ATLAS EXPERIMENT

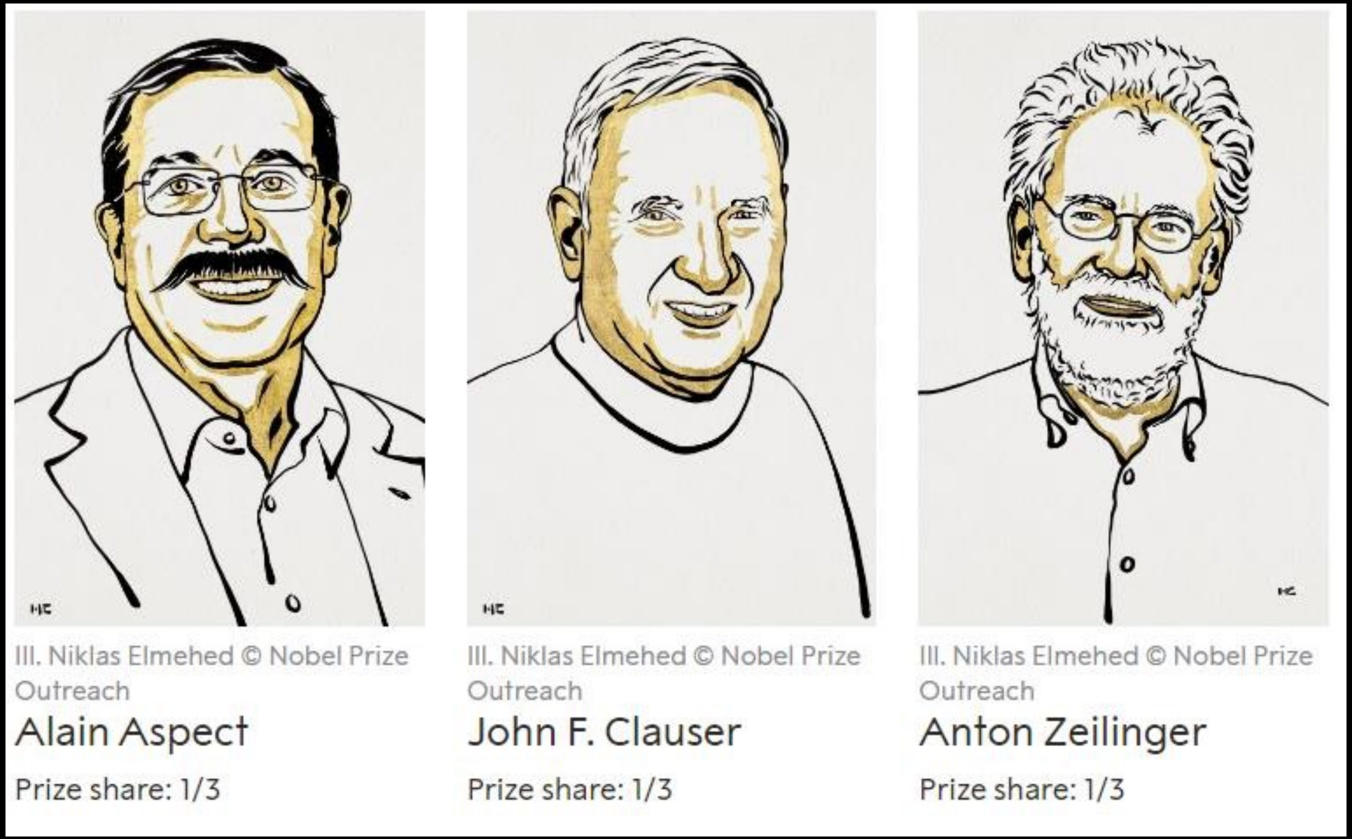
Entangled in Tops

How ATLAS turned the LHC into the world's largest quantum information experiment

Ethan Simpson
on behalf of the ATLAS Collaboration

LHC Top Working Group Meeting November 2023

2022 Nobel Prize



"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

ATLAS Result

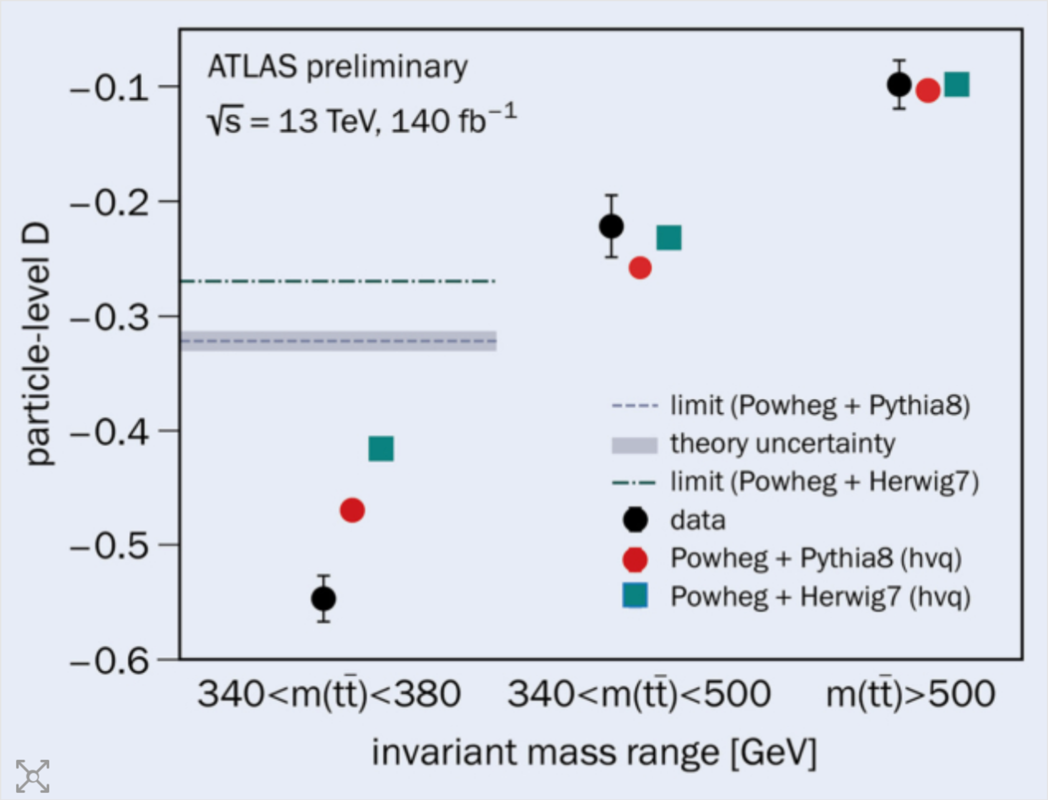
arXiv:2311.07288

STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.



Quantum State

Mixed quantum system:
density operator:

$$\rho = \sum_n p_n |\phi_n\rangle \langle\phi_n|$$

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

Our old friend the spin density matrix.

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Our old friend the spin density matrix.

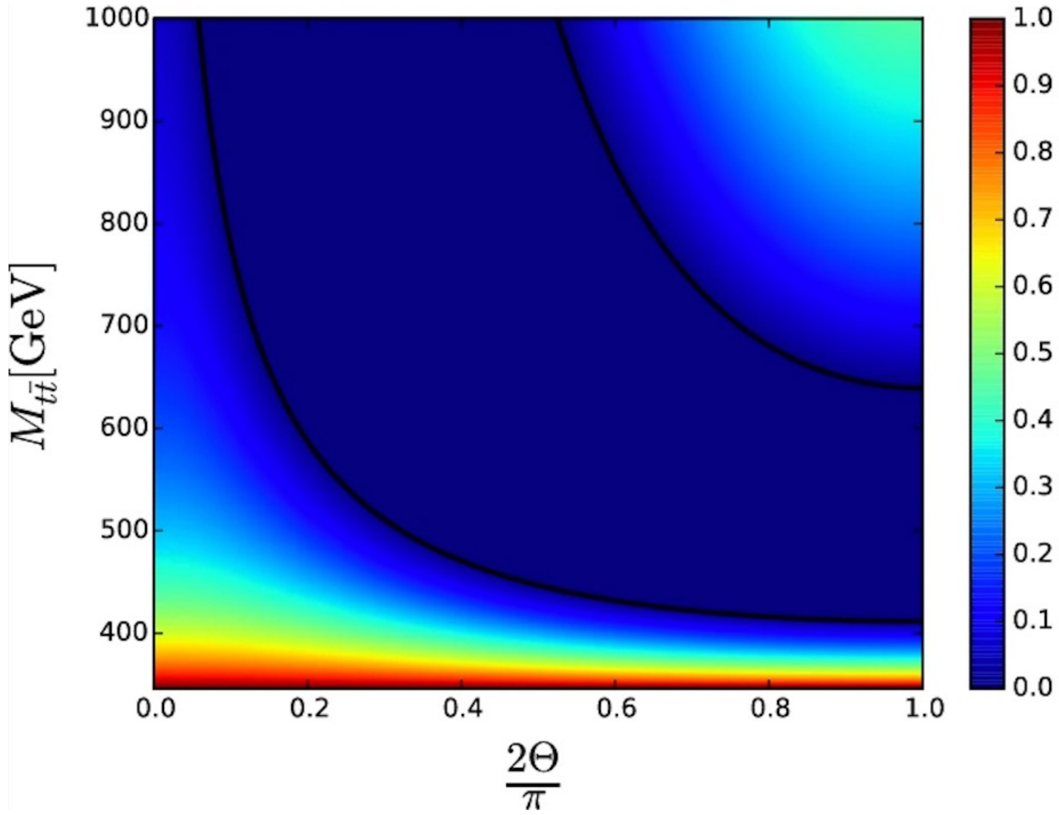
If density matrix "factorises", the state is not entangled.

$$\rho^{AB} = \sum_n p_n\, \rho^A \otimes \rho^B$$

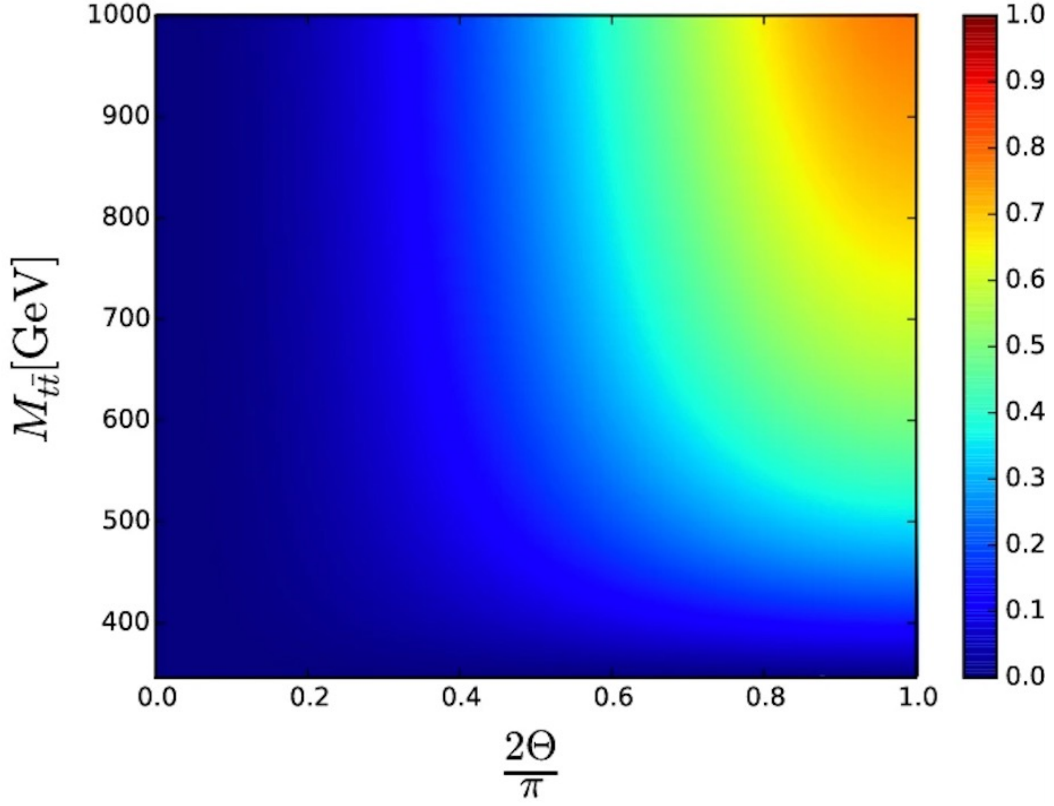
Concurrence

One measure of entanglement is concurrence of the density matrix.

$gg \to t\bar{t}$



$q\bar{q} \to t\bar{t}$



This tells us where to look for entanglement!

[Afik and de Nova, EPJP]

Peres-Horodecki Criterion

Useful entanglement marker

$$D = \frac{\mathrm{Tr}[\mathbf{C}]}{3} < -\frac{1}{3}$$

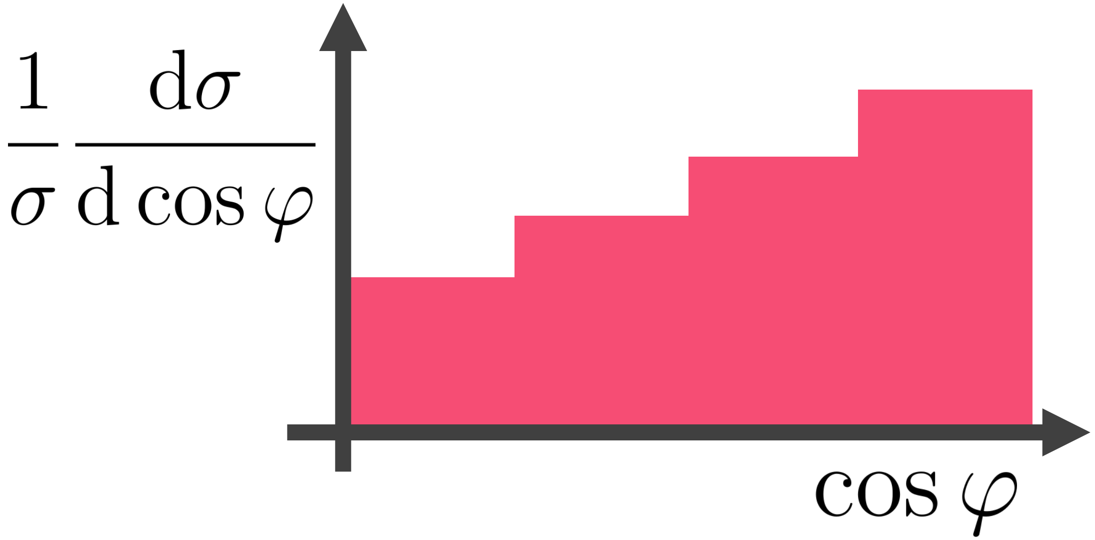
Peres-Horodecki Criterion

Useful entanglement marker

$$D = \frac{\mathrm{Tr}[\mathbf{C}]}{3} < -\frac{1}{3}$$

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

Expectation value

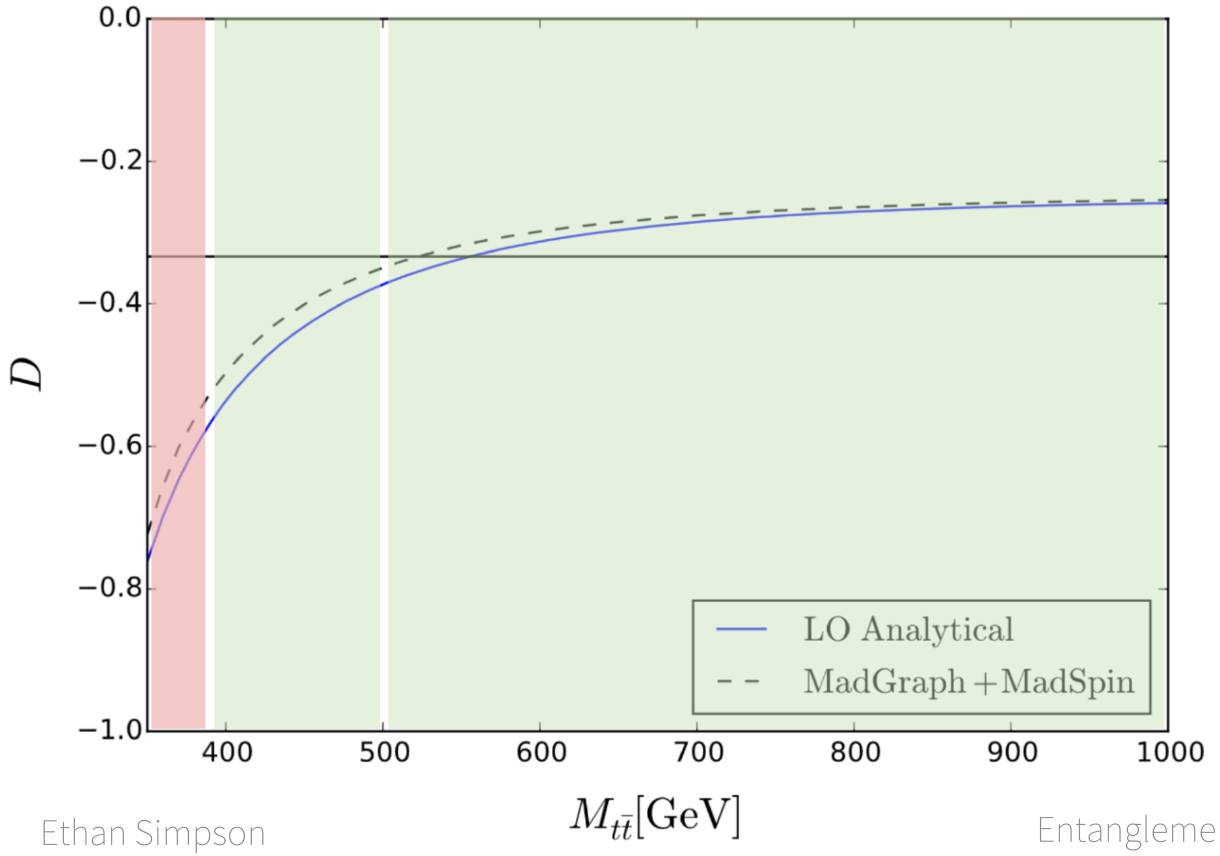


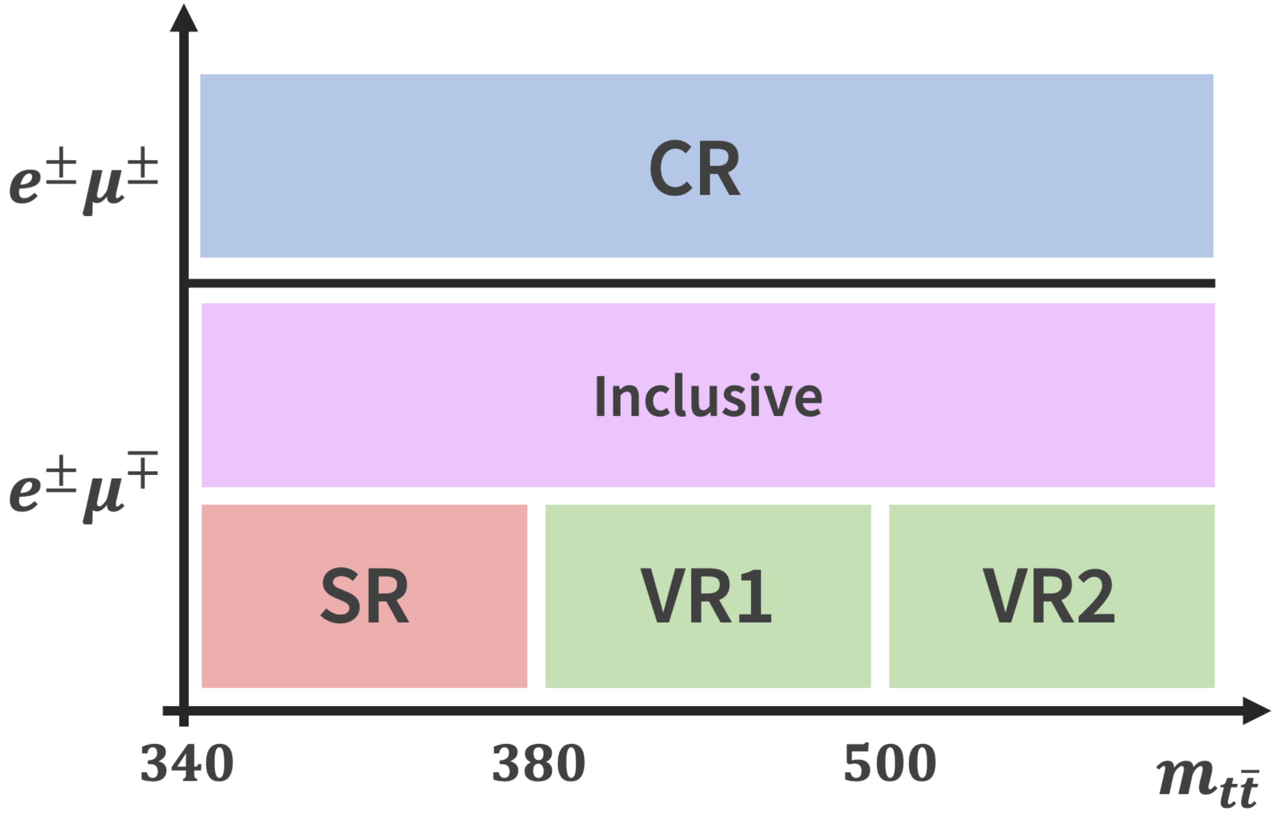
where $\cos\varphi$ is the scalar product of lepton directions in their parent tops' frame.

Selections

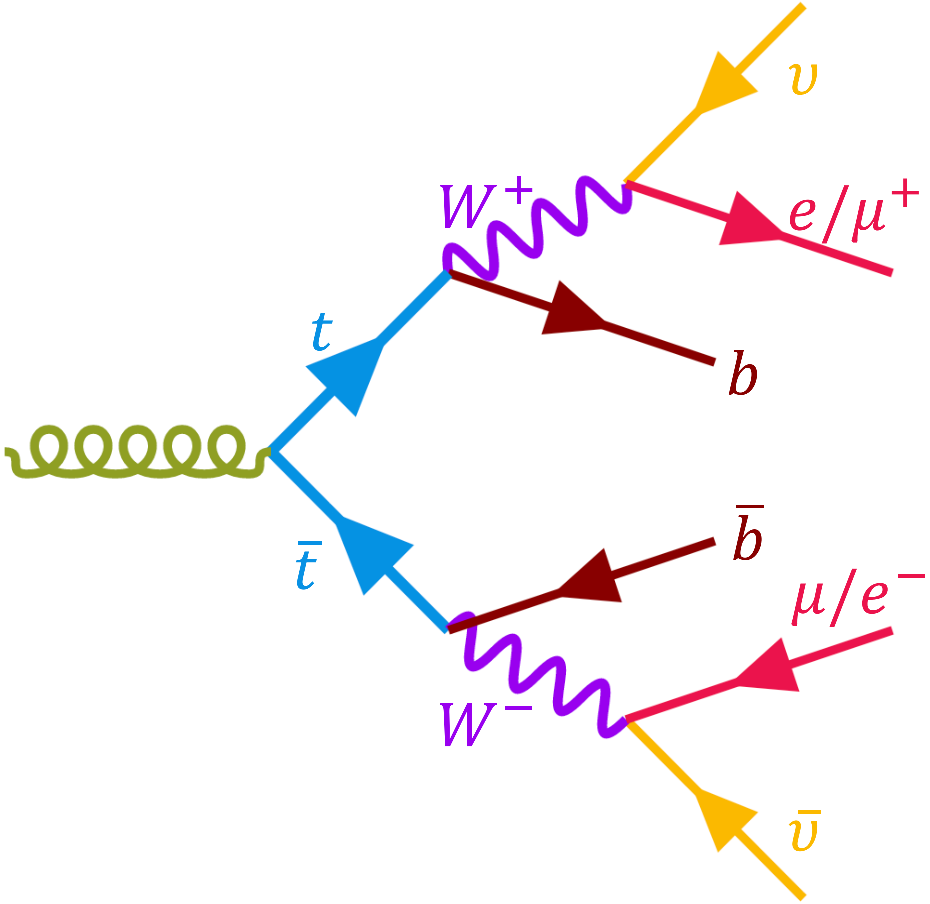
Isolating signal maximally-sensitive to entanglement

- 1 electron and 1 muon
- 2 jets
- At least 1 jet must be b-tagged (using the “loose” 85% working point)





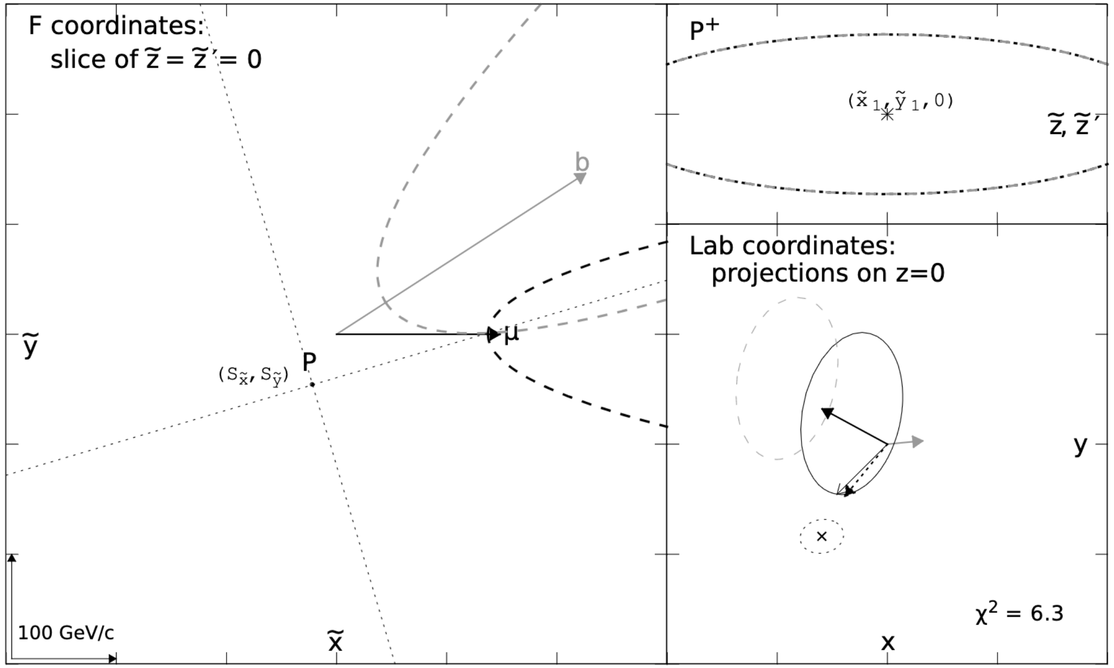
Di-leptonic Reconstruction



Primary reconstruction: Ellipse Method

Alternative reconstruction techniques implemented when Ellipse method fails:

- NeutrinoWeighter
- Simple kinematic matching



Signal and Backgrounds

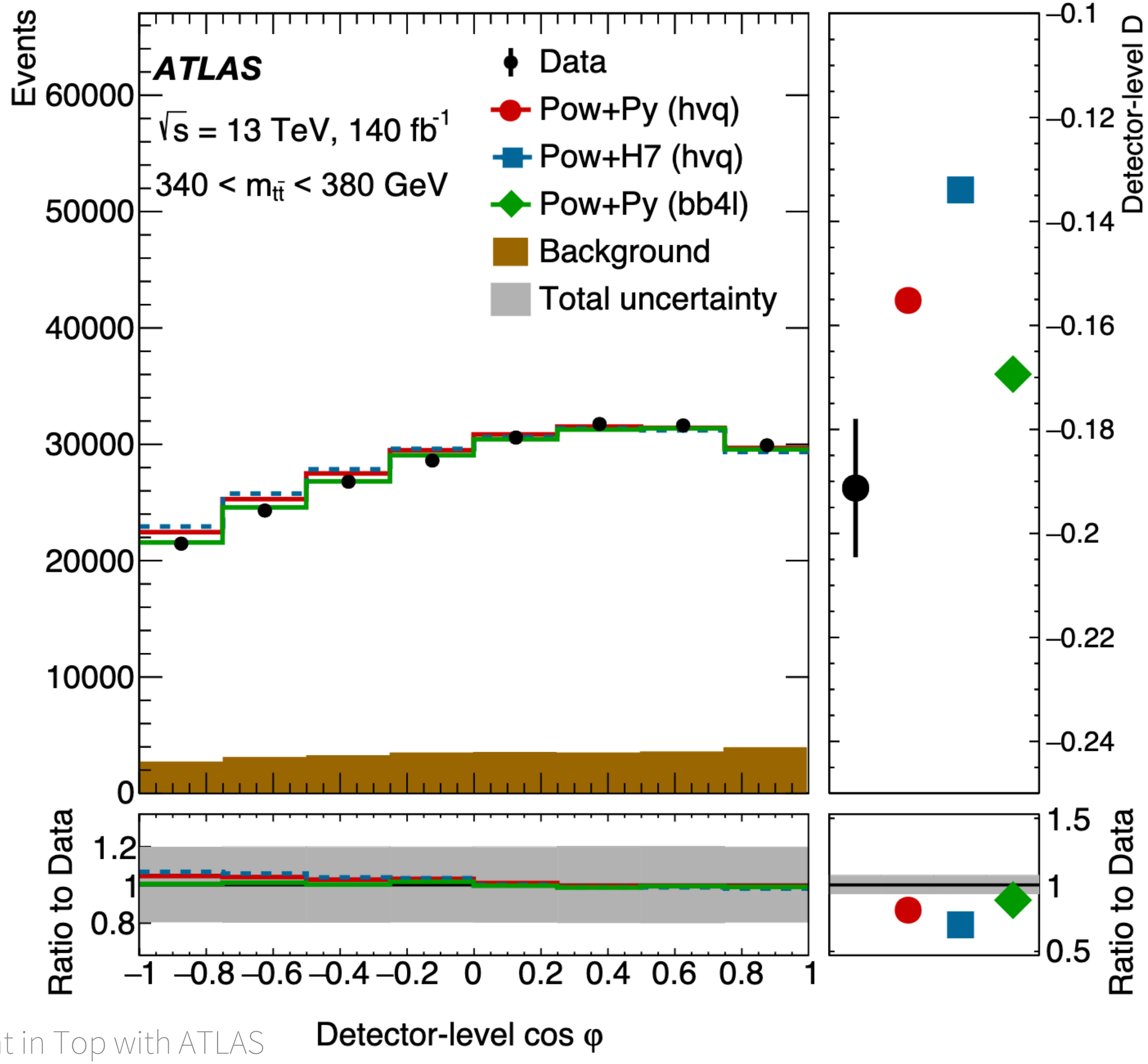
Signal

Modelled using MC simulation:

- Powheg (hvq) + Pythia8
- Powheg (hvq) + Herwig7
- Powheg (bb4l) + Pythia8

Background

- Backgrounds are estimated using simulation.
- Fake lepton prediction modified using a data-driven scale factor.

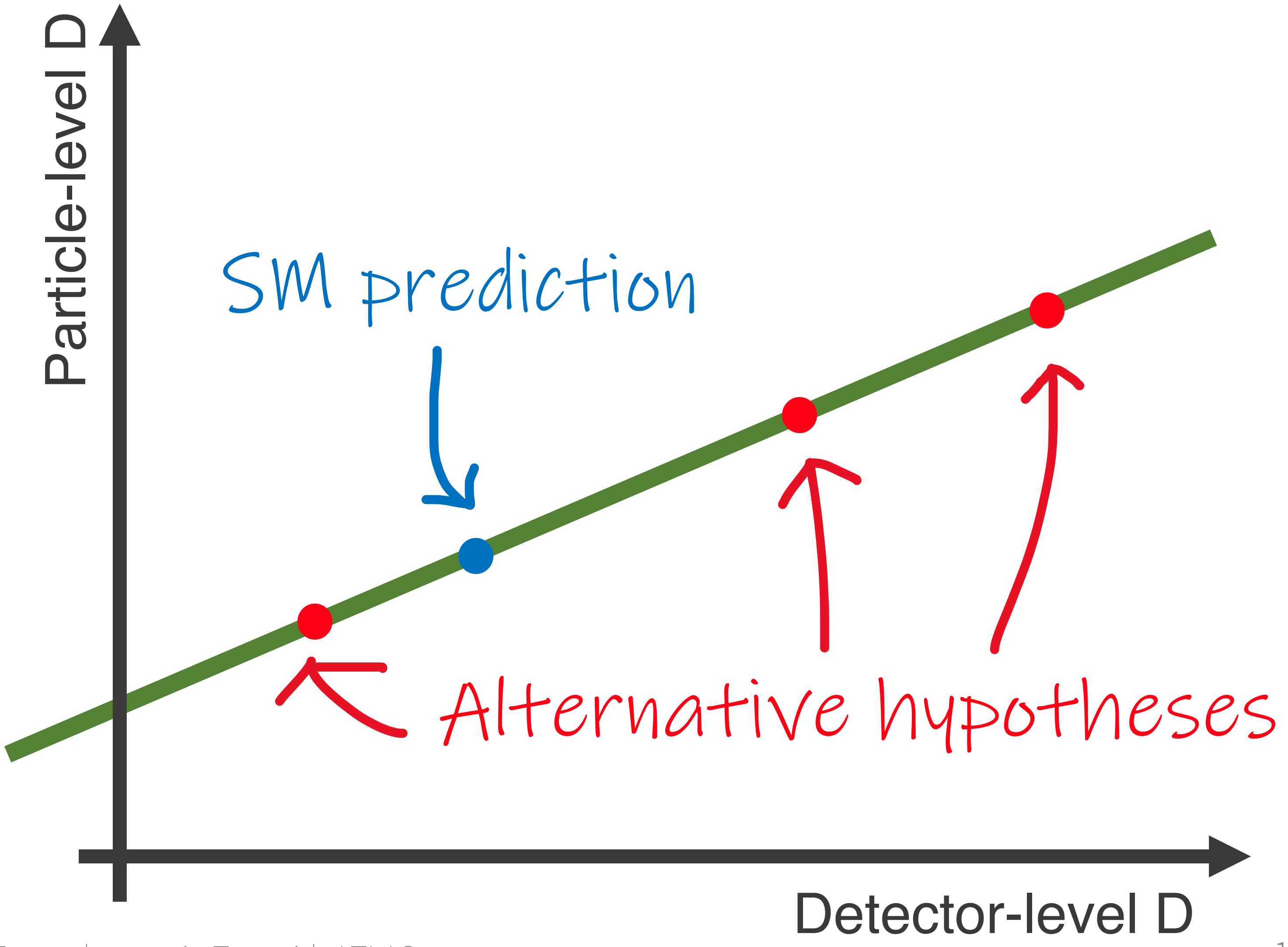


Calibration Curve

Parameterise variation in the detector effects on D.

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

Interpolate to give variation.



Calibration Curve

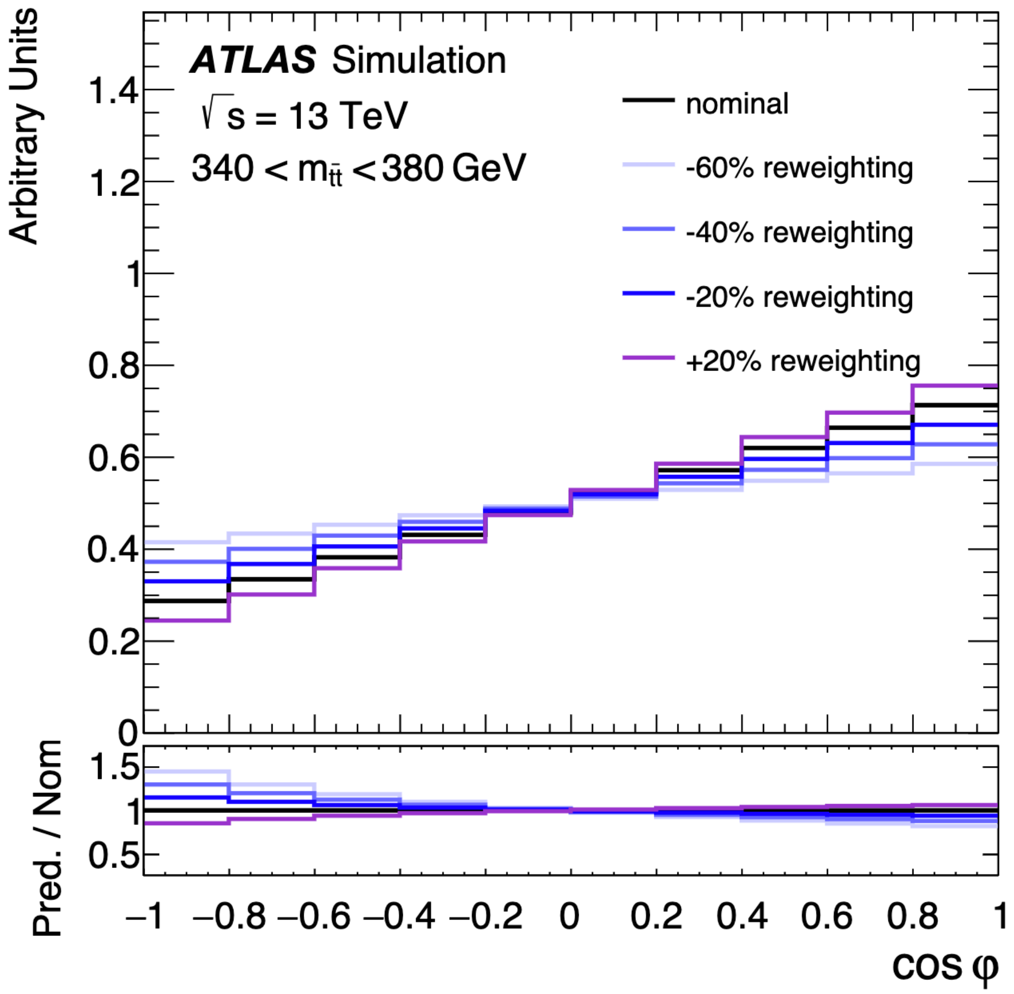
How to generate alternative hypotheses?

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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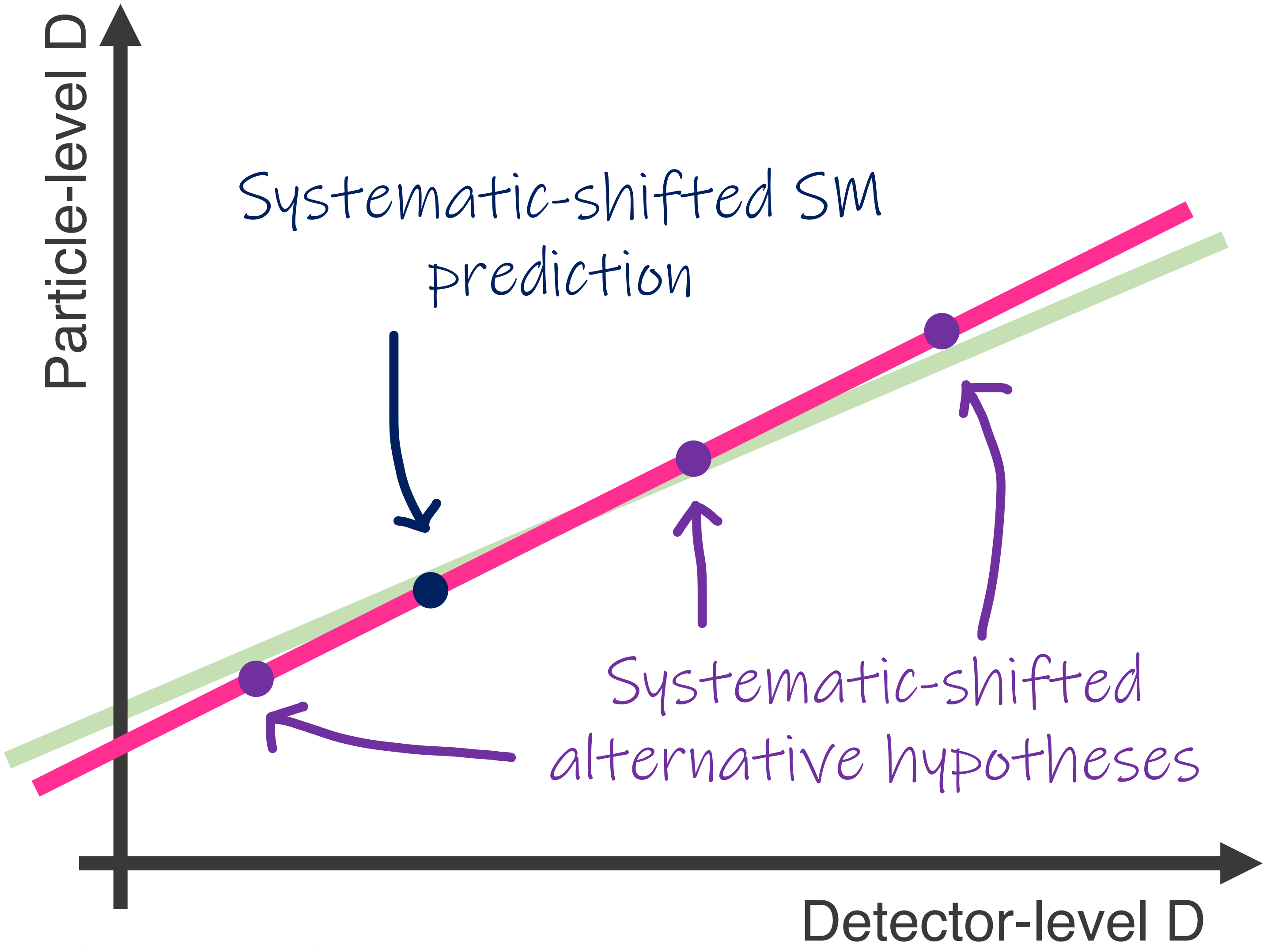
Systematics build different calibration curves.



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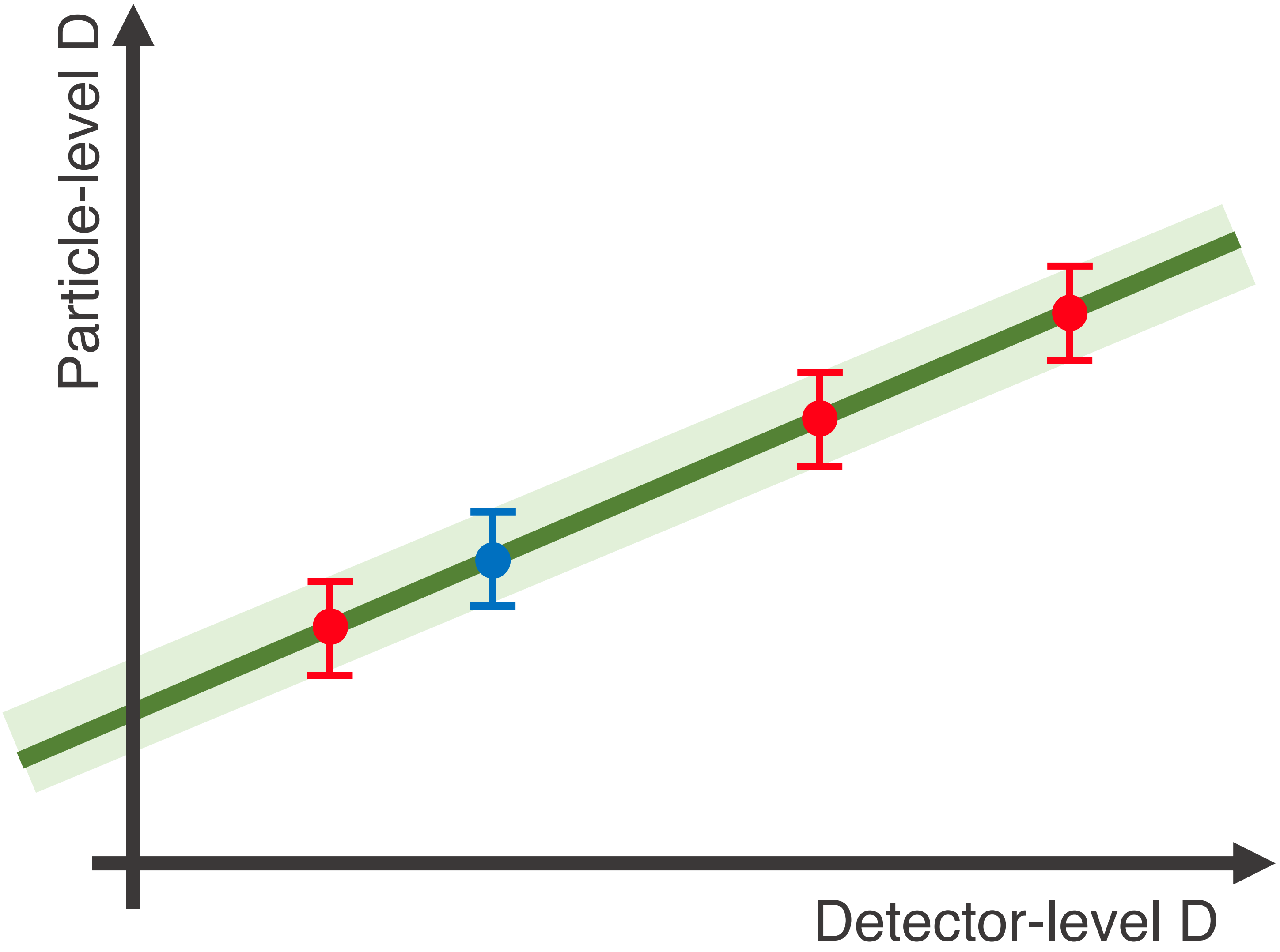
Combine all systematics to build nominal curve + uncertainty band.



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Parameterise variation in the detector effects on D.

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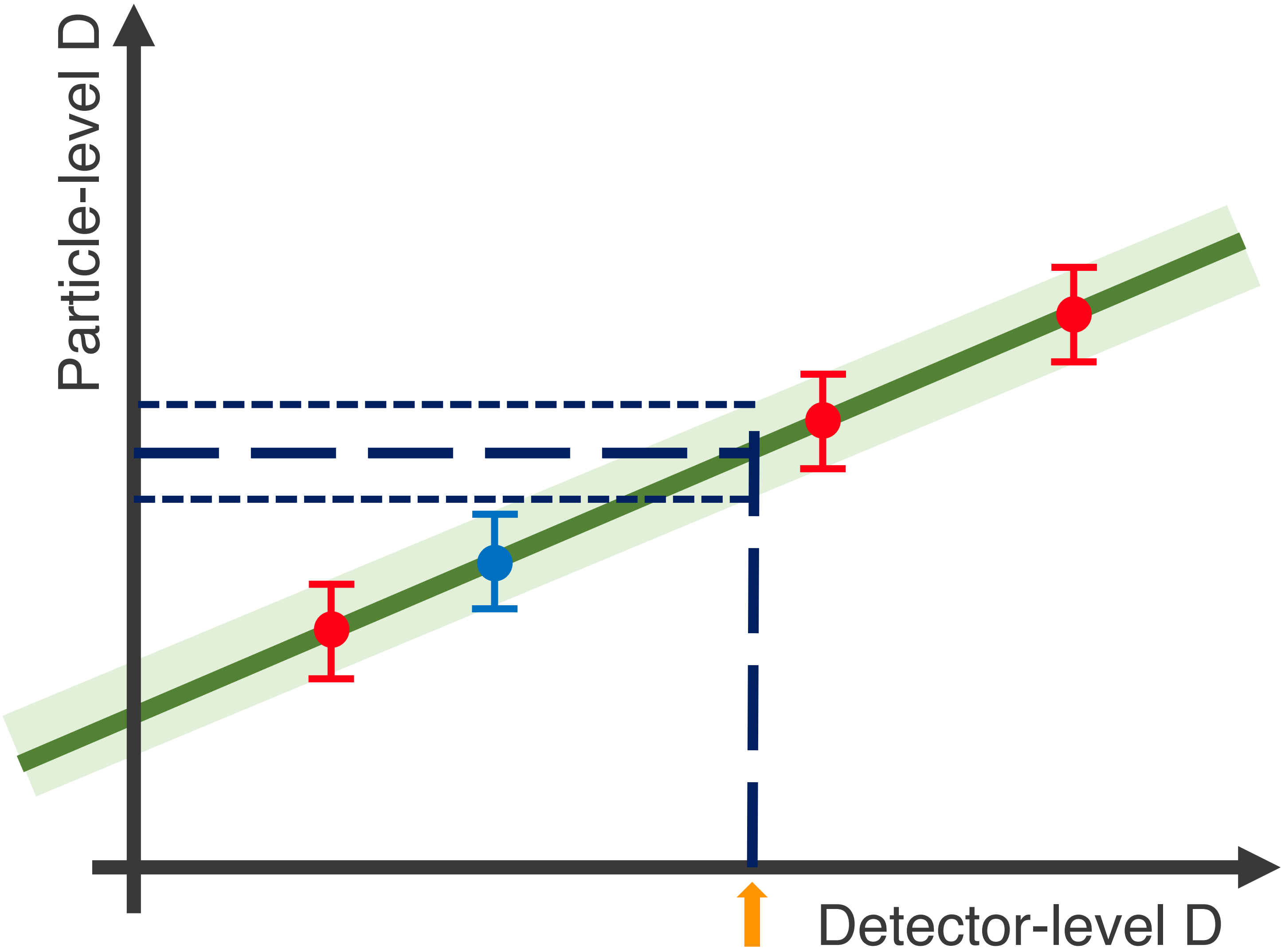
Combine all systematics to build nominal curve + uncertainty band.

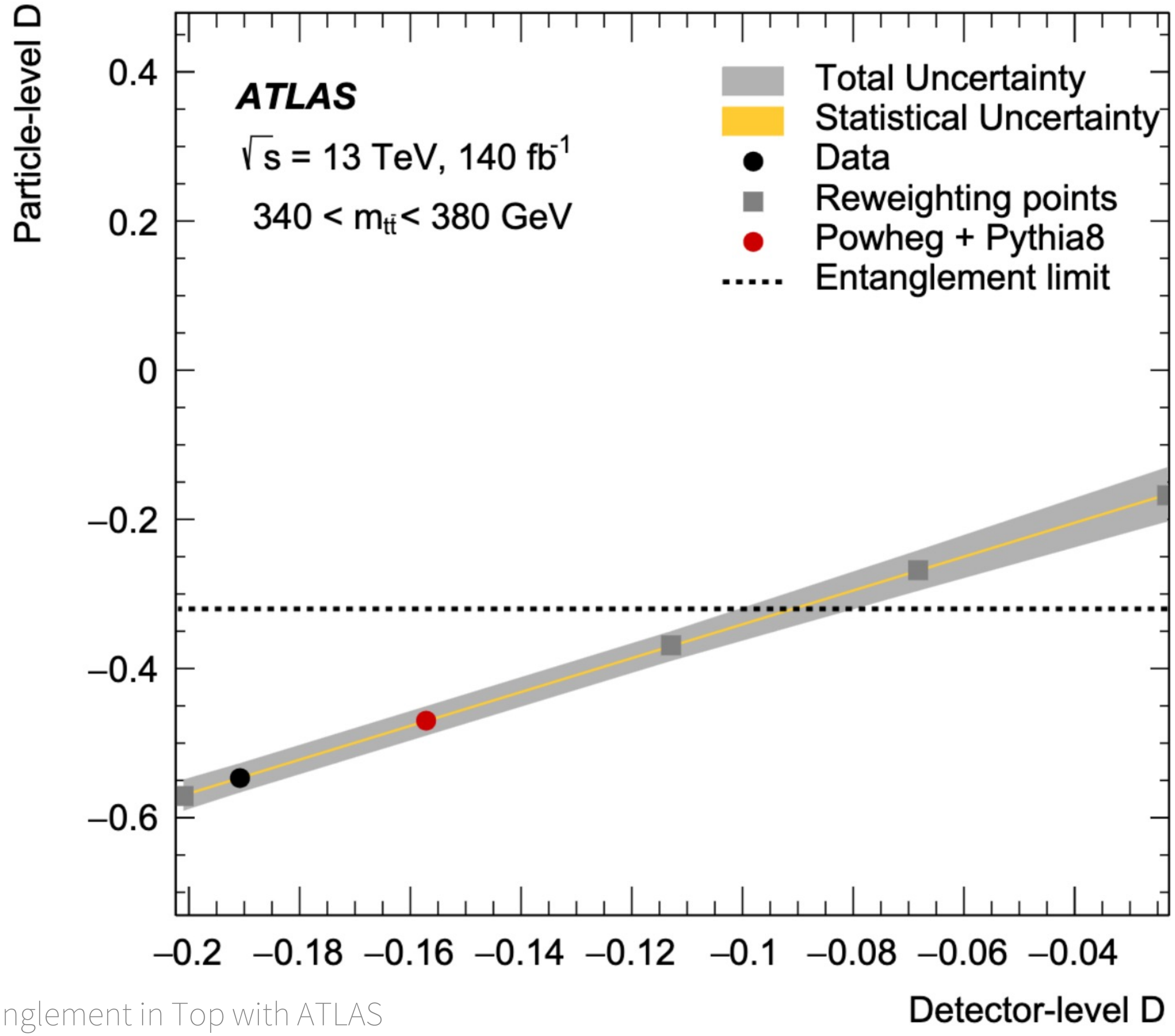
Map a measured *D* to truth-level, with associated uncertainties.



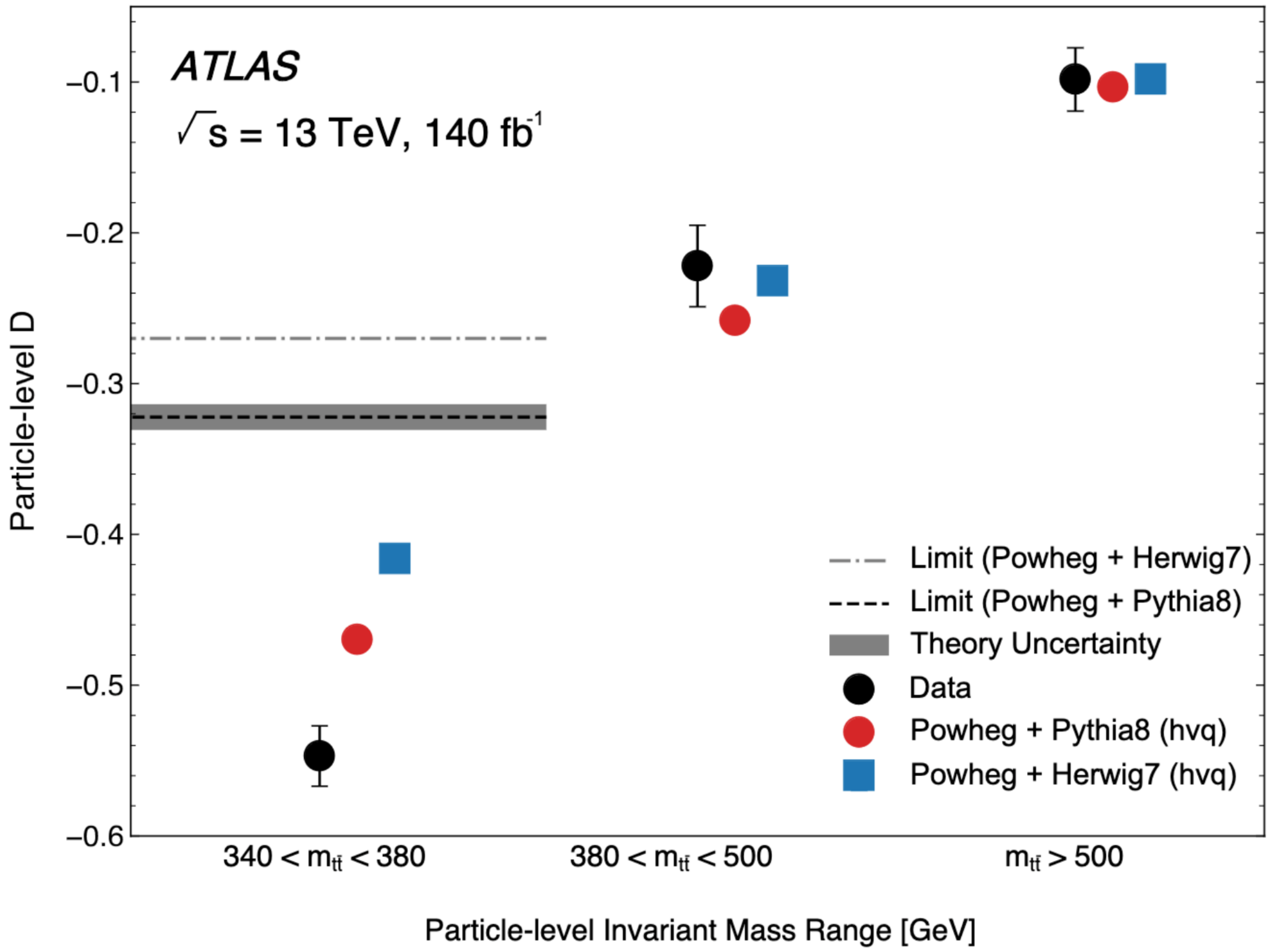
Calibration Curve

Parameterise variation in the detector effects on D.

Correction to D in the Signal Region



Result: Particle-Level



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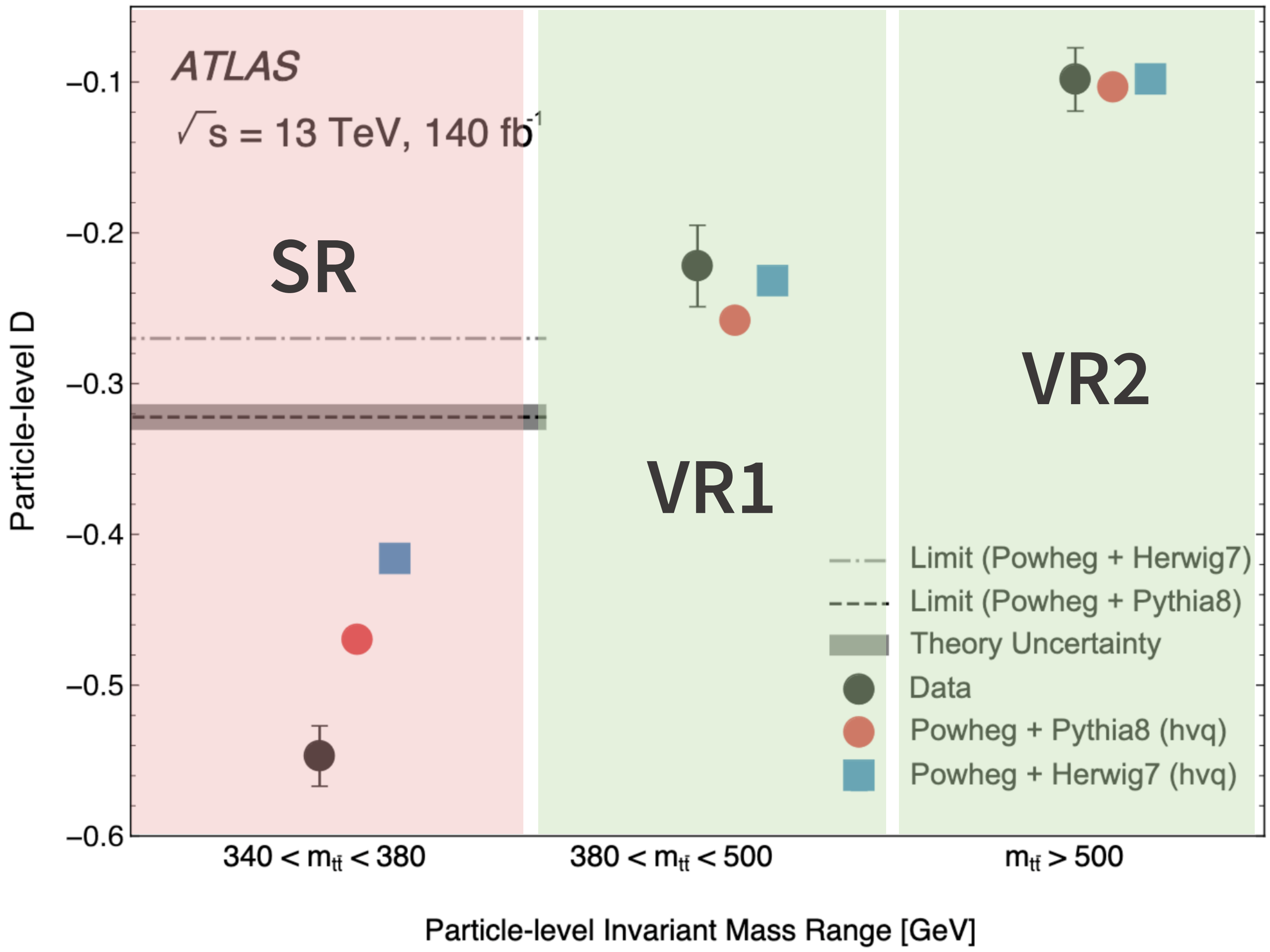


Particle-Level Entanglement Limits

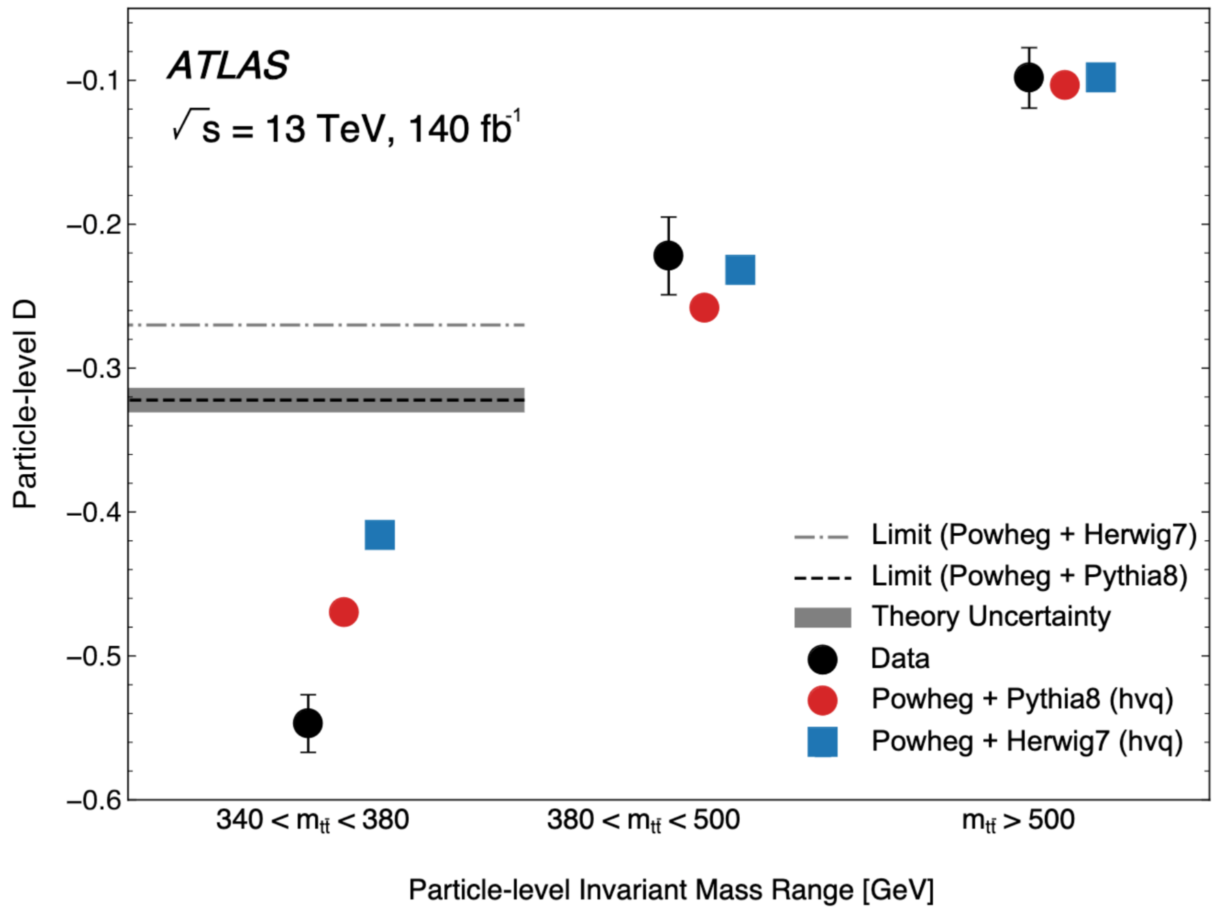
Map the entanglement limit to particle-level

We use parton → particle calibration curves to map -1/3 limit to particle-level.

This naturally depends on the simulation used to model the shower.

We have two predictions: Pythia & Herwig, hence a limit for each.

ATLAS has built its systematic model around Pythia: only include uncertainties on the Pythia correction – otherwise unfair comparison.



Systematic Uncertainties

Signal modelling biggest limitation

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

Some background addition due to loose b-tagging WP

Modelling 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%

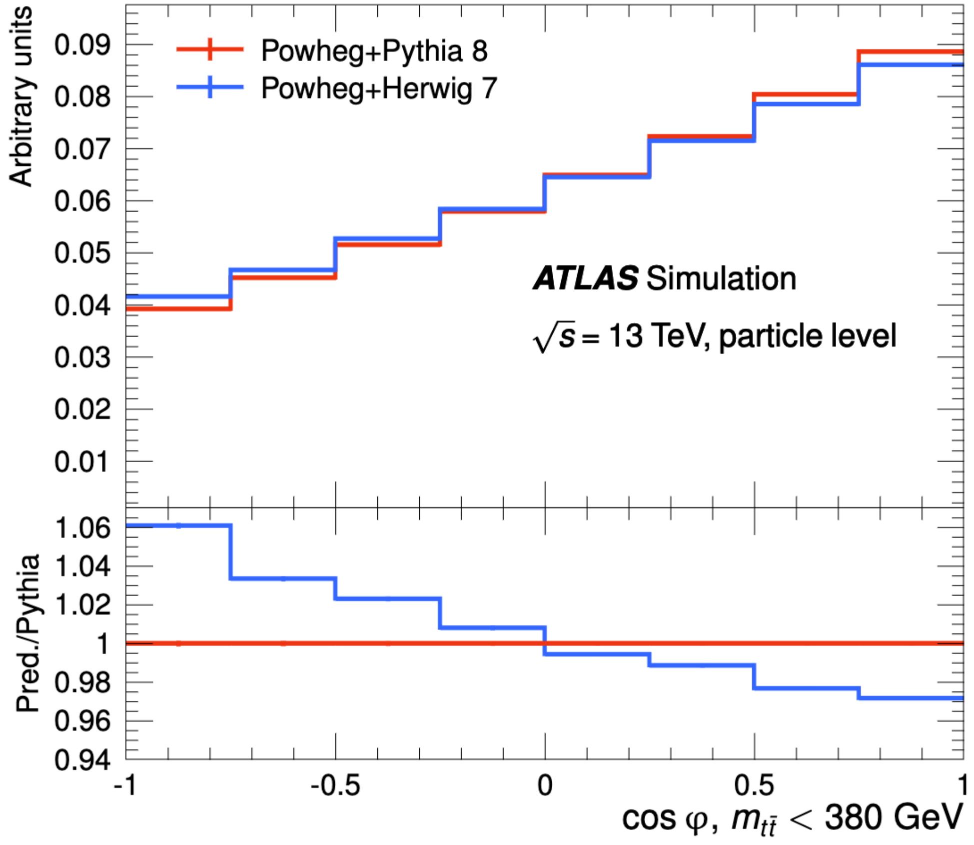
Difference between Pythia and MadSpin in handling top-quark decays (Lineshape)

Showering uncertainty small because of correction to particle-level

[See talk by Katharina Voss]

Why Particle-Level?

Dipole- vs angular-ordered shower



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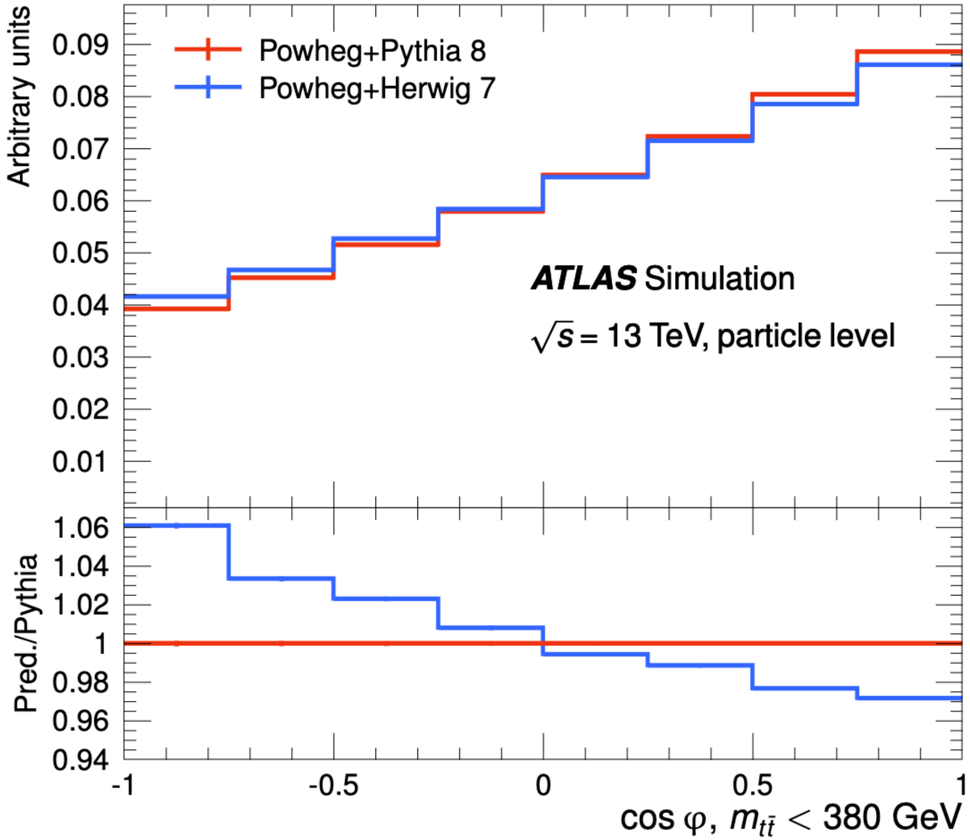
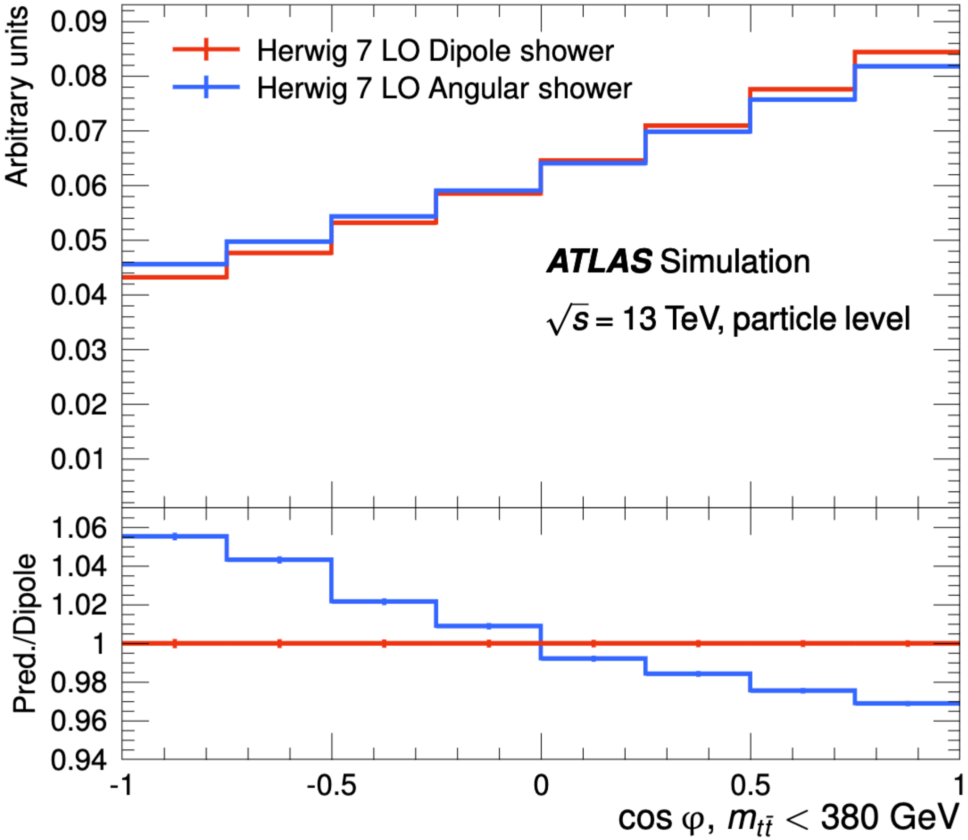


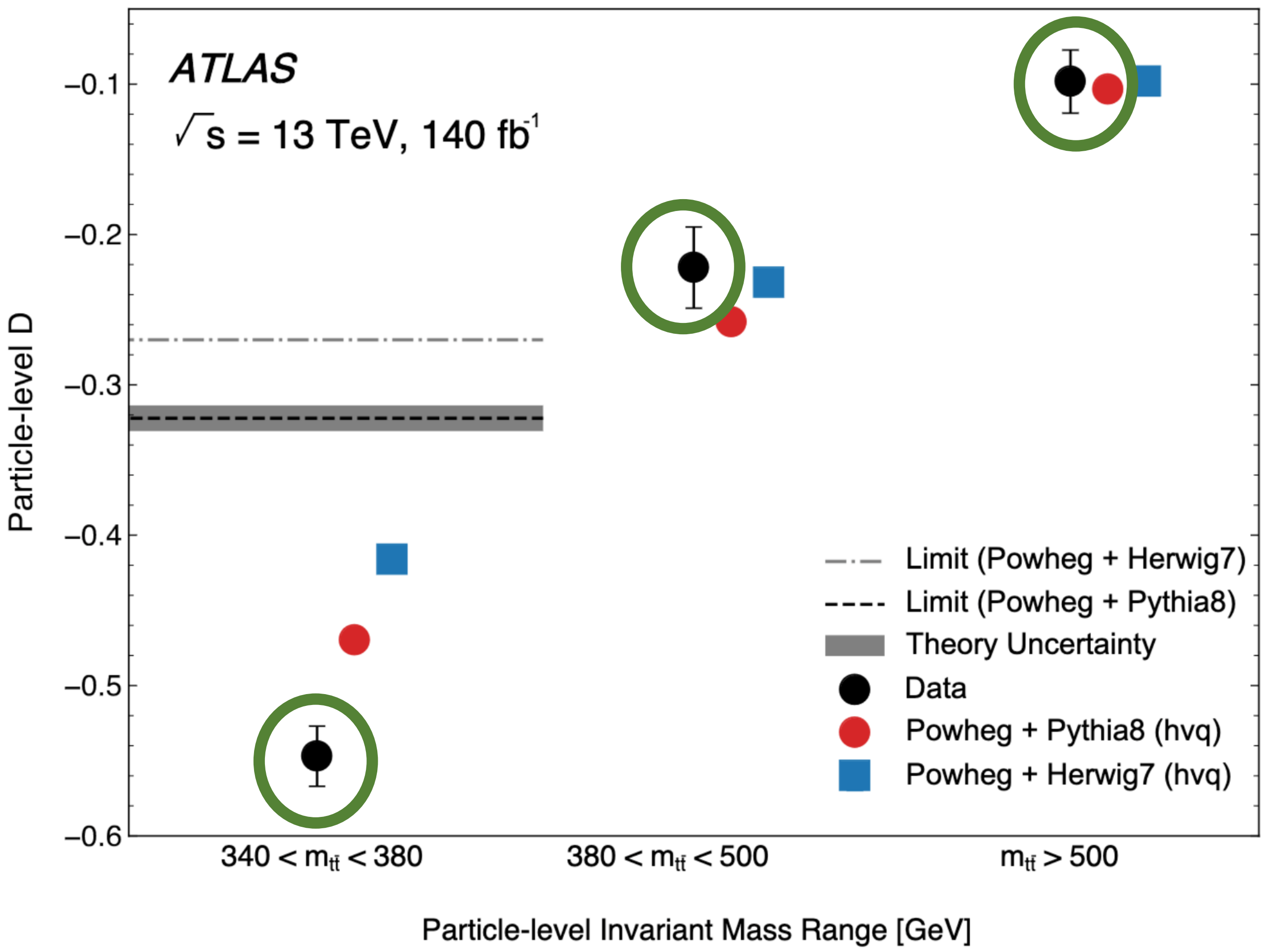


Ordering-parameter is seen to give large differences in particle-level distribution.

Correction to parton-level would induce extreme uncertainty.

Common Questions

How reliable is the calibration curve correction?



Very reliable ✓

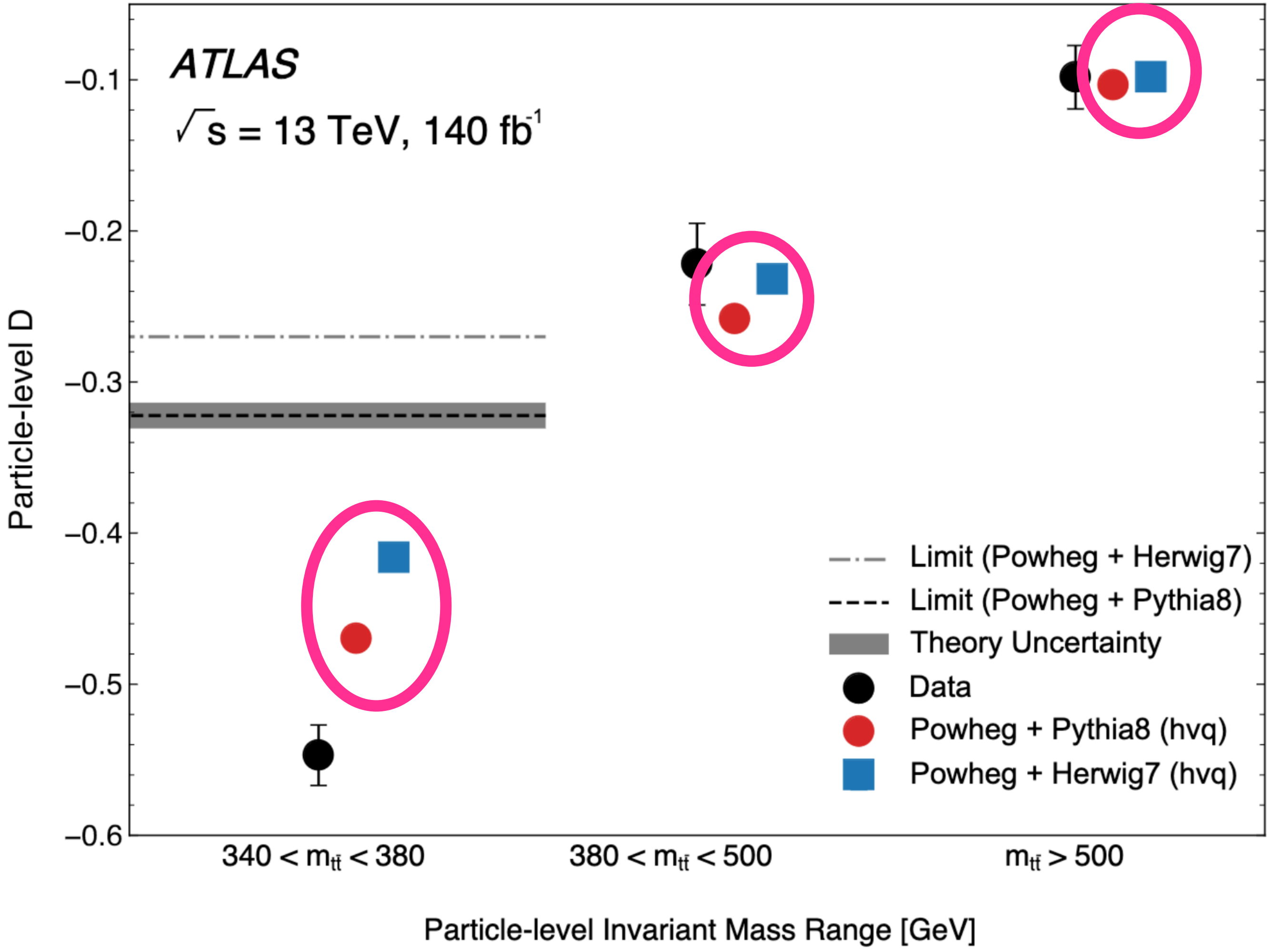
The correction contains a full suite of uncertainties, like all ATLAS Top analyses.

We understand our detector response extremely well.

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

Common Questions

How reliable are our SM predictions?



Reliable but limited

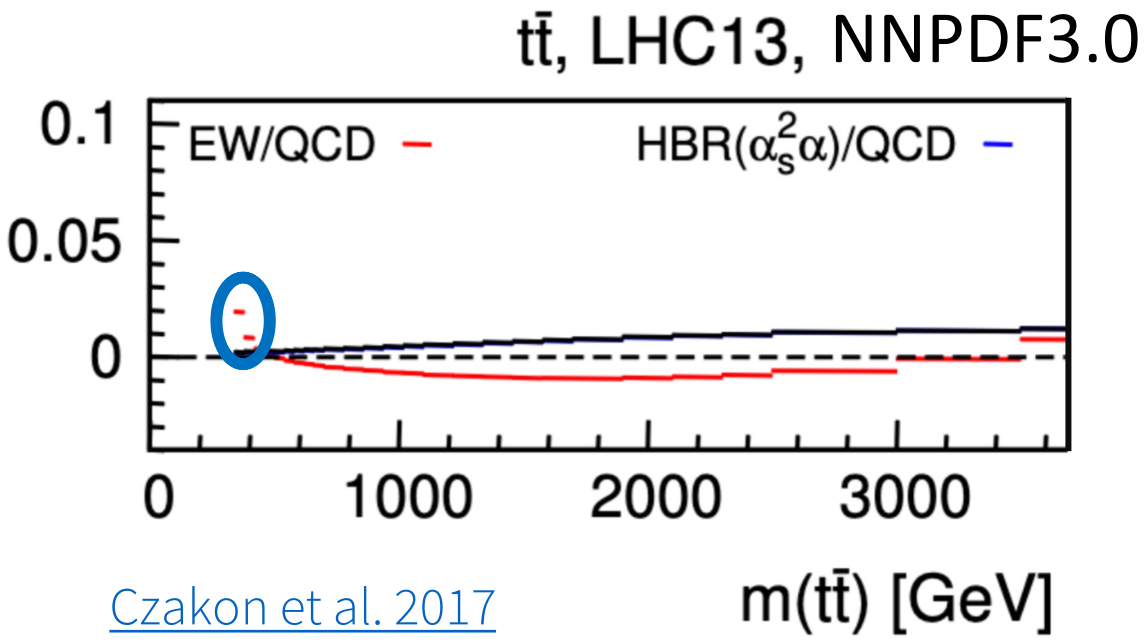
Derived from general-purpose MC event generators (powerful and widely used).

- Lack full spin information in shower
- Lack higher-order corrections to top quark decays

A systematic model built around something like *bb4l* should be deployed by ATLAS in future

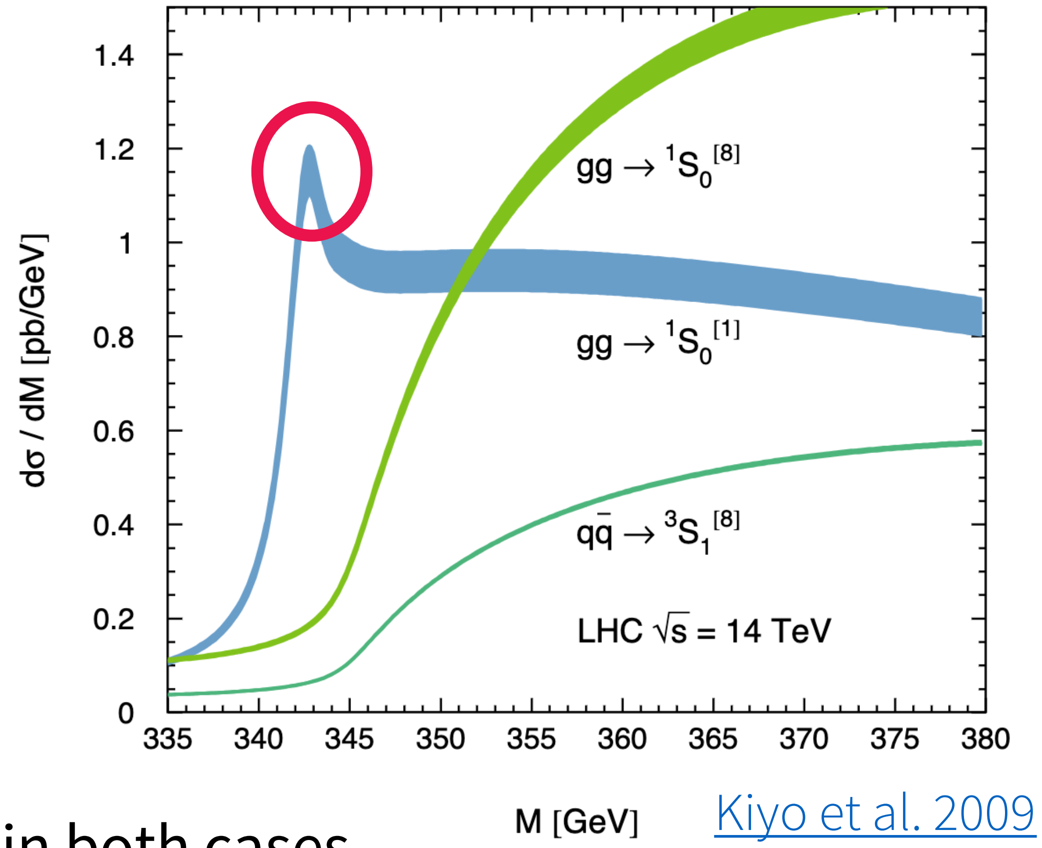
Missing Effects in Simulation

NLO EW



[Czakon et al. 2017]

Bound state



[Kiyo et al. 2009]

Cross-section enhancement near threshold in both cases.

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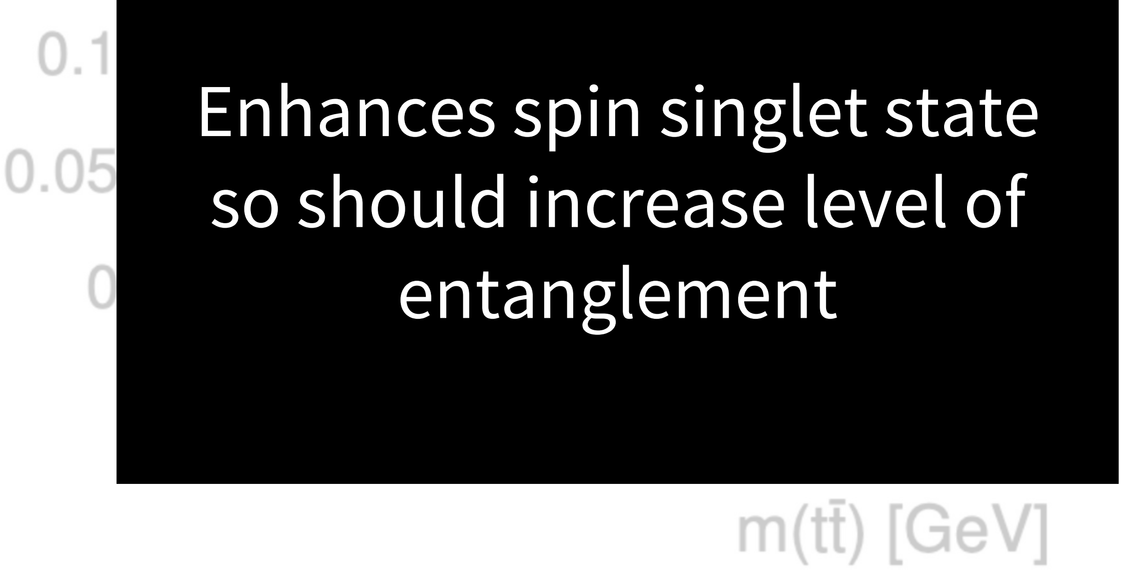
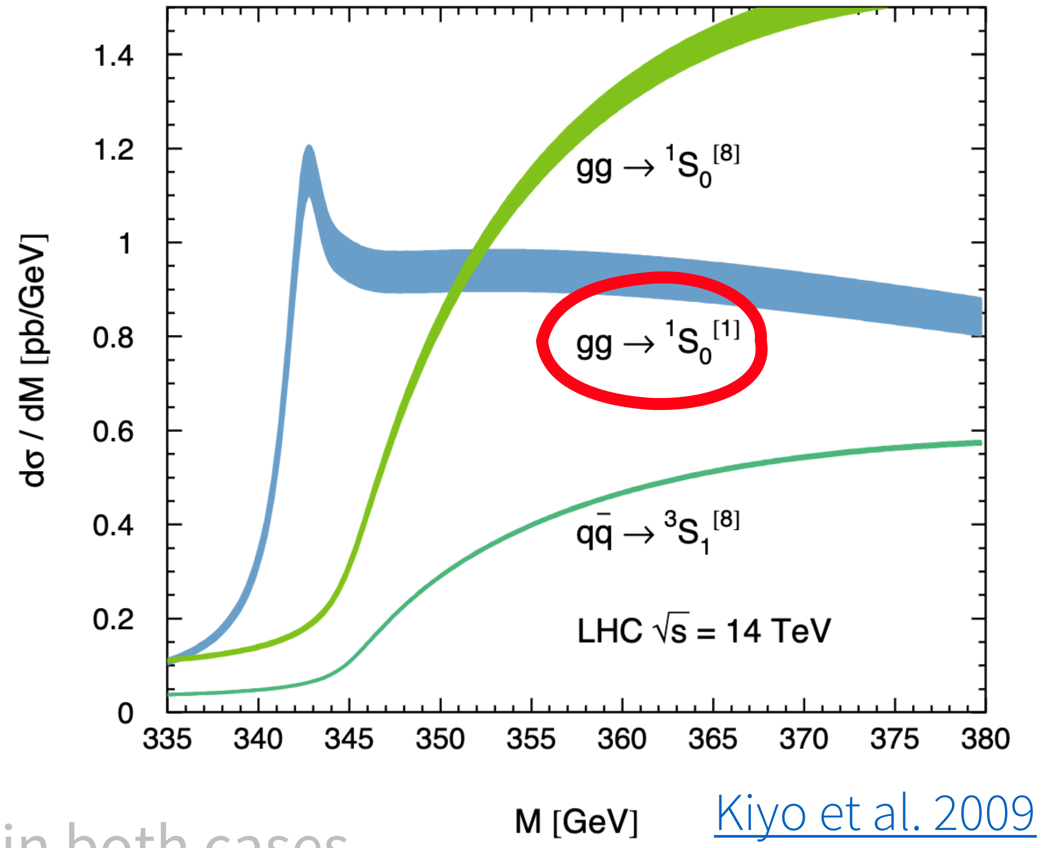


Enhances spin singlet state so should increase level of entanglement

Bound state

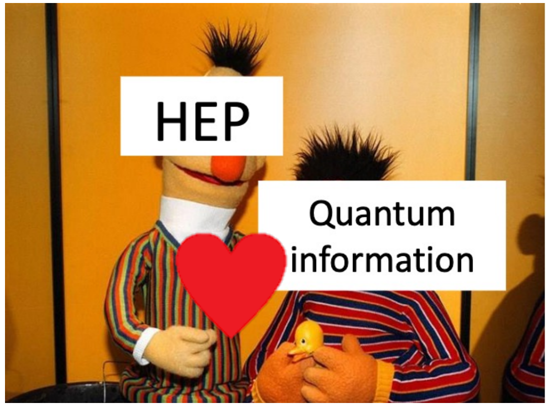


Kiyo et al. 2009

Cross-section enhancement near threshold in both cases.

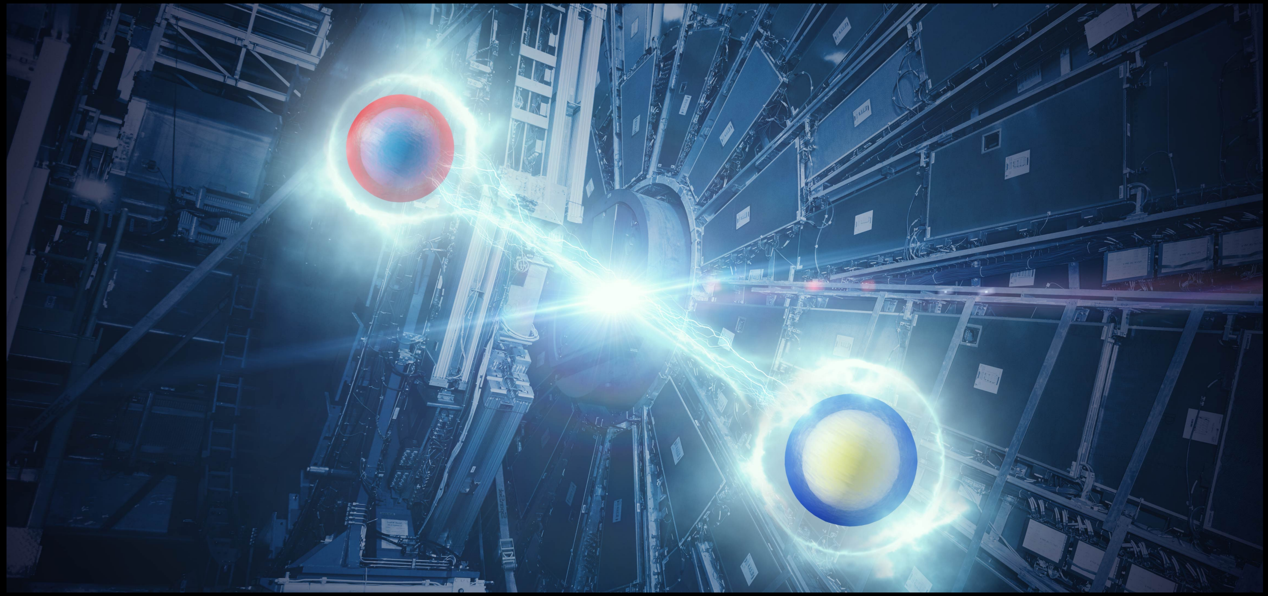
Conclusions

- **Separability of density matrix**: measure through marker *D*.
- **Extract D from angular distribution**: standard di-leptonic techniques.
- **Calibration curve**: corrects *D* to particle-level.
- **Observation of entanglement** at the LHC!
- **Modelling** remains a limitation.
- This result propels forward the union of QI and HEP!



Thank You

Spooky action at a distance is alive and well at the LHC!



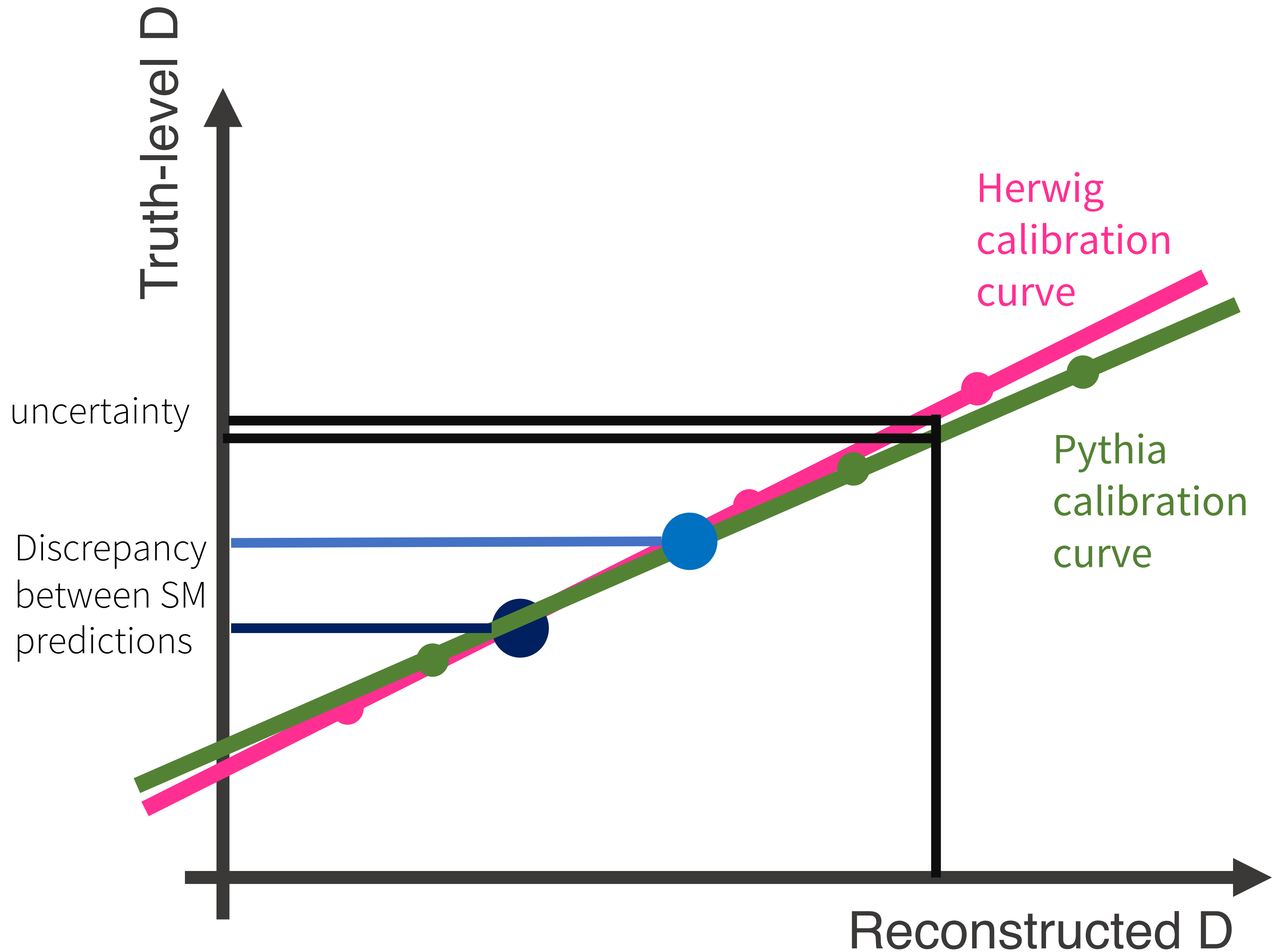
Auxiliary Materials

Summary of Arguments

- The precision of my result does not strongly depend on agreement between data and simulation, as shown.

- The accuracy of the simulation is limited because of:
    - Discrepancies between predictions understood to arise from difference in parton showers.
    - Discrepancy between data and simulation thought to arise from missing effects.

Large discrepancy, small uncertainty



A Lesson

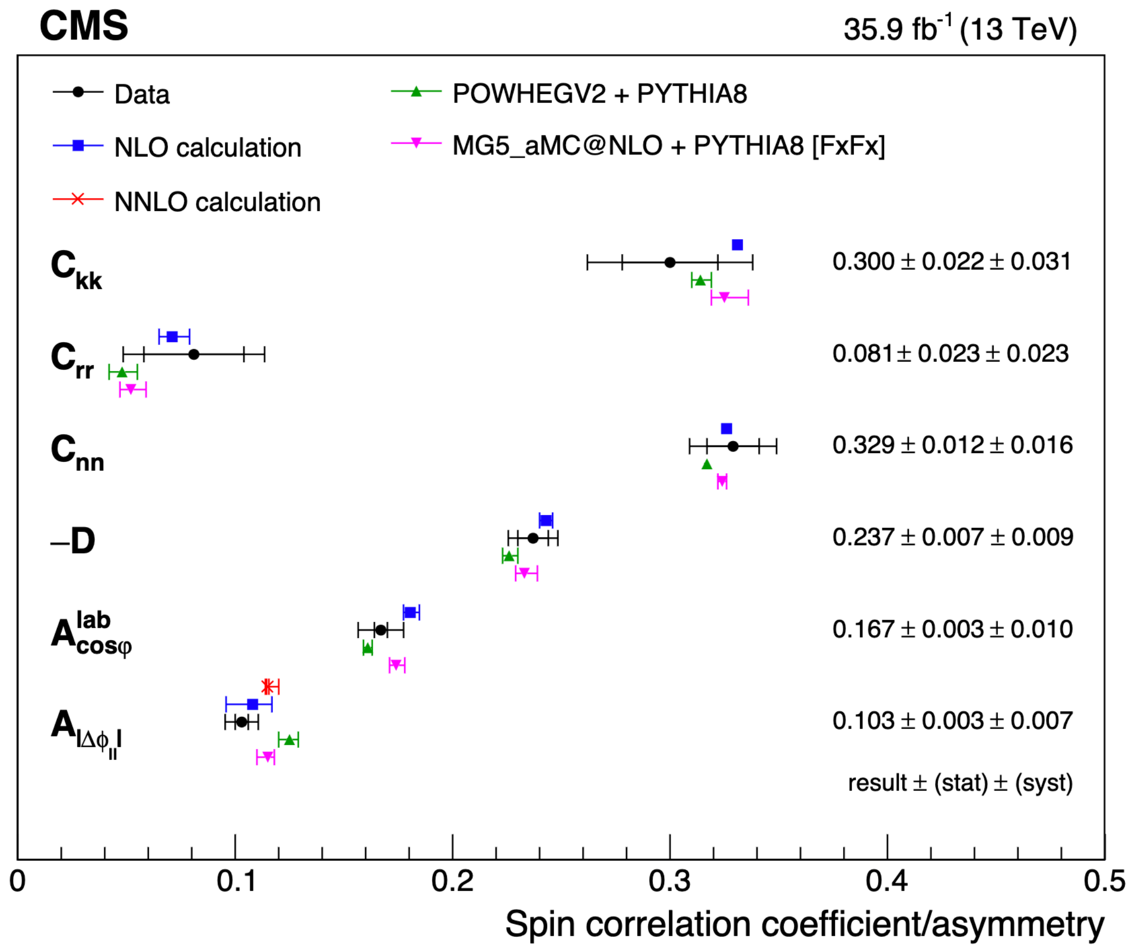
Many negligible issues are exacerbated by the narrow phase-space:

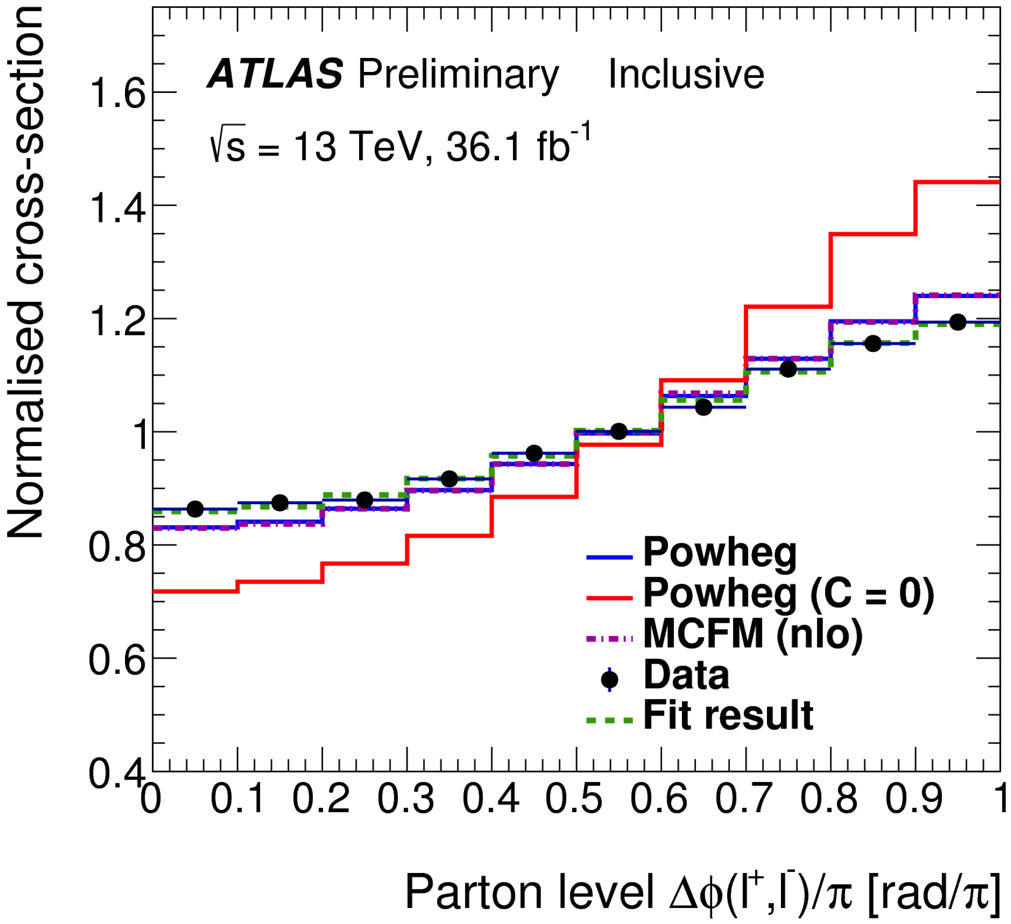
- Resolution of top reconstruction not good enough.
- Unfolding procedures biased.
- Larger discrepancies in parton showers
- Simulation lacks complete description

We are essentially at the limit of what we can do in such a phase-space region.

Measurements of Spin Correlations

Many precision measurements of spin parameters in the past





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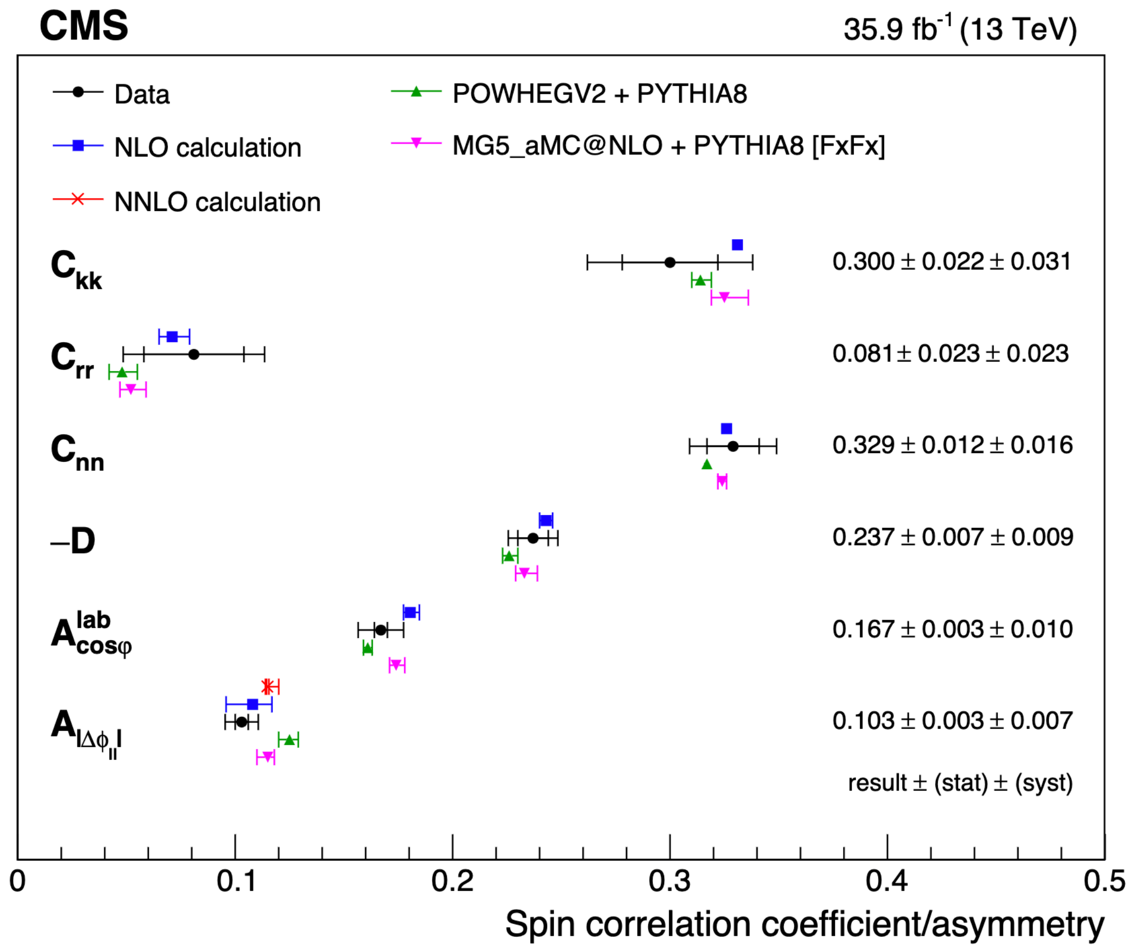


$$D = \frac{\mathrm{Tr}[\mathrm{C}]}{3} = \frac{1}{3}(C_{11} + C_{22} + C_{33})$$

View as an average spin correlation

Reweighting

Each event ascribed a weight through the expression:

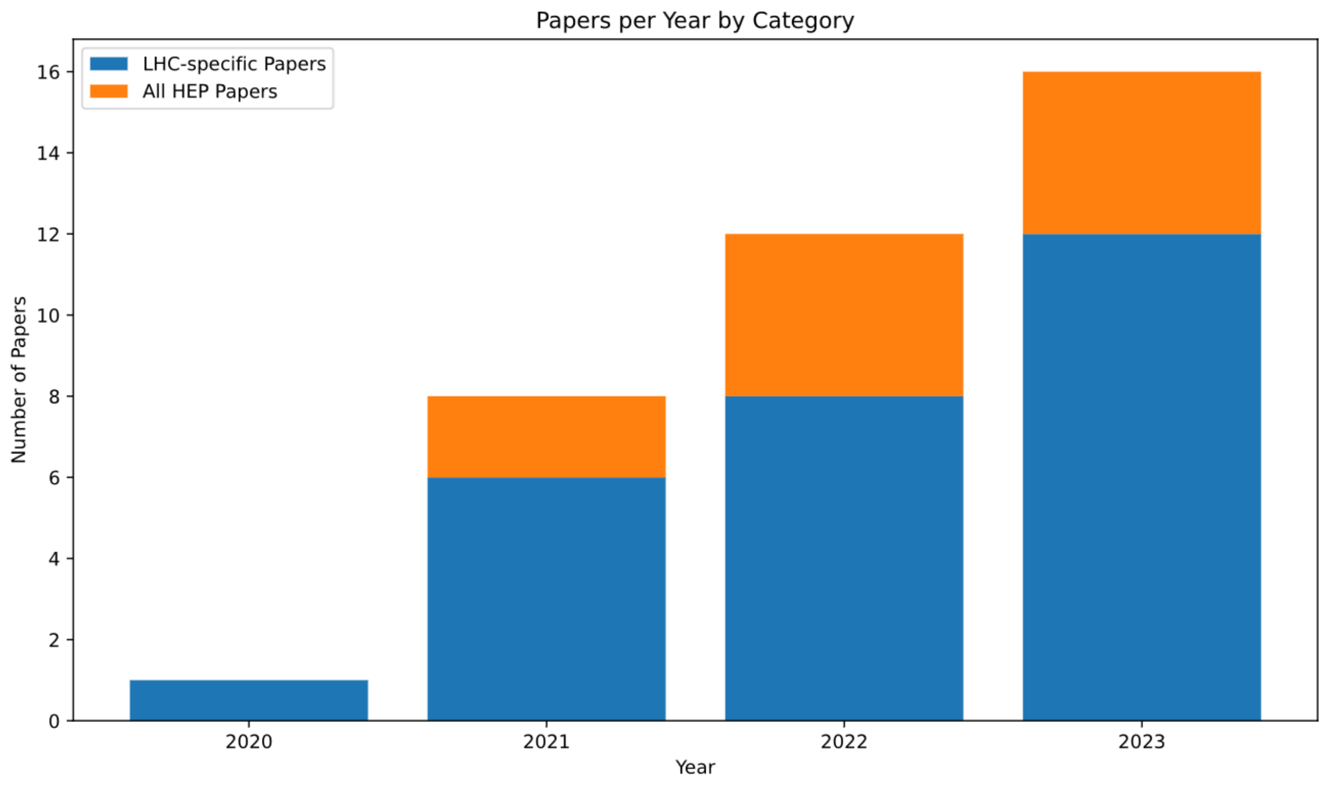
$$w = \frac{1 - D_{\Omega}\left(m_{t\bar{t}}\right) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_{\Omega}\left(m_{t\bar{t}}\right) \cdot \cos\varphi}$$

where

$$D_{\Omega}\left(m_{t\bar{t}}\right) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

is fitted from simulation (differs per MC generator).

QI-HEP Hype


Papers per Year by Category
LHC-specific Papers
All HEP Papers
Number of Papers
0
2
4
6
8
10
12
14
16
2020
2021
2022
2023
Year