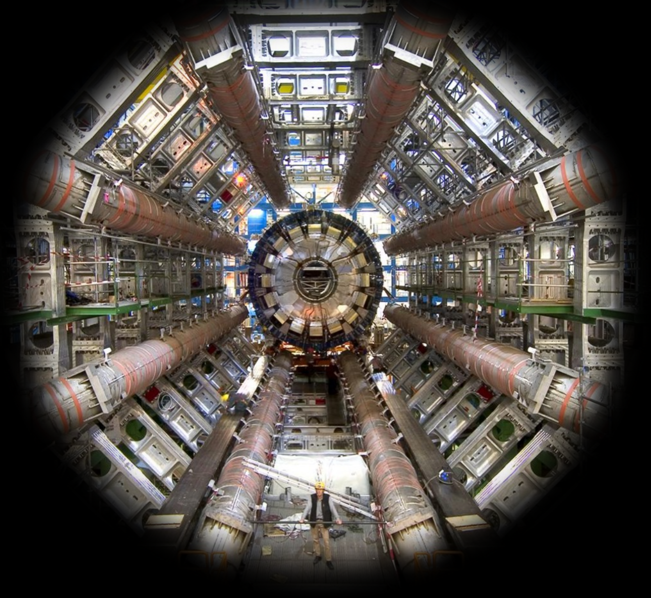
Standard Model top results overview



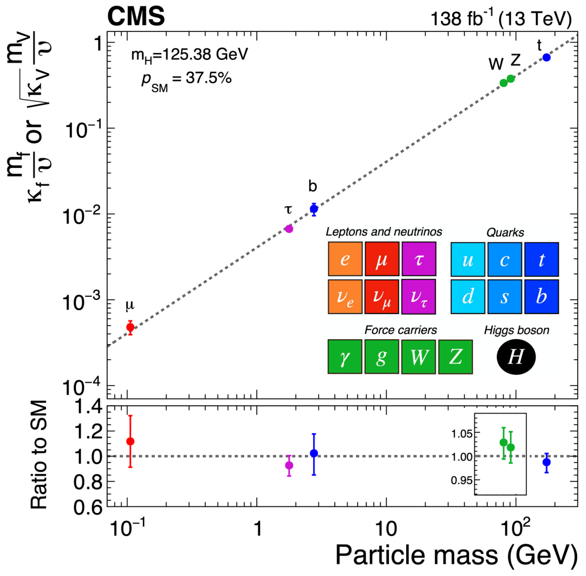
Didar Dobur
Ghent University

GHENT UNIVERSITY

On behalf of the CMS and ATLAS experiments

42nd International Conference on High Energy Physics
18-24 July 2024
Prague

Top quark production at LHC

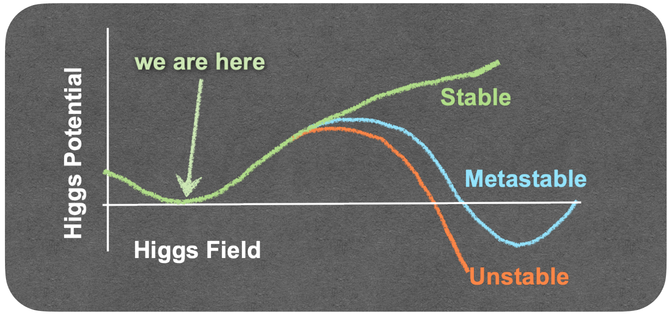


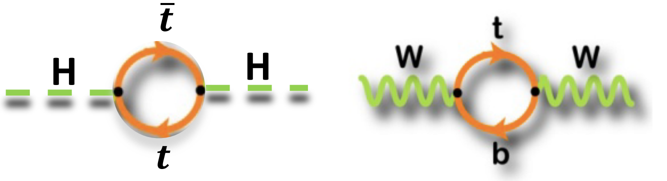
- The heaviest elementary particle

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

  → Quantum loop corrections

  → Impact on EWK vacuum stability

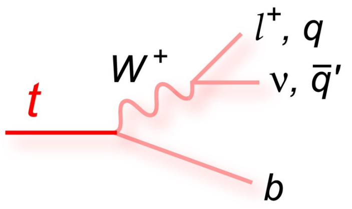




- Decays before hadronizing

  lifetime $<$ QCD timescale

  10^{-25}s $<$ 10^{-24}s



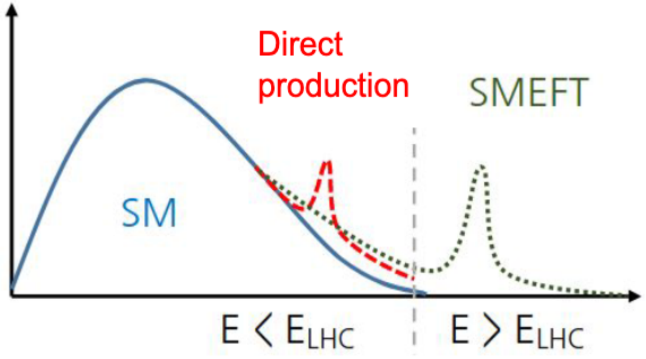
  → Access to 'bare' quark properties

- Excellent setting for testing pQCD predictions

  → Measurements $\sigma,\ \alpha_s,\ m_{Top}$, PDFs, …

- Potential portal to New Physics

→ Production & decay are sensitive to: anomalous couplings, cLFV, BNV, LFU, CP violation, FCNC, Charge asymmetry, Spin correlations …

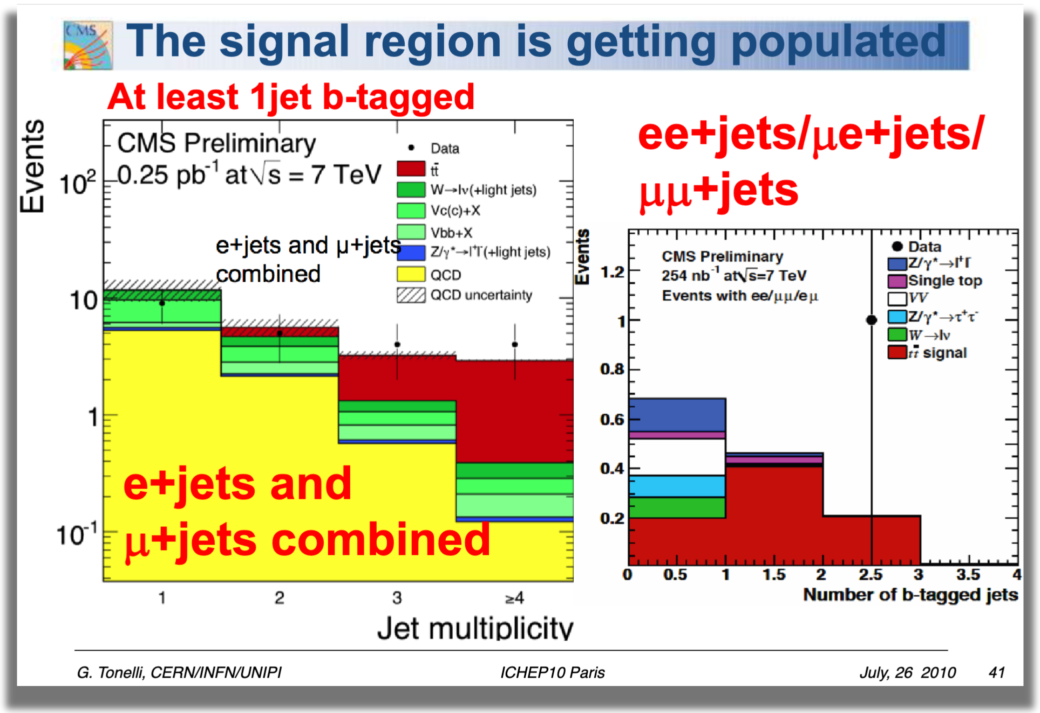


$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$$

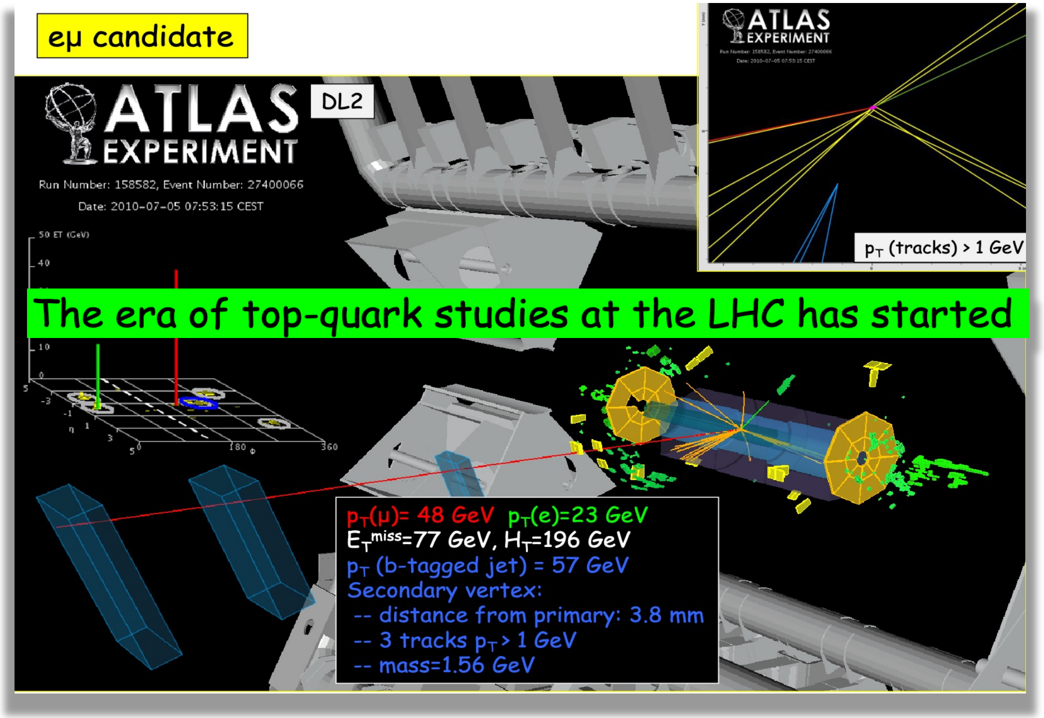
New for ICHEP`24

New

Top quarks at LHC at ICHEP 2010



CMS Spokesperson (G. Tonelli)'s report



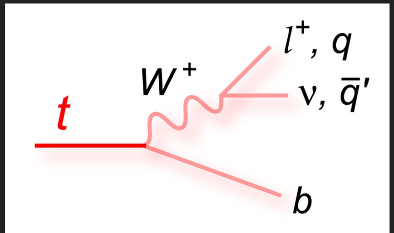
ATLAS Spokesperson (F. Gianotti)'s report

Since then, LHC provided ~200 M top-quark pairs to ATLAS & CMS

➡ more than 300 publications on top physics

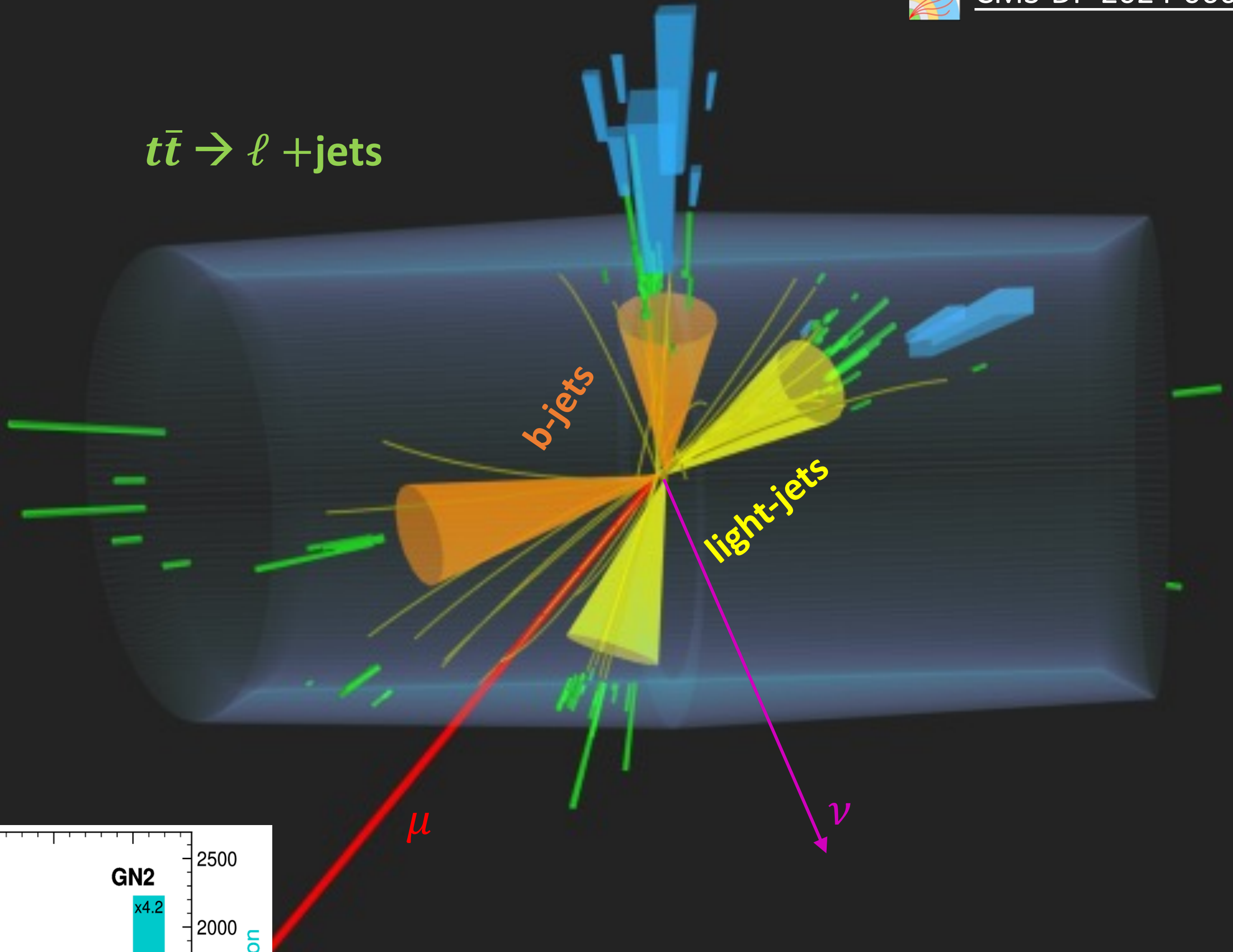
Top quark production at LHC

FTAG-2023-01
CMS-DP-2024-066



$\mathcal{B}(t \to Wb) \sim 100\%$

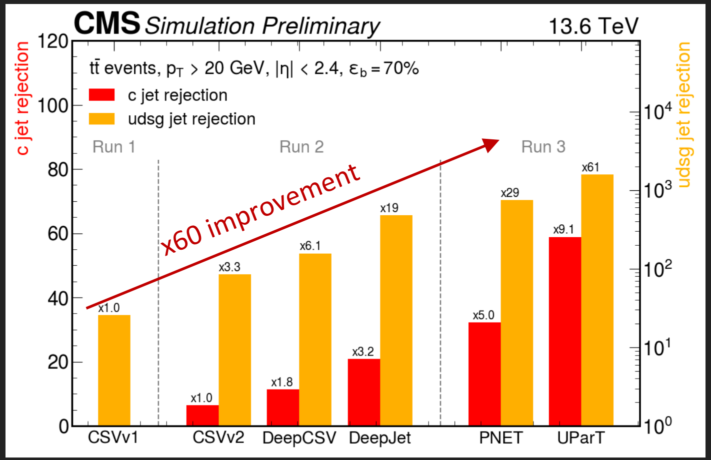
Dilepton: 9%
ℓ +jets: 45%
Fully hadronic: 46%

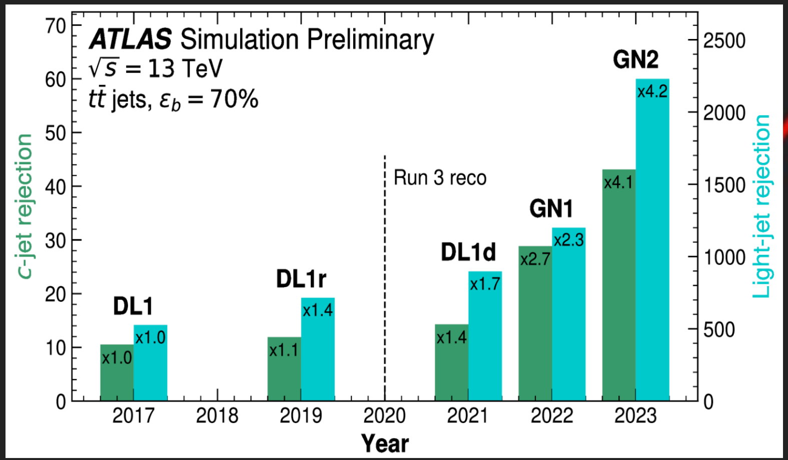


Ever increasing precision and performance of object identification and calibrations:

- Improved jet calibrations
- ML based lepton identification
- Luminosity uncertainty <1%

Improved b-jet tagging performance

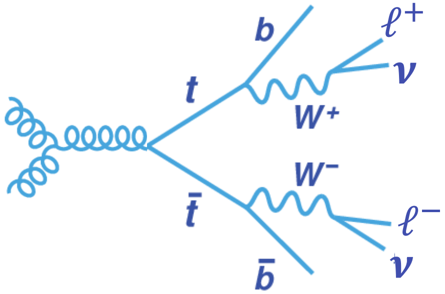




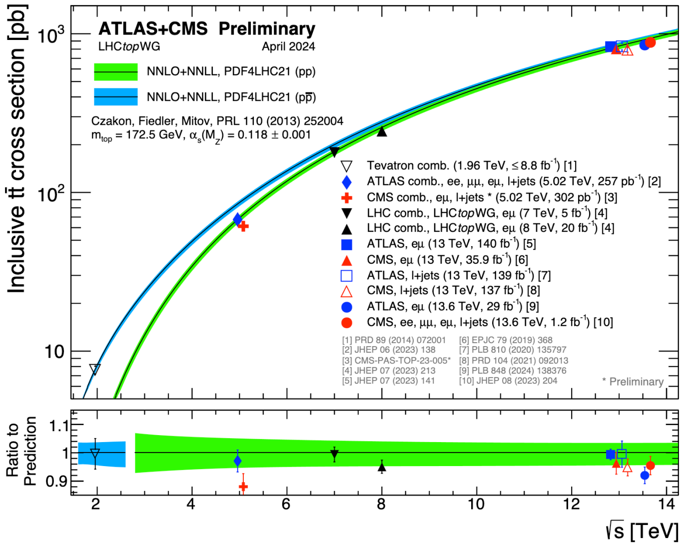
Top quark pair-production

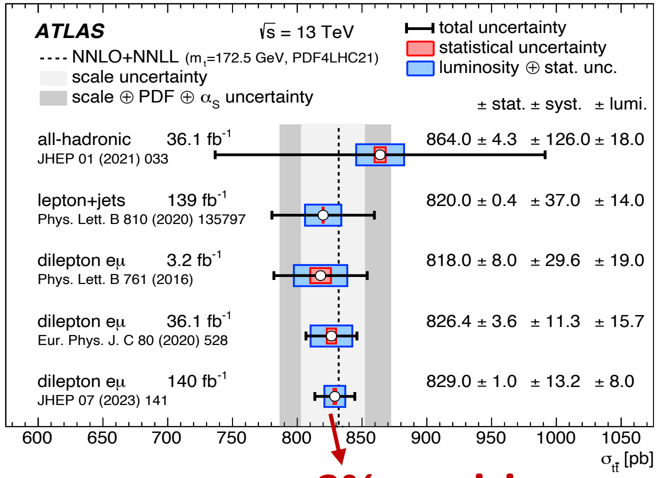
2404.10674 2406.19701

CMS-TOP-24-001



- Stringent tests of pQCD via inclusive and differential cross sections
- All decay channels and $\sqrt{s}$

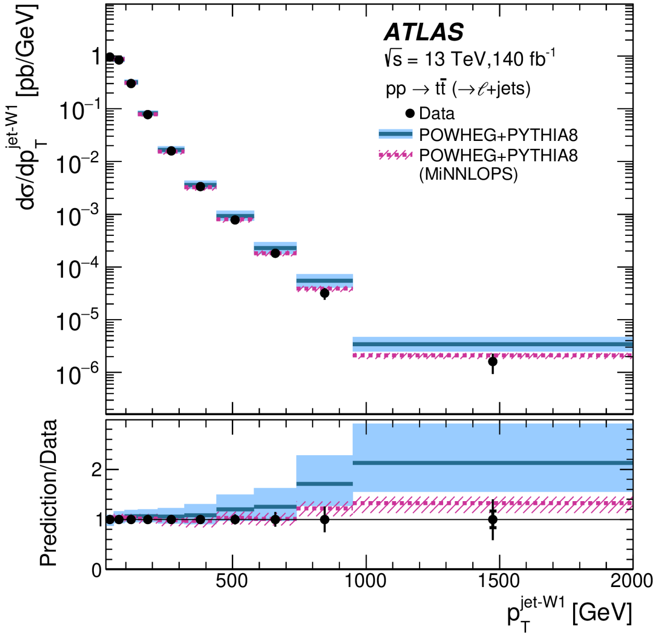




< 2% precision

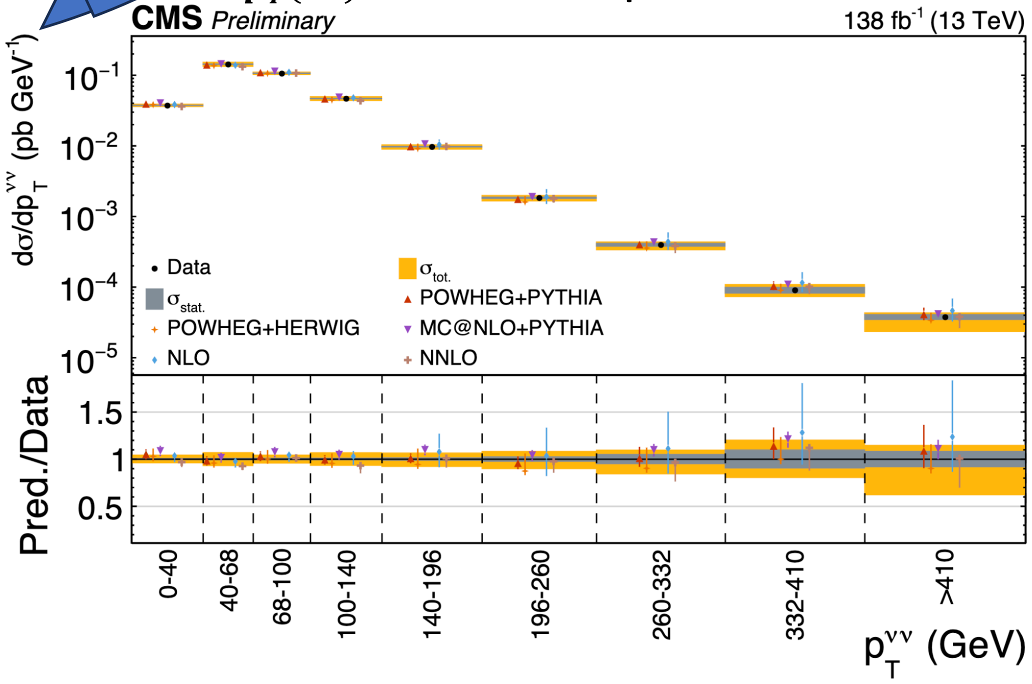
New

Jet p_T measured in $\ell + jet$ channel



New

$p_T(\nu\nu)$ measured in dilepton channel



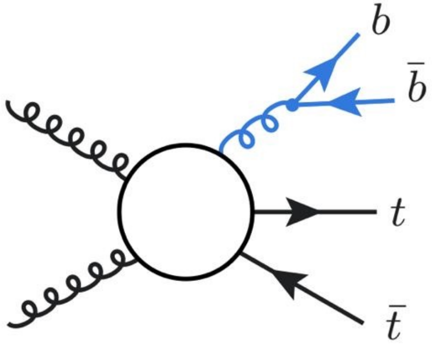
- First study of invisible part of $t\bar{t}$ system
- DNN to improve p_T^{miss} mismeasurements

Continuous exchange between the collaborations & theory community facilitated by LHCTopWorkingGroup

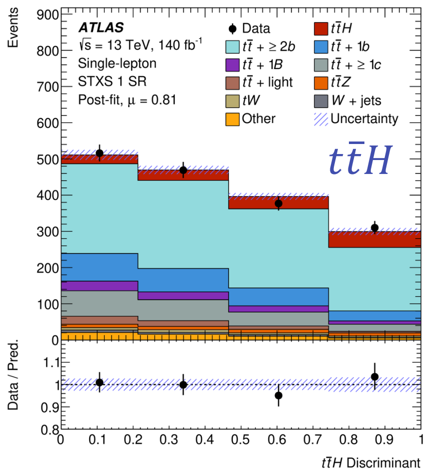
Measurements of $t\bar{t} + b\bar{b}$

2407.13473 2407.10904

JHEP 05 (2024) 042



- Sensitive to EFT operators
- Irreducible background for $t\bar{t}H, H \rightarrow b\bar{b}/c\bar{c}$, multi-top
- Difficult to simulate accurately



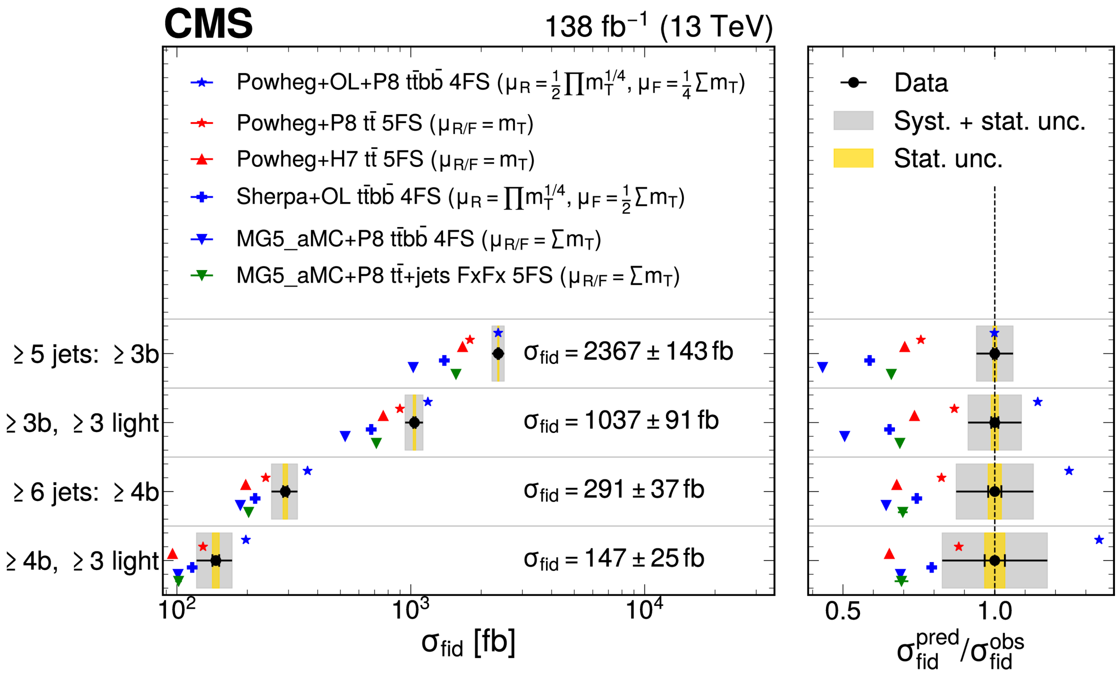
Extensive differential measurements:

→ various kinematic regions & modelling effects

→ Comparisons to state-of-the-art simulations

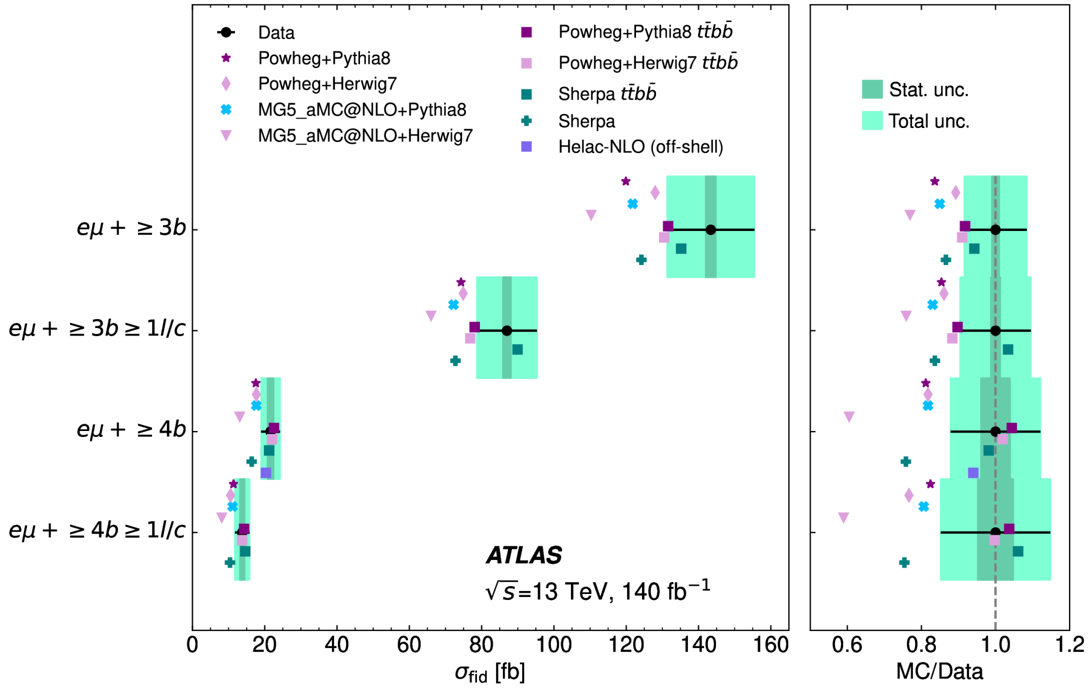
→ Additional b-quarks via ME(4FS) or via PS (5FS)

$\ell + jets$ channel

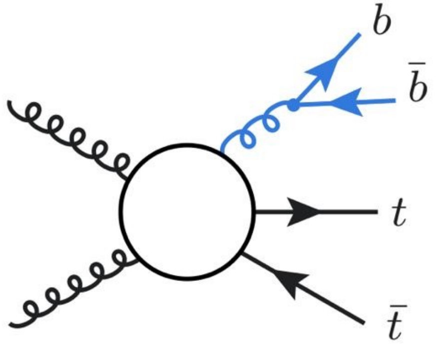


$e\mu$ channel

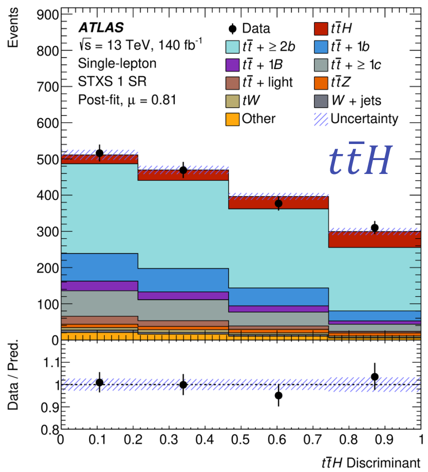
New



Measurements of $t\bar{t} + b\bar{b}$



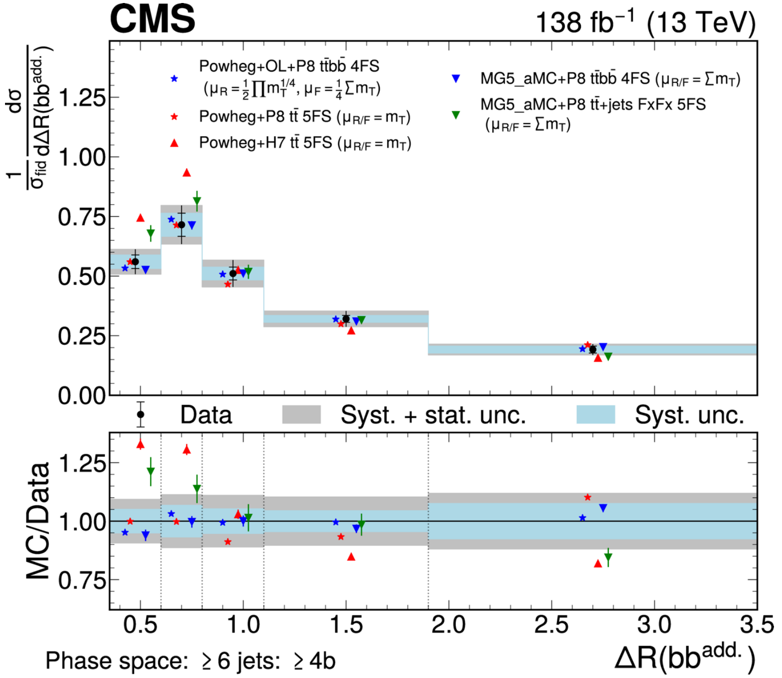
- Sensitive to EFT operators
- Irreducible background for $t\bar{t}H$, $H \to b\bar{b}/c\bar{c}$, multi-top
- Difficult to simulate accurately



Extensive differential measurements:

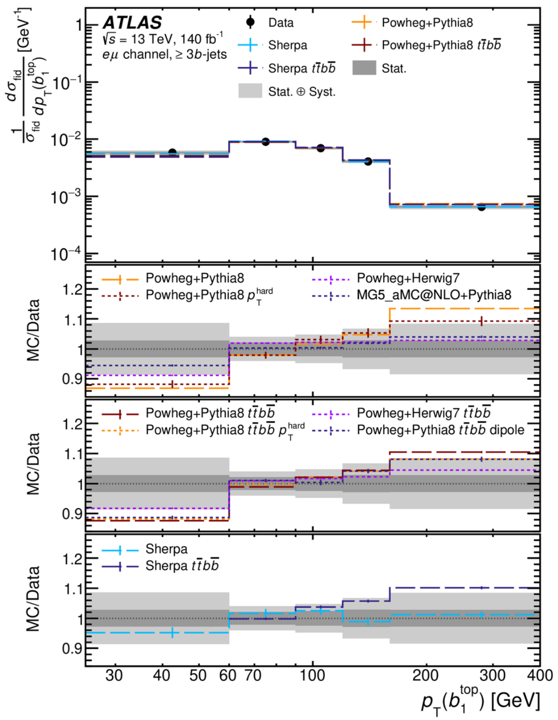
→ various kinematic regions & modelling effects
→ Comparisons to state-of-the-art simulations
→ Additional b-quarks via ME(4FS) or via PS (5FS)

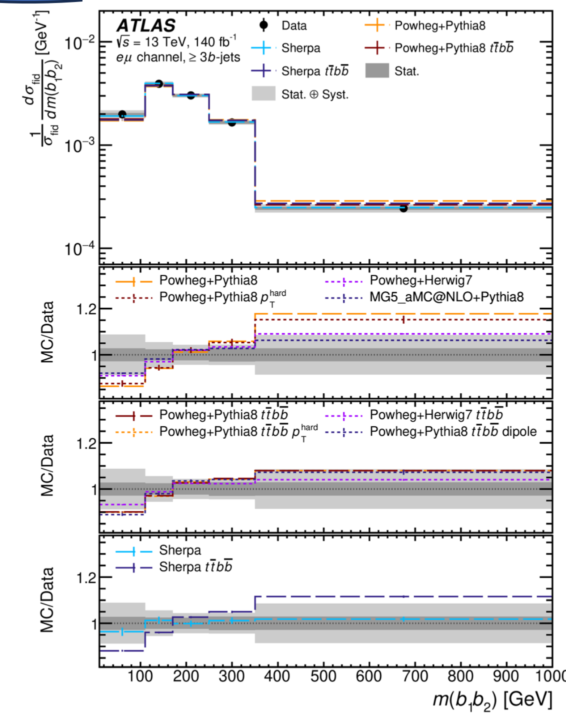
$\ell + jets$ channel



$e\mu$ channel

New

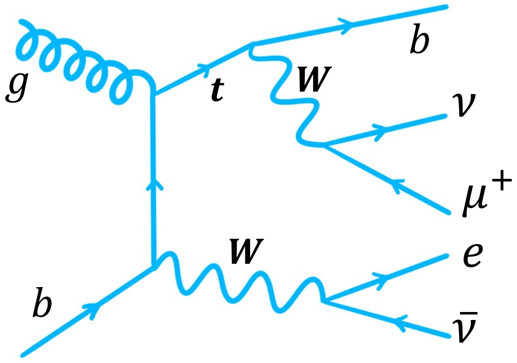




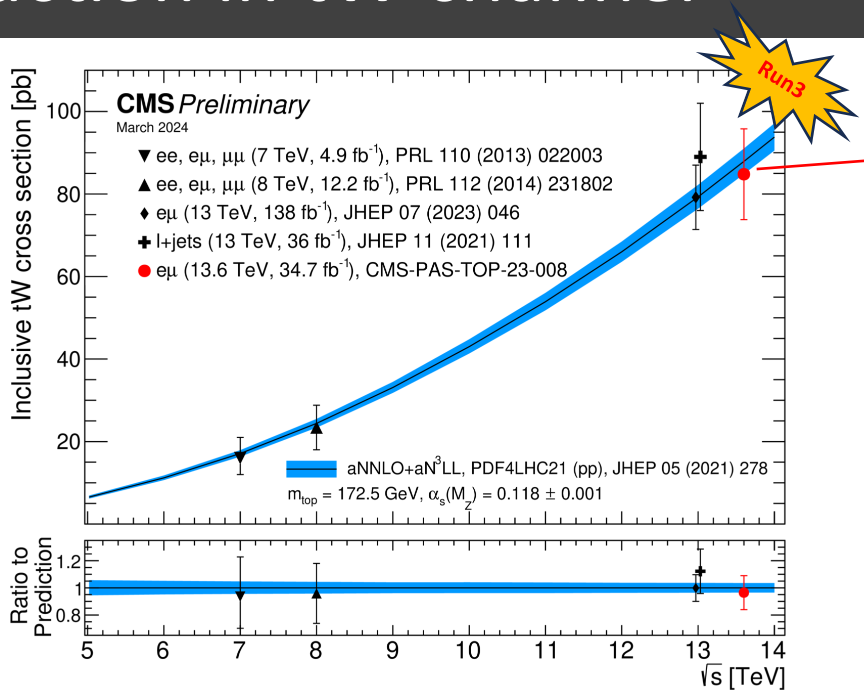
Single-top production in tW channel

CMS-TOP-23-008

2407.15594



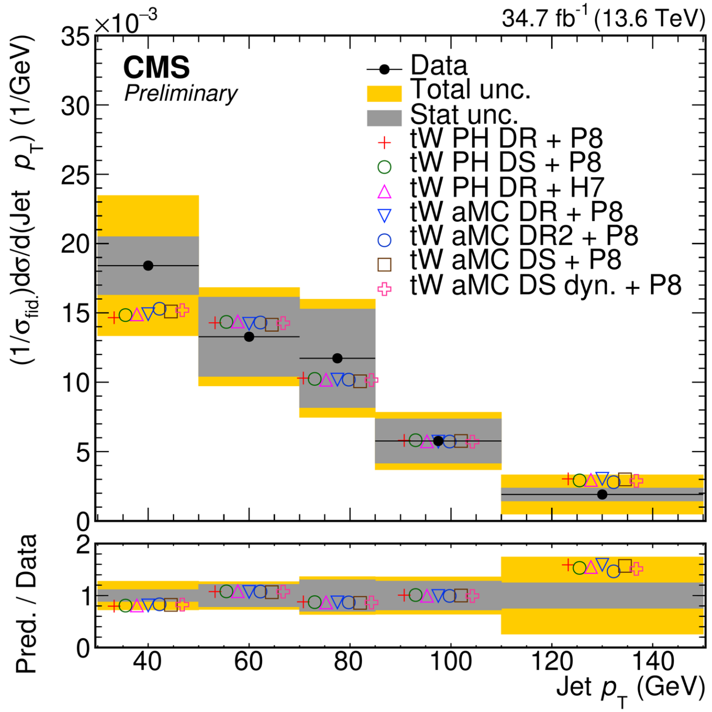
- Sensitivity to V_{tb} and b-PDF
- Large $t\bar{t}$ background
- tW @NLO interferes with $t\bar{t}$
- ML algorithms to separate tW from $t\bar{t}$



CMS measurement @13.6 TeV in $e\mu$ channel

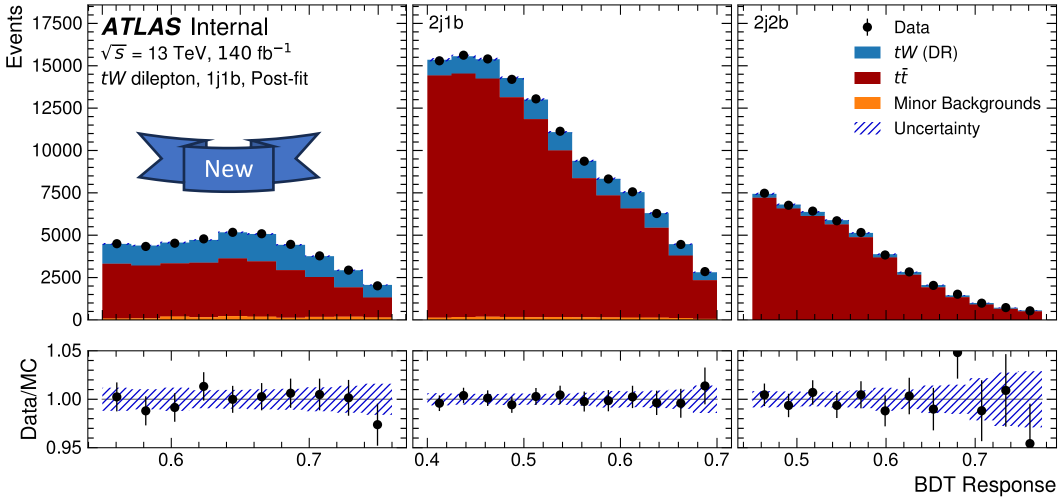
~13% precision

JES, b-jet, background



Comparisons to different models of handling the interference with $t\bar{t}$

ATLAS measurement in ee, $e\mu$, $\mu\mu$ channel



Measured @13 TeV (40% improved)

$$\sigma(tW) = 75.6^{+14.9}_{-14.3}\ \text{pb}$$

~19% precision

$t\bar{t}$ / tW modeling, JES, MET

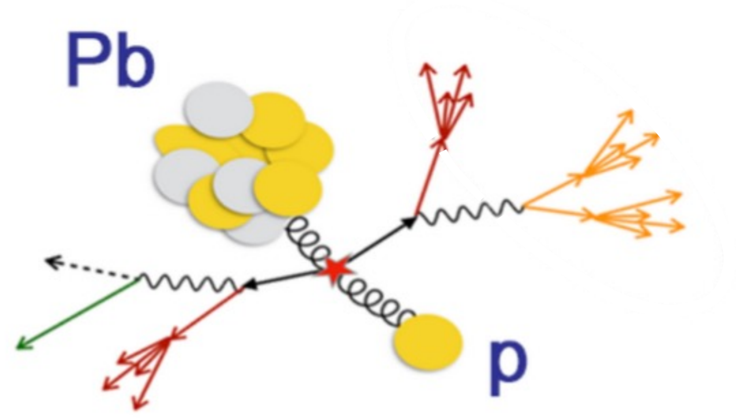
Measured V_{tb}:

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

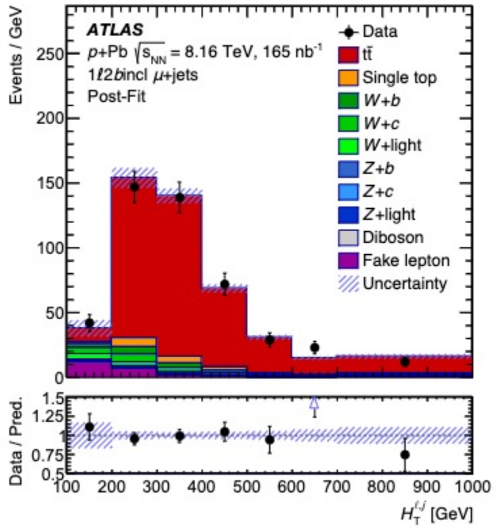
It is complementary to other measurements

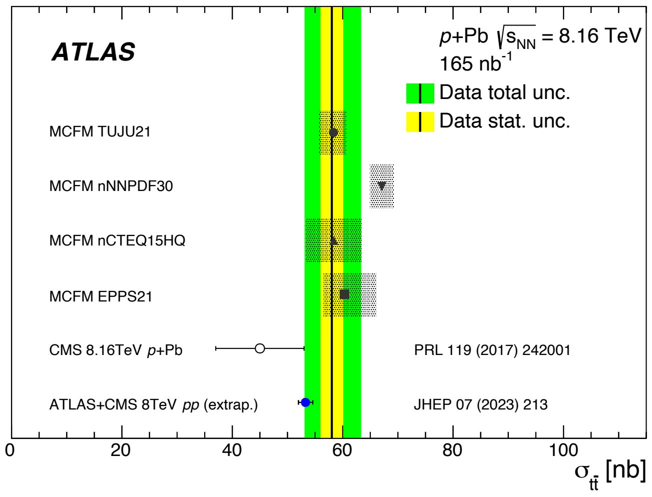
Top quark production in nuclear collisions

arXiv:2405.05078
PRL.119.242001
PRL. 125.222001

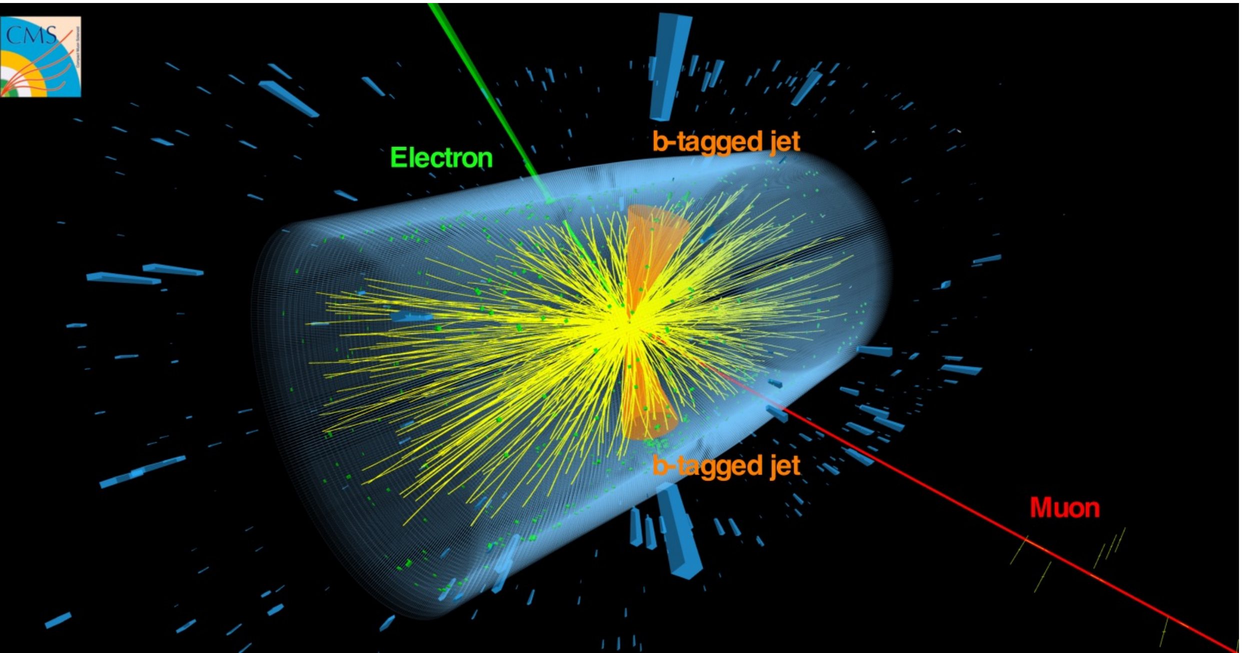


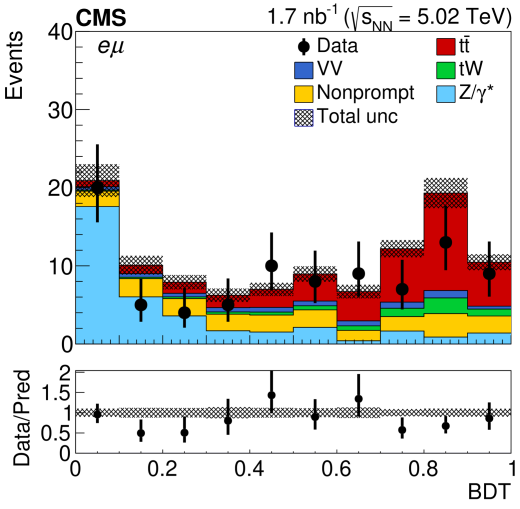
- $pPb\ (PbPb) \rightarrow t\bar{t}$
- Probes of nuclear PDF at high-x
- Observation of $t\bar{t}$ production in *p-Pp* collisions CMS & ATLAS

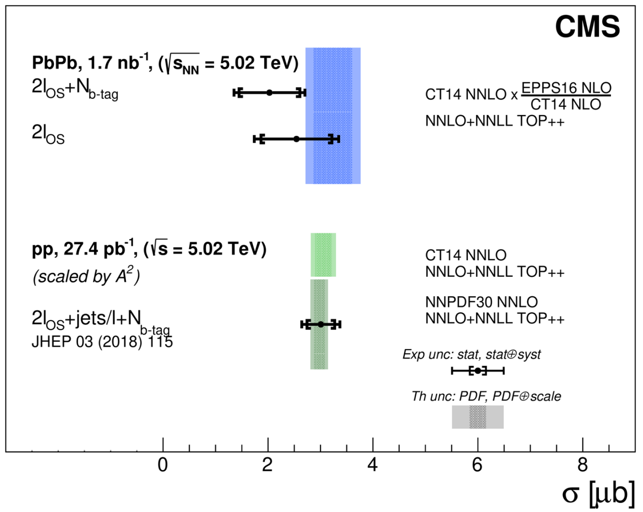


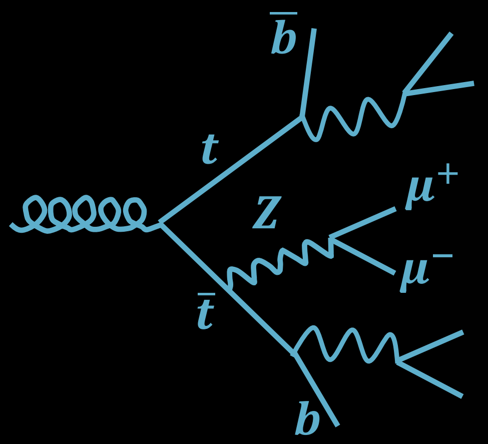


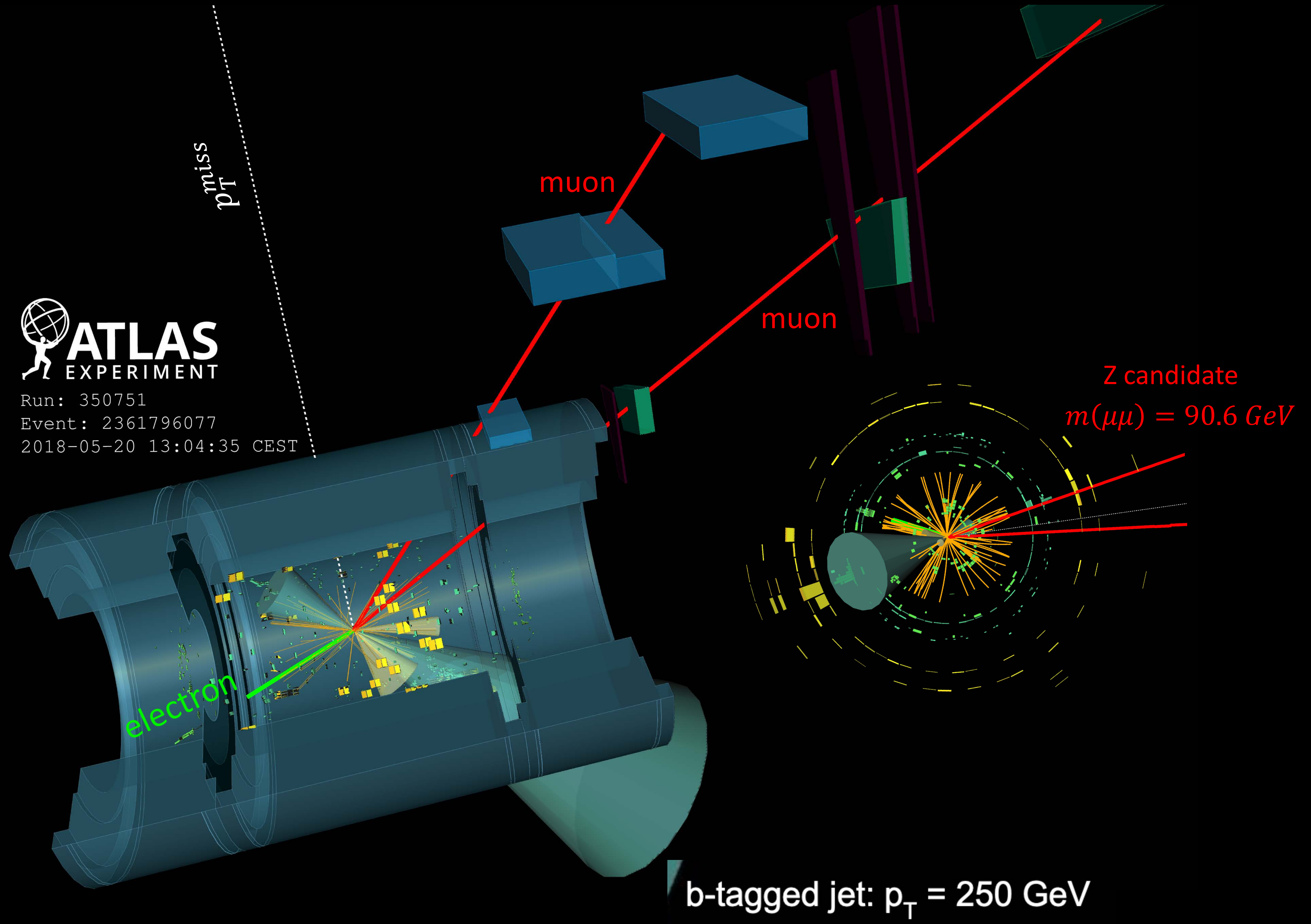
Evidence of top-pair production in *Pb-Pb* collisions by CMS







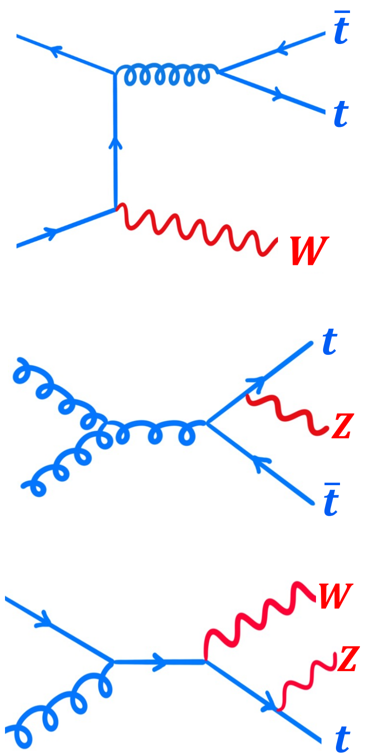


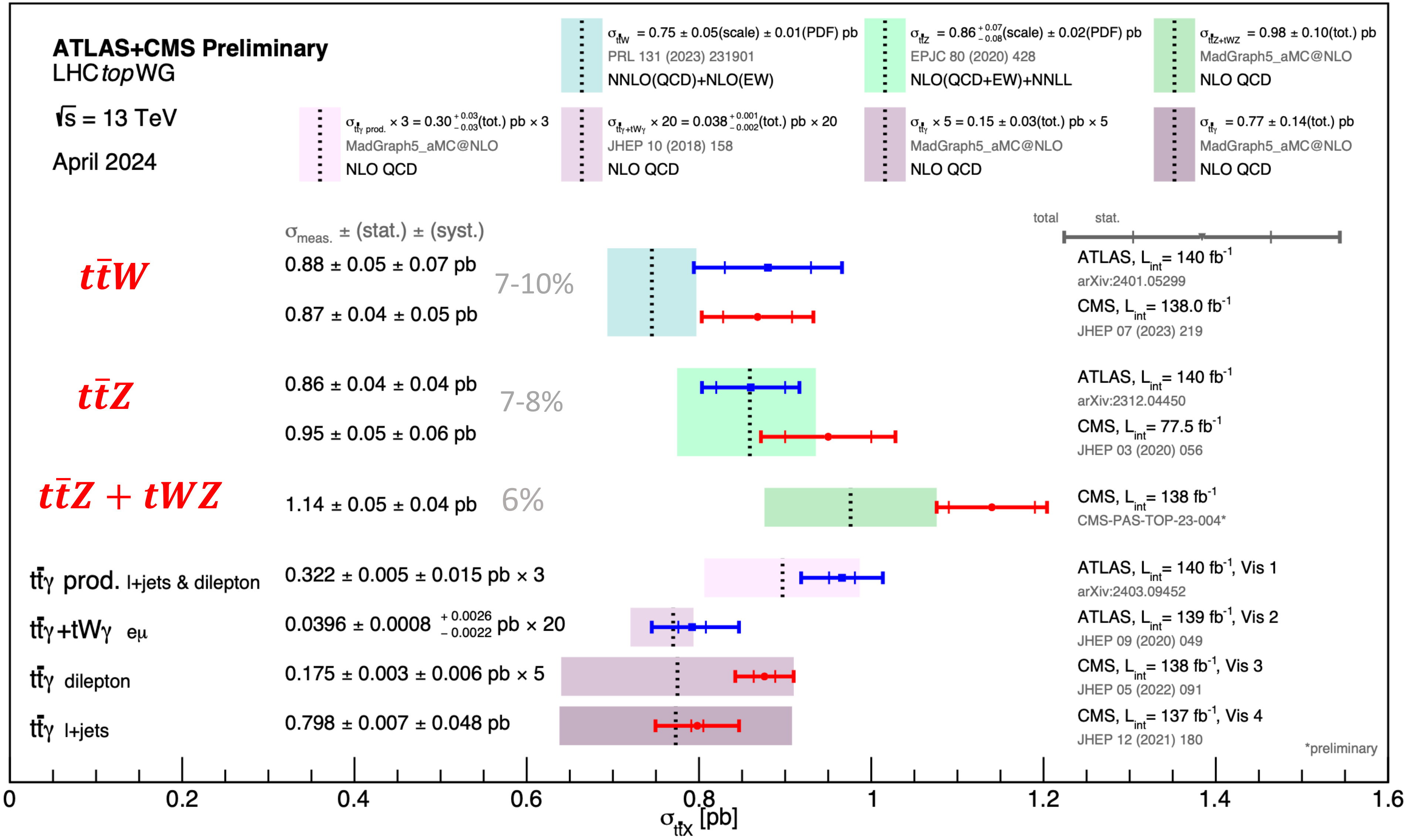


Candidate ttZ event with
- 2 muons + 1 electron
- 4 jets, of which 2 b-tagged
- 30 GeV missing transverse energy

Associated top quark production ($t\bar{t}$+V)

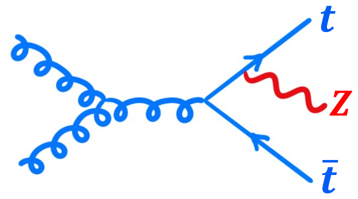
First observation at the LHC

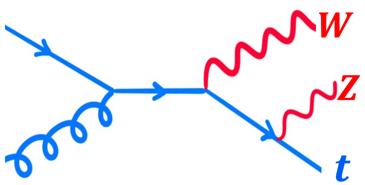


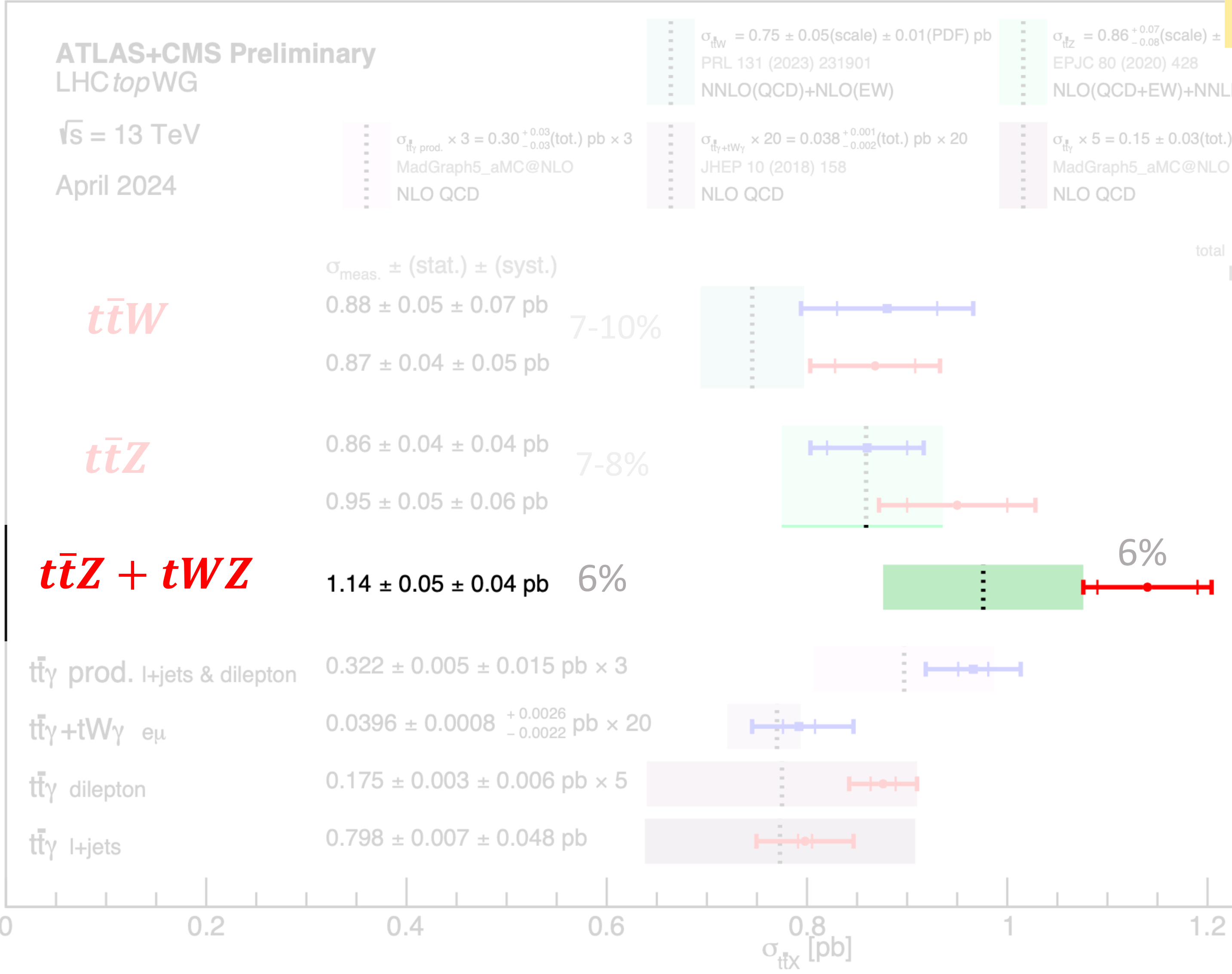


Associated top quark production ($t\bar{t}$+Z, tWZ)

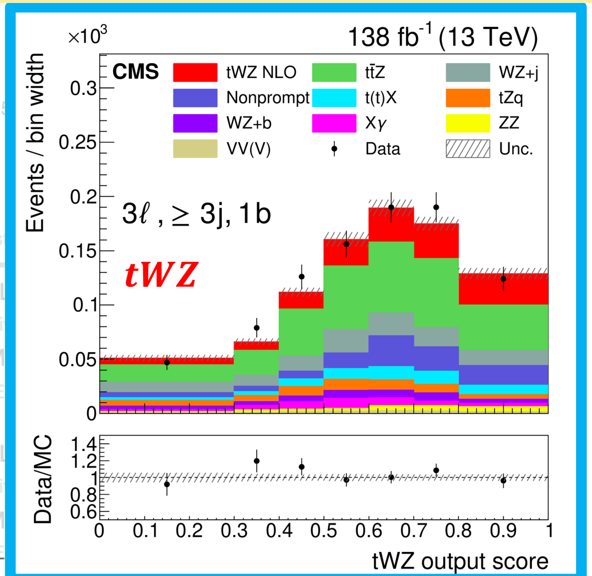
First observation at the LHC

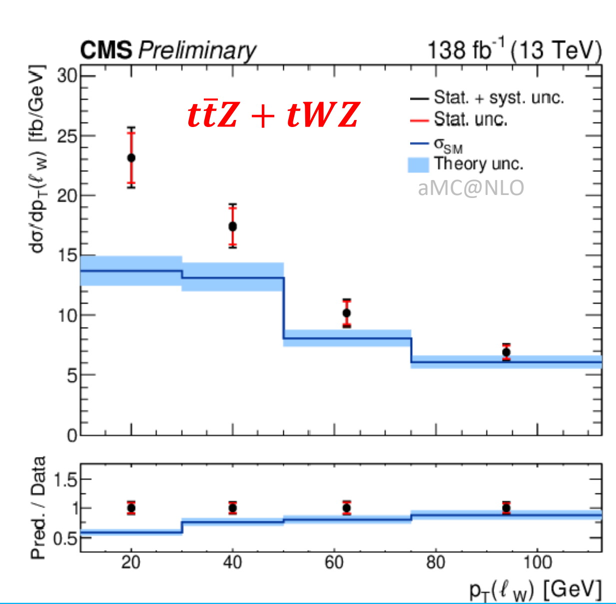






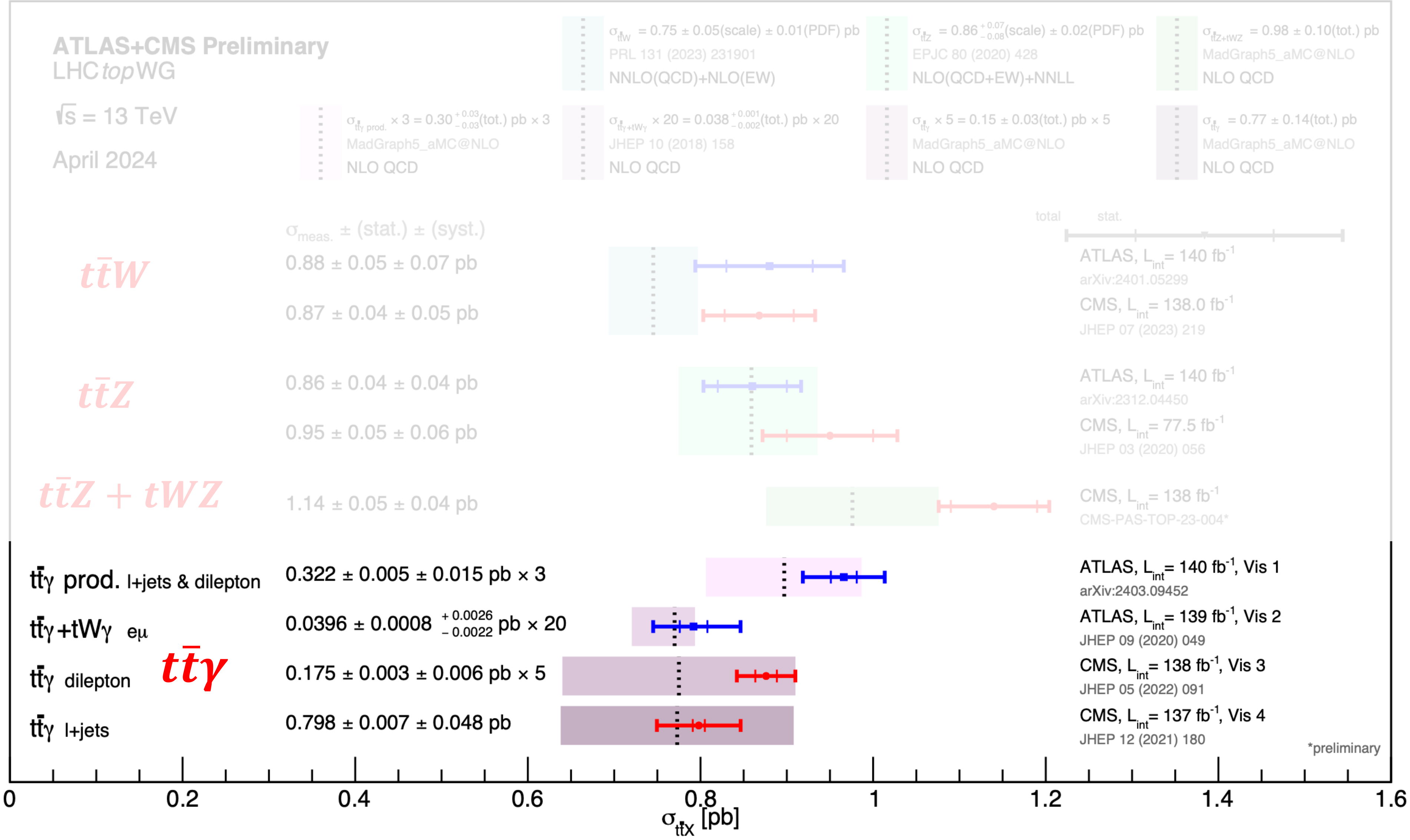
Evidence for tWZ: 3.4σ obs (1.4σ exp)

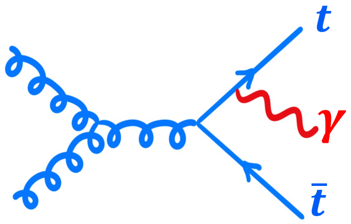




Associated top quark production ($t\bar{t}$+V)

First observation at the LHC

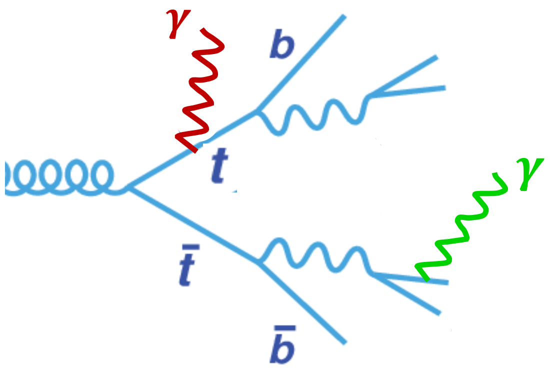




tt+V sensitive to anomolous couplings of top quark → EFT interpretations

Associated top quark production ($t\bar{t}\gamma$)

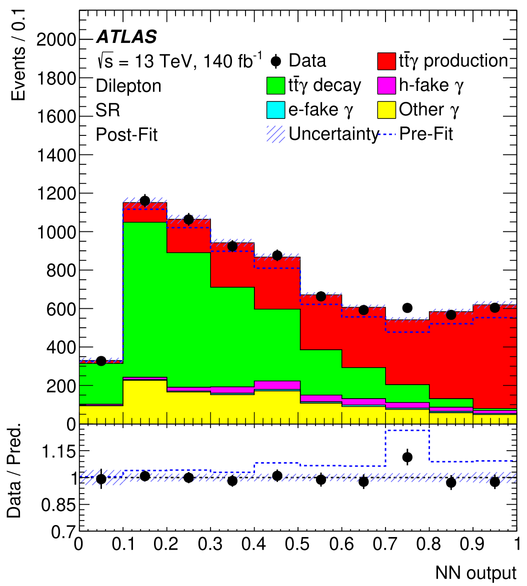
2403.09452



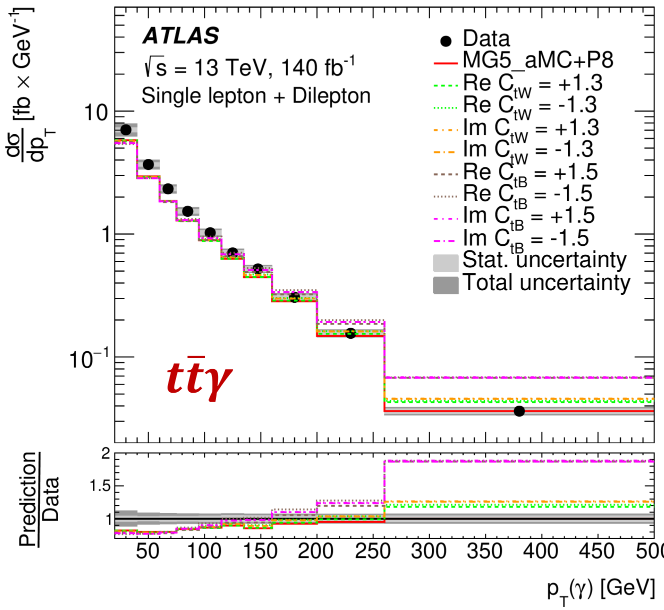
- $t\bar{t}\gamma$ at production/ $t\bar{t}\gamma$ at decay
- NN to separate two processes
  →Increased sensitivity to t-γ coupling

$$\mathcal{L}_{t\bar{t}X} = e\bar{t}\left[\gamma^{\mu}\left(C^{X}_{1,\mathrm{V}} + \gamma_5 C^{X}_{1,\mathrm{A}}\right) + \frac{i\sigma^{\mu\nu}q_{\nu}}{m_t}\underbrace{\left(C^{X}_{2,\mathrm{V}} + \gamma_5 C^{X}_{2,\mathrm{A}}\right)}_{\approx 0 \text{ in SM};\ \neq 0 \to \text{BSM}}\right]tX_{\mu}, \quad X = \gamma, Z$$

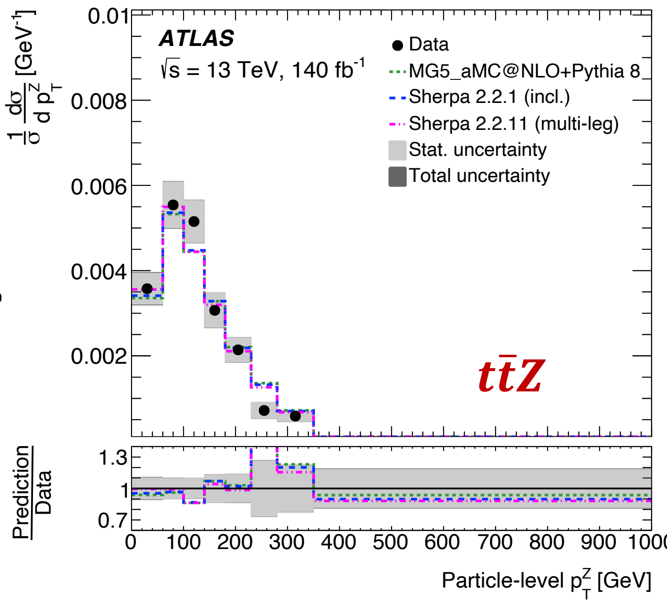
≈ 0 in SM
≠ 0 → BSM



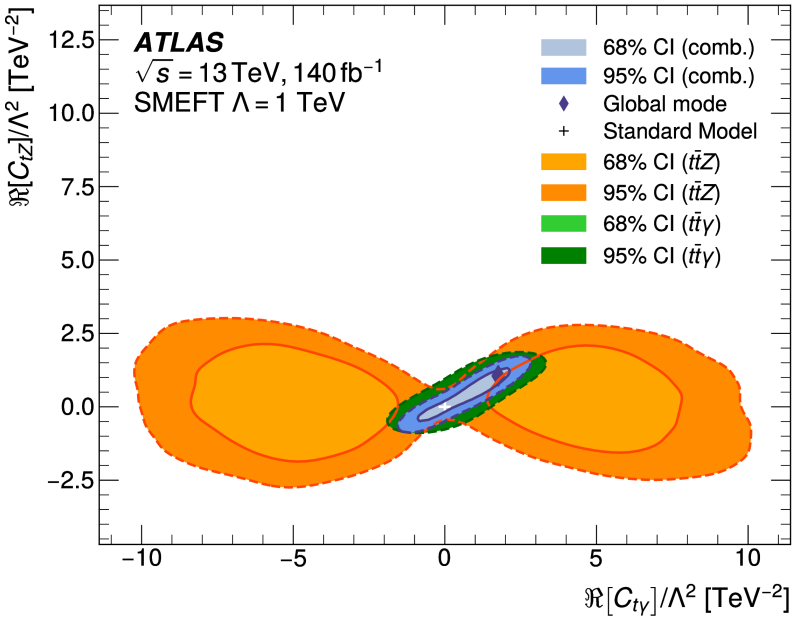
$p_T(\gamma), p_T(Z)$: sensitive to anomalous dipole couplings of the top quark



+



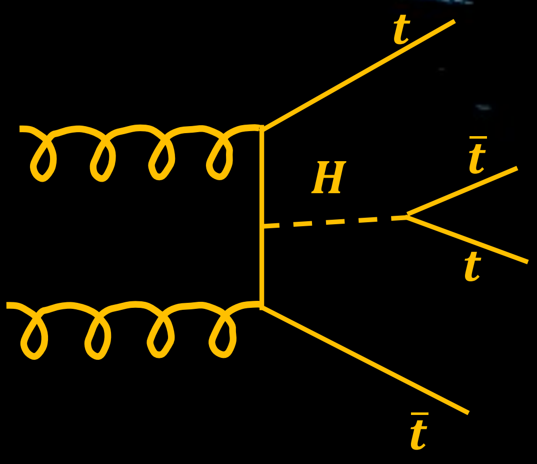
→

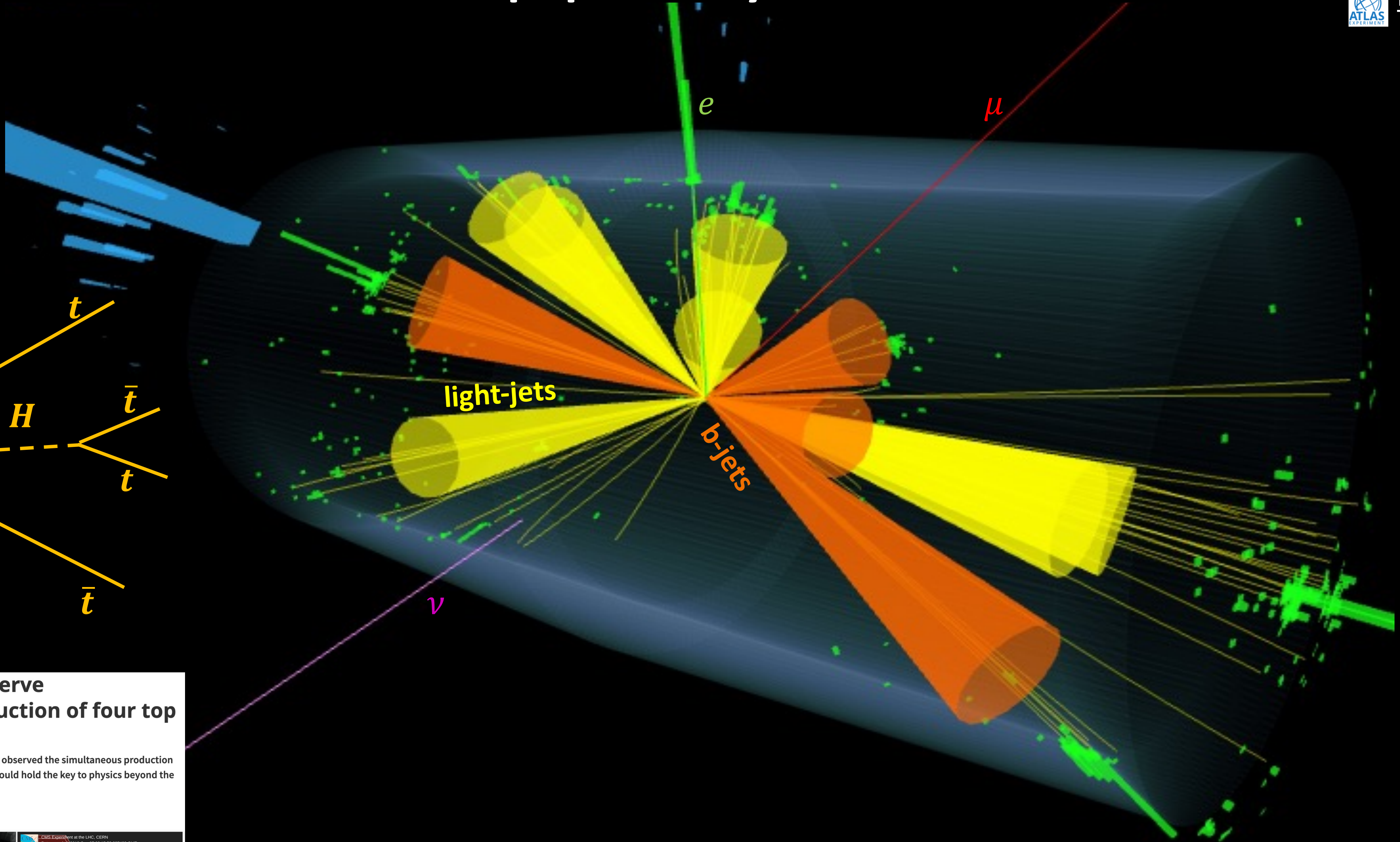


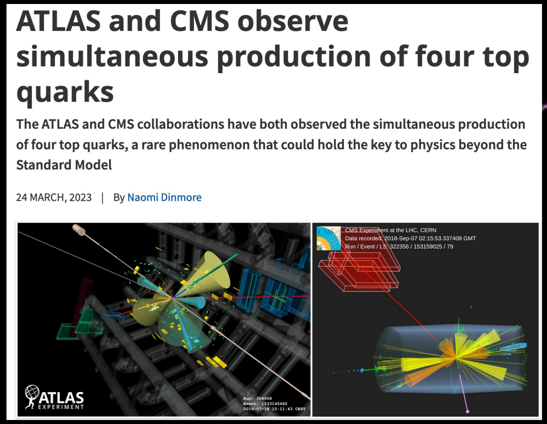
Observation of 4 top quarks by CMS and ATLAS

PLB 847 (2023) 138290

EPJ C 83 (2023) 496







ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

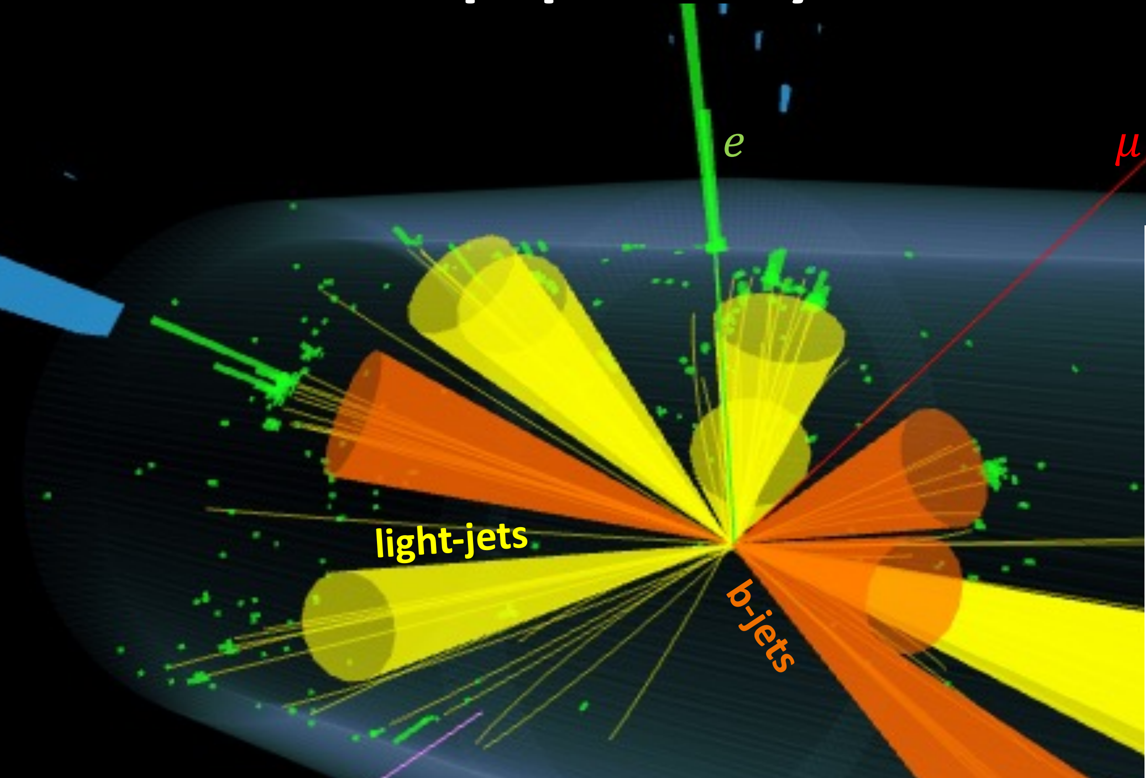
24 MARCH, 2023 | By Naomi Dinmore

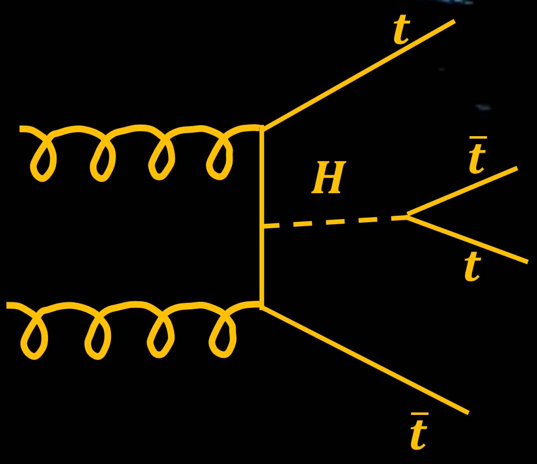
Observation of 4 top quarks by CMS and ATLAS

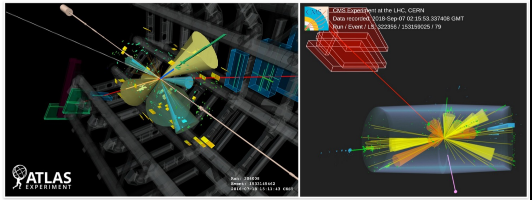
PLB 847 (2023) 138290

EPJ C 83 (2023) 496

2407.10631



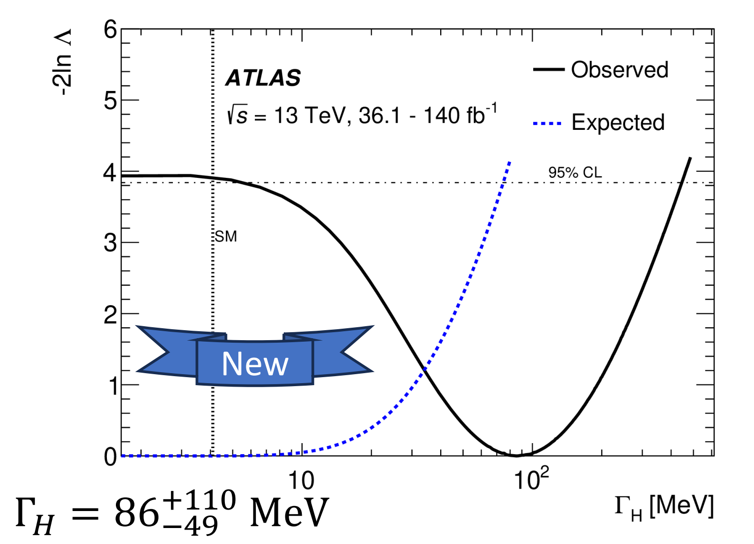


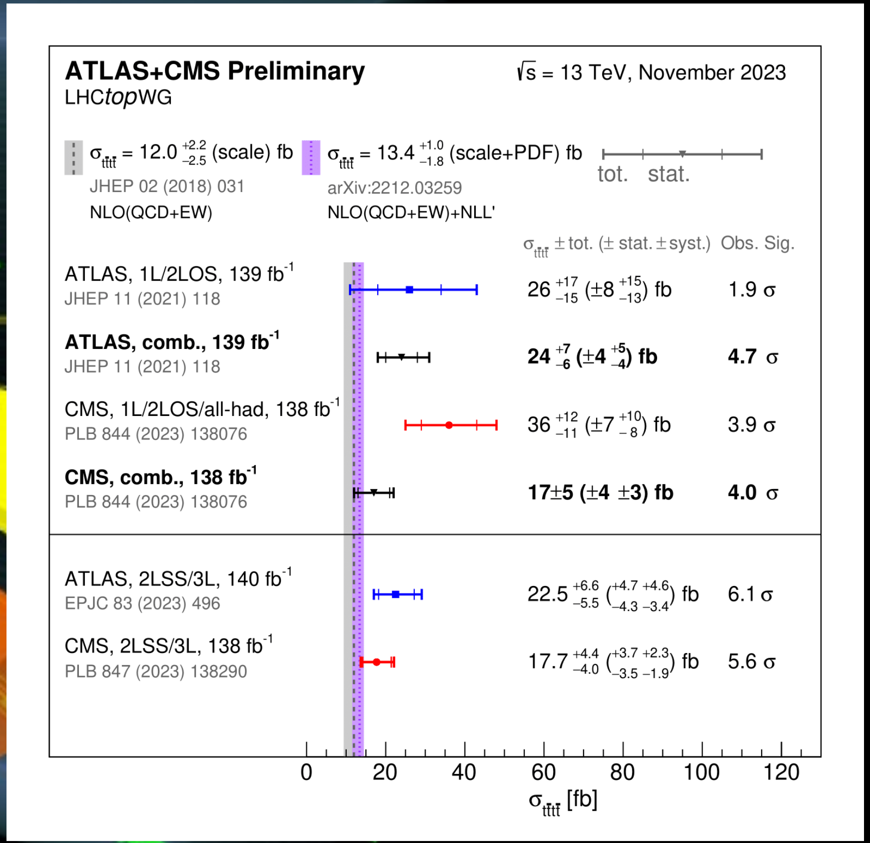


ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

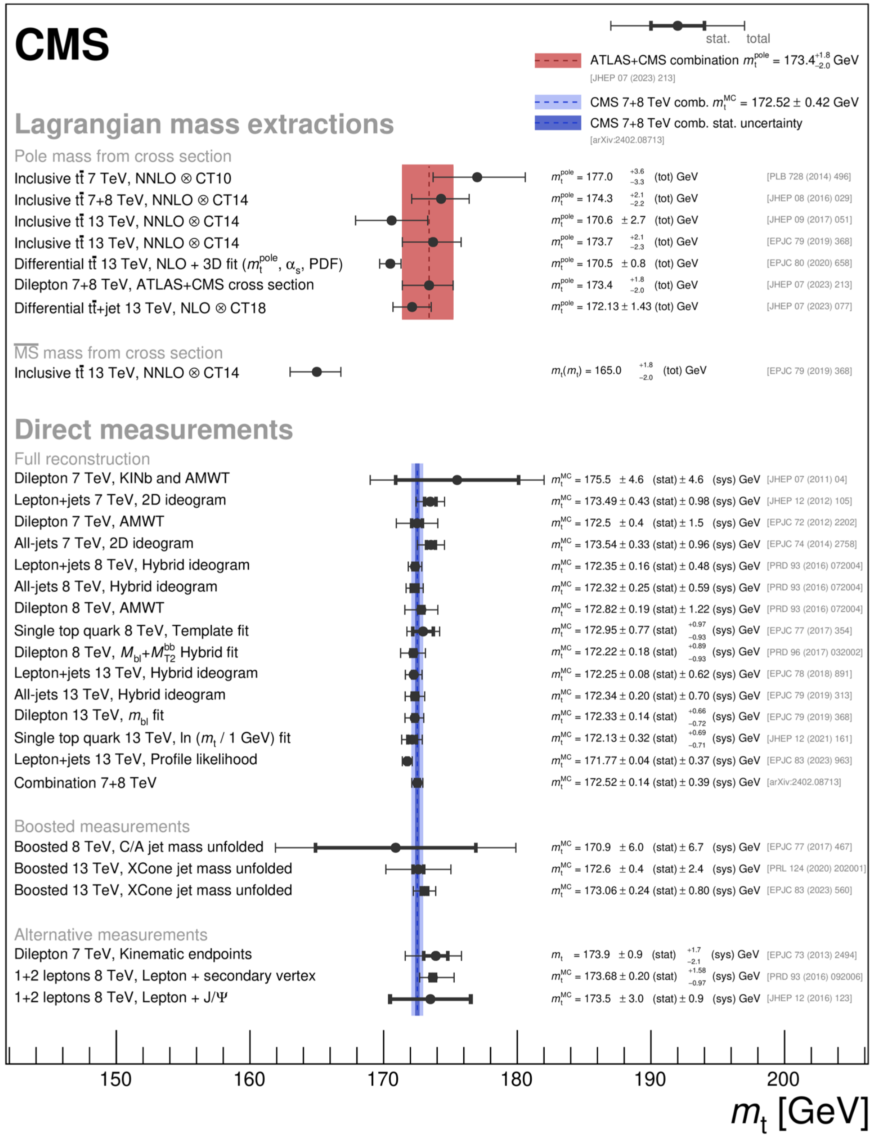




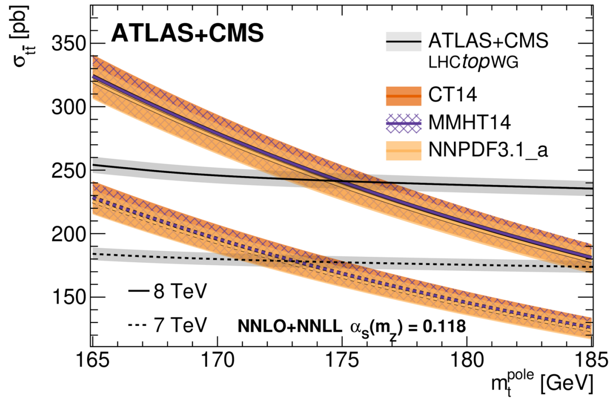
Measuring the heaviest particle mass

- **Significant improvements over the past years:** Better calibrations, alternative techniques, improved theoretical modelling

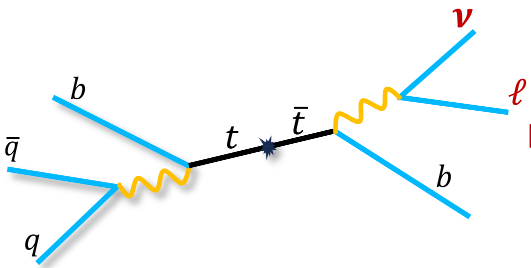
  → More than 40 publications by CMS and ATLAS collaborations



- **Indirect measurement** from cross section
  → ~1% precision



- **Direct measurements** from top quark decays
  → better precision

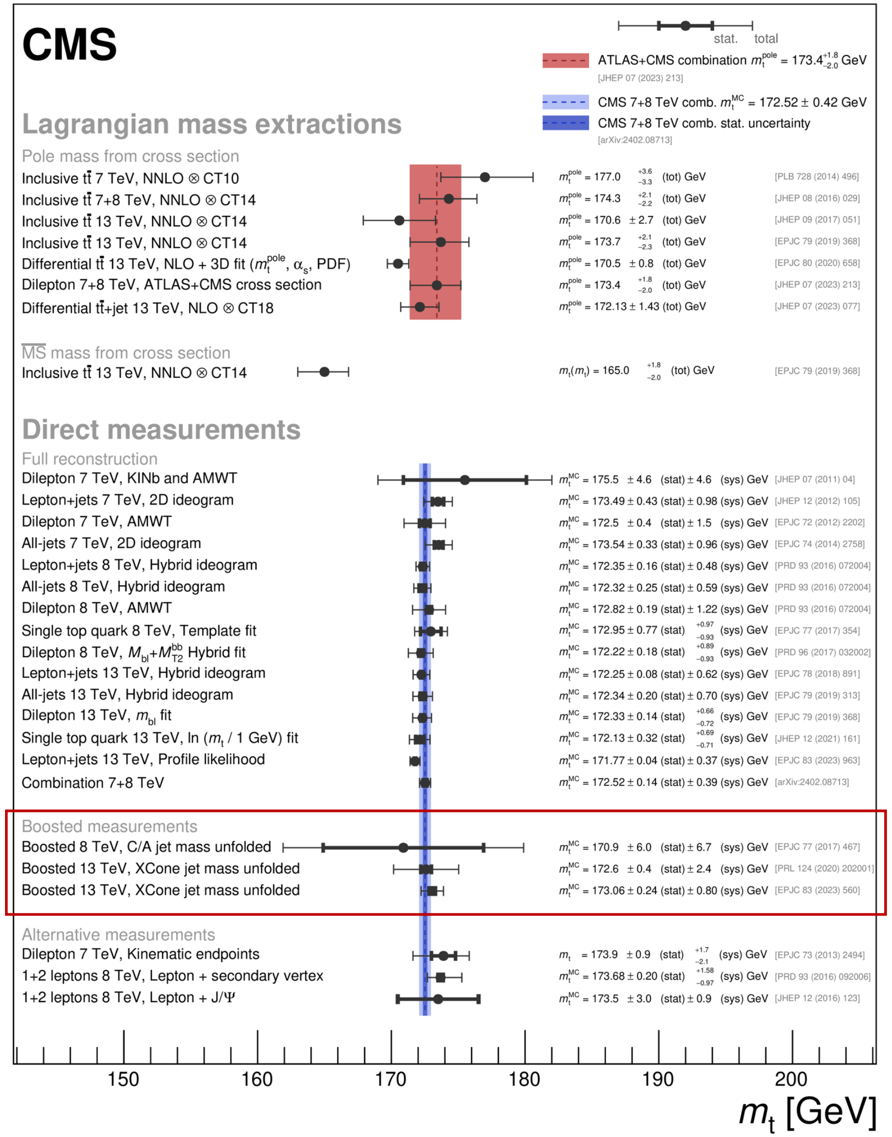


Extract m_{top} from decay products

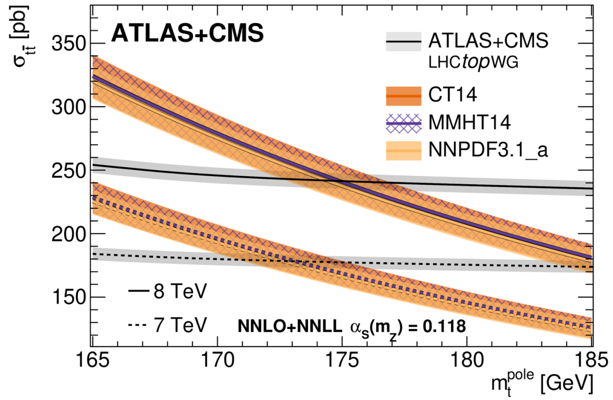
Measuring the heaviest particle mass

2403.01313
JHEP 2205.13830
EPJ C 83 (2023) 560

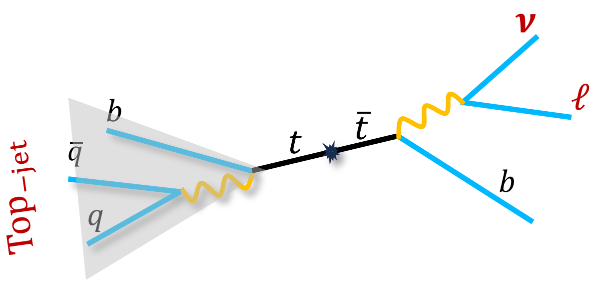
- **Significant improvements over the past years:** Better calibrations, alternative techniques, improved theoretical modelling
  → More than 40 publications by CMS and ATLAS collaborations



- **Indirect measurement** from cross section
  → ~1% precision

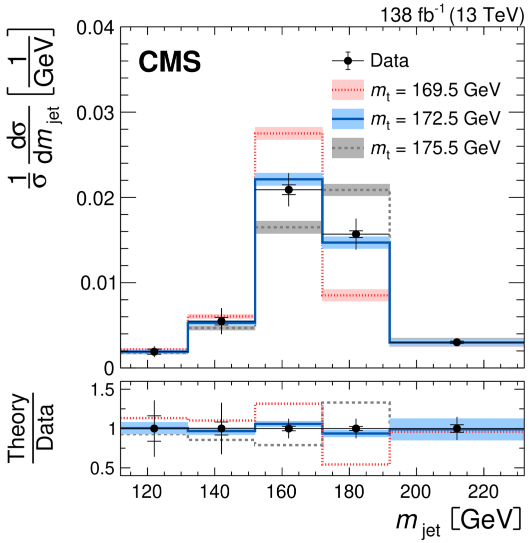


- **Direct measurements** from top quark decays
  → better precision
  → Mass from Boosted top-jet: Future prospects in precision & theoretical interpretability



Extract m_{Top} from m_{jet}

$p_{T,jet} > 400\ GeV$

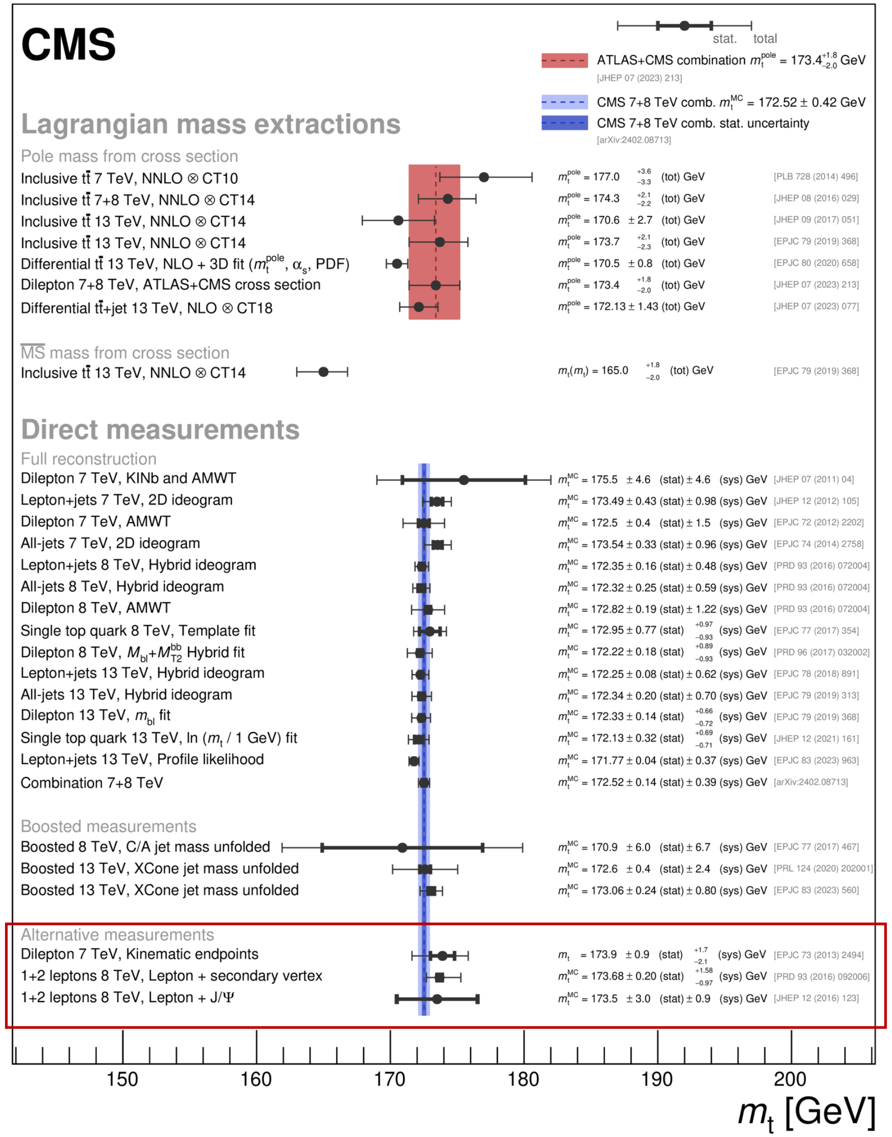


Measuring the heaviest particle mass

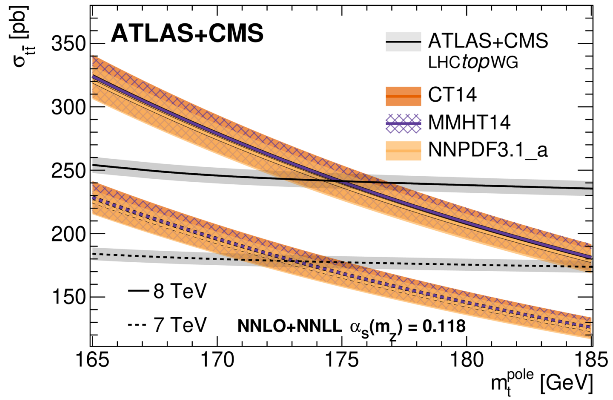
2403.01313
JHEP 2205.13830
JHEP 06 (2023) 019

- **Significant improvements over the past years:** Better calibrations, alternative techniques, improved theoretical modelling

  → More than 40 publications by CMS and ATLAS collaborations



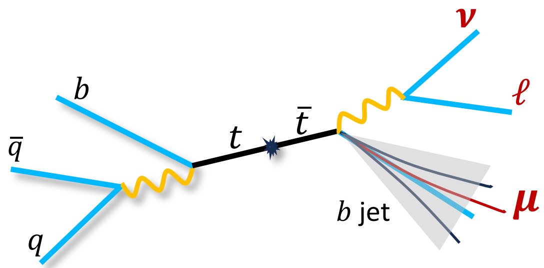
- **Indirect measurement** from cross section
  → ~1% precision



- **Direct measurements** from top quark decays
  → better precision

  → Mass from Boosted top-jet: Future prospects in precision & theoretical interpretability

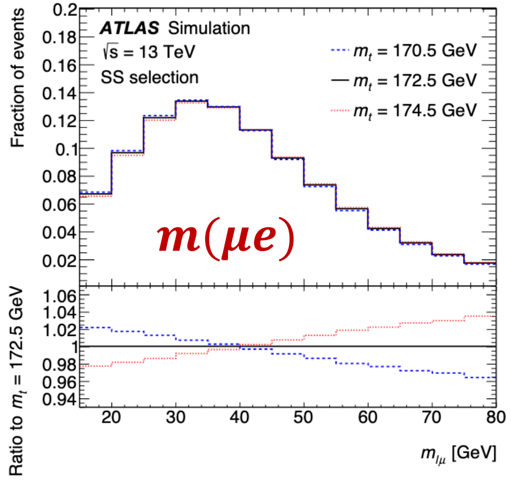
  → Alternative measurements: sensitive to different systematics



Extract m_{top} from $m_{\ell\mu}$

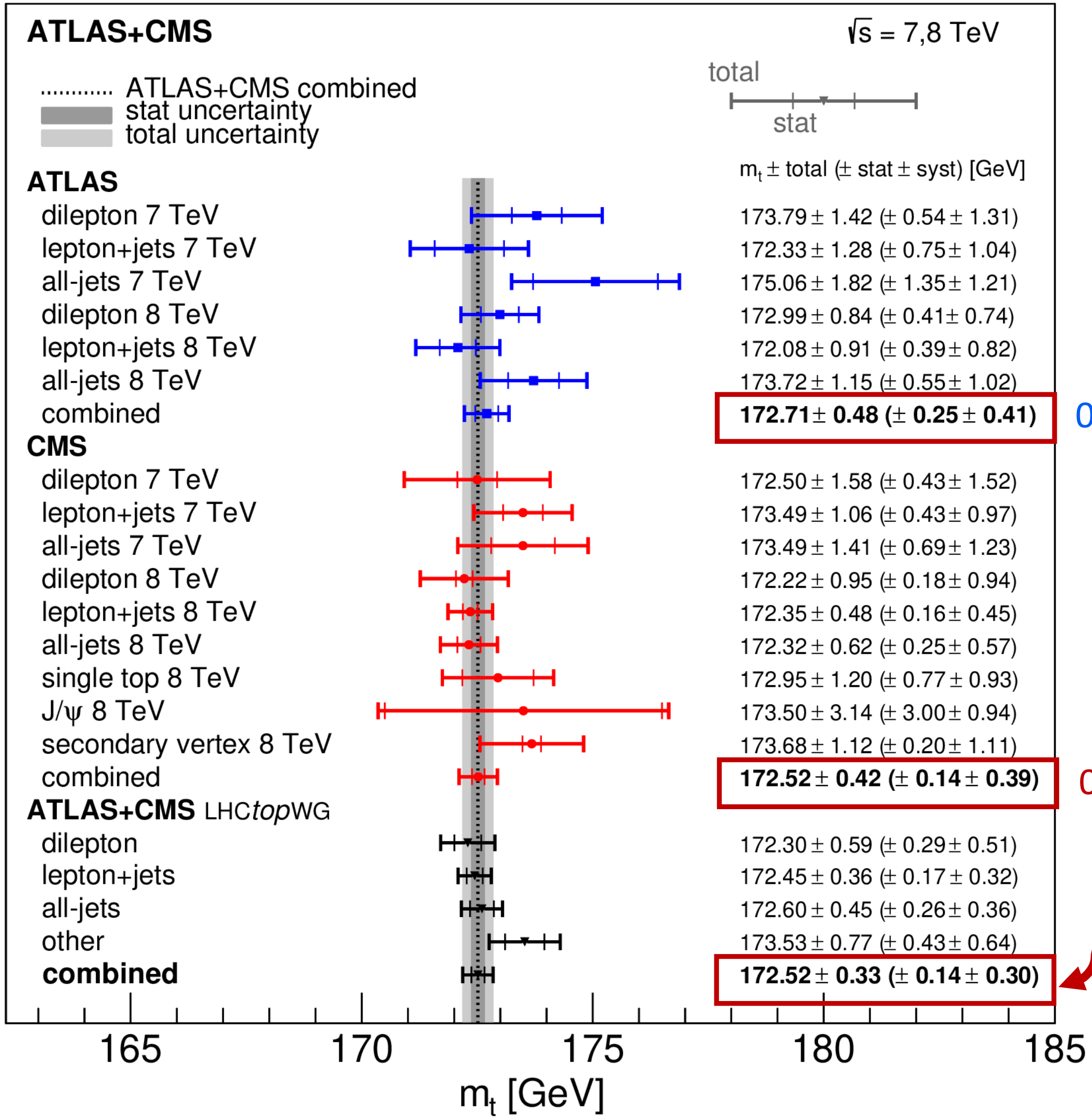
m_{top} = 174.41 ± 0.39 (stat.) ± 0.66 (syst.) ± 0.25 (recoil) GeV

sensitive to fragmentation effects



Top quark mass: Run I combination

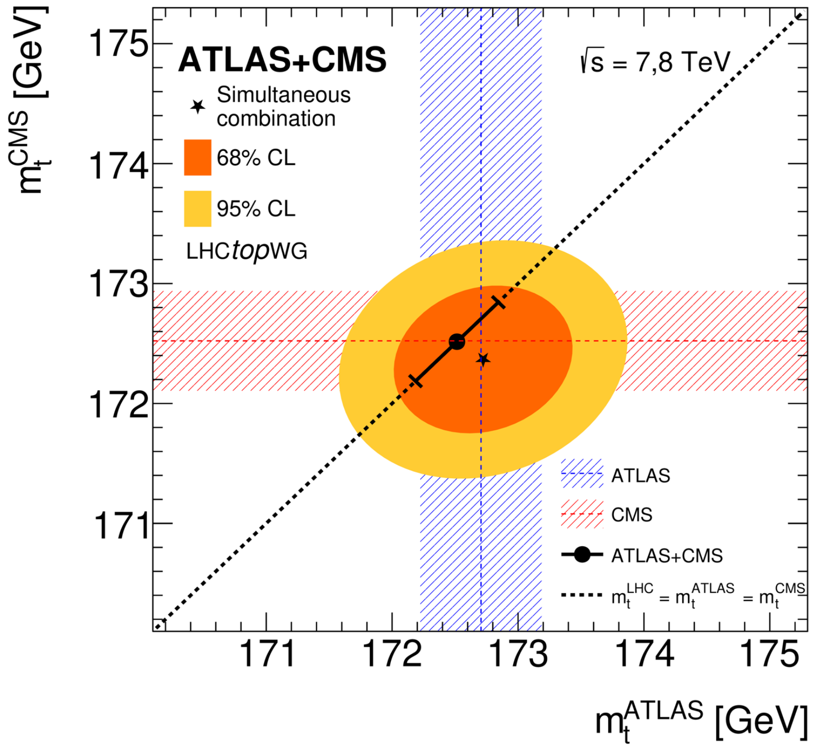
PRL 132, 261902



0.28% precision

0.24% precision

- Combination of **15 input measurements (6 ATLAS + 9 CMS)**
- Detailed study of correlations
- Consistency checks among measurements



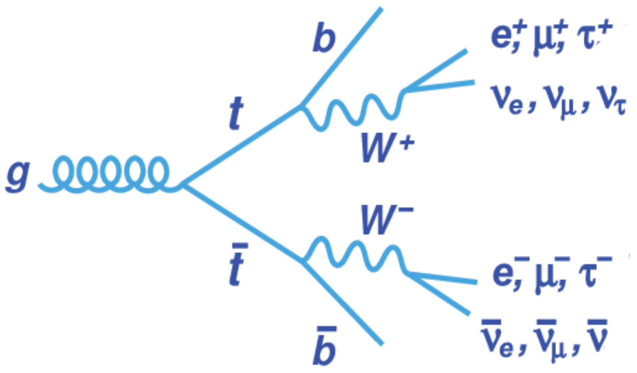
$$m_{top} = 172.52 \pm 0.14(stat) \pm 0.30(syst)\ \text{GeV}$$

< 0.2% precision → Limited by b-jet energy calibrations

Lepton Flavor Universality in top decays

2403.02133

PRD 105(2022) 072008



- Large and pure $t\bar{t}$ sample to measure $\mathcal{B}(W \to \ell\nu)$ and test LFU
- Simultaneous $t\bar{t}$ cross-section in $ee, \mu\mu, e\mu$
- ML fit to event categories with 10 parameters
- $R_W^{\mu/e}$: many uncertainties cancel
- In situ lepton/bjet efficiency calibrations

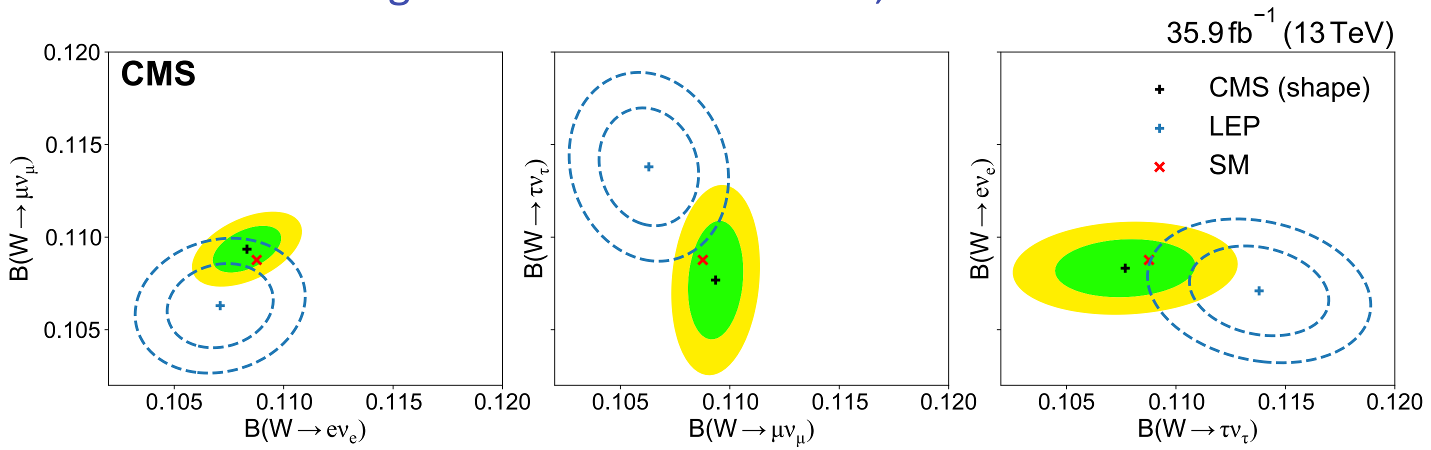
$$R_W^{\mu/e} = \frac{\frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)}}{\sqrt{\frac{\mathcal{B}(Z \to \mu\mu)}{\mathcal{B}(Z \to ee)}}} \cdot \sqrt{R_Z^{\mu\mu/ee}}$$

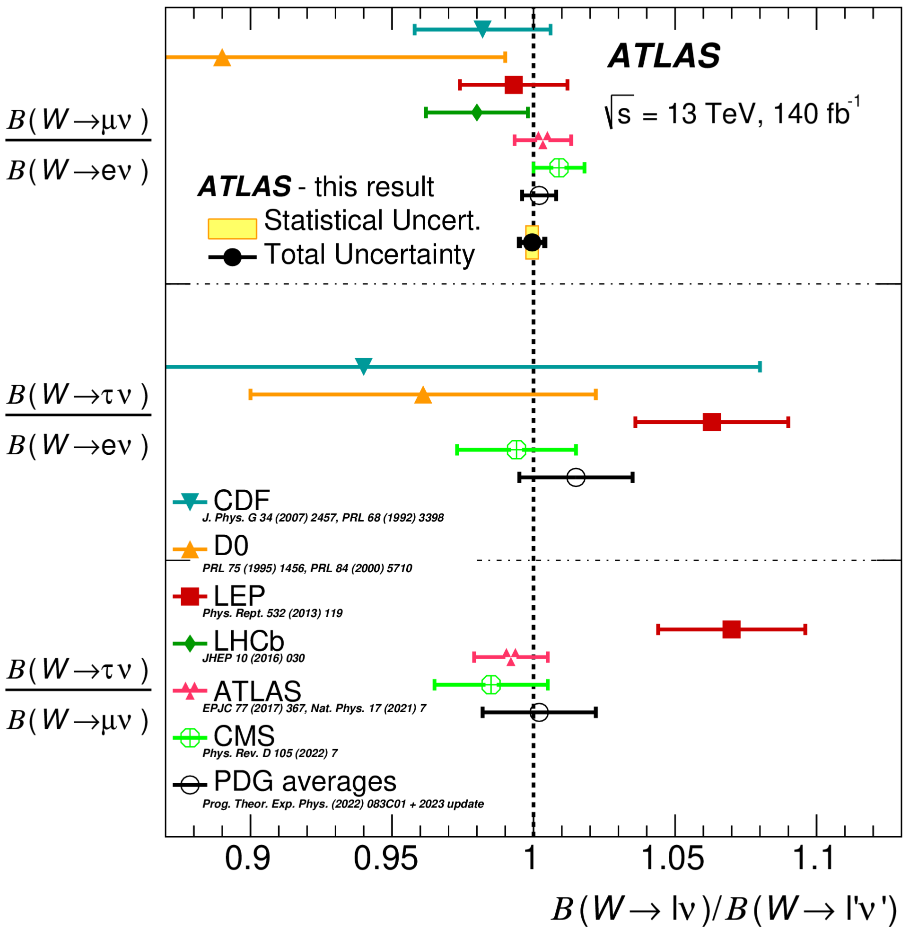
From LEP2/SLD

$$R_W^{\mu/e} = 0.9995 \pm 0.0045$$

- All $R_W^{\ell/\ell'}$ consistent with LFU
- More precise than LEP and do not confirm the anomalies

Precise W branching fraction measurements, consistent with SM

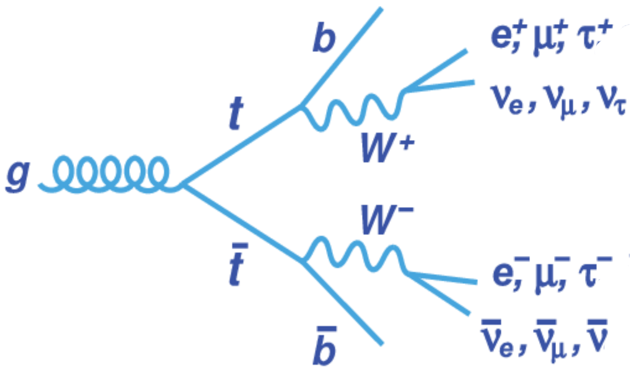




Lepton Flavor Universality in top decays

2403.02133

PRD 105(2022) 072008



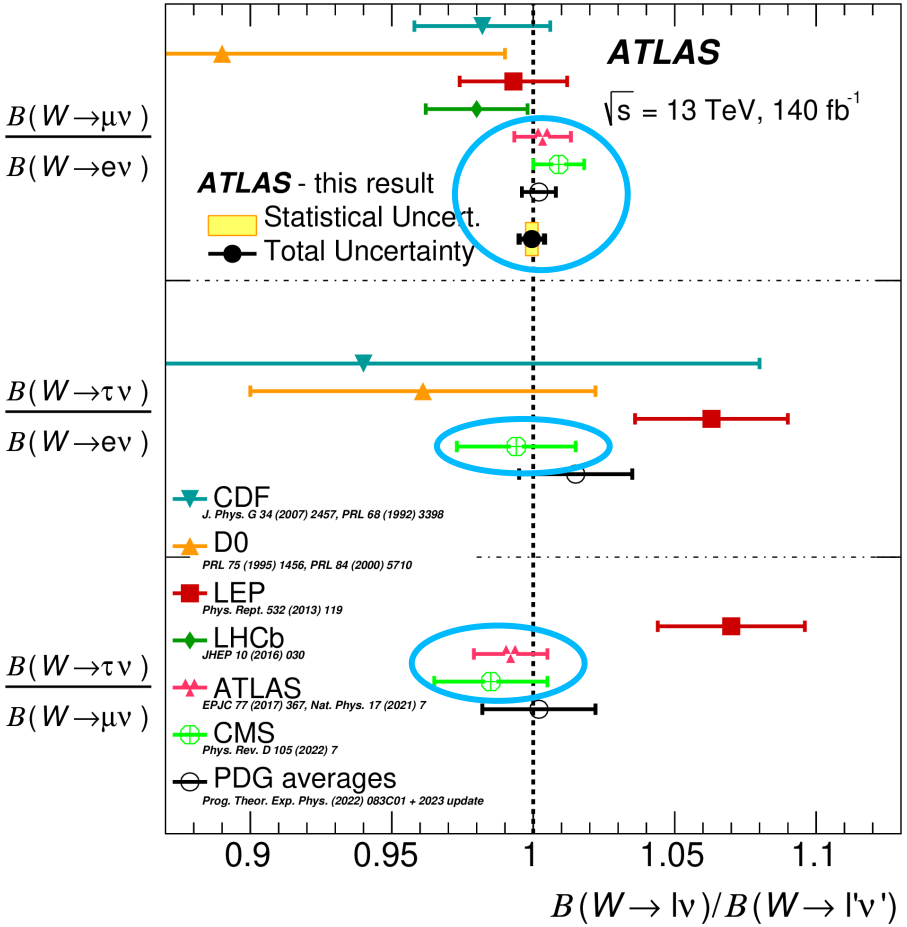
- Large and pure $t\bar{t}$ sample to measure $\mathcal{B}(W \to \ell\nu)$ and test LFU
- Simultaneous $t\bar{t}$ cross-section in $ee, \mu\mu, e\mu$
- ML fit to event categories with 10 parameters
- $R_W^{\mu/e}$: many uncertainties cancel
- In situ lepton/bjet efficiency calibrations

$$R_W^{\mu/e} = \frac{\frac{\mathcal{B}(W\to\mu\nu)}{\mathcal{B}(W\to e\nu)}}{\sqrt{\frac{\mathcal{B}(Z\to\mu\mu)}{\mathcal{B}(Z\to ee)}}} \cdot \sqrt{R_Z^{\mu\mu/ee}}$$

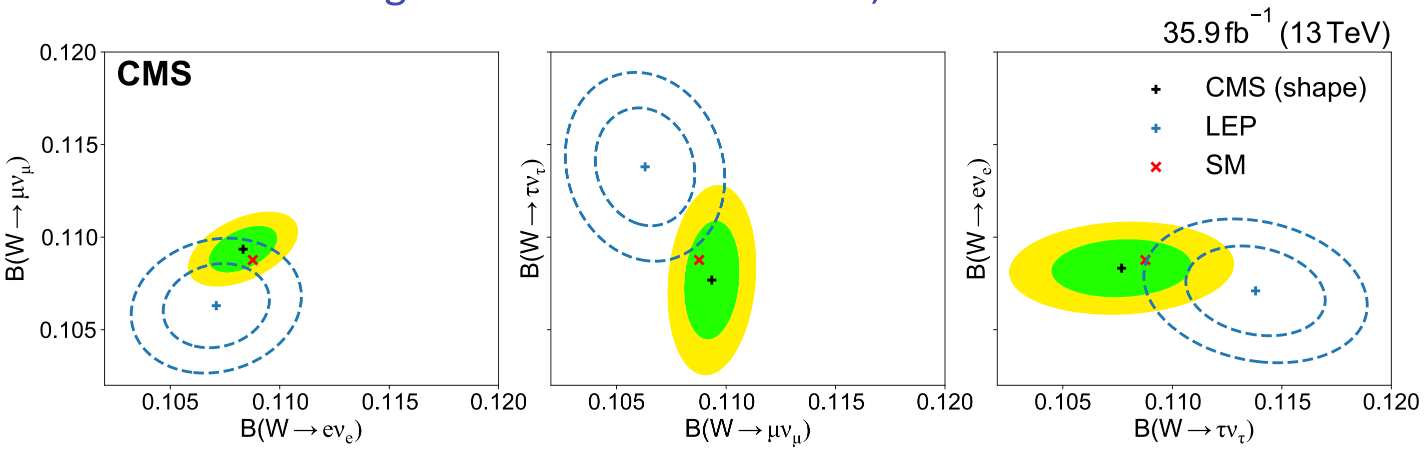
From LEP2/SLD

$$R_W^{\mu/e} = 0.9995 \pm 0.0045$$

- All $R_W^{\ell/\ell'}$ consistent with LFU
- More precise than LEP and do not confirm the anomalies



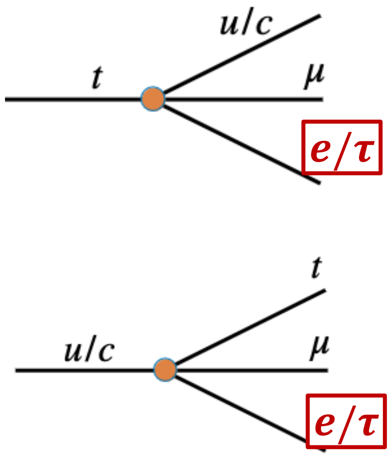
Precise W branching fraction measurements, consistent with SM

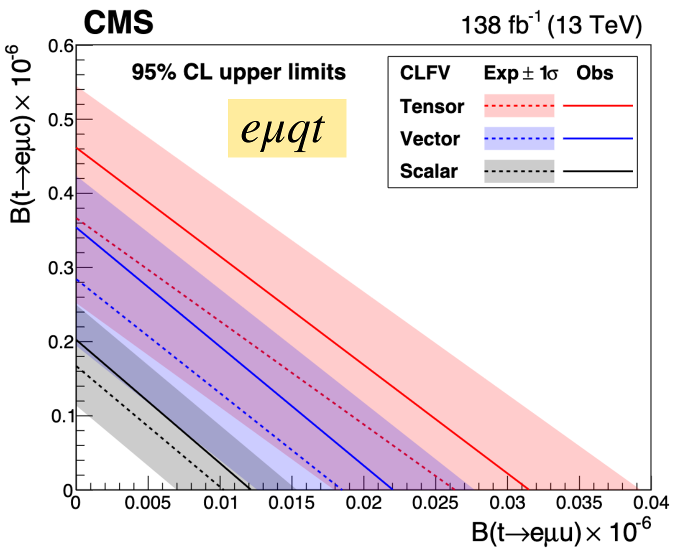


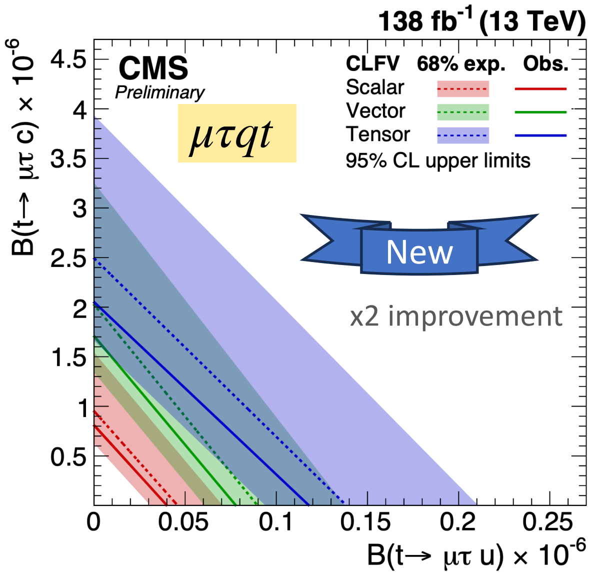
Charged Lepton Flavor Violation in top decays

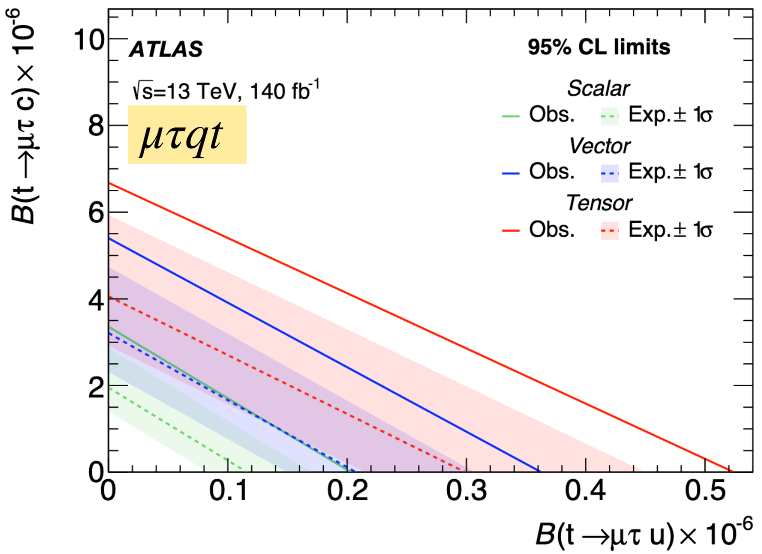
2403.06742
2312.03199
CMS-PAS-TOP-22-011

Search for cLFV in top-quark production and decay









Stringent limits on $\mathcal{B}(t \to \mu\tau q)$ and $\mathcal{B}(t \to \mu e q)$ $< 10^{-6}$ - 10^{-8} depending on the Lorentz structure of the vertex

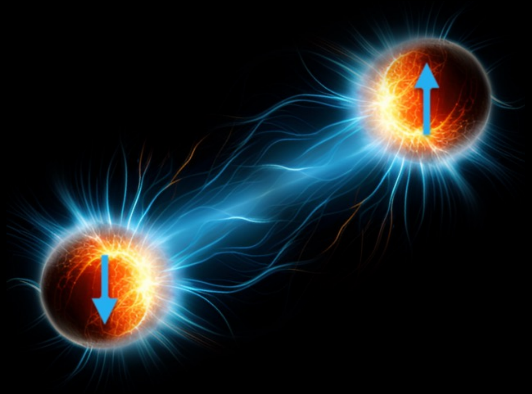
Searches for BNV/FCNC in top quark production and decay

CMS:
- arXiv:2402.18461 (BNV)
- JHEP 02 (2022) 169
- PRL 129 (2022) 3, 032001
- CMS-PAS-TOP-22-002

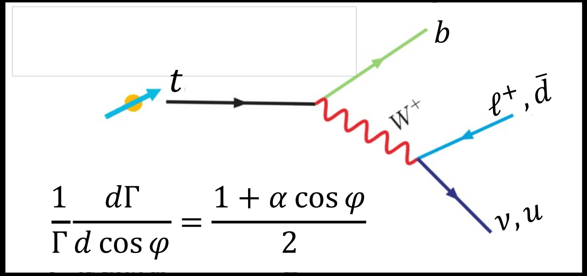
ATLAS EXPERIMENT:
- JHEP 06 (2023) 155
- JHEP 07 (2023) 199
- arXiv:2404.02123
- JHEP 12 (2023) 195

Covered in parallel talks

Spin Correlation, Polarization & Entanglement in $t\bar{t}$



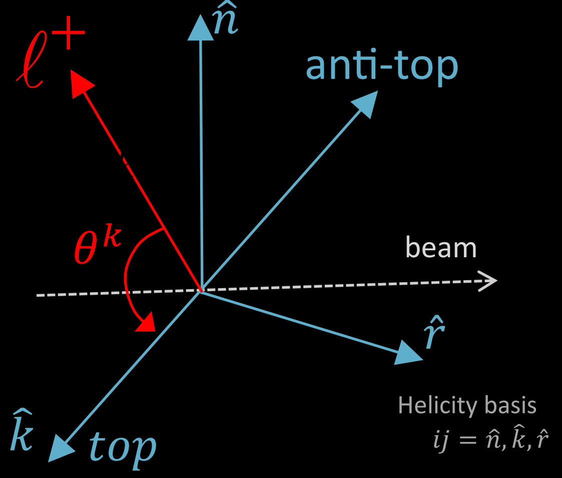
- Top-pairs @LHC are mainly unpolarized (parity invariance of QCD)
- Their spins are strongly correlated
- Spin information is passed onto ℓ *and* d-quark
  → preferentially radiated in the top spin direction



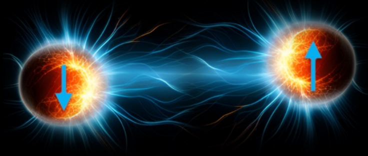
Polarization & spin correlation coefficients from differential measurements

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+^i \, d\cos\theta_-^j} = \frac{1}{2}\left(1 + \boldsymbol{B_+^i}\cos\theta_+^i + \boldsymbol{B_-^j}\cos\theta_-^j - \boldsymbol{C_{ij}}\cos\theta_+^i\cos\theta_-^j\right)$$

$$B_\pm = \begin{pmatrix} x \\ x \\ x \end{pmatrix} \qquad C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$



- NP can modify spin polarization and correlation structure
- Possibility to test the foundations of quantum physics



arXiv:2311.07288, Accepted by Nature

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: Nature

CERN-EP-2023-230
November 20, 2023

Observation of quantum entanglement in top-quark pairs using the ATLAS detector

The ATLAS Collaboration

We report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a center-of-mass energy of $\sqrt{s}$ = 13 TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.547 \pm 0.002$ (stat.) $\pm$ 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes both the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement to date.

2406.03976, Submitted to Reports on Progress in Physics

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS

CERN-EP-2024-137
2024/06/07

CMS-TOP-23-001

Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Entanglement is an intrinsic property of quantum mechanics and is predicted to be exhibited in the particles produced at the Large Hadron Collider. A measurement of the extent of entanglement in top quark-antiquark ($t\bar{t}$) events produced in proton-proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of 36.3 fb^{-1}. The events are selected based on the presence of two leptons with opposite charges and high transverse momentum. An entanglement-sensitive observable D is derived from the top quark spin-dependent parts of the $t\bar{t}$ production density matrix and measured in the region of the $t\bar{t}$ production threshold. Values of $D < -1/3$ are evidence of entanglement and D is observed (expected) to be $-0.480^{+0.026}_{-0.029}$ ($-0.467^{+0.026}_{-0.029}$) at the parton level. With an observed significance of 5.1 standard deviations with respect to the non-entangled hypothesis, this provides observation of quantum mechanical entanglement within $t\bar{t}$ pairs in this phase space. This measurement provides a new probe of quantum mechanics at the highest energies ever produced.

CMS-TOP-23-007

DRAFT
CMS Physics Analysis Summary

The content of this note is intended for CMS internal use and distribution only

2024/06/10
Archive Hash: 982a1b8-D
Archive Date: 2024/06/10

Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

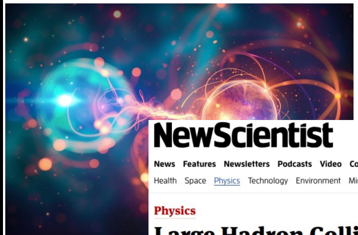
Abstract

Measurements of the polarization and spin correlations in top quark pairs ($t\bar{t}$) are presented using events with a single electron or muon and jets in the final state. The measurements are based on proton-proton collision data from the LHC at $\sqrt{s}$ = 13 TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}. All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously by performing a binned likelihood fit to the data. The measurement is performed in bins of additional observables such as the mass of the $t\bar{t}$ system and the top quark scattering angle. Inclusive coefficients are obtained by combining the results of all fitted bins. From the measured spin correlations, conclusions on the $t\bar{t}$ spin entanglement are drawn. The standard model predicts entangled spin $t\bar{t}$ states at the production threshold and at high masses of the $t\bar{t}$ system. Entanglement is observed for the first time in events with high $t\bar{t}$ mass, with an observed (expected) significance of 6.7 (5.6) standard deviations. The observed level of entanglement cannot be explained by classical exchange of information between the two particles alone. The observed (expected) significance for entanglement attributable to space-like separated $t\bar{t}$ pairs is 5.4 (4.1) standard deviations.

Einstein's "Spooky Action at a Distance" Between the Heaviest Particles at the Large Hadron Collider

TOPICS: CERN Large Hadron Collider Particle Physics Quantum Mechanics

By CMS COLLABORATION JUNE 17, 2024



NewScientist

News Features Newsletters Podcasts Video Comment Culture Crosswords | This week's magazine

Health Space Physics Technology Environment Mind Humans Life Mathematics Chemistry Earth Society

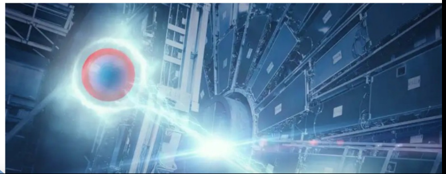
Physics

Large Hadron Collider turned into world's biggest quantum experiment

Physicists have used the famous particle smasher to investigate the strange phenomena of quantum entanglement at far higher energies than ever before

By Alex Wilkins

3 October 2023



JUNE 14, 2024 Editors' notes

Physicists confirm quantum entanglement persists between top quarks, the heaviest known fundamental particles

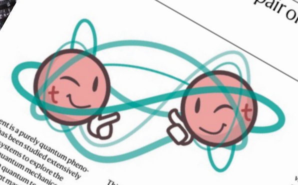
by David Andreatta, University of Rochester

nature reviews physics

Explore content About the journal Publish with us

Editors' picks 2023

Entanglement between a pair of top quarks



symmetry topics follow

Scientists measure entanglement at the LHC

12/18/23 | By Chiara Villanueva

Scientists on the ATLAS collaboration performed the highest-energy measurement of quantum entanglement.

On the smallest level, the universe operates in such a bizarre

CERNCOURIER Reporting on international high-energy physics

Physics Technology Community In focus Magazine

STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.

Yes, the Most Massive Particle Shows Some 'Spooky Action At a Distance'

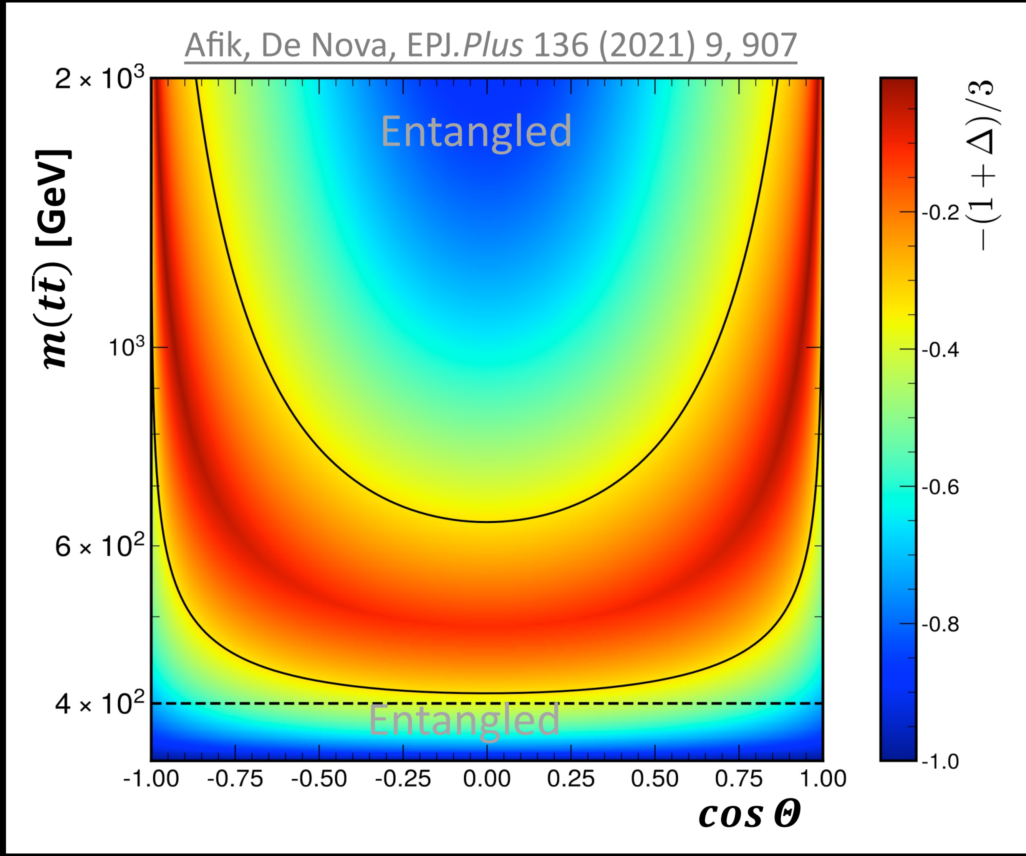
The top quark also experiences quantum entanglement, according to new discoveries by CERN.

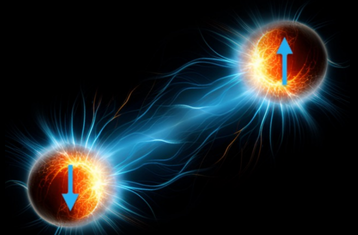
SAVE ARTICLE

Entanglement in $t\bar{t}$

- Spin correlation is $m(t\bar{t})$ and $\cos\Theta$ dependent

  → Entanglement in some phase-space regions





- $t\bar{t}$ in mixed states (eg. $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$) → two qubit system
- Peres–Horodecki criterion for entanglement

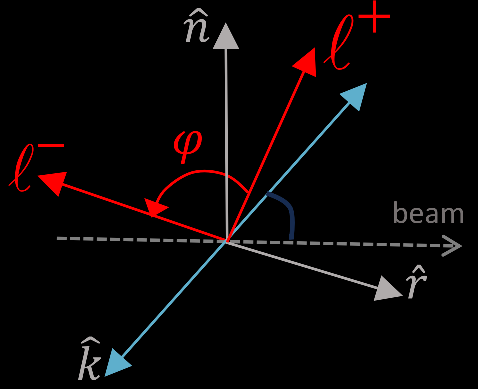
$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

Low m($t\bar{t}$): $D = -\frac{\Delta_E}{3} < -\frac{1}{3}$

High m($t\bar{t}$): $\widetilde{D} = \frac{\Delta_E}{3} > \frac{1}{3}$

Extract D and $\widetilde{D}$ from single differential measurement

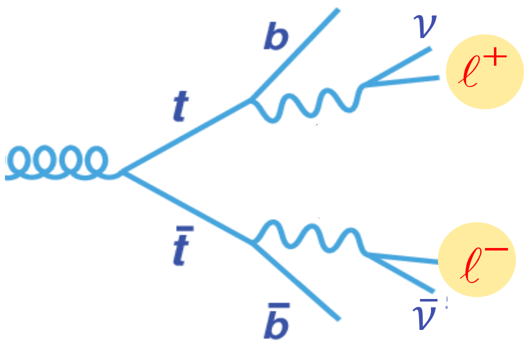
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi)$$



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

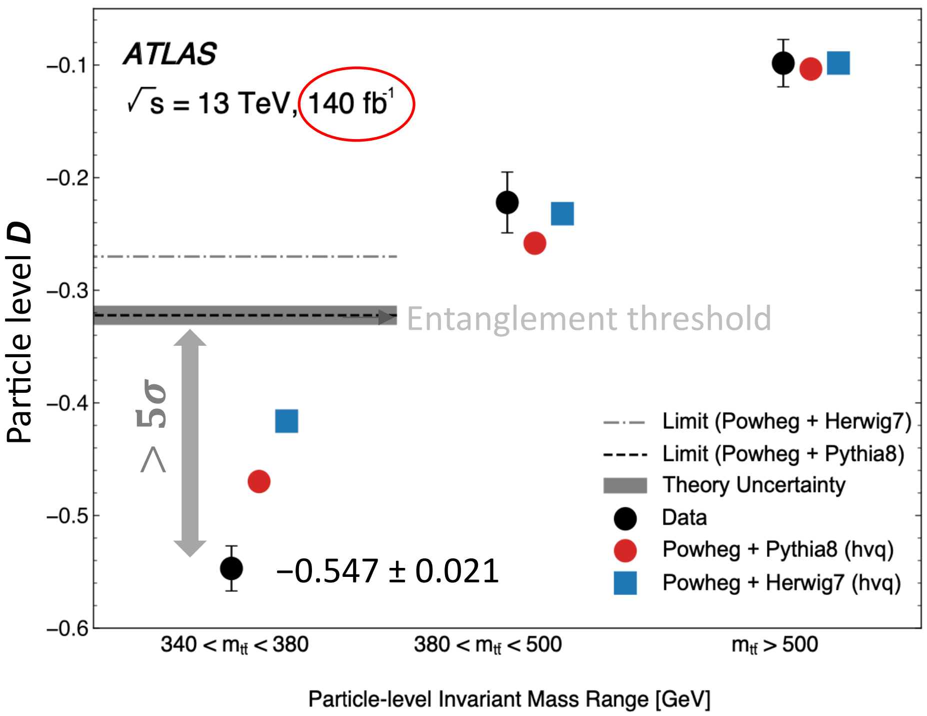
$\hat{\ell}$: unit vector in top rest frame

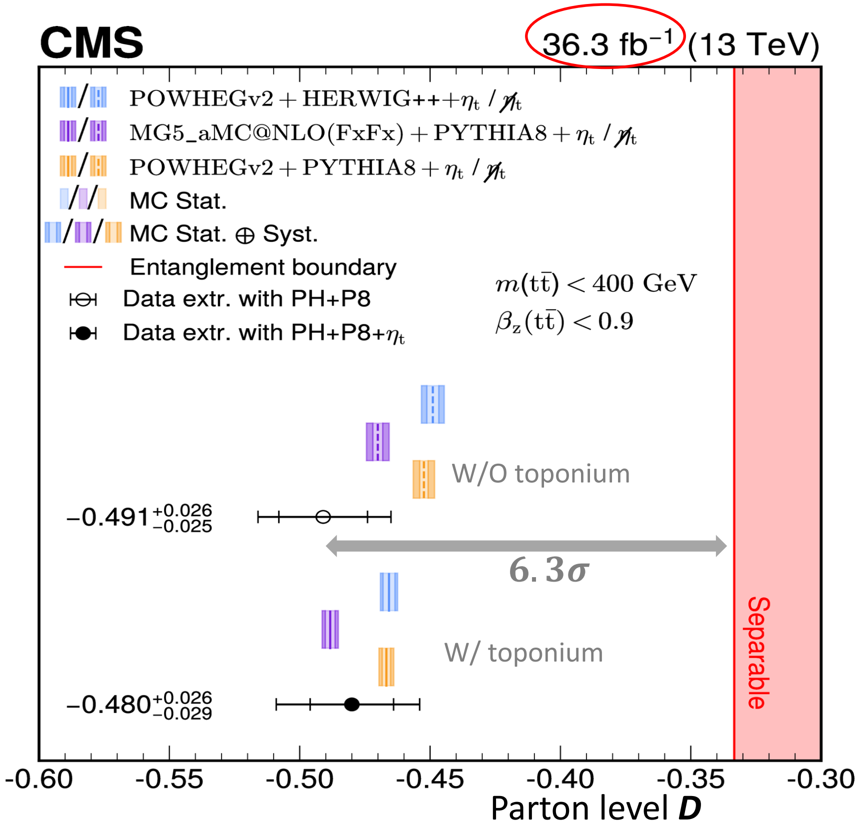
Entanglement in $t\bar{t}$ (dilepton channel)



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

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

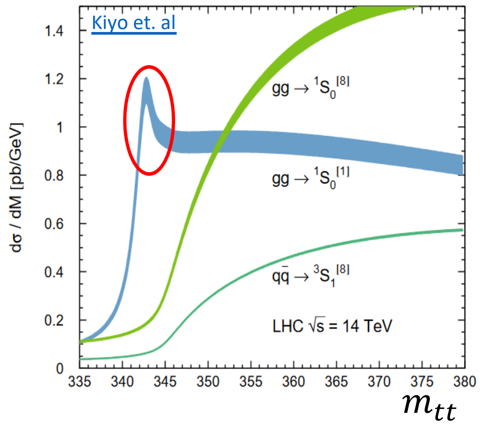




(CMS)

Include $t\bar{t}$ bound-state: toponium (η_t)*

- Pseudoscalar & maximally entangled
- $m(\eta_t) = 343\ GeV$
- $\sigma(pp \rightarrow \eta_t) = 6.43 \pm 0.90$ pb



Entanglement in $t\bar{t}$ is observed with $>5\sigma$ at low m_{tt}

Main uncertainties(ATLAS):

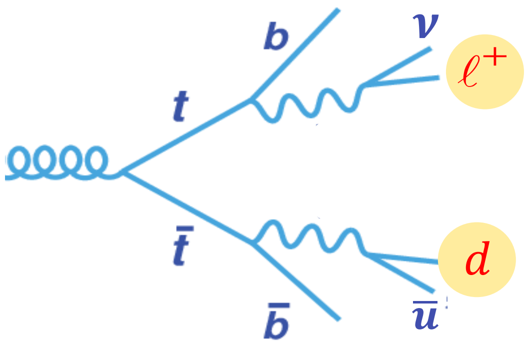
- Modeling of $t\bar{t}$ production/decay
- Background modeling
- Experimental (b-jet tagging, JES…)

Main uncertainties(CMS):

- η_t normalization
- Jet energy calibrations
- Statistical
- Modeling of $t\bar{t}$ production/decay

[*] Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)
Jezabek, Kuhn & Teubner (Z.Phys.C`92)
B. Fuks et al. (PRD 104 (2021) 034023), F. Maltoni et al. JHEP03(2024)099

Entanglement in $t\bar{t}$ ($\ell + jets$ channel)

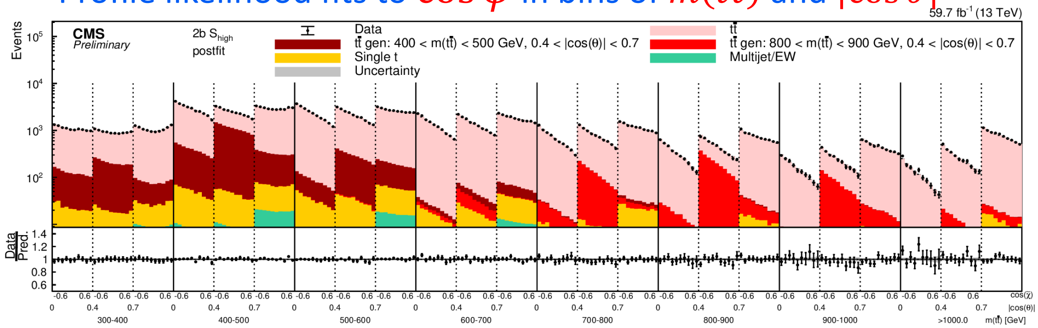


- Better sensitivity at **high $m_{t\bar{t}}$**
- Spin information via ℓ/d-quark

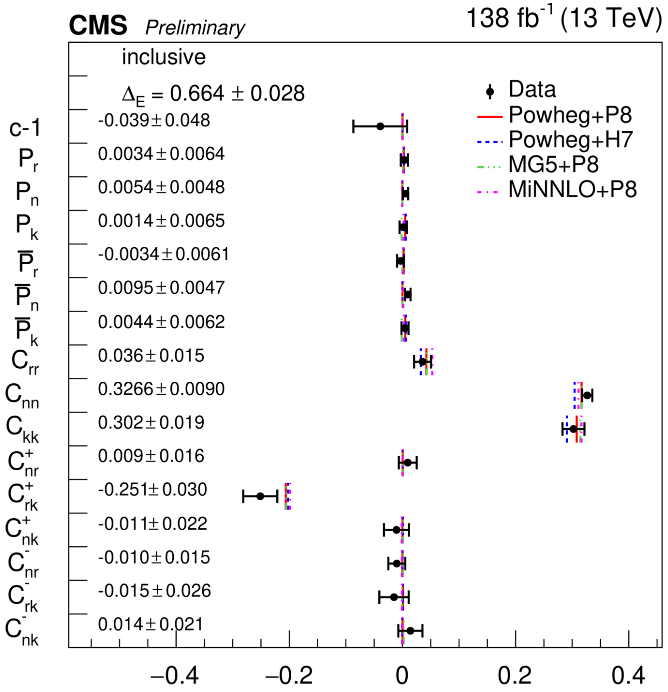
$$\cos\varphi = \hat{\ell} \cdot \hat{d}$$

- NN for correct assignment of top decay products (**up to 65% correct assignment**)

Profile likelihood fits to $\cos\varphi$ in bins of $m(t\bar{t})$ and $|\cos\theta|$

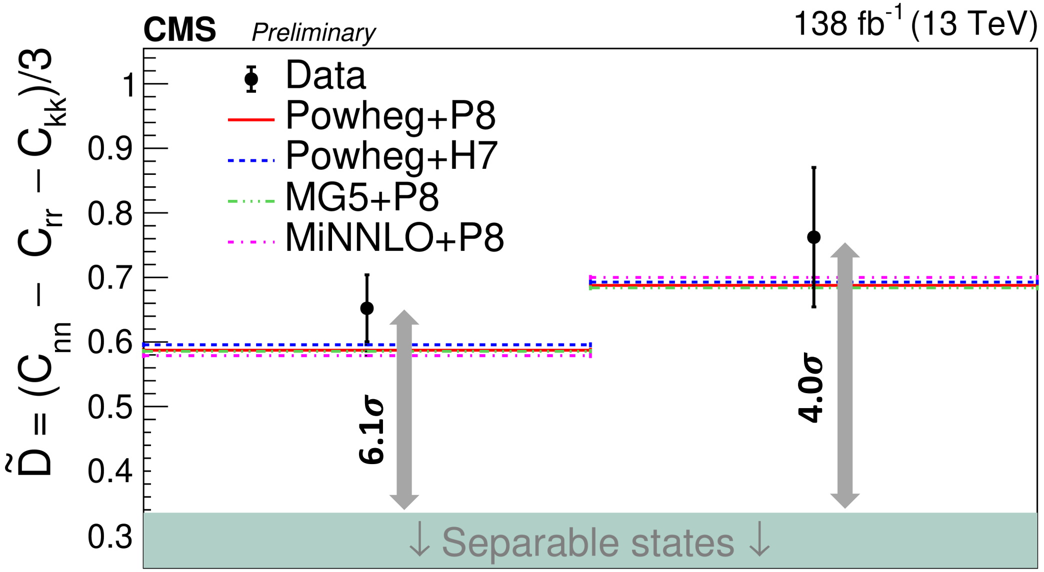


Low $m(t\bar{t})$ High $m(t\bar{t})$



Entanglement at high m($t\bar{t}$)
→ space-like separated region
→ prospects for Bell inequality tests

Demina, et al. 2407.15223



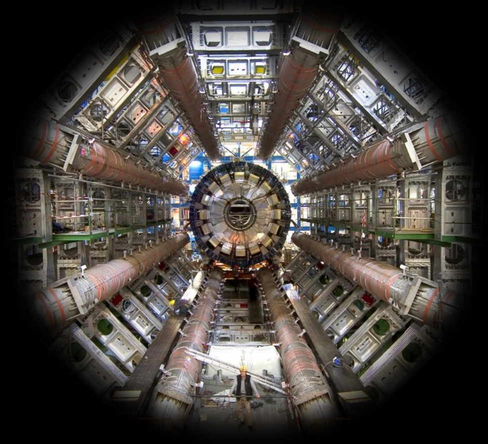
m($t\bar{t}$) > 800 GeV
|cos(θ)| < 0.4

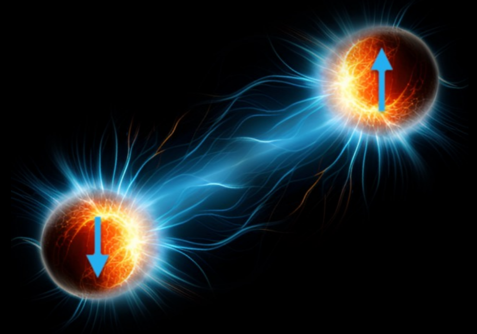
m($t\bar{t}$) > 1000 GeV
|cos(θ)| < 0.4

A new window to look for new physics effects

Severi, et al 2210.09330

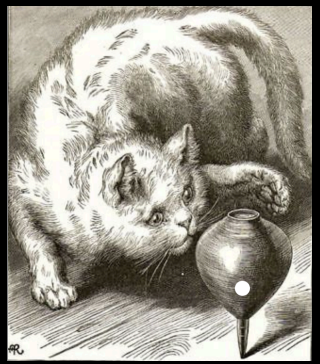
Summary





- Top quark physics is living its golden age
- Excellent precision in many areas thanks to:
  - Large LHC datasets
  - Improved analysis techniques/calibrations
  - Better theoretical modeling
- Combined ATLAS-CMS results prove to be powerful
- Observed quantum entanglement in top quark pairs

  → Multiple analyses in different phase-space regions!

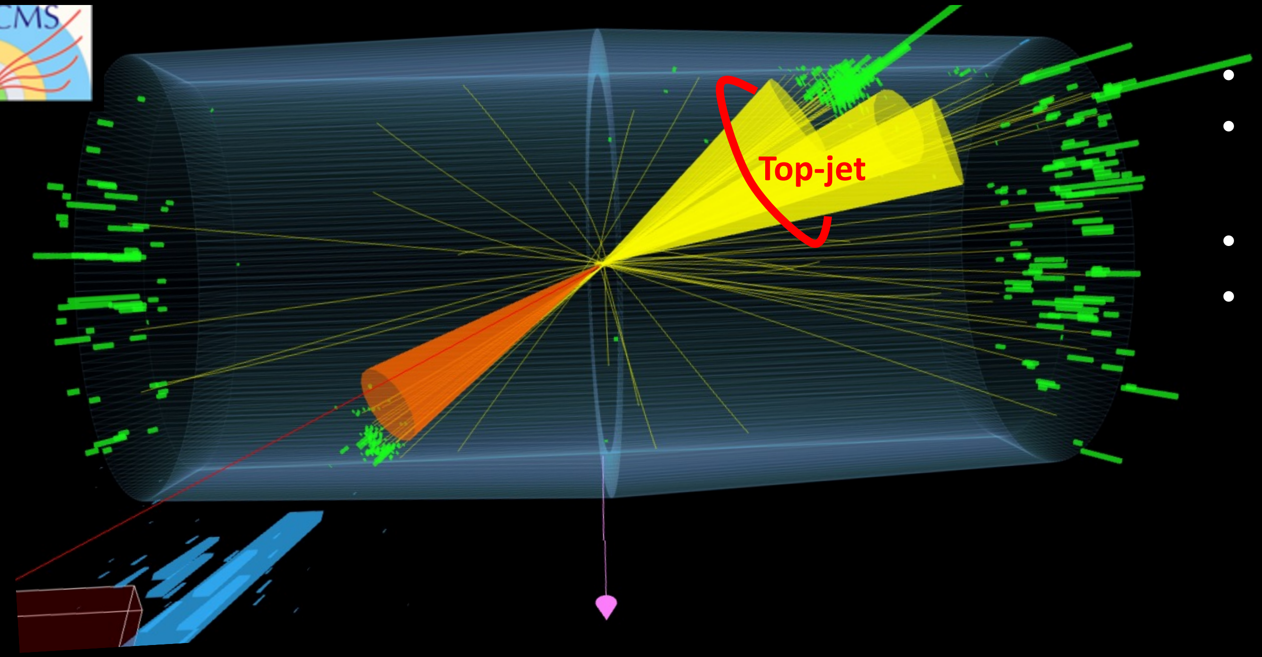


- More exciting results to come with Run3 data

Mass from boosted Top-jet

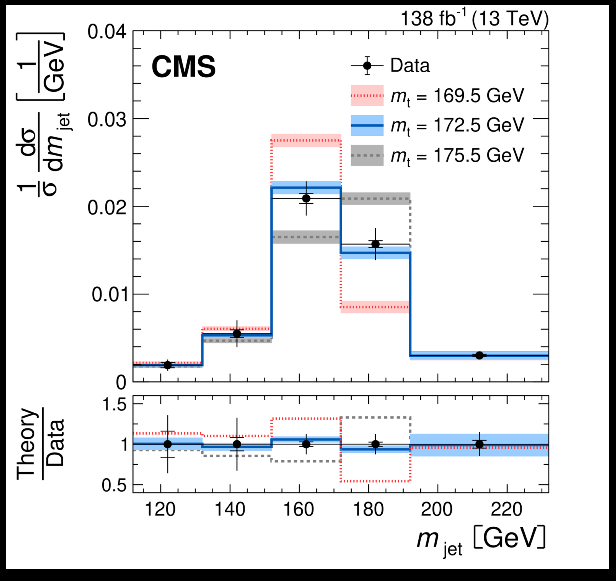
EPJC 83 (2023) 560

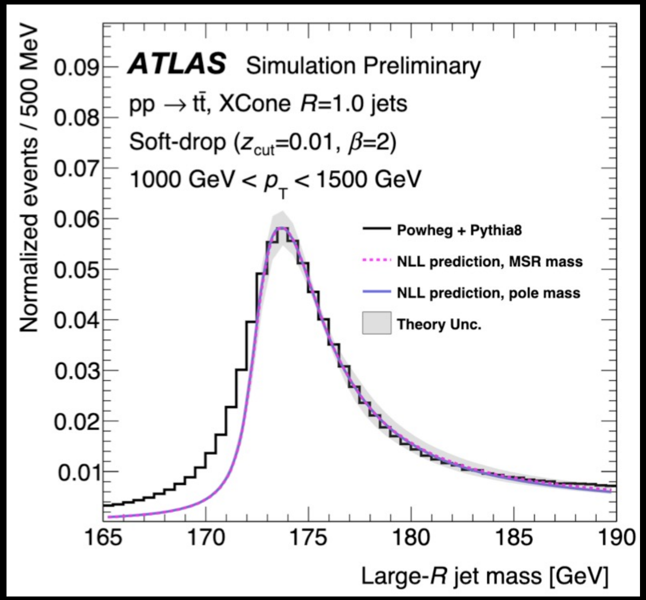
ATL-PHYS-PUB-2021-034



- $\ell + jets$ channel,
- Dedicated jet clustering(XCone) & calibrations using m_W^{jet}
- $p_{T,jet} > 400\ GeV$
- Extract m_{Top} from m_{jet}

Unfolded x-section to particle level





- m_{Top} measurements in the boosted regime compared to well-defined Lagrangian mass
- Simulation study by ATLAS gives:

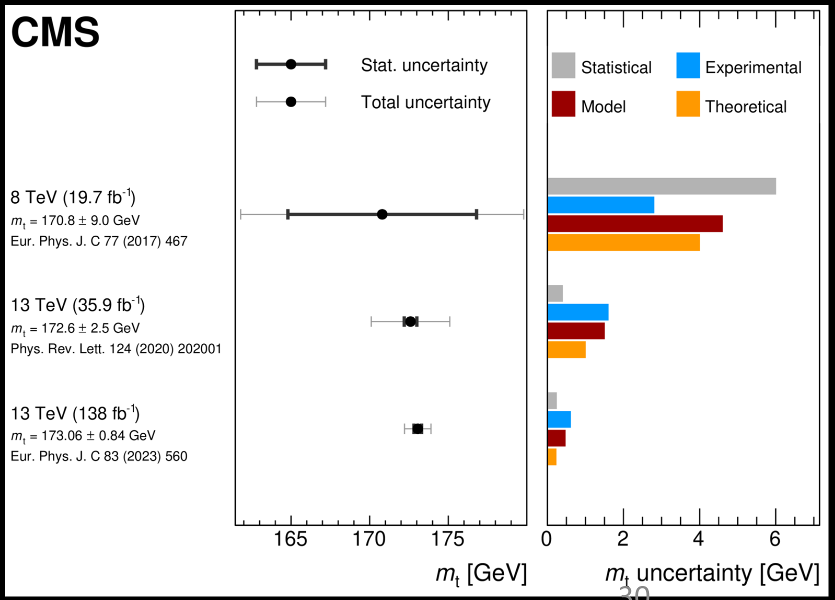
$$m_{Top}^{MC} - m_{Top}^{MSR} = 80^{+350}_{-410}\ \text{MeV}$$

- Scale variation
- Fit range, UE

9 GeV

Significant improvement

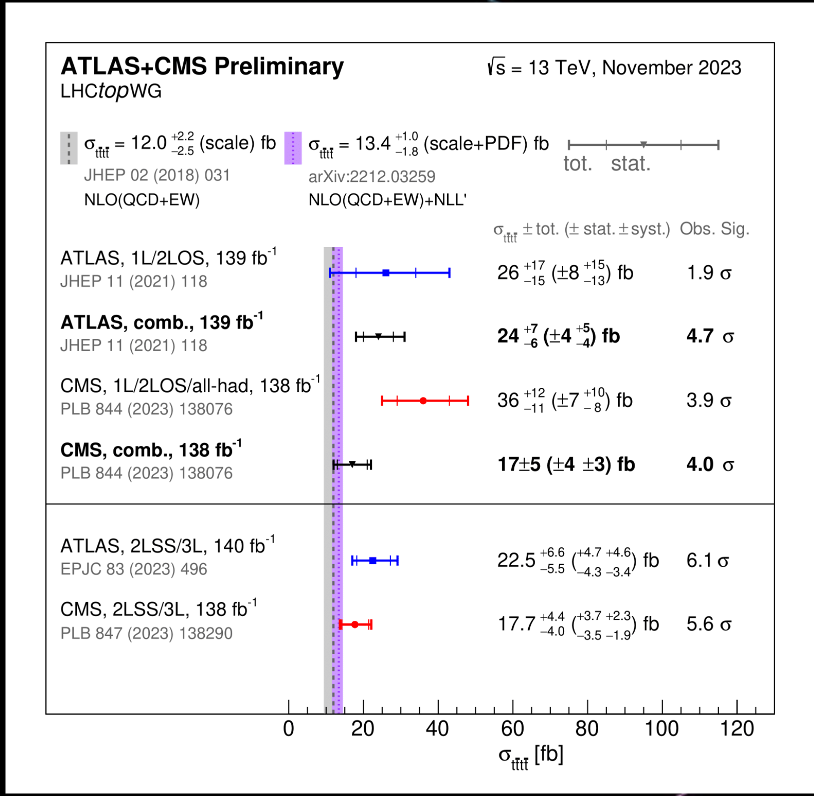
0.84 GeV

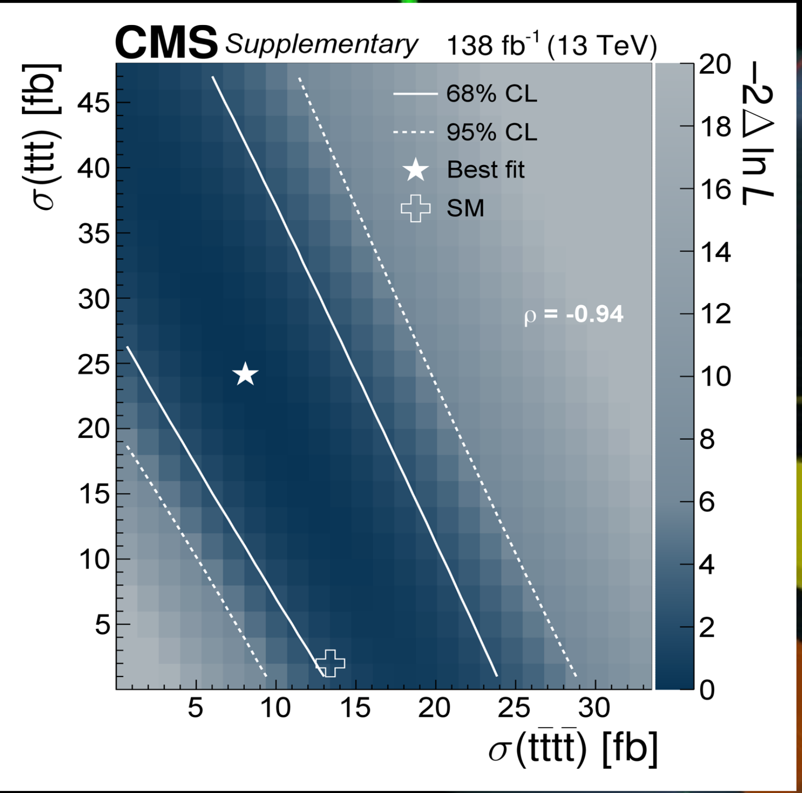


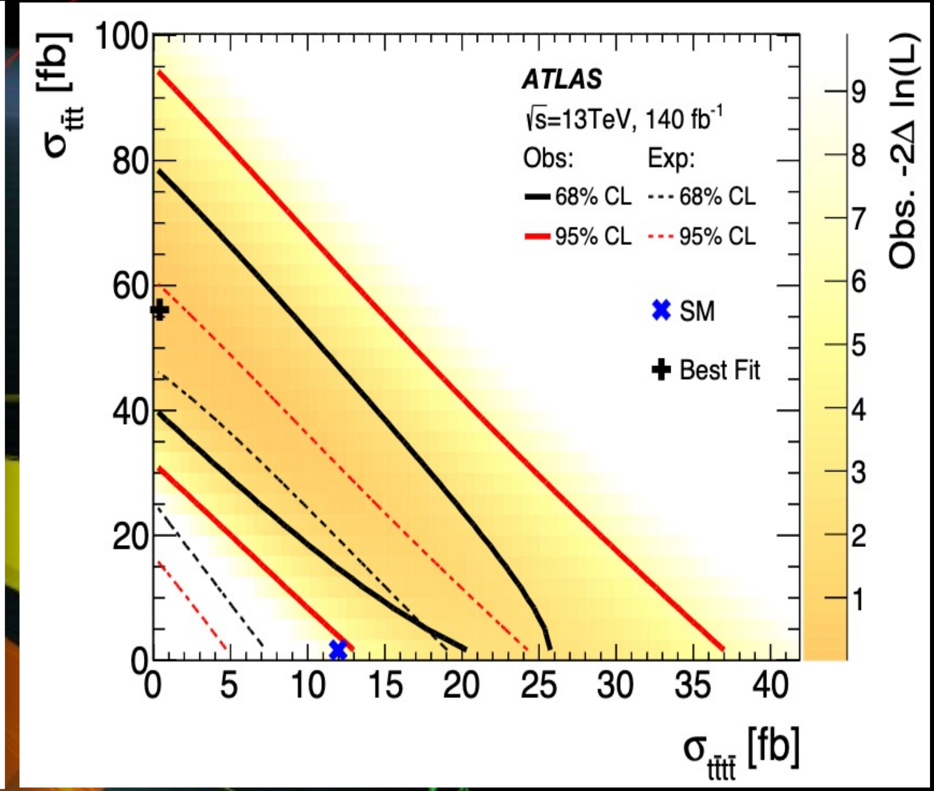
Observation of 4 top quarks by CMS and ATLAS

PLB 847 (2023) 138290

EPJ. C 83 (2023) 496

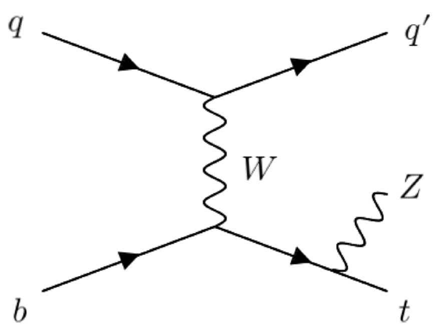


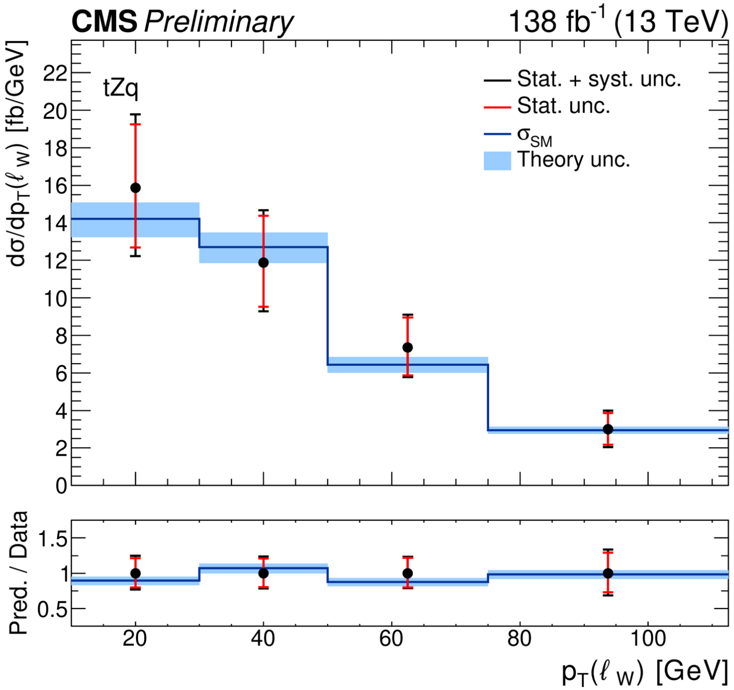


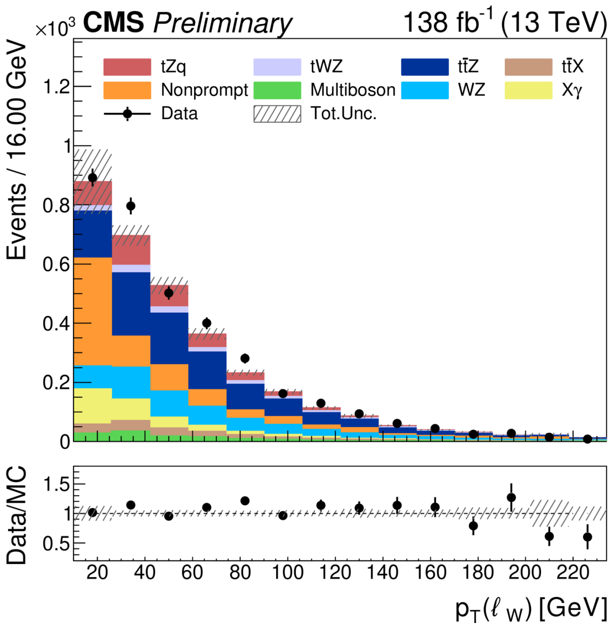


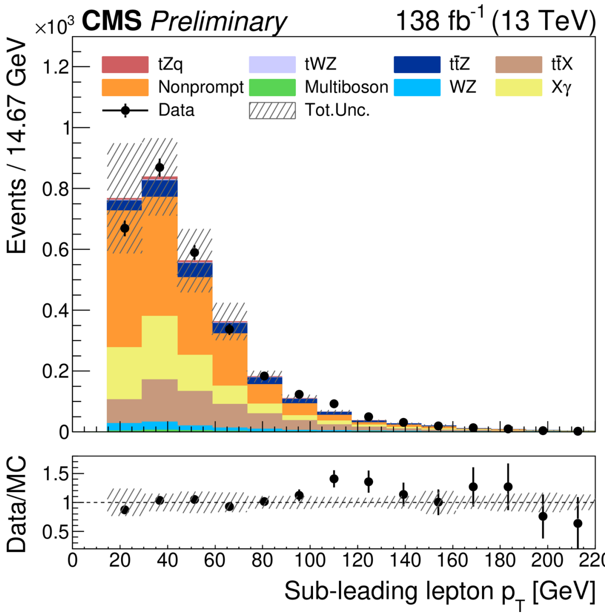
Is it four-tops ? Three-tops ? or New Physics ?

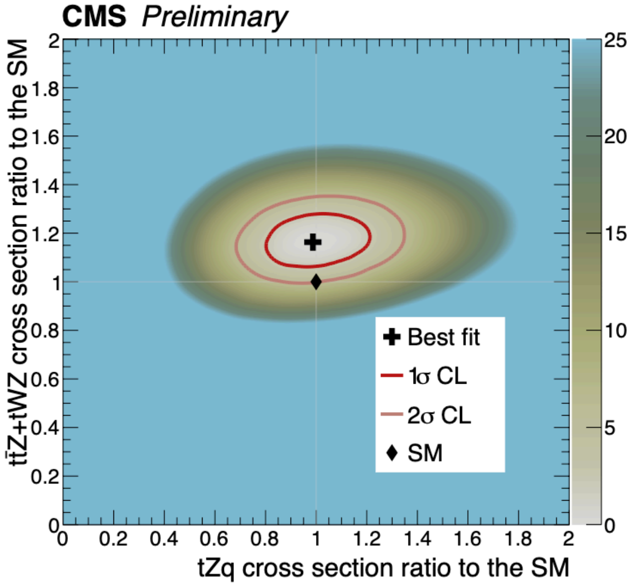
ttZ, tWZ, tZq production

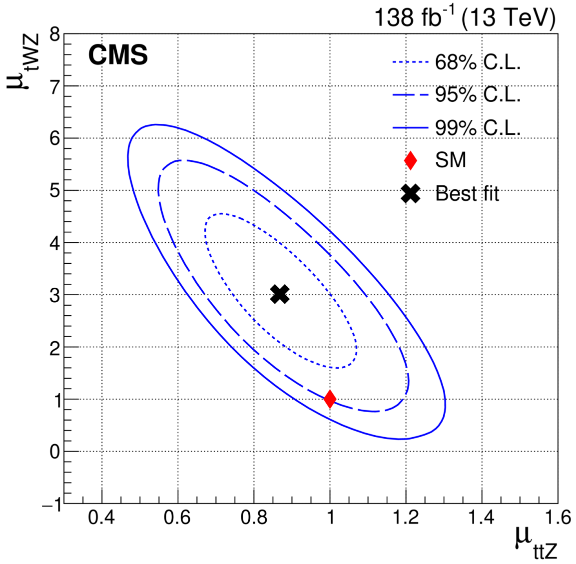






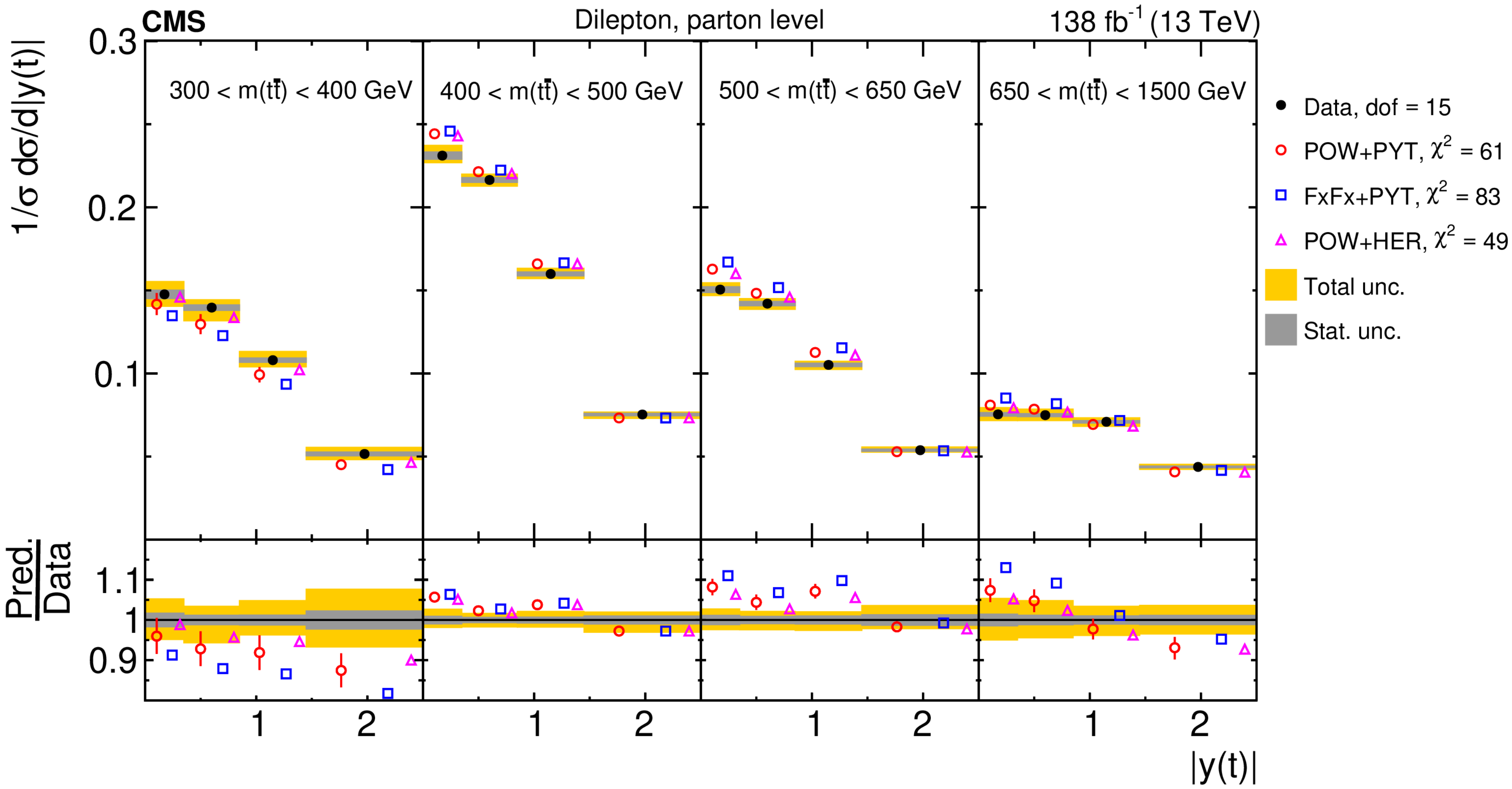




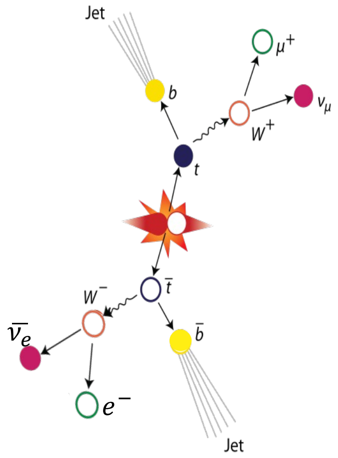


Differential cross sections

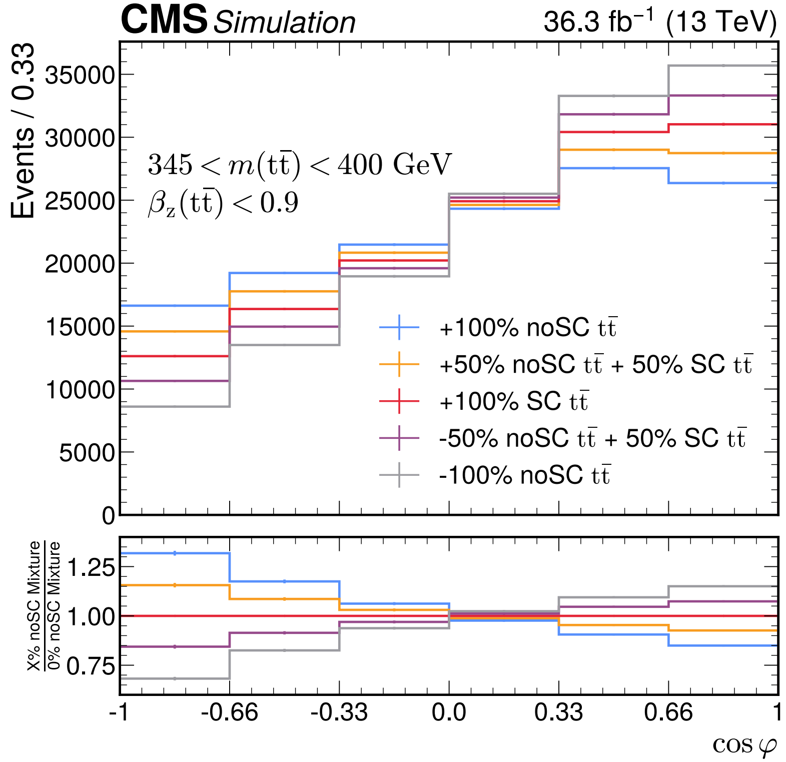
2402.08486



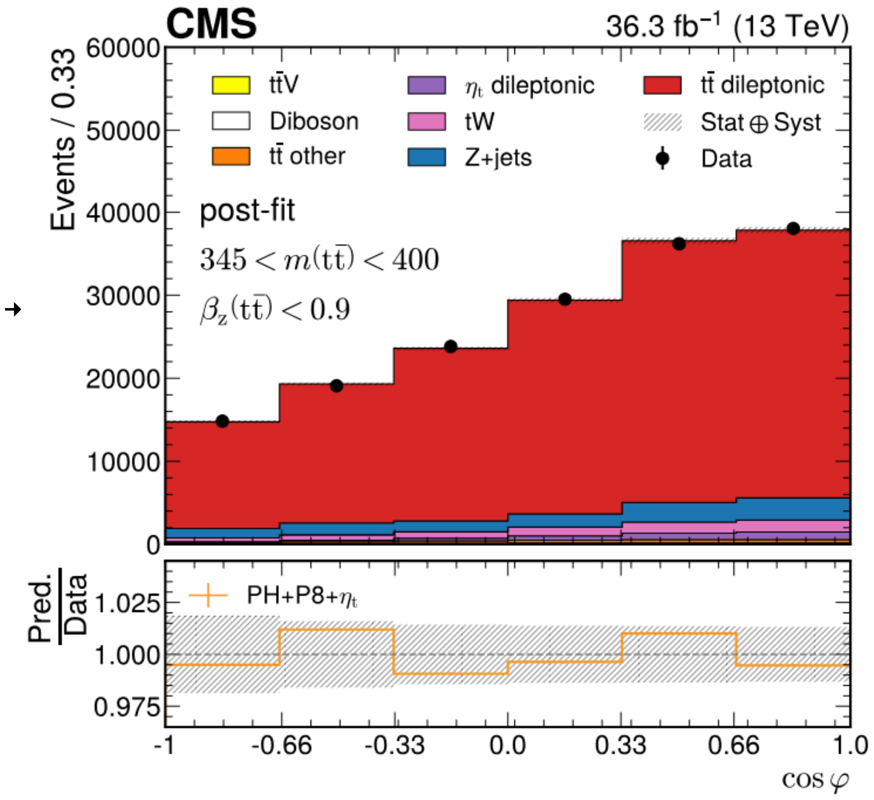
Entanglement in $t\bar{t}$ (dilepton channel)



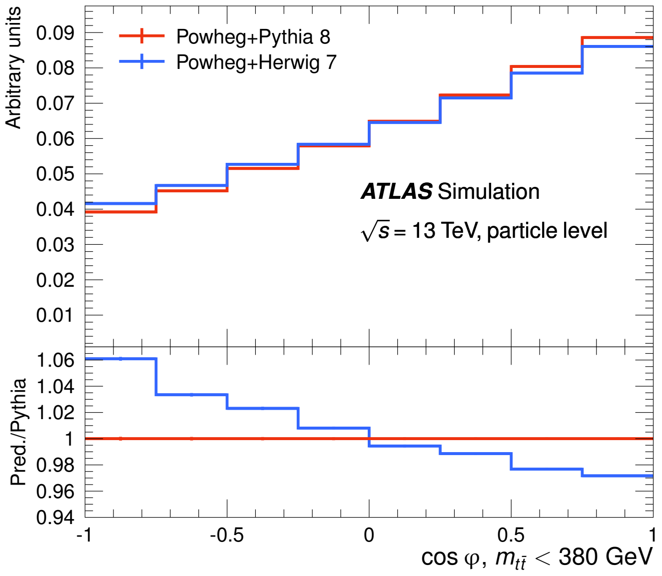
- 2016 data
- $e\mu, ee, \mu\mu$ channels, 2 jets >=1 bjet
- Top reconstruction assuming $p_T^{miss} = p_T^{\nu 1} + p_T^{\nu 2}$, m_W and m_t
- Solution with lowest m_{tt} is taken, 90% efficiency
- $m_{tt} < 400$ GeV, $\beta_z(t\bar{t}) < 0.9$ to enhance $\frac{gg}{qq}$



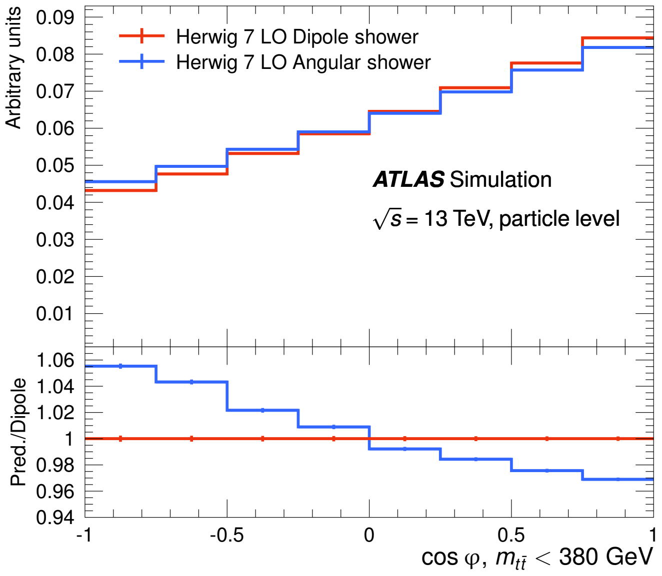
Postfit



Parton shower modeling (ATLAS)



(a)



(b)

ATLAS ttBar modelling:

- Powheg @NLO QCD with NNPDF3, top-decays & spin correlations @LO in QCD
- PowhegBOXRes (bb4l) to modell off-shell production (NLO) and decays& spincorrelations @NLO
- Parton shower: Pythia & Herwig