Entangled in Tops

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

SM @ LHC 2024

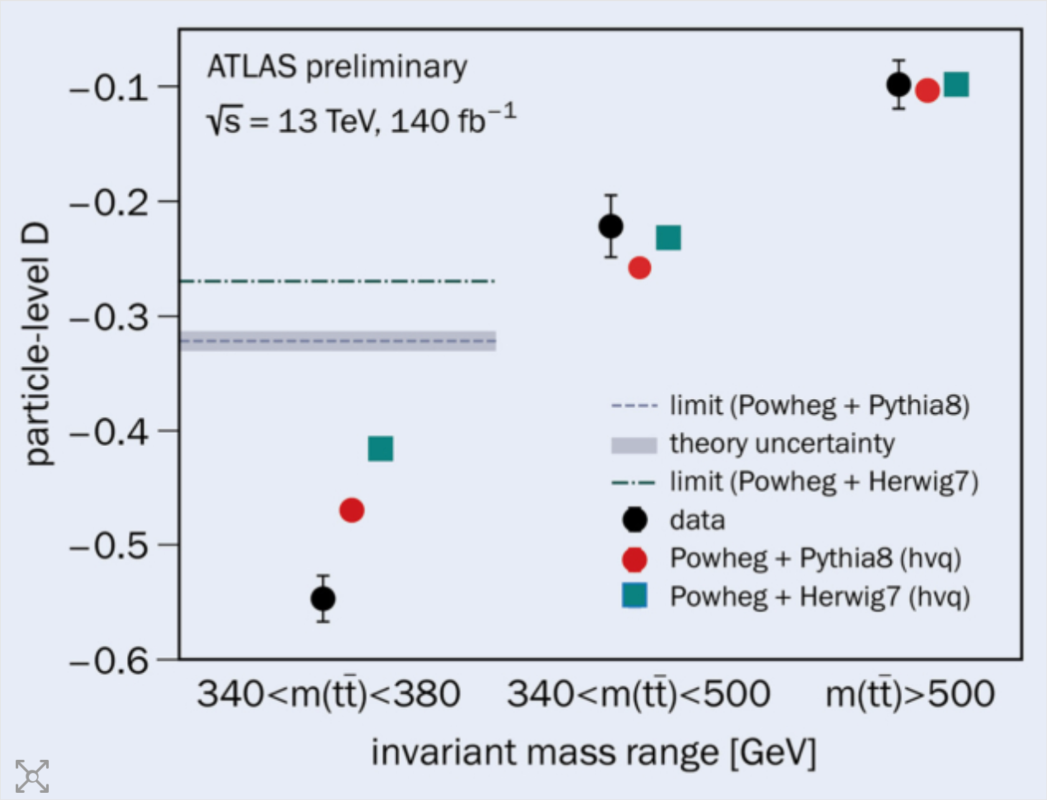
Ethan Simpson
on behalf of the ATLAS Collaboration

STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.



arXiv:2311.07288

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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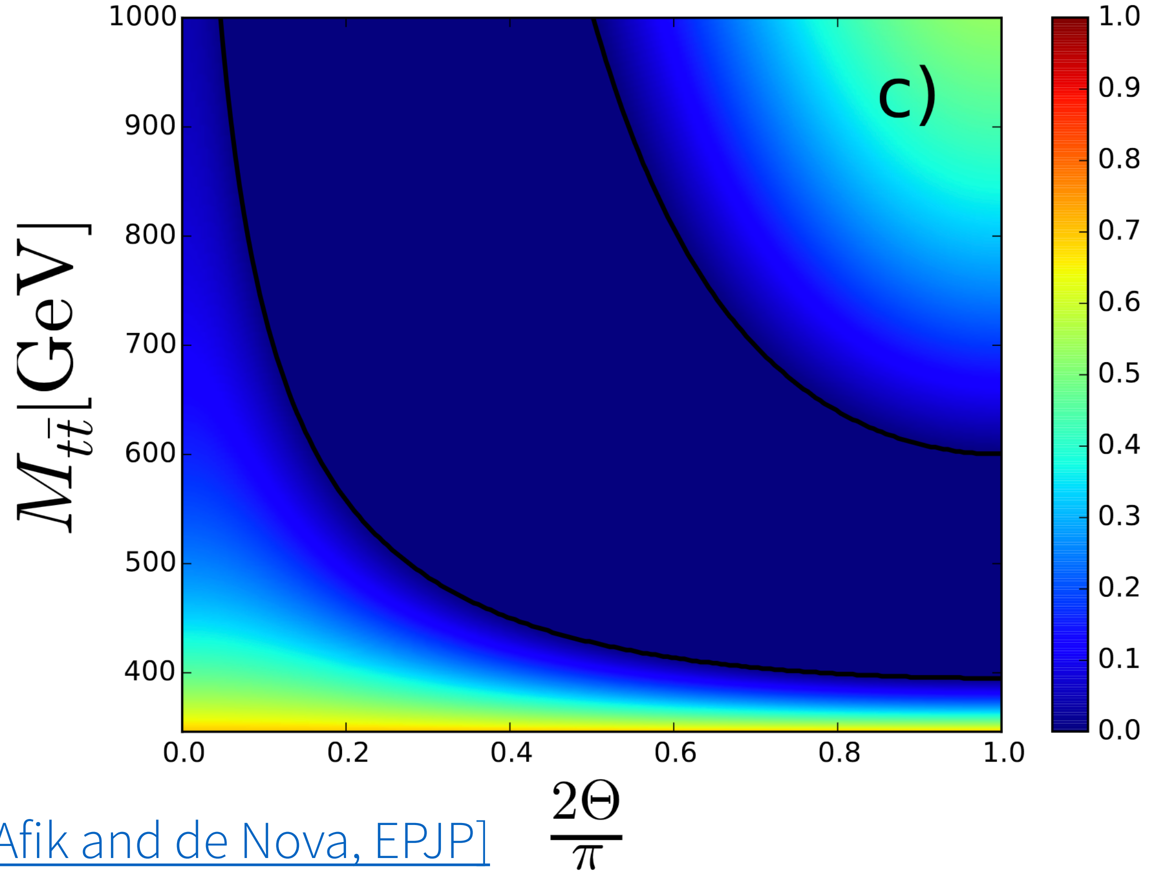
Our old friend the spin density matrix.

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.



[Afik and de Nova, EPJP]

Regions of entanglement at high and low invariant mass

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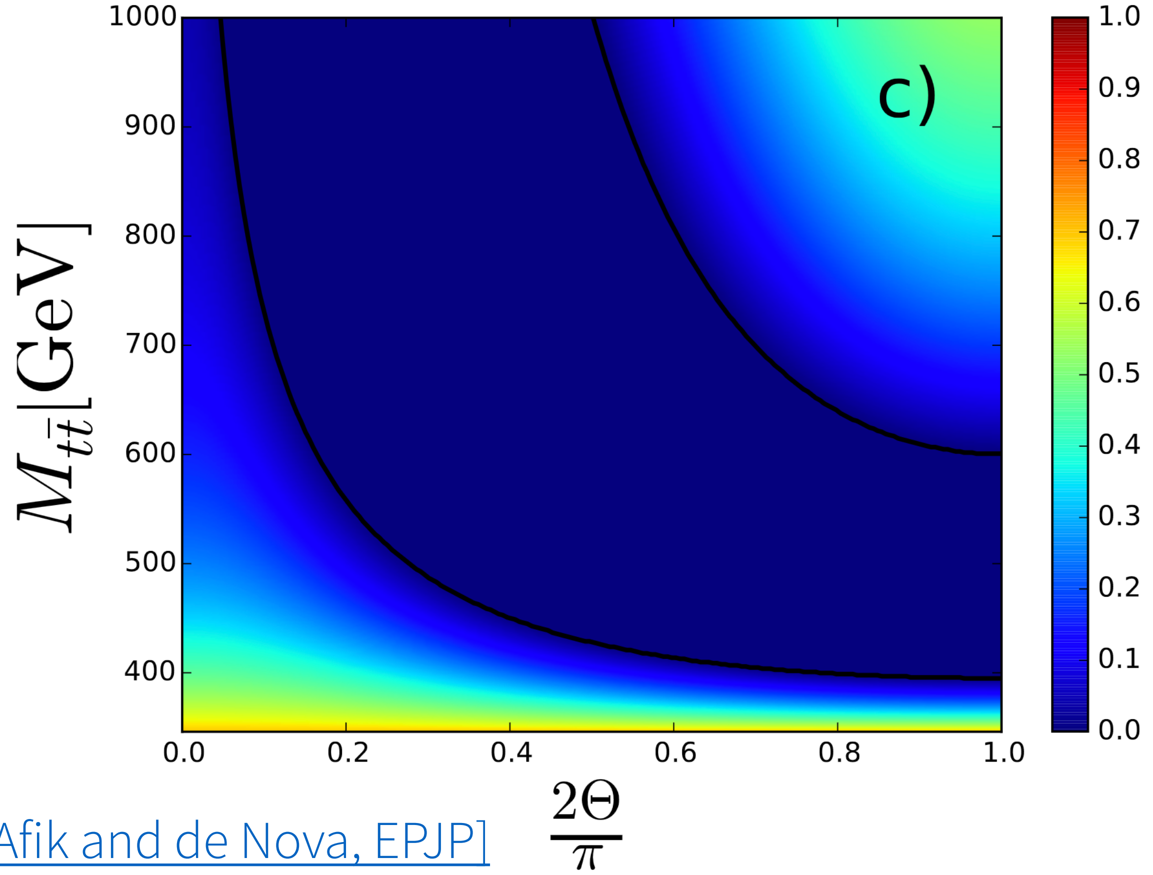

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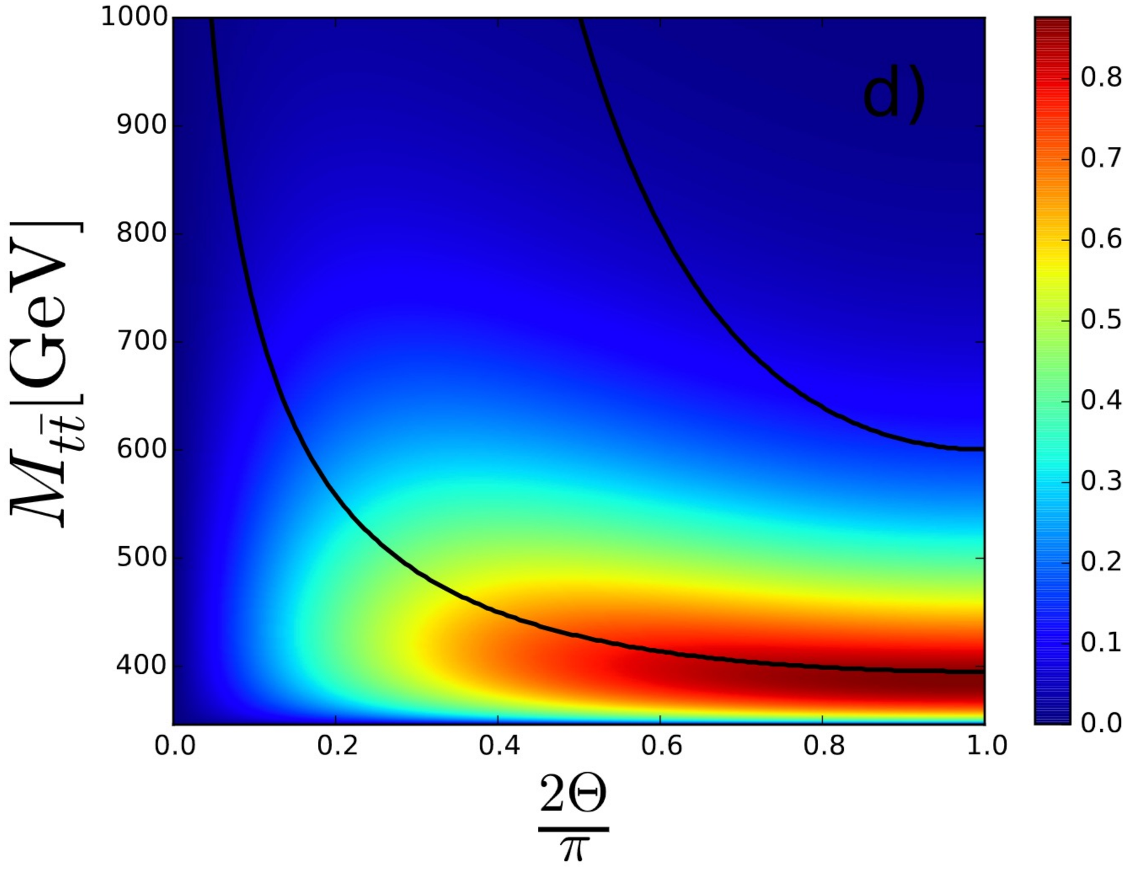
Regions of entanglement at high and low invariant mass



Cross-section i.e. where are the stats?

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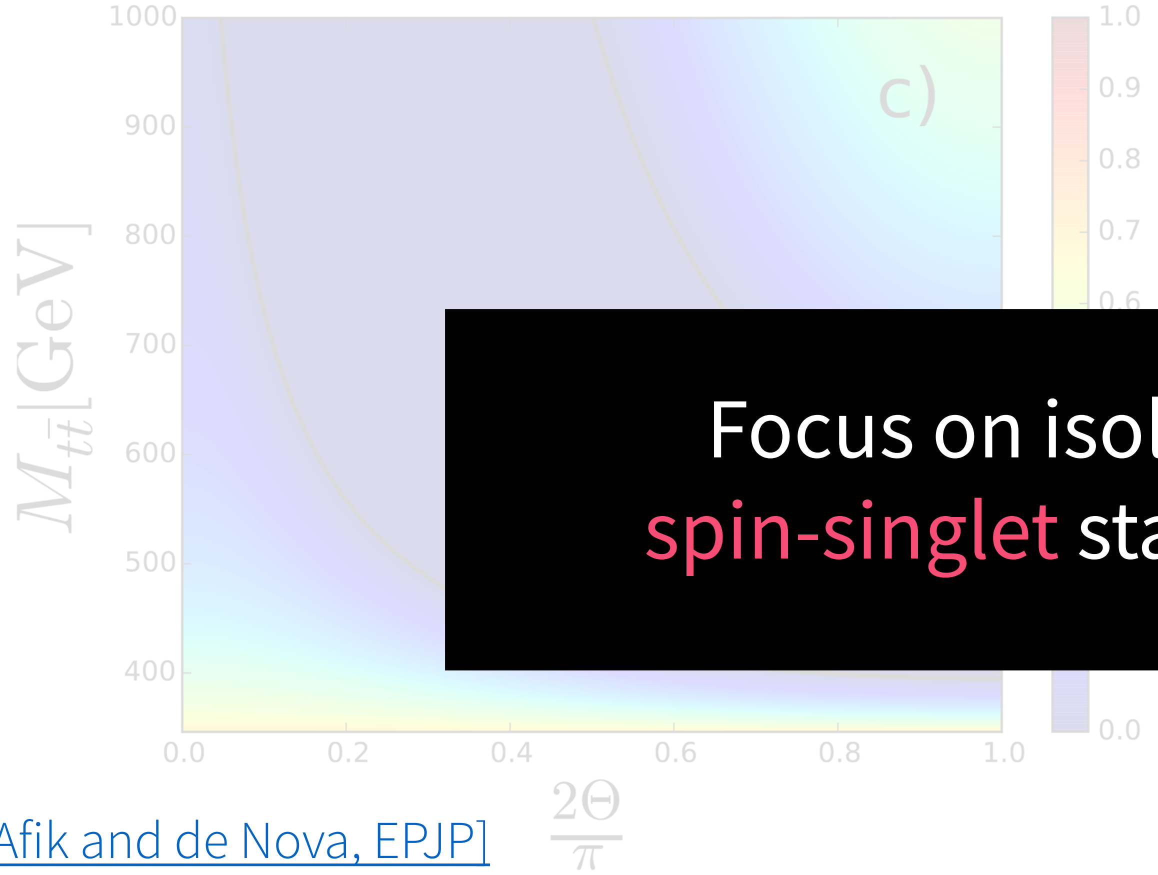
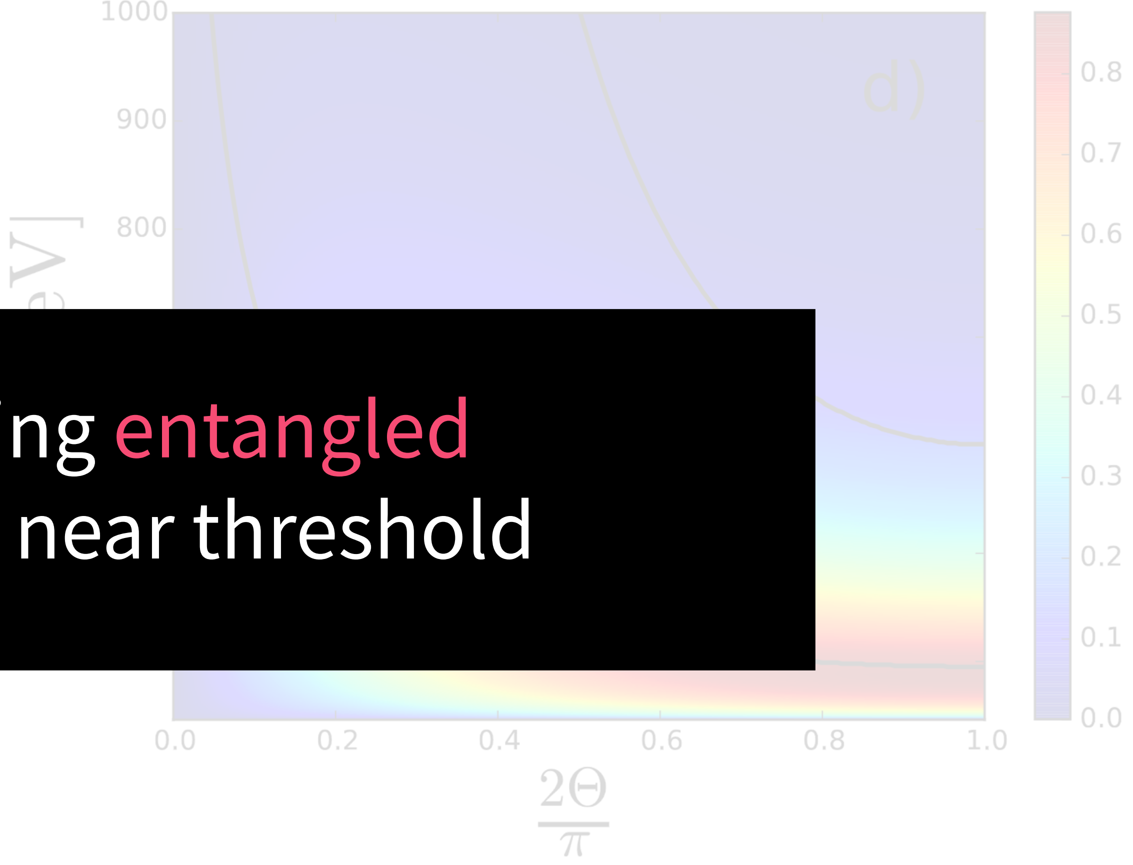




Focus on isolating entangled spin-singlet state near threshold

[Afik and de Nova, EPJP]

Regions of entanglement at high and low invariant mass

Cross-section i.e. where are the stats?

Peres-Horodecki Criterion

Useful entanglement marker

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

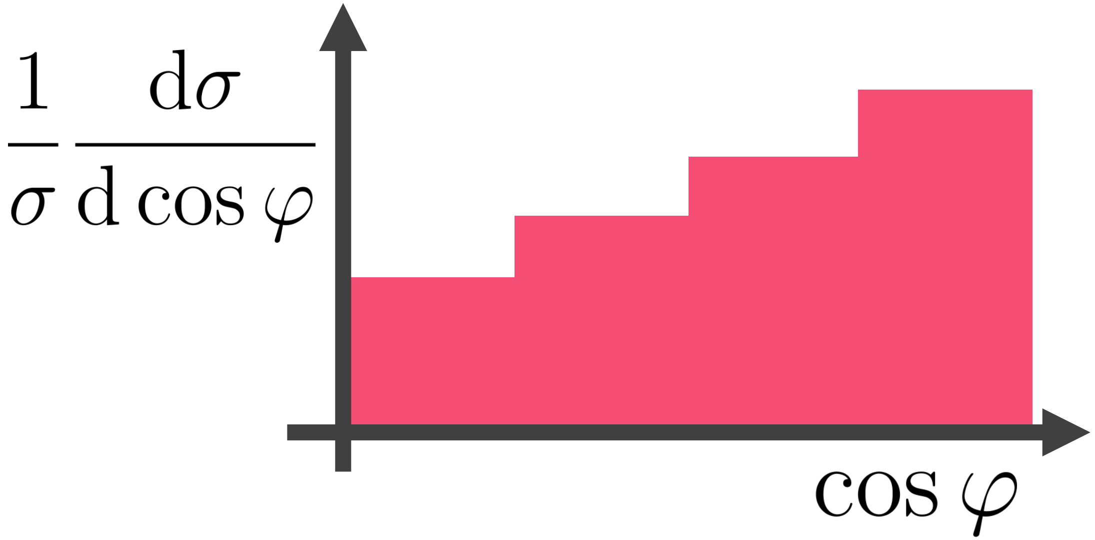
Peres-Horodecki Criterion

Useful entanglement marker

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

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

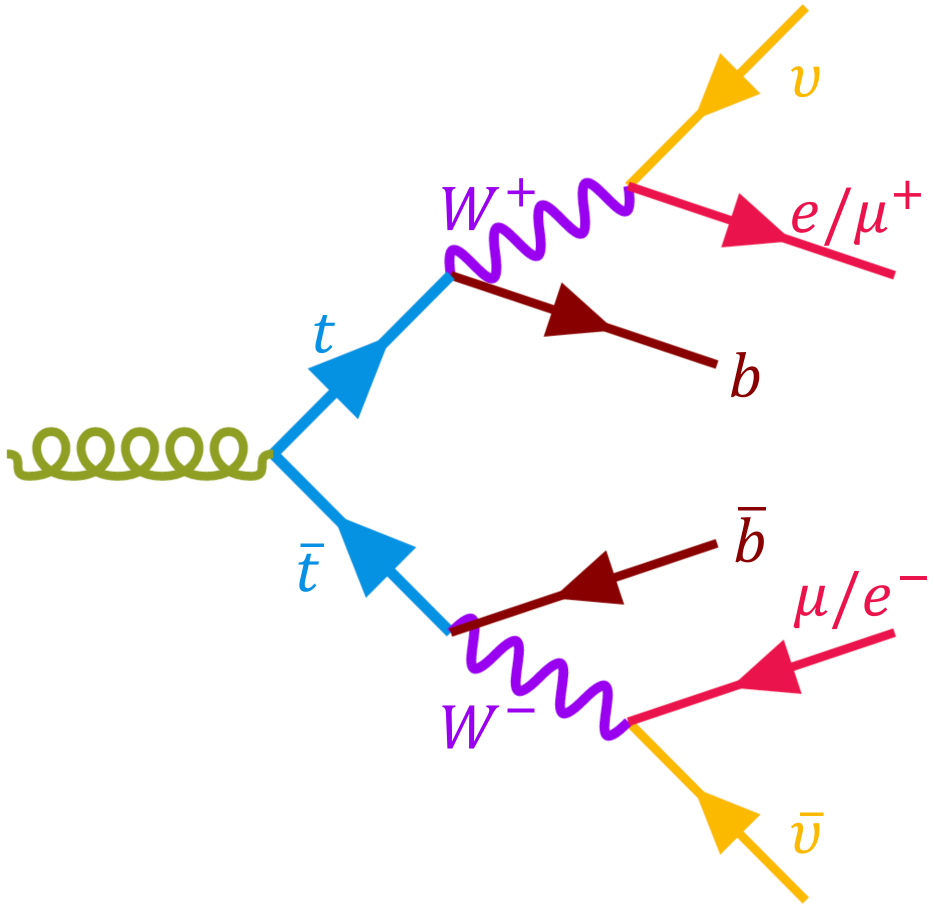
Expectation value

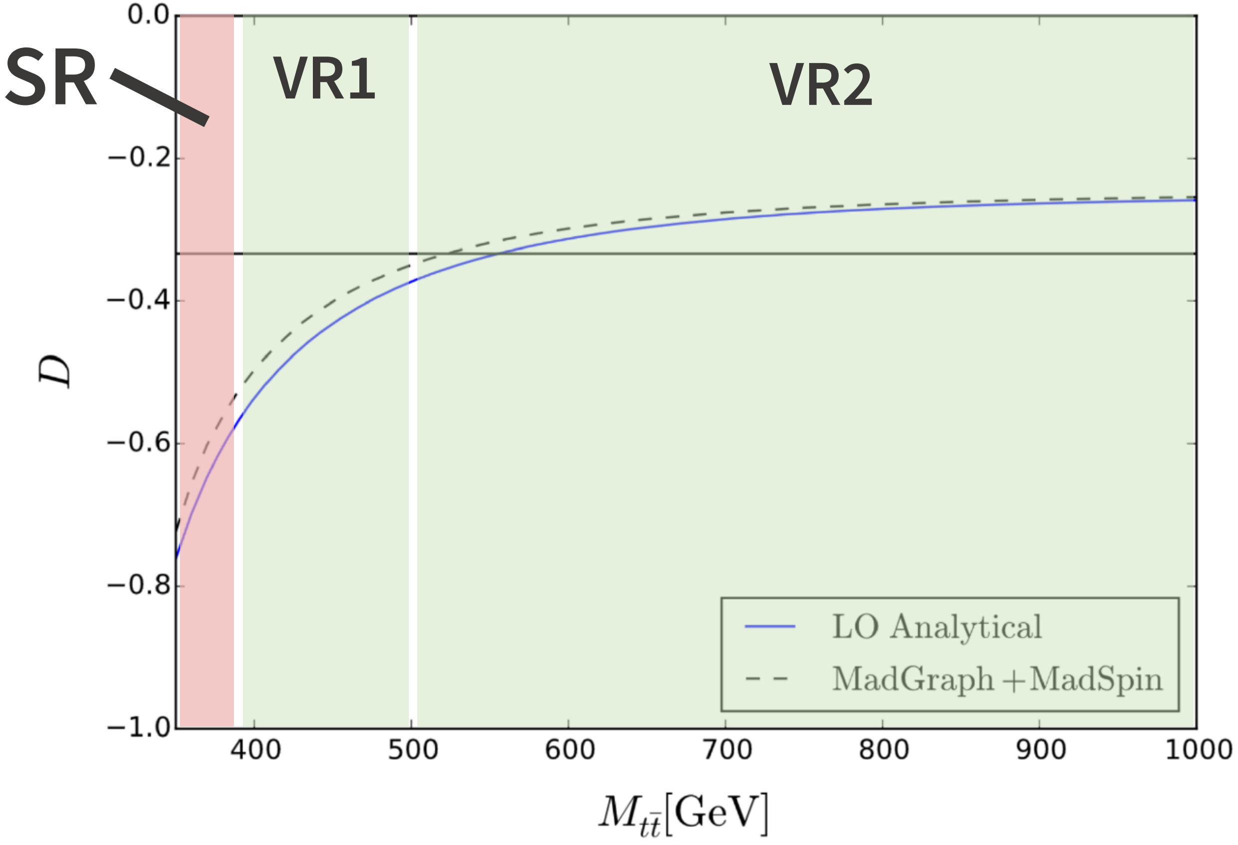


where $\cos\varphi$ is the scalar product of lepton directions in their parent tops' frame.

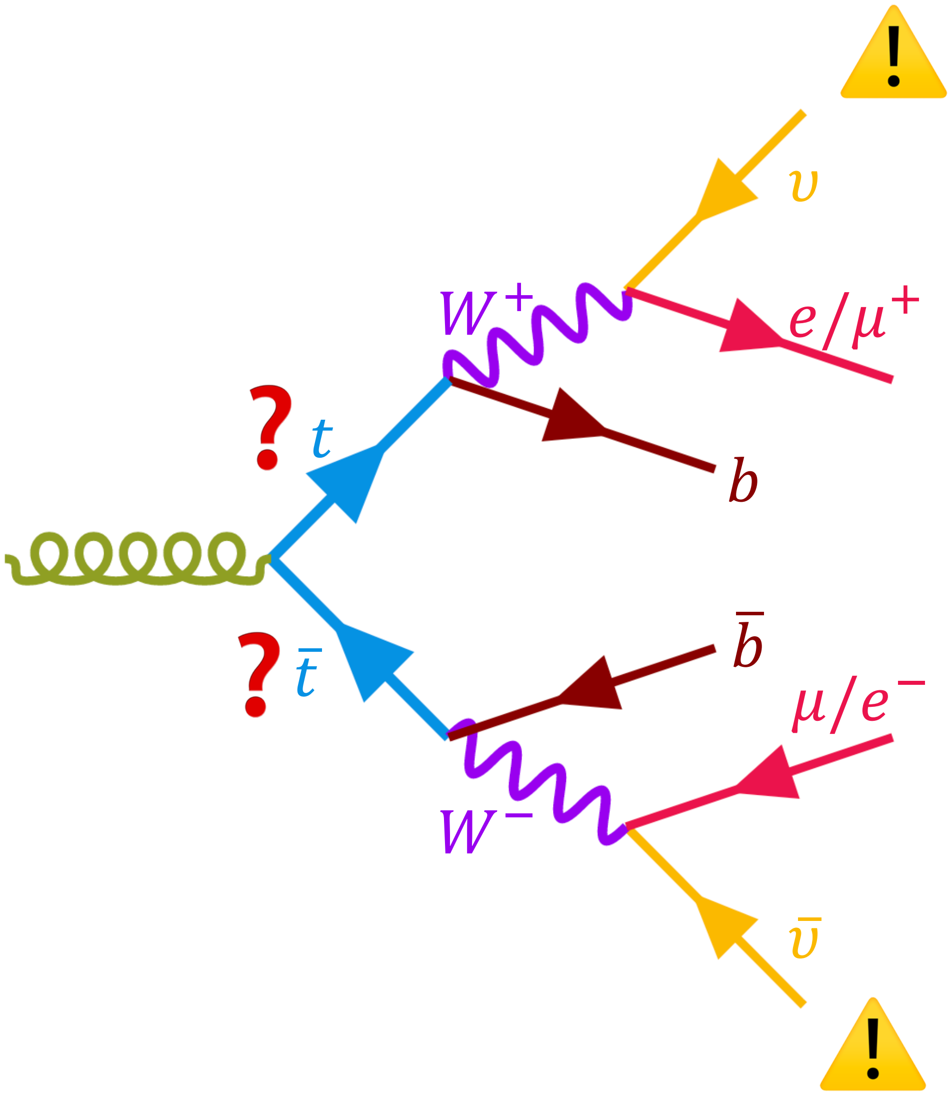
Selections

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





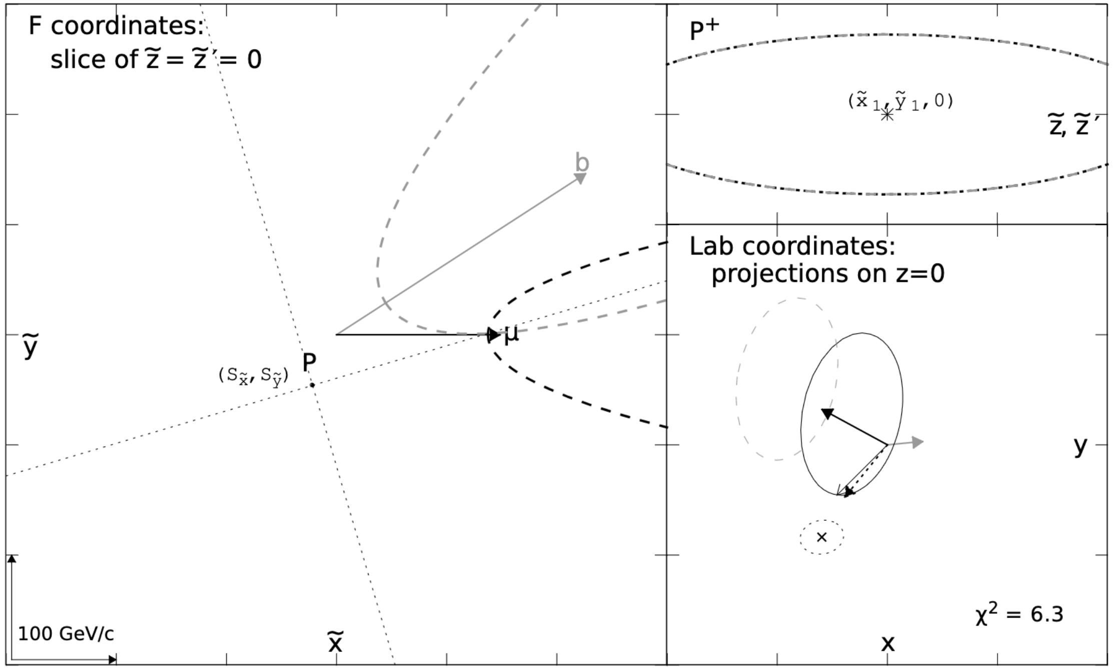
Di-leptonic Reconstruction



Require tops' kinematics to define the observables

Primary technique: Ellipse Method

(geometric technique for solving for neutrino kinematics)



Signal and Backgrounds

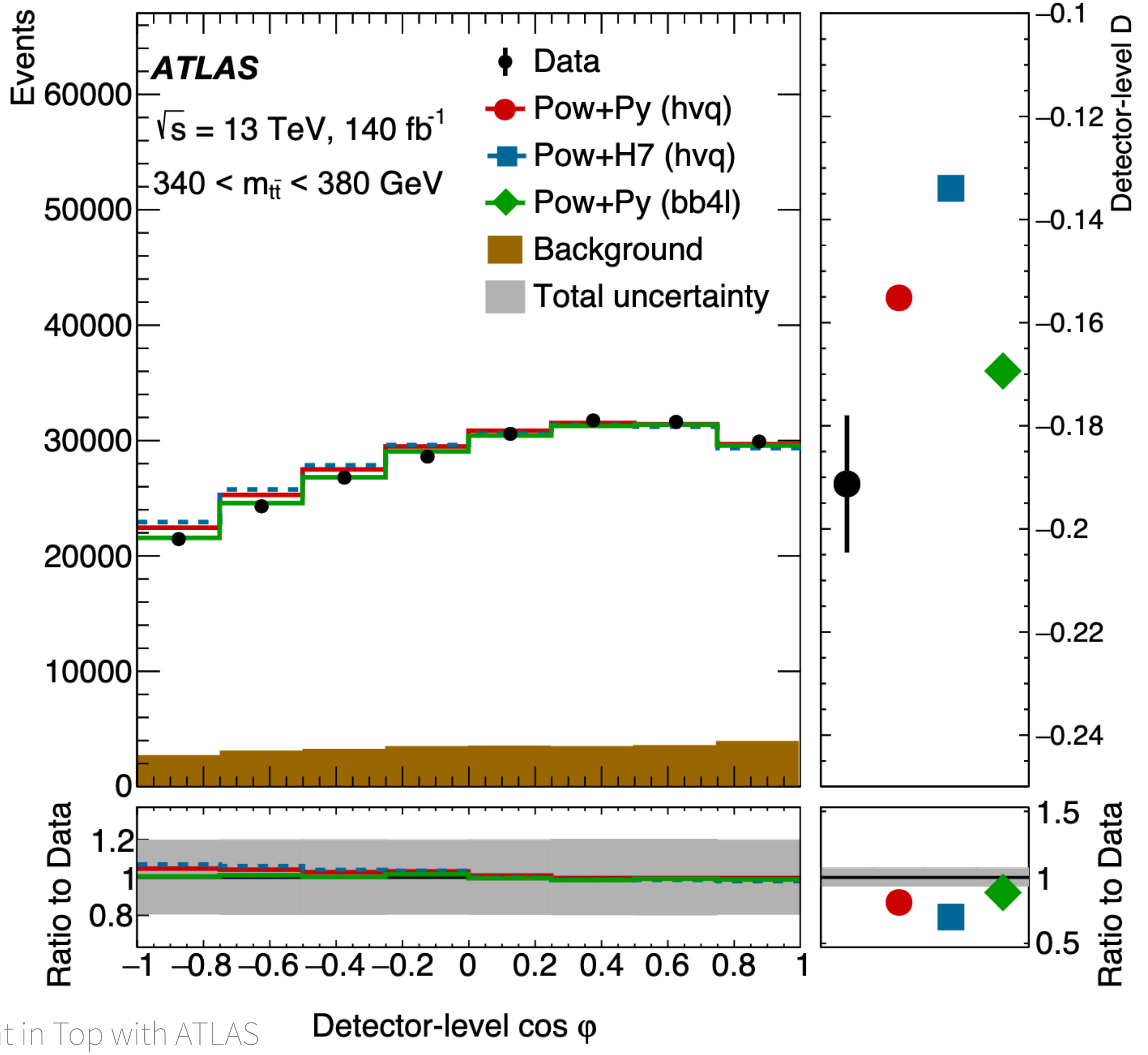
Signal

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.

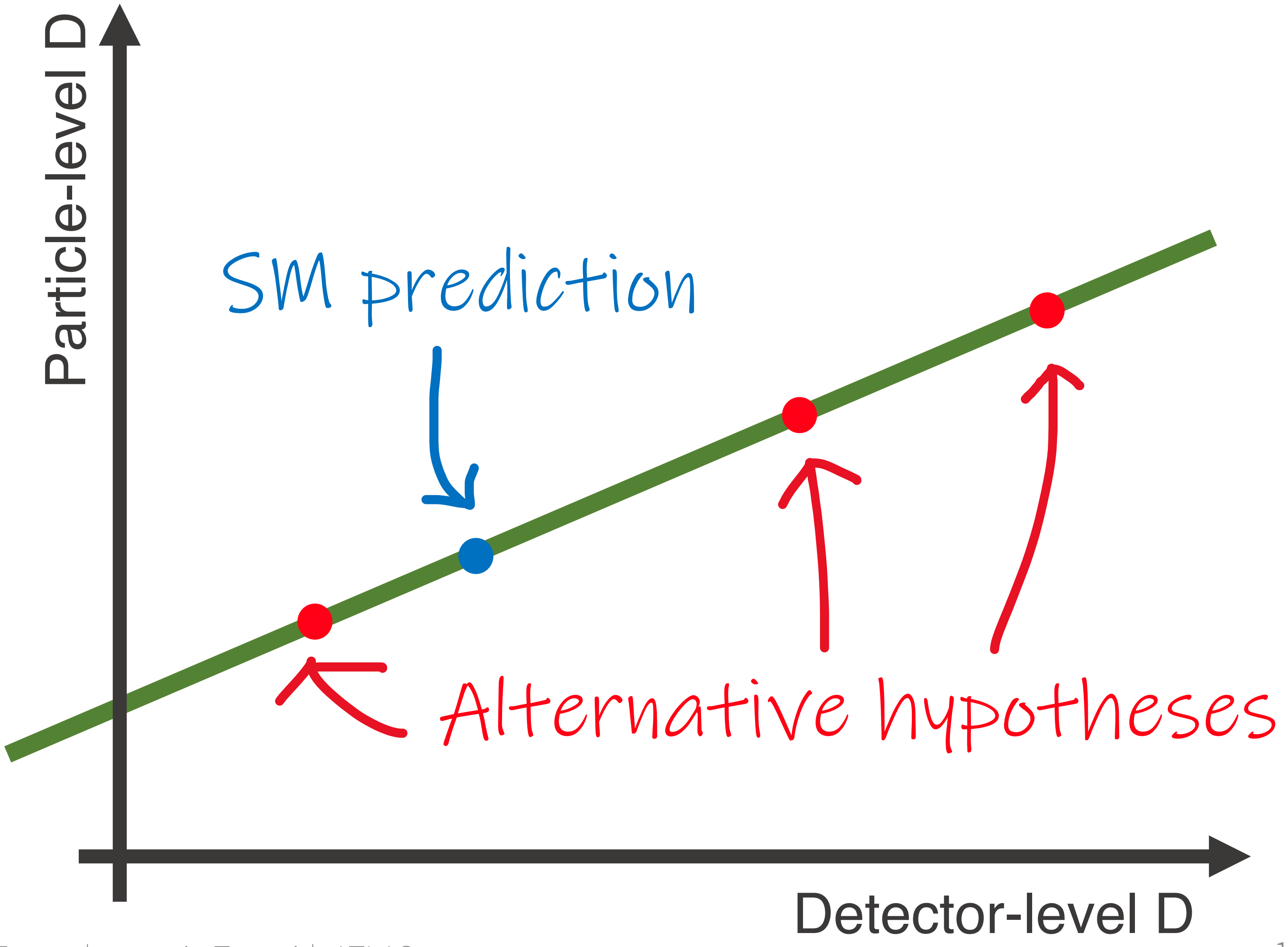


Calibration Curve

Parameterise variation in the detector effects on D.

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

Interpolate to give variation.



Calibration Curve

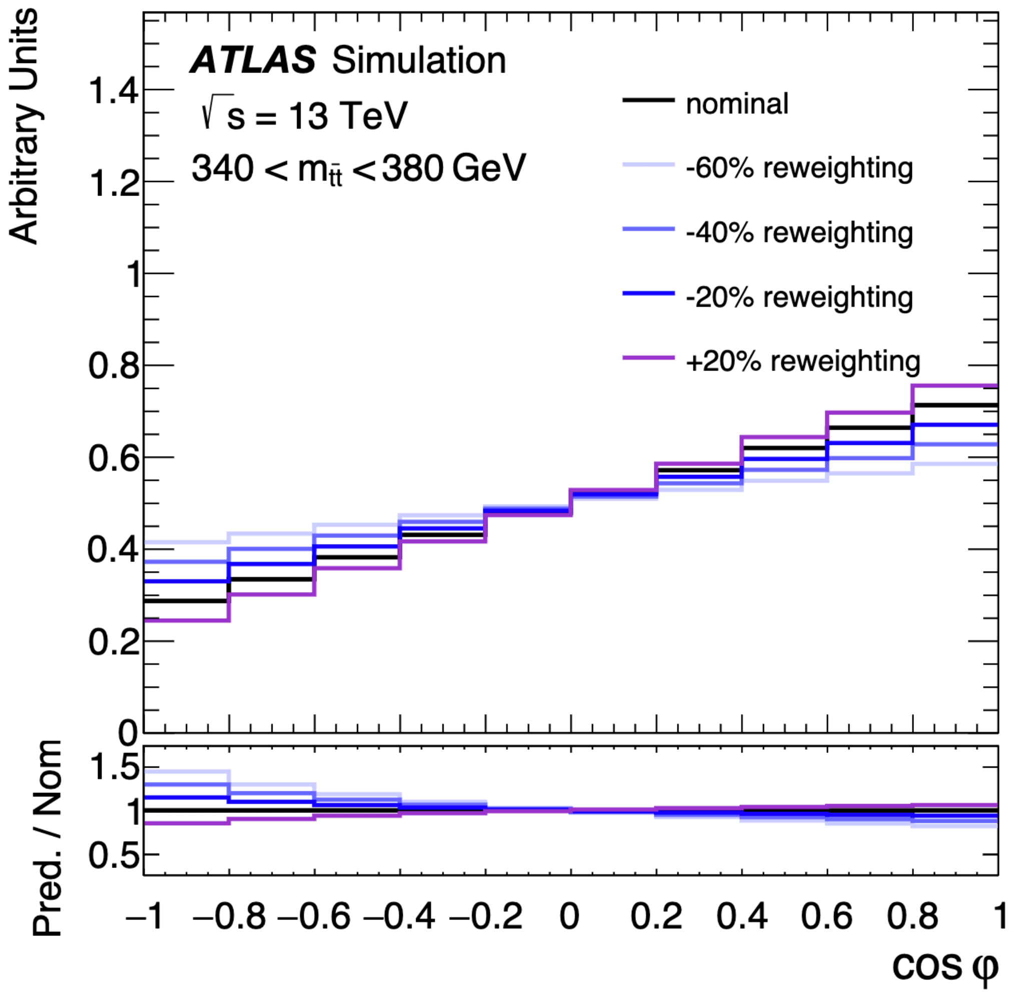
How to generate alternative hypotheses?

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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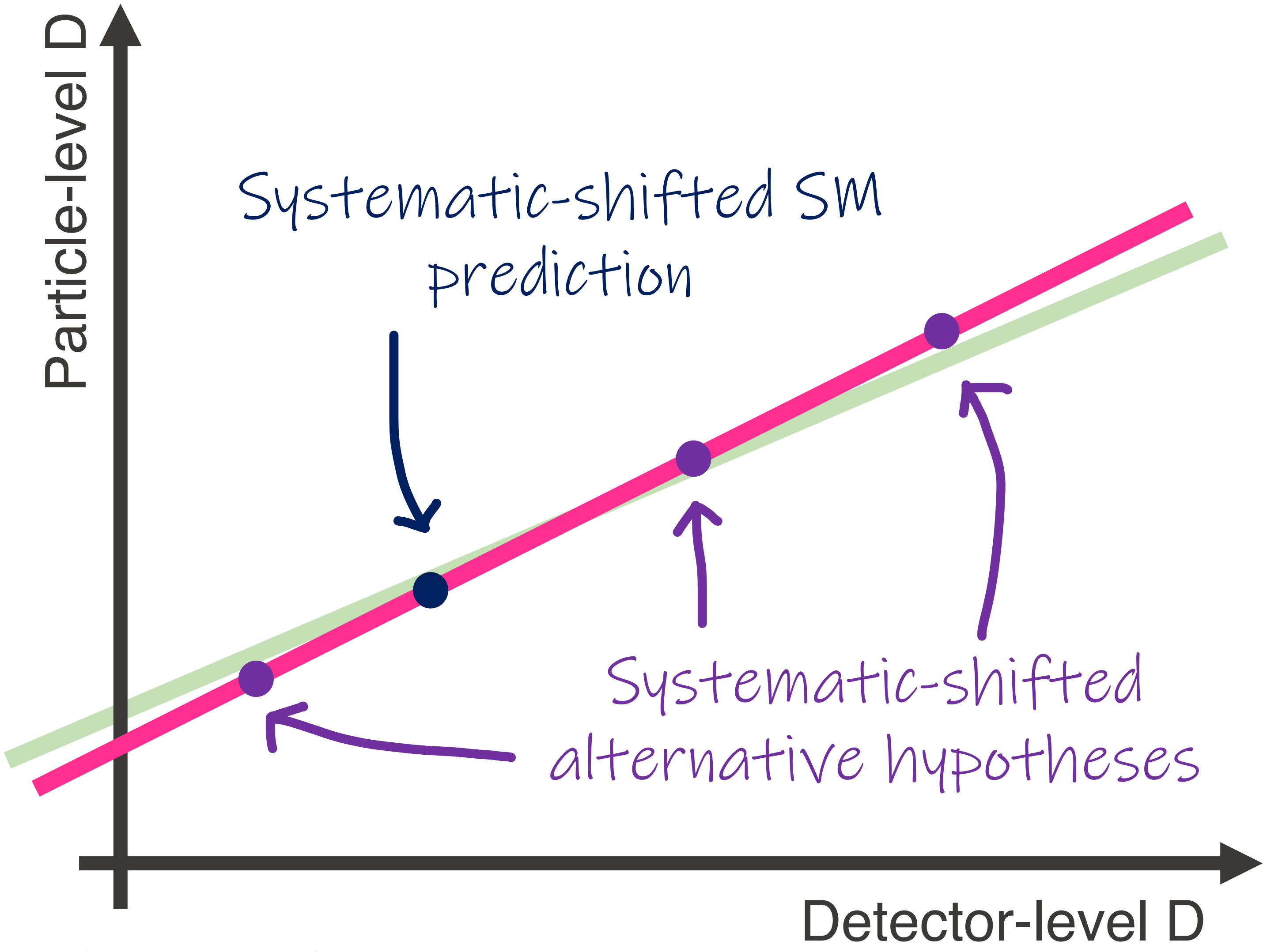
Systematics build different calibration curves.



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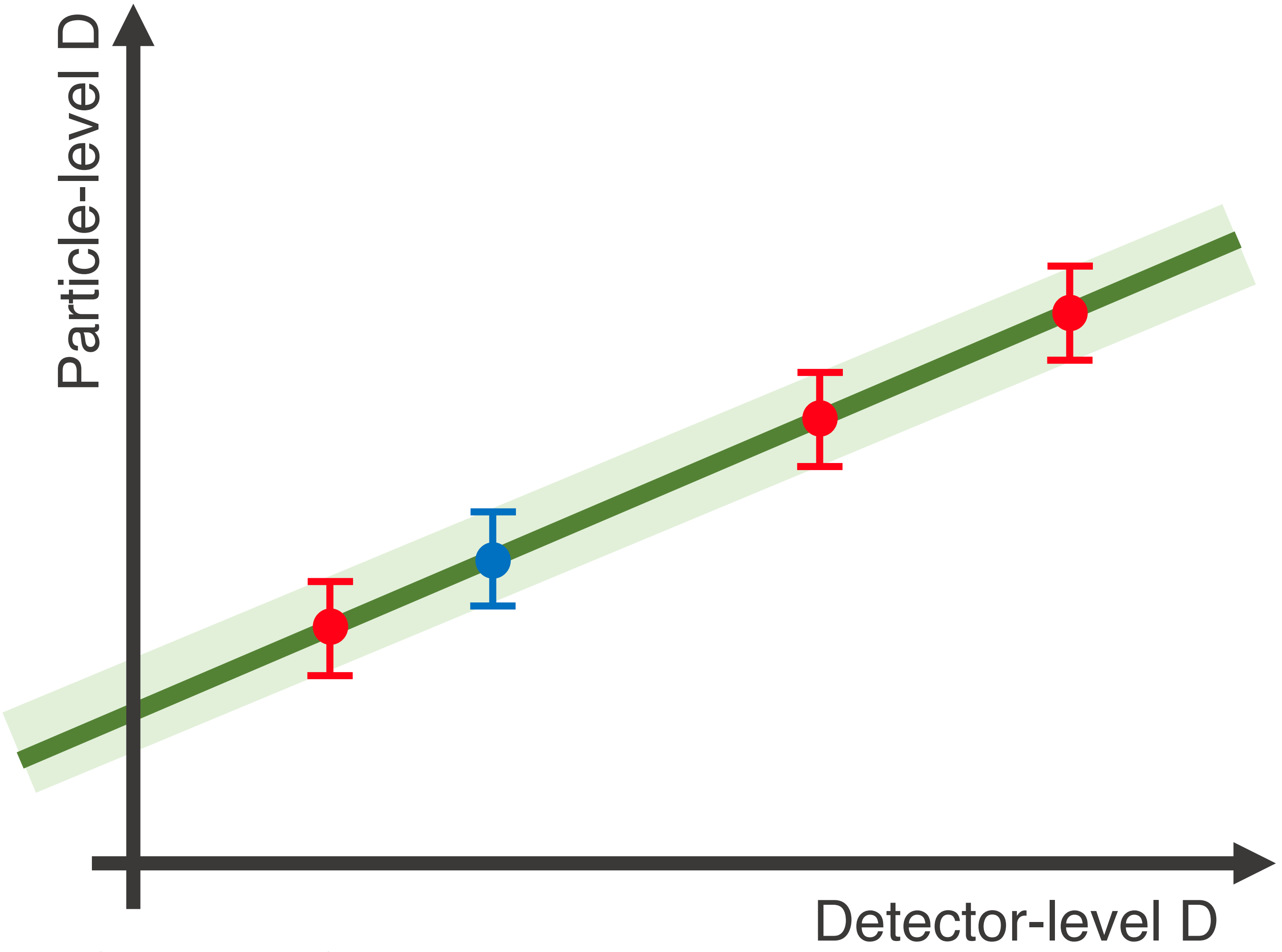
Combine all systematics to build nominal curve + uncertainty band.



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Parameterise variation in the detector effects on D.

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

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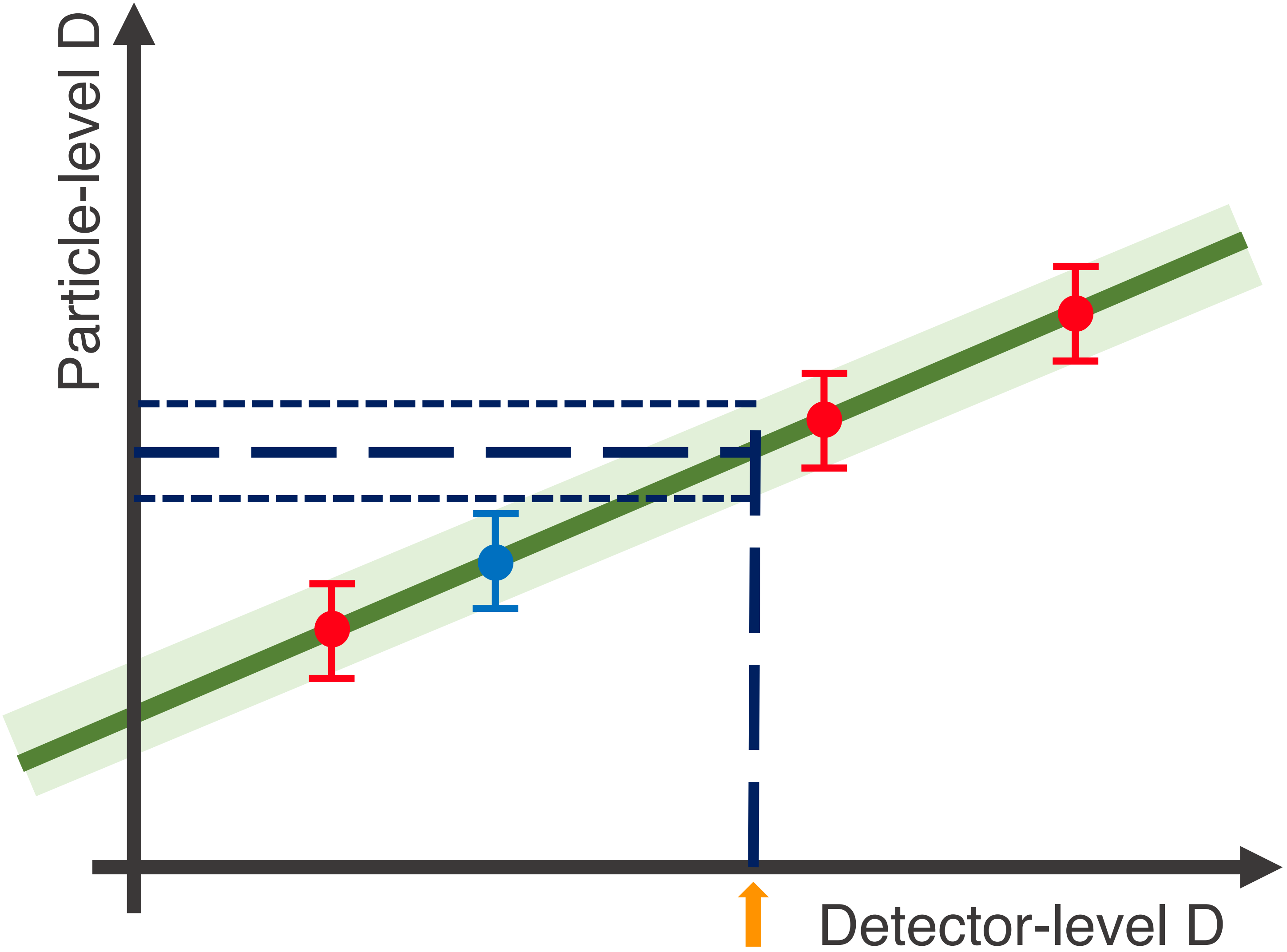
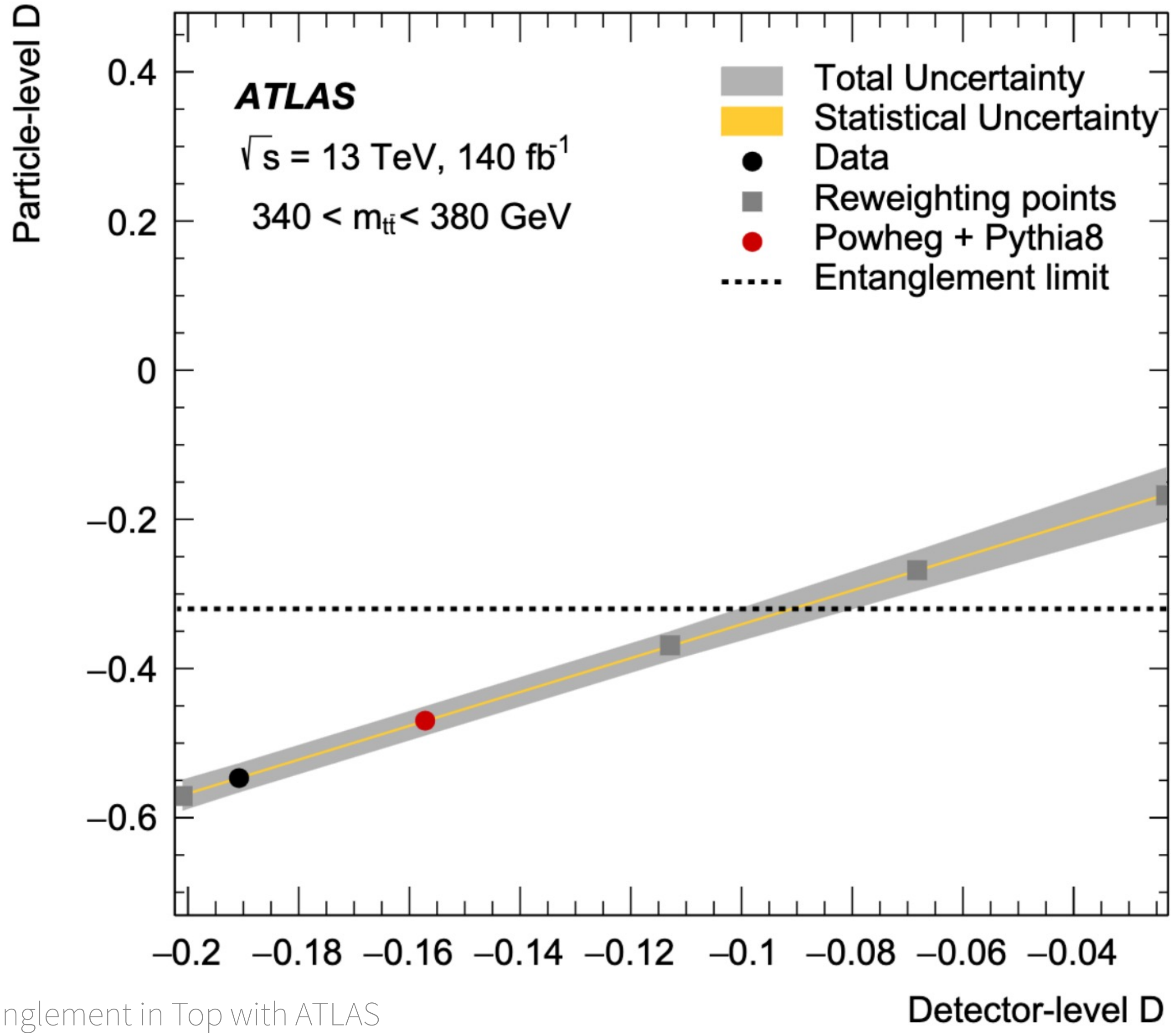
Map a measured *D* to truth-level, with associated uncertainties.



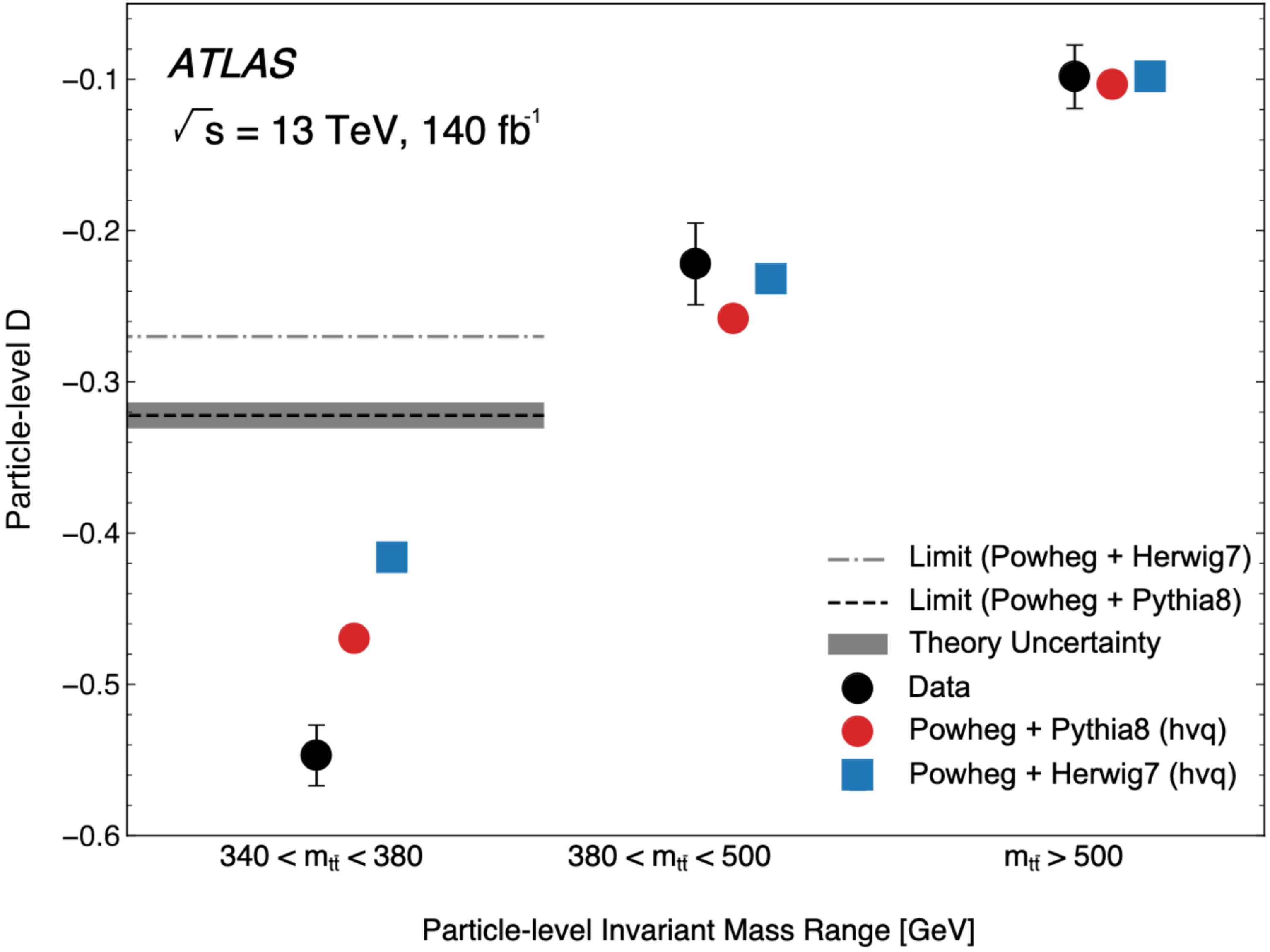
Calibration Curve

Parameterise variation in the detector effects on D.

Correction to particle-level in the Signal Region



Result: Particle-Level



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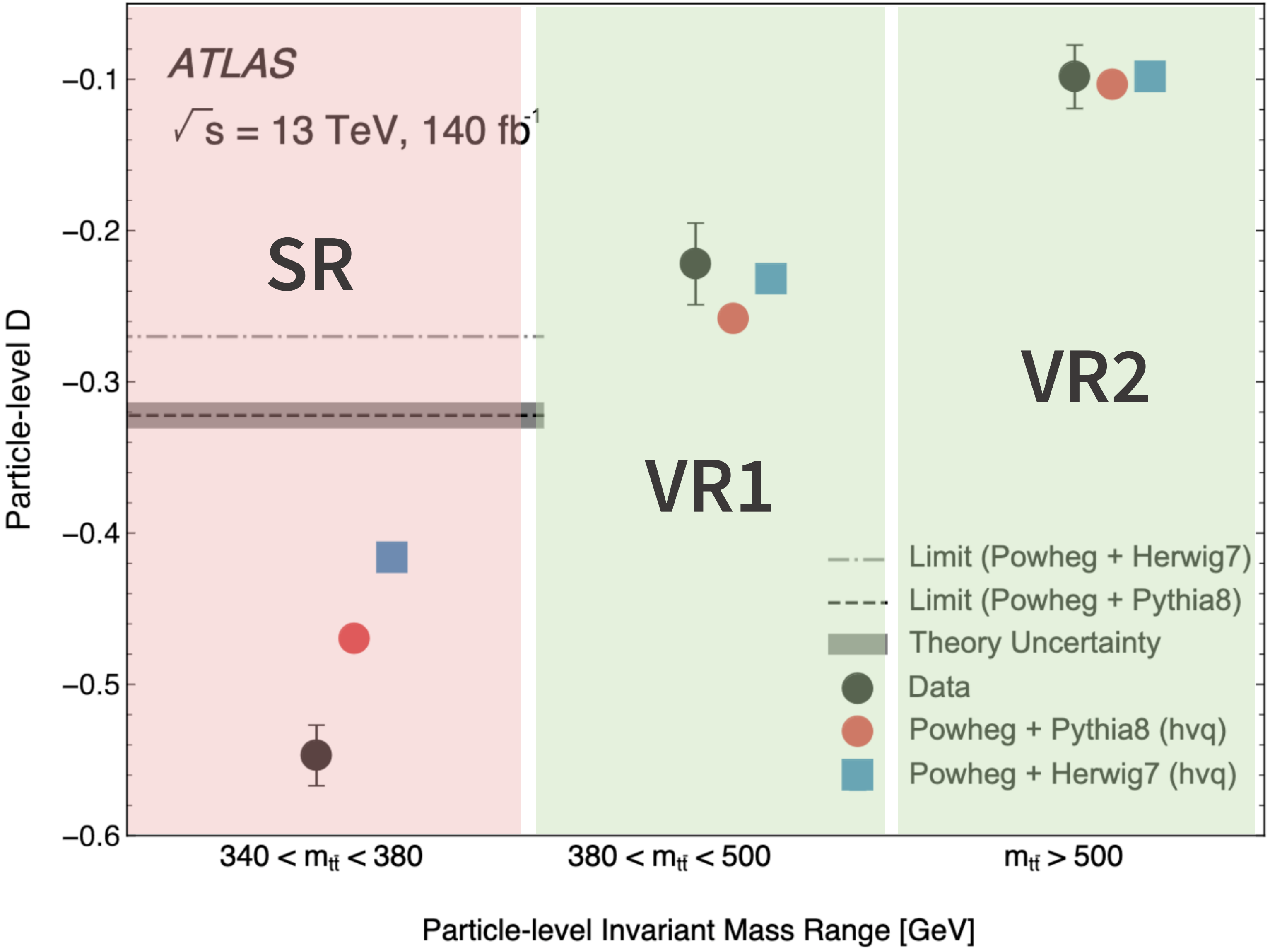
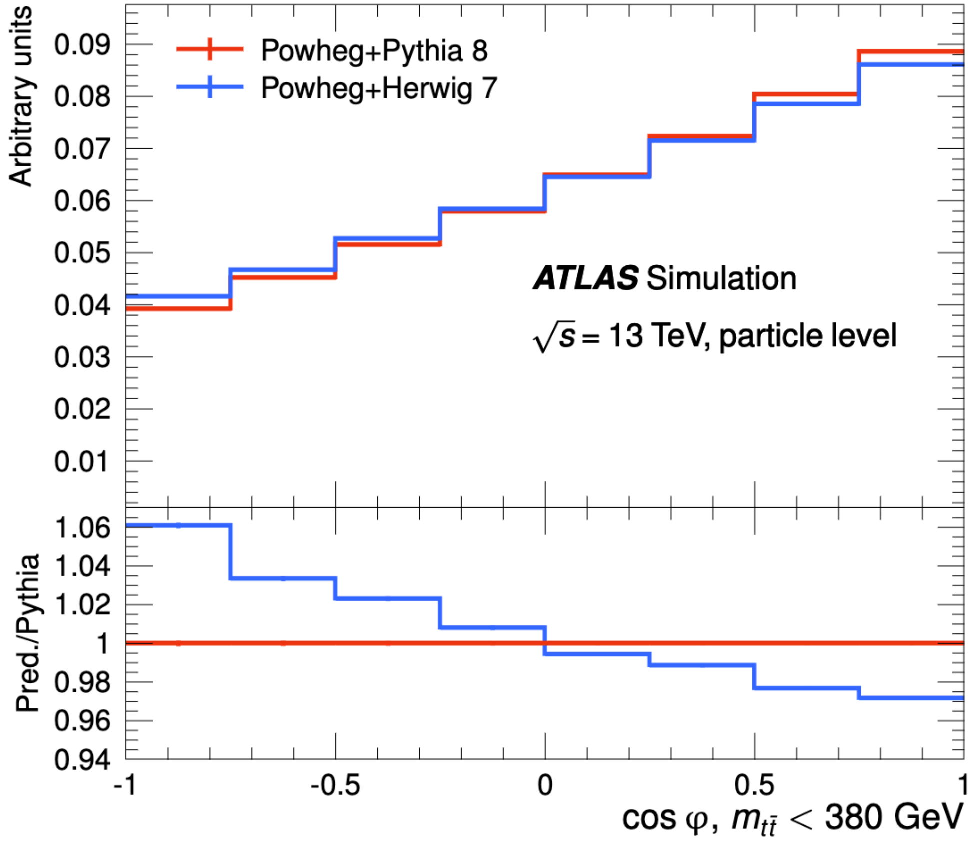


Why Particle-Level?

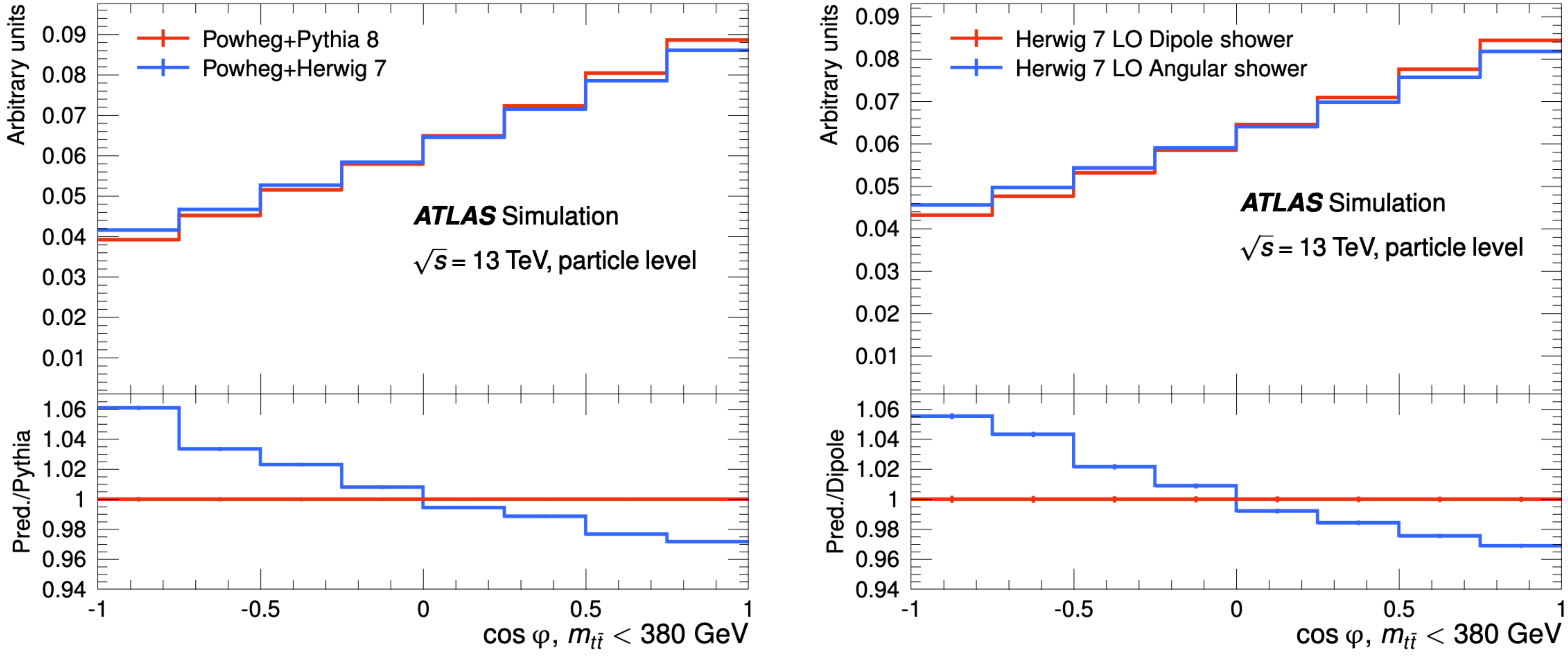
Dipole- vs angular-ordered shower



- Large difference between Pythia and Herwig
- Drives huge uncertainty under correction to parton-level

Why Particle-Level?

Dipole- vs angular-ordered shower



Cause seems to be the ordering-parameter in the shower

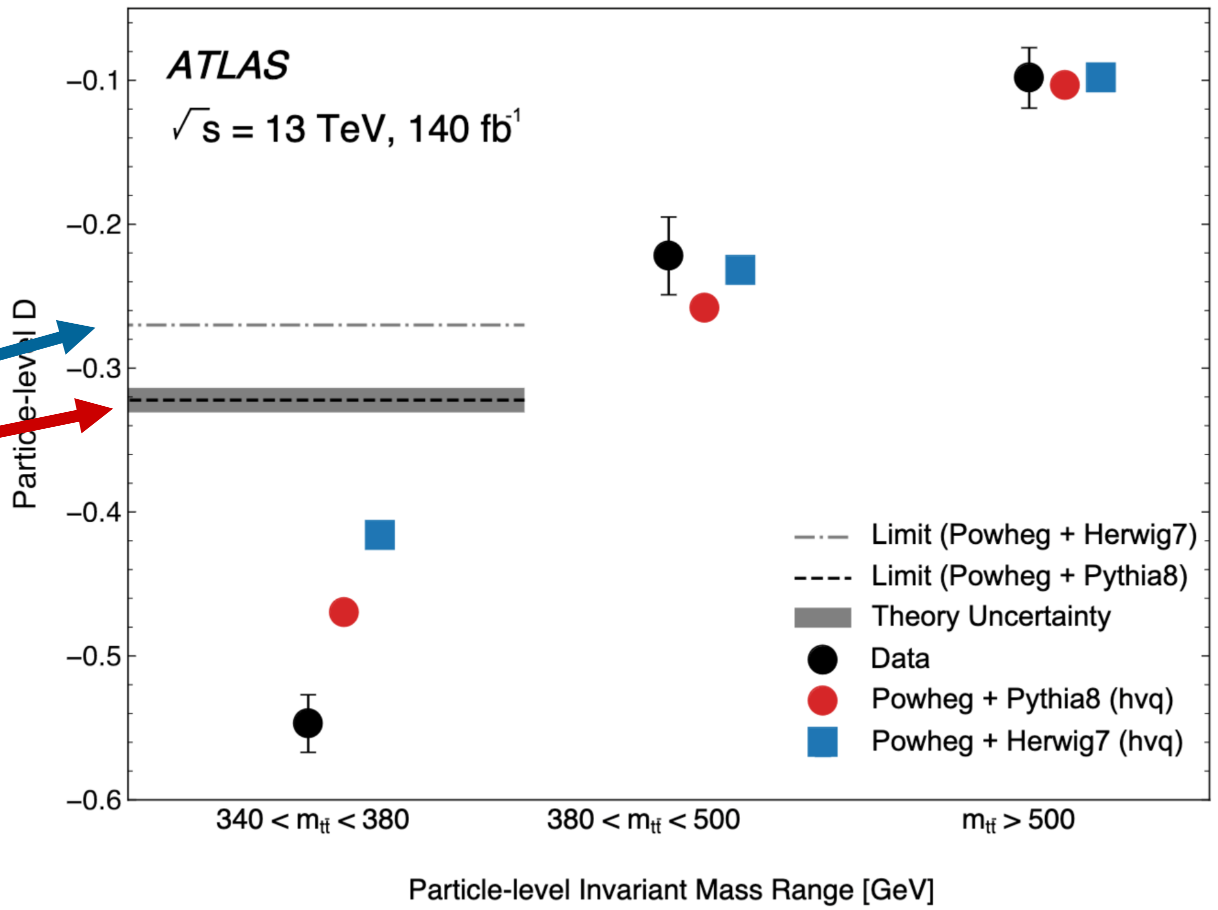
Particle-Level Entanglement Limits

Map the entanglement limit to particle-level

Use parton → particle calibration curve

This is done separately for both Pythia and Herwig

Systematics are only included on the Pythia limit (as we build our systematic model around Pythia)



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

Modelling Uncertainties

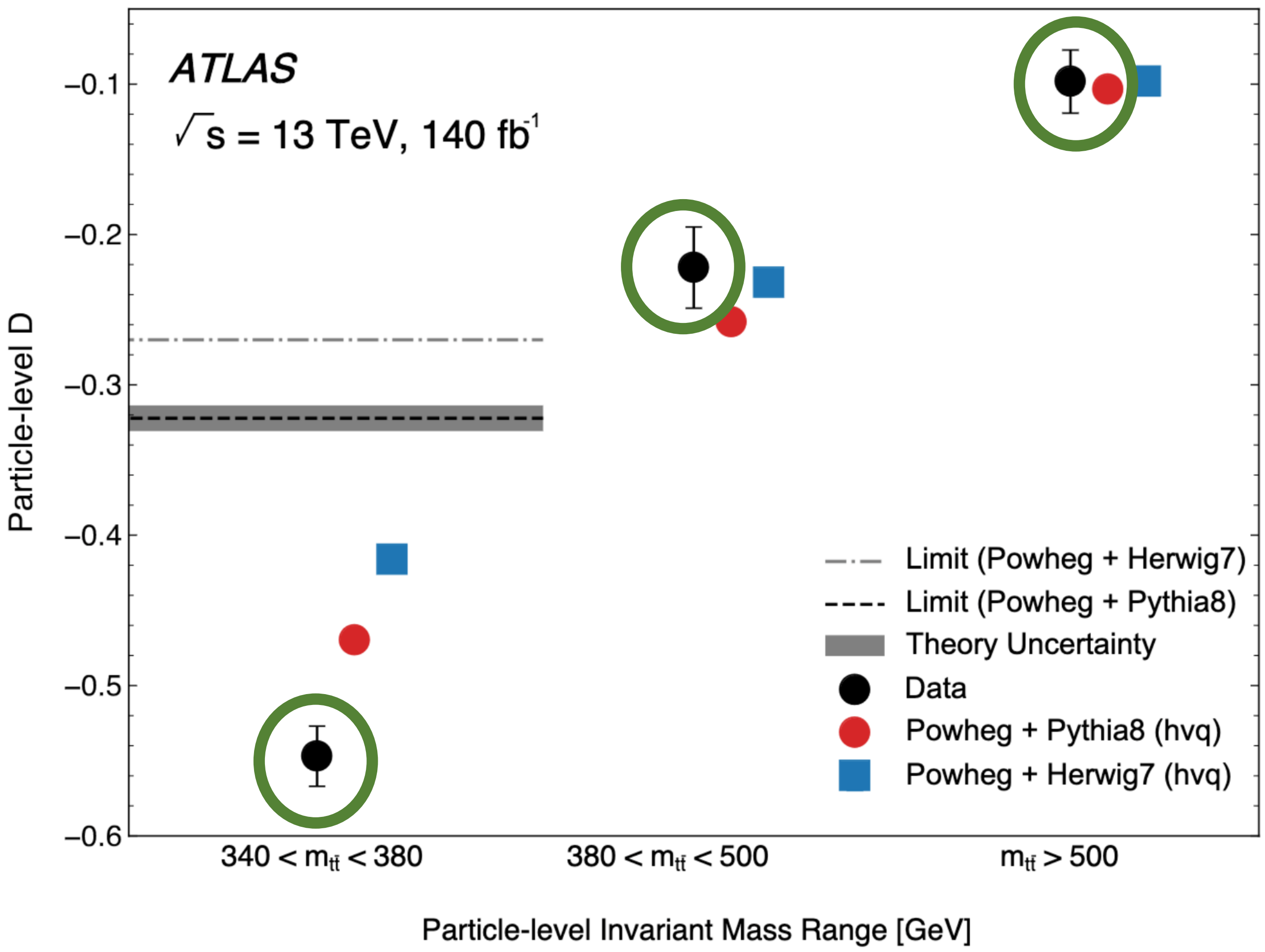
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization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

Difference between Powheg and MadSpin in handling top-quark decays

Showering uncertainty small because of correction to particle-level

Common Questions

How reliable is the calibration curve correction?



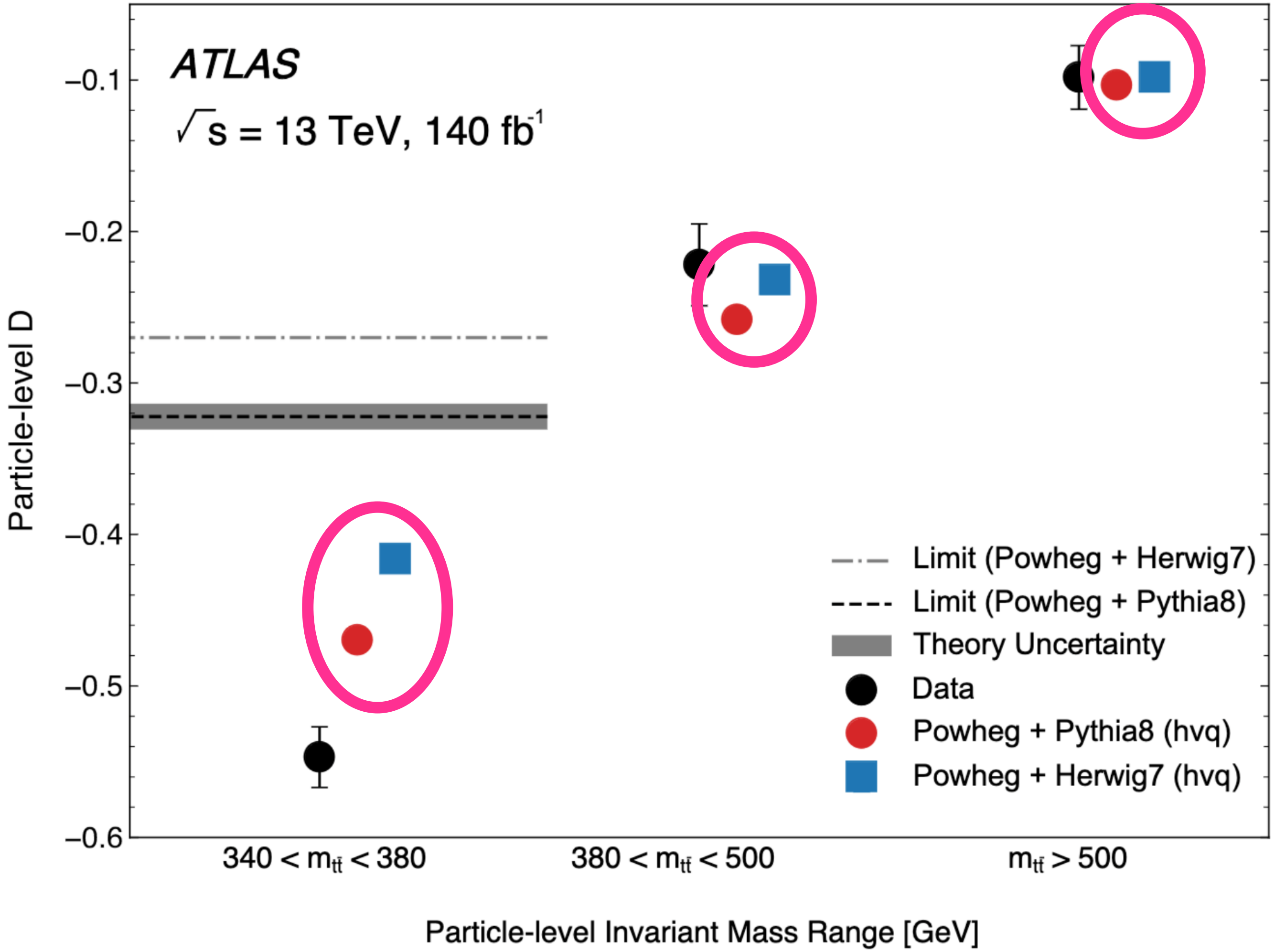
Very reliable ✓

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

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

Common Questions

How reliable are our SM predictions?



Reliable but limited

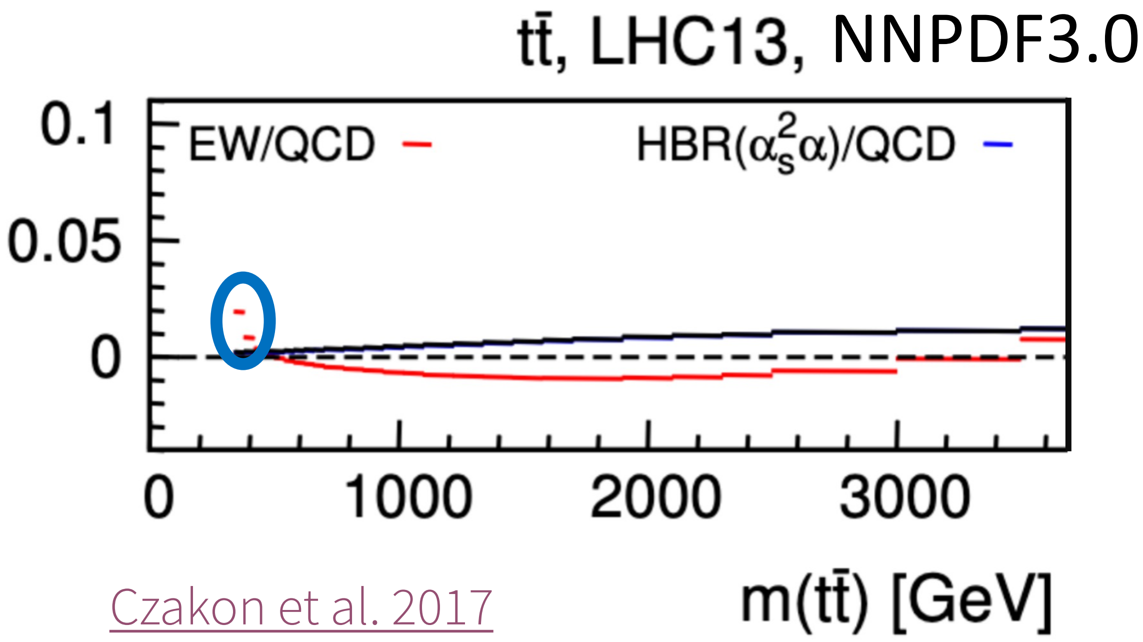
Derived from general-purpose MC event generators (powerful and widely used).

- 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

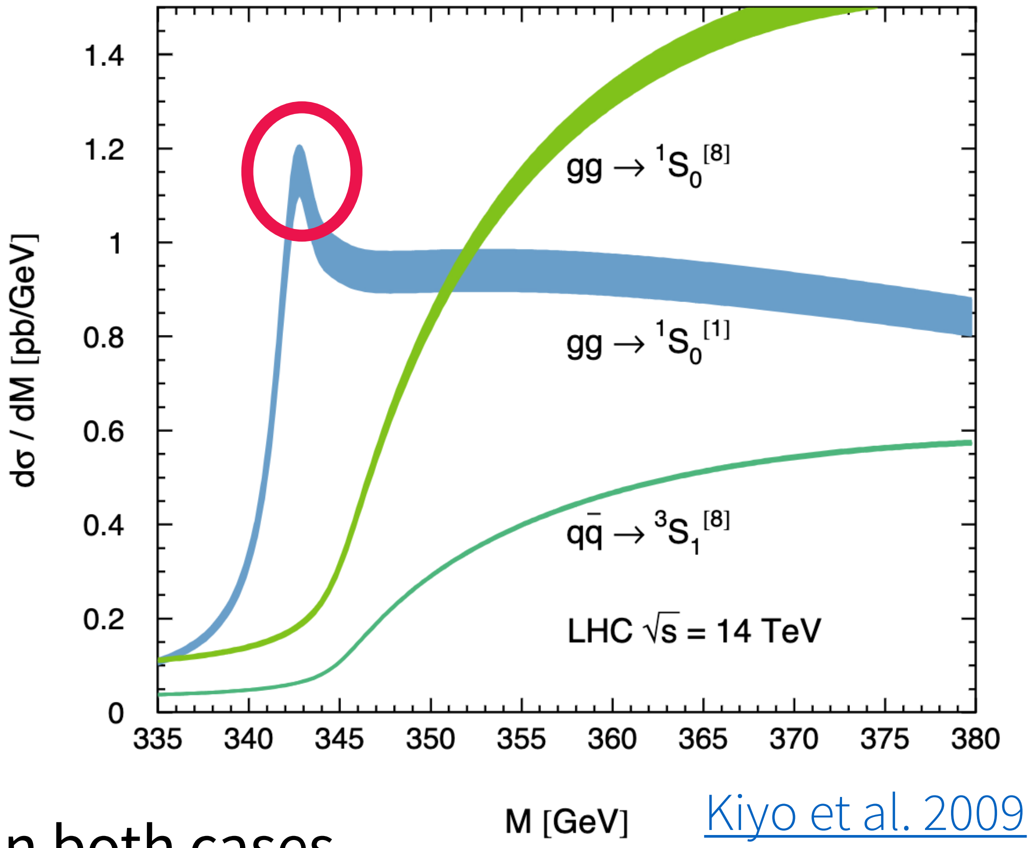
Missing Effects in Simulation

NLO EW



Czakon et al. 2017

Bound state



Kiyo et al. 2009

Cross-section enhancement near threshold in both cases.

Missing Effects in Simulation

NLO EW

Bound state

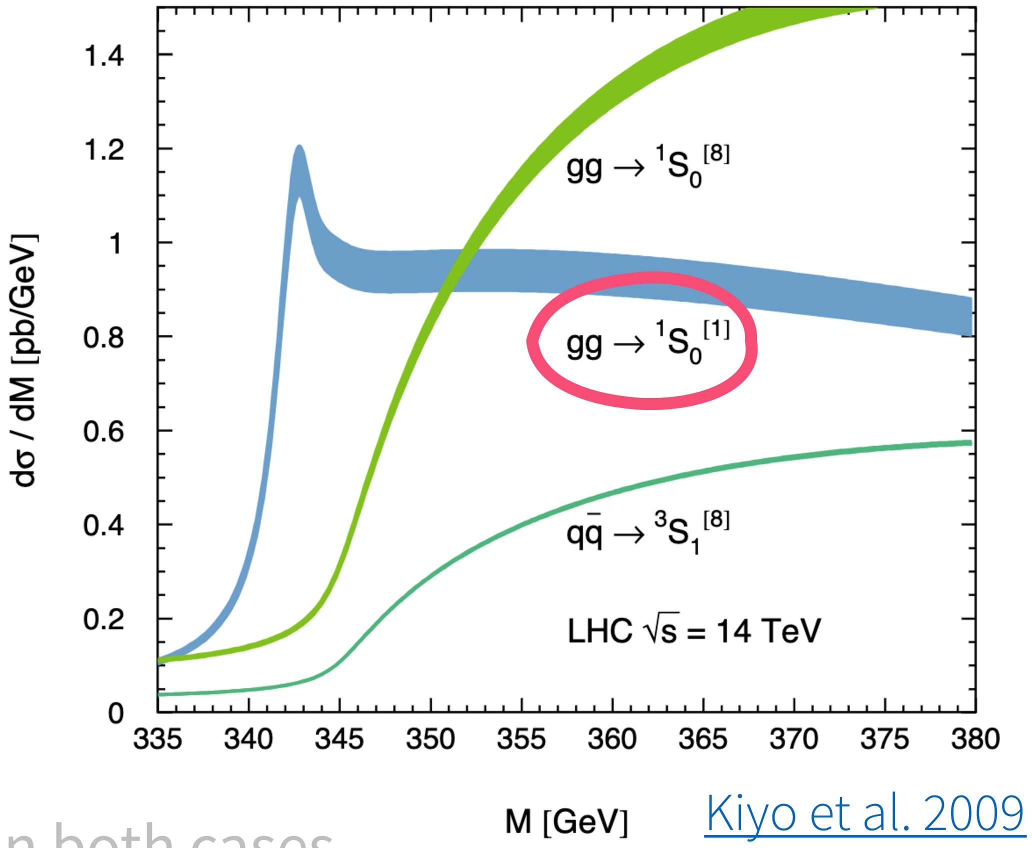
0.1

0.05

0

Enhances singlet state so should increase level of entanglement

m(tt̄) [GeV]

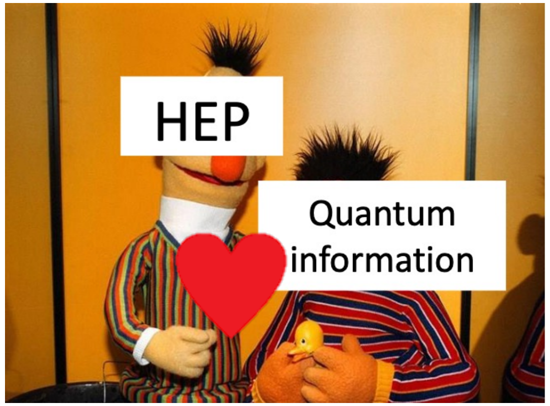


Kiyo et al. 2009

Cross-section enhancement near threshold in both cases.

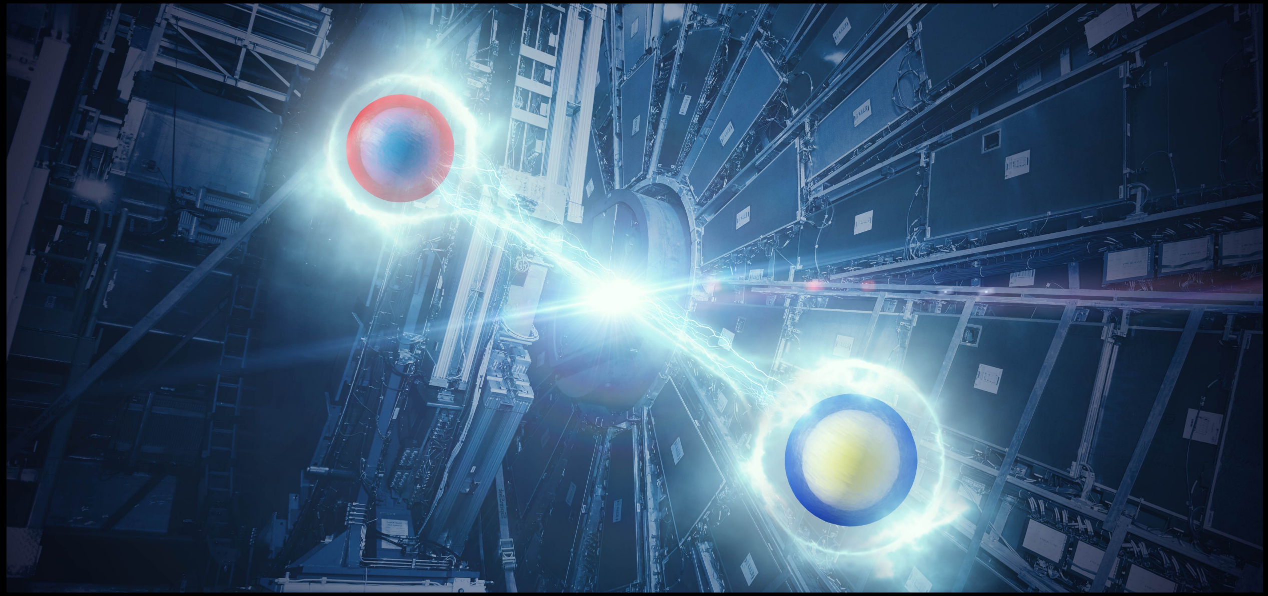
Conclusions

- **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!

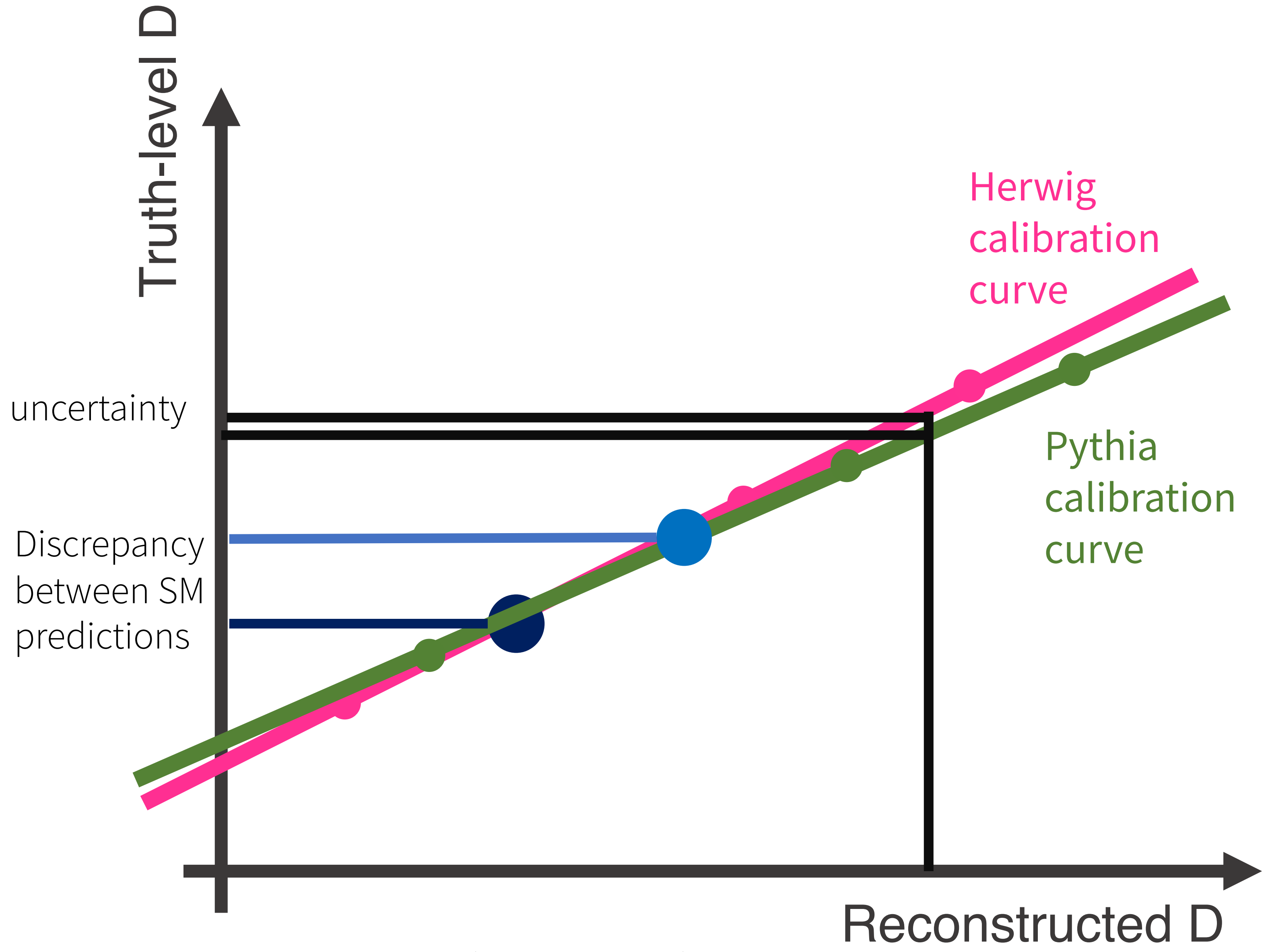


Auxiliary Materials

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

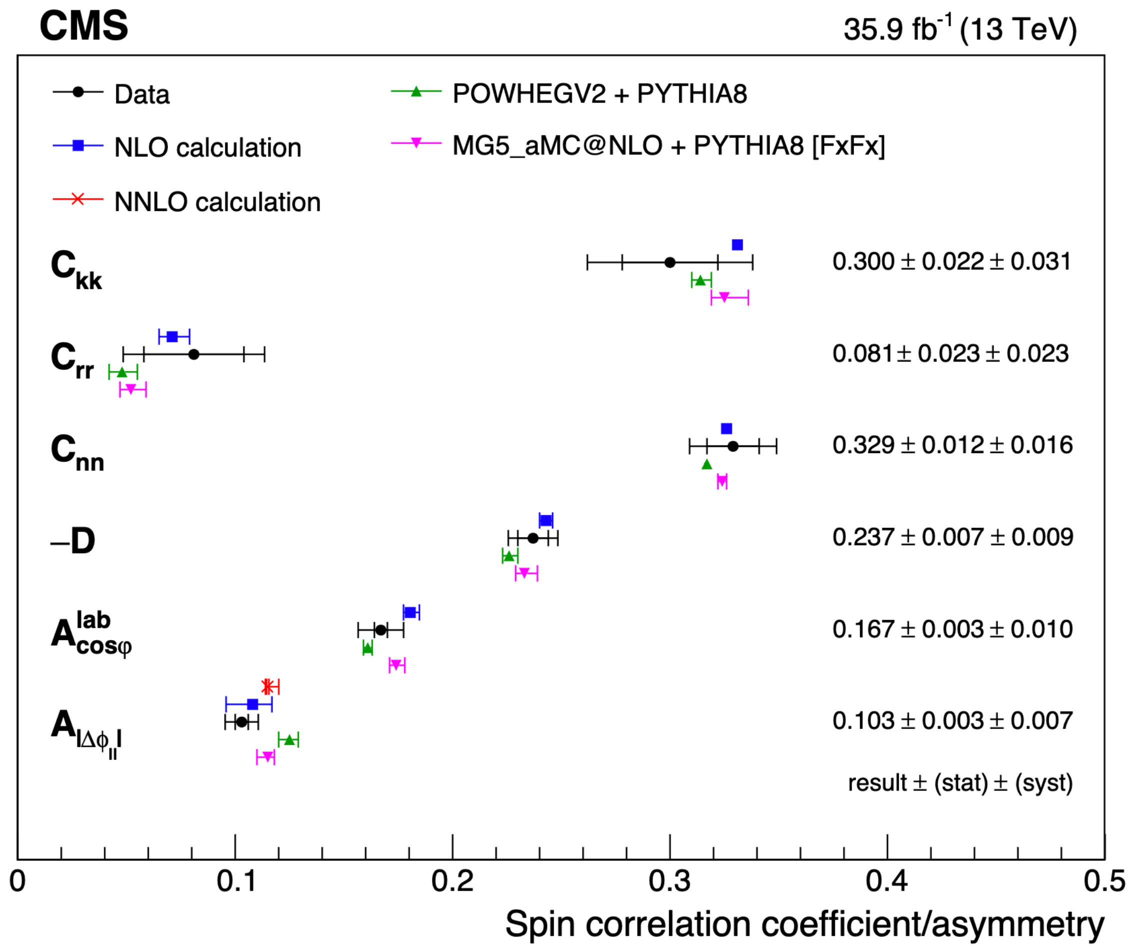
Many negligible issues are exacerbated by the narrow phase-space:

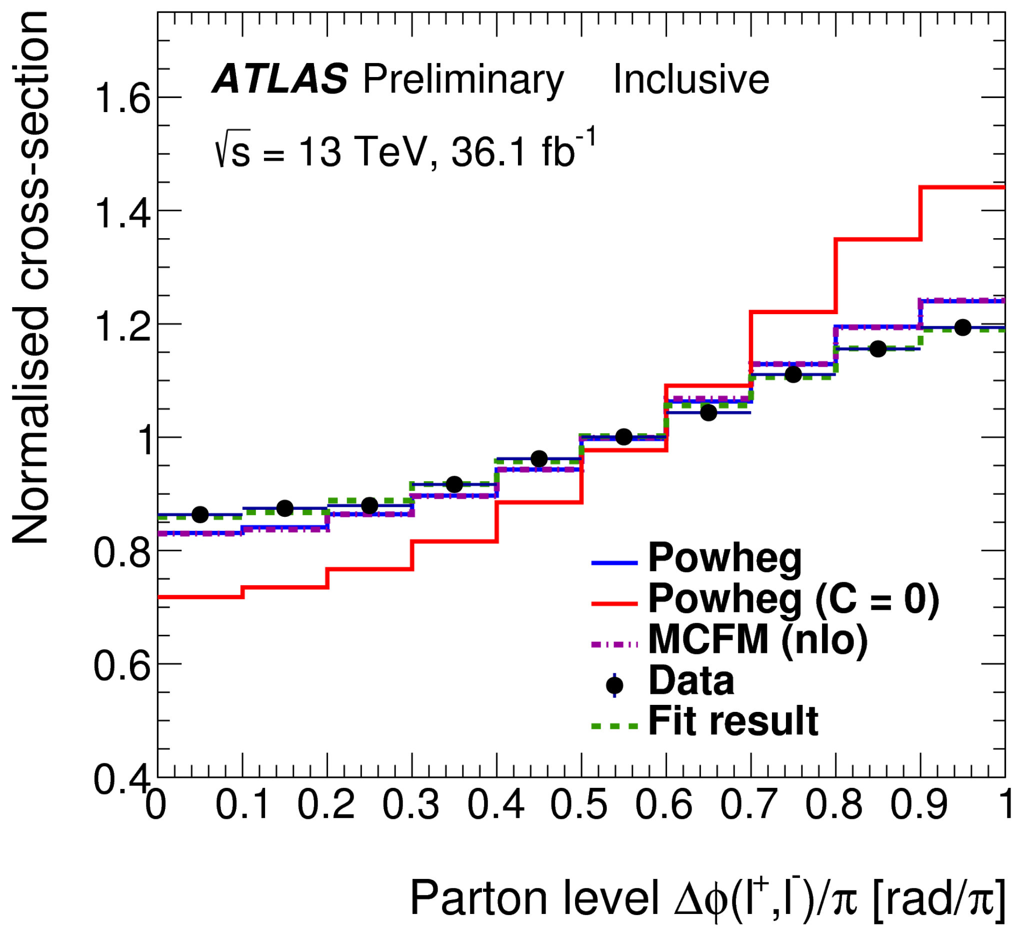
- Resolution of top reconstruction not good enough.
- Unfolding procedures biased.
- Larger discrepancies in parton showers
- Simulation lacks complete description

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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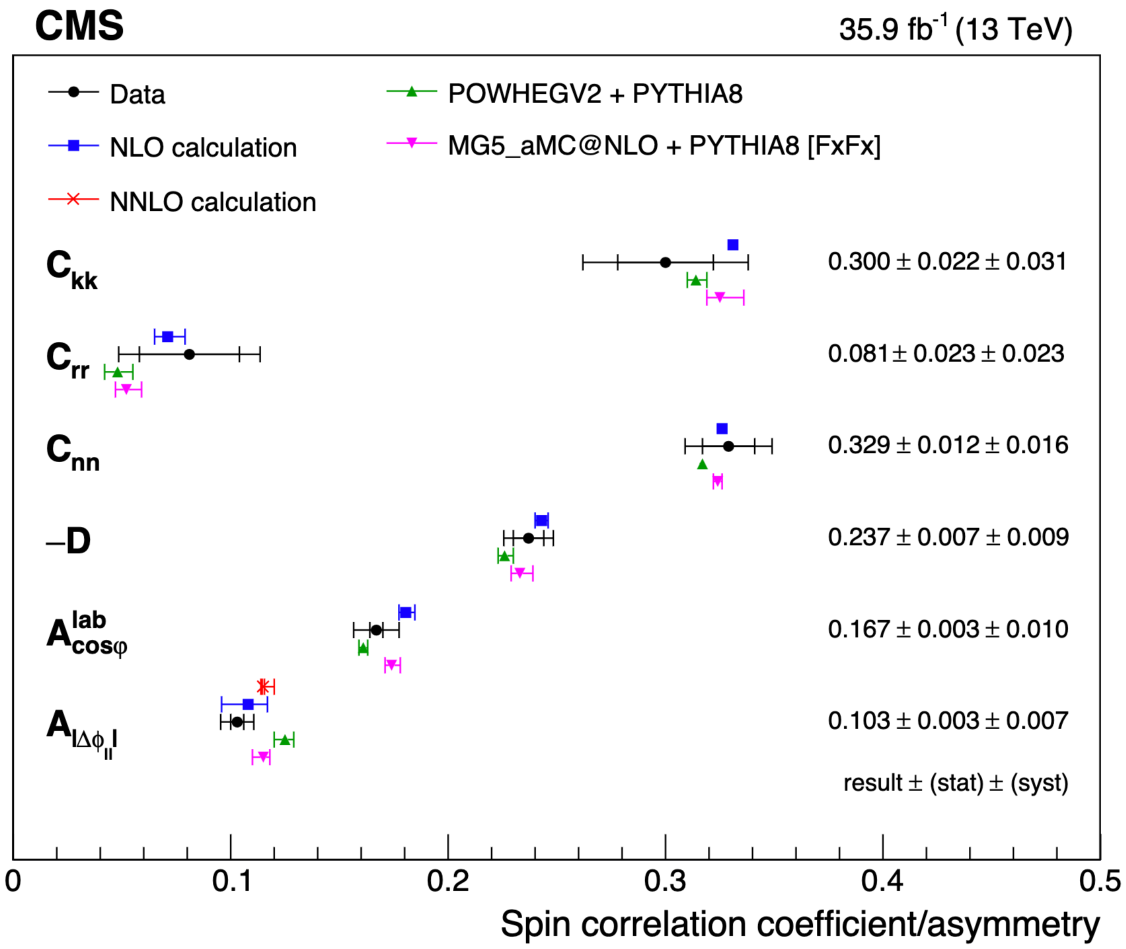

$$D = \frac{\mathrm{Tr}[\mathrm{C}]}{3} = \frac{1}{3}(C_{11} + C_{22} + C_{33})$$

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).