Highlights of Top Quark Physics from LHC

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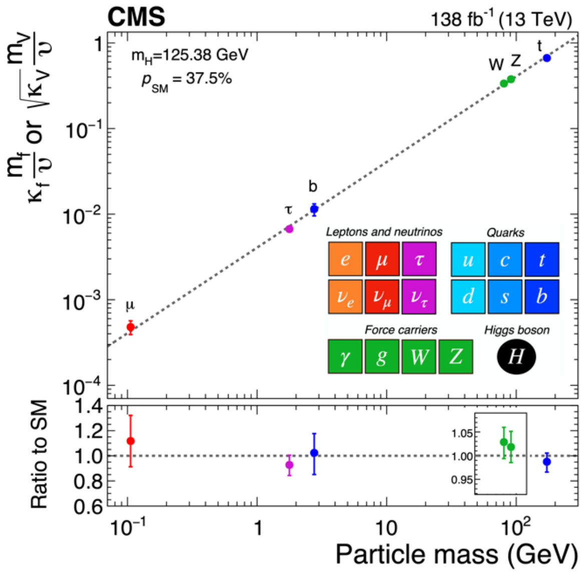
GHENT UNIVERSITY

Top quark production at LHC

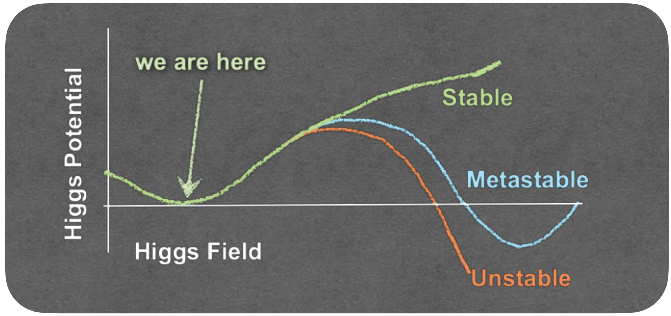


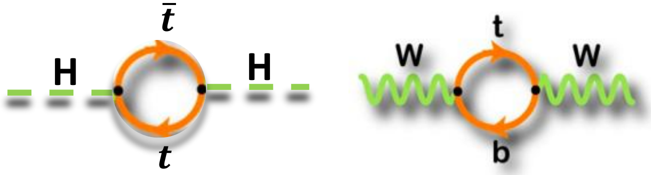
- The heaviest elementary particle

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

  → Quantum loop corrections

  → Impact on EWK vacuum stability

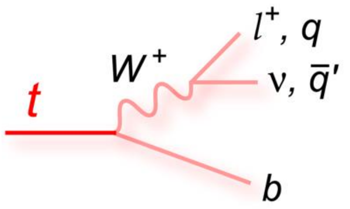




- Decays before hadronizing

  lifetime < QCD timescale

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



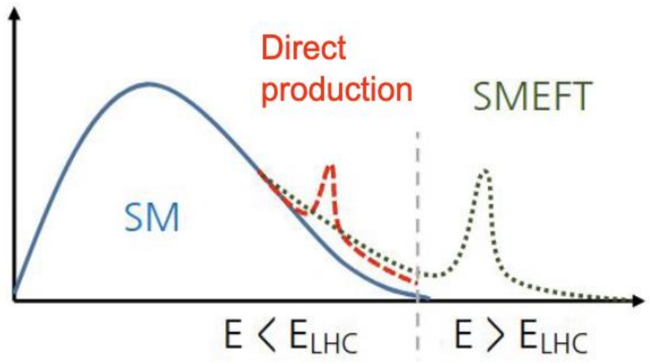
  → Access to 'bare' quark properties

- Excellent setting for testing pQCD predictions

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

- Potential portal to New Physics

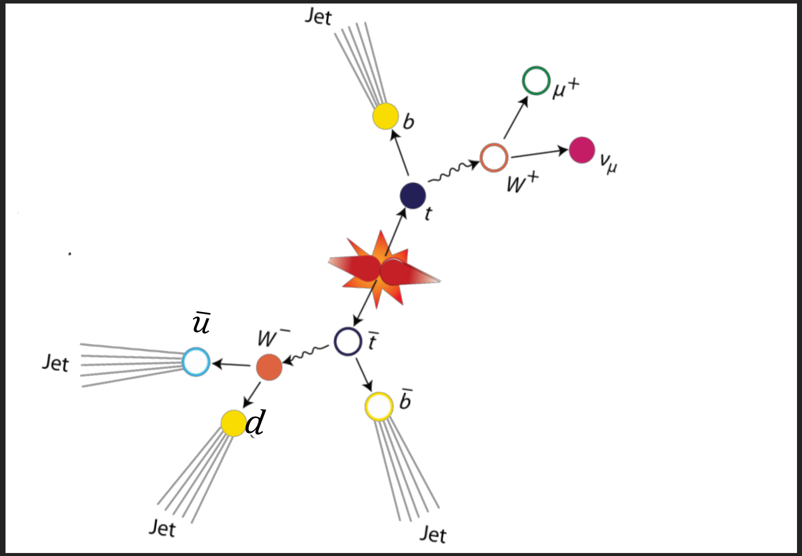
→ Production & decay are sensitive to: anomalous couplings, cLFV, BNV, LFU, CP violation, FCNC, Charge asymmetry, CKM, Spin correlations …



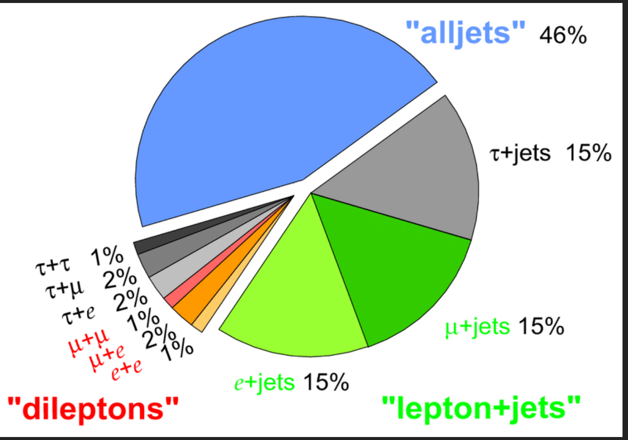
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$$

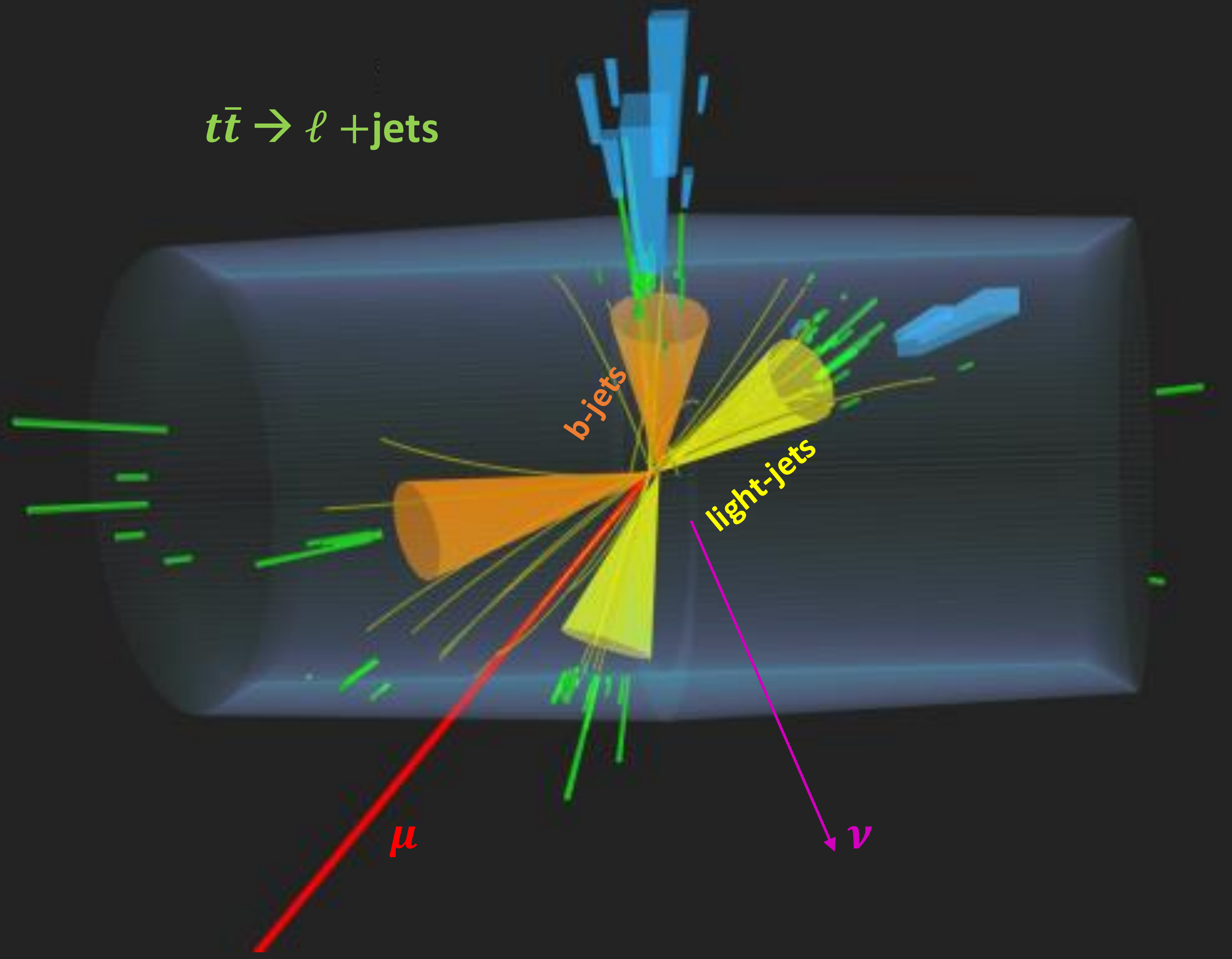
Top quark production at LHC

Top quarks mainly produced in pairs



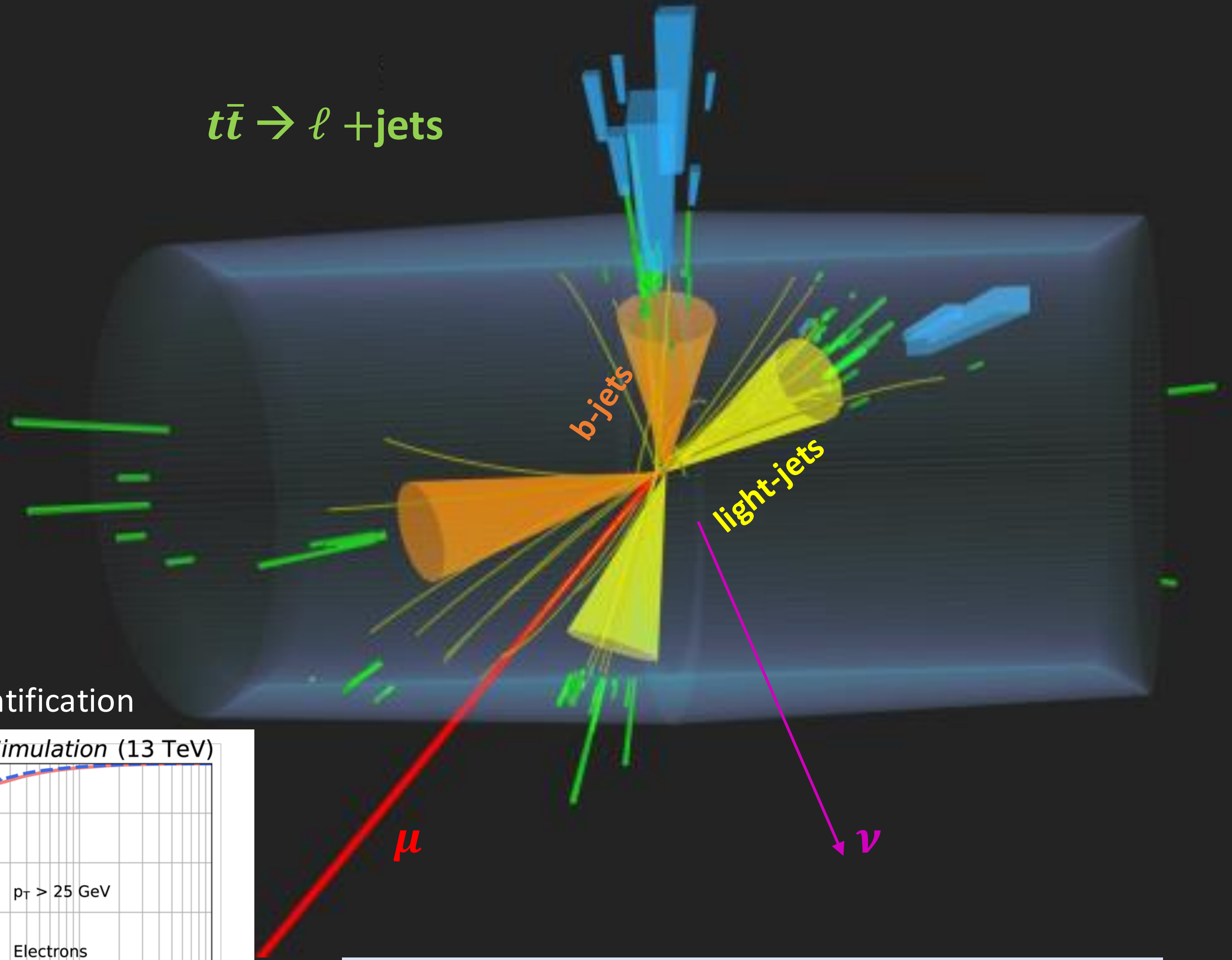
$\mathcal{B}(t \to Wb) \sim 100\%$





Top quark production at LHC

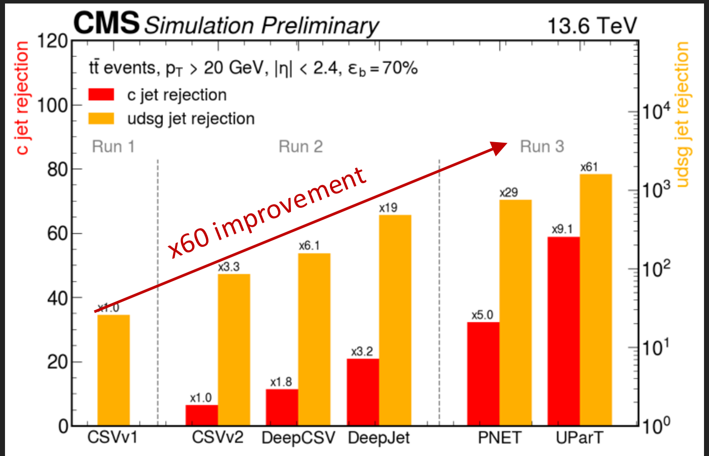
$t\bar{t} \rightarrow \ell$ +jets



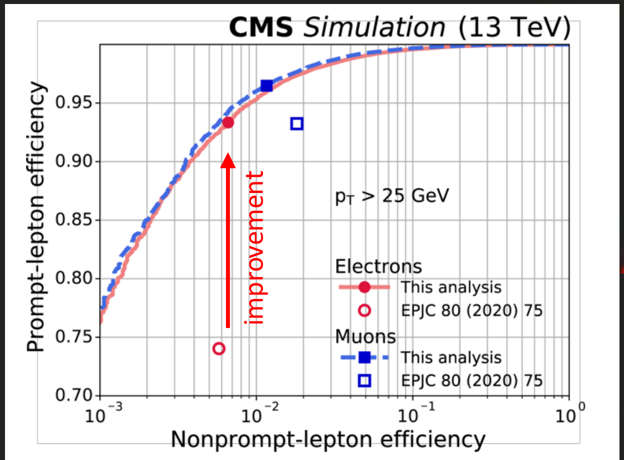
Ever increasing precision and performance of object identification a calibrations:

- ML based lepton identification
- Luminosity uncertainty <1%

Improved b-jet tagging performance



Lepton identification



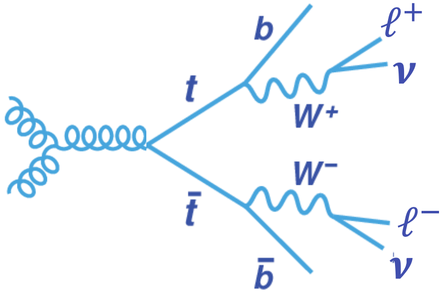
80-90% efficiency to correctly assign the top-decay products using m_W and m_{top}

iversity 4

Top quark pair-production

2404.10674 2406.19701

CMS-TOP-24-001



- Detailed inclusive and differential measurements by both ATLAS and CMS
- All decay channels and at all $\sqrt{s}$

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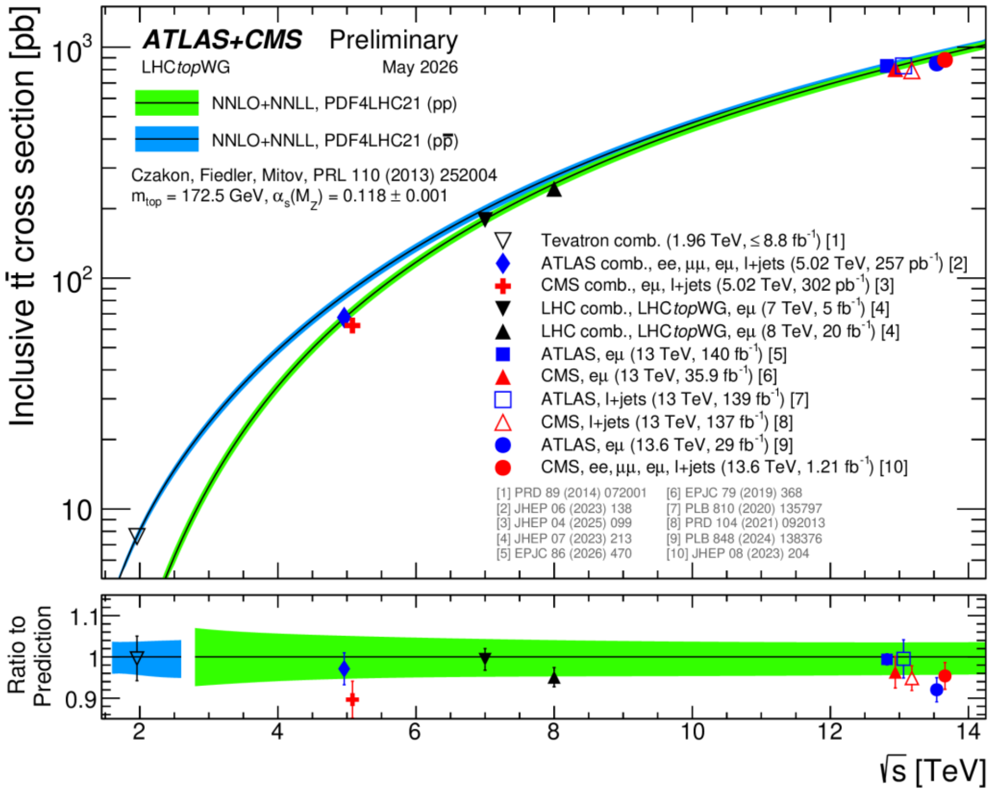
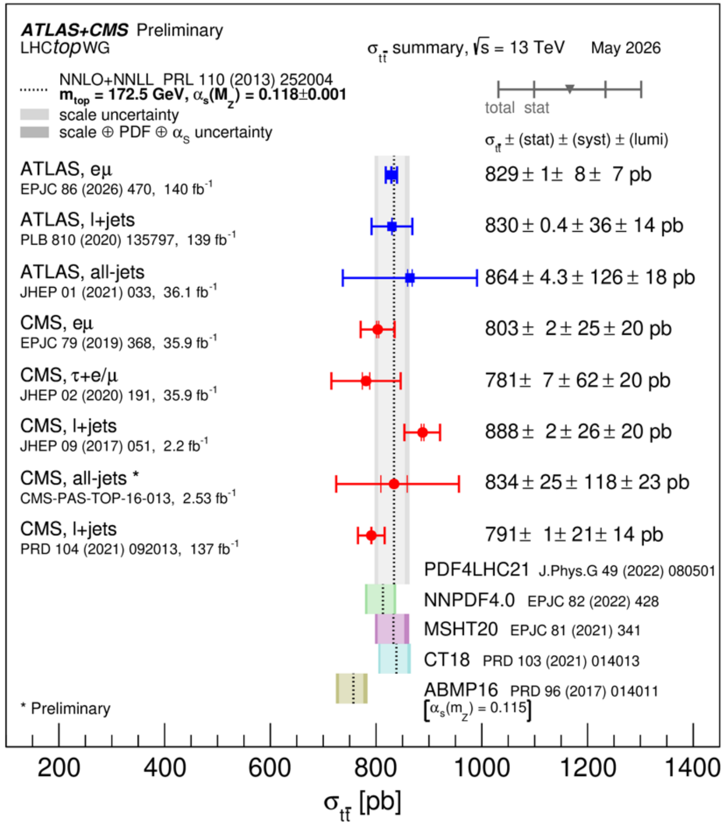




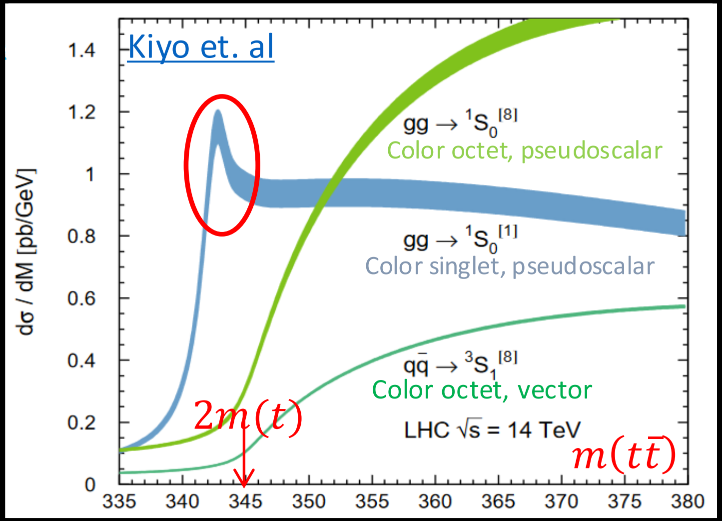
- Most precise inclusive $t\bar{t}$ measurement from ATLAS with **1.3% uncertainty**
- Results are used to extract m_{top}

Observation of $t\bar{t}$ bound state ?

[RoPP 88 087801 (2025)](#)
[CMS-PAS-TOP-25-002](#)

- Expect no stable $t\bar{t}$ bound-state is expected ($E_B \approx \Gamma_{t\bar{t}} \approx 2.8$ GeV)

→ But non-relativistic QCD predicts enhancements at the ttBar threshold



→ quasi bound-state: toponium (η_t)

- $m(\eta_t) = 343\ GeV,$
- $\Gamma_{\eta_t} = 2.8\ GeV$
- Mainly pseudoscalar

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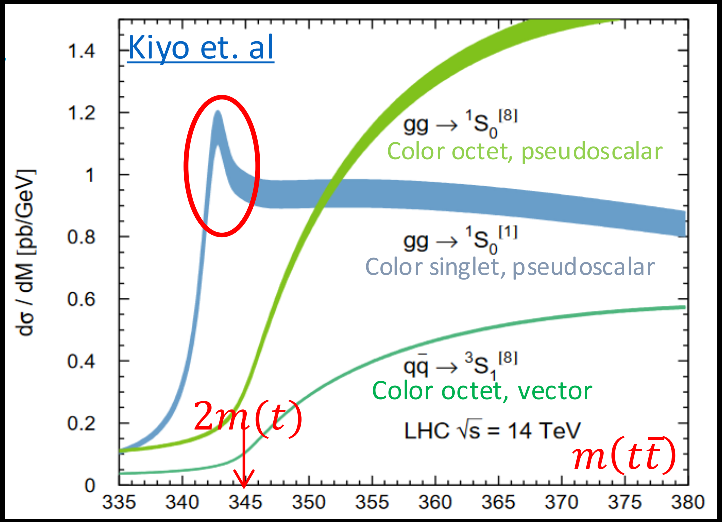

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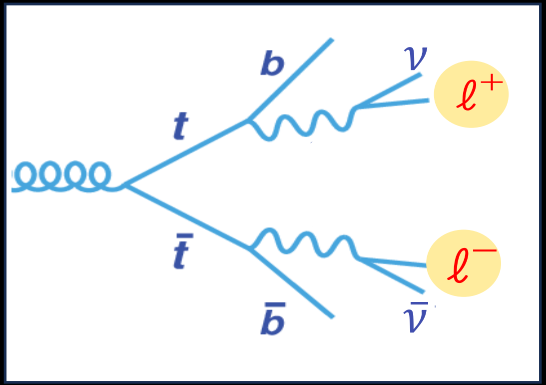
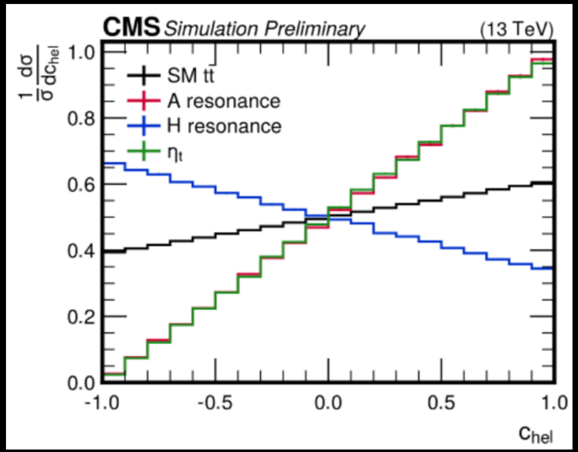
$\ell\ell$-channel

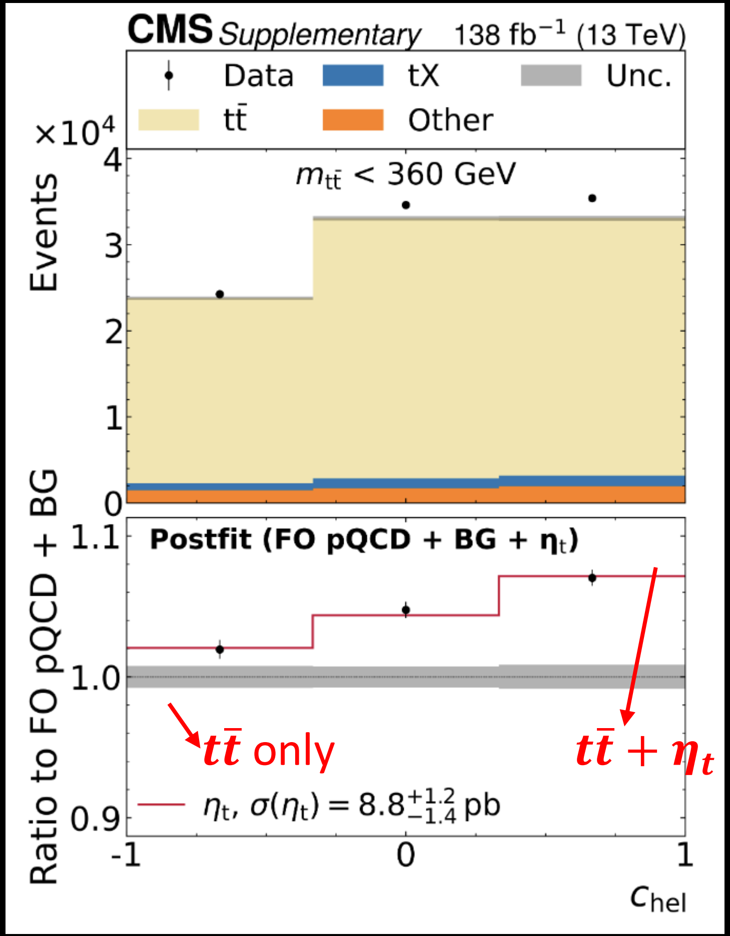


Discriminating observable



Use spin correlation observables (Chan, Chel) and Mtt to separate η_t from $t\bar{t}$

Observation with >5σ



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

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[RoPP 88 087801 (2025)](#)
[CMS-PAS-TOP-25-002](#)

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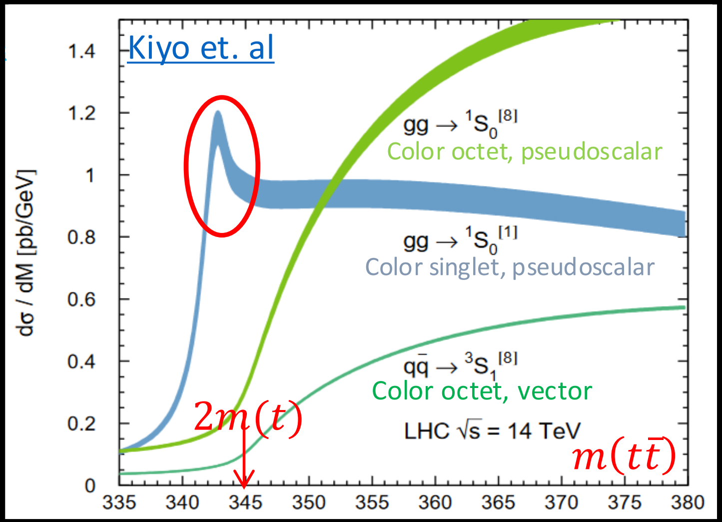

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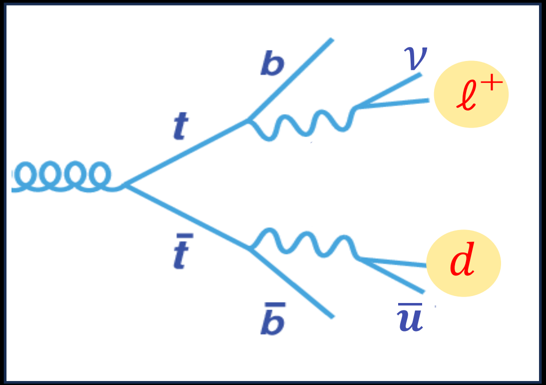
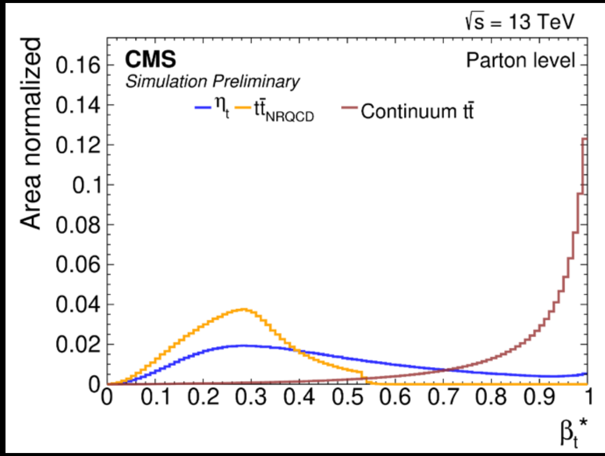
ℓ +jets



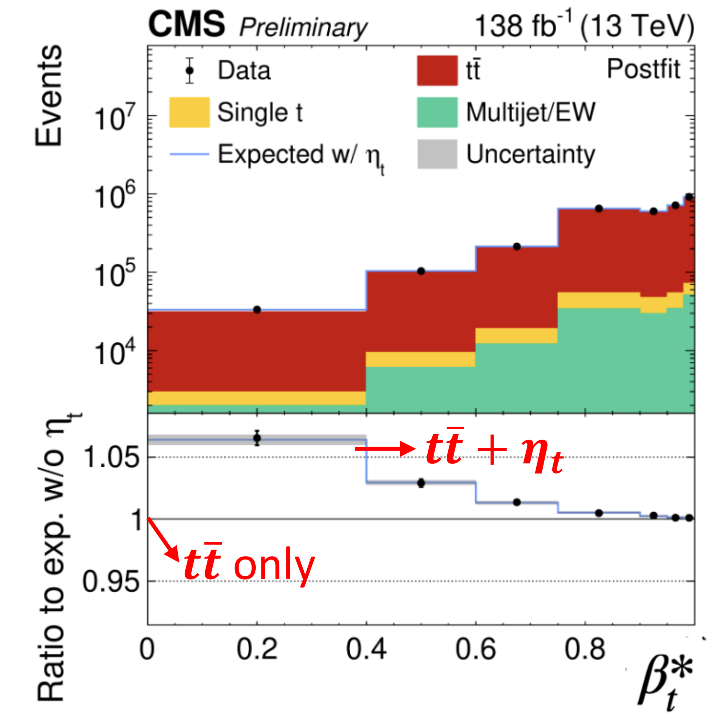
Discriminating observable

βt*: velocity of tℓ in th rest frame,



Fit in βt*,Chel, Chan, SNN and b tag

Observation with >5σ



$\boxed{\sigma(\eta_t) = 5.1 \pm 0.9\ \text{pb}}$

Observation of $t\bar{t}$ bound state ?

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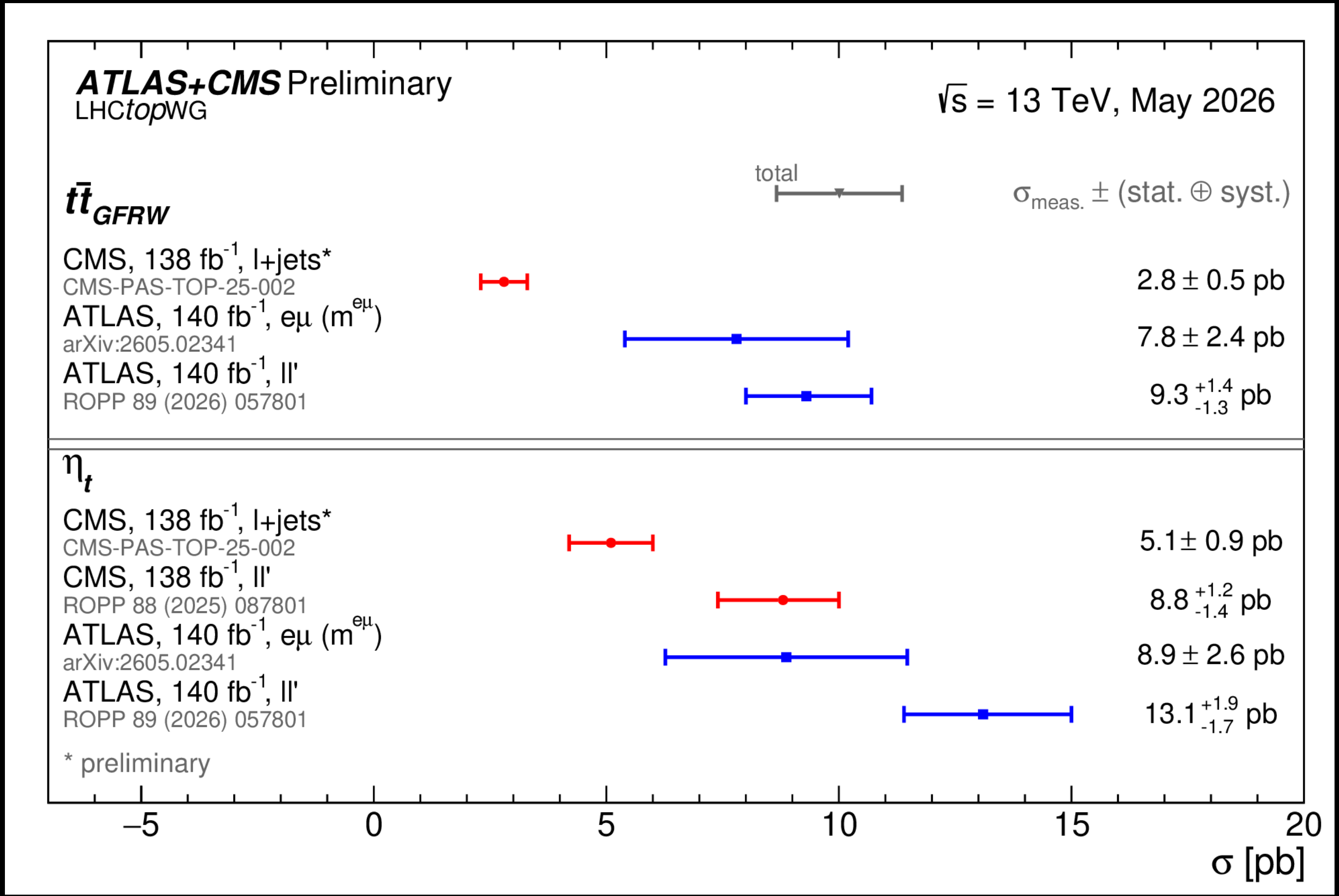
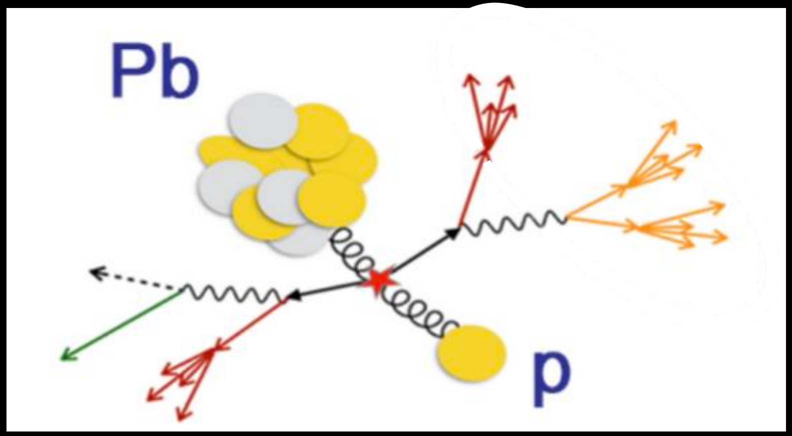


- → The enhancement below the m($t\bar{t}$) threshold is observed by both ATLAS and CMS in different top decay modes.
- → Measurements differ from each other with different signal models
- → Main limitation: modelling of both threshold and continuum
- → Great theory progress already - more advanced MC available

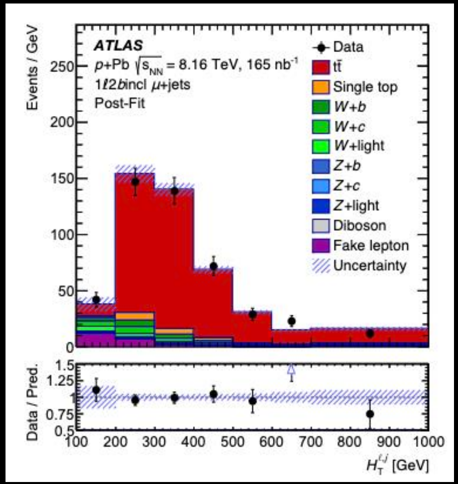
Theoretical predictions are $\sigma(pp \rightarrow \eta_t) \sim 3.35 \; - 6.43 \; pb$ depending on the approach they use

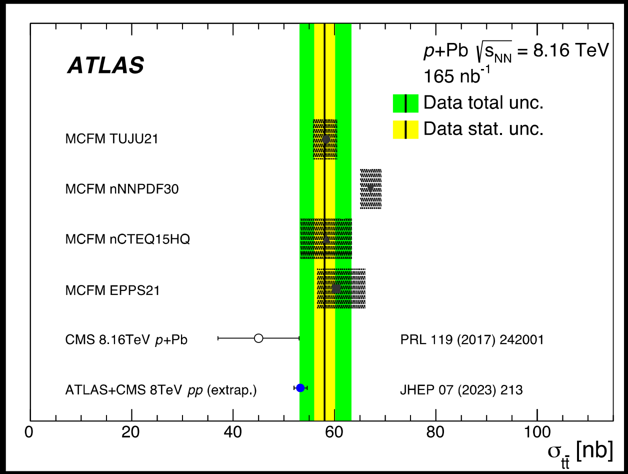
Top quark production in nuclear collisions

arXiv:2405.05078
PRL.119.242001
PRL. 125.222001
arXiv:2604.27091

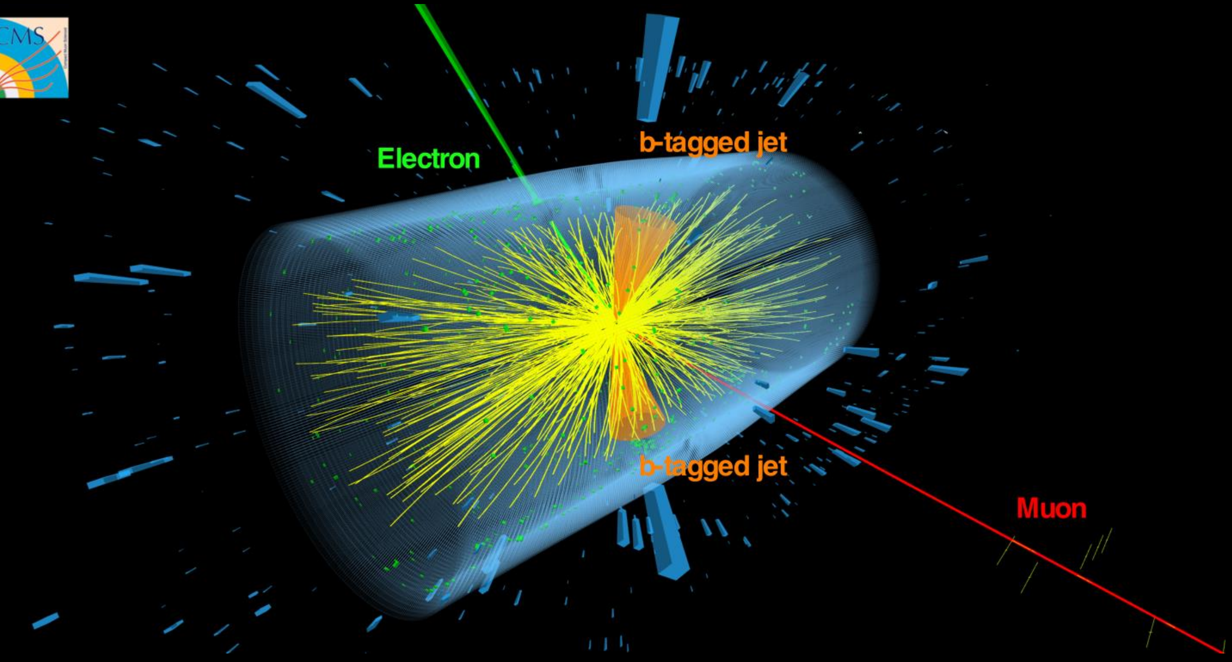


- $pPb\ (PbPb) \rightarrow t\bar{t}$
- Probes of nuclear PDF at high-x
- Observation of $t\bar{t}$ production in *p-Pp* collisions CMS & ATLAS

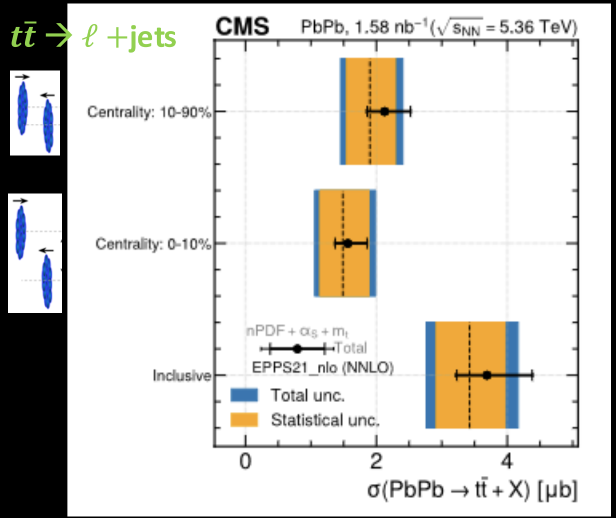


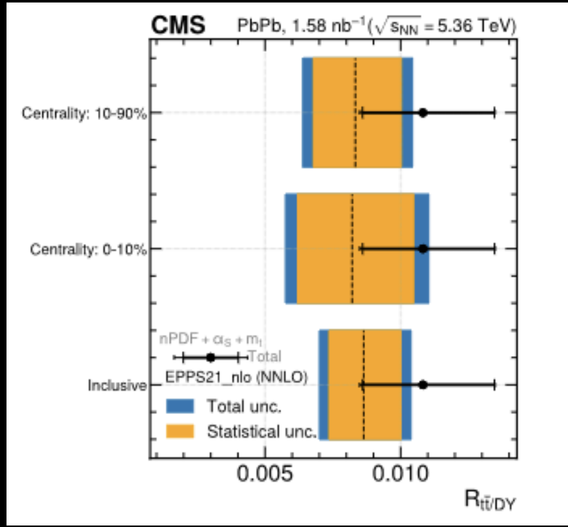


Observation of top-pair production in *Pb-Pb* collisions by CMS



$t\bar{t} \rightarrow \ell$ +jets

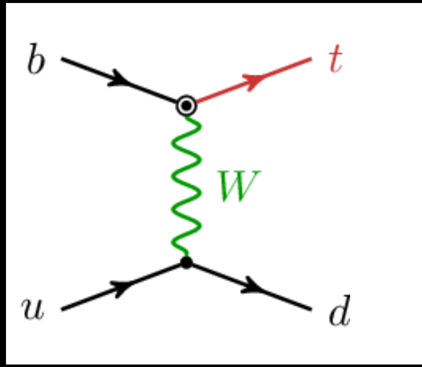




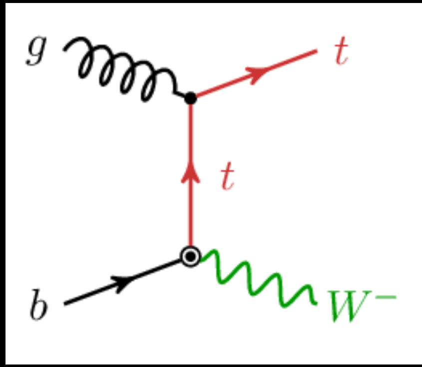
First observation, but 4 times more data available

Single-top quark production

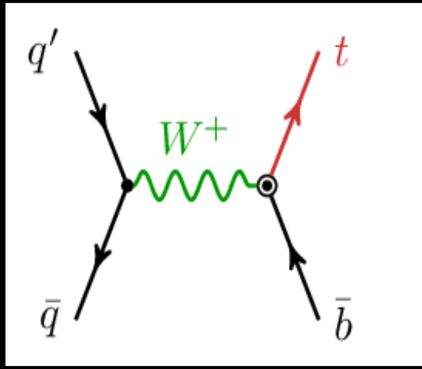
Rare but very interesting…



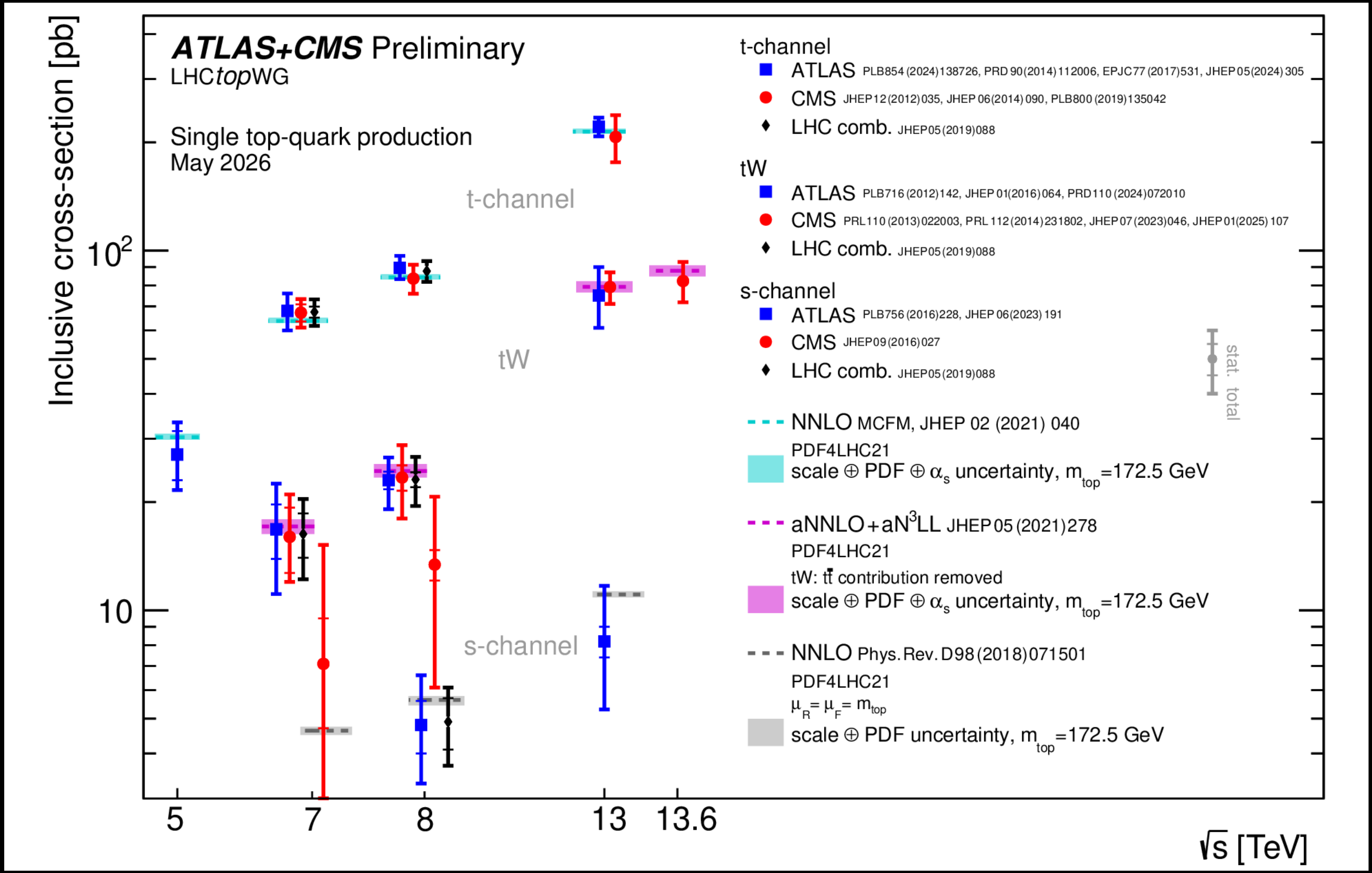
t-channel



tW channel



s-channel



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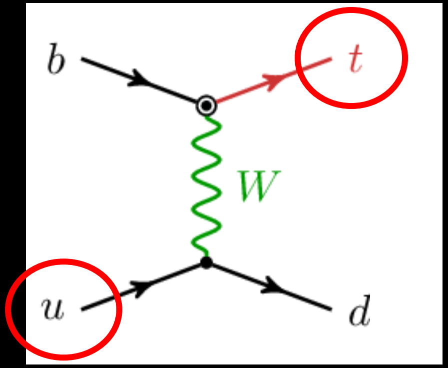
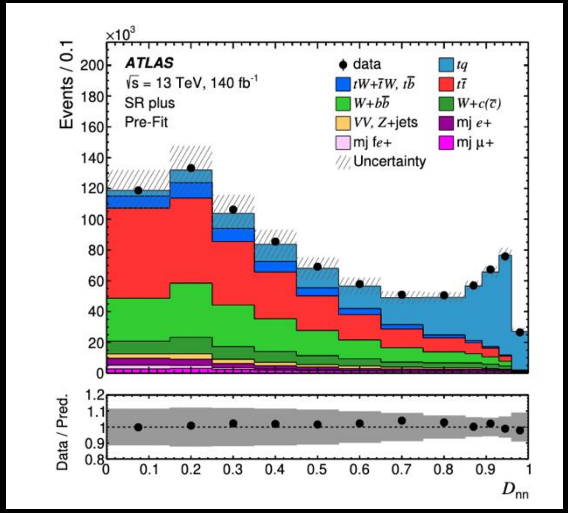
Single-top quark production

Rare but very interesting…

PDF sensitivity via $\mathrm{R} = \frac{\sigma(t)}{\sigma(\bar{t})}$



t-channel



$$\sigma_{tq} = 137 \pm 8\, pb$$

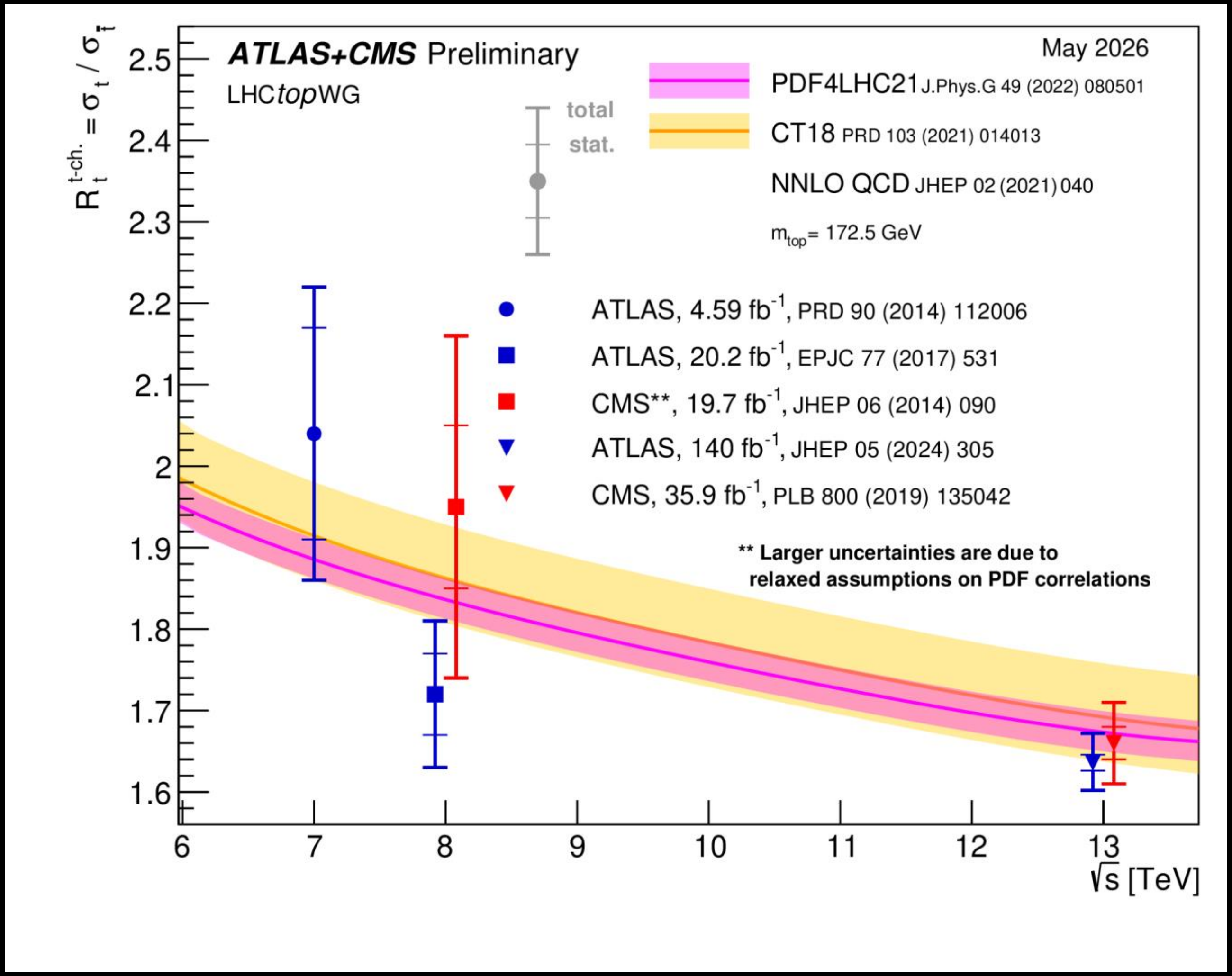
$$\sigma_{\bar{t}q} = 84^{+6}_{-5}\, pb$$

$$\sigma_{tq+\bar{t}q} = 221 \pm 13\, pb$$

~6%

$$R_t = \frac{\sigma_{tq}}{\sigma_{\bar{t}q}} = 1.636\ \pm 0.036$$ ~2%

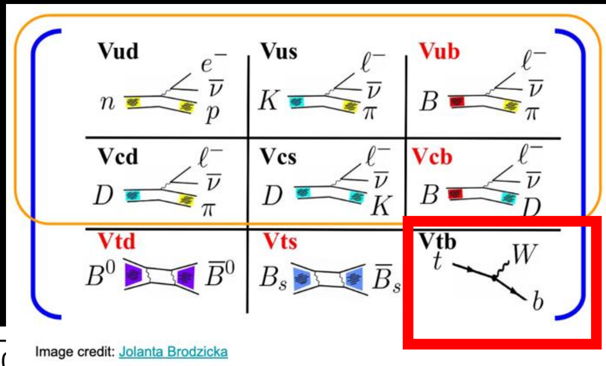
Several uncertainties cancel in $\mathrm{R_t}$



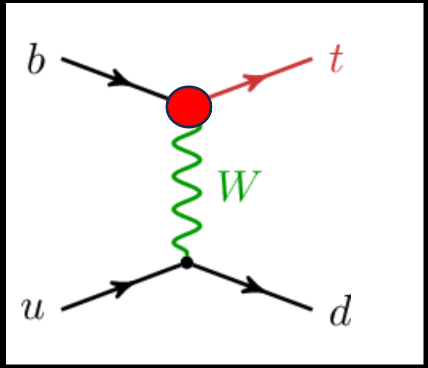
Single-top quark production

Rare but very interesting…

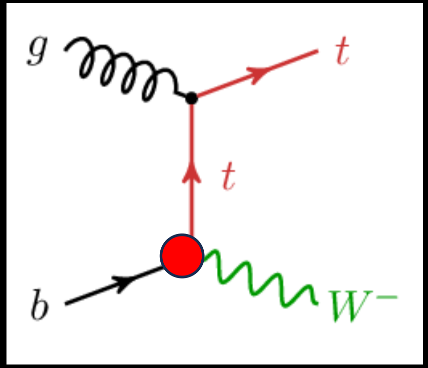
Direct access to V_{tb}



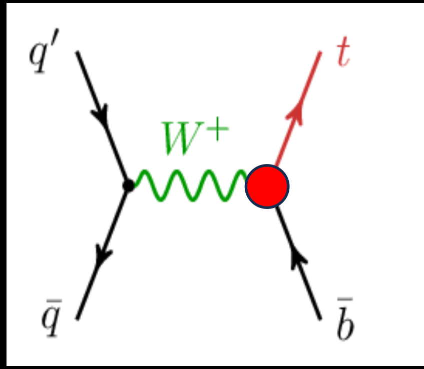
V_{tb}



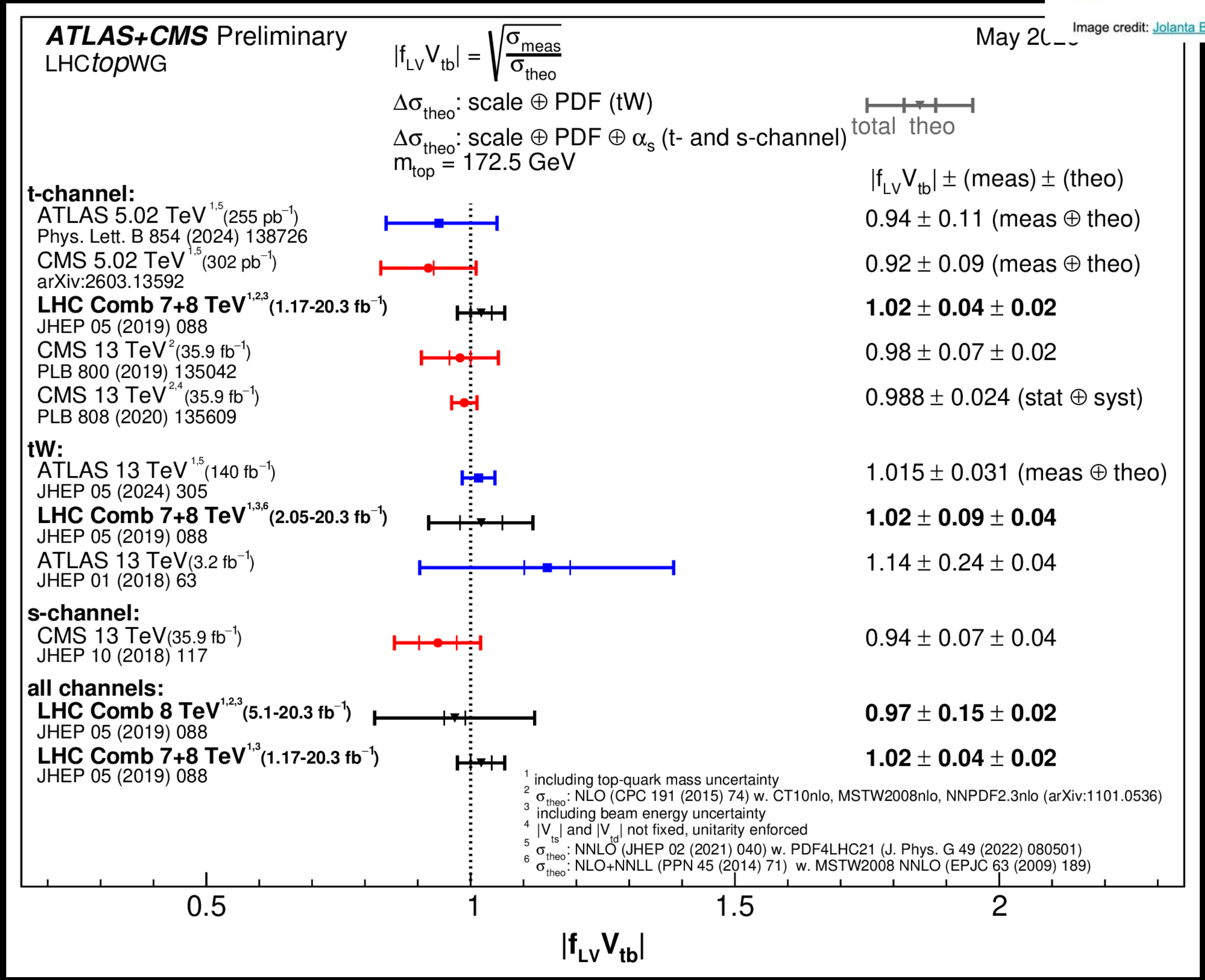
t-channel



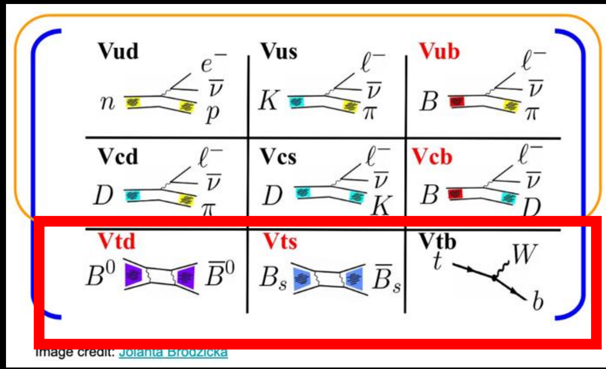
tW channel



s-channel



Generalized CKM interpretation



CMS uses t-channel production

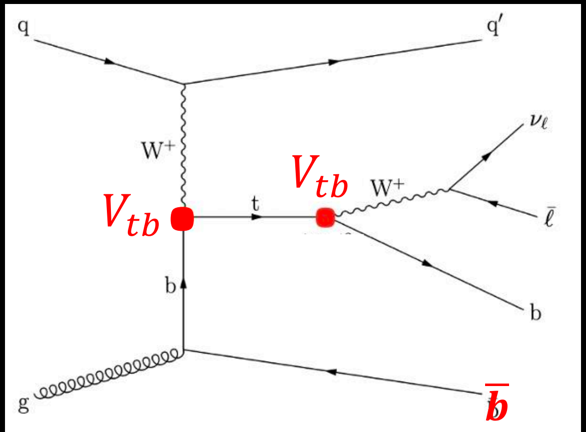
- Exploit kinematic & topological differences in t-channel
- Assuming CKM unitarity:

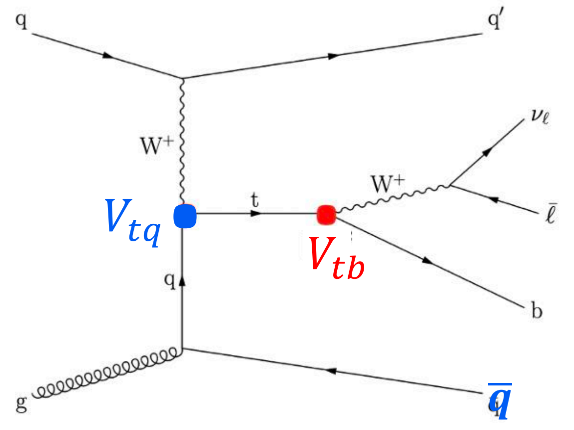
$$|V_{\mathrm{tb}}| > 0.970$$
$$|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 < 0.057.$$

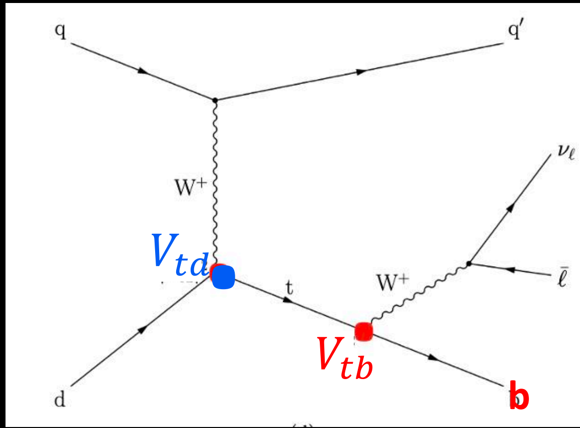
- General interpretation allowing BSM:

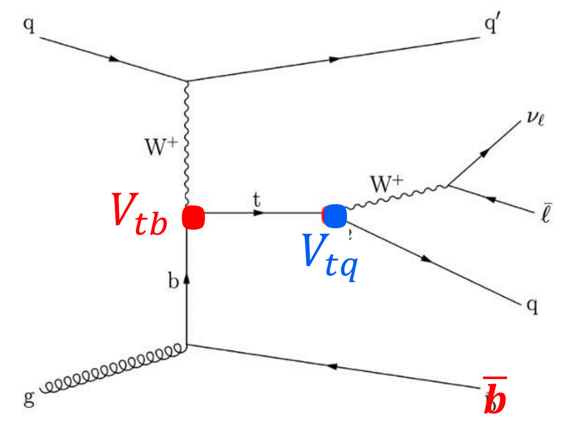
$$|V_{\mathrm{tb}}| = 0.988 \pm 0.024, \quad 2.4\%$$
$$|V_{\mathrm{td}}|^2 + |V_{\mathrm{ts}}|^2 = 0.06 \pm 0.06,$$

PLB 808 (2020) 135609

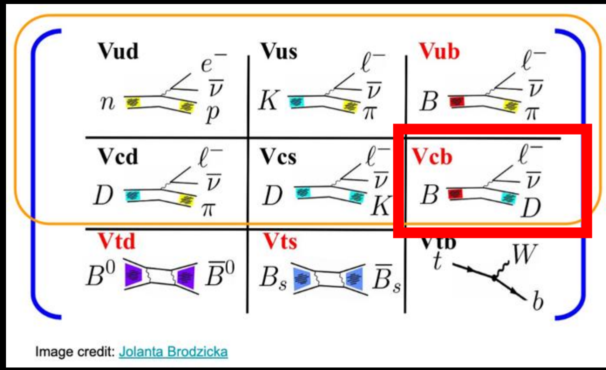


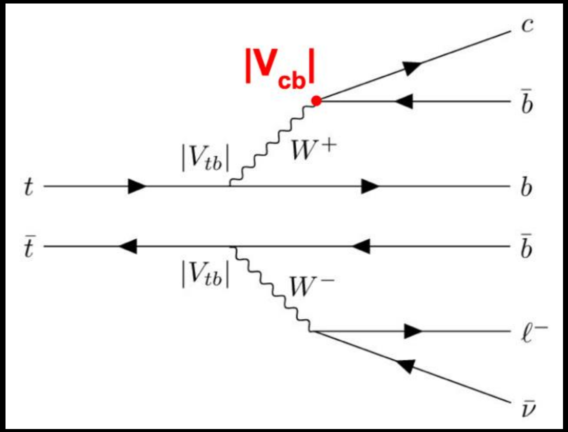






V_{cb} measurement events in $t\bar{t}$ events





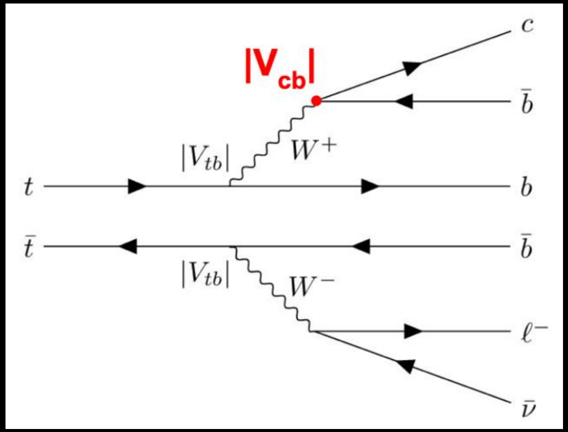
e/μ + 3 b-jets +1 c-jet

- |Vcb| usually measured in semileptonic B-hadron decays

$$|V_{cb}| = (42.2 \pm 0.5) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{cb}| = (39.8 \pm 0.6) \times 10^{-3} \quad \text{(exclusive)}$$

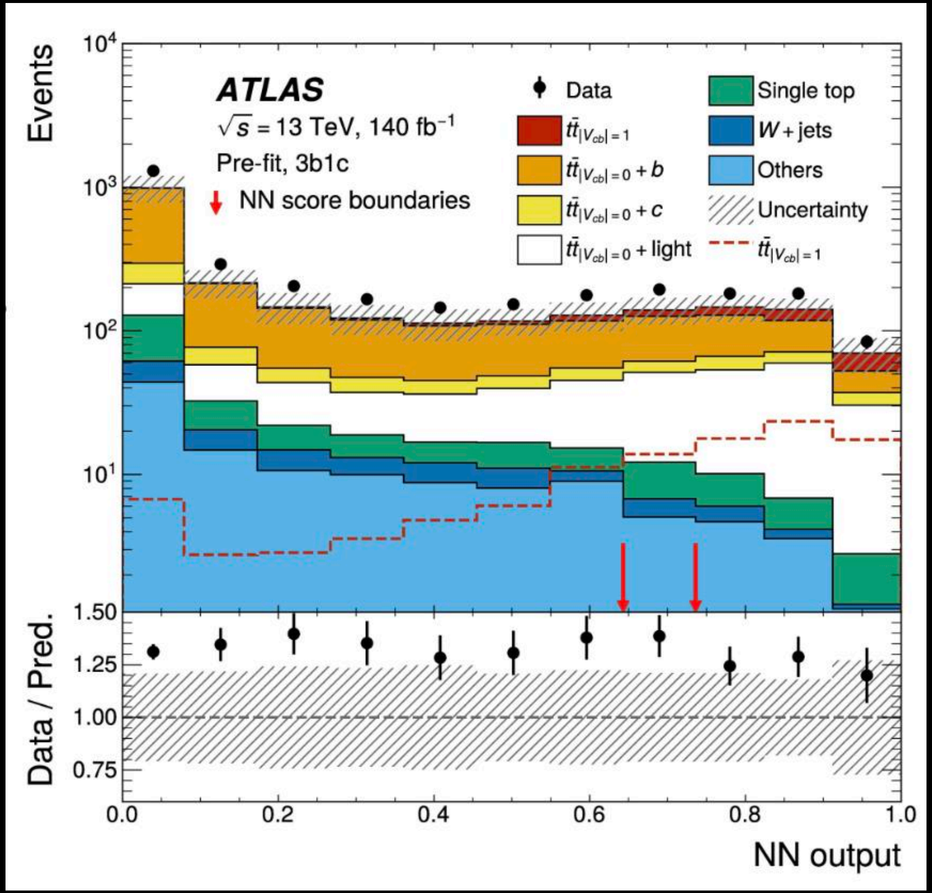
- Long lasting 3σ tention

V_{cb} measurement events in $t\bar{t}$ events



e/μ + 3 b-jets +1 c-jet

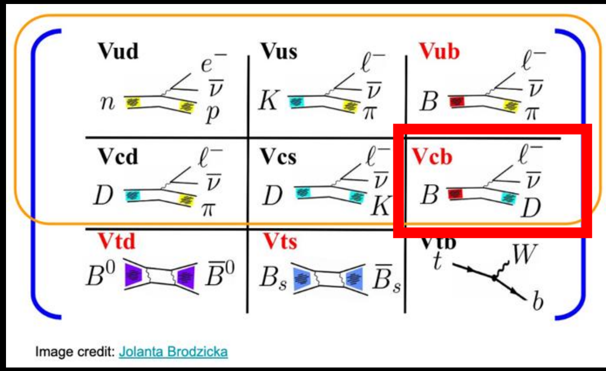
→ NN for jet assignment
→ In situ calibration for c-jets
→ Conrol regions for tt+HF backgrounds



|Vcb| extracted from the ratio of W → cq BFs:

$$|V_{cb}|^2 = \frac{\mathcal{B}(W^+ \to c\bar{b})}{\mathcal{B}(W^+ \to c\bar{q})} = \frac{\mathcal{N}(t\bar{t} \to bc\bar{b}\ \bar{b}\ell^-\bar{\nu})}{\mathcal{N}(t\bar{t} \to bc\bar{q}\ \bar{b}\ell^-\bar{\nu})}$$ [*]

$\approx 1.7 \times 10^{-3}$



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JHEP07(2026)078

$$|V_{cb}| = (50^{+7}_{-9}\ (\text{stat.})\ ^{+9}_{-10}\ (\text{syst.})) \times 10^{-3}$$

CMS-PAS-TOP-26-001

$$|V_{cb}| = 4.59^{+0.44}_{-0.48}\,(\text{stat})^{+0.64}_{-0.76}\,(\text{syst}) \times 10^{-2}$$

Not precise enough yet!

$t\bar{t}/t$ + friends

Light-quark jets

$b\bar{b}$

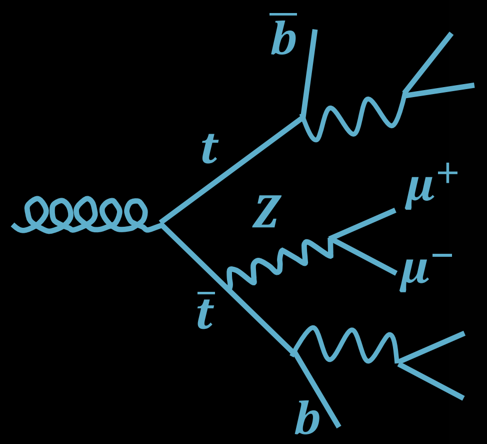
$c\bar{c}$

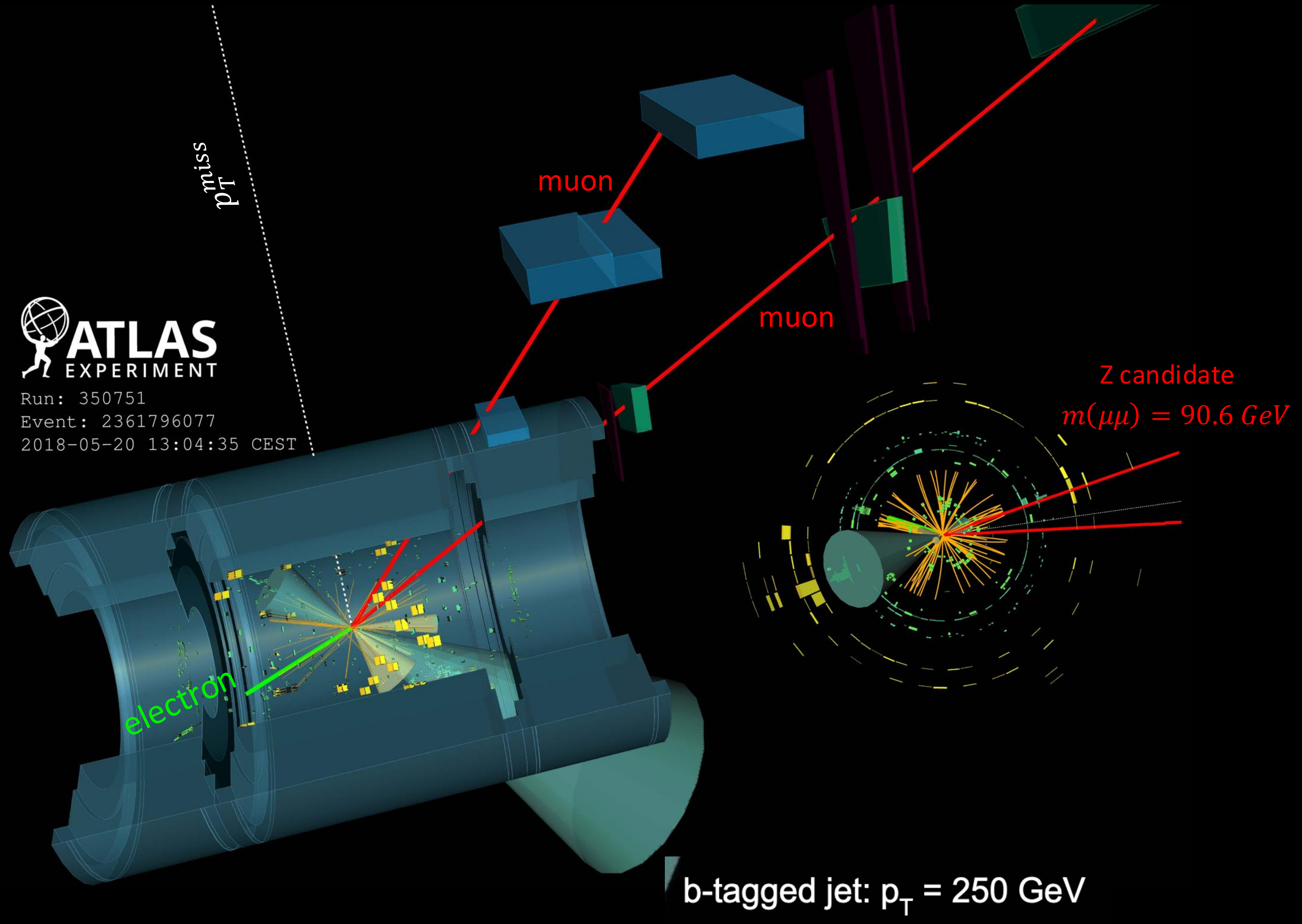
W, Z, γ

H

$t\bar{t}$

...



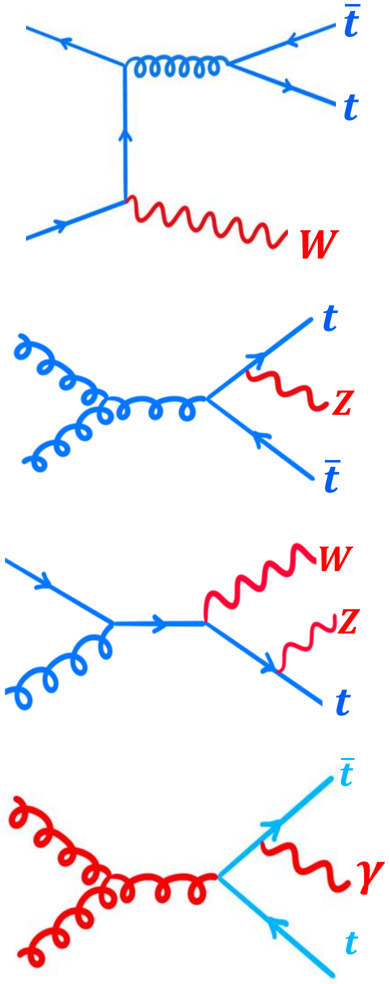


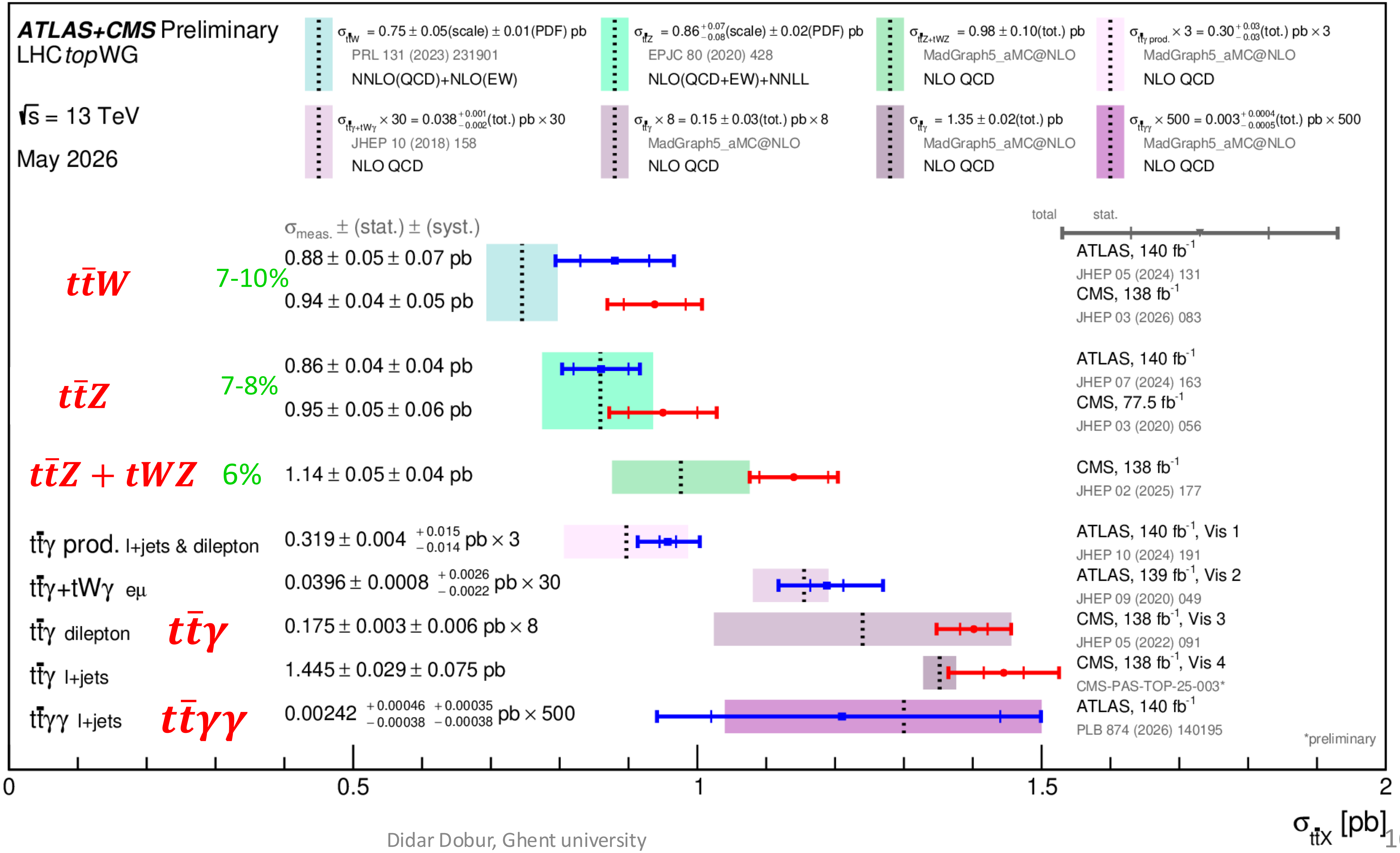
Candidate ttZ event with

- 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

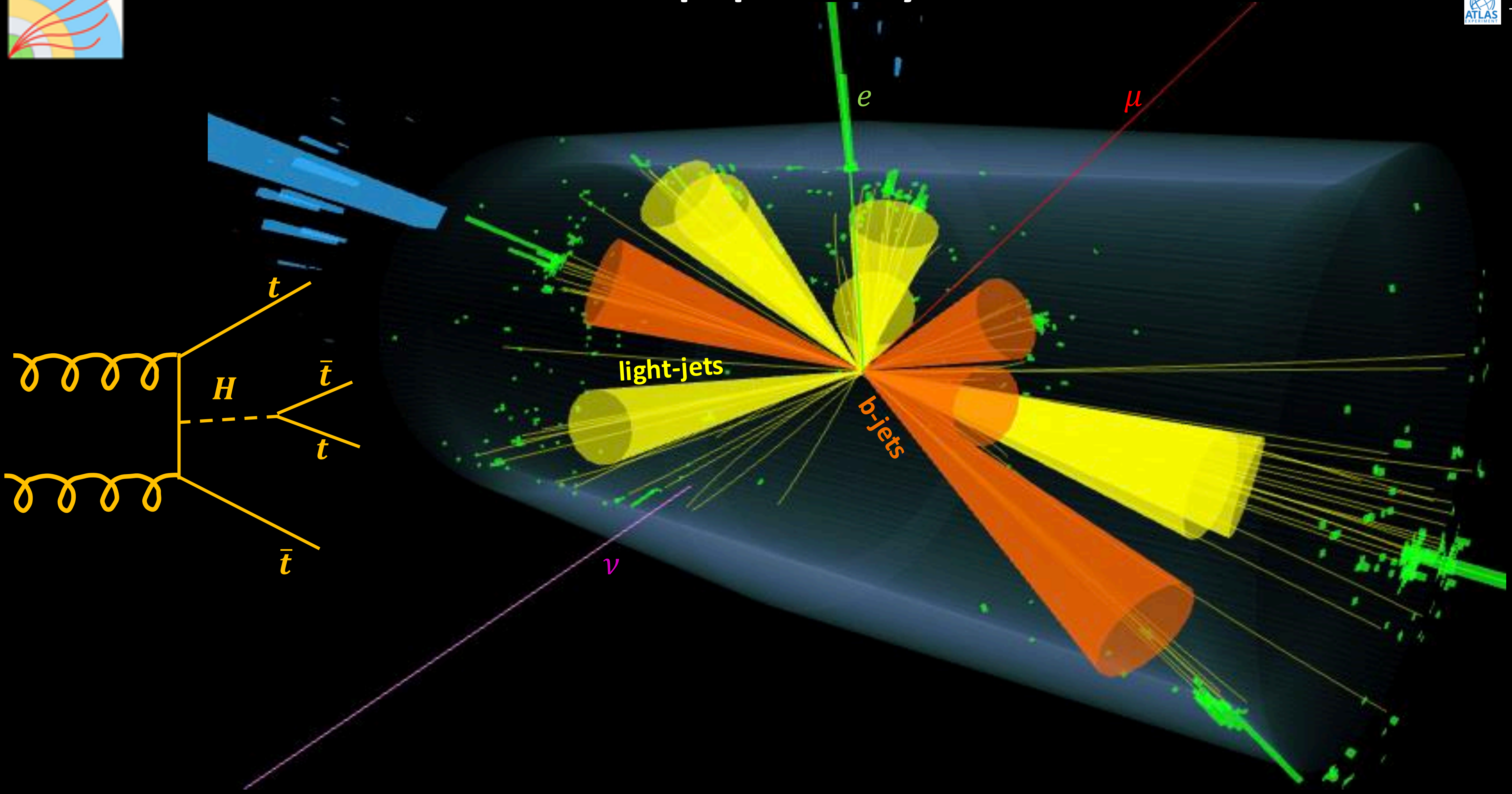




Observation of 4 top quarks by CMS and ATLAS

PLB 847 (2023) 138290

EPJ C 83 (2023) 496



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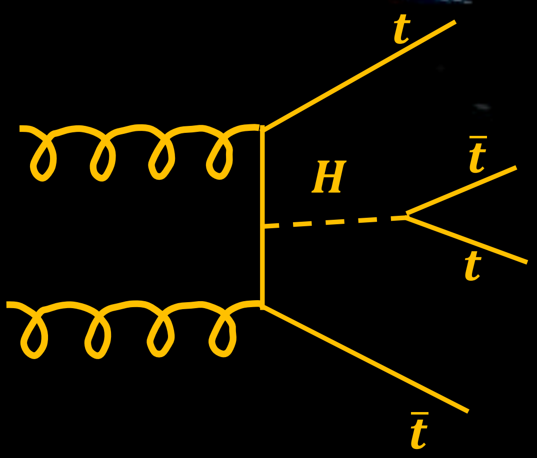

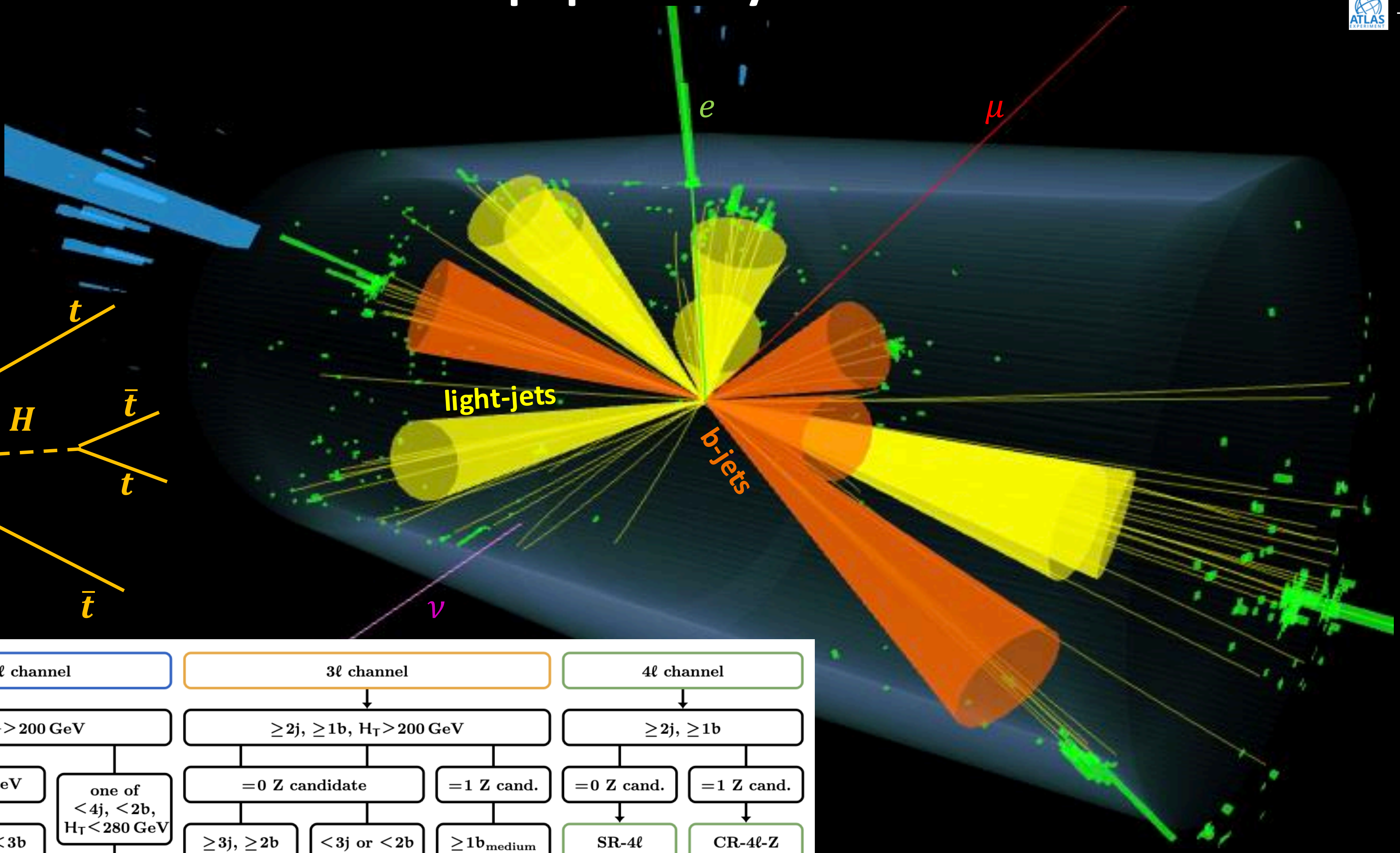

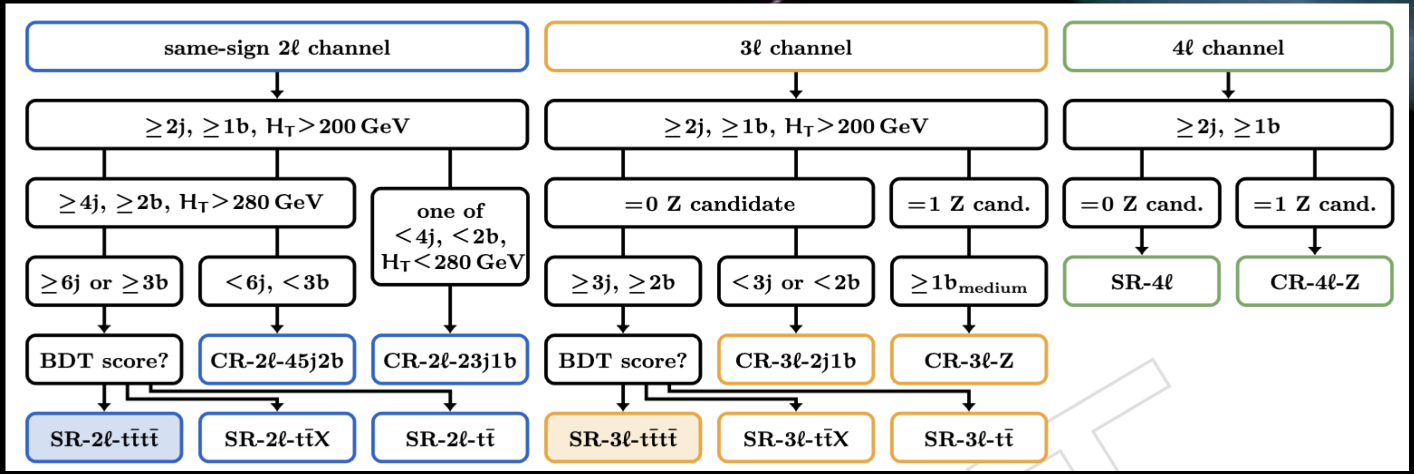

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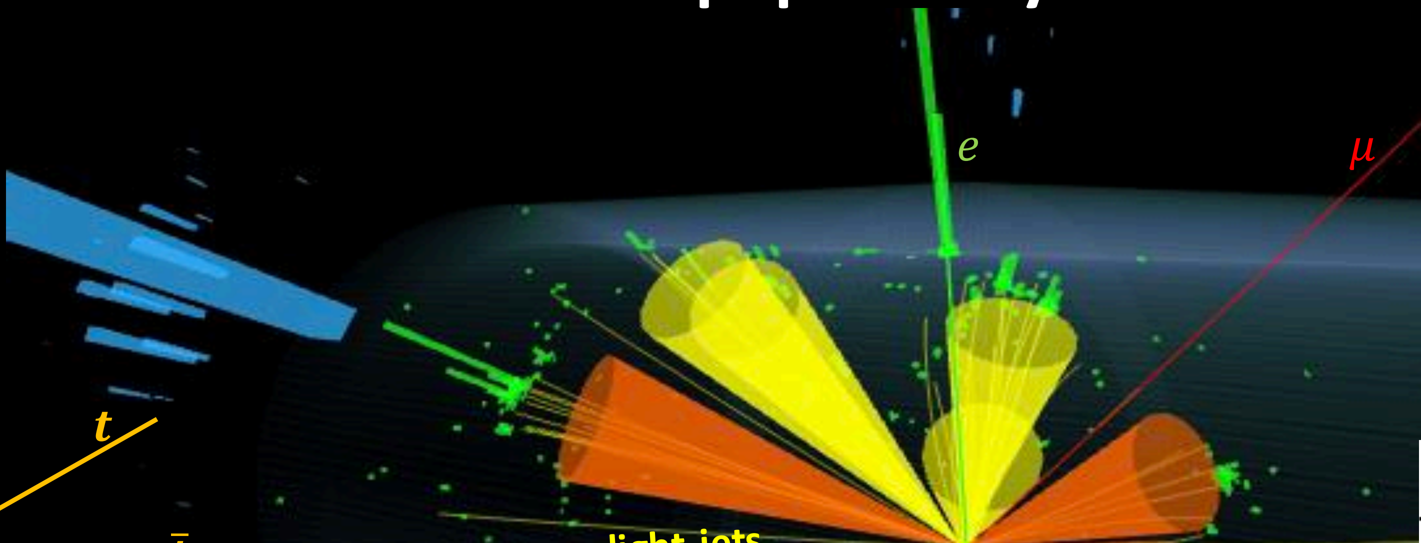
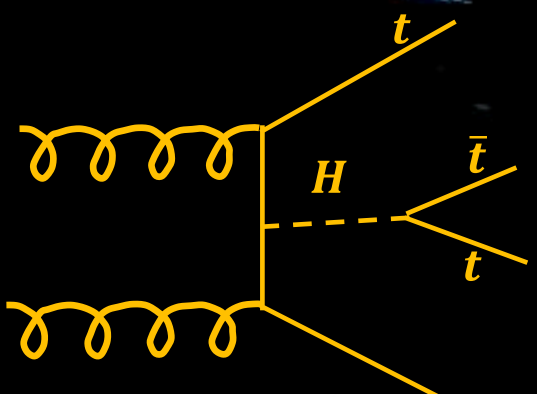
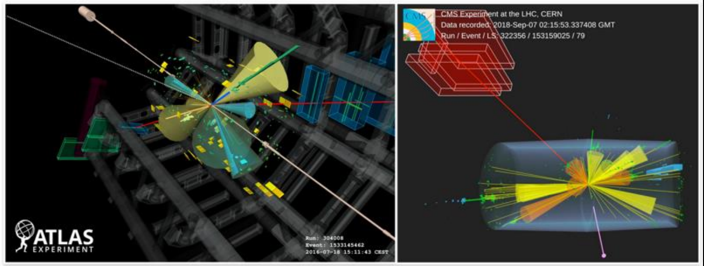


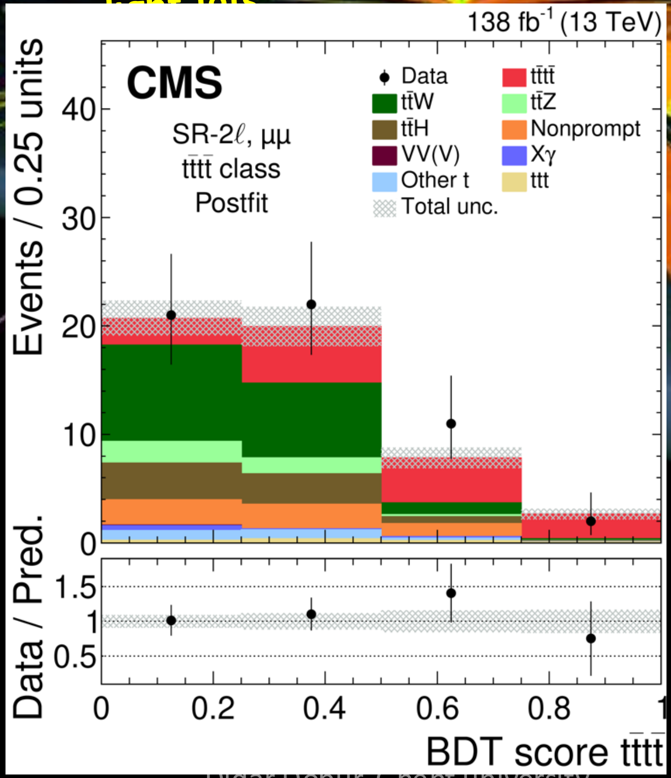


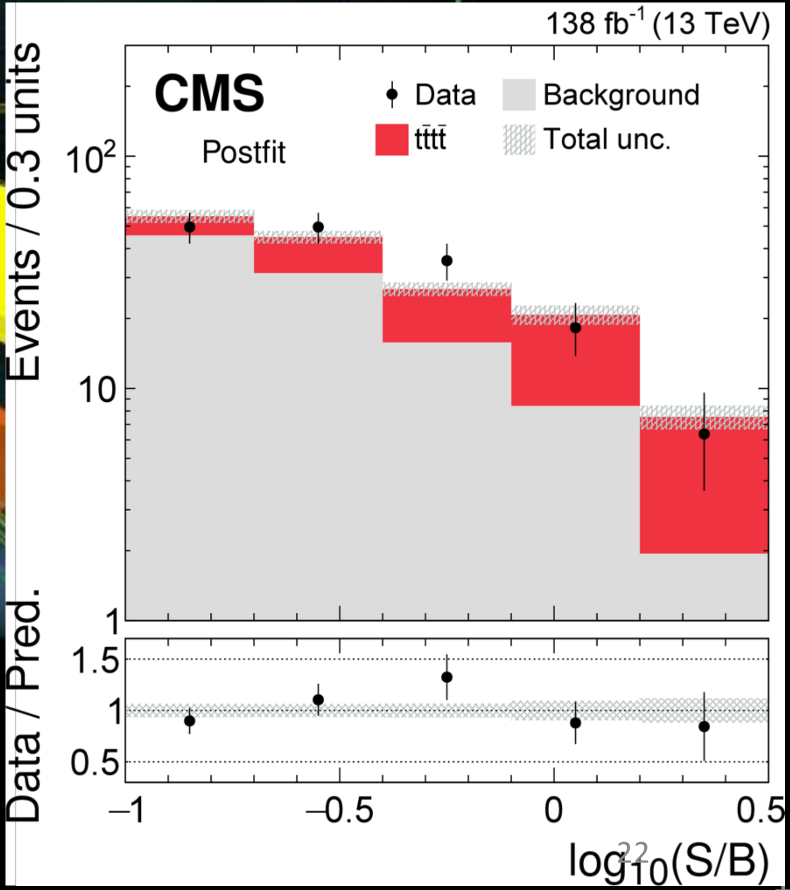


ATLAS and CMS observe simultaneous production of four top quarks

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

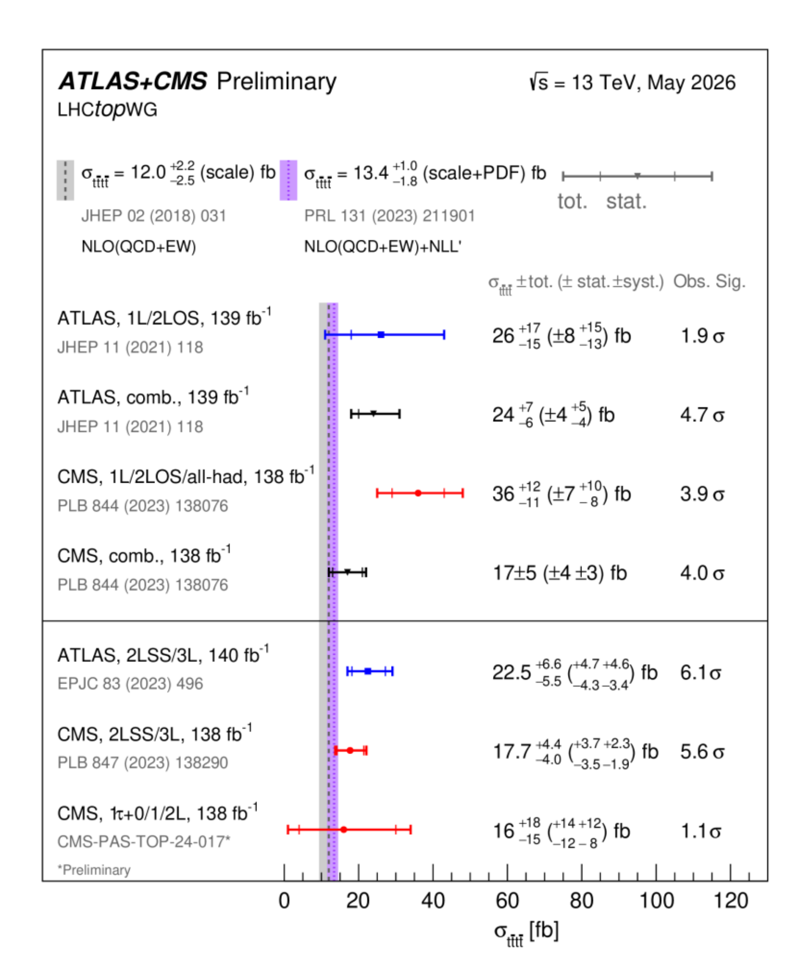
24 MARCH, 2023 | By Naomi Dinmore

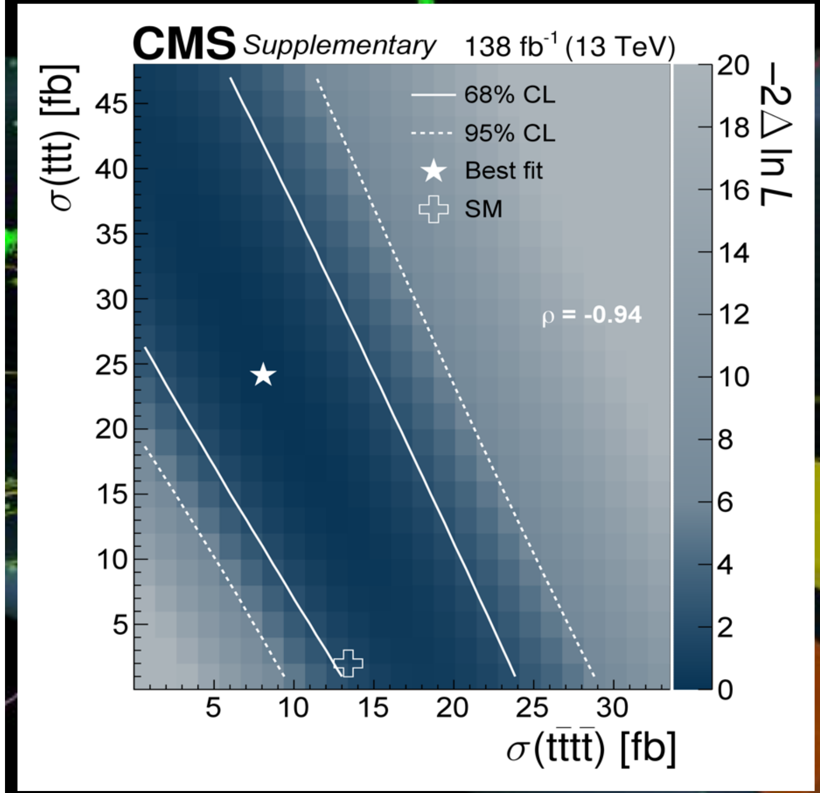


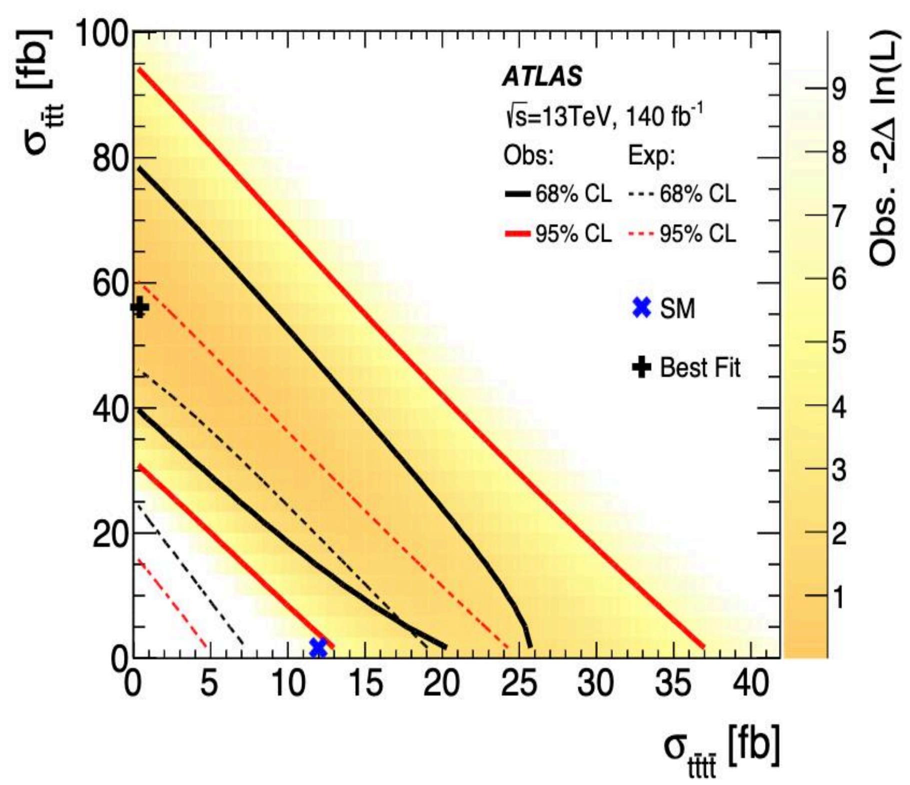


Observation of 4 top quarks by CMS and ATLAS

PLB 847 (2023) 138290
EPJ C 83 (2023) 496





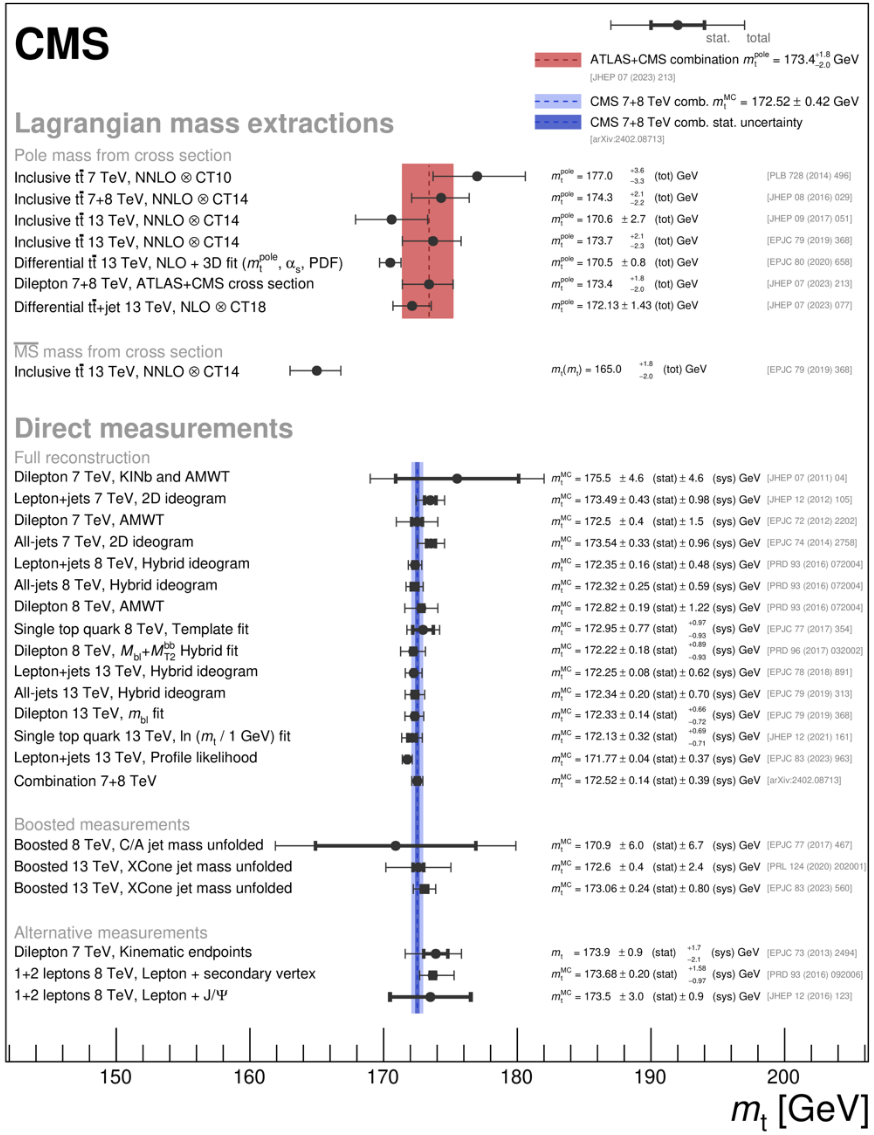


Is it four-tops ? Three-tops ? or New Physics ?

Measuring the heaviest particle mass

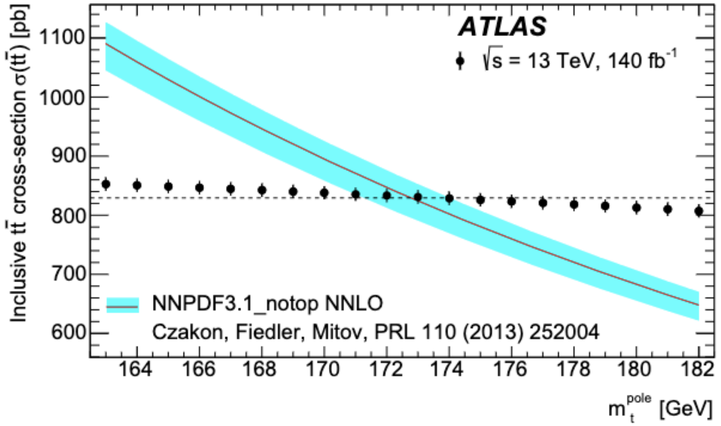
2403.01313
JHEP 2205.13830
EPJC 86, 470 (2026)

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

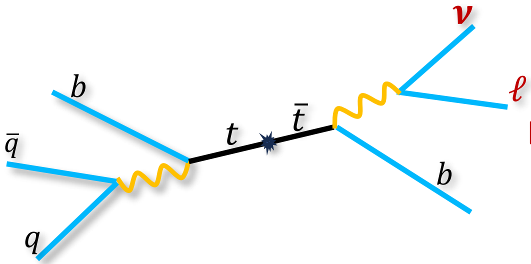


- **Indirect measurement** from cross section
  → ~1% precision, lmitted by PDF and scale uncertainties

$$m_t^{pole} = 172.8^{+1.5}_{-1.7}\,\text{GeV}$$



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

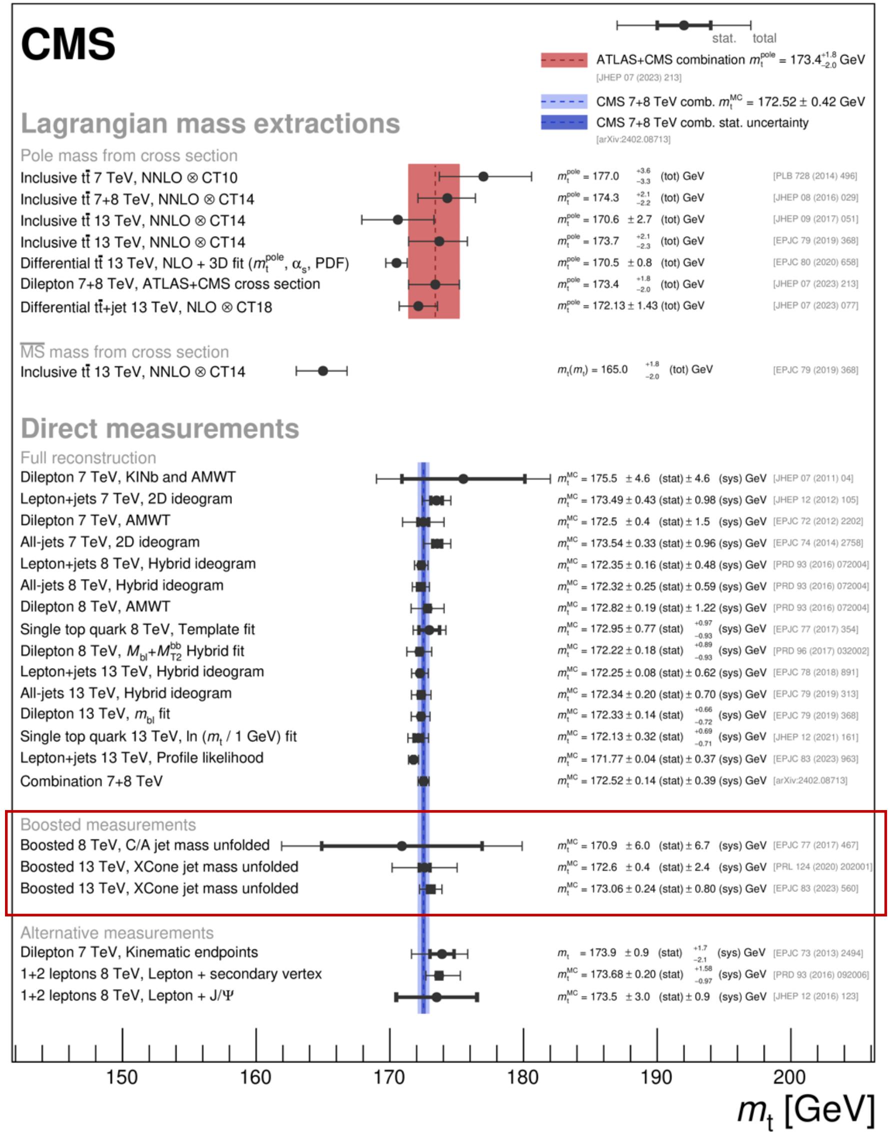


Extract m_{top} from decay products

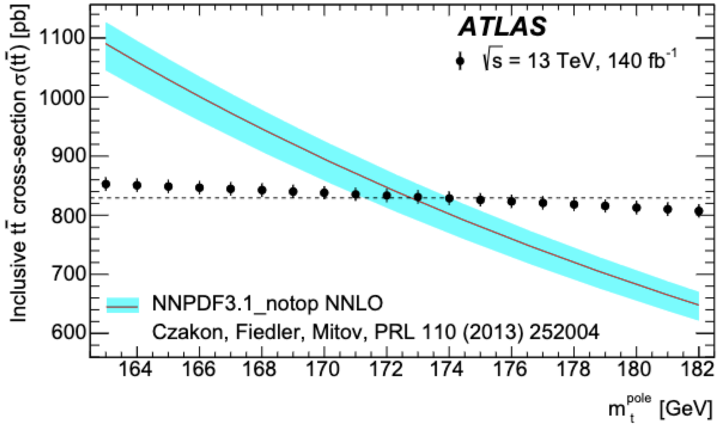
Measuring the heaviest particle mass

2403.01313
JHEP 2205.13830
EPJ C 83 (2023) 560

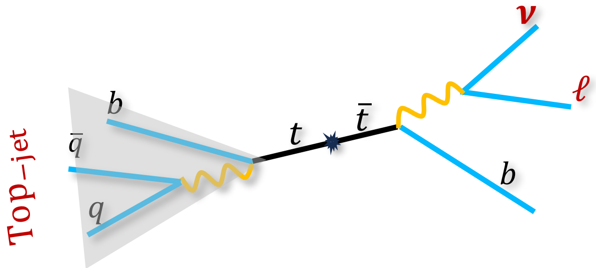
- **Significant improvements over the past years:** Better calibrations, alternative techniques, improved theoretical modelling
  → More than 40 publications by CMS and ATLAS collaborations

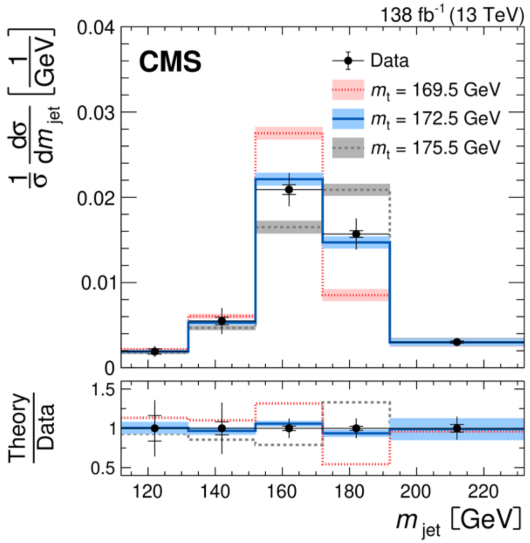


- **Indirect measurement** from cross section
  → ~1% precision



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





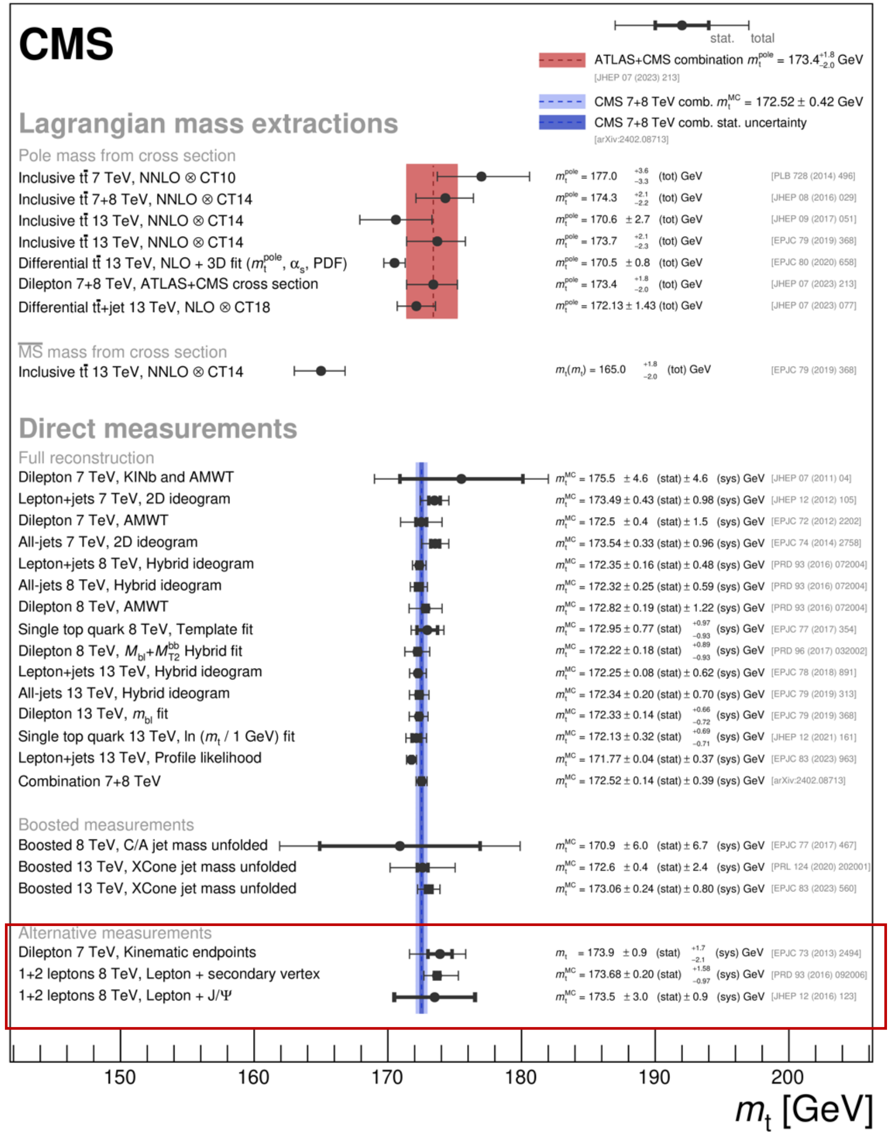
Extract m_{Top} from m_{jet}

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

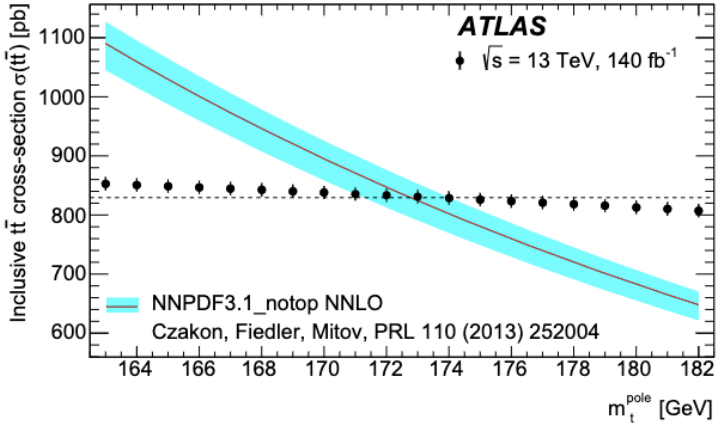
Measuring the heaviest particle mass

2403.01313
JHEP 2205.13830
JHEP 06 (2023) 019

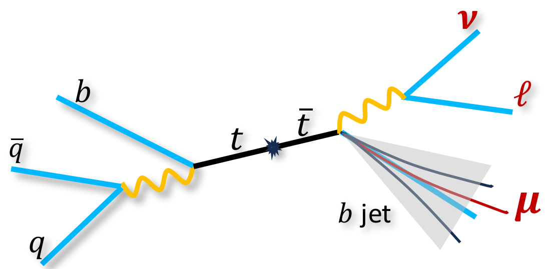
- **Significant improvements over the past years:** Better calibrations, alternative techniques, improved theoretical modelling
  → More than 40 publications by CMS and ATLAS collaborations



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



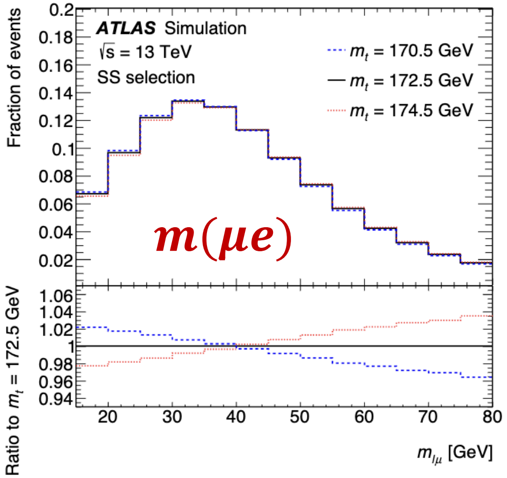
- **Direct measurements** from top quark decays
  → better precision
  → Mass from Boosted top-jet: Future prospects in precision & theoretical interpretability
  → Alternative measurements: sensitive to different systematics



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

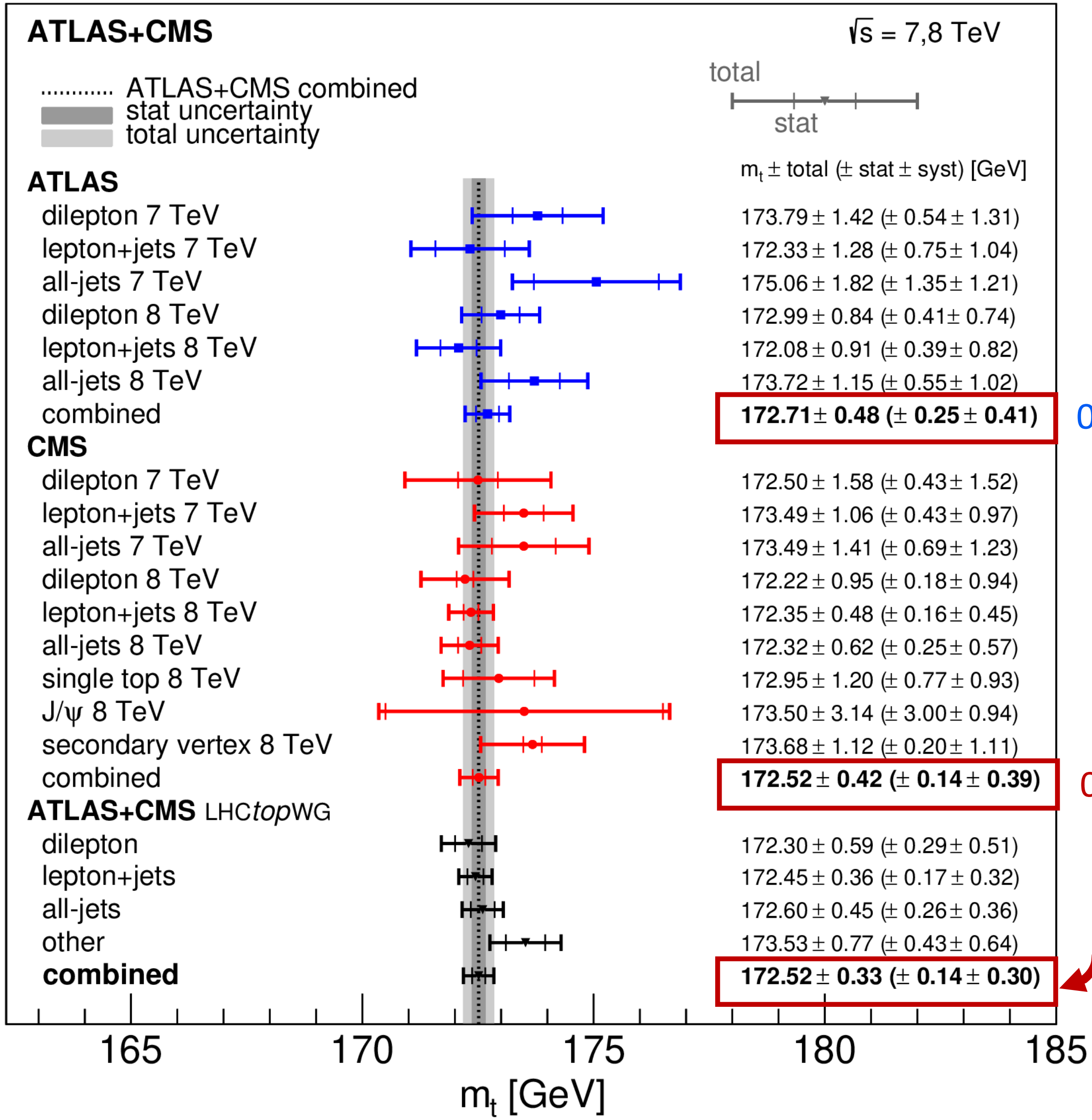
m_{top} = 174.41 ± 0.39 (stat.) ± $\underbrace{0.66 \text{ (syst.)} \pm 0.25 \text{ (recoil)}}$ GeV

sensitive to fragmentation effects



Top quark mass: Run I combination

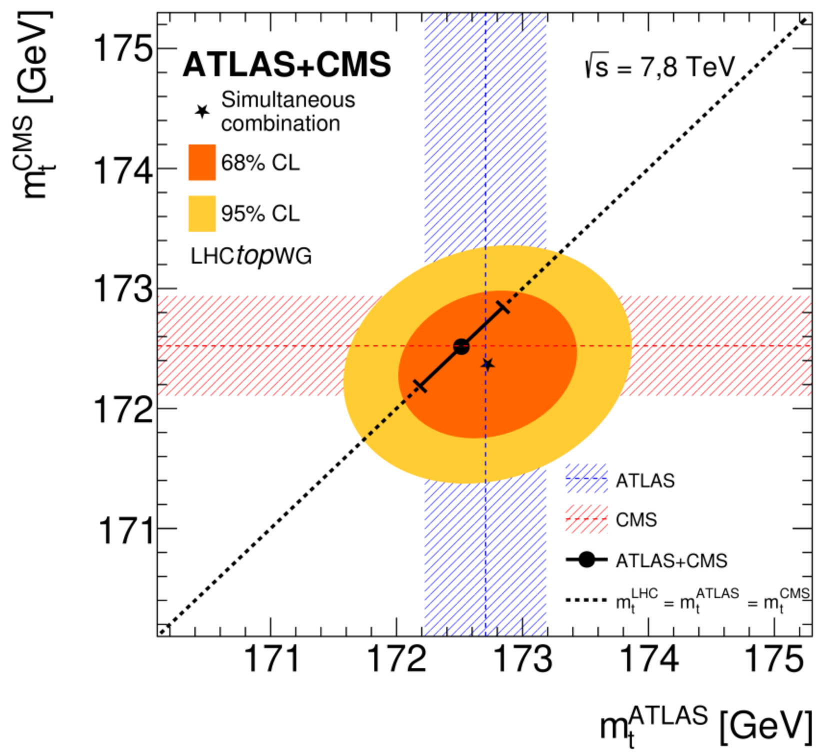
PRL 132, 261902



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

0.28% precision

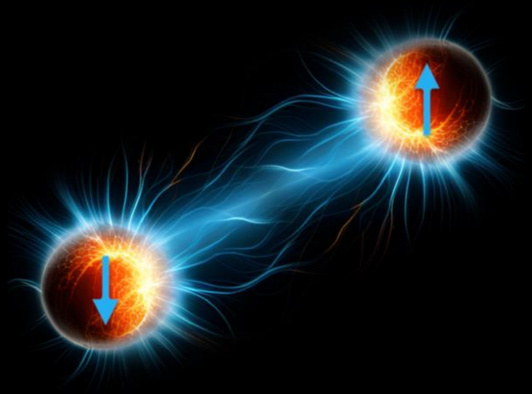
0.24% precision



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

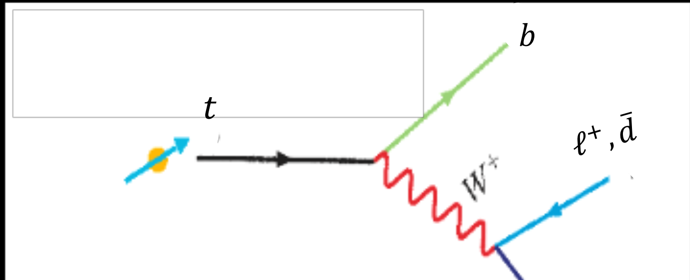
< 0.2% precision → Limited by b-jet energy calibrations

Top quark polarization and spin correlation



- Top-pairs @LHC are mainly unpolarized (parity invariance of QCD)
- Their spins are strongly correlated

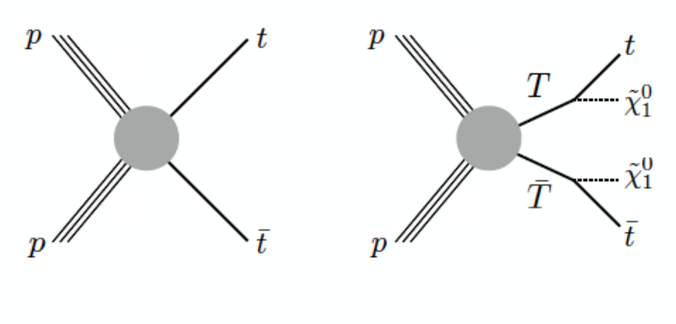
lifetime	<	QCD timescale	≪	Spin-flip timescale
10^{-25}s	<	10^{-24}s	≪	10^{-21}s



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\varphi} = \frac{1+\alpha\cos\varphi}{2}$$

- Spin information is passed onto $\ell^{\pm}$ *and* d-quark
  → preferentially radiated in the top spin direction

- Many NP models modify spin polarization and correlation of top quarks
  - New mediator ?
  - New particles decaying to tops ?



…but also interesting for testing the foundations of Quantum physics

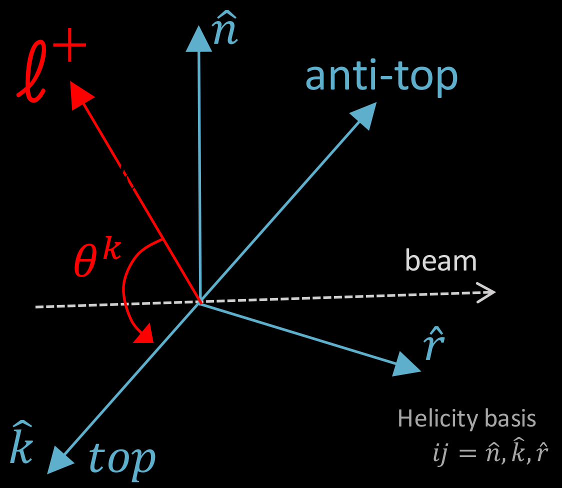
Top quark polarization and spin correlation

PRD 100 (2019) 072002

$t\bar{t}$ production cross section parametrized vs polarization & spin correlation coefficients

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

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



6 polarization and 9 spin correlation coefficients can be extracted from differential measurements

$\hat{k}$: top-quark direction in $t\bar{t}$ CMF ("helicity")

$\hat{n}$ = normal to $t\bar{t}$ scattering plane ("transverse")

$\hat{r}$ = normal to $\hat{k}$ in $t\bar{t}$ scattering plane

Top quark polarization and spin correlation

PRD 100 (2019) 072002

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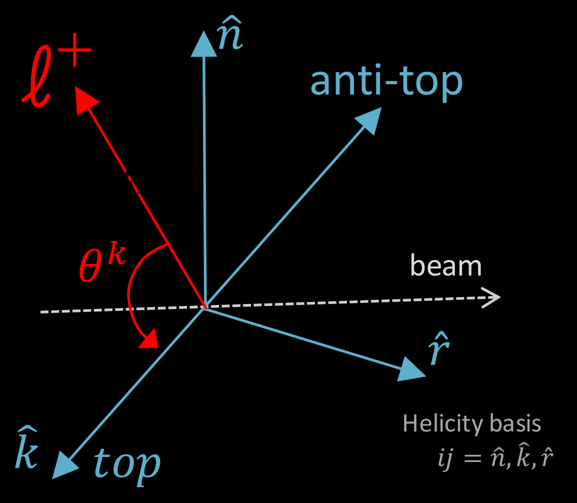

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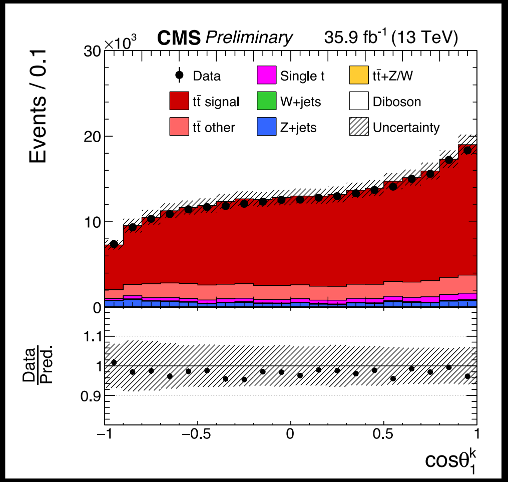
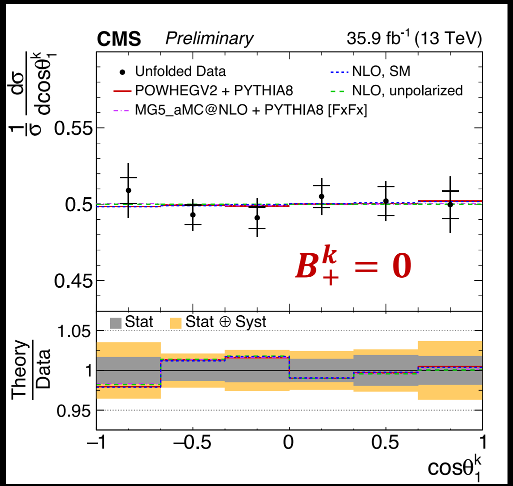
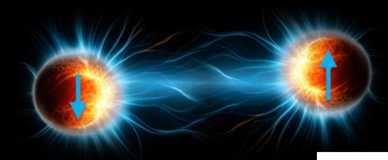
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+^k} = \frac{1}{2}\left(1 + \boldsymbol{B_+^k}\cos\theta_+^k\right)$$



Unfolded to parton level





Published in Nature
arXiv:2311.07288

Accepted by *Rep. on Prog. in Phys.*
arXiv:2406.03976

Accepted by Phys. Rev. D
arXiv:2409.11067

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.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS

CMS-TOP-23-001

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

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.

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 L
Hadron Collider

TOPICS: CERN Large Hadron Collider Particle Physics Quantum Mechanics

By CMS COLLABORATION JUNE 17, 2024

NewScientist

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

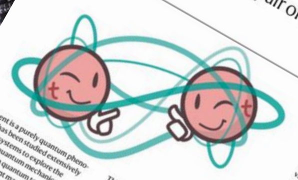
Physicists confirm quantum entanglement persists between top quarks, the heaviest known fundamental particles

by David Andreatta, University of Rochester

nature reviews physics

Editors' picks 2023

Entanglement between a pair of top quarks



symmetry

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

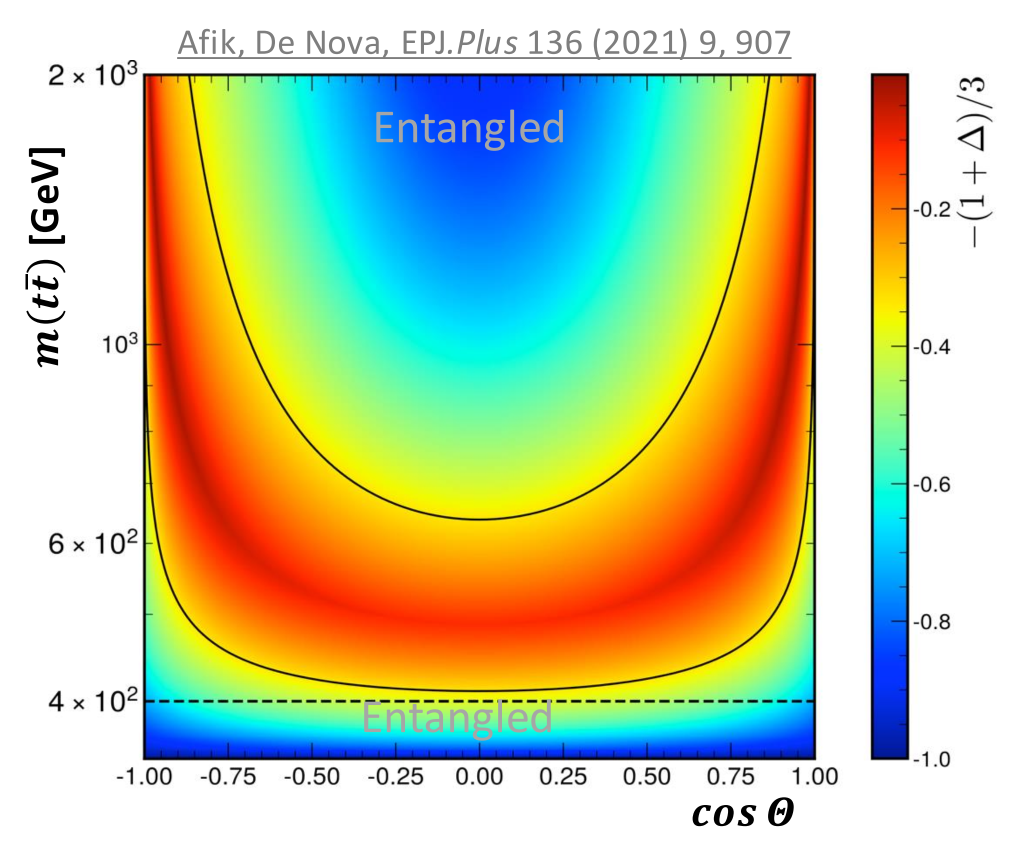
A report from the ATLAS experiment.

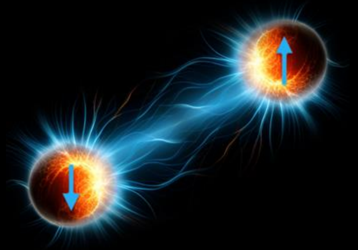
Yes, the Most Massive Particle Shows Some 'Spooky Action At a Distance'

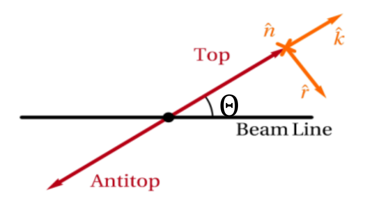
The top quark also experiences quantum entanglement, according to new discoveries by CERN.

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

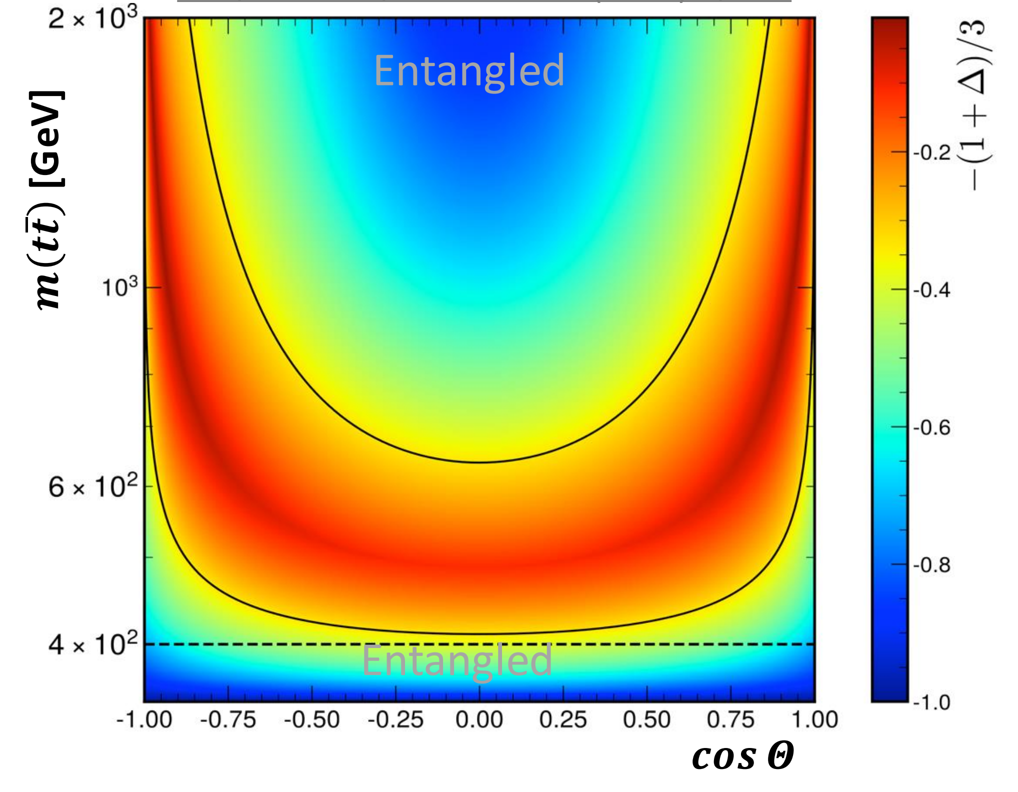
$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

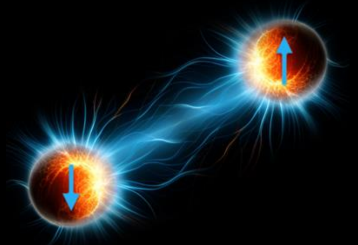
$$C = \begin{pmatrix} \times & & \\ & \times & \\ & & \times \end{pmatrix}$$

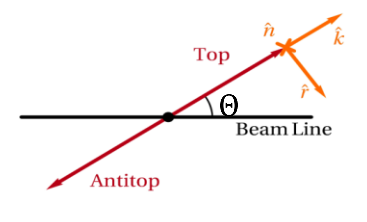
Entanglement in $t\bar{t}$

- Spin correlation is $m(t\bar{t})$ and $\cos\Theta$ dependent
  → Entanglement in some phase-space regions

Afik, De Nova, EPJ.*Plus* 136 (2021) 9, 907







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- Peres–Horodecki criterion for entanglement

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

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

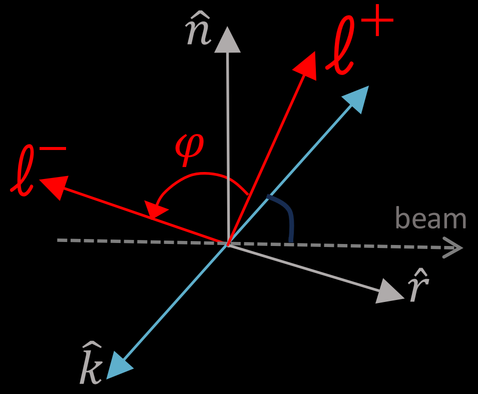
High m($t\bar{t}$): $\widetilde{D} = \frac{\Delta_E}{3} > \frac{1}{3}$

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

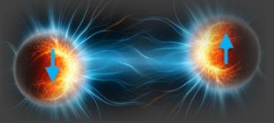
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi)$$

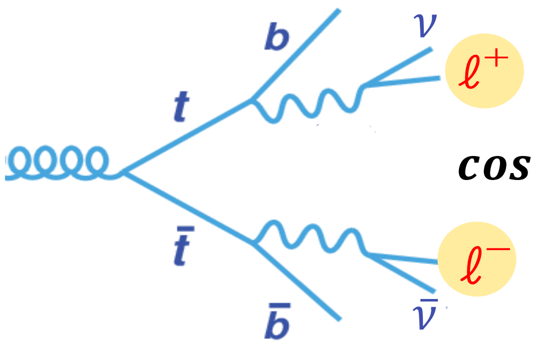
$\cos\varphi = \hat{\ell}^{+} \cdot \hat{\ell}^{-}$

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



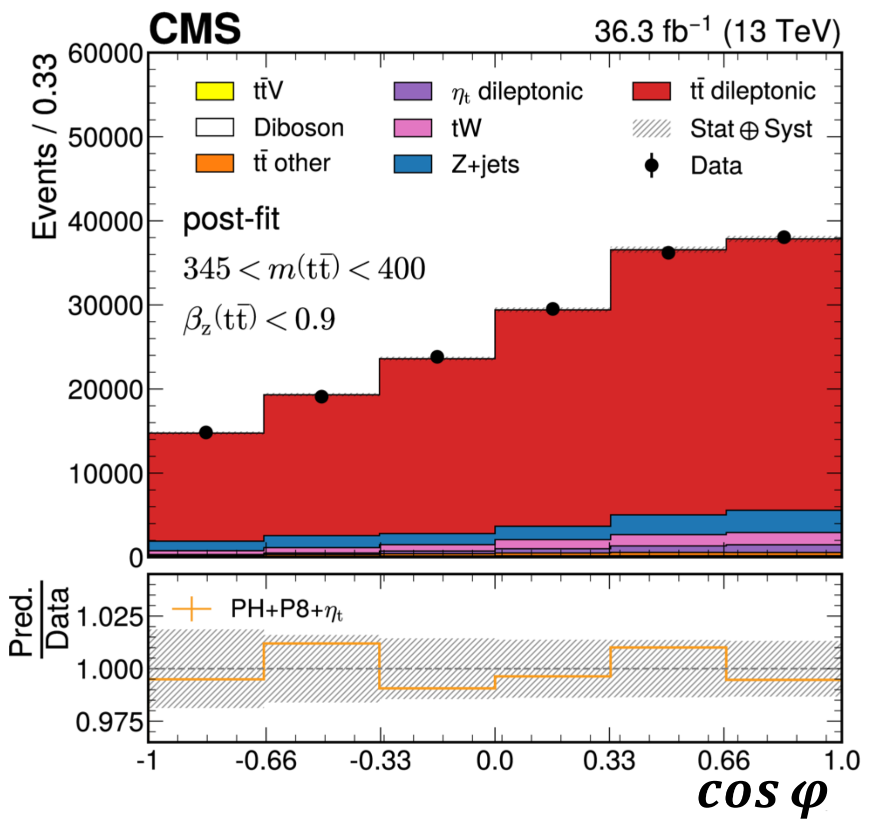
Entanglement in $t\bar{t}$ (dilepton channel)

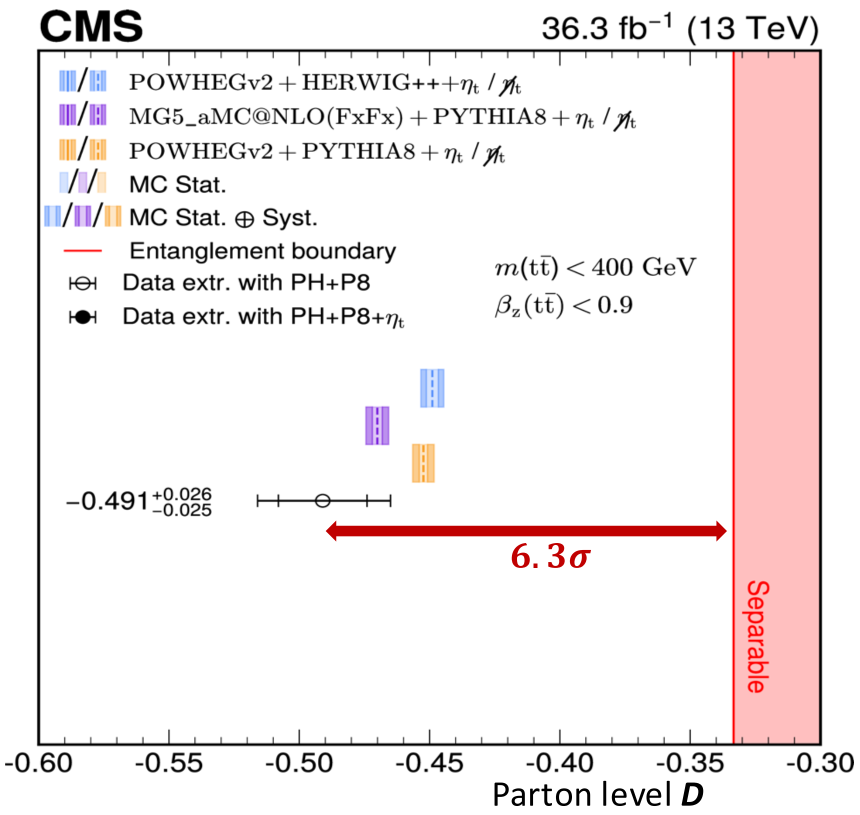




$$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$

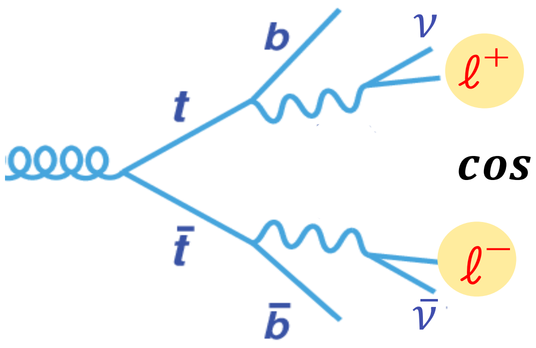
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi)$$



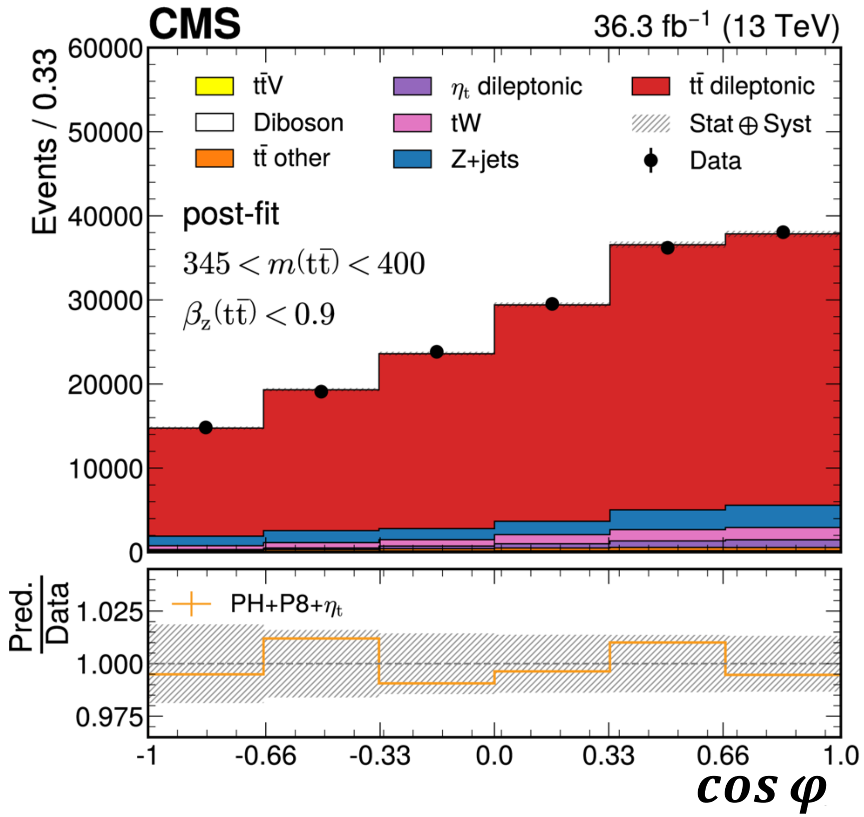


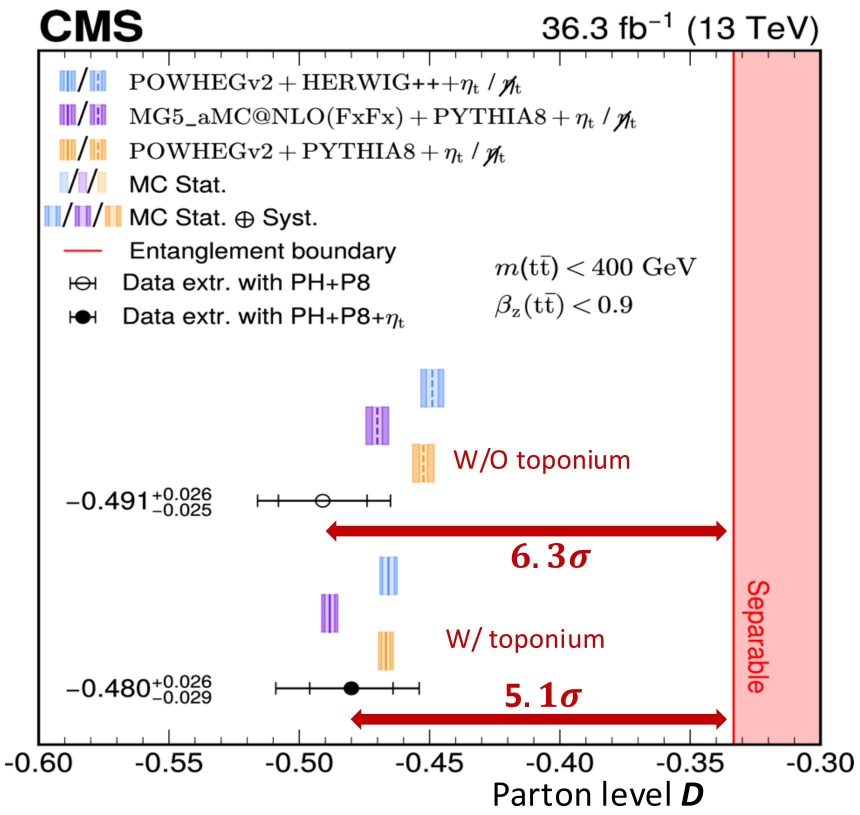
Entanglement in $t\bar{t}$ is observed with >5σ at low m_{tt}

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



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





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

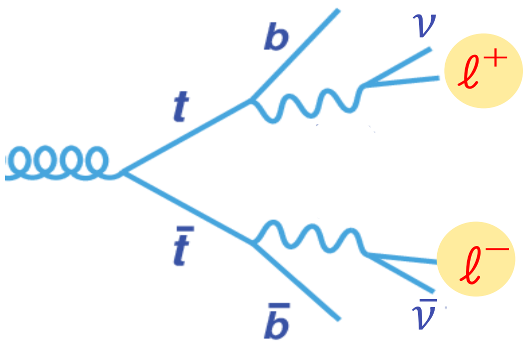
- Pseudoscalar & maximally entangled
- $m(\eta_t) = 343\ GeV$
- $\sigma(pp \to \eta_t) = 6.43 \pm 0.90$ pb

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

Main uncertainties(CMS):

- η_t normalization
- Jet energy calibrations
- Top p_T , PS modeling

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

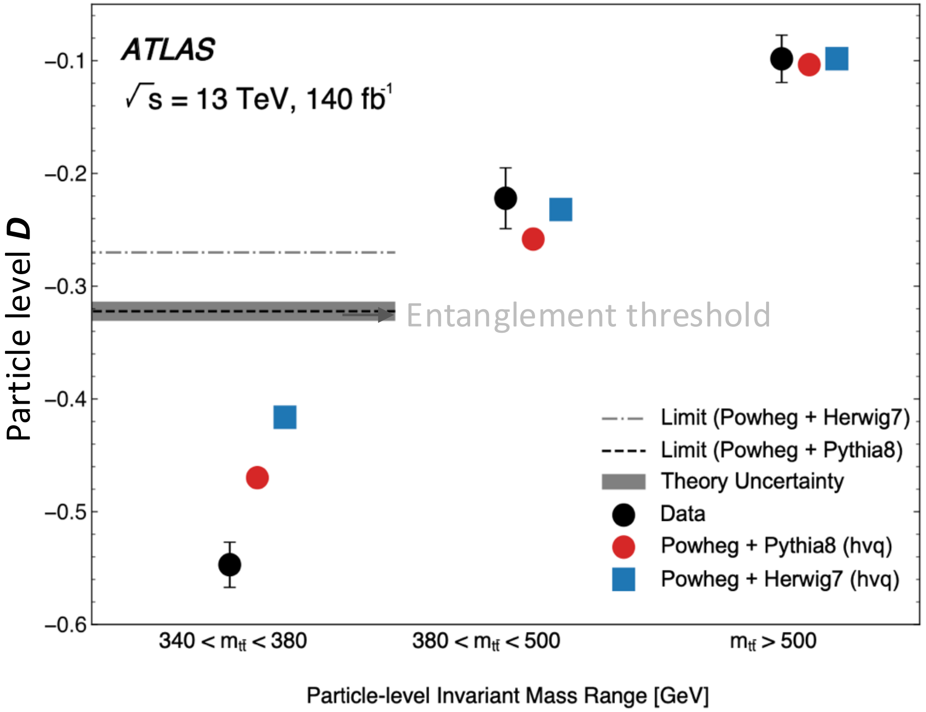


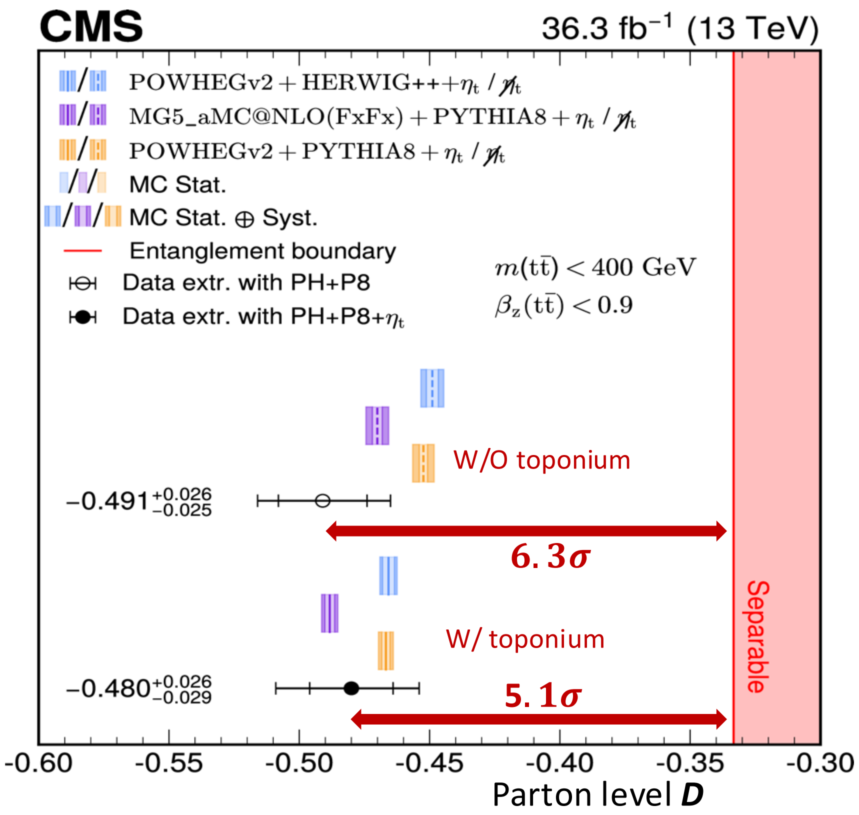
$$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$

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

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

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





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

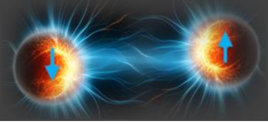
Main uncertainties (ATLAS):

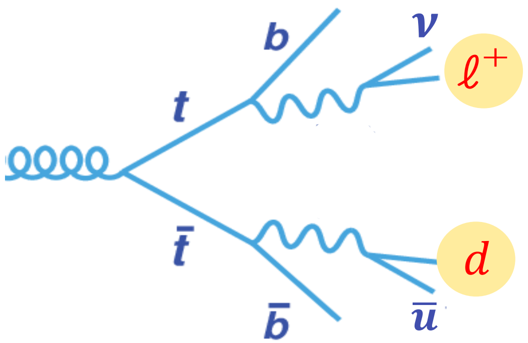
- Modeling of $t\bar{t}$ production and decay
- Background modeling
- Experimental (b-jet tagging, JES…)

Main uncertainties(CMS):

- η_t normalization
- Jet energy calibrations
- Top p_T , PS modeling

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



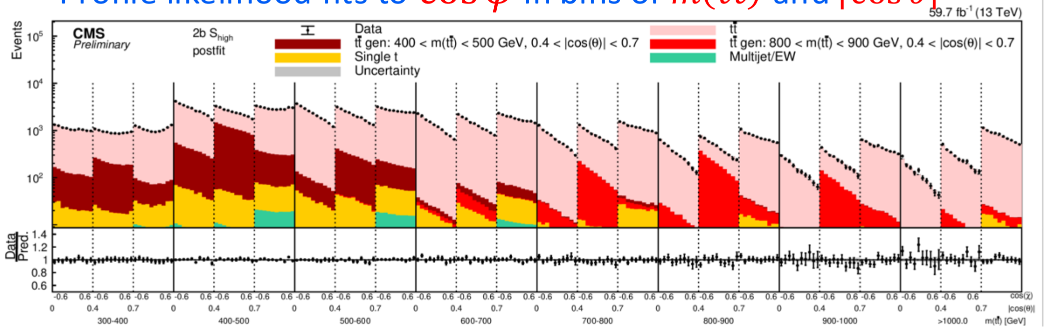


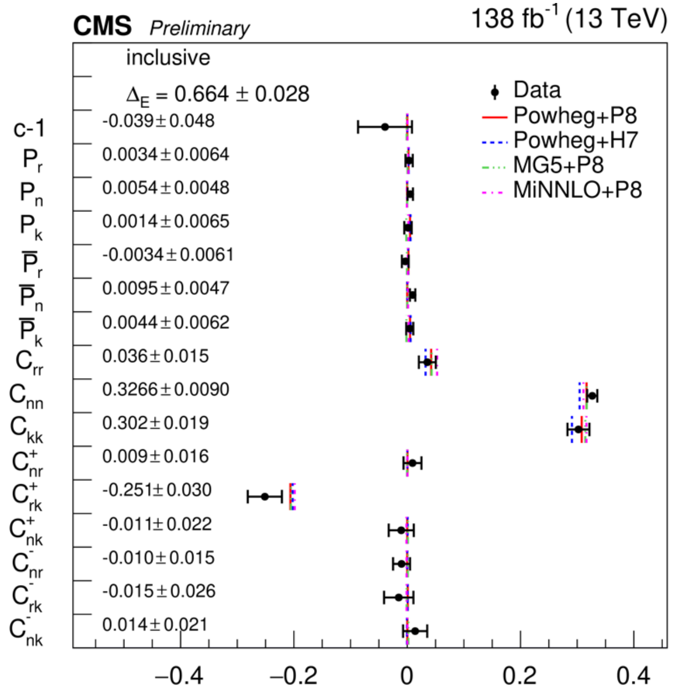
- Better sensitivity at **high $m_{t\bar{t}}$**
- Spin information via ℓ/d-quark

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

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

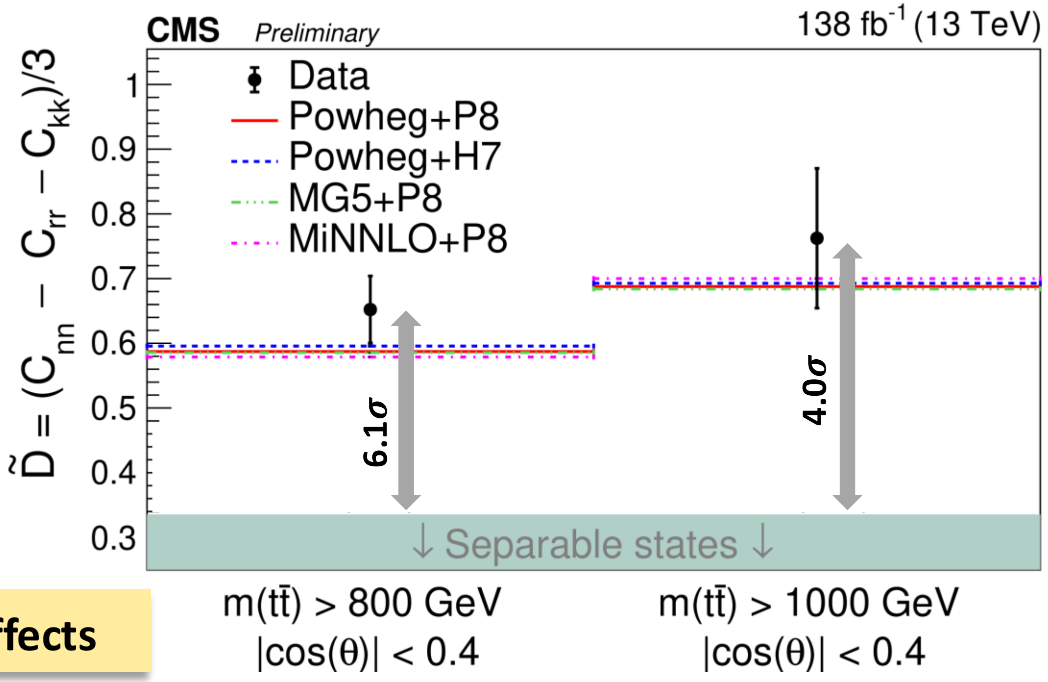
Profile likelihood fits to $\cos\varphi$ in bins of $m(t\bar{t})$ and $|\cos\theta|$





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

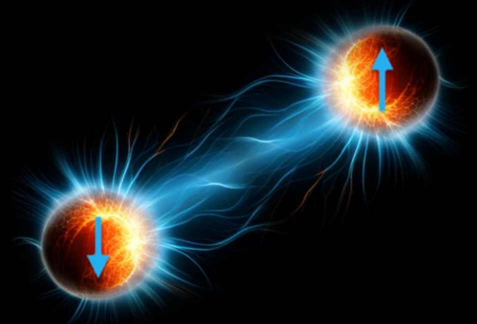
Demina, et al. 2407.15223



A new window to look for new physics effects

Severi, et al 2210.09330

Summary



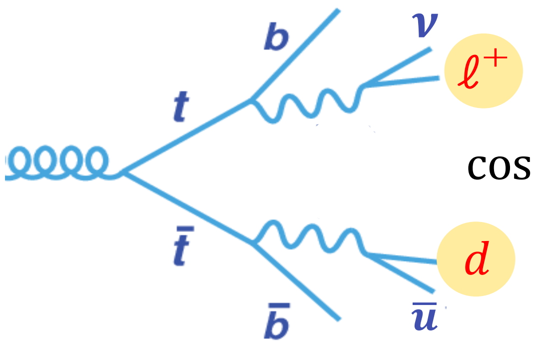
- Top quark physics is living its golden age
- Excellent precision in many areas
- Combined ATLAS-CMS results prove to be powerful
- Observed quantum entanglement in top quark pairs

  → Multiple analyses in different phase-space regions!

  → Led to observation of a quasi-bound tt state

- More exciting results to come with Run3 data

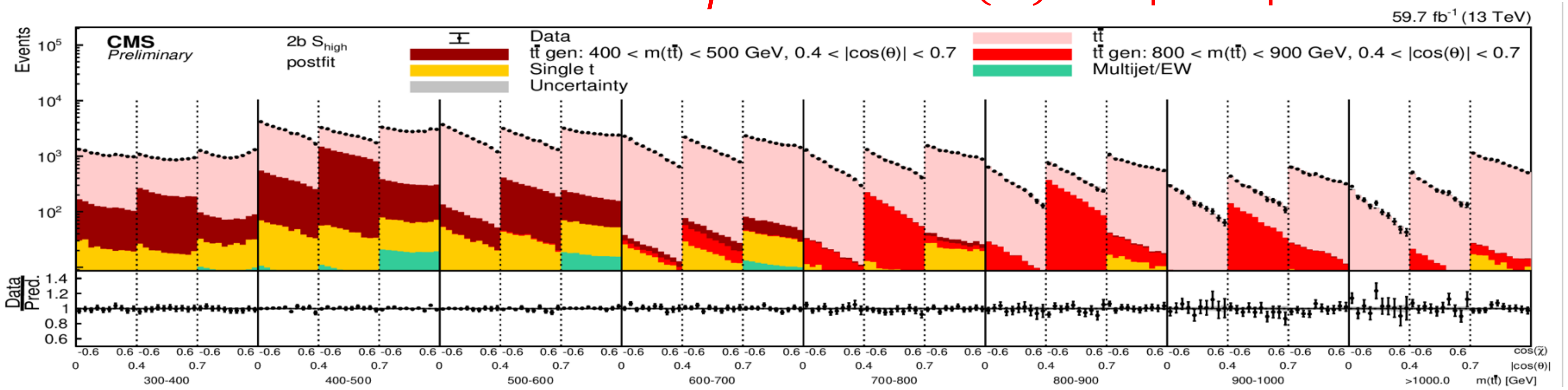
Entanglement in $t\bar{t}$ ($\ell + jets$ channel)



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

- e/μ + 4 jets, ≥1 bjets → better sensitivity at **high $m_{t\bar{t}}$**
- Spin information via ℓ/d-quark
- NN for assignment of top decay products (**up to 65% correct assignment**)

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

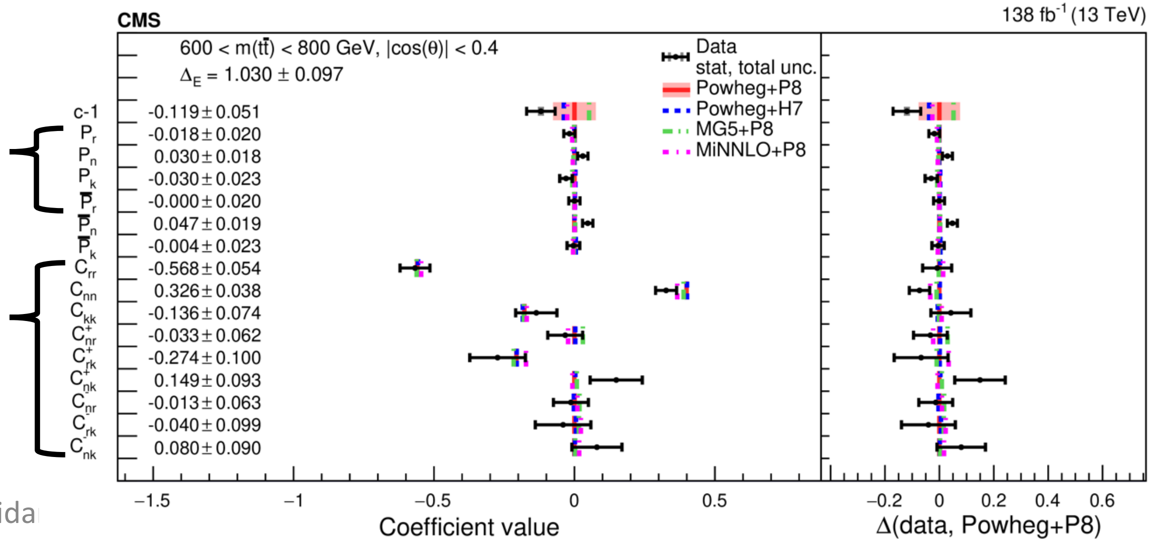


Low $m(t\bar{t})$ **High $m(t\bar{t})$**

- Extract the coefficients for polarisation vectors ($\boldsymbol{B}^{i}_{\pm}$), spin correlation matrix ($\boldsymbol{C_{ij}}$) as well as **D** and $\widetilde{\boldsymbol{D}}$
- Inclusive and in various kinematic phase-space

$$B_{\pm} = \begin{pmatrix} x \\ x \\ x \end{pmatrix}$$

$$C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

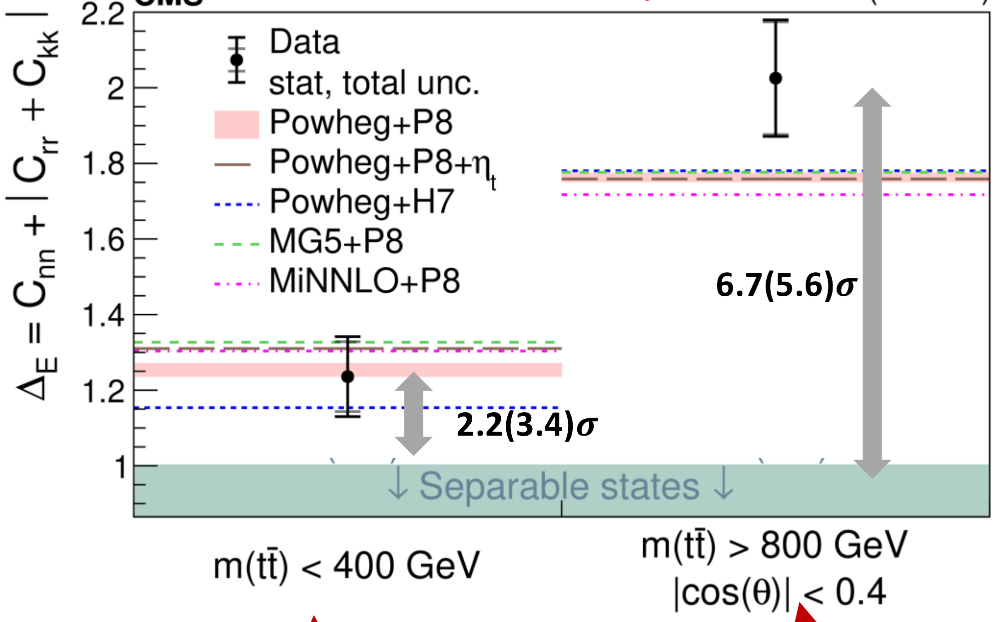


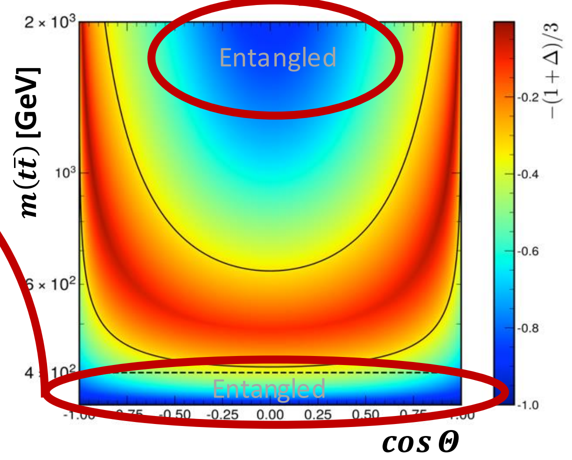
Dida

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

- Entanglement is established at **high m($t\bar{t}$) for the first time with >5σ**
- Complementarity wrt. dilepton channel

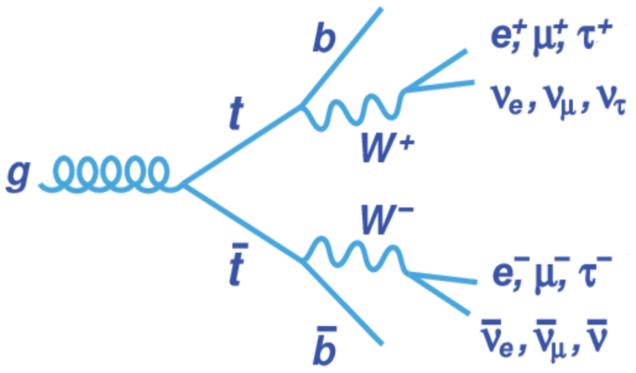
Extraction from C_{ij}





Lepton Flavor Universality in top decays

2403.02133
PRD 105(2022) 072008



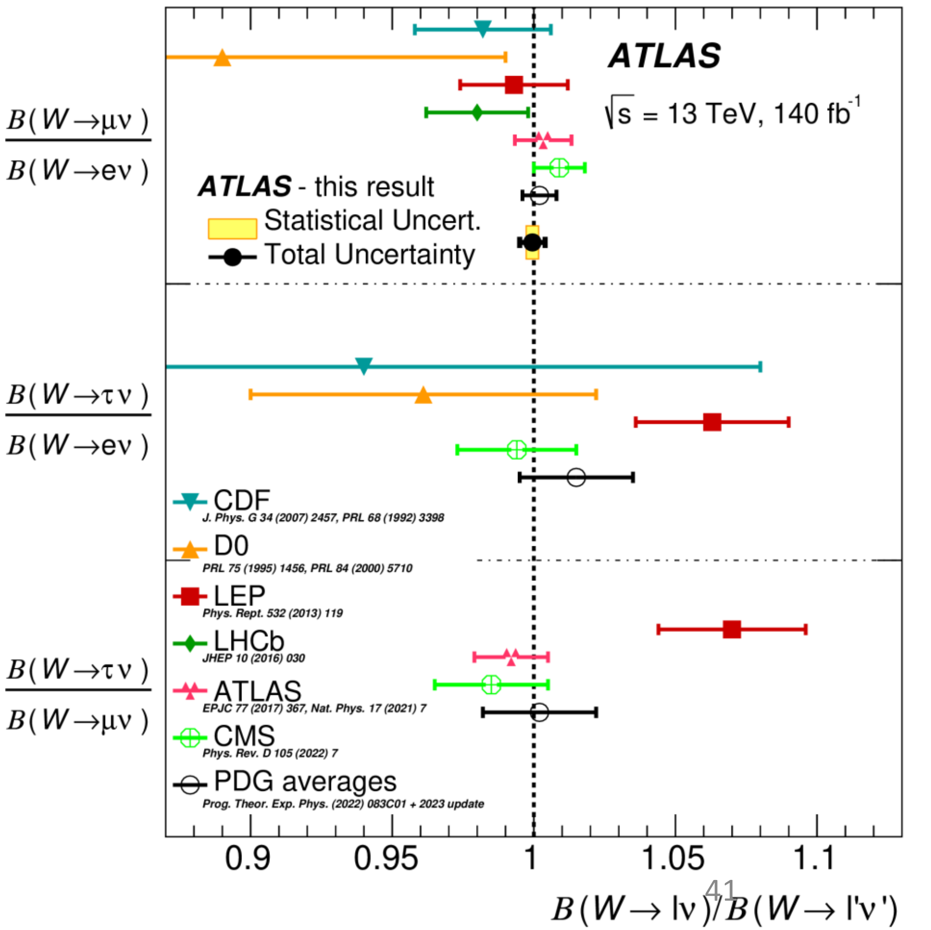
- Large and pure $t\bar{t}$ sample to measure $\mathcal{B}(W \to \ell\nu)$ and test LFU
- Simultaneous $t\bar{t}$ cross-section in $ee, \mu\mu, e\mu$
- ML fit to event categories with 10 parameters
- $R_W^{\mu/e}$: many uncertainties cancel
- In situ lepton/bjet efficiency calibrations

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

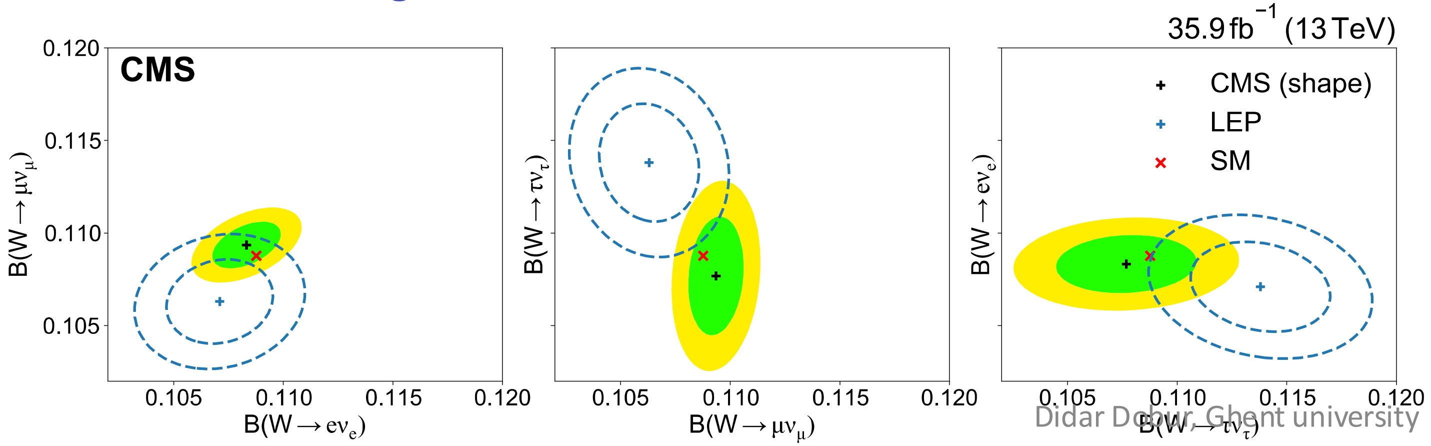
From LEP2/SLD

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

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

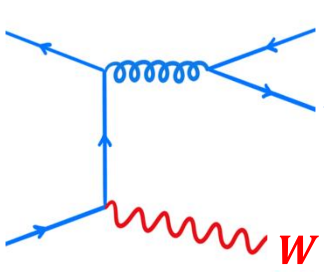


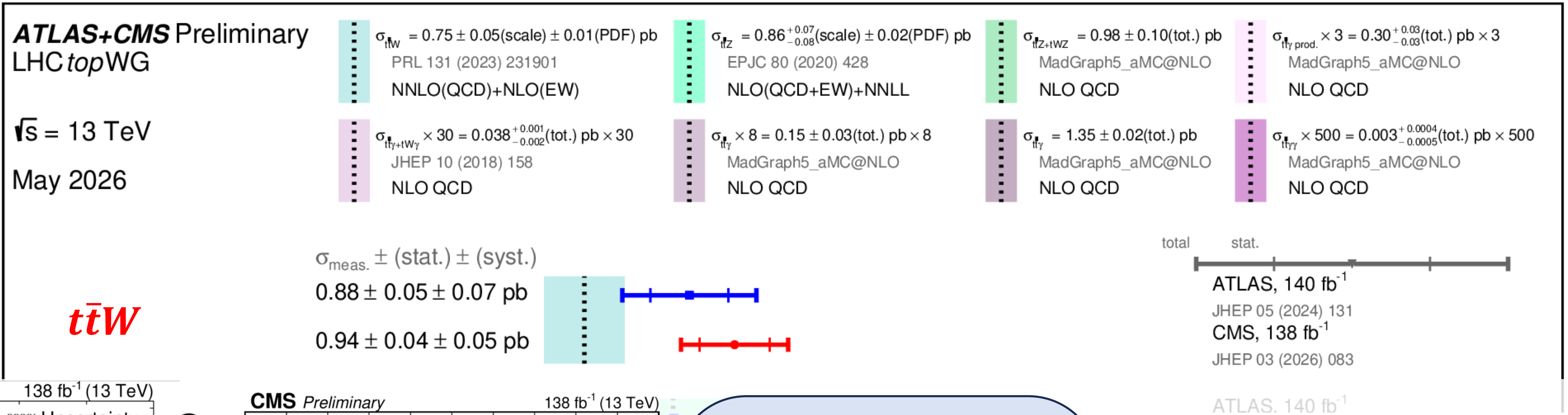
Precise W branching fraction measurements, consistent with SM

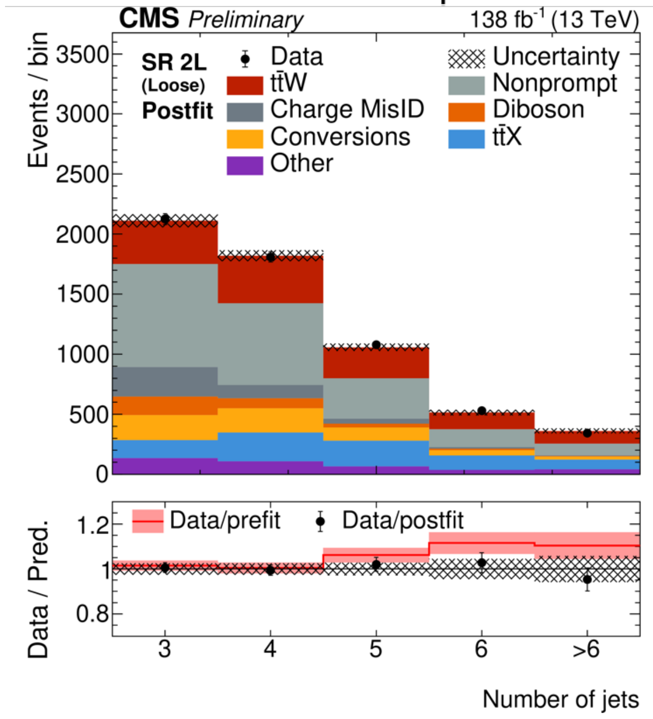


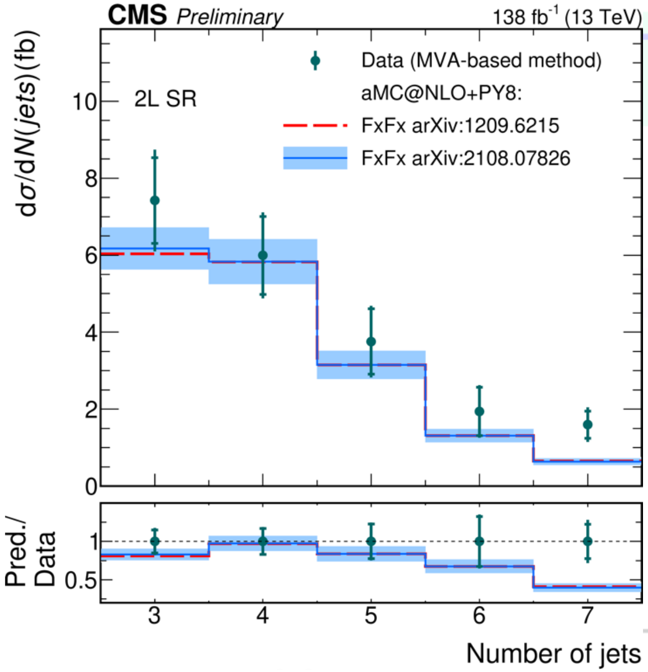
Associated top quark production ($t\bar{t}$+V)

First observation at the LHC





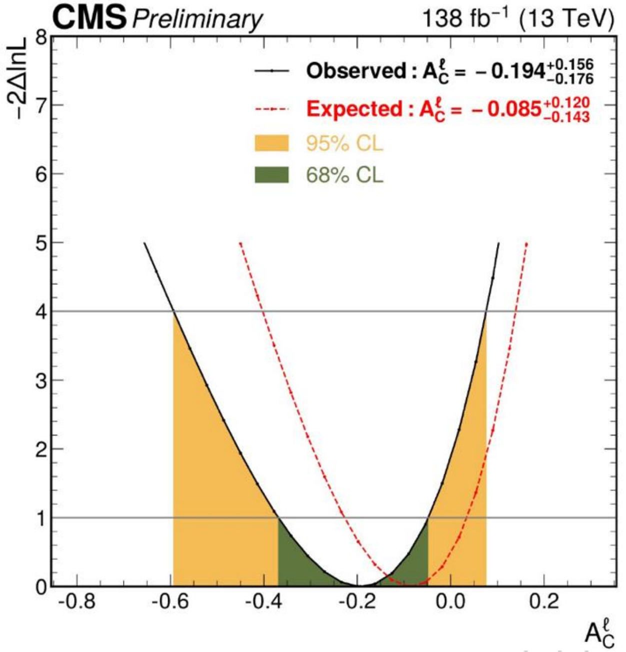




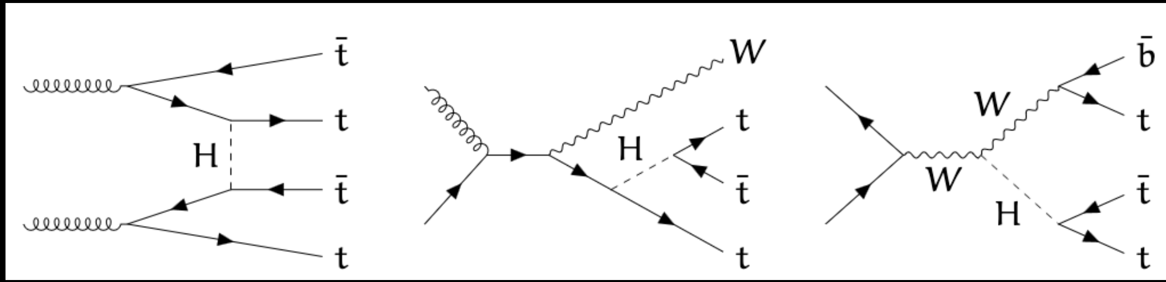
- $t\bar{t}$ charge assymetry in ttW events
- 3-lepton channel
- DNN to assign leptont to top-quark

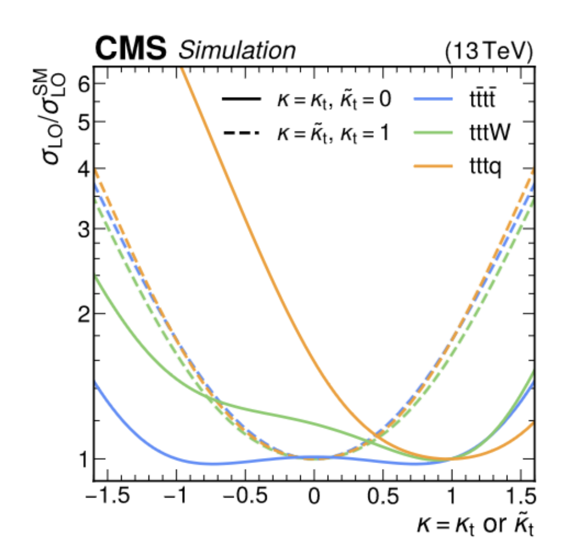
$$A_c^{\ell} = \frac{N(\Delta y_{\ell} > 0) - N(\Delta y_{\ell} < 0)}{N(\Delta y_{\ell} > 0) + N(\Delta y_{\ell} < 0)}$$

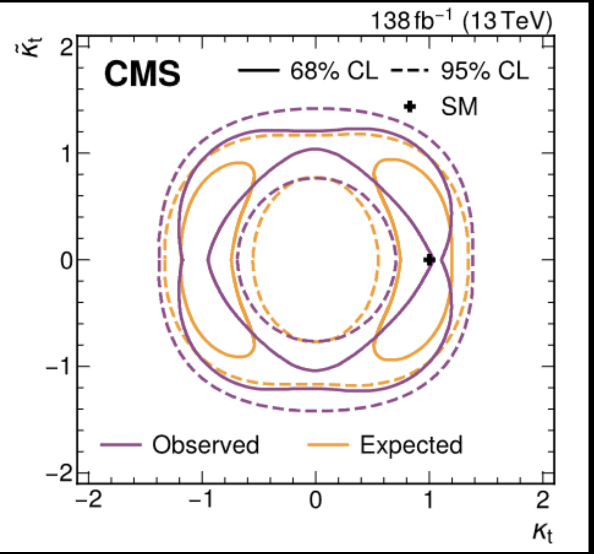
- Results are consistent with SM

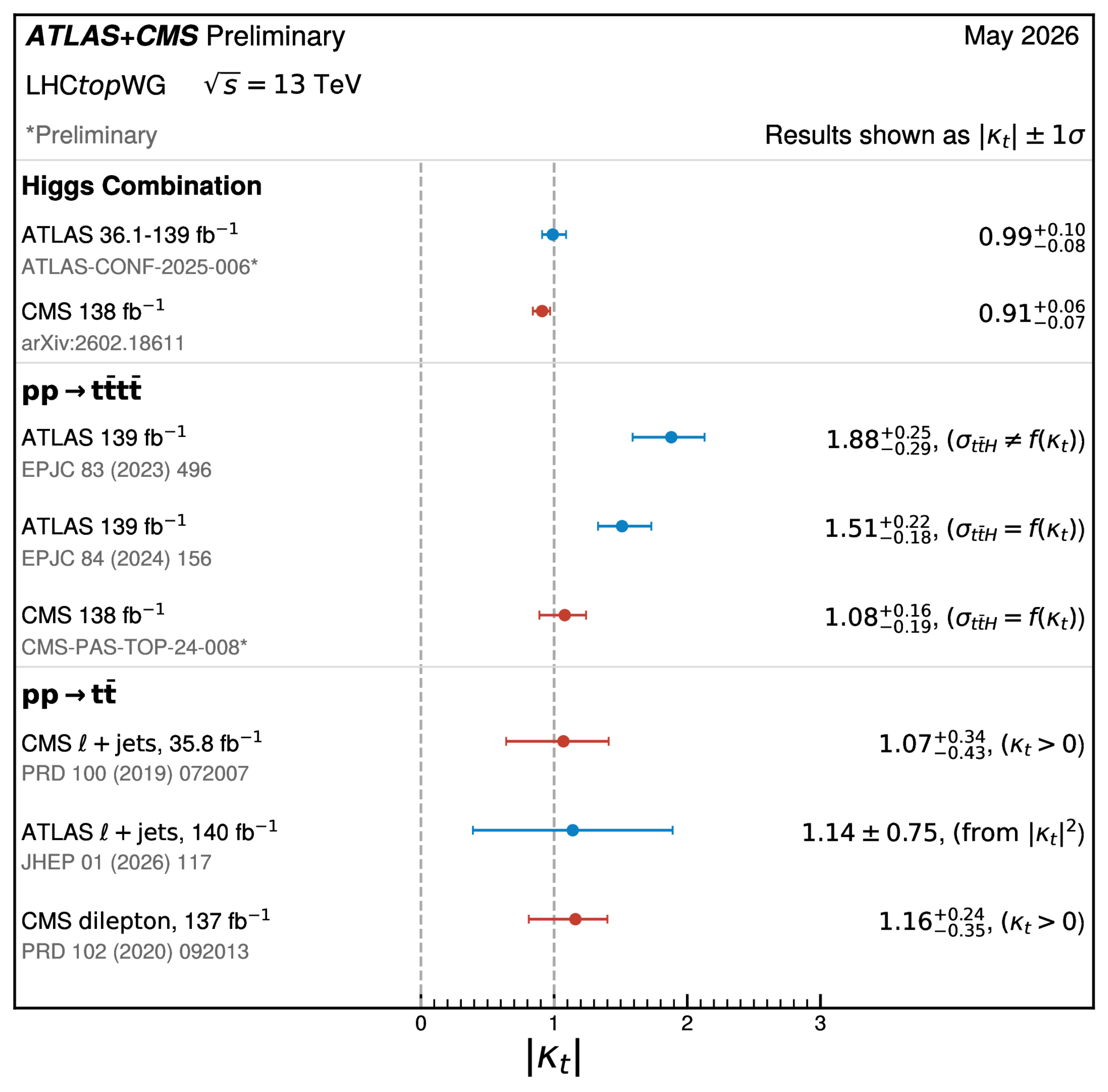


Interpretation of 4 top quark measurements





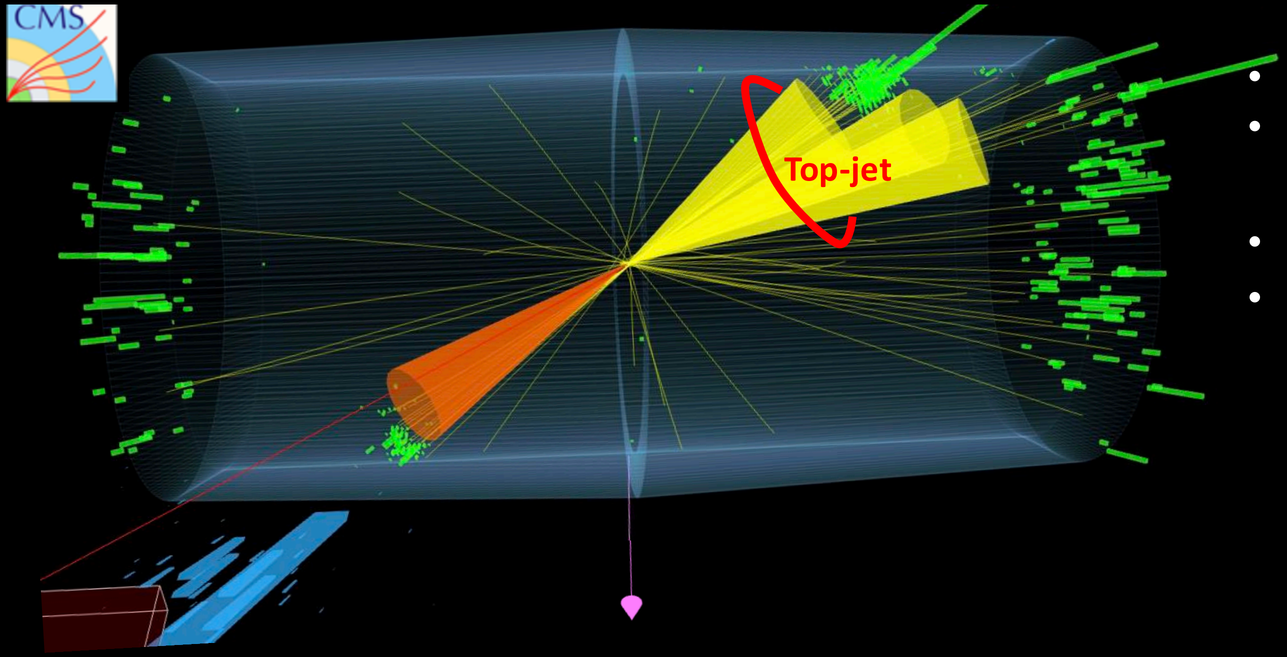




Mass from boosted Top-jet

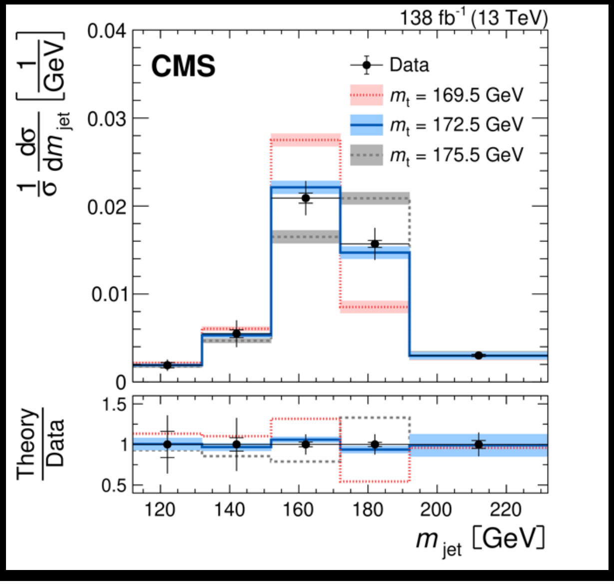
EPJC 83 (2023) 560

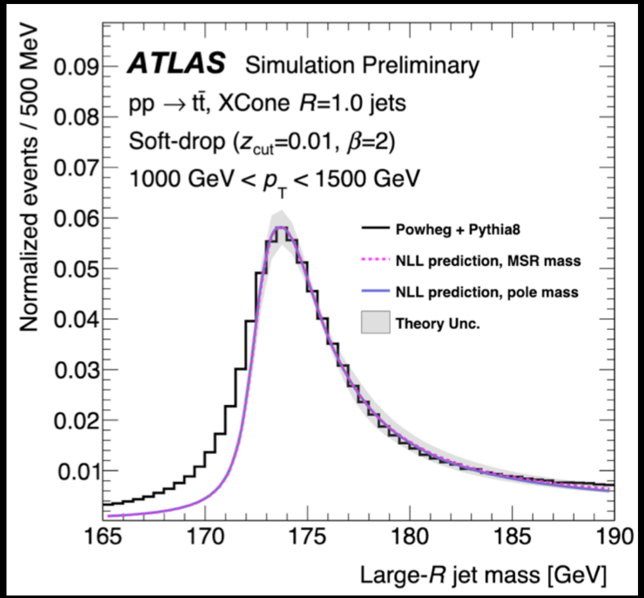
ATL-PHYS-PUB-2021-034



- $\ell + jets$ 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:

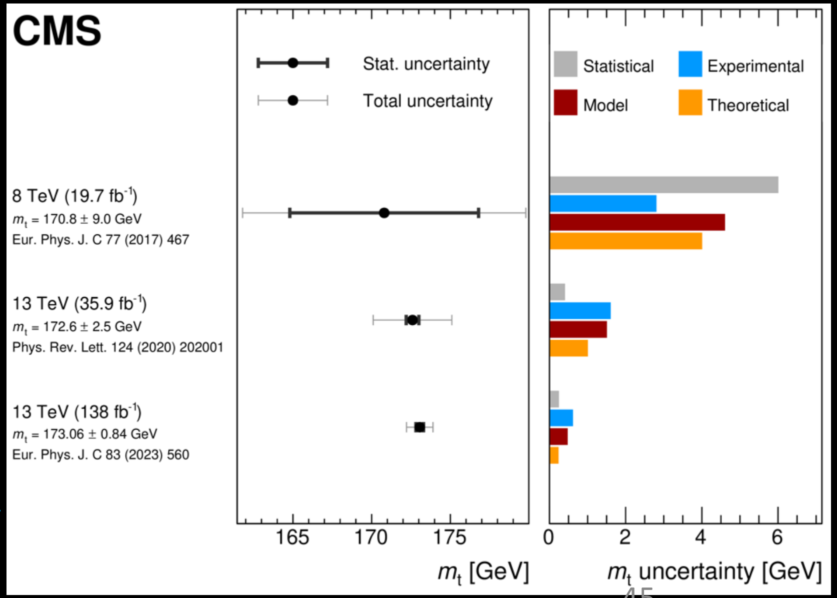
$$m_{Top}^{MC} - m_{Top}^{MSR} = 80^{+350}_{-410}\ \text{MeV}$$

- Scale variation
- Fit range, UE

9 GeV

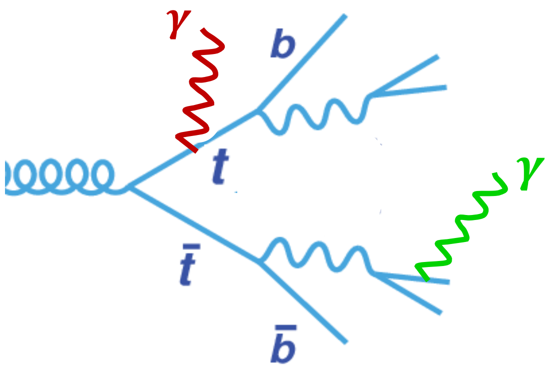
Significant improvement

0.84 GeV



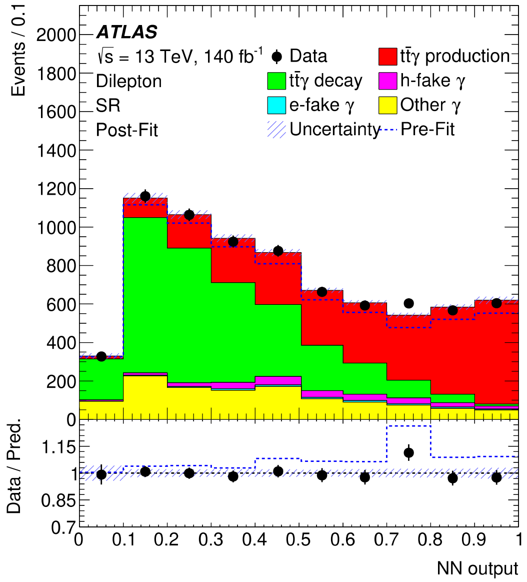
Associated top quark production ($t\bar{t}\gamma$)

2403.09452

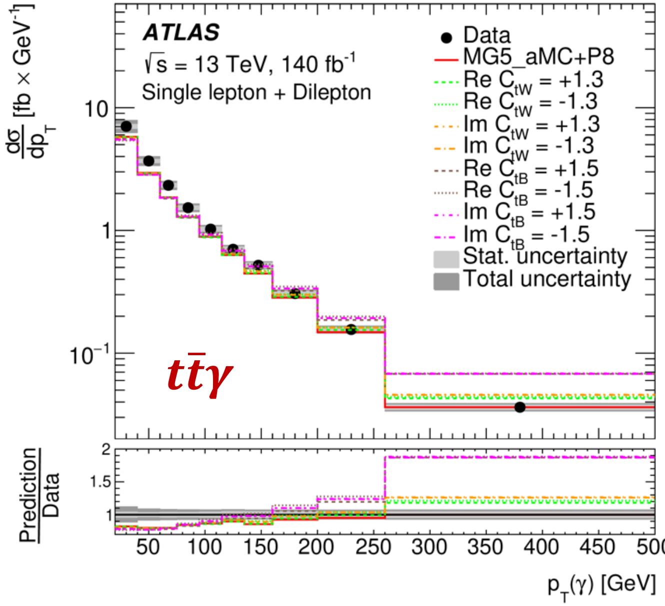


- $\boldsymbol{t\bar{t}\gamma}$ at production/ $\boldsymbol{t\bar{t}\gamma}$ at decay
- NN to separate two processes
  - →Increased sensitivity to $\boldsymbol{t}$-$\boldsymbol{\gamma}$ coupling

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



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



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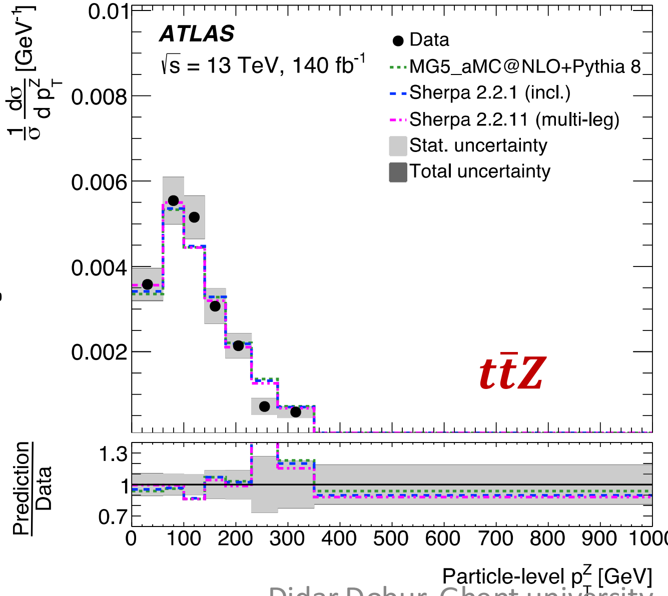
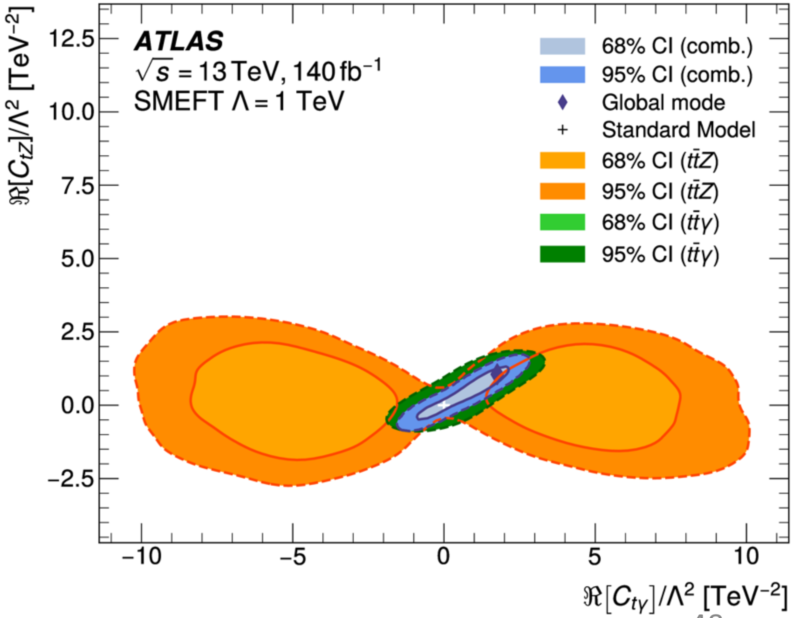
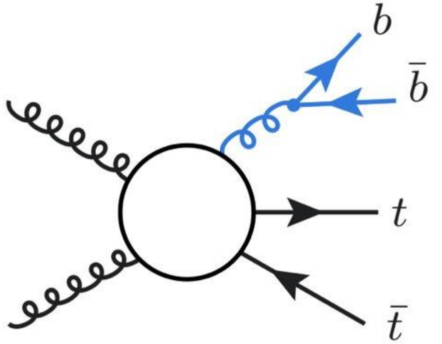


→

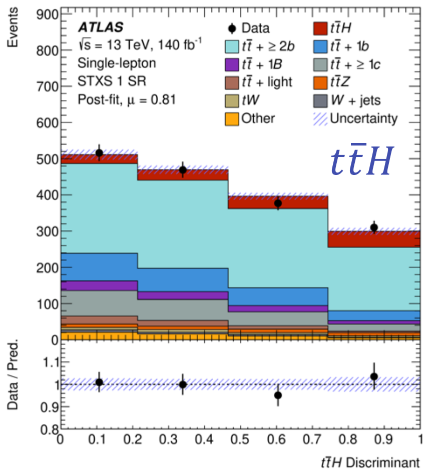


Measurements of $t\bar{t} + b\bar{b}$

2407.13473 2407.10904
JHEP 05 (2024) 042



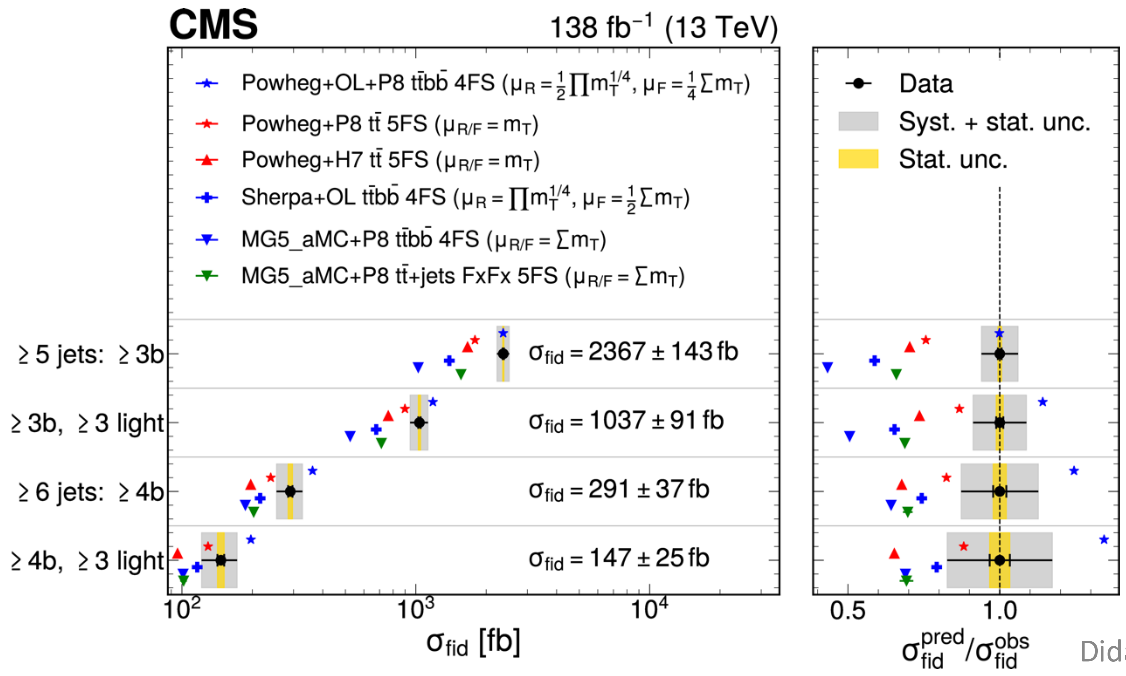
- Sensitive to EFT operators
- Irreducible background for $t\bar{t}H$, $H \to b\bar{b}/c\bar{c}$, multi-top
- Difficult to simulate accurately



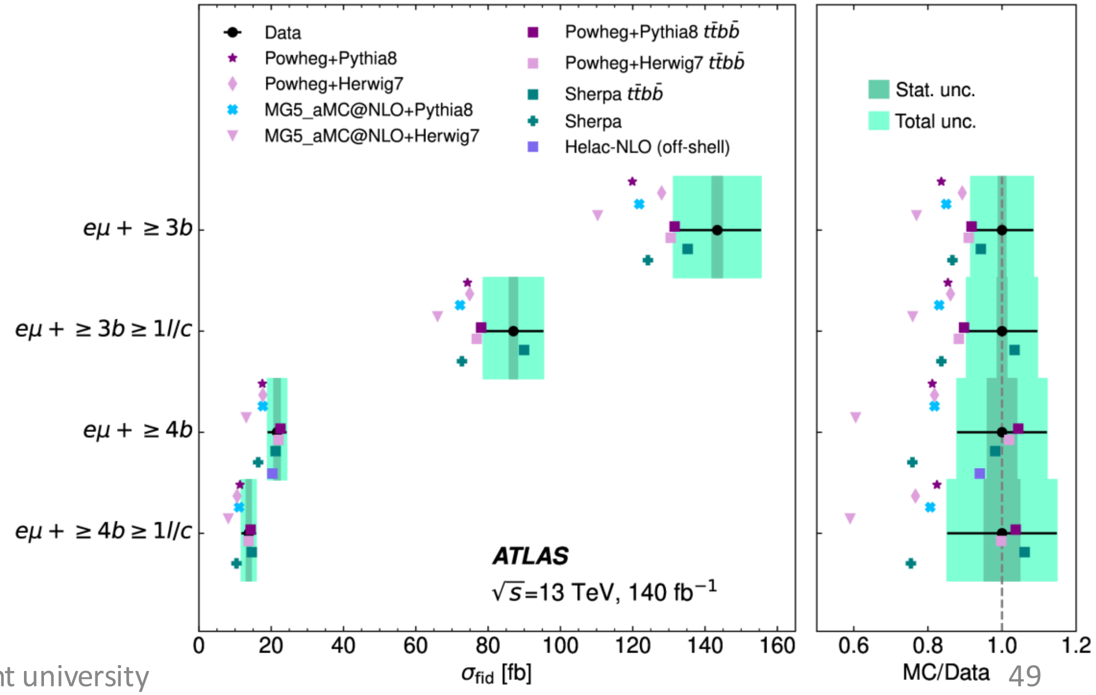
Extensive differential measurements:

→ 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



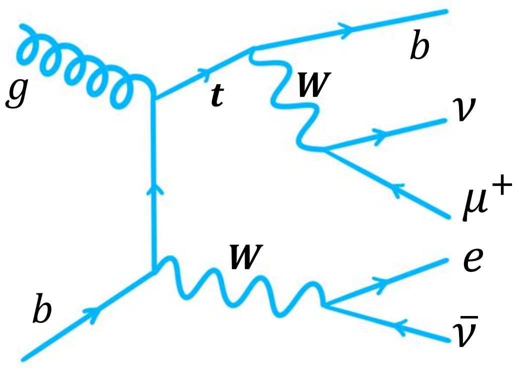
$e\mu$ channel



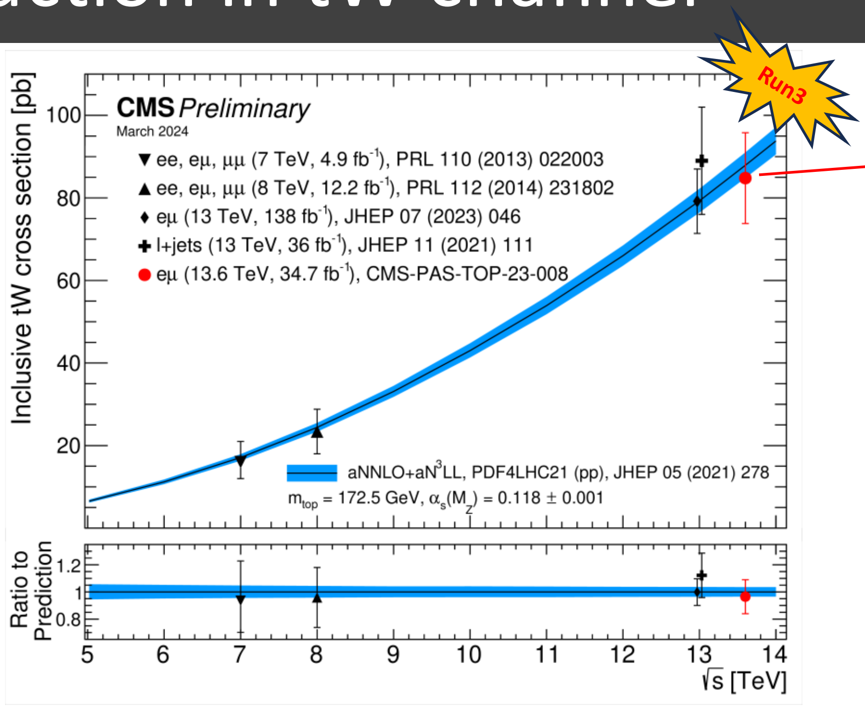
Single-top production in tW channel

CMS-TOP-23-008

2407.15594



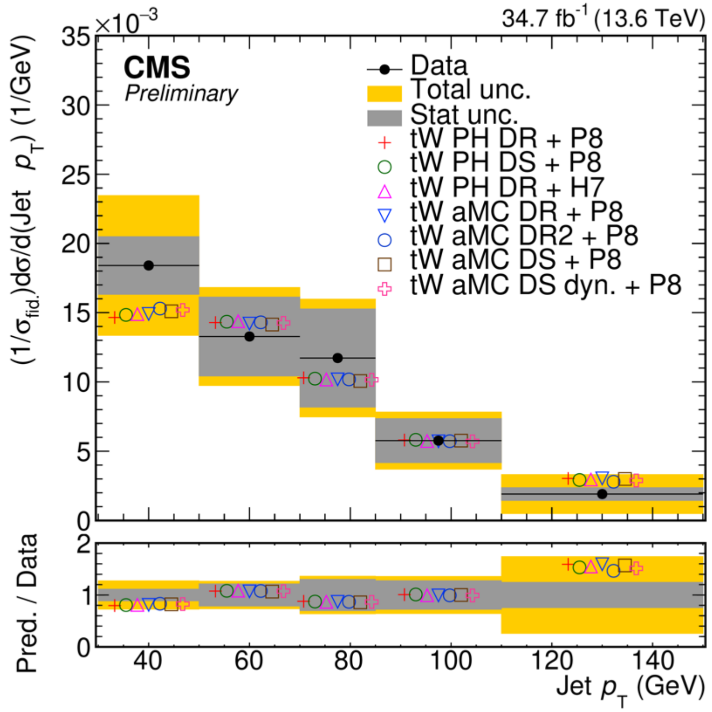
- Sensitivity to V_{tb} and b-PDF
- Large $t\bar{t}$ background
- tW @NLO interferes with $t\bar{t}$
- ML algorithms to separate tW from $t\bar{t}$



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

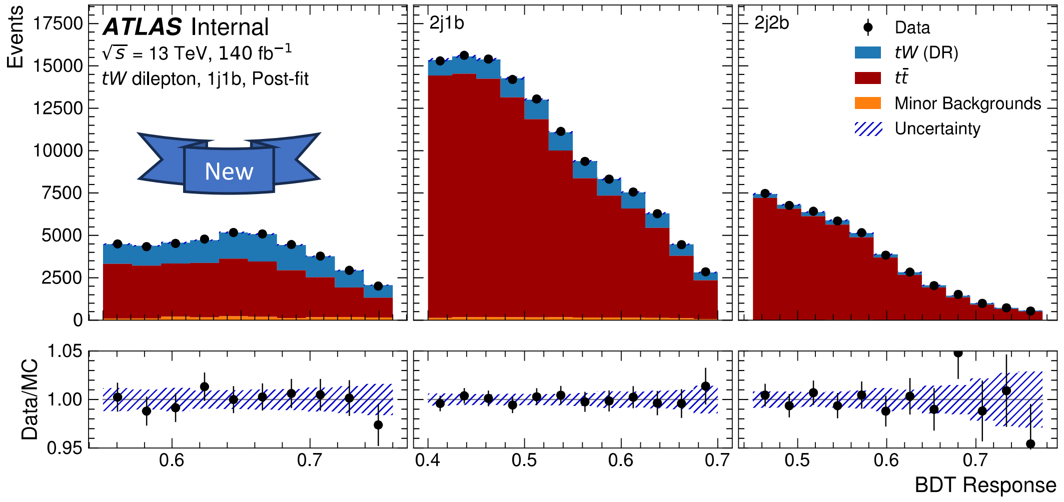
~13% precision

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}:

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

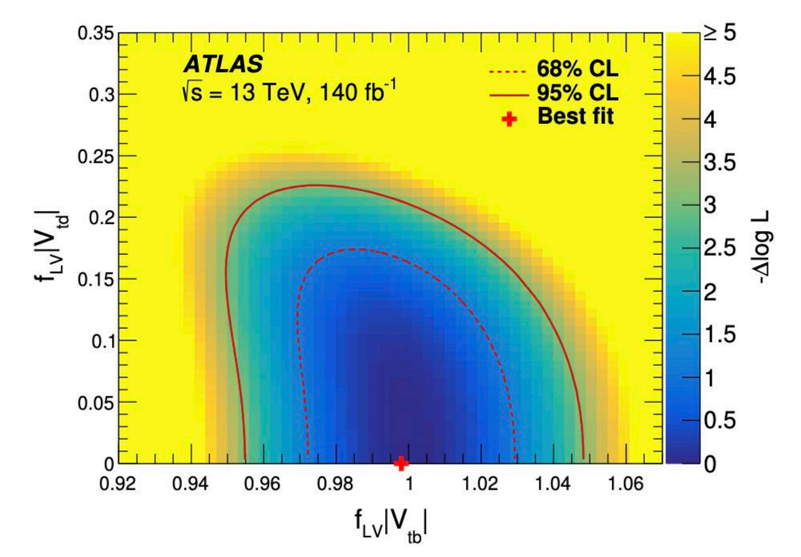
It is complementary to other measurements

Generalized CKM interpretation

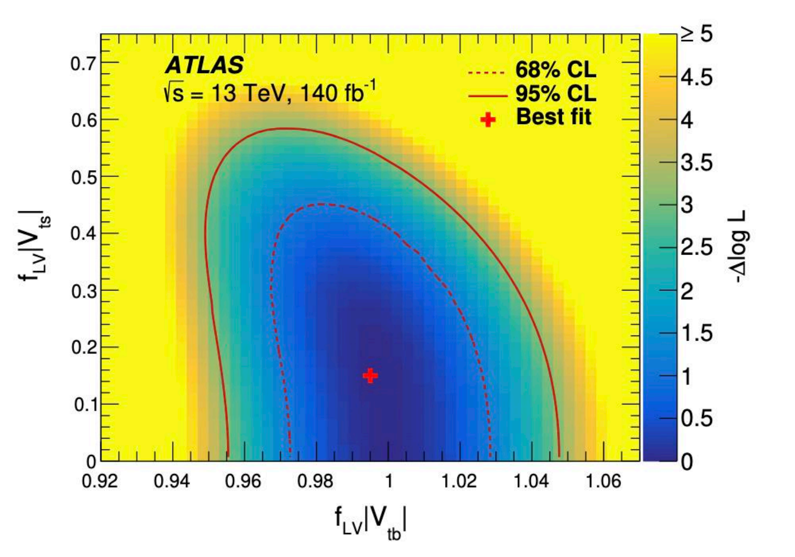
JHEP05(2024)305

- 9 **Wtq** vertices in production and decay are considered
- Top decays in $t\bar{t}$ treated consistently (improves sensitivity to V_{ts}, V_{td} by 20%)
- ML fit in three scenarios for two of the V_{tx}

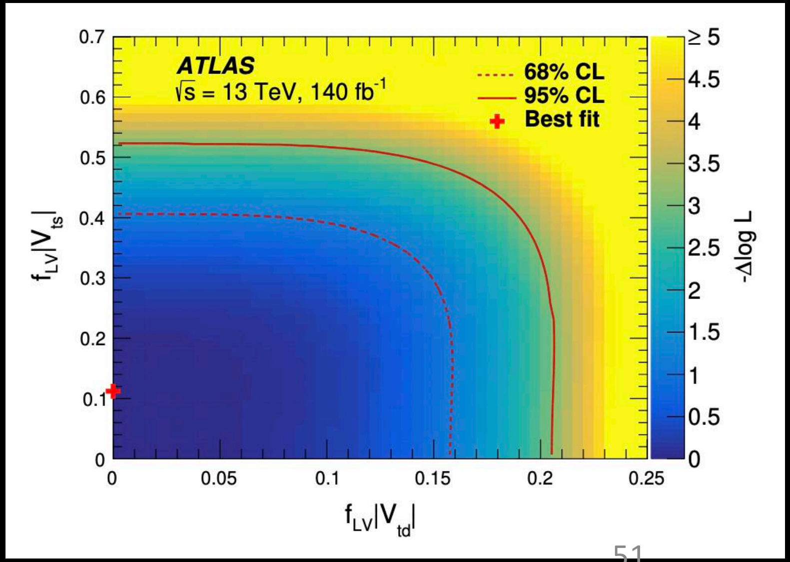
$|V_{ts}| = 0,$



$|V_{td}| = 0,$

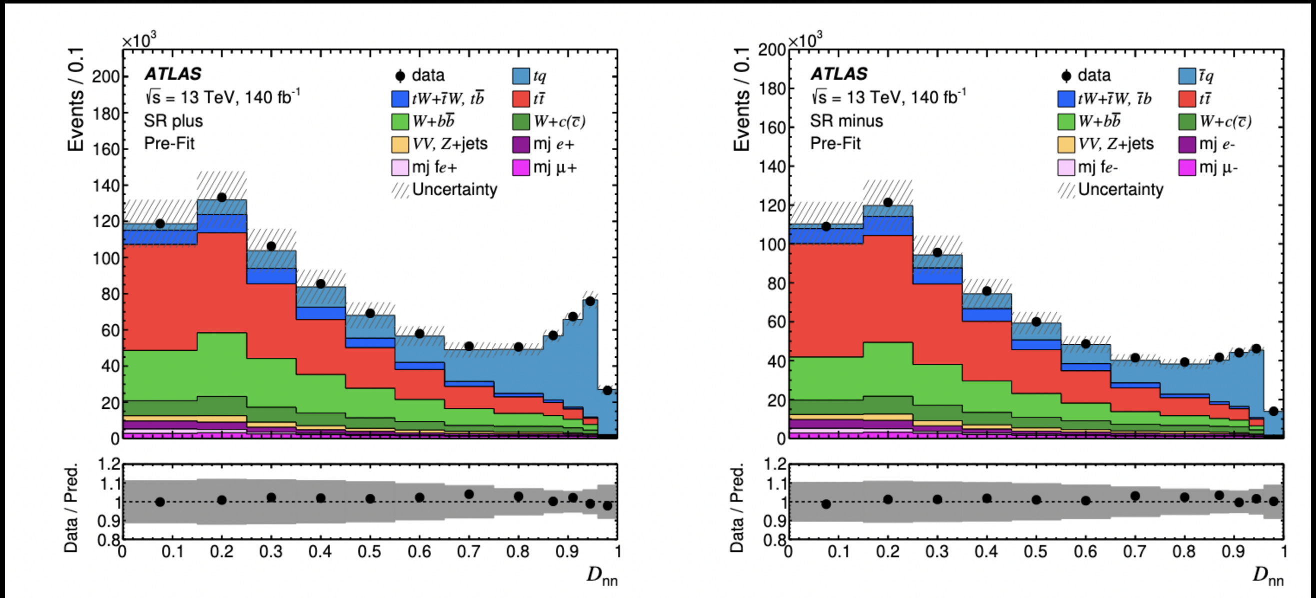


$f_{\rm LV}|V_{tb}| = 1$



t-channel single-top measurement by ATLAS

JHEP05(2024)305



$\sigma_{tq} = 137 \pm 8\, pb$ $\quad \sigma_{\bar{t}q} = 84^{+6}_{-5}\, pb$

$\sigma_{tq+\bar{t}q} = 221 \pm 13\, pb$ ~6%

$R_t = \dfrac{\sigma_{tq}}{\sigma_{\bar{t}q}} = 1.636\ \pm 0.036$ ~2%

Main systematic uncertainties

- tq signal modelling (Scale, PDF, FSR)
- Jet energy resolution (JER)
- b-tagging
- Background modelling

- Use measured $\sigma(tq + \bar{t}q)$ and theoretical prediction to extract $f_{LF}^2 \cdot |V_{tb}|^2$
- Theory prediction @NNLO:

2012.01574

$$214.2 \pm 3.4(\text{scale} + \text{PDF}) \pm 0.6(\Delta m_t)\ \text{pb}$$

1.6% precision

- No assumpion on CKM unitarity nor number of quark flavour
- Assume $|V_{tb}| \gg |V_{td}|, |V_{ts}|$ and Wtb has LH weak structure

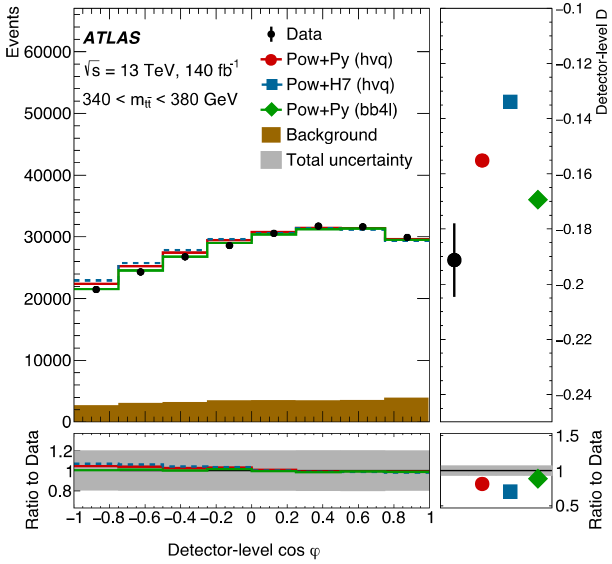
$$f_{\text{LV}} \cdot |V_{tb}| = 1.015 \pm 0.031,$$

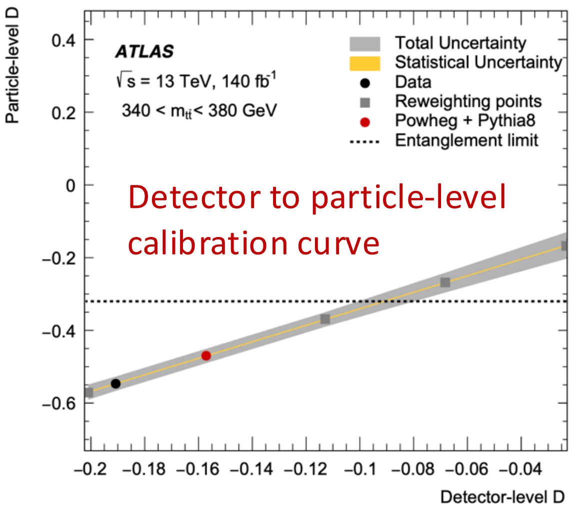
3%

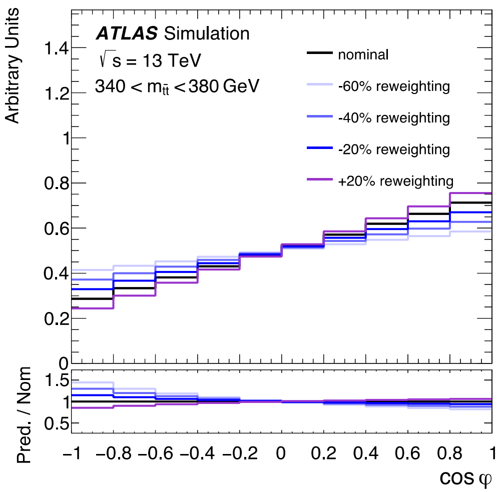
- Assuming SM , $V_{LV} = 1$

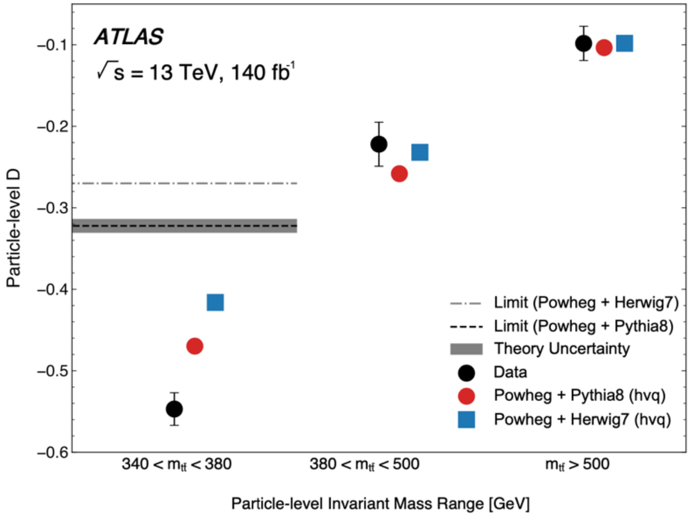
$$|V_{tb}| > 0.95 \text{ at the } 95\,\% \text{ CL}$$

Entanglement in $t\bar{t}$ (ATLAS)









Simple approach:
measure D in particle level

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

Uncertainties via calibration curve:

- Modeling of $t\bar{t}$ production and decay (3.2%)
  - Top decay modeling (Powheg vs.MadSpin)
  - PDF, ISR/FSR, Top p_T modeling
- Background modeling (1.8%)
- Experimental (b-jet tagging, JES…) (< 1%)

Event-by-event reweighting based on D is used to vary the degree of entanglement

- **Entanglement is observed with more than 5σ**

Obs: −0.547 ± 0.002 [stat.] ± 0.021 [syst.]
Exp: −0.470 ± 0.002 [stat.] ± 0.018 [syst.]

  - SM prediction has PS modelling dependence