Observation of Entanglement

in

Top Quark Pairs

02/10/2023

Jay Howarth

Introduction

- **Many other talks before this one have covered the theory better than I can.**

- **The goal of the ATLAS measurement is to measure:**

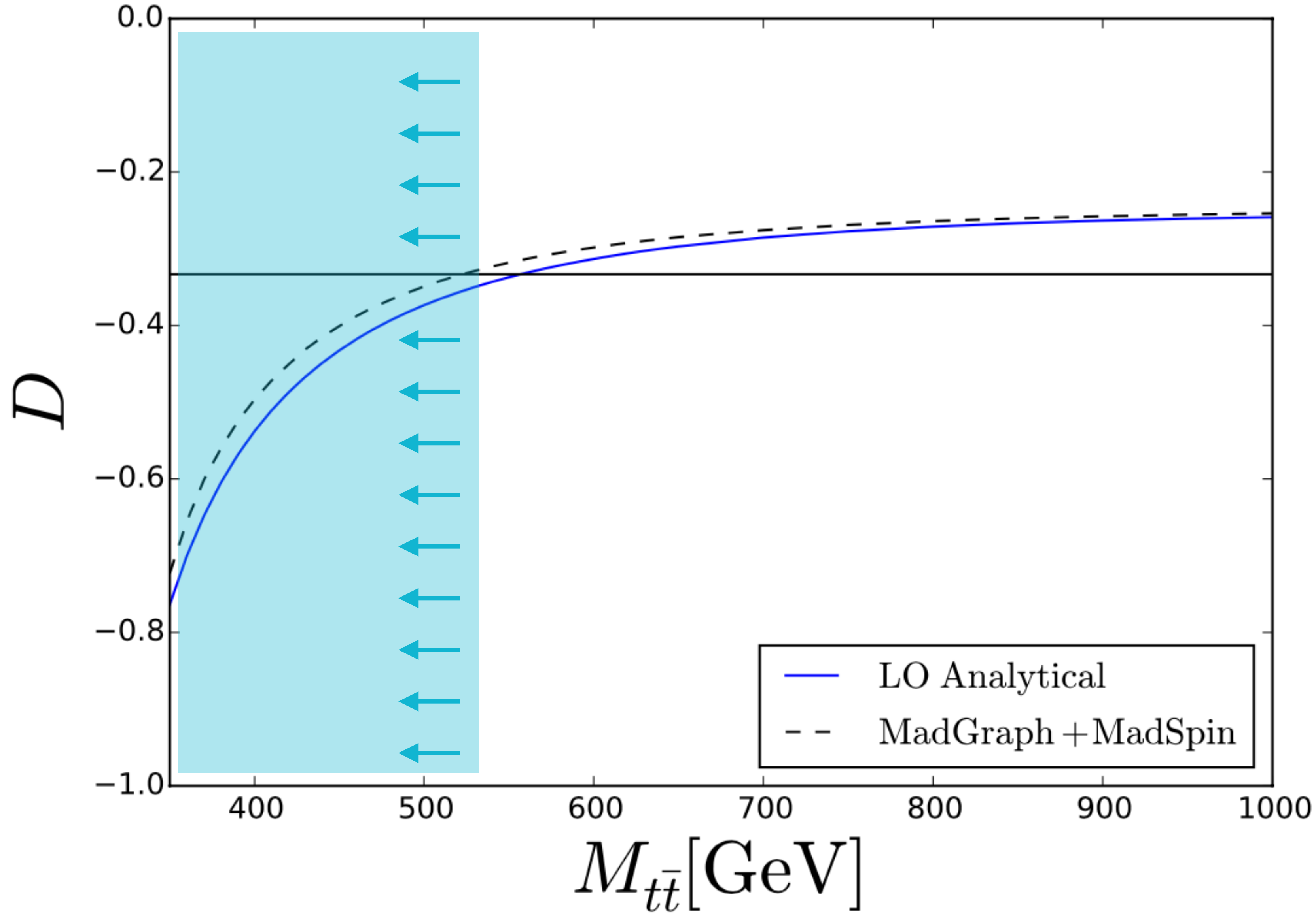
$$D = \frac{tr[C]}{3} = -3 \cdot < \cos(\phi) >$$

- **An observation of D < -1/3 is a sufficient condition to claim entanglement in $t\bar{t}$ pairs** (equivalently, that their density matrices are not factorable)**.**

- **ATLAS has measured this D in $t\bar{t}$ events using 140 fb^{-1} of 13 TeV data.**

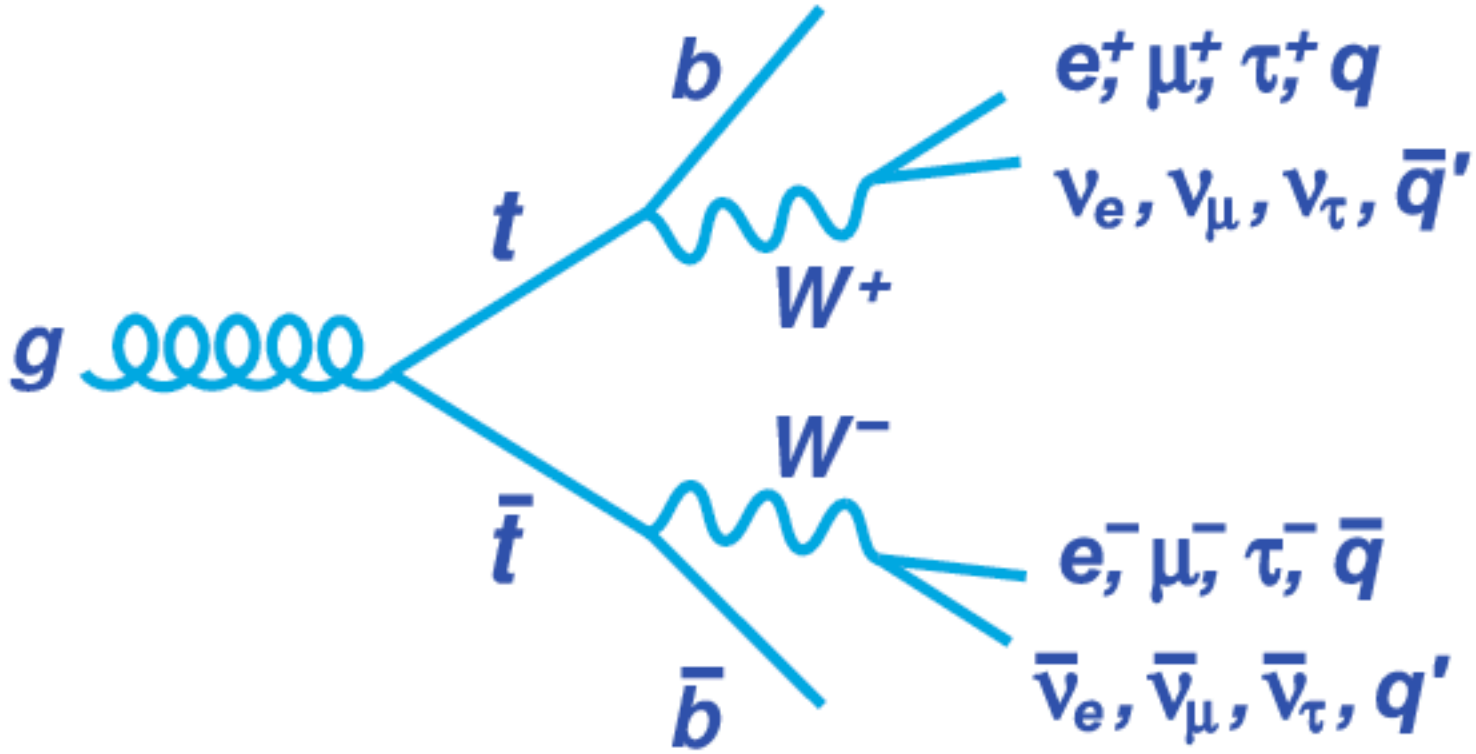
Introduction

- **The primary experimental challenges in this result are to reconstruct the tops with sufficient sensitivity to isolate the threshold region where tops are entangled.**



Top Decays

- **Why is it hard to reconstruct top quarks?**



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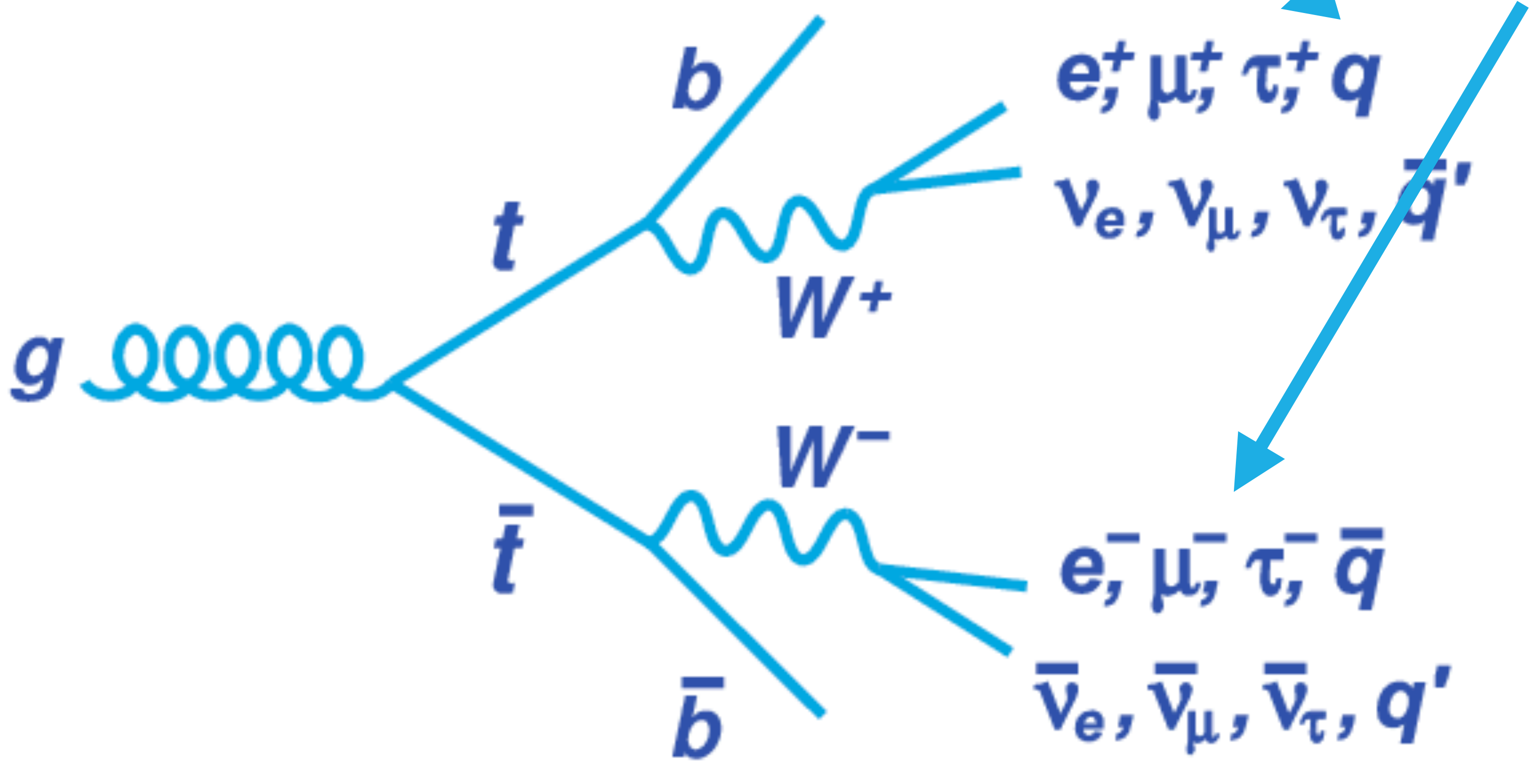

- **Charged leptons are the perfect spin analyser!**

Top Decays

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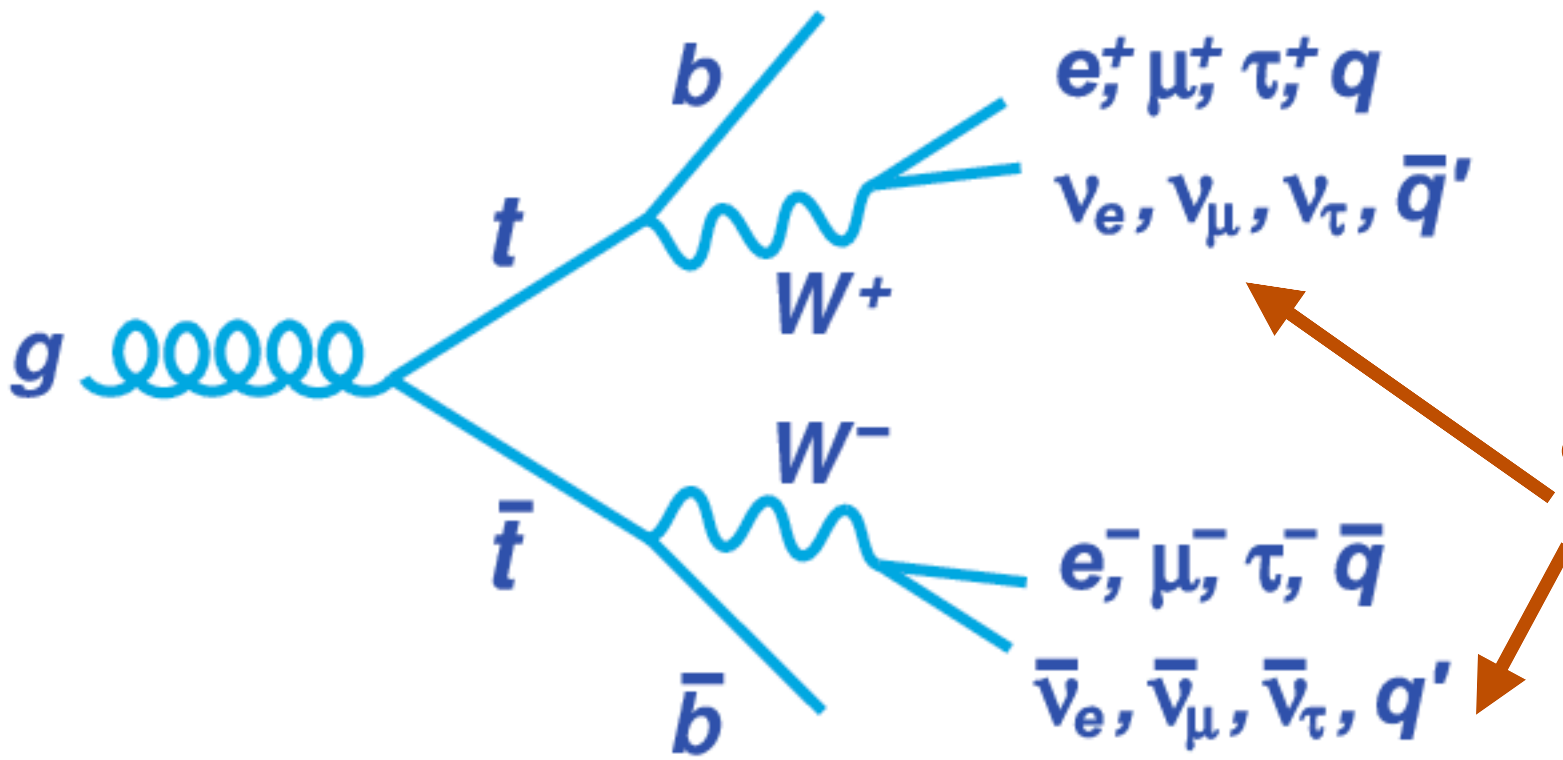

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Top Decays

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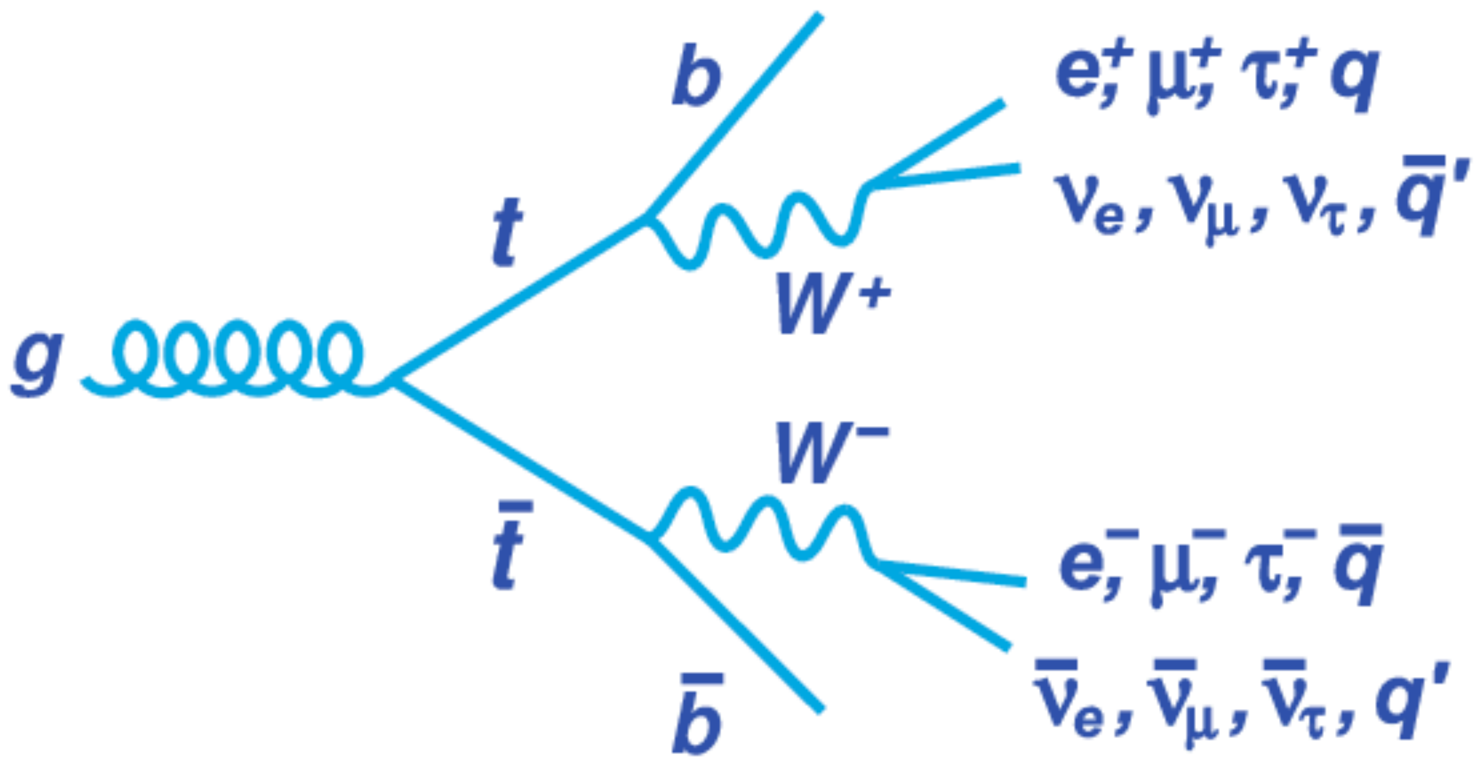


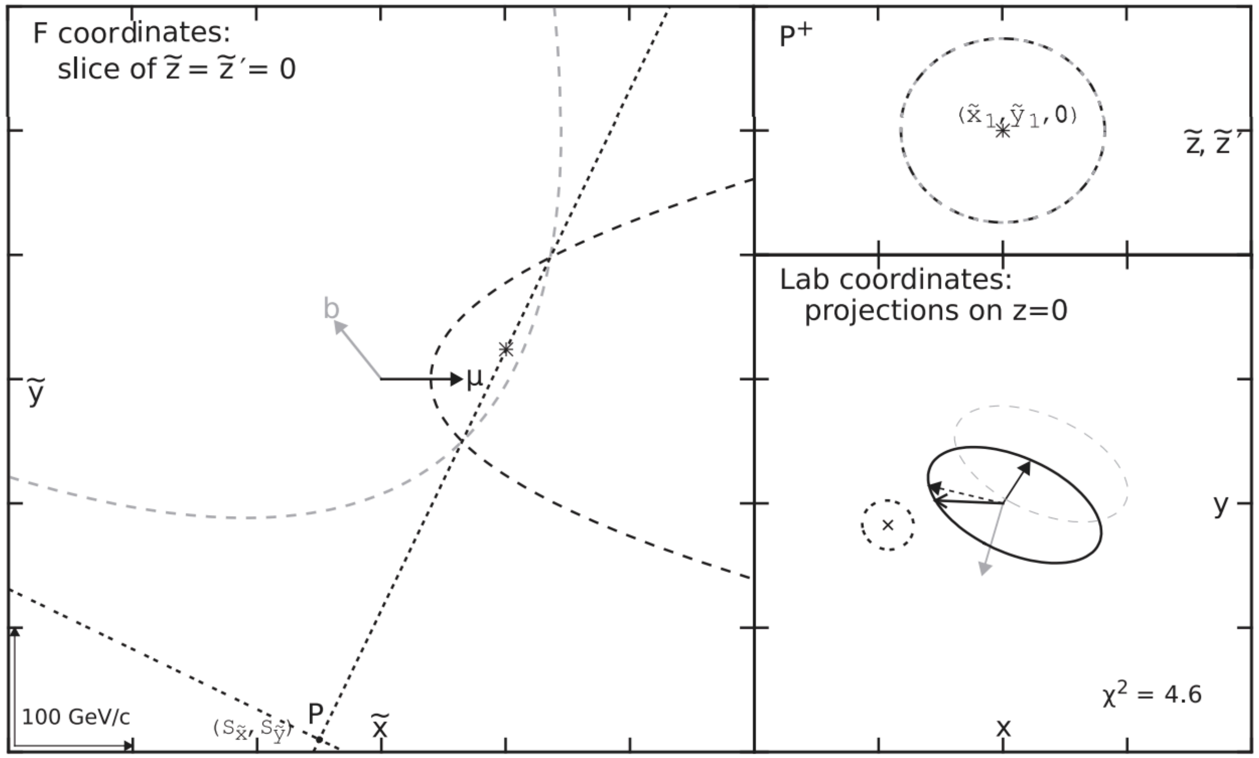
- **Charged leptons are the perfect spin analyser!**
- **Neutrinos not detected** (directly) **by ATLAS**

- **ATLAS selects events with two charged leptons in the final state** (+ 1 or more b-tagged jets)**.**

Reconstructing Tops

- **In order to measure D, we need to fully reconstruct both tops** (we need measure cos(Φ) in parent top rest frames)**.**
  ➡ **This means somehow dealing with two neutrinos**

- **There are a number of methods to achieve this, but this measurements relies heavily on the "**Ellipse method**".**



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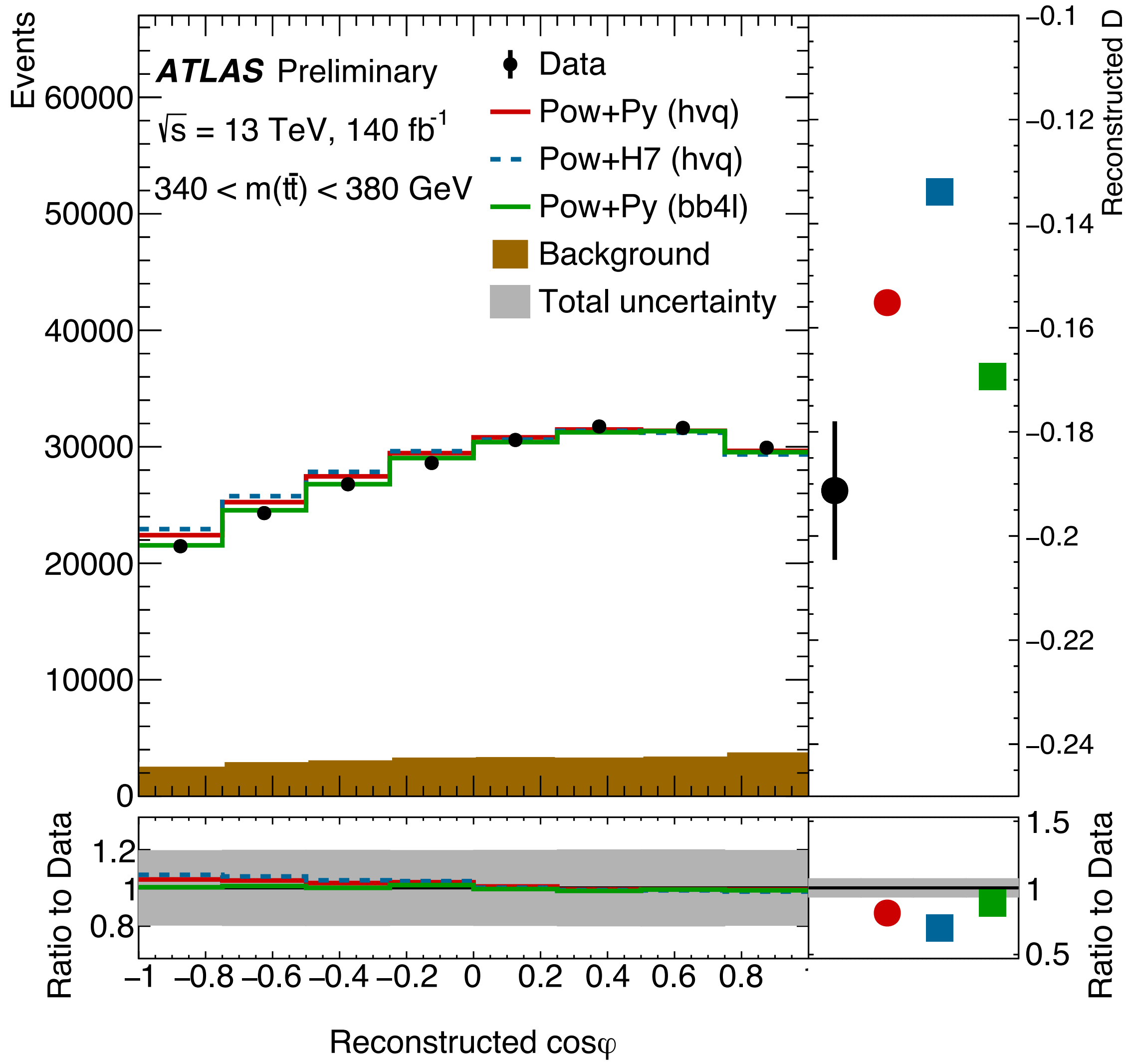
- **Employs a geometry approach to analytically solve the system using linear algebra.**

- **Some other numerical methods used in small number of events.**

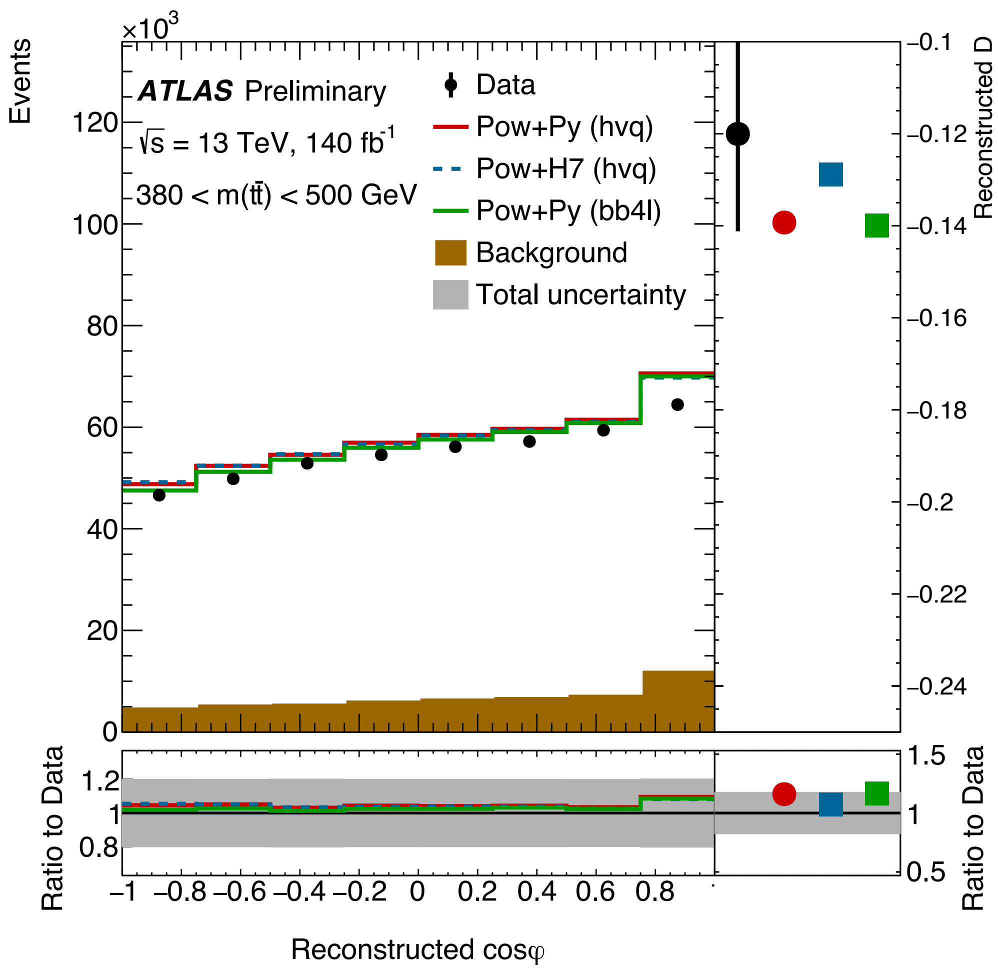
Selection

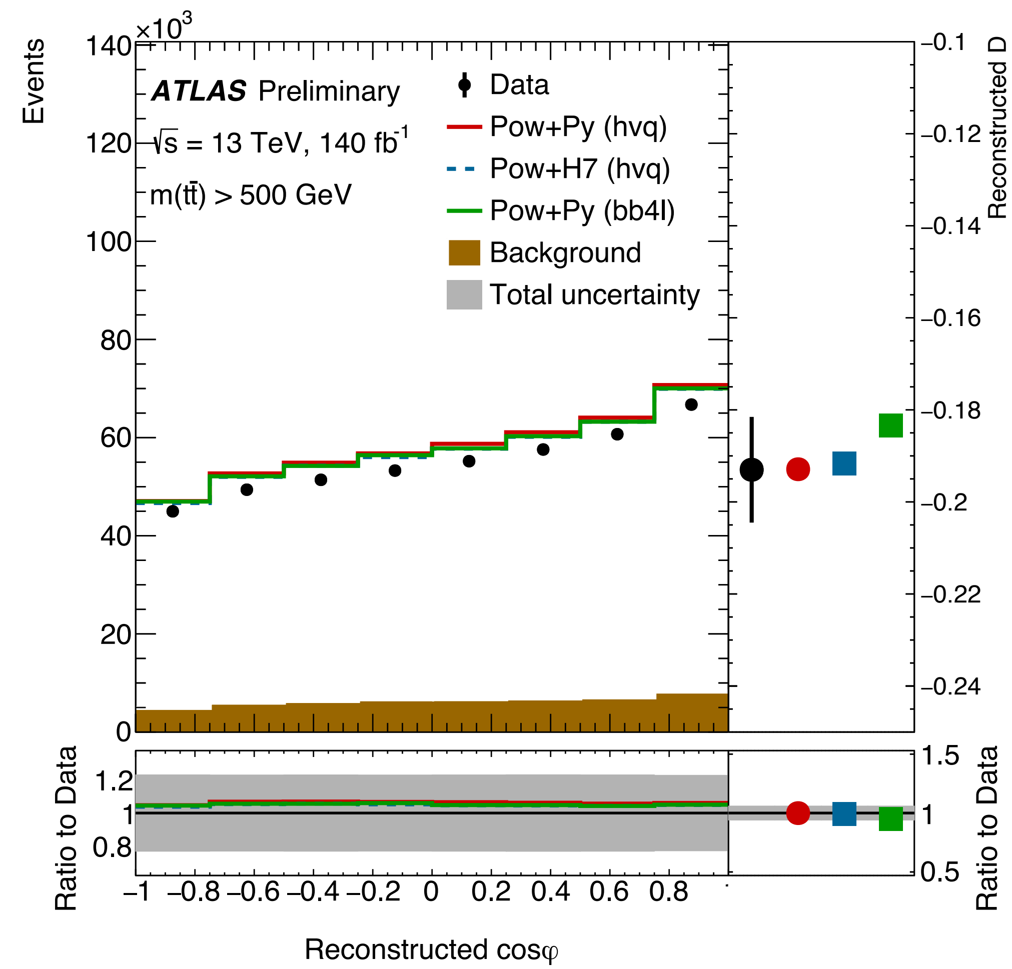


- **Events are selected with exactly 1 electron and 1 muon** (standard p_T, η cuts).
- **Require 1 or more b-tagged jets (85% W.P):**
  - ➡ loose working point to ensure high stats in signal region.
- **Three regions in $m(t\bar{t})$ are defined:**
  - ➡ **SR: 340 < $m(t\bar{t})$ < 380 GeV** [High degree of entanglement]
  - ➡ **VR1: 380 < $m(t\bar{t})$ < 500 GeV** [some entanglement]
  - ➡ **VR2: $m(t\bar{t})$ > 500 GeV** [no entanglement]

Selection

- **This selection is a very robust one** (similar selection used in dozens of analyses)**.**

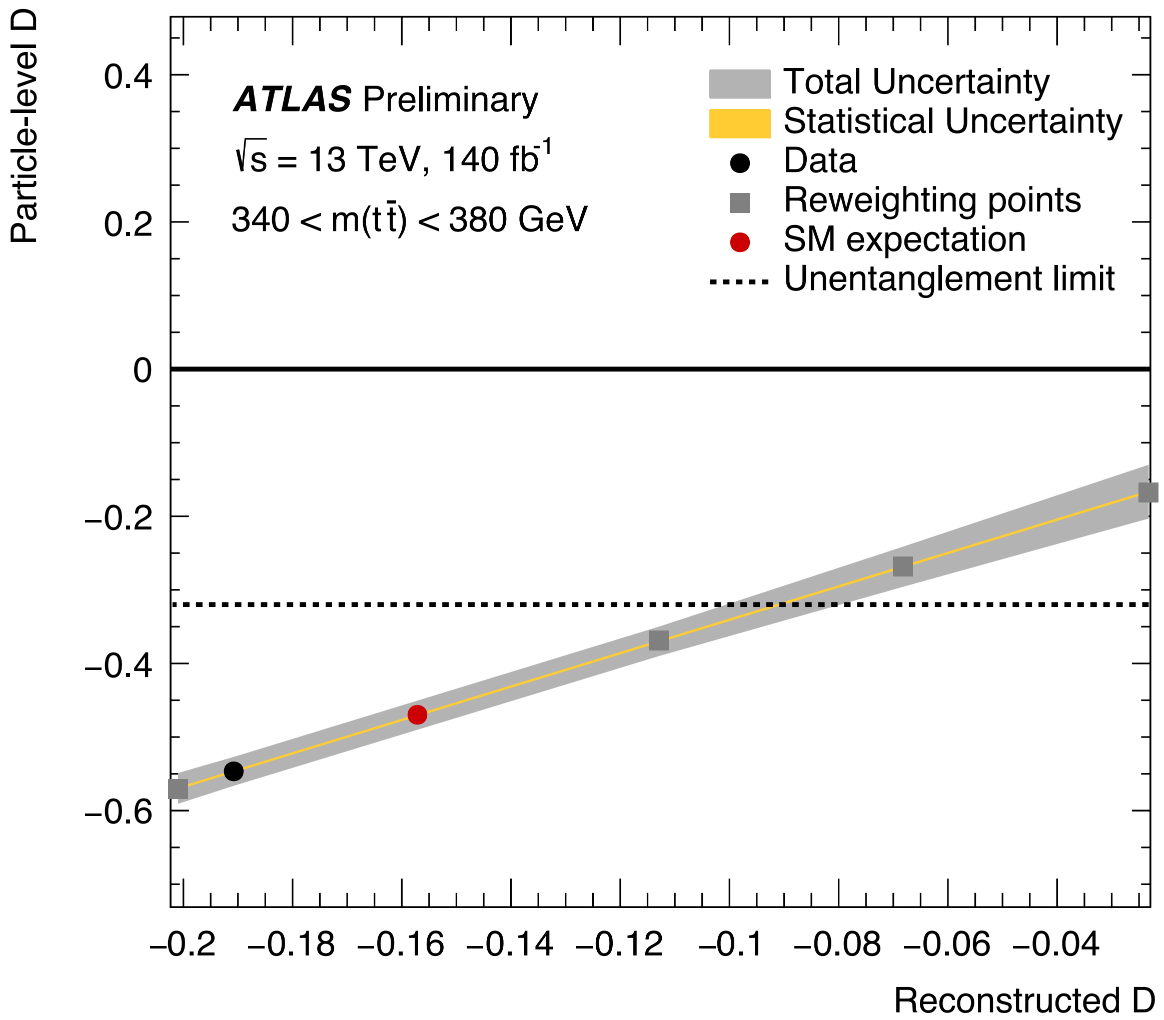




- **Very good overall agreement between the number of signal+background events and the observed number of events in data.**

Calibration Curve

- **We somehow need to correct our observed D for detector effects:**
  ➡ **We achieve this with a calibration curve.**

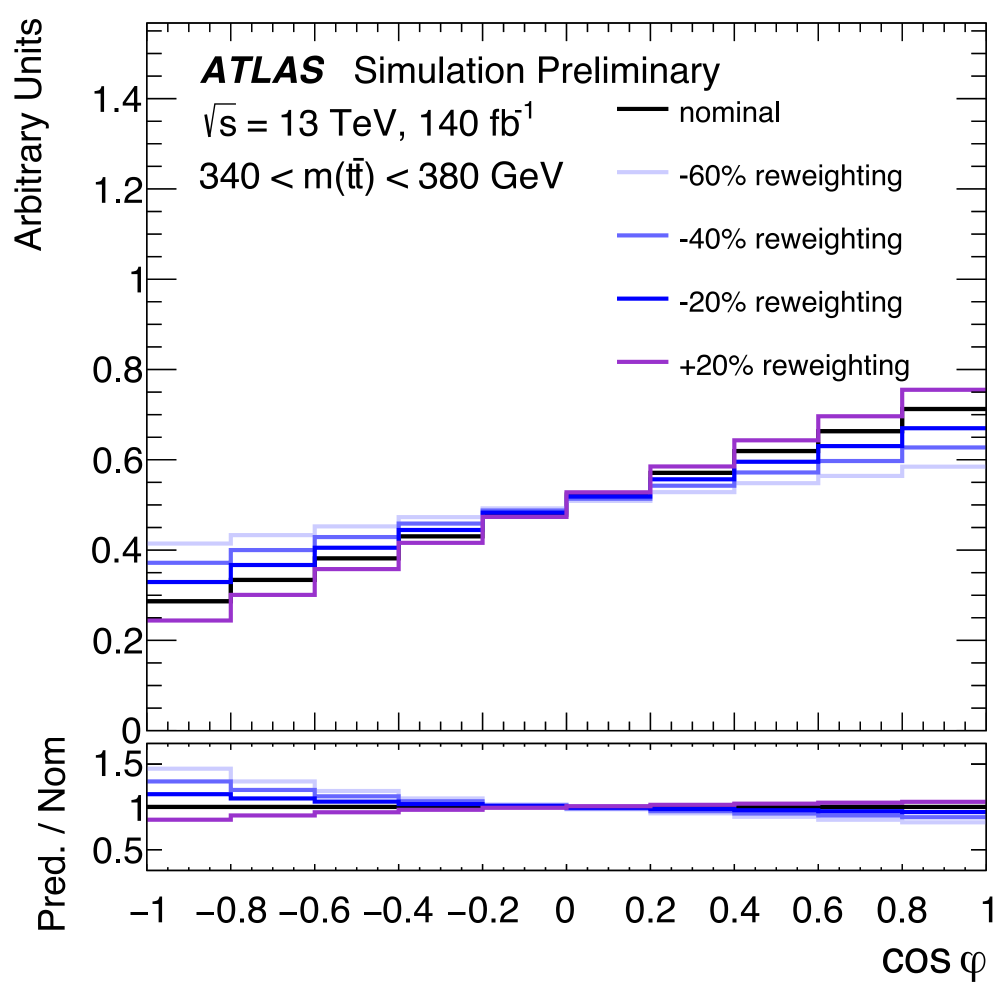


- **To construct this curve we need to change the amount of entanglement in our MC.**
- **We create 5 hypothesis points corresponding to the SM and 4 different reweighing points:**
  (+20%, -20%, -40%, -60%)

Reweighting

- **How these alternative hypothesis points are constructed is one of the key points of the measurement.**

- **We cannot dial entanglement up or down in the MC, so we reweight the cos(Φ) distribution as a function of m($t\bar{t}$).**



- **If this is not done correctly, the relation:**

$$D = \frac{tr[C]}{3} = -3 \cdot < \cos(\phi) >$$

does not hold.

- **The method we have used ensures that this relationship remains correct.**

Systematic Uncertainties

- **The relative size of the systematics is not fixed and changes at each hypothesis point:**

Systematic source	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD (%)	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD (%)
Signal Modelling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	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
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total Statistical Uncertainty	0.002	0.3	0.002	0.4
Total Systematic Uncertainty	0.021	3.8	0.018	3.9
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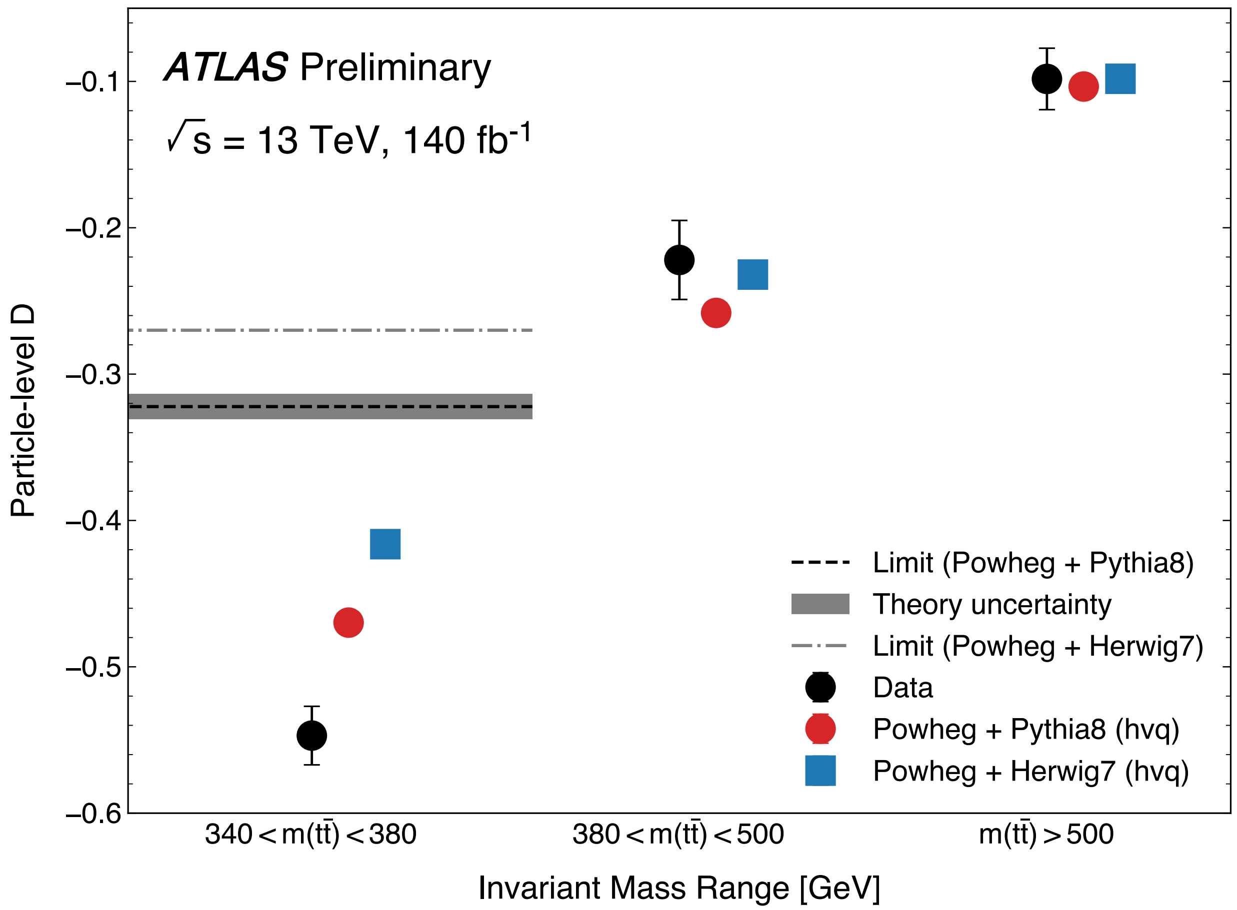
- **As with most top measurements, we are limited by signal modelling, though background modelling (Z+jets) matters too due to looser b-tag and shape of the background.**

Results

- **The observed (expected) results are:**

$$\textbf{SR} \quad D = -0.547 \pm 0.002\ [\text{stat.}] \pm 0.021\ [\text{syst.}]\ (-0.470 \pm 0.002\ [\text{stat.}] \pm 0.018\ [\text{syst.}])\ ,$$
$$\textbf{VR1} \quad D = -0.222 \pm 0.001\ [\text{stat.}] \pm 0.027\ [\text{syst.}]\ (-0.258 \pm 0.001\ [\text{stat.}] \pm 0.026\ [\text{syst.}])\ ,$$
$$\textbf{VR2} \quad D = -0.098 \pm 0.001\ [\text{stat.}] \pm 0.021\ [\text{syst.}]\ (-0.103 \pm 0.001\ [\text{stat.}] \pm 0.021\ [\text{syst.}])\ ,$$

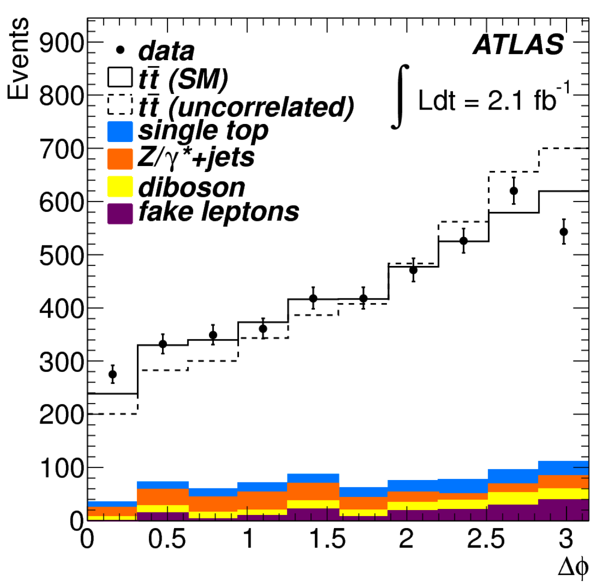


- **The observed results excludes the entanglement limit at more than 5 sigma significance.**

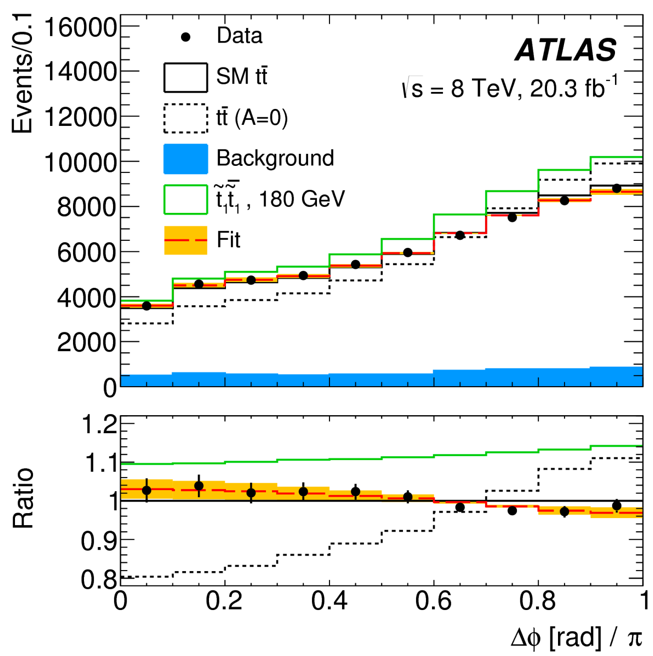
Is it just spin correlation?

- **This measurement is actually a fantastic success story for the progress in sophistication in top spin measurements.**

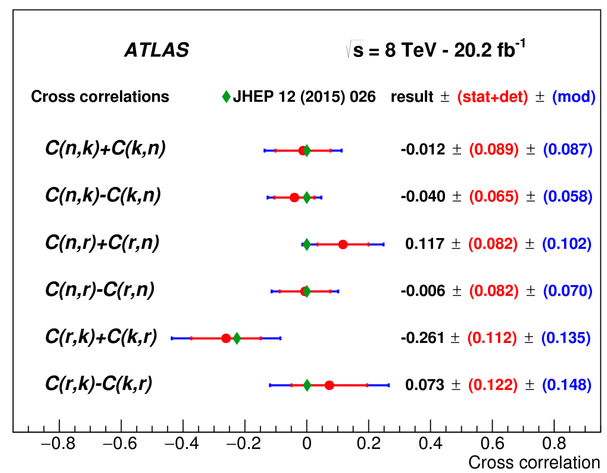
<u>First Observation</u>
(2012)



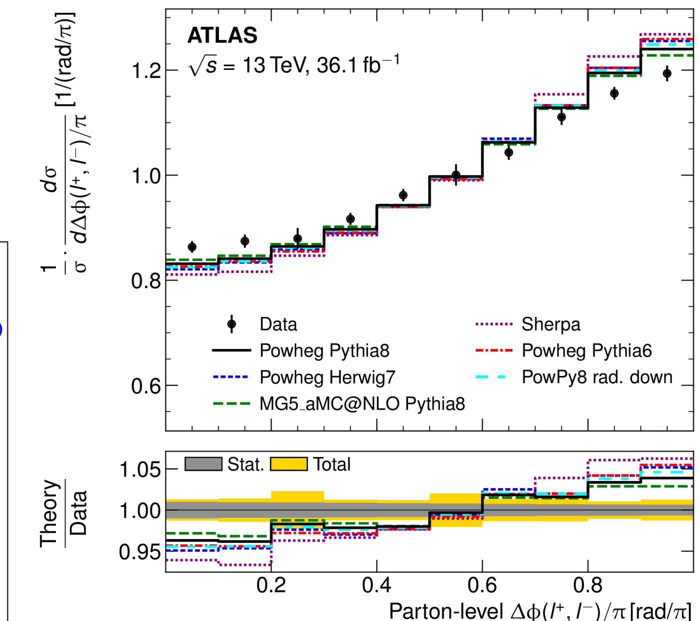
<u>First Stop Limits</u>
(2014)



<u>Full Density Matrix</u>
(2016)



<u>Tensions with SM</u>
(2019)



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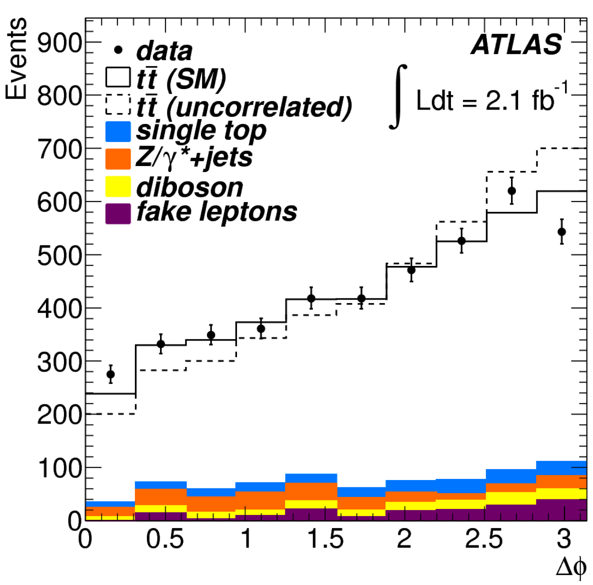

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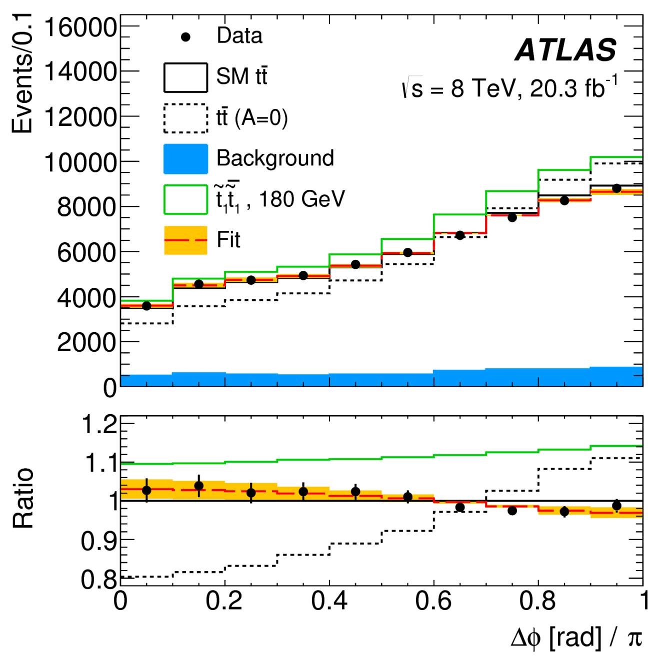

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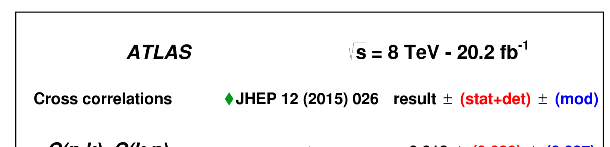

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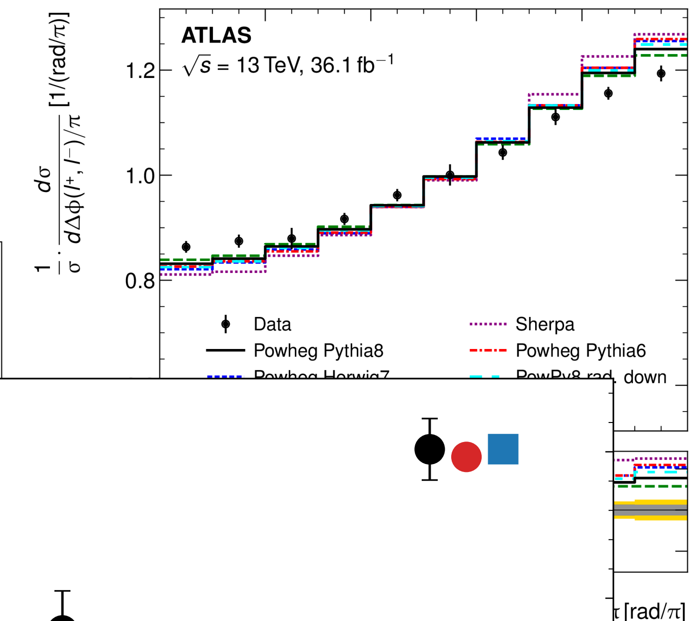

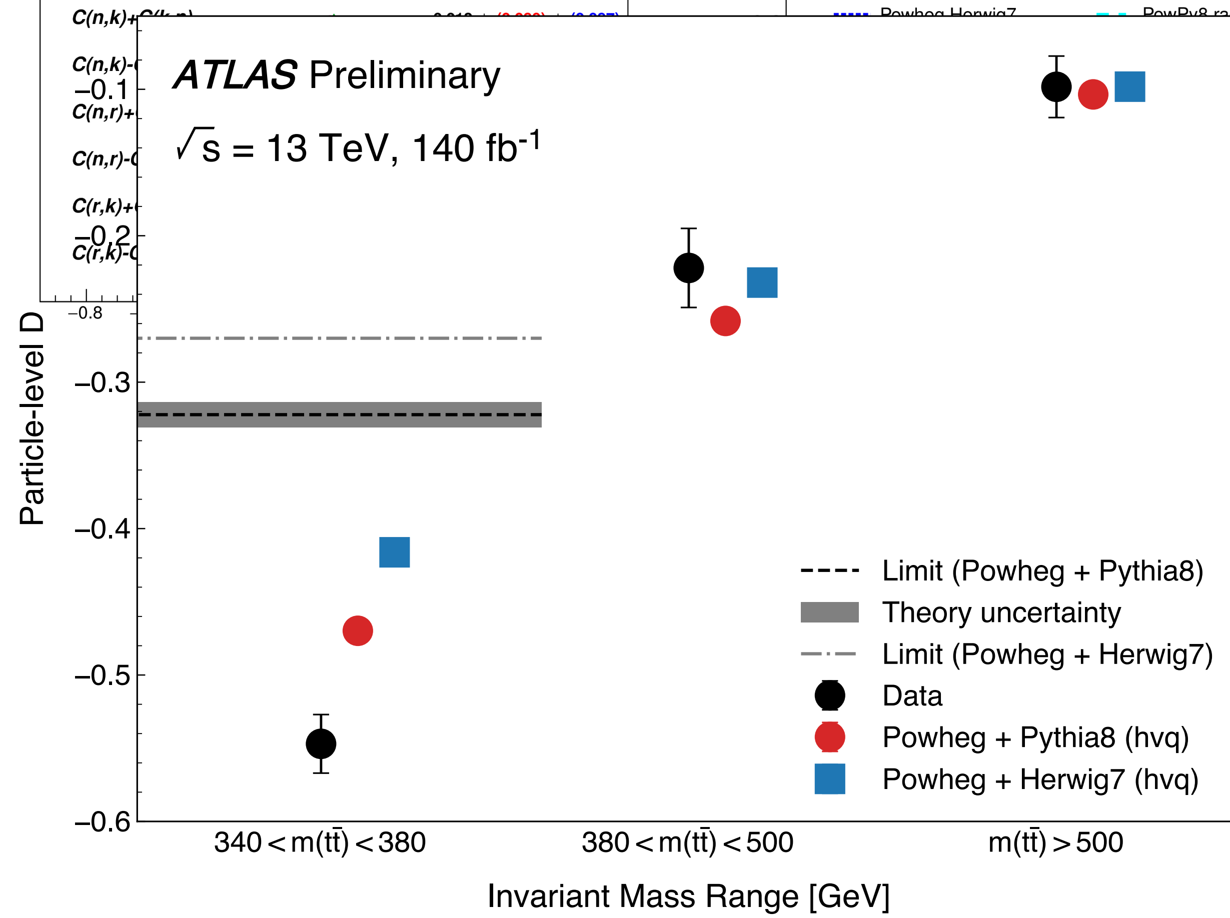

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$$\begin{aligned}
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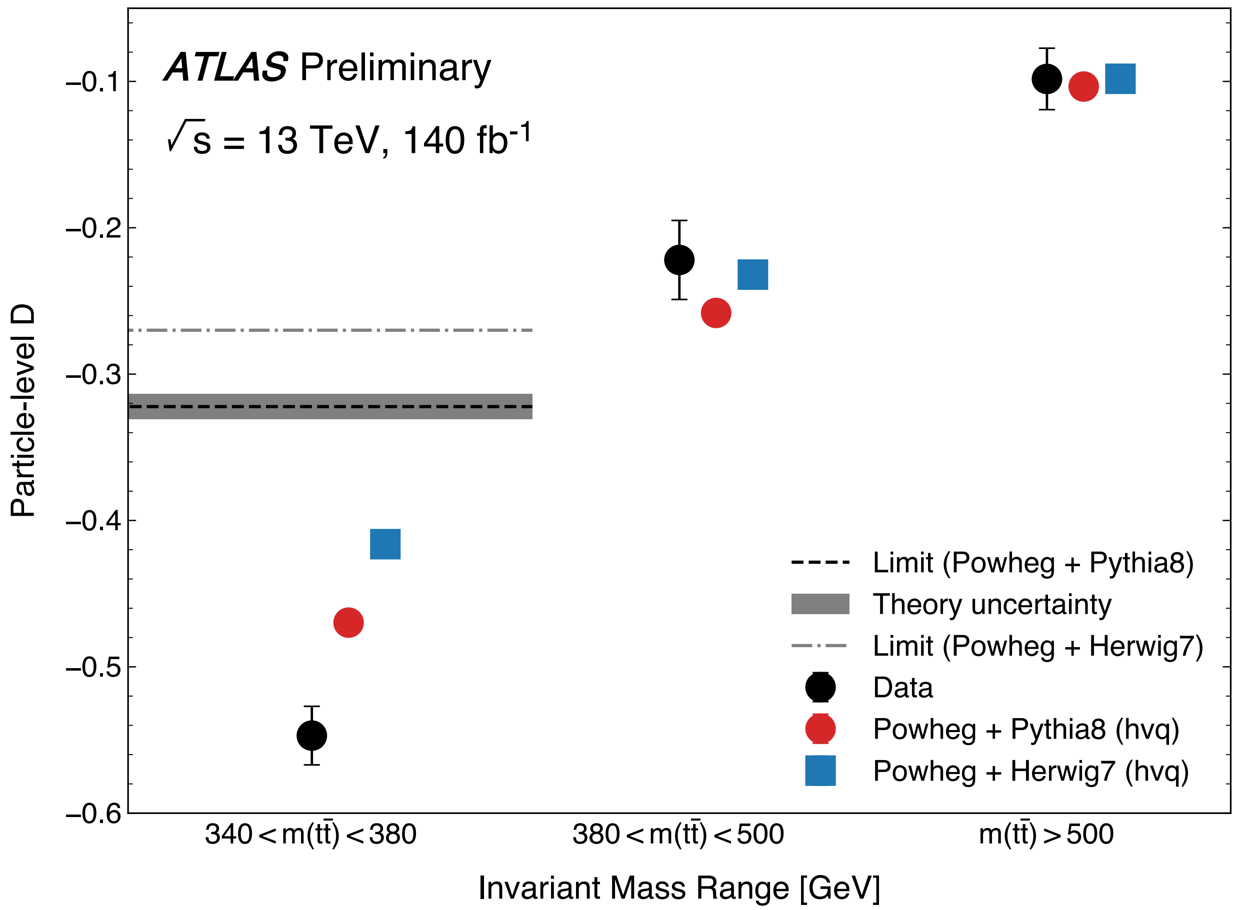

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- **The observed results excludes the entanglement limit at more than 5 sigma significance.**

Interpretation

- **From slides earlier in this workshop:**

Top pair production

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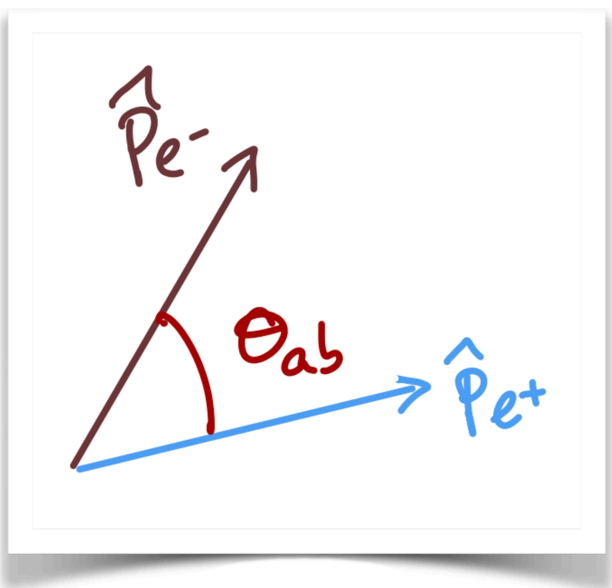
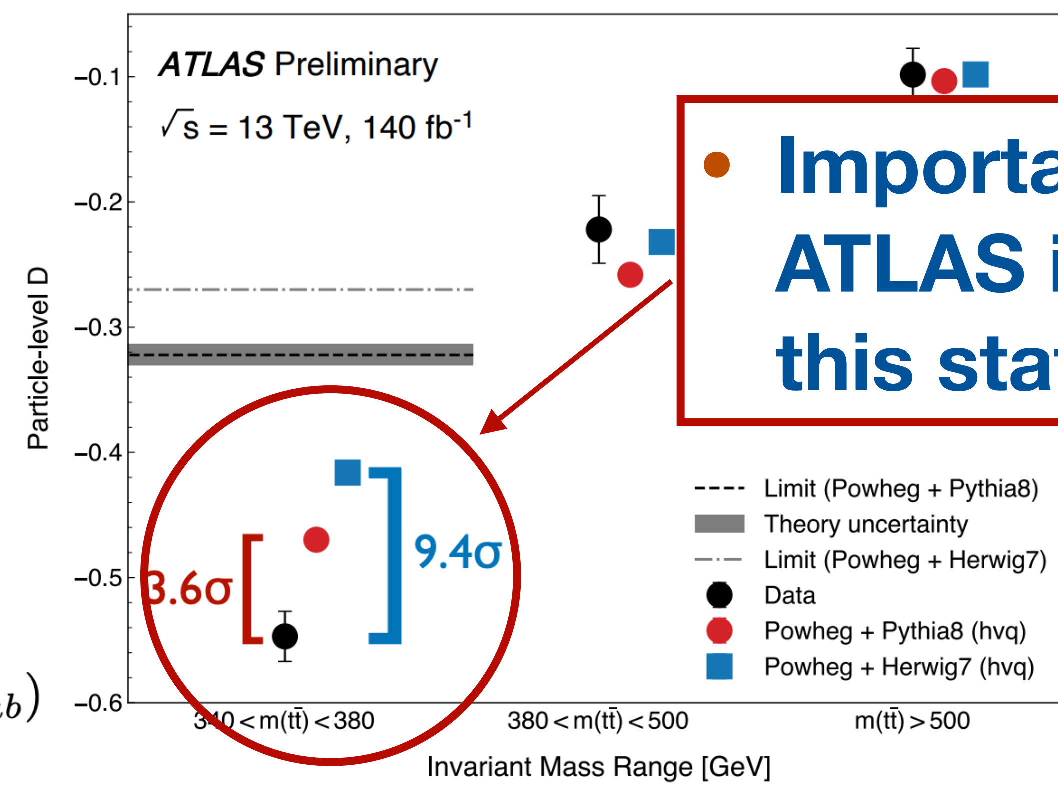
ATLAS has performed [and CMS is pursuing] a measurement at threshold using the D observable, related to the angle between the two leptons



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{ab}} = \frac{1}{2}(1 + \alpha_a\alpha_b D\cos\theta_{ab})$$

$$D = \frac{1}{3}(C_{11} + C_{22} + C_{33})$$



- **Important to note that ATLAS is NOT making this statement**

Entanglement test near threshold: $-3D - 1 > 0$

Conclusions

- **ATLAS has observed quantum entanglement for the first time in a pair of fundamental quarks, at the highest lab-made energies.**

- **This is the first step in a program to use the LHC as a tool for exploring quantum information.**

- **Important questions about how entanglement** (and spin correlation) **is modelled in this threshold region:**
  ➡ **Would be a very profitable area for further study in the theory community!**

Backup

Parton Shower