Observation of Entanglement in Top Quark Pairs at ATLAS

Firenze, 05/11/2023

Jay Howarth

Introduction

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- **Testing quantum entanglement at hadron colliders is a brand new idea! Isn't it?**

CORRELATION EXPERIMENTS AND THE NONVALIDITY OF

ORDINARY IDEAS ABOUT THE PHYSICAL WORLD*†

Henry P. Stapp

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 9, 1976

- **In 1968, Henry Stapp proposed using spin correlations in proton-proton scattering.**

- **Add in top quarks and you have the ATLAS paper title.**

Shameless Advertising

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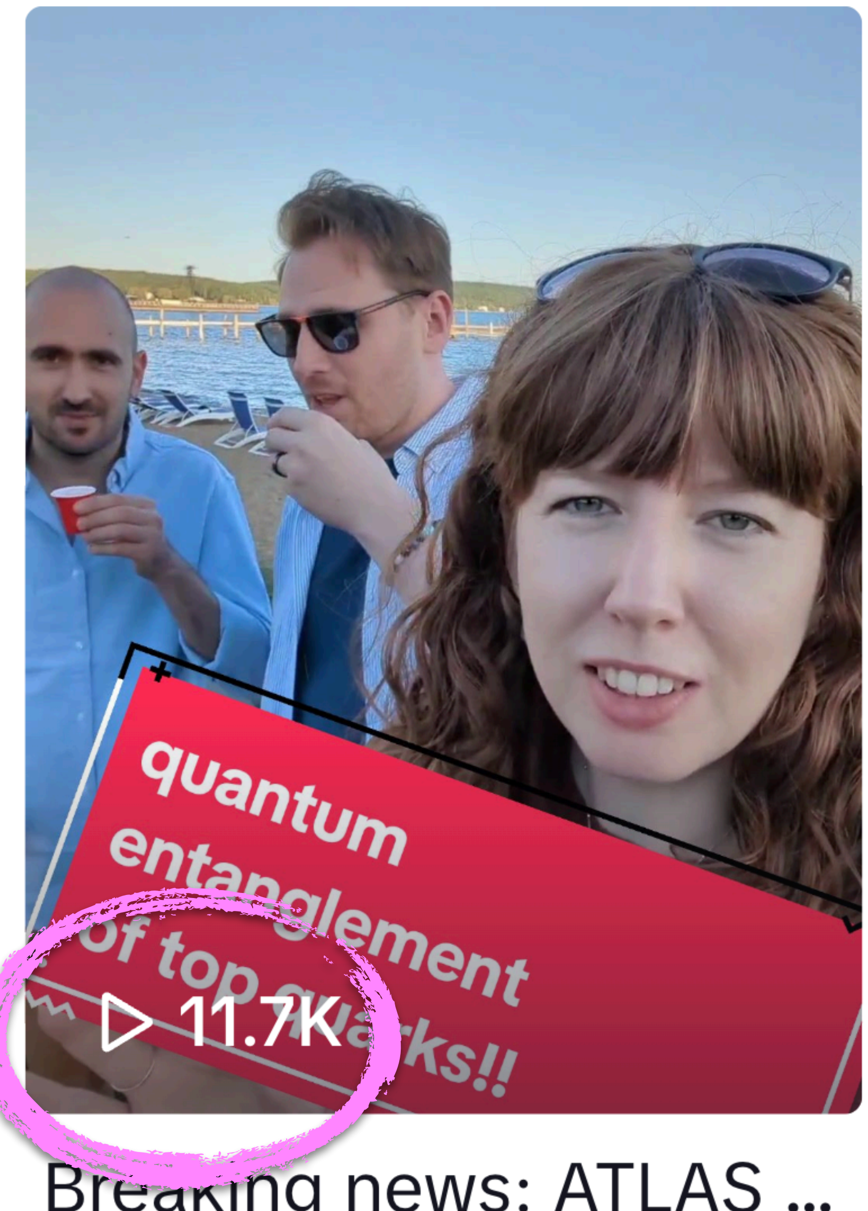
- Fair to say that the ‘buzzword’ effect is in full swing:

Shameless Advertising

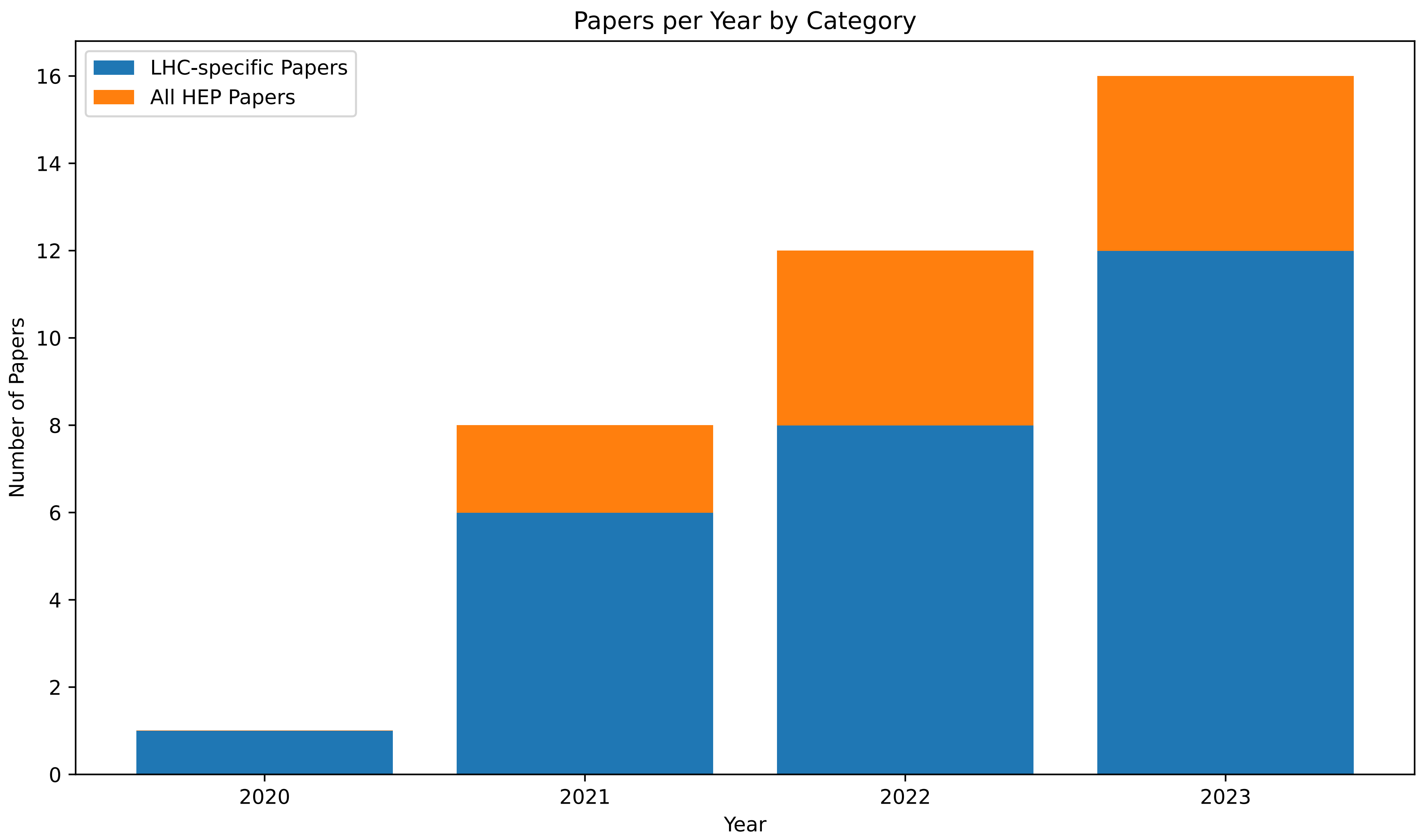
- Fair to say that the ‘buzzword’ effect is in full swing:



(one of Clara’s worst performing videos…)

Papers Vs Time

- **Interest appears to be growing** (plot from summer 2023)



- **Interesting increase in non-LHC paper!**

Introduction

- **What is quantum entanglement?**
  ➡ *"An entangled state is one that cannot be written as a convex combination of product states of density matrices"*

- **If two particles are entangled, the quantum state of one particle cannot be described independently from the other:**

$$|\psi\rangle = |a\rangle_A \otimes |b\rangle_B$$ **separable**

$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$ **non-separable**

- **Spin/polarisation is the canonical example of an observable to use to test entanglement.**

Introduction

- **Why do we care about doing this at the LHC?**

- **Entanglement has been measured before in composite systems:**
  ➡ Diamonds, Mesons,  Tardigrades, electrons in atoms)**.**

- **And in free particle systems** (photons)**.**

- **top quarks are the first time it has been measured in an unbound fundamental fermion.**

- **top quarks, even when produced near threshold, are genuinely relativistic** ($\beta \sim 0.4$) **and Entanglement has never been explored under such conditions**.

Introduction

- **How does QE manifest in $t\bar{t}$ events?**
- **Key feature of top quarks is that it is VERY heavy! This leads to some unique properties:**

Production		Lifetime		Hadronisation		Spin decorr.
$\frac{1}{m(t)}$	$<<$	$\frac{1}{\Gamma(t)}$	$<<$	$\frac{1}{\Lambda_{QCD}}$	$<<$	$\frac{m(t)}{\Lambda_{QCD}}$
$\sim 10^{-27}$ s		$\sim 10^{-25}$ s		$\sim 10^{-24}$ s		$\sim 10^{-21}$ s

- **QCD has no time to dilute the top's quantum numbers, and they are transferred directly to its decay particles** (where we can access them)**.**

Spin Correlation in $t\bar{t}$

- **QCD is P-conserving and T invariant → tops have no preferential polarisaton in $t\bar{t}$ production.**

- **But spins are correlated!**

$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- **More formally:**

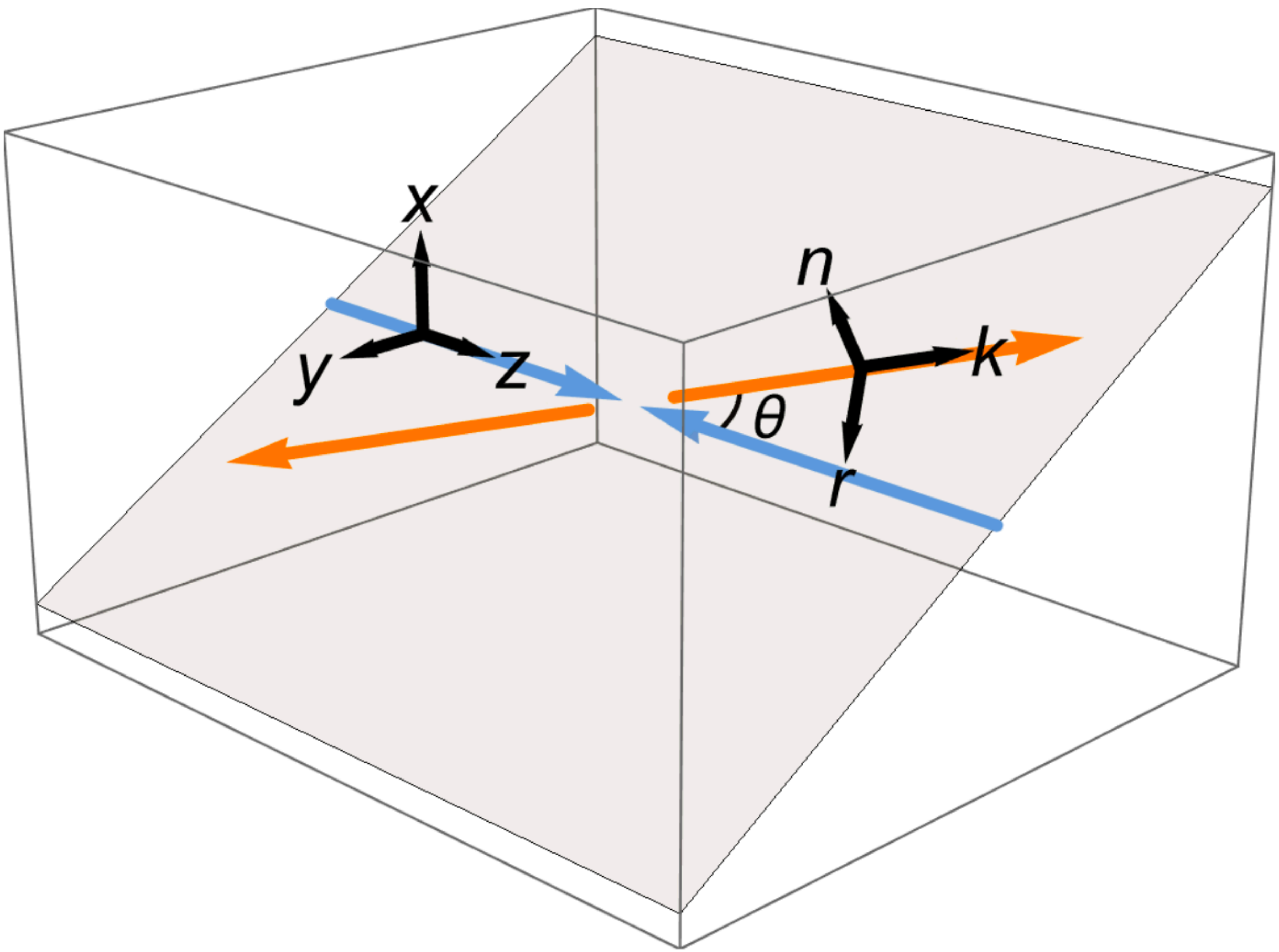
Polarisation **Spin Correlation**

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a \,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b)$$

- **Measuring B and C in $t\bar{t}$ essentially means constructing angles with the decay particles** (usually charged leptons)**.**

Spin Correlation in $t\bar{t}$

- **It matters how you measure these angles!**



Spin Correlation in $t\bar{t}$

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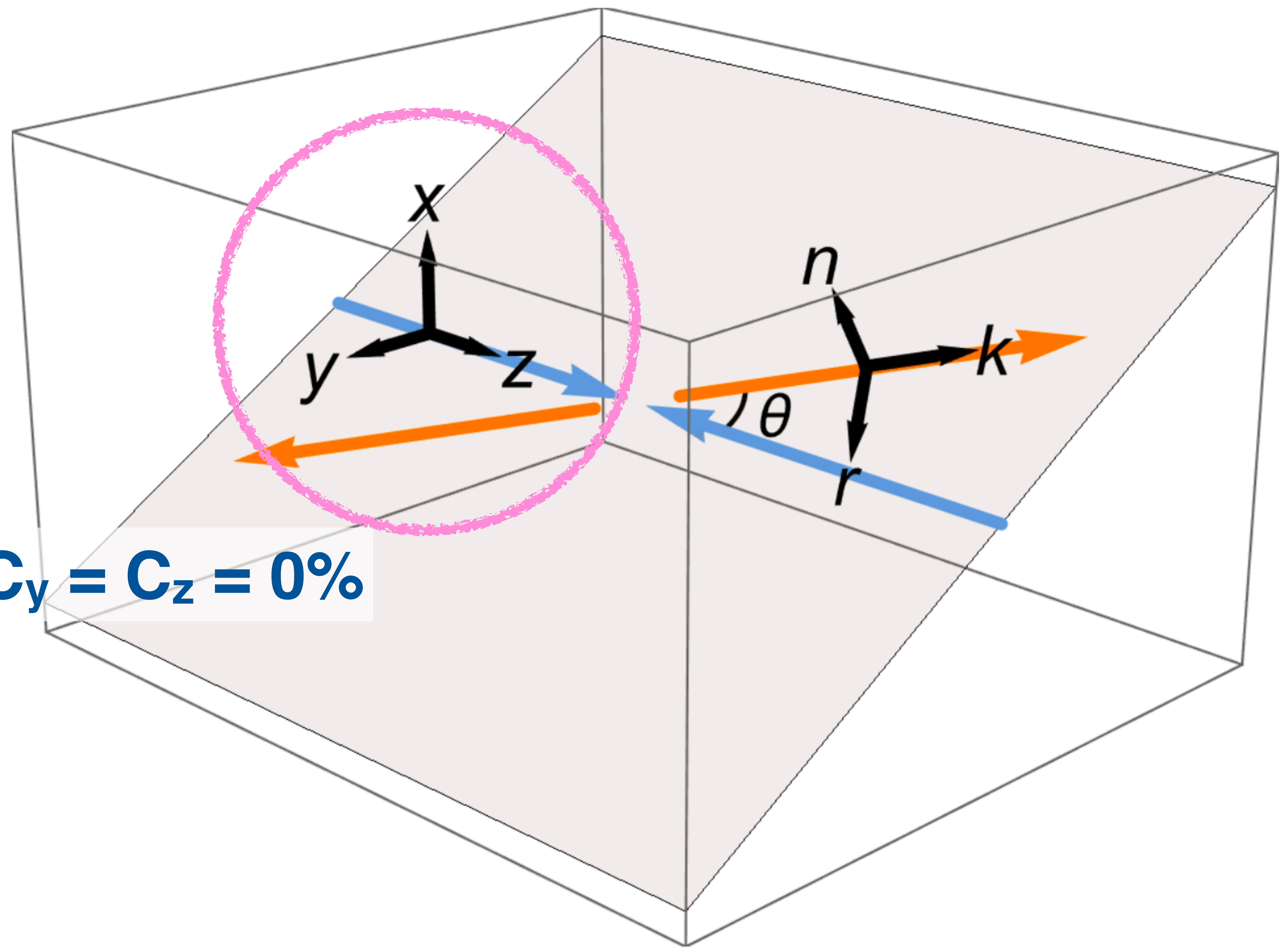

$C_x = C_y = C_z = 0\%$

Spin Correlation in $t\bar{t}$

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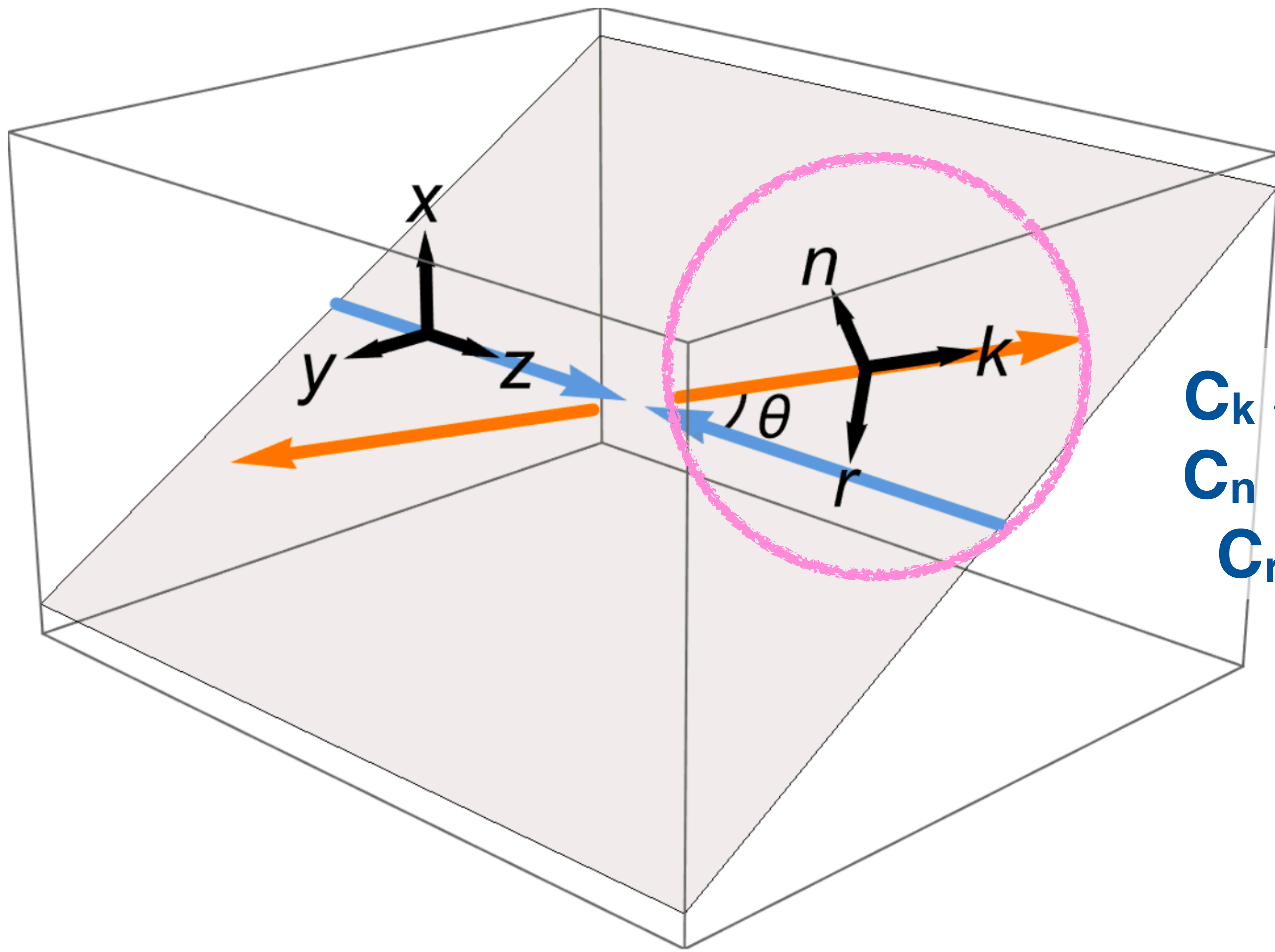


$C_k \sim -30\%$
$C_n \sim -30\%$
$C_r \sim 0\%$

Entanglement in $t\bar{t}$

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

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

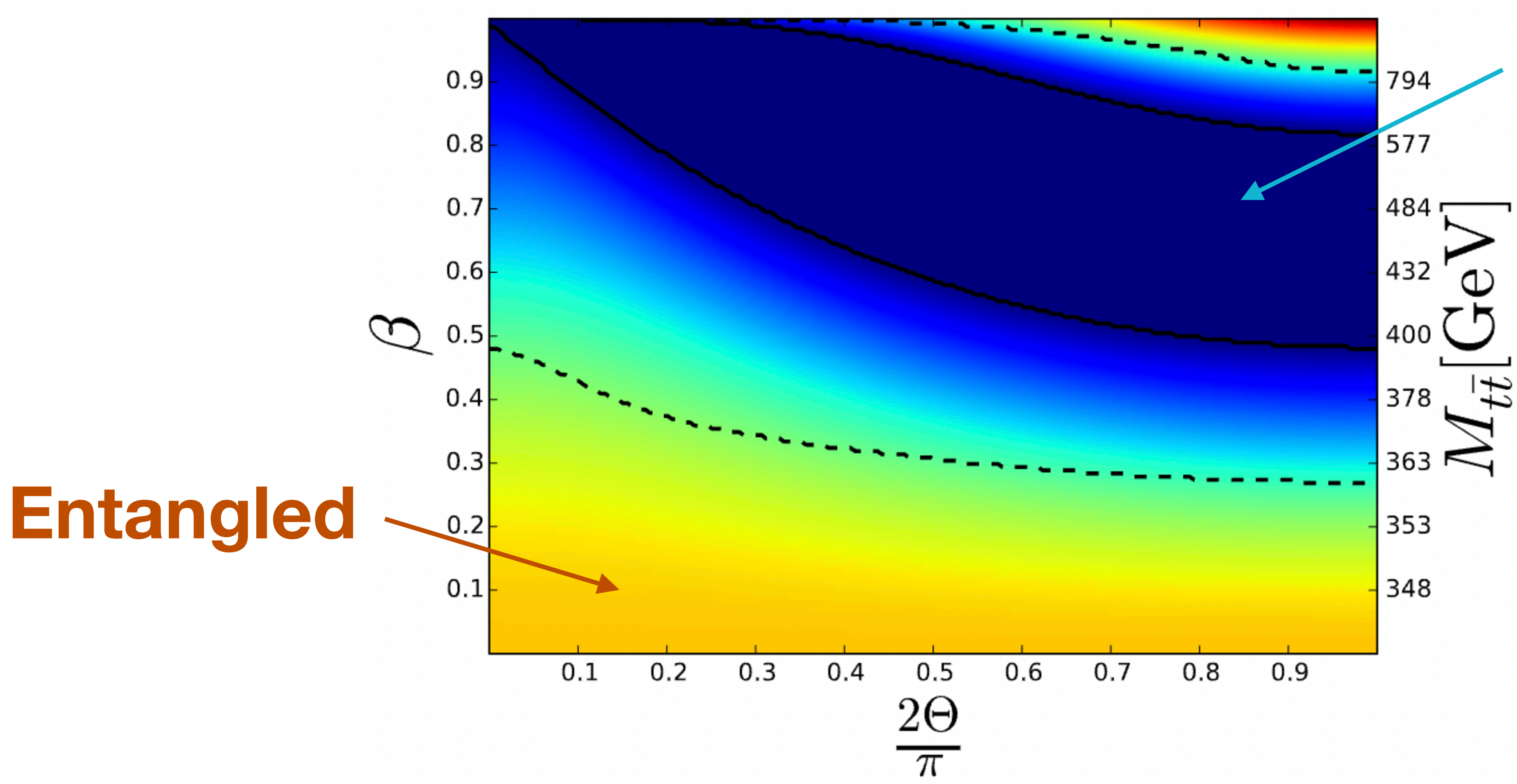
- **Where ϕ is the angle between the top spin analysers in their parent top rest frames.**

- **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.**

Getting the D

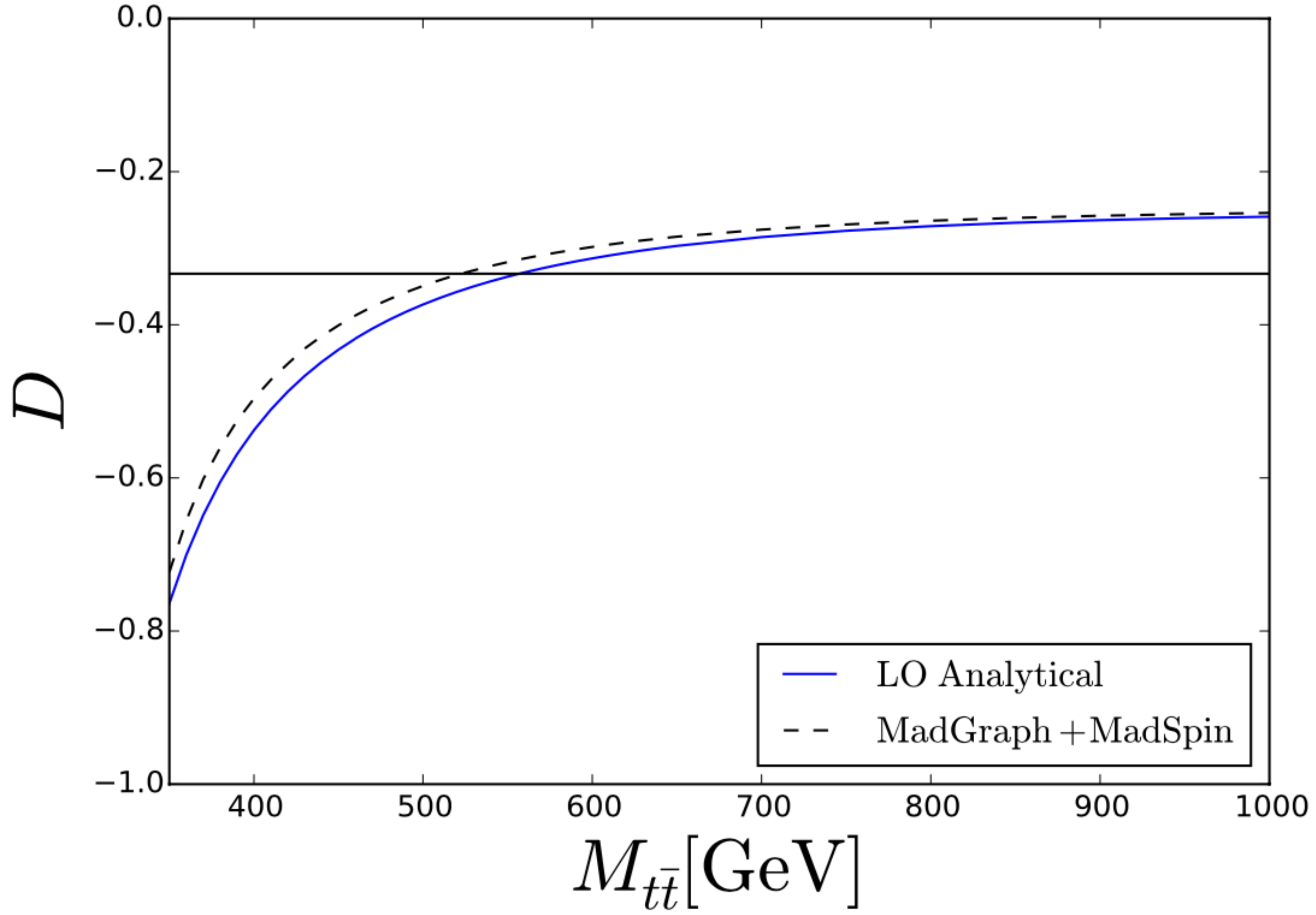
- **If D is observed to be less than -1/3, then the tops can be said to be entangled.**



- **This occurs in $t\bar{t}$ production when the tops are close to threshold** (in gg fusion) **or very boosted** (in qqbar)**. We focus on the former.**

Getting the small D

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



Getting the small D

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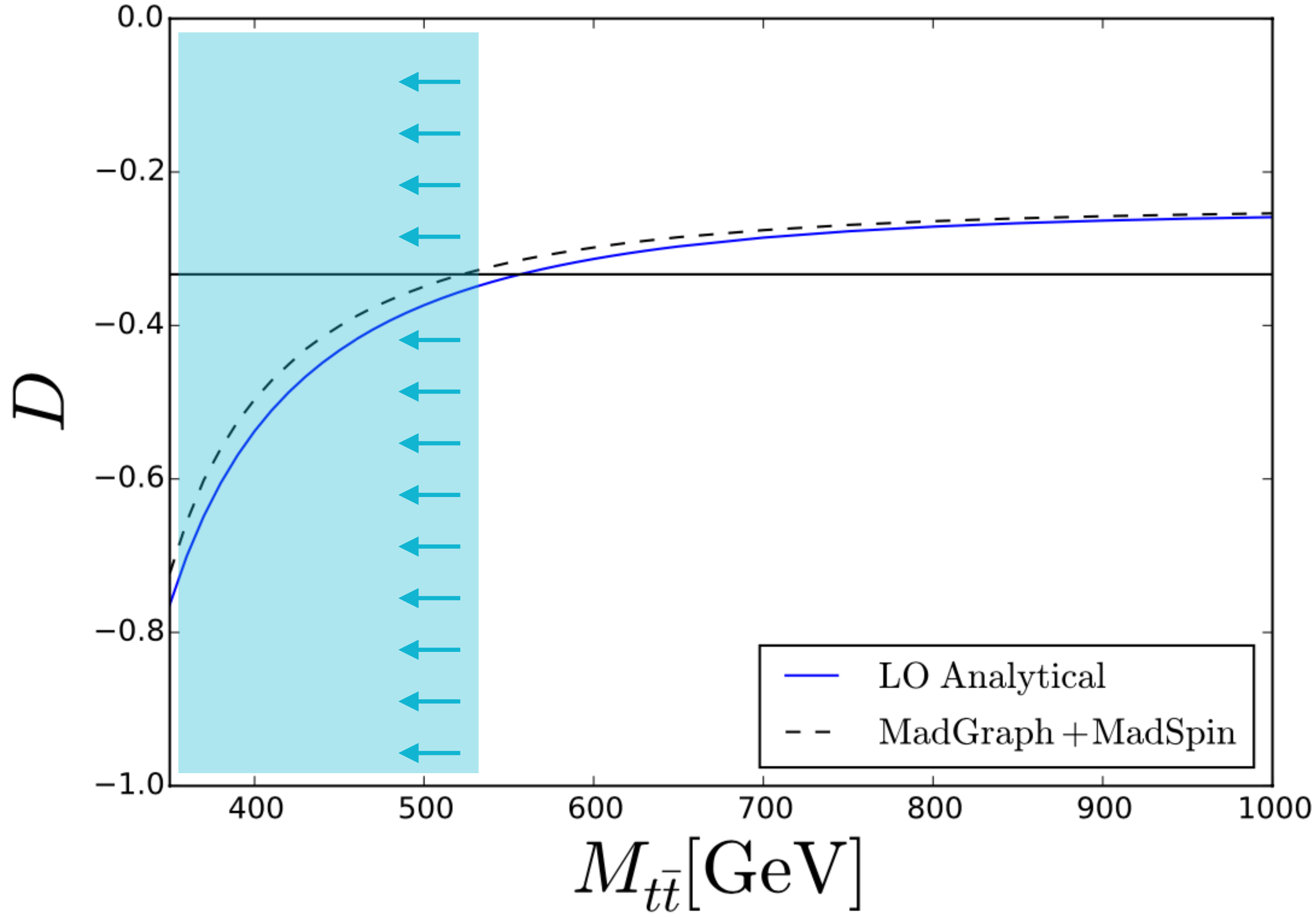
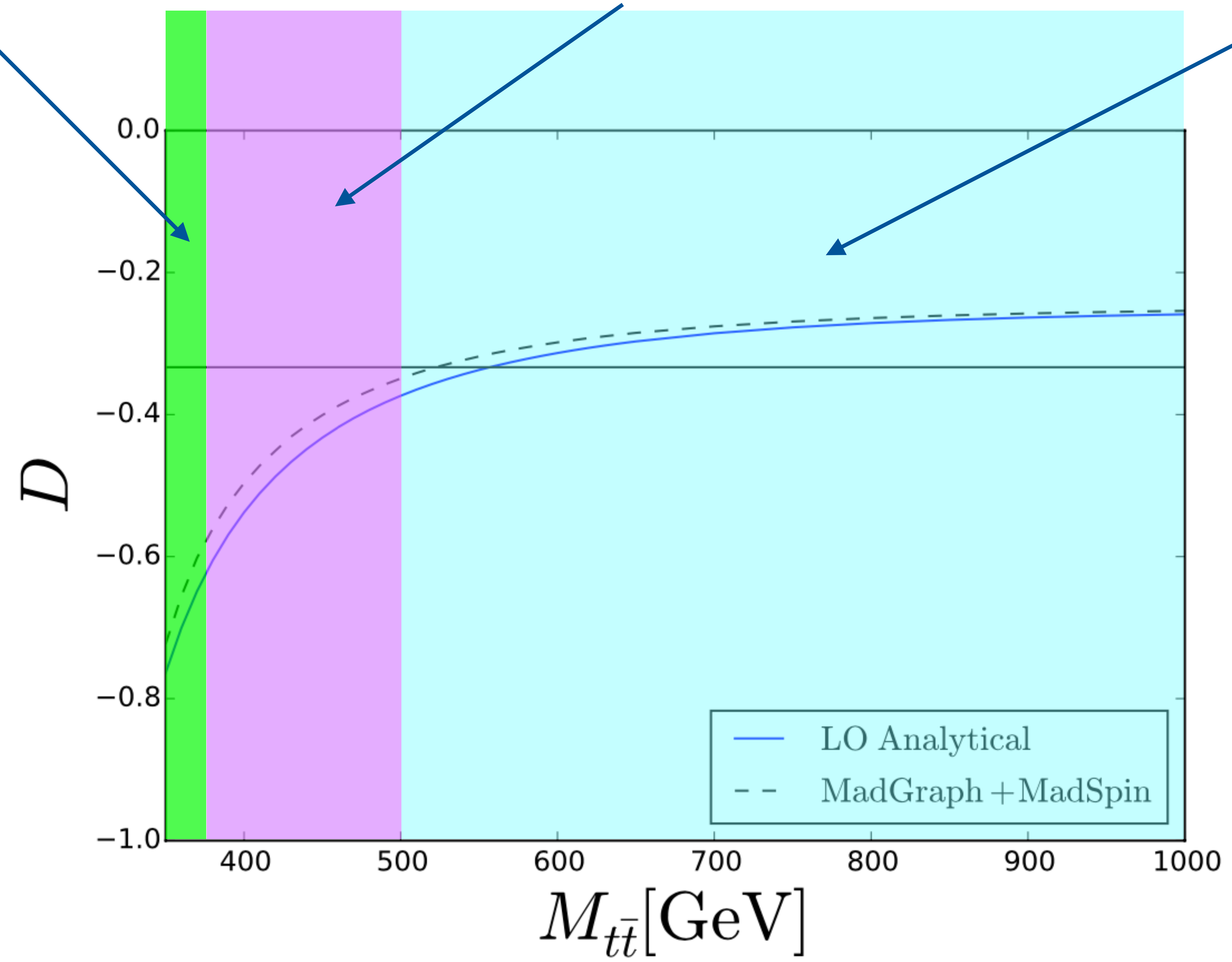


Signal/Validation Regions

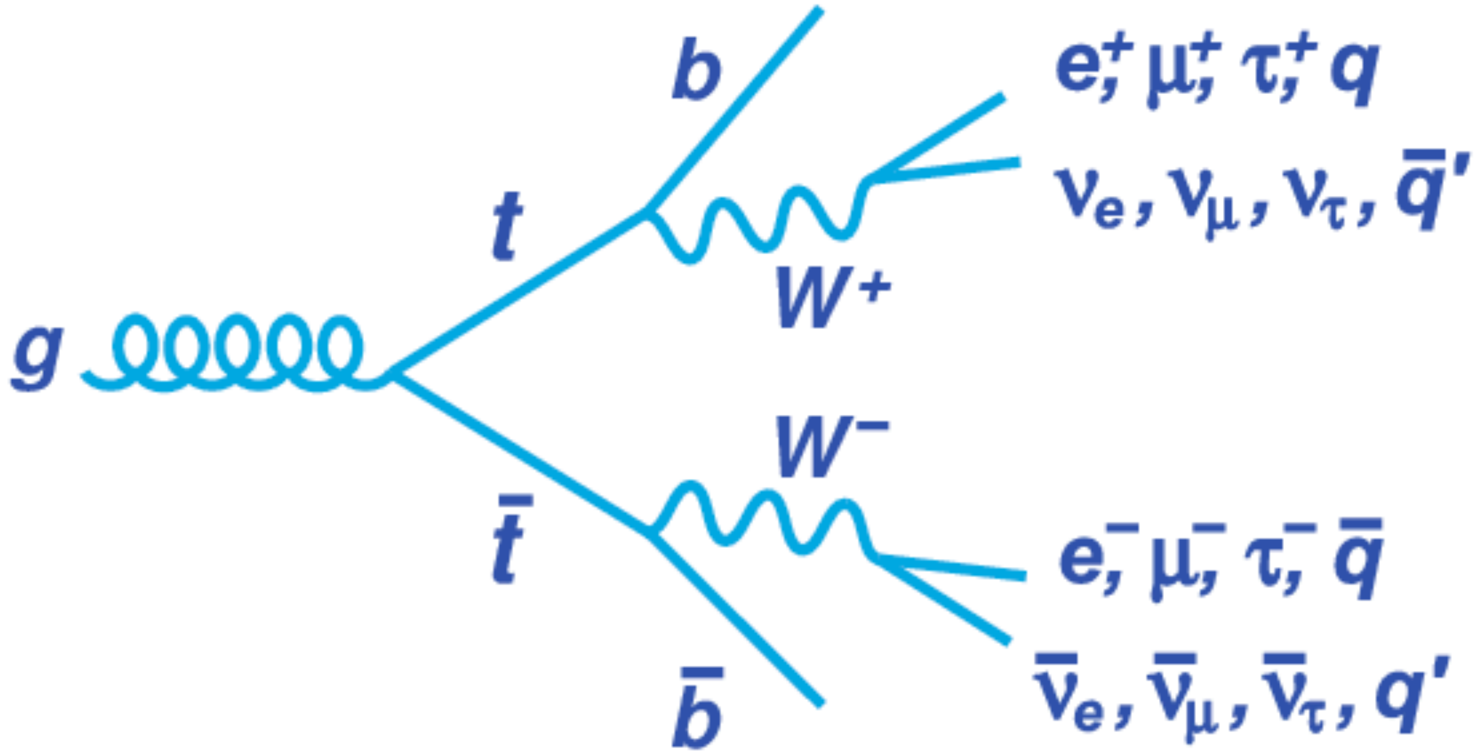
- **We split our measurement based on $m_{t\bar{t}}$:**

SR: 340 - 380 GeV   VR1: 380 - 500 GeV   VR2: > 500 GeV



Top Decays

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



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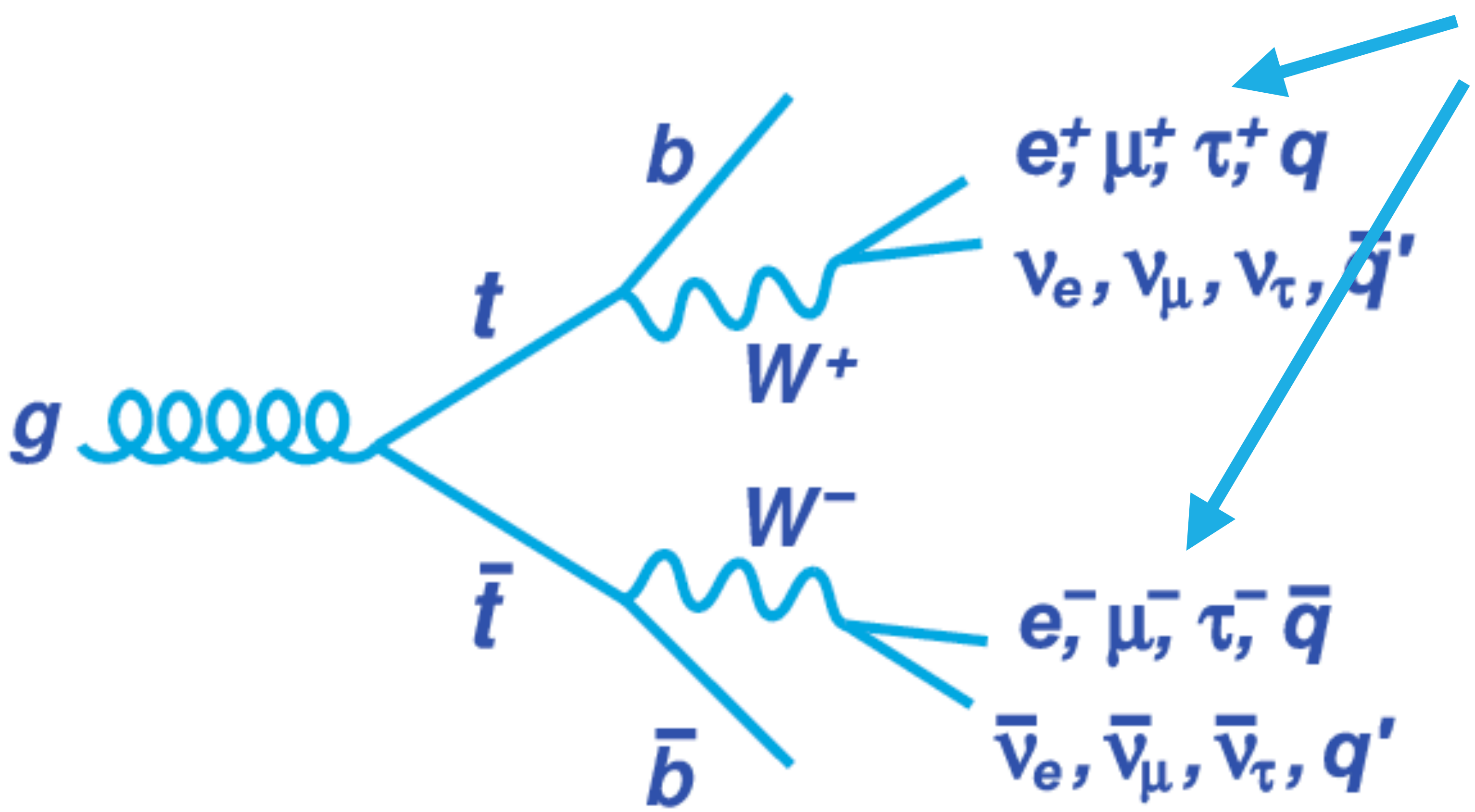
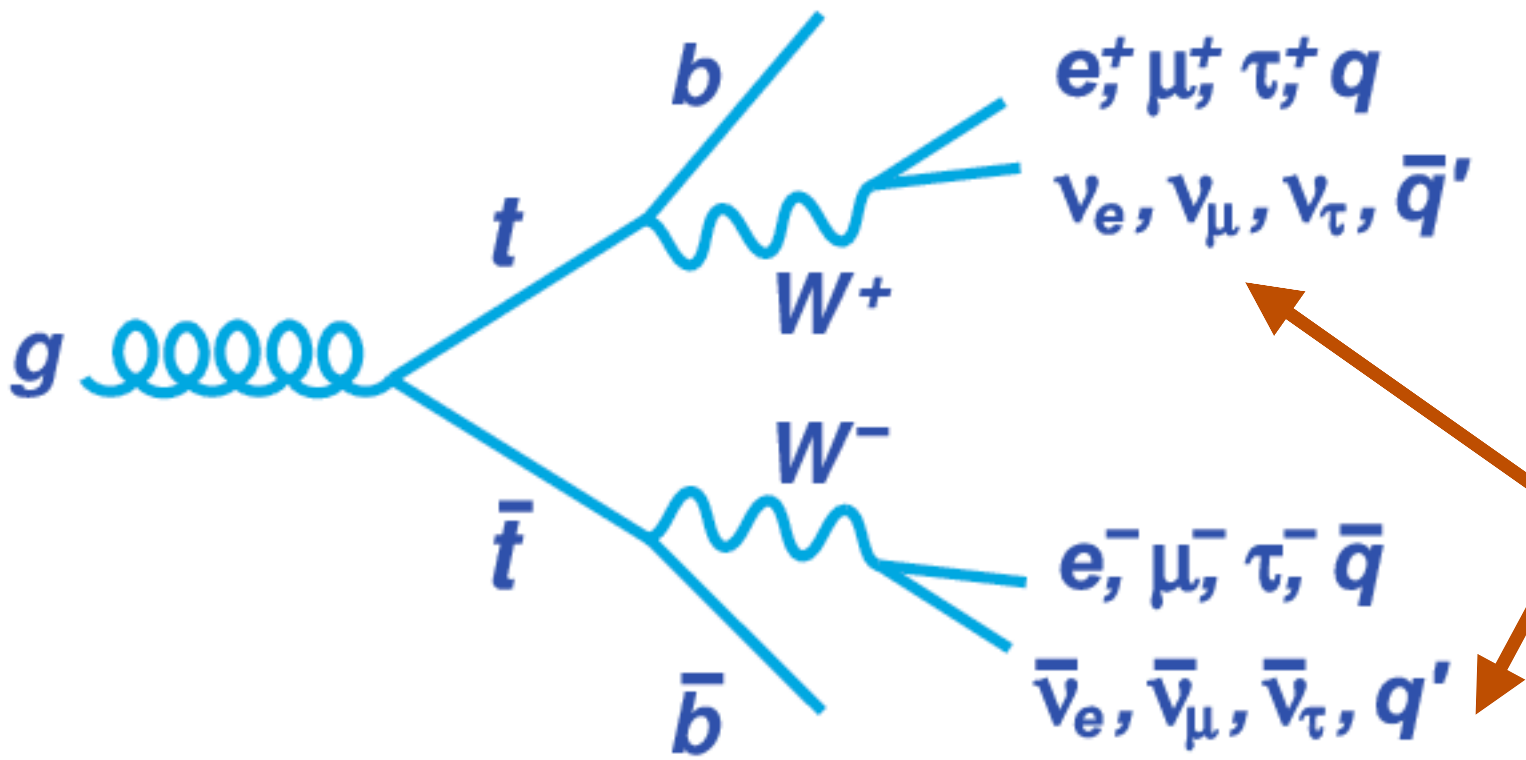


- **Charged leptons are the perfect spin analyser!**

Top Decays

- Why is it hard to reconstruct top quarks?



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- Neutrinos not detected (directly) by ATLAS

Top Decays

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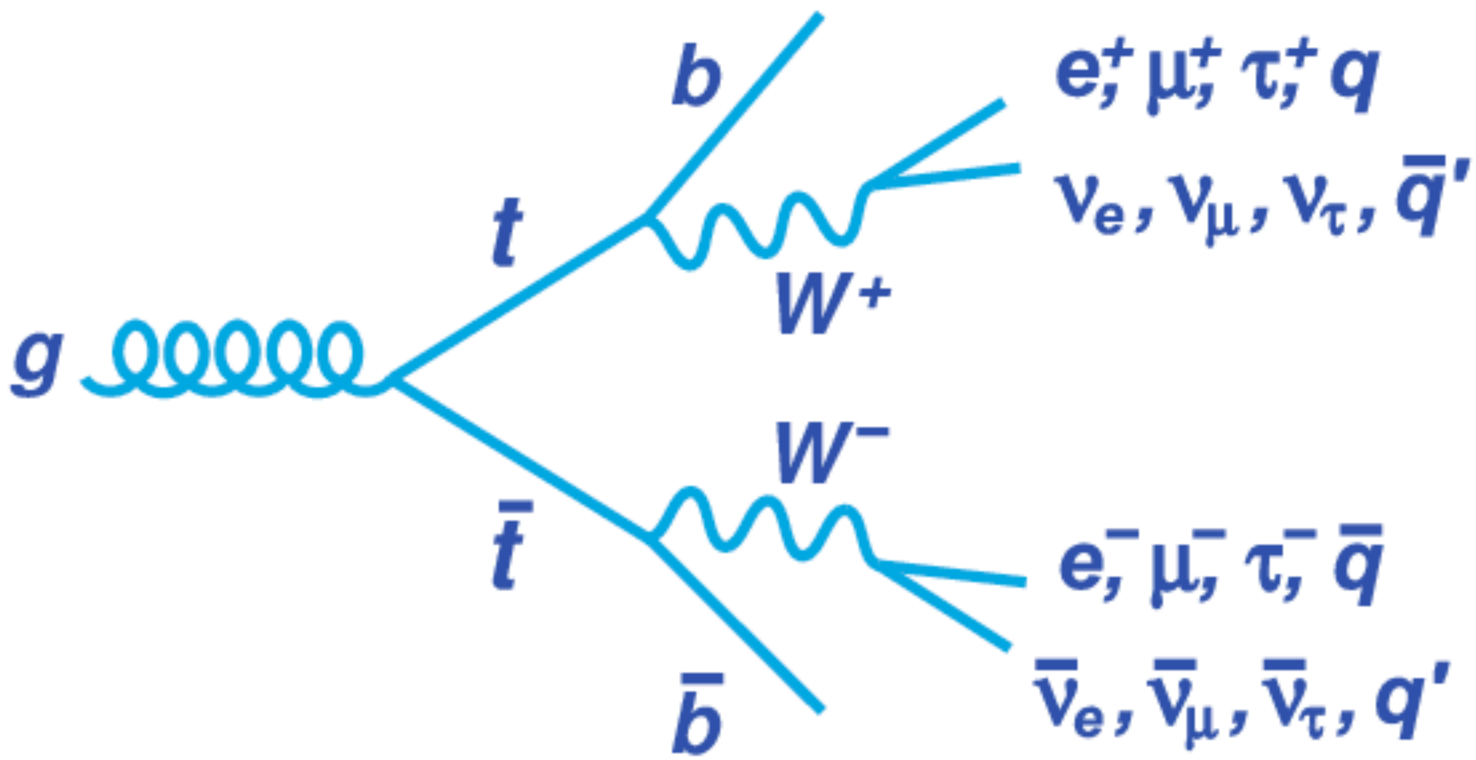


- **Charged leptons are the perfect spin analyser!**

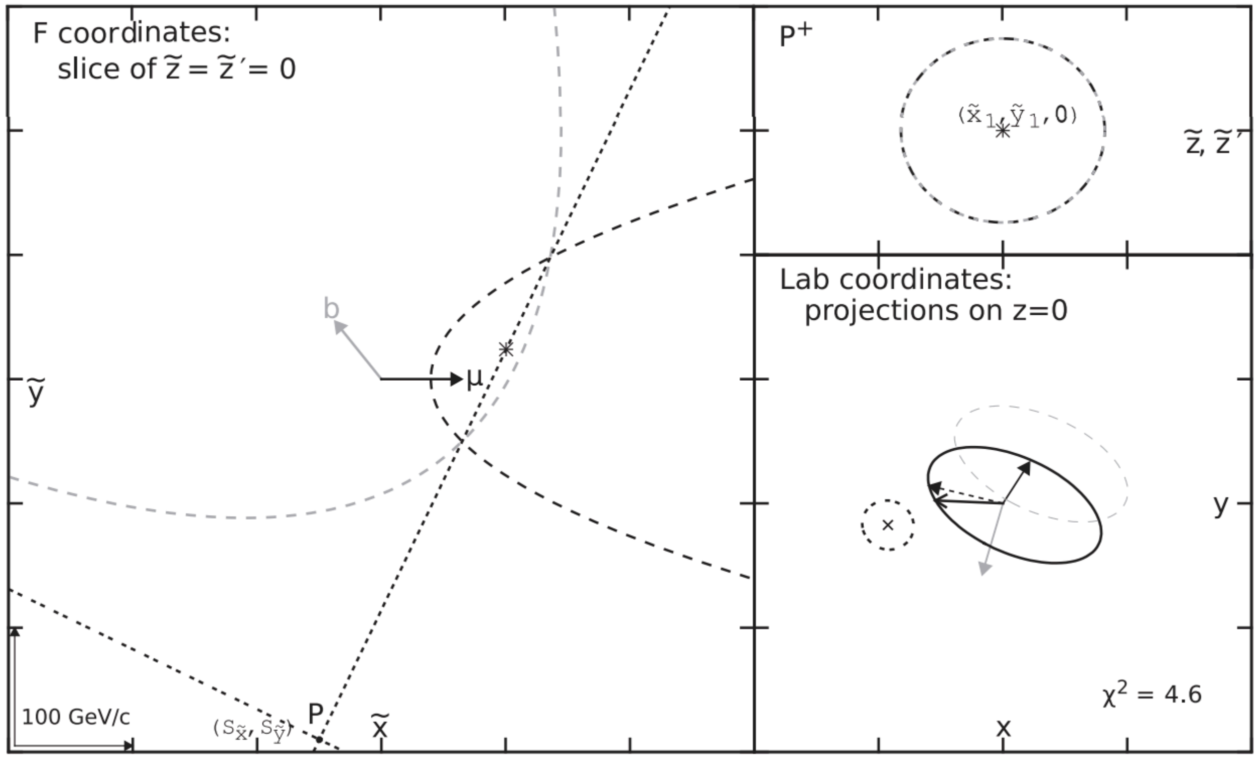
- **Neutrinos not detected** (directly) **by ATLAS**

- **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**".**



Nucl.Instrum.Meth.A 736 (2014) 169-178

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

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

Selection

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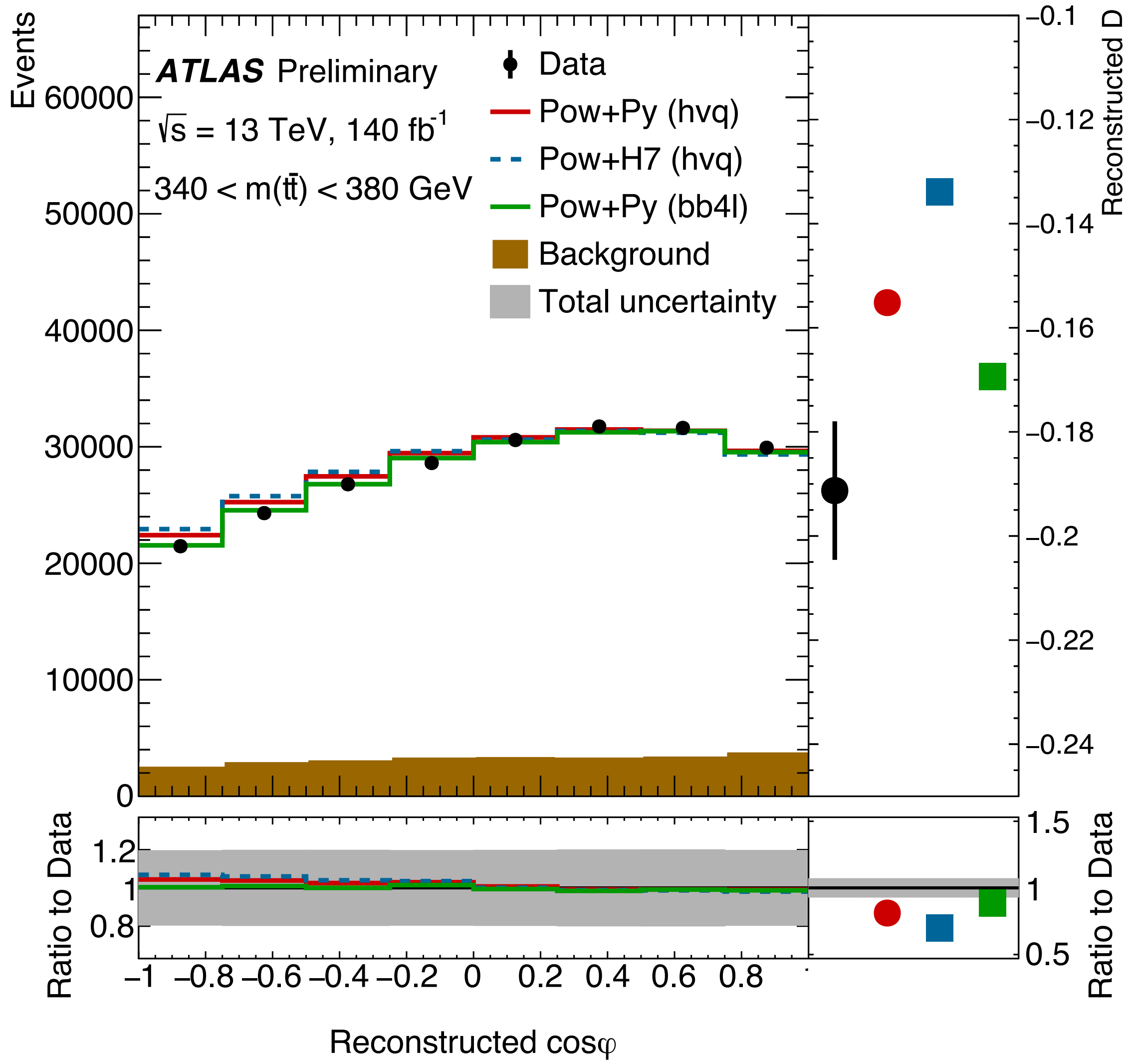
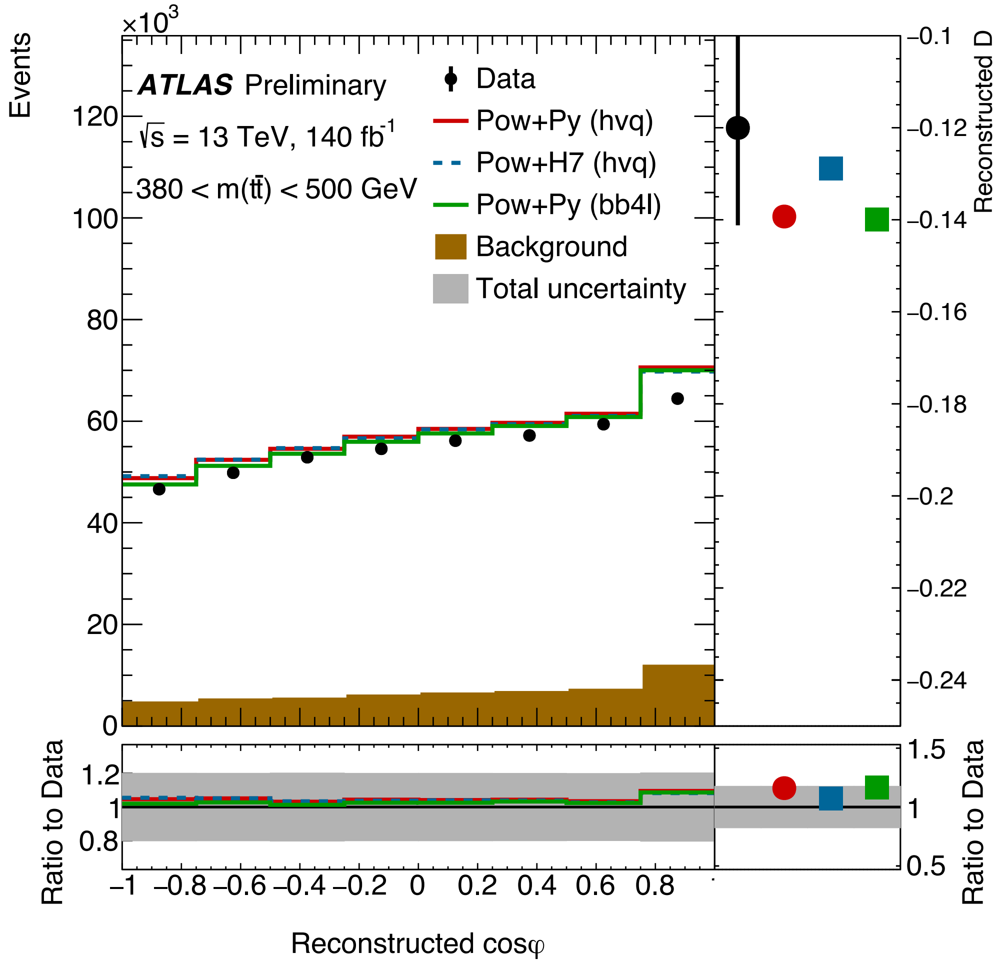
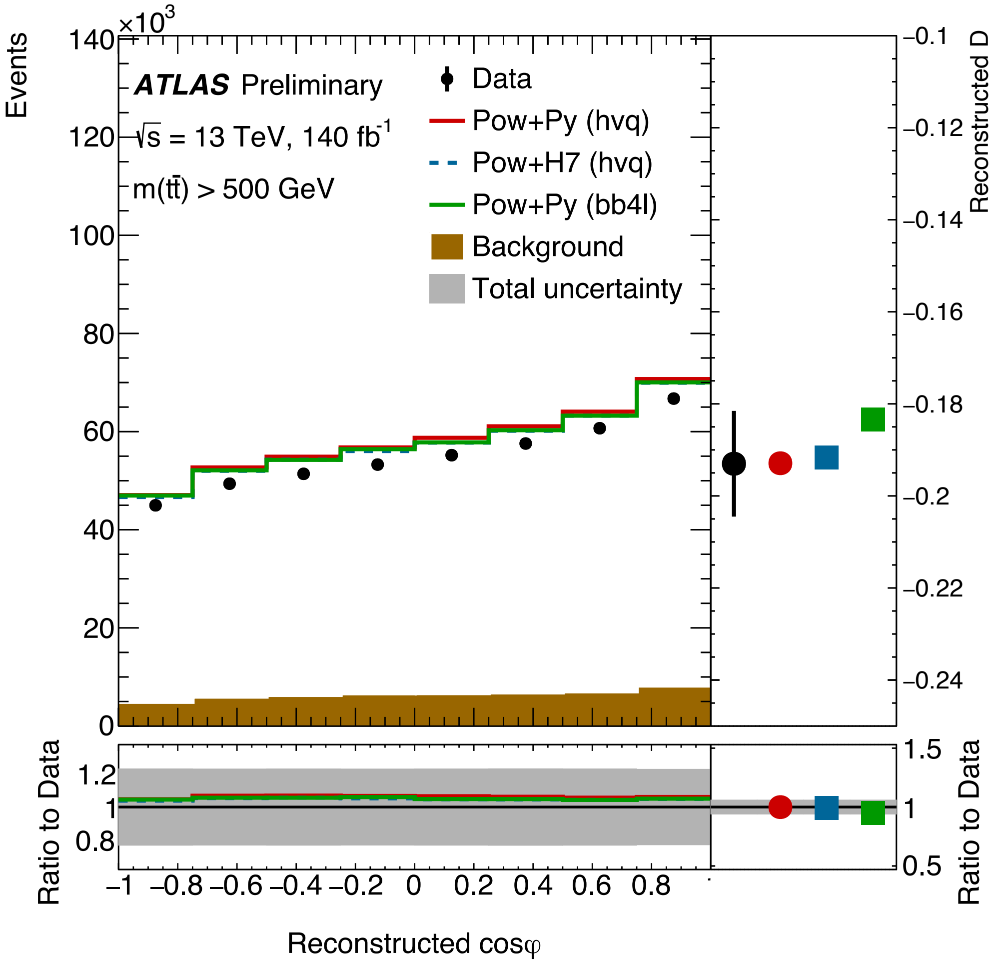


- **Events are selected with exactly 1 electron and 1 muon** (standard p_T, η cuts)**.**
- **Require 1 or more b-tagged jets (85% W.P):**
  - ➡ loose working point to ensure high stats in signal region**.**
- **Three regions in $m(t\bar{t})$ are defined:**
  - ➡ **SR: 340 < $m(t\bar{t})$ < 380 GeV** [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)**.**

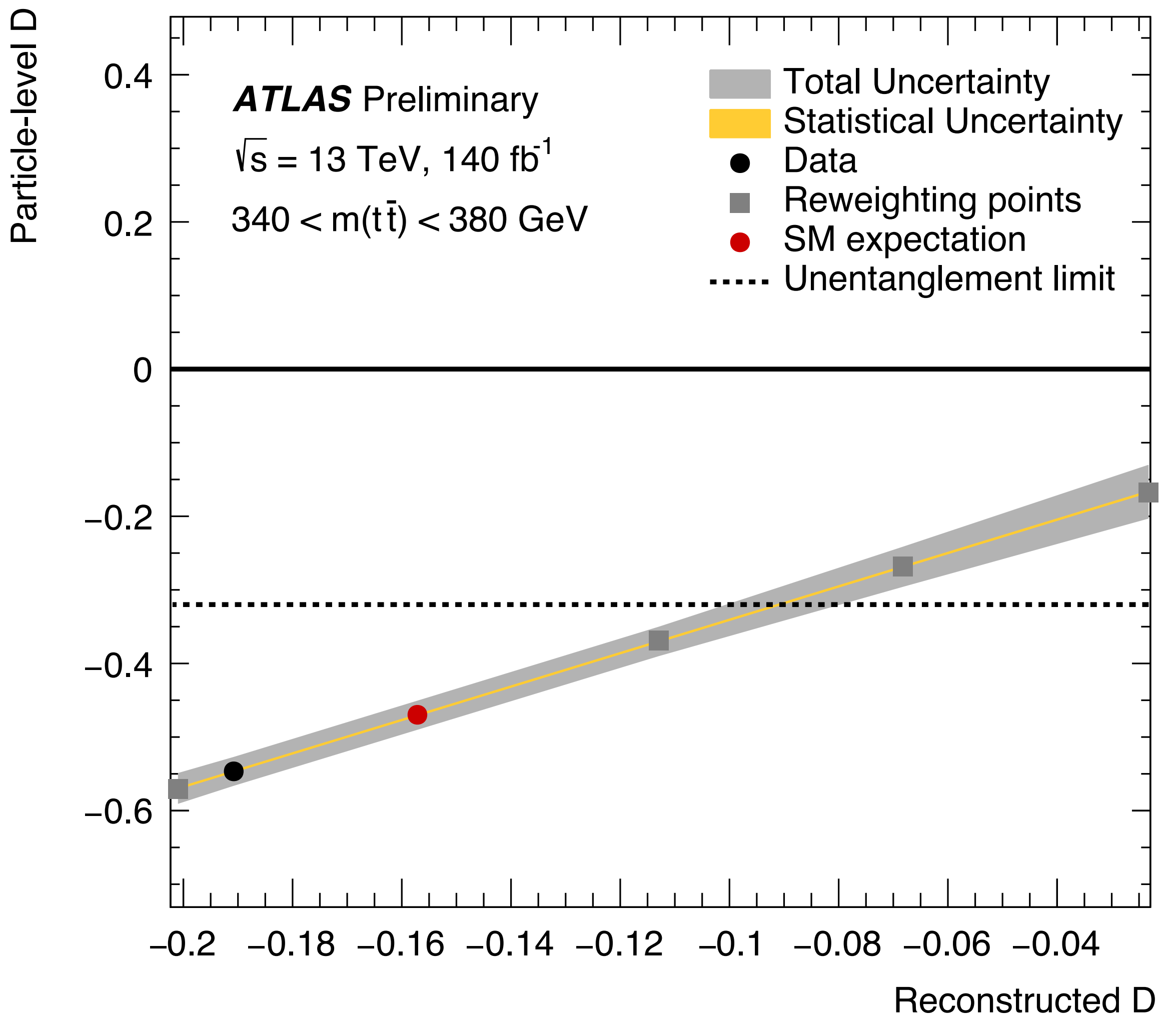




- **Very good overall agreement between the number of signal+background events and the observed number of events in data.**

Calibration Curve

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

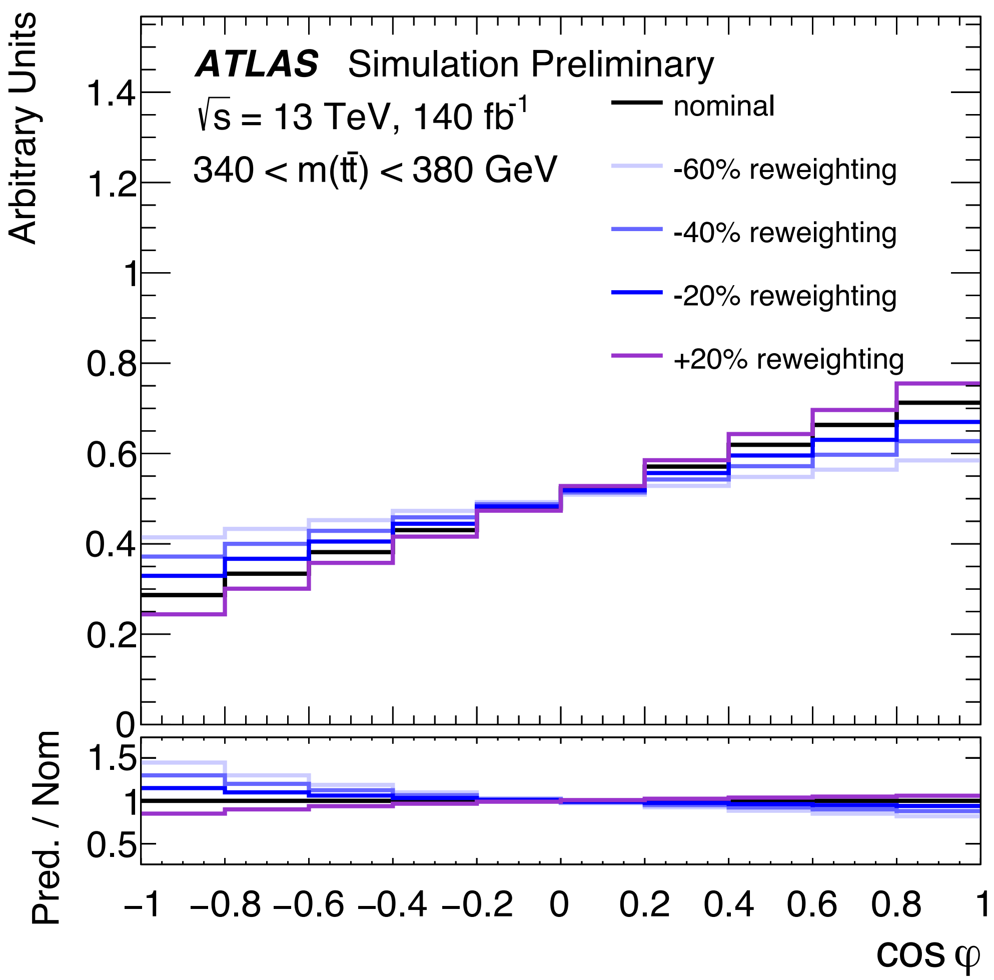


- **To construct this curve we need to change the amount of entanglement in our MC.**
- **We create 5 hypothesis points corresponding to the SM and 4 different reweighing points:**
  (+20%, -20%, -40%, -60%)

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:**

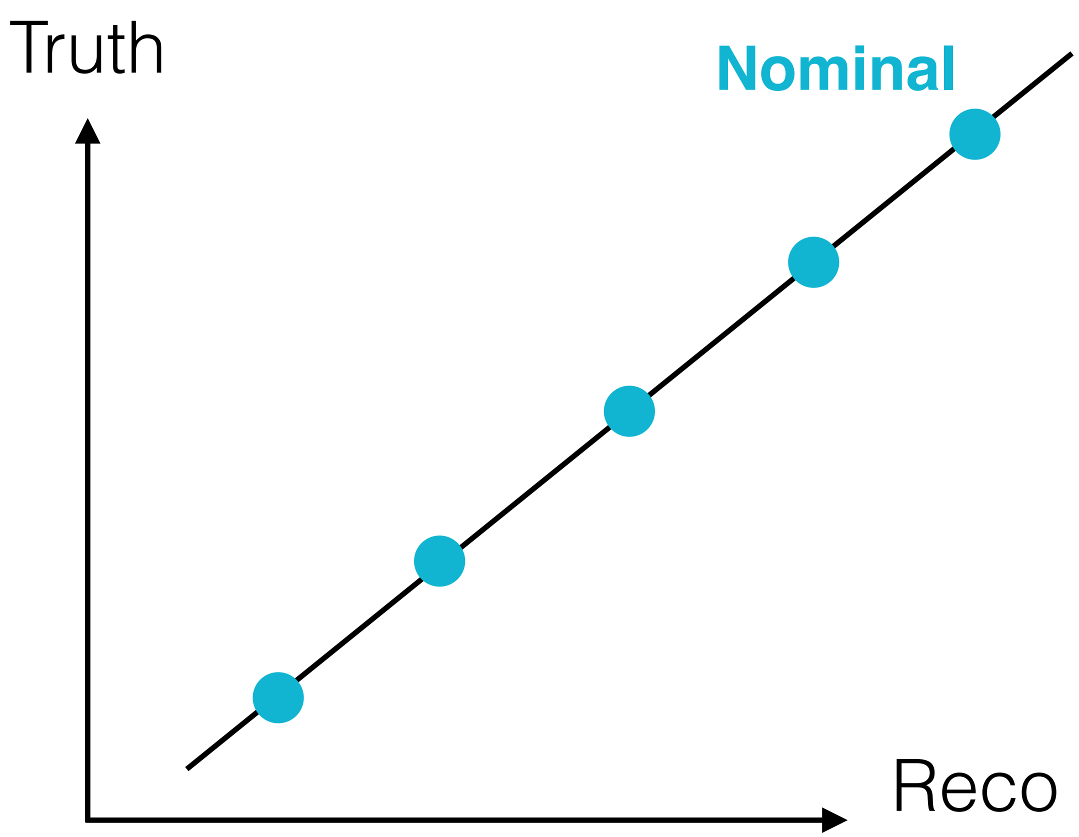
$$D = \frac{tr[C]}{3} = -3 \cdot < \cos(\phi) >$$

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:**



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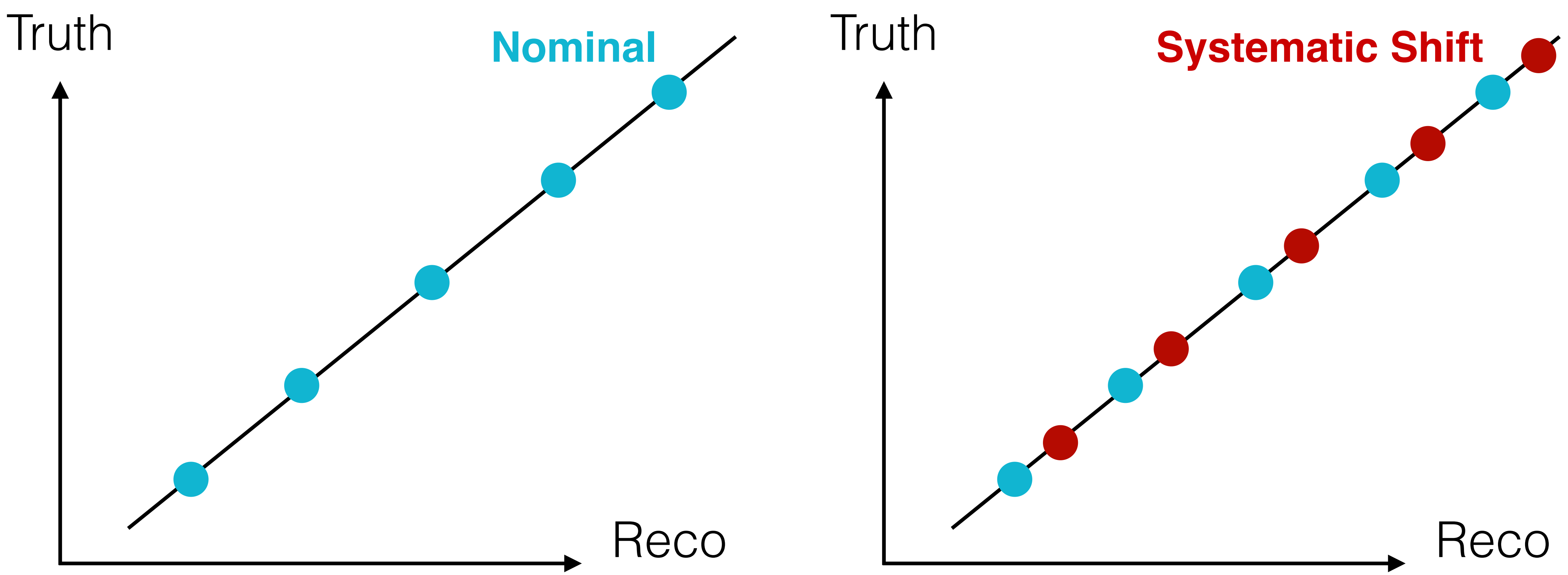

- **Ideally, truth and reco shift in a correlated way, and there is no resultant uncertainty.**

Systematic Uncertainties

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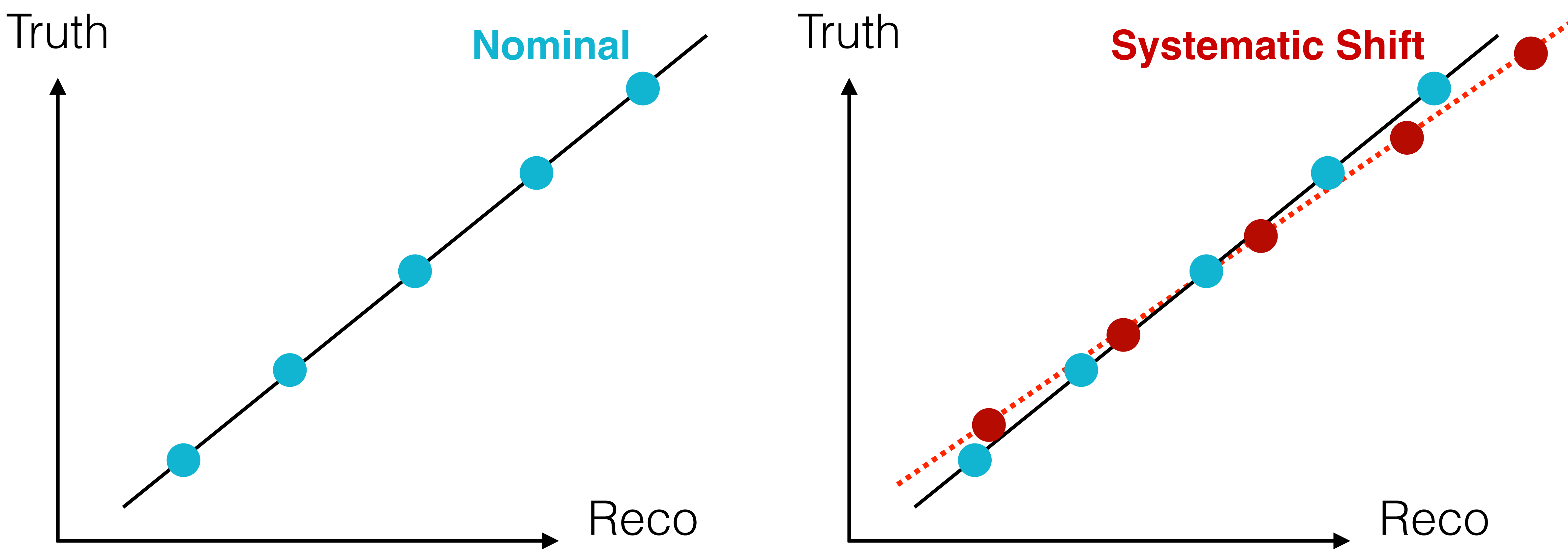
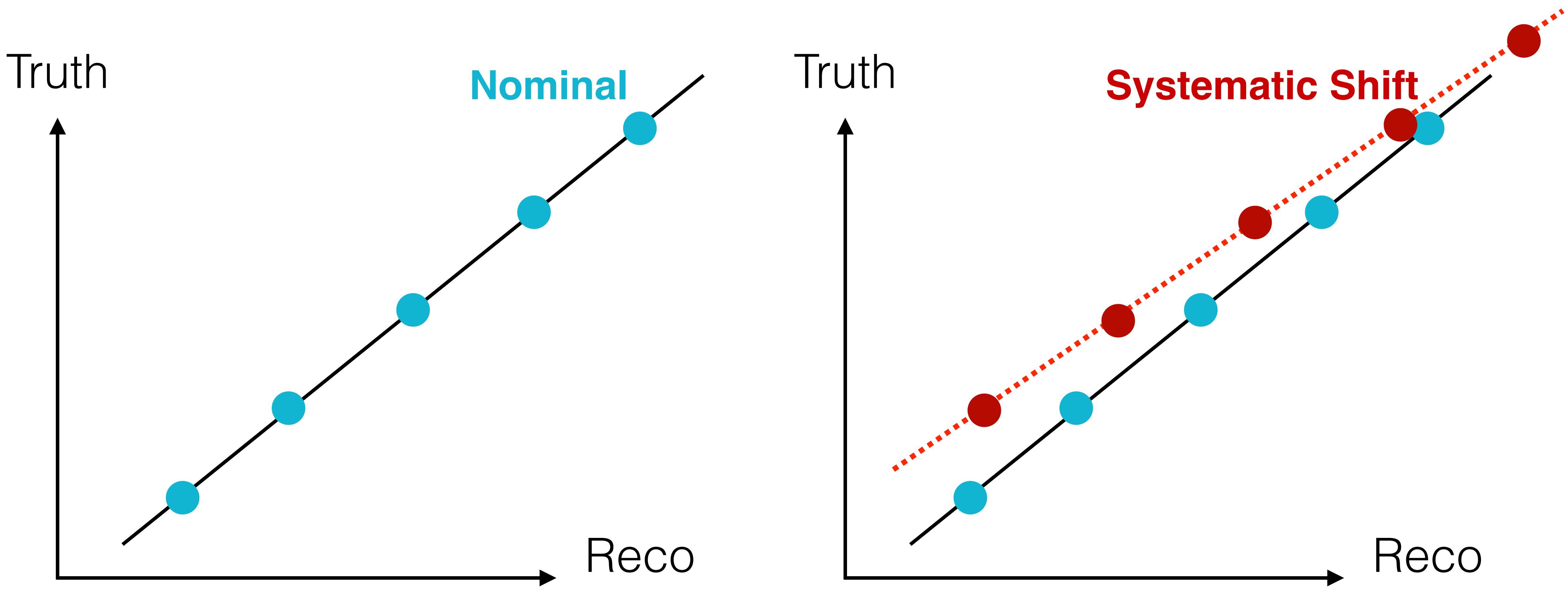


- **In practice, most uncertainties shift reco but not truth and therefore change the slope** (all detector uncertainties do this)**.**

Systematic Uncertainties

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



- **In the worst case, systematics shift slope and offset and have a large effect** (our dominant uncertainties behave this way)**.**

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
$E_{\text{T}}^{\text{miss}}$	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
Total Uncertainty	0.021	3.8	0.018	3.9

- **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.**

Systematic Uncertainties

- We have a large suite of MC modelling related systematic uncertainties:

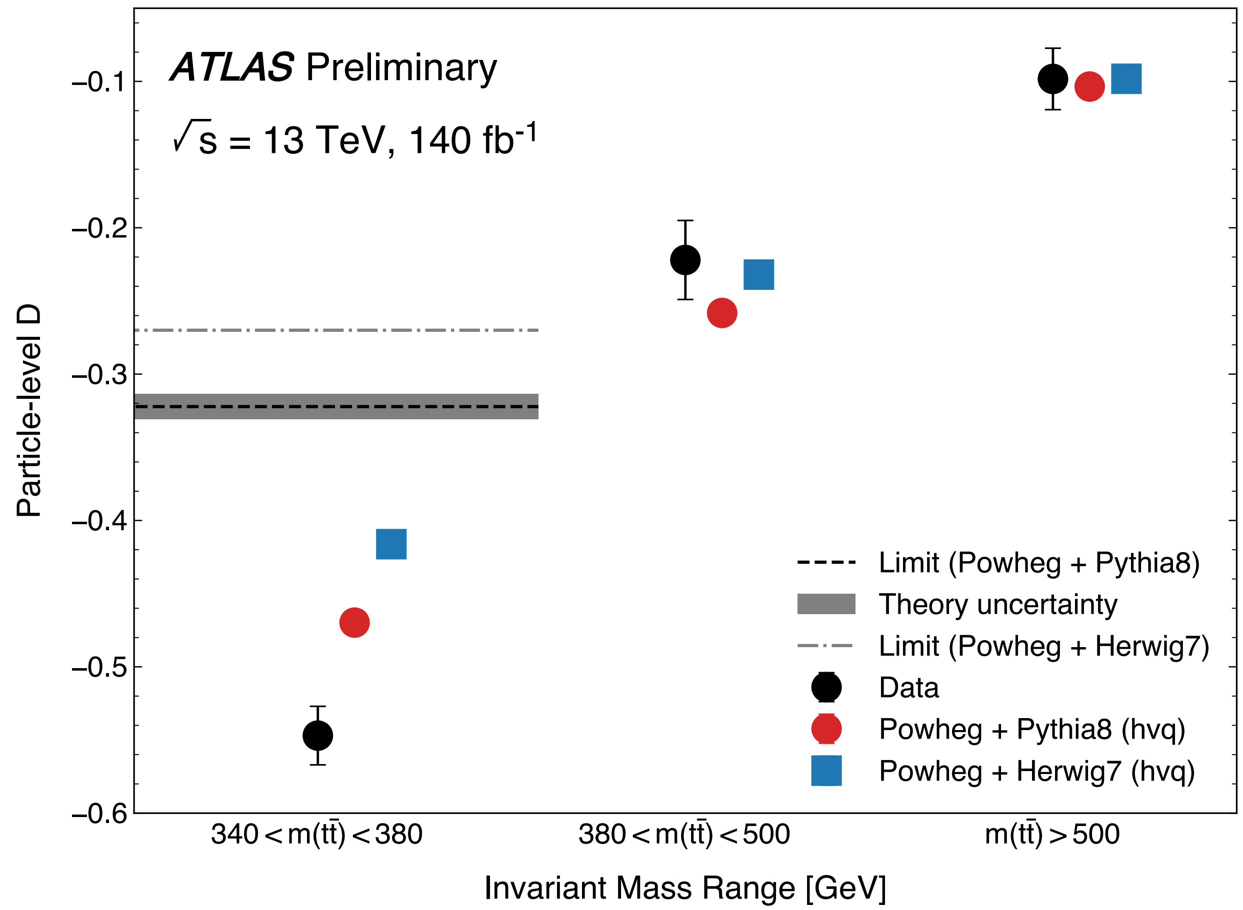
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization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

- Colour reconnection, string vs cluster fragmentation, spin correlation in parton shower, EW shower were all tested but found to be negligible effects.

Results

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

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

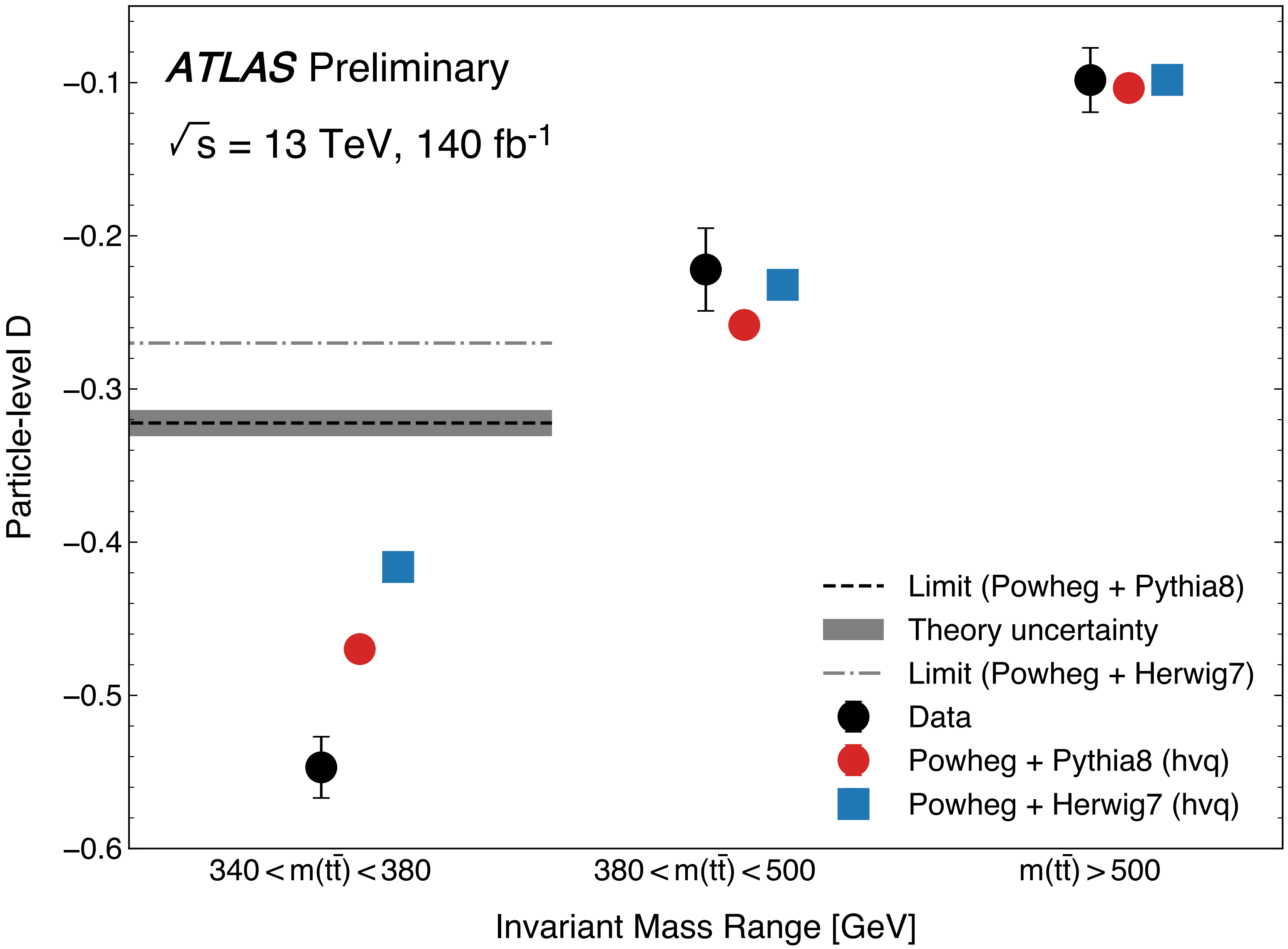


ATLAS-CONF-2023-069

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

Common Questions

- **How reliable are the elements of this result?**



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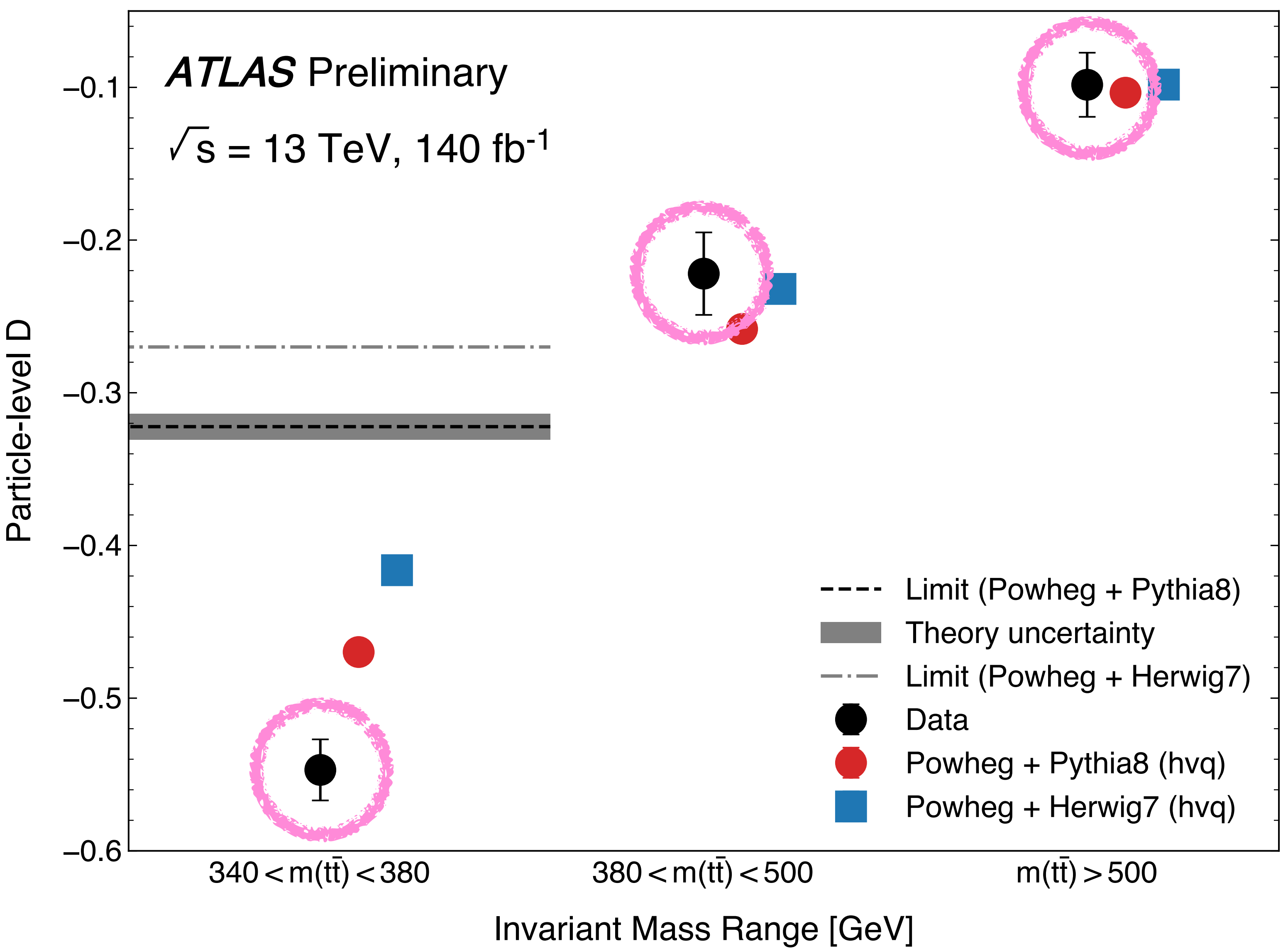

- **Corrections to the data: very reliable**
- **A comprehensive and conservative** (even by ATLAS's standards) **list of systematic uncertainties has been considered on all aspects of the analysis.**

Common Questions

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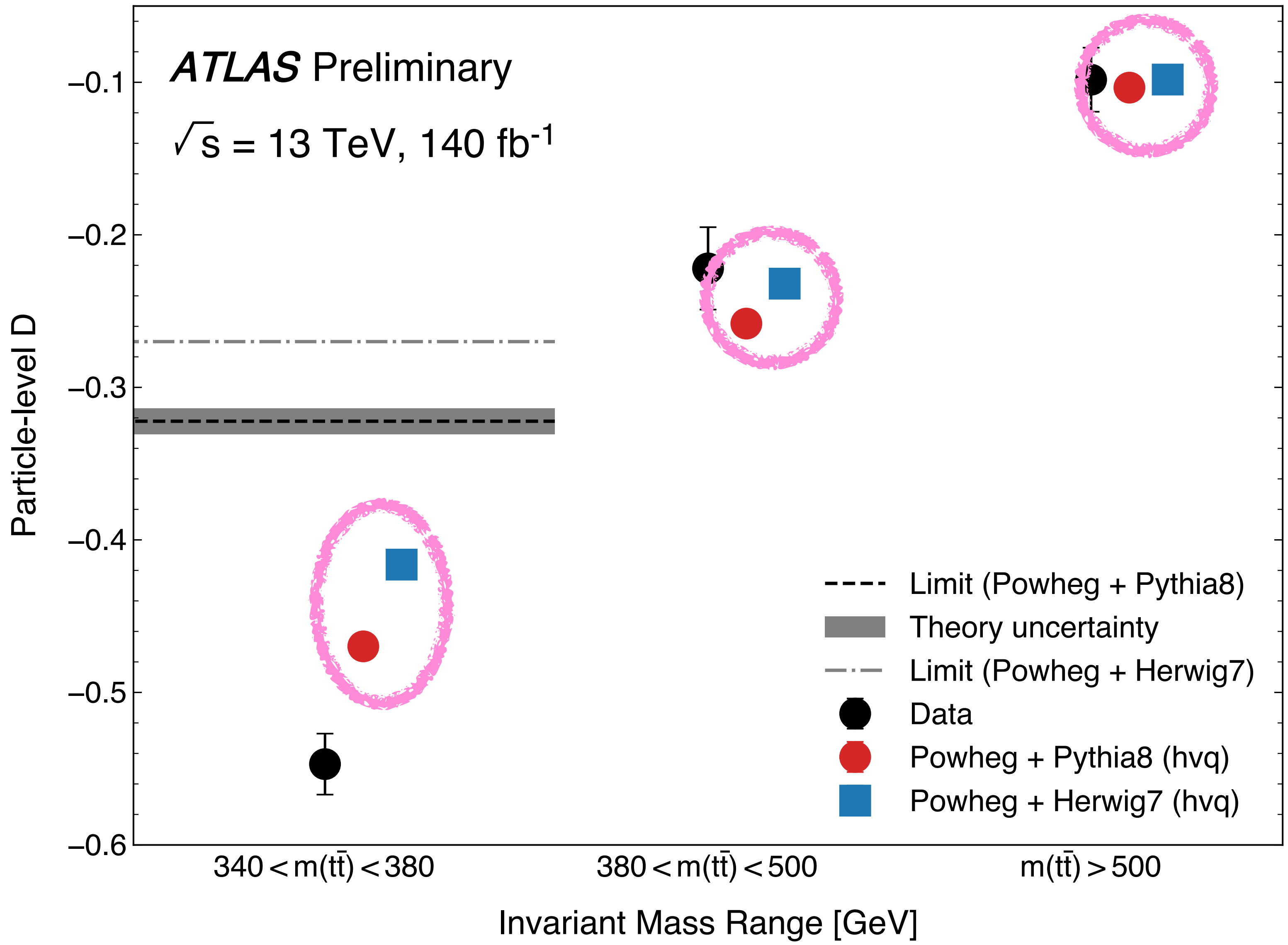

- **Predictions of the SM: Reliable but limited.**
- **These predictions come from general purpose MC generators:**
  ➡ We understand them very well, but they are not designed to model threshold perfectly.

Common Questions

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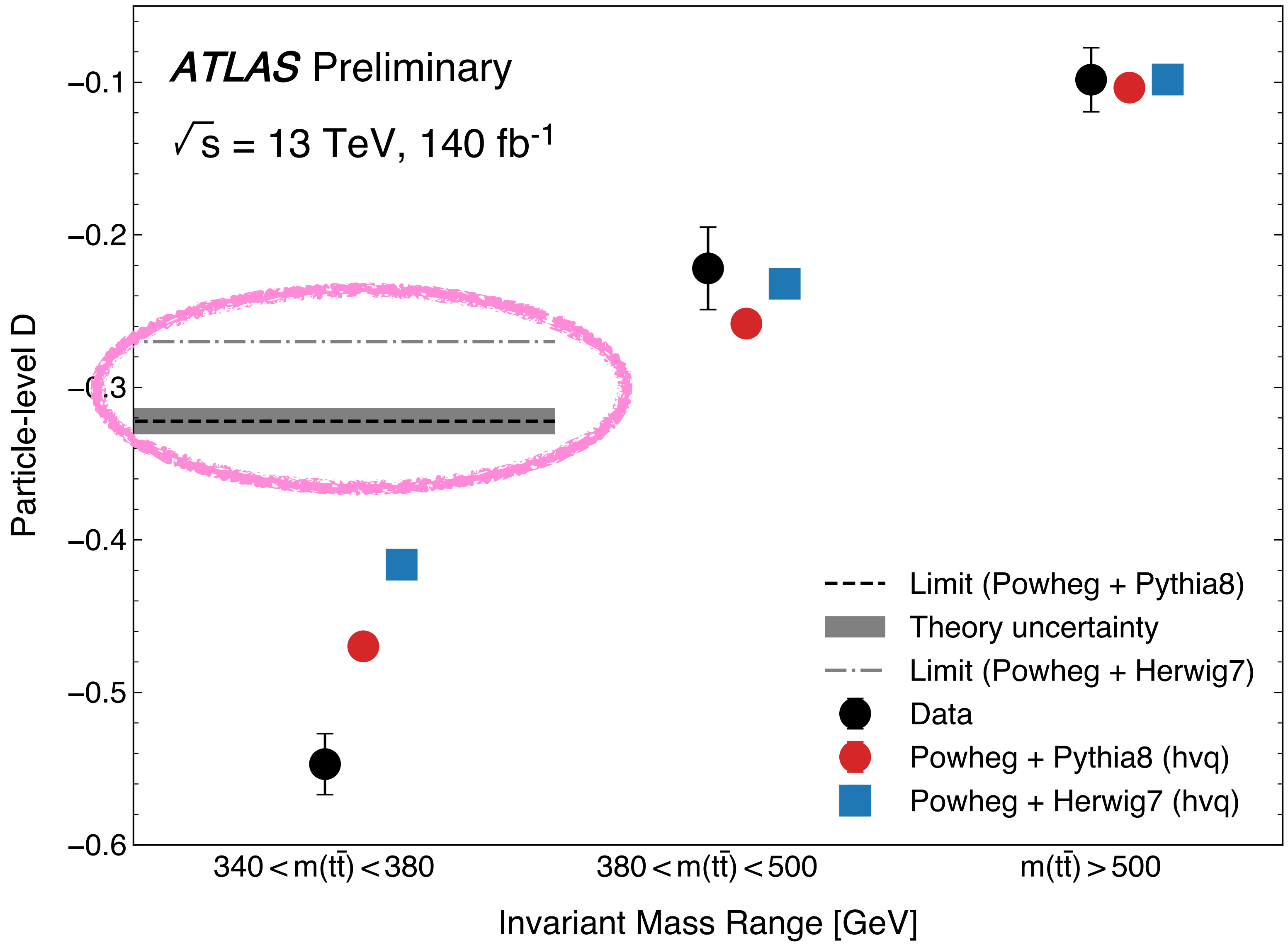
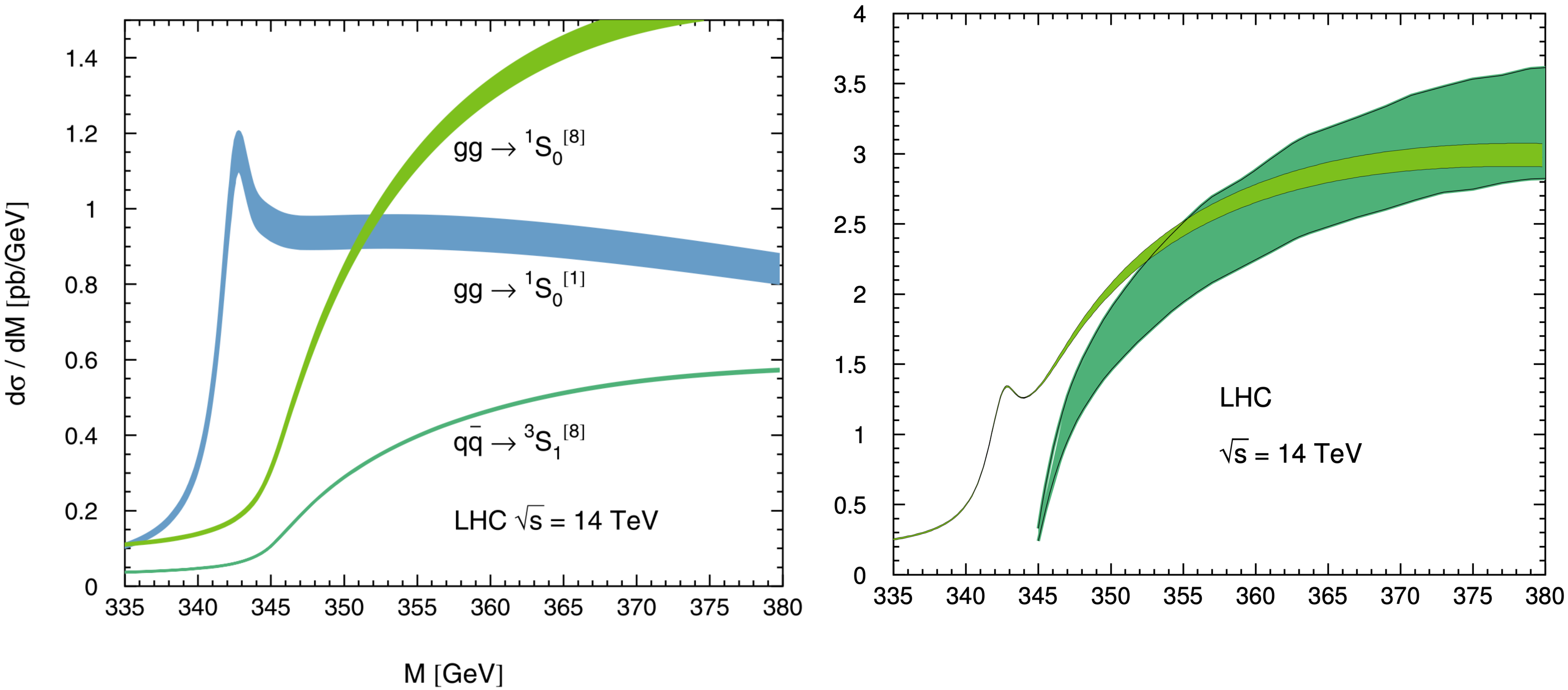


- **Entanglement limits: Reliable but limited.**
- **Same limitations as predictions.**
- **Two models give different limits, but source is understood and we've taken the most conservative of the two.**

What about Topponium?

- **Bound state effects are most prevalent in the region that we care about.**

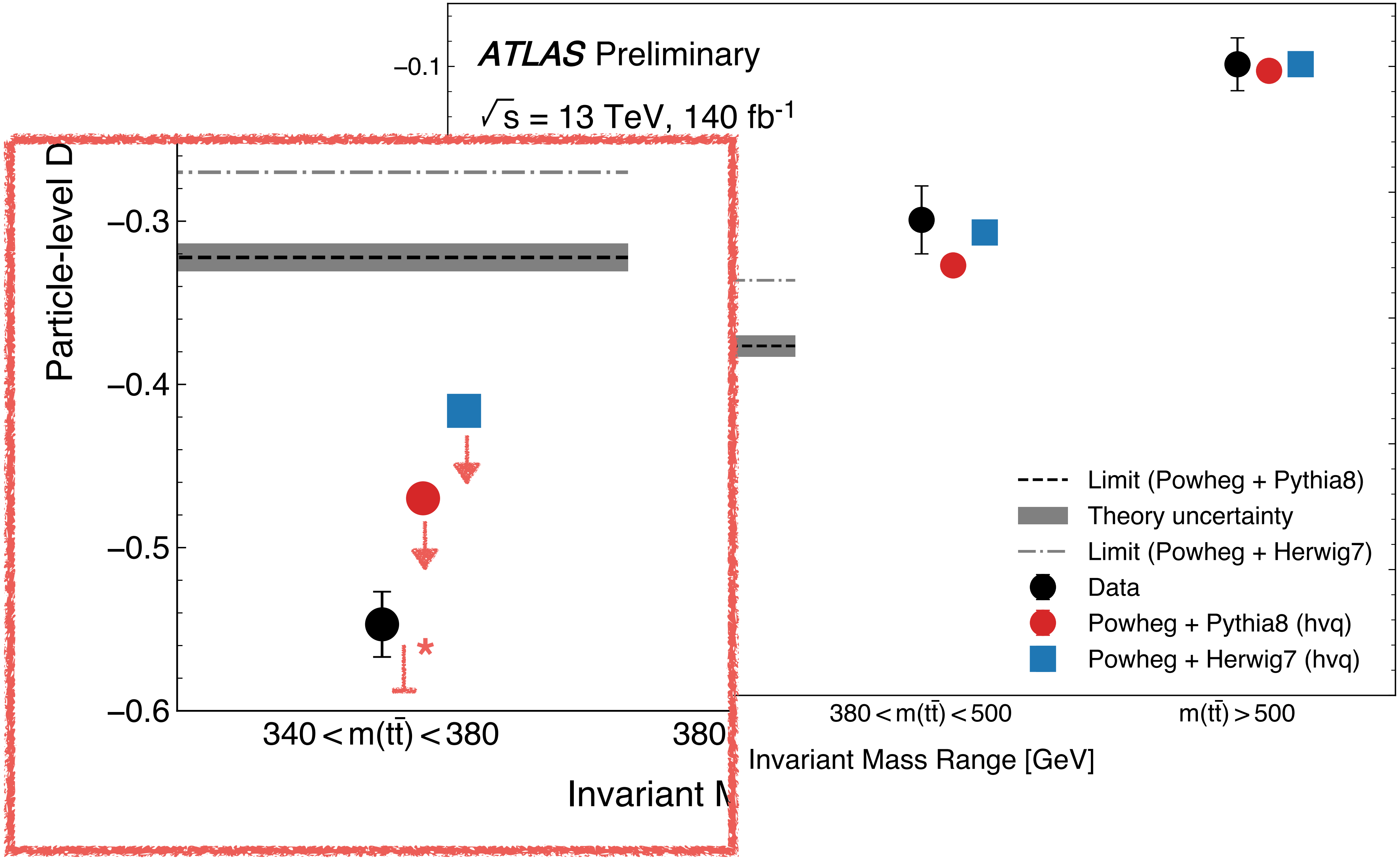
Kiyo, Kühn, Moch, Steinhauser, Uwer, 2009



- **These are not directly included in our MC simulations** (but we have attempted to introduce them as a cross-check and other uncertainties cover similar effects)**.**

Common Questions

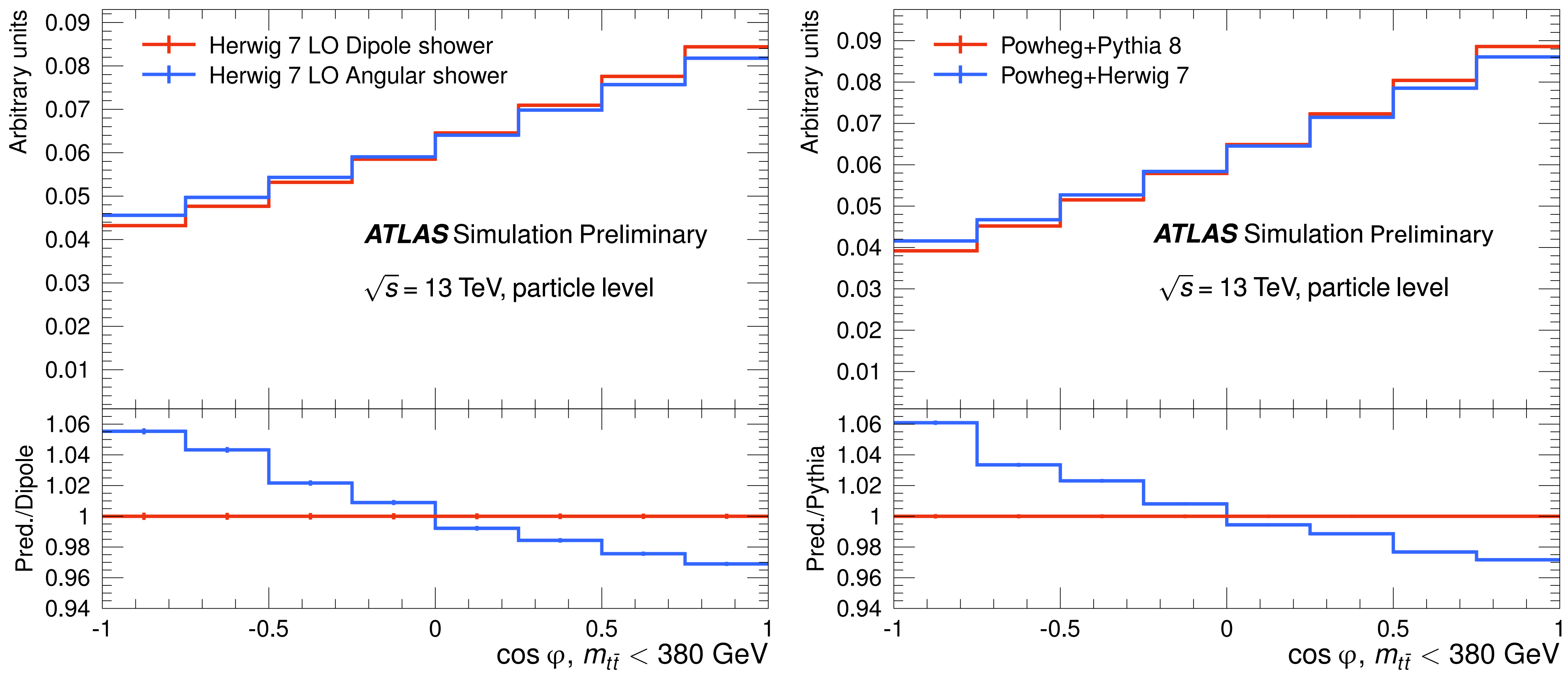
- **Bound state effects should be increasing entanglement:**
  - ➡ Including them only makes result <u>more</u> significant, not less.



***exaggerated, the effect on the error bars would be too small to see.**

Parton Shower

- **Difference seems to come from the ordering of the shower.**



- **Angular ordered showers have a large effect compared to dipole showers.**

- **Doesn't effect detector corrections significantly.**

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!**