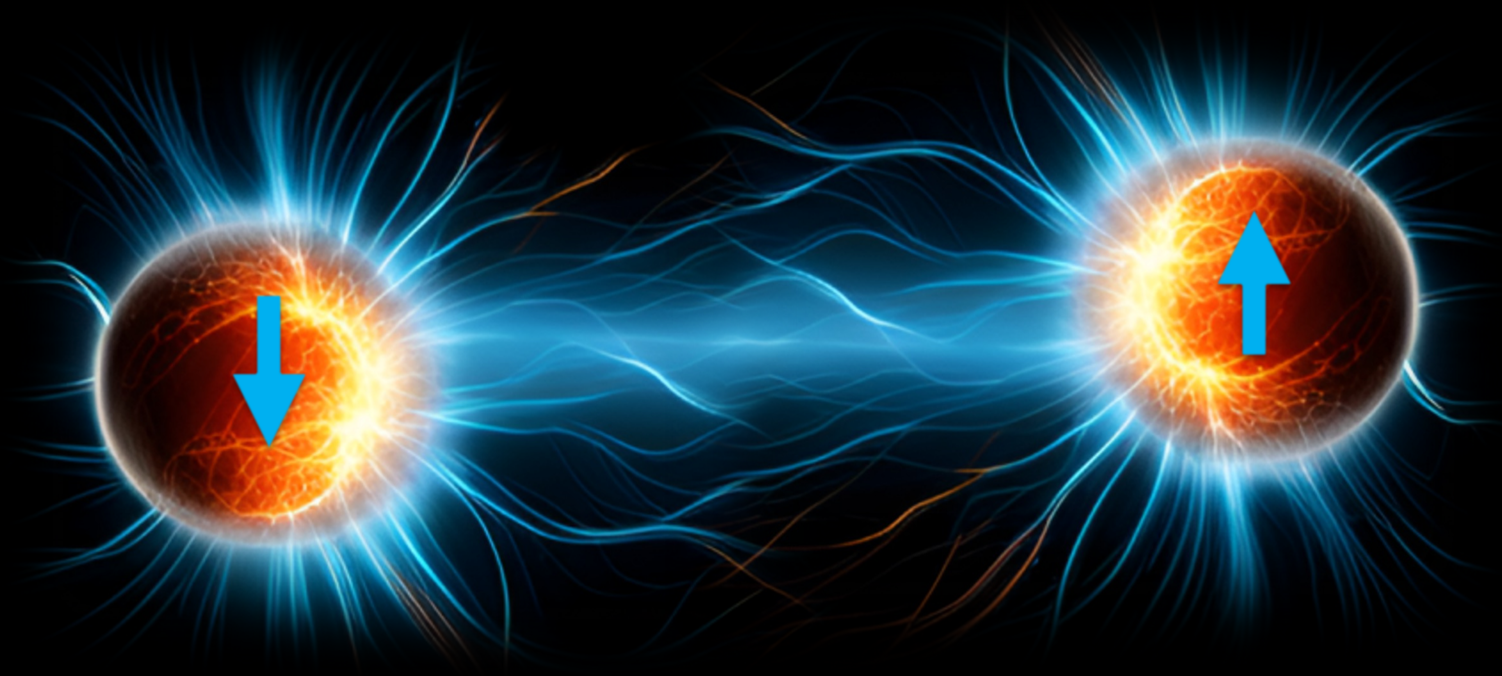
Quantum Tops @ LHC: Spin Correlation, Polarization & Entanglement in top-quark pairs

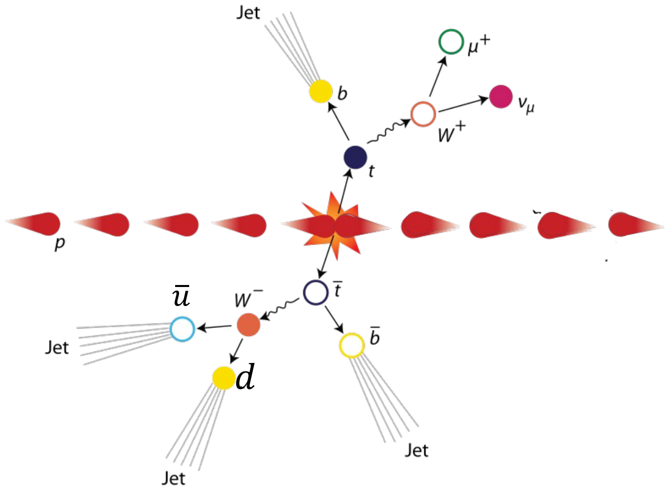


Didar Dobur
University of Ghent

Belgian HEP meeting
June 2024

Top quark production at LHC

Mainly produced in pairs via strong interaction

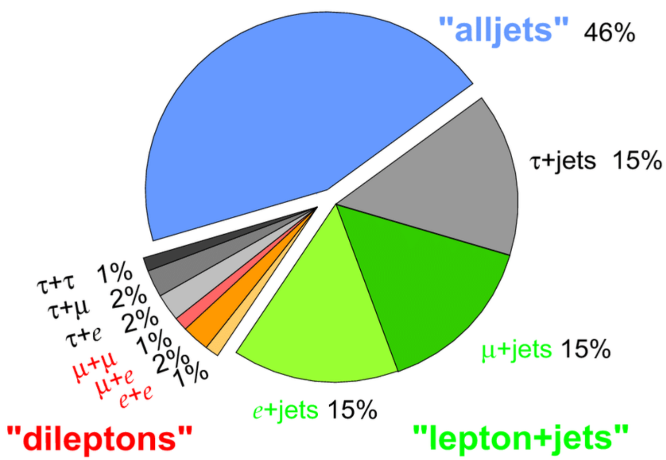


The heaviest elementary particle:

$m_{Top} = 172.52 \pm 0.33$ GeV

$$\text{lifetime} < \begin{matrix}\text{QCD}\\\text{timescale}\end{matrix} \ll \begin{matrix}\text{spin-flip}\\\text{timescale}\end{matrix}$$

$$10^{-25}\,\text{s} < 10^{-24}\,\text{s} \ll 10^{-21}\,\text{s}$$



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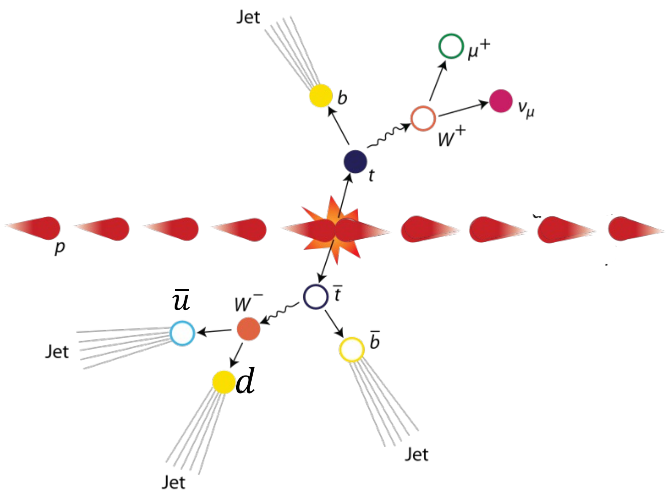

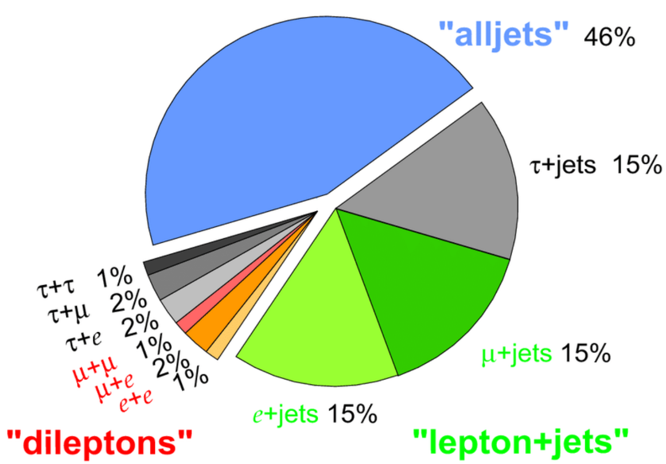

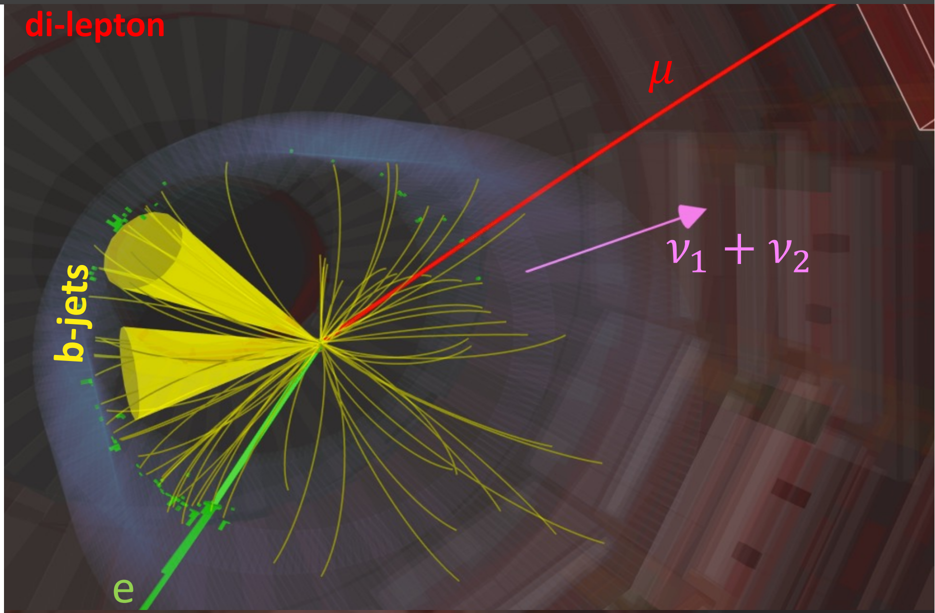

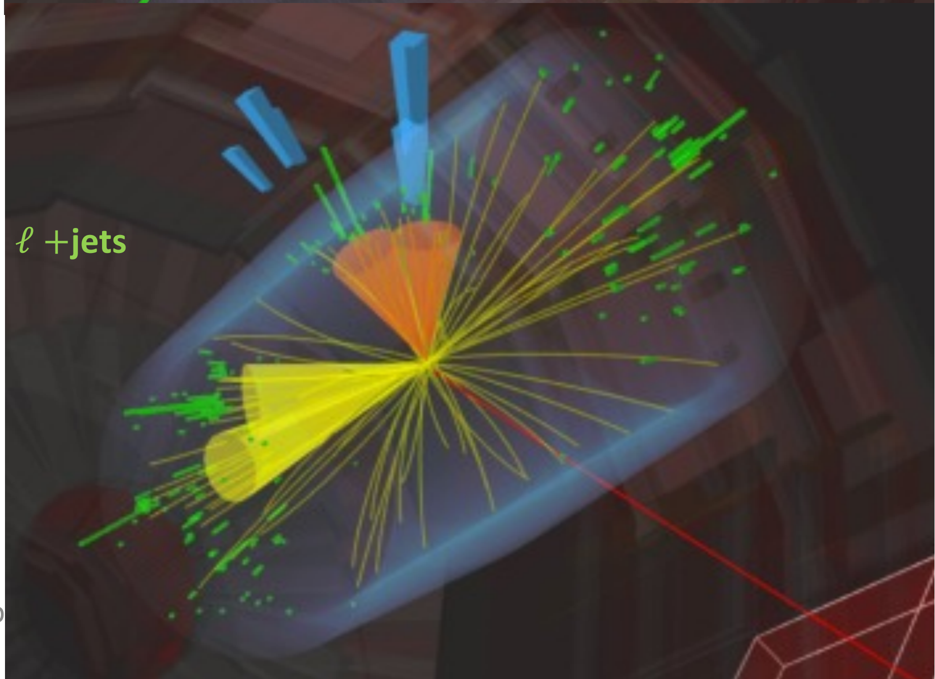

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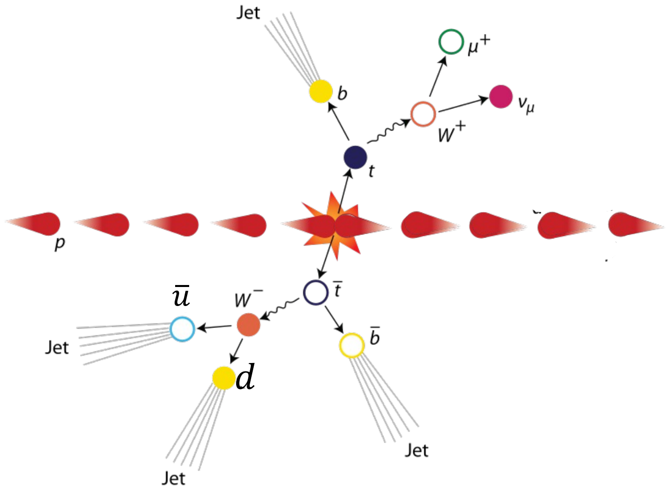

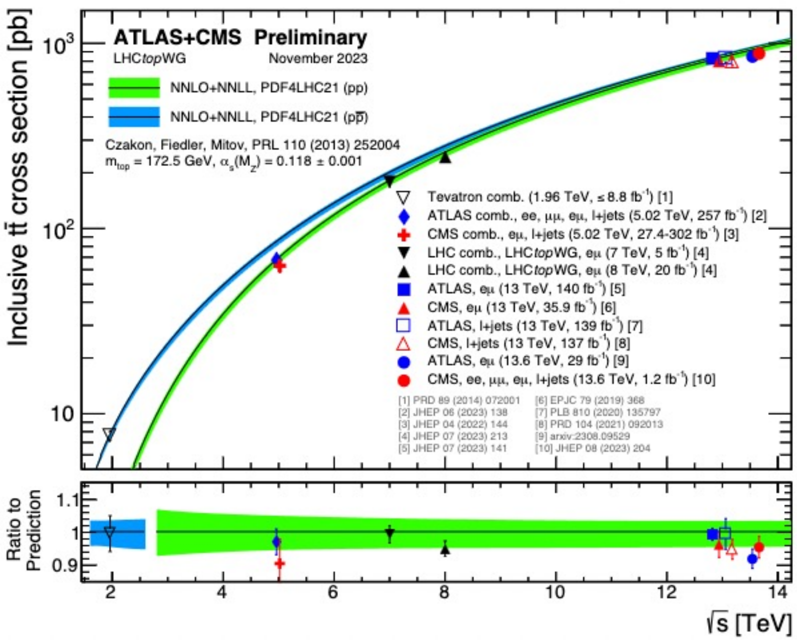

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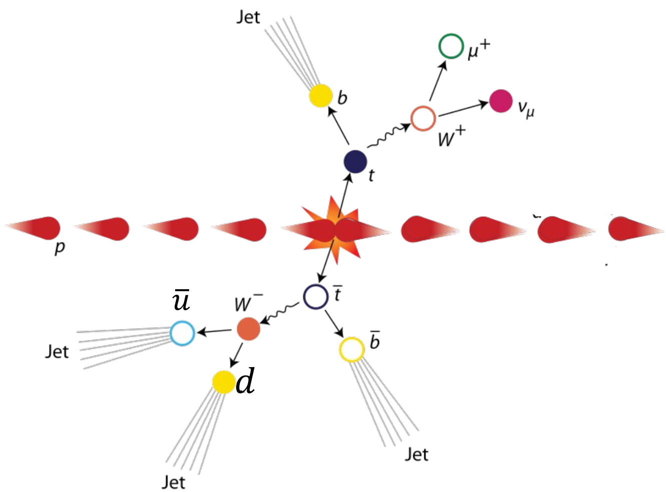
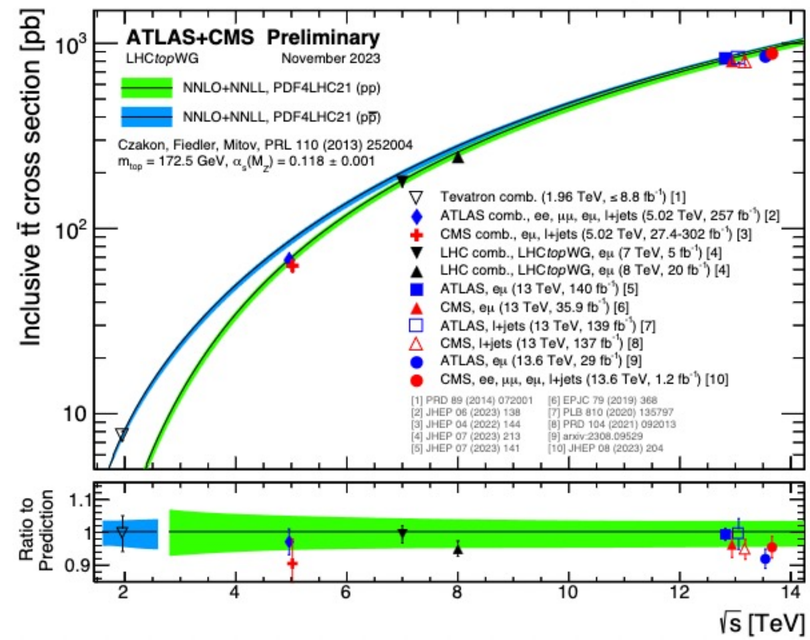
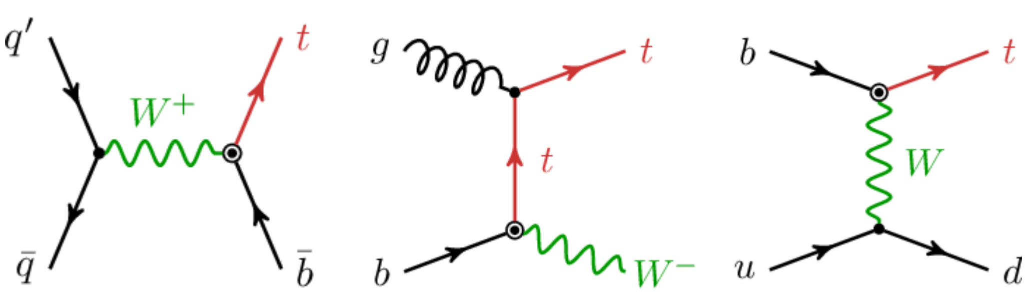
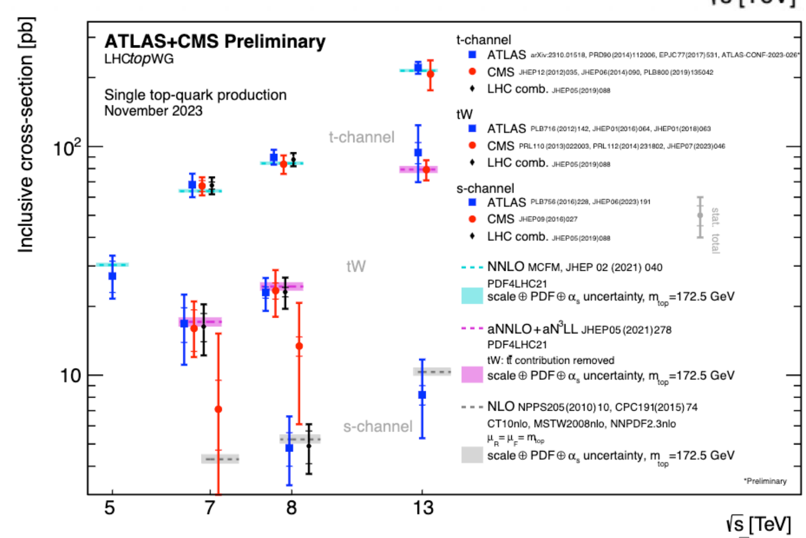


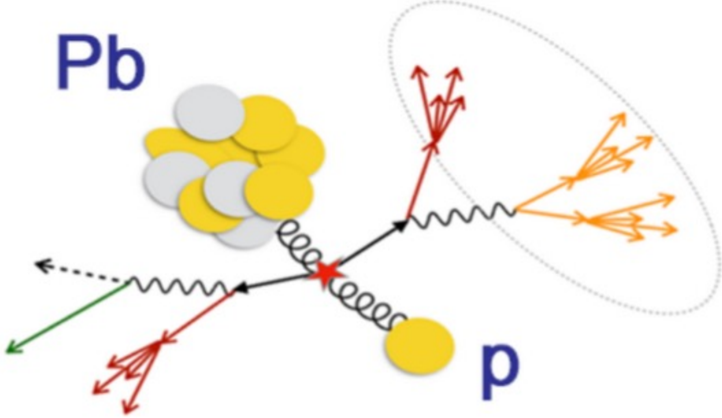


Single-top production via weak interaction

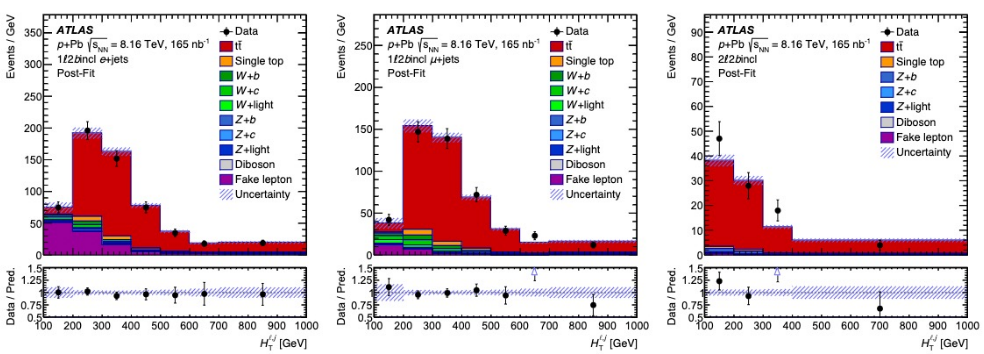


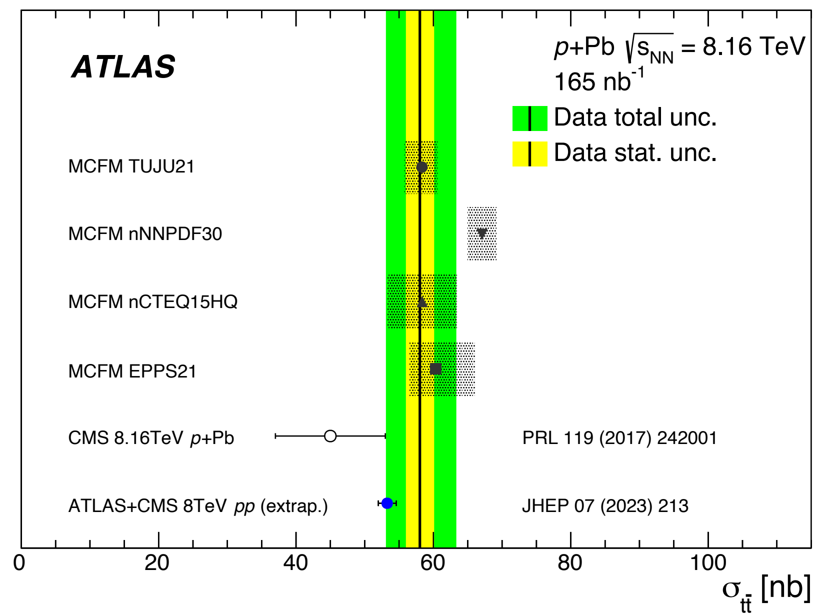


Top quark production in Nuclear collisions



- $pPb\ (PbPb) \rightarrow t\bar{t}$
- Probes of nuclear PDF at high-x
- Observation of $t\bar{t}$ production in p-Pp collisions
  - CMS (PhysRevLett.119.242001)
  - ATLAS (arXiv:2405.05078)

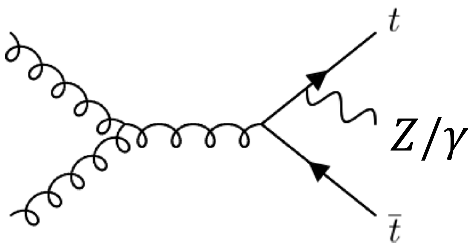


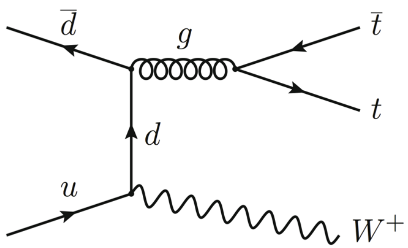


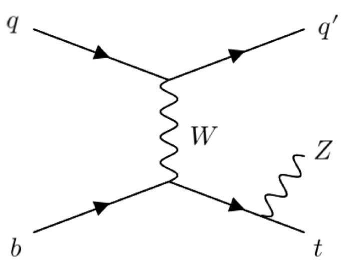
- CMS has also published evidence of top-pair production in Pb-Pb collisions

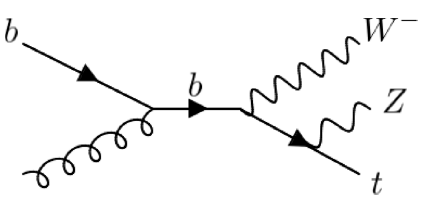
  Phys. Rev. Lett. 125 (2020) 222001

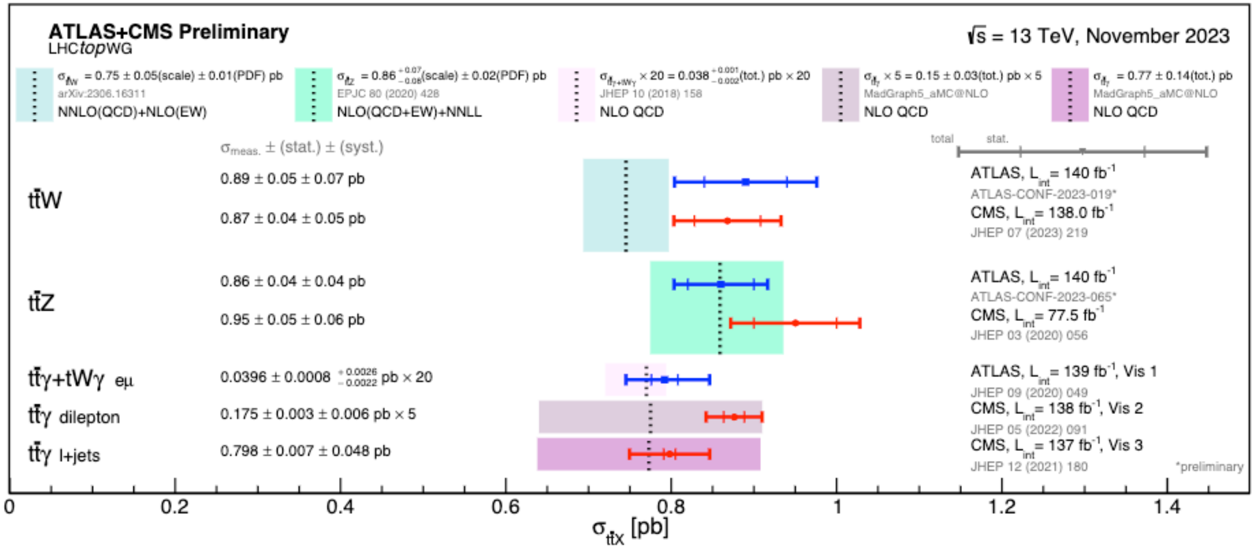
t(t)+V production

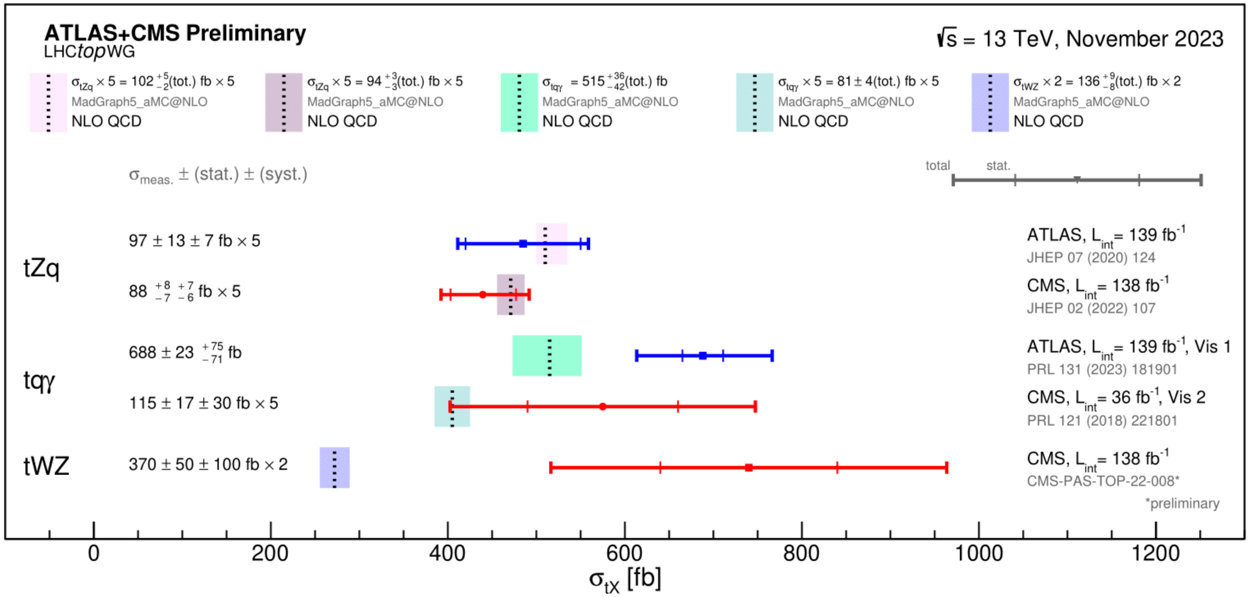




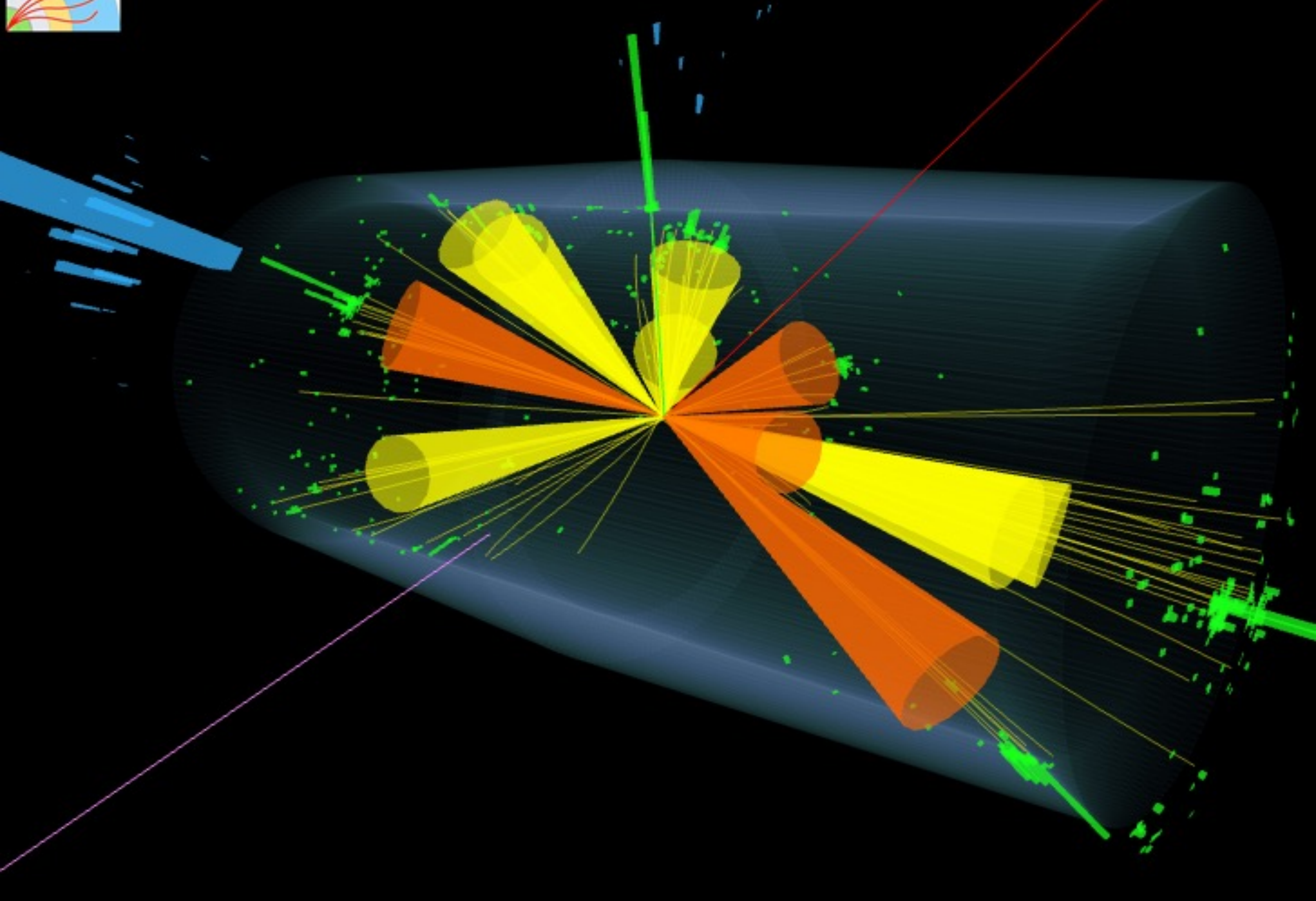








Observation of 4-top quarks by CMS and ATLAS



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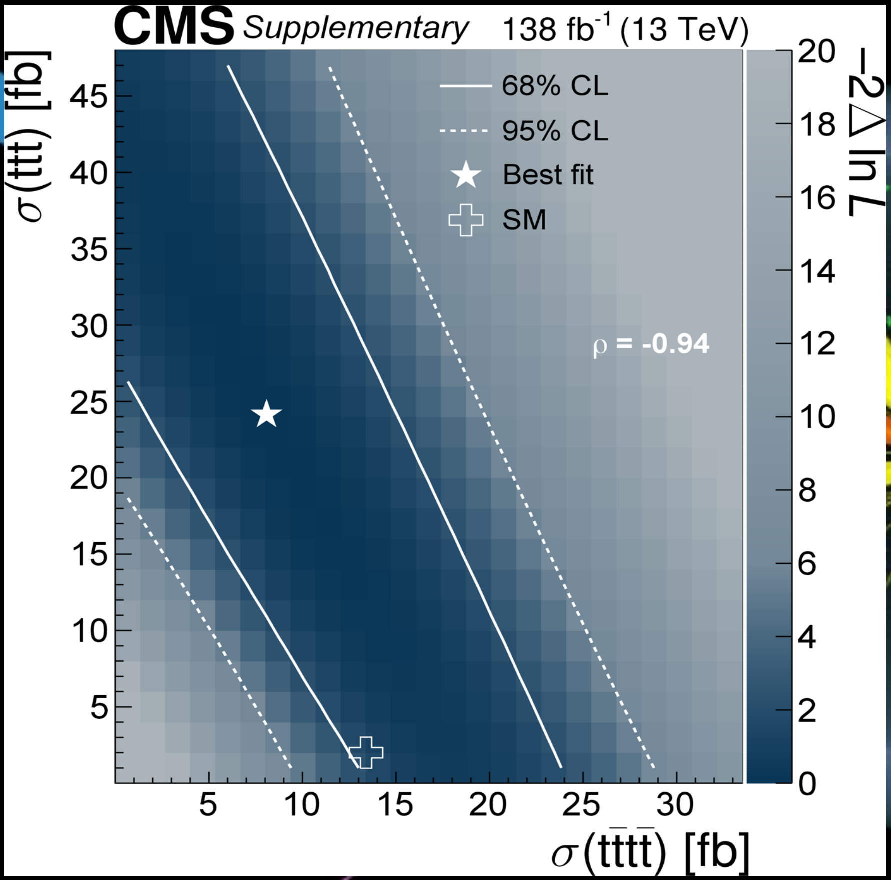
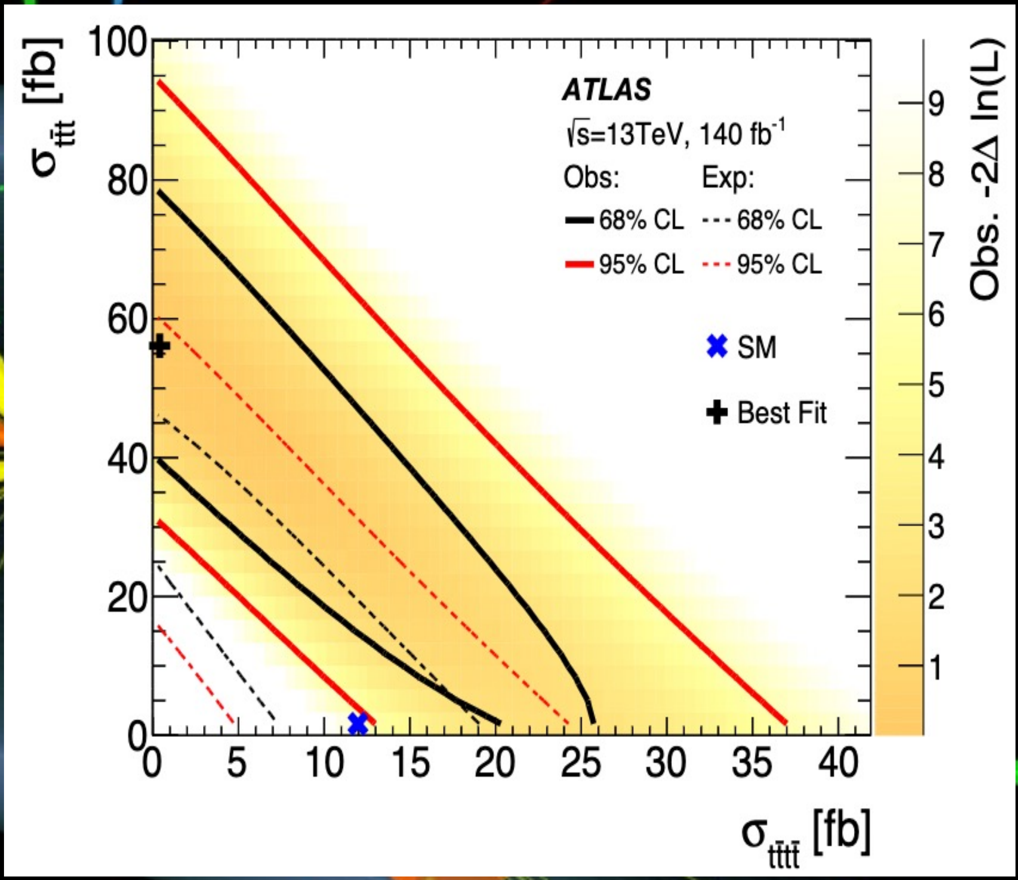




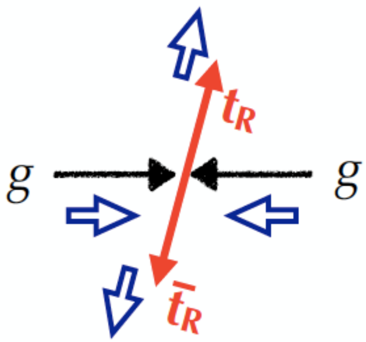
Is it four-tops ? Three-tops ? or New Physics ?

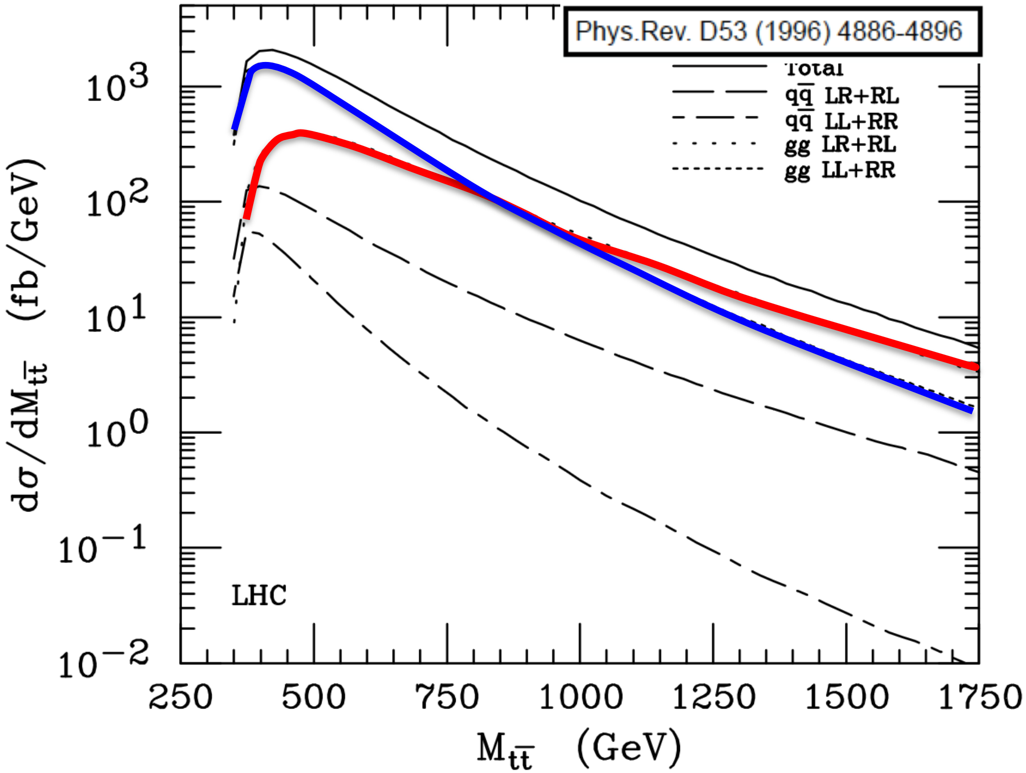
Spinning tops…

- Top quark polarization and $t\bar{t}$ spin correlations using dilepton final states by CMS, PRD 100 (2019) 072002
- Observation of quantum entanglement in top quark pairs in dilepton channel by ATLAS, arXiv:2311.07288, submitted to Nature.
- Observation of quantum entanglement in top quark pairs in dilepton channel by CMS, 2406.03976, Submitted to ROPP
- Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events by CMS, CMS-TOP-23-007

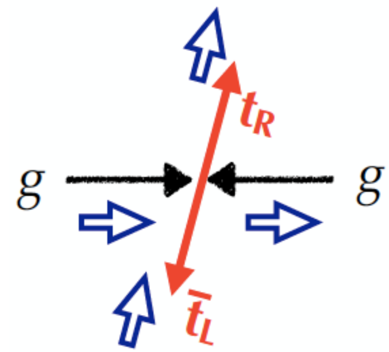
Top-quark polarization & spin correlation

same helicity





opposite helicity



- Tops are mainly unpolarized (parity invariance of QCD)
- Spins of top-pairs are strongly correlated
- The degree of spin correlation depend on M_{tt},
    - Low M_{tt}: RR/LL helicity pairs dominate
    - High M_{tt}: RL/LR helicity pairs dominate

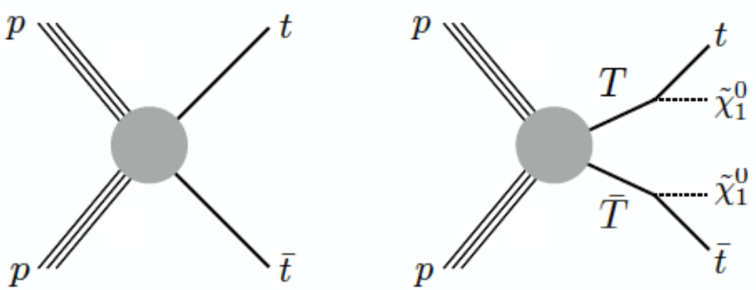
Why top-quark spin is interesting ?

- Top quark decays before it can form hadrons
- Spin information transferred to daughter particles

$$\text{lifetime} < \begin{matrix}\text{QCD}\\ \text{timescale}\end{matrix} \ll \begin{matrix}\text{spin-flip}\\ \text{timescale}\end{matrix}$$

$$10^{-25}\,\text{s} < 10^{-24}\,\text{s} \ll 10^{-21}\,\text{s}$$

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



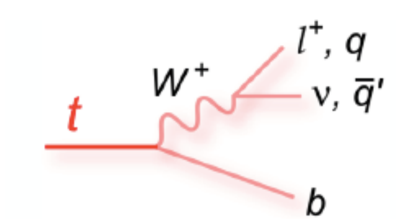
➡ Excellent laboratory to search for new physics but also for testing the foundations of Quantum physics

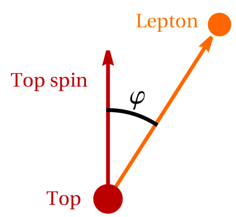
Experimental observables

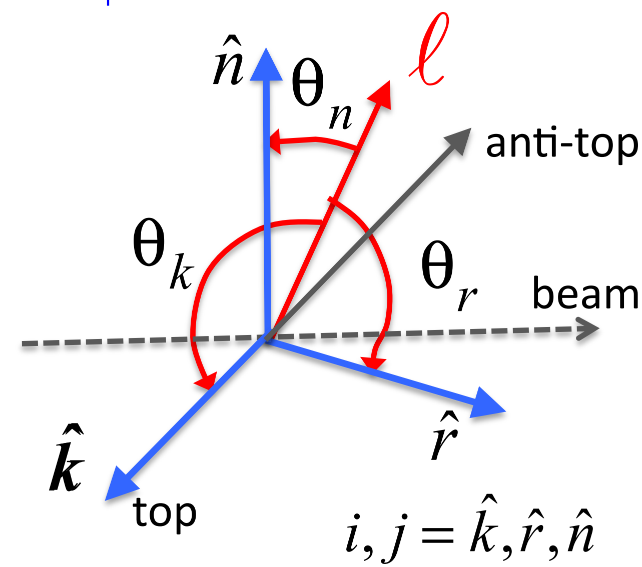
Coefficients of the spin density matrix can be extracted from :

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

Top quark's spin determines the angular distribution of its daughters







ℓ *and* d-quark preferentially produced in top spin direction
(V-A structure of the Weak interaction)

$\hat{p}$: incoming parton
$\hat{k}$: 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

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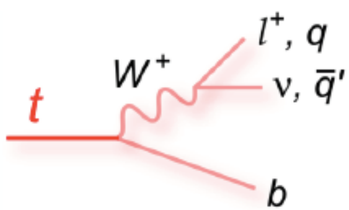

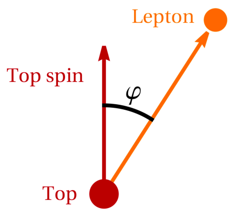

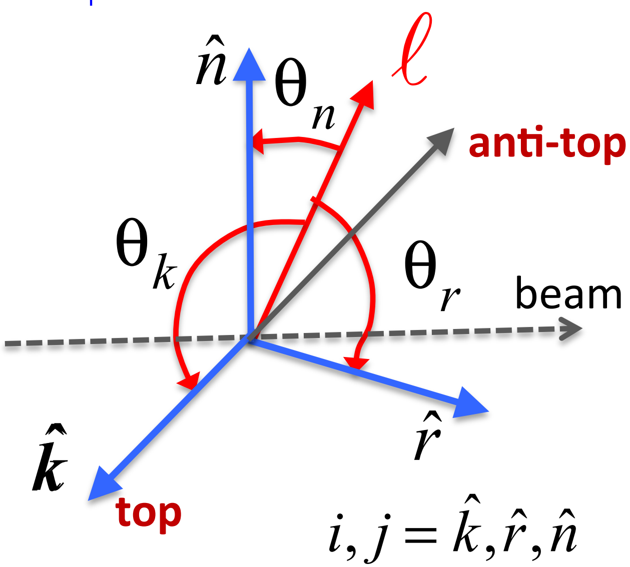

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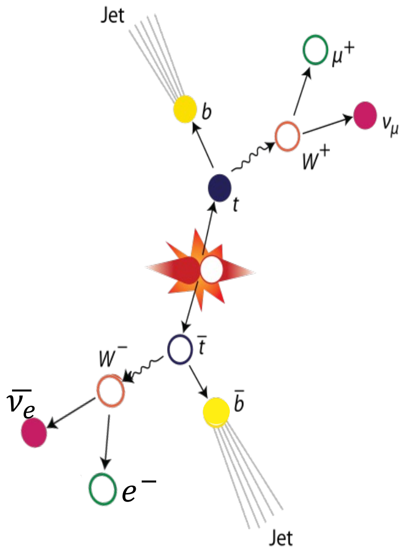
Measure differential cross sections:

- 6 $\cos\theta^i$ distributions for B_i
- 3 $\cos\theta_1^i \cos\theta_2^i$ distributions for the C_{ii}
- 6 $\cos\theta_1^i \cos\theta_2^j \pm \cos\theta_1^j \cos\theta_2^i$ distributions for the $C_{ij} \pm C_{ji}$

$t\bar{t}$ event selection (dilepton)



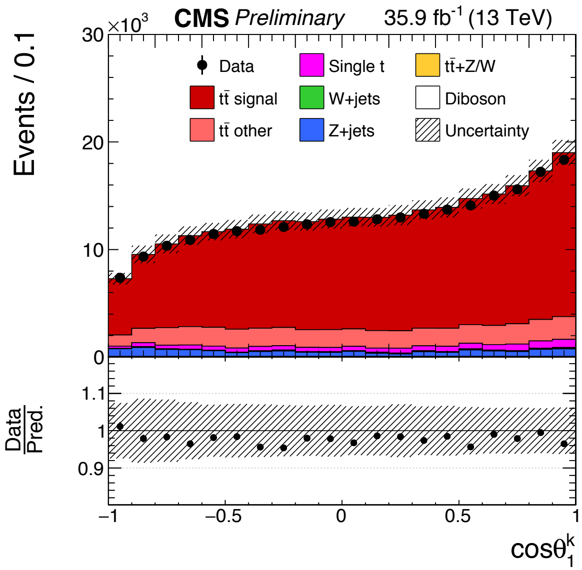
- Two oppositely charged leptons $ee, \mu\mu, e\mu$
- $p_T(\ell) > 25(20)$ GeV
- $p_T(jet) > 30$ GeV
- $N_{jets} \geq 2$, $N_{bjets} \geq 1$
- $m(\ell\ell) > 20$ GeV
- In $ee, \mu\mu$ channels, Z veto & $E_T^{miss} > 40$ GeV

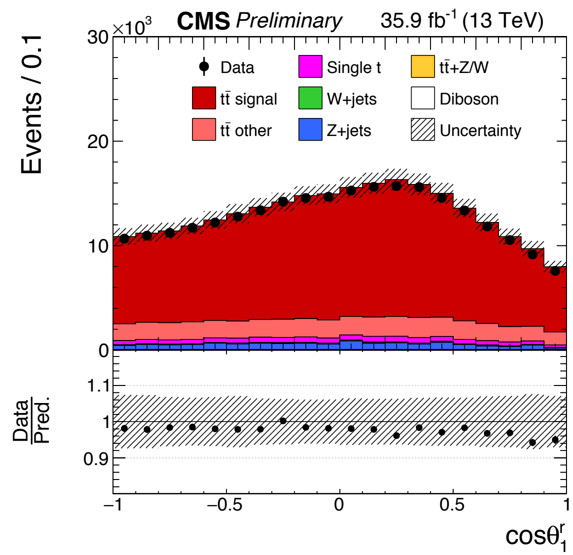
- Relatively pure sample of ttBar events $t \rightarrow \tau\nu b$ considered as background
- Top 4-vectors from kinematic reconstruction
  - all possible assignments of jets, leptons and bjets
  - Impose m_W , m_{top} & $E_T^{miss} = \vec{p}_T(\nu) + \vec{p}_T(\bar{\nu})$
  - 90% efficiency

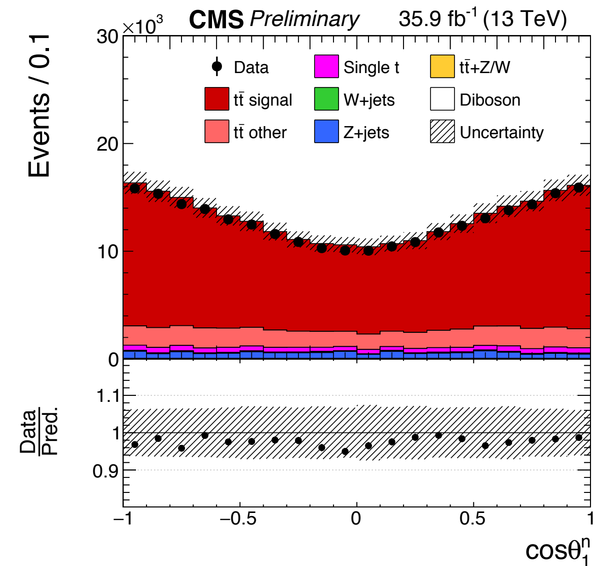
Top quark polarization

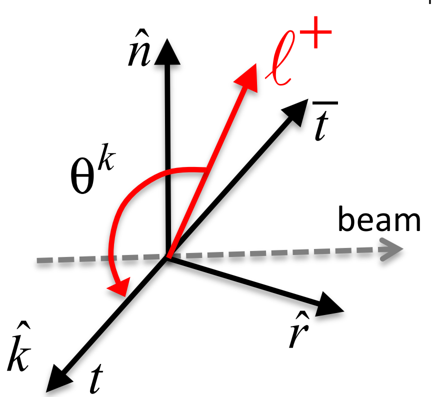
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^i_\pm} = \frac{1}{2}(1+B^i_\pm\cos\theta^i_\pm)$$

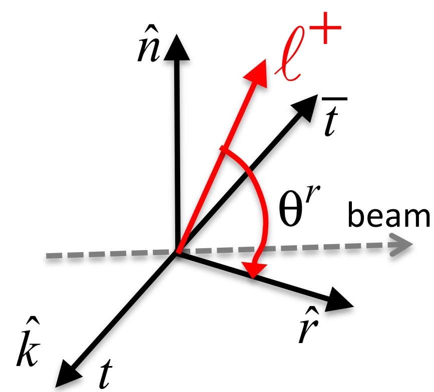
Measured distributions as seen by the detector

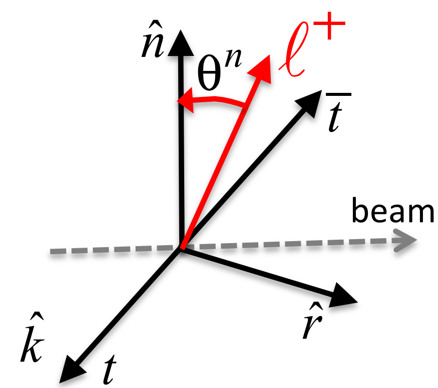












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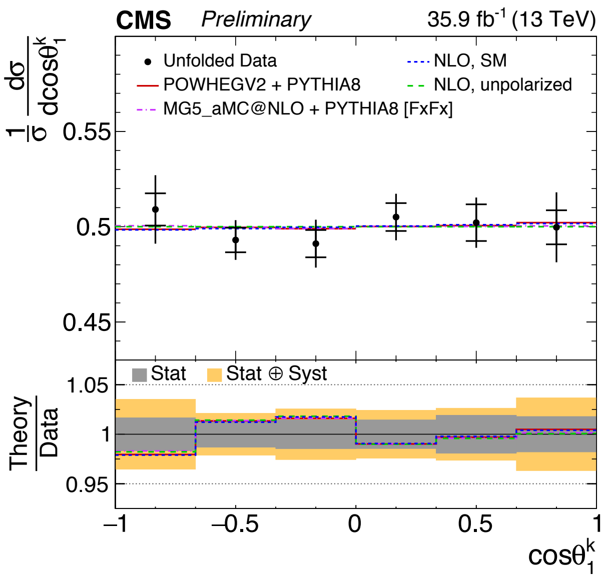
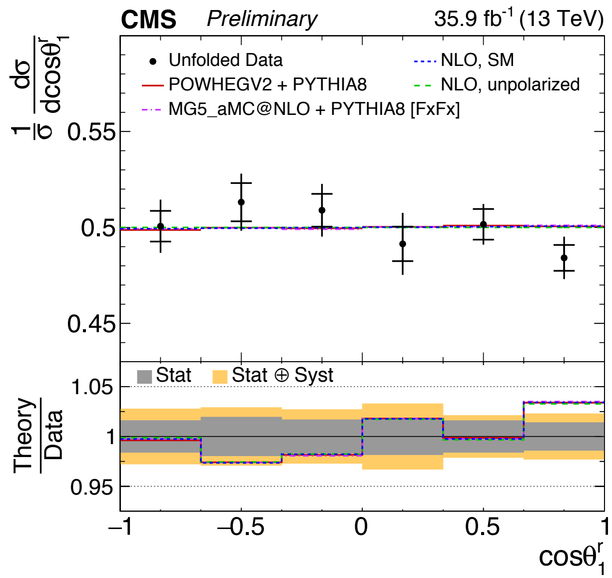
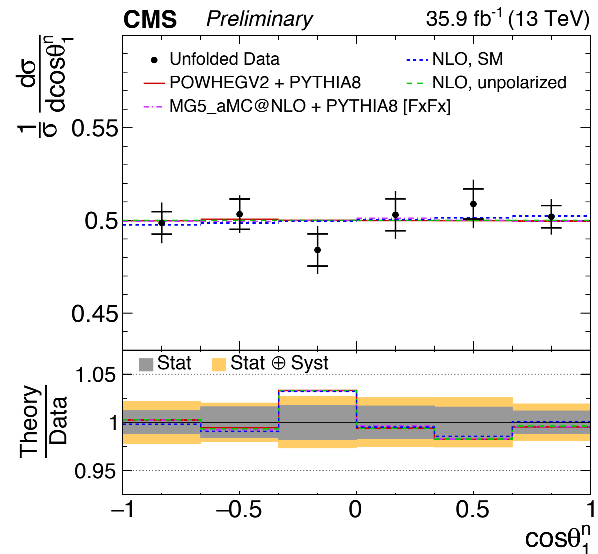
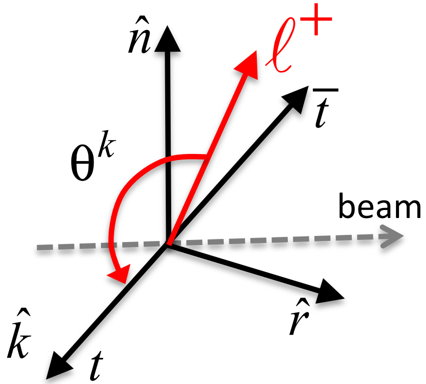
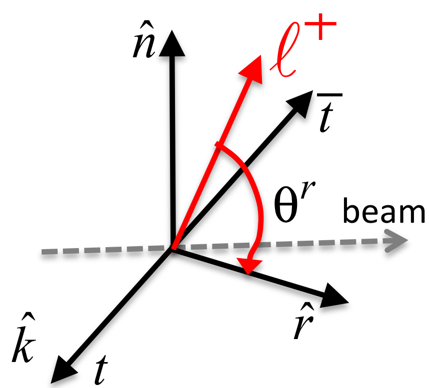
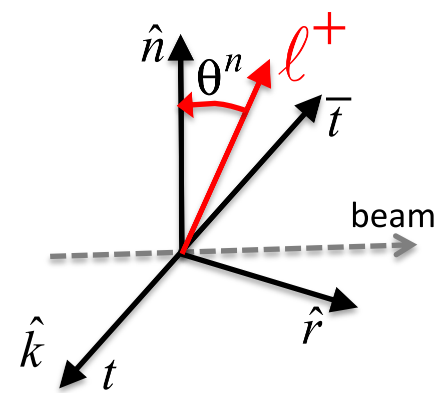








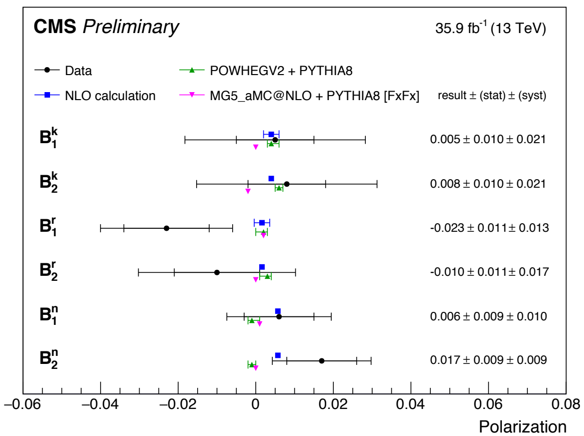




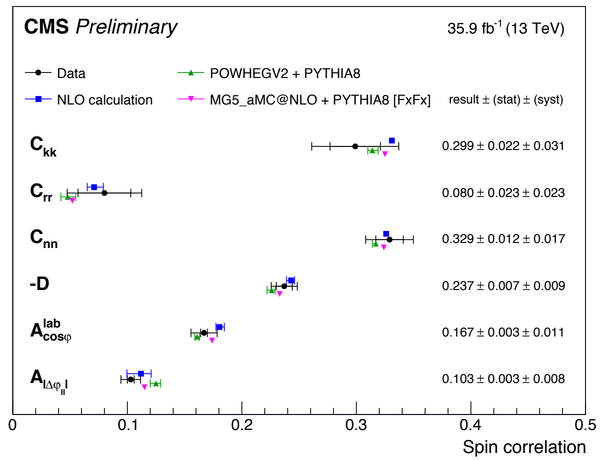
- Flat distributions → Top quarks are unpolarized

Spin-correlation coefficients

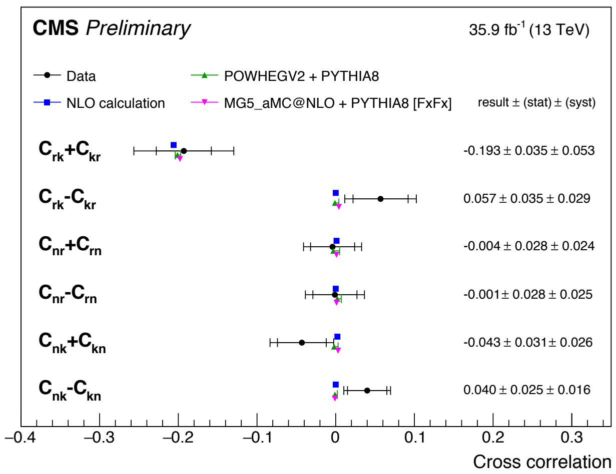
Polarization coefficients



Diagonal elements in the spin density matrix



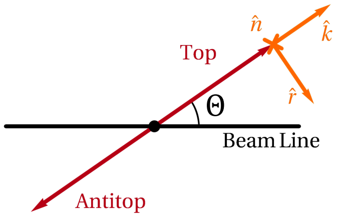
Off-diagonal elements in the spin density matrix

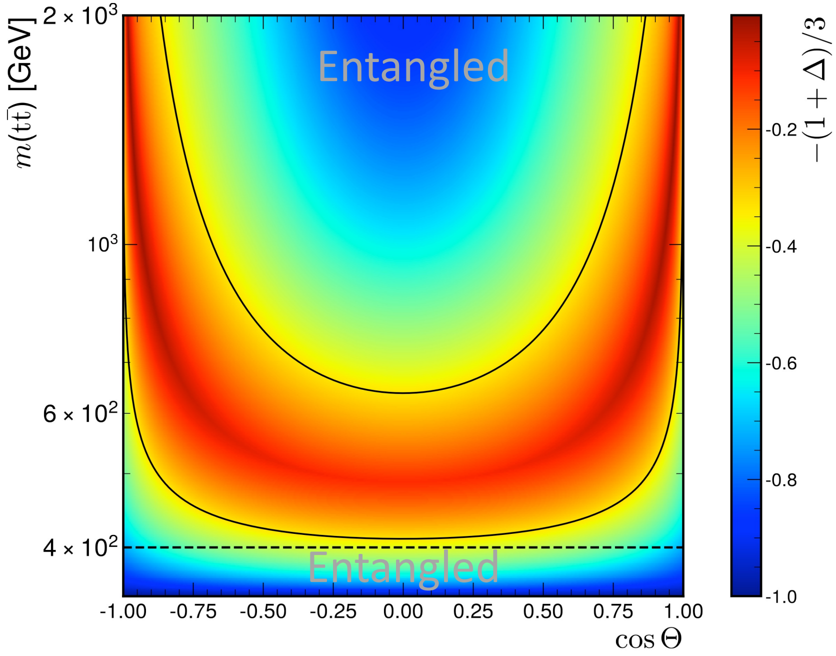


- Spins correlation has been observed by both the ATLAS and CMS experiments… already long time ago

Entanglement in $t\bar{t}$

- $t\bar{t}$ produced in mixed states (eg. $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$) → two qubit system
- Spin correlation is $m(t\bar{t})$ and $\cos\Theta$ dependent
- Some regions of phase-space → entangled tops
- Peres–Horodecki criterion* $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$





- **Low m($t\bar{t}$)**
  - $gg \to t\bar{t}$ spin-singlet ($^1S_0$) Dominant & max. entangled

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

* arXiv:quant-ph/9604005
arXiv:quant-ph/9605038

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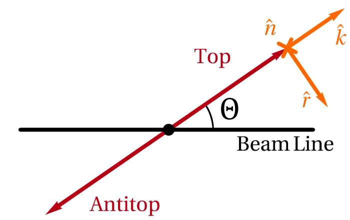

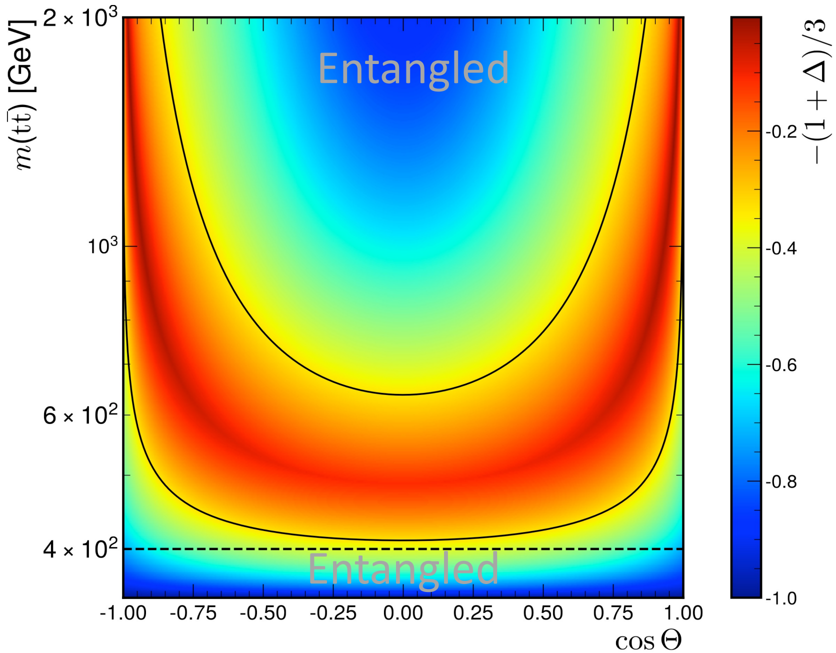

- **High m($t\bar{t}$)**
  - $gg/qq \to t\bar{t}$ spin triplet ($^3S_1$)

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

- **Low m($t\bar{t}$)**
  - $gg \to t\bar{t}$ spin-singlet ($^1S_0$) Dominant & max. entangled

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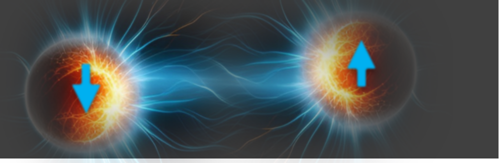
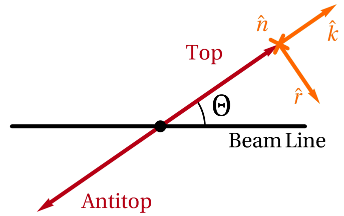
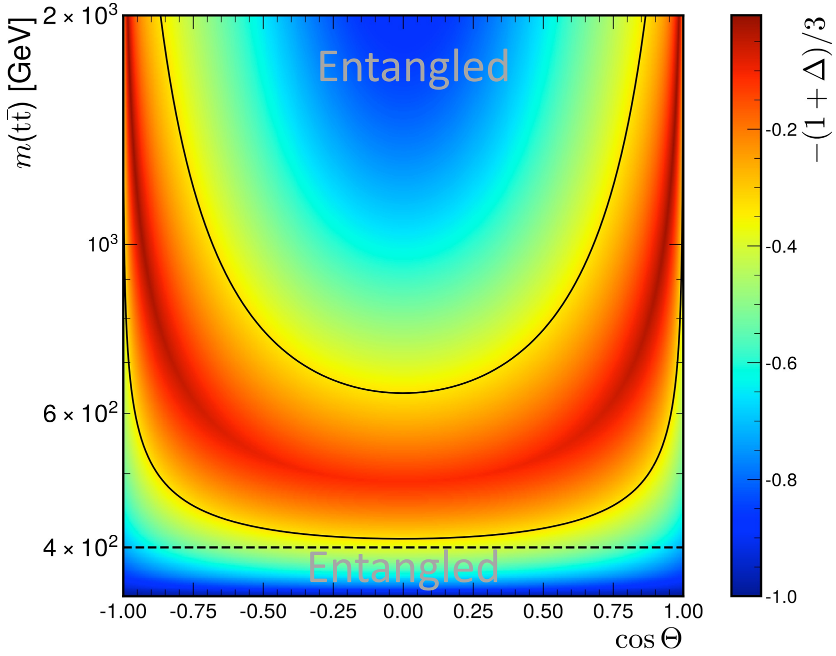
Entanglement in $t\bar{t}$





- $t\bar{t}$ produced in mixed states (eg. $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$) → two qubit system
- Spin correlation is $m(t\bar{t})$ and $\cos\Theta$ dependent
- Some regions of phase-space → entangled tops
- Peres–Horodecki criterion* $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$



- **High $m(t\bar{t})$**
  - $gg/qq \rightarrow t\bar{t}$ spin triplet ($^3S_1$)

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

$$\widetilde{D} = \frac{\Delta_E}{3}$$

- **Low $m(t\bar{t})$**
  - $gg \rightarrow t\bar{t}$ spin-singlet ($^1S_0$) Dominant & max. entangled

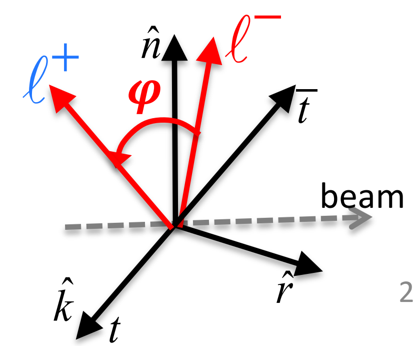
$$\Delta_E = C_{nn} + C_{rr} + C_{kk} > 1$$

$$D = -\frac{\Delta_E}{3}$$

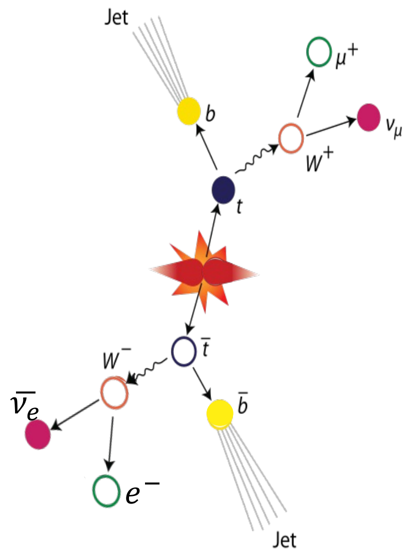
Single differential cross-section to capture the entanglement

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

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



Entanglement: ATLAS



- Full Run II
- $e\mu$ channel, 2 jets >=1 bjet
- Top reconstruction: *Ellipse method* or *Neutrino reweighting* to find P_ν & assume $m_W = 80.5\ GeV$
- Use all *b W* combinations and minimize

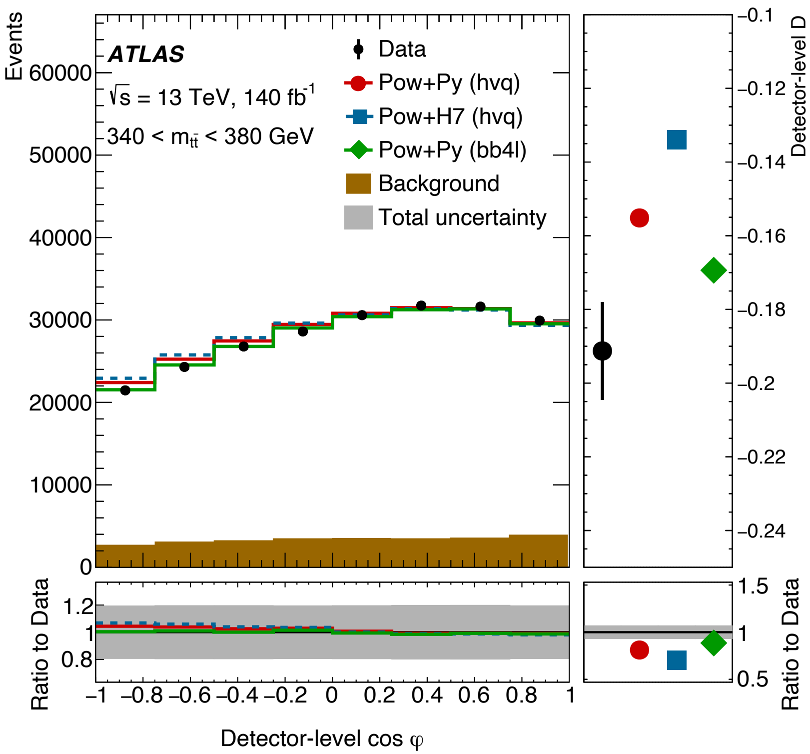
$$|m_t - m(W_1 + b_{1/2})| + |m_t - m(W_2 + b_{2/1})| \quad m_t = 172.5\ GeV$$

Simple approach: measure D in particle level

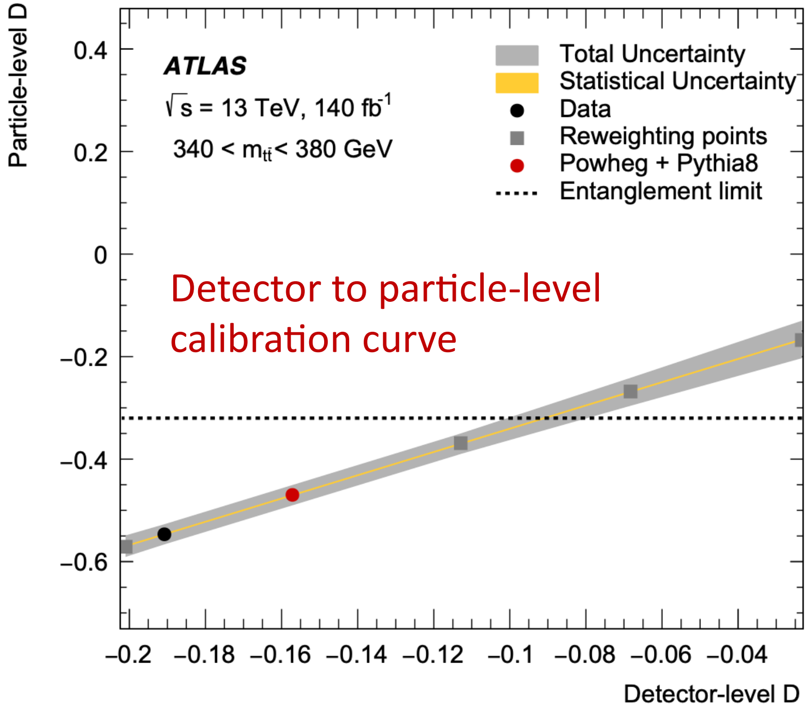
$$D = -3 \cdot \langle \cos \varphi \rangle$$

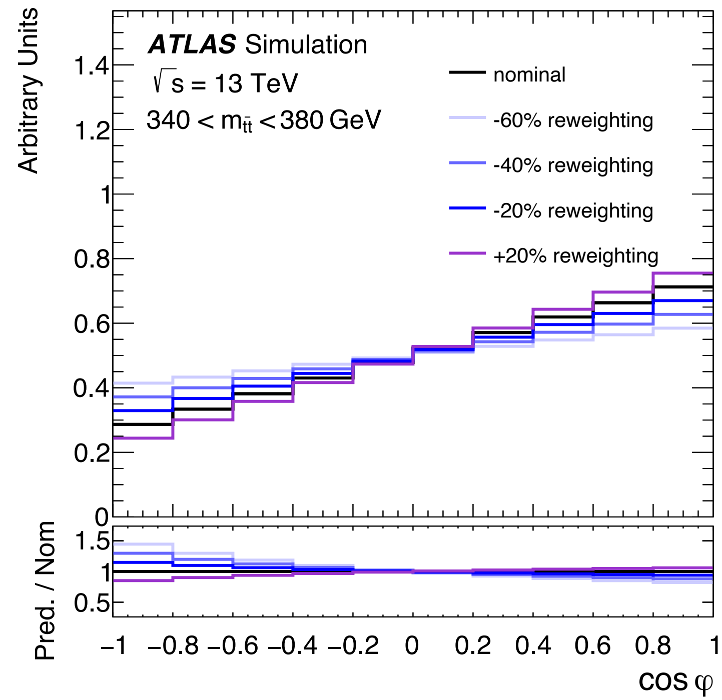
Background modeling:

- W/Z+jets, VV, ttV,Higgs: state-of-the-art MC simulations
- Nonprompt leptons: data-driven



Entanglement: ATLAS



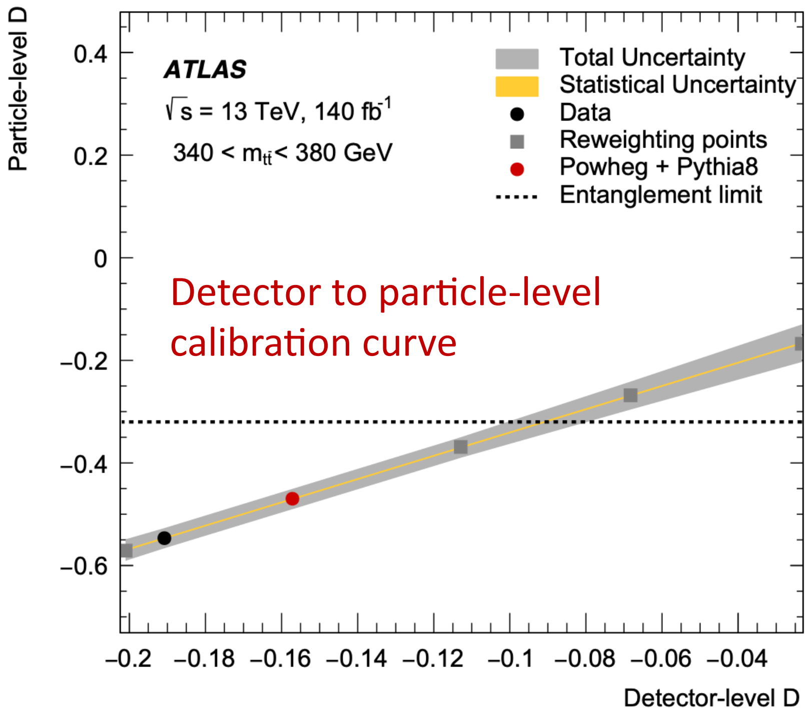


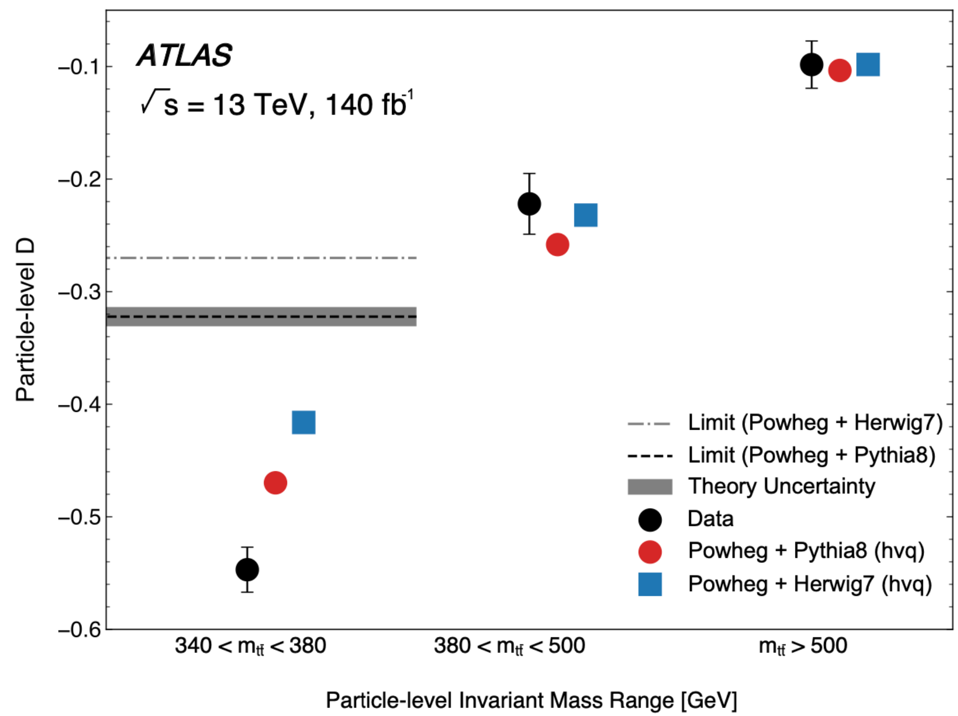
Uncertainties via calibration curve:

- 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: ATLAS





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…) $(< 1\%)$

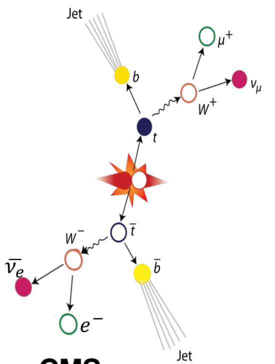
- **Entanglement is observed with more than 5σ**

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

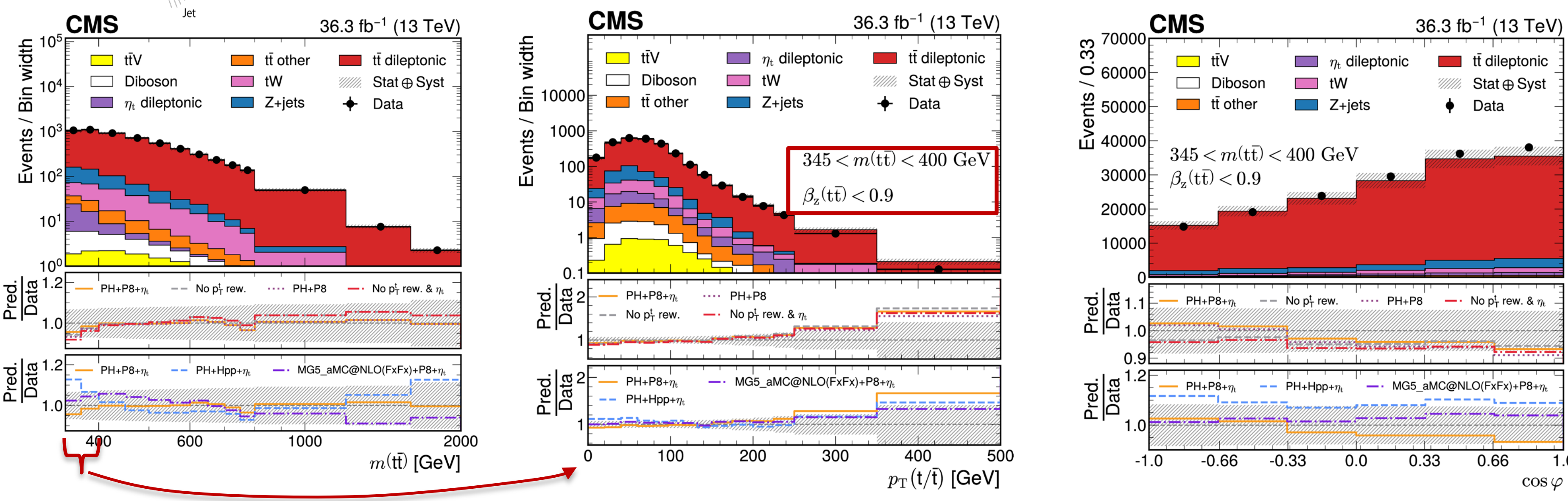
  Exp: −0.470 ± 0.002 [stat.] ± 0.018 [syst.]

  - First time in a quark-antiquark system at such high energies
  - SM prediction has PS modelling dependence

CMS: 2ℓ channel



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

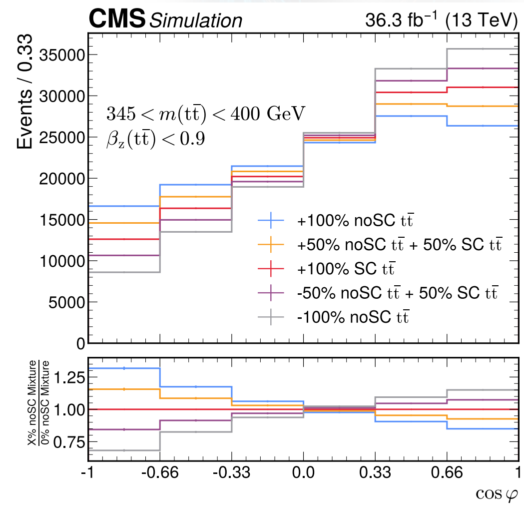


Signal region

- Measure the entanglement at the parton level instead of particle level.
- Binned likelihood fit to extract D instead of using a calibration curve.
- Non-relativistic bound-state effects in the production threshold

Signal Modeling

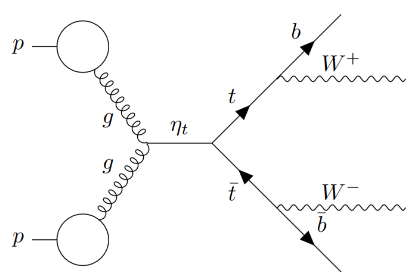
- POWHEG+Pythia8 @NLO QCD
- TOP++ for x-section @NNLO QCD
- EWK corrections @NLO with Higgs exchange (HATHOR)
- NNLO effects via $p_T(top)$ reweighting to match the top quark p_T spectrum from a fixed order ME calculation at NNLO

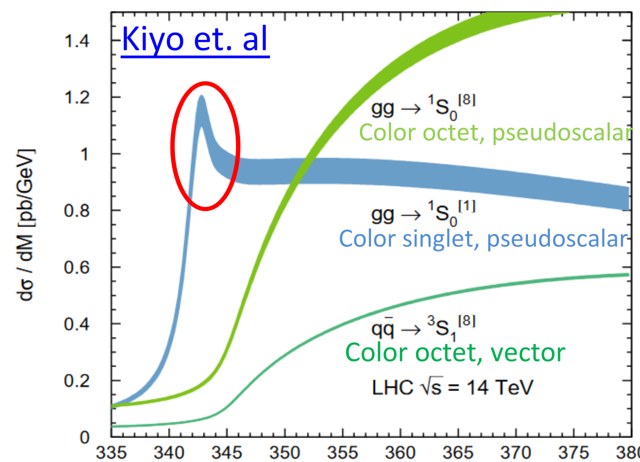


- Add “toponium” (pseudo-scalar color singlet predicted by non-relativistic QCD)*

A simple model:

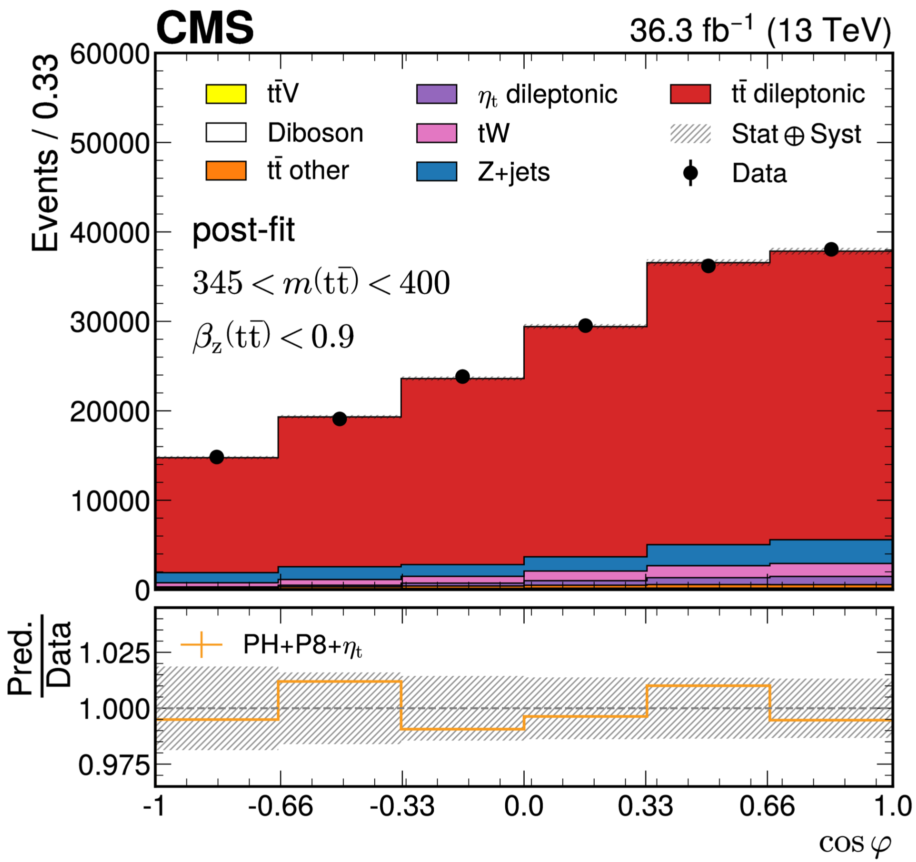
- Color singlet, pseudoscalar
  → maximally entangled
- Interacts only with t and g
- $m(\eta_t) = 343\ GeV$
- $\sigma(pp \to \eta_t) = 6.43\ \pm 0.90$ pb
- $\Gamma_{\eta_t} = 7\ GeV$

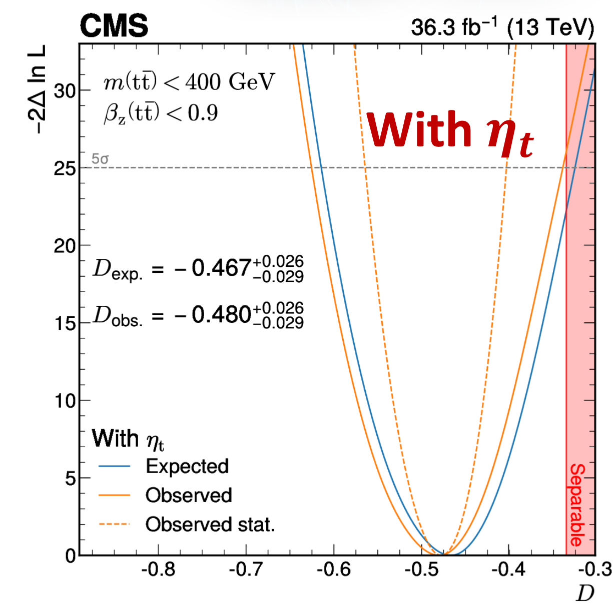


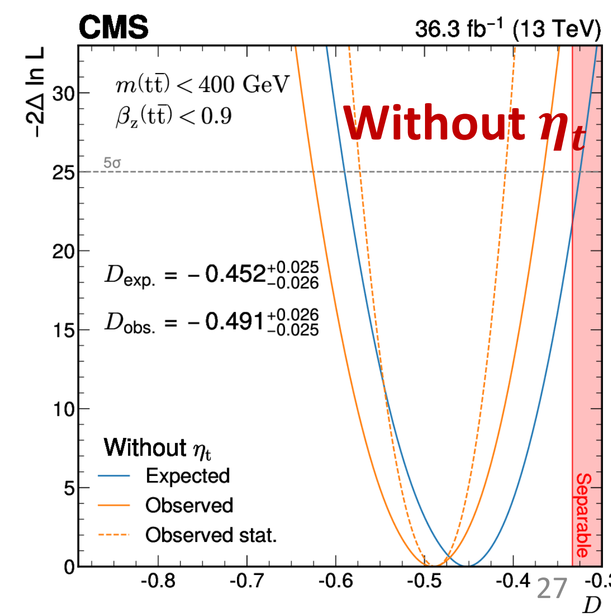


[*] Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)
Jezabek, Kuhn & Teubner (Z.Phys.C`92)
B. Fuks et al. (PRD 104 (2021) 034023)
F. Maltoni et al. JHEP03(2024)099

Entanglement: 2ℓ channel

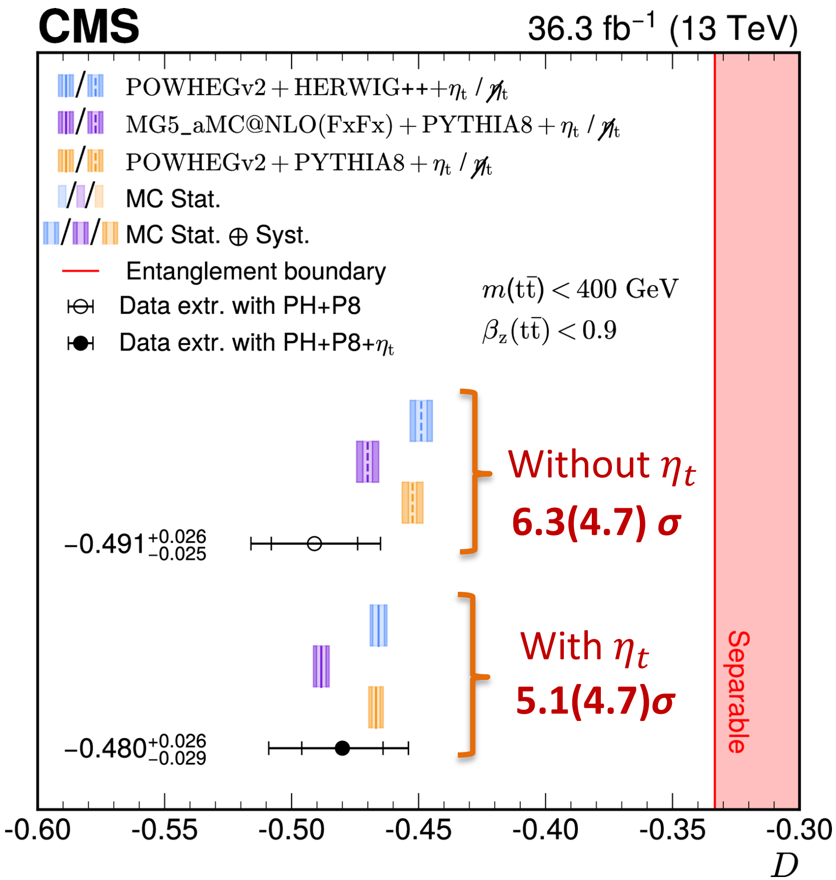






Profile likelihood scan as a function of D, when including (top) or excluding (bottom) the η_t contribution

Entanglement: 2ℓ channel

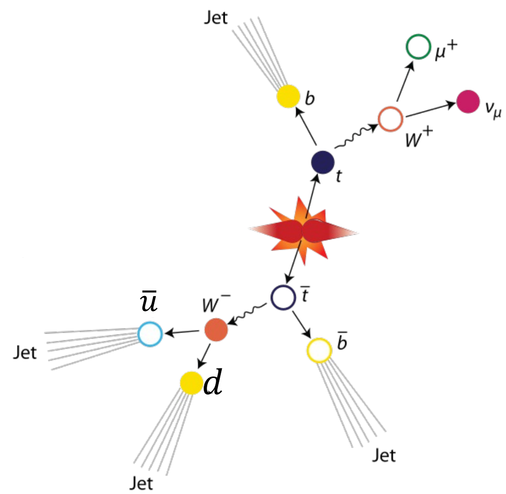


- Entaglement observed with $> 5\sigma$ for $345 < m(t\bar{t}) < 400\ GeV,\ \beta < 0.9$
- ~1.5σ tension with the expectation if toponium is not included

Main uncertainties:

- η_t normalization
- Jet energy calibrations
- Top p_T modeling
- Parton Shower modeling

CMS, $\ell + jets$ channel

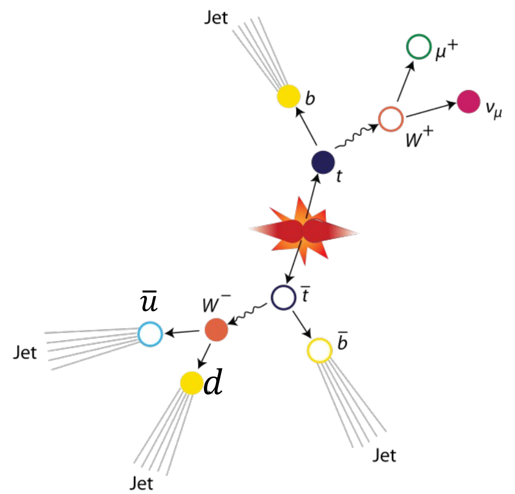


- Full Run II data
- e/μ + 4 jets, ≥1 bjets

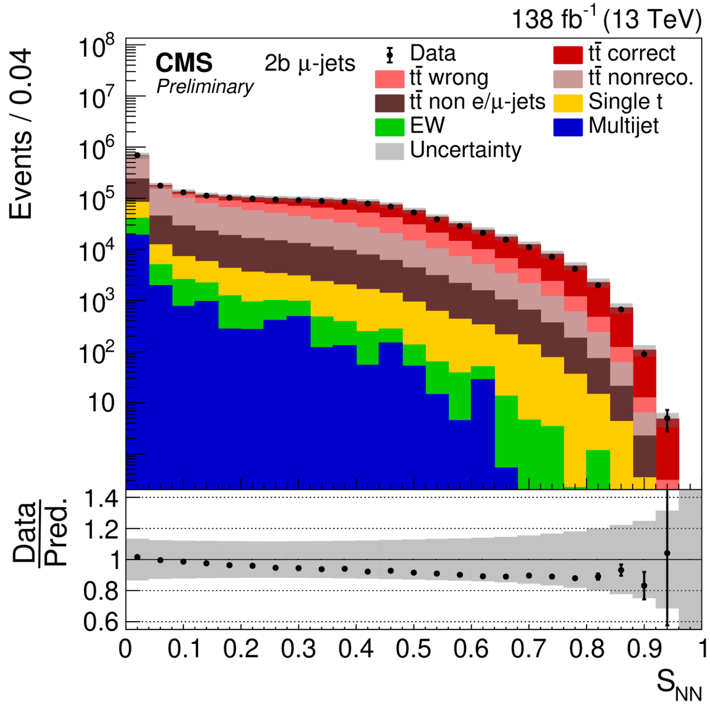
Complementary in many aspects…

- Higher branching fraction, larger statistics at high $m_{t\bar{t}}$
- Spin information via ℓ/d-quark as opposed to $\ell\ell$
- Higher p_T thresholds → less sensitive to low $m_{t\bar{t}}$
- Better $m_{t\bar{t}}$ resolution (only 1 ν)
- More space-like $t\bar{t}$ as opposed to time-like in di-leptons
- di-leptons have potential discovery of toponium
- Higher potential to observe *Bell inequality*

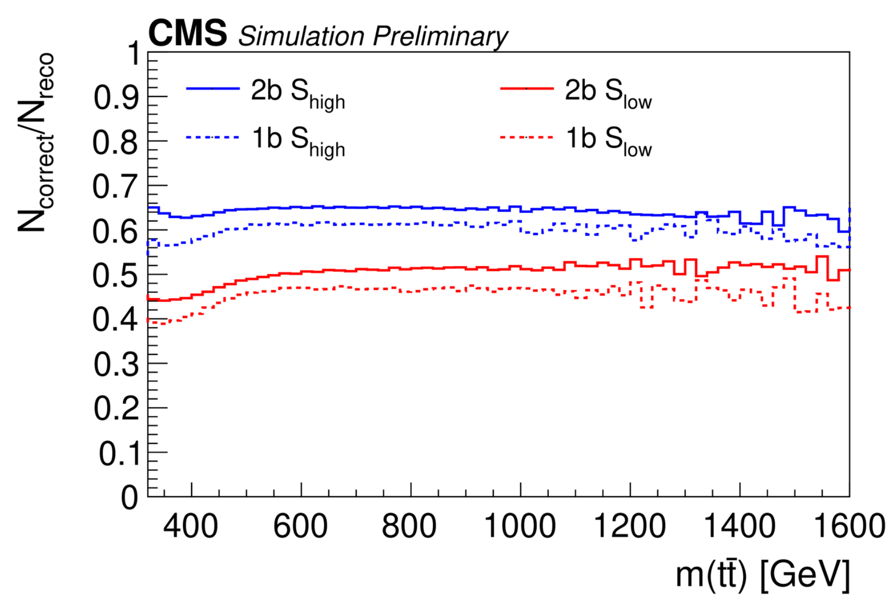
CMS, $\ell + jets$ channel



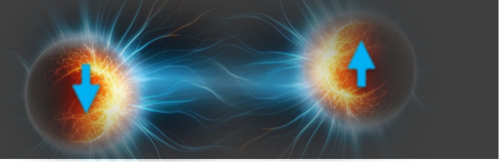
- Full Run II data
- e/μ + 4 jets, ≥1 bjets
- Top recostruction, NN, correct assignment
- Use all possible permutations of up to eight jets in $t\bar{t}$ and train against correctly assigned $t\bar{t}$

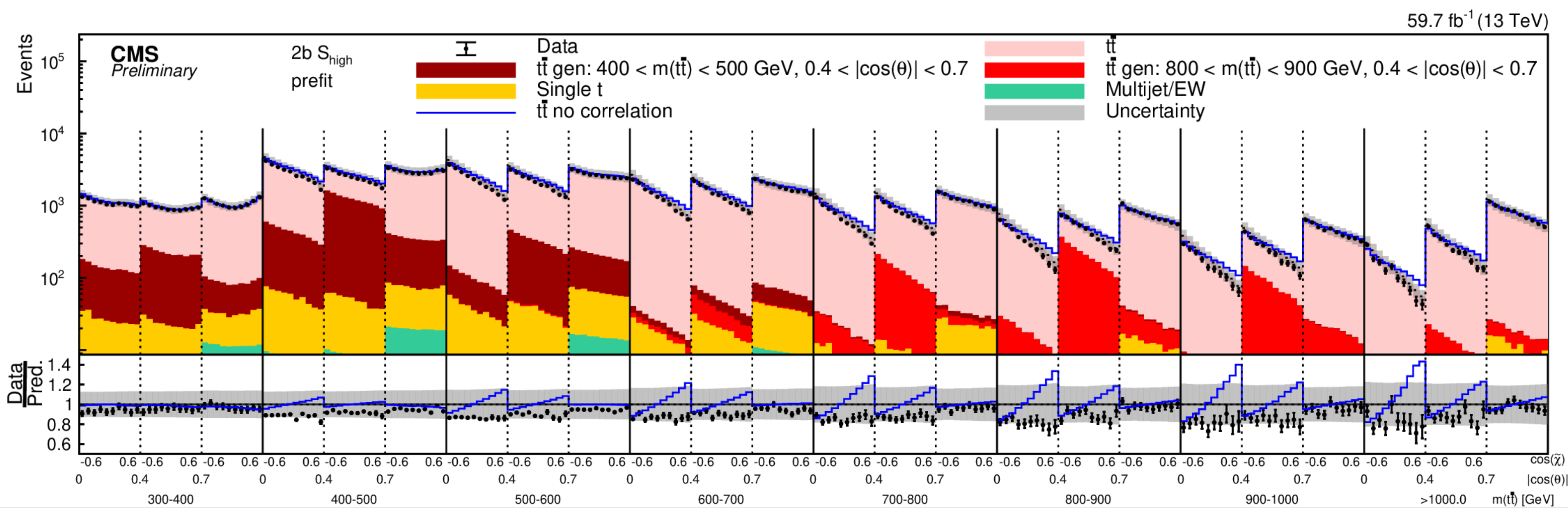


The fraction of correctly reconstructed events



Fitted distributions of $\cos\varphi$

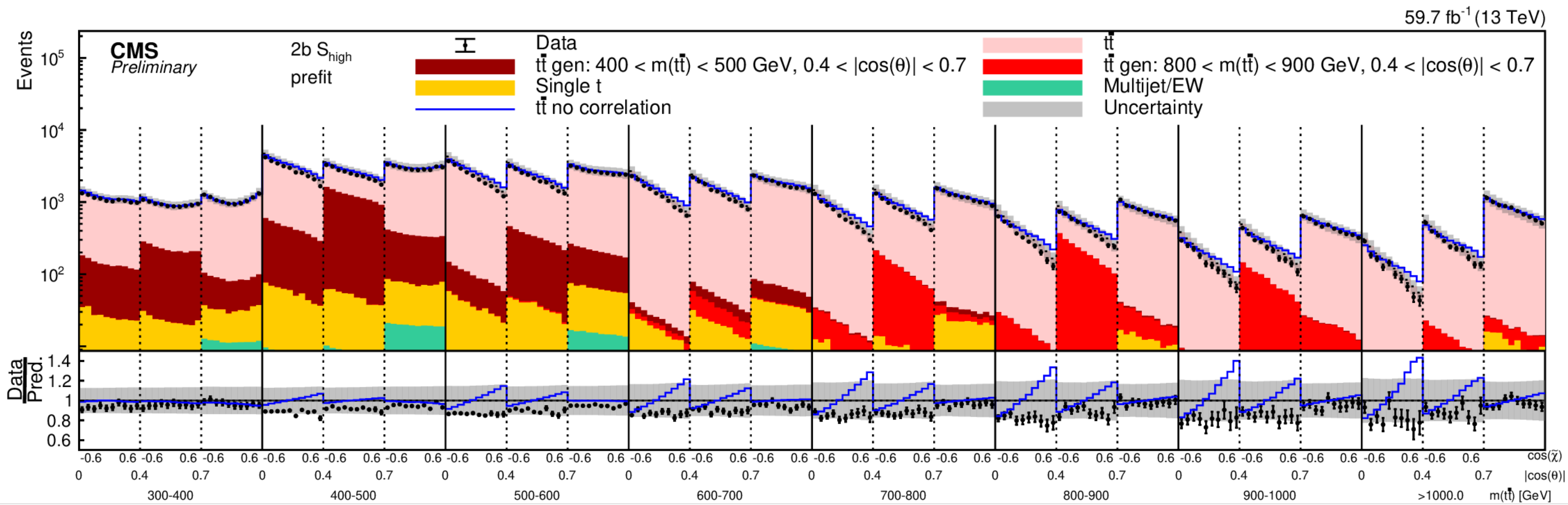


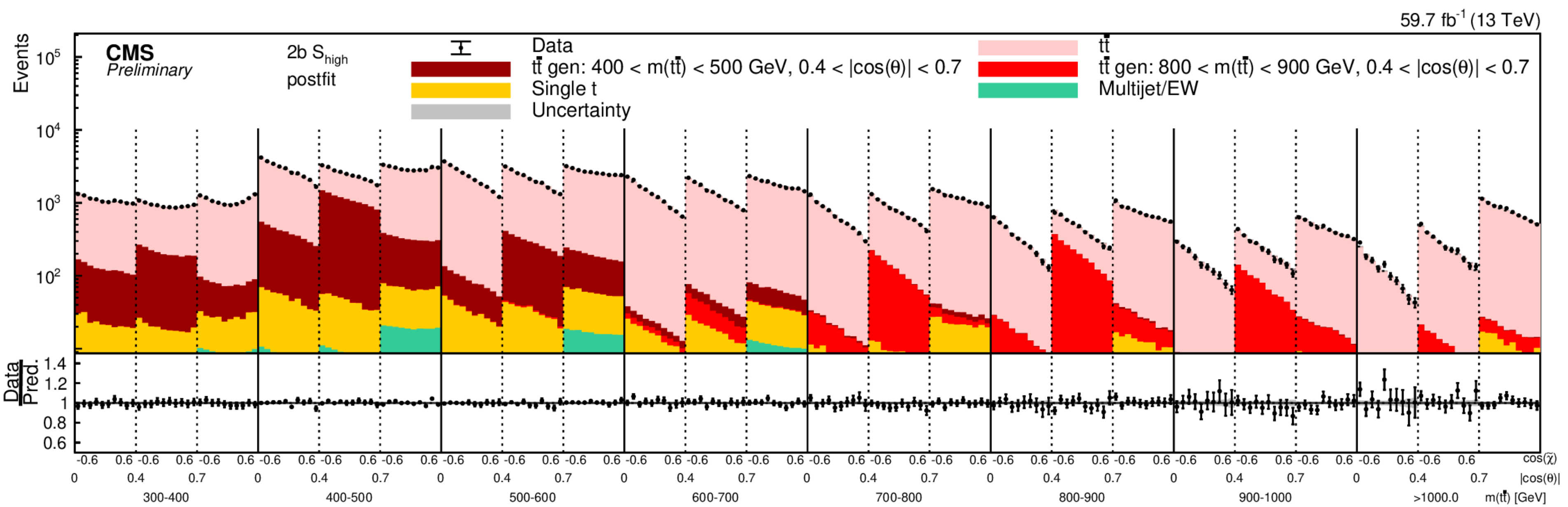


Low $m(t\bar{t})$ High $m(t\bar{t})$

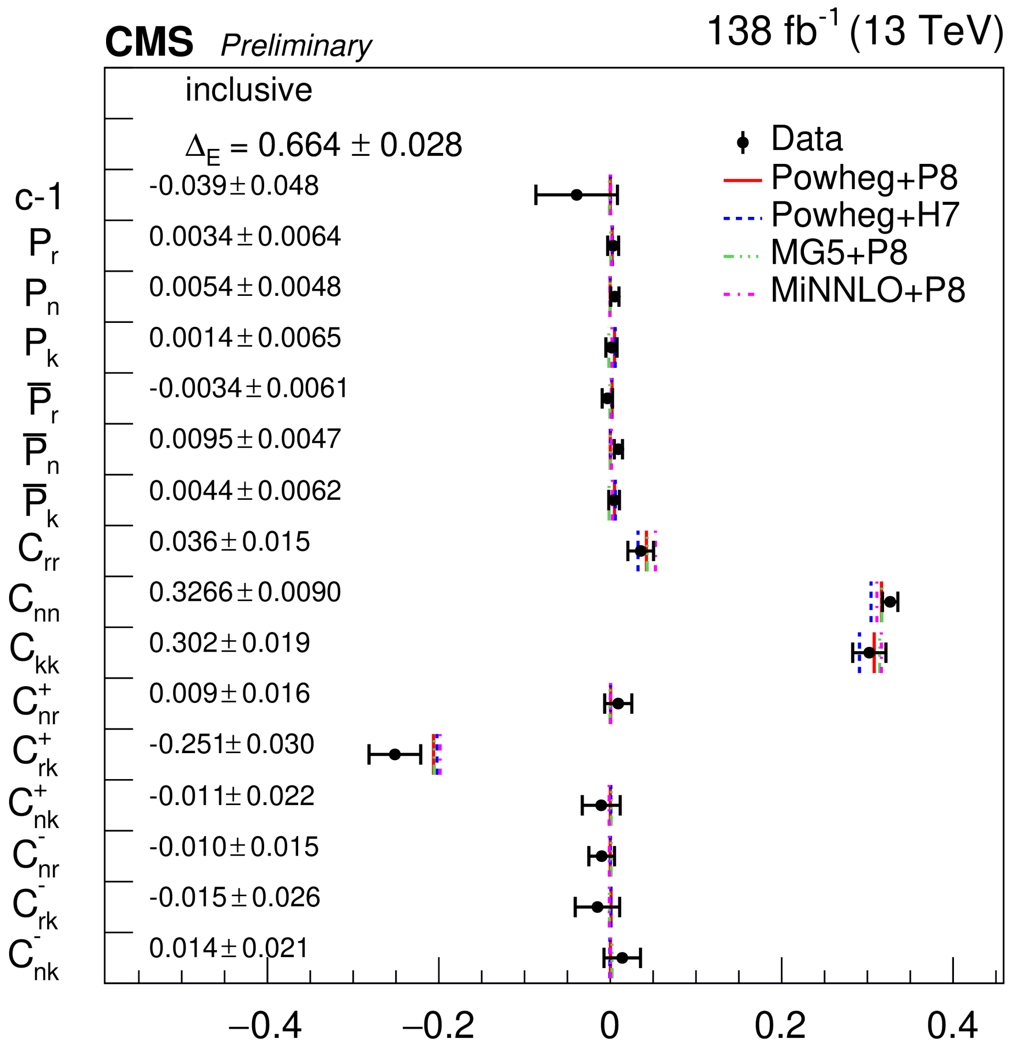
Profile likelihood fits to $\cos\varphi$ in bins of $m(t\bar{t})$ and $|\cos\theta|$

Fitted distributions of cos φ



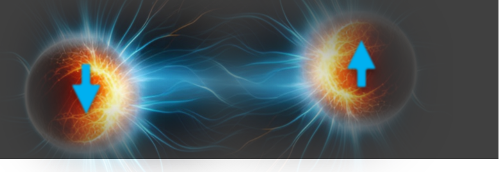


Measured P_i and C_{ij}

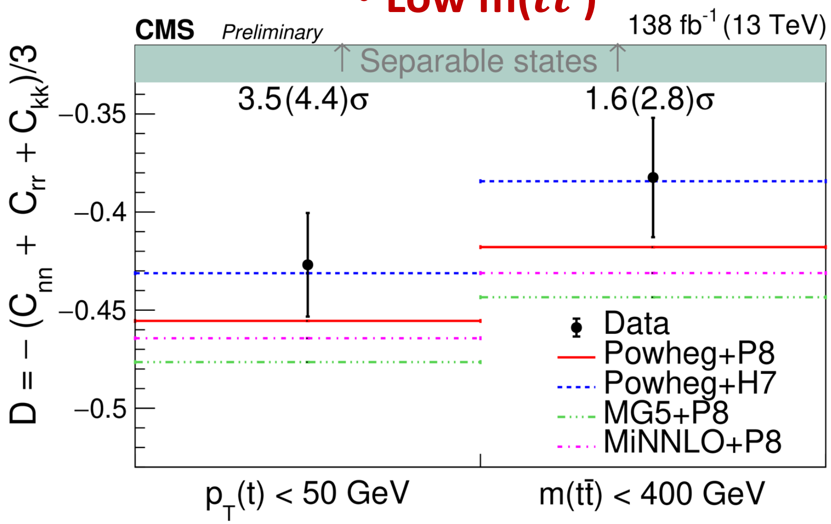


- Full extraction of ttBar polarization & spin-correlation matrix in various kinematical regions.
- Data agrees with the SM predictions within uncertainties

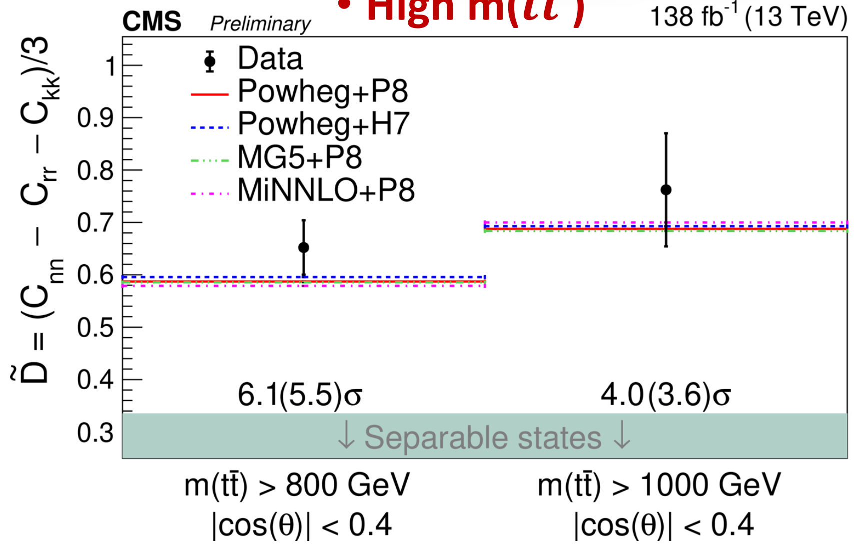
Entanglement: $\ell + jets$ channel



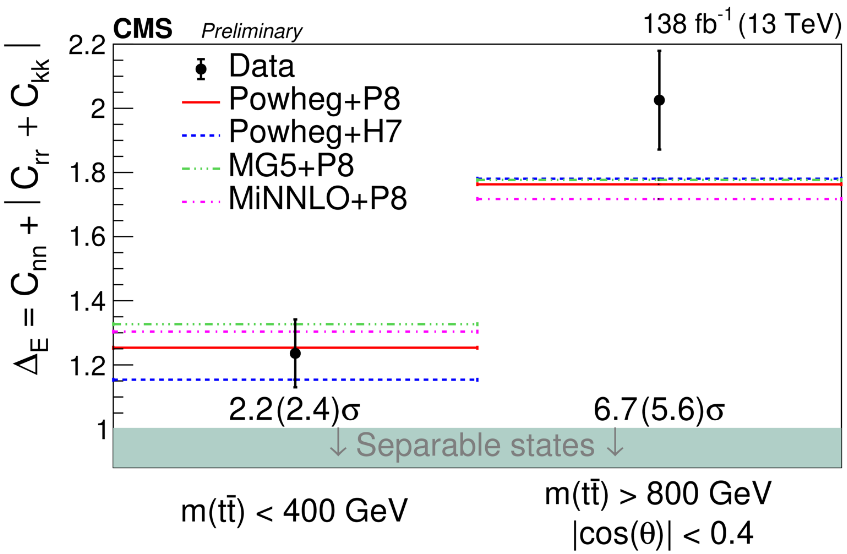
- **Low $m(t\bar{t})$**



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

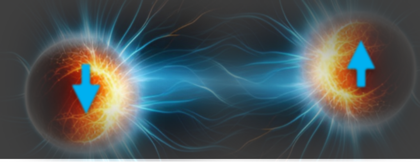


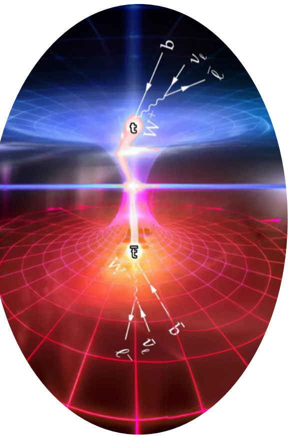
Extraction via Spin correlation matrix C_{ii}



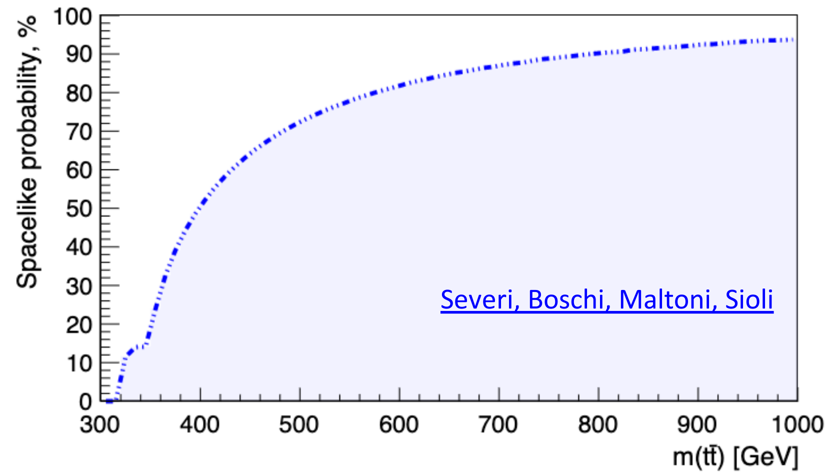
- Complementarity wrt. dilepton channel
- Entanglement is established at **high $m(t\bar{t})$ for the first time with >5σ**
- D is in general lower wrt. data when entanglement is significant

Excluding classical explanation



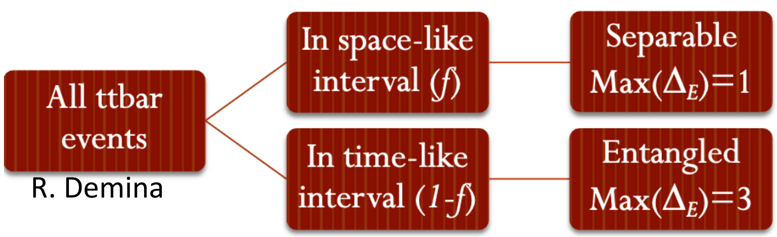


- What is the maximum value of ΔE that can still be explained by the non-quantum communication ($v \leq c$)?
- In this case only t and $\bar{t}$ decays separated by a time-like interval are entangled
- The rest of the events must be separable



- $t\bar{t}$ decay vertices are not observed, the fraction of space-like events, f, can only be determined statistically

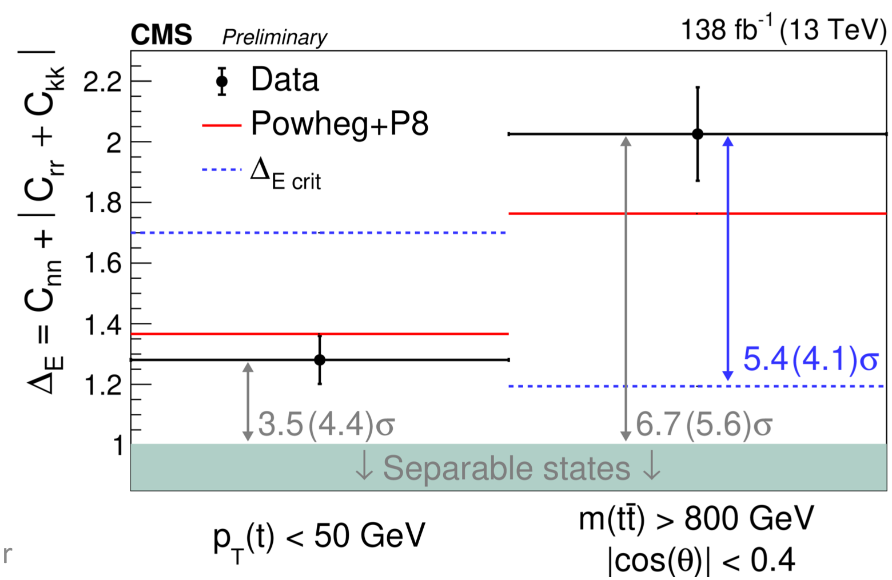
→ Form a new Δ_E threshold



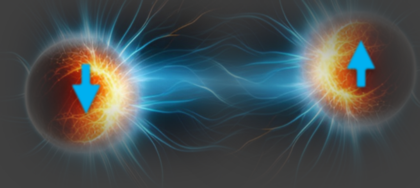
R. Demina

$$Max(|C_{ii}|) = 1$$

$$\Delta_{Ecritical} = f(\Delta_E = 1) + (1 - f)(\Delta_E = 3)$$



D. Dobur



• Tops at LHC rock!

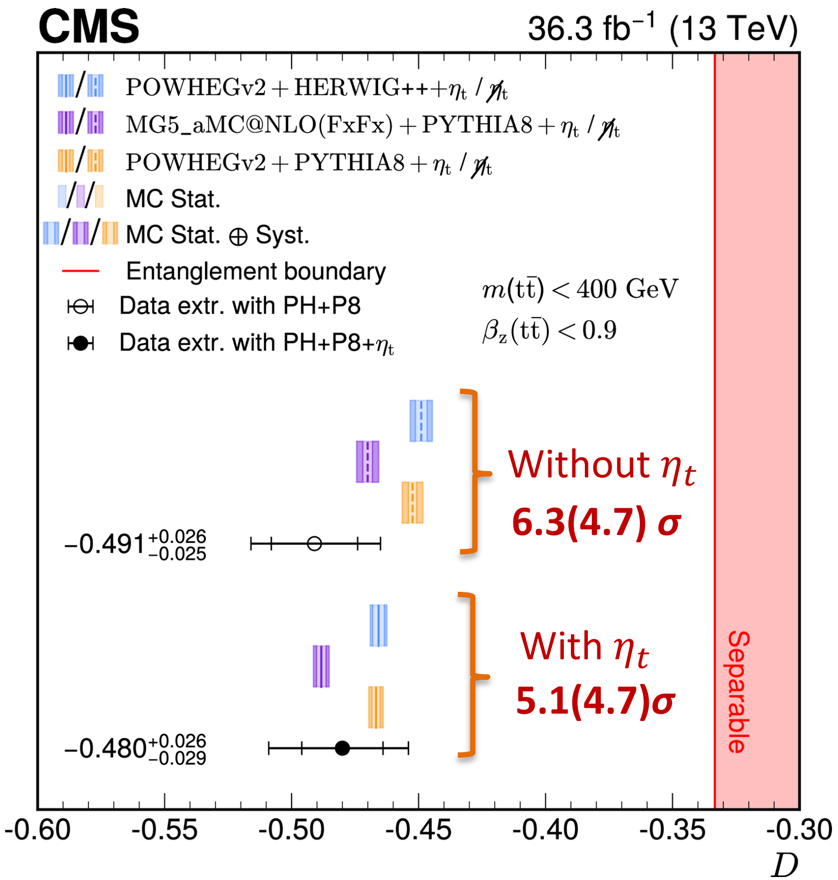
- Entanglement in top quark pairs is observed with $> 5\sigma$
  - By both CMS and ATLAS
  - Multiple analyses in different phase-space regions!
- Tests quantum entanglement in a new environment…
- A new experimental tool to search for new physics!
- Exciting sensitivity to toponium state!
- More work on the theoretical side is needed… modelling sensitivity & toponium

Backup

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

by David Andreatta, University of Rochester

Entanglement: 2ℓ channel



- Entaglement observed with $> 5\sigma$ for $345 < m(t\bar{t}) < 400\ GeV,\ \beta < 0.9$
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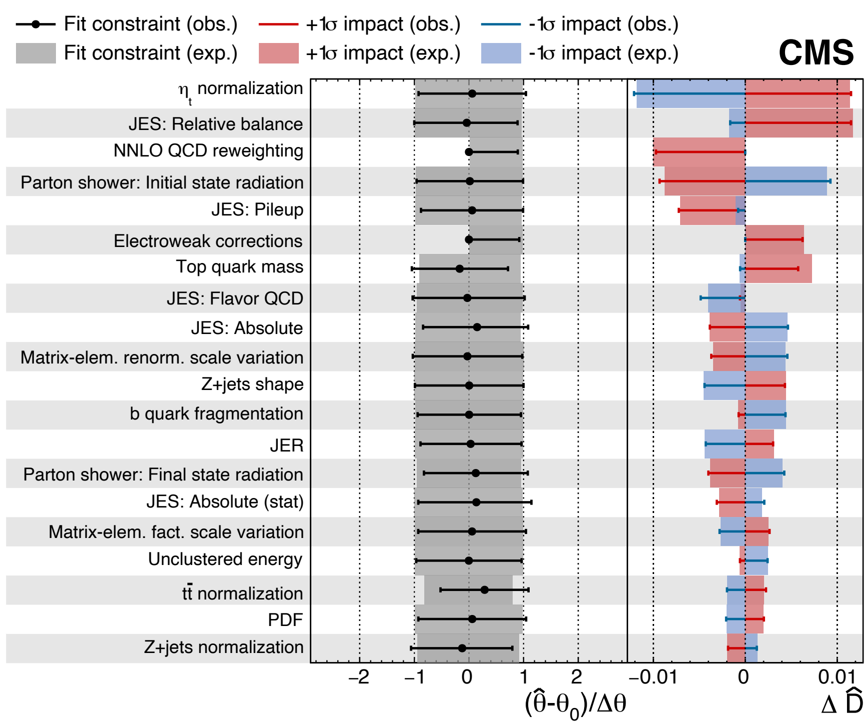


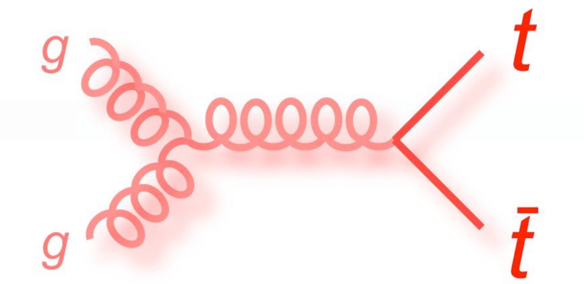
<u>Main uncertainties:</u>

- η_t normalization
- Jet energy calibrations
- Top p_T modeling
- Parton Shower modeling

D. Dobur

Spin correlation in top-pairs

10.1007/JHEP12(2015)026
Bernreuther et al.



- NWA → production and decay can be factorized

$$|\mathcal{M}|^2 \sim \mathrm{Tr}[\rho R \bar{\rho}]$$

$\rho / \bar{\rho}$: top decay density matrices
R : Spin density matrix

- Study the properties of R, sensitive to new physics effects
- R can be decomposed in $t / \bar{t}$ spin space using Pauli matrices

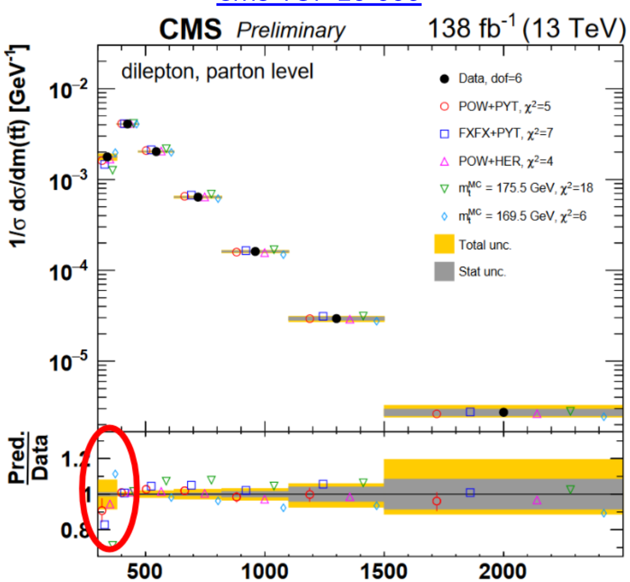
$$R \propto \left[\tilde{A}\, \mathbb{I} \otimes \mathbb{I} + \tilde{B}_i^{+}\, \sigma^i \otimes \mathbb{I} + \tilde{B}_i^{-}\, \mathbb{I} \otimes \sigma^i + \tilde{C}_{ij}\, \sigma^i \otimes \sigma^j\right]$$

- $\tilde{A}\, \mathbb{I} \otimes \mathbb{I}$: total cross-section and top kinematics
- $\tilde{B}_i^{+}\, \sigma^i \otimes \mathbb{I} + \tilde{B}_i^{-}\, \mathbb{I} \otimes \sigma^i$: 3 – vectors of functions characterizing $t\bar{t}$ polarization along each axis
- $\tilde{C}_{ij}\, \sigma^i \otimes \sigma^j$: 3x3 matrix of functions characterizing spin correlation of $t\bar{t}$

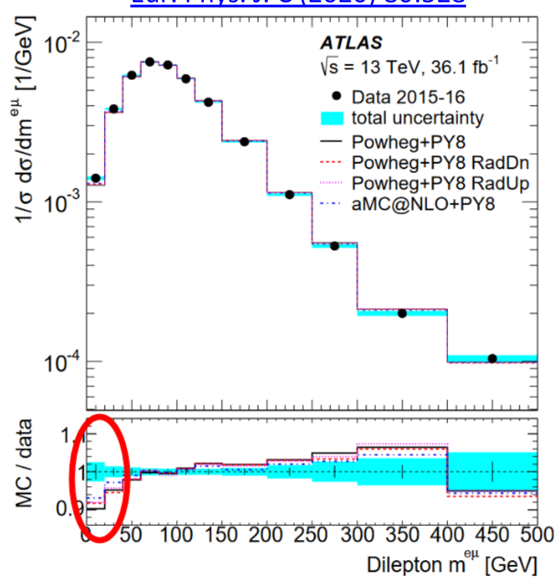
$m_{t\bar{t}}$ mismodeling

- Mismodeling around $m_{t\bar{t}} \approx 345\ GeV$ is not new and observed across different analyses and experiments

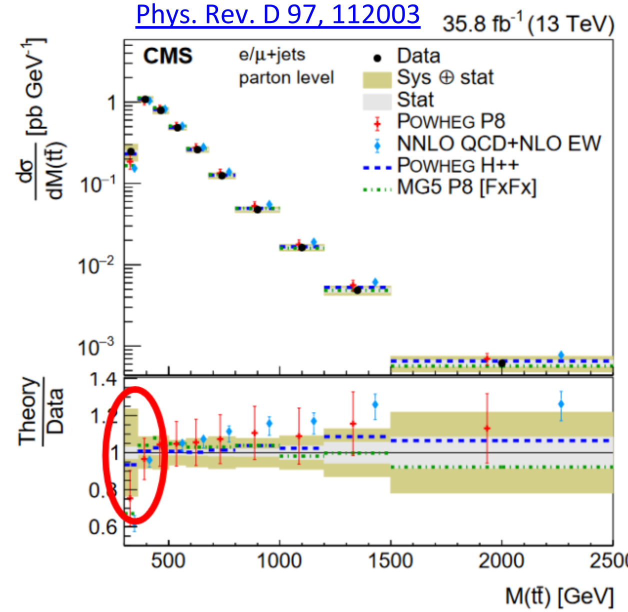
CMS-TOP-20-006



Eur. Phys. J. C (2020) 80:528



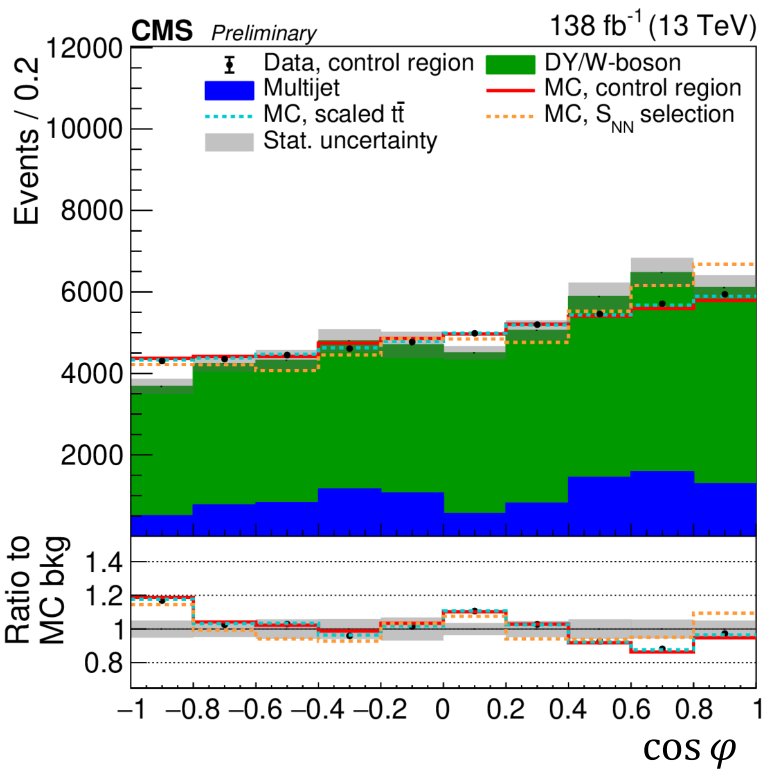
Phys. Rev. D 97, 112003

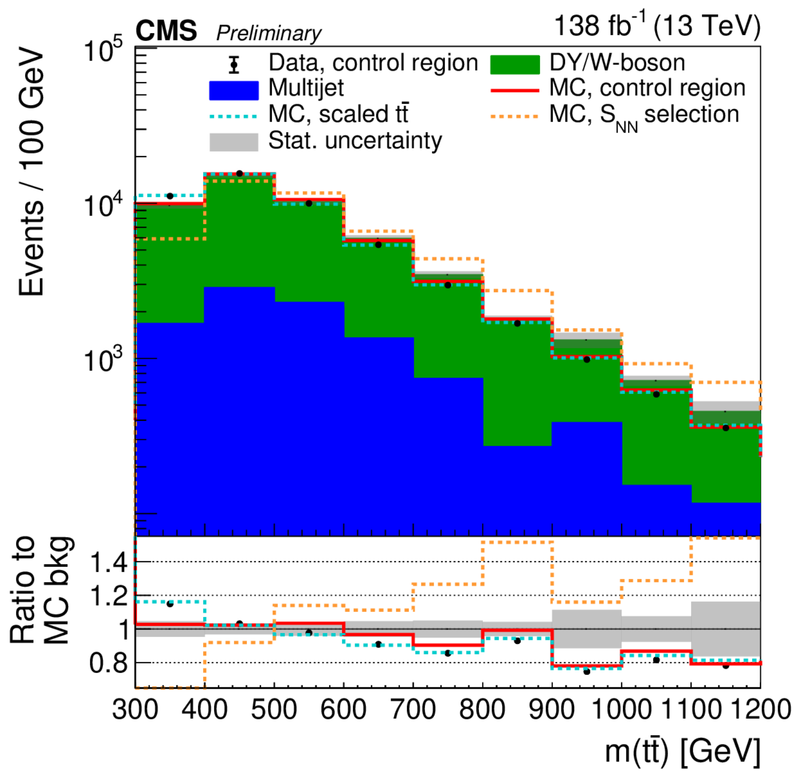


$\ell + jets$ channel

Backgrounds:

- Small contriutions… ~10% in signal regions: DY, W+jets, QCD,
- Background templates obtained from reduced b–jet control region
- Systematic uncertainties from these omparissons, up to 50%, mainly statistical





- Single-top from simulation (<4%)

Bell Theorem: Bell carried the analysis of quantum entanglement much further. He deduced that if measurements are performed independently on the two separated particles of an entangled pair, then the assumption that the outcomes depend upon hidden variables within each half implies a mathematical constraint on how the outcomes on the two measurements are correlated. This constraint would later be named the **Bell inequality**. Bell then showed that quantum physics predicts correlations that violate this inequality. Consequently, the only way that hidden variables could explain the predictions of quantum physics is if they are "nonlocal", which is to say that somehow the two particles are able to interact instantaneously no matter how widely they ever become separated.[4][5]

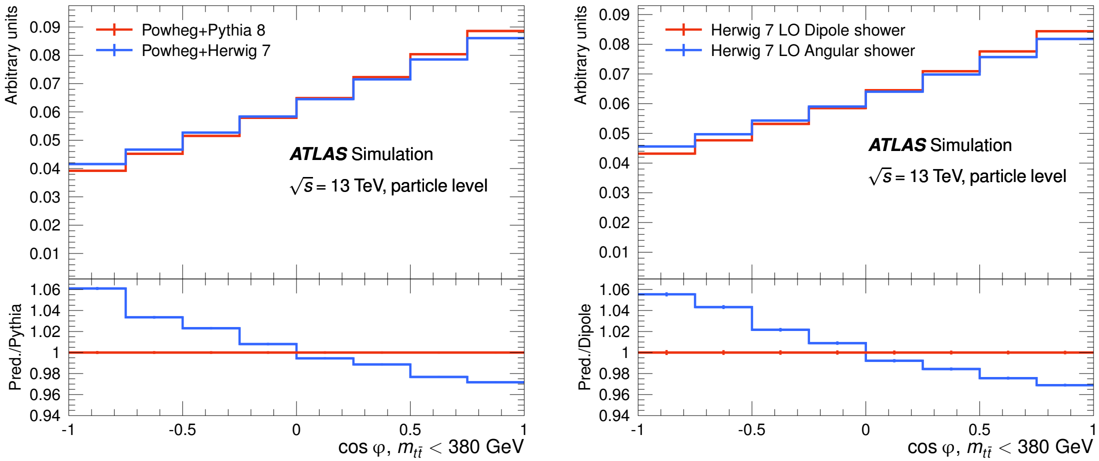
CMS, $\ell + jets$ channel

- Dilepton based on PRD 100 (2019) 072002
  - Lower branching ratio
  - |κ|=1 for charged leptons, which are easy to ID →Ideal channel for spin correlation
  - Lower p_T cuts for leading/subleading lepton (25/20 GeV) → higher efficiency at the threshold
  - Worse M_{tt} resolution, not ideal for differential measurement
  - **Best for threshold**
    - **high entanglement**
    - **potential for "toponium" observation**
    - **mostly time-like separated events**
  - **CMS Top-23-001**

- Lepton+jets
  - Higher branching ratio
  - |κ|=1 for down-type quarks, but they are harder to identify – employ AI (~66%)
  - Higher p_T cut for single lepton (30 GeV) and for 4 jets (30 GeV)→ lower efficiency at the threshold, but OK for high M_{tt}
  - Better M_{tt} resolution, good for differential measurement
- **Advantage for high M_{tt}**
  - **high entanglement**
  - **potential for observation of Bell Inequality violation**
  - **mostly space-like separated events**
- **CMS Top-23-007**

Slide from R. Demina

Parton shower modeling



(a) (b)

Figure 4: Comparison between cos φ distributions in the signal region with $m_{t\bar{t}} < 380$ GeV for different MC event generator setups at stable-particle level. Figure (a) compares events simulated with Powheg Box which are interfaced with either Pythia (red line, p_{T}-ordered dipole shower) or Herwig (blue line, angular-ordered shower) while figure (b) compares events simulated with Herwig using either a dipole-ordered shower (red line) or an angular-ordered shower (blue line).

Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

ATLAS ttBar modelling:

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

Top Reconstruction

- Three methods:
  - 85%: Ellipse Method. Calculates two ellipses for p_T^{ν} and finds the intersections.
  - 5%: Neutrino Weighting.
  - 10%: Rudimentary pairing.
- The solution with the smallest $m_{t\bar{t}}$ is taken.

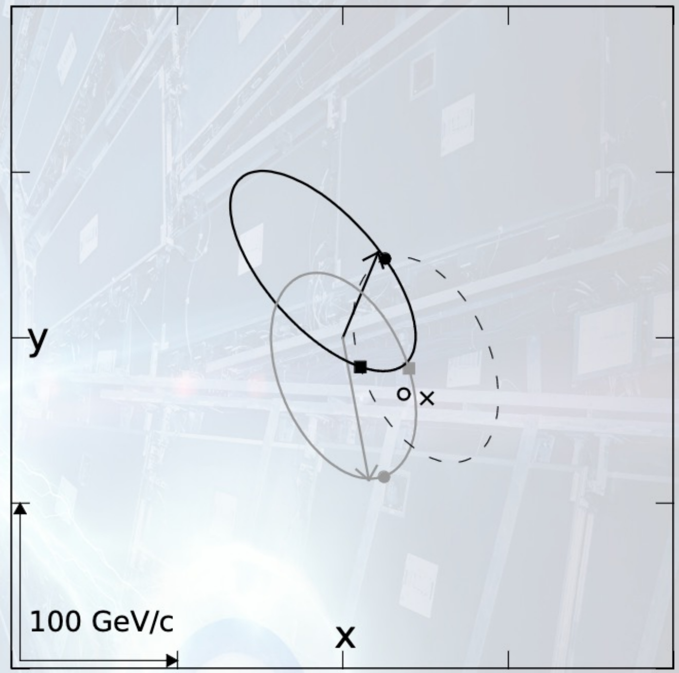


Figure: Constrain on neutrino momenta. Figure is from Nucl.Instrum.Meth.A 736 (2014) 169-178.

Systematic Uncertainties

- Three categories:
  - Signal ($t\bar{t}$) modeling.
  - Background modeling.
  - Detector uncertainties.

Systematic source	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD (%)
Signal Modelling	0.015	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.8
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.4
Backgrounds	0.009	1.8
Stat.	0.002	0.4
Syst.	0.018	3.9
Total	0.018	3.9

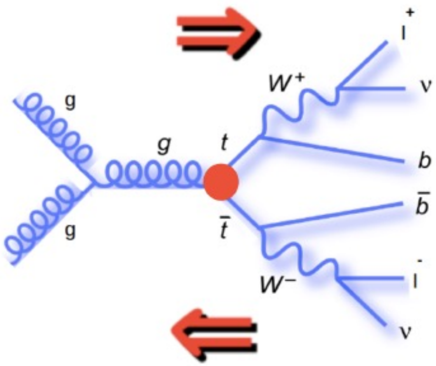
Table: Systematic uncertainties for the **expected** D.

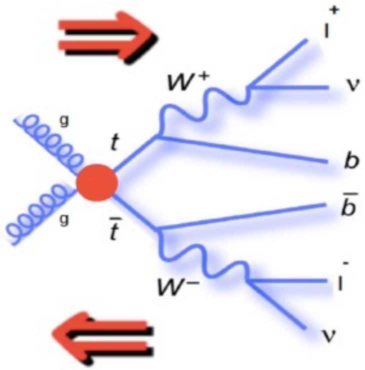
- Signal ($t\bar{t}$) modeling breakdown:
  - Top decay (MadSpin): 1.6%
  - PDF (PDF4LHC): 1.2%
  - Recoil To Top: 1.1%
  - FSR: 1.1%
  - Scales (μ_R, μ_F): 1.1%
  - NNLO Reweighting: 1.1
  - pThard1 (`pThard = 1`): 0.8%
  - m_t (172.5 ± 0.5 GeV): 0.7%
  - ISR: 0.2%
  - Parton Shower (Herwig): 0.2%
  - h_{damp}: 0.1%
- Background modeling is dominated by $Z \to \tau^+\tau^-$ uncertainty.
- For each systematic, we extract a curve. The difference w.r.t. the nominal curve is the uncertainty.

Constraining CMDM (1)

- Several BSM scenarios predict anomalous Chromomagnetic Dipole Moment → modified cross-sections and top kinematics
- Use EFT framework to constrain anomalous CMDM at NLO precision

$$O_{tG} = y_t g_s (Q\sigma^{\mu\nu} T^a t)\tilde{\phi} G^a_{\mu\nu}$$

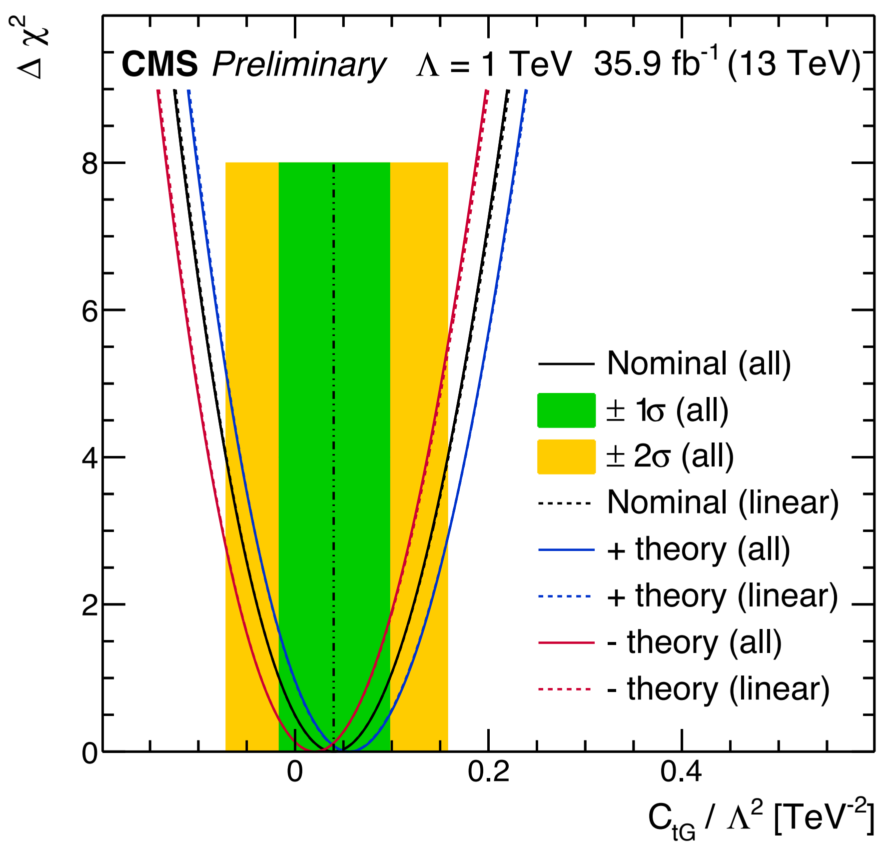




- O_{tG} induces top chirality flip → spin density matrix measurement is a perfect ground for testing
- Signal samples with MG5_aMC@NLO+MadSpin+Pythia
- χ^2 minimization using 20 normalized differential distributions at parton level and the covariance matrix

Constraining CMDM (2)

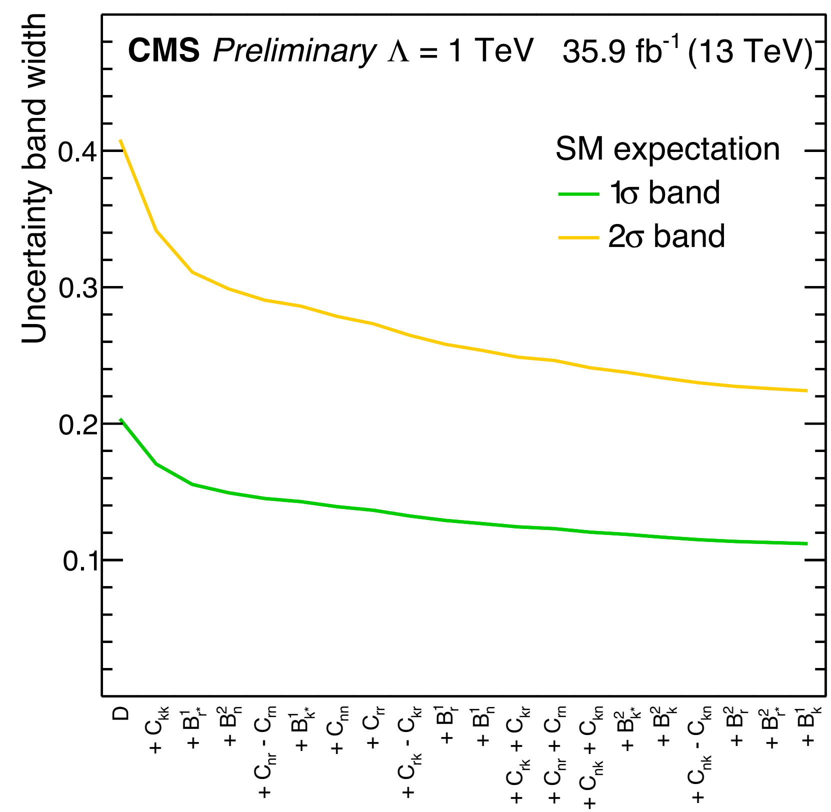
Best constraint to date



- ~55% more stringent constraints compared to those obtained by using $\Delta\phi(\ell\ell)$ only

arXiv:1811.06625 (CMS)

sensitivity evolution

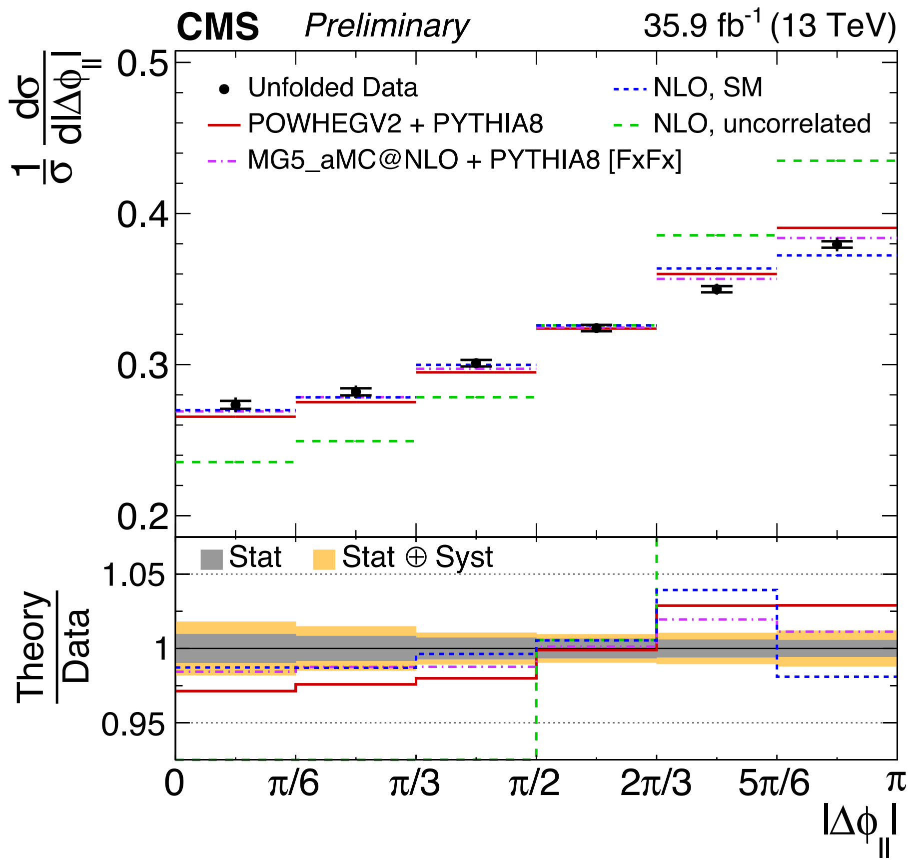


- Largest constrain from:

$$D = -(C_{kk} + C_{rr} + C_{nn})/3$$

but all measurements contribute

$\Delta\phi(\ell\ell)$ at parton level



- Data is compared to:
  - NLO predictions from POWHEG and MADGRAPH
  - NLO (QCD) + EWK corrections (JHEP 12 (2015) 026, W. Bernreuther, et.al)
  - NLO with no spin correlation

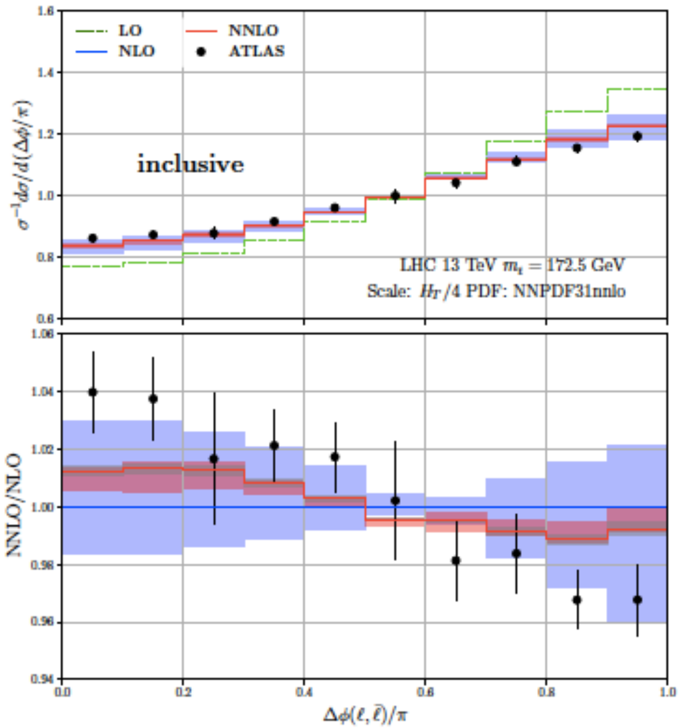
- POWHEG: steeper than data
- NLO calculations: improved description

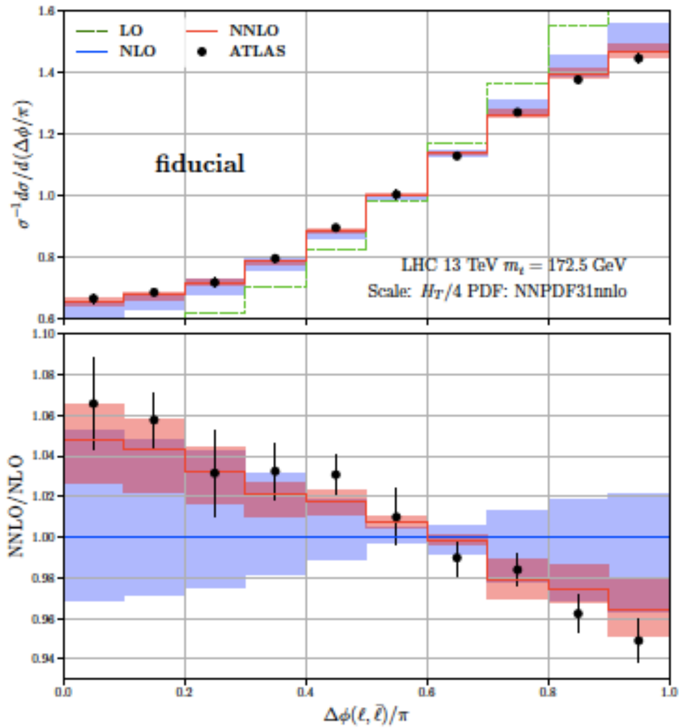
Main systematic uncertainties:

- Top p_T modeling
- ME-PS Matching
- QCD scale choice
- Background & PDF

from LPCC meeting by R.Poncelet

$\Delta\phi(\ell, \bar{\ell})$ Theory vs. data from ATLAS-CONF-2018-027

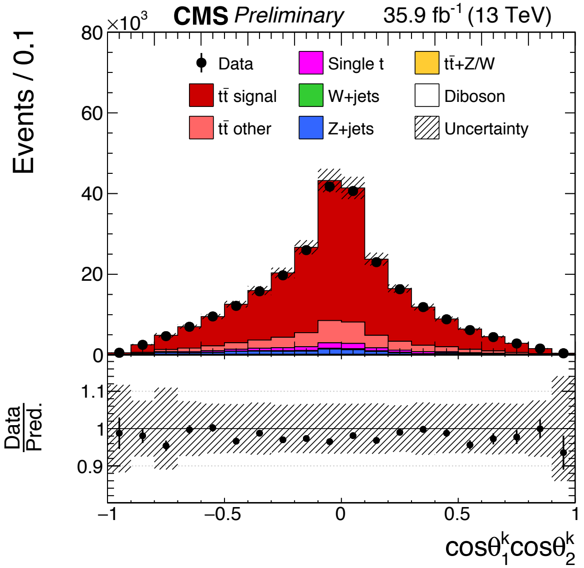




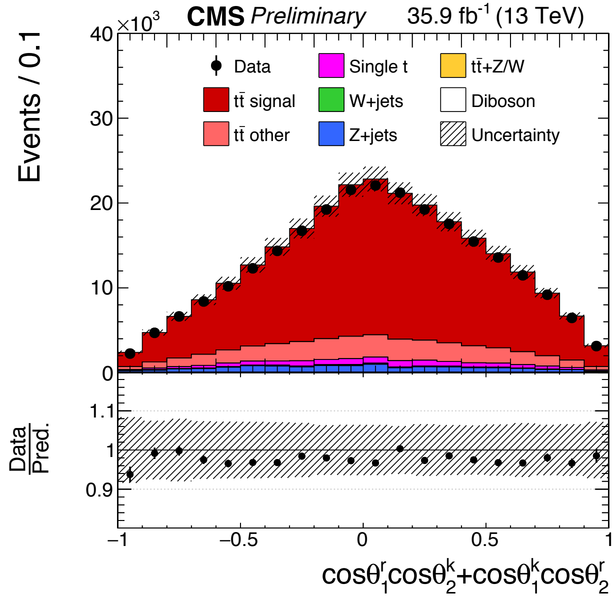
Perfect agreement in fiducial, differences in inclusive phase space
$\rightarrow$ possibly hints at differences in the extrapolation to inclusive phase space

Measured distributions (2)

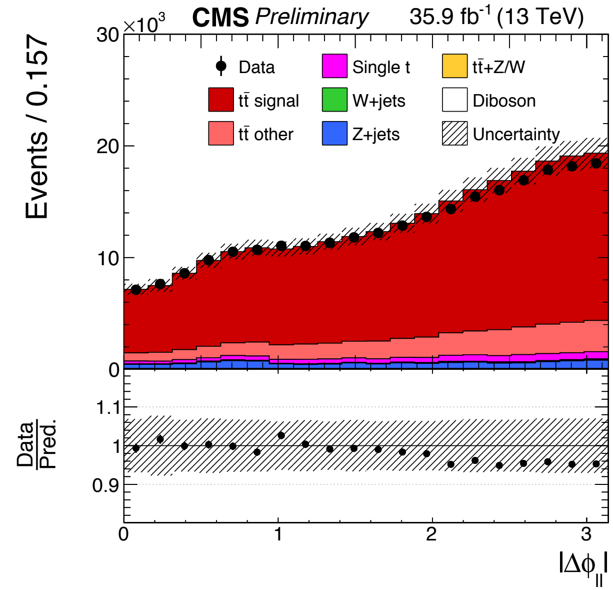
$\cos\theta_1^k \cos\theta_2^k$

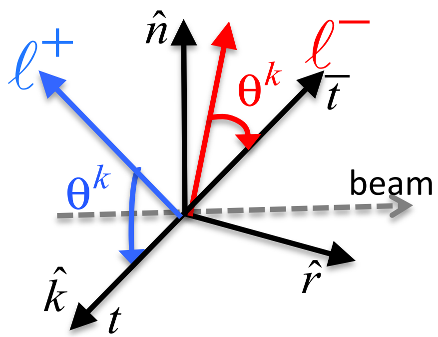


$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$



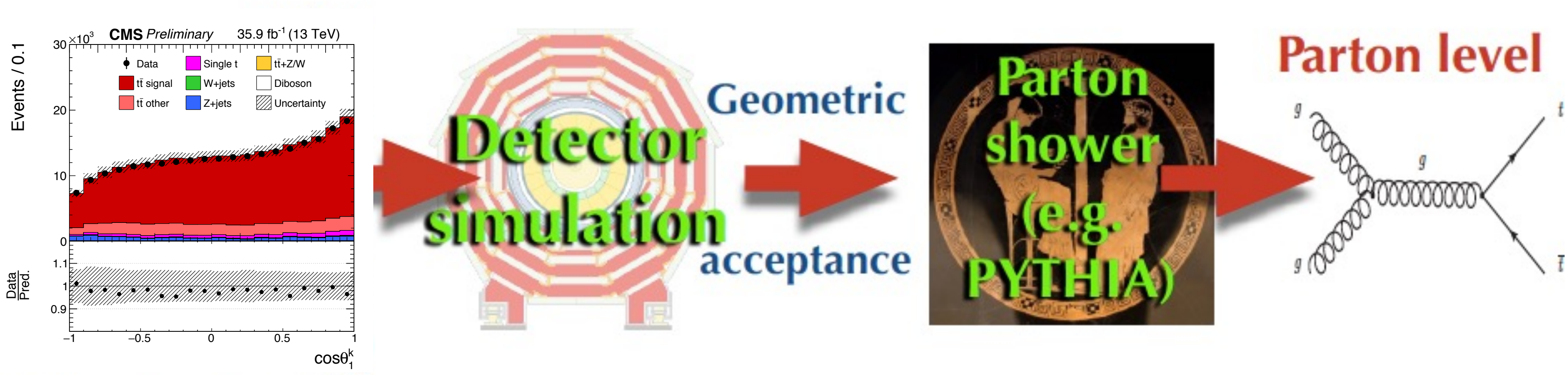
$|\Delta\phi(\ell\ell)|$





- Overall good agreement between observed and expected distributions
- Slight tension in $\Delta\phi(\ell\ell)$ shape, but within the uncertainties

Unfolding to parton level



- Unfold the distributions to parton level (TUnfold (arXiv:1205.6201))
- 6 equal bins in all distributions → detector resolution
- An optimized method to reduce the bias from unfolding:
  - regularization based on the known functional forms at parton-level, which are unaffected by NP effects in production
- Experimental and theory modeling uncertainties estimated via repeated unfolding each with a systematic shift

Experimental observables

Coefficients of the spin density matrix can be extracted from :

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^i_+ \, d\cos\theta^j_-} = \frac{1}{2}(1 + B^i_+\cos\theta^i_+ + B^j_-\cos\theta^j_- - C_{ij}\cos\theta^i_+ \, d\cos\theta^j_-)$$

Can be reduced to single differential cross sections

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^i_\pm} = \frac{1}{2}(1 + B^i_\pm\cos\theta^i_\pm)$$

Polarization coefficients

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 - C_{ii}x)\ln(|x|^{-1})$$

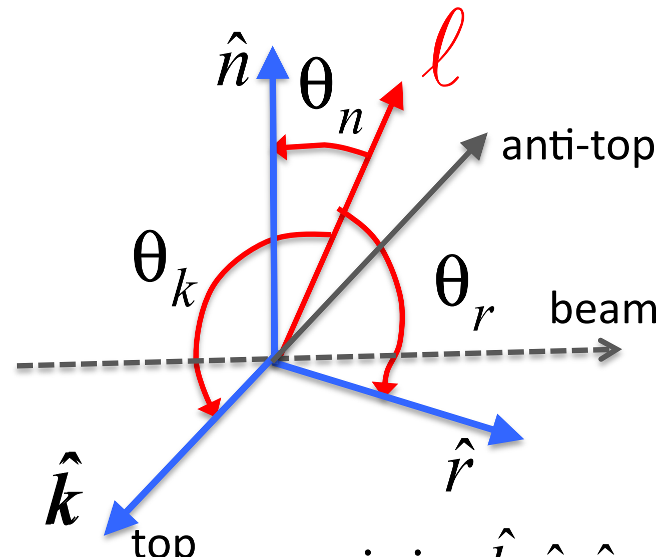
$$x = \cos\theta^i_+\cos\theta^i_-$$

diagonal elements of spin density matrix

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 - \frac{C_{ij} \pm C_{ji}}{2}x\right)\cos^{-1}|x|,$$

$$x = \cos\theta^i_+\cos\theta^j_- \pm \cos\theta^j_+\cos\theta^i_-$$

off-diagonal elements of spin density matrix



$$i, j = \hat{k}, \hat{r}, \hat{n}$$

spin density matrix

$\tilde{B}_i^{\pm}$ and $\tilde{C}_{ij}$ can be decomposed in terms of orthonormal basis $\{\hat{k},\hat{r},\hat{n}\}$:

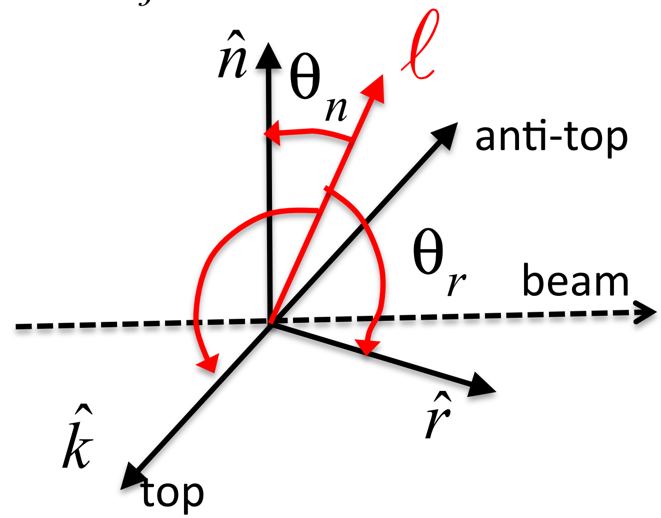
$$\tilde{B}_i^{\pm} = b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{k}_i + b_n^{\pm}\hat{k}_i$$

$$\begin{aligned}\tilde{C}_{ij} &= c_{kk}\hat{k}_i\hat{k}_j + c_{rr}\hat{k}_i\hat{k}_j + c_{nn}\hat{n}_i\hat{n}_j \\ &+ c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j) \\ &+ c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j)\end{aligned}$$

$\hat{p},\hat{k}$: incoming parton & top-quark direction in $t\bar{t}$ CMF

$\hat{n} = r^{-1}(\hat{p}\times\hat{k})$

$\hat{r} = r^{-1}(\hat{p} - y\hat{k}), \quad y = \hat{k}\cdot\hat{p}, \quad r = \sqrt{1-y^2}$

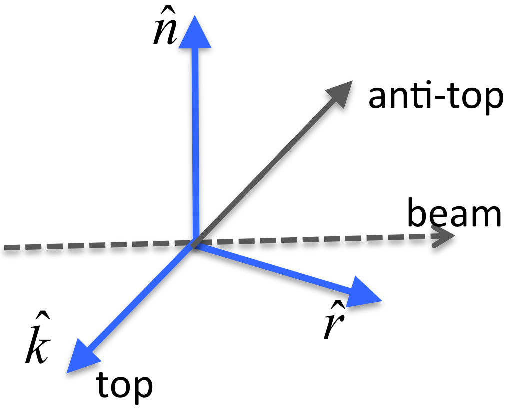


- $b_i^{\pm}$, c_{ij}, c_i are functions of partonic center of mass energy and y $(\cos\theta_t^*)$
- Coefficient functions can be classified w.r.t P,CP,T and Bose symmetry

Decomposition basis

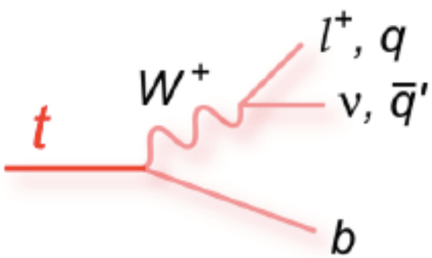
$\tilde{B}_i^{\pm}$ and $\tilde{C}_{ij}$ can be further decomposed in terms of orthonormal basis $\{\hat{k},\hat{r},\hat{n}\}$:

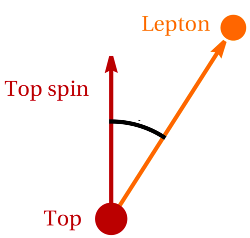
$\hat{p}$: incoming parton
$\hat{k}$: top-quark direction in $t\bar{t}$ CMF ("helicity")
$\hat{n}$ = normal to $t\bar{t}$ scattering plane ("transverse")
$\hat{r}$ = normal to $\hat{k}$ in $t\bar{t}$ scattering plane

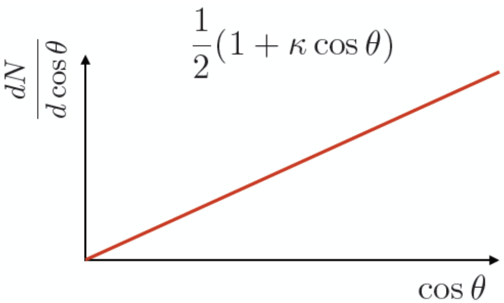


- In this basis the coefficient functions have definite P,CP,T → in case of a deviation can do NP characterization

Top quark's spin determines the angular distribution of its daughters



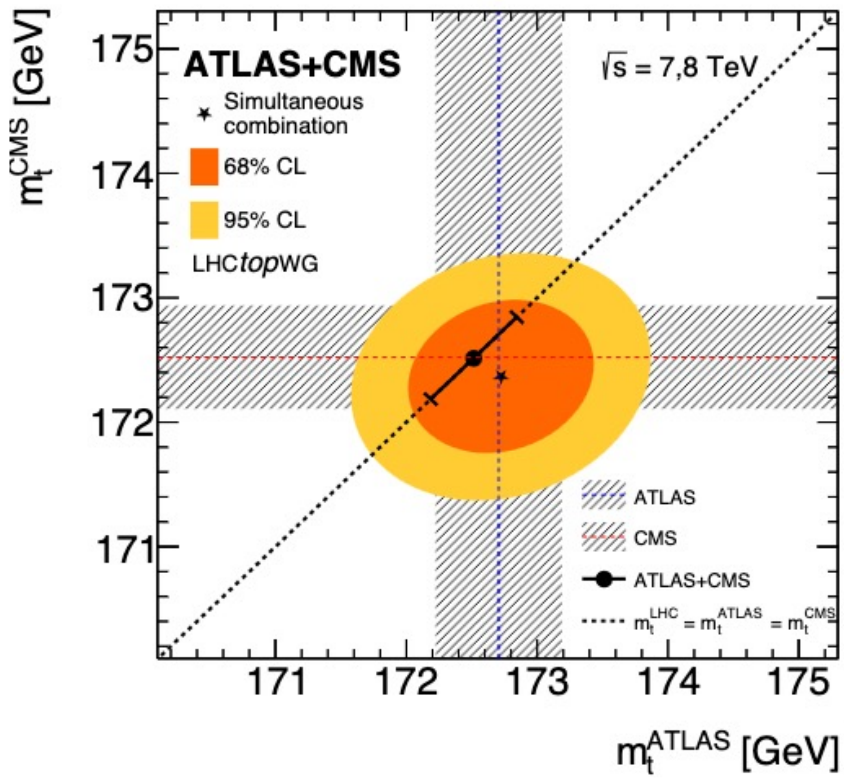


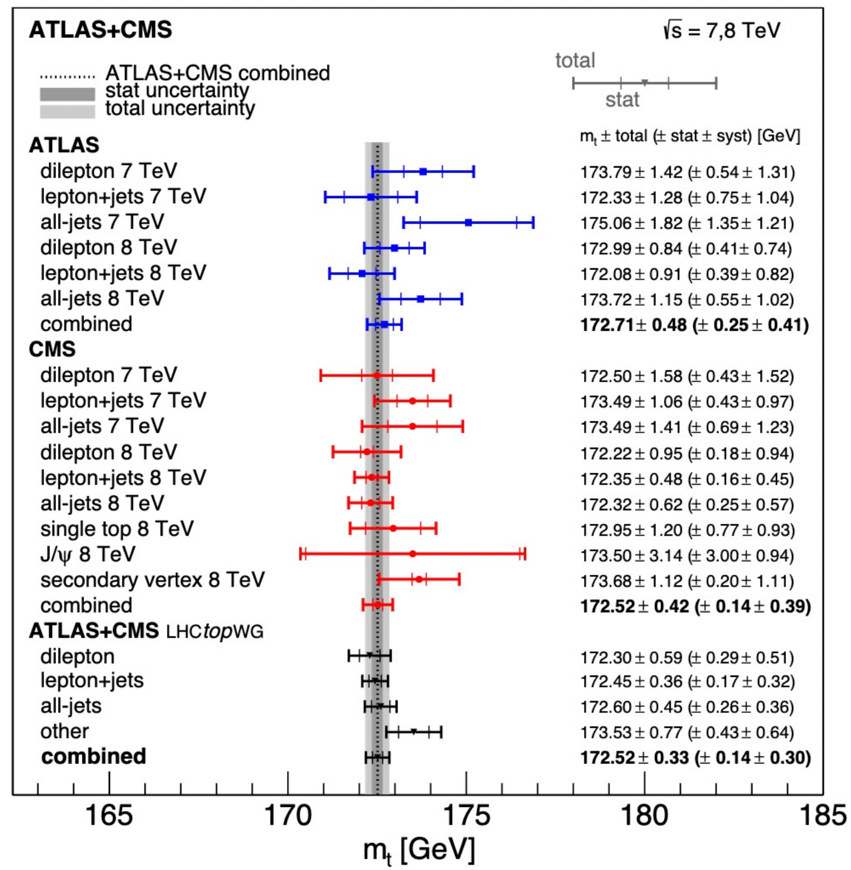


- Charged lepton has the best spin analyzing power, K=1
- Preferentially produced in top spin direction (V-A structure of Weak interaction)

At the LHC, $t\bar{t}$ pairs are produced mainly via gluon–gluon fusion. When they are produced close to their production threshold, i.e. when their invariant mass $m_{t\bar{t}}$ is close to twice the mass of the top quark ($m_{t\bar{t}} \sim 2 \cdot m_t \sim 350$ GeV), approximately 80% of the production cross-section of $t\bar{t}$ pairs arises from a spin-singlet state [28–30], which is maximally entangled. After averaging over all possible top-quark directions, entanglement only survives at threshold because of the rotational invariance of the spin singlet. This invariance implies that the trace (the sum of all of the diagonal elements) of the correlation matrix $\mathbf{C}$, where each diagonal element corresponds to the spin correlation in a particular direction, is a good entanglement witness. It is an observable that can signal the presence of entanglement, with $\mathrm{tr}[\mathbf{C}] + 1 < 0$ as a sufficient condition for entanglement [18].

Top quark mass





To be completed