Top physics in ATLAS and CMS

Hugo Alberto Becerril Gonzalez
on behalf of the ATLAS and CMS collaborations

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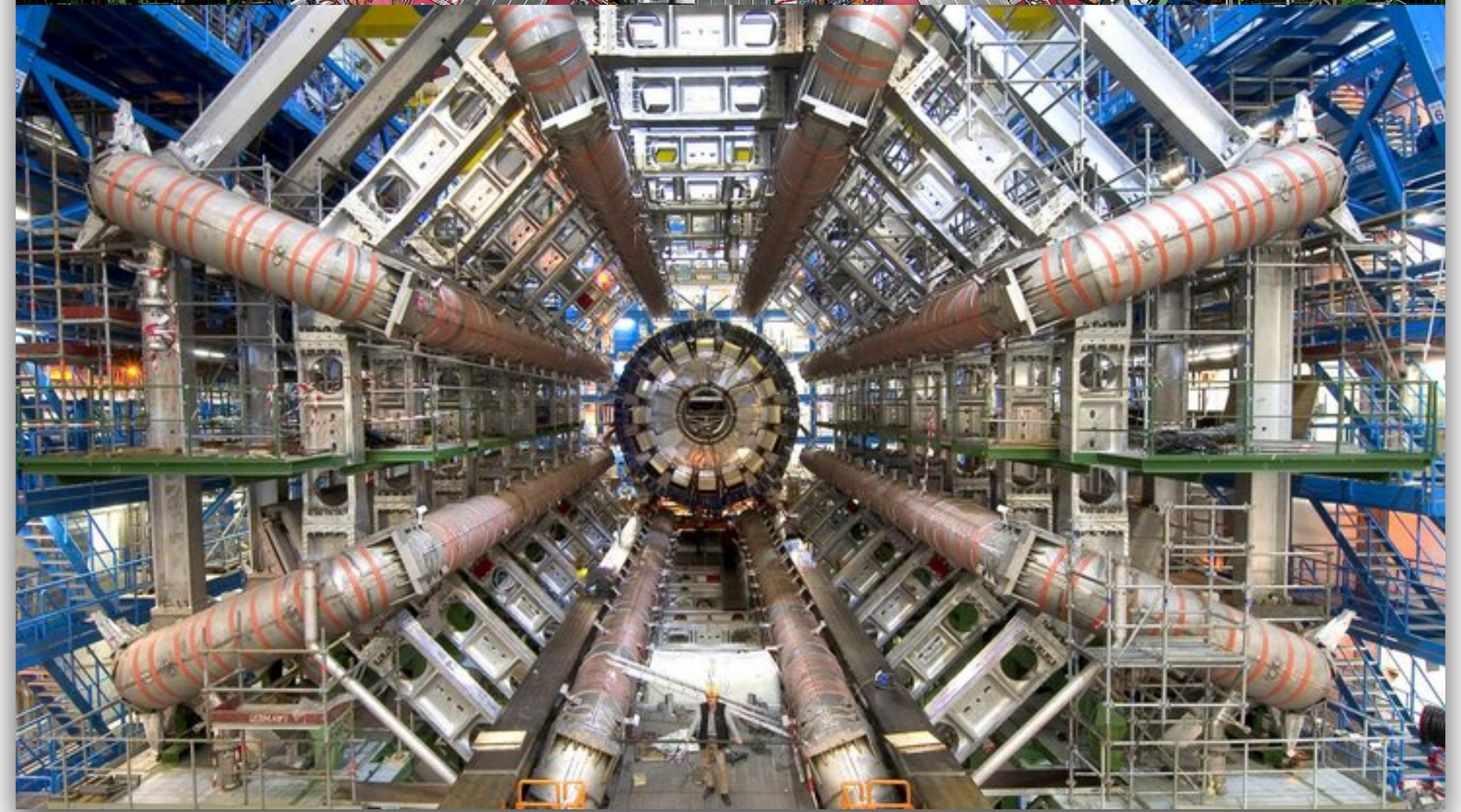
LHC Days 30 September - 4 October
Hvar, Croatia



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The top quark, a very unique particle

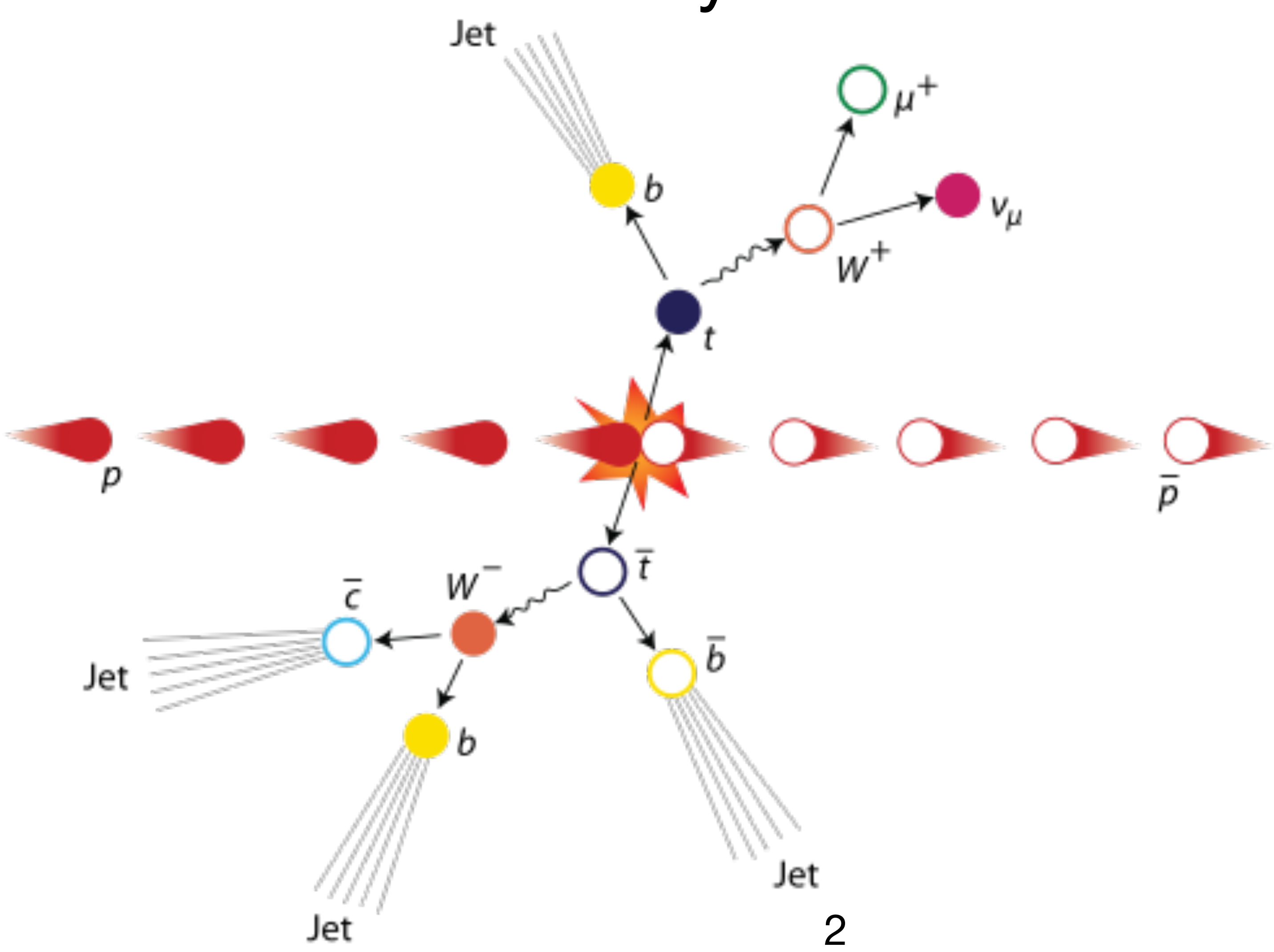
- **The heaviest elementary particle**

$y_t \sim 1, m_{Top} = 172.52 \pm 0.33$ GeV

  - Quantum loop effects
  - Influence on electroweak vacuum stability

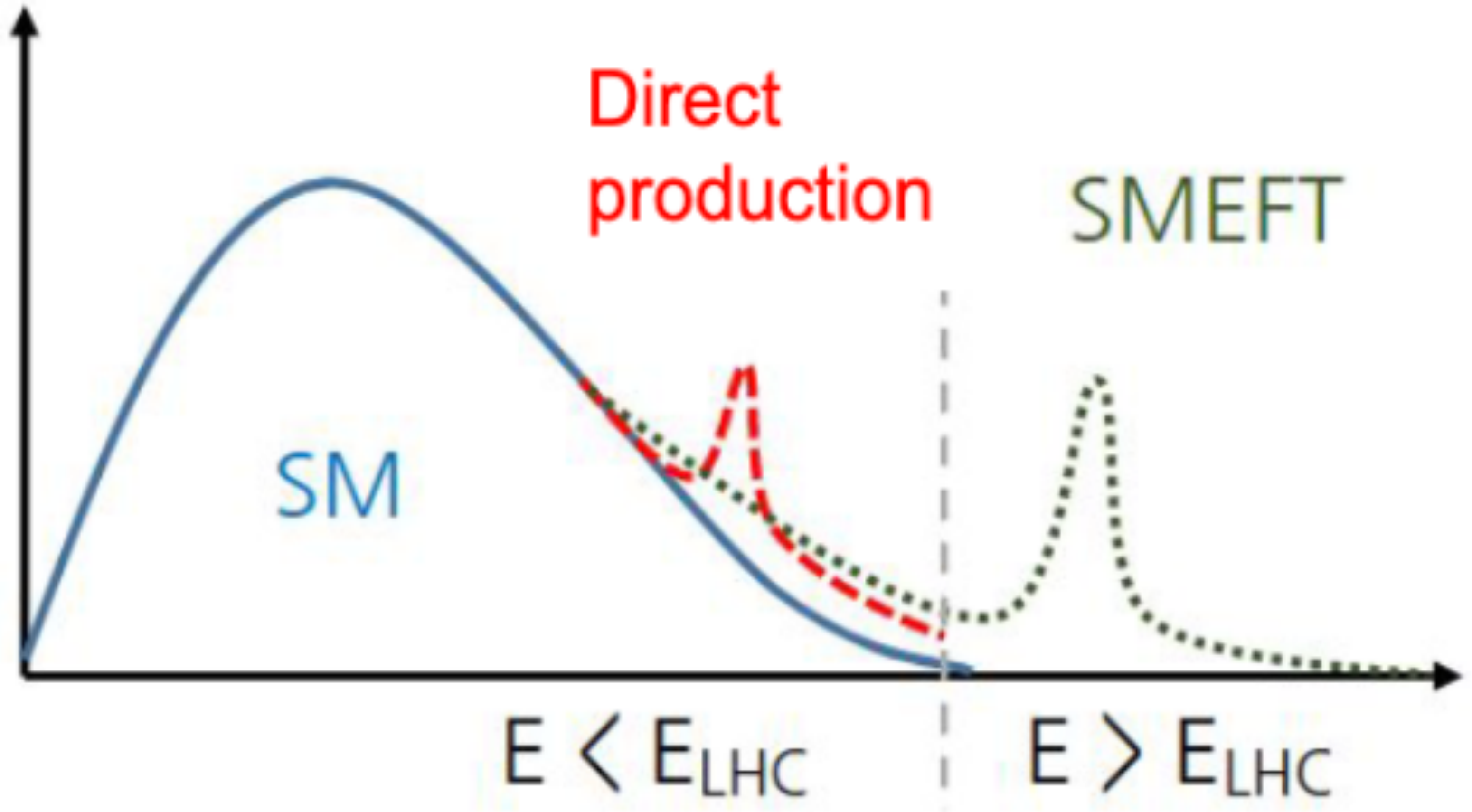
- **Top decays before hadronization**

  - Lifetime of ~5 * 10-25 seconds. This allows the study of bare quark properties



- **Potential portal to New Physics**

Production and decay are influenced by anomalous couplings, charged lepton flavor violation (cLFV), baryon number violation (BNV), lepton flavor universality (LFU), CP violation, flavor-changing neutral currents (FCNC), charge asymmetry, spin correlations, and more.



LHC has provided ~200 M top quarks pairs to ATLAS and CMS

=> 300 papers

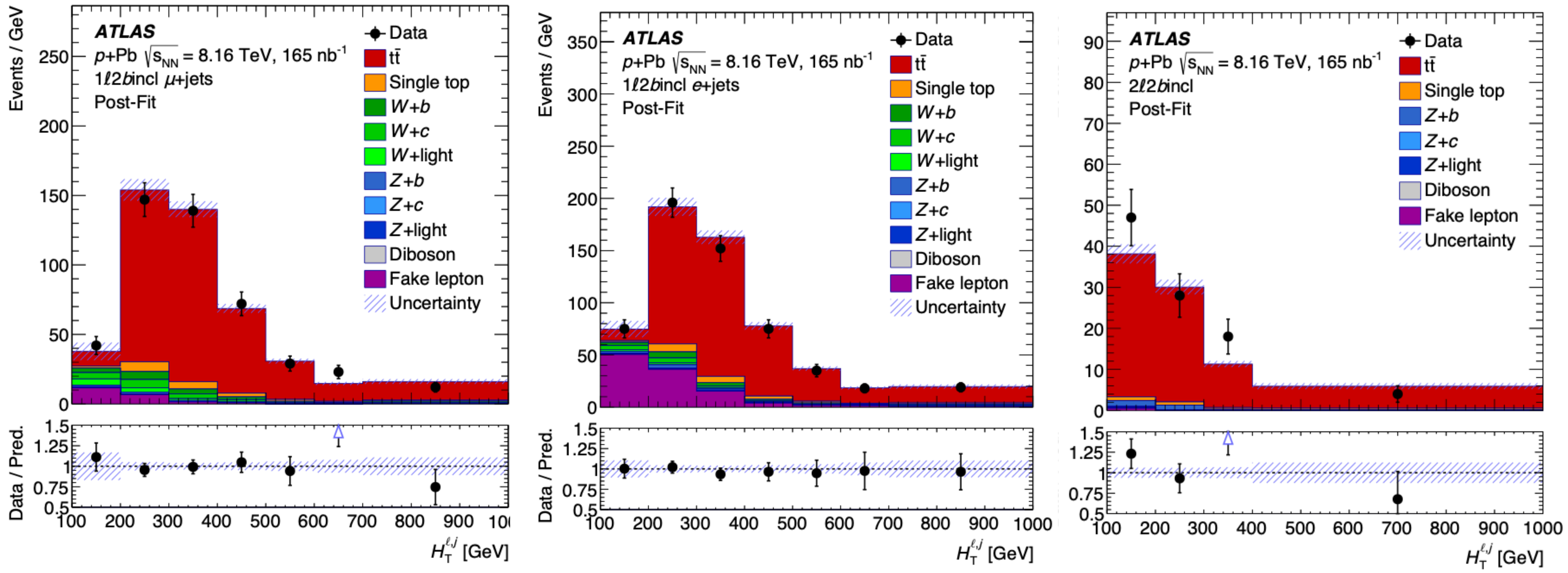
CMS HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN DESY. ATLAS EXPERIMENT

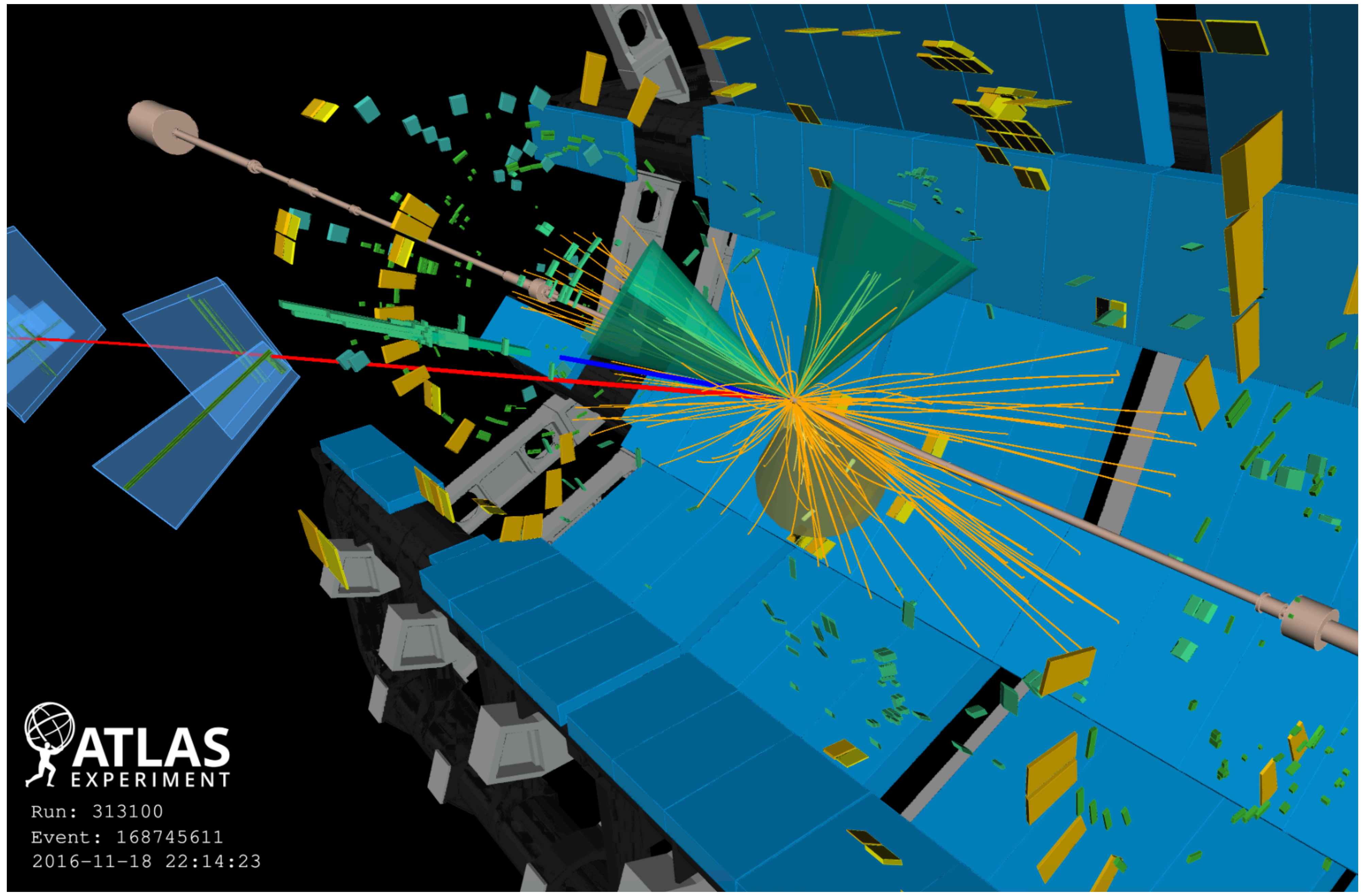
Top quark pair production at the LHC p+Pb

2405.05078

8.16 TeV pp

- In p+Pb collisions t quarks provide novel probes of nPDF
- Provide precise information on the nuclear gluon distribution function at high Bjorken-x region
- Measurement performed using 165 nb^{-1} combining the l + jets and dileptonic channel



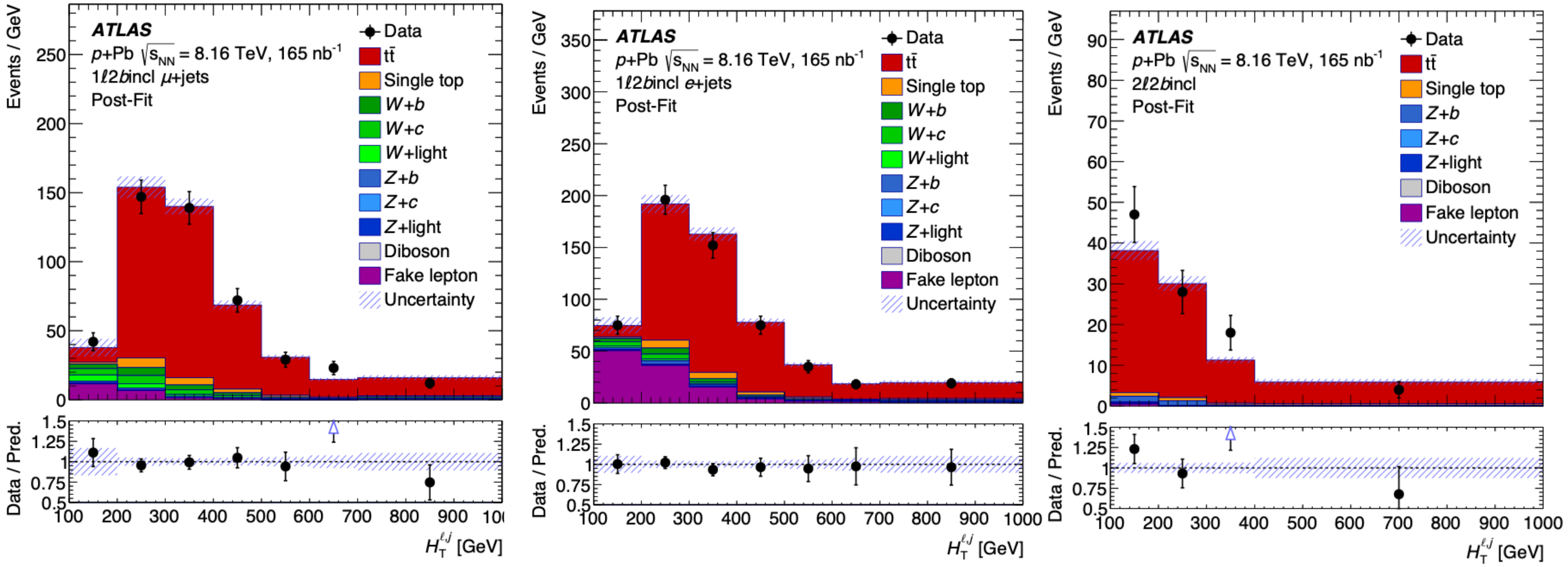


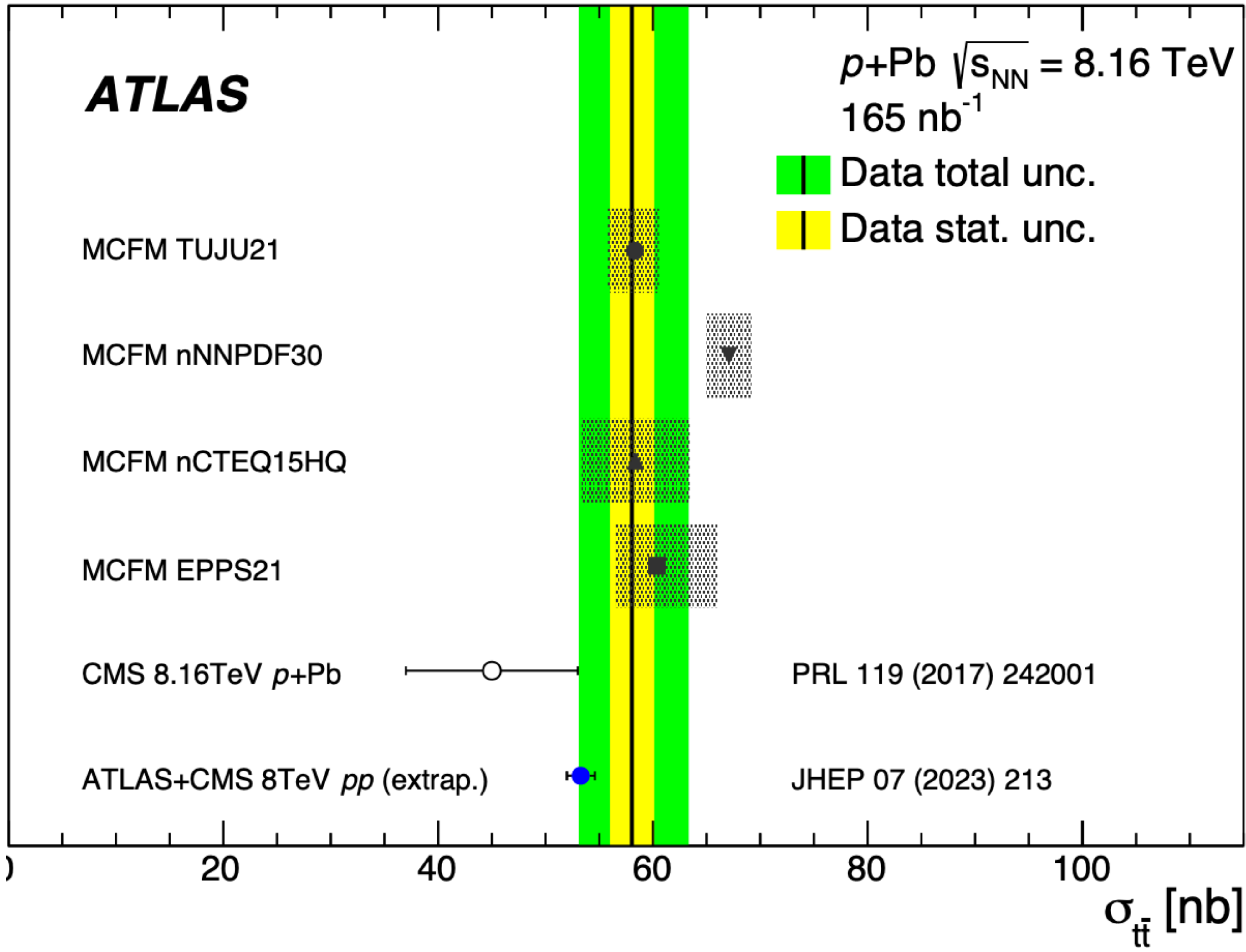
Top quark pair production at the LHC p+Pb

2405.05078

8.16 TeV pp

- Observed significance > 5 SD
- $\sigma = 58.1 \pm 2\,(stat.)^{+4.8}_{-4.4}\,(syst.)\,nb$
- Total uncertainty ~ 9%
    - Dominated by jet related uncertainties ($^{+4.6}_{-.41}$)





CMS DESY. HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

ATLAS EXPERIMENT

Top quark pair production at the LHC (13.6TeV)

JHEP 08 (2023) 204

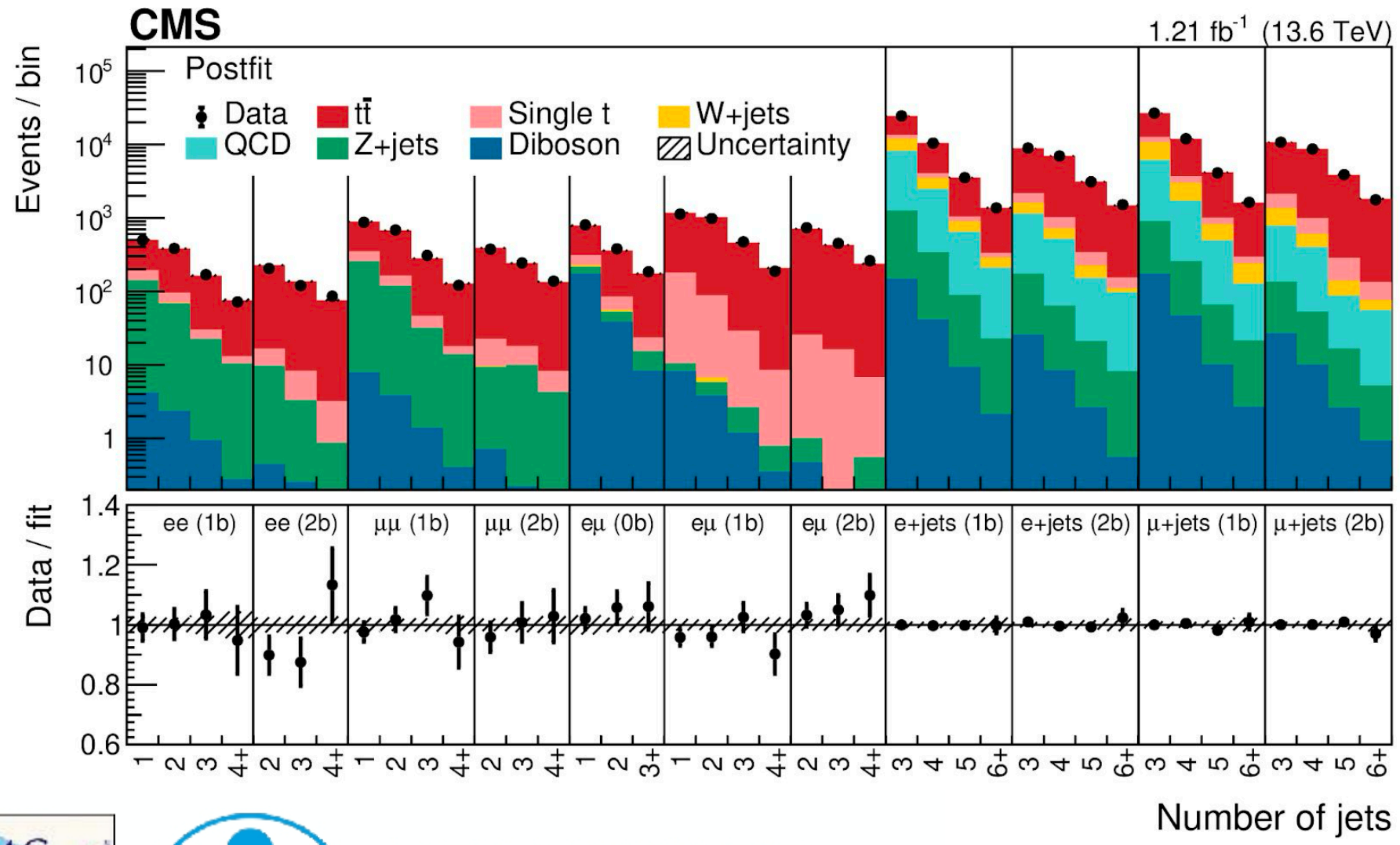
First measurement with 13.6 TeV data at the LHC

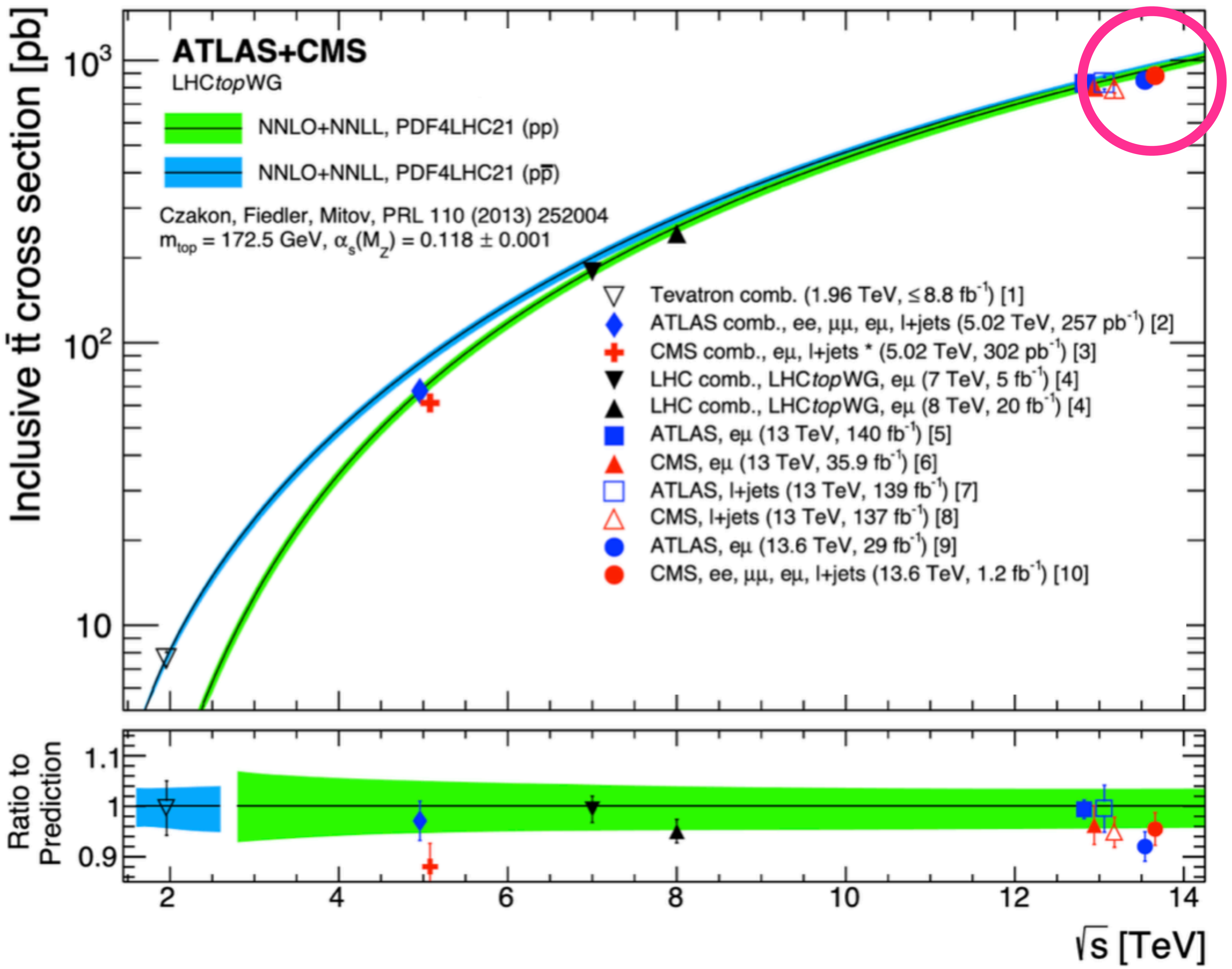
Dilepton and l+jets:

Fit to Njet and Nbjet bins

Leading syst. Uncertainties:

- Lepton efficiency: 1.6%
- b-tagging efficiency: 1.1%
- tW background: 0.7%





σ_{tt} = 881 ± 23 (stat+syst) ± 20 (lumi) pb (~3.5%)

σ_{theory} = 924 +32 (scale+PDF) pb (NNLO+NNLL)

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Top quark pair production at the LHC (13.6TeV)

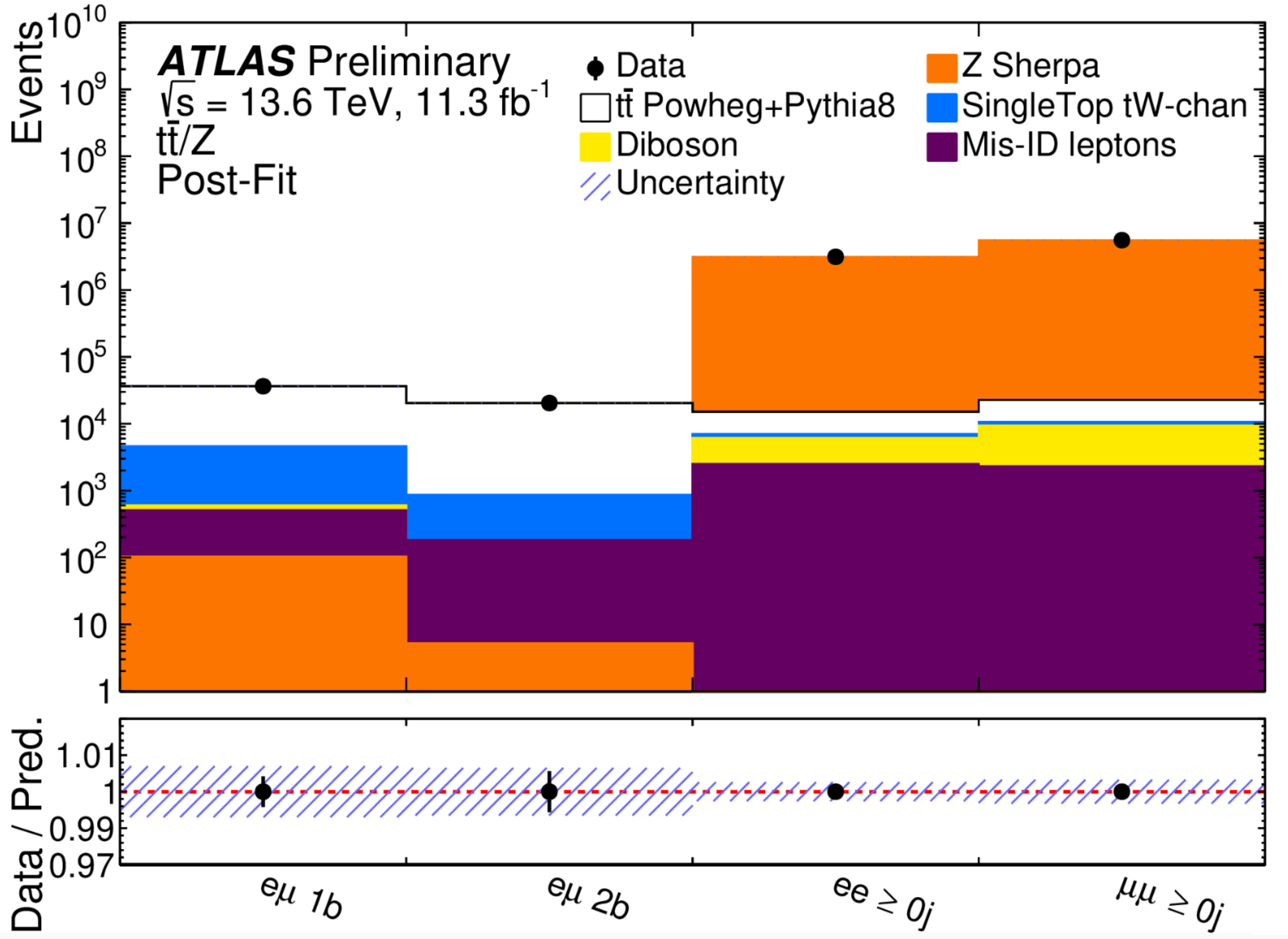
Phys. Let. B 848 (2024) 138376

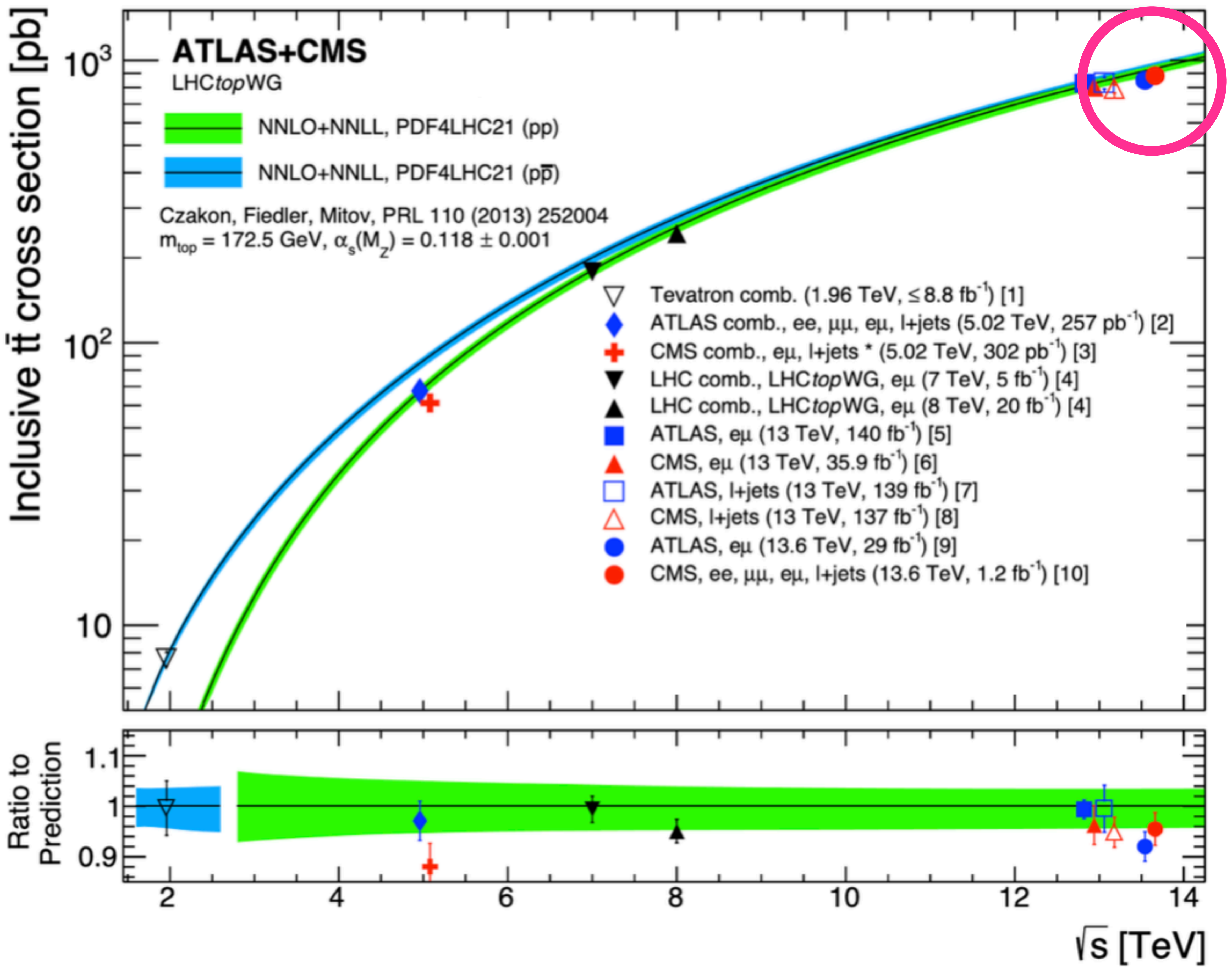
Combined measurement of tt (eμ) and Z (ee+μμ)

Fit to b jet multiplicity bins

Leading syst. Uncertainties:

- Luminosity 2.3% (externalized)
- Muon reco. 1.5%
- tt PS 1.1%
- PU 1.1%





σ_{tt} = 859 ± 4 (stat) ± 22 (syst) ± 19 (lumi) pb (~3.5%)

σ_{theory} = 924 +32 (scale+PDF) pb (NNLO+NNLL)

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Single top production at the LHC

2409.06444
2407.15594

First measurement of the tW process at **13. 6 TeV**

Full 2022 dataset with 34.7 fb−1

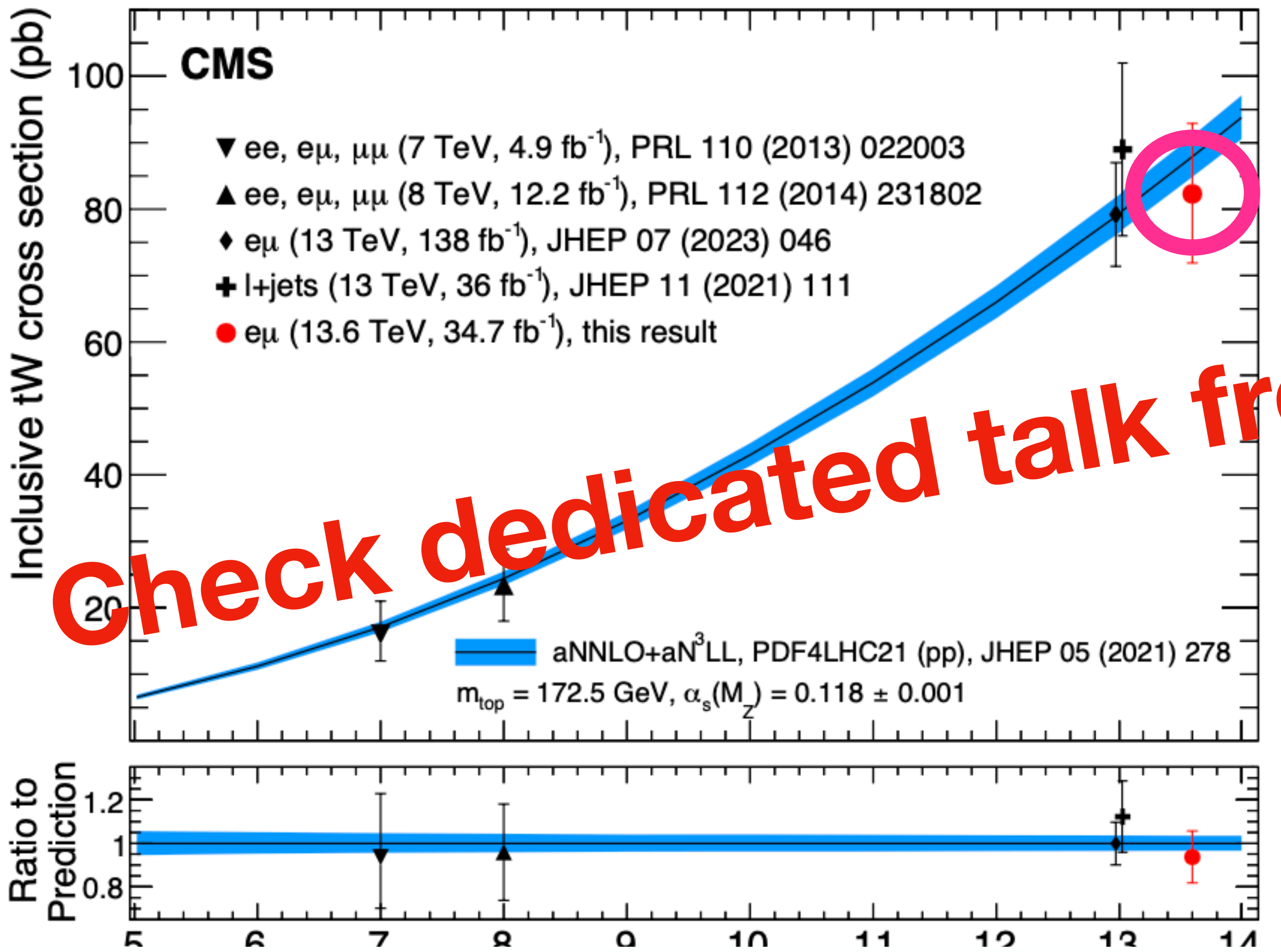
ML learning technics used to
discriminate between tW and tt events

The leading uncertainties are:

- jets energy corrections
- b tagging

σ_{tW}^{SM} **= 87.9$^{+2.0}_{-1.9}$ (scale) ± 2.4 (PDF + αS) pb** (aN^{3}LO)

$$\sigma_{tW}^{obs} = 84.1 \pm 2.1\,(\text{stat})\,^{+9.8}_{-10.2}\,(\text{syst}) \pm 3.3\,(\text{lum})\,\text{pb}$$



Check dedicated talk from Javier

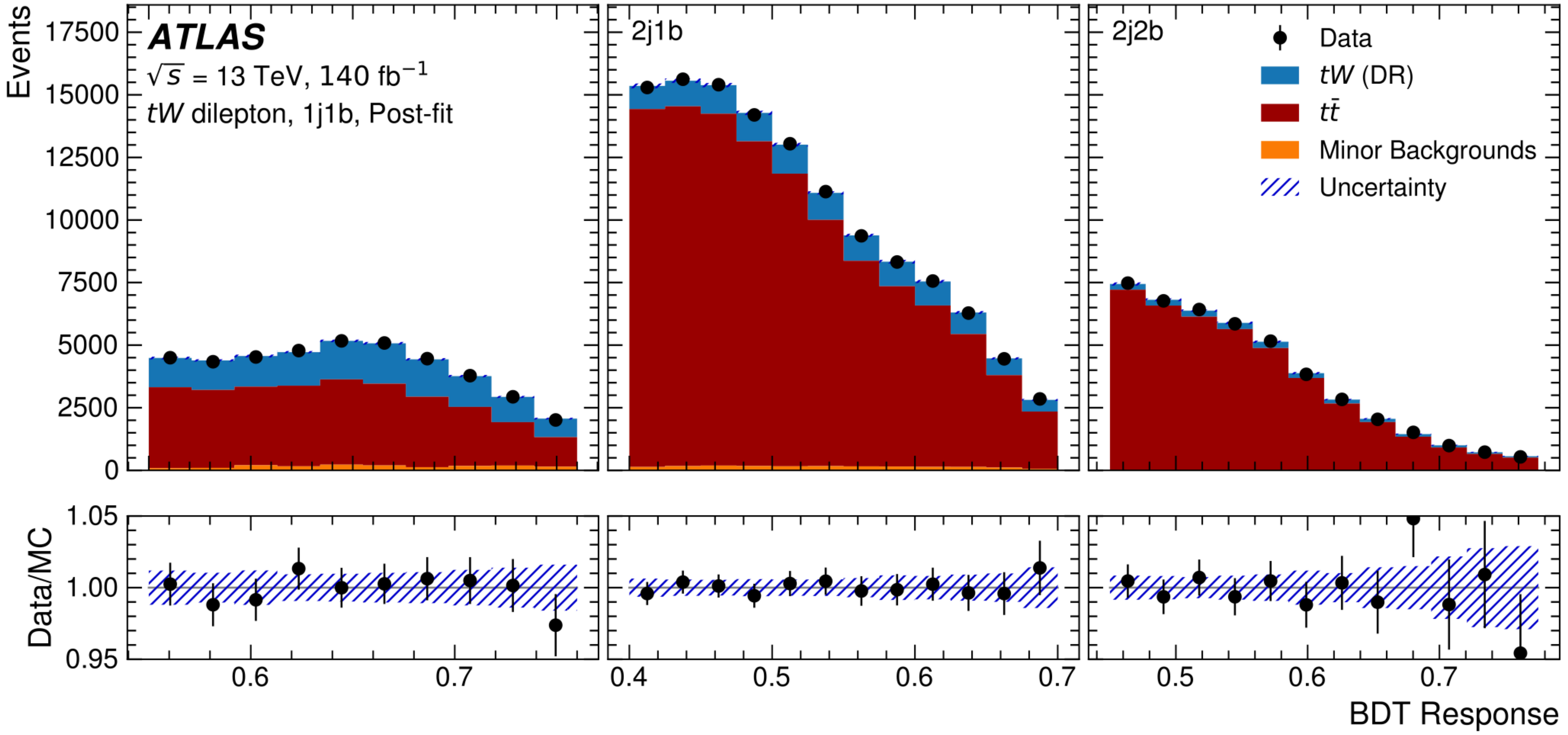
Final states with two oppositely charged leptons ($e\pm\,\mu\mp$ events)

BDTs are used to separate the signal from the dominant tt background.

$$\sigma_{tW} = 75\,^{+15}_{-14}\,\text{pb} = 75 \pm 1\,(\text{stat.})\,^{+15}_{-14}\,(\text{syst.}) \pm 1\,(\text{lumi.})\,\text{pb},$$

In good agreement with the SM prediction: $\sigma_{tW}^{\text{theory}} = 79.3\,^{+1.9}_{-1.8}\,(\text{scale}) \pm 2.2\,(\text{PDF})\,\text{pb}.$

40% more precise than previous measurement from ATLAS



Constraints on $|f_{LV}V_{tb}|$

$$|f_{LV}V_{tb}| = 0.97 \pm 0.10$$

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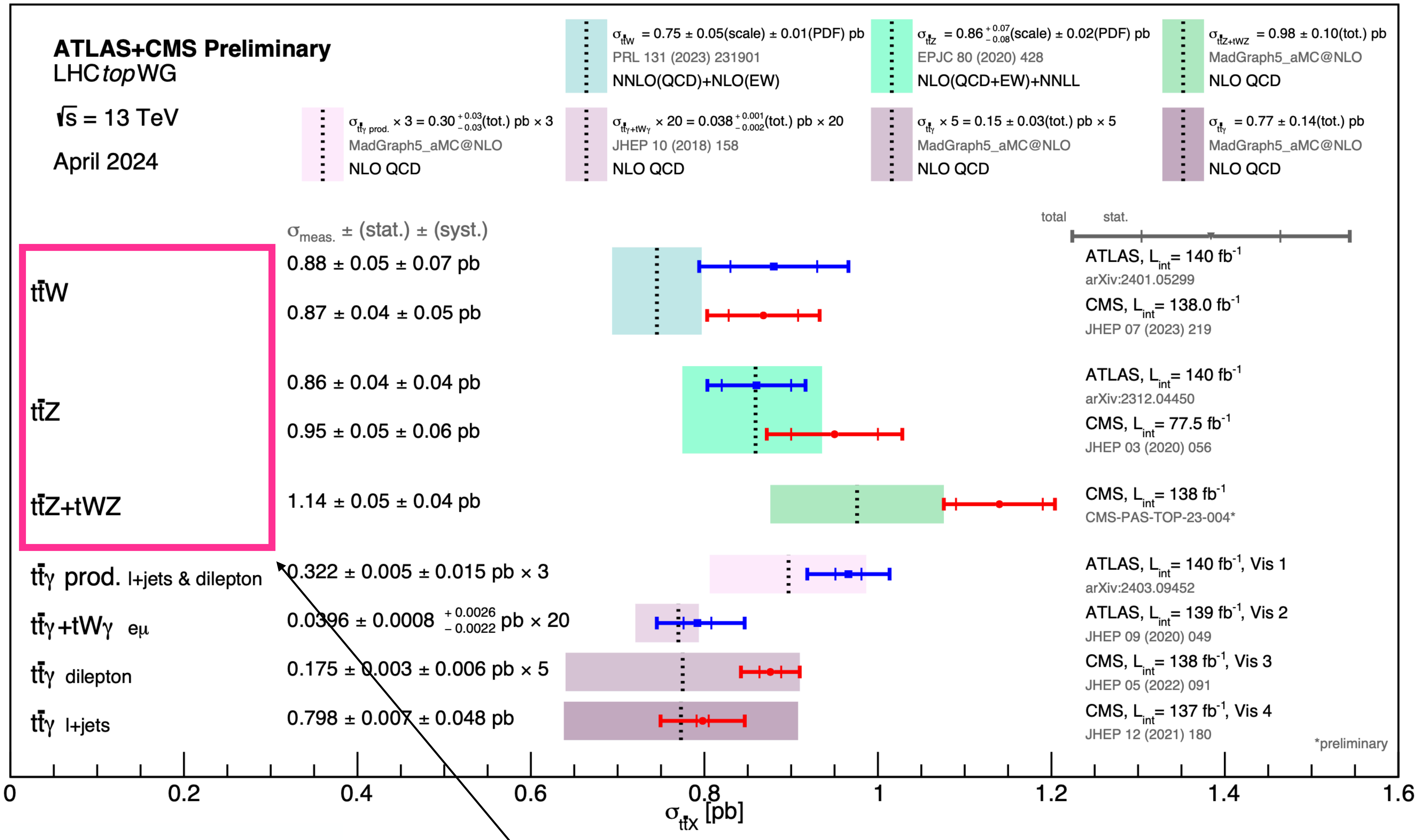
Top quark pair + V production at the LHC



All of them first observed at the LHC

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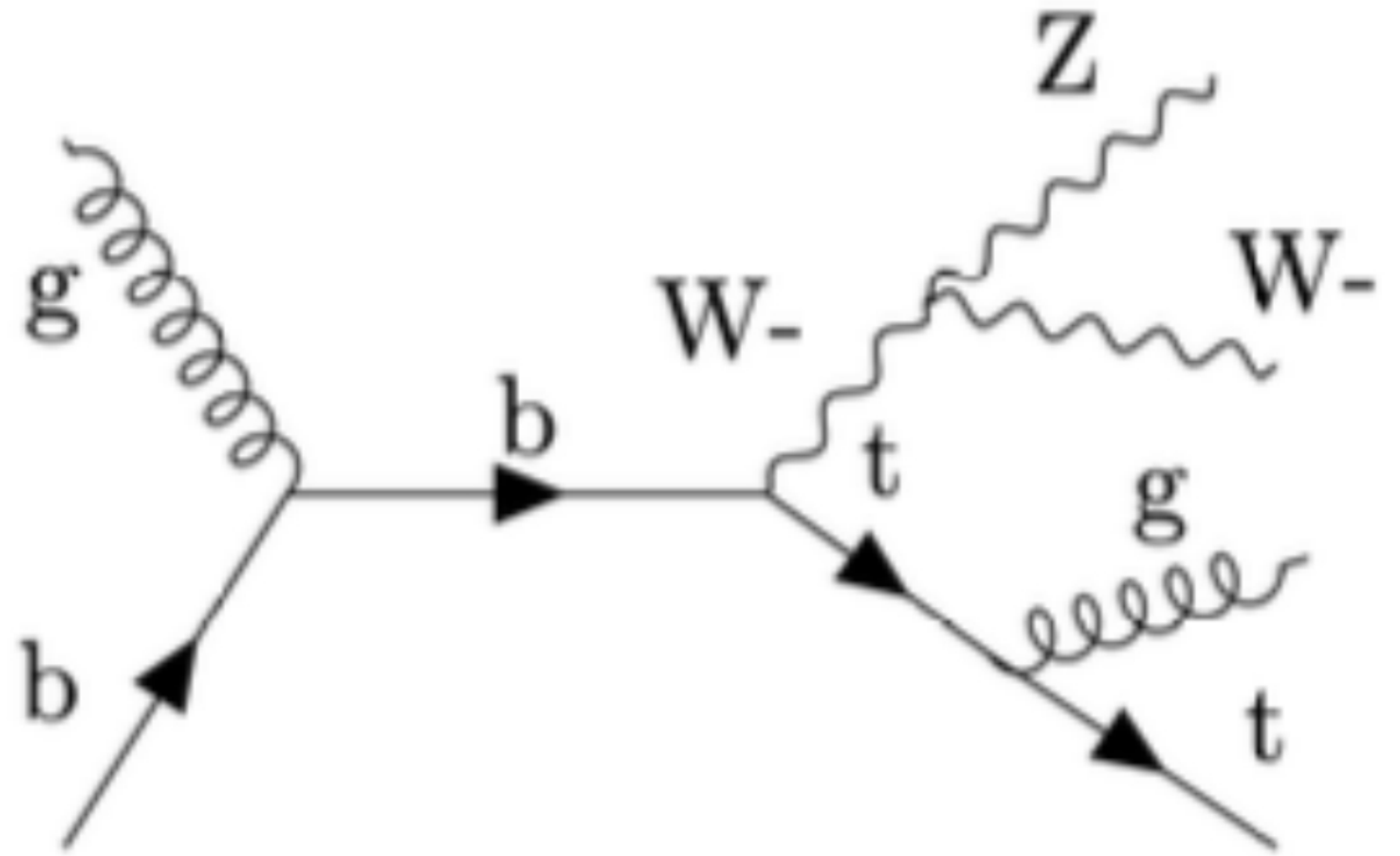
tWZ at the LHC

Phys. Lett. B 855 (2024) 138815

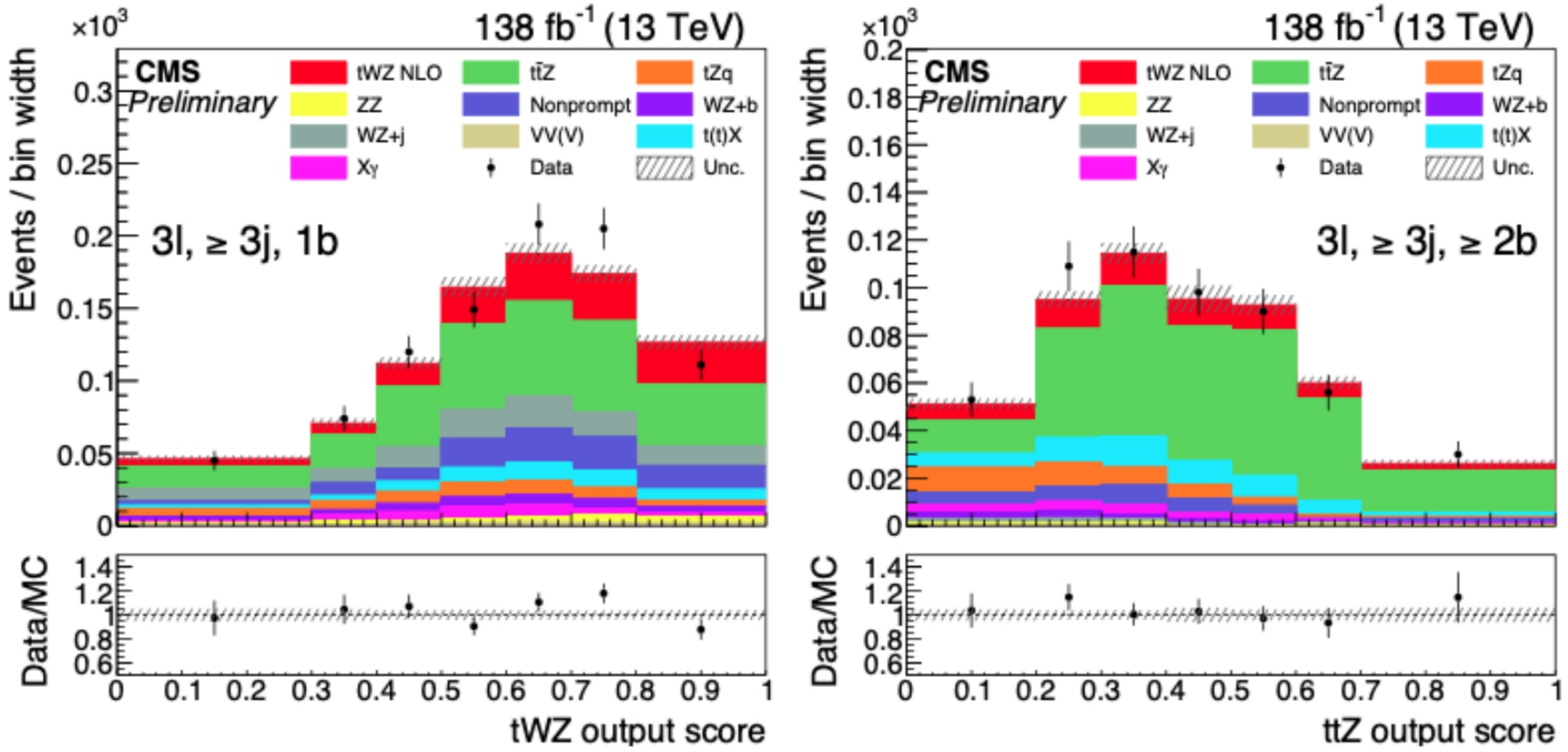


- Extremely rare process: ~ 136 fb only (expected)
  - Depending on the decay of the W boson from the top quark, the final state consists of three or four leptons
  - Use of binary and multiclass NNs for background/signal discrimination.
- First evidence for the standard model production of a top quark in association with a W and a Z boson in multilepton final states:

  obs (exp) significance : 3.5 (1.4) s.d.

10

$\sigma_{tWZ} = 0.37 \pm 0.05\ \text{(stat)} \pm 0.10\ \text{(syst) pb}$



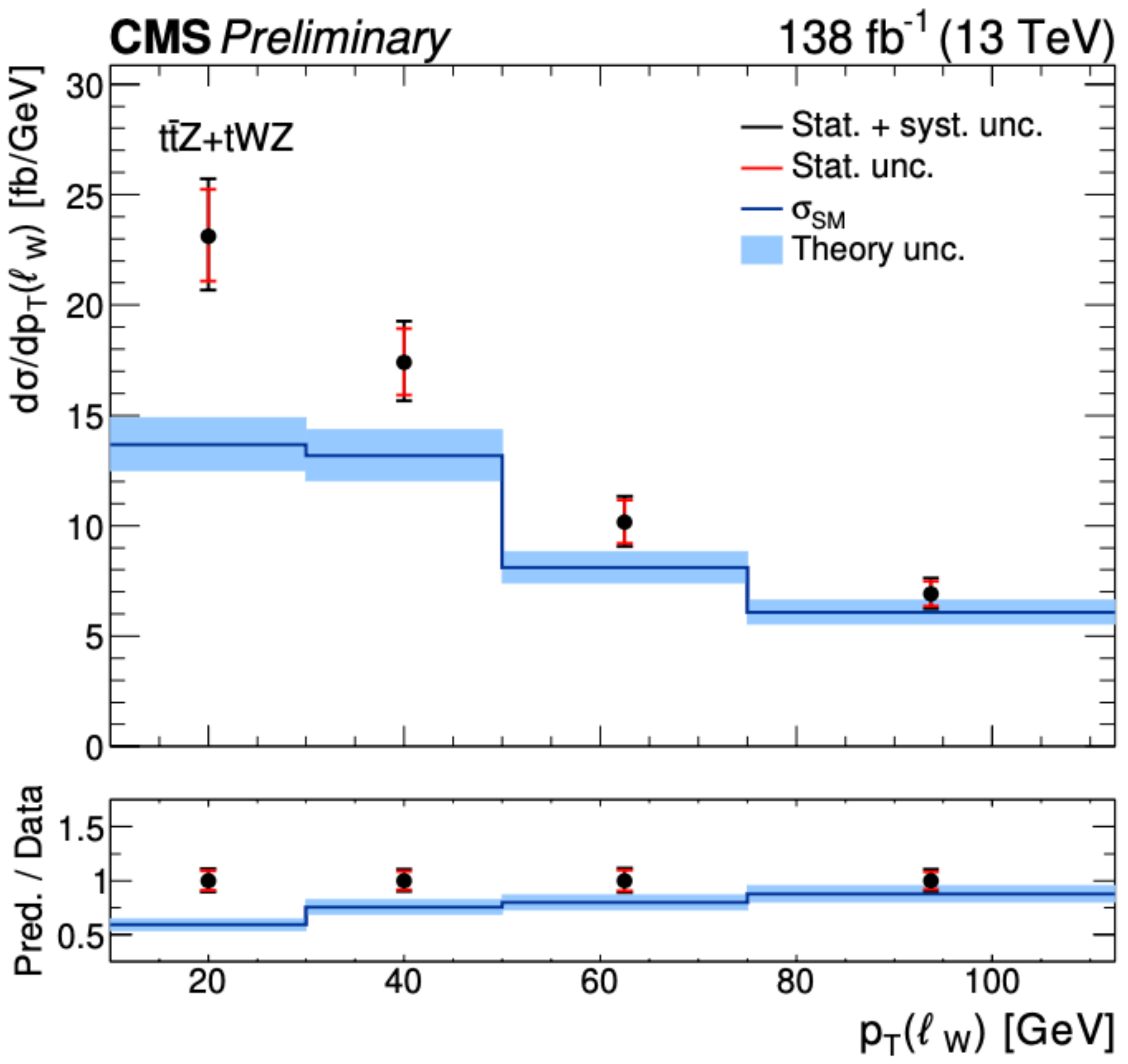
Top quark pair + Z production at the LHC

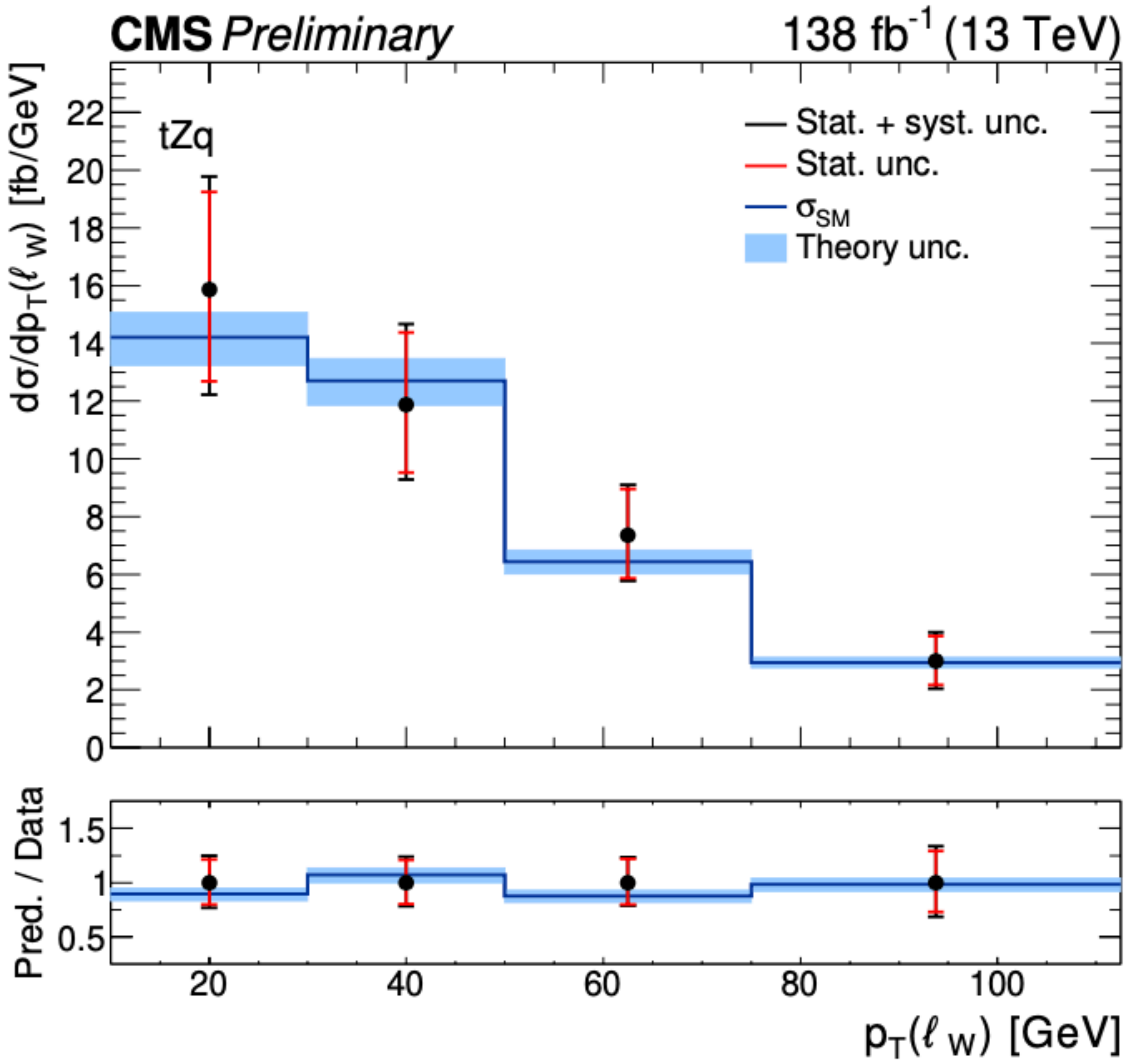
CMS-TOP-23-004

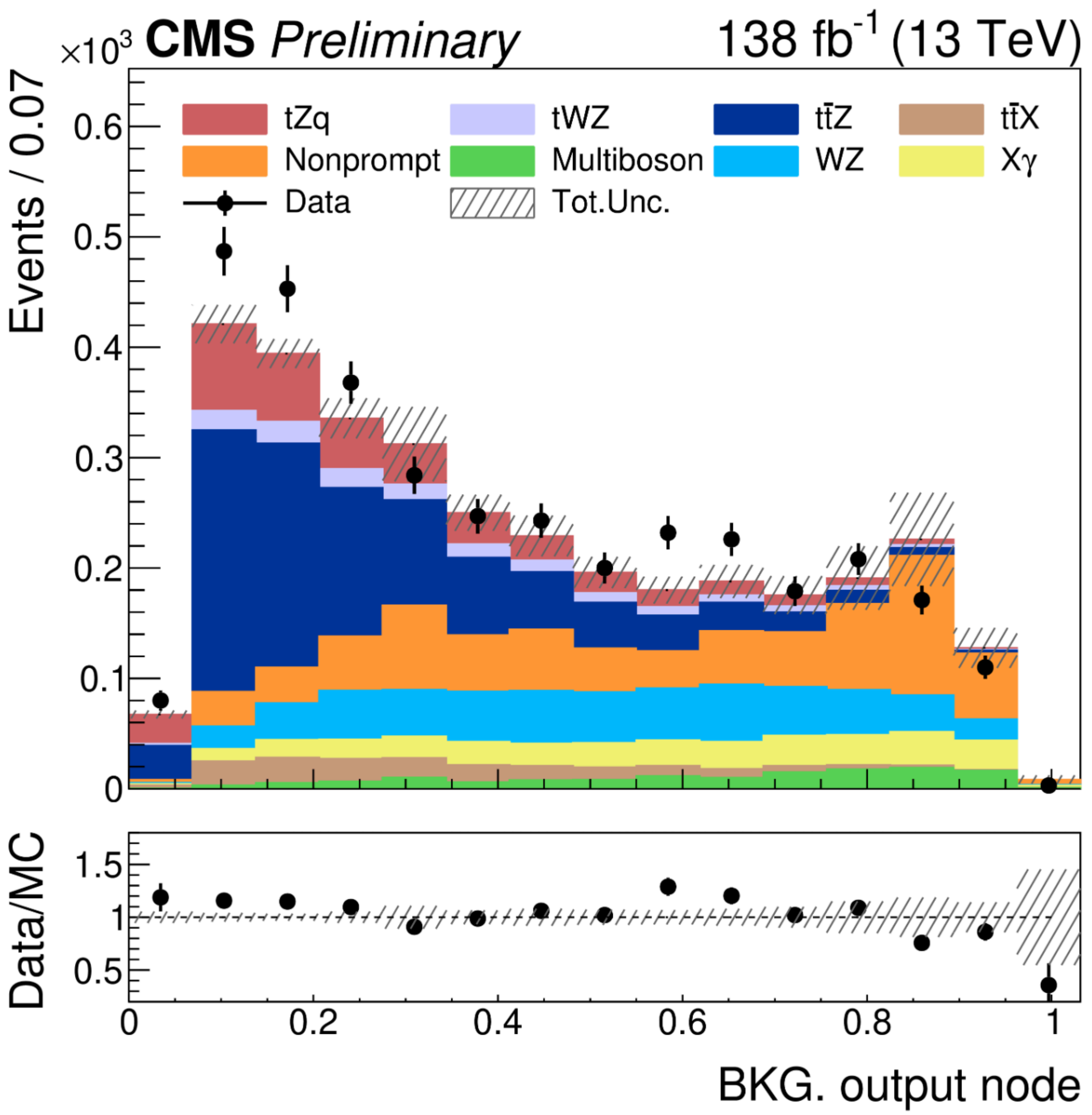
Check dedicated talk from Javier

- Simultaneous measurement of ttZ and tWZ
- Less dependent on signal modeling assumptions
- Enhance sensitivity to deviation from SM across signals
- **Multiclass classifier** with 3 output nodes:

  tZq, ttZ+tWZ, backgrounds







$$\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.07\, pb$$

$$\sigma(tZq) = 0.81 \pm 0.10\, pb$$

→ Excess also observed on previous tWZ measurement

Phys. Lett. B 855 (2024) 138815

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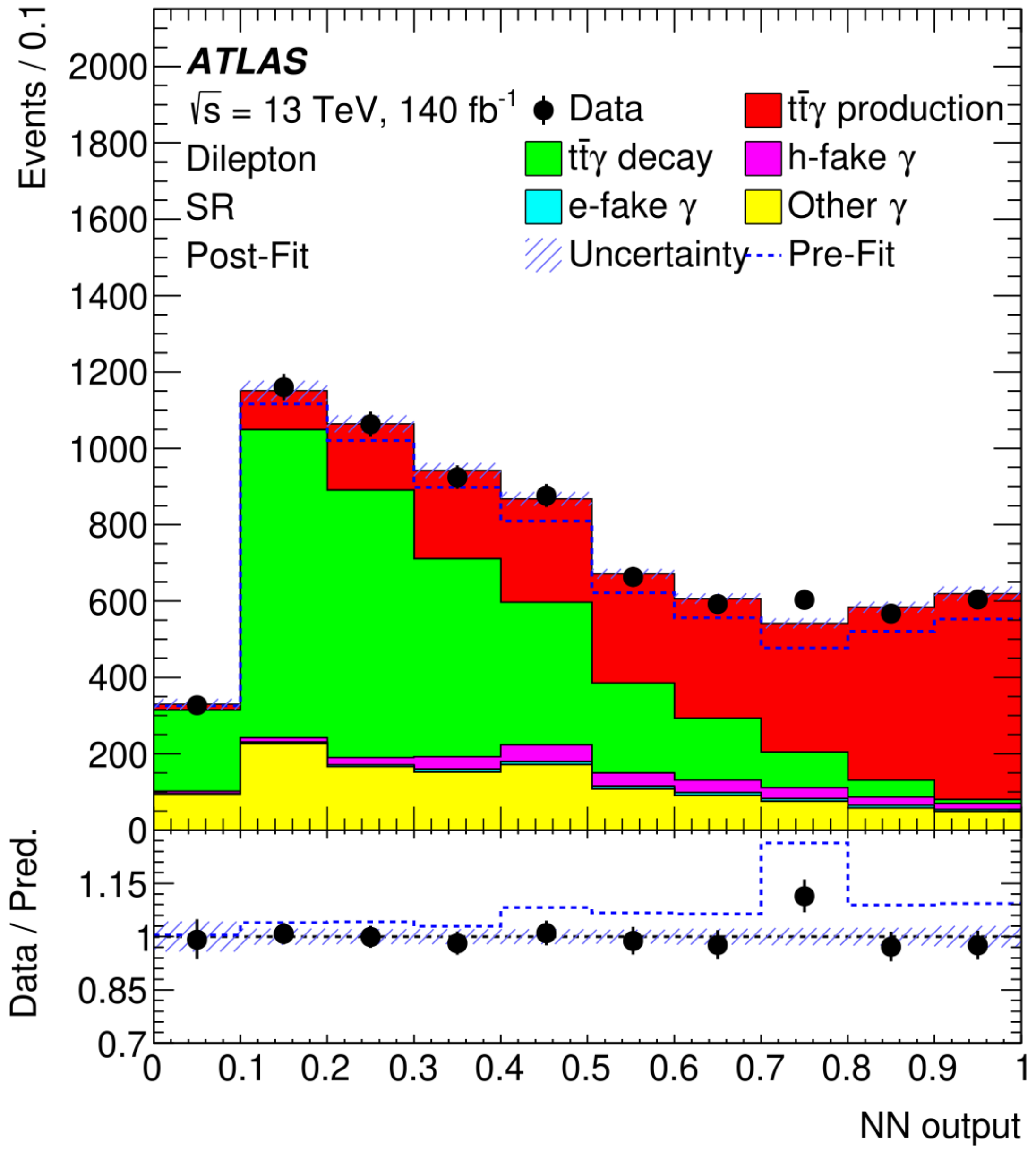
Top quark pair + γ production at the LHC

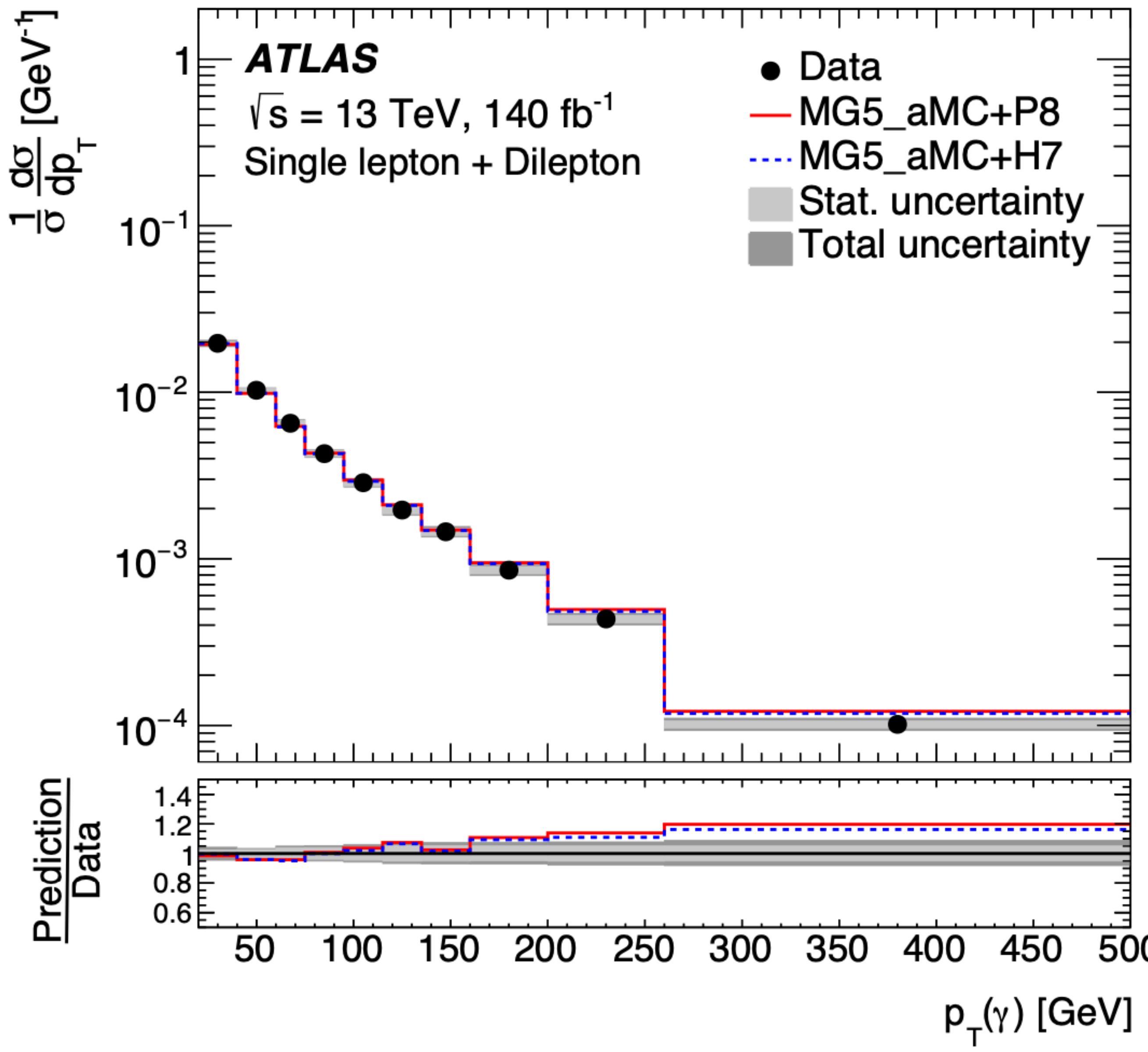
$tt\gamma$ inclusive and differential cross sections with single lepton and dilepton final states :

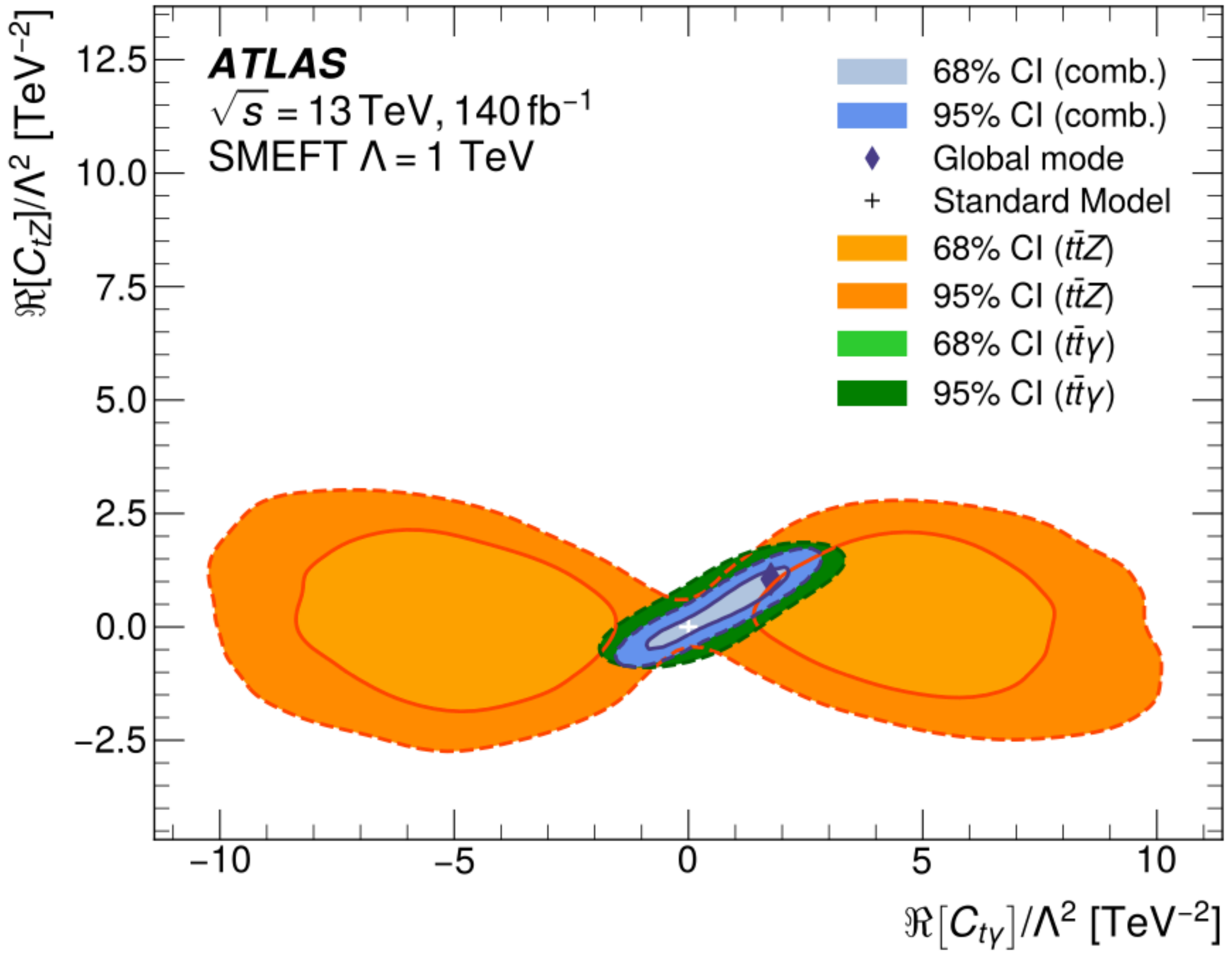
$\sigma_{t\bar{t}\gamma}$ = 322 ± 5 (stat) ± 15 (syst) fb (γ from incoming quark or top) **[First time]**

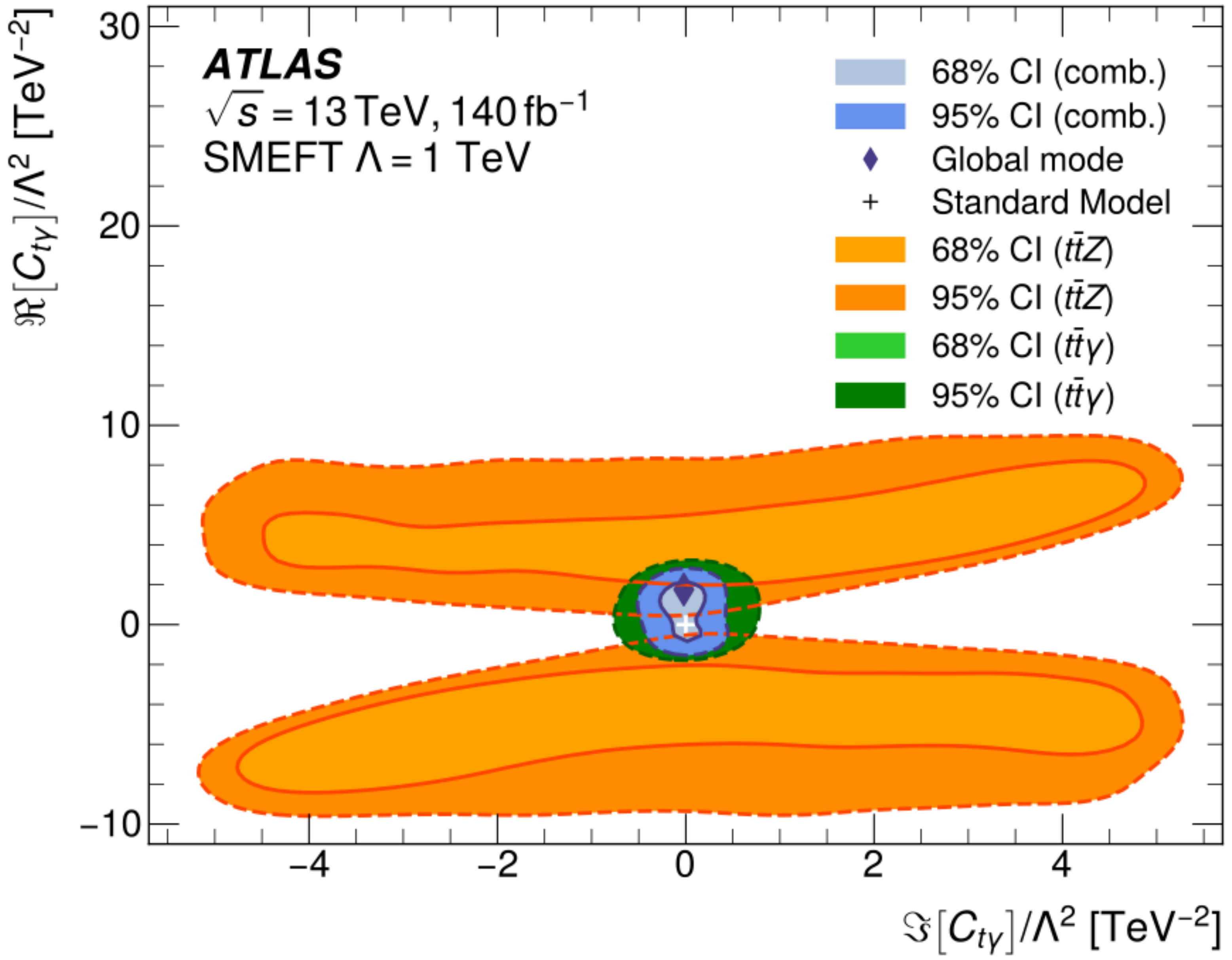
$\sigma_{t\bar{t}\gamma} = 793 \pm 38$ fb $= 793 \pm 5\,(\text{stat})\,^{+38}_{-37}\,(\text{syst})$ fb (combination)

- Unfolded differential cross sections in many variables
- Use unfolded pT (γ) to constrain C_{tB} and C_{tW}, or C_{tZ} and $C_{t\gamma}$









Limits obtained from simultaneous measurement with ttZ

JHEP 07 (2024) 163

2403.09452

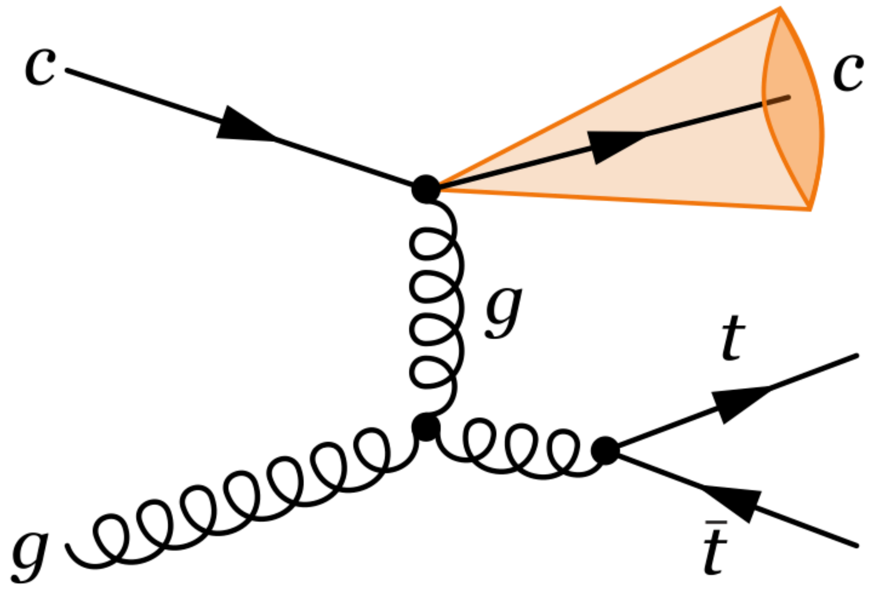
Top quark pair + c production at the LHC

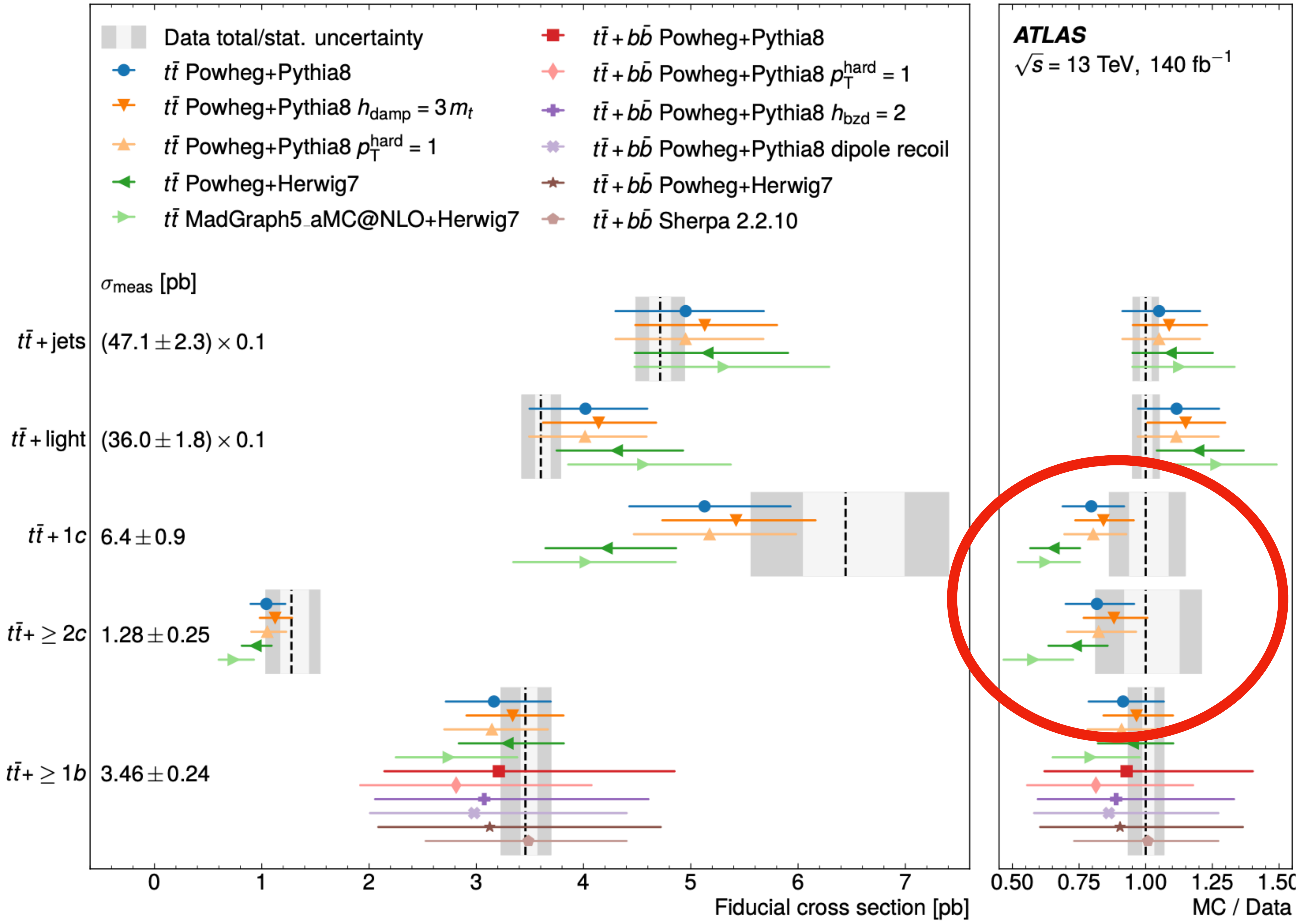
2409.11305

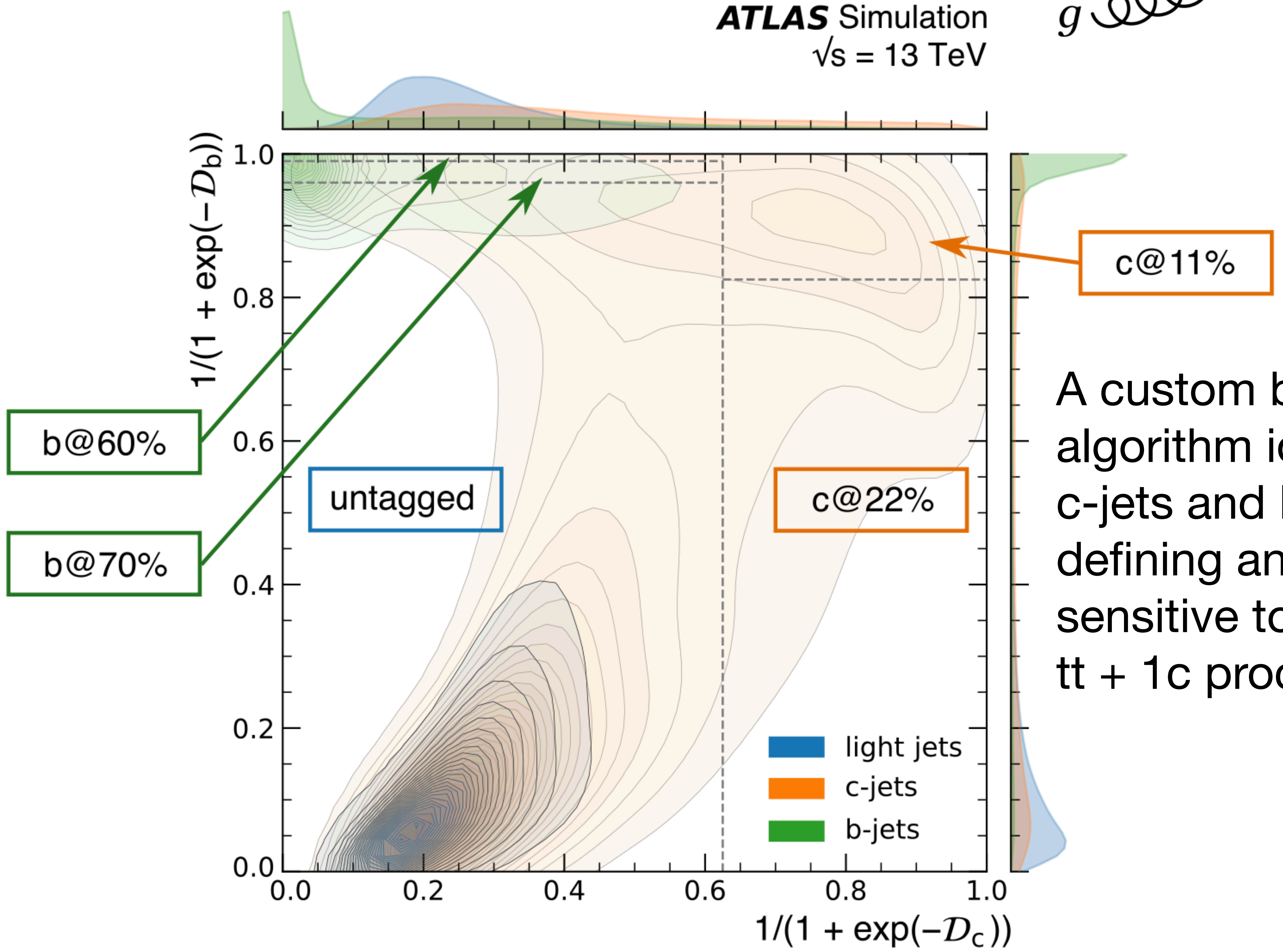
$t\bar{t}$ pair production in association with heavy-flavor jets is a main background in many BSM searches

Considered events with one or two charged lepton in the final states.

$$\sigma_{fid}(t\bar{t} + \geq 2c) = 1.28^{+0.27}_{-0.24}\,\text{pb} \quad \text{and} \quad \sigma_{fid}(t\bar{t} + 1c) = 6.4^{+1.0}_{-0.9}\,\text{pb}$$







A custom b/c-tagger algorithm identifies both c-jets and b-jets, defining analysis regions sensitive to tt + ≥2c and tt + 1c processes.

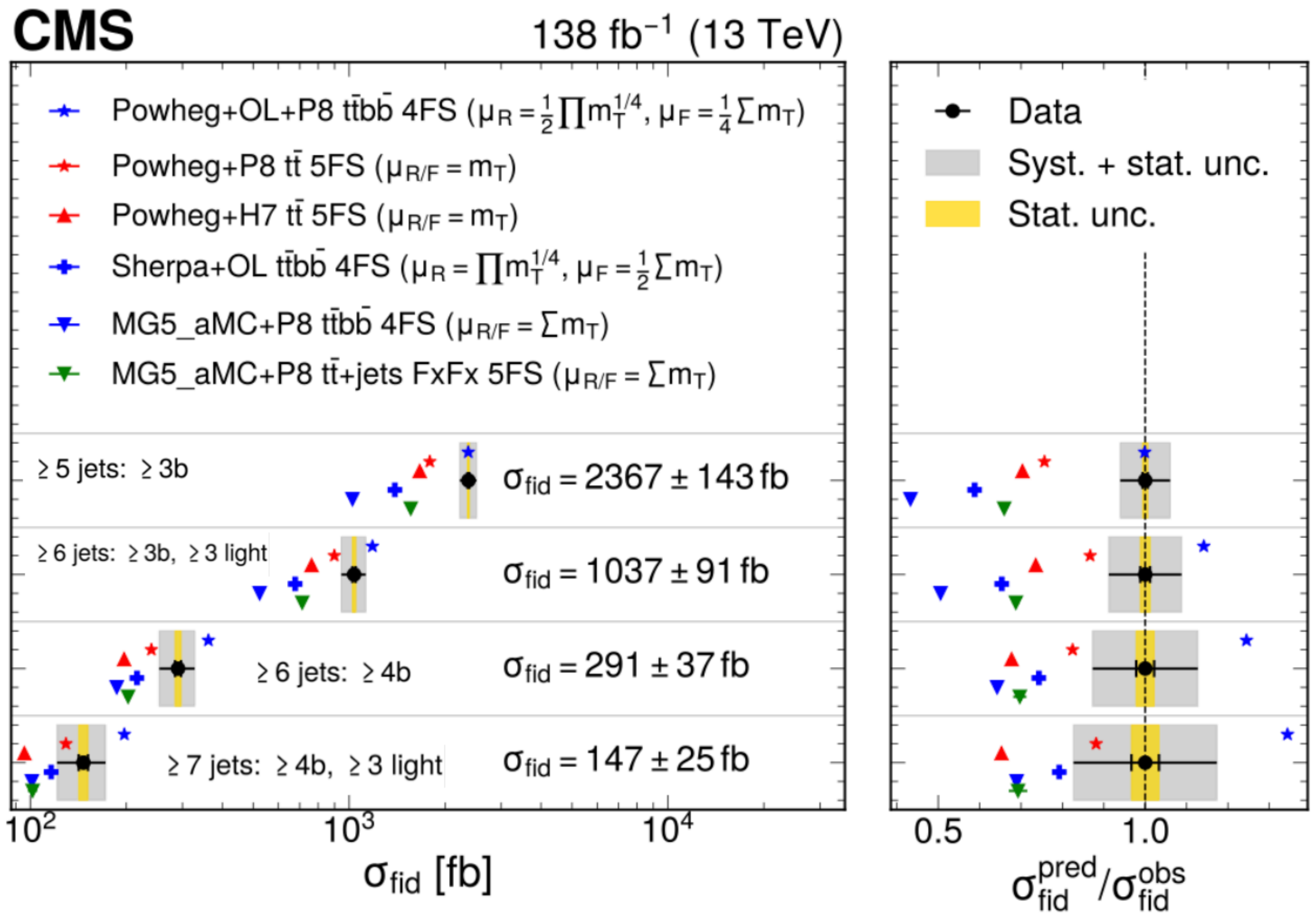
MC simulation predictions align with measurements but under-predict by 0.5 to 2.0 standard deviations.

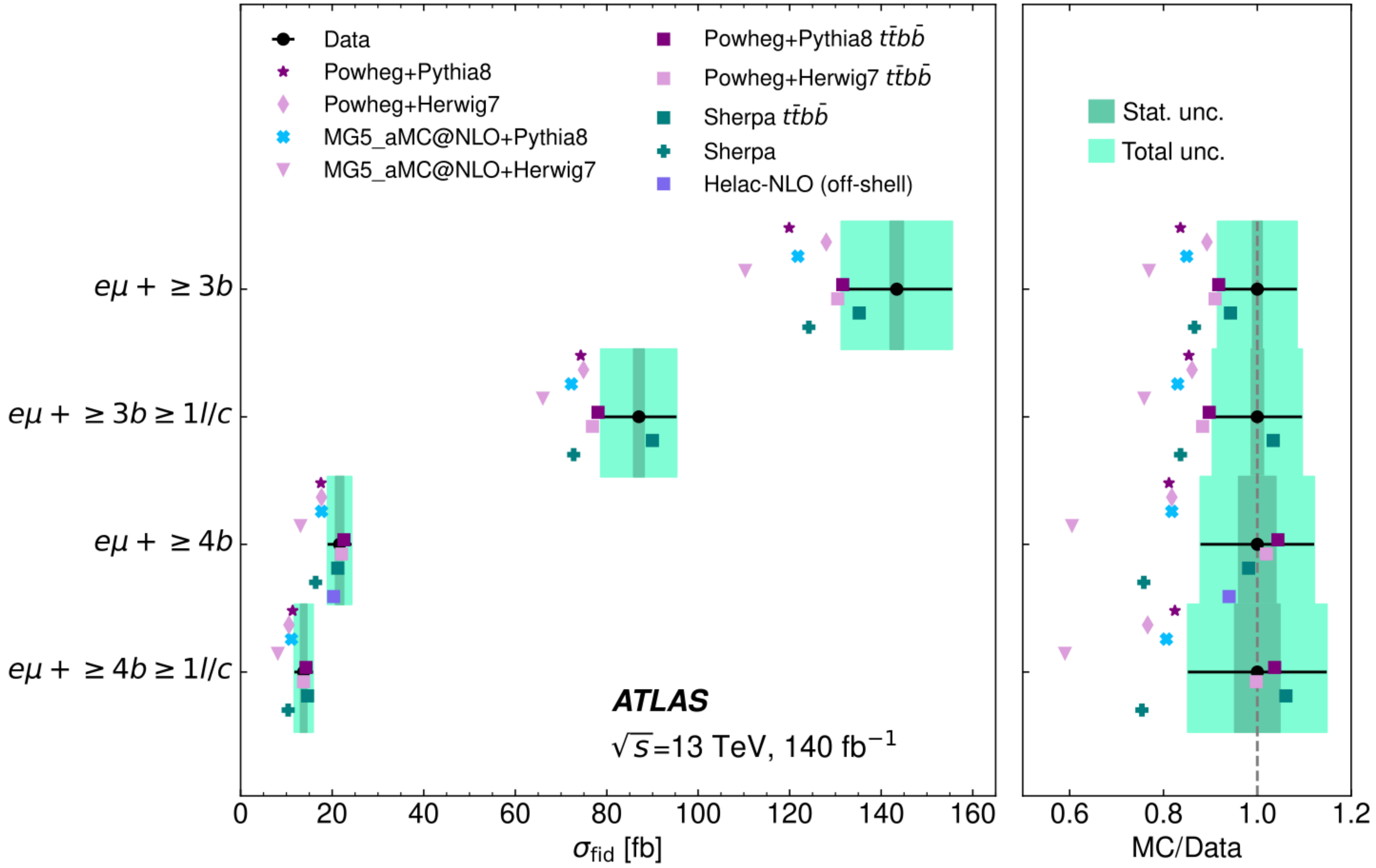
Top quark pair + $b\bar{b}$ production at the LHC

JHEP 05 (2024) 042

2407.13473

- Crucial to improve the modelling for measurements such as ttH(bb)
- Difficult to simulate
- Additonal b-quarks via ME(4FS) or via PS(5FS)





No good description of the data by any of the theoretical predictions

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Top quark pair + $b\bar{b}$ production at the LHC

JHEP 05 (2024) 042

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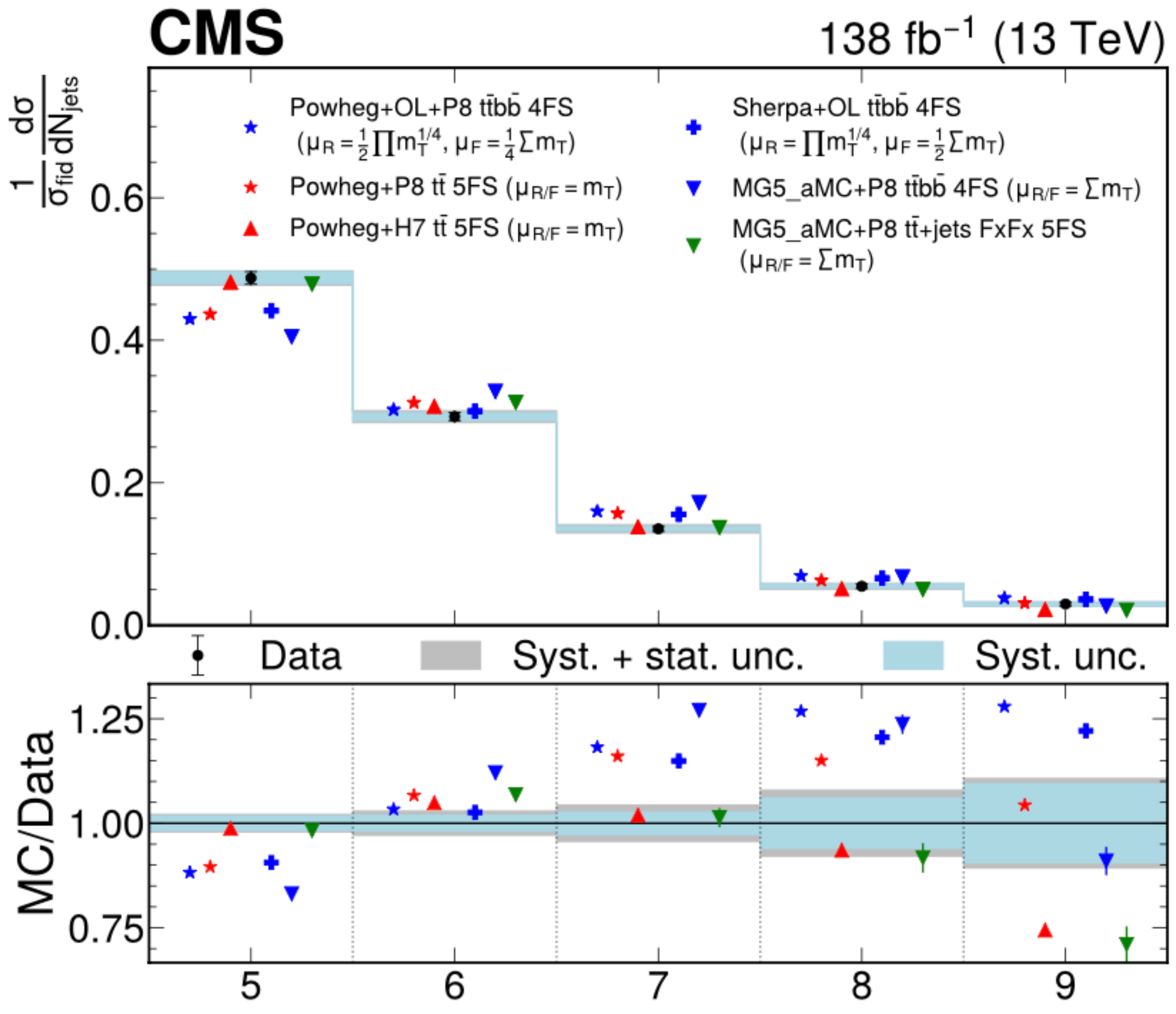
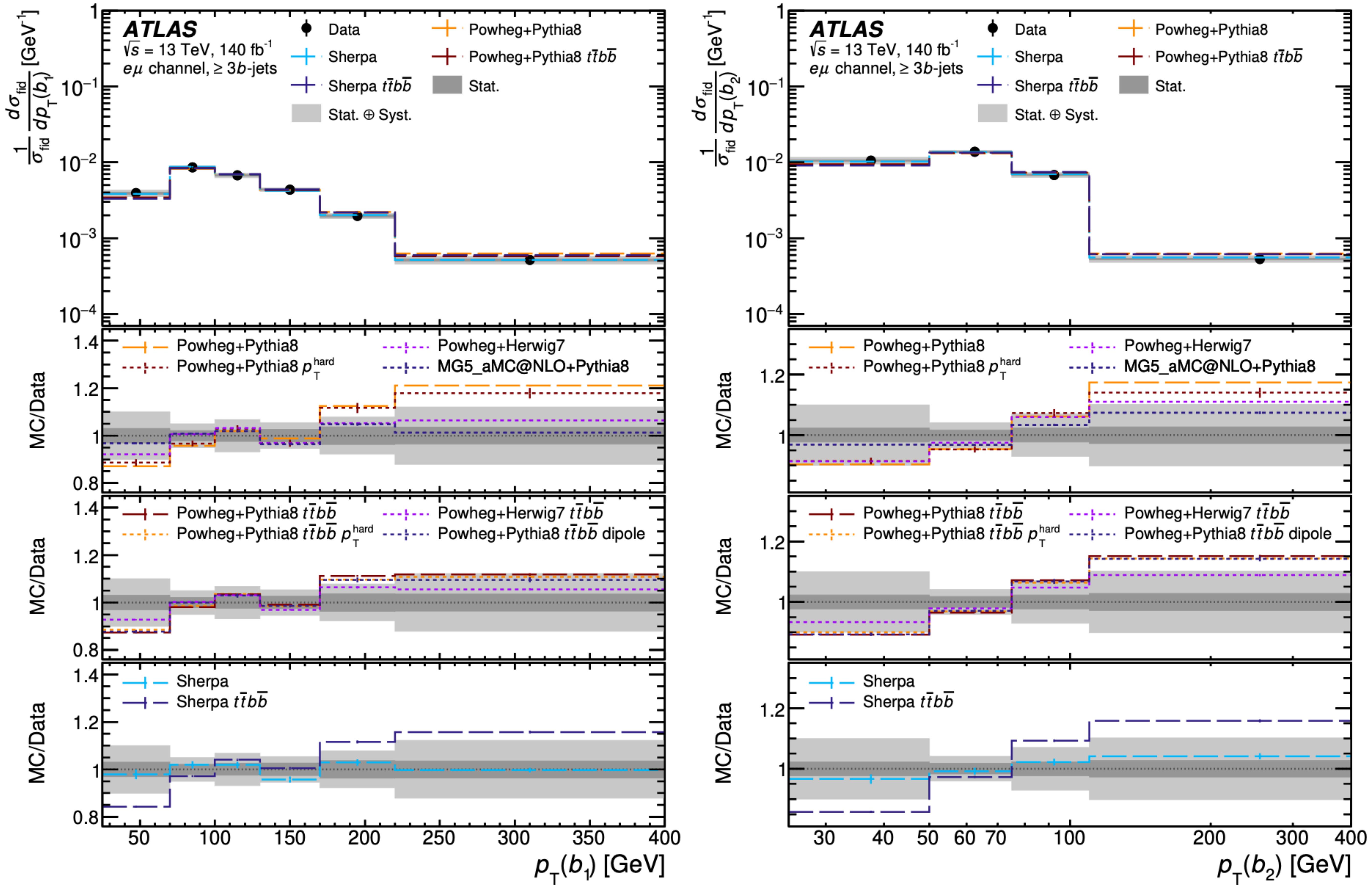




No good description of the data by any of the theoretical predictions

Top quark pair + $H \to b\bar{b}$ production at the LHC

arXiv:2407.10904

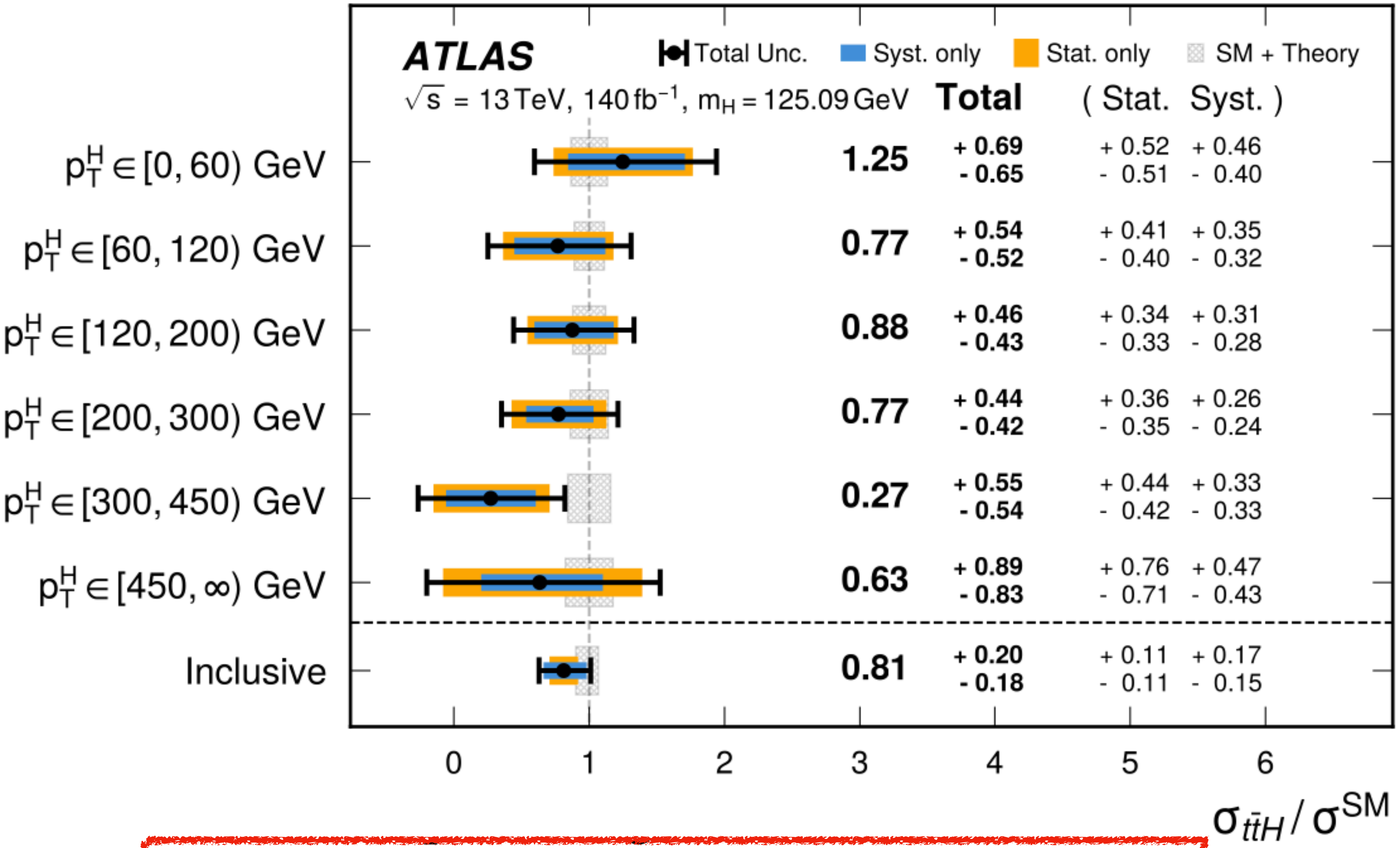
Previous result: $\mu = 0.35^{0.36}_{0.34}$ (JHEP06(2022)097)

observed (expected) significance = 1.0 (2.7)σ

Compared with the previous analysis using the same dataset:

- Looser selection and improved b-jet ID → 64% (29%) more events in single-lepton (dilepton) SR
- CR defined using a stronger multiclass NN
- Data-driven corrections for $t\bar{t}+\geq 1c$ and $t\bar{t}+$ light components
- Dedicated MC simulation for $t\bar{t}+\geq 1b$, no longer dominant

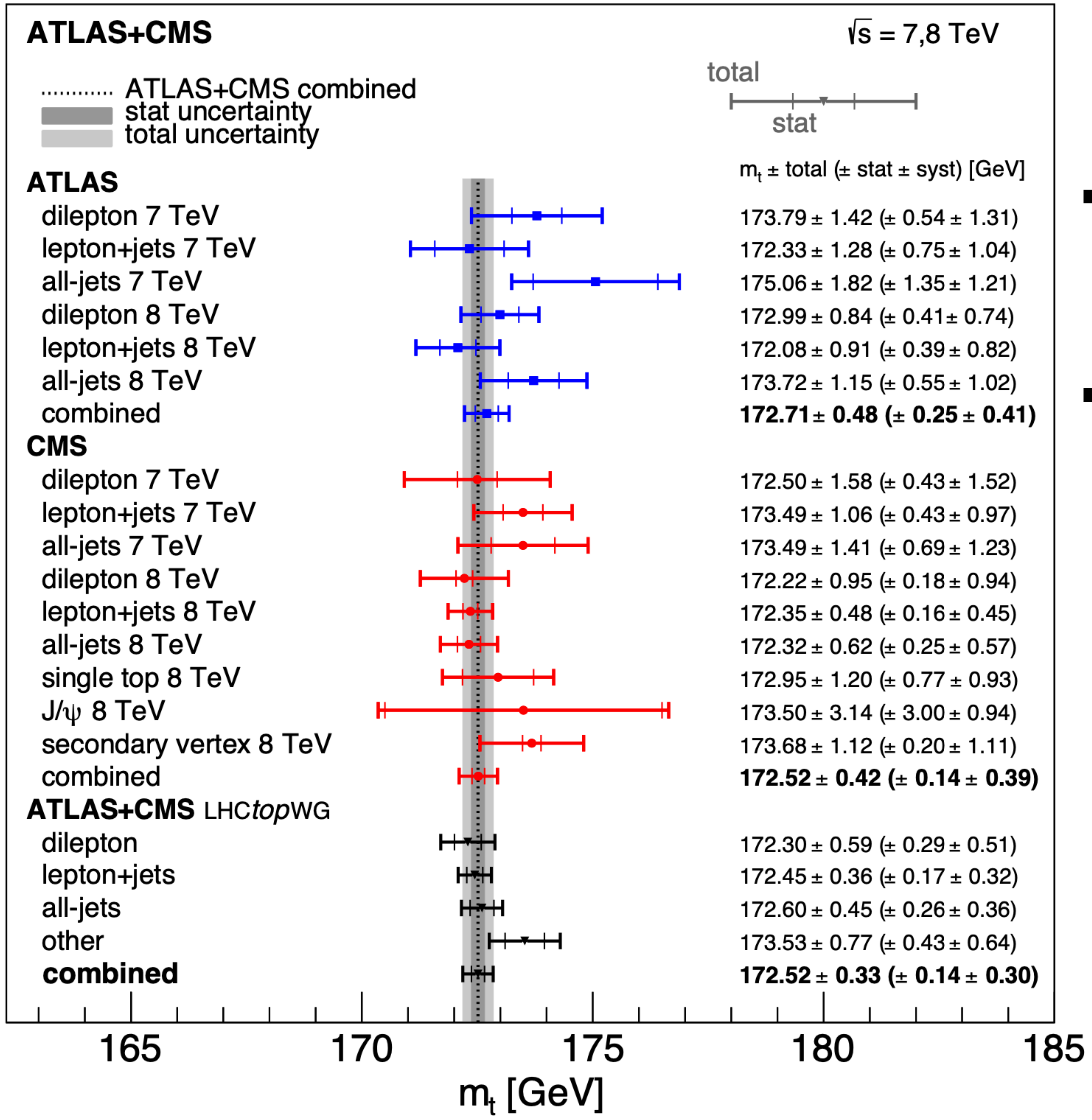
observed (expected) significance = 4.6 (5.4)σ



$$\sigma_{t\bar{t}H} = 411\ ^{+101}_{-92}\ \text{fb} = 411 \pm 54(\text{stat.})\ ^{+85}_{-75}(\text{syst.})\ \text{fb}$$

CMS + ATLAS top quark mass: Run I combination

Phys. Rev. Lett. 132 (2024) 261902



6 ATLAS inputs

Dilepton: Eur. Phys. J. C 72 (2012) 2202, Phys. Rev. D 96 (2017) 032002

Lepton+jets: JHEP 12 (2012) 105, Phys. Rev. D 93 (2016) 092006

All-hadronic: Eur. Phys. J. *C* 74 (2014) 2758, Phys. Rev. D 93 (2016) 092006

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CMS + ATLAS top quark mass: Run I combination

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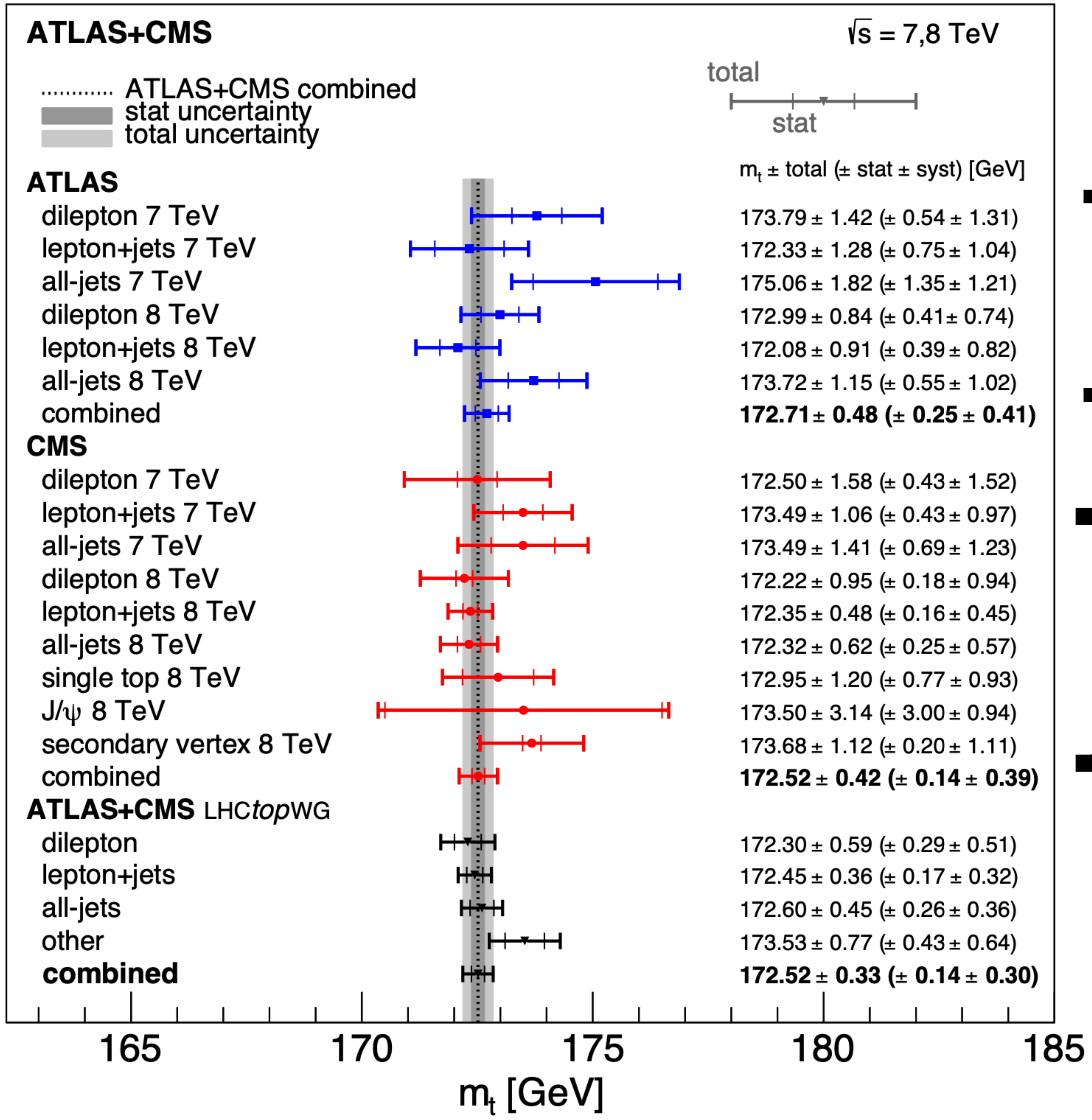

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Dilepton: Eur. Phys. J. C 72 (2012) 2202, Phys. Rev. D 96 (2017) 032002

Lepton+jets: JHEP 12 (2012) 105, Phys. Rev. D 93 (2016) 092006

All-hadronic: Eur. Phys. J. *C* 74 (2014) 2758, Phys. Rev. D 93 (2016) 092006

9 CMS inputs

Dilepton: Eur. Phys. J. C 75 (2015) 330, Phys. Lett. B 761 (2016) 350

Lepton+jets: Eur. Phys. J. C 75 (2015) 330, Eur. Phys. J. C 79 (2019) 290

All-hadronic:Eur. Phys. J. C 75 (2015) 158, JHEP 09 (2017)118

+

Single top: *Eur. Phys. J. C* **77** (2017) 354

J/psi: *JHEP* **12** (2016) 123

Secondary vertex: *Phys. Rev. D* **93 (2016) 092006**

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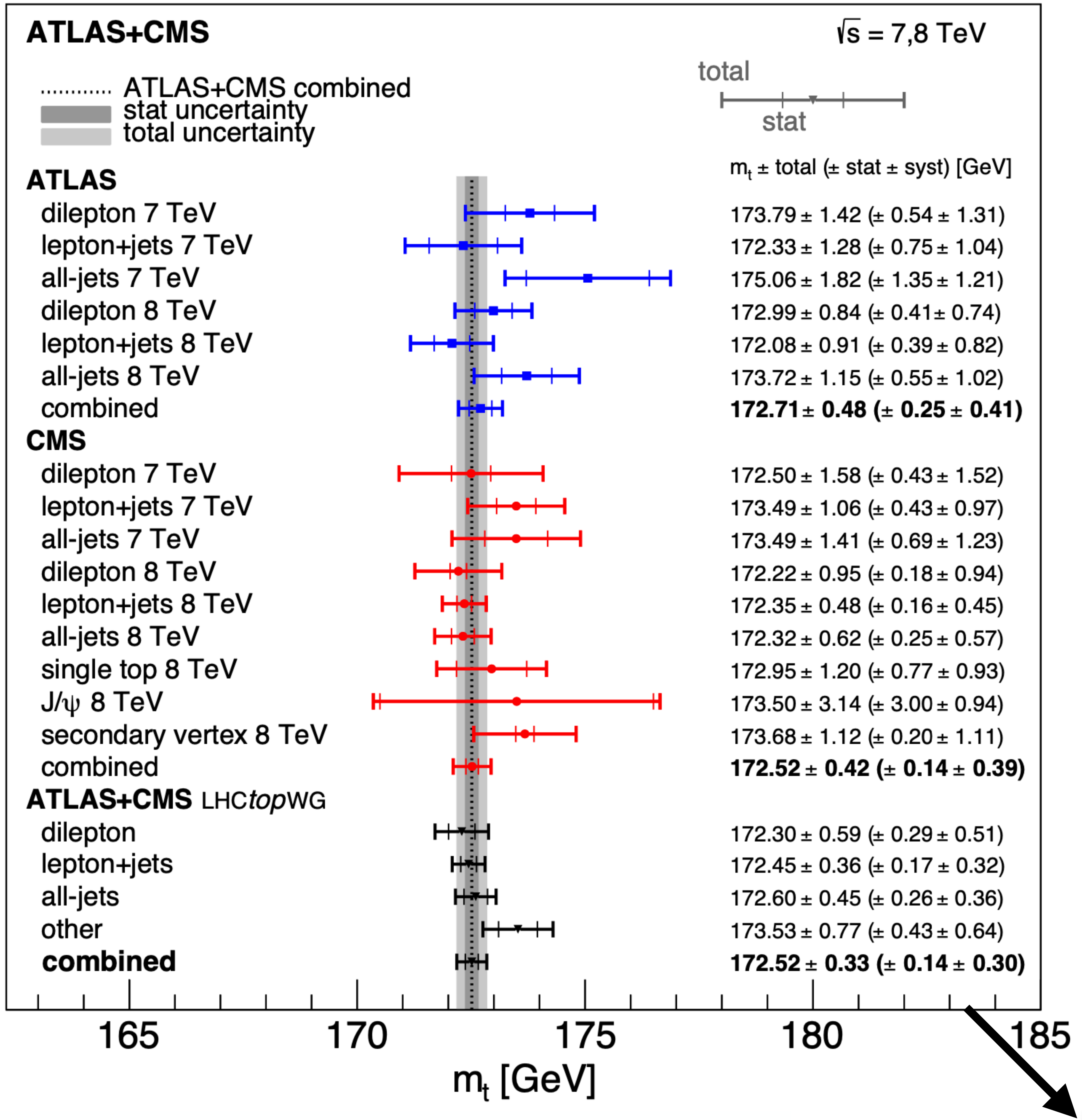
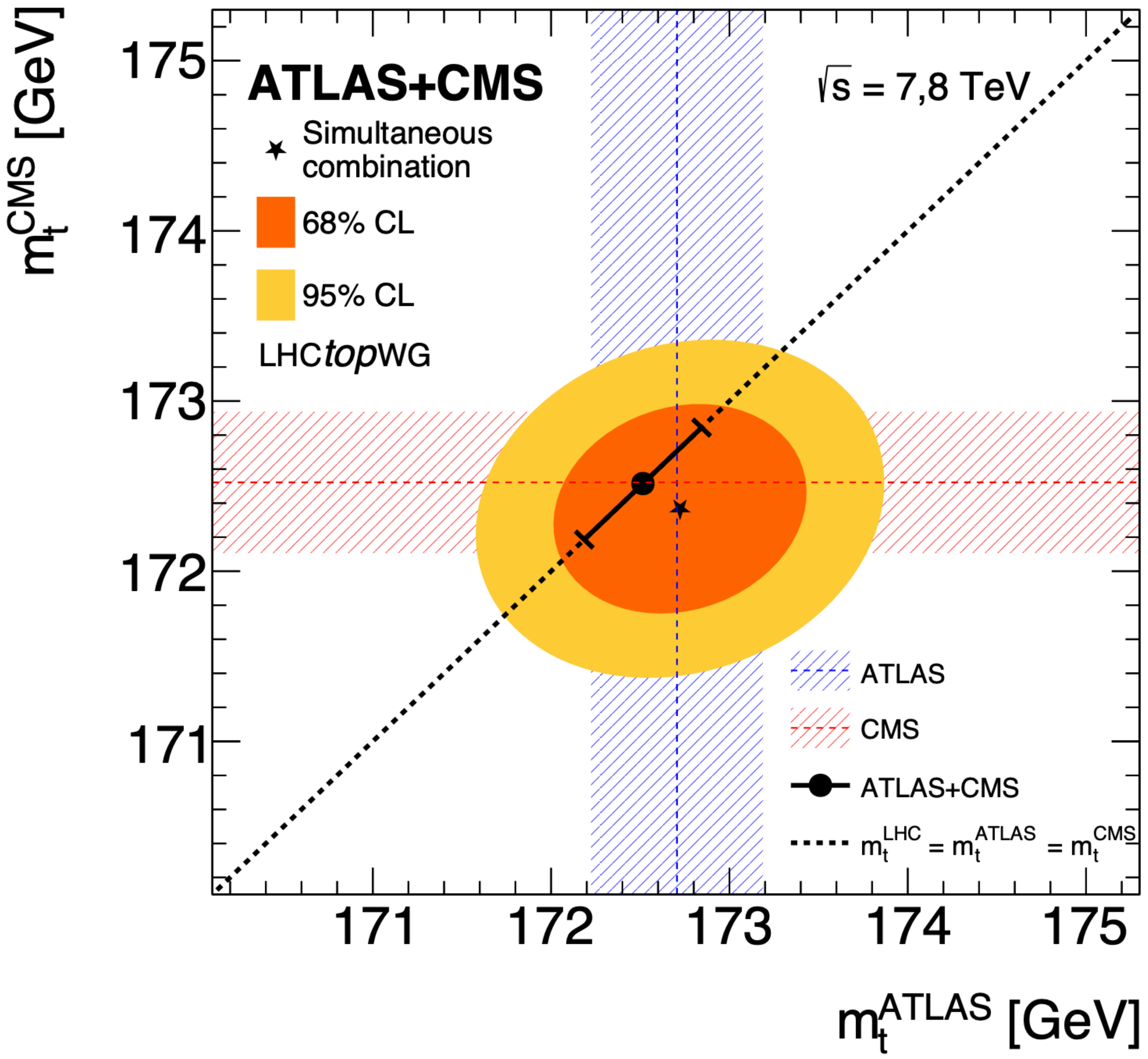
CMS + ATLAS top quark mass: Run I combination

Phys. Rev. Lett. 132 (2024) 261902



Comprehensive analysis of correlations: BLUE = Best Linear Unbiased Estimator



Overall correlation and consistency between ATLAS and CMS can be assessed via **simultaneous ATLAS-CMS combination**

$$m_t = 172.52 \pm 0.14\ (\text{stat}) \pm 0.30\ (\text{syst.})\ \text{GeV}$$

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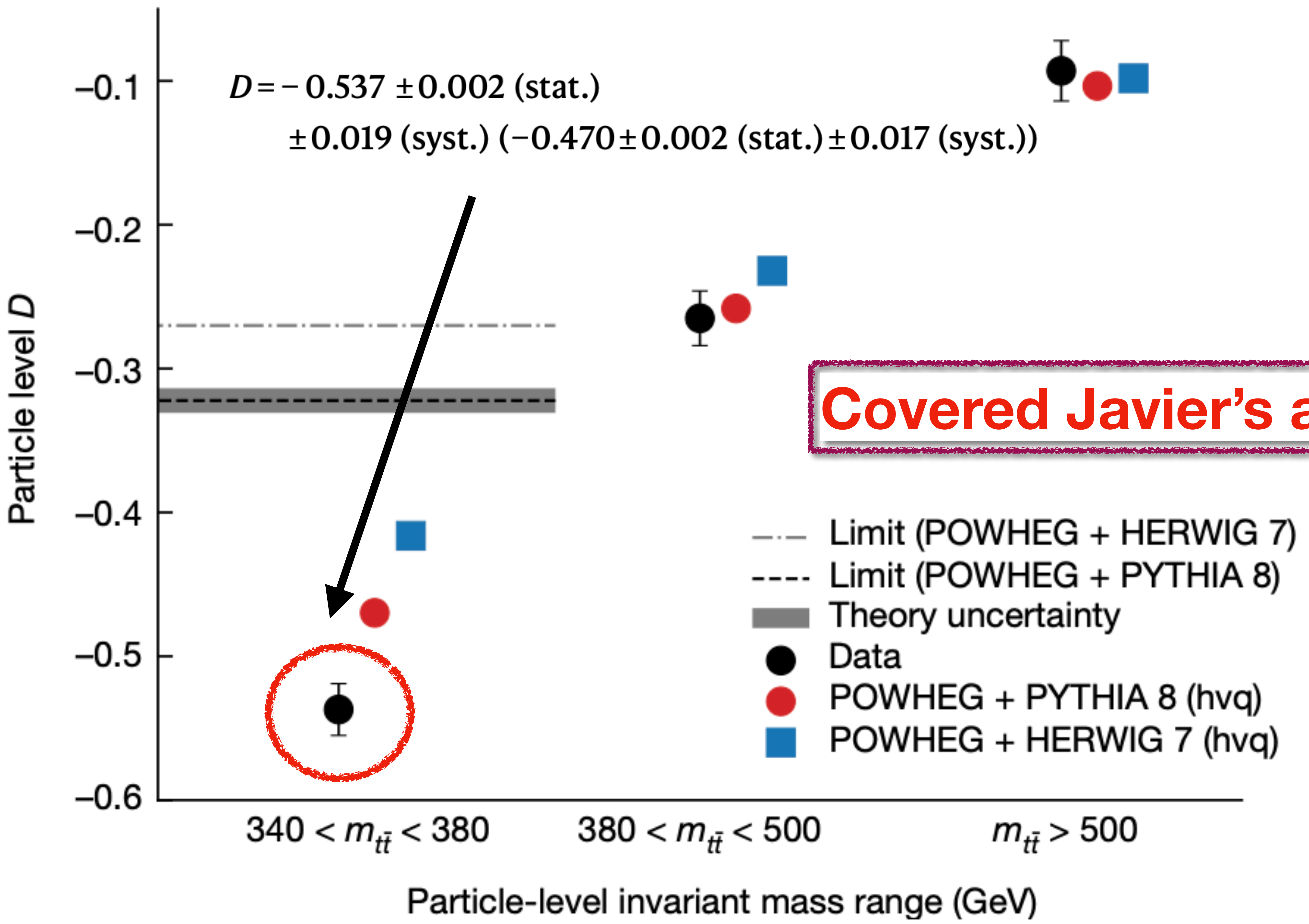
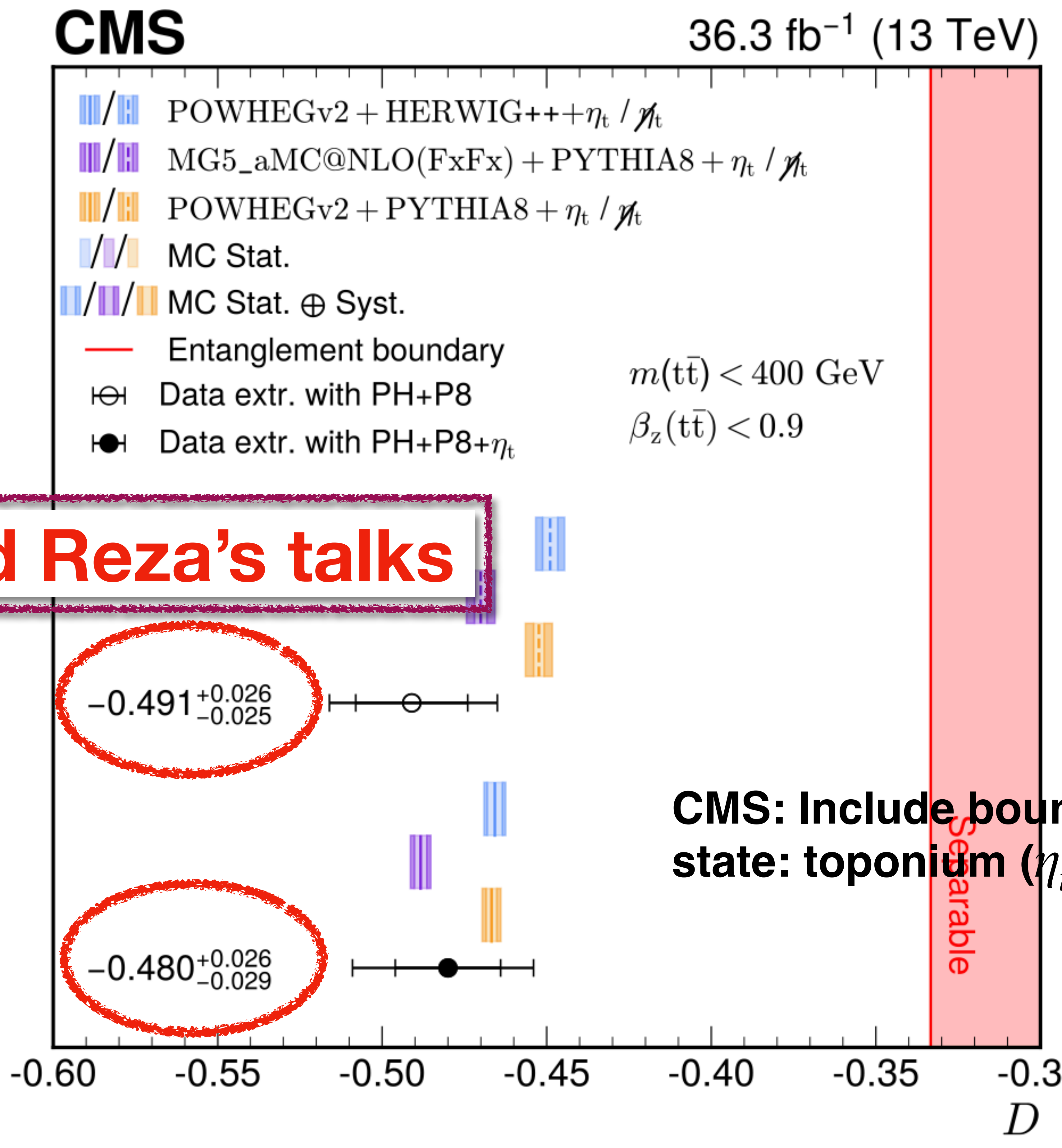
Entanglement in $t\bar{t}$

Nature 633 (2024) 542
arXiv:2406.03976





Covered Javier's and Reza's talks

CMS: Include bound-state: toponium (η_t)

Summary

Many excellent analysis in the top quark sector, here were mentioned just a few

Major precision improvements are thanks to:

- Enhanced analysis techniques and calibrations
- Larger LHC data sets
- Joint ATLAS and CMS efforts

The first 13.6 TeV results have been released, with many more expected in the coming years. Stay tuned for further updates.

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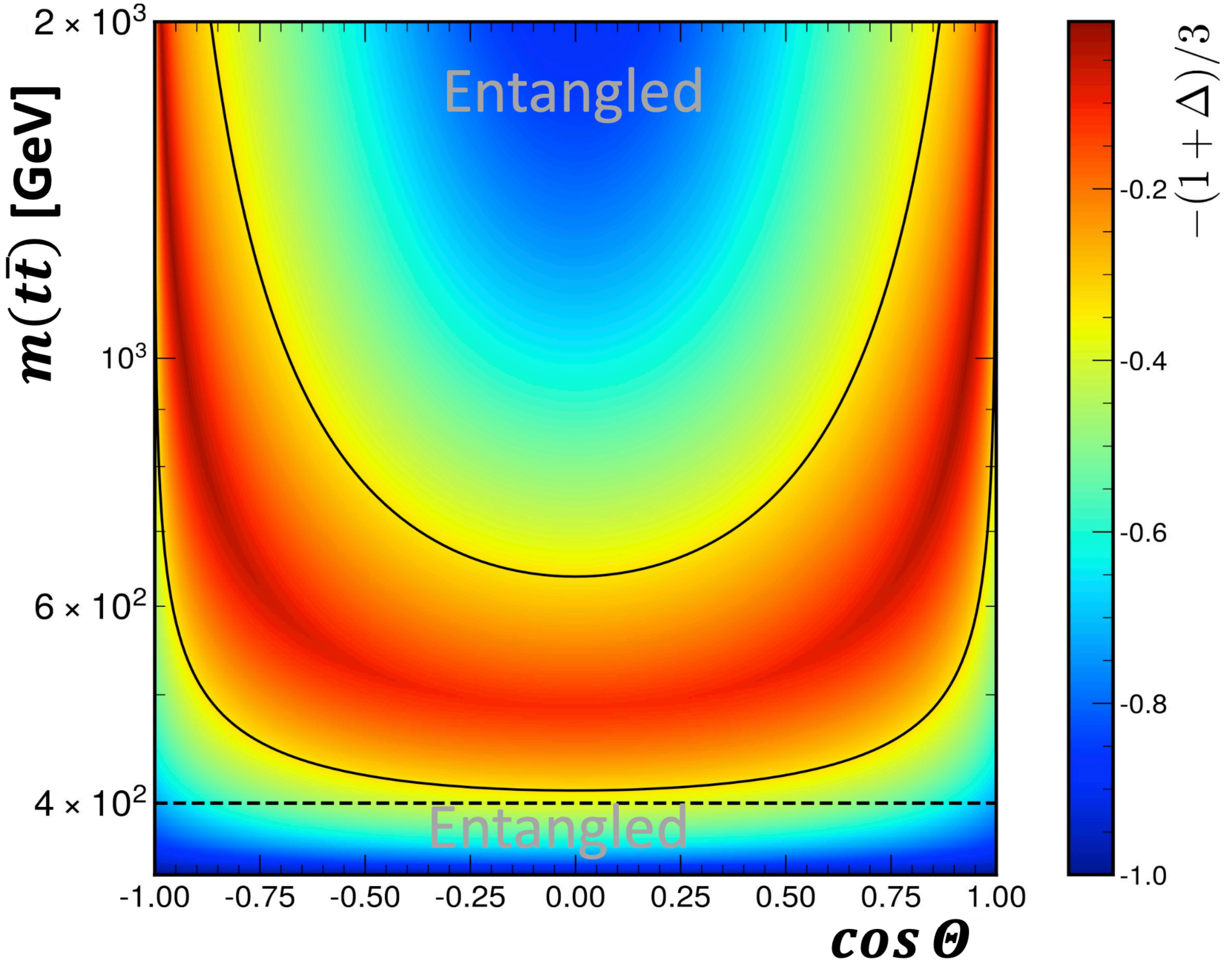
Backup

Entanglement in $t\bar{t}$

- Lifetime notably shorter than the timescale needed for hadronization
  => spin information is transferred to its decay products
- Recently, the top quark was proposed as a new laboratory to study quantum entanglement EPJP 136.907

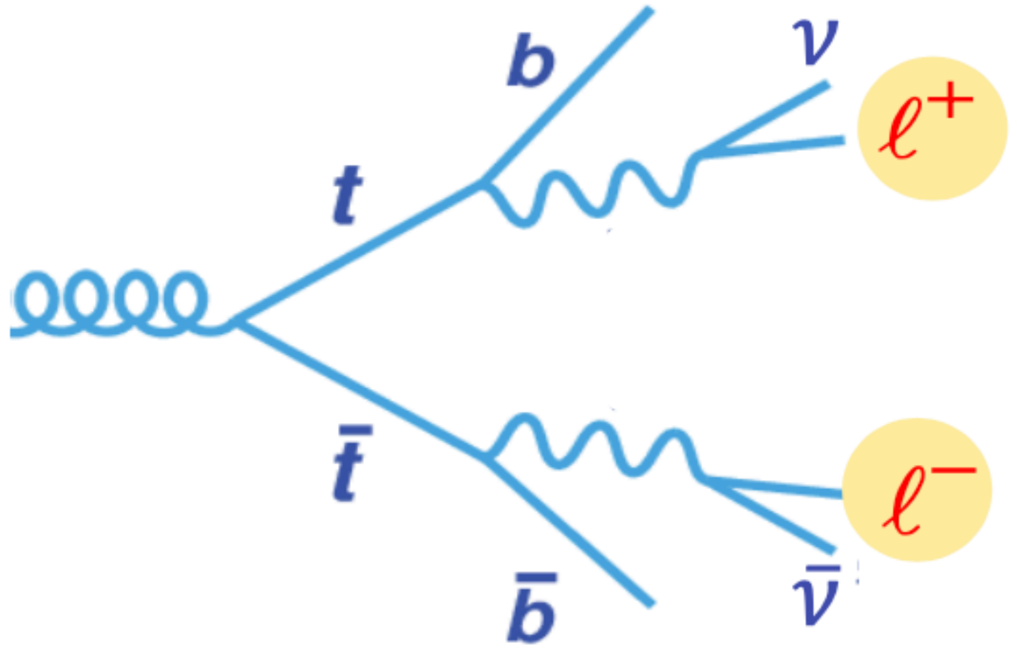
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$



Normalized differential cross-section can be written as:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi)$$

where $D = -3 < cos(\varphi) >$



To claim the existence of entanglement::

$$D < -\frac{1}{3}$$

$$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$

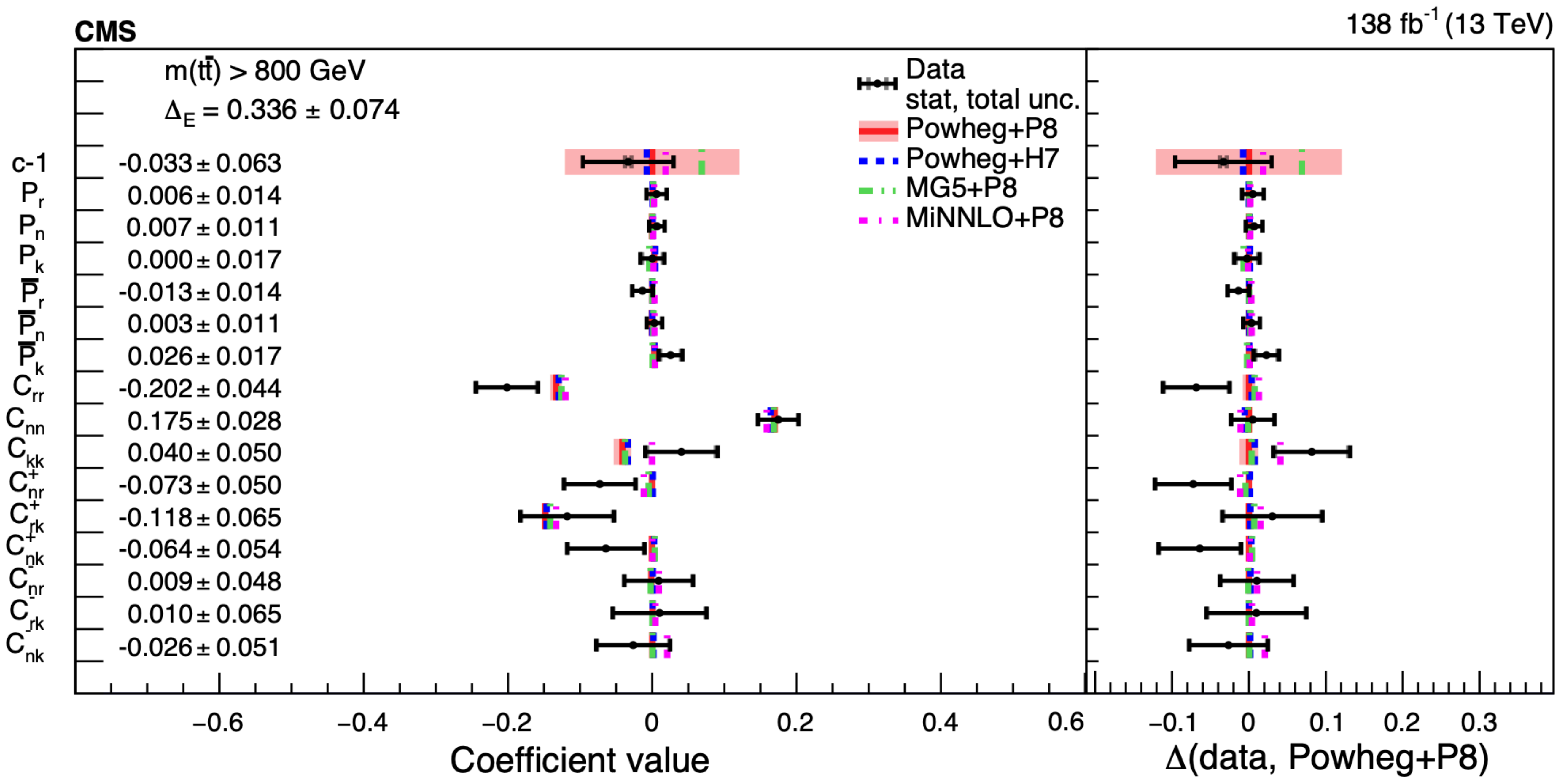
CMS DESY. HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN ATLAS EXPERIMENT

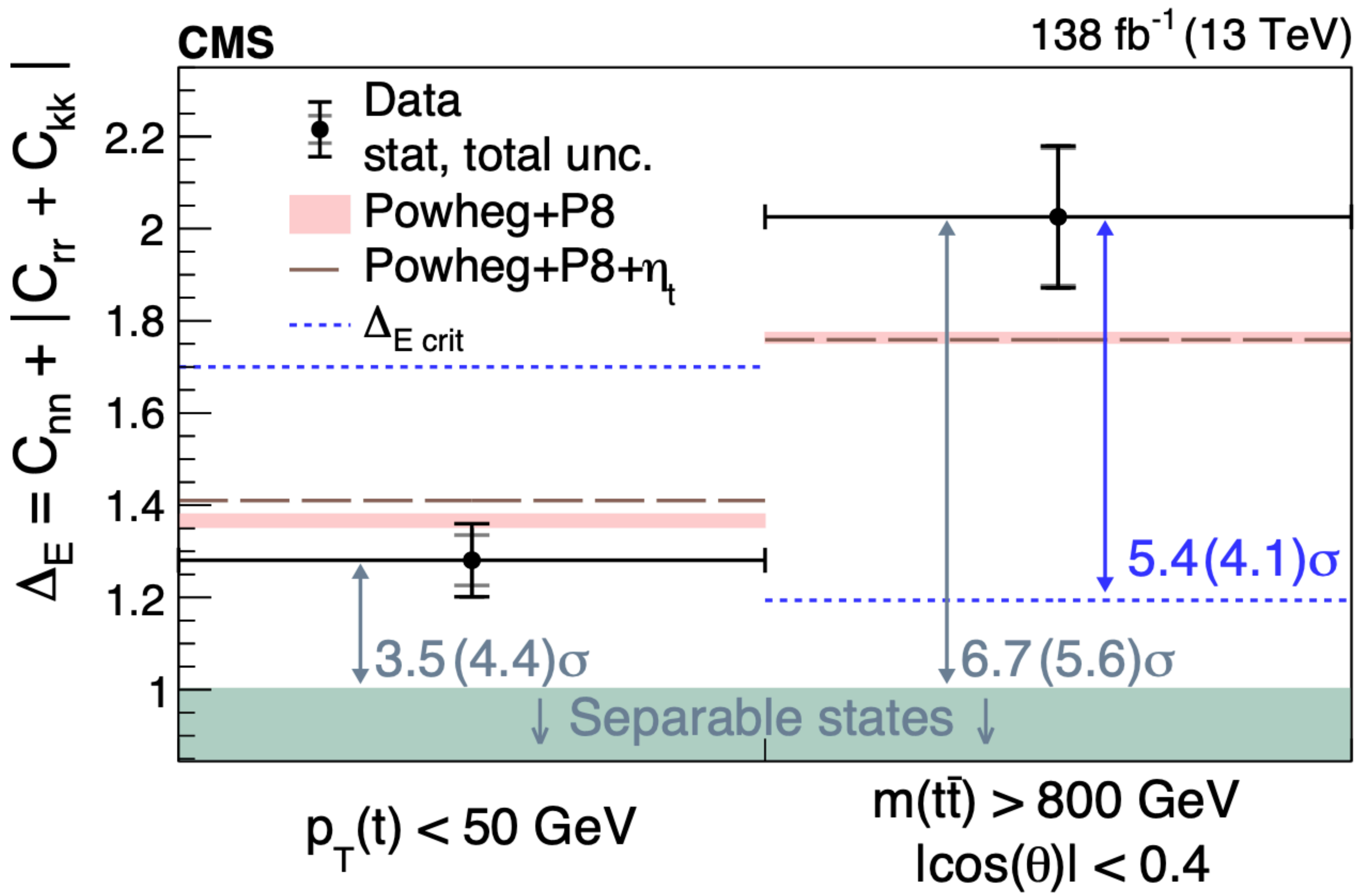
Polarization and Spin correlation in $t\bar{t}$ (l+jets)

arXiv:2409.11067

All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously

Measurement performed inclusively and in bins of m_{tt} and $\cos(\theta)$





Conclusion on the $t\bar{t}$ spin entanglement can be drawn from Peres–Horodecki criterion

$$\Delta E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

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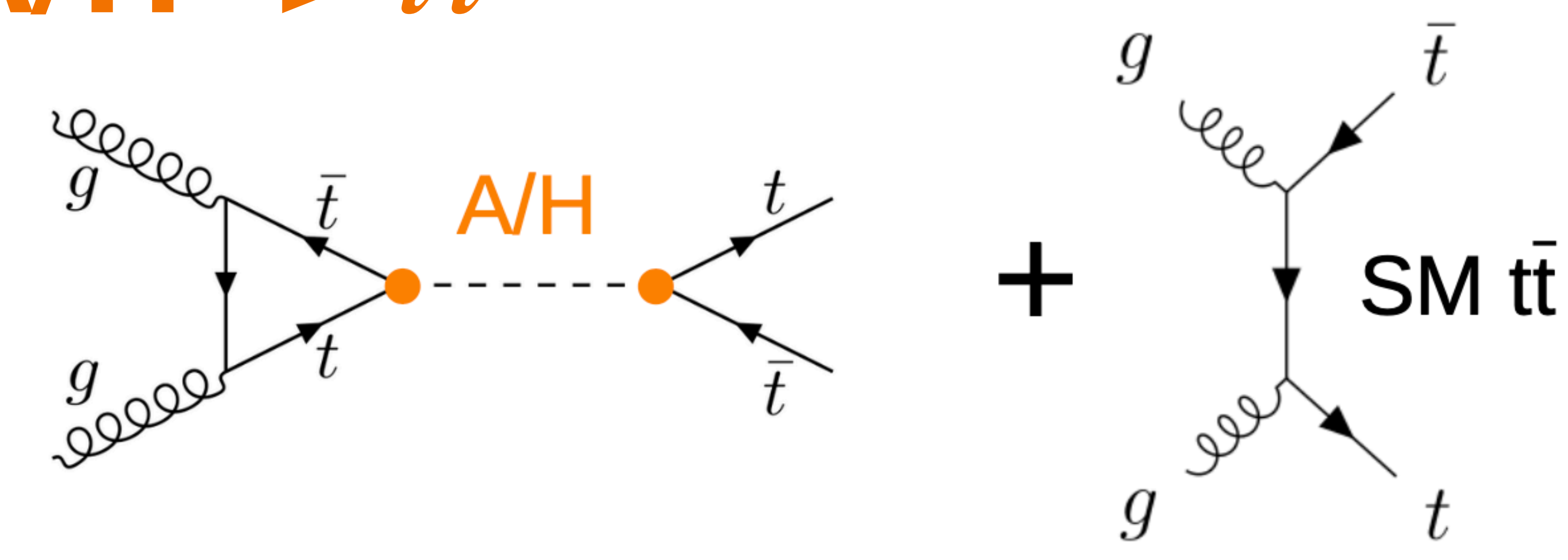
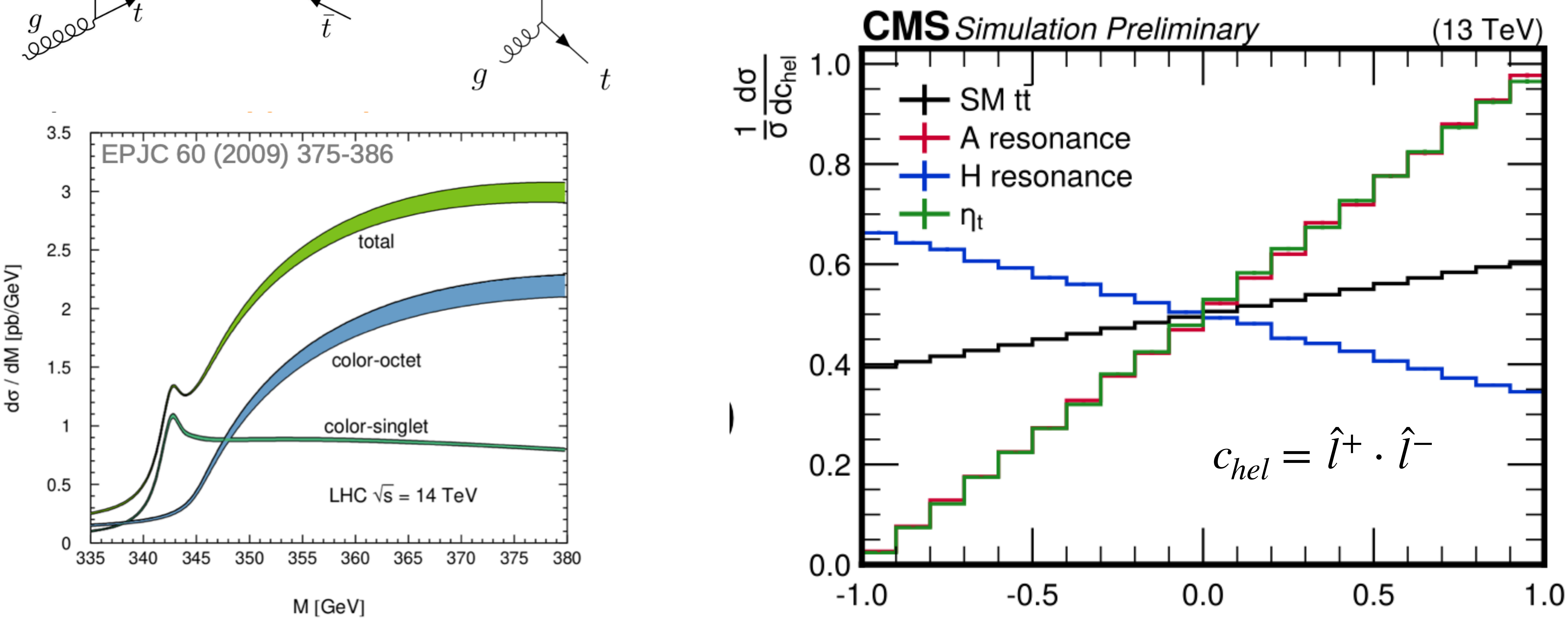
A/H -> $t\bar{t}$



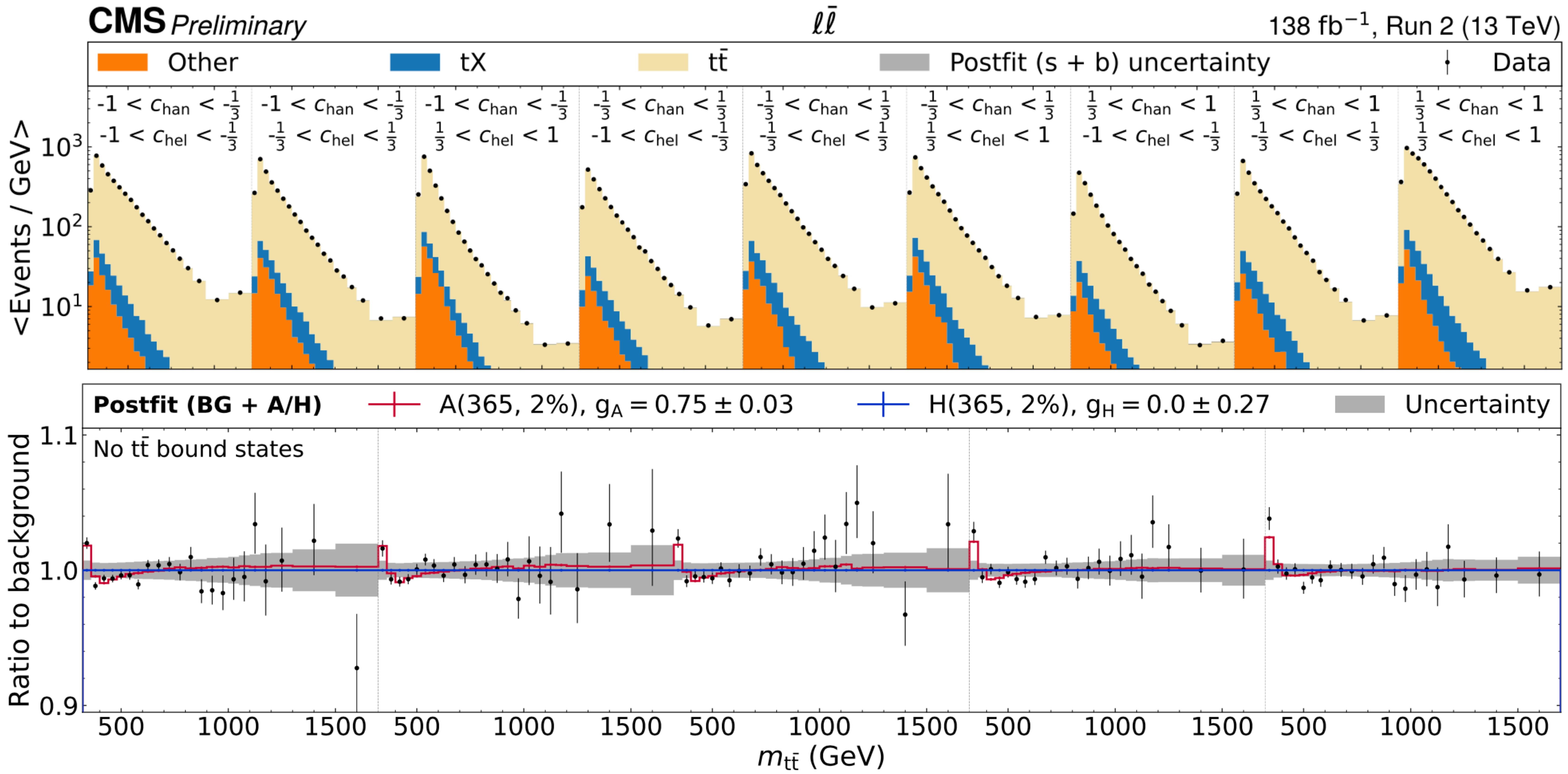
- SM predicts tt (quasi-)bound states below the tt threshold
- Not observed yet (but there are hints: differential tt, entanglement…)
- Measurement performed using m_{tt}, c_{hel}, c_{han}
- Final states with 1 or 2 charged leptons used

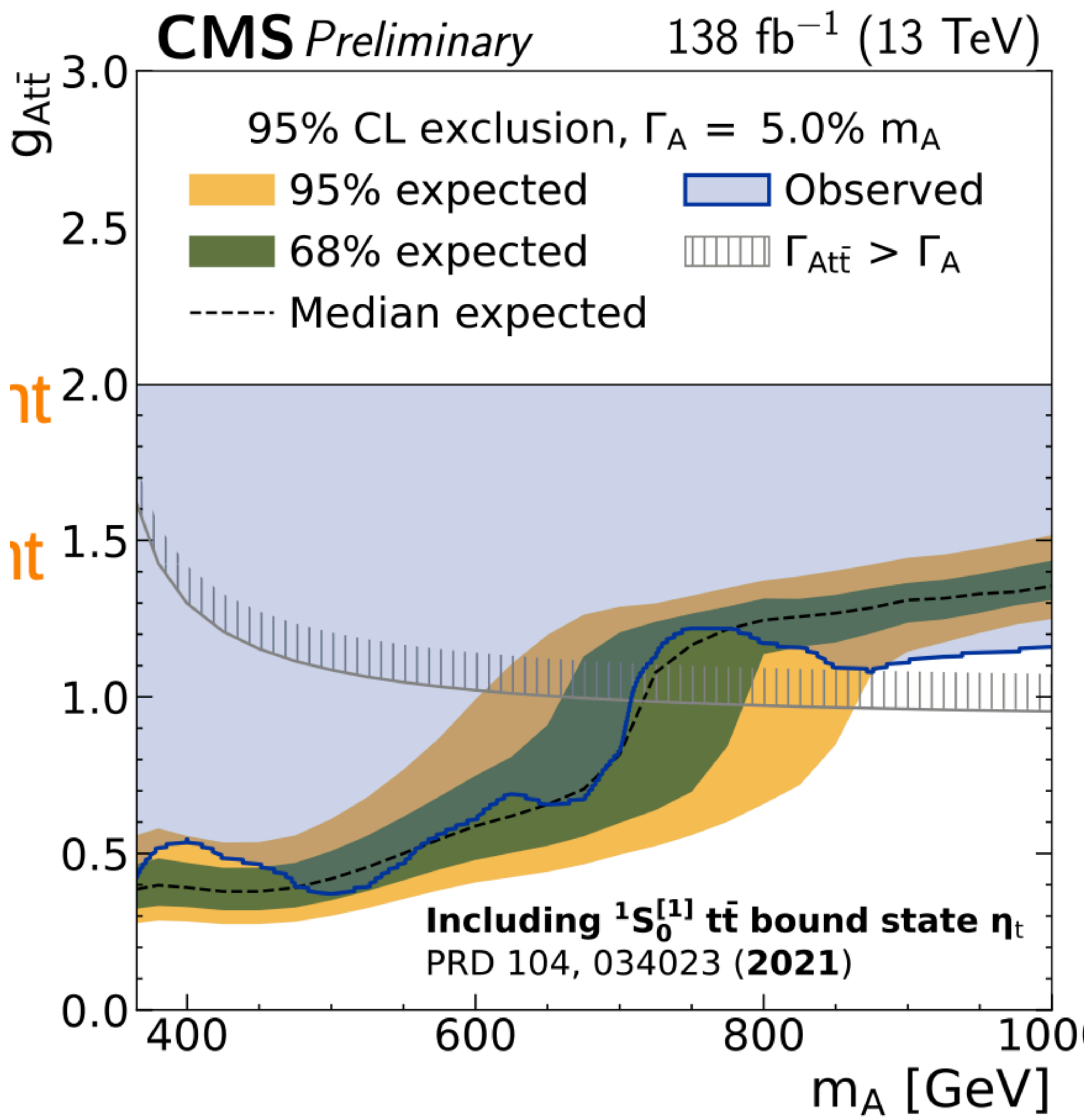


CMS-PAS-HIG-22-013

A/H -> $t\bar{t}$

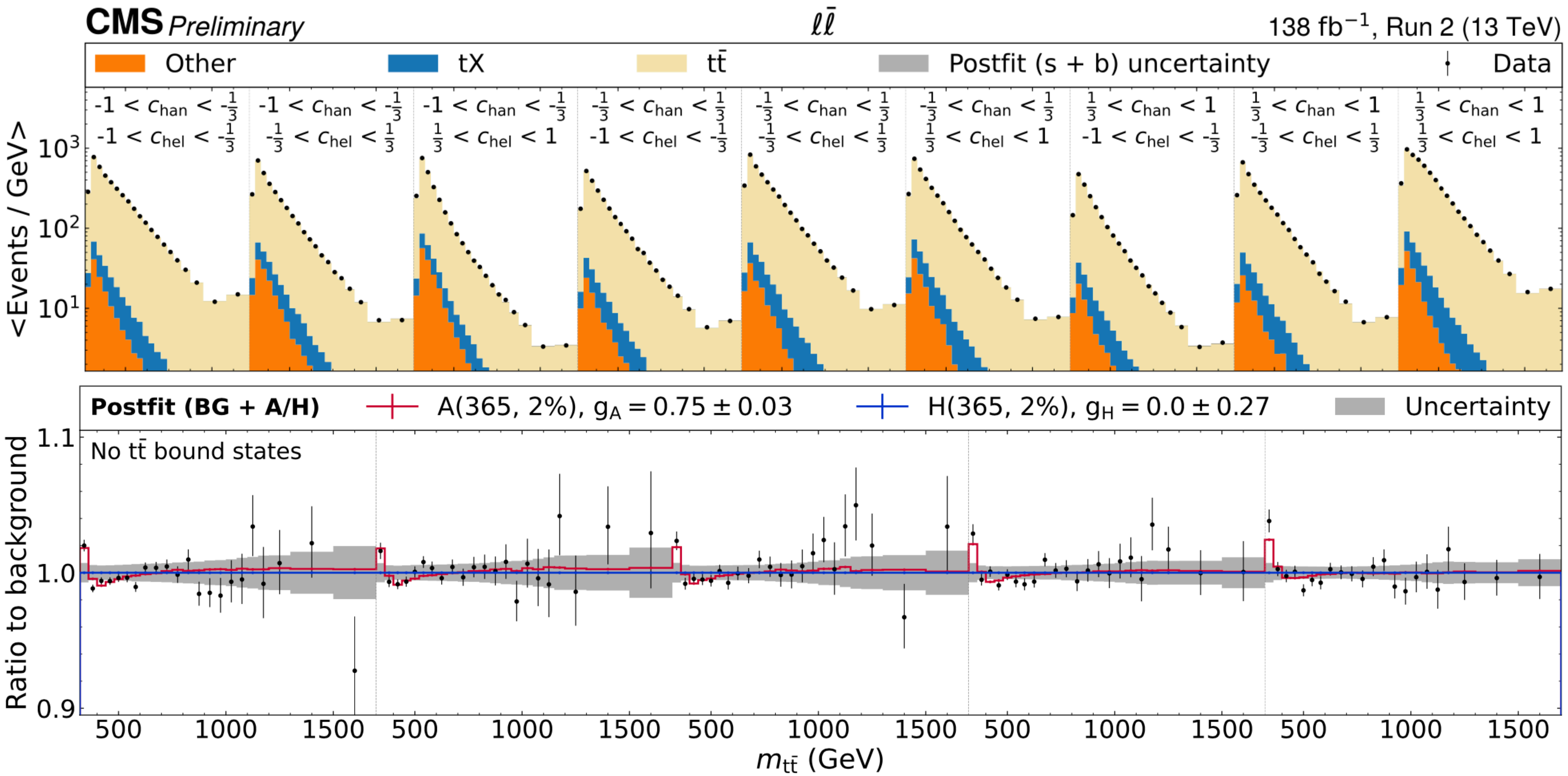
CMS-PAS-HIG-22-013

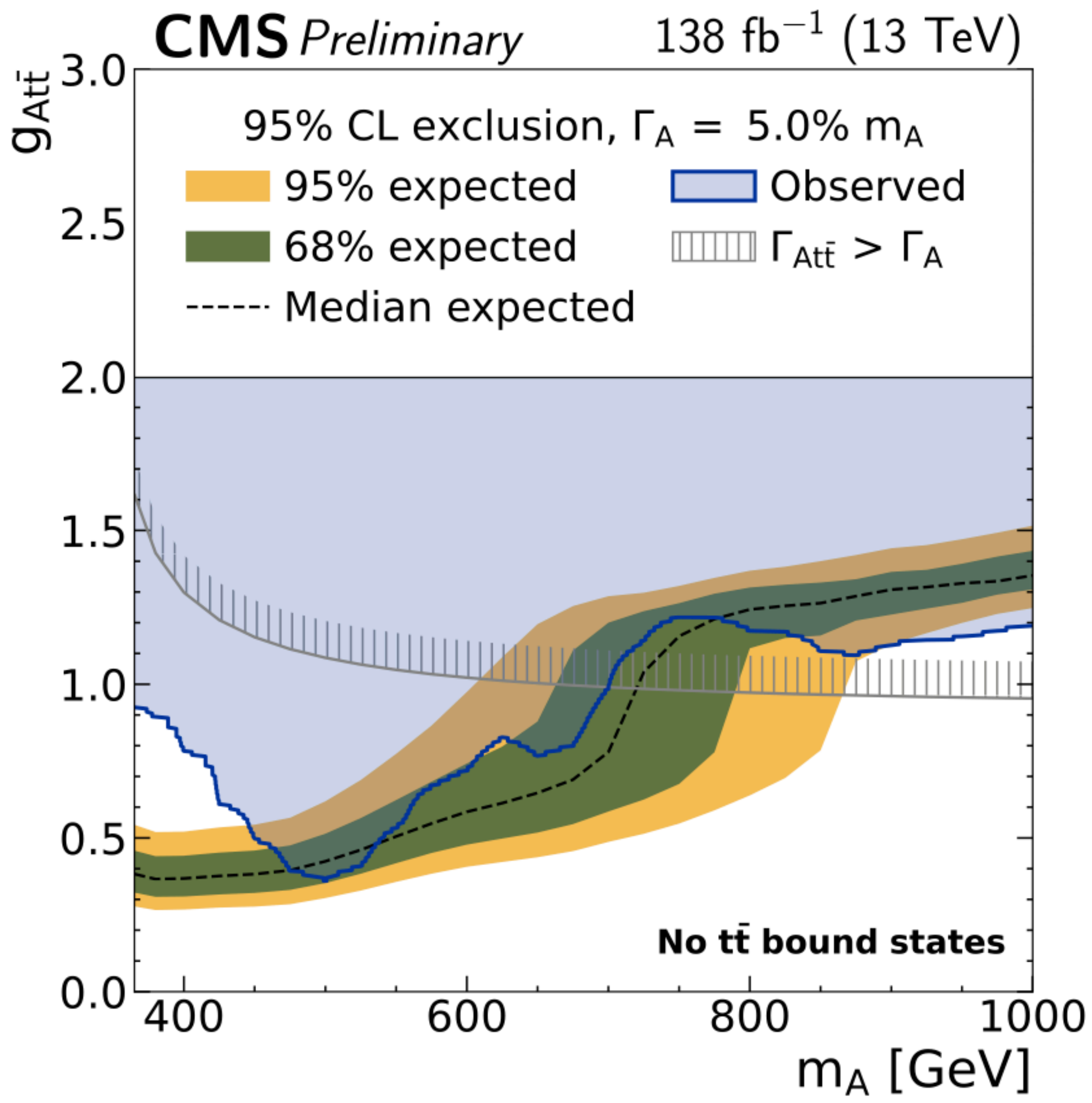




A/H -> $t\bar{t}$

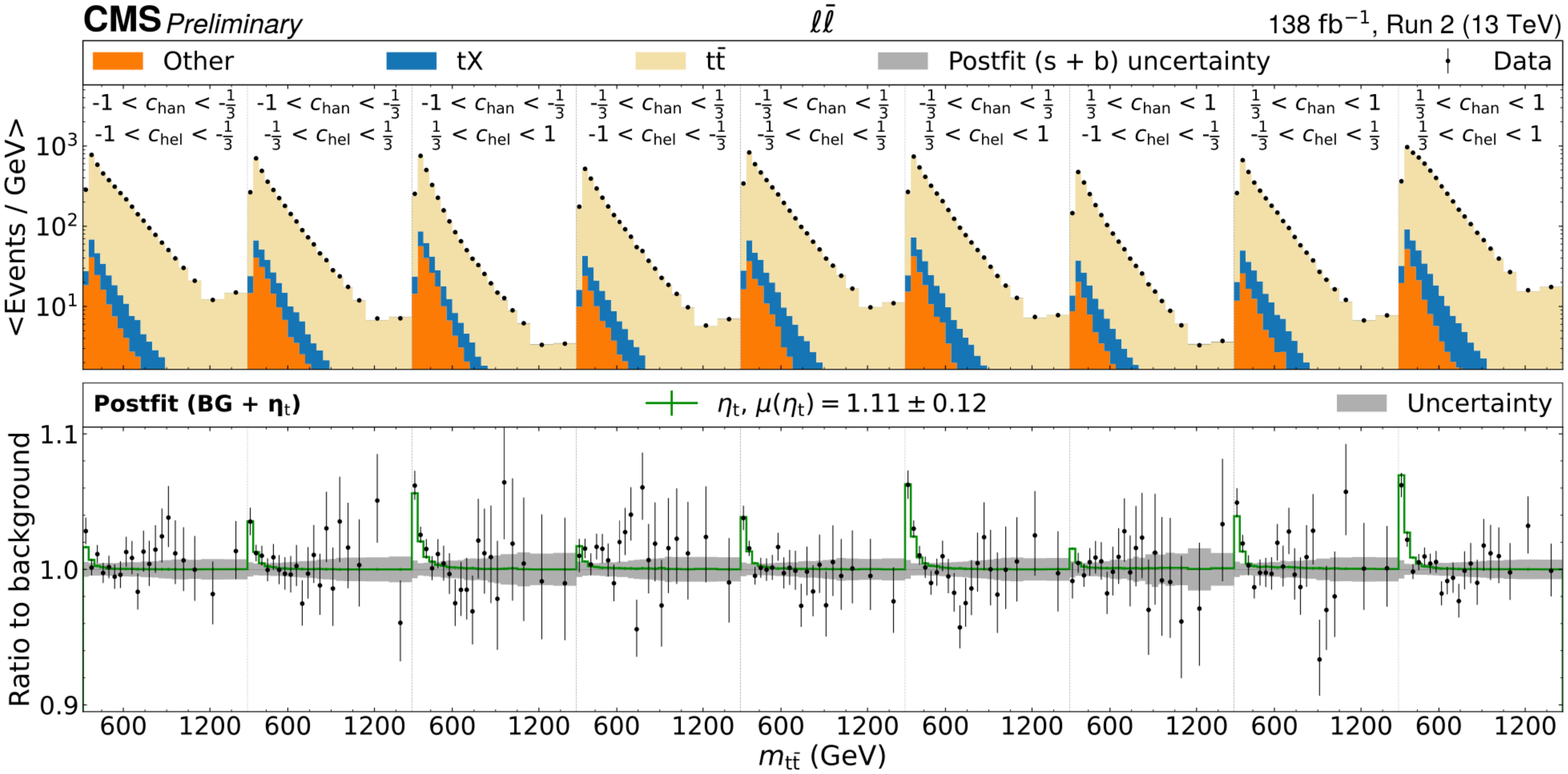
CMS-PAS-HIG-22-013





A/H -> $t\bar{t}$

CMS-PAS-HIG-22-013



Measured η_t cross section, 7.1 pb +/- 11%

using tt + tW MC at NLO (NLO QCD+NLO QED corrections)

NRQCD prediction for singlet toponium: 6.4 pb

PRD 104 (2021) 034023

Excess >5 SD, consistent with pseudosclar A or η_t

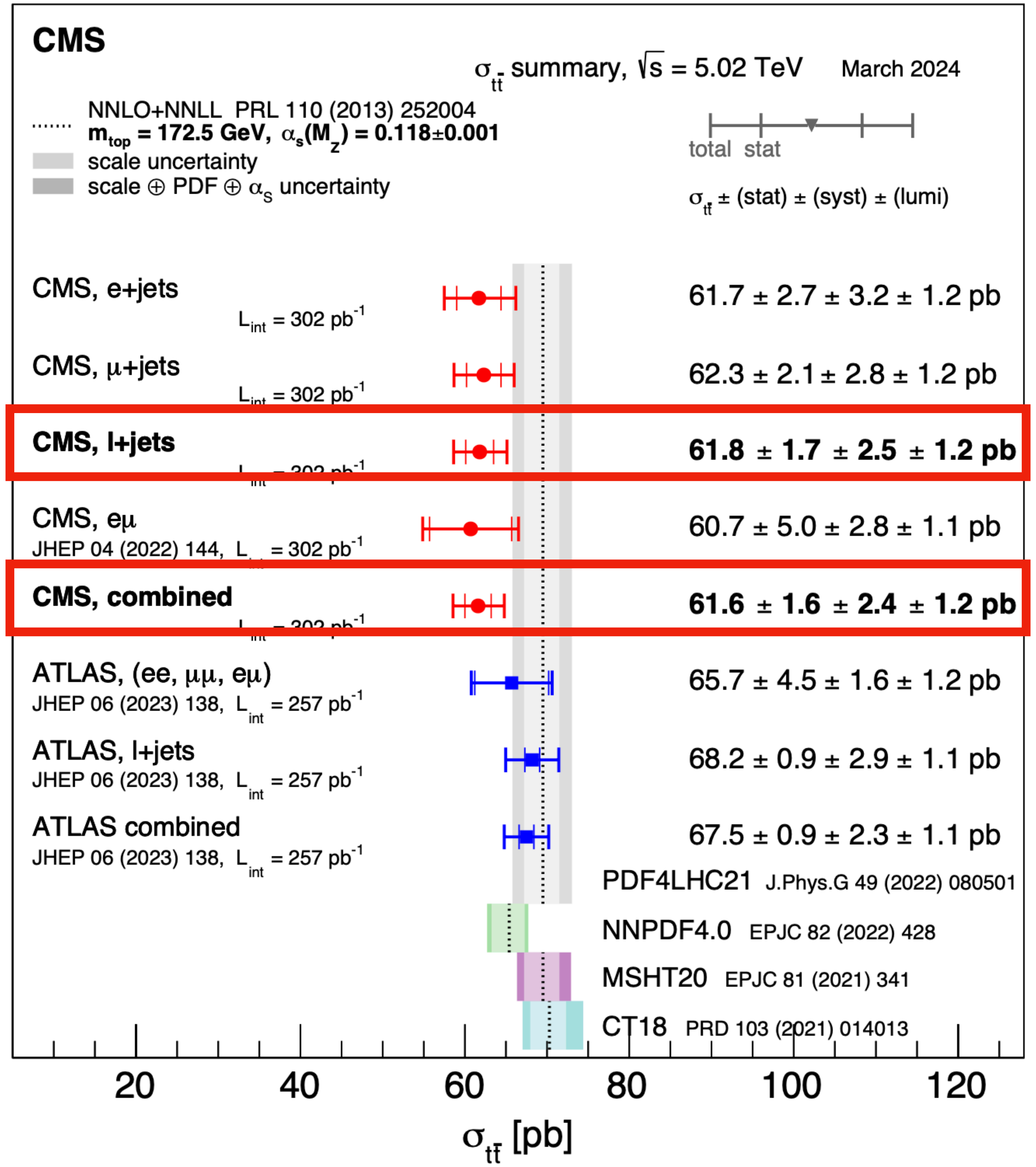
A complete non-relativistic QCD calculation of tt bound state effects is crucial!

Input from theory needed

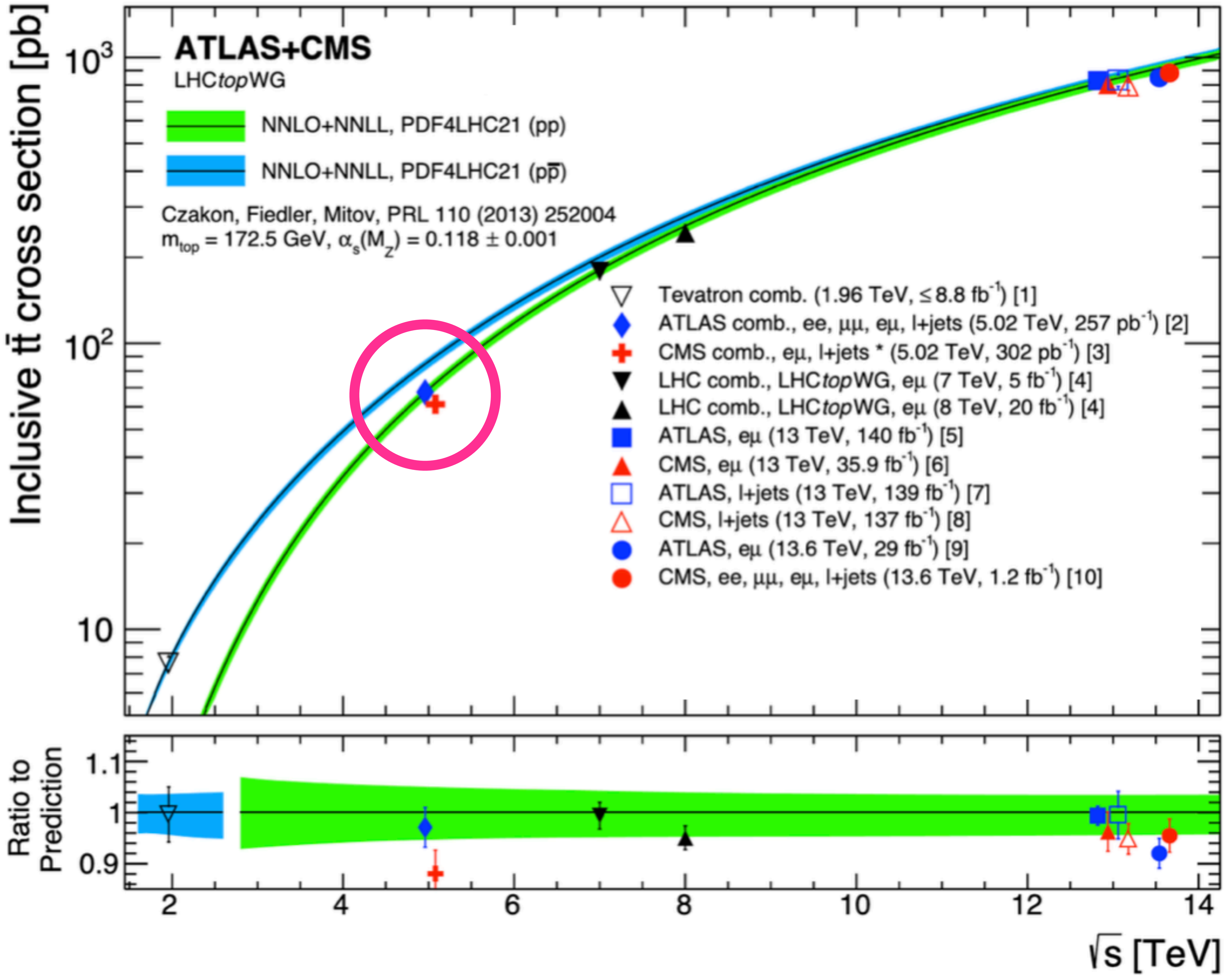
Top quark pair production at the LHC

CMS-PAS-TOP-23-005

5 TeV pp

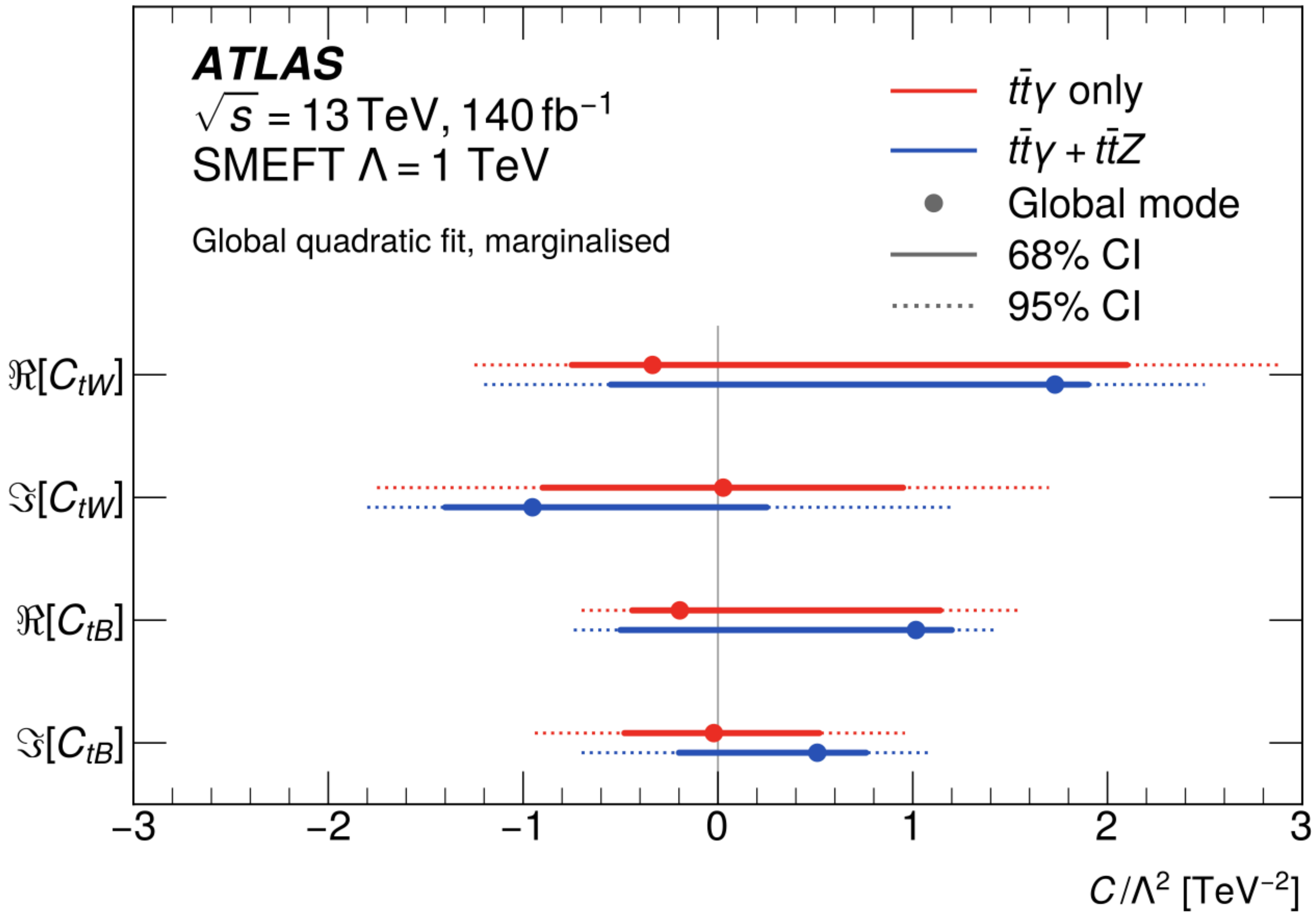


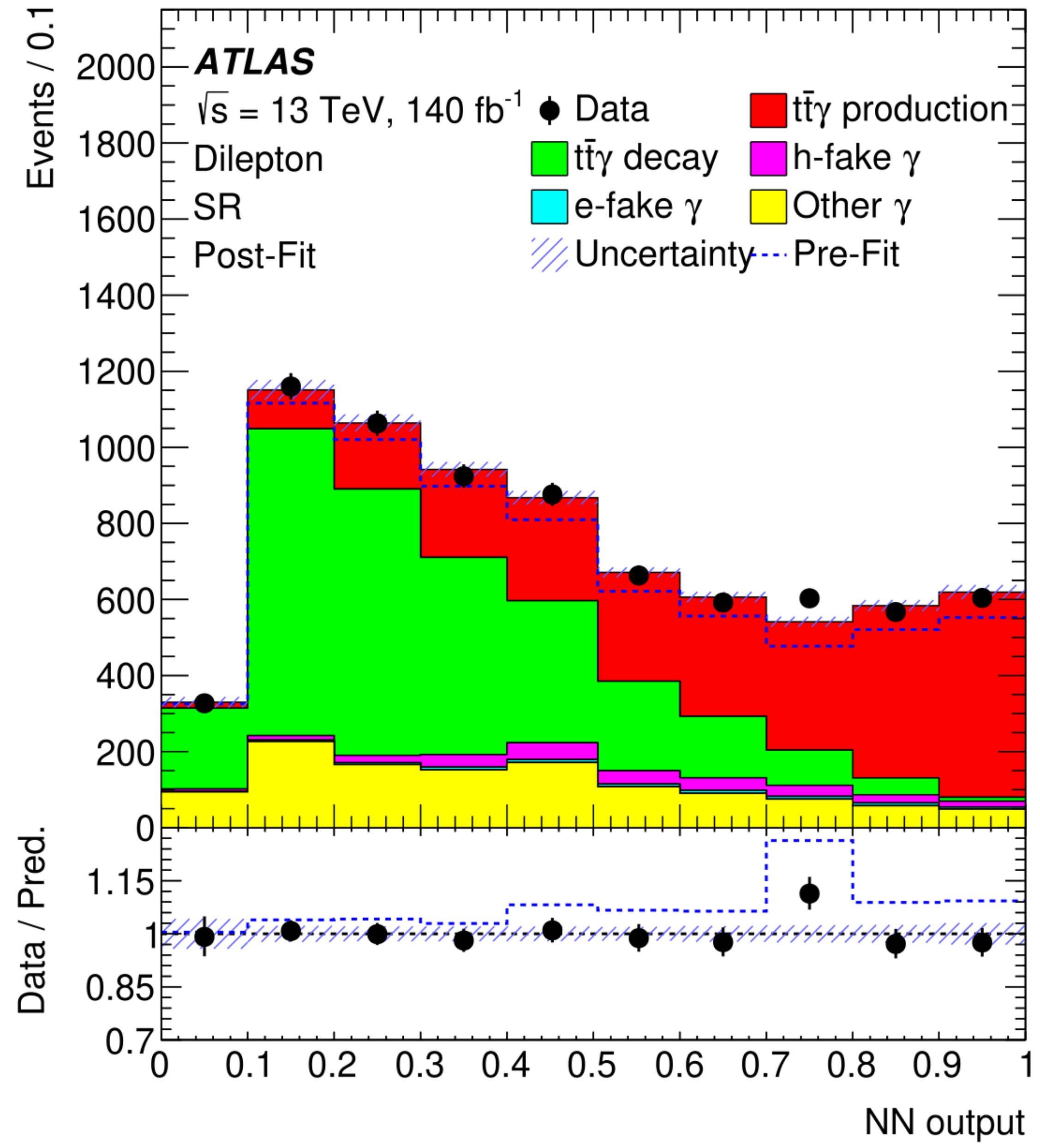
→ 5.2%

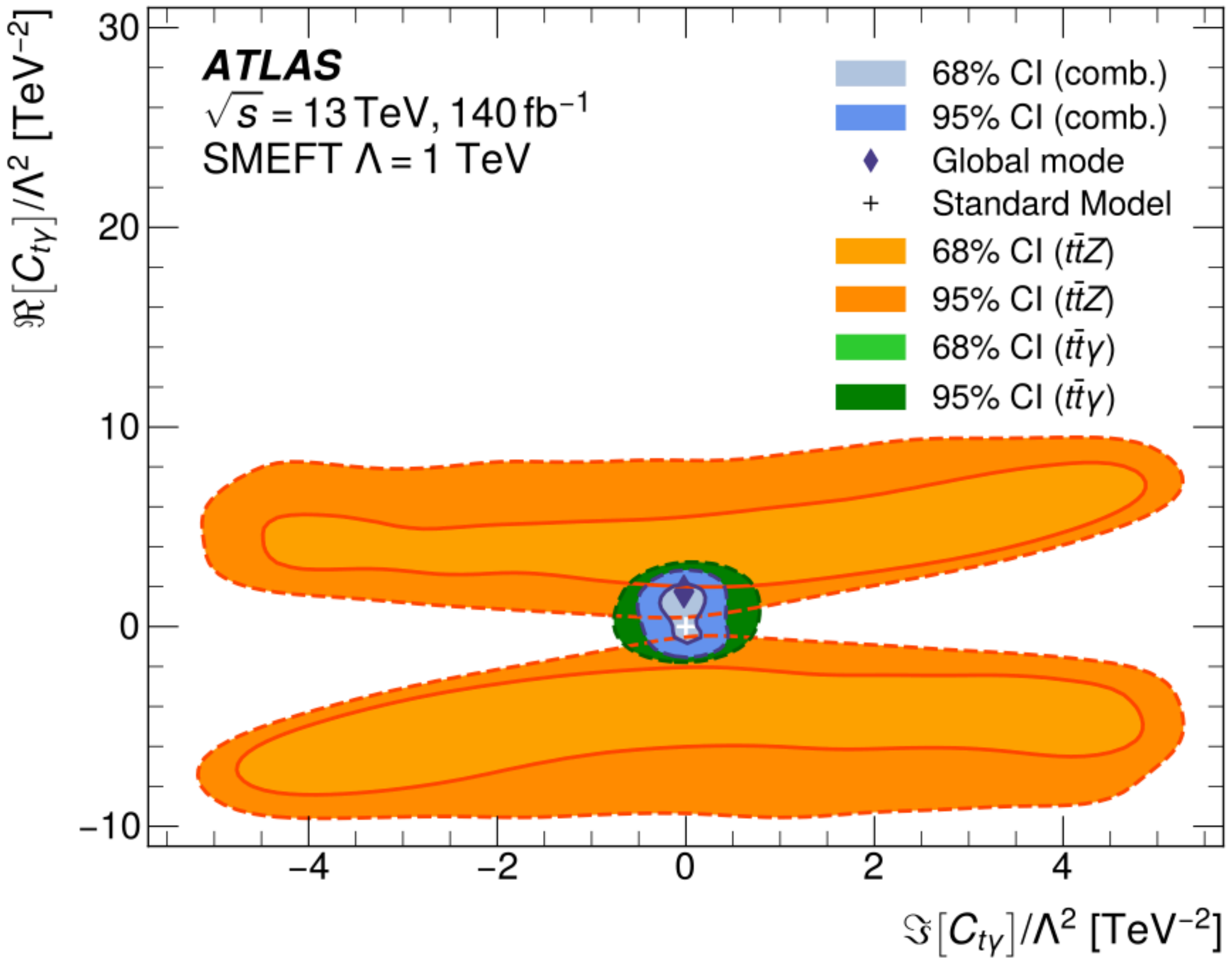


Top quark pair + γ production at the LHC

$$\mathcal{L}_{t\bar{t}X} = e\bar{t}\left[\gamma^{\mu}\left(C^{X}_{1,\mathrm{V}} + \gamma_5 C^{X}_{1,\mathrm{A}}\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\left(C^{X}_{2,\mathrm{V}} + \gamma_5 C^{X}_{2,\mathrm{A}}\right)\right] tX_{\mu},$$



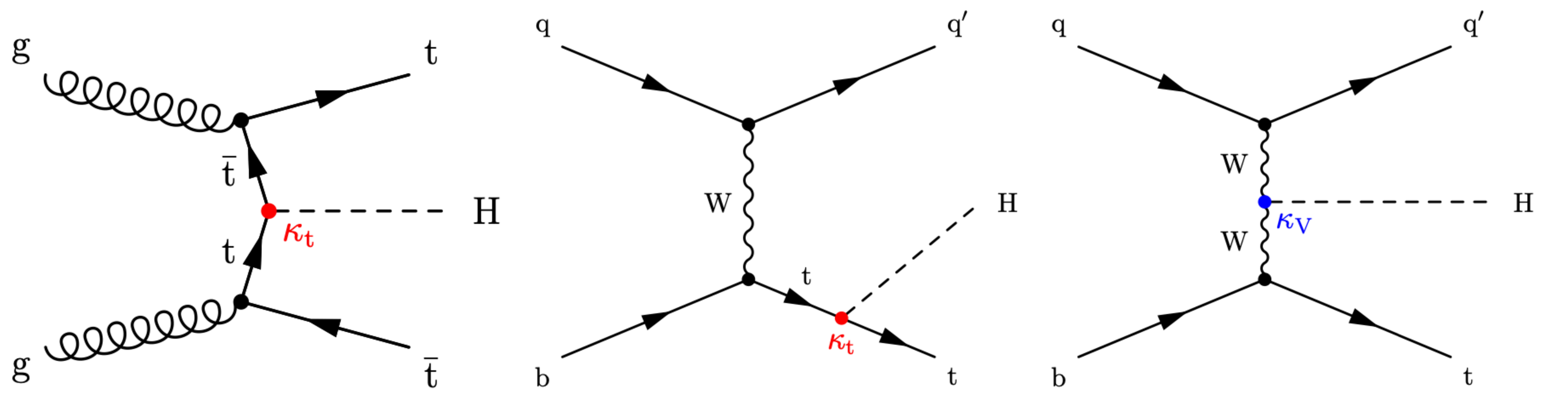


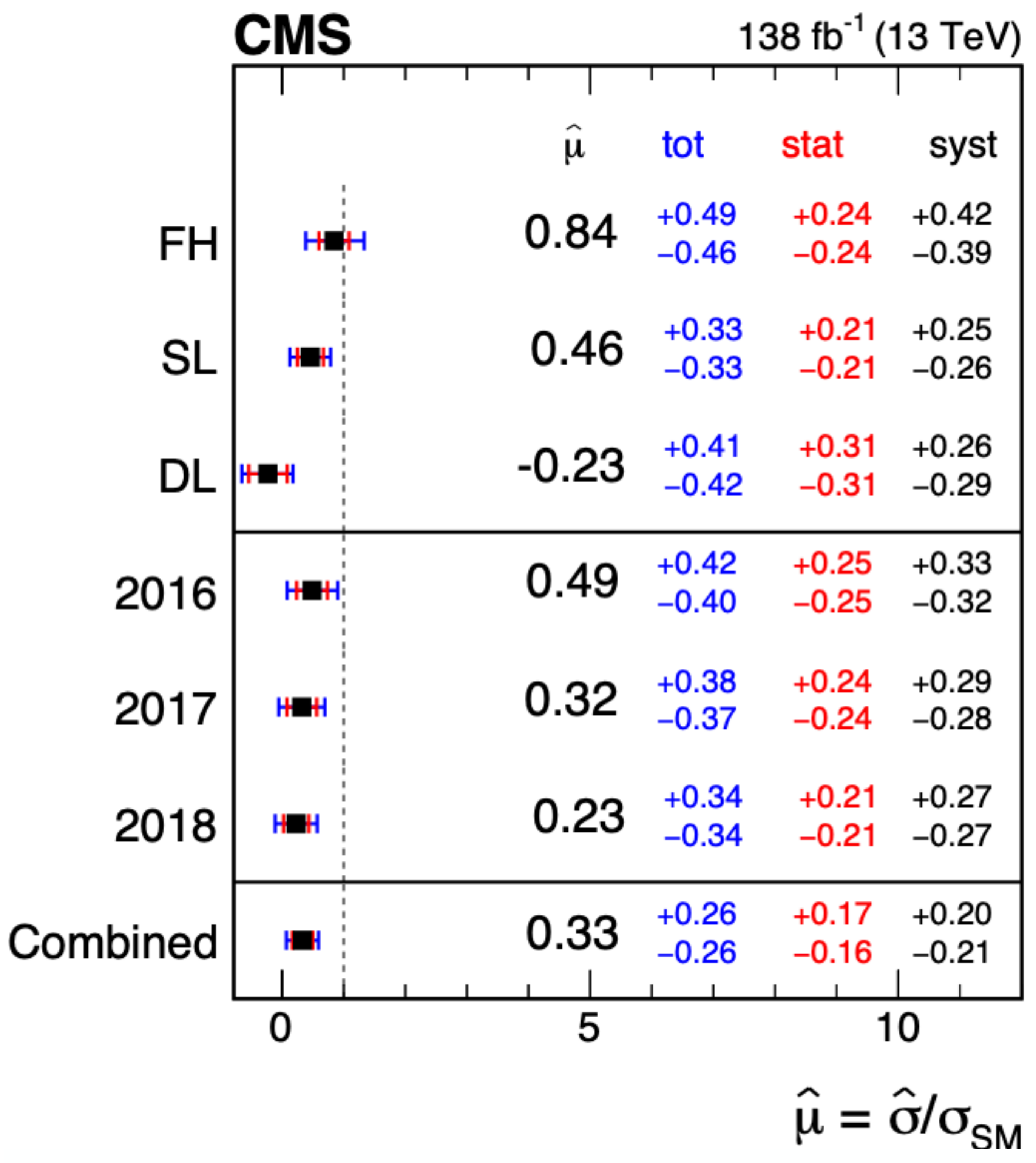


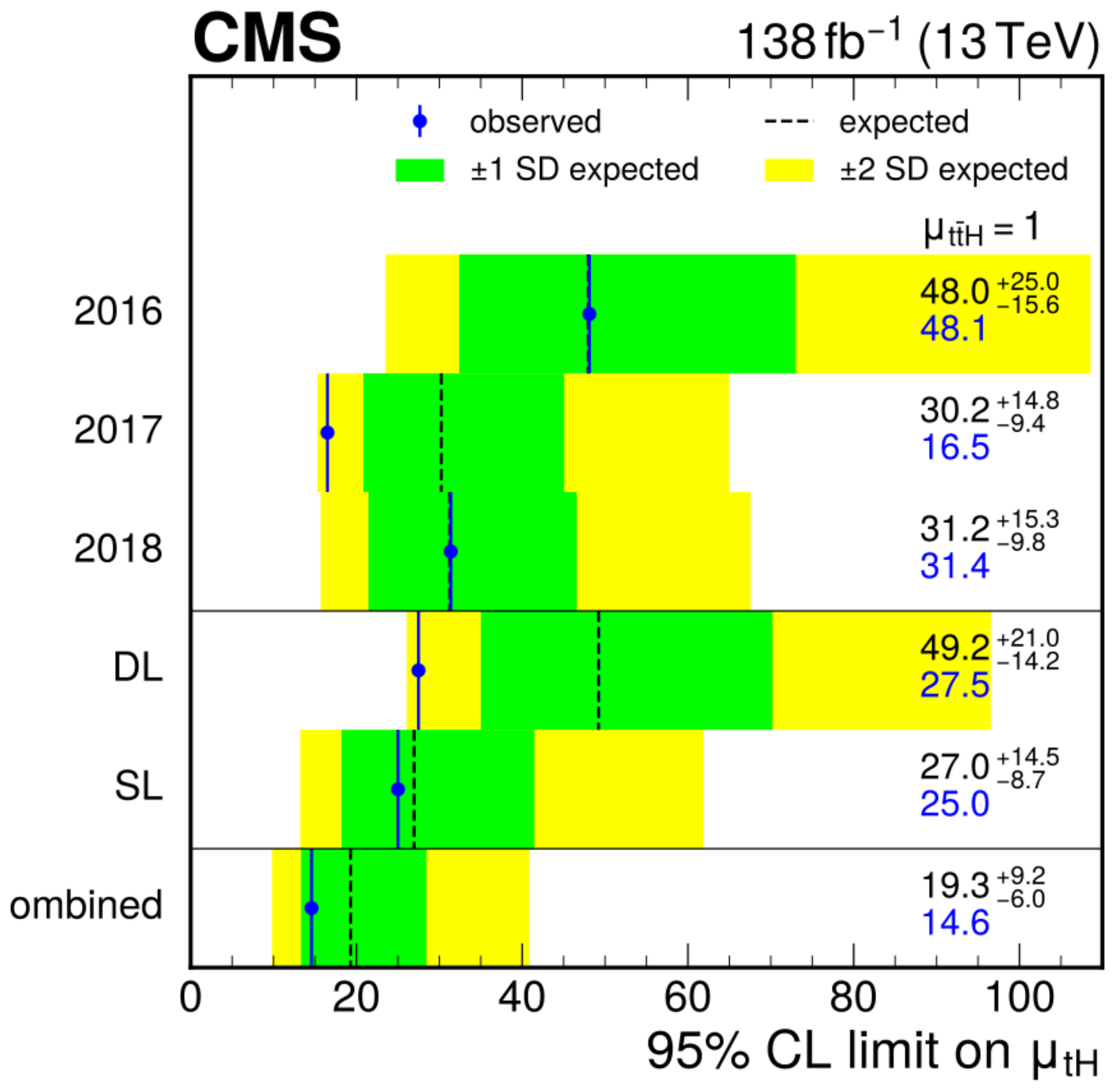
2403.09452

Top quark pair + H production at the LHC

arXiv:2407.10904







$t\bar{t}$ H production rate (relative to SM expectation):

μ_{ttH} **= 0.33 ± 0.17 (stat) ± 0.21 (syst)**

In agreement with previous ATLAS result

An observed (expected) upper limit on the tH production rate relative to the SM expectation of 14.6 (19.3) at 95% is derived

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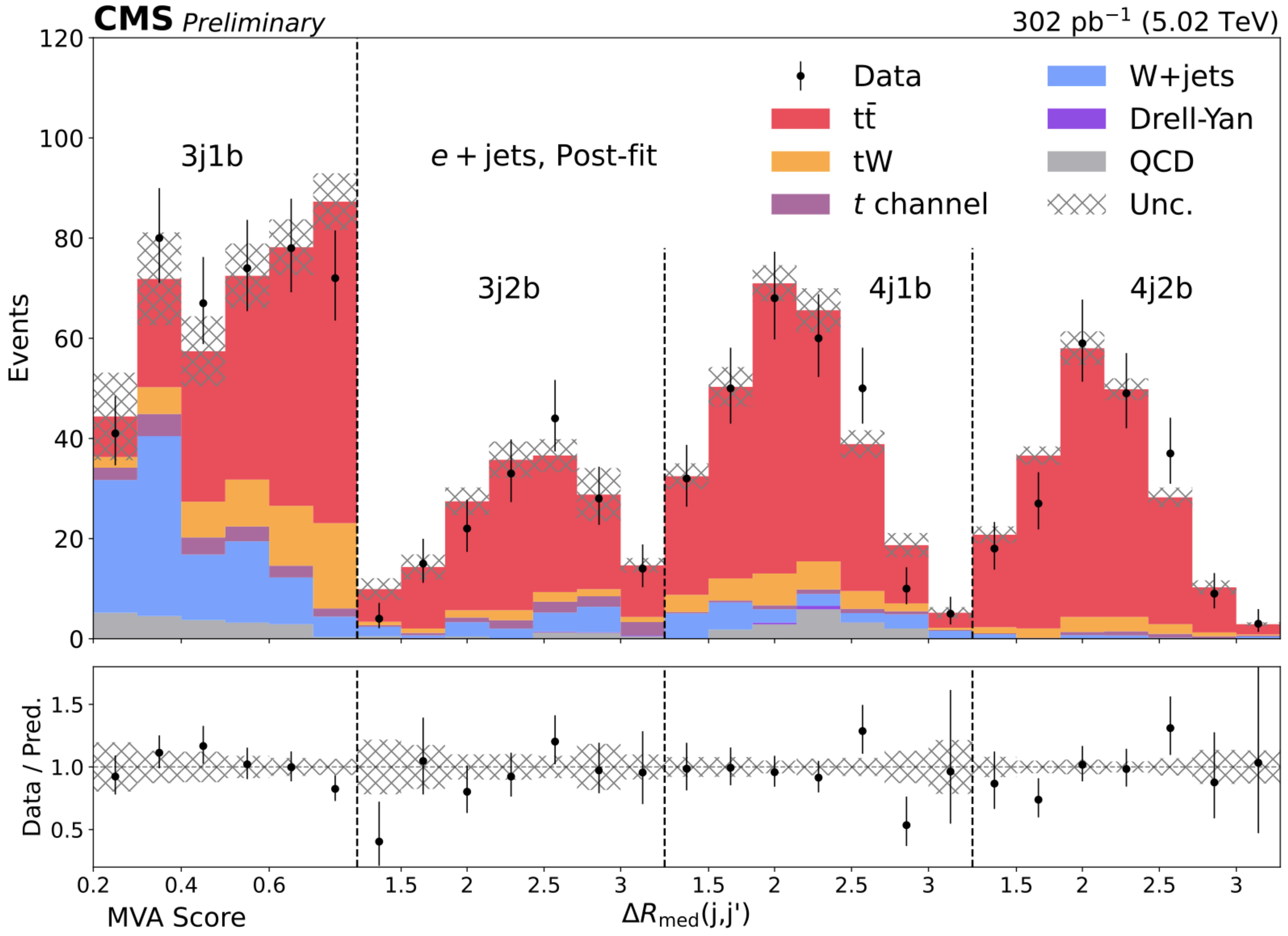
ATLAS EXPERIMENT

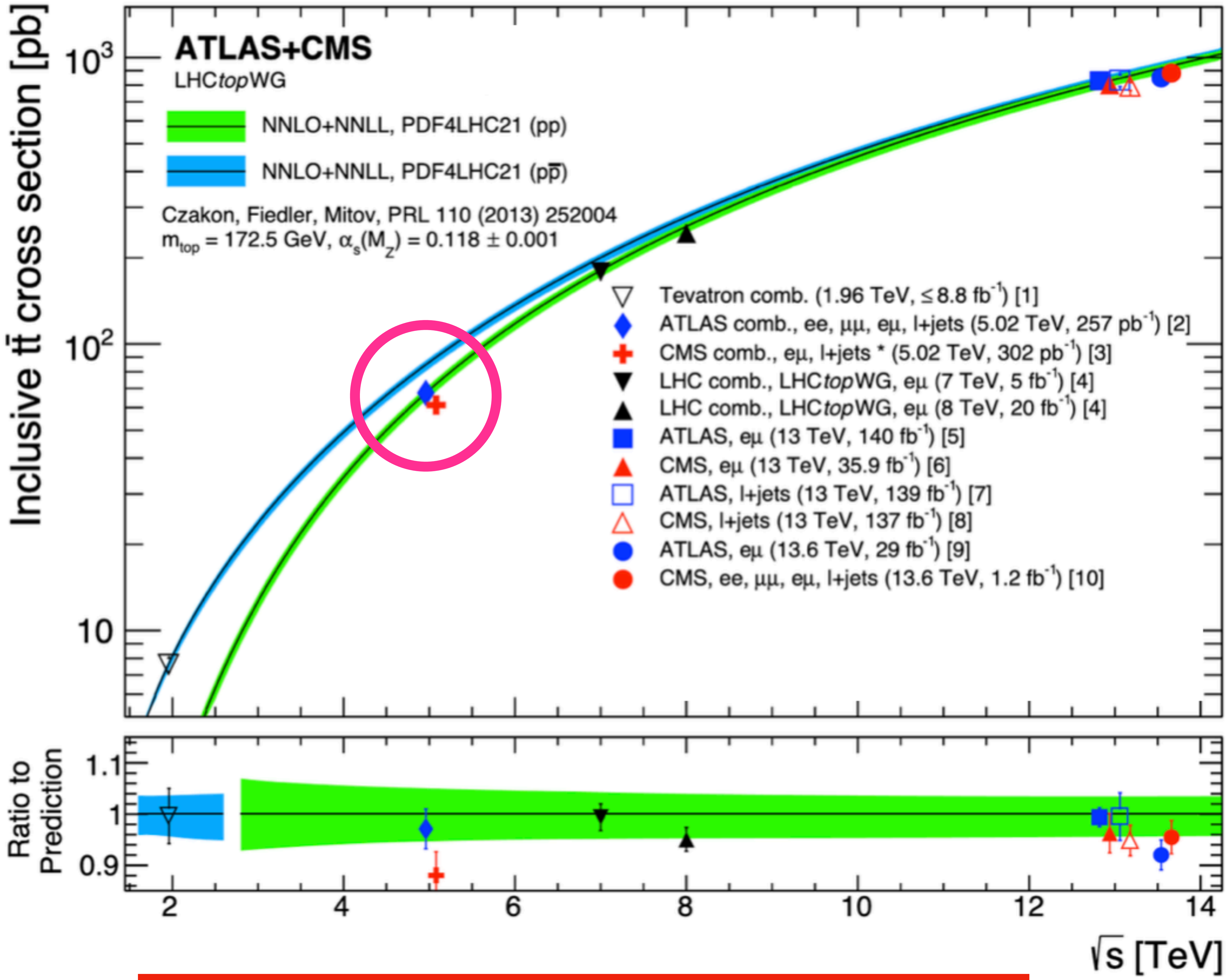
Top quark pair production at the LHC (5TeV)

CMS-PAS-TOP-23-005

5 TeV pp



- Low-intensity/low pileup run in 2017
- Top quark pair (tt) in single lepton channel, and data-driven QCD
- Events are classified based on the number of all reconstructed jets and of the b-tagged jets; the signal selection includes the usage of multivariate analysis techniques



61.4 ± 1.6 (stat)+2.7 (syst) ± 1.2 (lumi) pb.

In combination with dilepton channel

JHEP03(2018)115

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