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Measurements of top quark production and its properties

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CMS Top quark results:
papers, preliminary results

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GOBIERNO DE ESPAÑA
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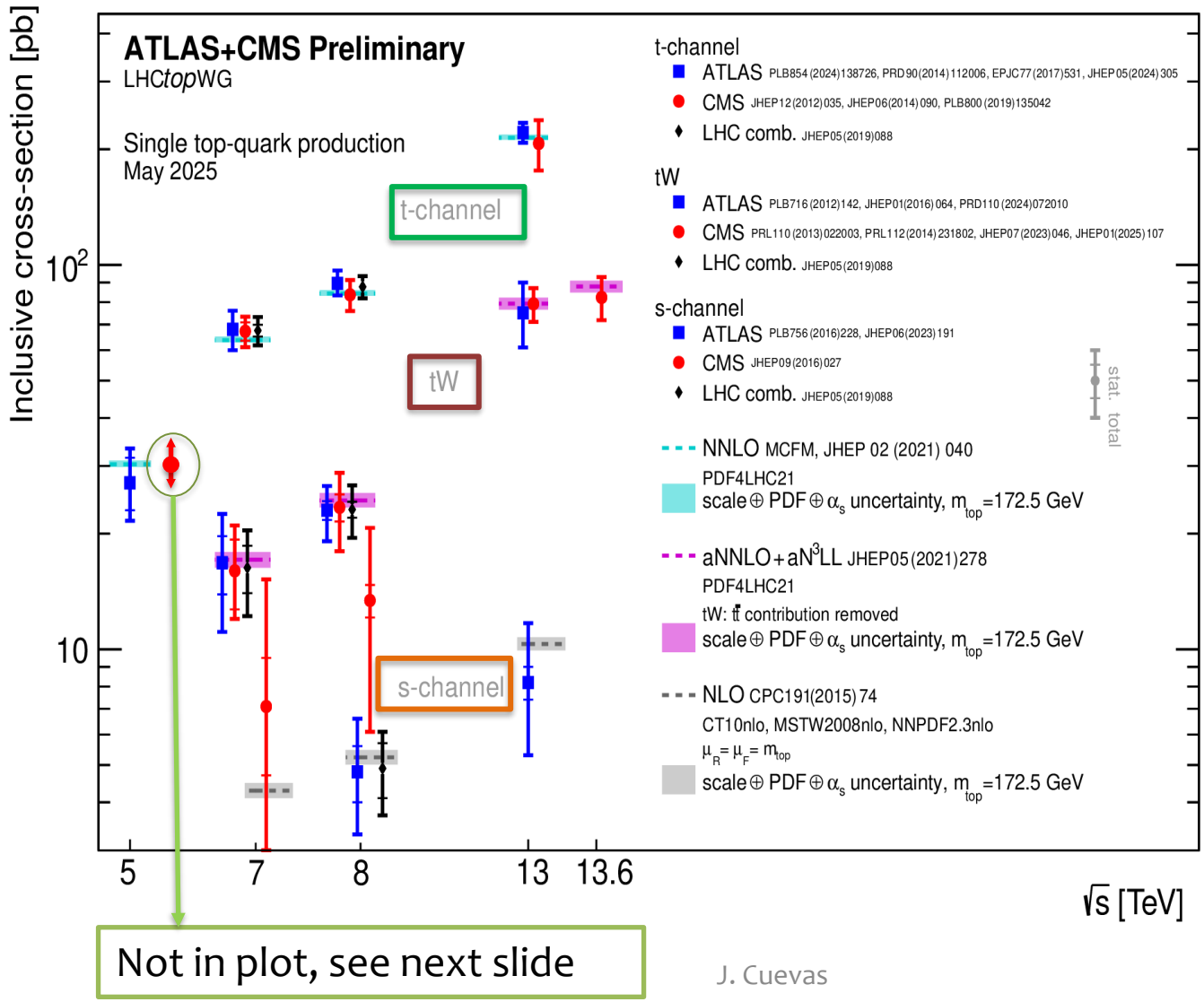
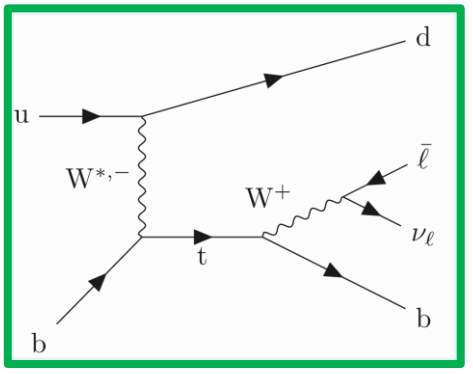
Introduction

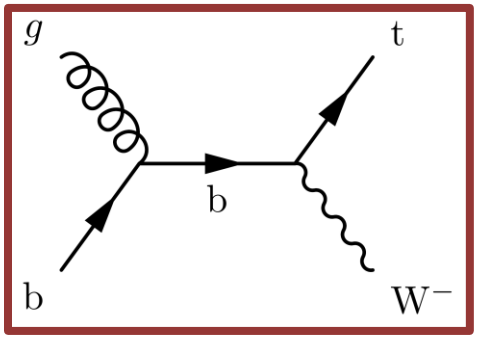
- **Measure single top and $t\bar{t}$ still very important at LHC**
  - High cross section + high luminosity
  - Precision measurements
    - t-channel is charge asymmetric: probes ratio of u and d PDFs, and as it is b quark induced: probes b PDF
    - stress-test modeling
  - Access to subtle effects:
    - quantum correlations, **$t\bar{t}$** threshold…
    - system = 2-qubit state, quantum correlations between **$t\bar{t}$** and entanglement
    - purity, entropy, discord… Bell tests?, infer spin correlations from angular distributions of top decay products
    - **"Excesses" at the $t\bar{t}$ threshold in the dilepton and lepton + jets final states**

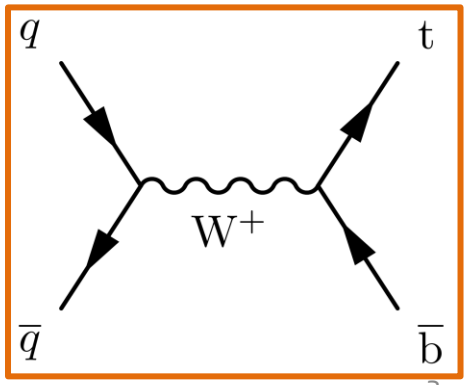
Single top production

- **Largest cross section of single top production processes —> precision measurements, subdominant** when compared to $t\bar{t}$ (~1-2 orders) -> **MVA techniques to extract signal.**
- **Electroweak** production.





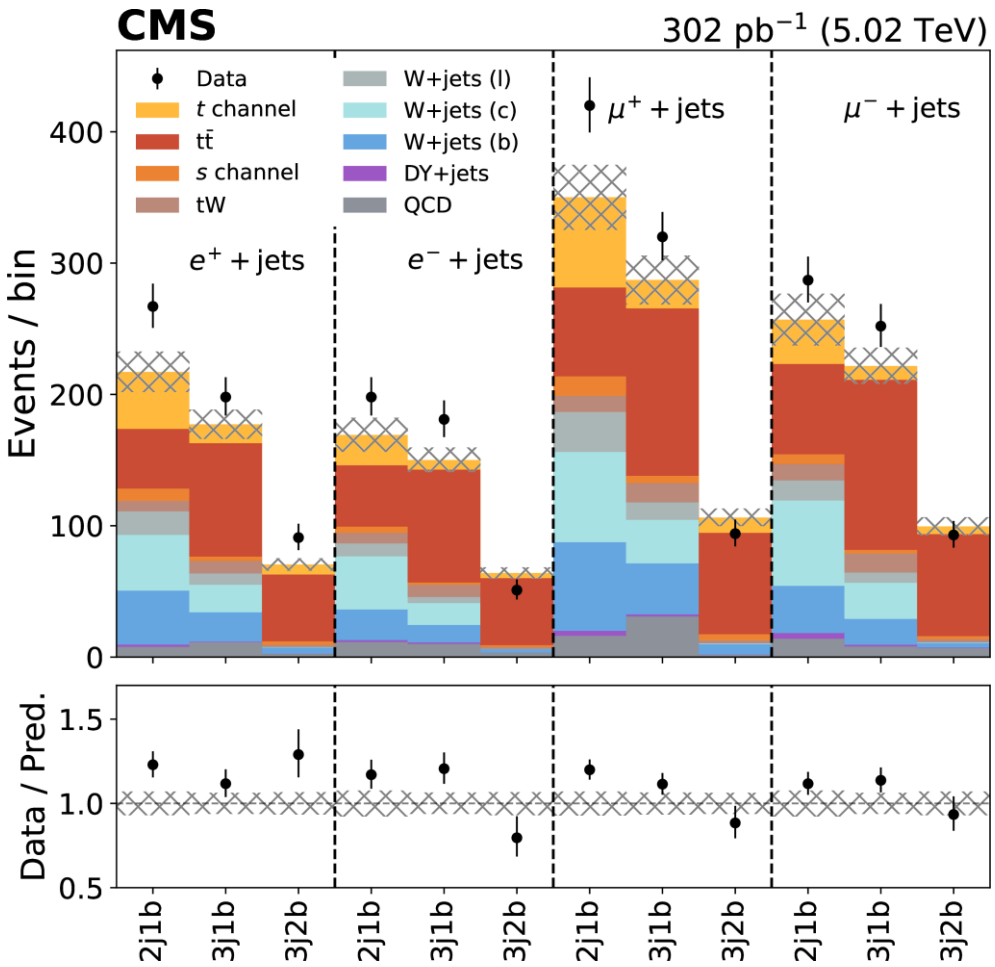




Not in plot, see next slide

t-channel at $\sqrt{s}$ = 5.02TeV

arxiv:2603.13592



The $\sqrt{s}$=**5.02** TeV run: dataset of 0.3 fb^{-1} from 2017, with mean PU of 2. Reference for heavy ion physics, but also as SM stress tests.

First CMS result at this energy in l+jets channel,

- **reconstruct top quark from lepton, jet & P_t^{miss}**
- **MVA to separate signal from BG (tt, W+jets)**

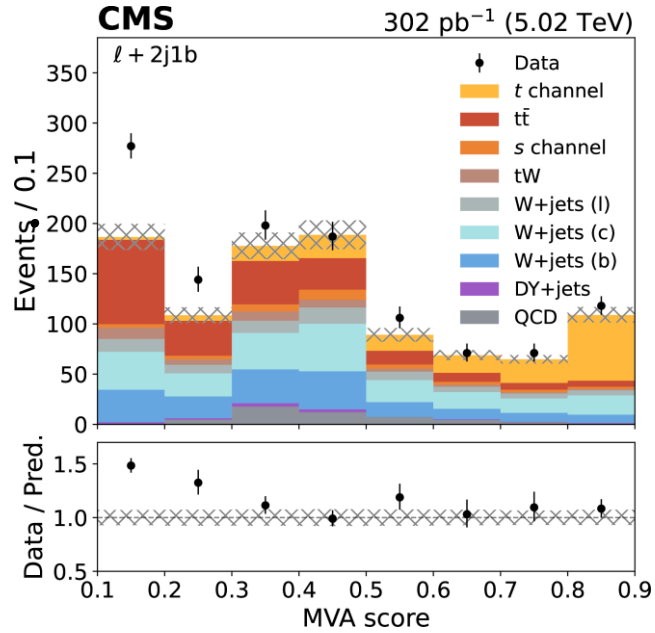
σ measured using a maximum likelihood fit to **12 event categories** defined in terms of the njets, lepton flavour, b-tagged jets, and charge.

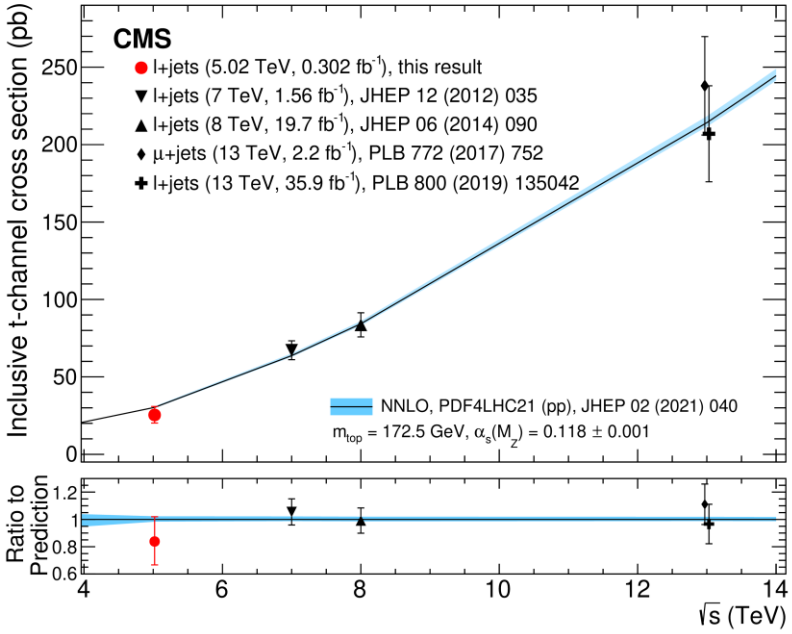
Single top t-channel production @ 5.02 TeV [arxiv:2603.13592]

Measurement of $\sigma(tq + \bar{t}q)$, $\sigma(tq)$, $\sigma(\bar{t}q)$ and $\mathbf{R}_{t-ch}$ profiting from **MVA techniques** & the distinct **forward jet's signature** in the signal.

- $\boldsymbol{\sigma(tq + \bar{t}q) = 25.4^{+3.6}_{-3.5}\,(stat)^{+4.2}_{-3.9}(syst) \pm 0.5\,(lumi)\,pb}$
- $\boldsymbol{\sigma(tq) = 17.6^{+2.8}_{-2.7}\,(stat)\,^{+2.6}_{-2.4}(syst) \pm 0.3\,(lumi)\,pb}$
- $\boldsymbol{\sigma(\bar{t}q) = 8.2^{+2.4}_{-1.6}\,(stat)\,^{+2.1}_{-2.5}(syst) \pm 0.1\,(lumi)\,pb}$

Competitive uncertainties despite tiny luminosity.





- **All** measurements in **good agreement** with the SM. **Main uncertainties: W+jets normalization, b-tagging efficiencies.**

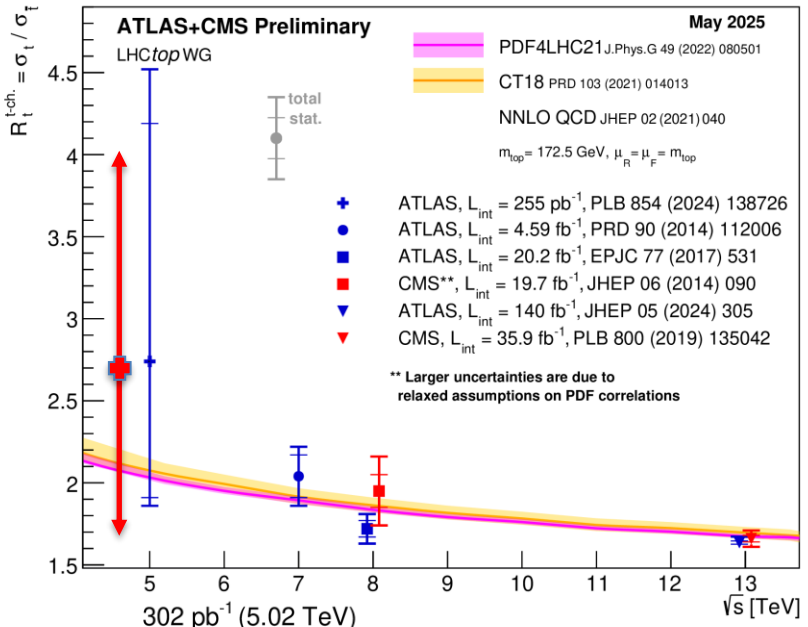
t-channel at $\sqrt{s}$ = 5.02TeV

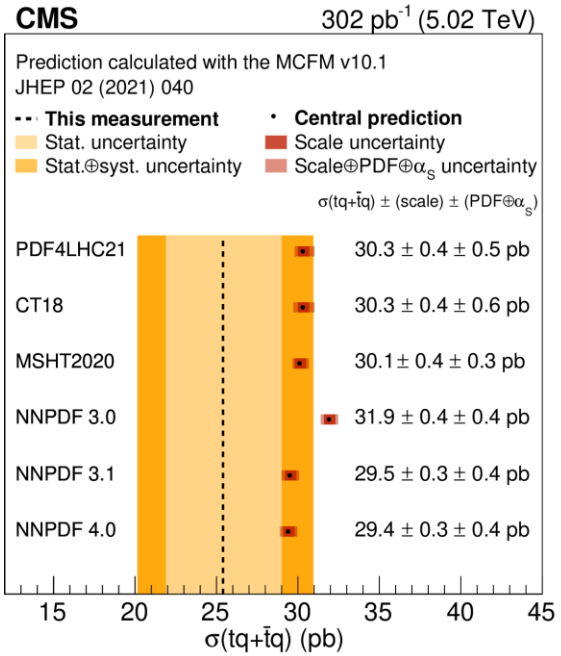
The ratio between the individual cross sections is found to be

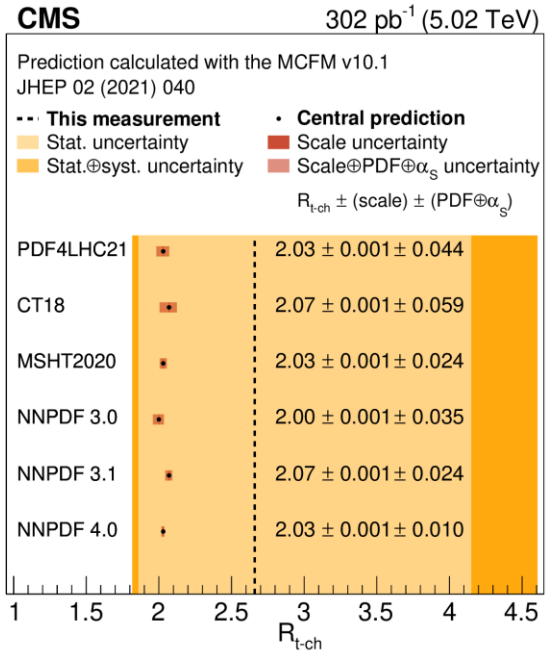
$$\mathcal{R}_{t-ch} = 2.7^{+1.5}_{-0.8}\,(stat)\,^{+1.3}_{-0.3}(syst)$$

The measurements are compared to NNLO QCD using the PDF4LHC21 and CT18 PDF sets, and others, as shown in the plot.

Input for PDF fits: b PDF at lower s = higher x





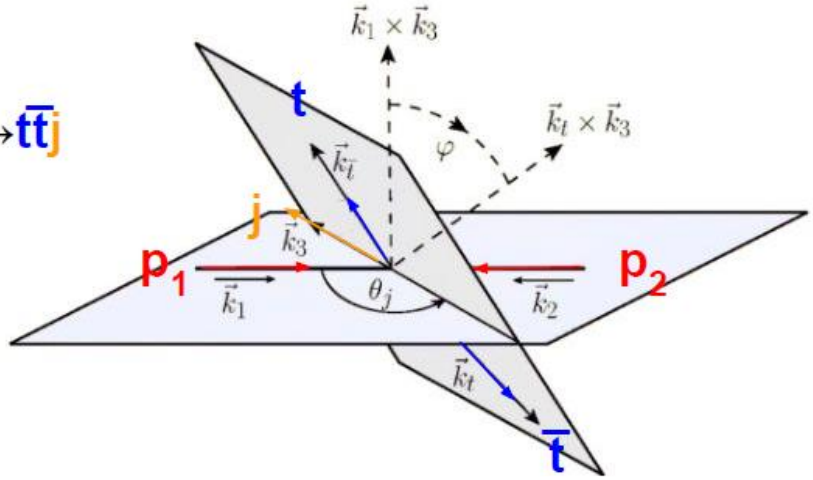


Also measure CKM matrix element $|V_{tb}|$ $|f_{LV}V_{tb}| = 0.92 \pm 0.09\,(exp) \pm 0.01\,(theo)$

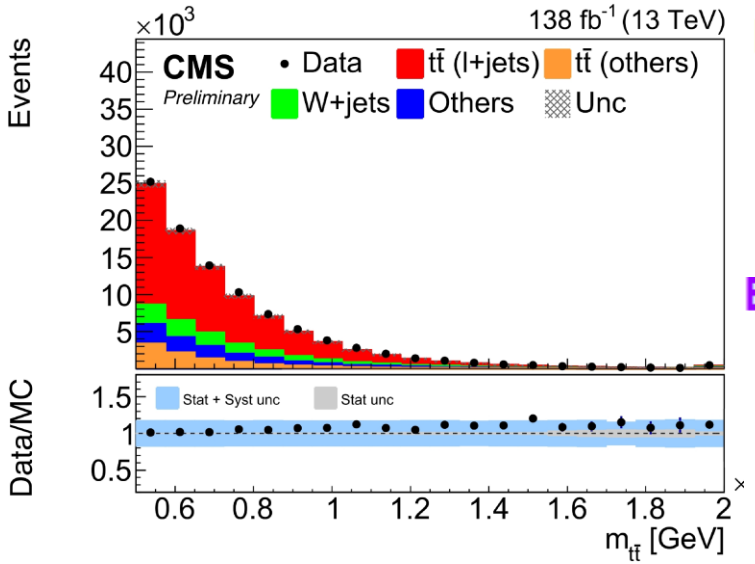
tt+j Charge Asymmetry [CMS-PAS-TOP-24-015]

In SM: kinematic differences between **top** and **anti-top** due to higher-order interference effects → **BSM effects may enhance asymmetry**

$p_1 p_2 \to t\bar{t}j$



Real gluon emission in tt+j production induces charge asymmetry already at tree level, enhanced when j emitted perpendicular to the beam axis



Incline asymmetry probes **qq** channel

- Angular correlation between t and j in $t\bar{t}j$ frame

$$A_I \equiv \frac{\sigma^{\varphi}(y_{t\bar{t}j} > 0) - \sigma^{\varphi}(y_{t\bar{t}j} < 0)}{\sigma_{\text{tot}}},$$

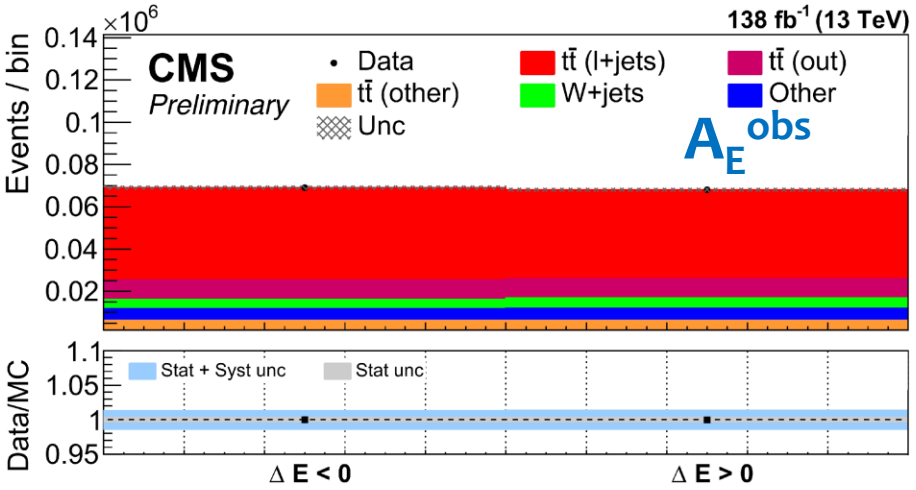
Energy asymmetry probes **qg** channel

- Energy difference of t and $\bar{t}$ in partonic CM frame

$$A_E = \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma_{\text{tot}}},$$

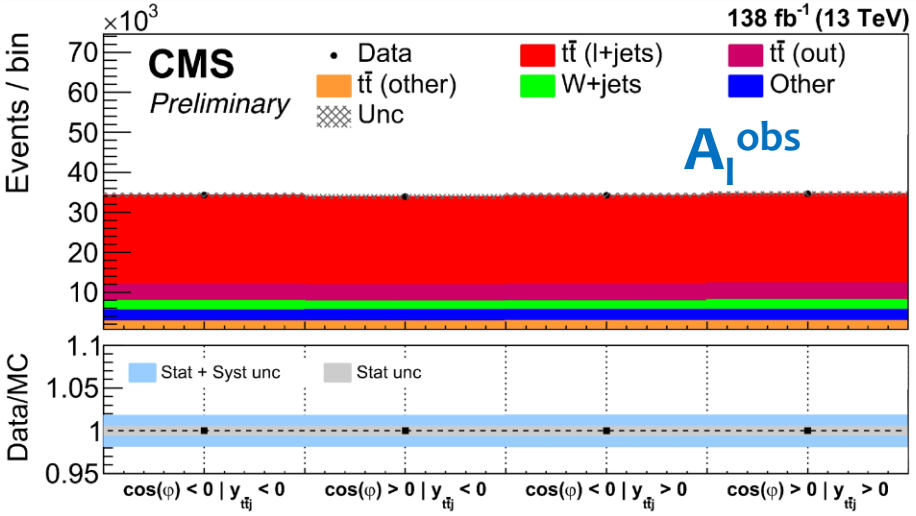
tt+j Charge Asymmetry [CMS-PAS-TOP-24-015]

- **BDT to separate signal from main bckgs** (W+jets) - score used to define SR
- **Profile likelihood unfolding** to particle level fiducial phase space
- Results **compared to reference** (*MG5_aMC@NLO + Pythia 8*), and **alternative predictions**



- Uncertainty **dominated by statistics**
- Systematic contribution comparable (dominant W+jets modelling, limited MC size)

- **No significant deviation from SM prediction (A_E within 2σ)**



$$A_I^{\text{obs.}} = (2.5 \pm 2.3)\%$$

Compatible with SM expectation of (-0.5±0.5)%

$$A_E^{\text{obs.}} = (-6.3 \pm 2.3)\%$$

2σ tension with SM, Powheg+Pythia, expectation of (-1.6±0.3)%

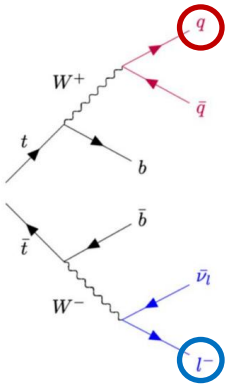
Quantum properties of $t\bar{t}$ pairs

- Top decays **before** hadronizing -> products **preserve spin** information -> $t\bar{t}$ is an ideal **two qubit** system. Access to **quantum properties**.
- In **ℓ+jets decay**, spin analysers
  - **Lepton**
  - **u-type quark**
- Density matrix via Fano-Bloch [add. ref.] decomposition:

$$\rho = \frac{1}{4}\left(I \otimes I + \sum_i P_i \sigma_i \otimes I + \sum_j \overline{P}_j I \otimes \sigma_j - \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

Polarization coefficients of t and $\bar{t}$ (decay products)

Spin correlation matrix



15 coefficients to obtain **results**

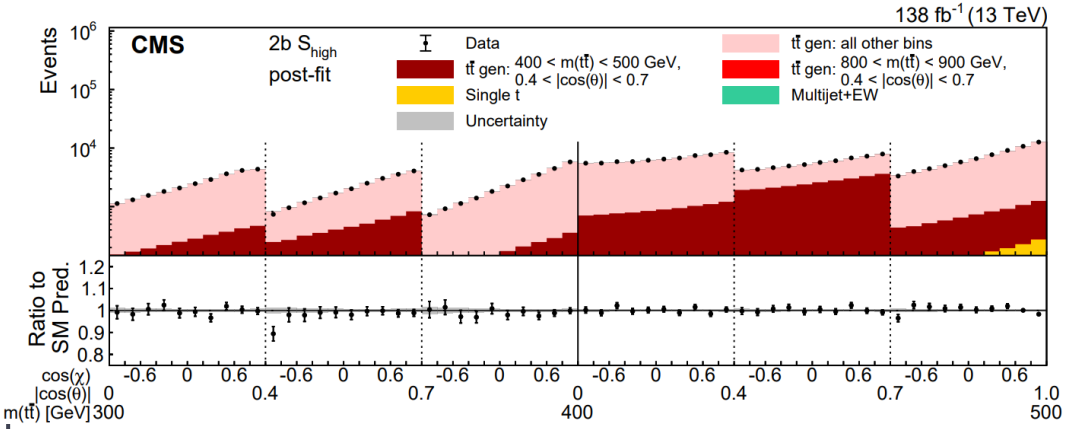
Plenty of quantum-related results:

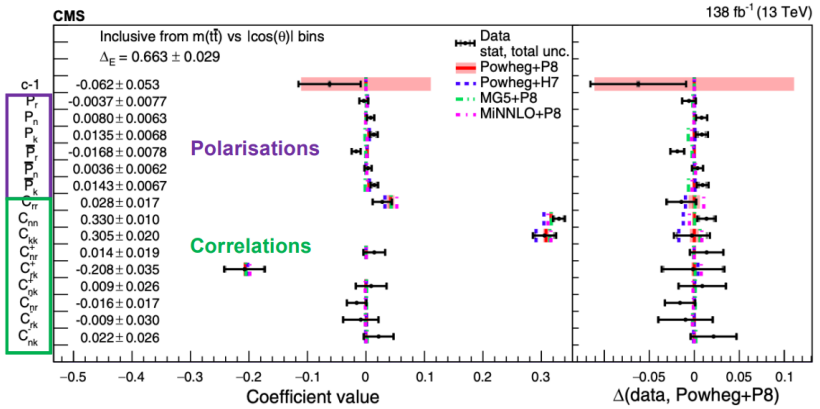
- Spin **correlation** observation and top quark **polarization** by CMS (PRL 112 (2014) 182001) and ATLAS (PRL 108, 212001 (2012)) already with **Run 1** data.
- More recently, **quantum entanglement** was **observed** with **Run 2** data.

} Dilepton channels

Quantum properties of $t\bar{t}$ pairs

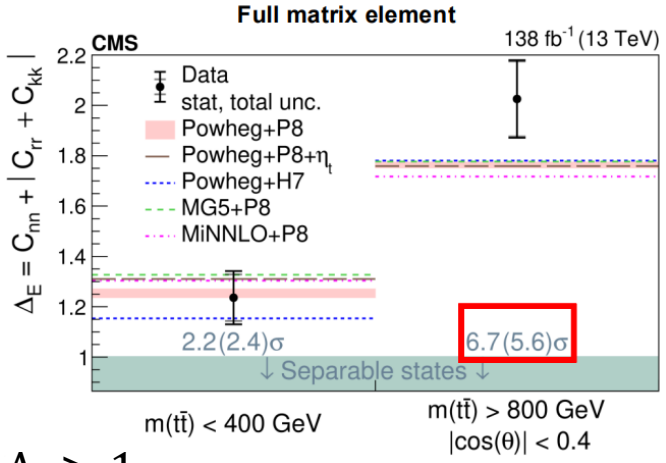
- In this context, CMS (PRD 110 (2024) 112016) used full **Run 2** in **ℓ+jets,** extraction of all **15 coefficients** in regions of $m_{t\bar{t}}$ vs $|\cos(\theta)|$, $p_T(t)$ vs $|\cos(\theta)|$ and inclusively.





- Coefficients follow **SM predictions.**

- Additionally,quantum **entanglement** is **observed** for **first** time in events with **high $m_{t\bar{t}}$**



In general, if $\Delta_E > 1$
=> entanglement

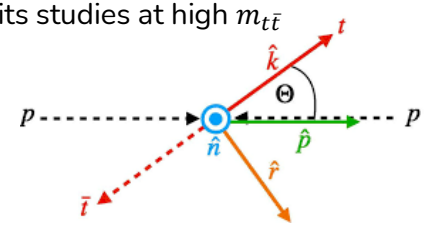
Quantum state of $t\bar{t}$ pairs @ 13 TeV

arXiv:2512.17557

- Measure full spin correlation matrix of tt in the lepton+jets final state in full Run 2 using not only the **helicity** basis (= relative to top direction of flight) but **also** the **beam** basis (first time done).
- Measure also **purity,** $\gamma(\rho)$ & Von-Neumann **entropy,** $S(\rho)$ in both bases.

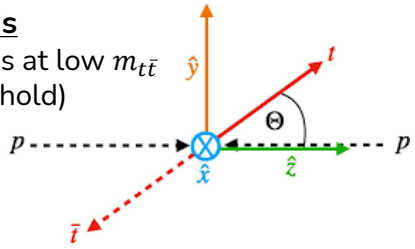
Helicity basis

Suits studies at high $m_{t\bar{t}}$



Beam basis

Suits studies at low $m_{t\bar{t}}$ (prod. threshold)



Purity

$$\gamma(\rho) = \mathrm{Tr}\,(\rho^2)$$

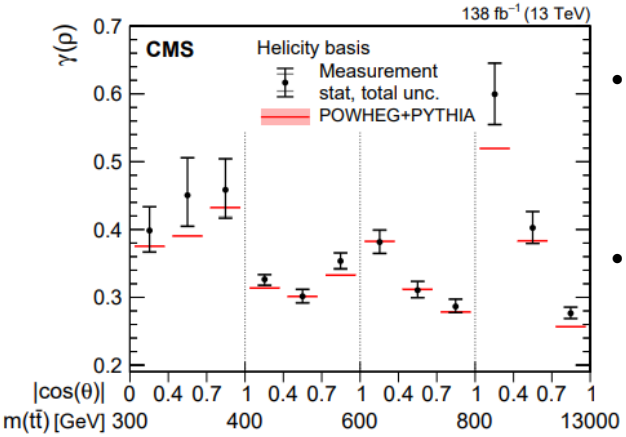
How mixed a state is: 1 if pure, < 1 if mixed

Entropy

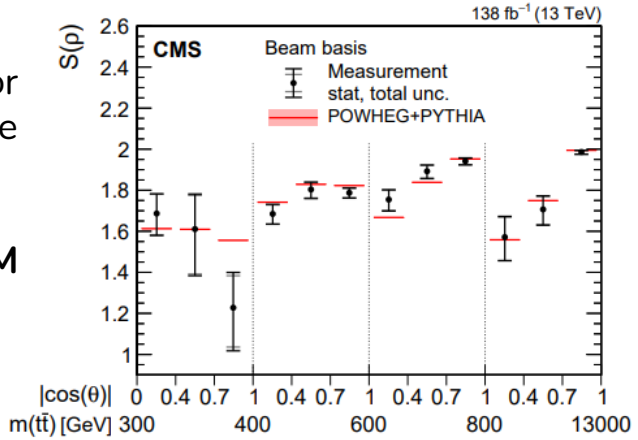
$$S(\rho) = -\,\mathrm{Tr}\,(\rho \log_2 \rho)$$

$$0 < S(\rho) < 2$$

Minimal for pure states, maximal for very mixed states



- Overall neither $S(\rho)$ =0 nor $\gamma(\rho)$=1, indicating some degree of **mixing across regions.**
- Overall **consistency with SM** (within 2 s.d.).



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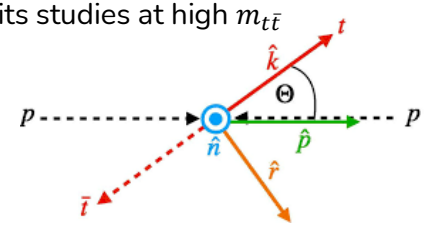

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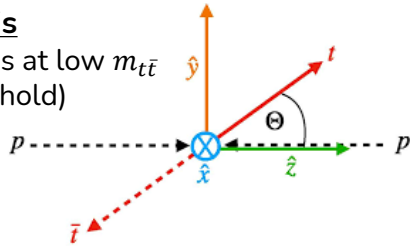

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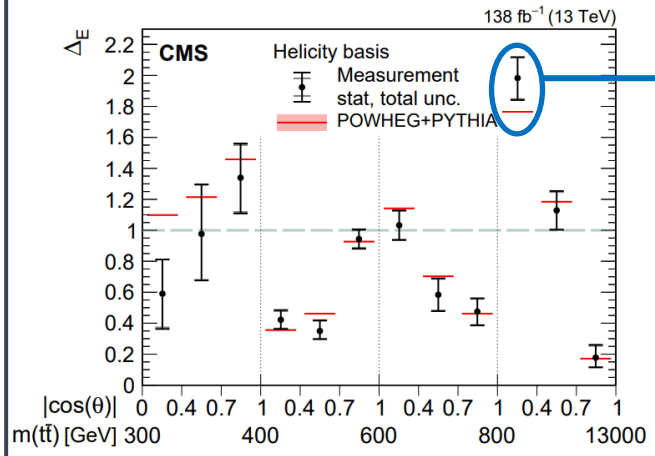
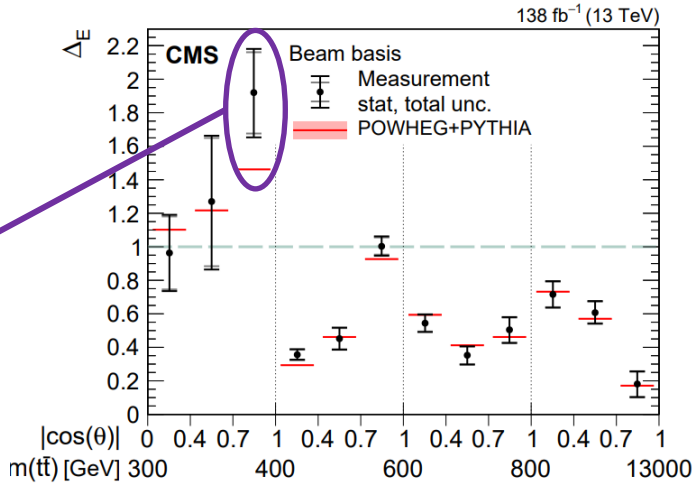


Observation of **entanglement** at **high** $m_{t\bar{t}}$

Evidence (>3 s.d.) of **entanglement** at **low** $m_{t\bar{t}}$

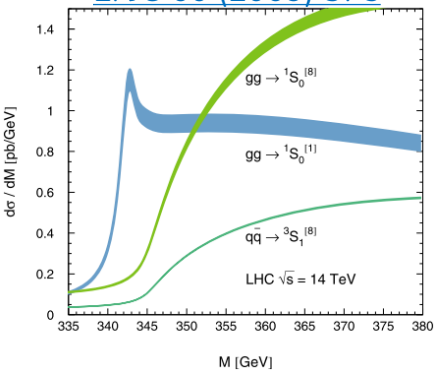


All results consistent with SM

Excesses at the $t\bar{t}$ threshold

- Since time ago, quasi-bound state: **“toponium”** postulated.

EPJC 60 (2009) 375

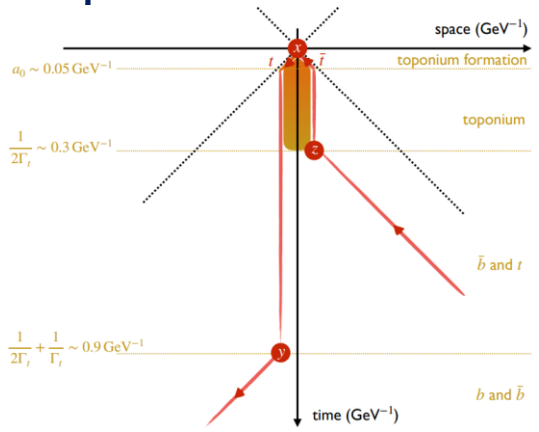


Properties

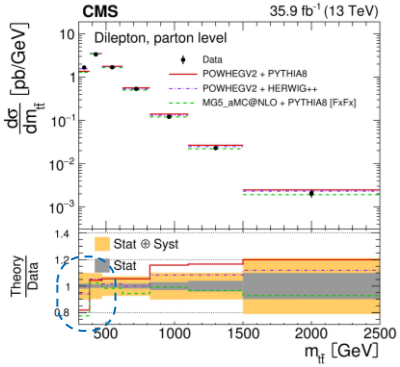
- Colour & spin singlet.
- Pseudoscalar.
- Peak below threshold (~$2m_{top}$ ~345 GeV.)
- Near threshold QCD gluon exchange -> mimic bound states.

Experimental effects of “toponium”

- Enhancement of $t\bar{t}$ close to threshold.
- Entanglement -> favoured if exists.

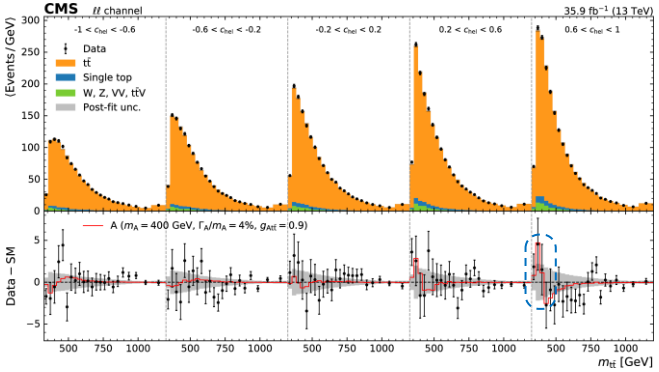


(B. Fuks et al., EPJC 85 (2025) 157)

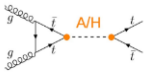


$t\bar{t}$ differential measurement

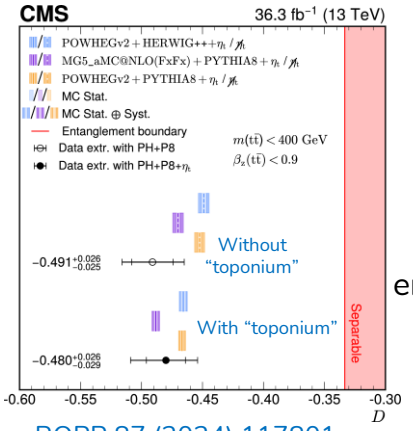
JHEP 02 (2019) 149



Search for heavy H-> $t\bar{t}$



JHEP 04 (2020) 171



ROPP 87 (2024) 117801

$t - \bar{t}$ entanglement

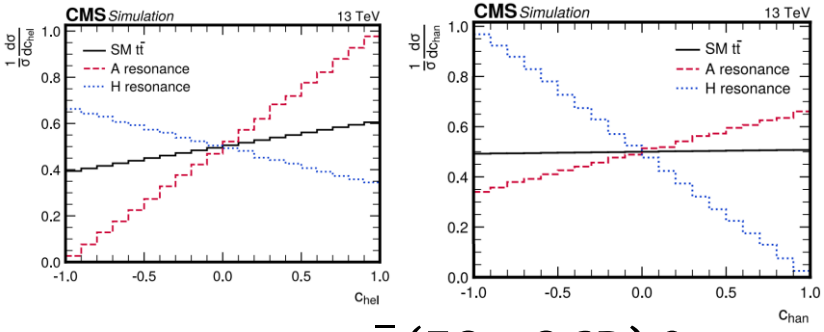
Already experimental hints in the past

Pseudoscalar excess at $t\bar{t}$ threshold at 13 TeV

[Rep. Prog. Phys. 88 (2025)]

- Full **Run 2**, in **dilepton** channel.
- Observables besides $m_{t\bar{t}}$:

- c_{hel}: scalar product of leptons in parent top
- c_{han}: similar but sign flip in top direction



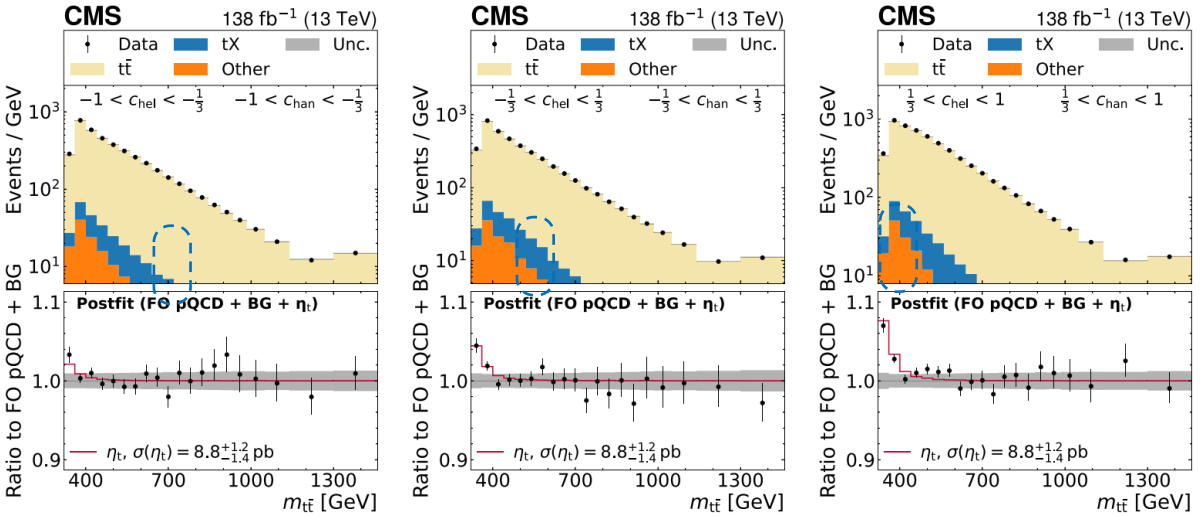
- Fit to 20 $m_{t\bar{t}}$ x 3 c_{hel} x 3 c_{han} bins including non-resonant $t\bar{t}$ (FO pQCD) & pseudoscalar (A, η_t) contributions. Some examples:

- **Observation** of pseudoscalar excess:

$$\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}\ pb,$$

compatible with NRQCD

estimate $\sigma(\eta_t) = 6.4\ pb$



Pseudoscalar excess at $t\bar{t}$ threshold at 13 TeV

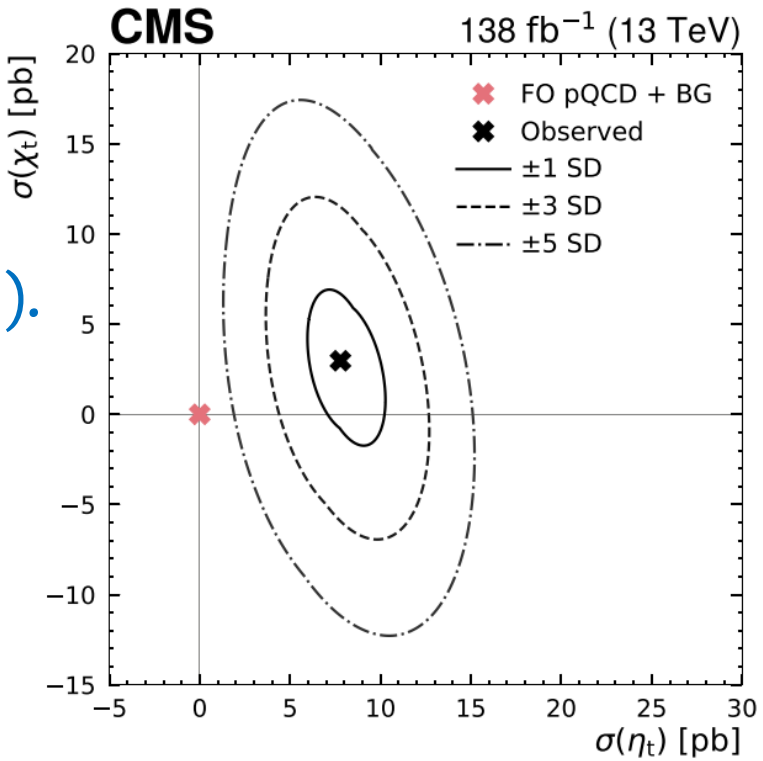
Rep. Prog. Phys. 88 (2025)

- **Alternative** fit including **scalar** (H, x_t) component shows **compatibility** with **zero** x_t contribution while **excluding** by **5** s.d. the **zero** η_t contribution ⟶ confirms **observation.**

- Leading uncertainties:

- Off-shell + $t\bar{t} - tW$ interference (bb4l).
- FSR, m_{top}, Yukawa coupling.
- PS modelling (Herwig comparison).

- **Alternative** models all **confirm** the **excess**.



Excesses at the $t\bar{t}$ threshold: Lepton + jets final state

- **e/μ and >=4 jets**
- **Define β_t^* as the magnitude of the velocity (|p|/E) of t_ℓ in t_h rest frame**

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$$\frac{m^2(t\bar{t}) - m^2(t_\ell) - m^2(t_h)}{2m(t_\ell)m(t_h)} = \frac{1}{\sqrt{1-\beta_t^{*2}}}$$

- "Bound states" → low relative velocity between the tops, **p** and E likely to be similarly affected by systematics such as **jet energy corrections** → β_t^* is less affected since it is the ratio of the two
- β_t^* measures the deviation of $m^2(t\bar{t})$ from $m^2(t_\ell) + m^2(t_h)$
  - less sensitive to **variation in m_t assumption**
  - partial cancellation of **resolution effects** shared by m(tt̄) and top masses

- **Systematic uncertainties of m(tt̄):** E.g. m_t and jet energy correction
- **Smearing of m(tt̄):** Parton shower and detector effects degrades the m(tt̄) peak
- **up- and down-type jets:** important for angular-observables

- Neural network S_{NN}, assigns jets to the top quark decay products [PRD110(2024)112016], including up/down jet assignment
  - Input objects: e/μ and jet kinematics and b-tagging categories

$t\bar{t}$ threshold: Lepton + jets final state

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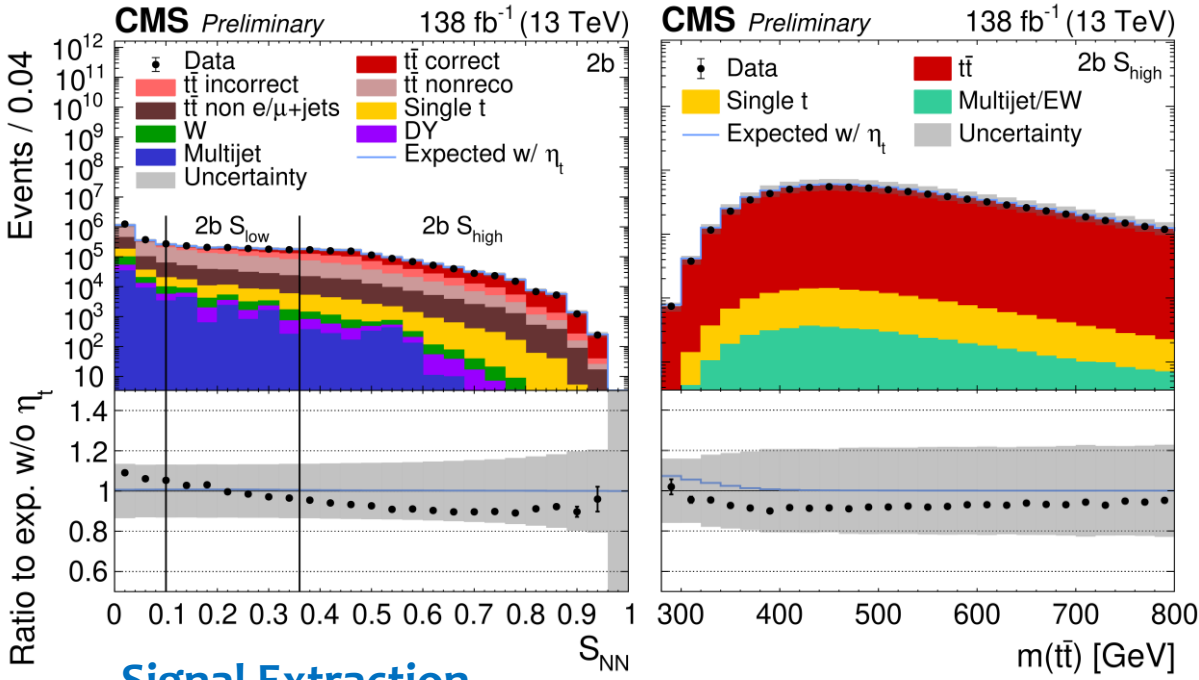
- Categorize based on the number of b-jets and S_{NN}: (1b, 2b), (S_{low}, S_{high})

- Correct ud jets assignment ≈ 70%

Backgrounds

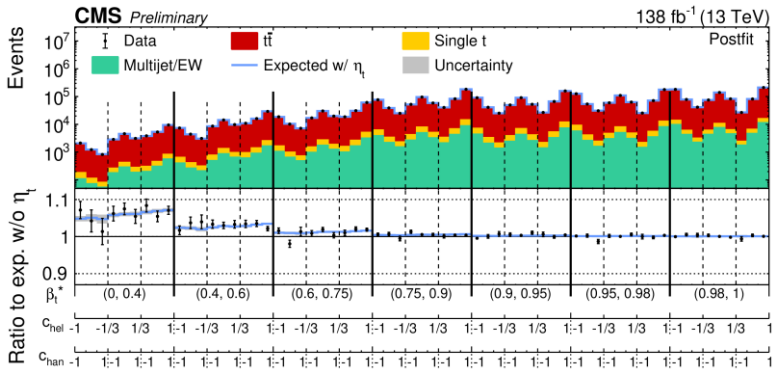
- Continuum $t\bar{t}$, QCD multijet, Drell-Yan (DY), W boson, and single top quark
- **Continuum $t\bar{t}$ & Single top: estimated using MC,** $t\bar{t}$ reweighted to NNLO using an NN method and included EW correction

- **QCD multijet, DY, and W boson (Multijet/EW) combined template** using a **data-driven** method in a b-tag control region



Signal Extraction

Profile-likelihood fit to β_t^* x c_{hel} x c_{han} (7x3x3) histograms, **Expected significance = 7.3 σ**



η_t x-section:
5.1 ± 0.9 pb

Observed significance:
6.1 σ

$t\bar{t}$ threshold: Lepton + jets final state

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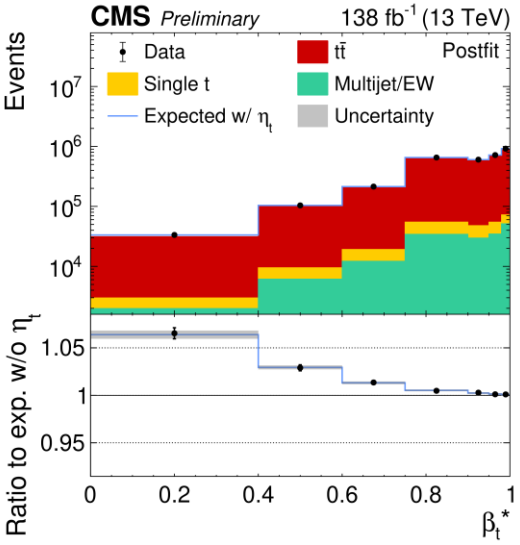
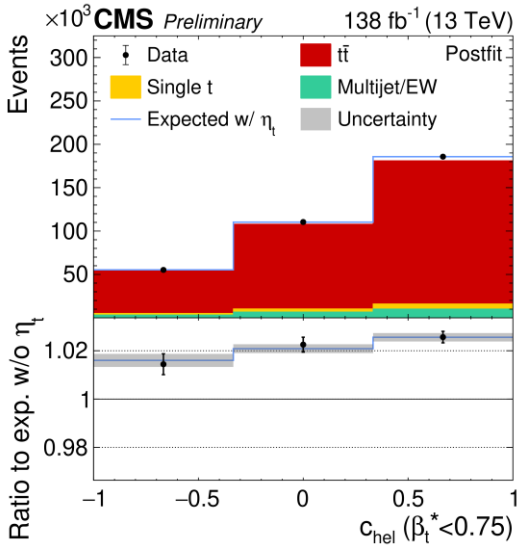
β_t^* shows a clear excess, and c_{hel} shows a clear slope consistent with η_t
Uncertainties dominated by **tt modeling**

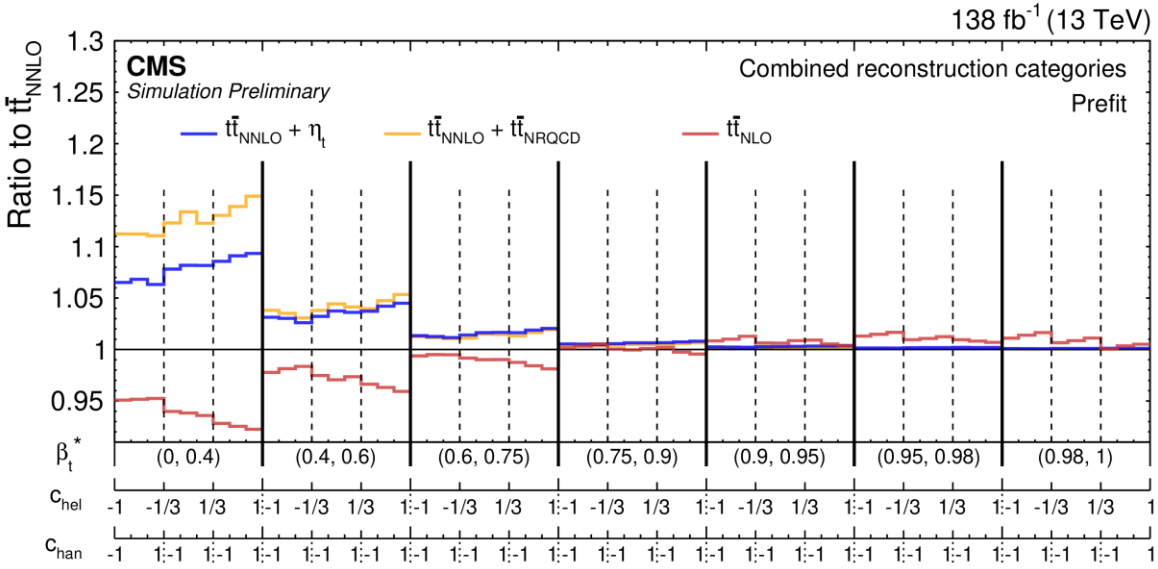




$t\bar{t}_{NRQCD}$ cross section: 2.8 ± 0.5 pb

Observed significance = 5.9 σ → similar to η_t

More concentrated excess for $t\bar{t}_{NRQCD}$ at the lowest β_t^* bin → explains the lowered cross section compared to η_t



Summary

- **t-channel cross-section at $\sqrt{s}$ = 5.02TeV, competitive uncertainties despite tiny luminosity, arxiv:2603.13592**
- **tt+j Charge Asymmetry**, No significant deviation from SM prediction (A_E within 2σ) CMS-PAS-TOP-24-015
- **Quantum state of $t\bar{t}$,** extracted quantum information properties: purity, von Neumann entropy, entanglement arXiv:2512.17557
- **Significant excess in data at the $t\bar{t}$ threshold**
- Observation in dilepton channel: RoPP 88 (2025) 087801
- Independent observation in the **ℓ+jets channel,** CMS-PAS-TOP-25-002
  - Fits well with η_t and $t\bar{t}_{NRQCD}$ models, observed significance above 5 σ for both
    - Total measured η_t cross section of 5.1 ± 0.9 pb
    - Total measured $t\bar{t}_{NRQCD}$ cross section of 2.8 ± 0.5 pb