Observation of quantum entanglement in top-quark pair production at ATLAS

LHC days in Split

3rd October 2024

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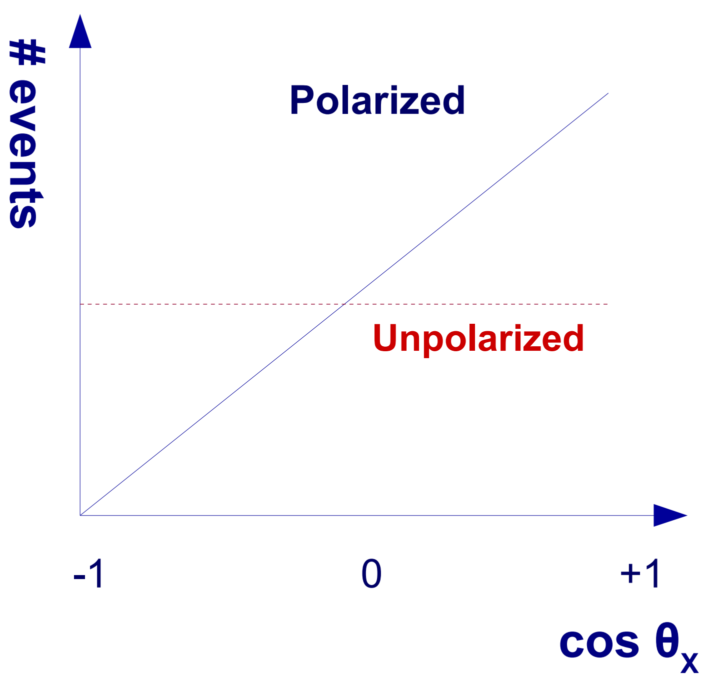
for the ATLAS collaboration

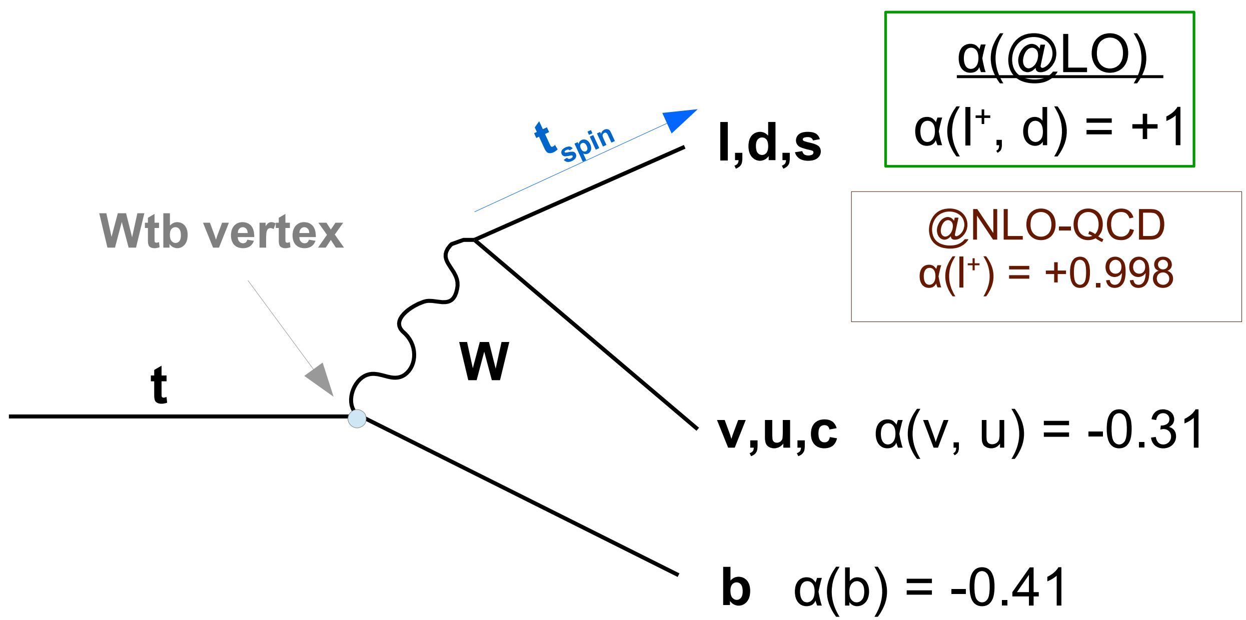
Top-quark spin measurements

- Within the Standard Model the **top quark decays through the electroweak interaction into an on-shell W boson and a b-quark** (almost exclusively).
- Due to the large mass of the top quark, the decay happens very quickly (~$5 \cdot 10^{-25}$ s) before hadronization can occur (~10^{-23} s).
- The information on the **top-quark spin** can be obtained from **its decay products**.
- In the top-quark rest frame, the angular distribution of any decay product follows:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1 + \alpha_X P \cos\theta_X)$$

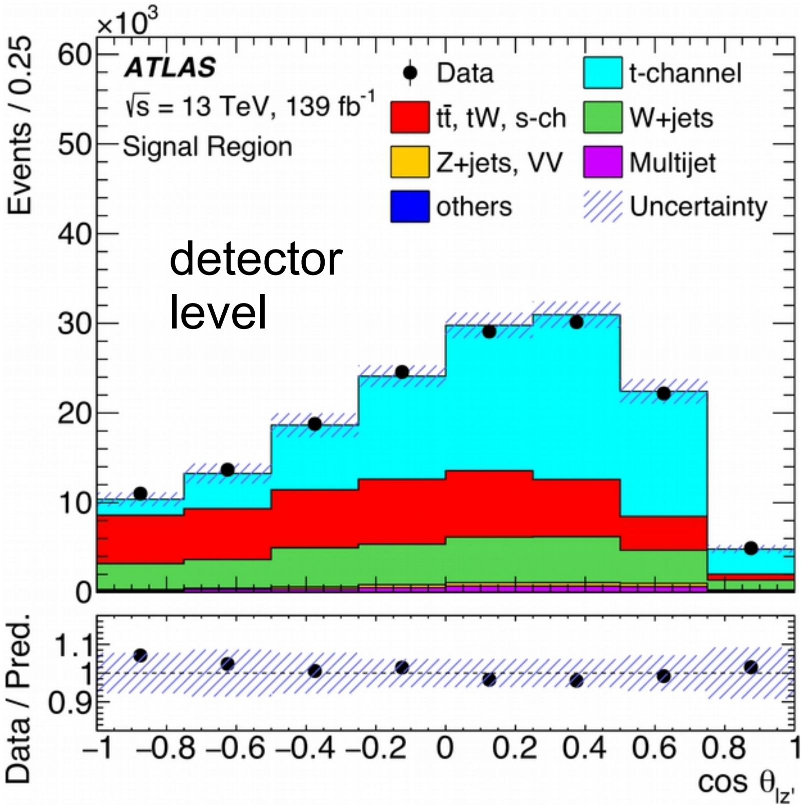
- **Charged leptons** and down-type quarks are **ideal probes of the top-quark spin**.

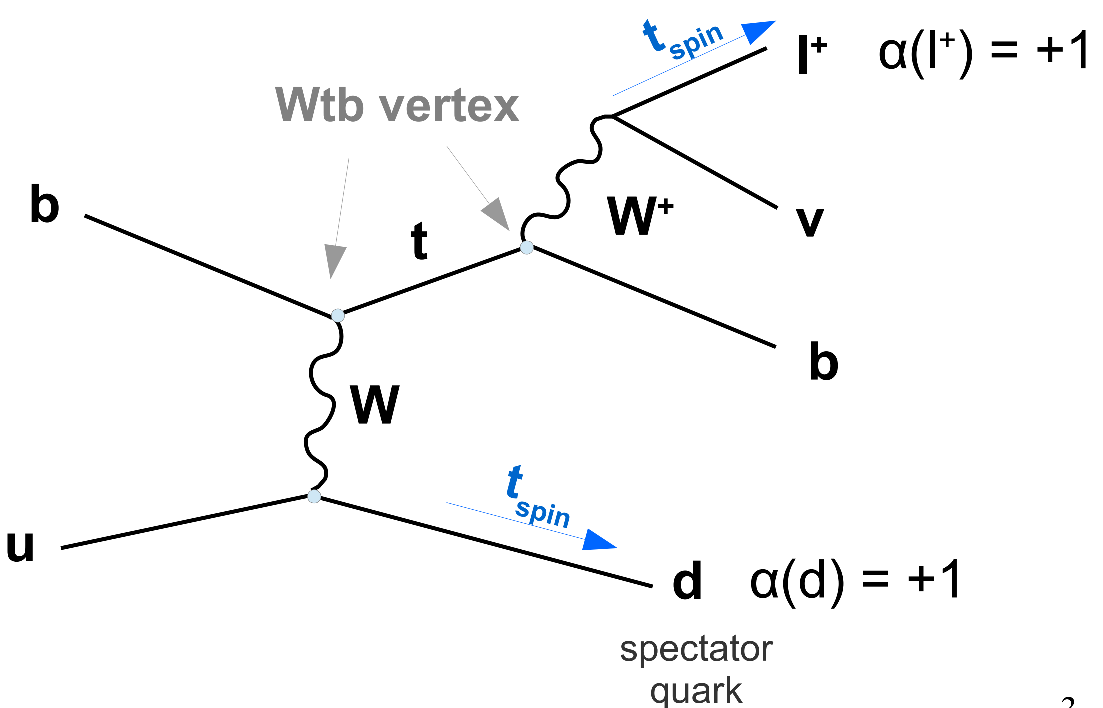




Top-quark polarization with single top-quarks

- Top-quarks produced singly via the t-channel at the LHC are **highly polarized along the direction of the spectator quark:**
- Single top-quark polarization has been extensively studied as it is relatively clean.
- The top rest frame can be reconstructed easily: **Only one neutrino**.
- The spectator-quark is used to determine top-quark spin in production, while the lepton determines the spin at decay: **polarization measurement**.
- Initial light quark follows LHC's beam direction: allows a 3D spin determination.





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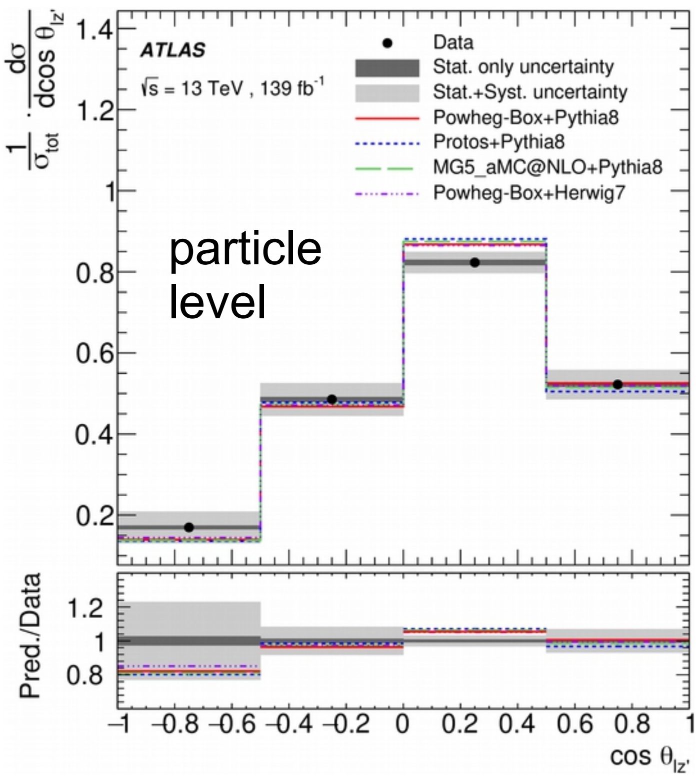

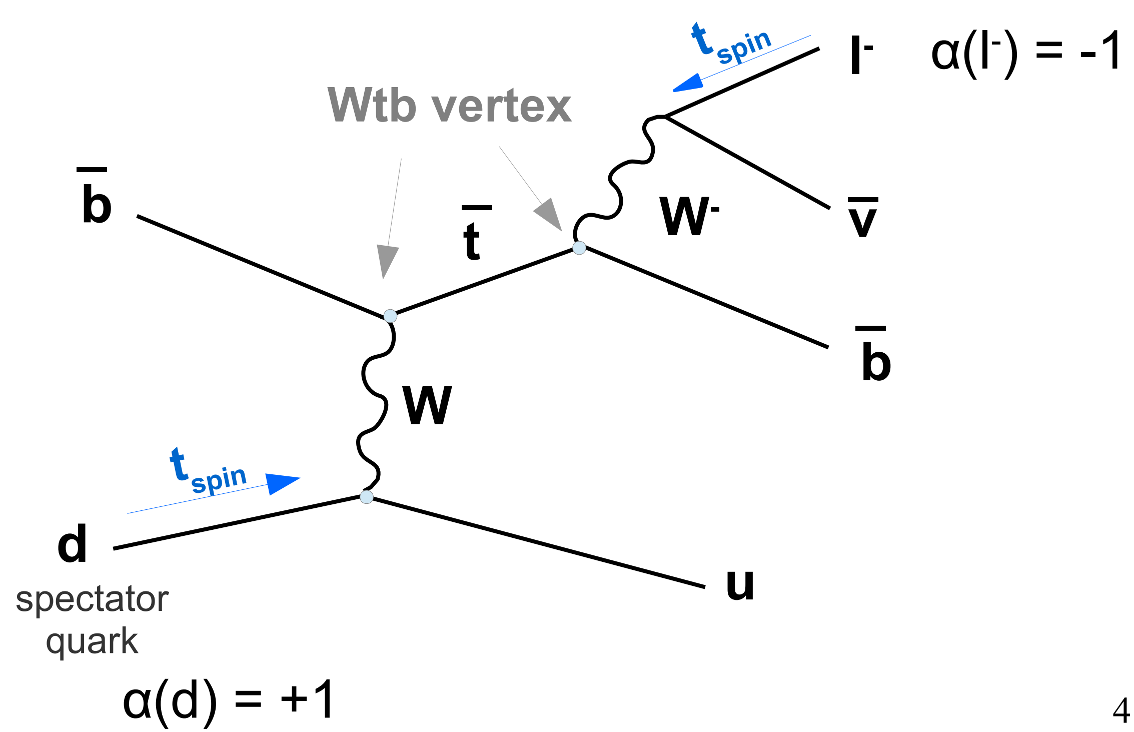

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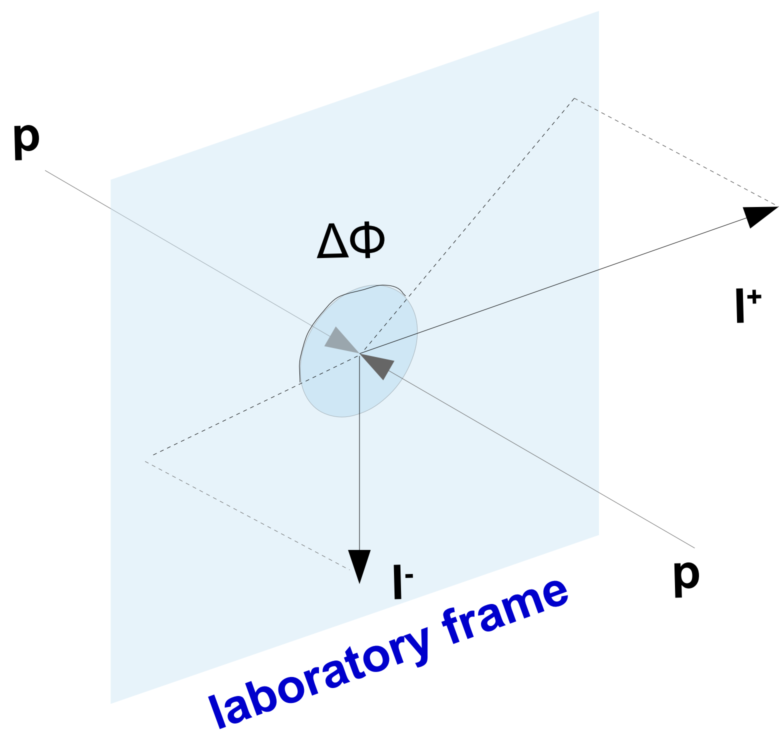
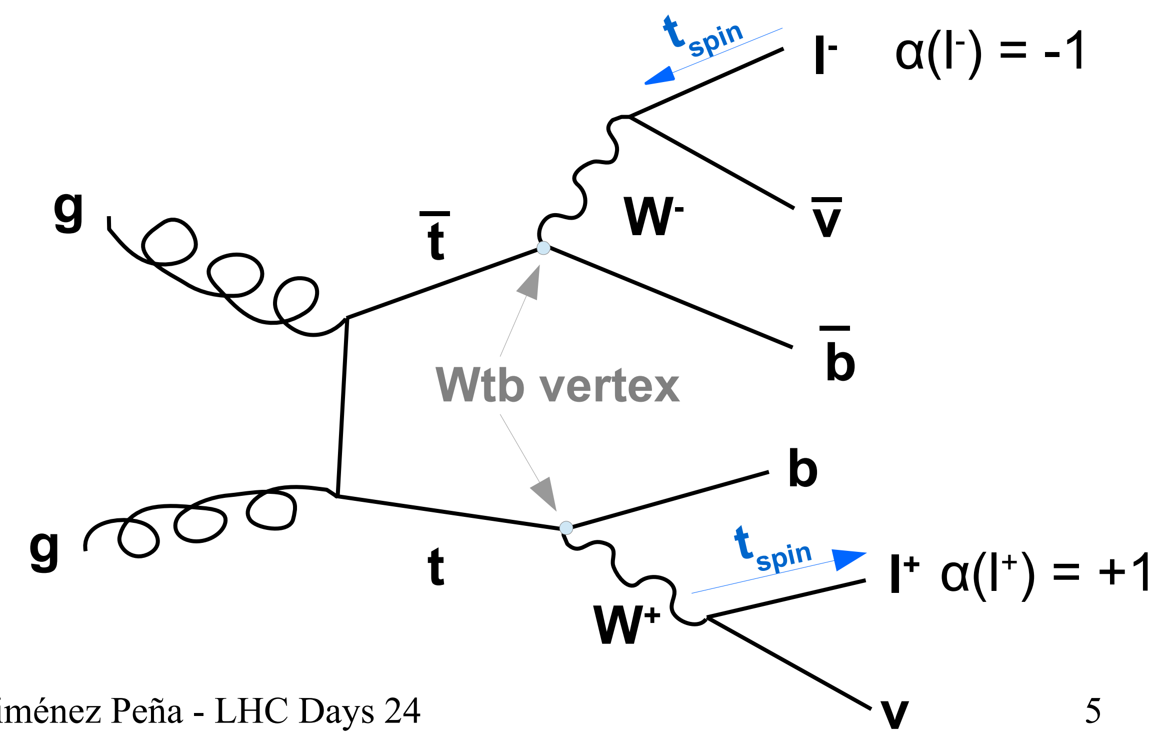
Further details in backup :)

Top-quark spin correlation in top-quark pair production

- At the LHC, **top-quarks are mainly produced in pairs via the strong interaction.**
- Top-quarks produced in this way aren't polarized in any particular direction.
- However, the **spins of top- and antitop-quarks** are predicted to be **correlated**.
- **ΔΦ(l+, l-)**, the absolute **azimuthal opening angle between the two charged leptons**, measured in the laboratory frame in the plane transverse to the beam line.
- Simplest observable to test spin-correlation: **No ttbar-system reconstruction.**





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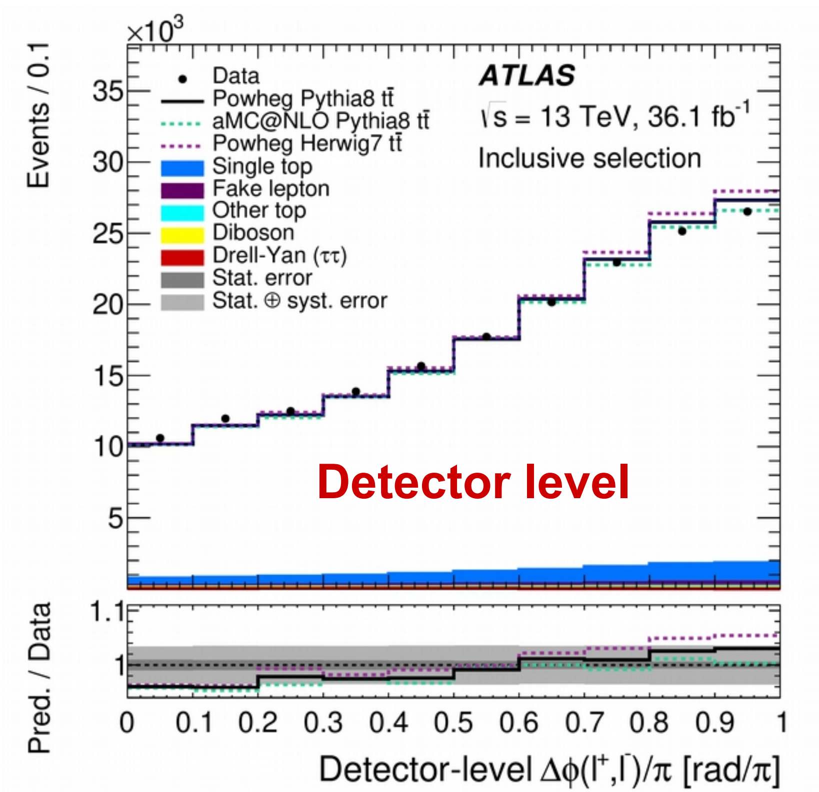

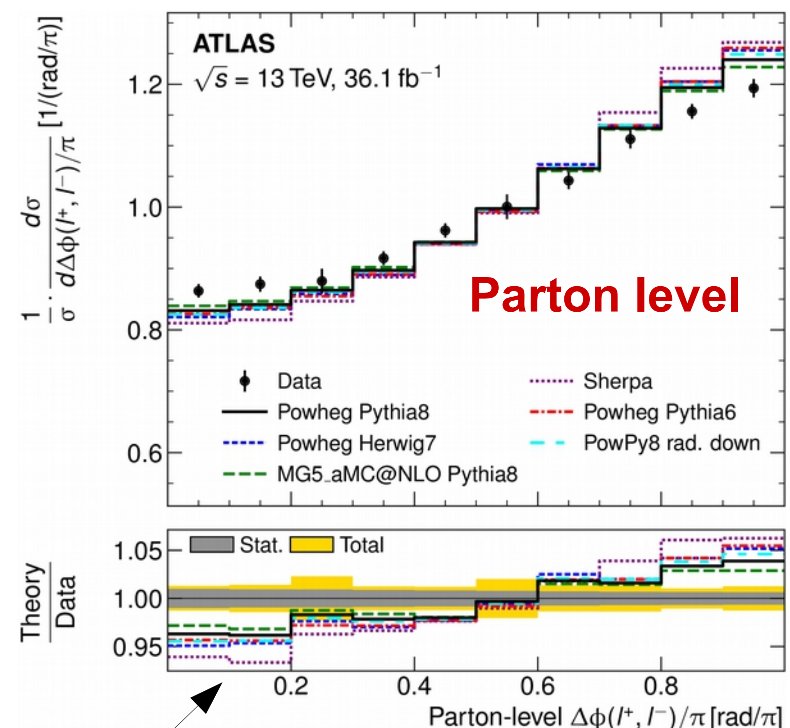

2.2 σ deviation

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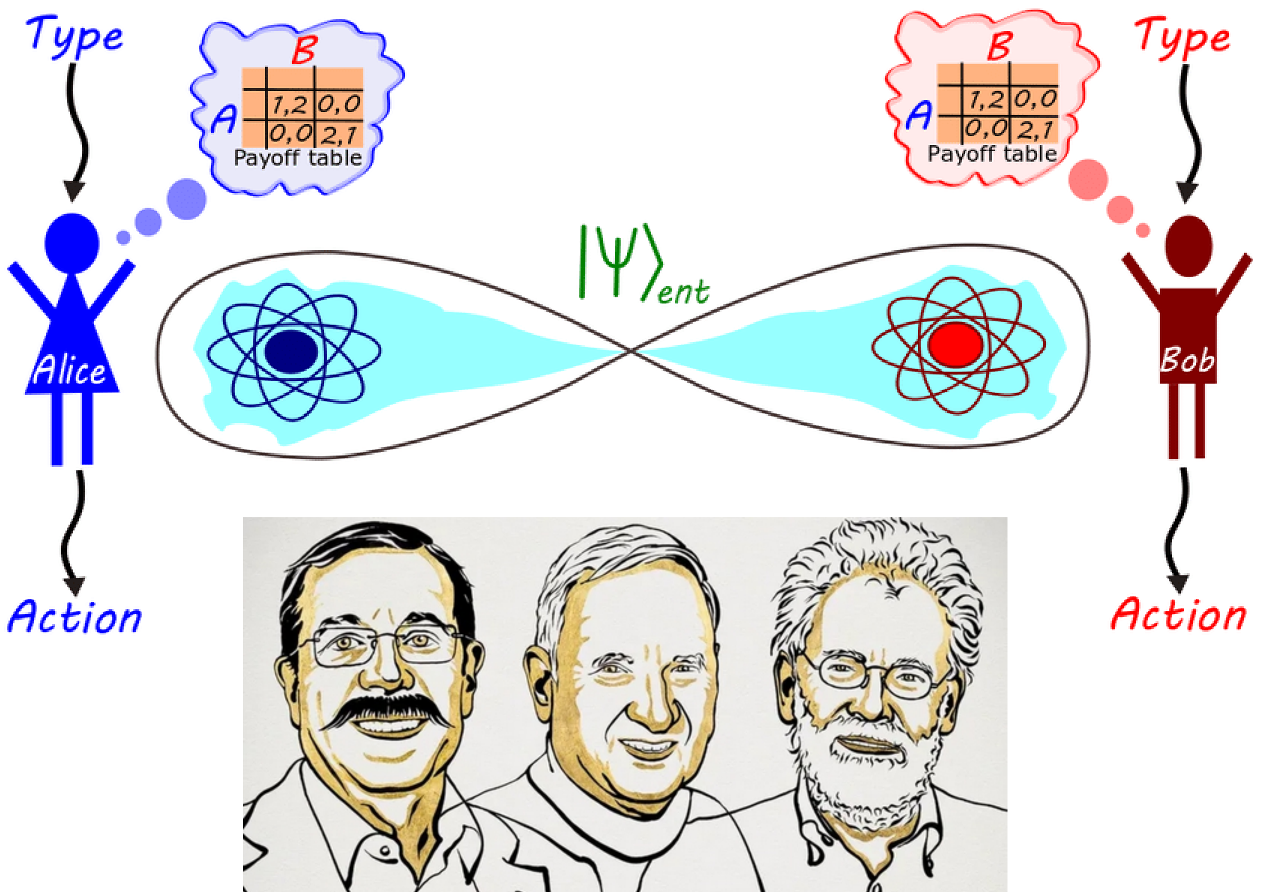
Further details in backup :)

Quantum entanglement in top-quark pair production

Quantum entanglement

- **The SM is a quantum field theory:** special relativity + quantum mechanics.
- Entanglement is one of the most striking features of quantum mechanics:
  - Two **entangled particles can't be described by individual quantum states**, but only by a single state considering the system as a whole
  - **Correlated properties:** The measurement of one of the particle “affects” the other.

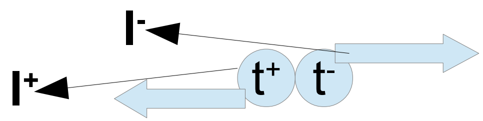
- Quantum entanglement have been observed in photons, atoms, superconductors, mesons and even macroscopic diamonds.



Entangled top-quark pairs at the LHC

- Recent publications proposed using the LHC as a laboratory to test quantum mechanics at the highest energies ever.
- Close to production threshold ($m_{ttbar} \sim 2 \cdot m_{top}$) top-quarks are predicted to be produced in an entangled state:

  Correlation of top and antitop-quark spins is larger than classical limit.



- The **top quark spin** can be analyzed through the **lepton direction** in top rest frame.
- A top-quark pair forms a two-qubit system, with a spin density matrix given by:

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j \right]$$

- The trace of the correlation matrix C is a good entanglement witness:

  Sufficient condition for entanglement: tr[C] + 1 < 0 (or **D = tr[C]/3 < -1/3**)

- Experimentally, it can be measured as: $D = -3\langle \cos\varphi \rangle$

  being φ the angle between the two leptons, each at its parent top-quark rest frame.

Theory refs: Eur. Phys. J. Plus 136, 907 (2021), Quantum 6, 820 (2022), Eur. Phys. J. C 82, 285 (2022)

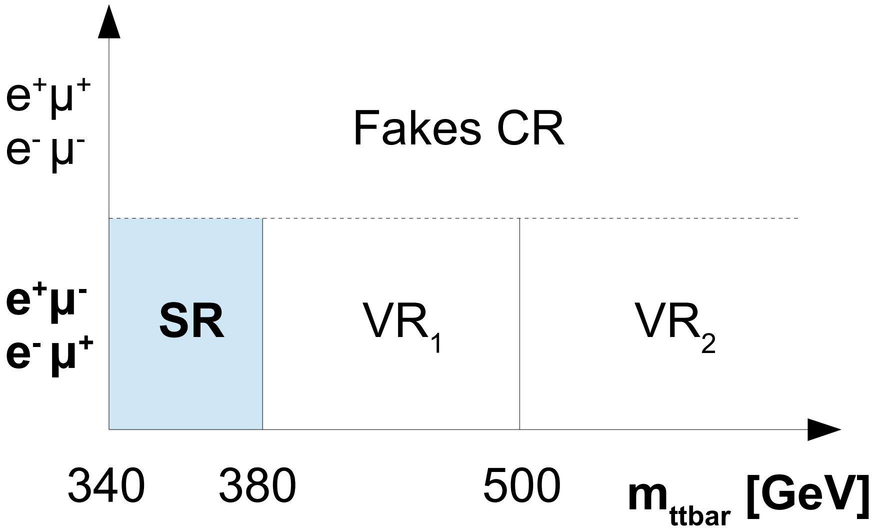
Analysis strategy 1

Selection: 1 electron and 1 muon of OS. Single lepton trigger. At least 1 b-jet (85%).

Backgrounds: tW, tt+X, fakes, VV and $Z \rightarrow \tau\tau$

Events categorized by m_{ttbar}:

- One signal region with expected entanglement
- Two validation regions without entanglement.



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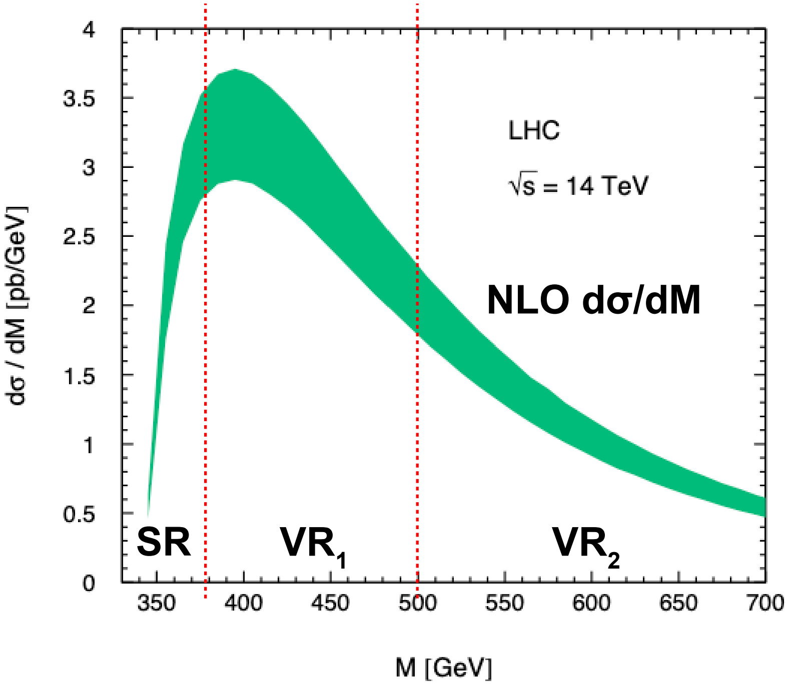

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Analysis strategy 2

Events passing selection split into three analysis regions, based on the detector-level, particle-level or parton-level m_{ttbar}

- **A calibration curve is used to correct the reconstructed value of D to particle level.**
- It corrects both for detector effects and for migration of events due to m_{ttbar} resolution
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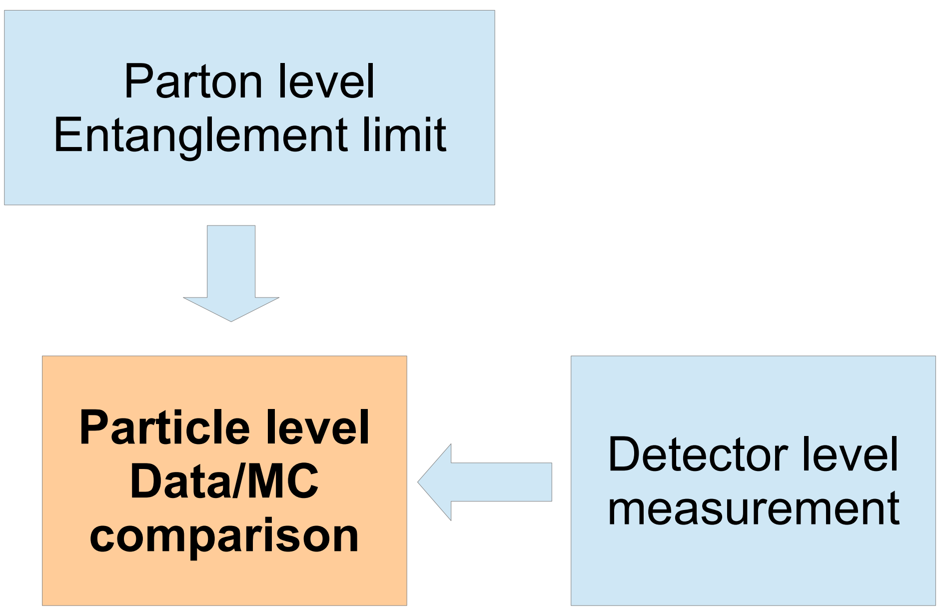

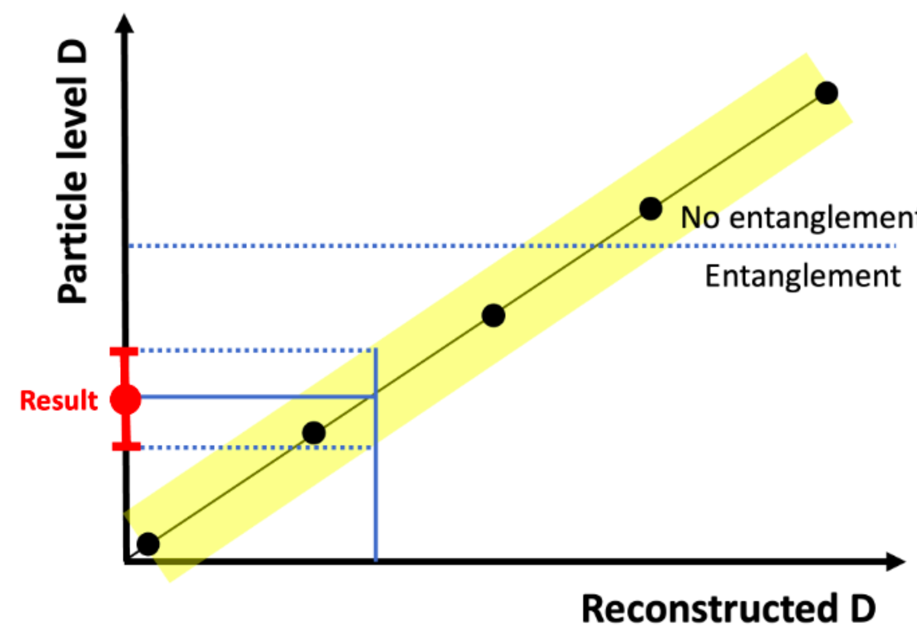

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Top reconstuction method

A precise reconstruction of the top-antitop-quark system is needed:

- Very narrow phase space in m_{ttbar} for the SR.
- Boosts to each lepton's parent top/antitop quark rest frame for cos φ calculation.

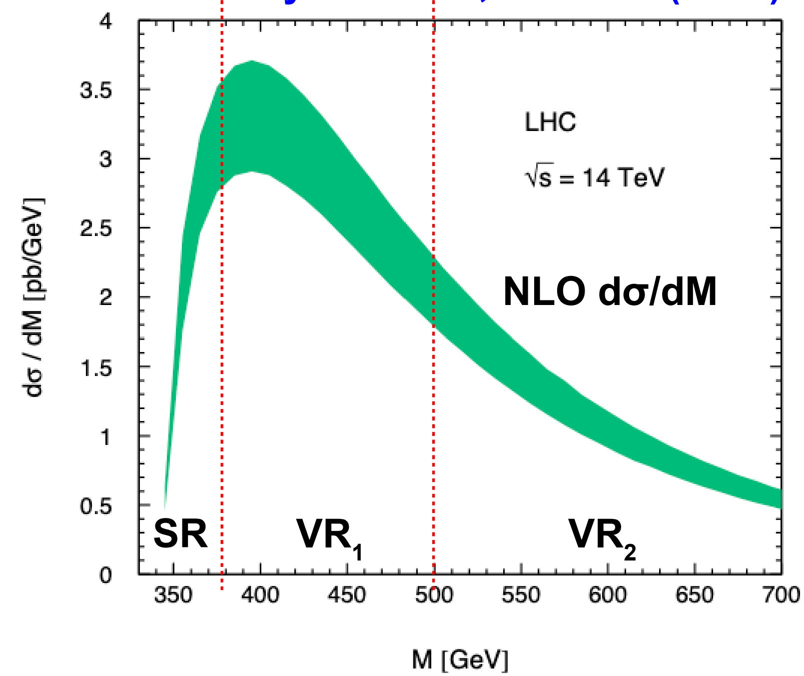
Several methods for **reconstructing the two neutrinos** momenta from the **MET.**

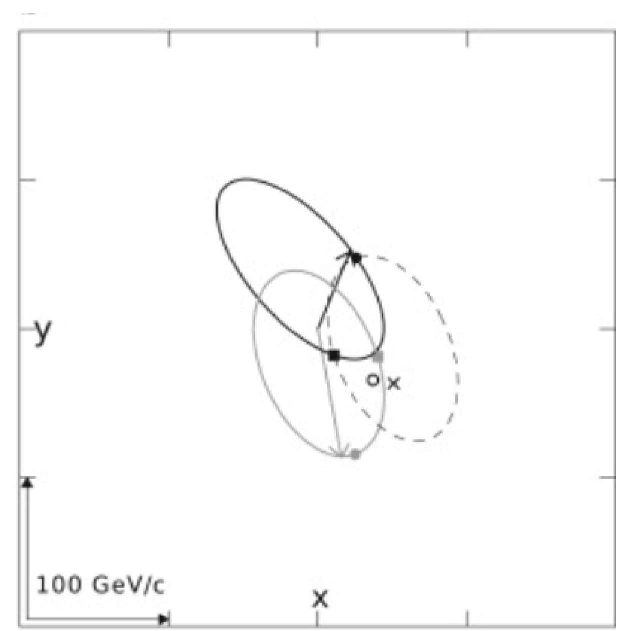
The main method used is the **Ellipse method**, which is a geometric approach to analytically calculate the **neutrino momenta**. The method gives at least one real solution for **85% of the events**.

If EM fails, use the **neutrino weighting** method: scan possible values of the neutrinos η and asses compatibility of the neutrino momenta and the MET in the event. **5% of the events**.

Remaining **10%** only use the lepton and jets.

Eur. Phys. J. C 60, 375–386 (2009)





Nucl. Instrum. Meth. A 736, 169–178 (2014)

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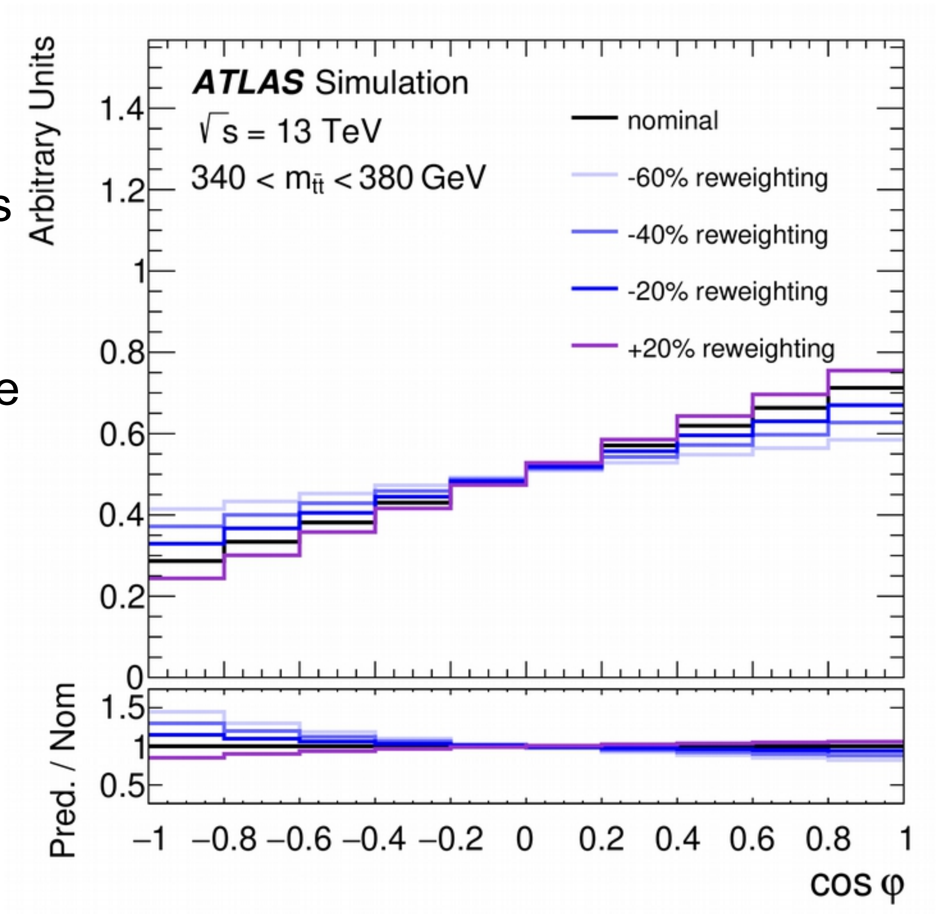
Reweighting method and calibration curve

- The amount of entanglement is not a parameter of the MC generators that can be changed (Inherent in particle generators).
- Alternative test hypotheses with varied values of D are needed.
- Each event is reweighted at parton level to modify D, taking into account m_{ttbar} to preserve the linearity of the cos φ distribution.

$$w = \frac{1 - D_{\Omega}(m_{t\bar{t}}) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_{\Omega}(m_{t\bar{t}}) \cdot \cos\varphi}$$

$$\mathcal{X} = 0.4, 0.6, 0.8, 1.2$$



- $D_{\Omega}(m_{ttbar})$ is calculated for every modelling uncertainty (different at parton level).
- The reweighting is done for every systematic uncertainty, obtaining a dedicated calibration curve for each uncertainty.

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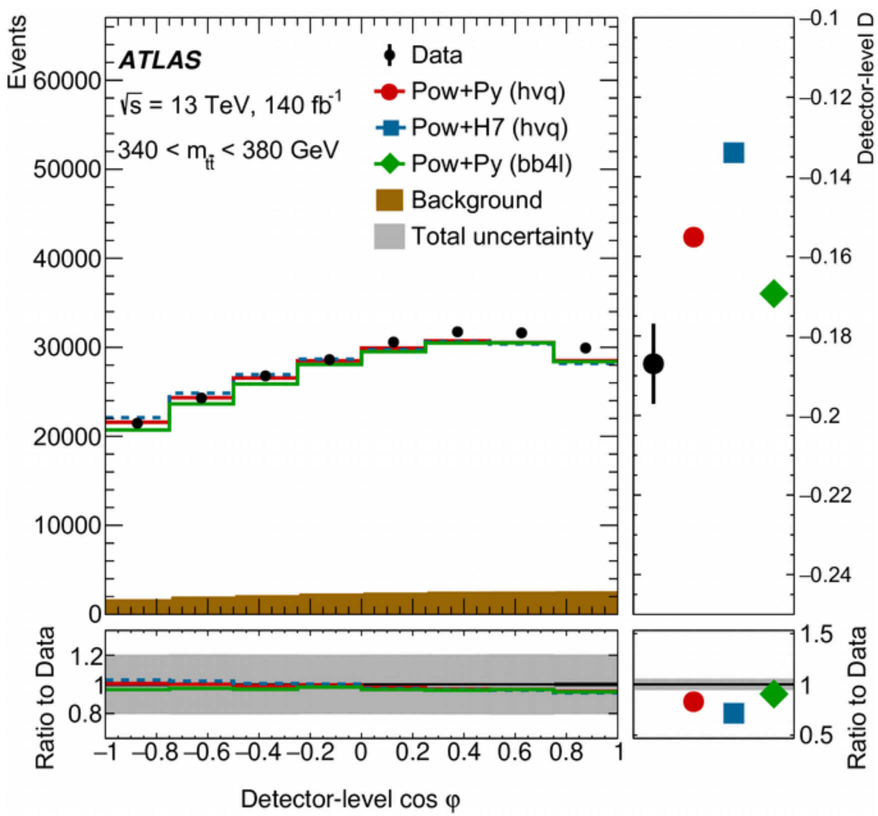
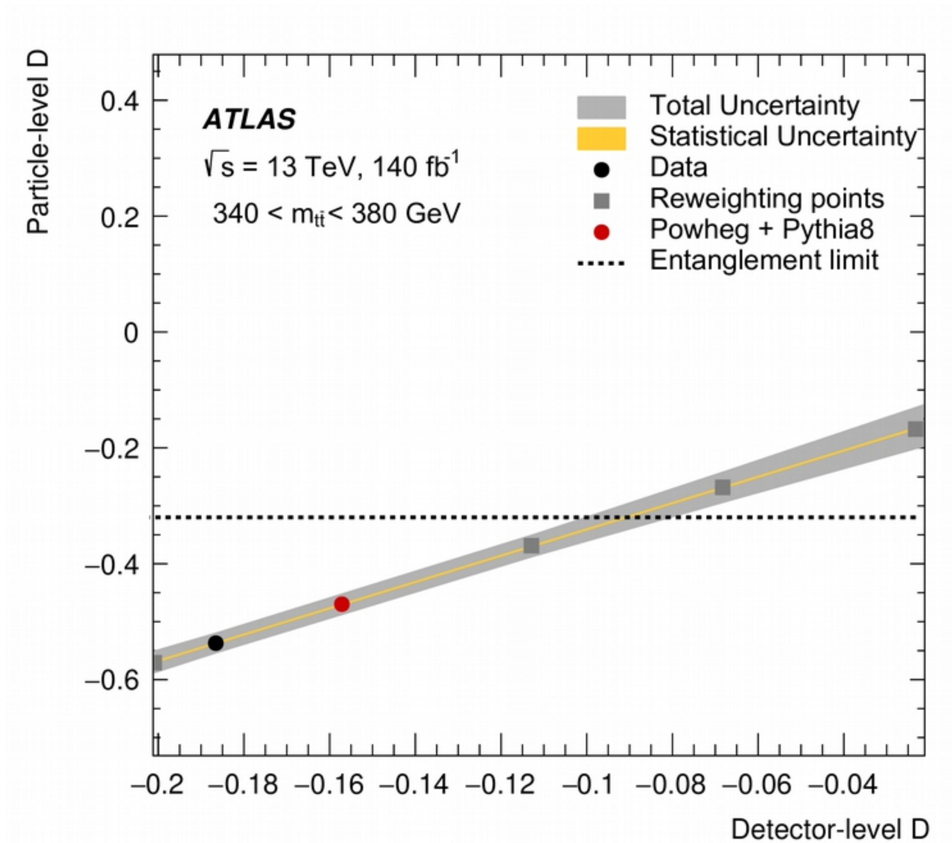
Observation of entangled top-quark pairs

- Entanglement marker D measured from ‹ cos φ › at detector level: $D = -3\langle \cos\varphi \rangle$
- Corrected to particle level using the calibration curve.
- Systematic uncertainties evaluated from alternative calibration curves.





Measured value: D = − 0.537 ± 0.002 (stat.)± 0.019 (syst.)

Expected value (Pow+Py): D = − 0.470 ± 0.002 (stat.)± 0.017 (syst.)

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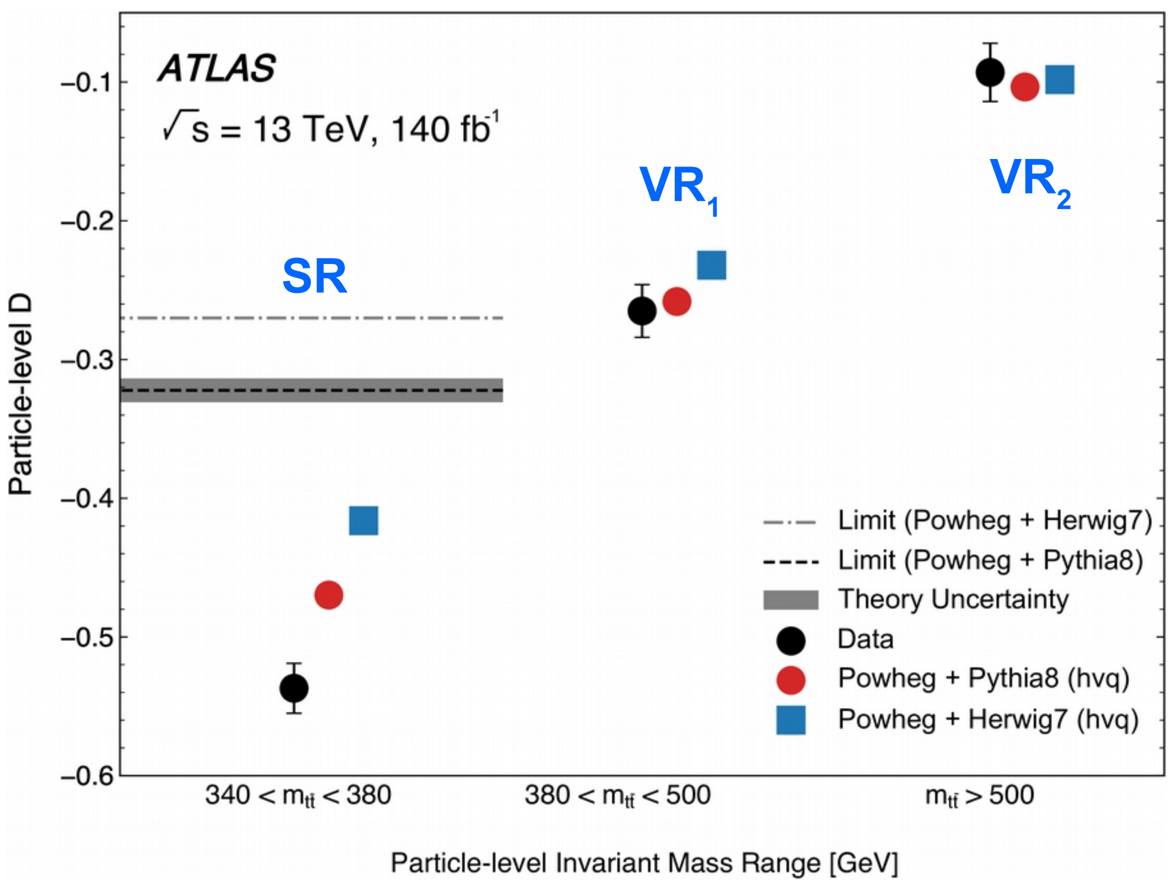
Observation of entangled top-quark pairs

- Entanglement in top-quark pairs **observed for the first time** with more than 5 sigmas.
- Main uncertainties arise from the modeling of the signal.
- Large difference in predicted value of D in SR between Powheg+Pythia8 and Powheg+Herwig7. Main origin: ordering of the parton shower (details in backup)
- Not a large uncertainty at particle level: Entanglement observed with both models.
- Measurement in **data shows a larger degree of entanglement** than MC predictions.



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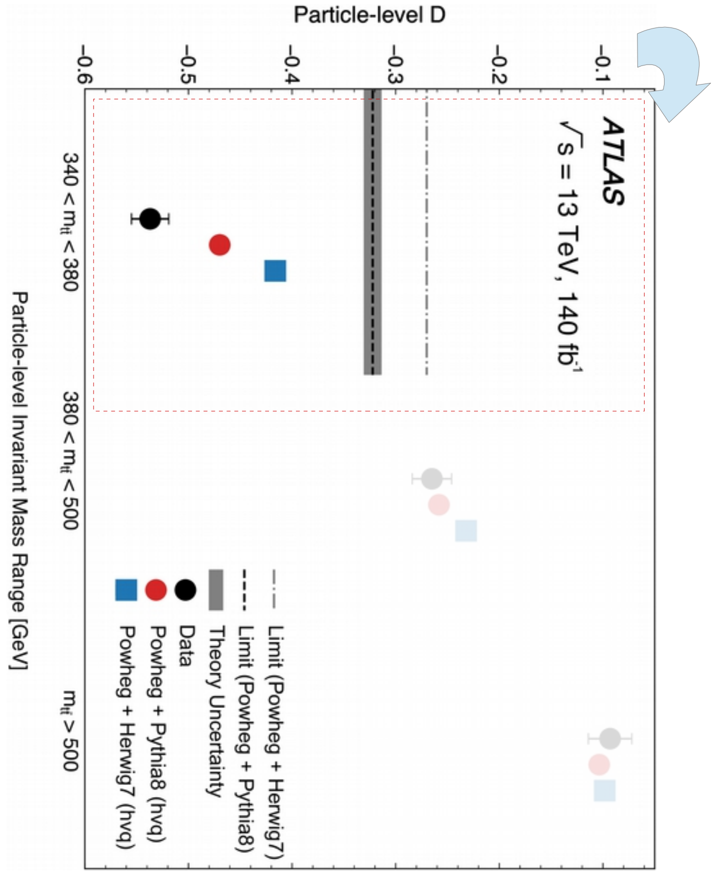
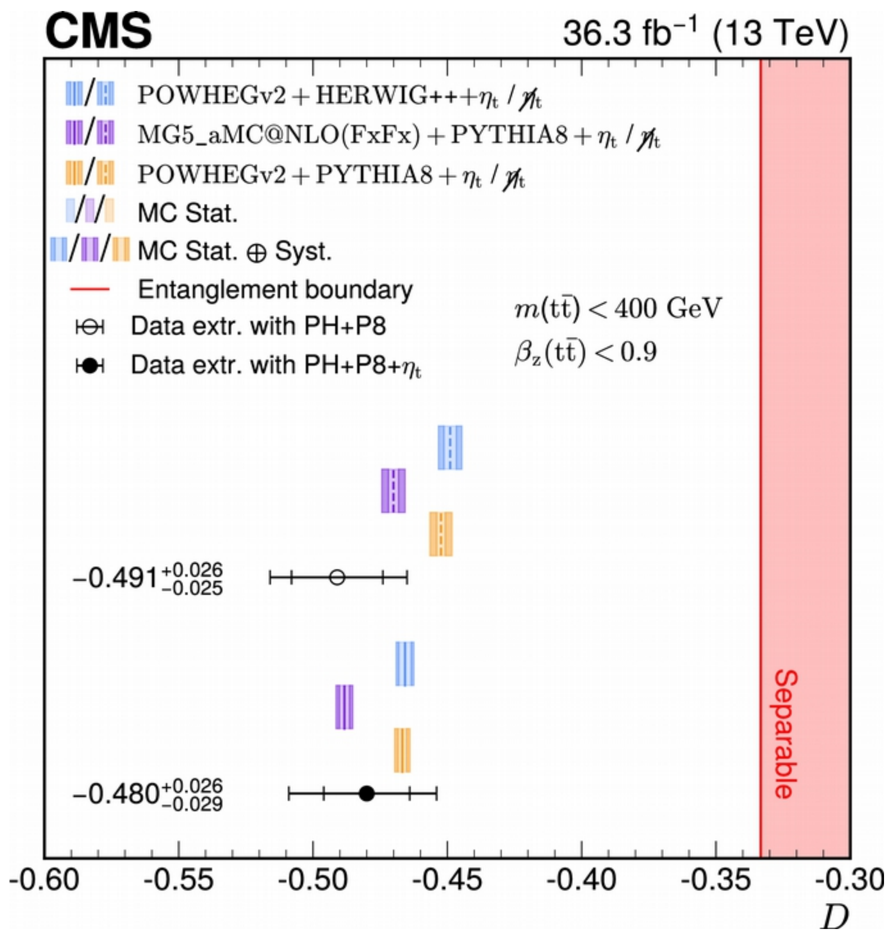
Comparison with CMS measurement

- Posterior measurement by CMS **confirmed the observation** of entangled top-quarks.
- Similar measurement with some differences: unfolded to parton level.
- Also considers the impact of possible presence of toponium (top-antitop bound state)
- Inclusion of toponium brings Data/MC closer. Larger Data/MC difference in ATLAS.





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arXiv:2406.03976

Summary and conclusions

Summary and conclusions

- The top-quark spin is accessible through the decay products. Charged leptons are an ideal tool to measure it.
- This property has been largely exploited in ATLAS and other top-factories:
  - Powerful test of the SM and possible SM extensions.
- Single top-quark t-channel allows for a full 3D determination of the top-quark polarization.
- In top-quark pair production, top-quarks and antitop-quarks aren't produced with any particular polarization, but their spins are correlated.

- **Entanglement of two quarks have been observed for the first time at the LHC**.
- The analysis exploits the close-to-production-threshold phase space.
- Future measurements will require better understanding of parton shower.
- Also other effects as toponium or boundstates of top-quarks may have a role.

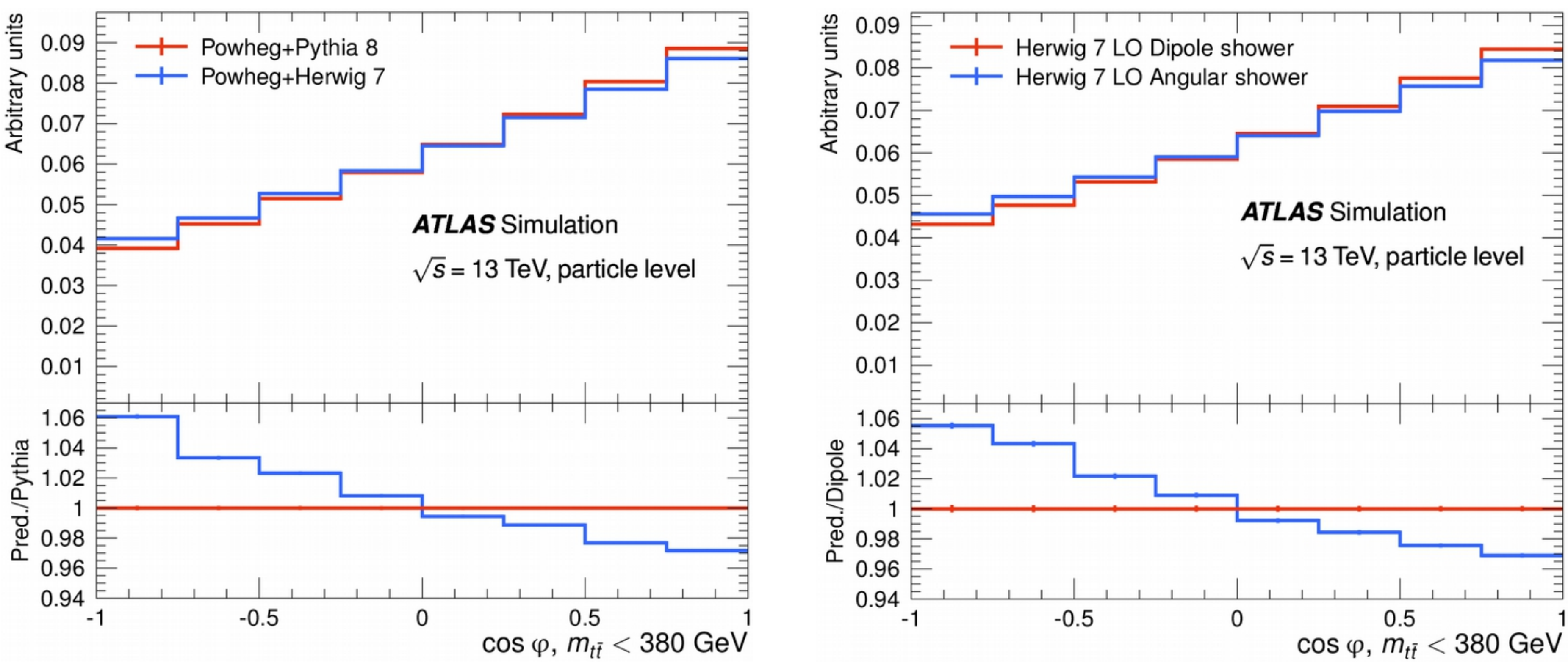
- Further experiments exploiting the LHC as a quantum information laboratory are been proposed.

Thanks for your attention

Backup

Parton shower and top quark spin correlation

- Choice of parton shower ordering has a large effect close to threshold.
- Pythia8 uses a dipole shower mode: additional emissions ordered by p_T .
- Herwig7 uses an angular ordering for additional emissions by default.
- Alternative Herwig7 with dipole shower shows same distribution than Pythia8.
- Future measurements would benefit from improved understanding of parton shower mechanisms.



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Toponium

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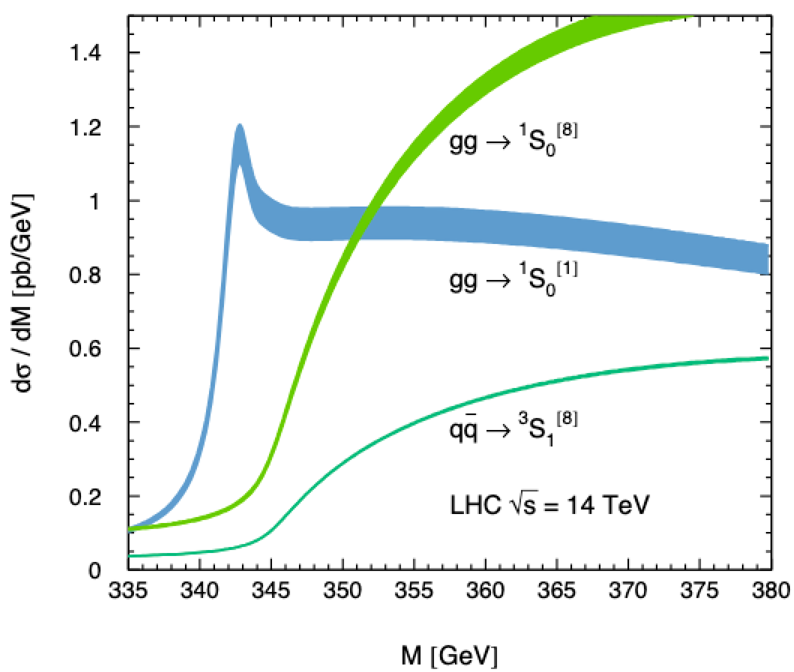
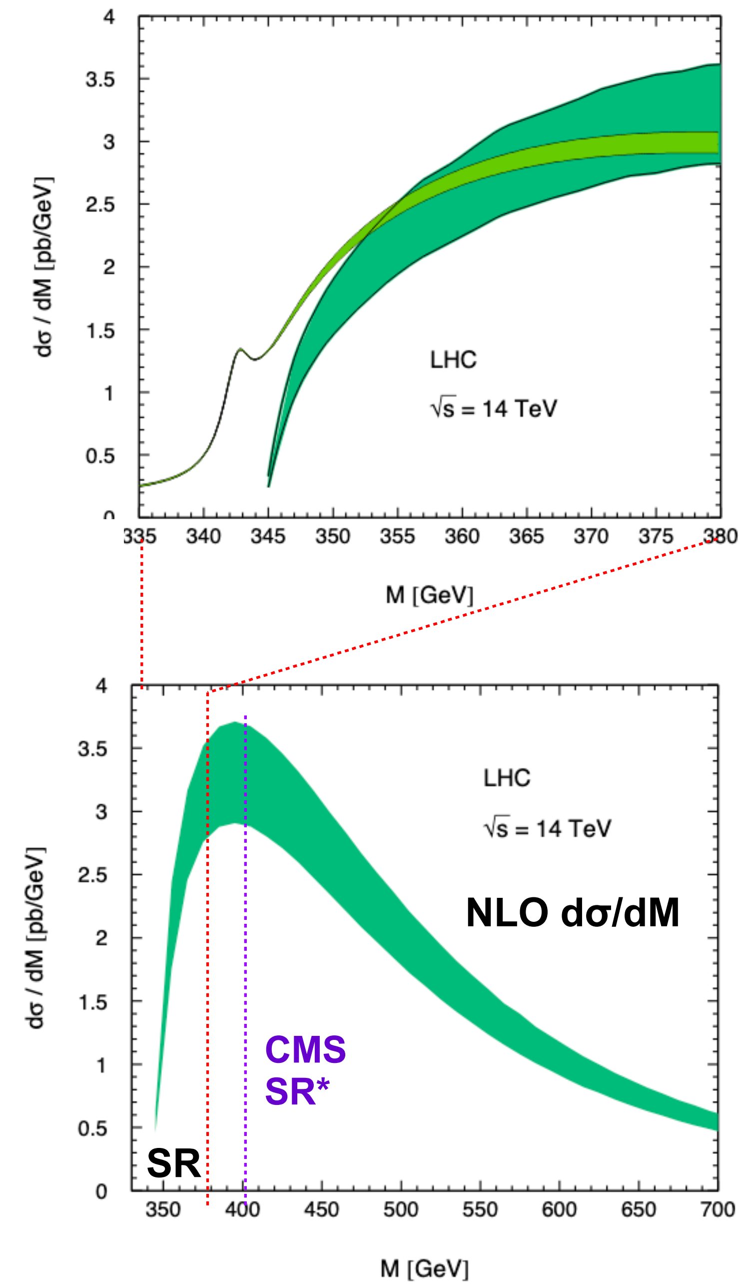


Figure 2: Invariant mass distributions for leading subprocesses: $gg \to {}^1S_0^{[1,8]}$ (blue a... ...
green, respectively) and $q\bar{q} \to {}^3S_1^{[8]}$(green). For each process the bands take into account scale variation of the hard cross sections.



*missing cut in β

Systematic uncertainties entanglement measurement

Source of uncertainty	$\Delta D_{observed}(D = -0.537)$	ΔD [%]	$\Delta D_{expected}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
E_T^{miss}	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
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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 QCD + NLO EW 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%

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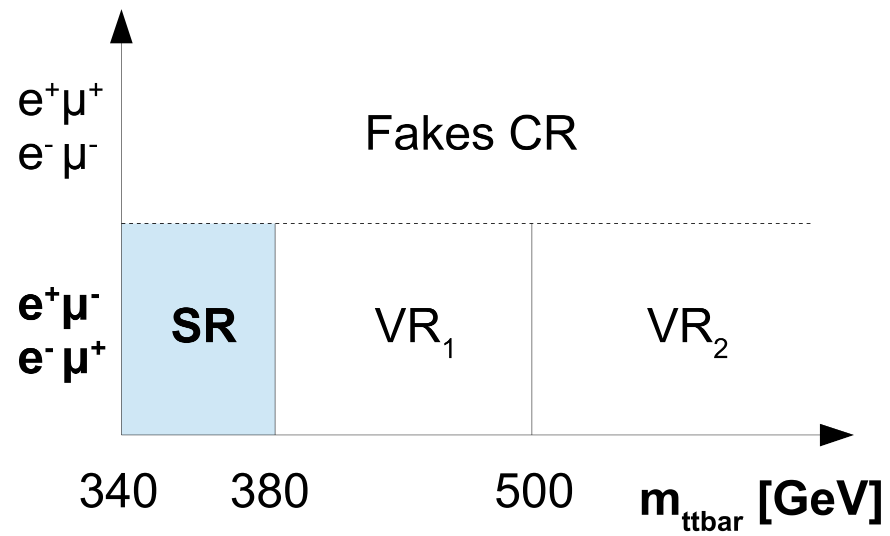

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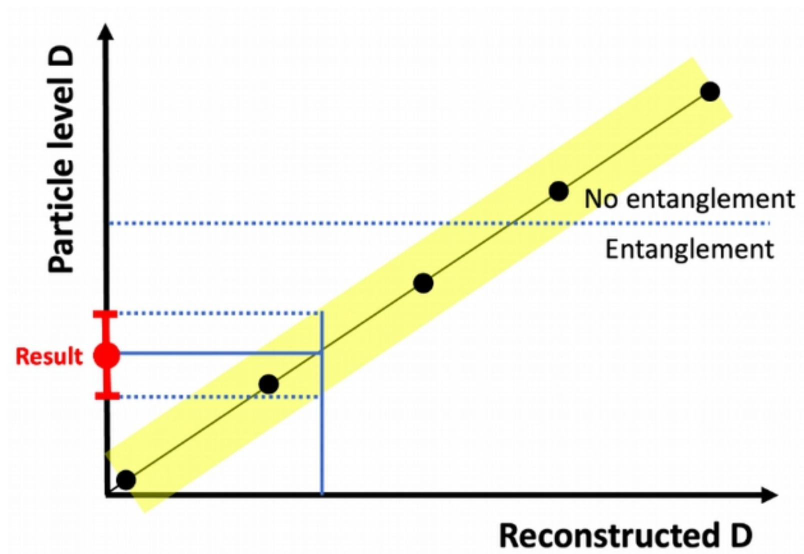

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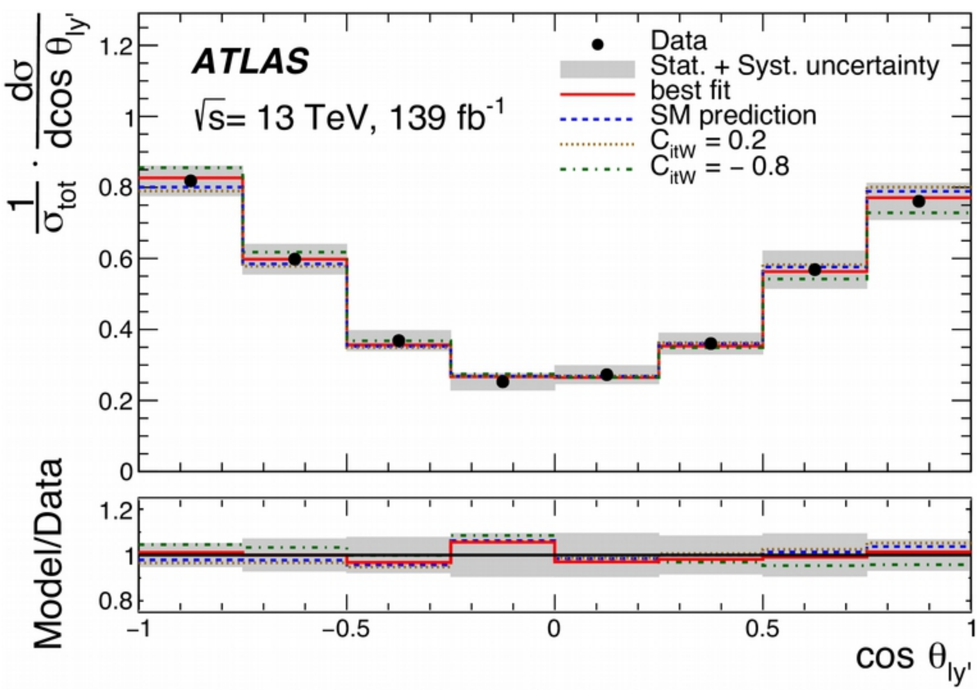
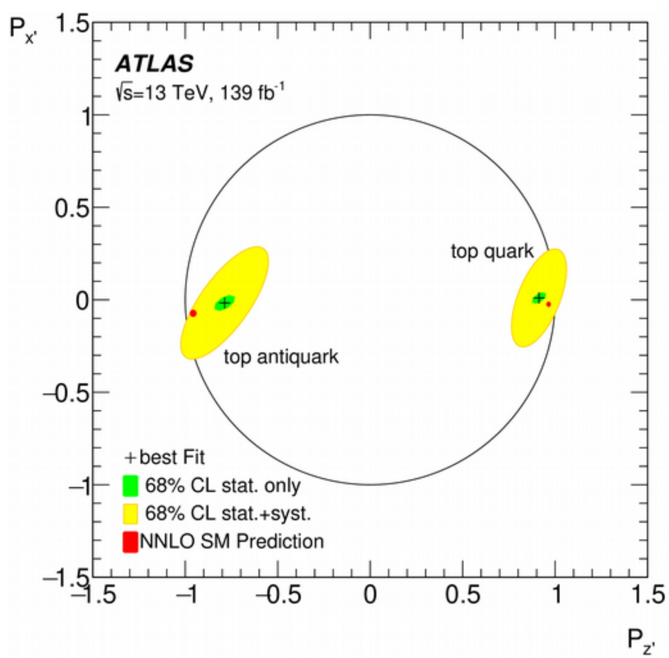
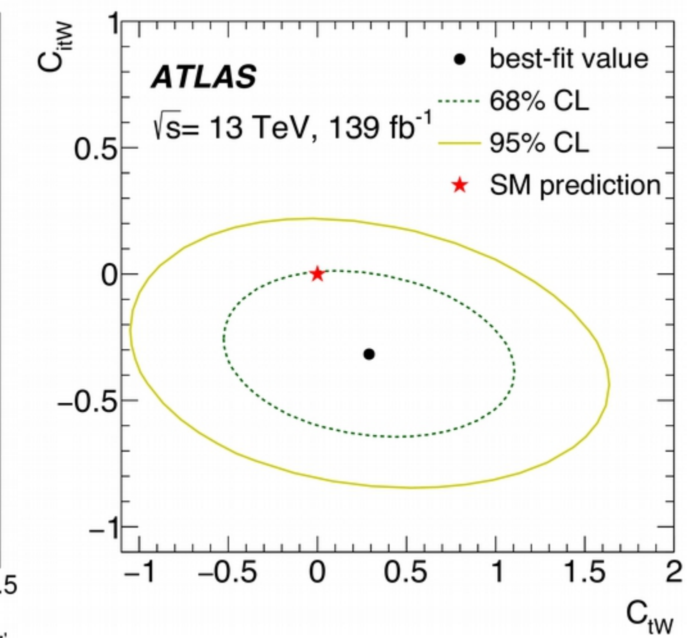
Extra details on introduction analyses

Top-quark polarization with single top-quarks

- The full Run-2 dataset of proton-proton collisions at 13 TeV has been used to measure the **3D polarization** of single top-quarks produced via the t-channel.
- The 3D polarization is also used to set limits to the dimension-six operator **CtW**, both to its **real and imaginary parts**.
- The measurements are performed at **particle level** after removing contributions from background processes.
- **No deviations from the SM are found**.







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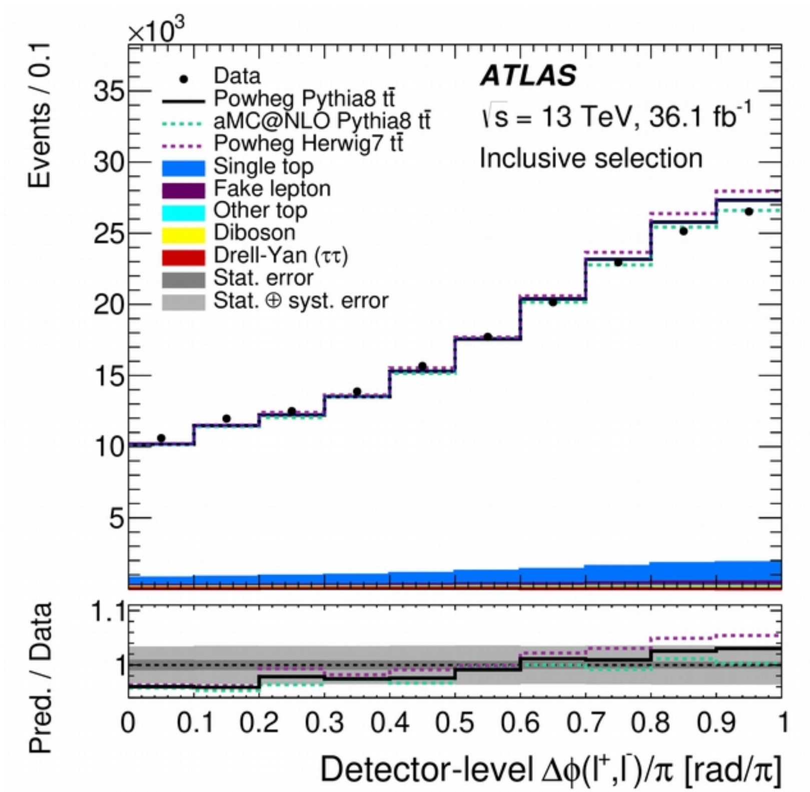
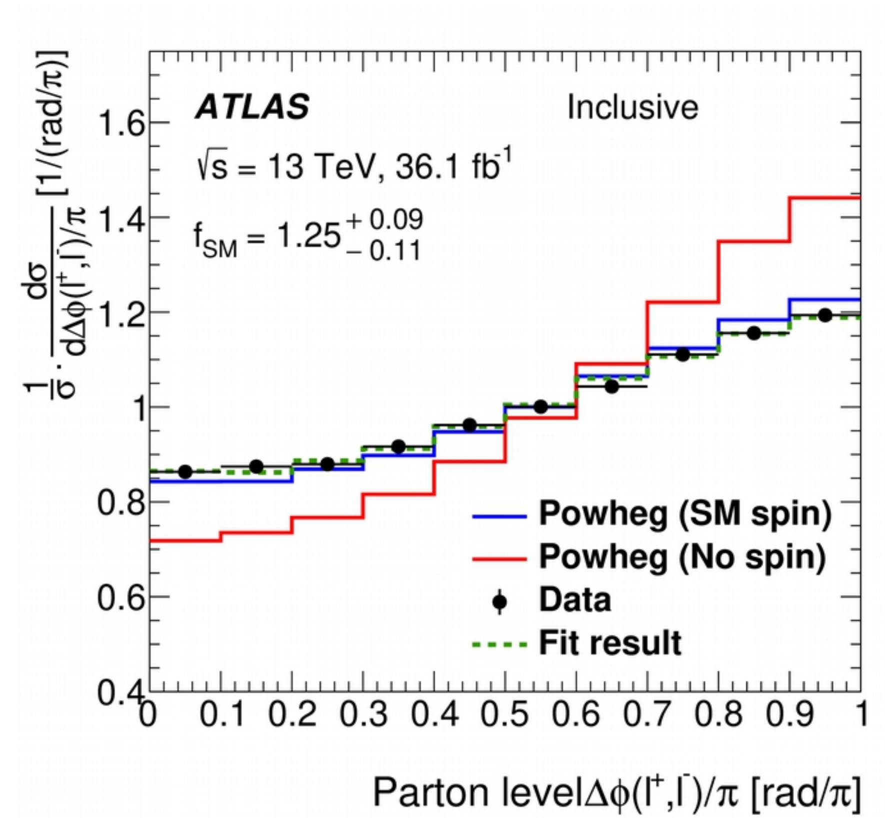
Top-quark spin correlation in top-quark pair production

- The Run-2 dataset from 2015-2016 at 13 TeV was used to measure the spin correlation in top-quark pair events.
- The selection consists of an electron, a muon and two jets (at least one b-tagged).
- The measured **ΔΦ(l+, l-)** differential cross-section is compared to several NLO Monte Carlo generators and fixed-order calculations at parton level.
- The level of correlation is assessed by quantifying it in relation to the amount of correlation expected in the SM, f_{SM}. No Spin hypothesis: Decay with MadSpin.





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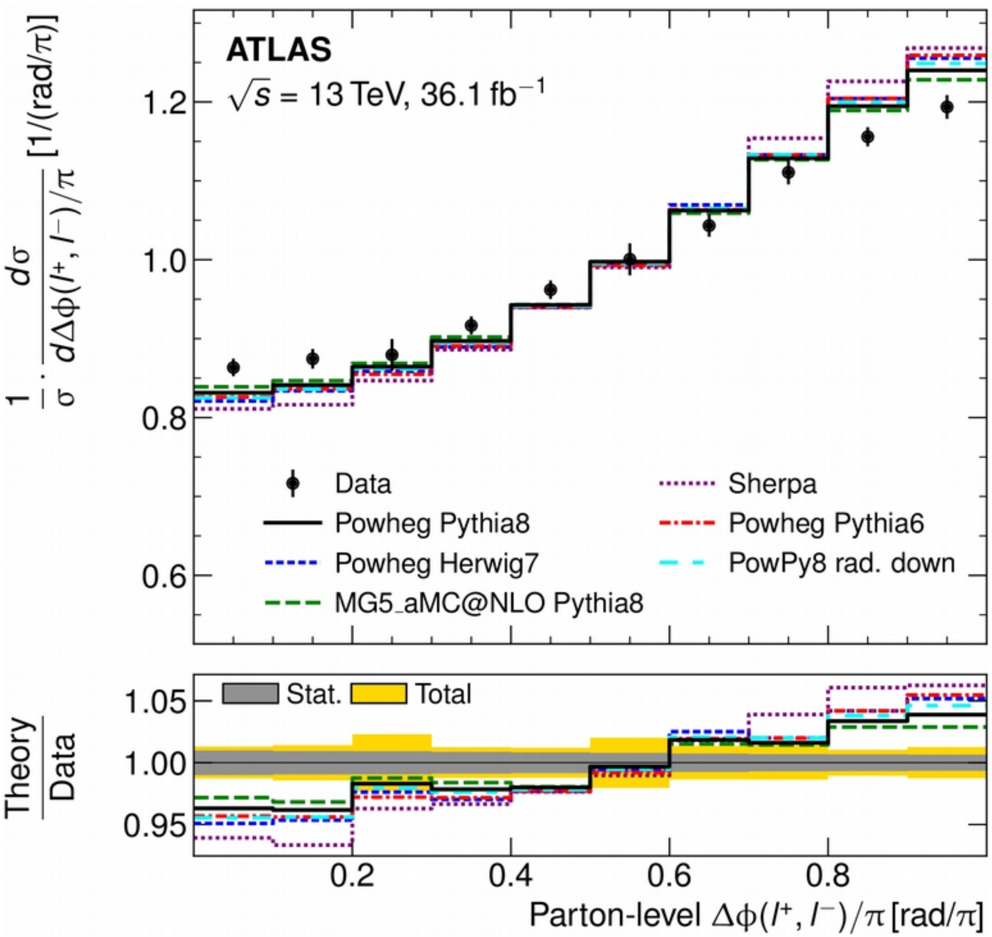
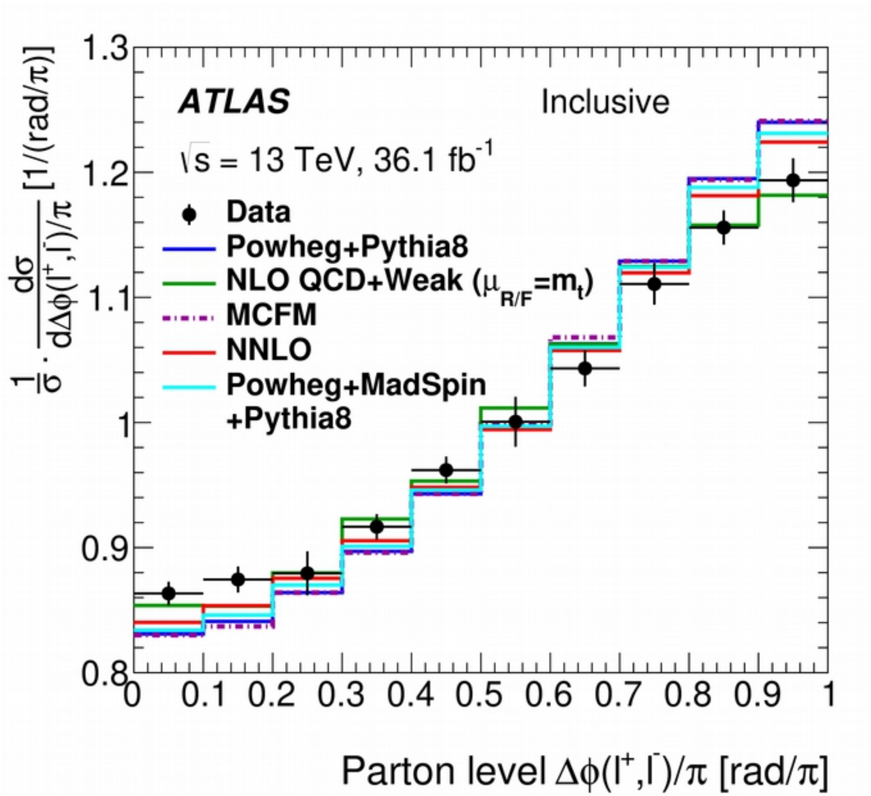
Further details in backup :)

Top-quark spin correlation in top-quark pair production

- The observed degree of spin correlation is significantly higher than predicted by the generators used (2.2σ) . Compatible results are observed by CMS analysis.
- Fixed-order NNLO predictions are closer to data but still do not agree fully.
- Data agrees well with the an alternative differential prediction at NLO in EWK/QCD.





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