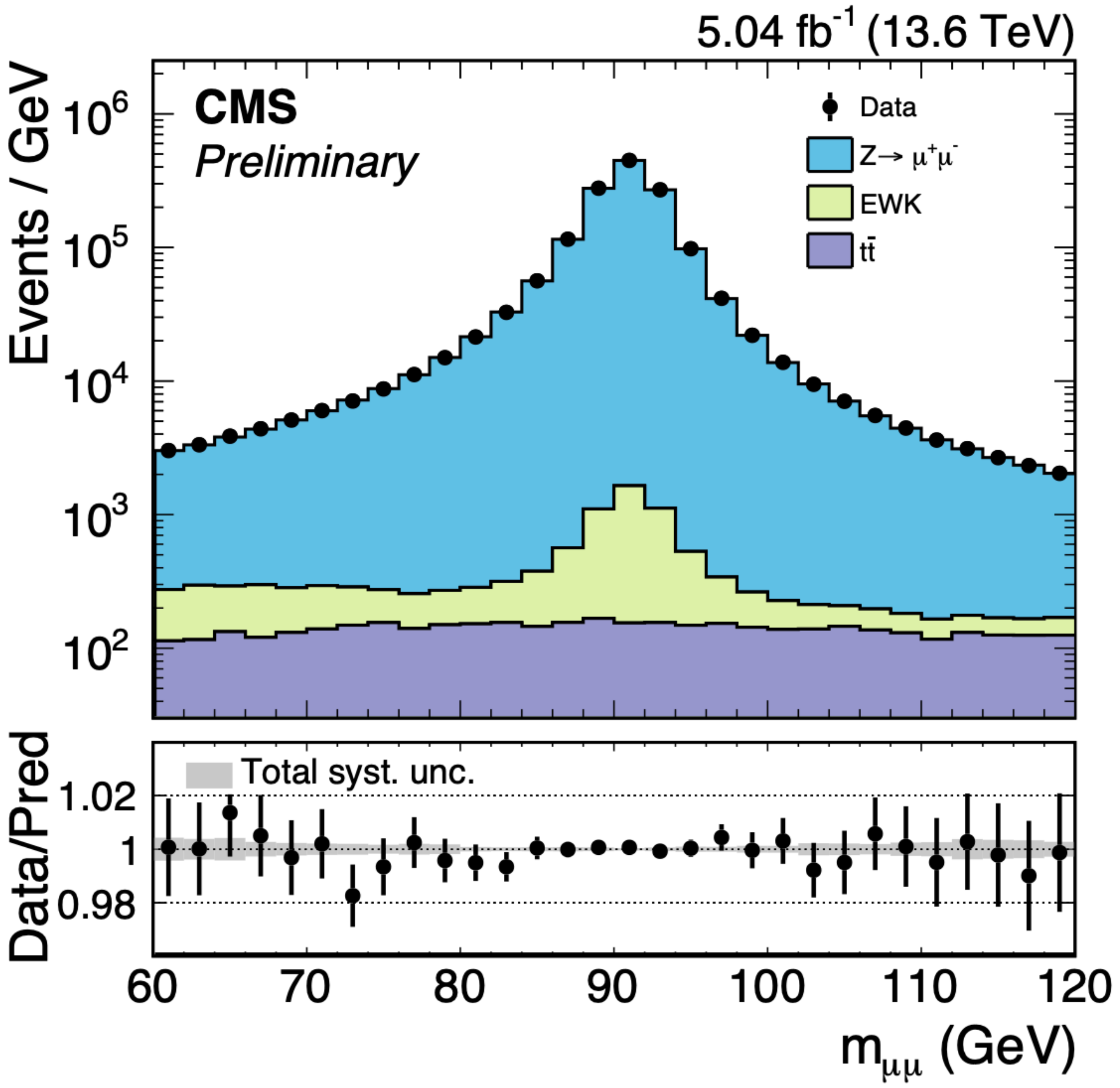
Single boson production at 13.6 TeV

- Cornerstone of experimental program. **New opportunities at 13.6 TeV**
  - Test of perturbative calculations, important input for PDFs
  - ***Experimentally challenging!***
    - Precise understanding of reconstruction eff.
  - Estimation of non-prompt backgrounds for W
    - Large uncertainty in ATLAS analysis, no 13.6 TeV CMS σ_W

➡First steps towards detailed study of 13.6 TeV data

CMS-SMP-22-017





$$(\sigma_{\text{fid}}\mathcal{B})_{\text{measured}} = (0.7635 \pm 0.0004(\text{stat}) \pm 0.0069(\text{syst}) \pm 0.0176(\text{lumi}))\,\text{nb},$$
$$(\sigma_{\text{fid}}\mathcal{B})_{\text{predicted}} = (0.7666 \pm 0.0065(\text{PDF})^{+0.0021}_{-0.0045}(\text{scale}))\,\text{nb},$$

CMS

Channel	$\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat}\oplus\text{syst}}$ [pb]
$Z \to e^+e^-$	740 ± 22
$Z \to \mu^+\mu^-$	747 ± 23
$Z \to \ell^+\ell^-$	744 ± 20

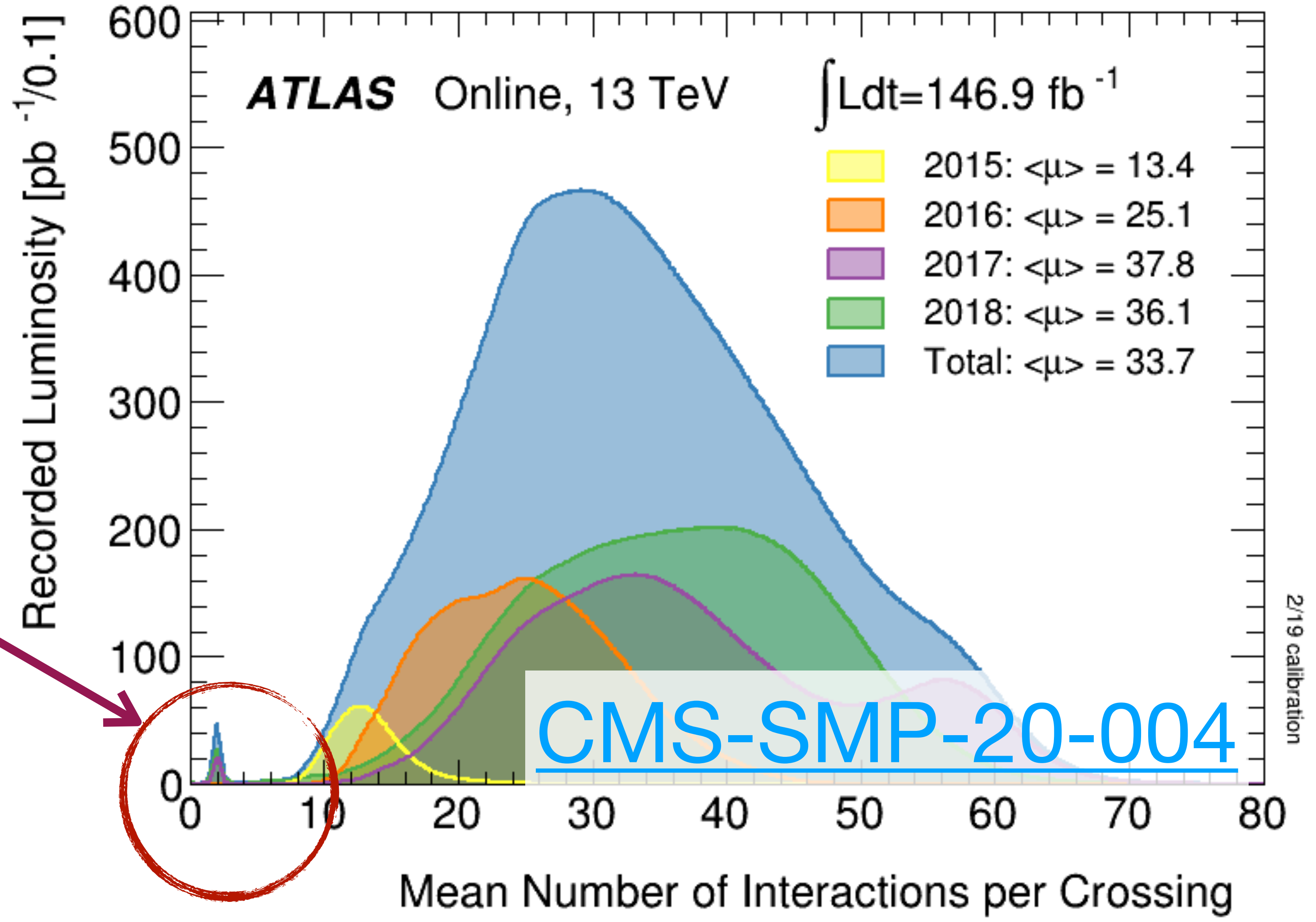
ATLAS

	$\sigma^{\text{fid}} \pm \delta\sigma_{\text{stat}} \pm \delta\sigma_{\text{scale}} \pm \delta\sigma_{\text{PDF}}$ [pb]
$\sigma_{\text{pred.}} =$	$746.1^{+0.1\%}_{-0.1\%}{}^{+0.4\%}_{-0.6\%}{}^{+2.8\%}_{-2.8\%}$

(Slightly different mass windows/fiducial regions)

W and Z measurement in special LHC runs: 5 and 13 TeV

- **"Special" LHC runs** have strong value for W/Z measurements
- Lower pileup permits lower trigger and reco thresholds; lower degradation of pileup-impacted variables (**especially W recoil, m_T^W**)
- Measurements by ATLAS and CMS using ~2-350 pb^{-1} of low PU 13 TeV data + ~300 pb^{-1} of 5 TeV data (Heavy-Ion reference runs)
  - Precise measurements of σ, ratios, and energy scaling
- Could play **important role in LHC precision SM program** in future



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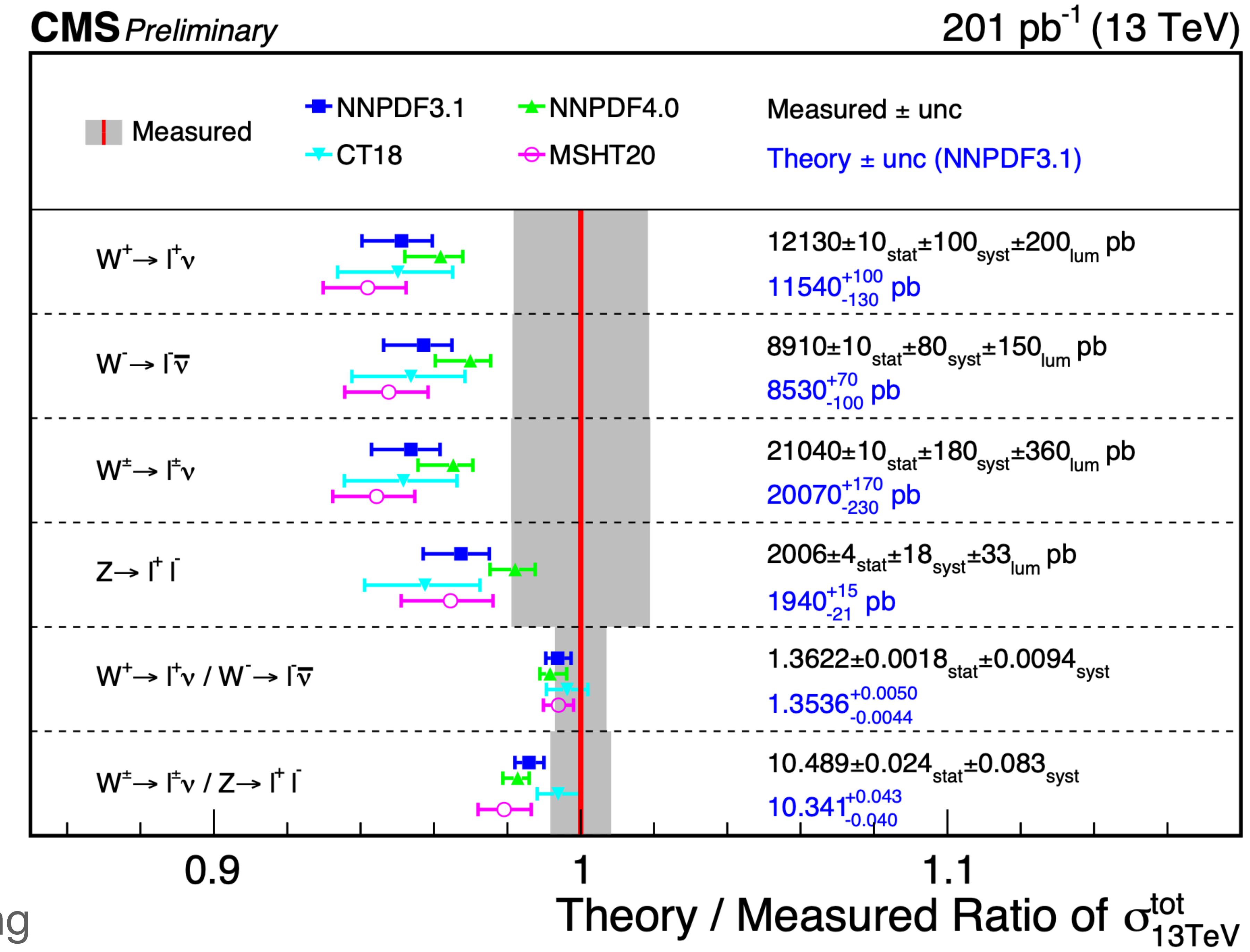
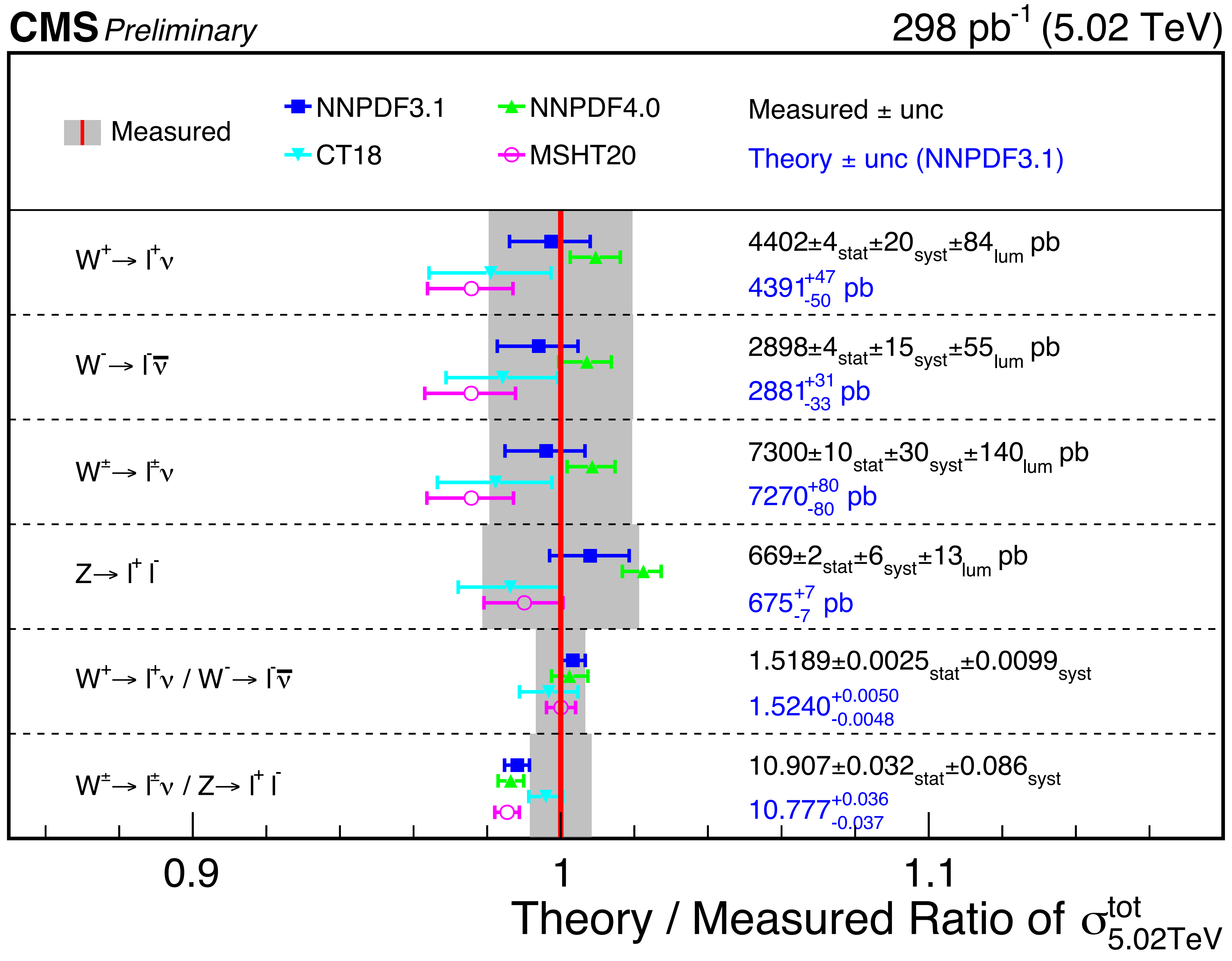


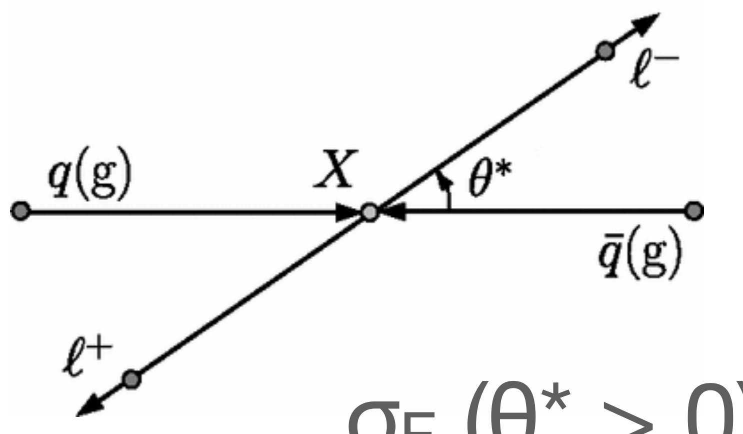


Electroweak precision: Measurement of $\sin\theta^{\ell}_{eff}$

- Drell-Yan angular properties, non-zero A_{FB} arise from different Z/γ^* vector/axial couplings, interference
  - $\sin^2\theta^{\ell}_{eff} := \kappa_F(1 - m^2_W/m^2_Z)$
    - **Modification impacts A_{FB}, angular distributions**
- Unlike e+e-, qq reference frame is not direct observable
  - Sensitivity through sign($y^{\ell\ell}$): q has higher momentum
- **Longstanding ~3σ tension** between most precise results

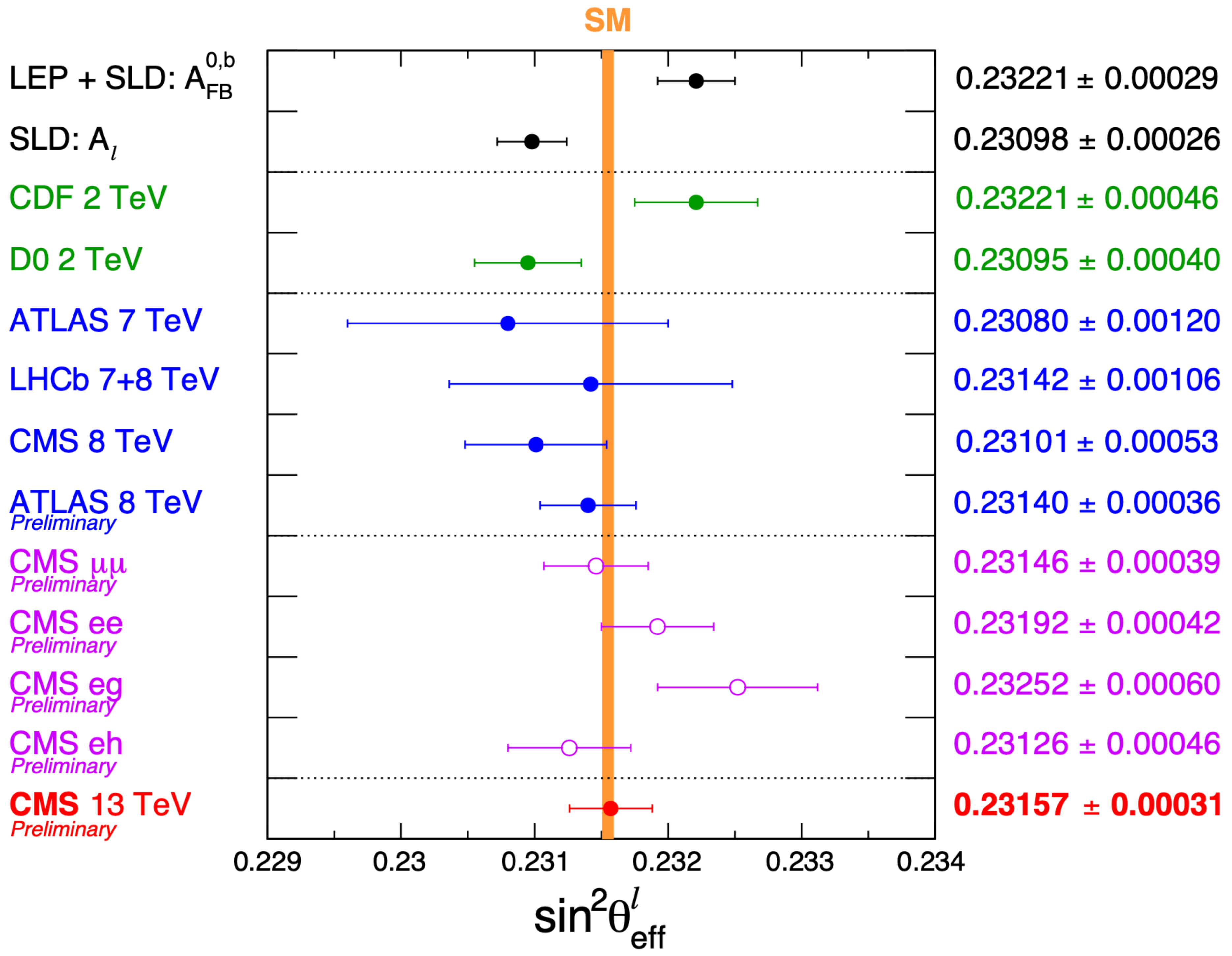
$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}\cos\theta^*\right]$$

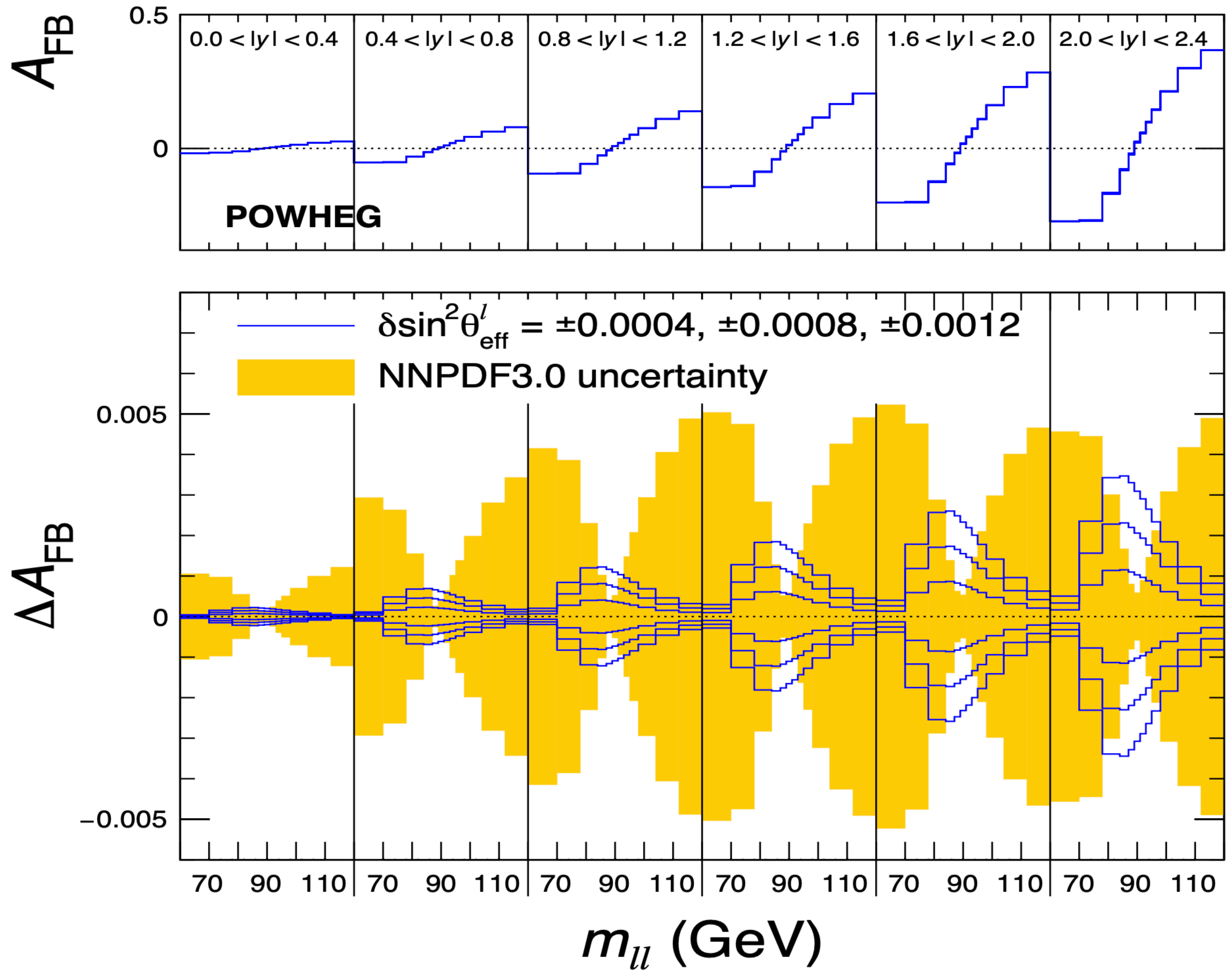
Axial vector/ vector interf.



σ_F ($\theta^* > 0$)
σ_B ($\theta^* < 0$)

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

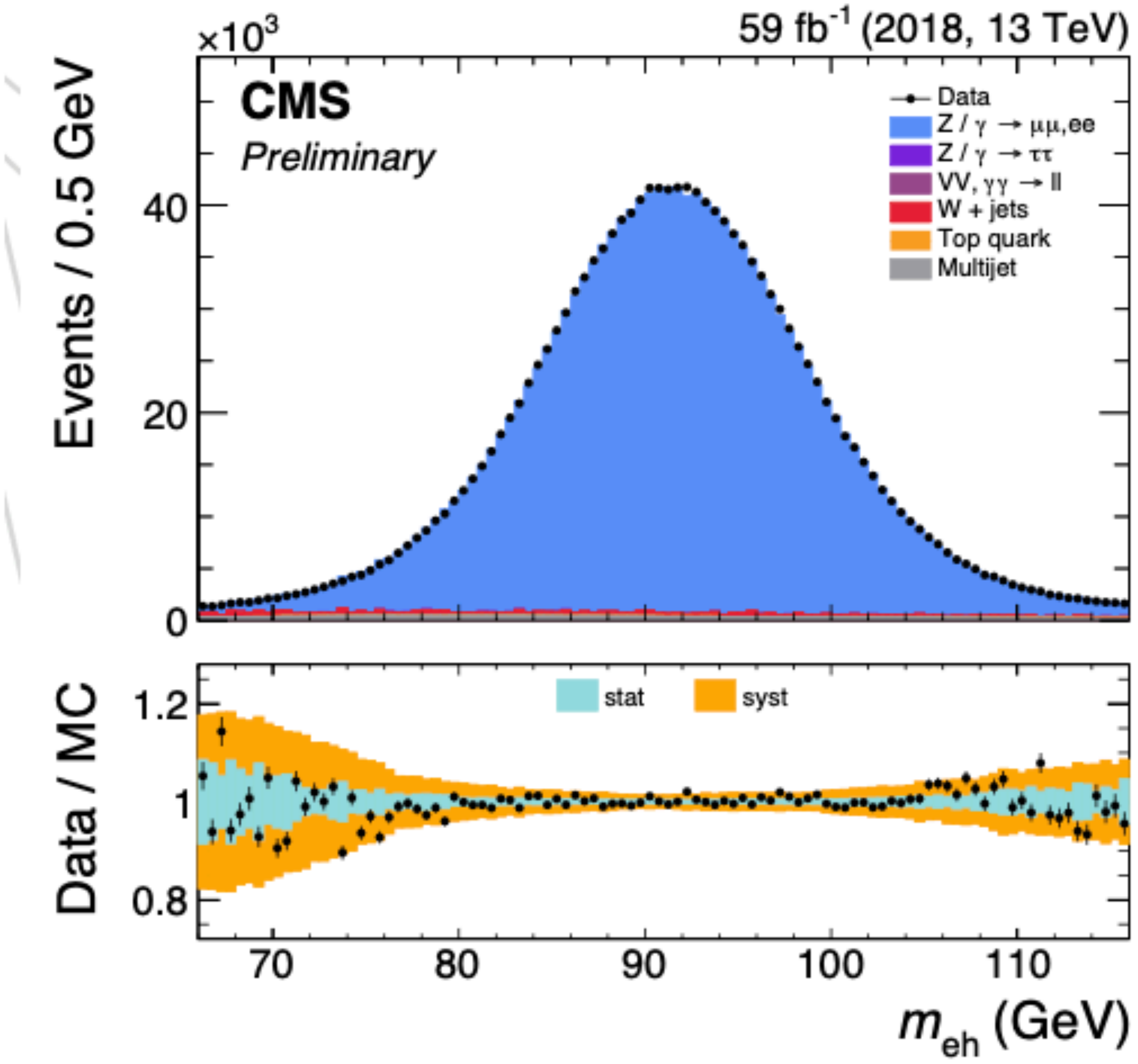




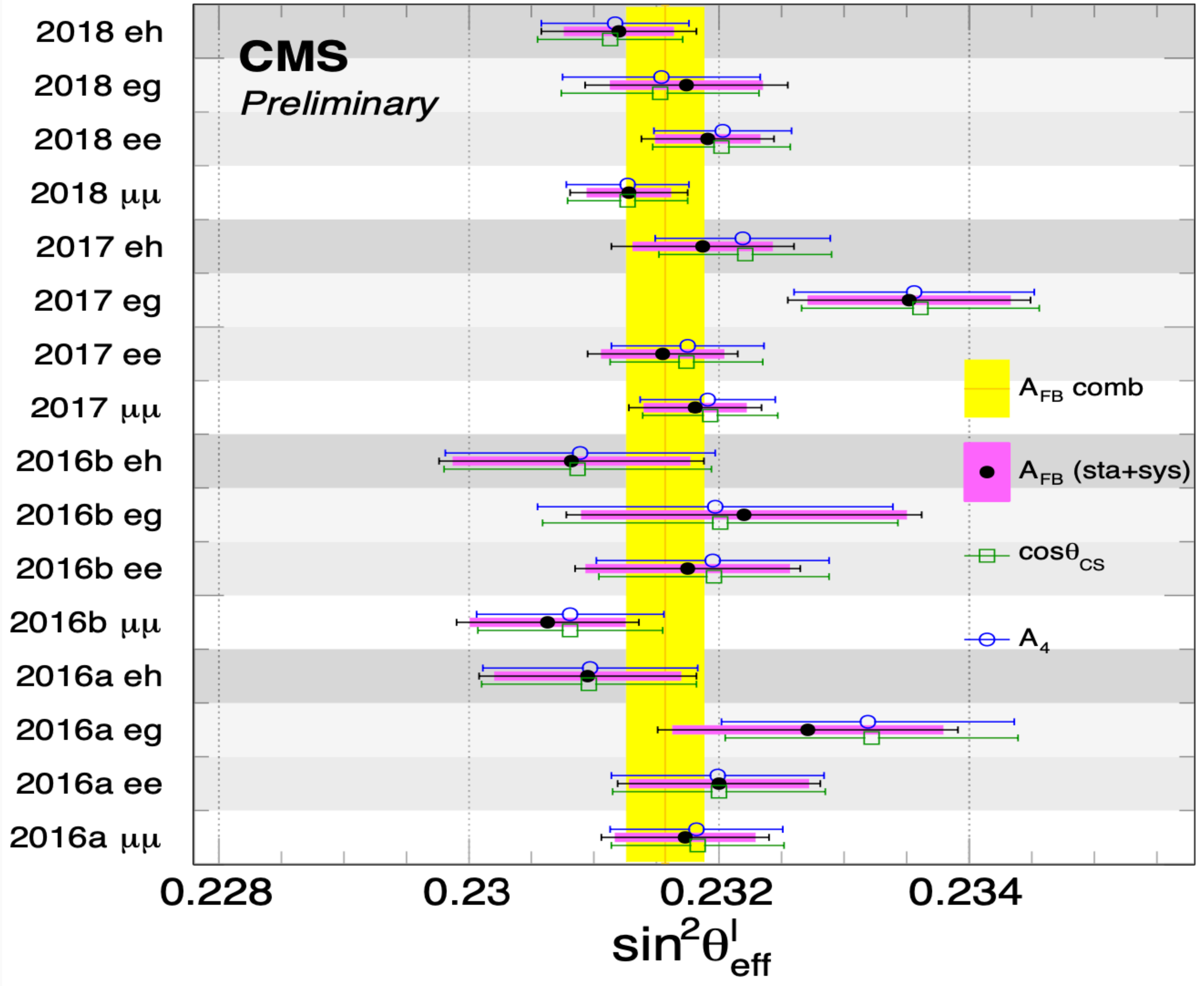
Electroweak precision: Measurement of $\sin\theta^{\ell}_{eff}$

CMS-SMP-22-010

- *Huge experimental challenge*
- Include electrons outside of tracking/only in forward calor. (h)
  - **|η| acceptance up to 4.36**, increase sensitivity to A_{FB}
    - Major challenge to ID, calibrate without tracking!
- Result extracted from reconstructed A_{FB}, cosθ*; unfolded A_4
  - Modeling at NNLO+PS with MiNNLO



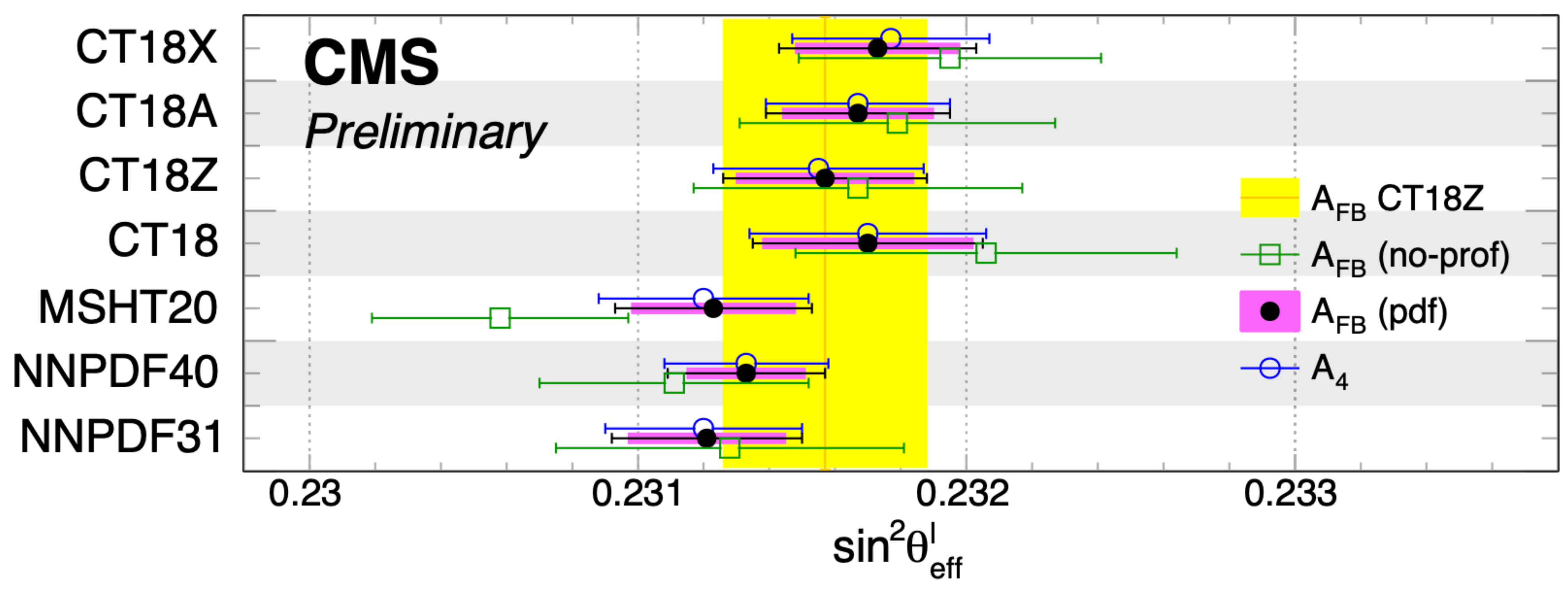
- Impressive consistency across channels

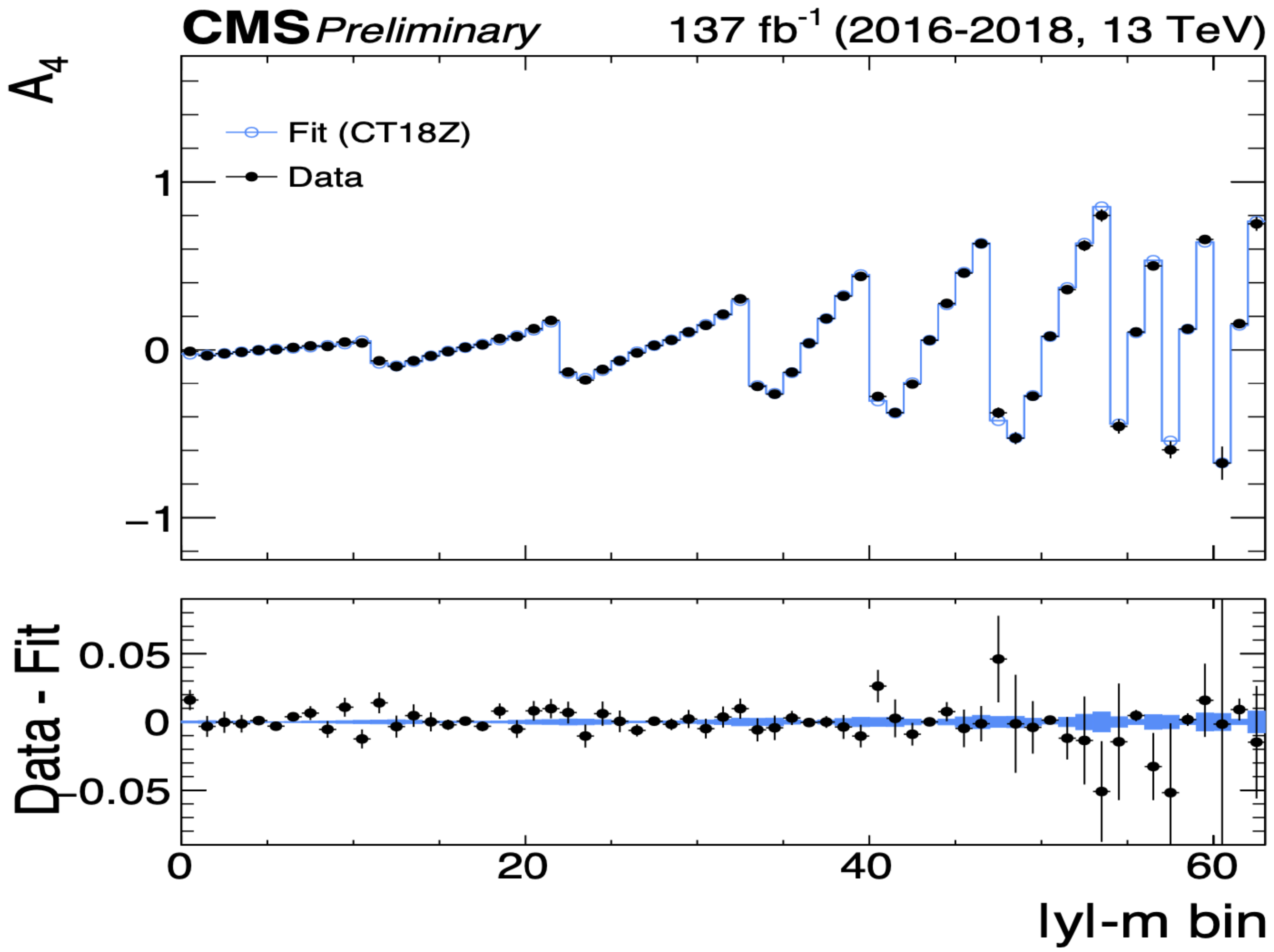


Electroweak precision: Measurement of sinθ^{ℓ}_{eff}

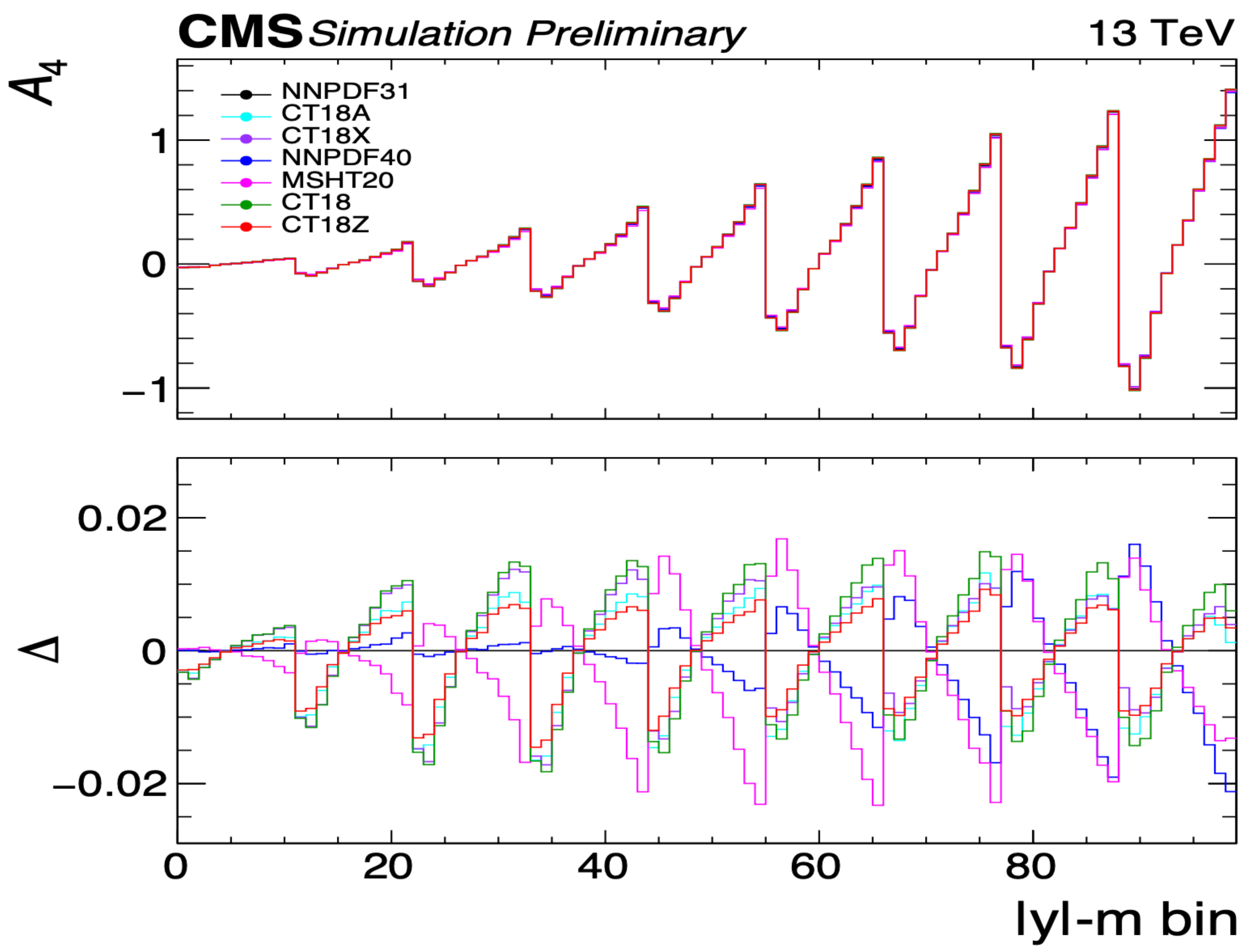
CMS-SMP-22-010

- **Best hadron collider measurement**, near LEP, SLD sensitivity
  - PDF unc. dominate
- In-situ profling of PDF uncertainties
  - **CT18Z chosen as nominal** (before unblinding) due conservative unc, consistency with other sets
  - PDF vars, unc. from event weights in MiNNLO



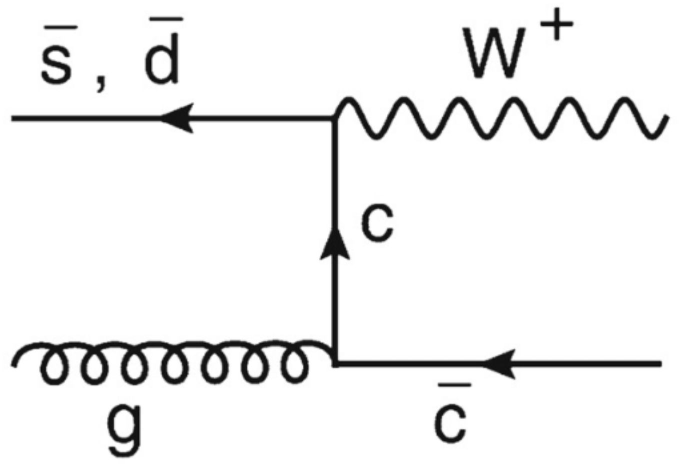


- Distributions of A_{FB}, A_4, cosθ^* unfolded



(0.00027 from PDF) $\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00031$ 0.23155 ± 0.00004 (EW fit expectation)

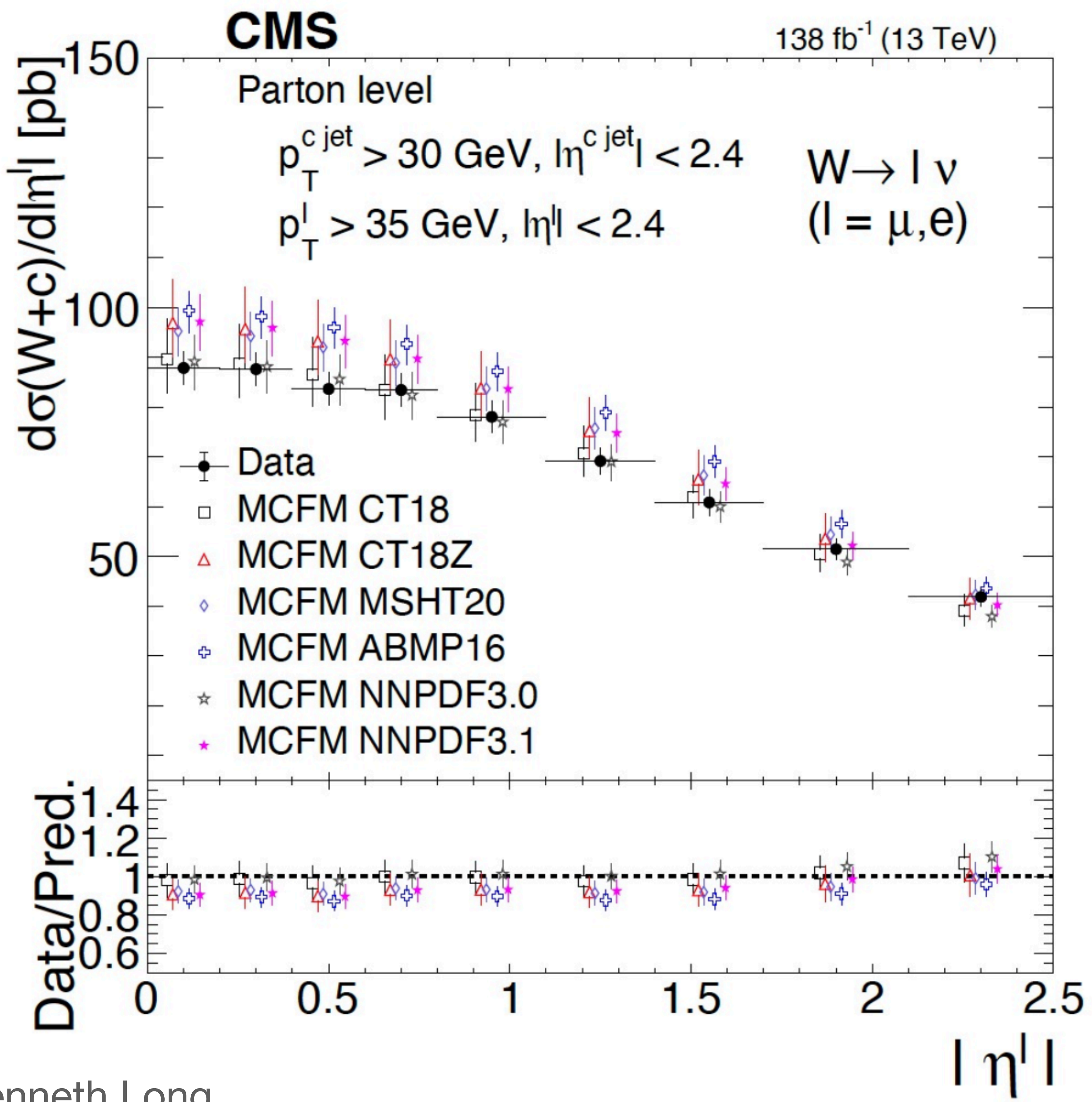
W+charm production

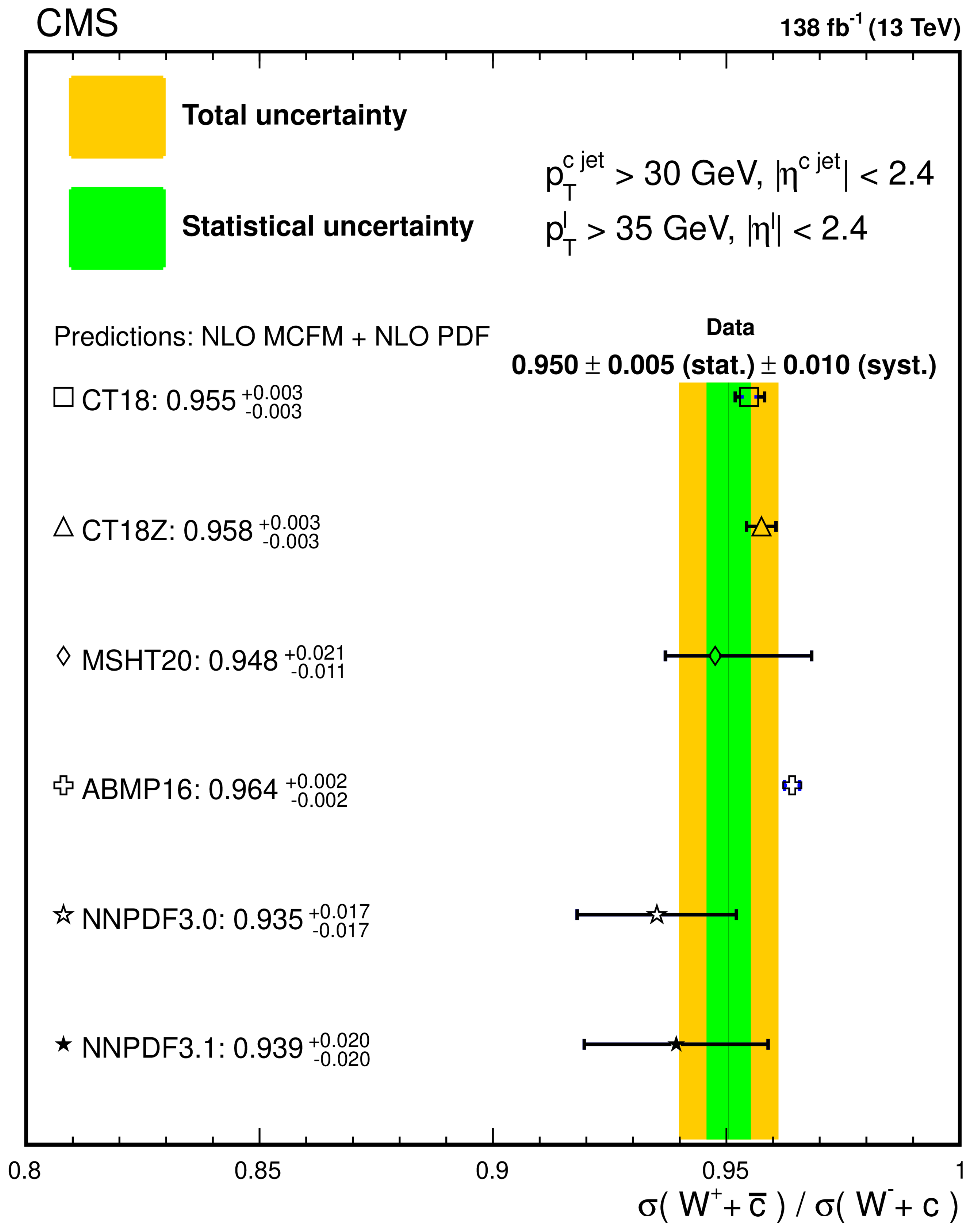


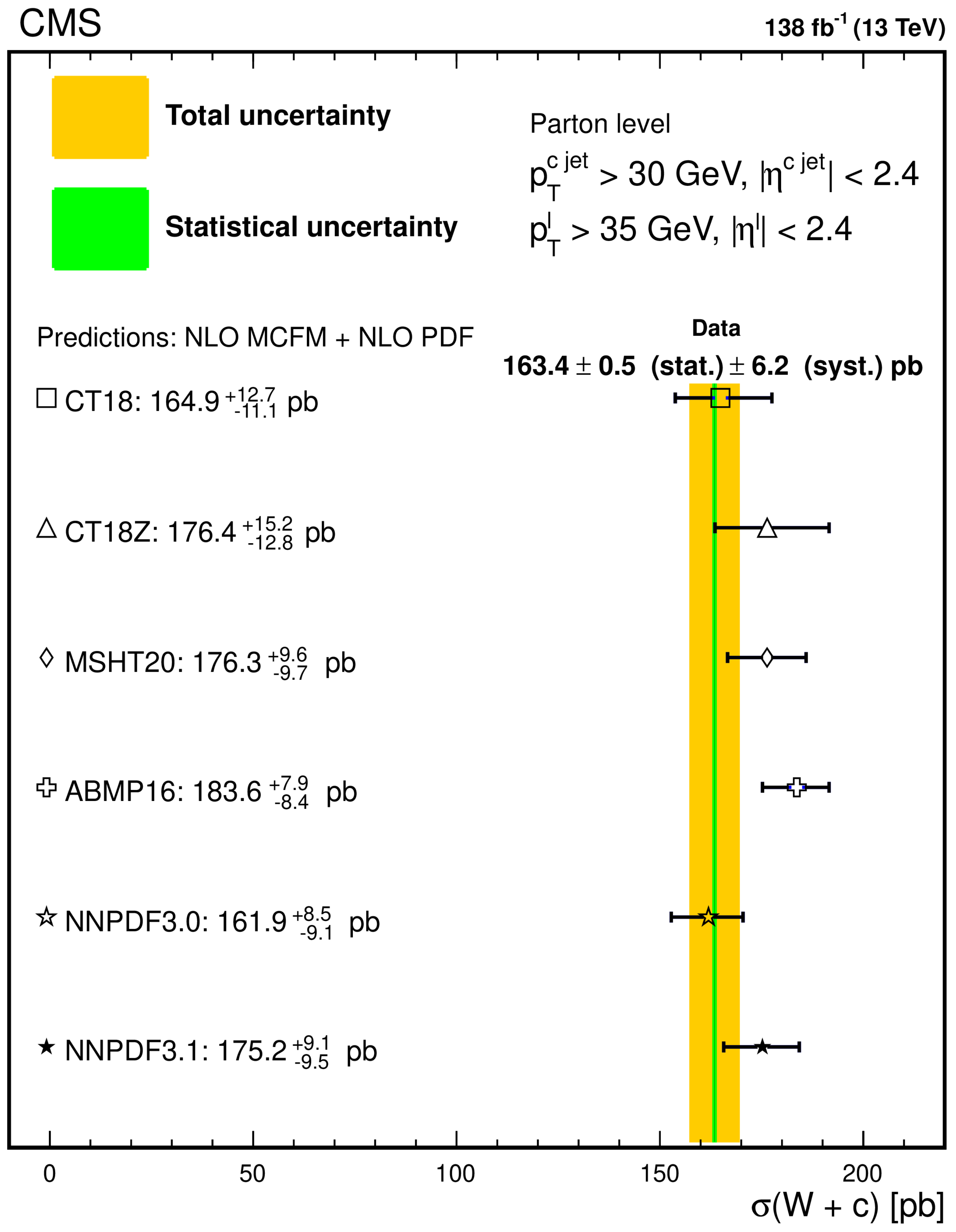
[EPJC 84 (2024) 27](https://doi.org/)

- Excellent **probe of proton strange content**
- **Very pure sample** by exploiting opposite-sign criteria for W, c
  - Charm tagging with DeepCSV, muons from secondary vertex
- σ, ratio W^+/W^-, unfolded distributions

➡ Well described by PDFs, NLO MCFM







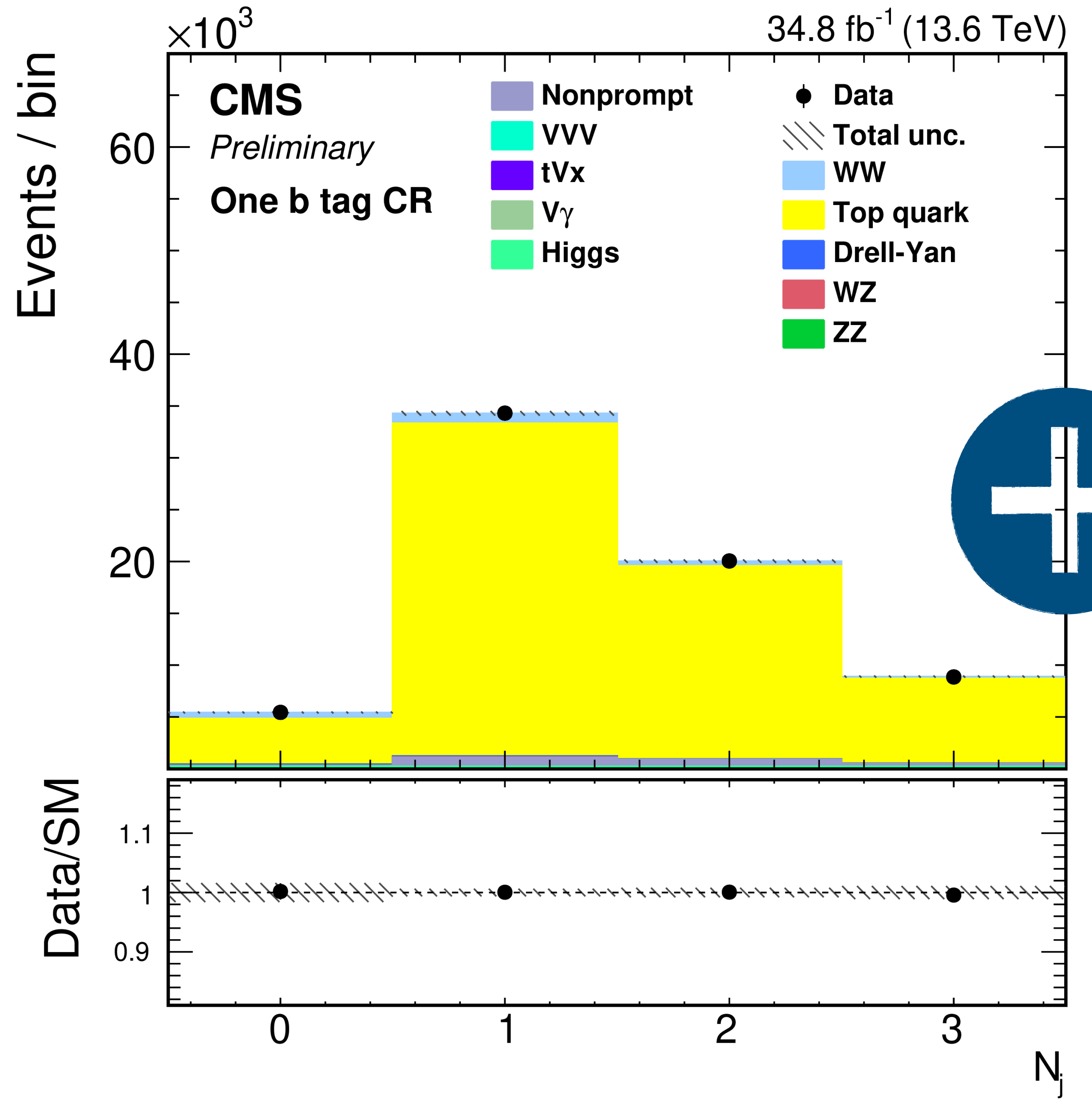
Diboson production

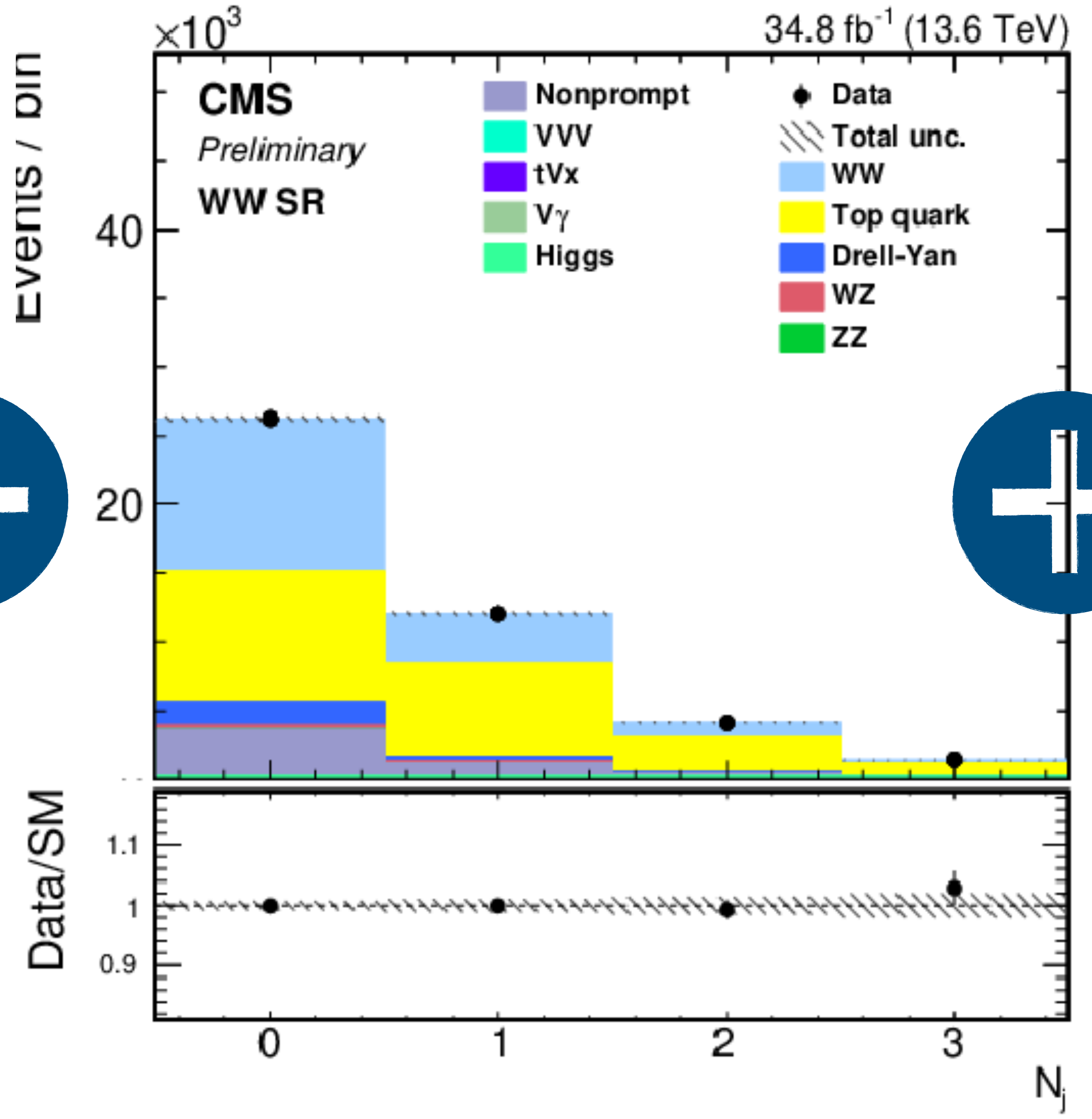
WW at 13.6 TeV

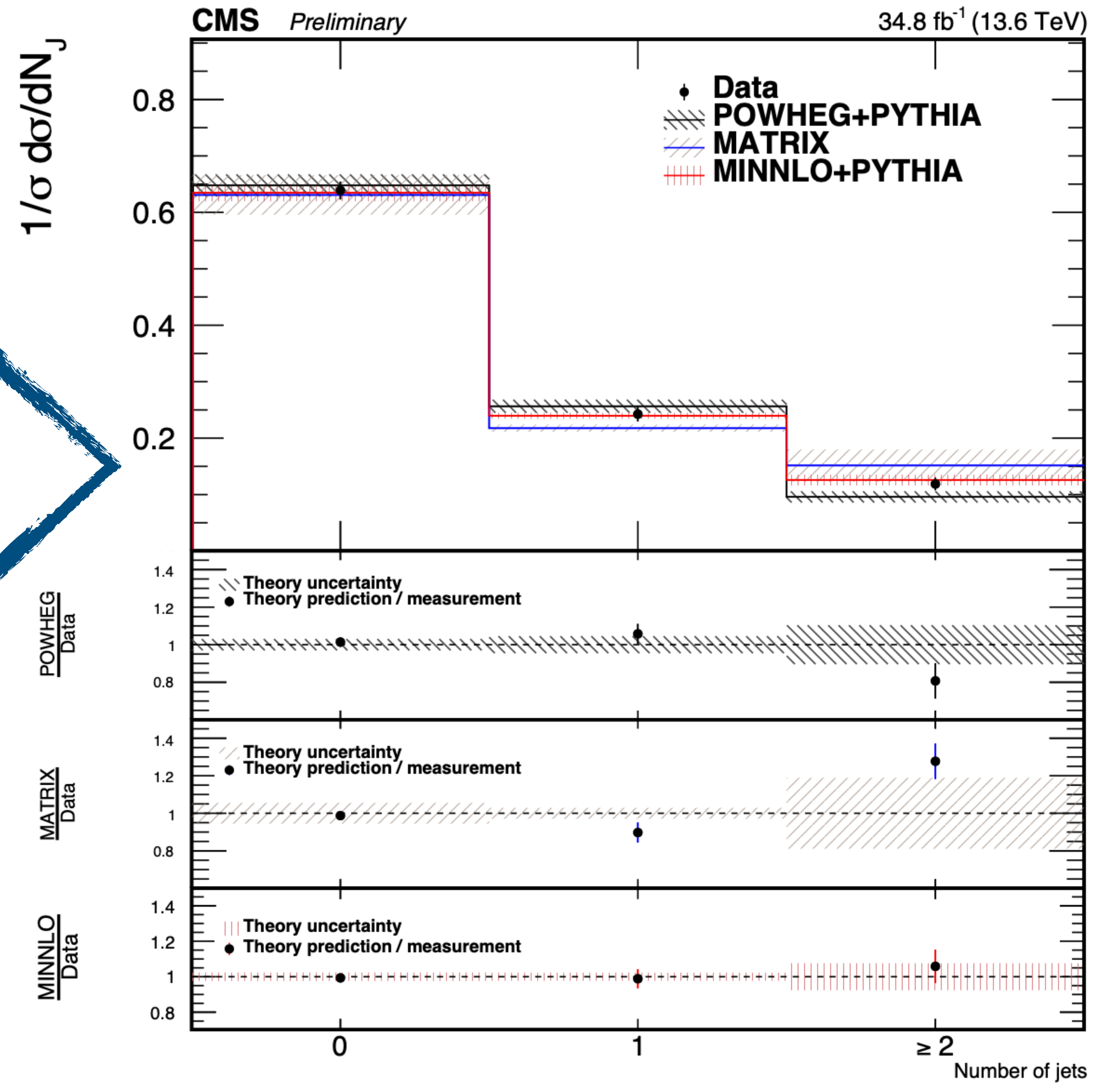
- **First diboson cross section measurement at 13.6 TeV**
  - Test pQCD predictions
  - Explicit jet vetos (sensitive to resummation) no longer used
    - ➡ Simultaneous fit to b-tagged (top), 2/3/4 lepton (DY/WZ/ZZ), mis-ID (non-prompt lepton) regions
    - eμ channel only (reduce Z background)
- Precision takes time, but already competitive with Run 2 result (σ_{tot} syst. limited)

CMS-SMP-24-001

Excellent agreement with NNLO+PS (MiNNLO)





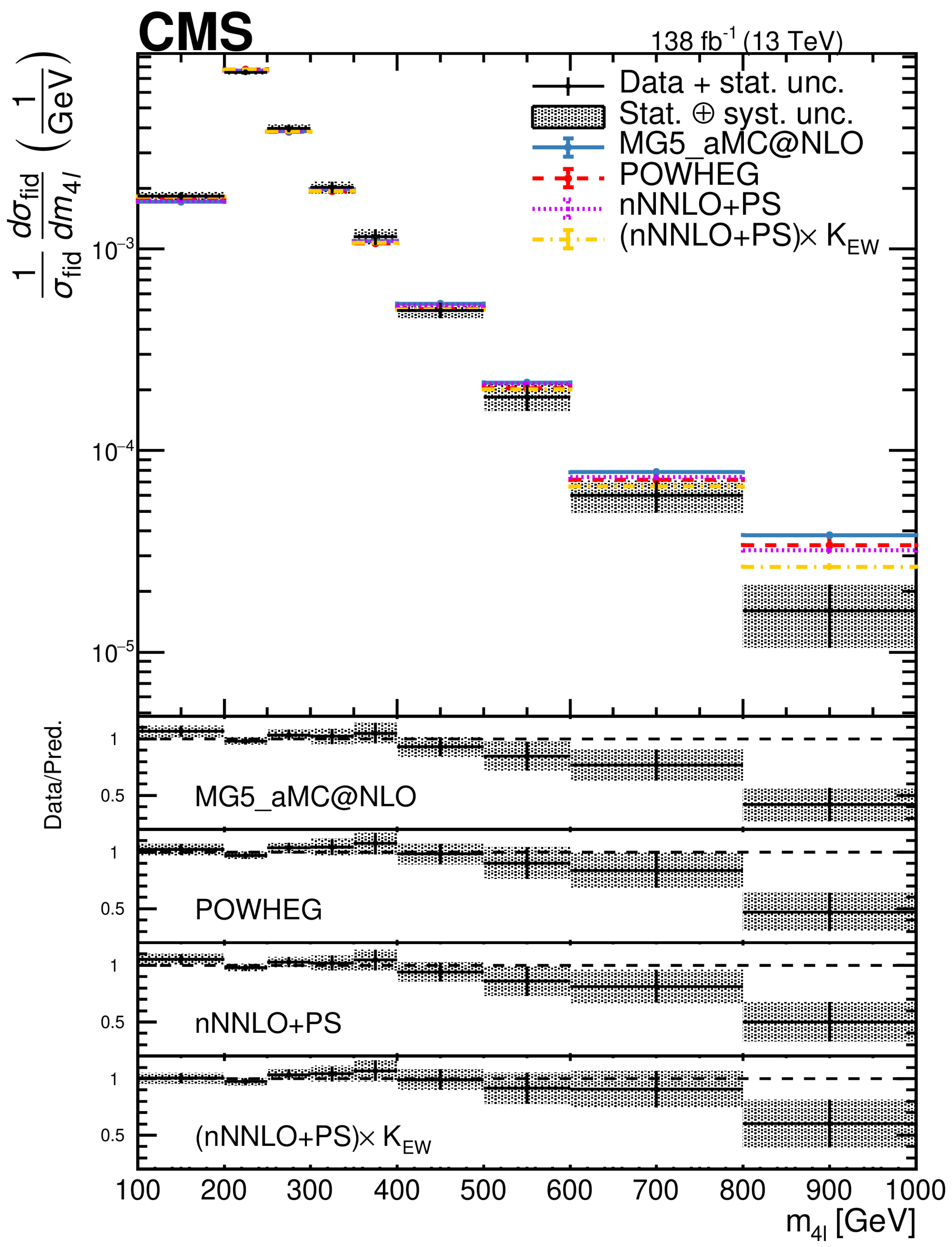


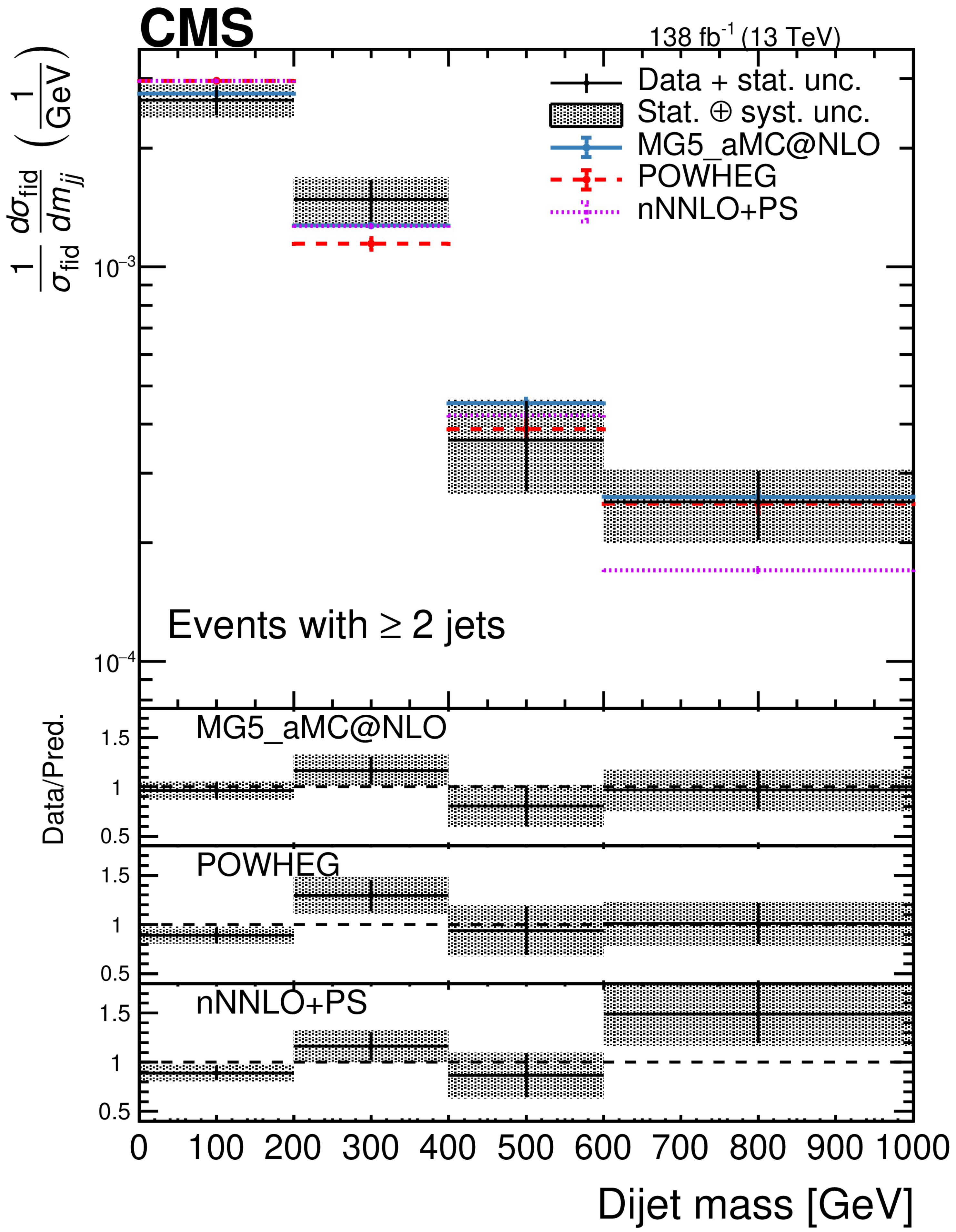
$$125.7 \pm 2.3\,(\text{stat}) \pm 4.8\,(\text{syst}) \pm 1.8\,(\text{lumi})\,\text{pb}$$

Diboson measurements: towards precision

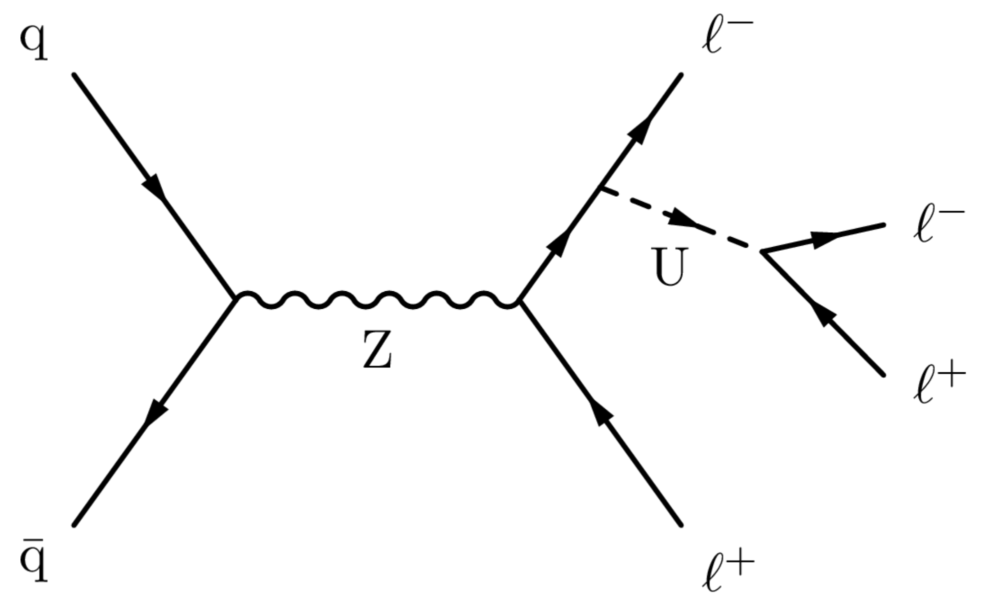
[CMS-SMP-22-001](#)
[CMS-SMP-19-007](#)

- **Huge Run 2 (+Run 1) data set allows precise study** of rare (but clean) ZZ(4ℓ) process
  - Extensive study of ZZ production differential in jet observables
    - **Comparison to NNLO+PS and gg@NLO+PS via MiNNLO**; MG5_aMC w/ ≤2j@NLO
  - Full 8+13 TeV for Z(4ℓ) branching fraction measurement





	95% CL UL [$\times 10^{-6}$]	
Channel	Expected	Observed
4μ	1.28	1.34
$2\mu 2e$	2.48	2.33
4e	1.37	1.32
4ℓ	4.95	4.91

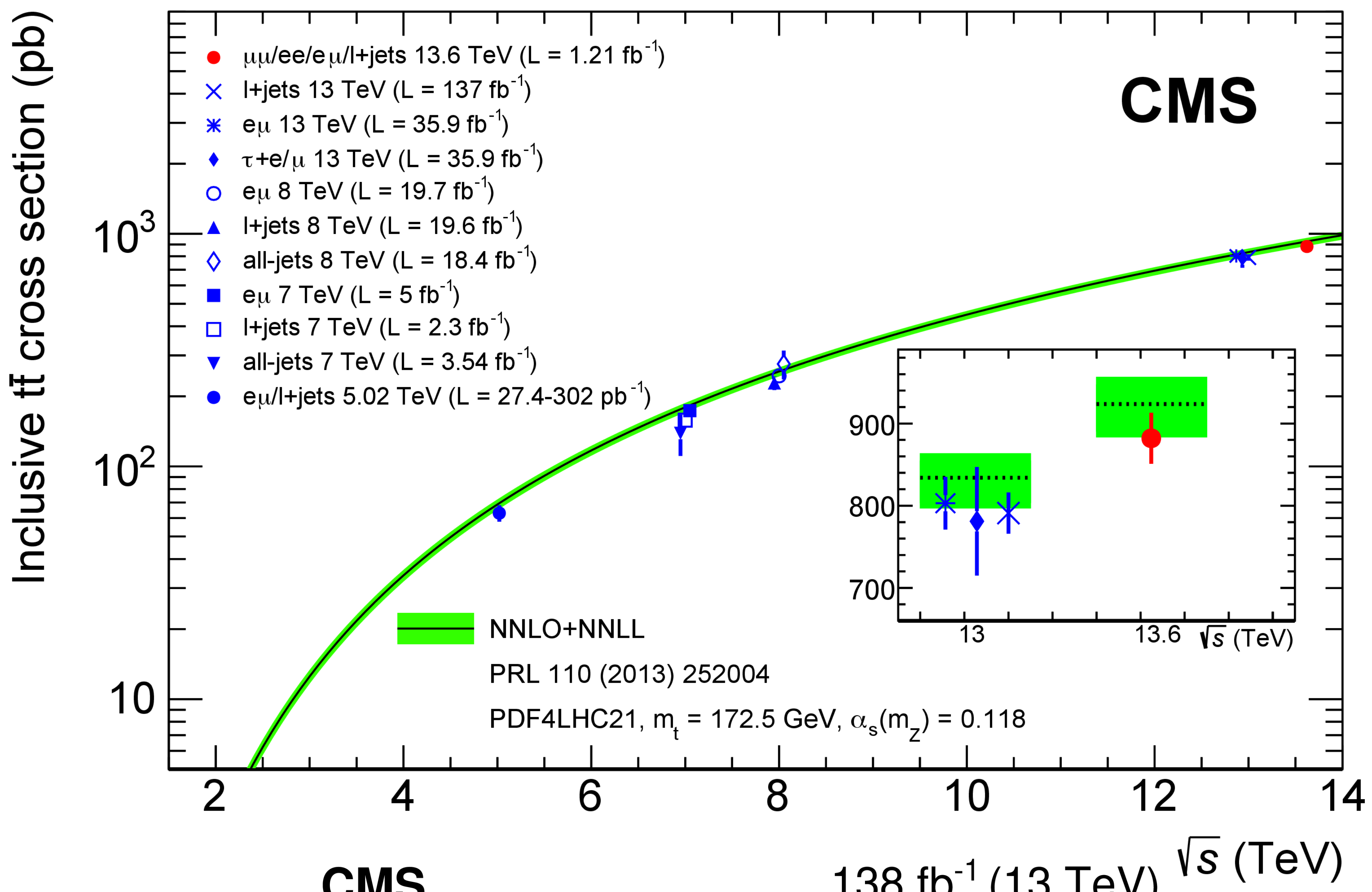


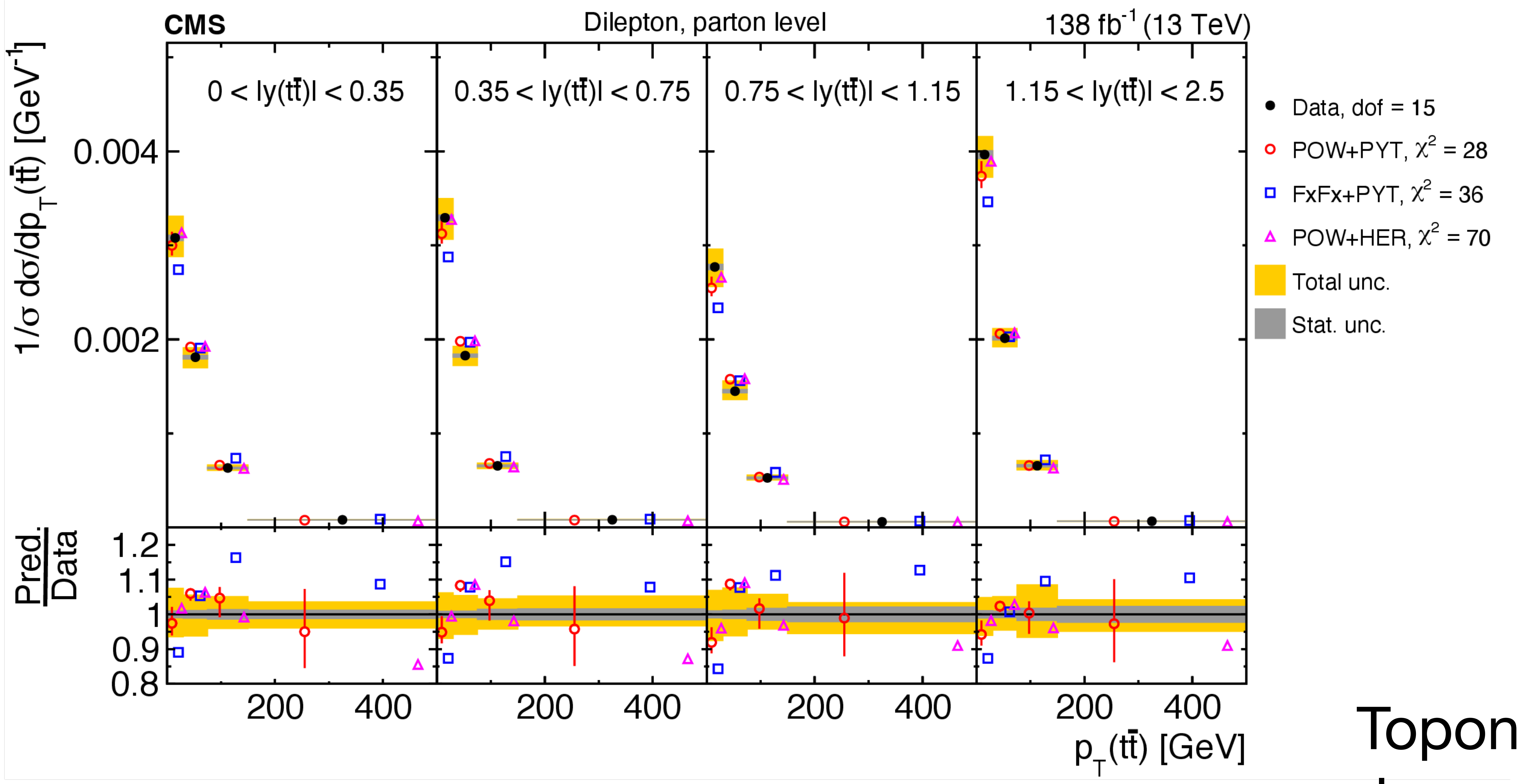
Sensitivity to NP light boson

CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-27 18:33:11.804352 GMT
Run / Event / LS: 356309 / 137565256 / 156
ATLAS+CMS Preliminary
LHCtopWG
November 2023
NNLO+NNLL, PDF4LHC21 (pp)
NNLO+NNLL, PDF4LHC21 (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_{top} = 172.5 GeV, $\alpha_s(M_Z)$ = 0.118 ± 0.001
Tevatron comb. (1.96 TeV, ≤ 8.8 fb^{-1}) [1]
ATLAS comb., ee, μμ, eμ, l+jets (5.02 TeV, 257 fb^{-1}) [2]
CMS comb., eμ, l+jets (5.02 TeV, 27.4-302 fb^{-1}) [3]
LHC comb., LHCtopWG, eμ (7 TeV, 5 fb^{-1}) [4]
LHC comb., LHCtopWG, eμ (8 TeV, 20 fb^{-1}) [4]
ATLAS, eμ (13 TeV, 140 fb^{-1}) [5]
CMS, eμ (13 TeV, 35.9 fb^{-1}) [6]
ATLAS, l+jets (13 TeV, 139 fb^{-1}) [7]
CMS, l+jets (13 TeV, 137 fb^{-1}) [8]
ATLAS, eμ (13.6 TeV, 29 fb^{-1}) [9]
CMS, ee, μμ, eμ, l+jets (13.6 TeV, 1.2 fb^{-1}) [10]
[1] PRD 89 (2014) 072001
[2] JHEP 06 (2023) 138
[3] JHEP 04 (2022) 144
[4] JHEP 07 (2023) 213
[5] JHEP 07 (2023) 141
[6] EPJC 79 (2019) 368
[7] PLB 810 (2020) 135797
[8] PRD 104 (2021) 092013
[9] arxiv:2308.09529
[10] JHEP 08 (2023) 204
Inclusive tt̄ cross section [pb]
Ratio to Prediction
$\sqrt{s}$ [TeV]

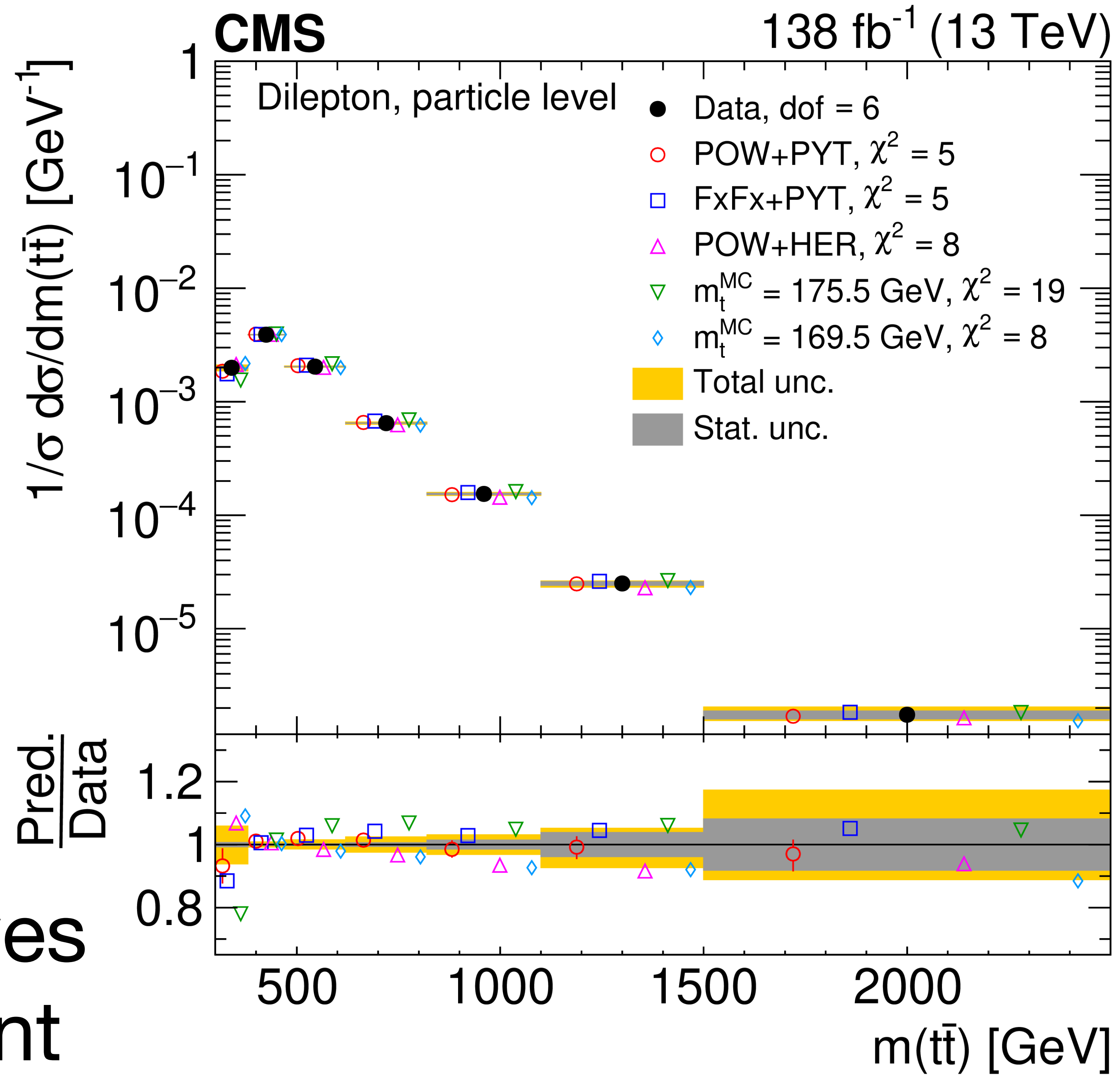
$t\bar{t}$ production cross sections [arXiv:2402.08486, arxiv:2303.10680]

- **Key high-rate process**: access to top properties, test predictions
  - Background for ~every other analysis
- **Extending studies to energy frontier**
  - Small 5 TeV data set motivates MVA-driven measurement
  - First 13.6 TeV performed with extensive in-situ constraints (ℓℓ)
- Huge Run 2 data set used for precise differential exploration (ℓℓ)





Toponium improves low m_{tt} agreement

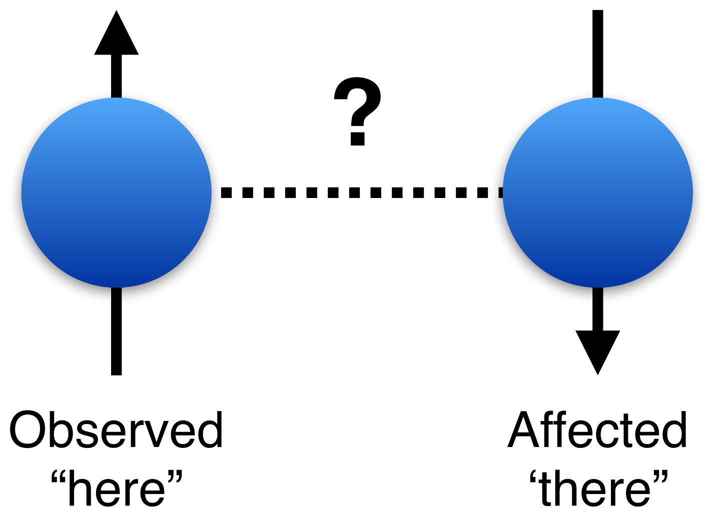


$t\bar{t}$ spin entanglement [TOP-23-001]

- Cross section dependent on decay-lepton properties
  - Spin-density matrix already measured by ATLAS [1] + CMS [2]

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

Spin correlations



$$D = -3 \cdot \langle \cos\varphi \rangle$$

$$D < -1/3$$

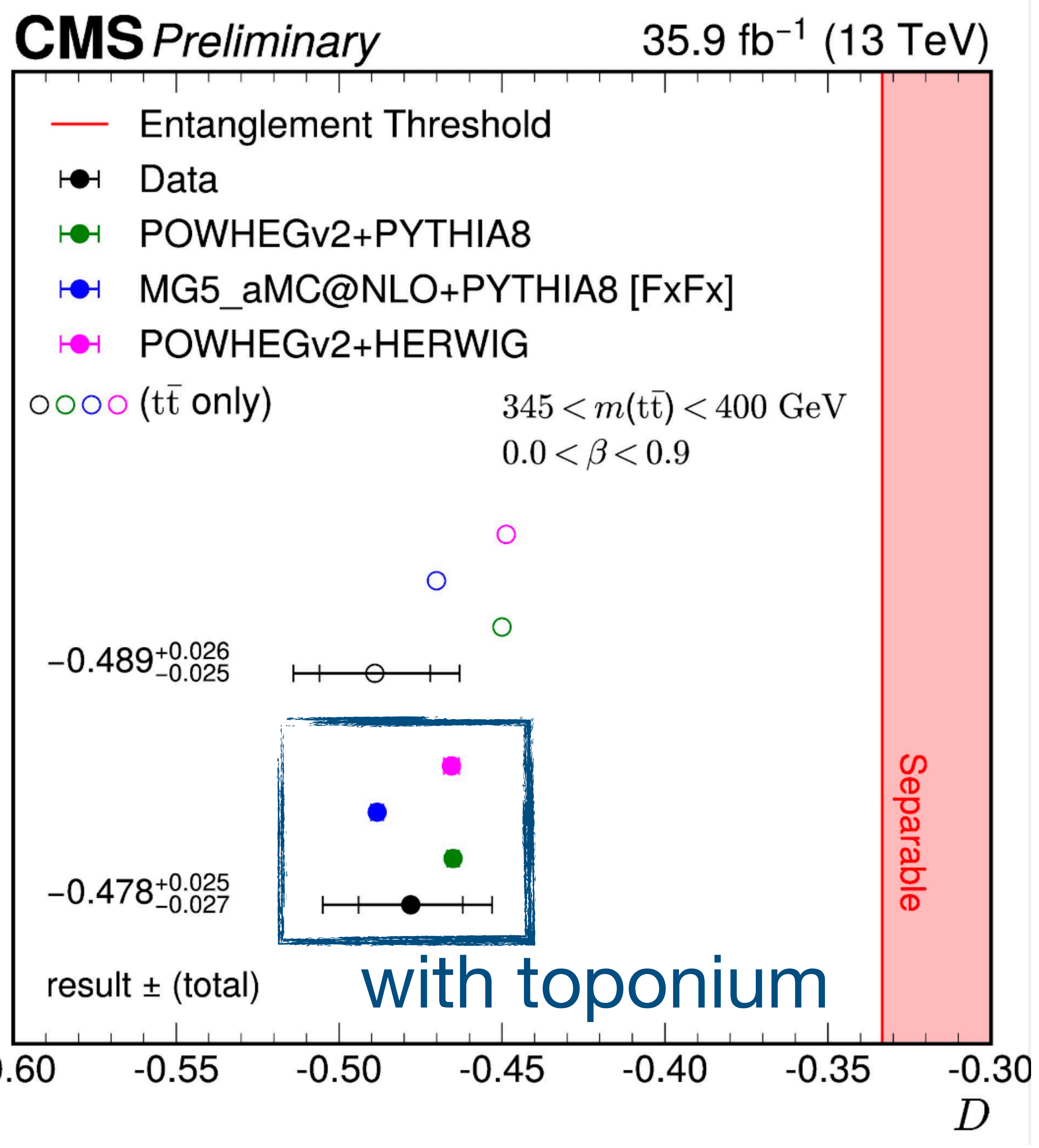
Entanglement marker

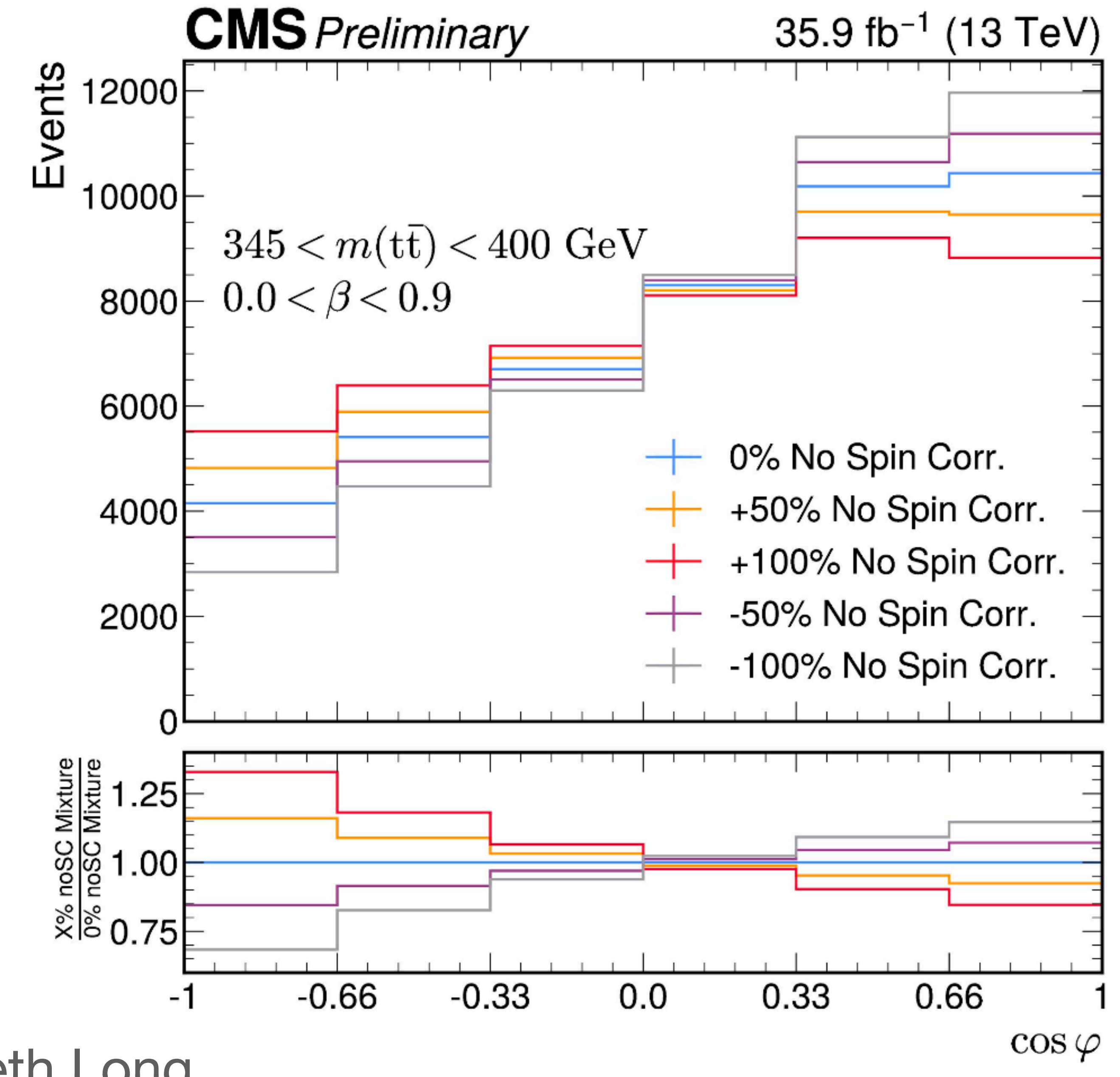
- **$t\bar{t}$ system described as two-qubit system**
  - Entanglement measured from angle between $\ell\ell$ in $t\bar{t}$ rest frame

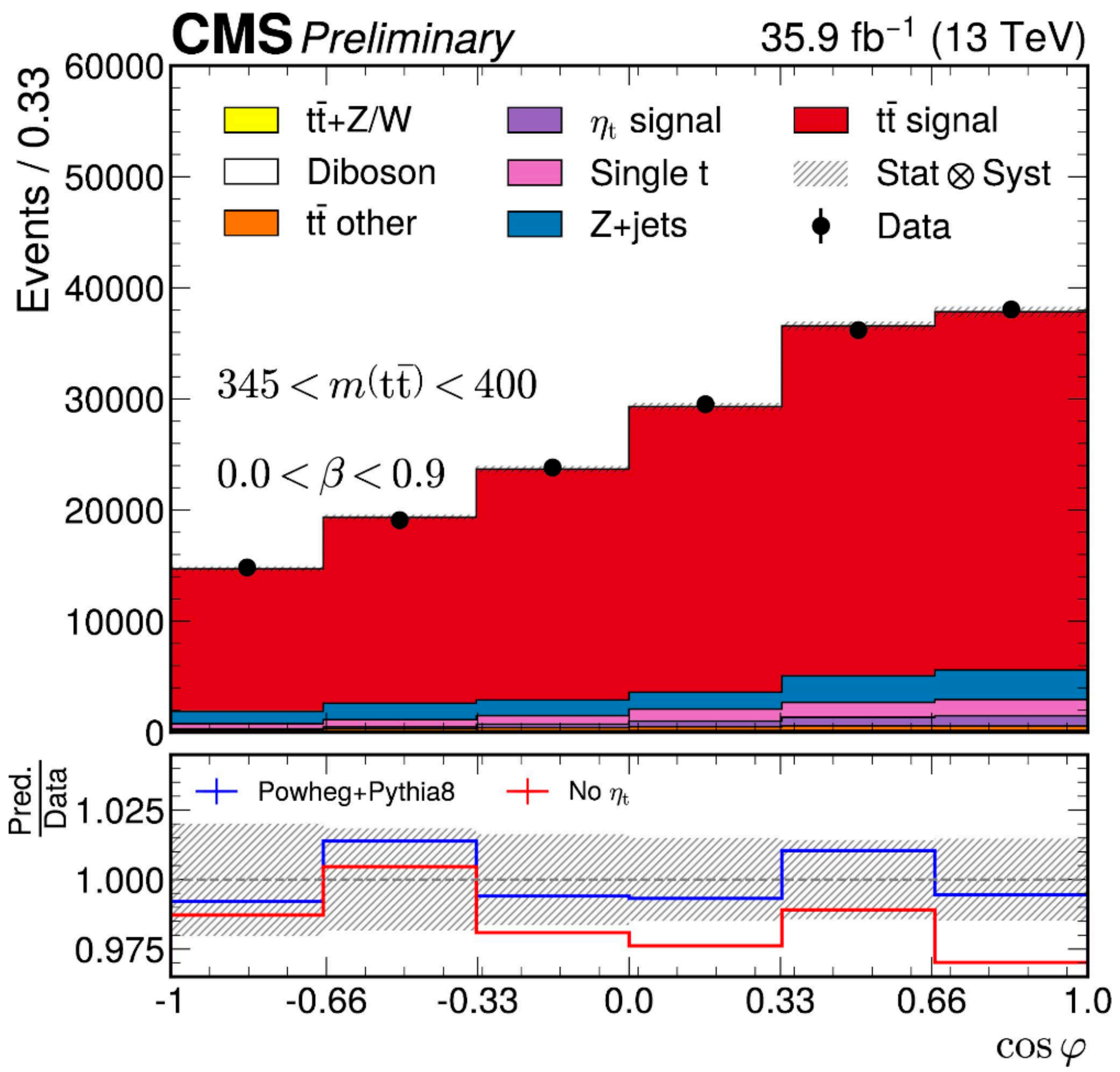
➡Observed at 5σ level

  - Agreement with data improved by toponium simulation

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi}$$







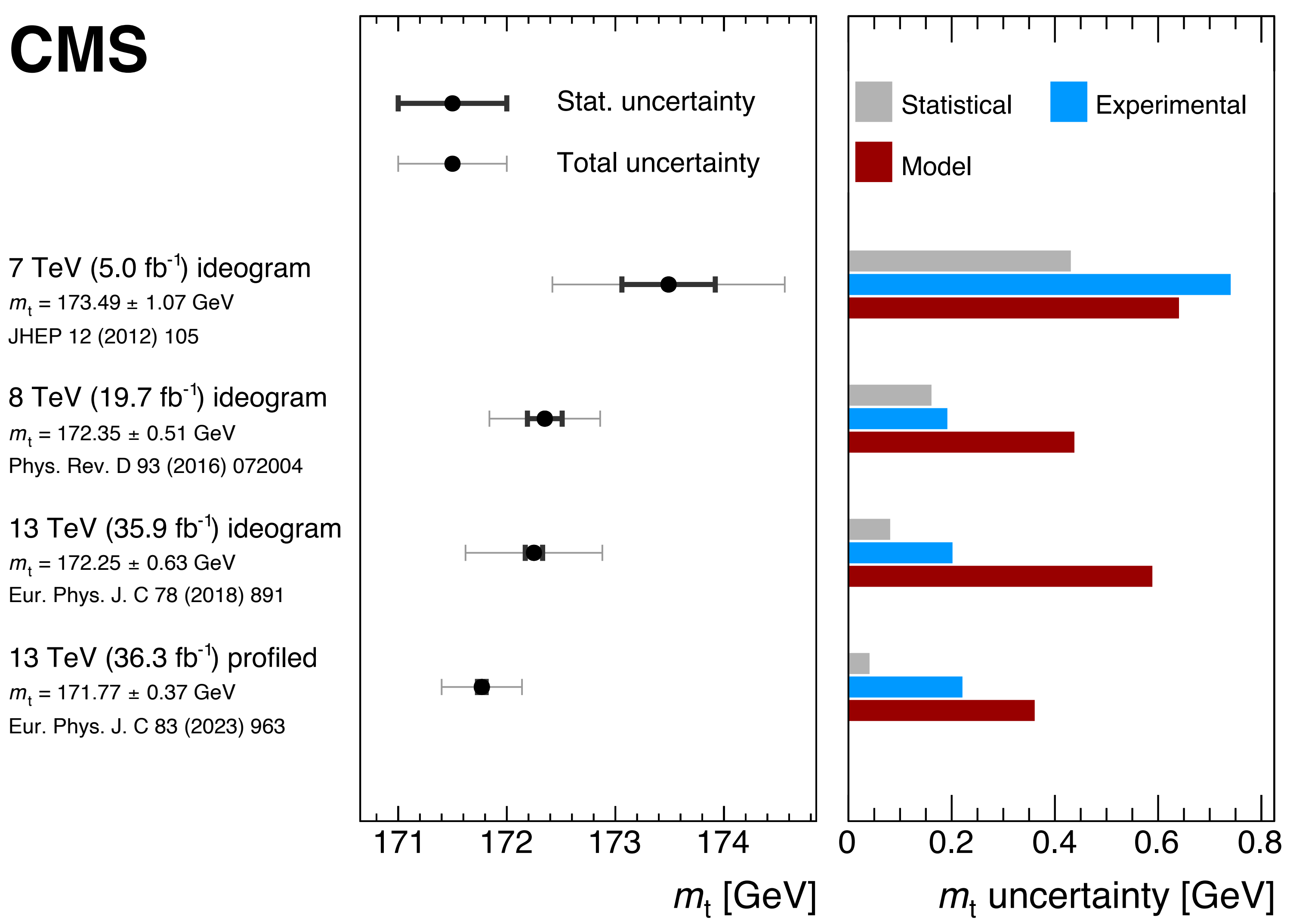
[1] [JHEP 03 (2017) 113][2] [Phys. Rev. D 100, 072002]

Review of CMS top mass measurements [arXiv:2403.01313]

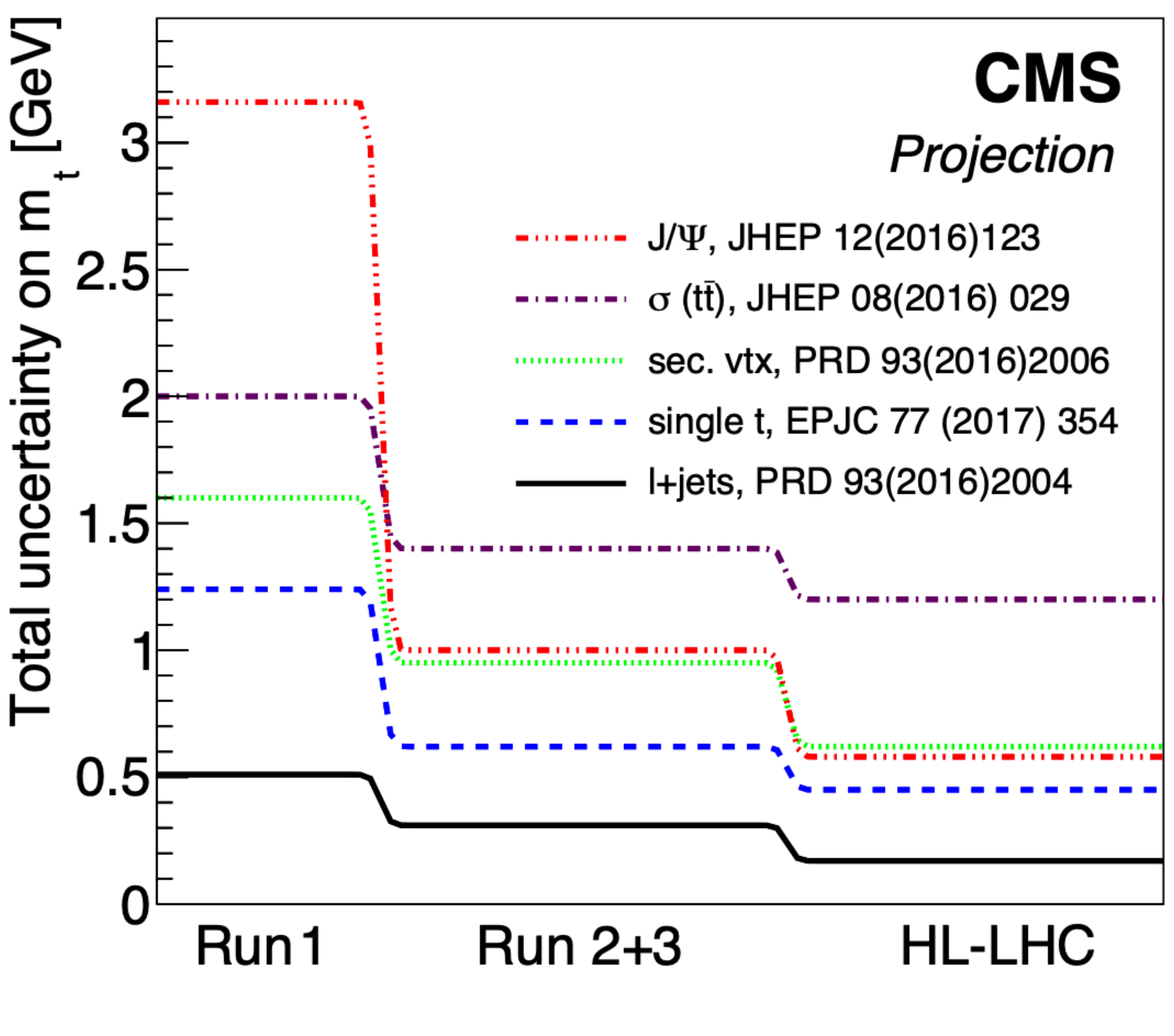
- **Comprehensive review** of all CMS m_t measurements
  - Perspectives on evolution of techniques, comparison of results

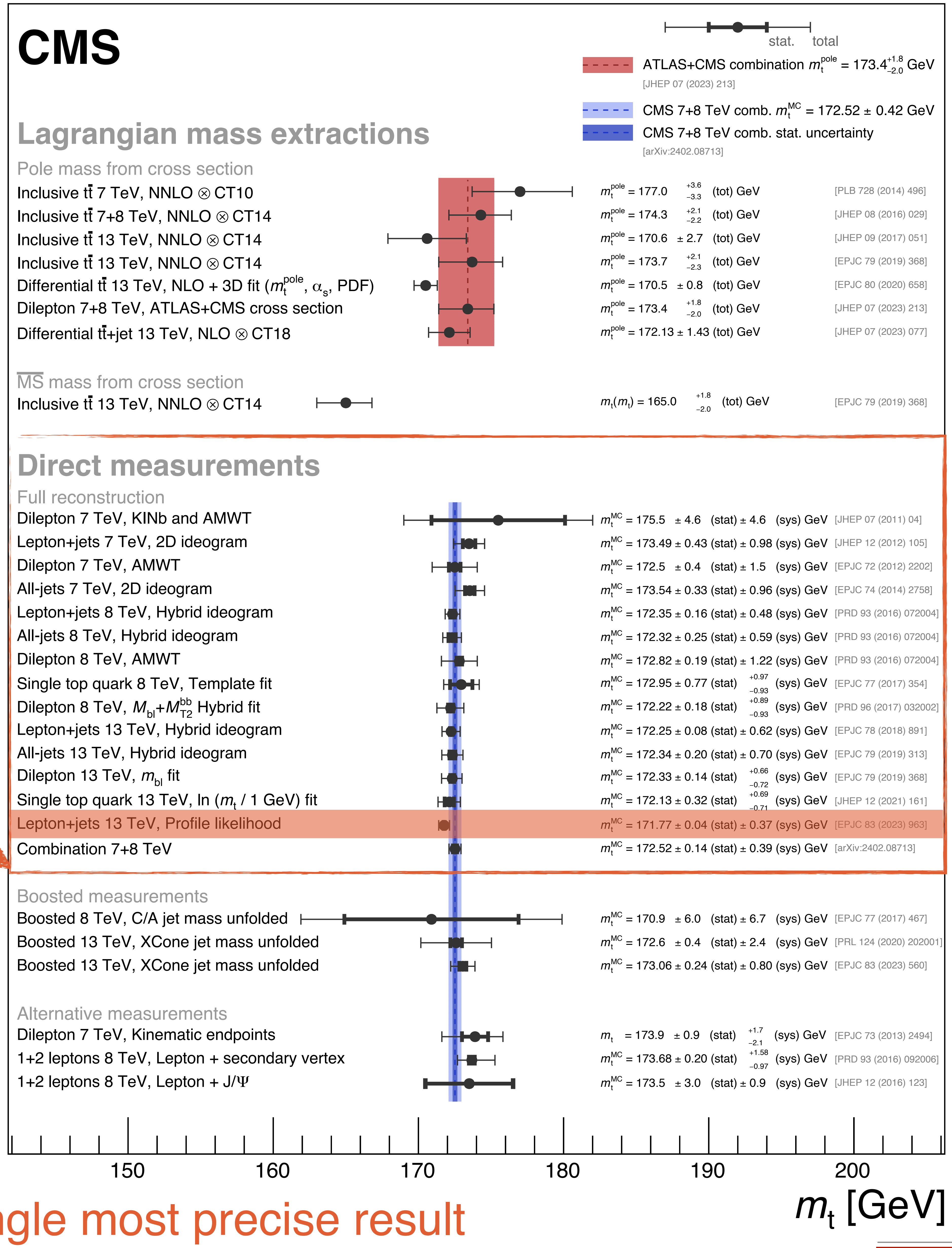
  ➡ We hope it is a useful reference

Improvement from Run 1



Extrapolation to HL-LHC



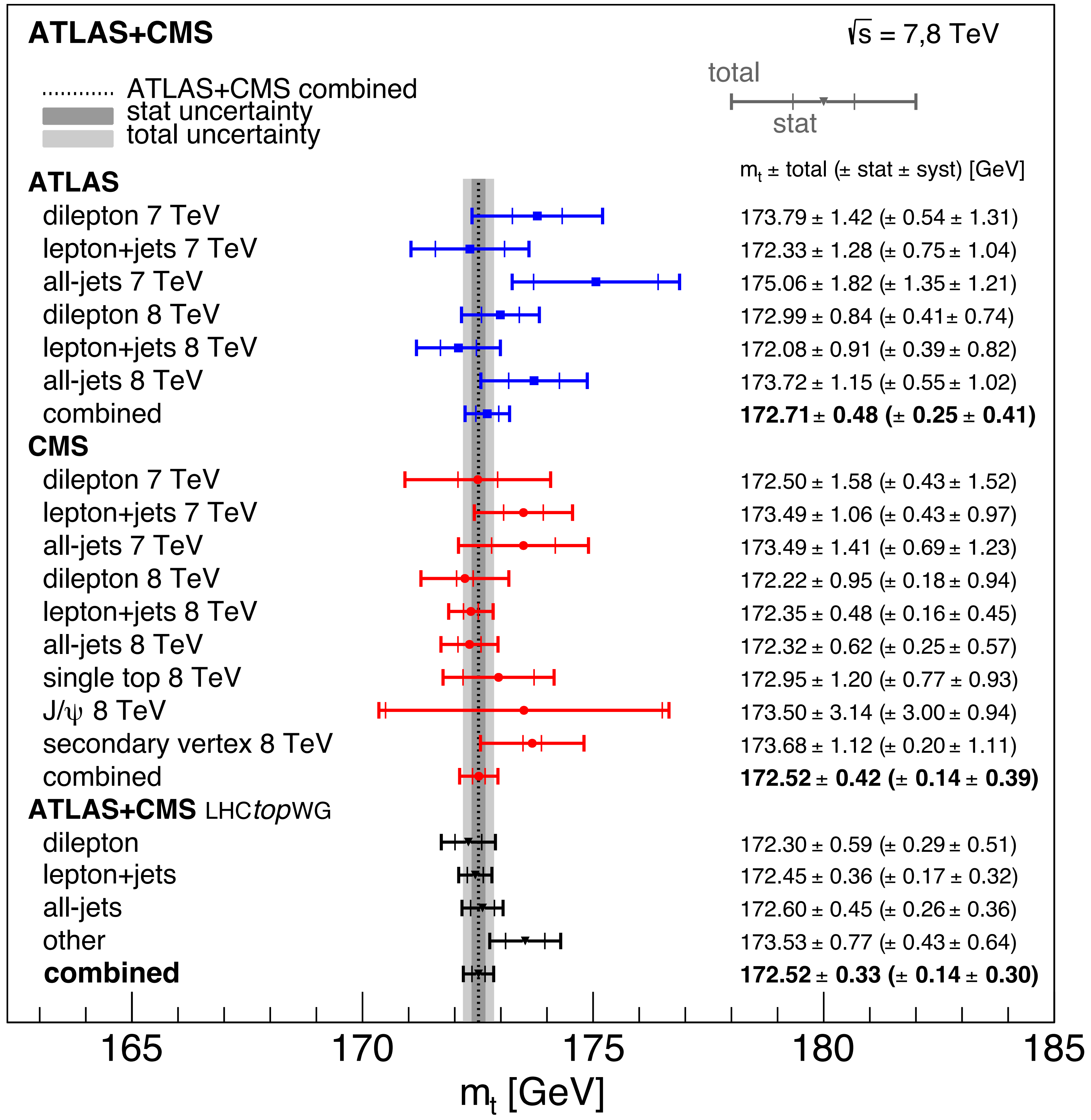


Single most precise result

- Impressive evolution, expect to continue towards HL-LHC

Top quark mass: combination with ATLAS [arXiv:2403.01313]

- **Combination of Run-1 ATLAS+CMS** m_t measurements with BLUE (Best Linear Unbiased Estimator)
  - 6 (ATLAS) + 9 (CMS) individual measurements across final states
    - Study impact of correlation of unc. across exp.



Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	[−0.25, +0.25]	8	7
JES 3	0.5	[+0.25, +0.75]	1	<1
b-JES	0.85	[+0.5, +1]	26	5
g-JES	0.85	[+0.5, +1]	2	<1
l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
QCD radiation	0.5	[+0.25, +0.75]	7	1
Hadronization	0.5	[+0.25, +0.75]	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
CMS top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

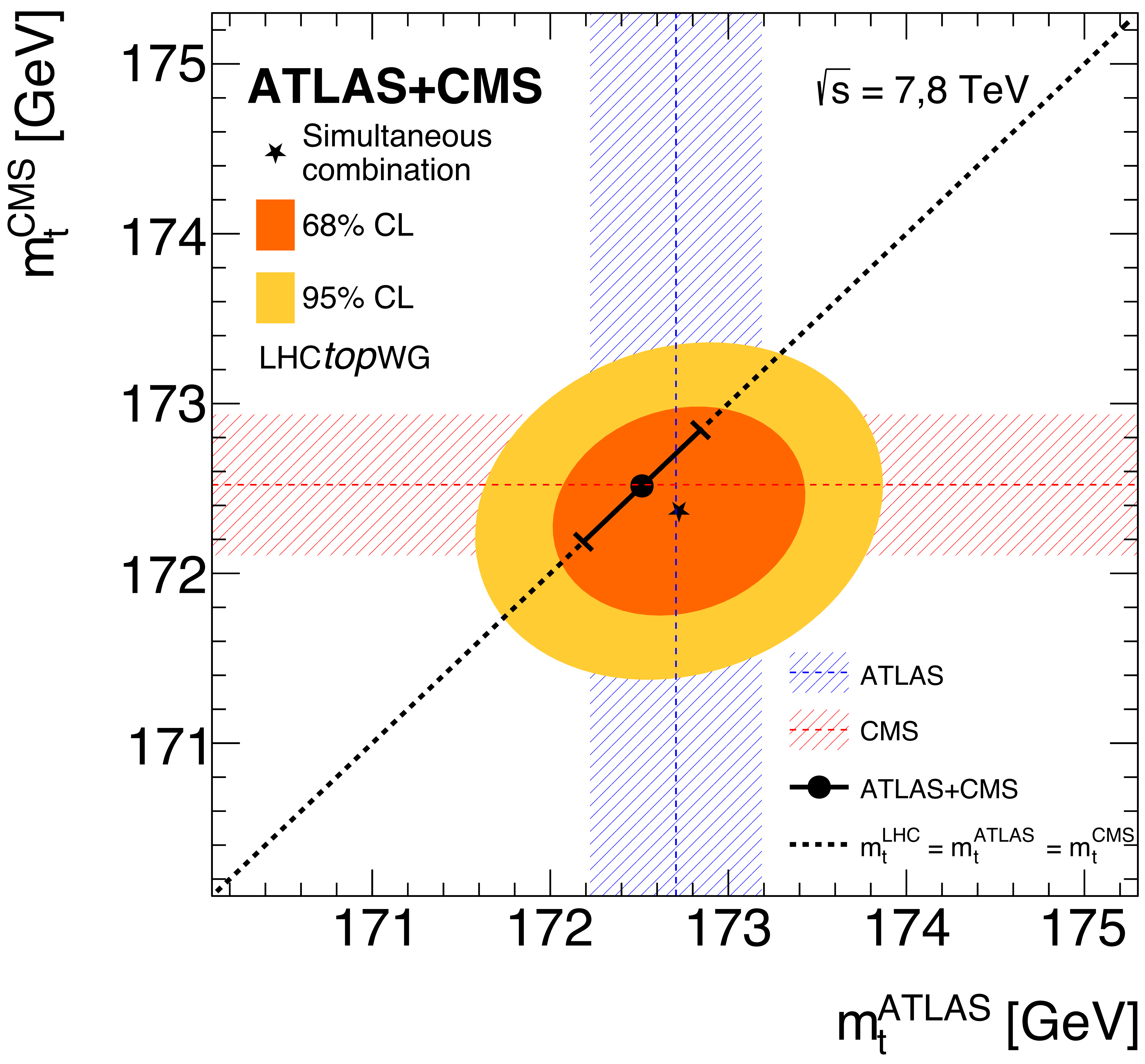
The “only correlation that matters"

Stable wrt. variations

- Very detailed study of systematics, their correlations, and impacts

Top quark mass: combination with ATLAS [arXiv:2403.01313]

- **Improvement wrt previous comb**: 0.48 GeV → 0.33 GeV
- Lower precision results play important role
  - Most precise CMS 0.48 GeV → 0.42 GeV
- Major investment of effort, also pays off in understanding of techniques and collaboration across exps.



Dominant in the LHC combination

Dominant in individual combinations

Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Higgs production

Higgs mass and width in the four lepton channel

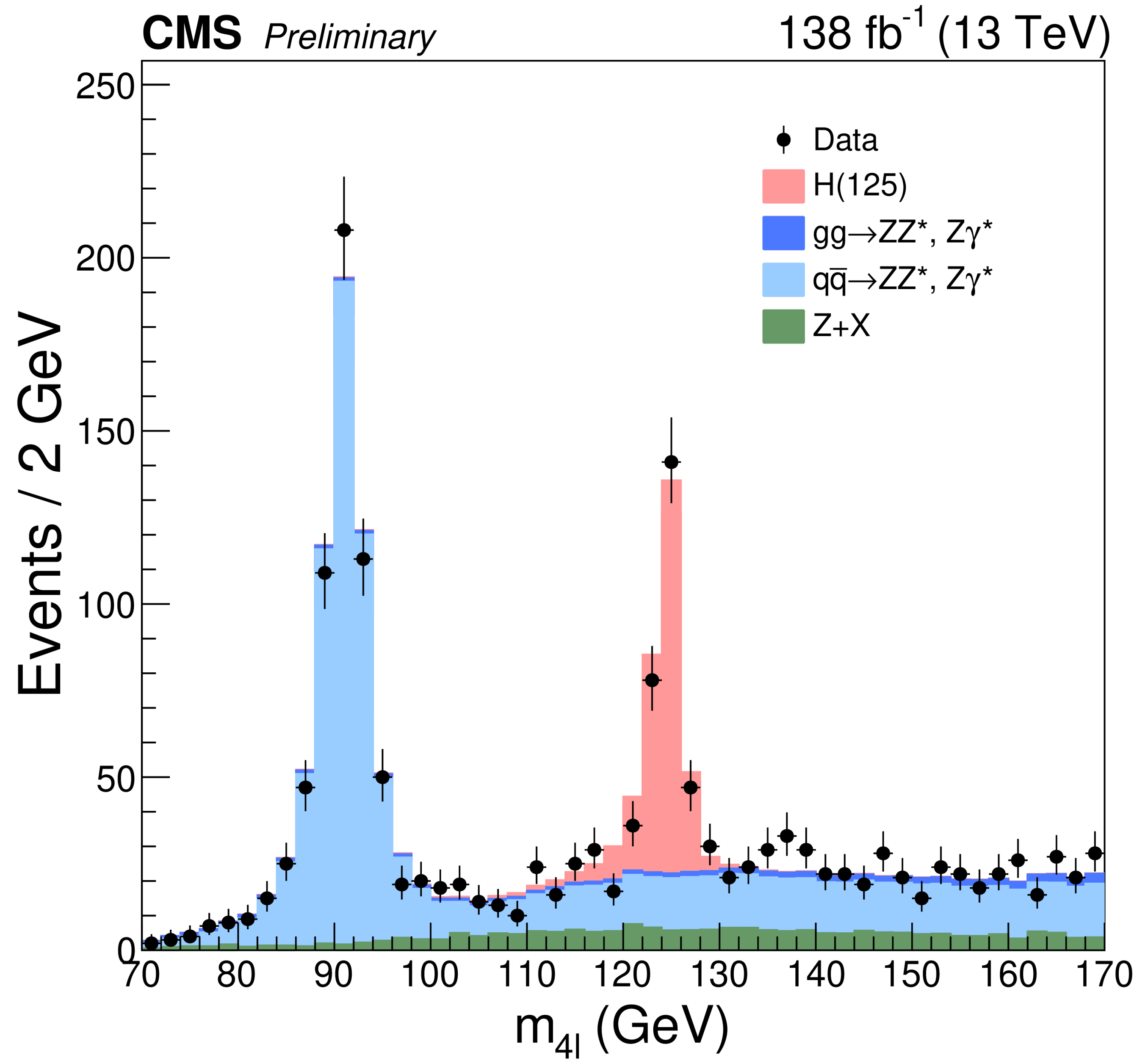
HIG-21-019

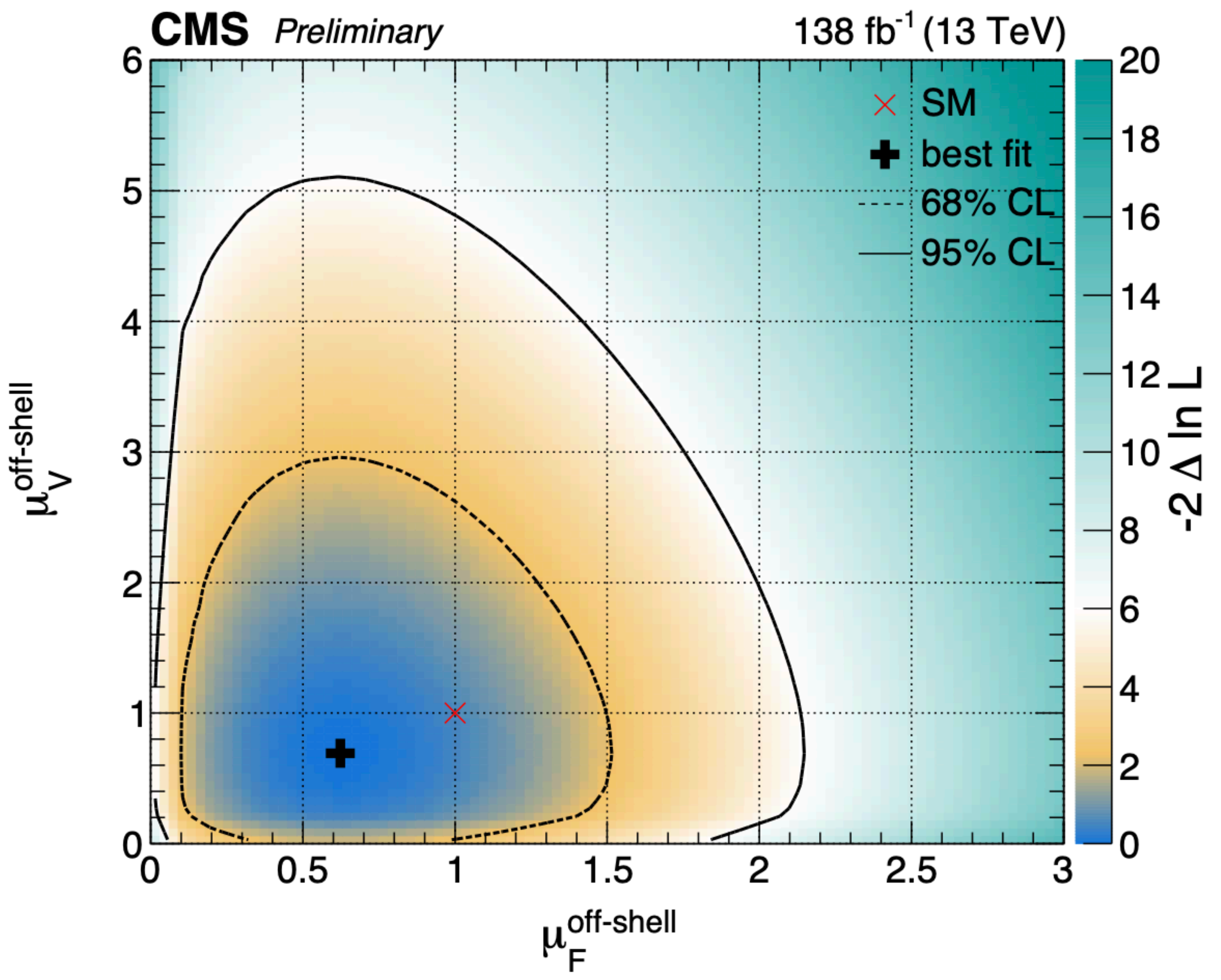
- Very clean channel (4e/2e2μ/4μ) only increasing in power with higher luminosity
  - Dominant uncertainty from lepton momentum scale calibration
    - Improved in this analysis by 3-8% via beamspot constraint on 4 tracks
  - Mass extracted w/categorization by per-event uncertainty (from track unc.)

➡ **Most accurate single mass measurement**

- Γ_H **from on-shell to off-shell production ratio** (assume same couplings)

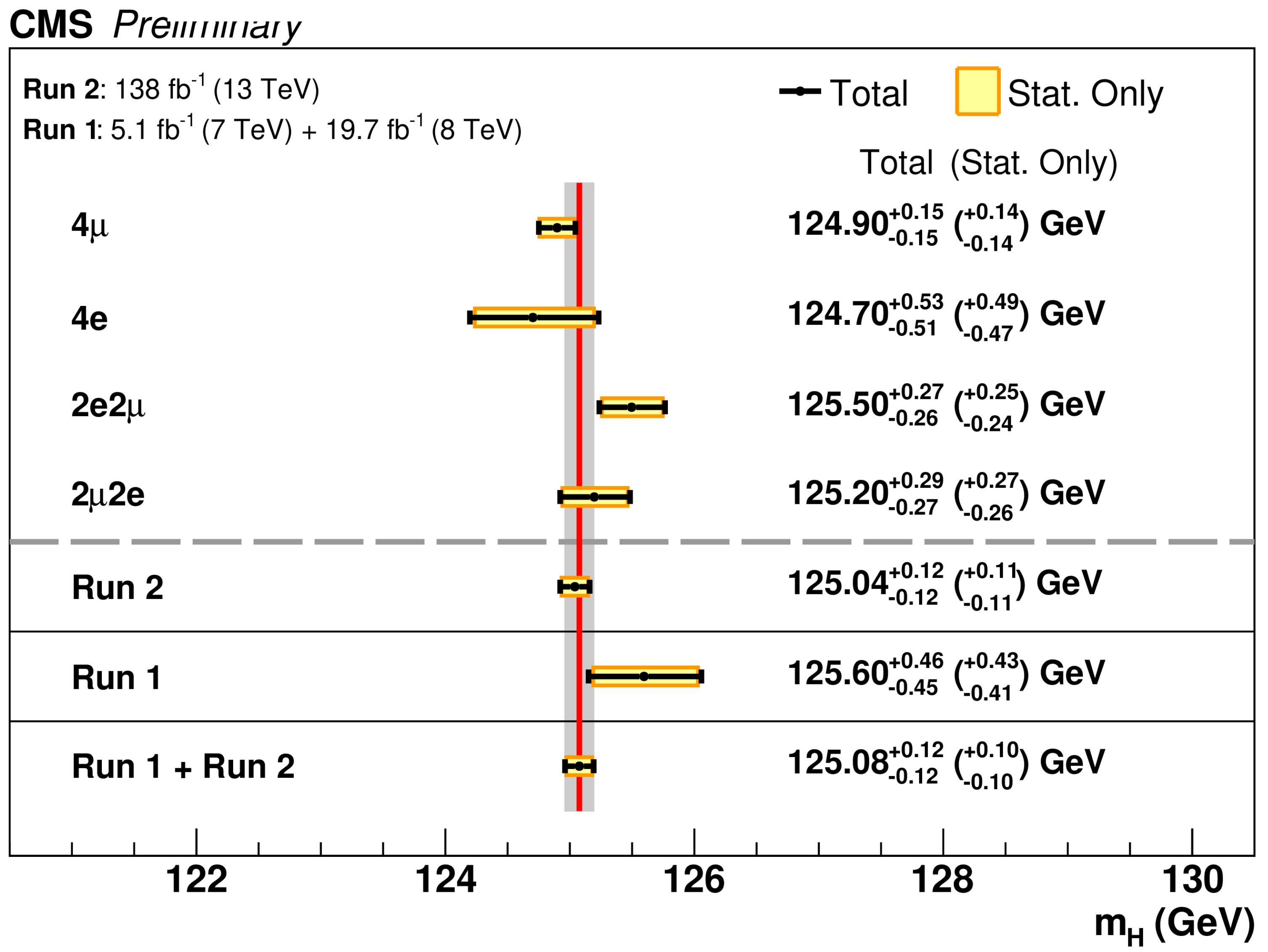
$$\mu_{\mathrm{on(off)}} = \frac{\sigma(i \to H^{(*)} \to f)}{\sigma(i \to H^{(*)} \to f)_{\mathrm{SM}}} \qquad \text{On-shell} \sim \frac{g_i^2 g_f^2}{m_H \Gamma} \qquad \text{Off-shell} \sim \frac{g_i^2 g_f^2}{\hat{s}}$$





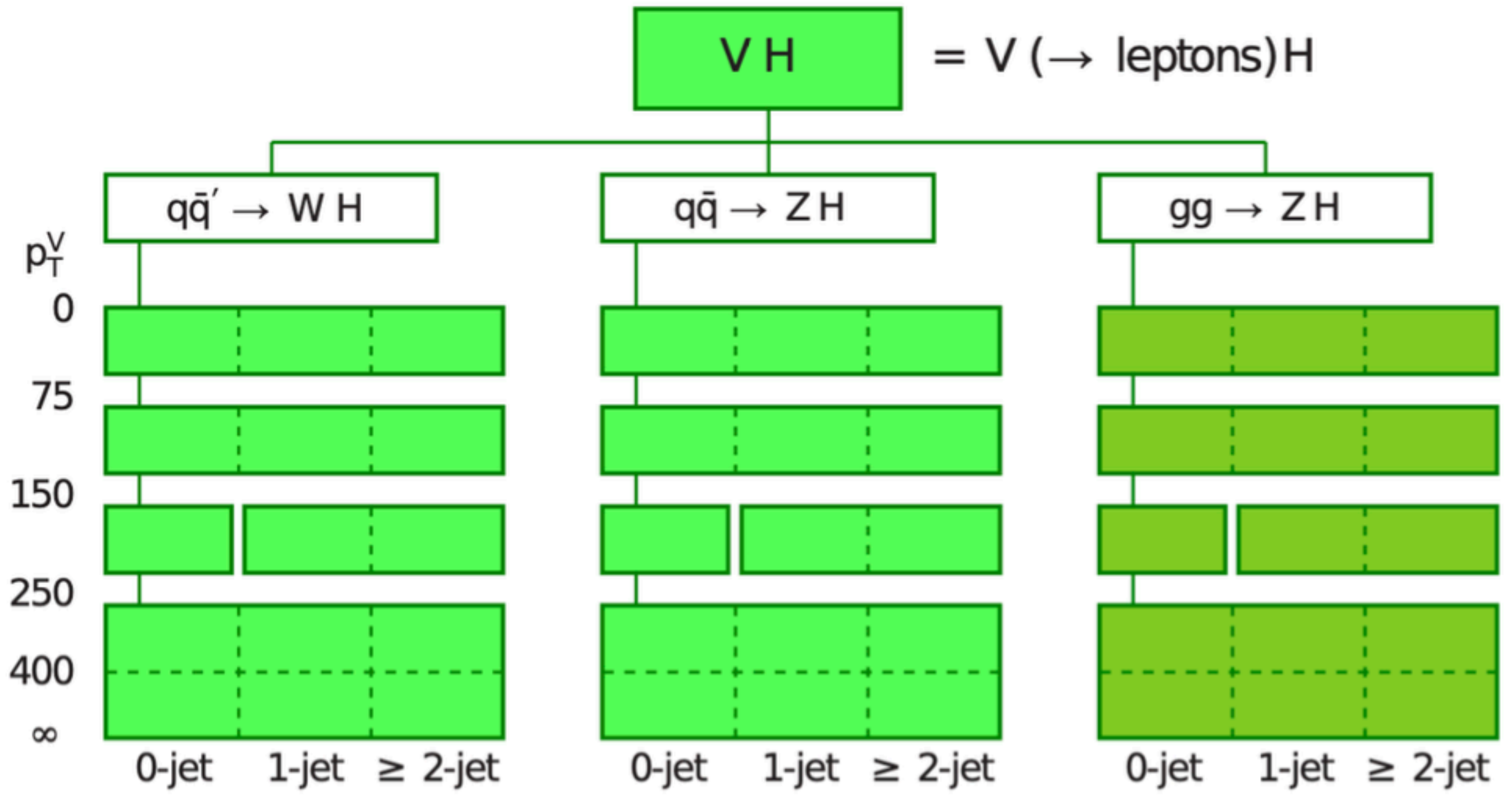
Parameter	Observed	Expected
m_H (GeV)	125.08 ± 0.12	± 0.12
on-shell Γ_H (MeV)	0^{+60}_{-0} $[0, 330]$	0^{+360}_{-0} $[0, 750]$
off-shell Γ_H (MeV)	$2.9^{+2.3}_{-1.7}$ $[0.3, 7.9]$	$4.1^{+4.1}_{-4.0}$ $[0.0, 11.7]$

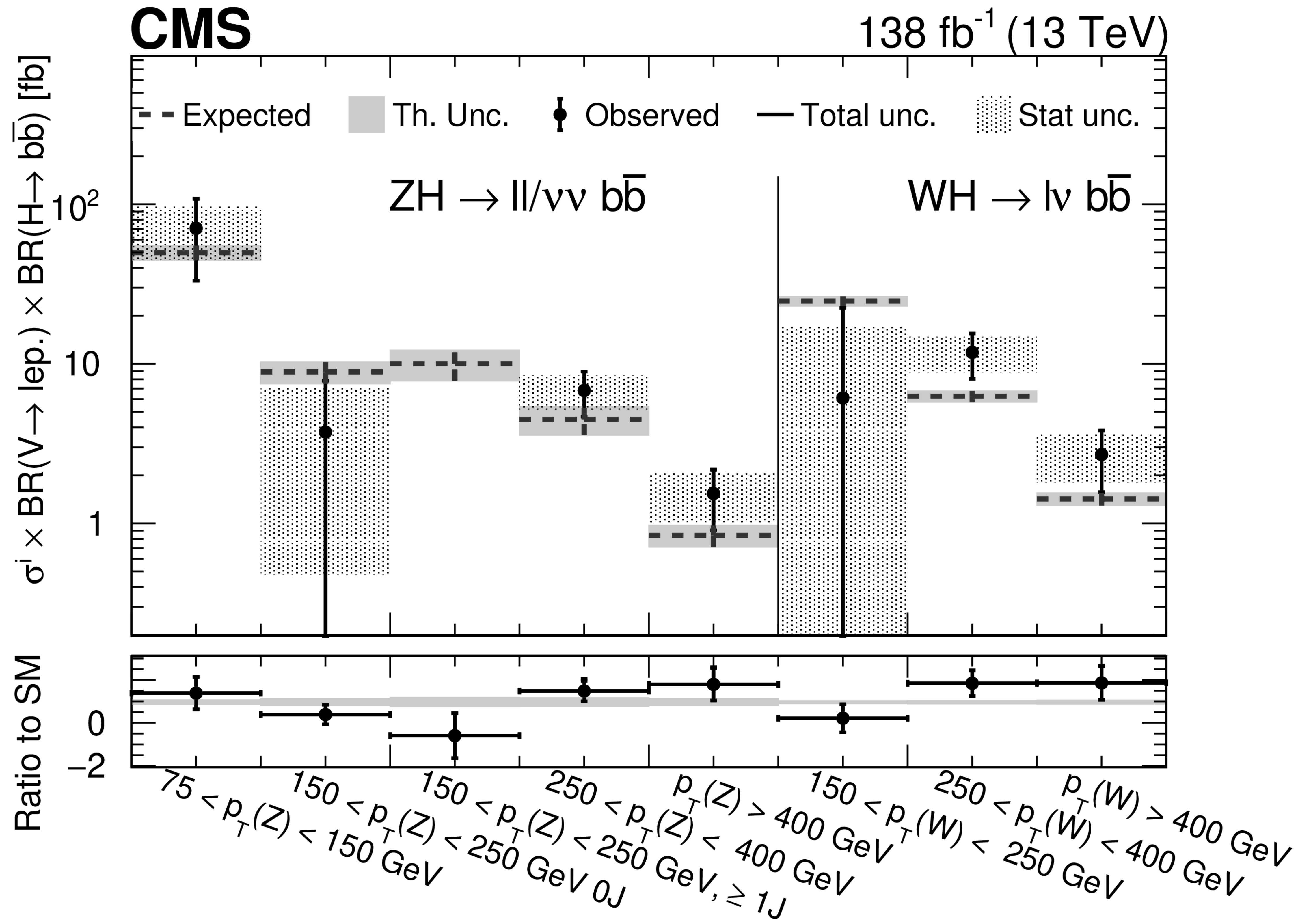
- Modeling of ZZ background dominant unc. in off-shell Γ_H
  - POWHEG+ kNNLO QCD+NLO EW

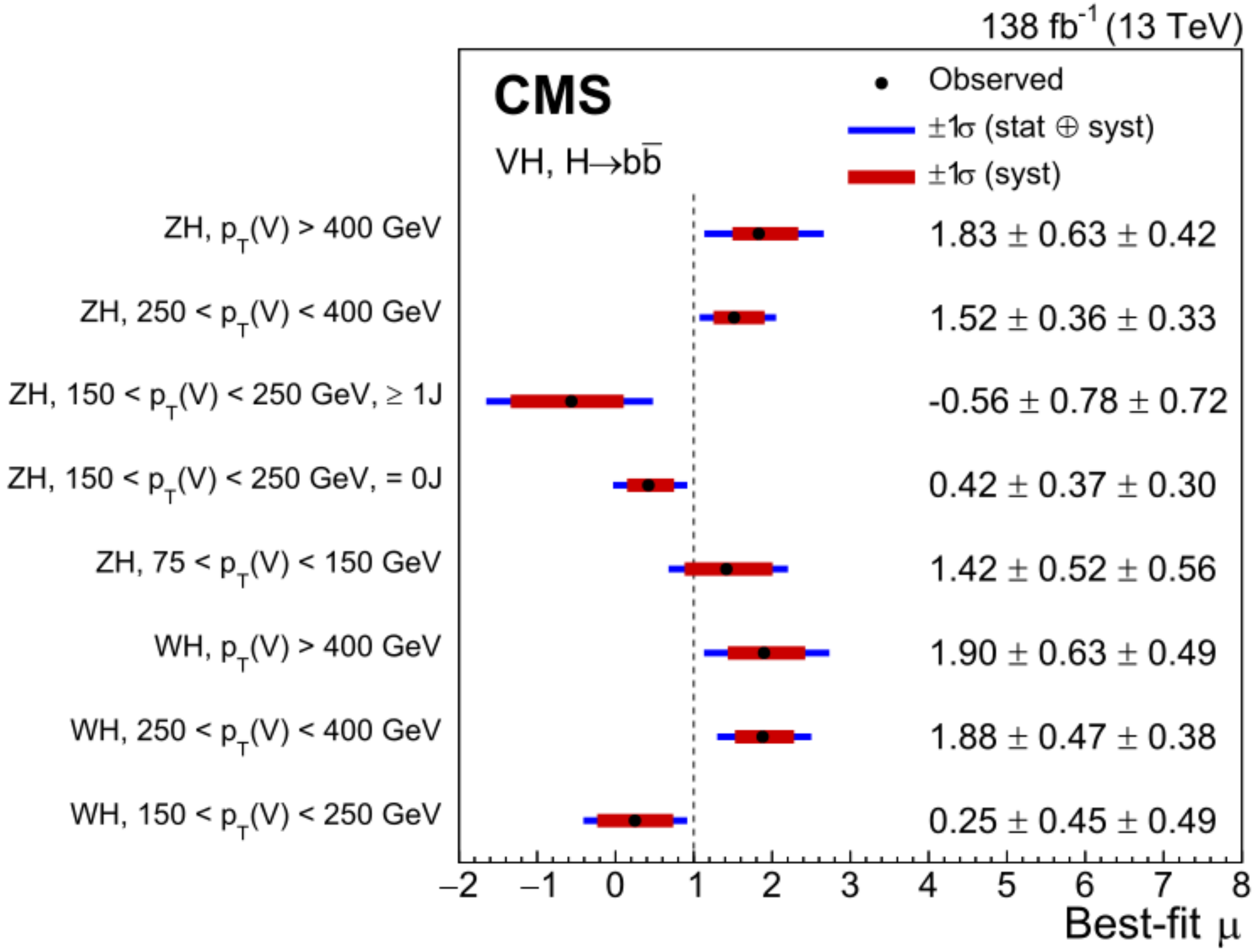


Differential VH(bb) production [arXiv:2312.07562]

- Highly challenging experimentally due to significant V(bb) background
  - Use W/ZV(bb) as standard candle
  - **Extract results in DNN/BDT observables** for sensitivity
- Total production observed at 6.5σ level
  - Differential measurement in course STXS bins

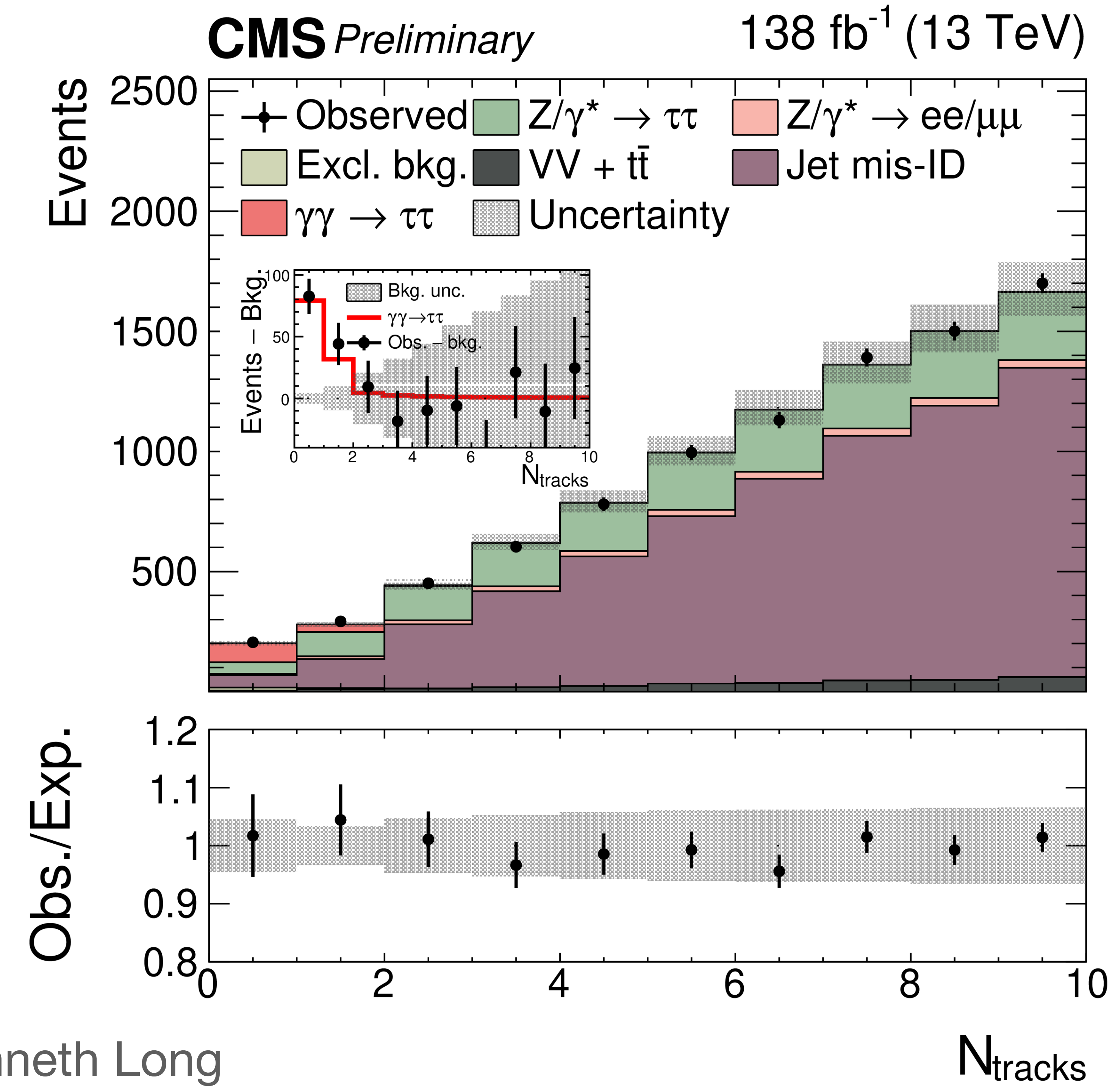


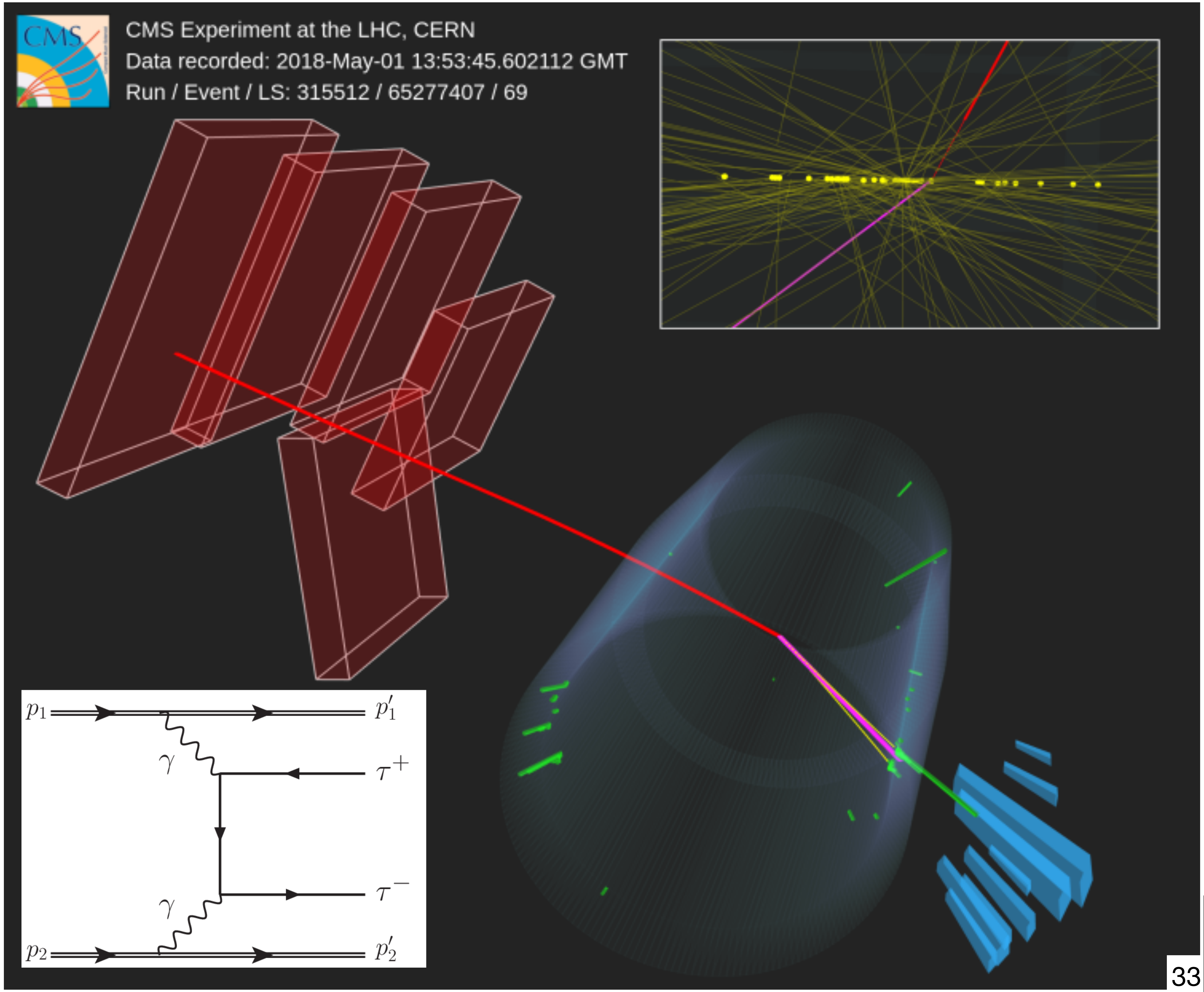




Diffractive γγ → ττ production [SMP-23-005]

- LHC as a photon collider
  - Previously observed in PbPb collisions (more radiation)
  - Elastic channel (protons intact)
- Distinct signature
  - ττ and "nothing else" from PV
    - $n_{tracks} = 0$ at primary vertex (PV)





Diffractive γγ → ττ production [SMP-23-005]

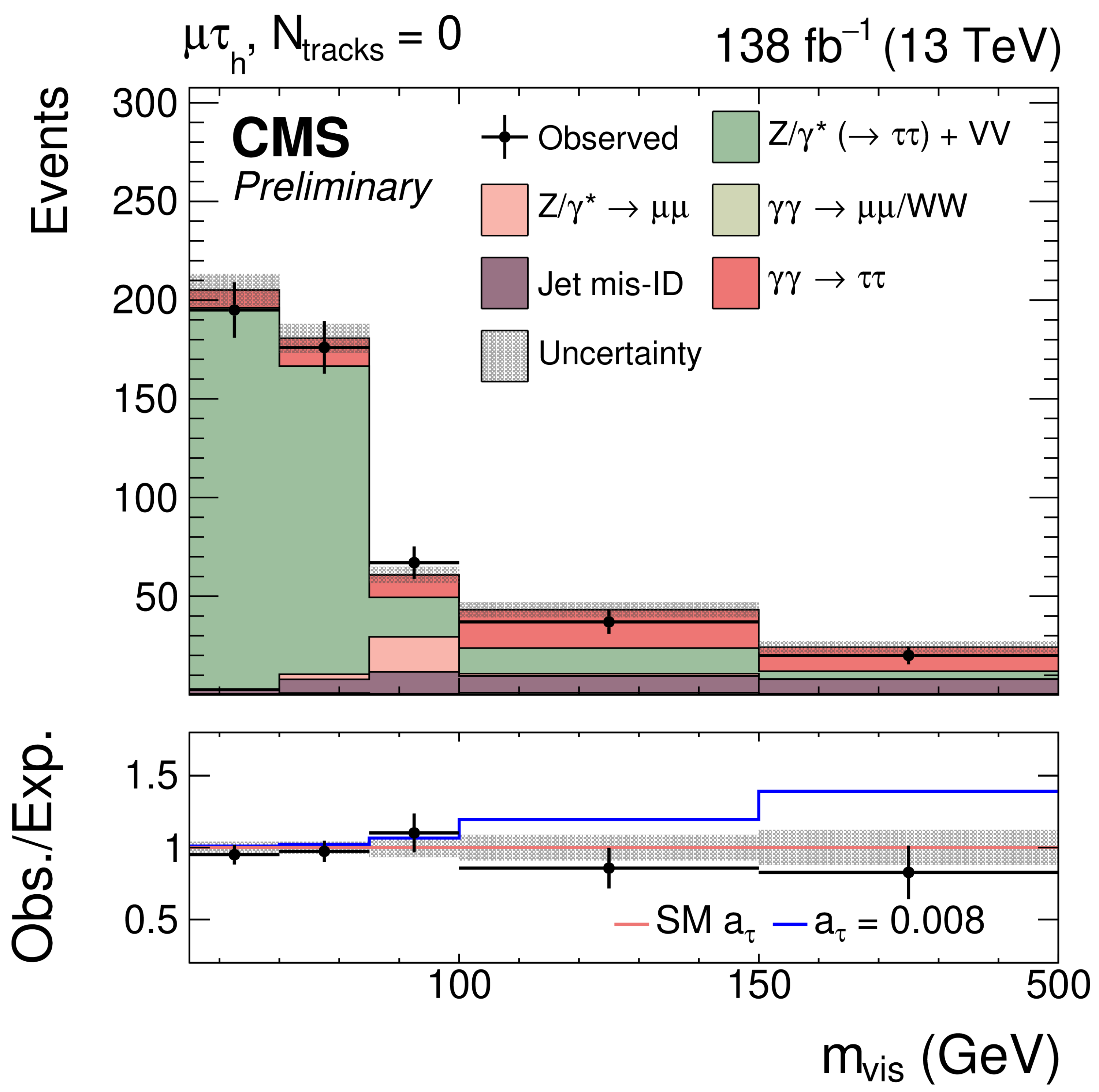
- First observation in pp collisions
  - 5.3σ observed, 6.5σ expected
- **Sensitivity to τ g-2 within a factor of 3 of Schwinger term**

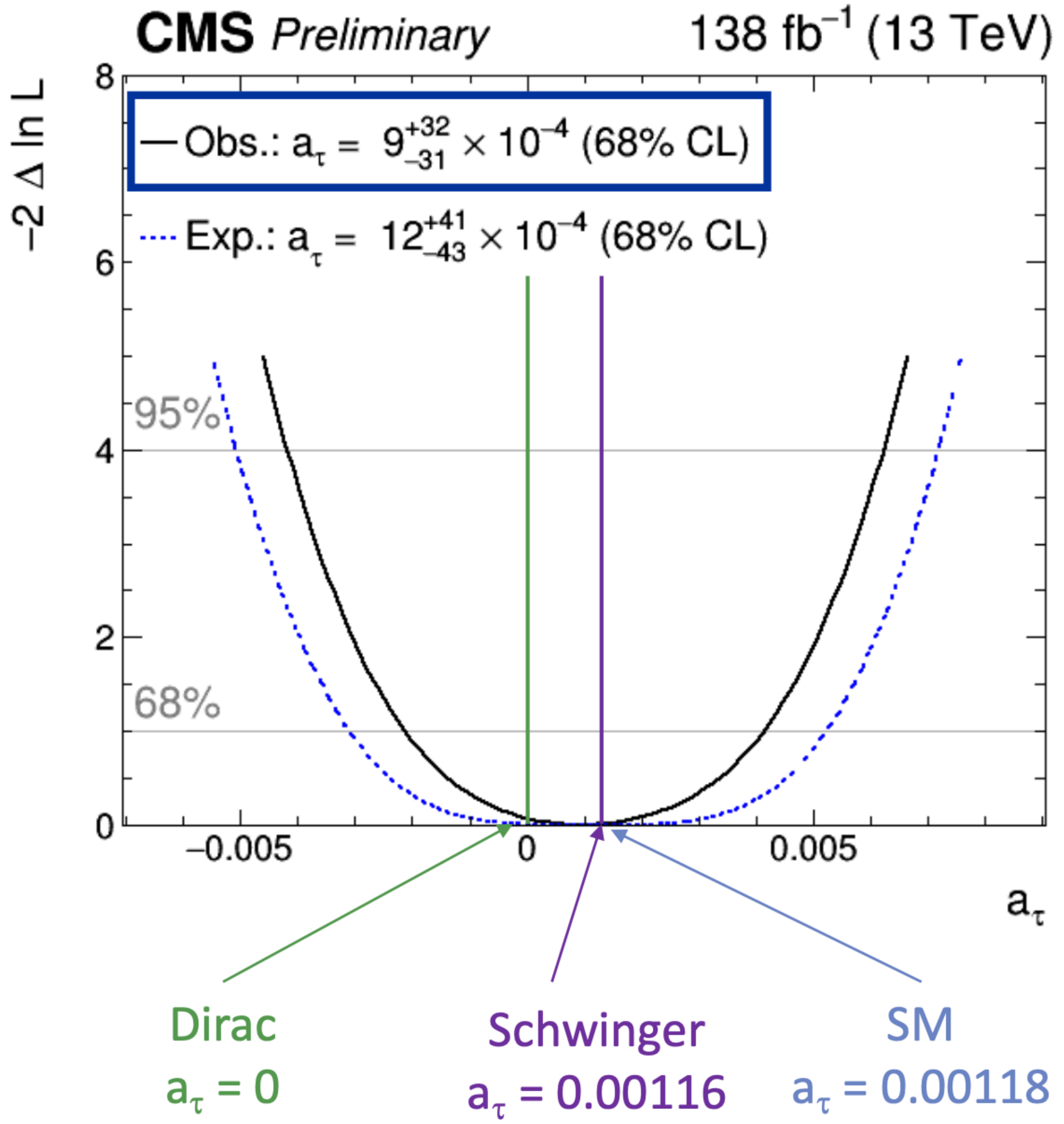
$$\Gamma^{\mu} = \gamma^{\mu} F_1(q^2) + \frac{\sigma^{\mu\nu} q_{\nu}}{2m}\left[iF_2(q^2) + F_3(q^2)\gamma_5\right]$$

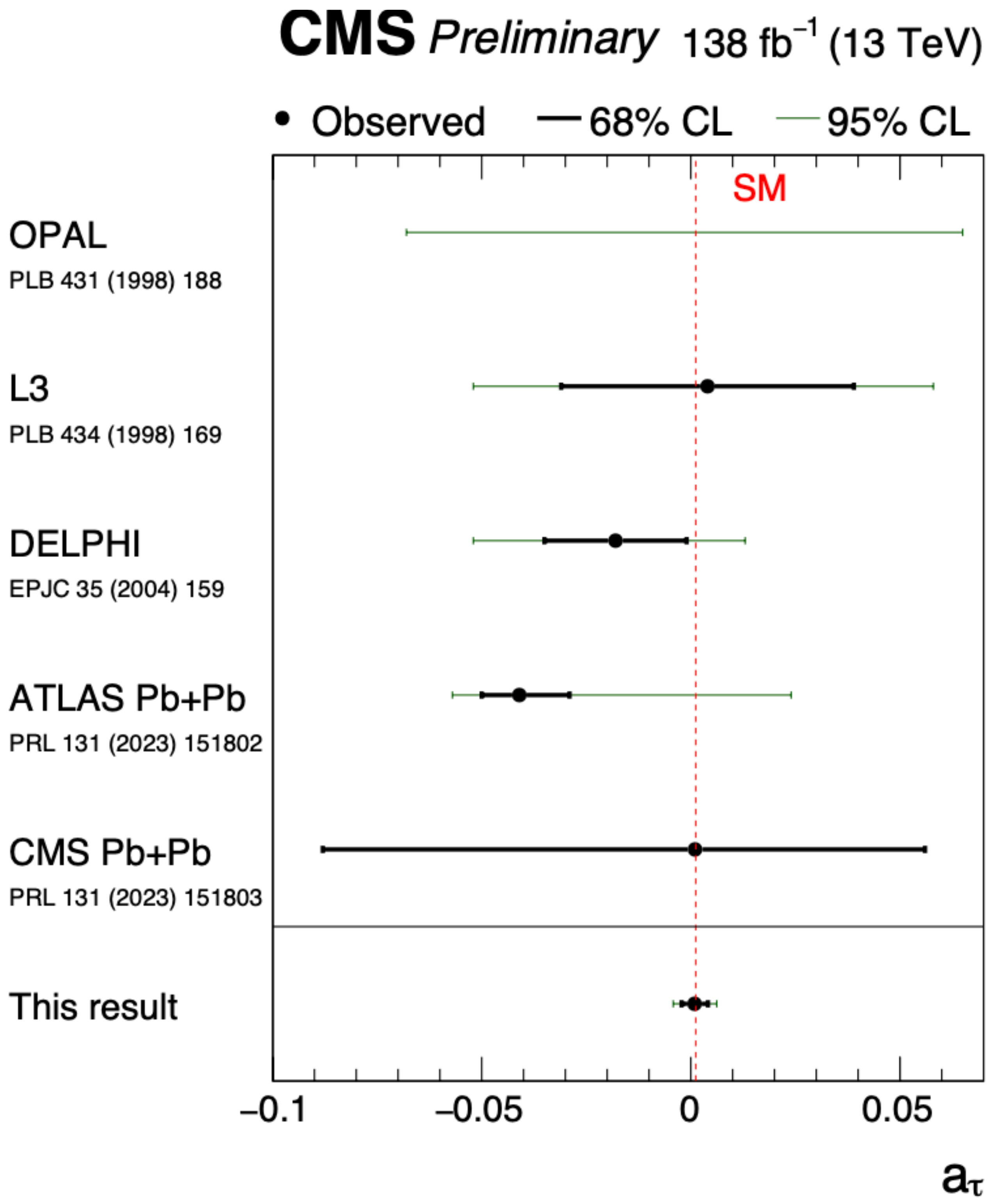
$$F_2(0) = a_{\ell} \equiv (g_{\ell} - 2)/2$$

$$a_{\ell} = \frac{\alpha}{2\pi} \simeq 0.00116$$

- 1-loop contribution ("Schwinger term")







Summary and conclusions

- The LHC and its experiments have **proven to be precision tools**, competitive with measurements of fundamental parameters at purpose-designed colliders such as LEP and SLC

➡Thanks to years of collecting very high quality data, developing understanding of detector, and **incredible performance of theoretical tools**

- The Run II (and Run I) data has proven rich environment for precise measurements. Run III and special runs are also providing new avenues of exploration

- Techniques built for precision physics become **increasingly relevant with huge data sets**, especially towards HL-LHC