Top Quark Measurements

Physics in Hadronic and Nuclear Collisions 2025

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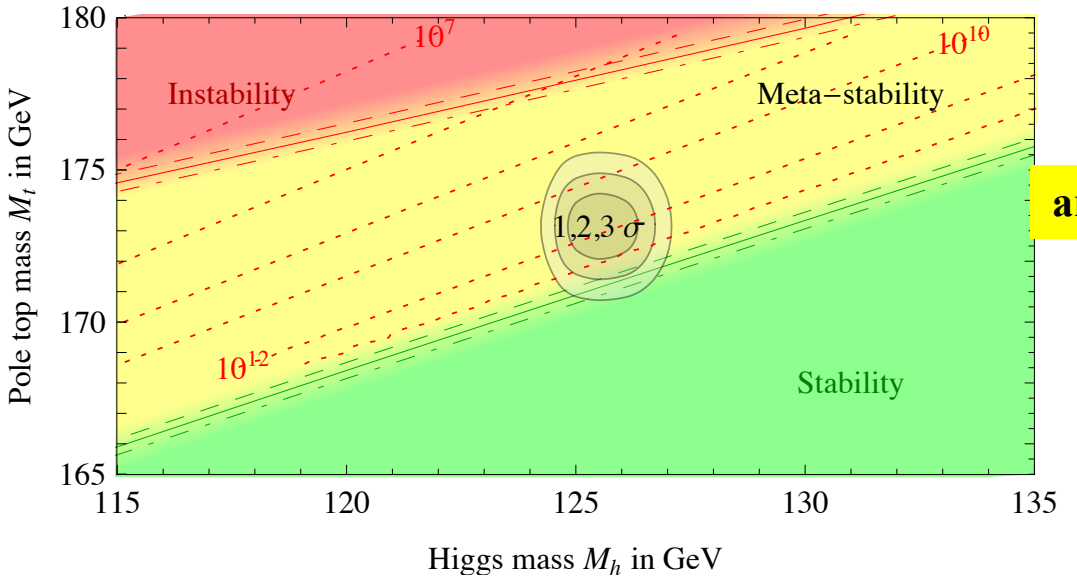
What's special with Top?

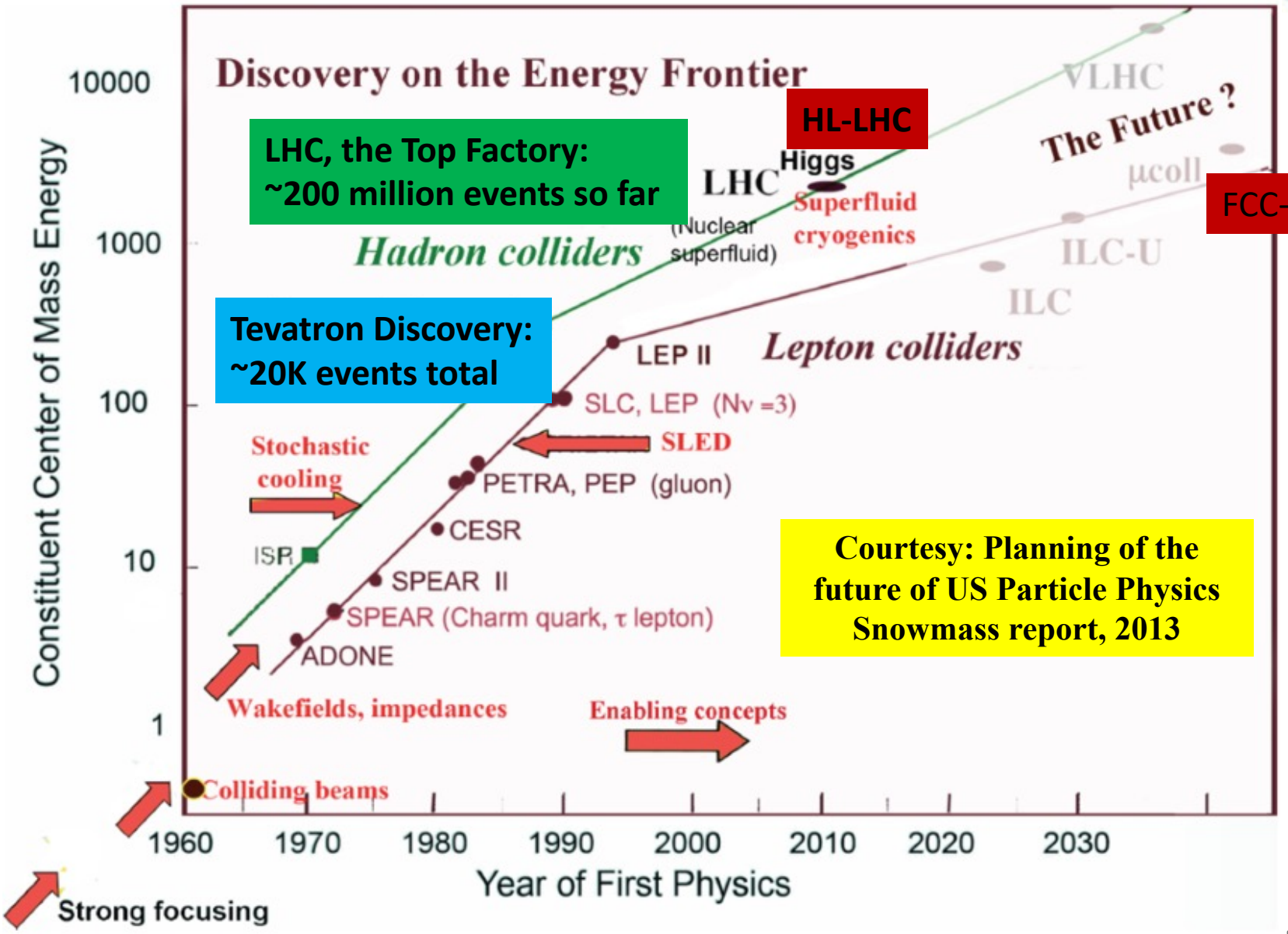
- **Decays before the hadronization [lifetime 0.5x10-24 sec]**
  - **Unique opportunity to study the bare quark**
- **Strong coupling with the Higgs boson, top Yukawa coupling, y_t~1**
- Constraints the Higgs mass along with W boson mass
  - influences the electroweak vacuum stability



arXiv:1205.06497 [hep-ph]

- Many new physics models result in same signature, e.g, SUSY "stop" can decay into top

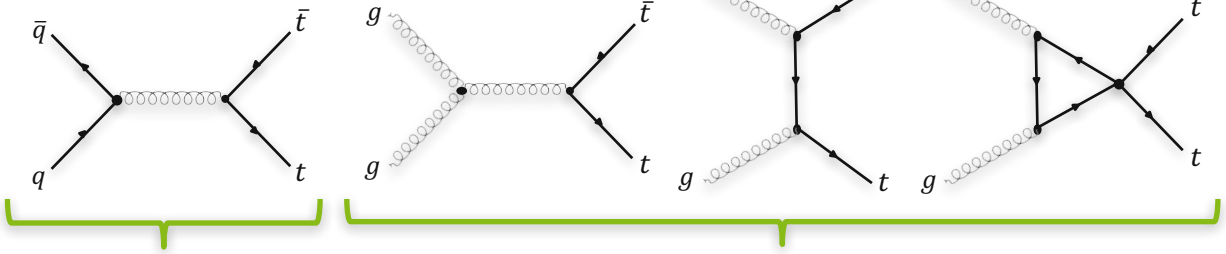
Top Production in Colliders



Courtesy: Planning of the future of US Particle Physics Snowmass report, 2013

Top quark production modes at LHC

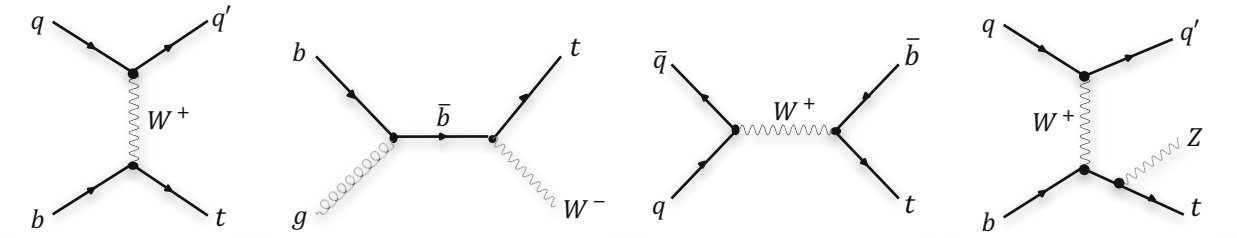
Dominated by $t\bar{t}$ pairs productions



quark-antiquark annihilation (~10%)

gluon-gluon fusions (~ 90%)

Single top-quark productions



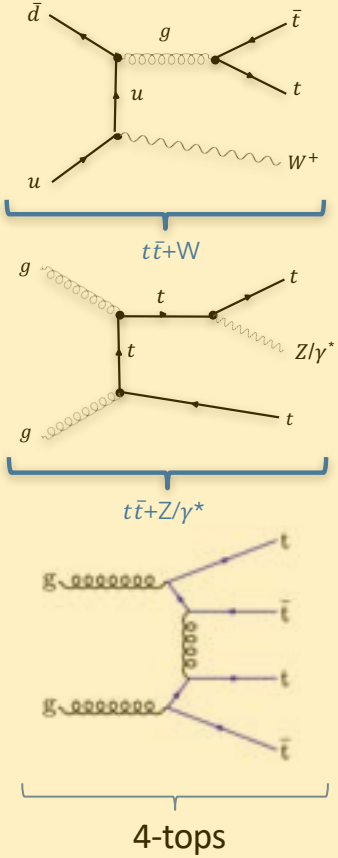
t-channel (~73%)

tW associated production (~24%)

s-channel (~3%)

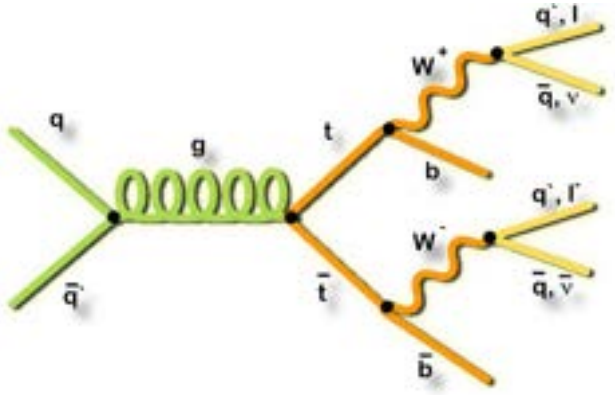
tZ production (<1%)

Other productions

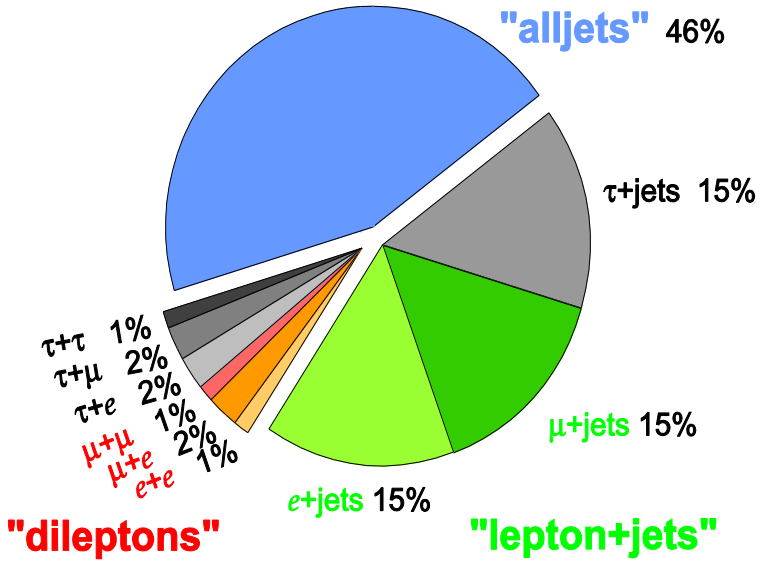


Decay of Top quark

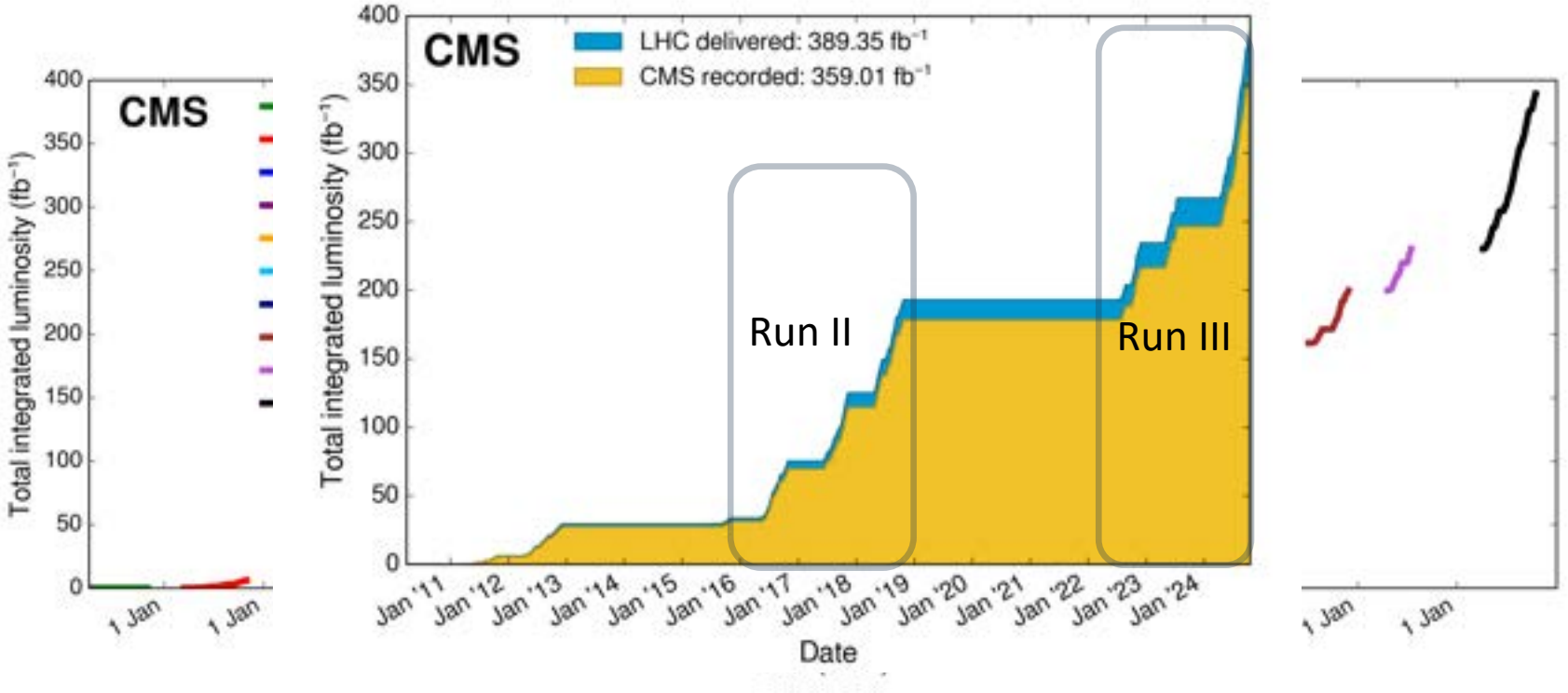
- SM Br(t→W⁺b)=100%
- Final states determined through the decay of W± bosons from top and antitop quarks.
  - All jets: $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}q\bar{q}'q\bar{q}'$
    - **High branching ratio but large QCD background**
    - **≥ 6 jets, 2 b-jets**
  - **lepton+jets:** $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}q\bar{q}'l^-\bar{\nu}$
    - Moderately high branching ratio but relatively low background
  - dilepton: $t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow b\bar{b}l^+\nu l^-\bar{\nu}$
    - Low branching ratio but clean signal
- Similarly different final states for single top/electroweak top production
  - Dilepton: $tW^- \rightarrow bW^+W^- \rightarrow bl^+\nu l^-\bar{\nu}$
  - Semileptonic s-channel: $t\bar{b} \rightarrow bW^+\bar{b} \rightarrow b\bar{b}l^+\nu$



Top Pair Branching Fractions



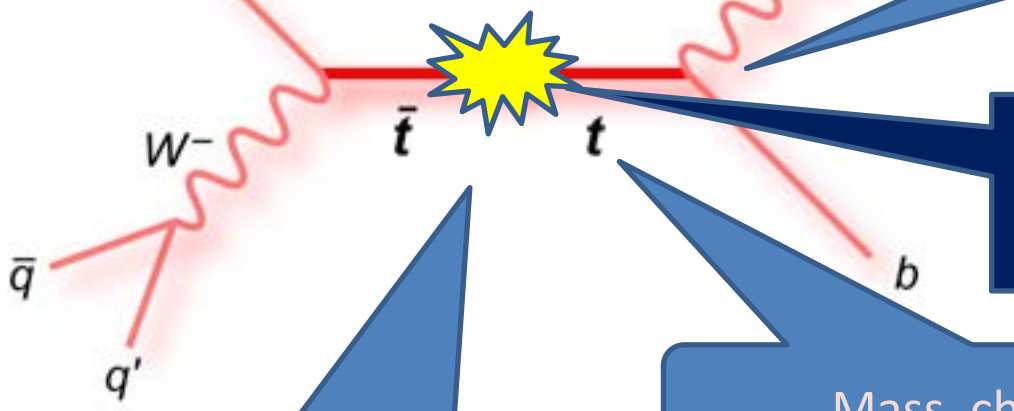
LHC Performance



- After the glorious Run I, LHC started operated at √s=13 TeV during 2015-18 (Run II)
- CMS have completed Inner detector upgrades during the Extended Year-End Technical Stop (EYETS) at the end of 2016 operation
- LHC has been performing exceedingly well; during Run II, CMS have recorded >150 fb^{-1} of pp collision datasets at √s=13 TeV
- Finally, unprecedentedly large volume of proton-proton collisions data at √s=13.6 TeV being recorded during the LHC Run III

Top Quark Measurements

Measurements performed in 30 years (Tevatron +LHC)



W helicity

Branching ratio
Rare decays, New physics
Anomalous couplings

Spin correlation
Charge Asymmetry

Mass, charge, width

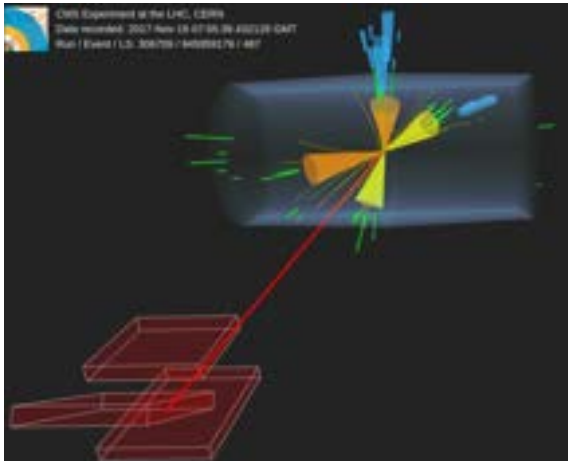
Cross sections
Differential cross sections
New physics

+ electroweak single top production

Top Cross-section Measurement

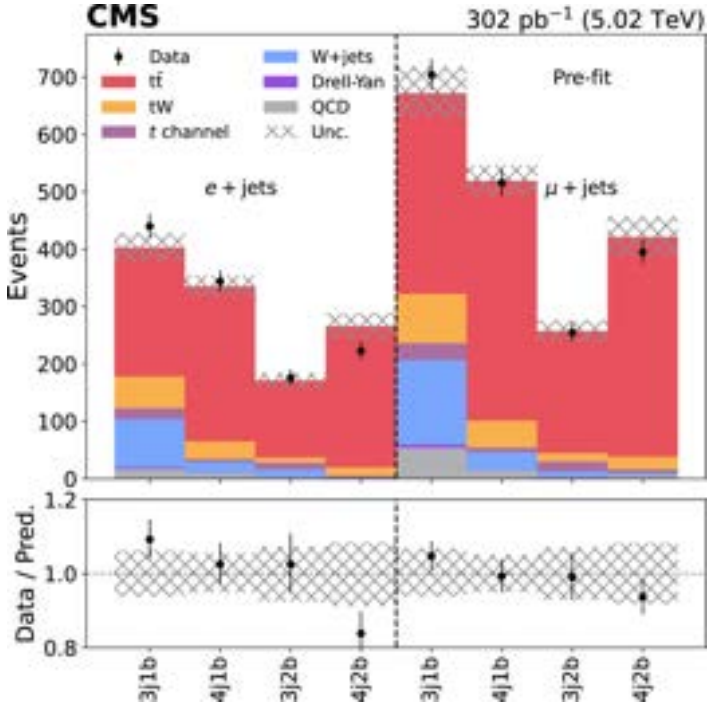
Inclusive $t\bar{t}$ production cross-section at √s=5.02 TeV

- **Exactly 1 lepton (electron or muon)** (p_T > 20 GeV, |η| < 2.4). Veto on sub-leading lepton of opposite flavour, p_T > 10 GeV.
- **At least 3 jets** (p_T > 25 GeV, |η| < 2.4).
- **MET > 30 GeV.**
- Events are further categorized into **8 categories** depending on the **number of jets and b-tagged jets, and the lepton flavour** (electron or muon). Among those:
  - All are signal-dominated
  - $\ell + 3j \geq 2b$ and $\ell + 4j \geq 2b$ are purest in signal (89% of total MC)
  - $\ell + 3j1b$ provide the greatest contribution from tW and W+jets backgrounds (12% and 18% of total MC)



l+jets analysis 2017 dataset

arXiv:2410.21631 [hep-ex] accepted by JHEP



➢ **4 main backgrounds: Single top (tW + t-channel), W+jets, QCD multijets** (cut in **MET > 30GeV** to suppress it, estimated from data) and **Drell-Yan.**

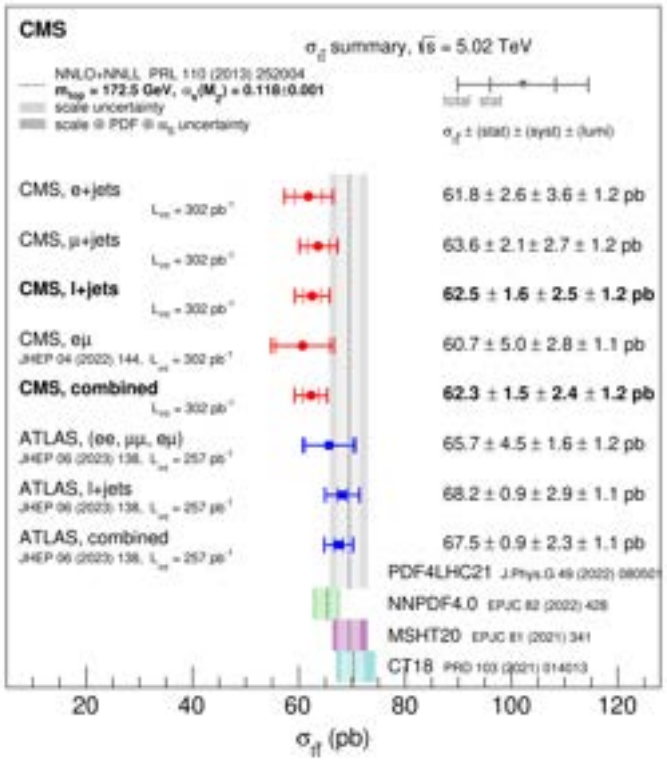
Inclusive $t\bar{t}$ production cross-section at √s=5.02 TeV

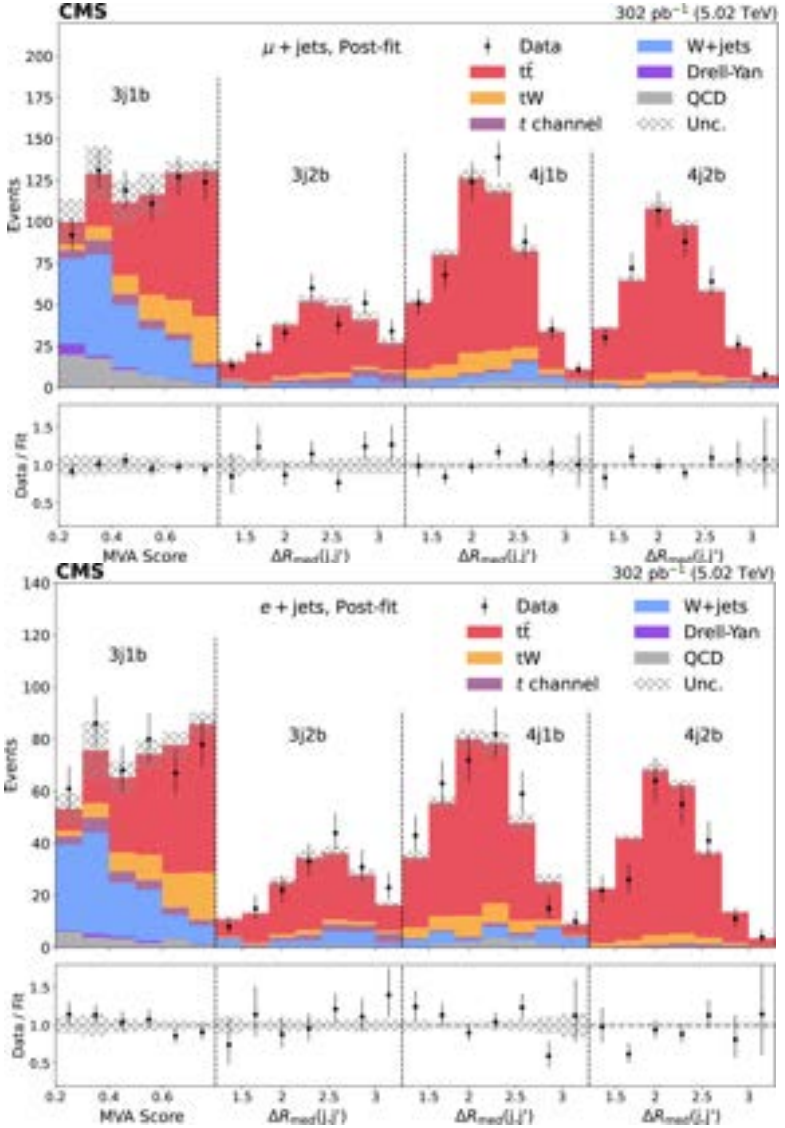
arXiv:2410.21631 [hep-ex] accepted by JHEP

- **Final distributions in 27 bins x 2 (e/μ) = 54 bins : median [ΔR(j,j')] & MVA score (for 3j1b category)**
- **Simultaneous maximum-likelihood fit to extract the cross-sections**

  62.5 ± 1.6 (stat) $^{+2.6}_{-2.5}$ (syst) ± 1.2 (lumi) pb
- **In combination with the CMS dilepton results**

  62.3 ± 1.5 (stat) ± 2.4 (syst) ± 1.2 (lumi) pb



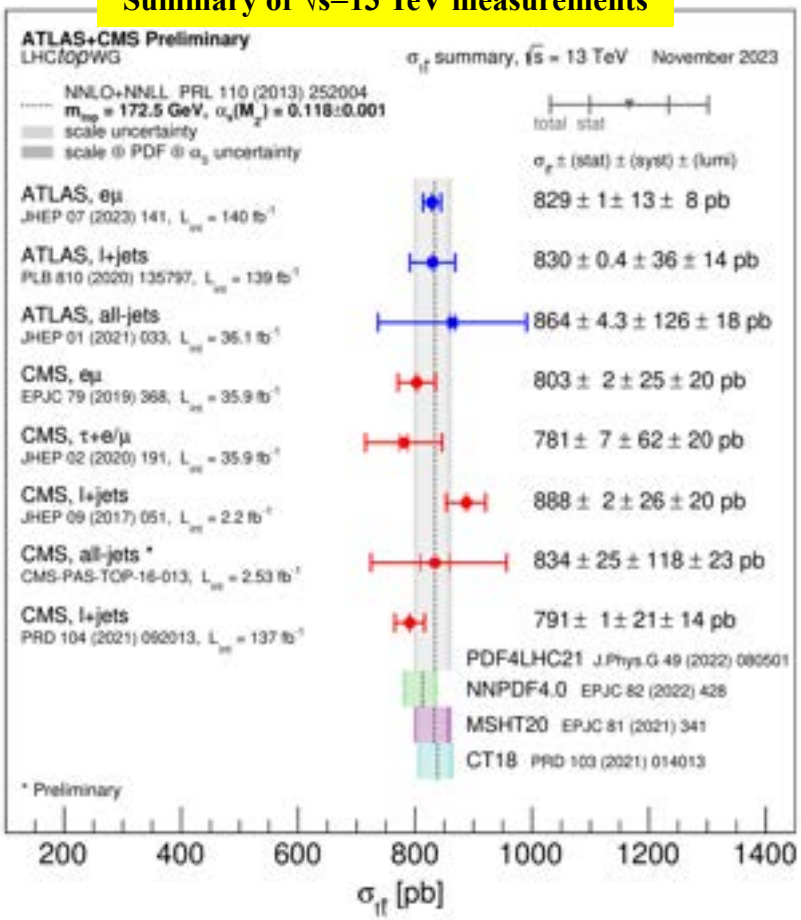


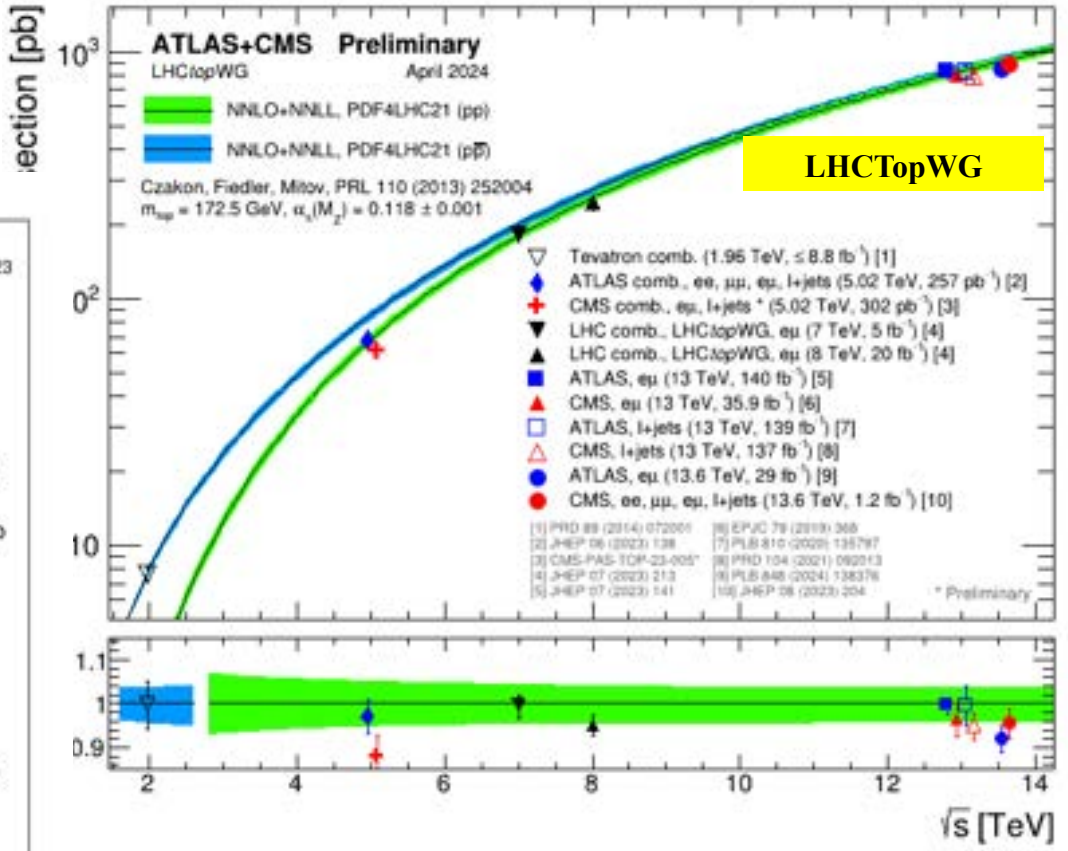
Summary of Inclusive $t\bar{t}$ production cross-section

$$\sigma\left(t\bar{t}\right) = \frac{N_{events} - N_{bkg}}{\varepsilon \bullet A \bullet L}$$

LHCTopWG

Summary of √s=13 TeV measurements





LHCTopWG

- **Numerous measurements at different center-of-mass energies at the LHC along with the Tevatron ones exploring different final states**
- **Precise cross-section measurements are quite crucial**
  - **Scrutinizes the QCD predictions**
  - **Possibility to extract several SM parameters e.g., α_s, m_{top}…**
- **All inclusive cross-section measurements are consistent with the SM**

W-boson associated single top production at √s=13.6 TeV

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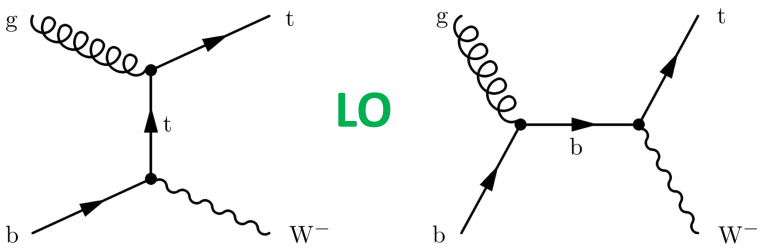
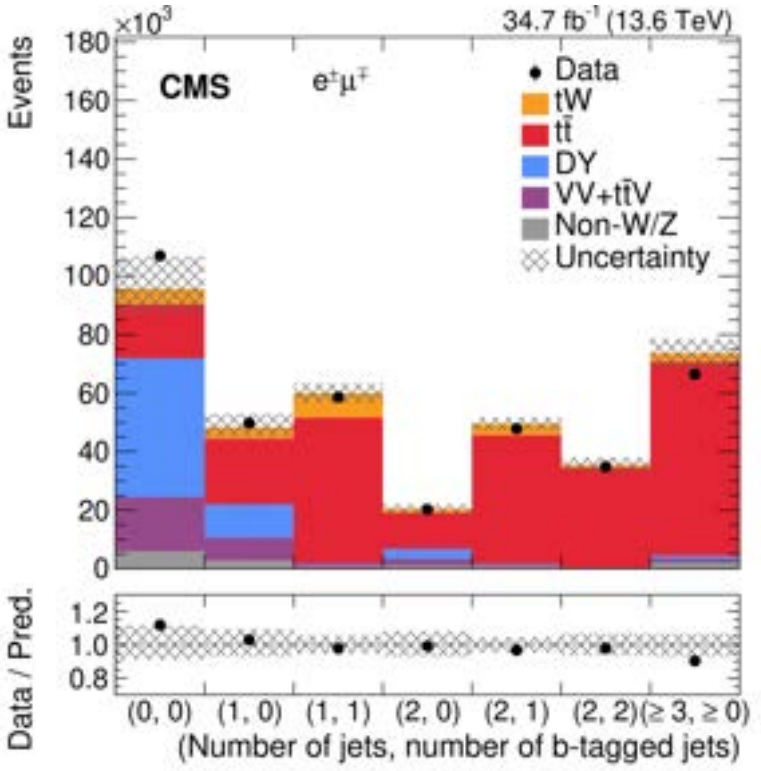
- **Inclusive and differential cross-section measurement using 34.7 fb^{-1} Run III dataset (2022)**
  - **Sensitive to V_{tb} & b-PDF**
  - **tW@NLO interferes with ttbar which is large**
  - **ML techniques applied for separation between tW & ttbar**



Basic event Selection

- **At least 2 leptons opposite charge and flavour ($e^{\pm}\mu^{\mp}$)** (p_T > 20 GeV, $|\eta| < 2.4$). Leading lepton p_T > 25 GeV.
- **Jets** (p_T > 30 GeV, $|\eta| < 2.4$).
- **$m(\ell_1, \ell_2)$ > 20 GeV.**
- **Categories** depending on the **number of jets and b-tagged jets.** Among those, used are **1j1b, 2j1b** (SRs) and **2j2b** ($t\bar{t}$ CR)



W-boson associated single top production at √s=13.6 TeV

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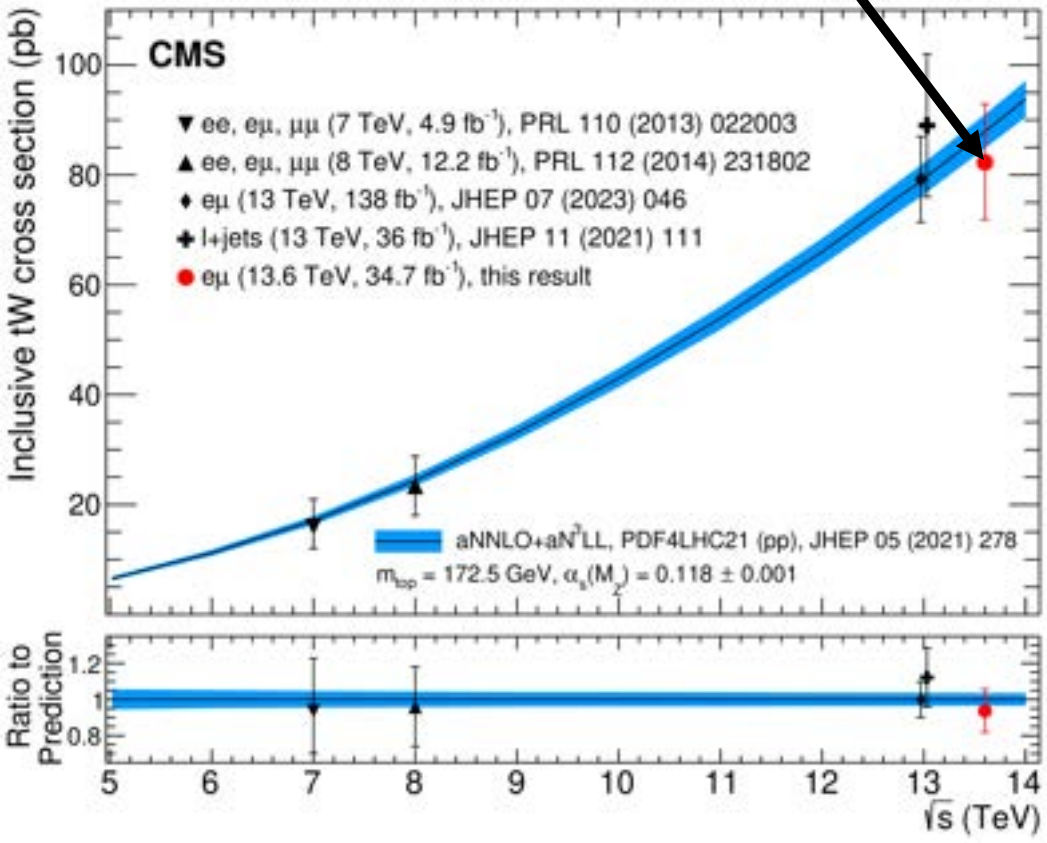
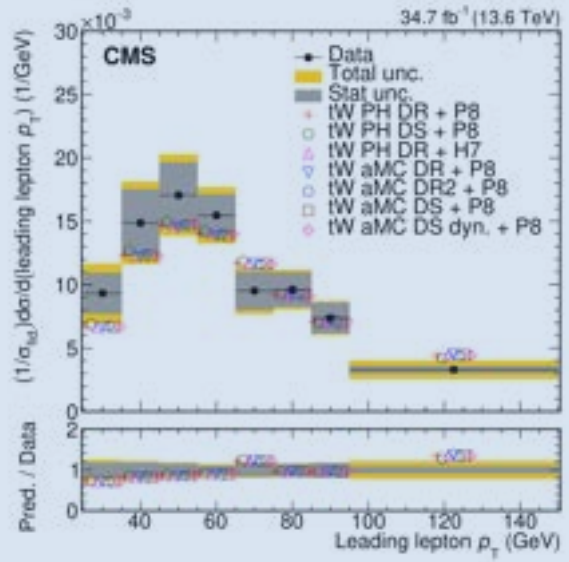
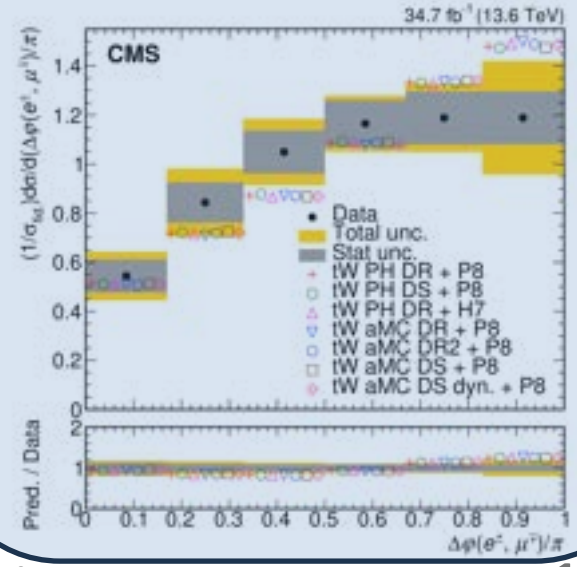
σ_{tW}= 82.3 ± 2.1 (stat) $^{+9.9}_{-9.7}$ (syst) ± 3.3 (lumi) pb
~13% uncertainty, JES and b-jet identification





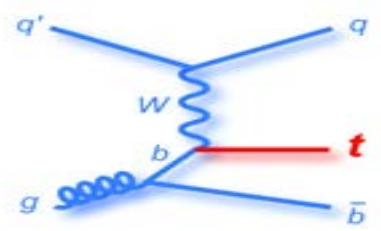
Differential x-sec compared with different event generators



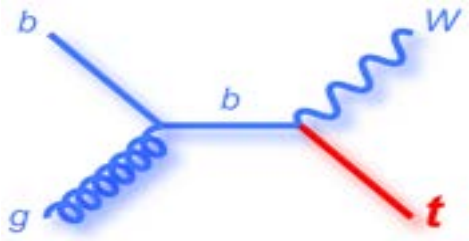
Summary of Electroweak Top Production

Single top-quark production via electroweak interaction, involving a *Wtb* vertex

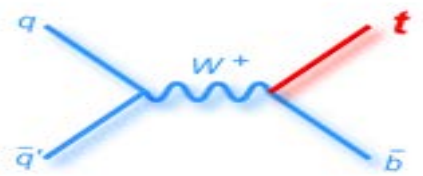
***t*-channel**



***Wt* channel**



***s*-channel**



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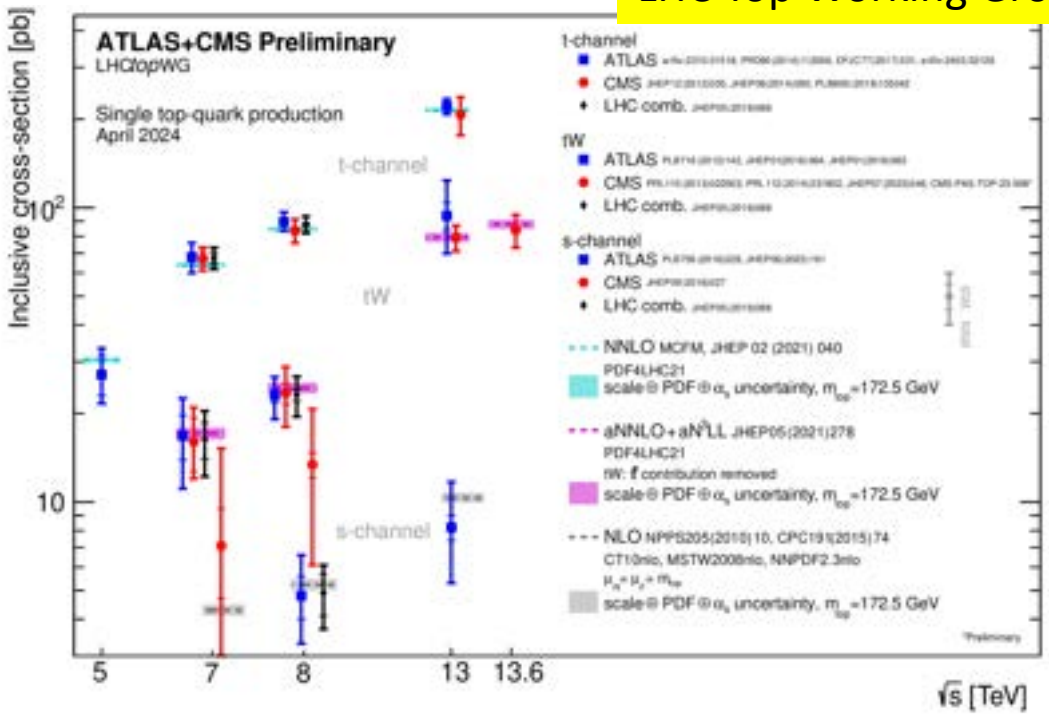

- ✧ Direct determination of the CKM Matrix element ($|V_{tb}|$)
- ✧ Background process for Higgs and BSM searches
- ✧ Major probe in BSM physics scenarios
- ✧ Precision calculations available at NLO QCD, NNLO QCD complemented with N3LL resummation

Rare Top production processes

Simultaneous measurement of ttZ, tZW and tZq

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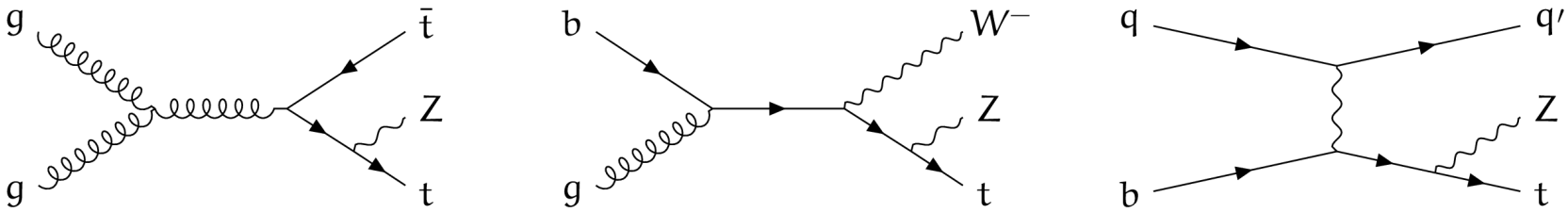
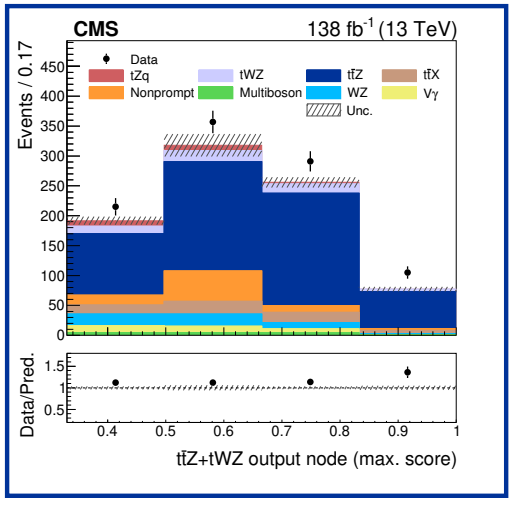
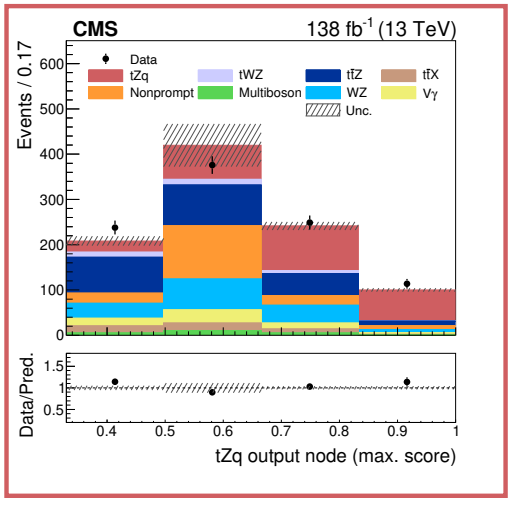
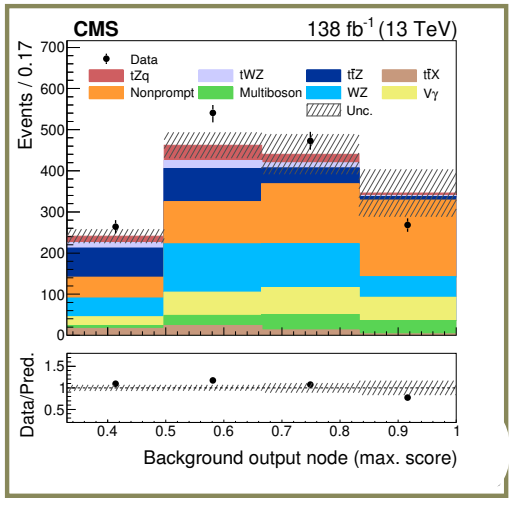


- Signal region with three leptons (e or μ), $\geq$2 jets, $\geq$1 b-tagged jet
- **Nonprompt lepton contribution** is estimated from data, **WZ** and other smaller backgrounds from simulation
- Neural network (multi-class classifier) to disentangle different signals and backgrounds
  - 3 output nodes for **$t\bar{t}Z$+tWZ**, **tZq**, and **background** (maximum-score splitting to build fit categories)







Simultaneous measurement of ttZ, tZW and tZq

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- Simultaneous fit to 3 max-score output nodes in SR and number of jets / b jets in two extra regions - 4 leptons ($t\bar{t}Z$ enriched), and no b jets (WZ enriched)

- Profiled likelihood-ratio scan for $\sigma_{t\bar{t}Z+tWZ}$ and σ_{tZq}

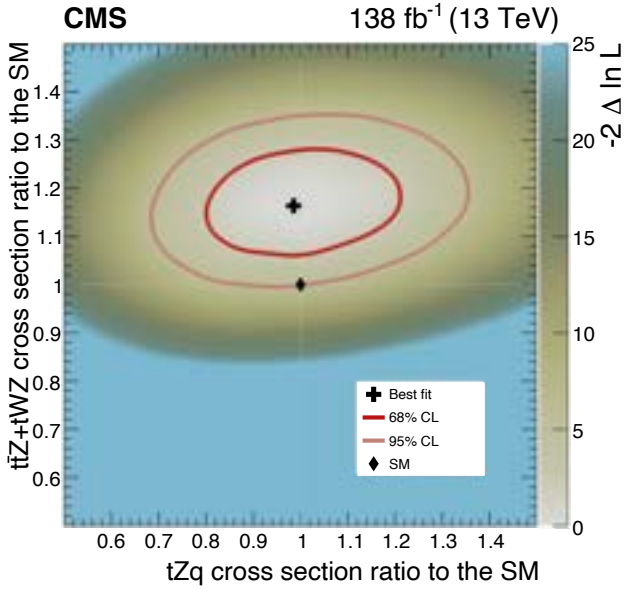
- Limited by statistics, main syst. uncertainties on background modelling and b tagging

- Inclusive cross sections measured to be:

$$\sigma_{t\bar{t}Z+tWZ} = 1.14 \pm 0.07 \text{ pb}$$

$$\sigma_{tZq} = 0.81 \pm 0.10 \text{ pb}$$

- Fixing the $t\bar{t}Z$ (tWZ) and tZq processes to the SM prediction yields a tWZ ($t\bar{t}Z$) cross section consistent with previous measurements



consistent with SM for tZq,
slight excess for $t\bar{t}Z$+tWZ

Compatible with the previous measurements

Summary of Vector boson associated $t\bar{t}$ production

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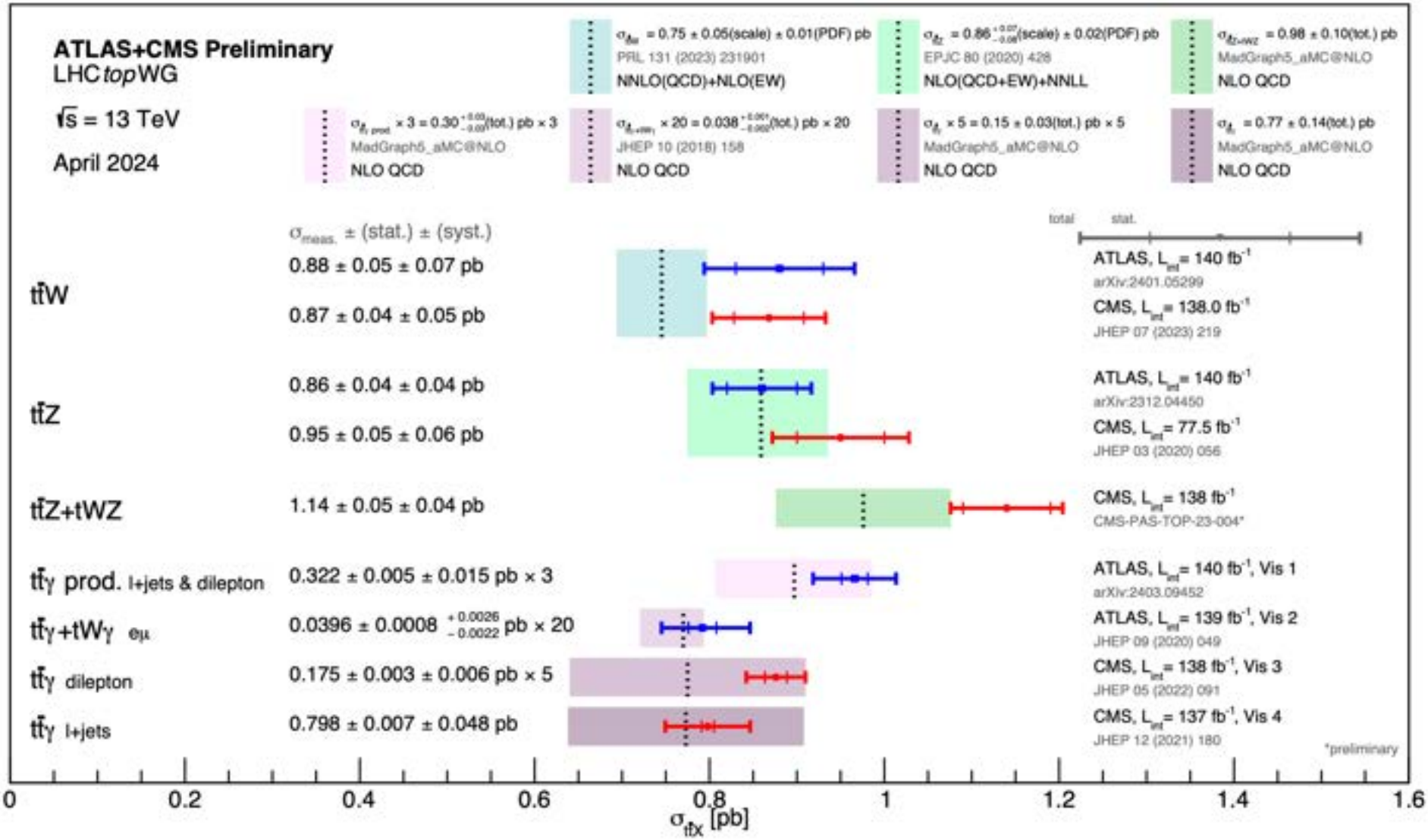
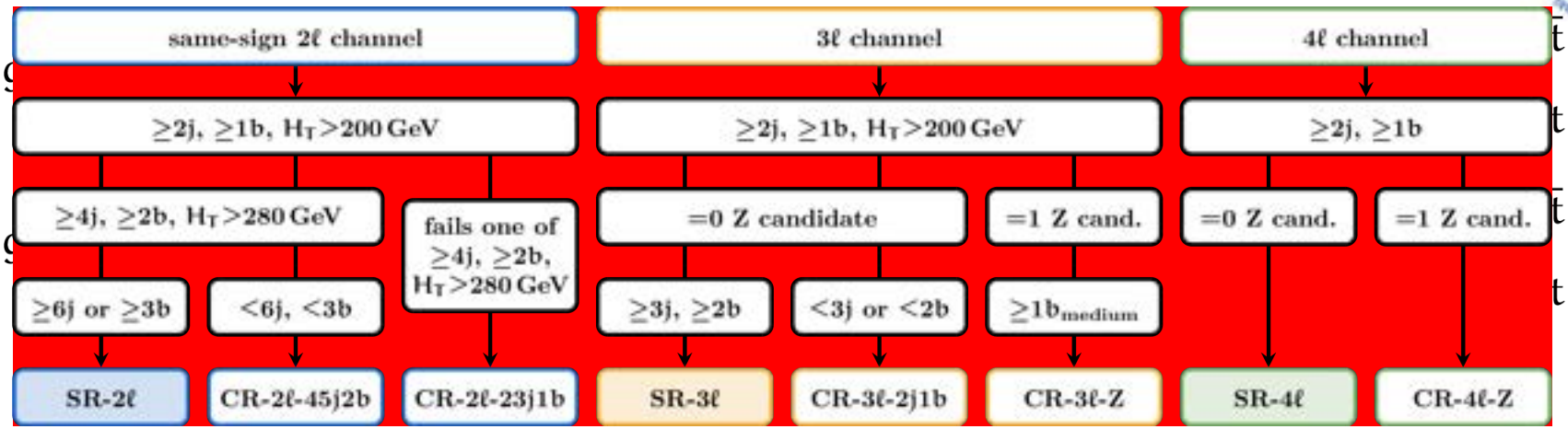
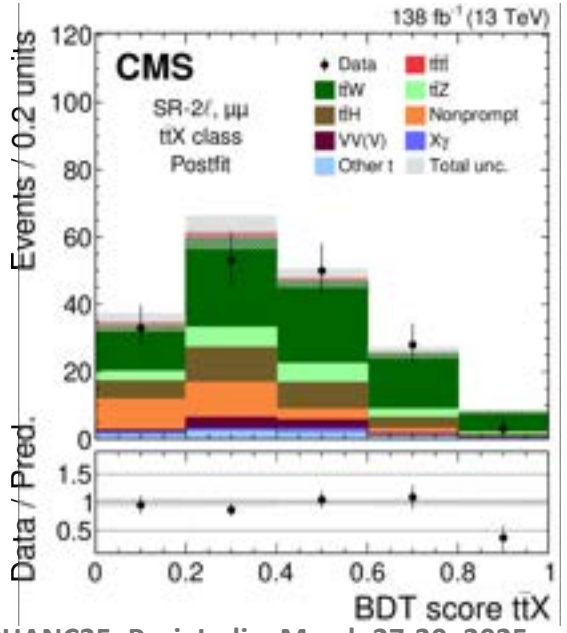


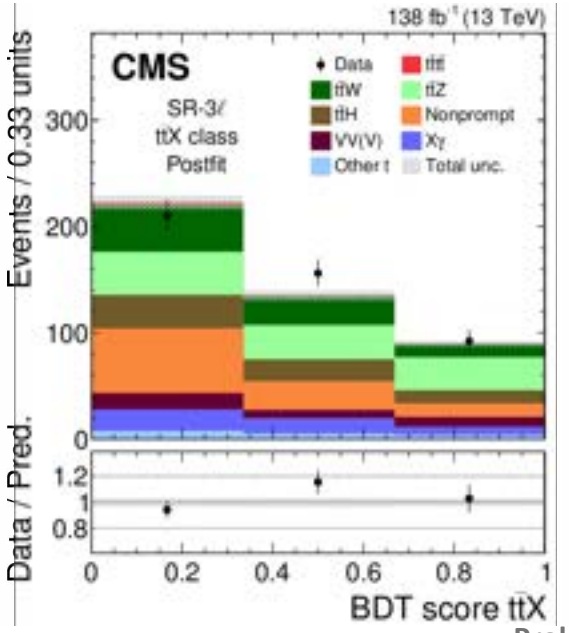
4-top production

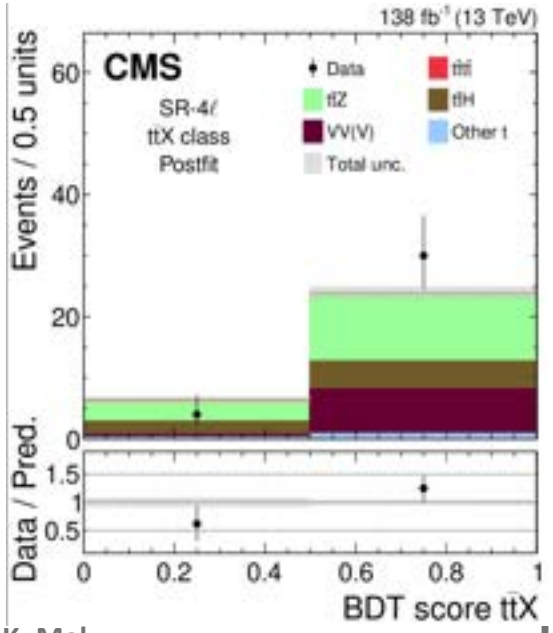


Measured σ=17.7$^{+3.7}_{-3.5}$ (stat) $^{+2.3}_{-1.9}$ (syst) fb

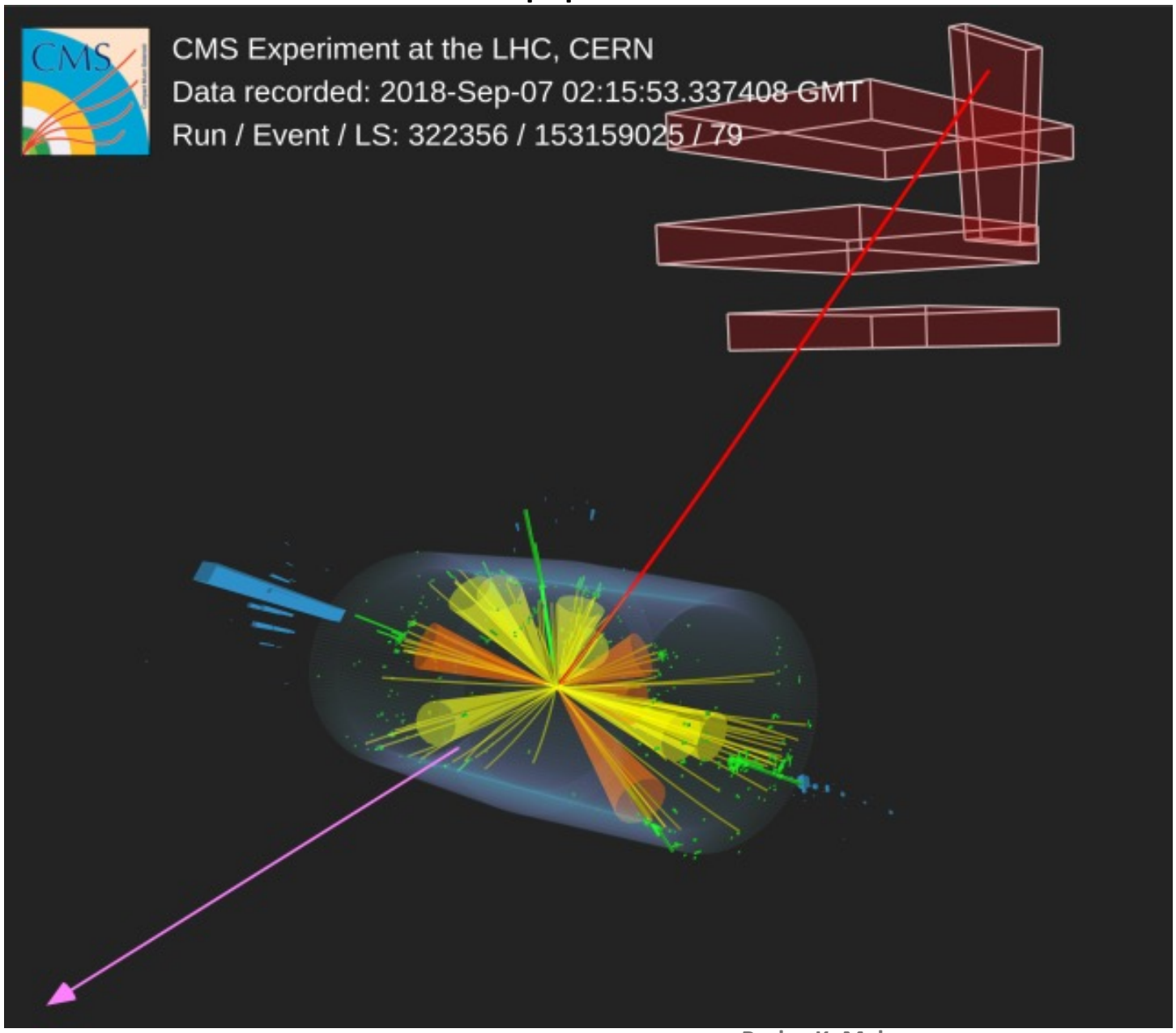
PLB 847 (2023) 138290







4-top production



Summary of 4-top production

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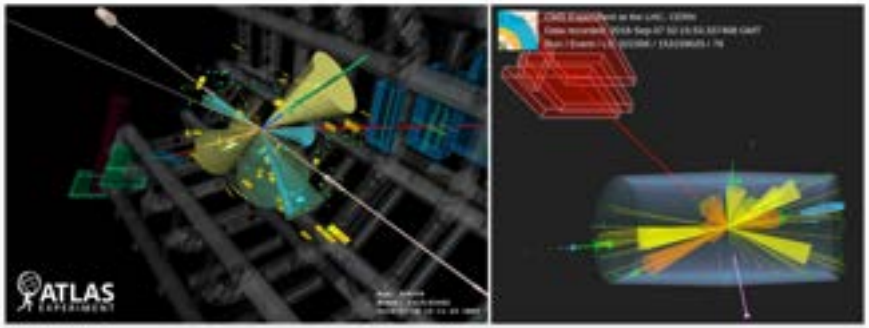
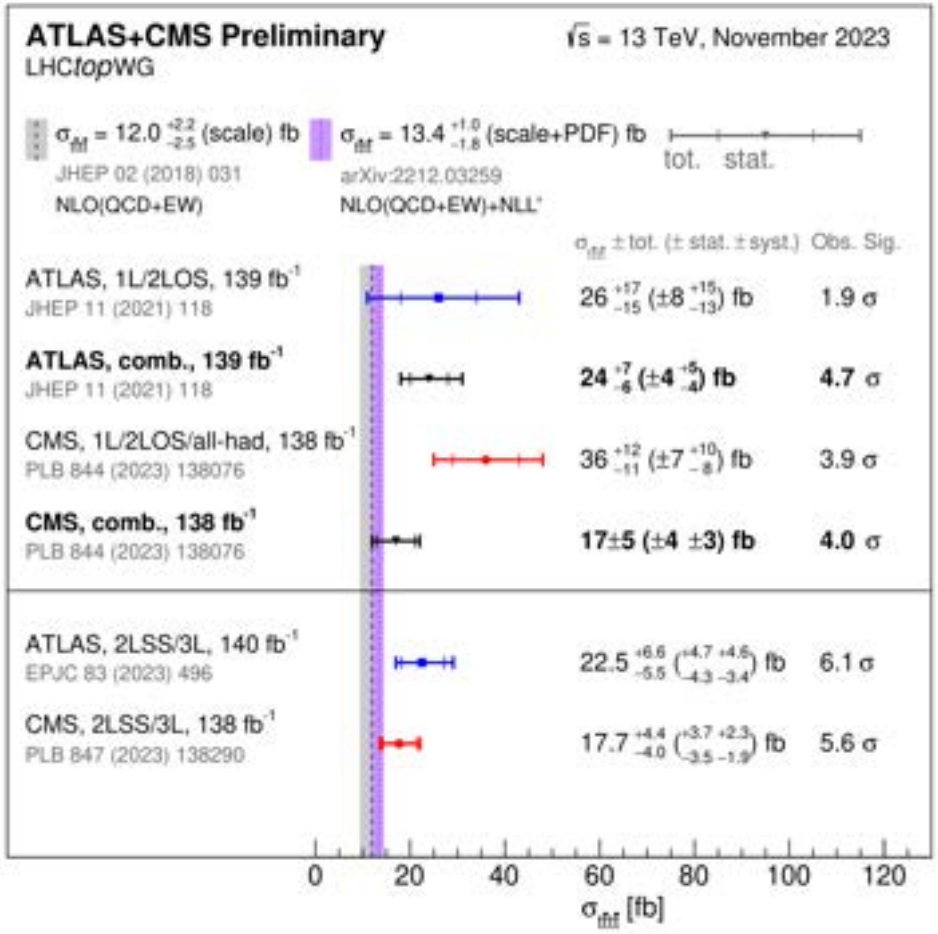
ATLAS and CMS observe simultaneous production of four top quarks

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





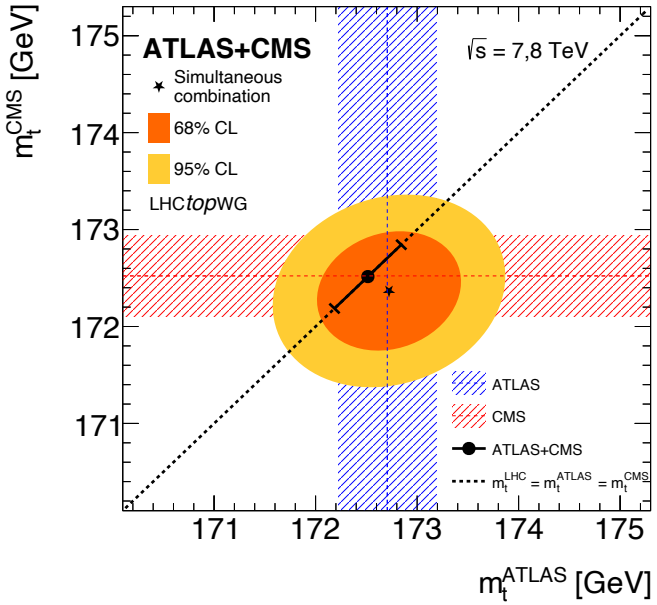
Observation significance

- **CMS : 5.6σ**
- **ATLAS: 6.1σ**

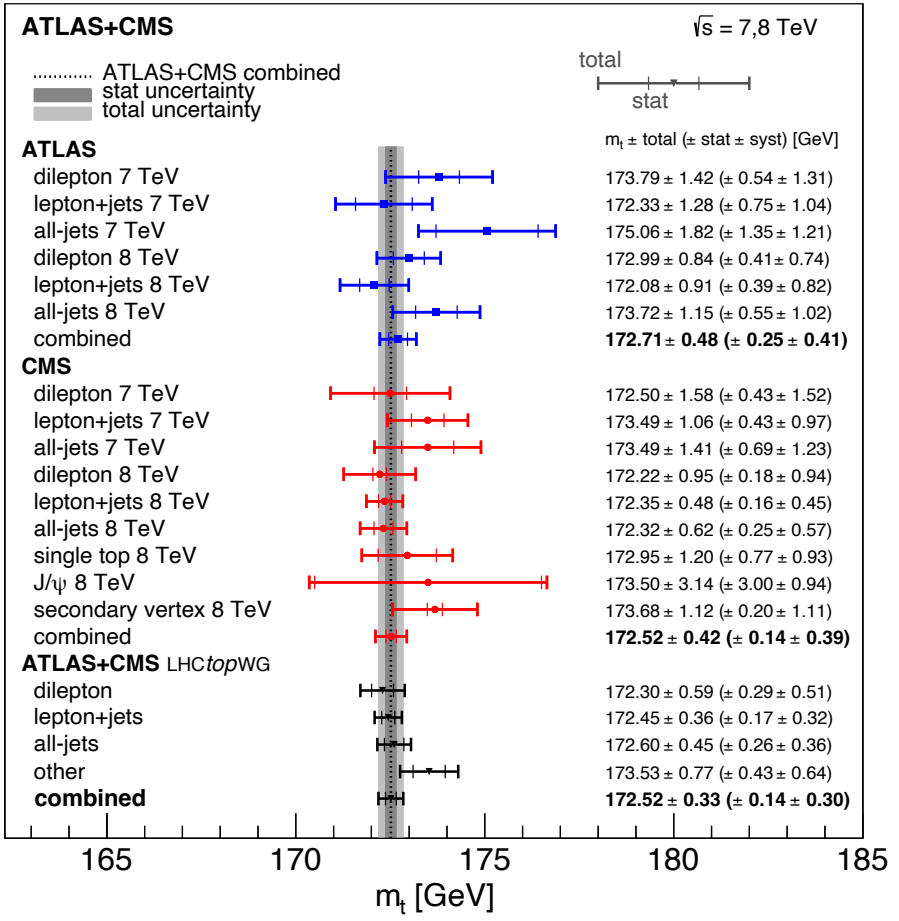
Top quark Mass

Top quark mass from $t\bar{t}$ events

- Many experimental methods to extract the top quark mass using different decay modes
- Significant improvements in terms of better calibrations, theoretical modelling, advanced techniques
- Latest Run 1 combination with 6 ATLAS & 9 CMS results
  - **Relative uncertainty ($\delta m_{top}/m_{top}$): 0.2%**
  - Limited by the b-jet energy scale
- **Consistent between ATLAS and CMS**



PRL 132 (2024) 261902



m_{top}=172.52 ± 0.14 (stat) ± 0.30 (syst) GeV

What's next on m_{top}?

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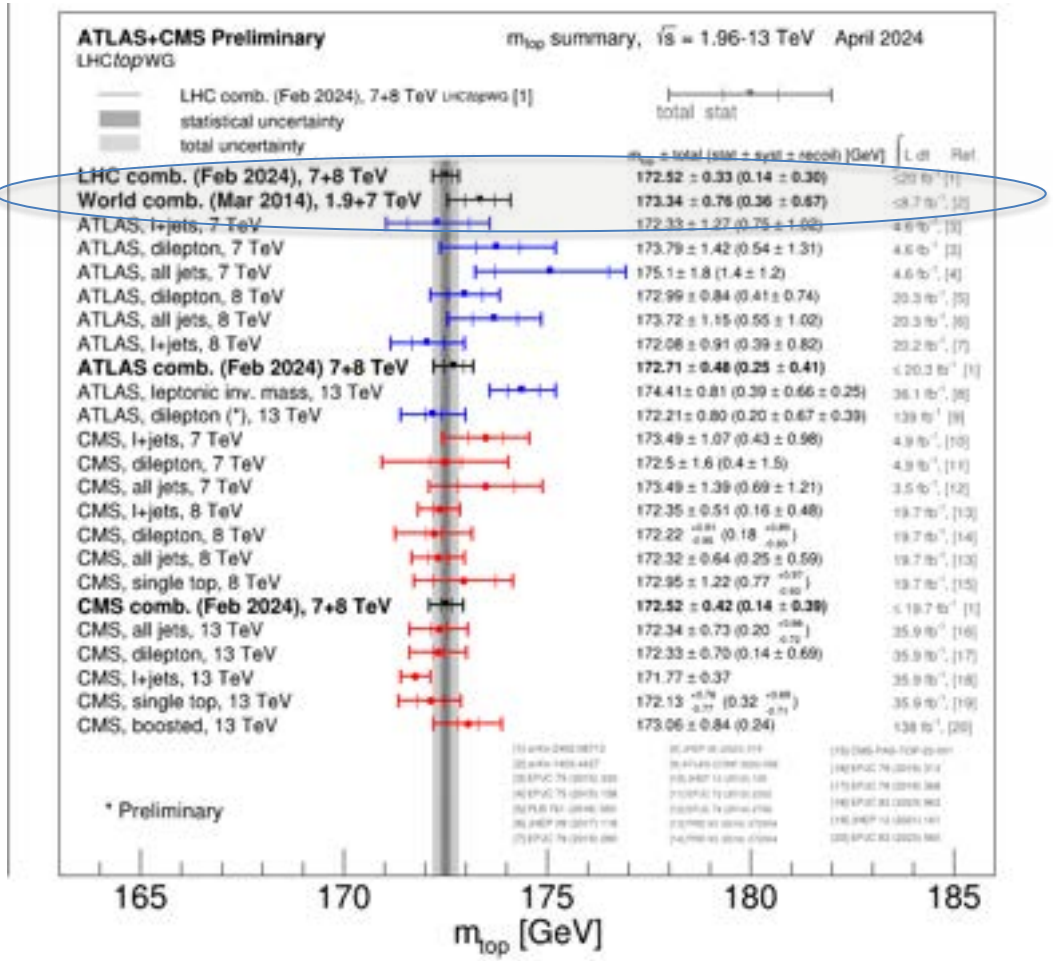
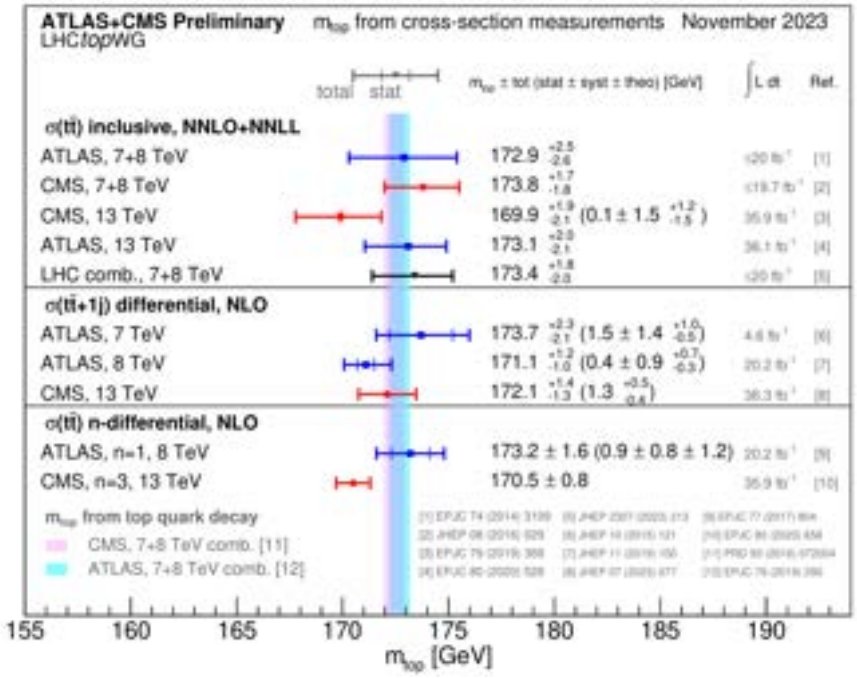


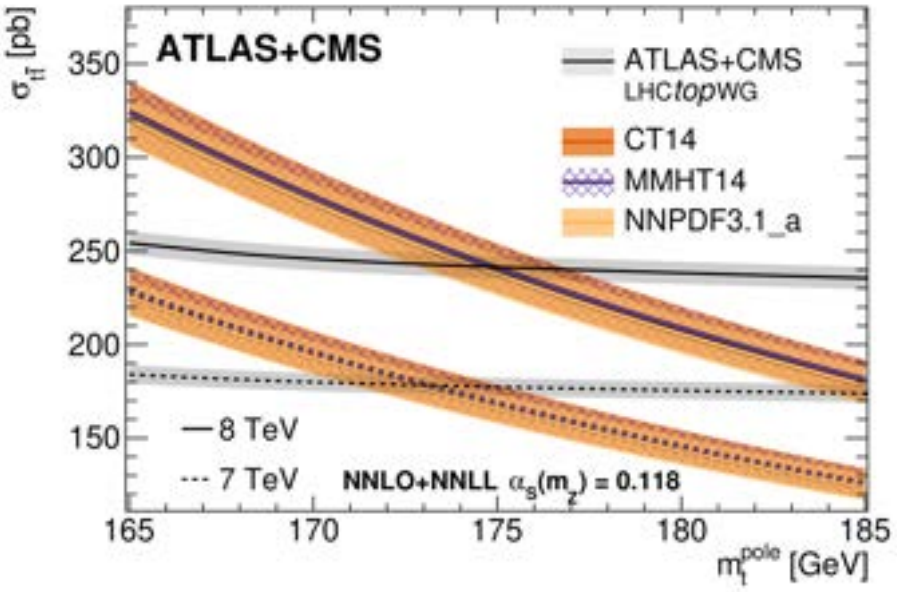
- Results from Tevatron and LHC experiments are combined together → World Combination, 2014
- Reached a precision of 0.33 GeV (<0.2%) LHC Run I combination
- Precision is limited by the understanding of hadronization modeling, color reconnection, Jet Energy Scale correction….
- Usage of experimentally clear observables avoiding jets
  - charged track & leptons
  - Vertex-lepton invariant mass
  - Using Charm mesons
- Top quark 'pole' mass?

Summary on m_t^{pole}

- Extraction of top quark pole mass (m_t^{pole}) from inclusive production cross-section (σ_{tt})
- σ_{tt} can be calculated theoretically at NNLO for different values of m_t^{pole}
  - Acceptance also depends on m_t^{pole}
  - Fixed value of α_s
- Overall precision ~1%

LHC Top Working Group

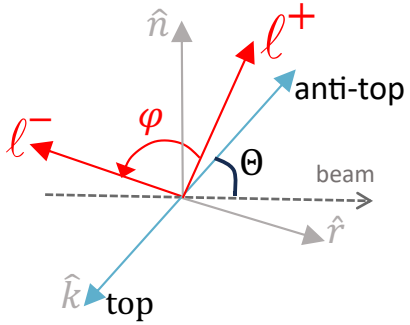




Spin Correlation, Polarization & Entanglement

Spin Correlation, polarization and Entanglement in $t\bar{t}$

- Top-pairs at the LHC are unpolarized, but their spins are strongly correlated
- Spin information is passed through the W-decay products (lepton or d-quark)



entangled state e.g.: $|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle\right)$

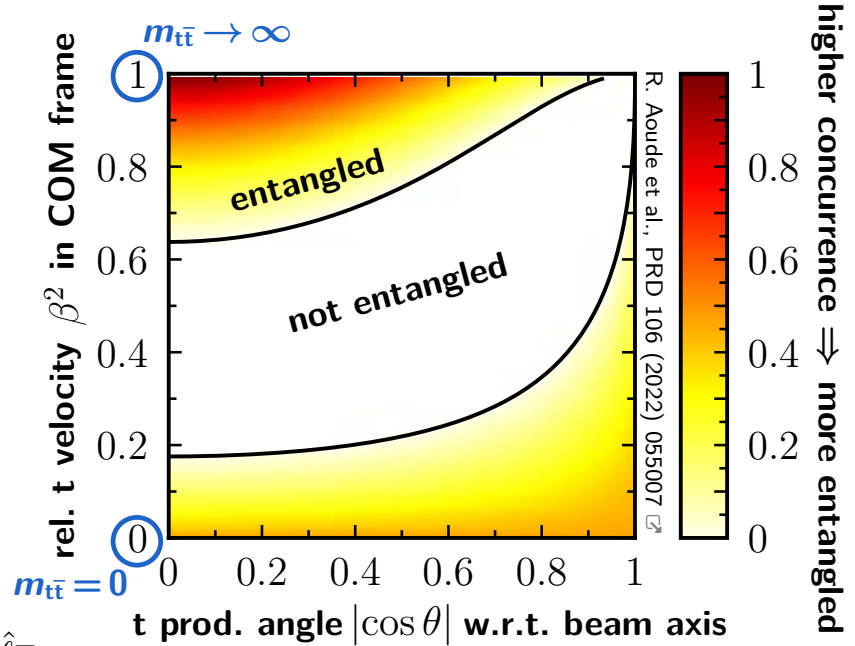
probe **polarization** and **spin correlations** in angular distribution of decay products:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_+\mathrm{d}\Omega_-} \sim \left(1 + B^+\cdot\hat{\ell}^+ + B^-\cdot\hat{\ell}^- - \hat{\ell}^+\cdot C\cdot\hat{\ell}^-\right)$$

sufficient condition for **entanglement**: $\mathrm{tr}[C] < -1$

can be probed in single distribution:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}\left(1 + \frac{\mathrm{tr}[C]}{3}\cos\varphi\right), \text{ with } \cos\varphi = \hat{\ell}^+\cdot\hat{\ell}^-$$



Many new physics models modify the polarization and spin correlation of top quarks

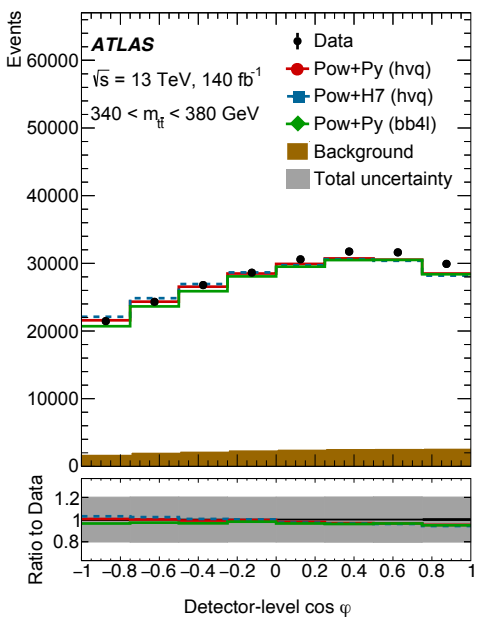
Spin Correlation, polarization and Entanglement in $t\bar{t}$

Nature 633 (2024) 542
arXiv:2311.07288 [hep-ex]

Rep. Prog. Phys 87 (2024) 117801
arXiv:2406.03976 [hep-ex]

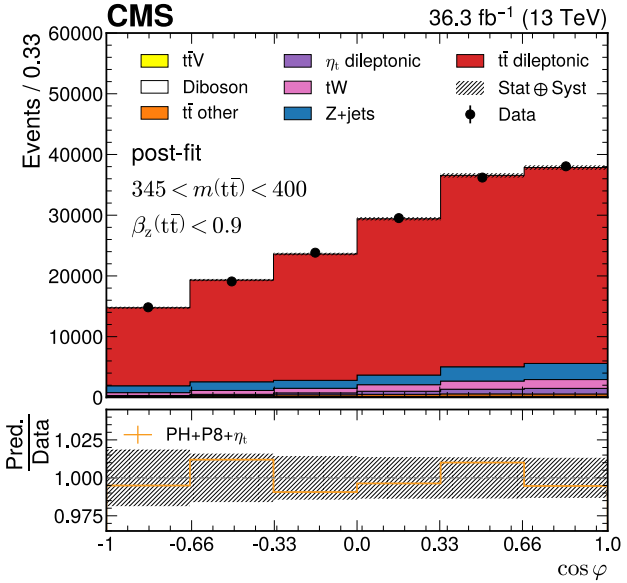
PRD 110 (2024) 112016
arXiv:2409.11067 [hep-ex]

=1e, =1μ, ≥2j, ≥1b



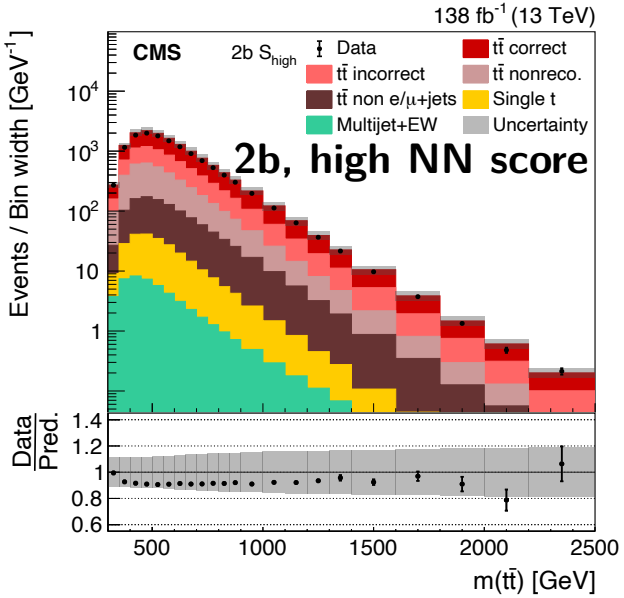
$340 < m_{t\bar{t}} < 380$ GeV

=2ℓ, ≥2j, ≥1b



$345 < m_{t\bar{t}} < 400$ GeV
$\beta_z(t\bar{t}) < 0.9$

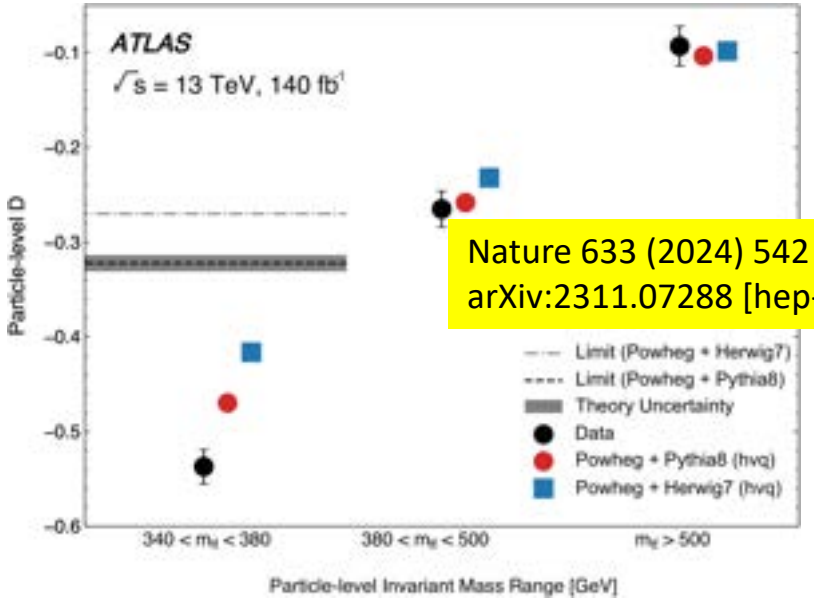
=1ℓ, ≥4j, ≥1b



$t\bar{t}$ reconstruction with NN
both low and high $m_{t\bar{t}}$

Kinematic distributions are match quite well with data

Spin Correlation, polarization and Entanglement in $t\bar{t}$



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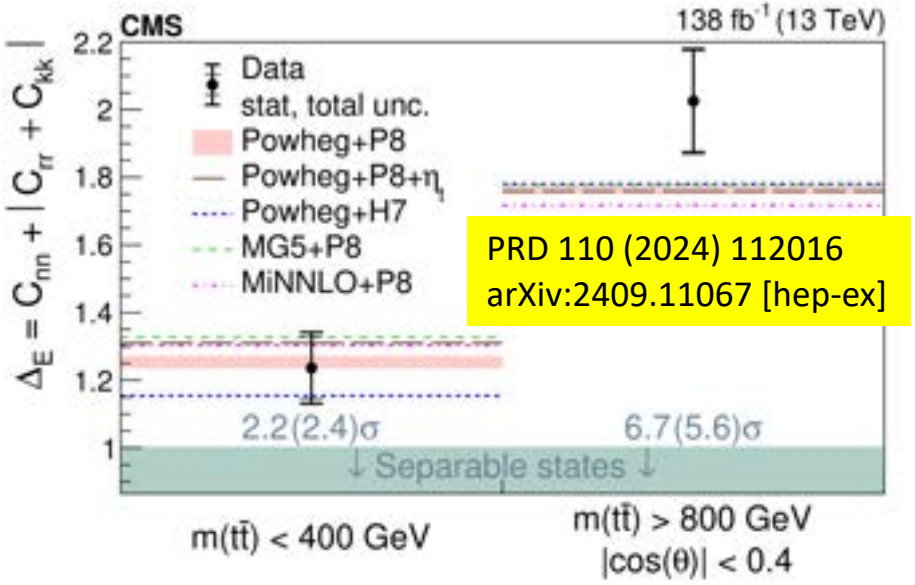

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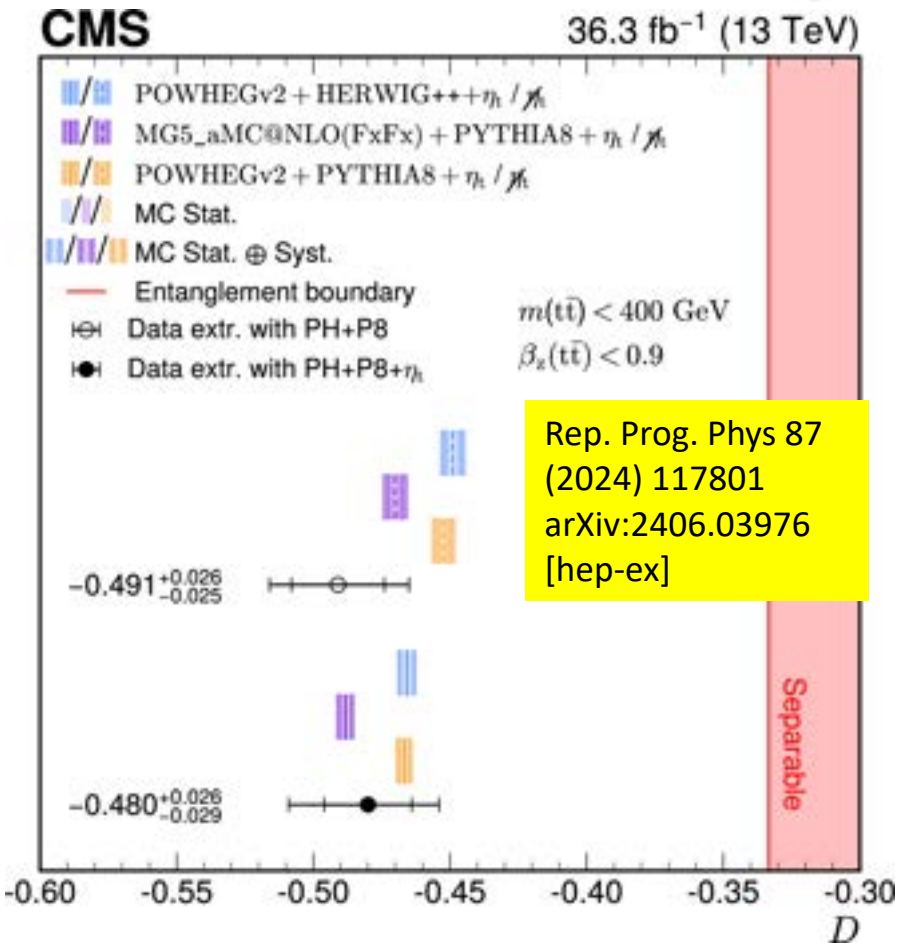
arXiv:2409.11067 [hep-ex]



Rep. Prog. Phys 87 (2024) 117801
arXiv:2406.03976 [hep-ex]

✧ Entanglement of ttbar system have been observed by the ATLAS & CMS with >5σ significance

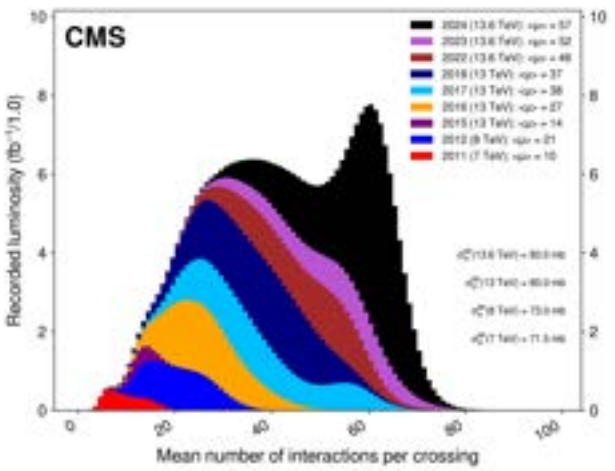
Quantum Entanglement in $t\bar{t}$ system

Courtesy: D. Dobur, ICHEP2024

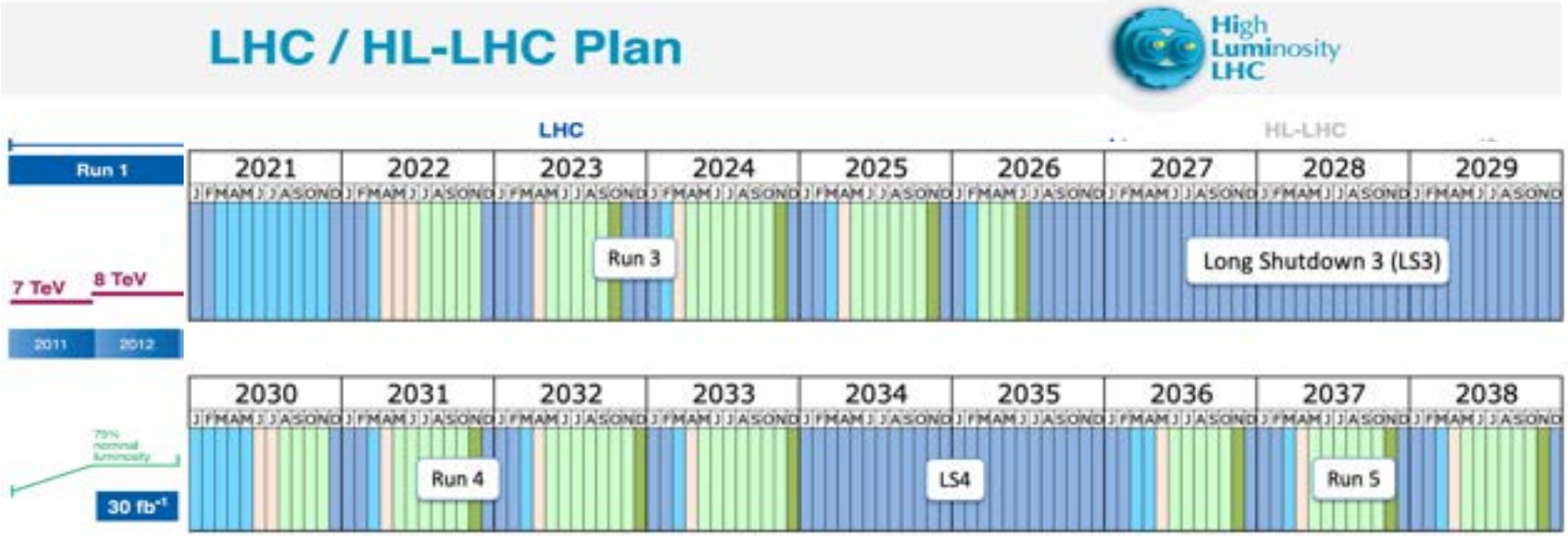
Summary & Conclusions

- During the LHC era, the top quark properties are being measured with unprecedented precision
  - Both ATLAS and CMS have completed the Run I & II legacy papers
  - Some key measurements have been performed with the full Run II dataset
- Measurement of various properties of top quark are providing crucial tests on the SM itself while probing the BSM physics; no excess observed over the SM predictions.
- Some of the limiting systematics affecting these measurements are related to
  - ttbar modeling (top mass, ttbar scale, ttbar matching scale)
  - Experimental uncertainties related to the jets (Jet Energy Scale, Jet Energy Resolution), W+jets and QCD background determination

LHC Outlook (Run 3 & beyond)



- LHC Run 3 at √s=13.6 TeV began in 2022; Top properties from the full Run 3 dataset are yet to be explored
- New Physics discovery may be at the door-step and top quark properties would play the key role; In addition, we would also be able to probe tiny SM predictions
- Many more upgrades with the LHC and the detectors are scheduled for next two decades. Improved analyses techniques would be refined further



References

- LHCTopWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP