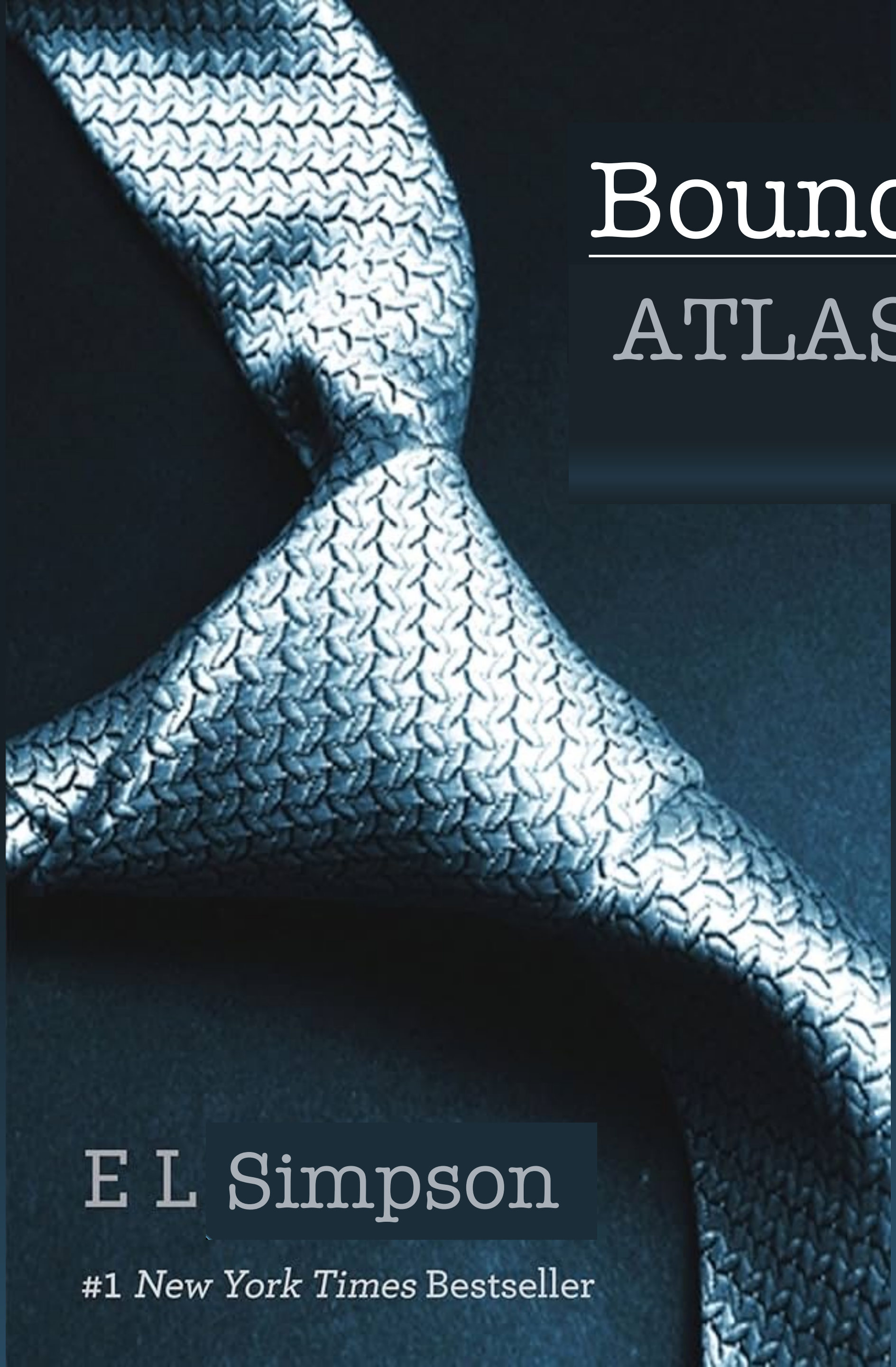
Bound and Entangled

ATLAS adventures at the $t\bar{t}$ threshold



Quantum Observables for Collider Physics,
9th April 2025

Is the $t\bar{t}$ threshold the most interesting place in collider physics right now?

This is a talk on ATLAS results,
but not on behalf of ATLAS

Opinions are my own

This Talk

Top quark pair production at threshold: entanglement measurement and search for new physics at ATLAS

1. ATLAS Entanglement in $t\bar{t}$ (10.1038/s41586-024-07824-z)
2. ATLAS search for H/A → $t\bar{t}$ (10.1007/JHEP08(2024)013)

Entanglement

Is the density matrix factorisable?

$$\rho^{t\bar{t}} = \sum_n \omega_n \, \rho^t \otimes \rho^{\bar{t}}$$

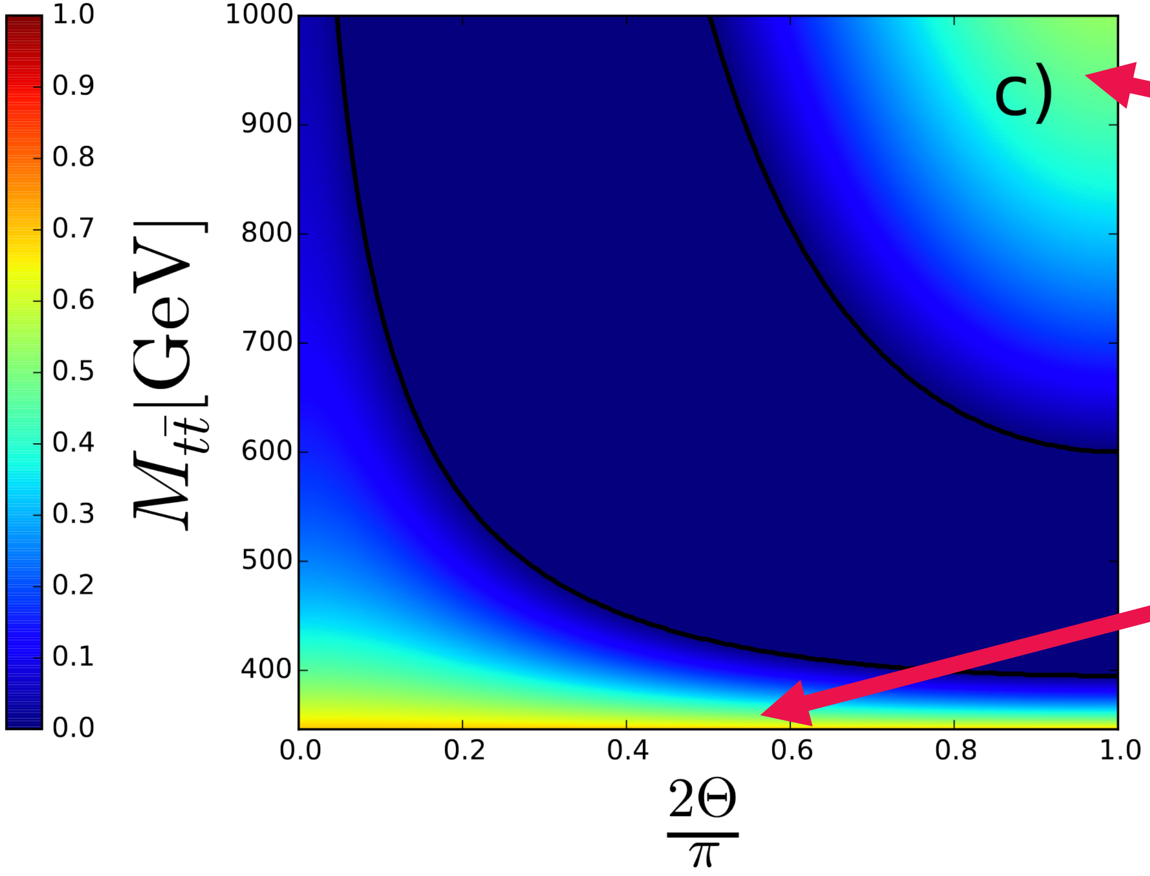
```
if density_matrix.separable == False:
    state.entangled = True
```

Quantum Separability Problem: Determining whether an arbitrary density matrix is separable is in general NP-hard [arXiv:0303055].

Concurrence

Marker #1: measure of how entangled

(Related to the eigenvalues of the density matrix)



- Low statistics
- Larger jet uncertainties
- Driven by subdominant qq

- High statistics
- Driven by dominant gg

Peres-Horodecki

Marker #2: What we measure

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

$$D \leq -\frac{1}{3}$$ Entanglement condition

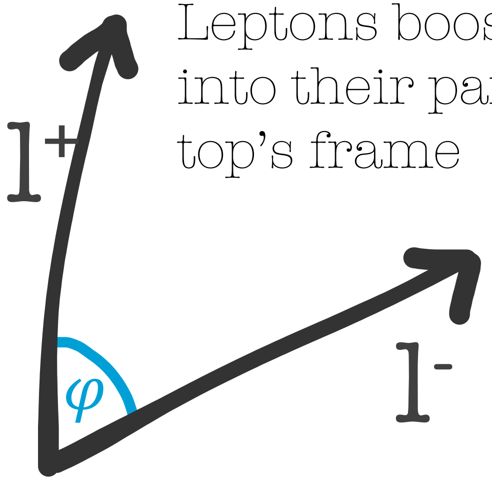
Peres-Horodecki

Marker #2: What we measure

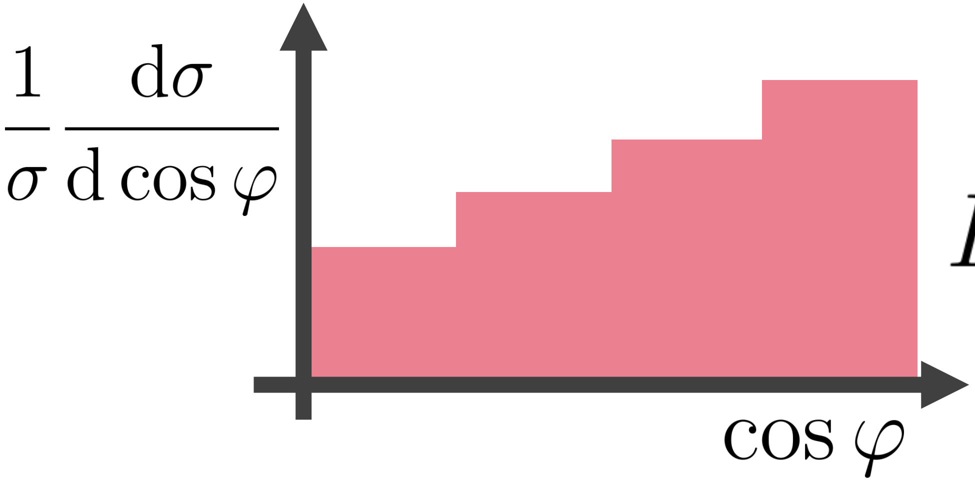
$$D = \frac{1}{3}\left(C_{11} + C_{22} + C_{33}\right)$$

$$D \leq -\frac{1}{3}$$ Entanglement condition

D can be extracted from a single angular distribution

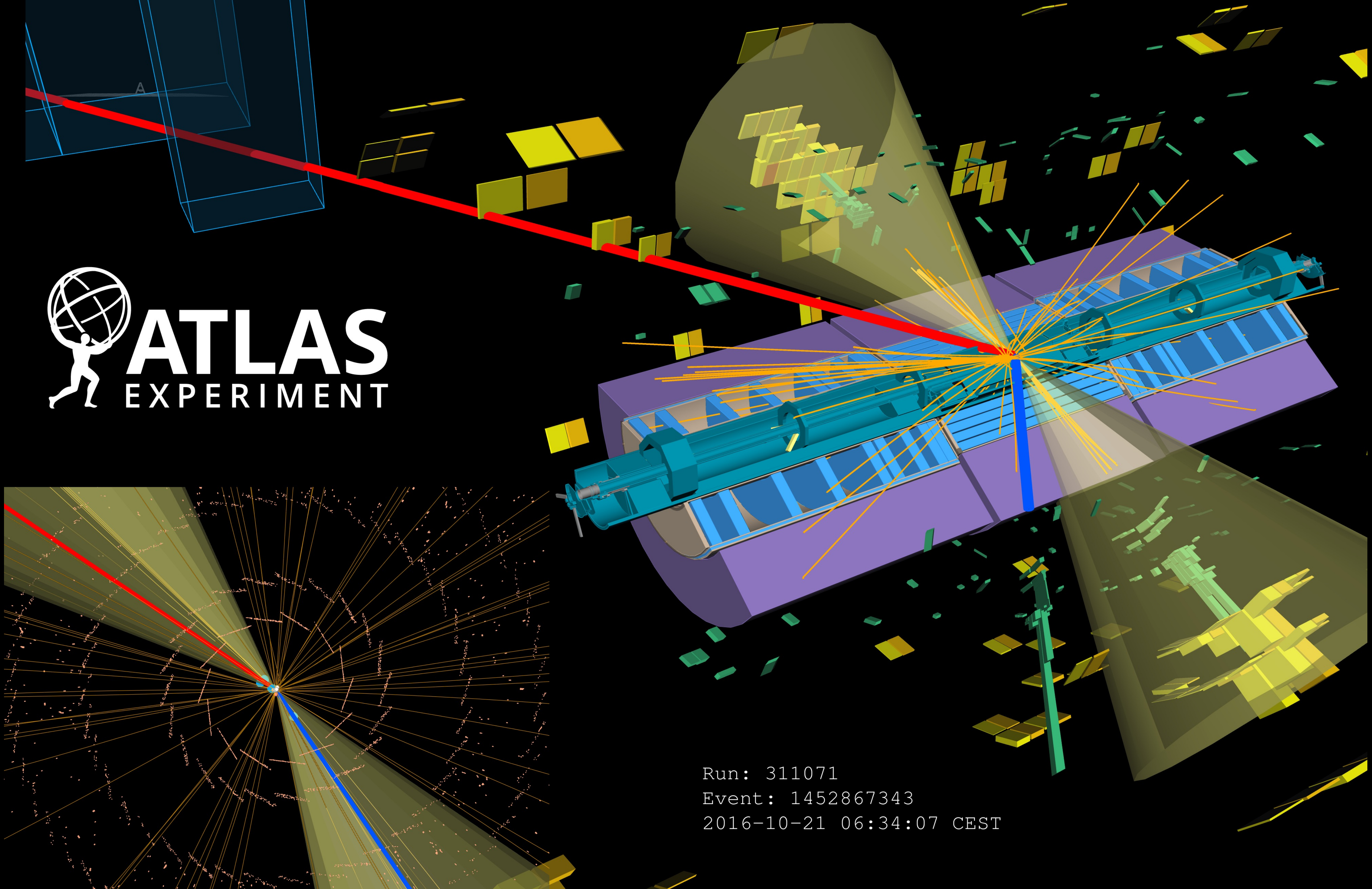


Leptons boosted into their parent top's frame

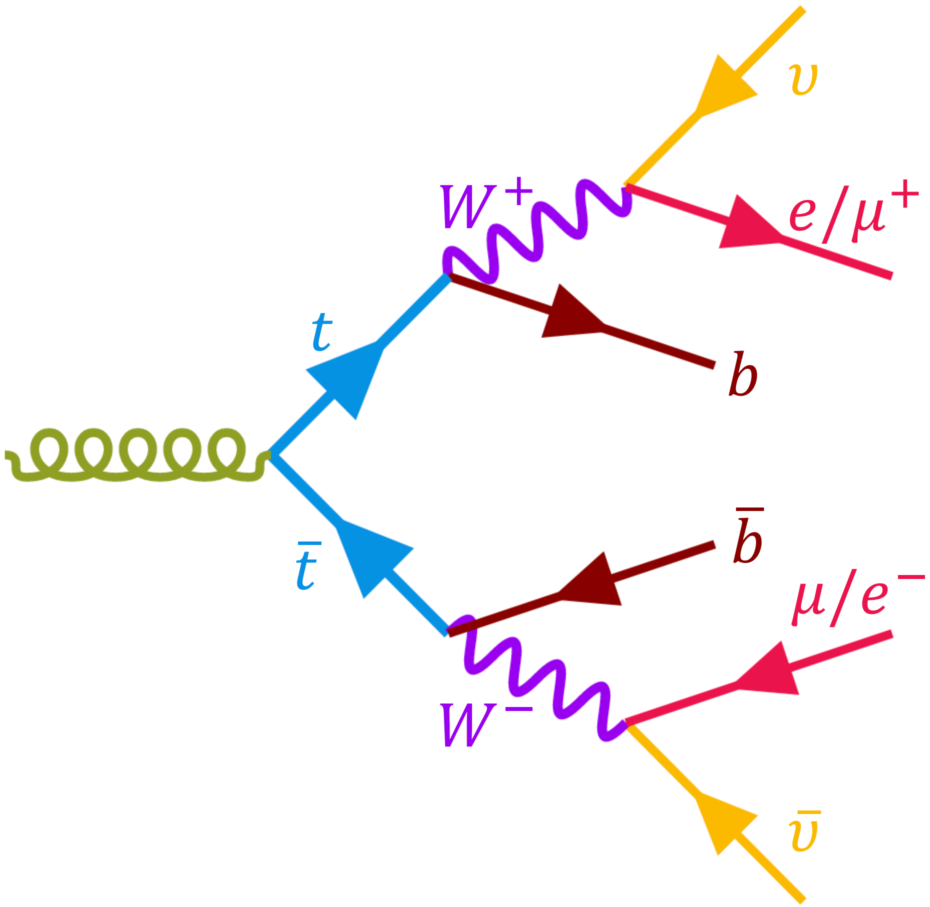


$$D = -3\langle\cos\varphi\rangle$$

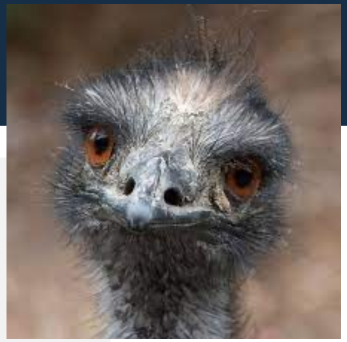
ATLAS Entanglement

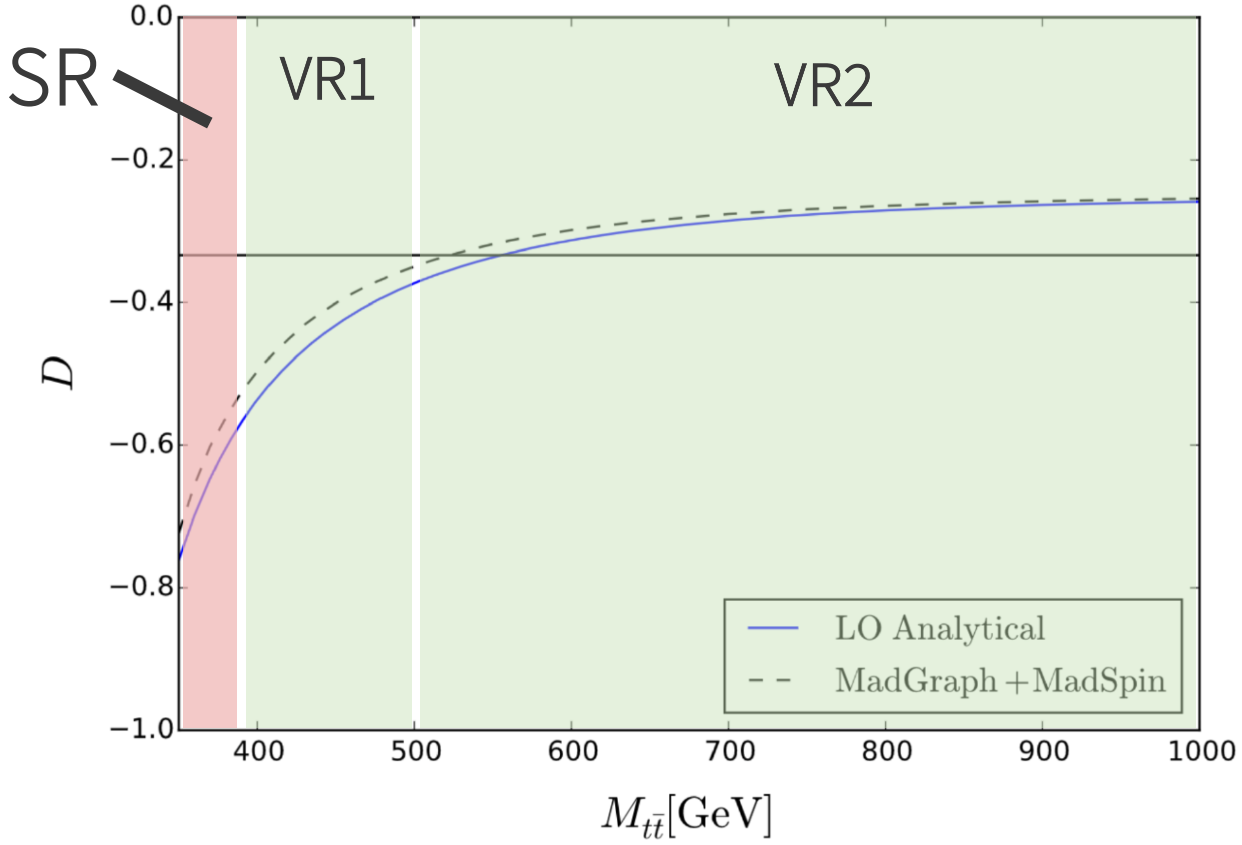

ATLAS
EXPERIMENT
Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST

Selections



- 1 electron and 1 muon
- 2 jets, at least 1 b-tagged

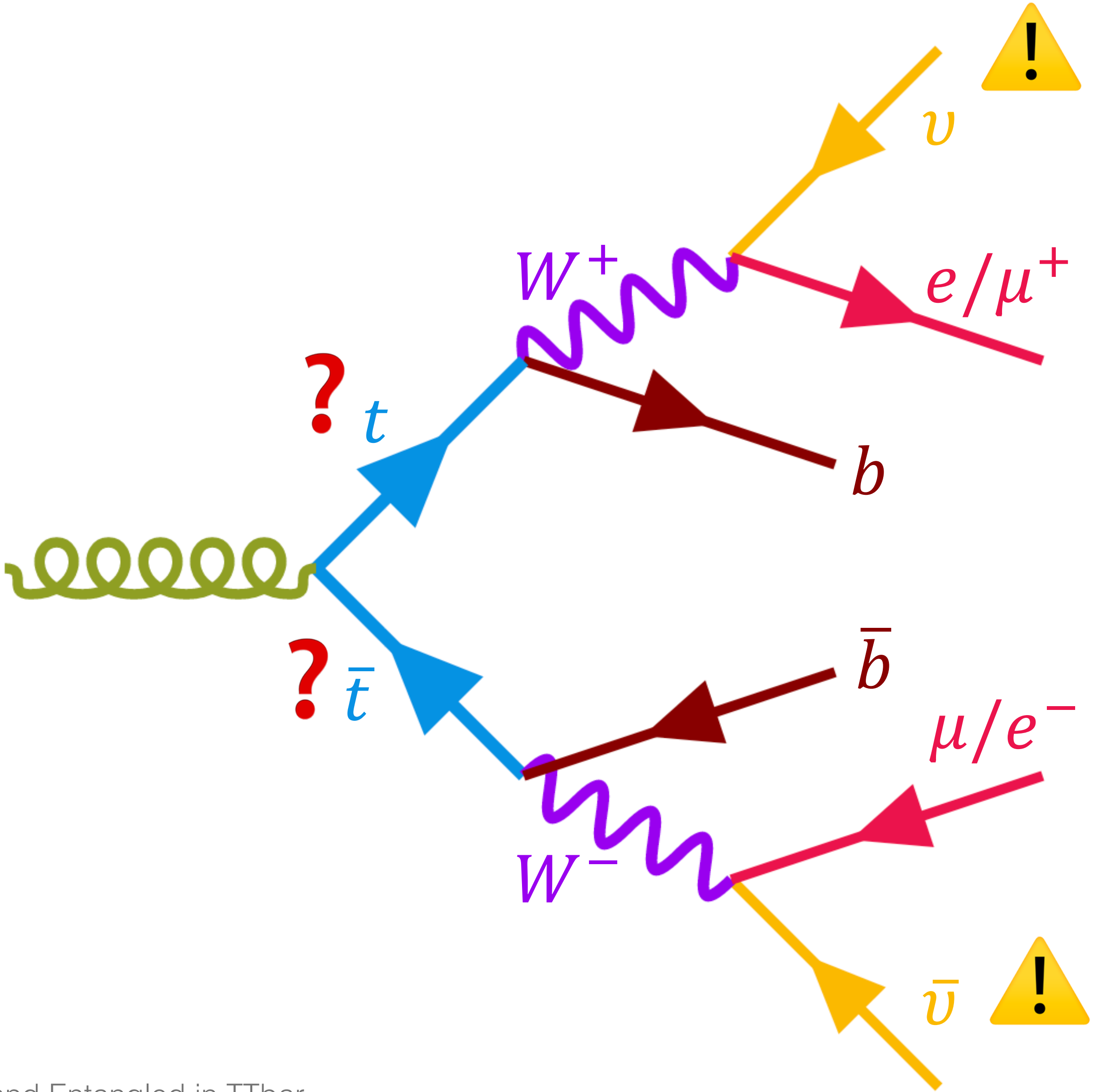




Dileptonic Reconstruction

$$t = b + e/\mu^{+} + \upsilon$$

...is challenging because of MET.
Several techniques exist to solve.



Dileptonic Reconstruction

$$t = b + e/\mu^{+} + \upsilon$$

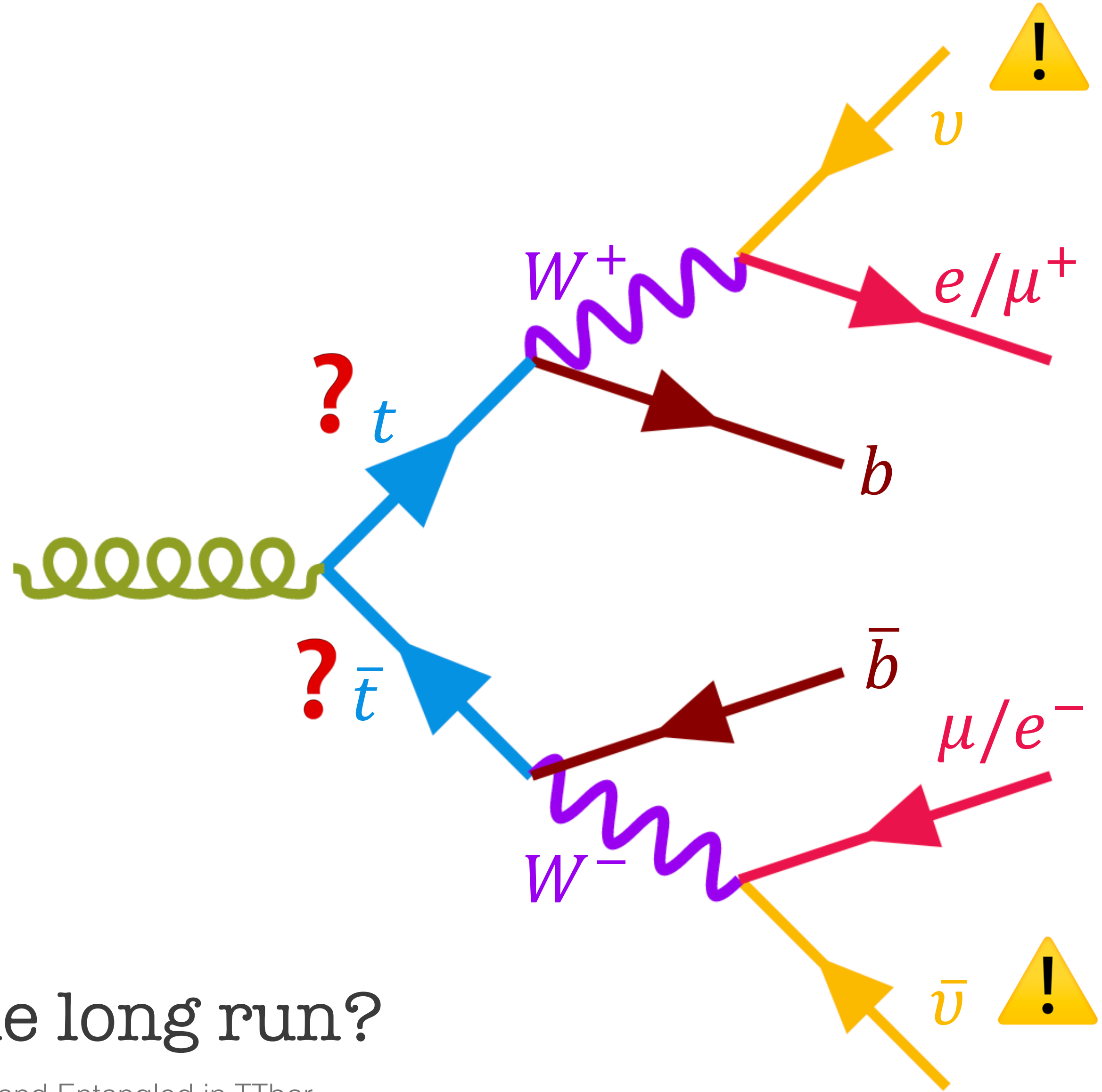
...is challenging because of MET.
Several techniques exist to solve.

Primary technique: Ellipse Method

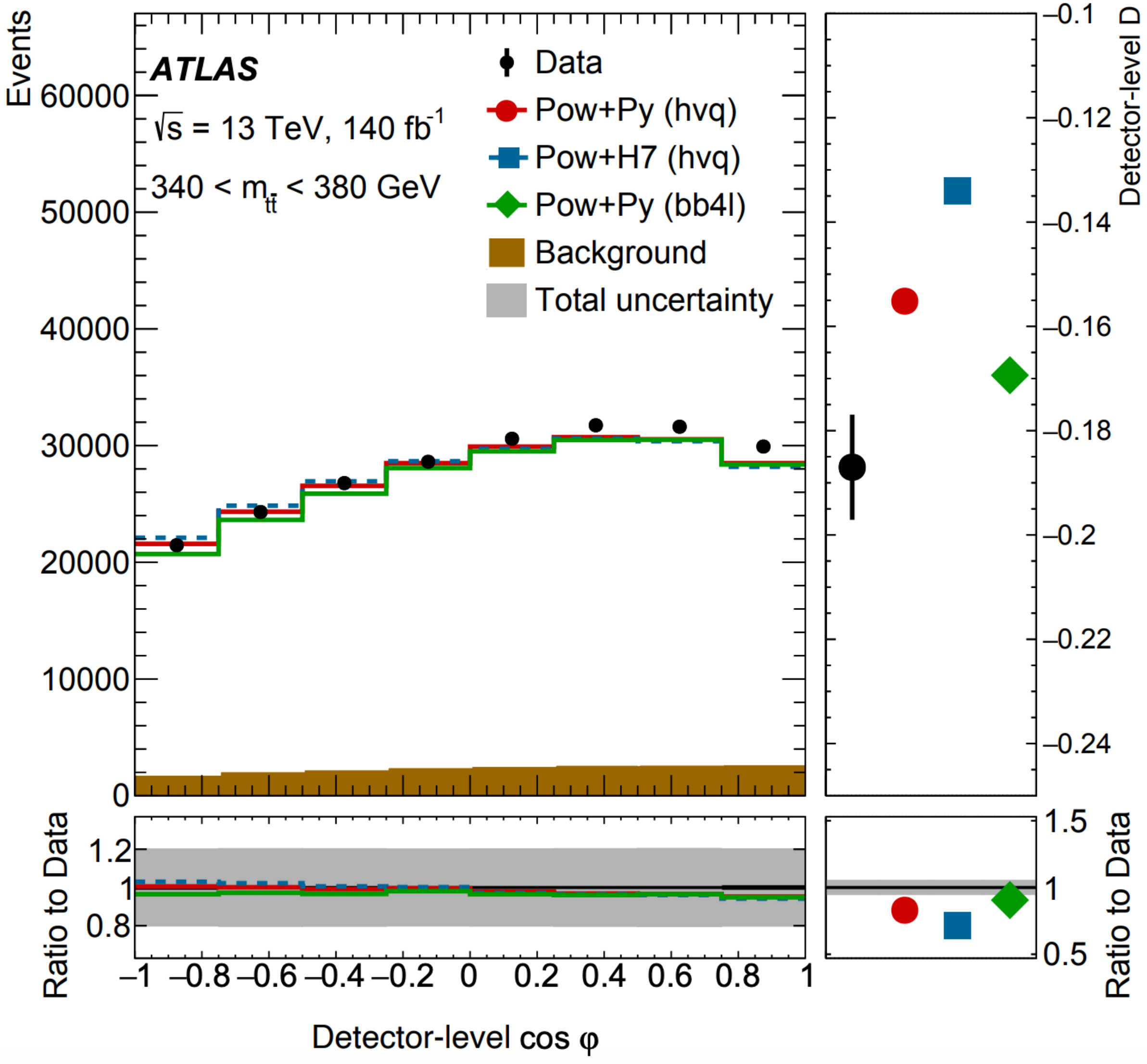
Alternative techniques:

- NeutrinoWeighter
- Simple kinematic matching

Will machine learning help in the long run?



Data-Simulation Comparison



- Distortion from detector effects (resolution, acceptance)
- The agreement is decent for the distribution.
- Tension in D

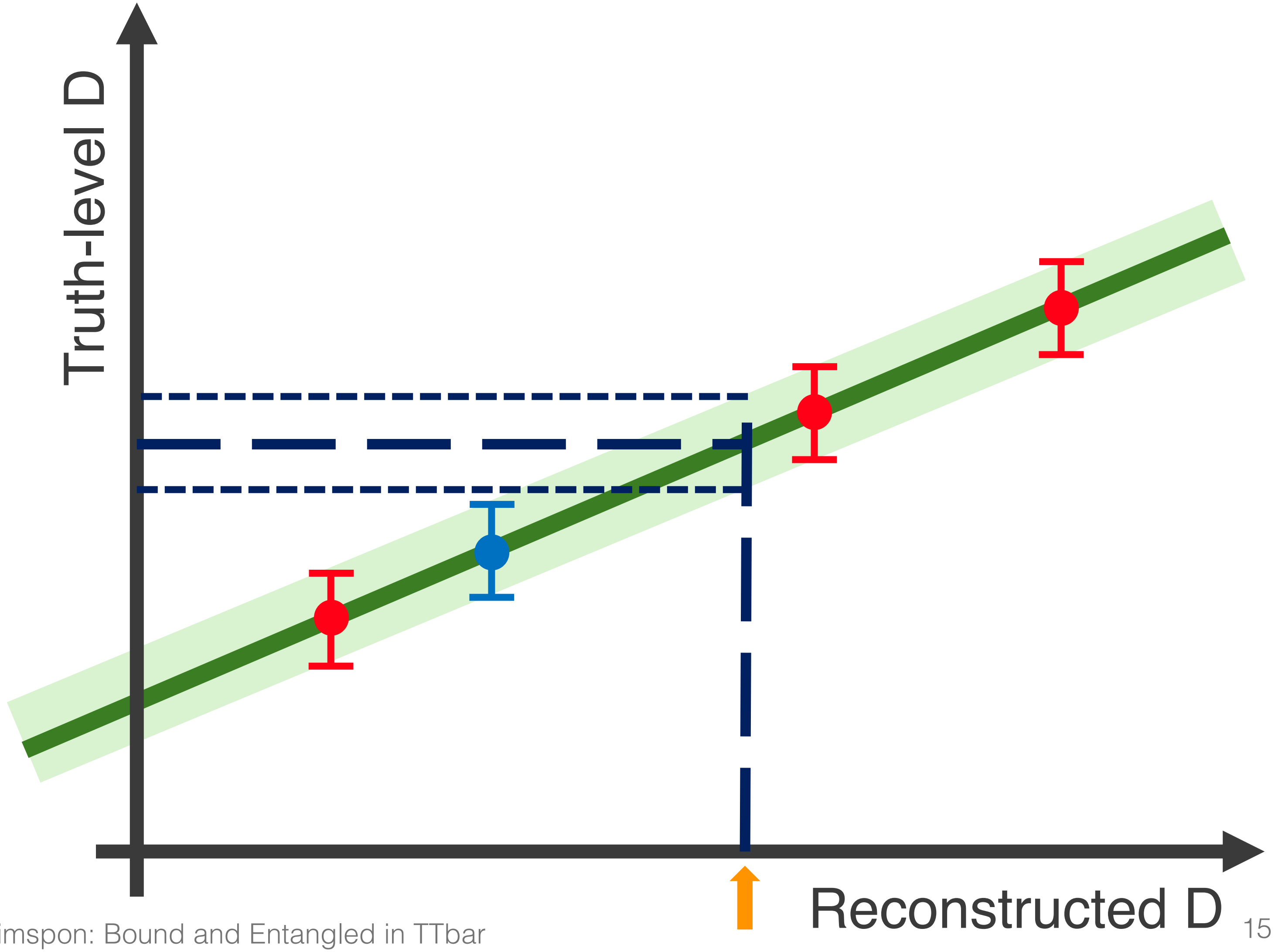
Calibration Curve

Parameterise variation in D

Reweight the simulation to generate alternative entanglement hypotheses.

Interpolate to find reco–truth relationship

Repeat for all systematics



Calibration Curve

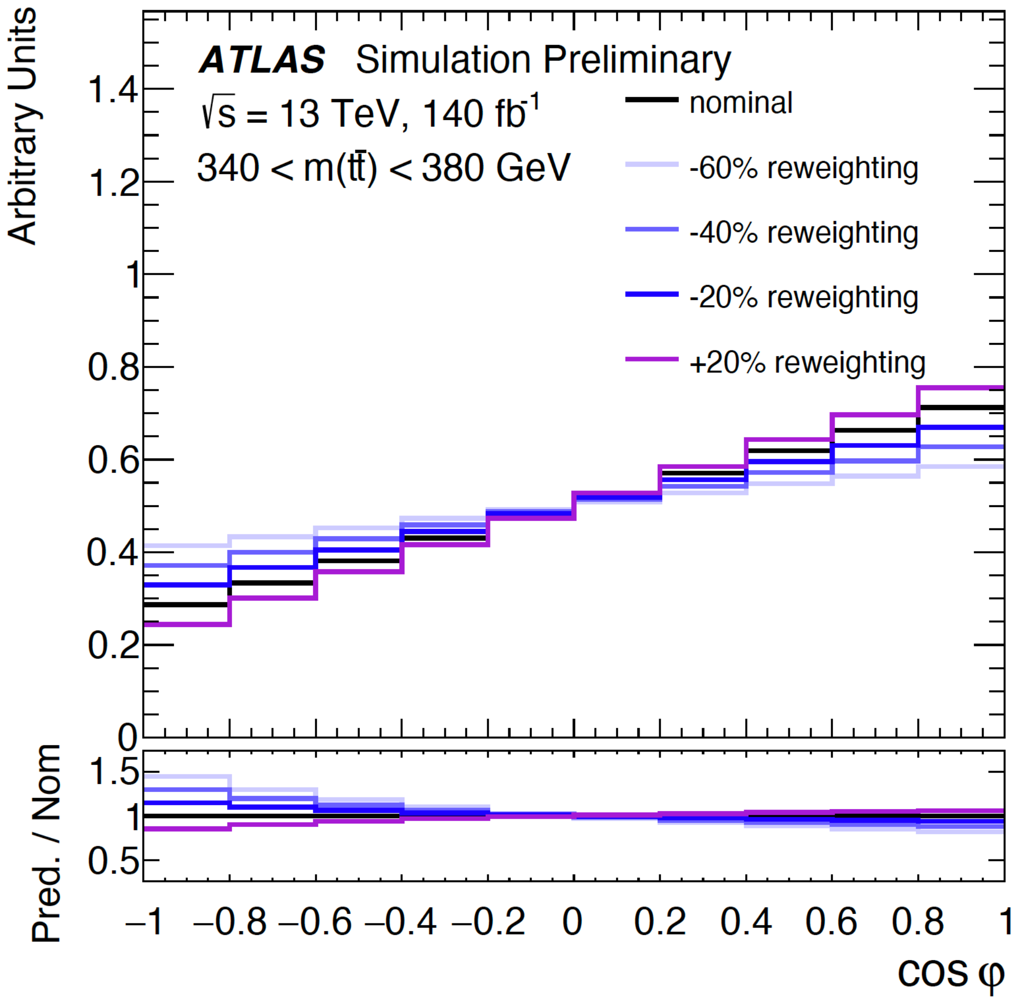
Generate alternative hypotheses

Apply a per-event re-weighting of the simulation!

$$w = f(m_{t\bar{t}}, \cos\varphi, K)$$

Choose such that distribution remains linear

Scaling parameter



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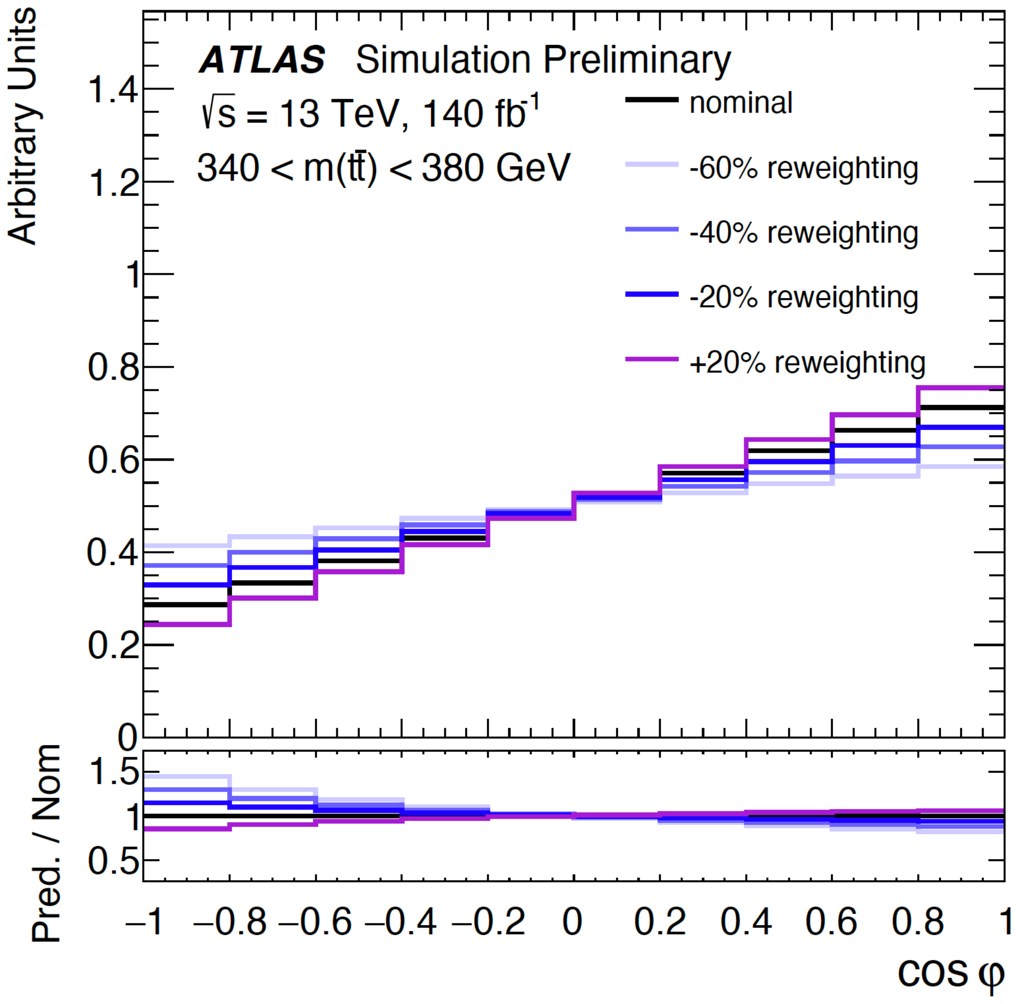
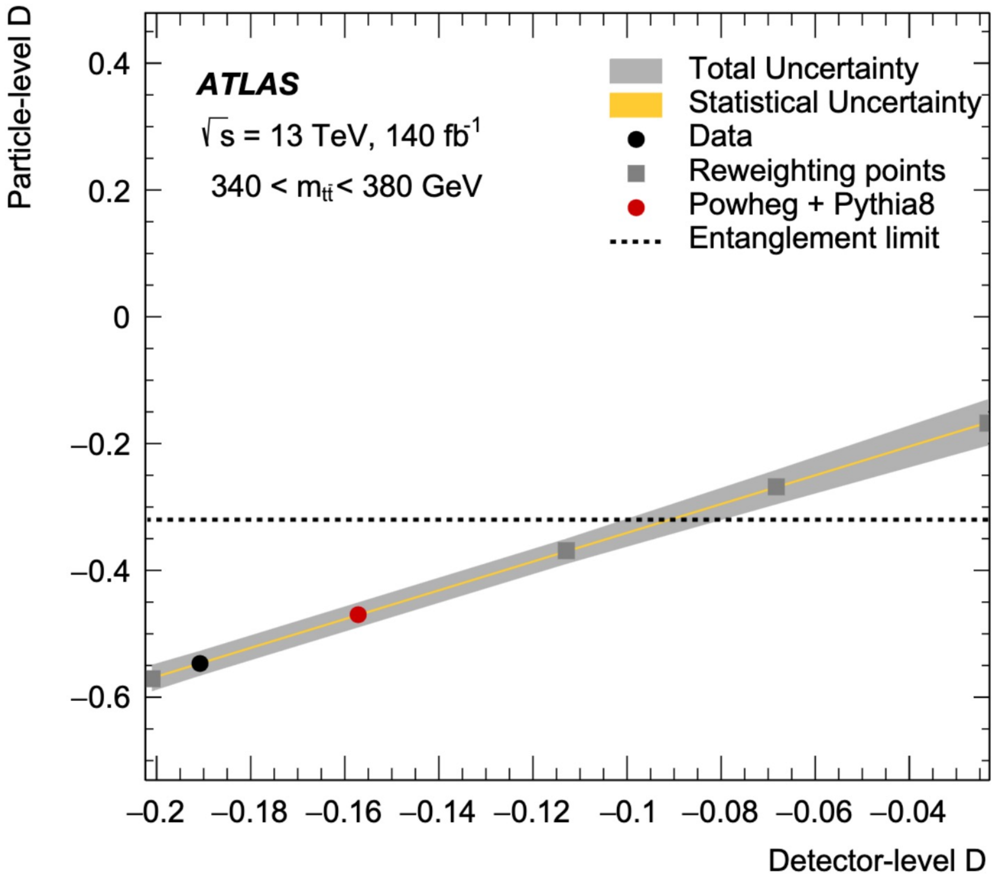
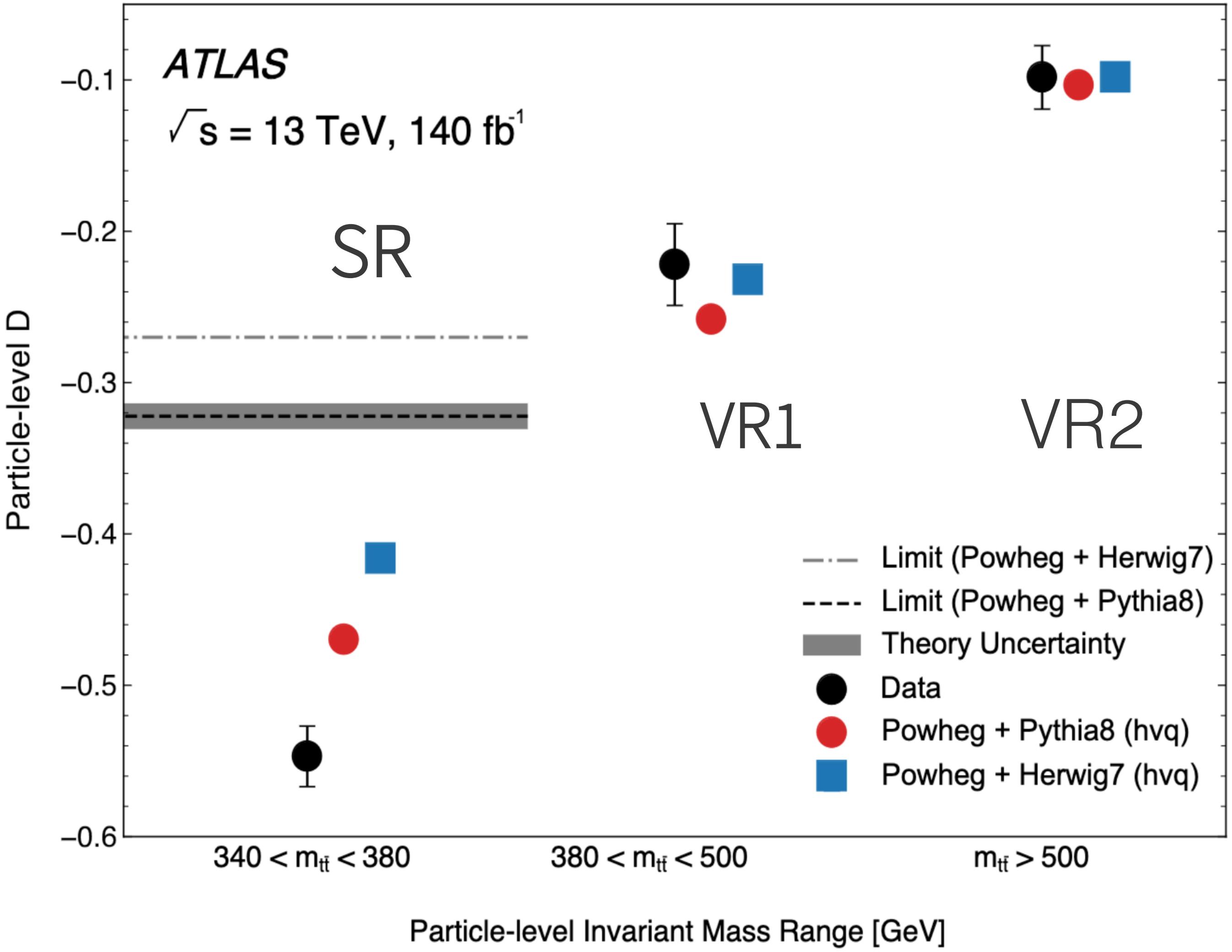


Results

Data suggests simulation under-predictions entanglement





Systematic Uncertainties

Signal modelling biggest limitation

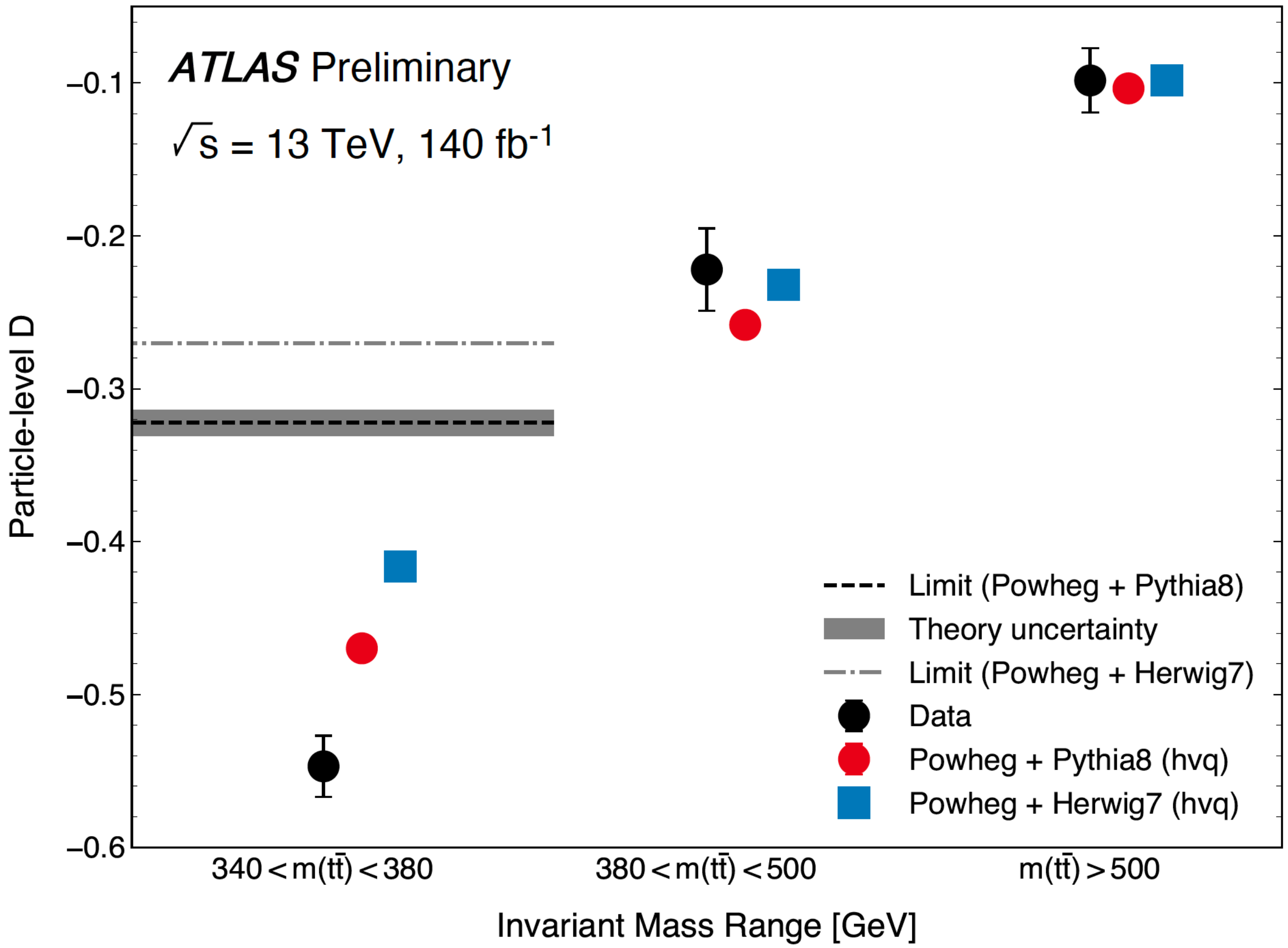
Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	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
Total uncertainty	0.019	3.5	0.017	3.6

Propagation of spin information

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%

Common Questions

How reliable are the simulation predictions?



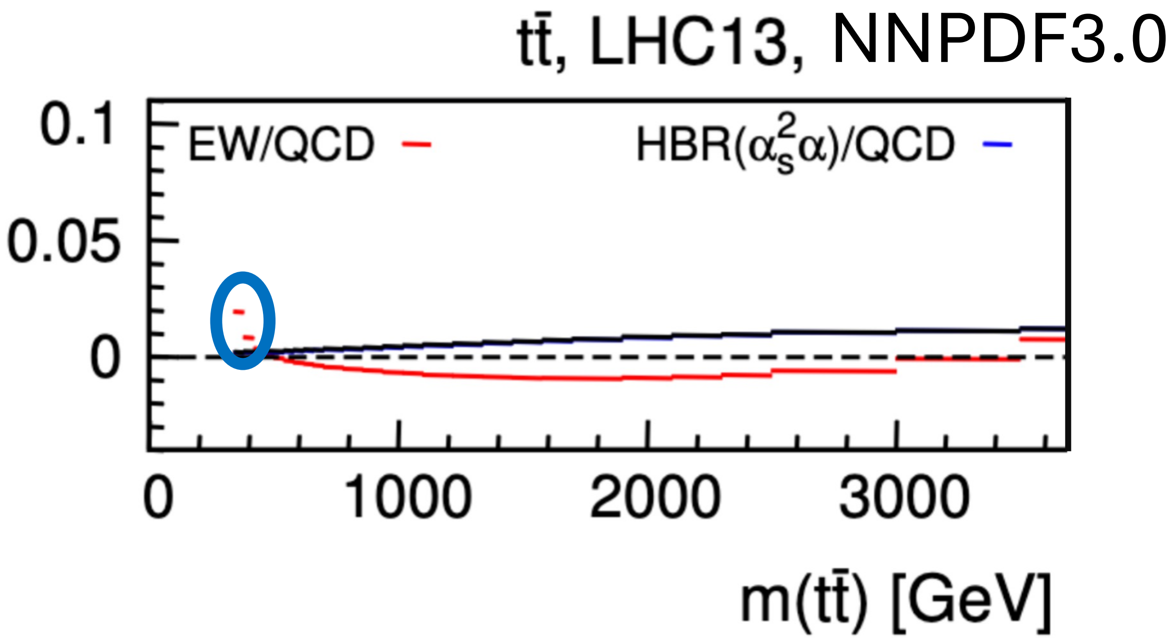
Reliable but limited

Derived from general-purpose MC event generators (powerful and widely used).

- Disparate shower descriptions
- Lack full spin info in shower
- Lack higher-order corrections to top quark decays
- Lack of bound-state effects?

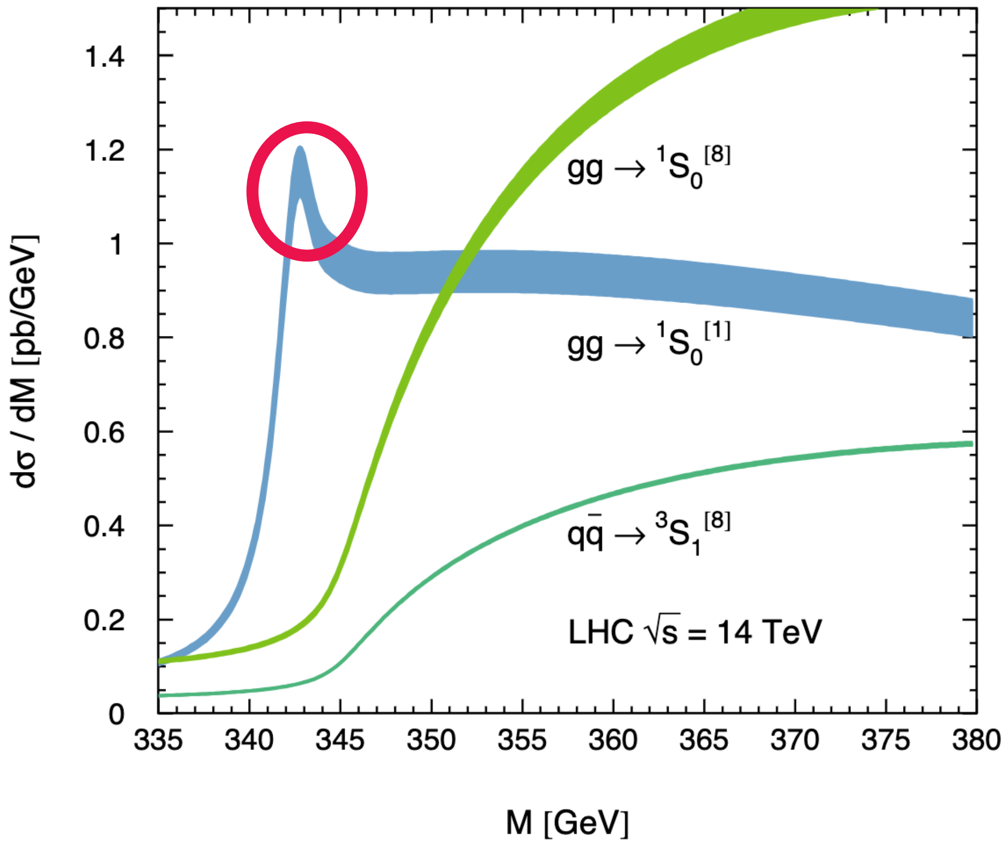
Sources of mis-modelling

NLO EW



Cross-section enhancement
(10.1007/JHEP10(2017)186)

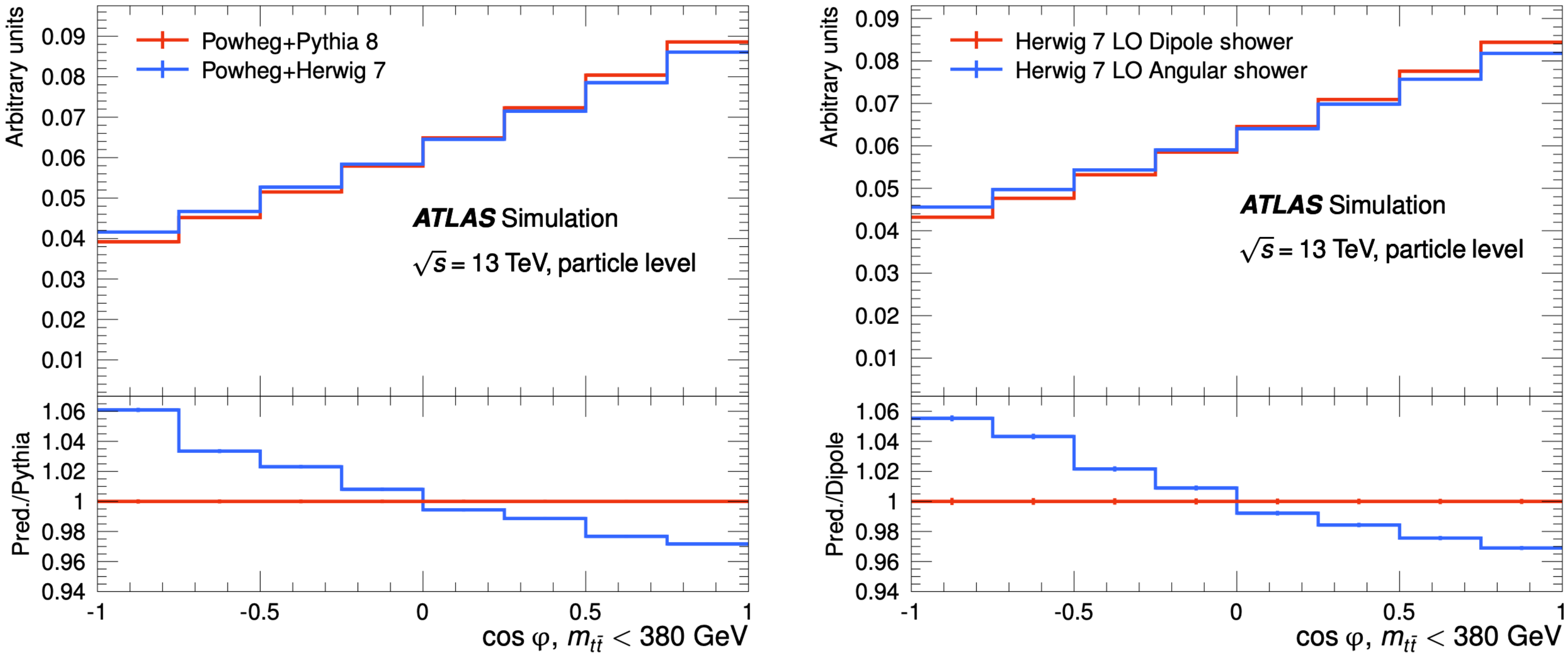
Bound state



Spin-, colour-singlet enhancement

Let’s not forget about parton showers

Angular vs dipole showers give different results



Do we understand this, and have we seen it elsewhere?

ATLAS Summary

- Observation of quantum entanglement at the LHC
- Data suggests stronger entanglement than is present in simulation.
- Different parton showers algorithms yield different predictions.

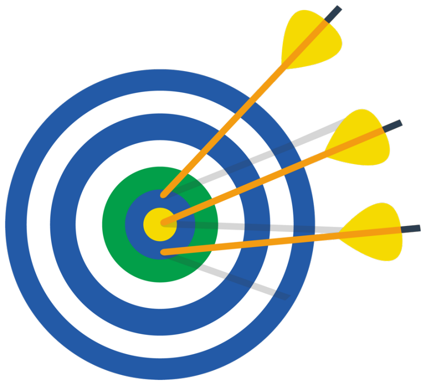
Simulation Improvements

Precision

- Spin correlations in top decays
- Backgrounds are second largest systematic

Accuracy

- Bound-state effects (toponium)
- Higher-order EW corrections

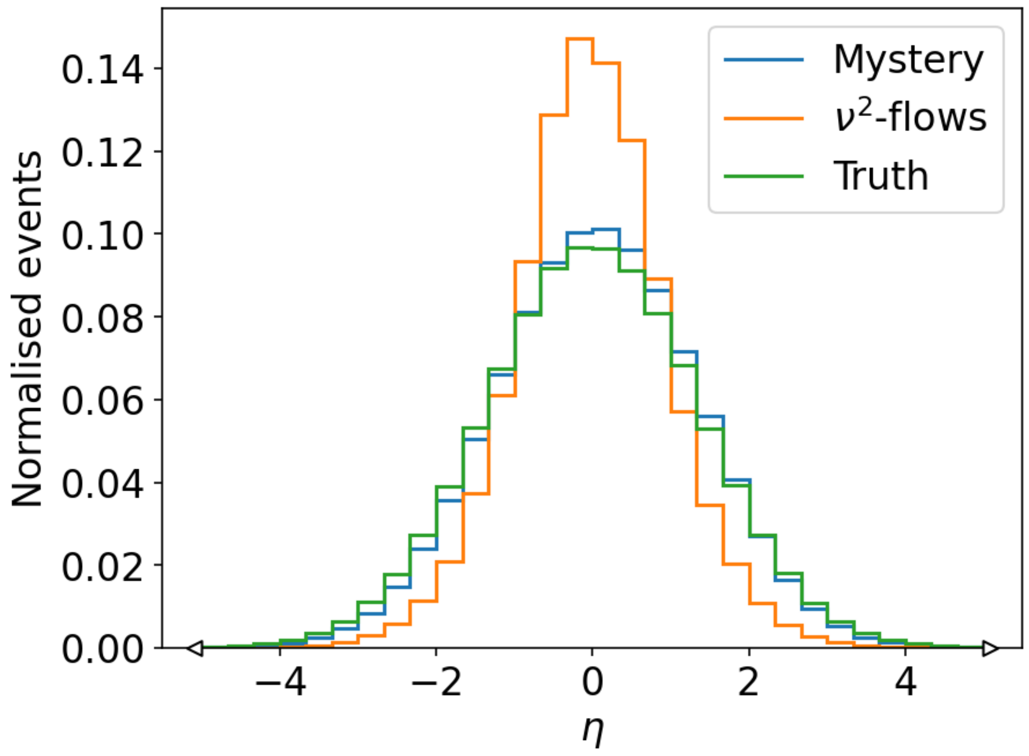


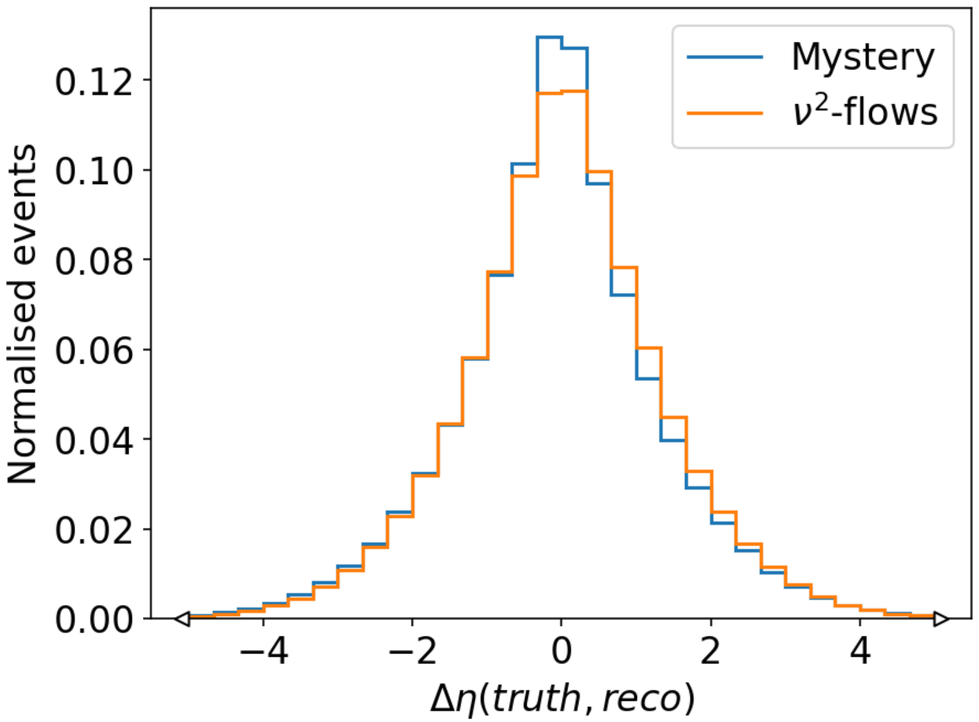
Reconstruction Improvements

Better top reconstruction will drive better m_{tt} resolution

Important to quantify performance

NOT ATLAS!





Ethan musings…

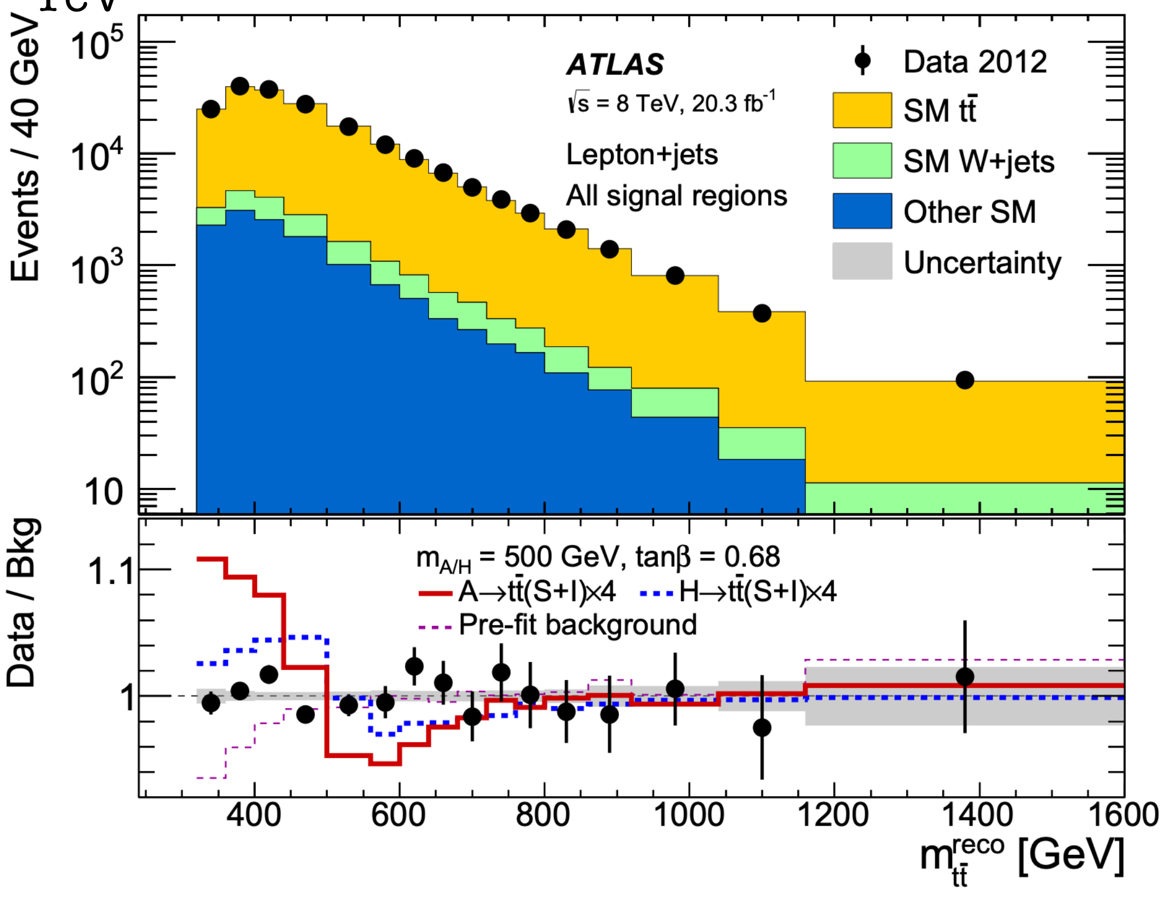
1. Could we agree on some m_{tt} binning for refined entanglement measurements?

ATLAS Toponium


SCENE
MISSING

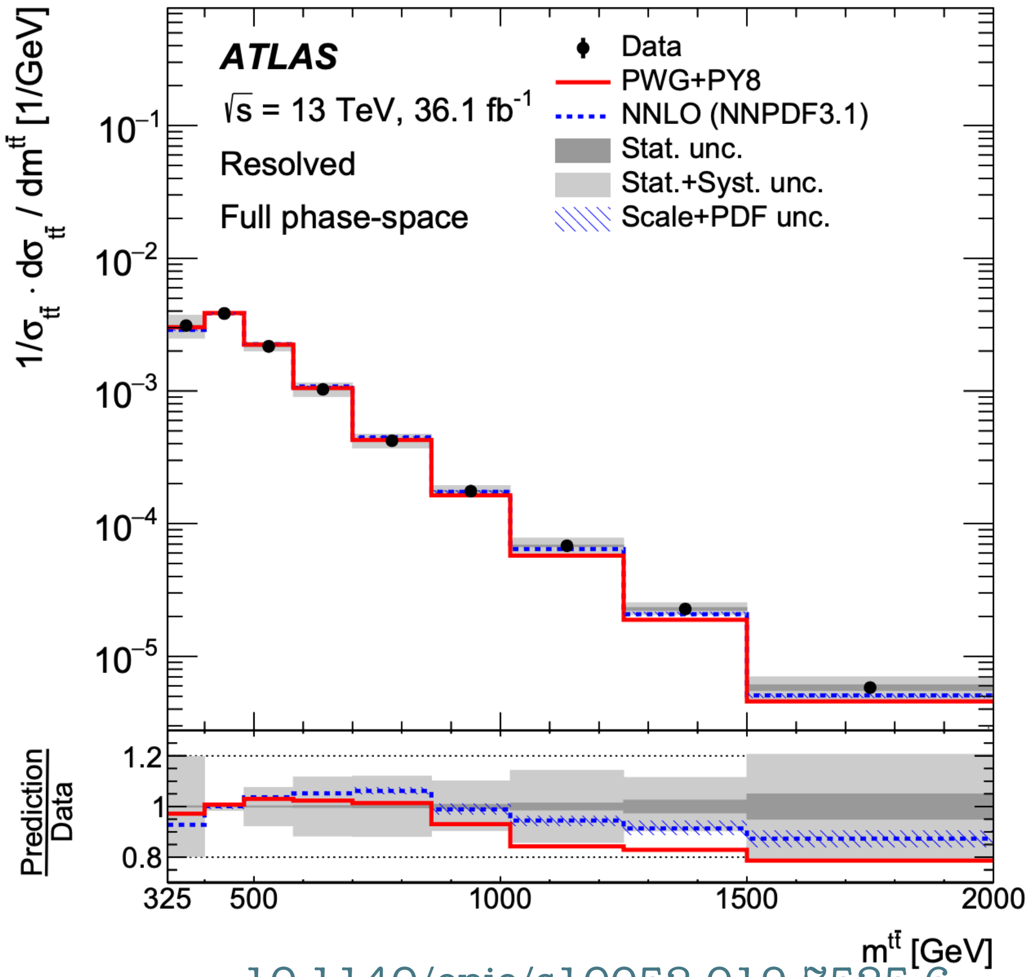
ATLAS Historic

Post-fit under background-only hypothesis at 8 TeV



10.1103/PhysRevLett.119.191803

Full phase-space mttbar diff xsec, ljets, Run2



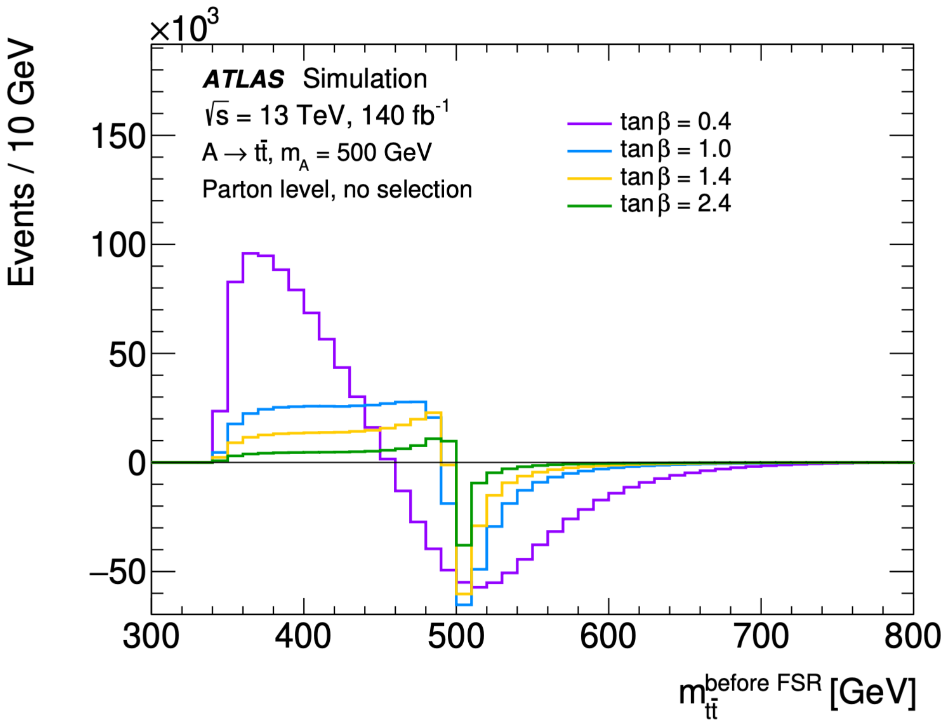
10.1140/epjc/s10052-019-7525-6

Most Recent Search

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *May 1, 2024*
ACCEPTED: *July 2, 2024*
PUBLISHED: *August 2, 2024*

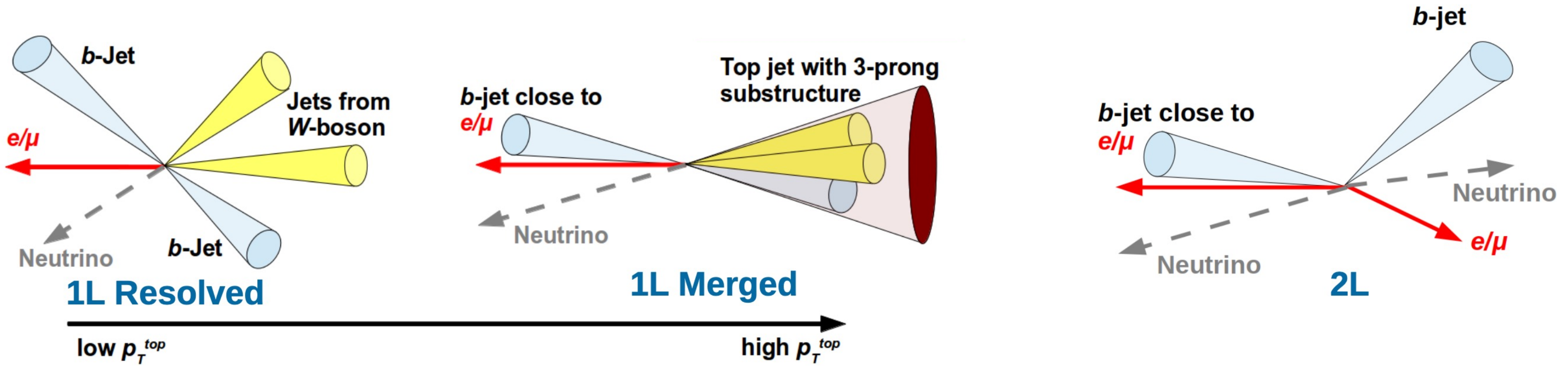
Search for heavy neutral Higgs bosons decaying into a top quark pair in 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector



Signal was type-II 2HDM scalar and pseudo-scalar

(in the alignment limit)

Analysis Specifics



1-Lepton	2-Lepton
$m_{t\bar{t}}$ $\cos\theta^*$	m_{llbb} $\Delta\phi$

Fit

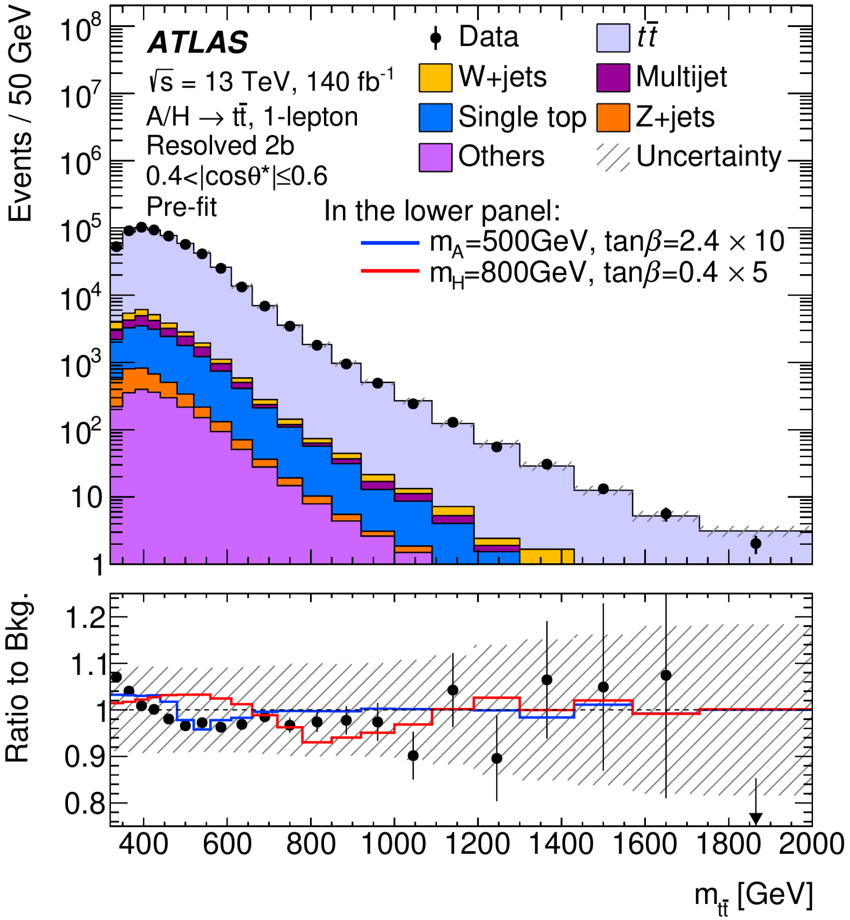
- Binned profile likelihood fit
- Inputs are expected distributions of m_{tt} in 1L and m_{llbb} in 2L
- Relate mu to signal, background and interference

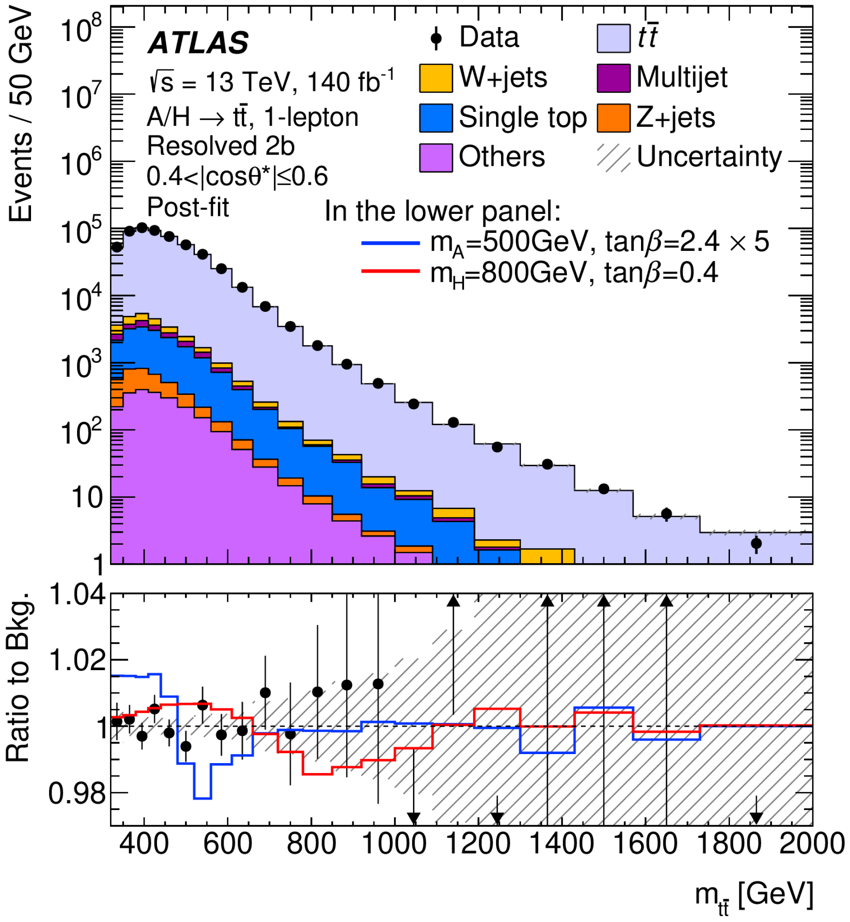
$$(\mu - \sqrt{\mu})\, S + \sqrt{\mu}\, (S + I) + B$$

- Modelling systematics dominate

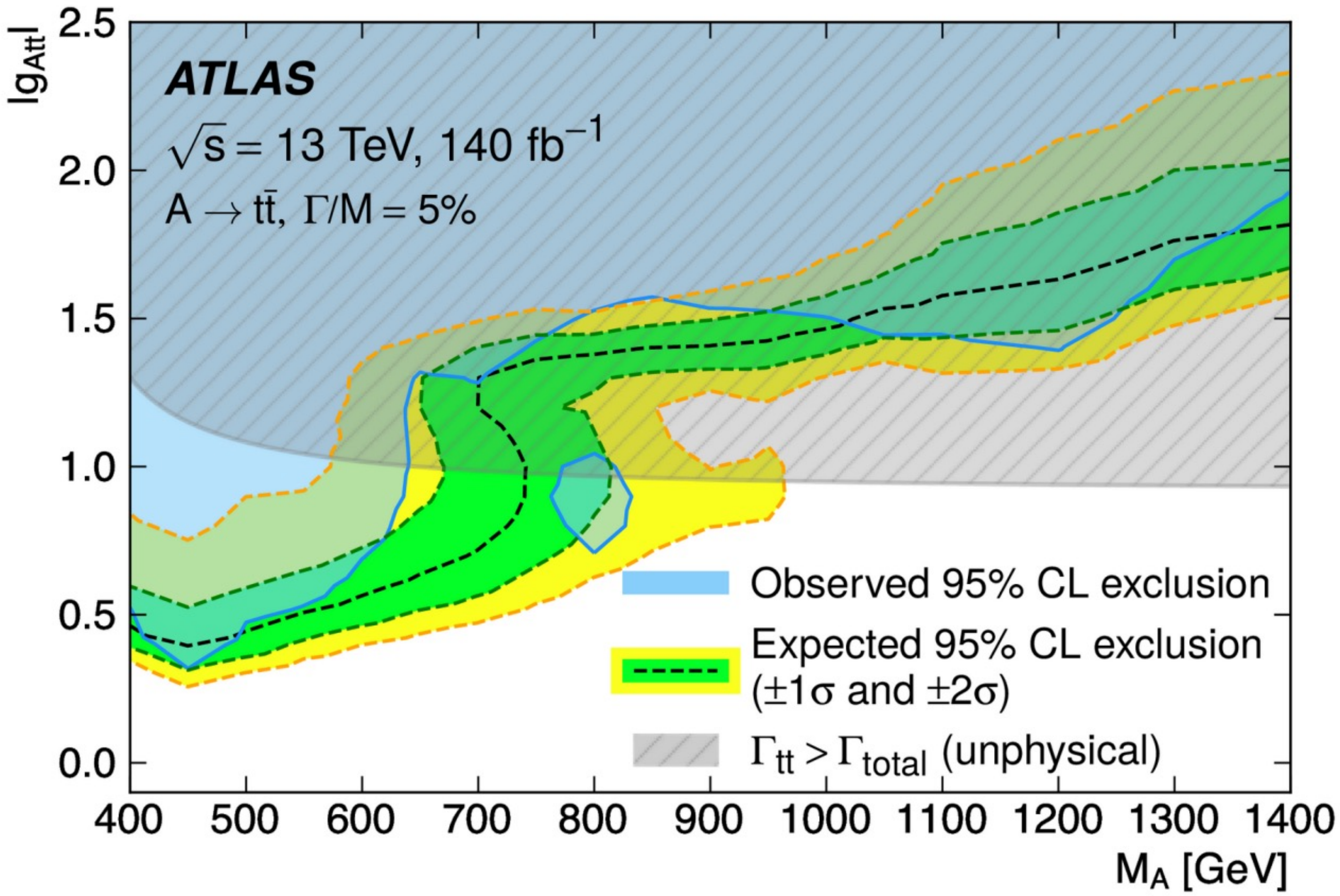
1L Distributions

Background-only fit: trend near threshold in the pre-fit





Limits on BSM model



Limits set on mass of type-2 2HDM mass-degenerate (pseudo)scalars

Limit's lower bound at 400 GeV

Summary

- No toponium interpretation **yet**
- Observed trend in pre-fit but “fitted away”
- 1-lepton channel drive sensitivity, but at high masses
- Next steps:
  - Full top reconstruction + spin information
  - Include NRQCD toponium model

Conclusions

Overall Conclusions

- Entanglement result well established
- No evidence yet for toponium in ATLAS
- Lot’s of work on-going using spin information at threshold – an exciting place to be!

Publicity

symmetry topics follow +

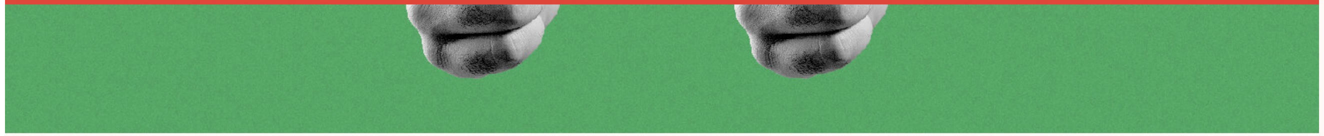


Illustration by Sandbox Studio, Chicago

Scientists measure entanglement at the LHC

12/18/23 | By Chiara Villanueva

Scientists on the ATLAS collaboration performed the highest-energy measurement of quantum entanglement.

Illustration by Sandbox Studio, Chicago with Corinne Mucha

Don’t call it toponium

04/01/25 | By Sarah Charley

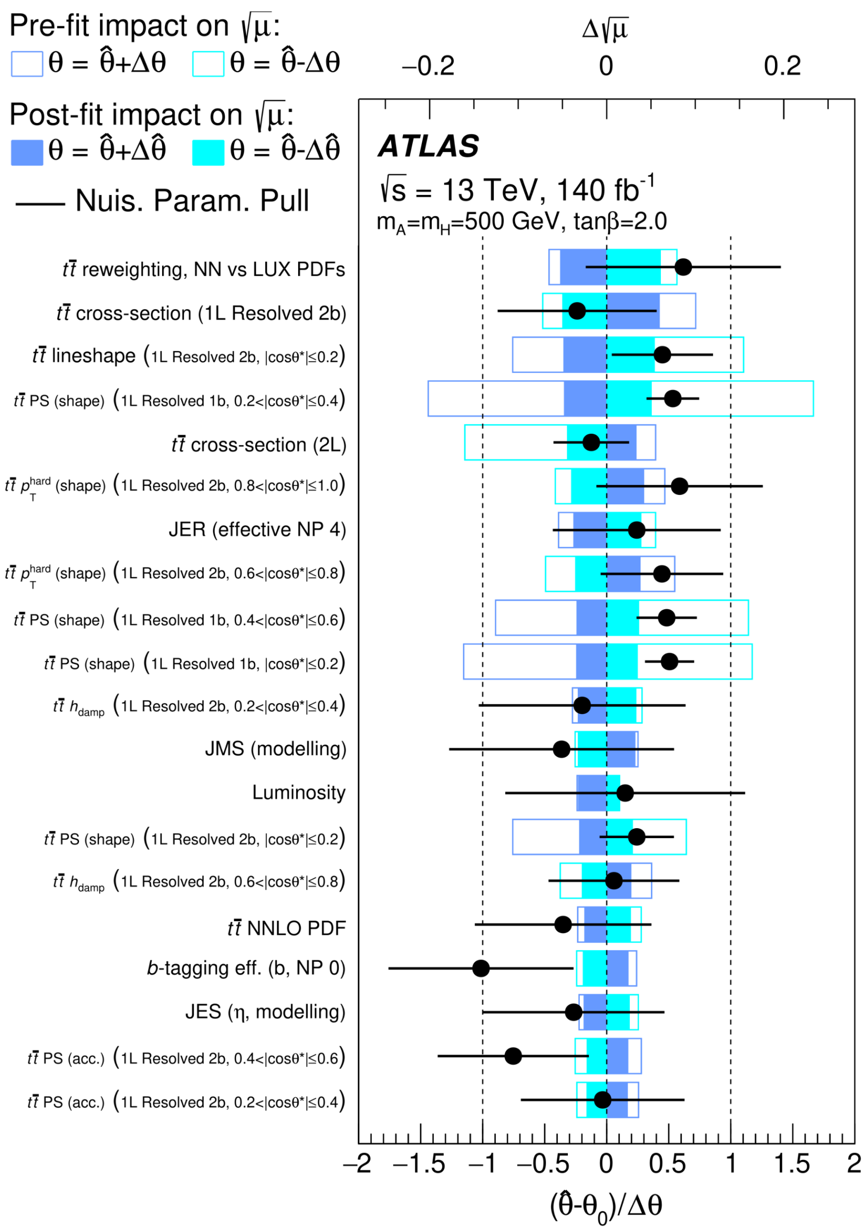
A large and unexpected excess of top quark pairs has the physics community excited, but the interpretation is still up for debate.

In 1995, Alexander Grohsjean cut out a story from the local German newspaper *Saarbrücker Zeitung*. He was 16 years old and mystified by what he read.

Thank you

Auxiliary Material

Uncertainty component	Fractional contribution [%]	
	$m_A = 800$ GeV	$m_A = m_H = 500$ GeV
	$\tan\beta = 0.4$	$\tan\beta = 2.0$
Experimental	**30**	**42**
Small-R jets (JER, JES)	22	29
Large-VR jets	11	20
Flavour tagging	13	17
Leptons	4	5
Other (E_T^{miss}, luminosity, pile-up, JVT)	10	14
Modelling: SM $t\bar{t}$ and signal	**91**	**79**
$t\bar{t}$ NNLO	49	28
$t\bar{t}$ lineshape	27	29
$t\bar{t}$ ME-PS (p_T^{hard})	36	30
$t\bar{t}$ ME-PS (h_{damp})	41	25
$t\bar{t}$ ISR& FSR	9	13
$t\bar{t}$ PS	29	41
$t\bar{t}$ cross-section	21	31
$t\bar{t}$ Scales & PDF	21	16
m_t	6	4
Signal	19	9
Modelling: other	**41**	**16**
W+jets	11	8
Z+jets	1	2
Multijet	27	10
Fakes	<1	1
Other bkg.	29	10
MC statistics	**18**	**26**
Total systematic uncertainty	**±100**	**±100**
Total statistical uncertainty	**< 1**	**< 1**

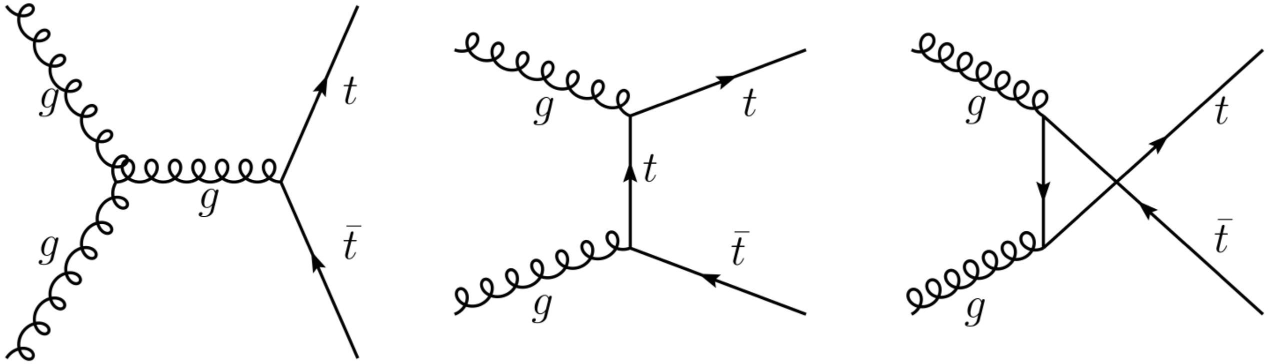


The Top Quark

We have produced hundreds of millions of top quarks at the LHC.

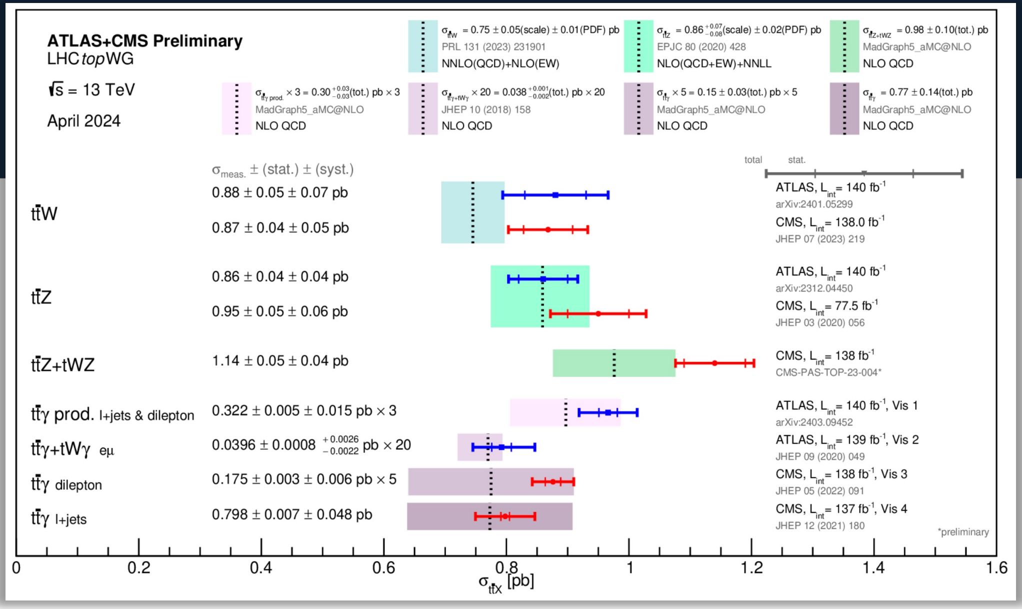
Tops have unique properties, driven by their huge mass

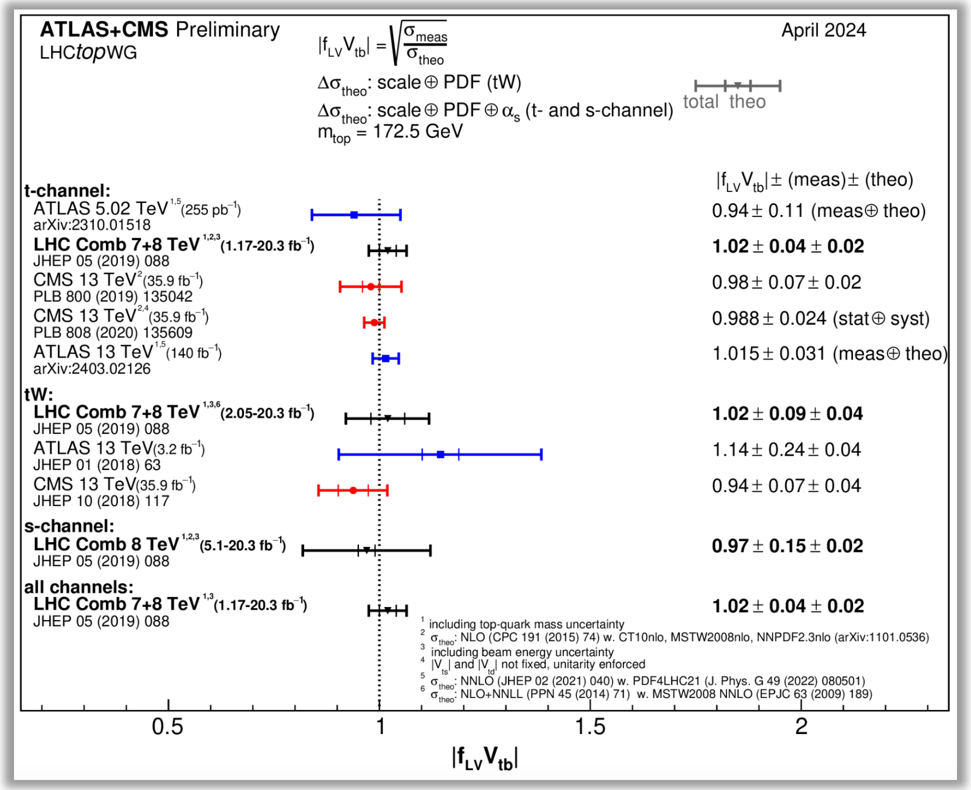
Mostly produced in pairs

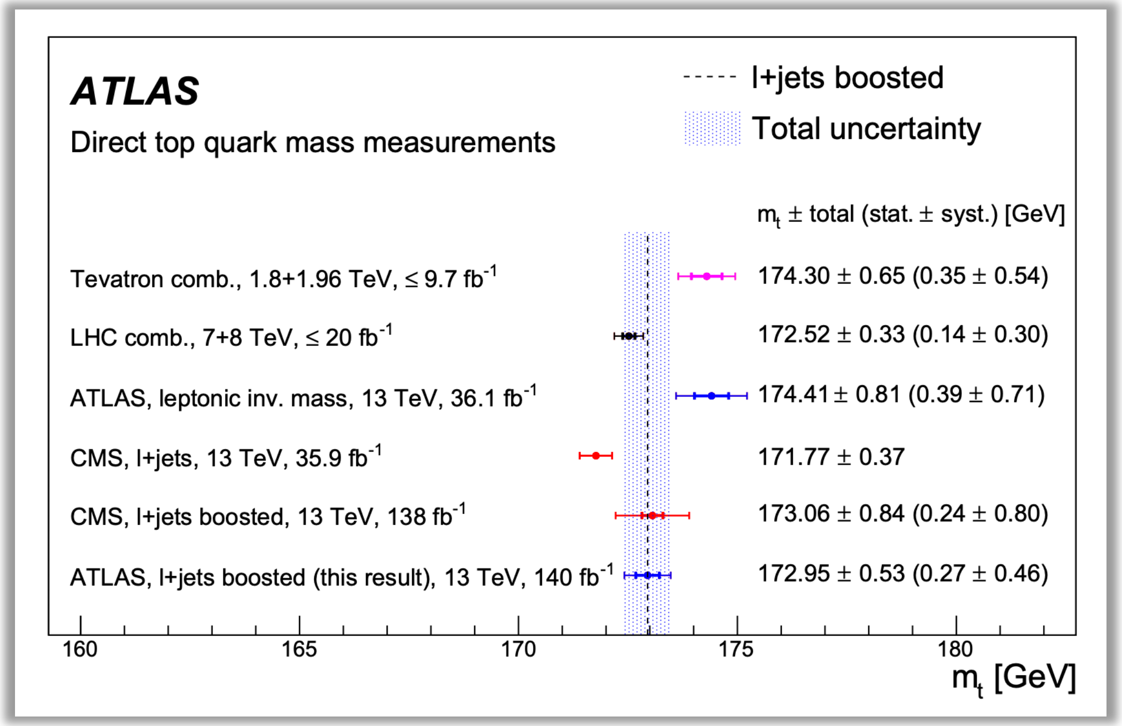


The Top Quark

The top quark is now a precision tool for testing the SM

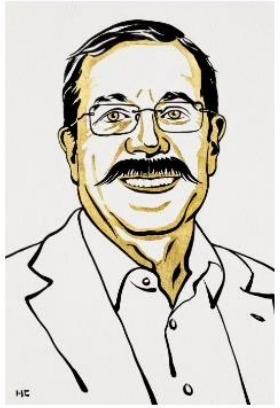






Dogmas?

1. We can't make quantum information-type measurements at the LHC...



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Alain Aspect
Prize share: 1/3

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John F. Clauser
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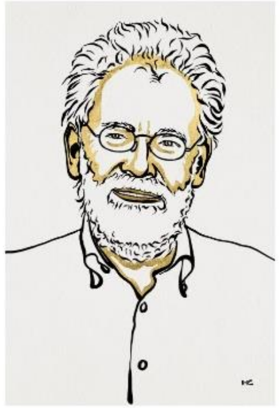

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Dogmas?

1. We can't make quantum information-type measurements at the LHC…

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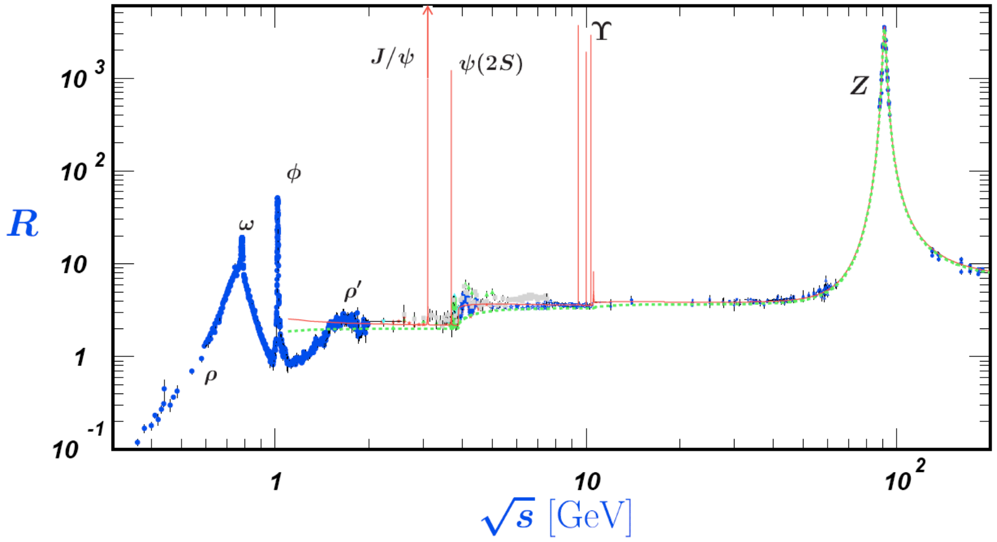
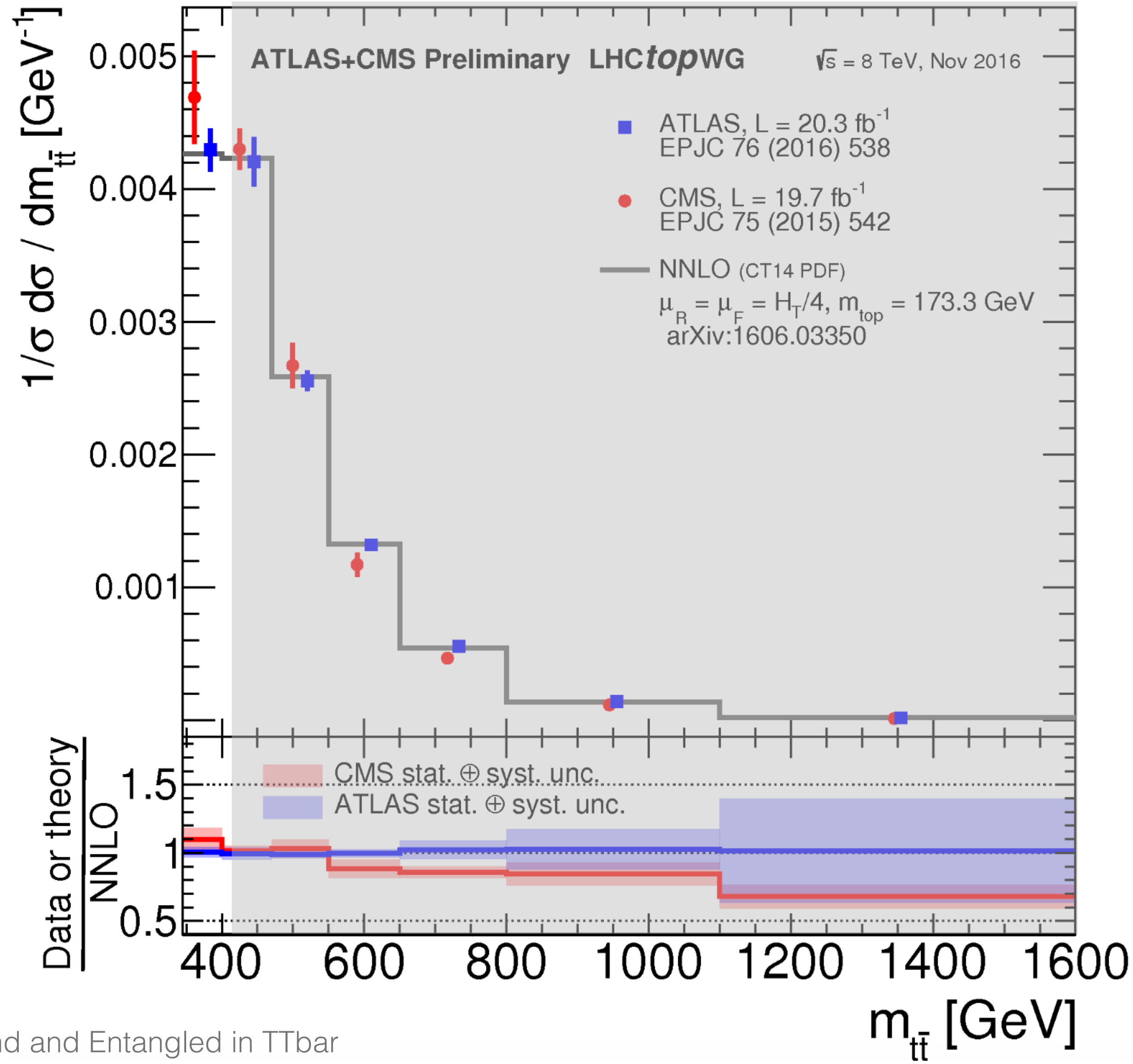
2. Top quarks don't form bound states…



Dare you cross the threshold?

- Threshold = low invariant mass
- Tops have low relative velocities
- At LHC, dominant production is gg-fusion spin-singlet, colour-singlet.



$t\bar{t}$ production

In terms of density matrices

$$\sigma_{t\bar{t}} \propto \mathrm{Tr}\left[\underbrace{\Gamma_{\bar{t}\to\bar{b}ff}}_{\text{Decay}} \times \underbrace{R_{gg\to t\bar{t}}}_{\text{Production}} \times \underbrace{\Gamma_{t\to bff}}_{\text{Decay}}\right]$$

$t\bar{t}$ production

In terms of density matrices

$$\sigma_{t\bar{t}} \propto \mathrm{Tr}\left[\Gamma_{\bar{t}\to\bar{b}\bar{f}f} \times \mathrm{R}_{gg\to t\bar{t}} \times \Gamma_{t\to b\bar{f}f}\right]$$

Decay — Production — Decay

$$\mathrm{R} = A + \sum_i \left(B_i^+ \sigma^i + B_i^- \bar{\sigma}^i\right) + \sum_{i,j} C_{ij} \sigma^i \bar{\sigma}^j$$

Polarisations (of individual tops)

Correlations (between tops' spins)

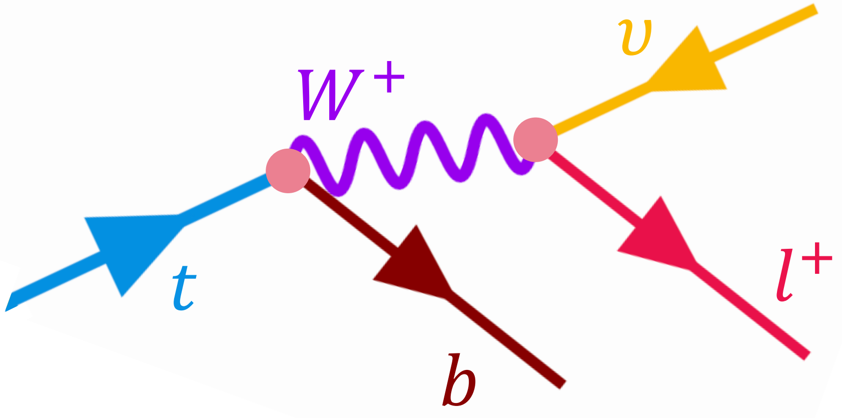
Accessing Top Spin

Unique top properties mean spin information accessible

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		$\sim 10^{-22}$ s

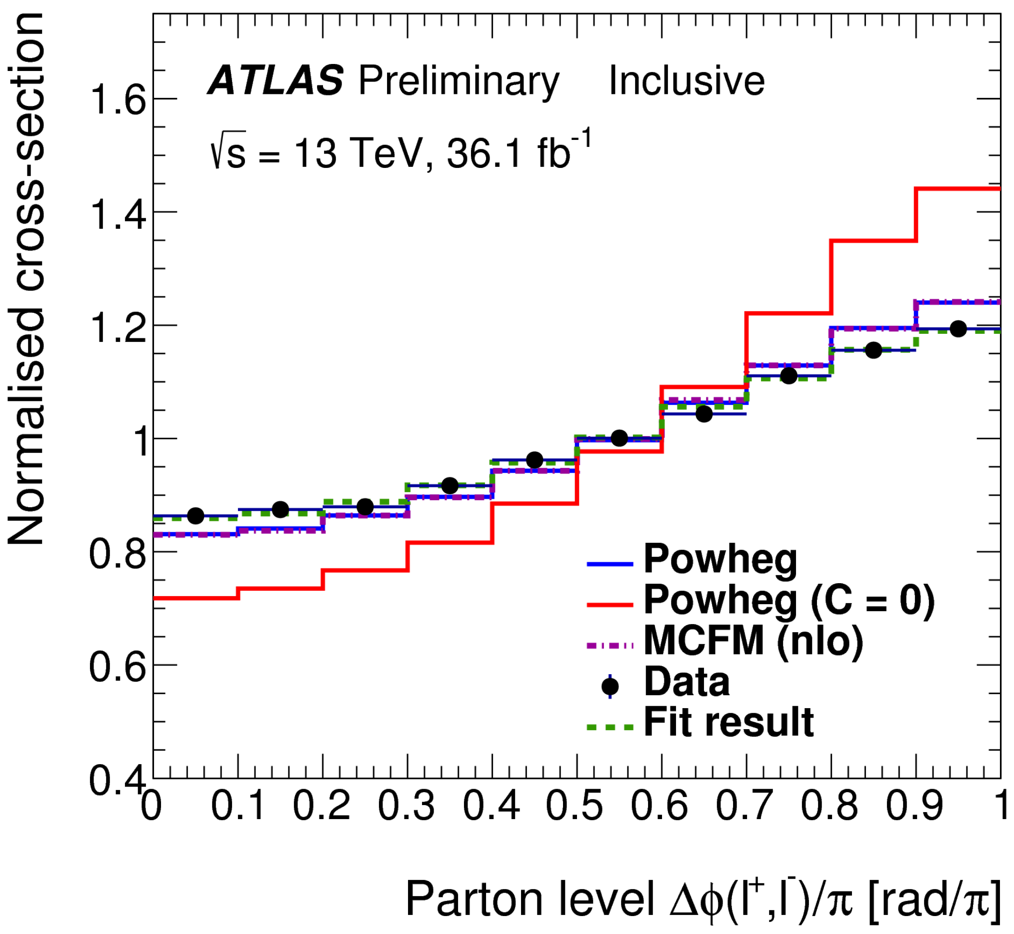
The weak decay facilitates this...

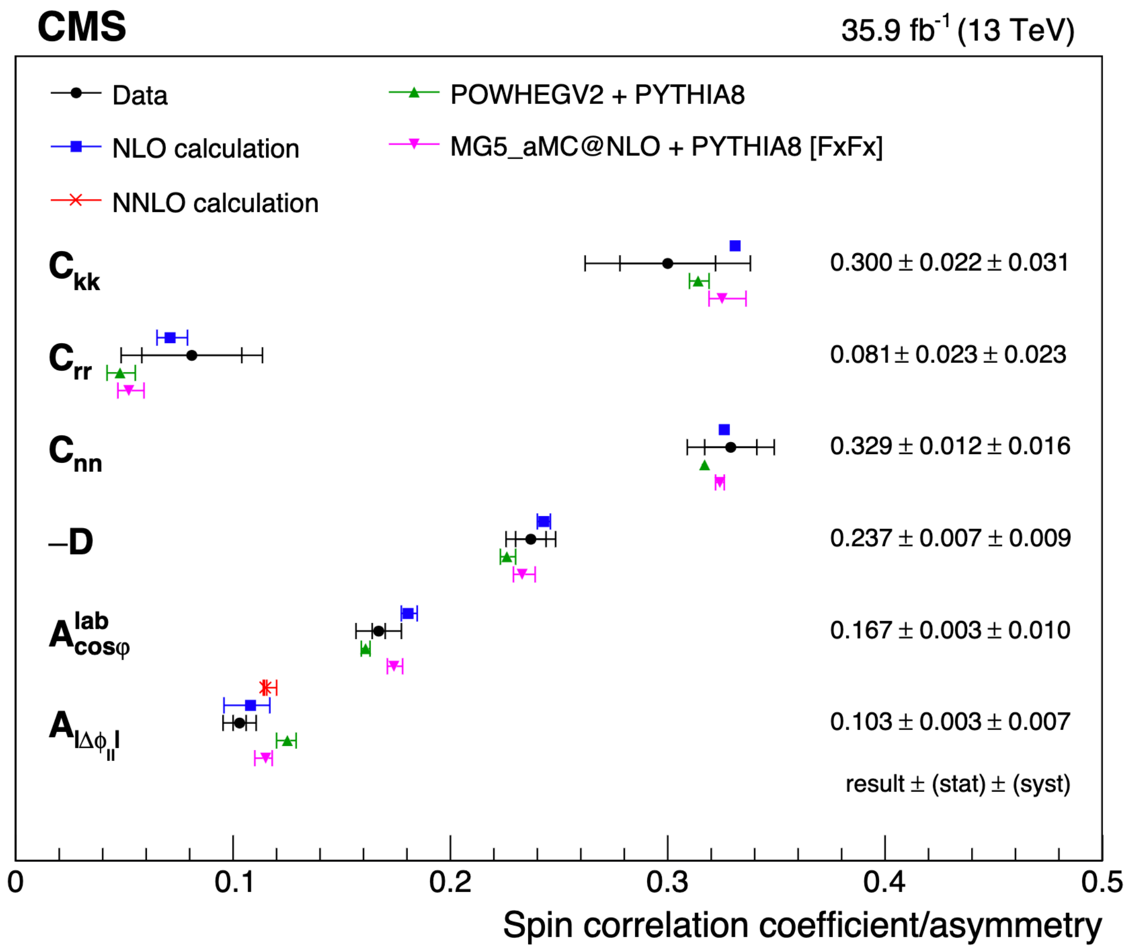
The spin information of the quark...



...controls (on average) the direction of the decay product

Spin Measurements





Back to the density matrix

We can calculate and measure the density matrix for $t\bar{t}$ production!

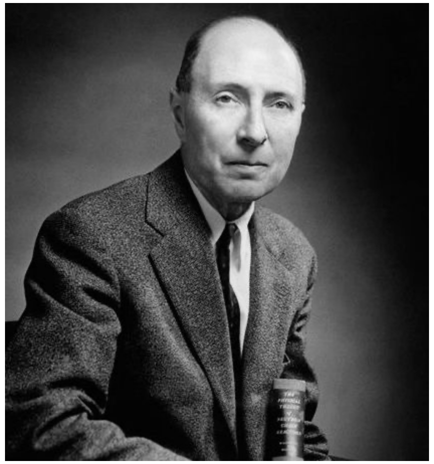
$$\mathrm{R} = A + \sum_i \left(B_i^+ \sigma^i + B_i^- \bar{\sigma}^i \right) + \sum_{i,j} C_{ij} \sigma^i \bar{\sigma}^j$$

Polarisations (of individual tops)

Correlations (between tops' spins)

Mathematical properties of the density matrix reveal aspects of the quantum state.

("The unreasonable effectiveness of mathematics" - Wigner)



Peres-Horodecki

Accessing experimentally

Threshold (Singlet)

$$D = \frac{1}{3}(C_{nn} + C_{kk} + C_{rr})$$

$$D \leq -\frac{1}{3}$$ Entanglement condition

High-mass (Triplet)

$$\tilde{D} = \frac{1}{3}(C_{nn} - C_{rr} - C_{kk})$$

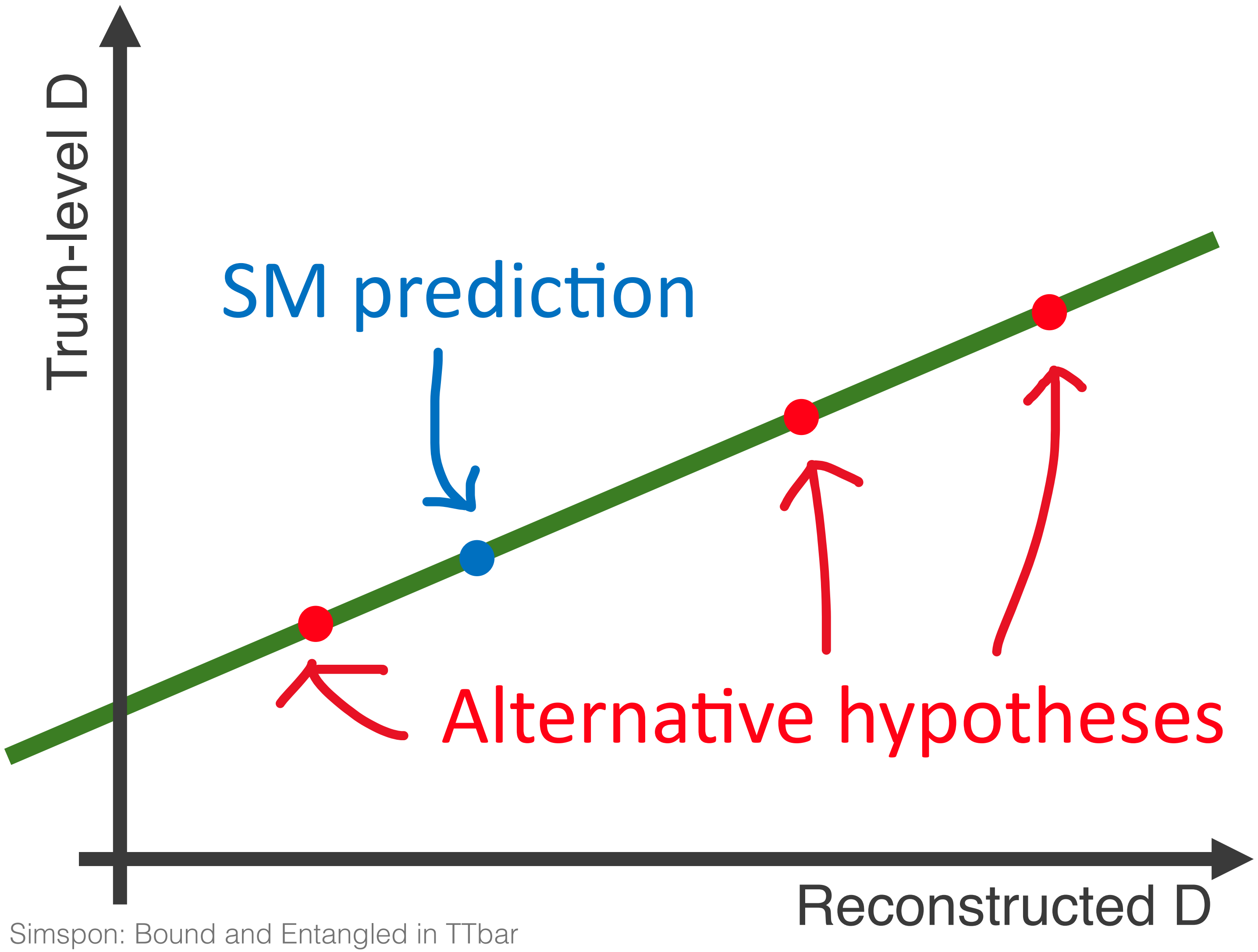
$$D \geq \frac{1}{3}$$ Entanglement condition

Calibration Curve

Correct measured value of D to truth

Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.



Calibration Curve

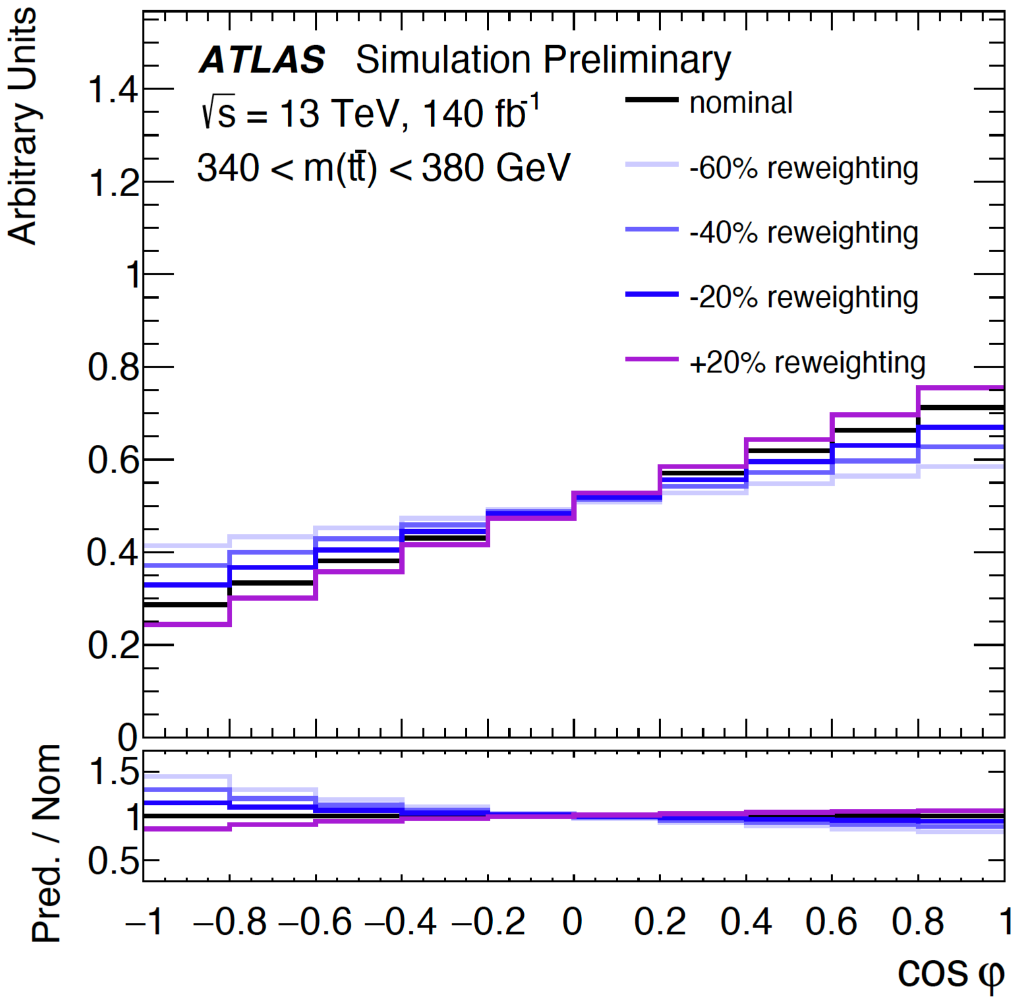
Generate alternative hypotheses

Apply a per-event re-weighting of the simulation!

$$w = f(m_{t\bar{t}}, \cos\varphi, K)$$

Choose such that distribution remains linear

Scaling parameter

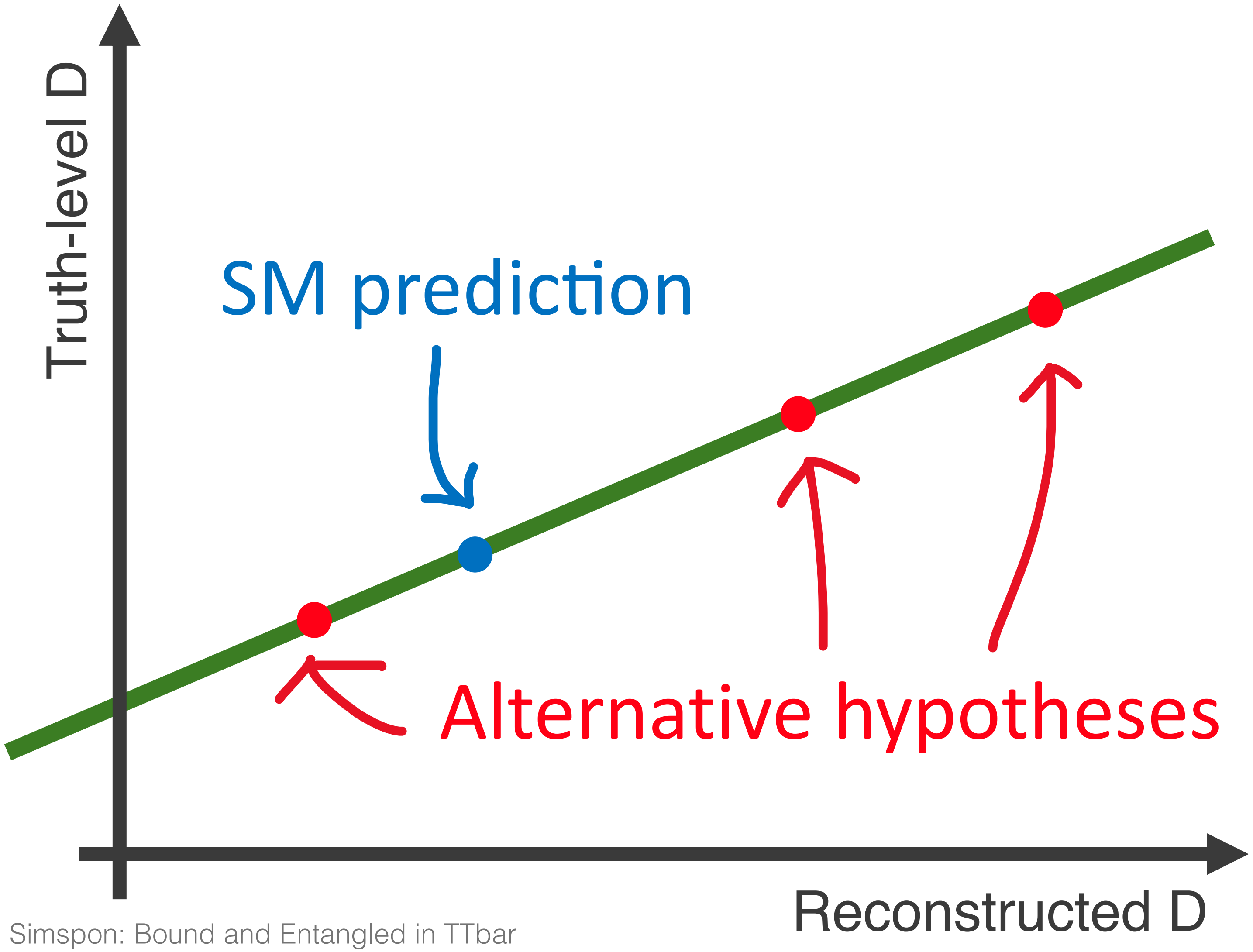


Calibration Curve

Parameterise variation in D

Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.



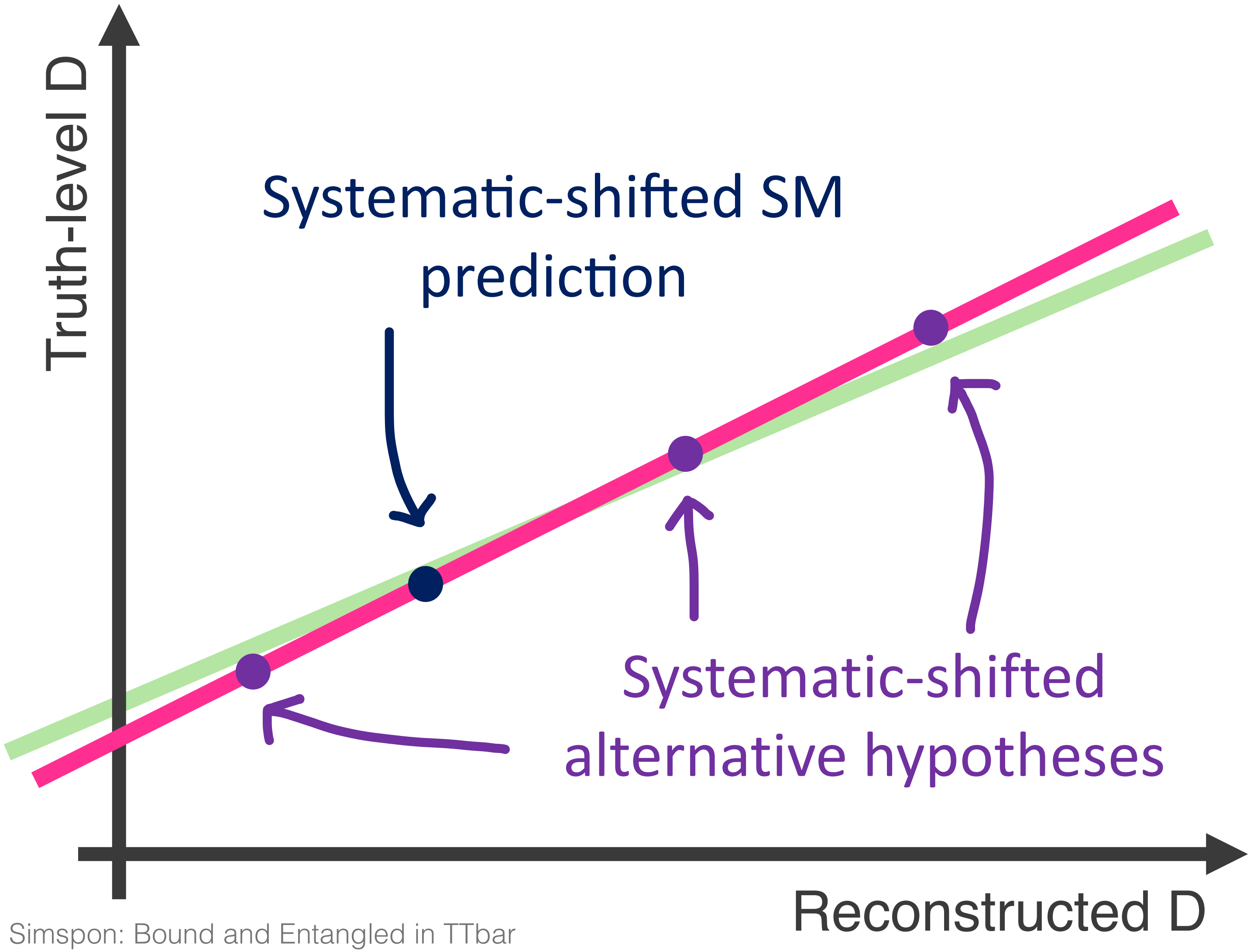
Calibration Curve

Parameterise variation in D

Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.

Systematics build different calibration curves.



Calibration Curve

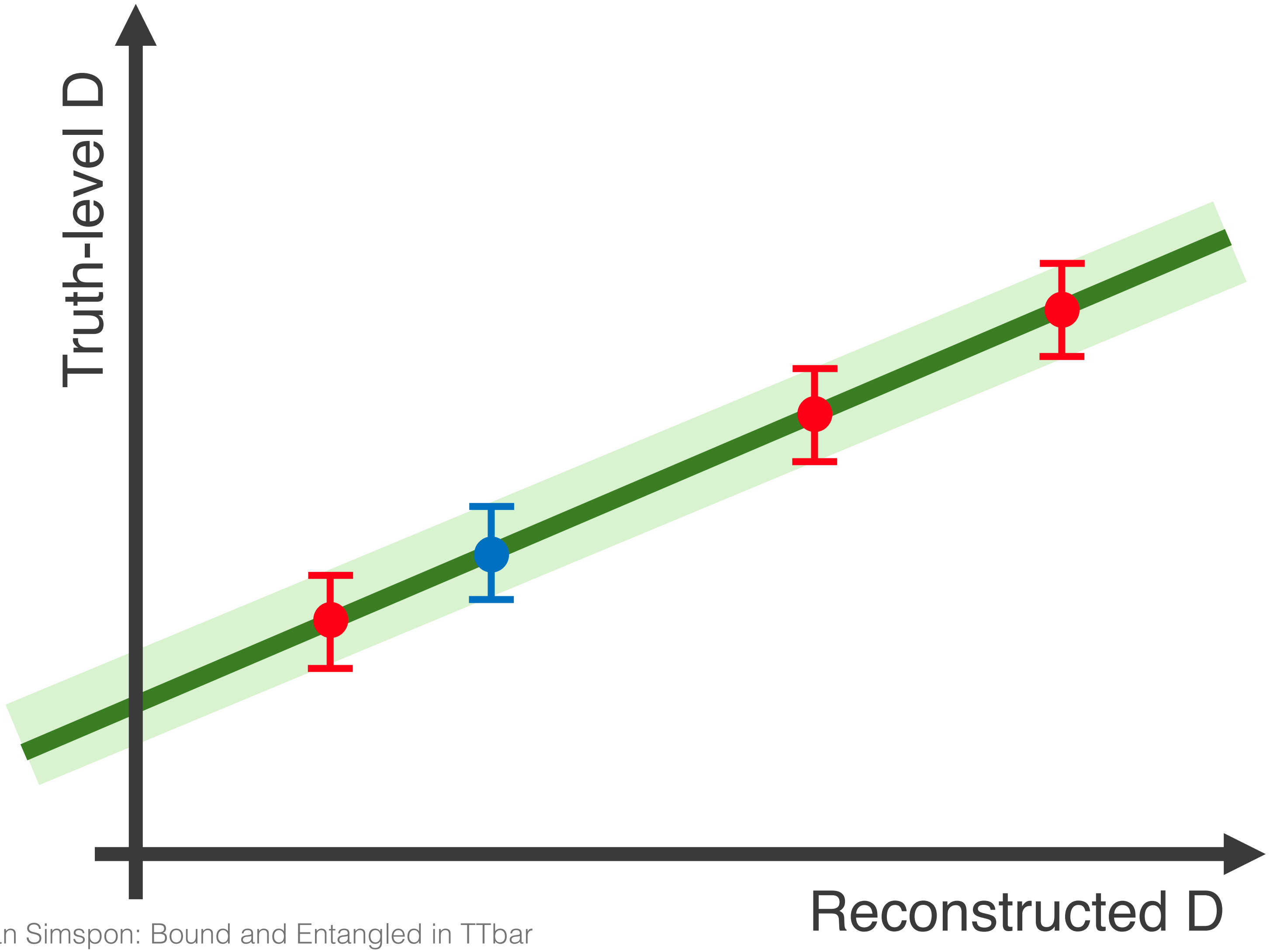
Parameterise variation in D

Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.

Systematics build different calibration curves.

Combine all systematics to build nominal curve + uncertainty band.



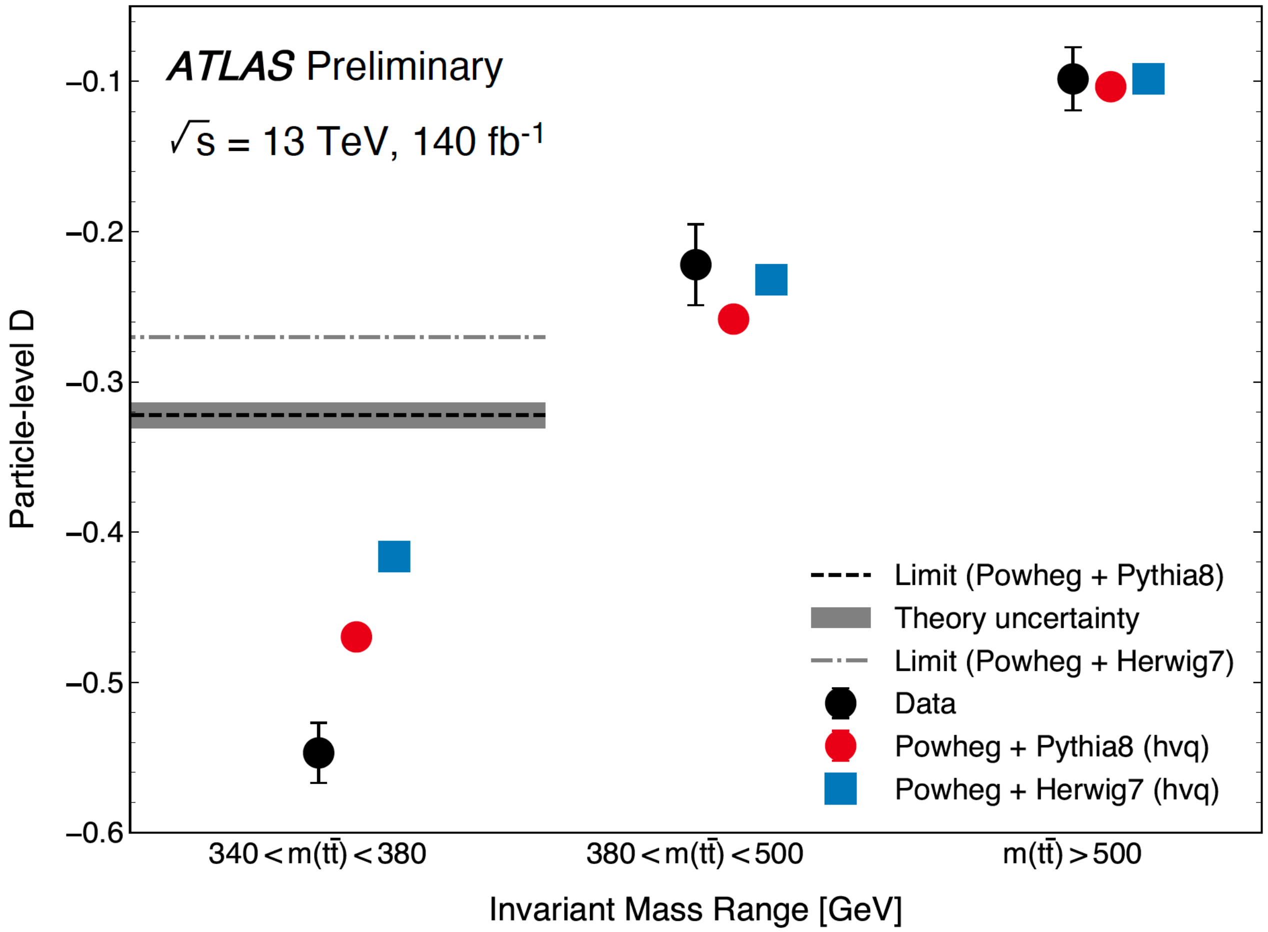
Results

Mapping limit to particle-level

Map entanglement limit using parton→particle calibration curves.

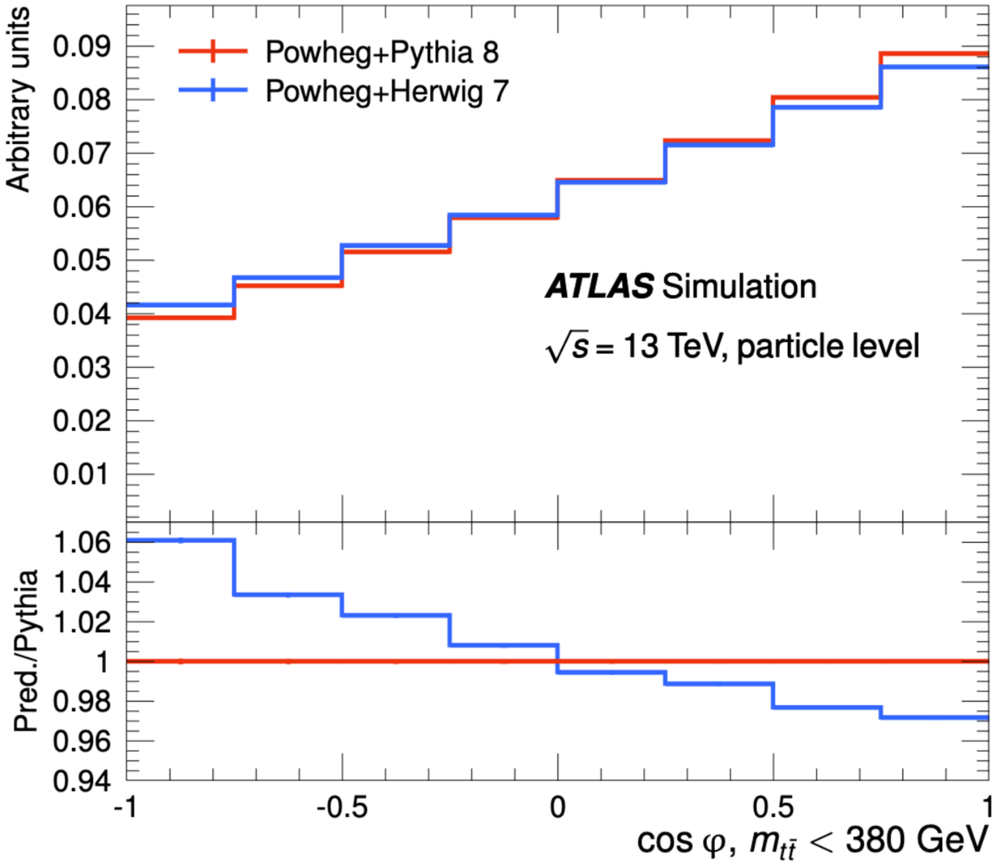
We derive a separate mapping for both Pythia and Herwig parton showers.

Our systematic model is built around Pythia, therefore only include uncertainties on the Pythia bound.

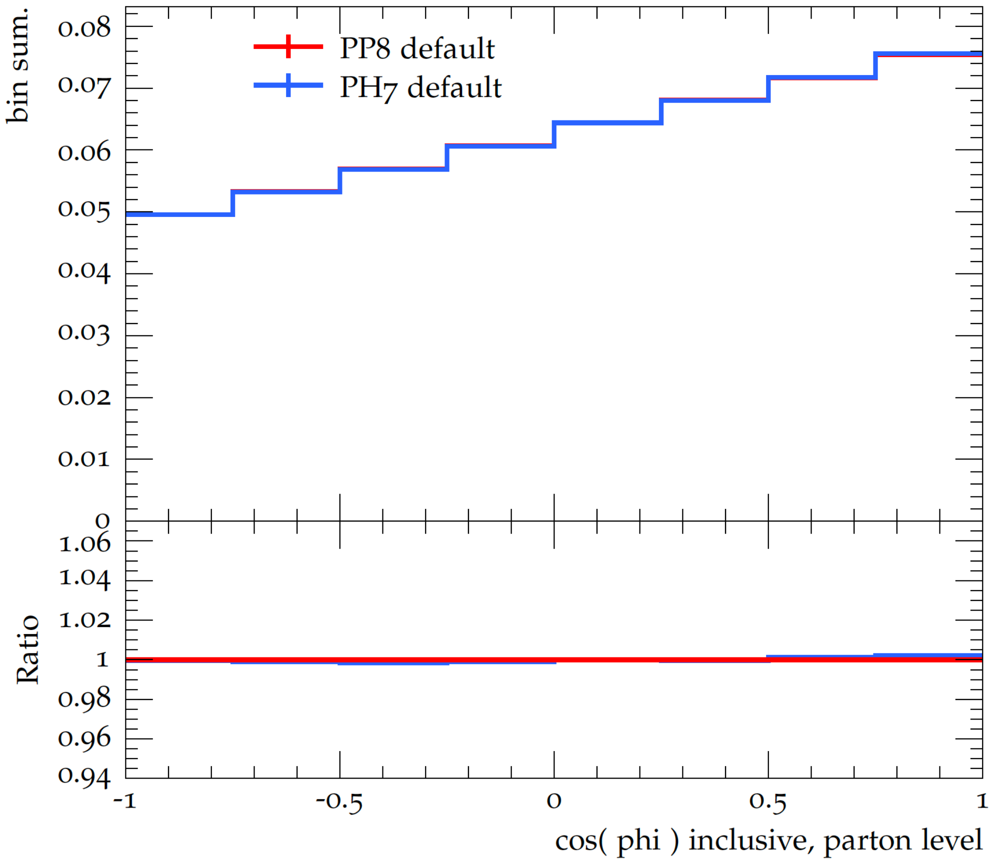


Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



Large difference at particle-level



No difference at parton-level

Common Questions

Is this just another spin correlation measurement?

The observable is a measure of spin correlation…

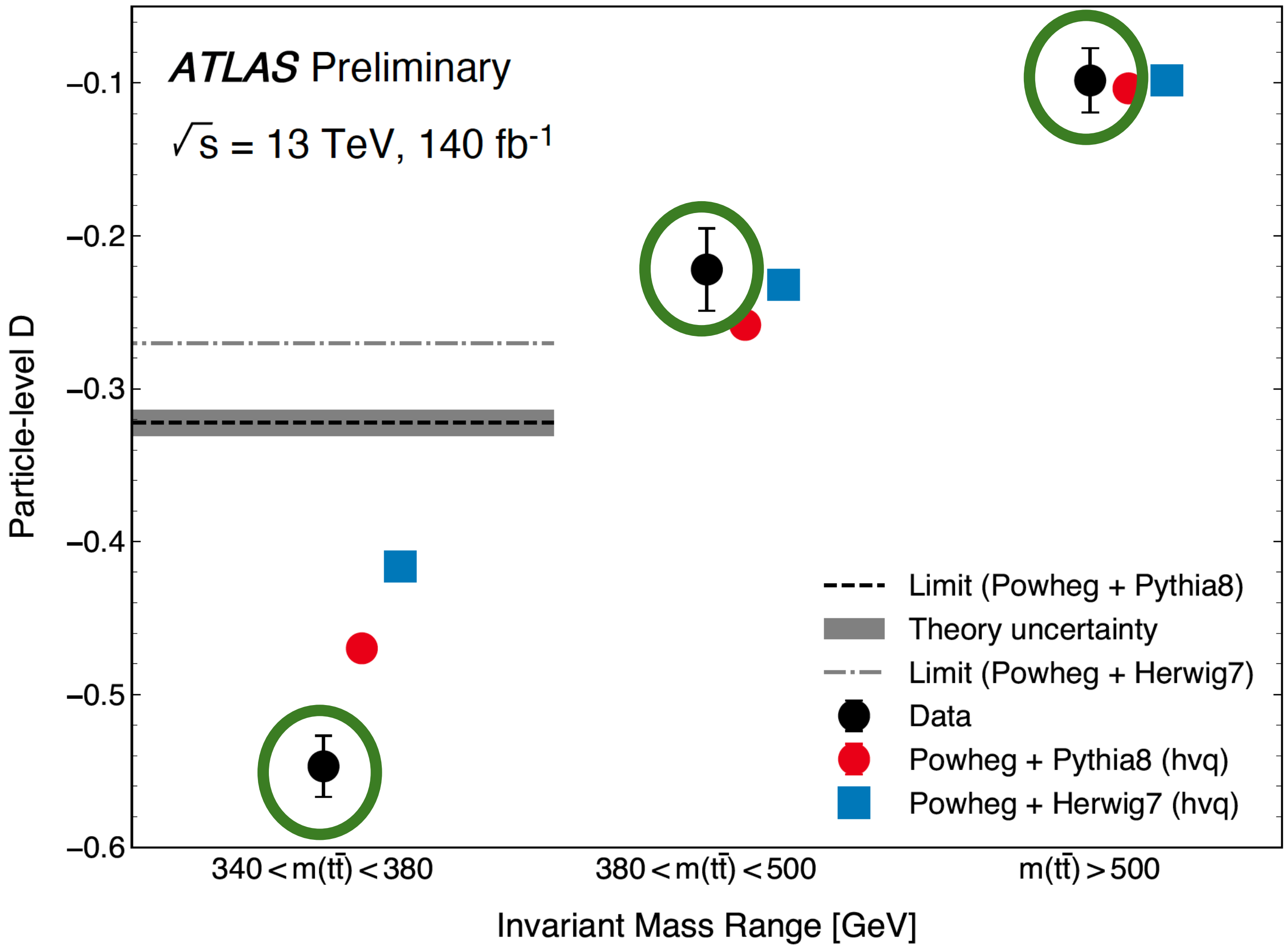
> but is also a genuine entanglement marker, a real quantum observable.

<u>Experimental highlights</u>

- Never been done in this phase-space.
- Developed refined analysis techniques

Common Questions

How reliable is the calibration curve method?



Very reliable ✓

The correction contains a full suite of uncertainties, like all ATLAS Top analyses.

We understand our detector response extremely well.

The detector responds the same way to Pythia and to Herwig simulation.