

Entangled in Tops

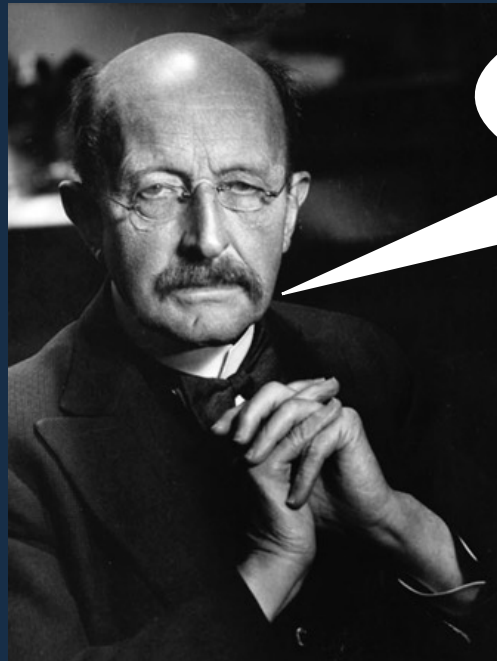
Turning the LHC into the world's
largest quantum information
experiment

Ethan Simpson,
University of Manchester

Birmingham Particle Physics
Seminar, 5th June 2024

**As a particle physicist, do
you ever think about
quantum mechanics?**

**As a particle physicist, do
you ever think about
quantum mechanics?**



Shame on you...

What about **quantum computing**?

Use **quantum computers** to improve HEP techniques

Quantum walk approach to simulating parton showers

Khadeejah Bepari, Sarah Malik, Michael Spannowsky, and Simon Williams
Phys. Rev. D **106**, 056002 – Published 2 September 2022

Quantum algorithm for Feynman loop integrals

Regular Article – Theoretical Physics | [Open access](#) | Published: 16 May 2022

Volume 2022, article number 100, (2022) [Cite this article](#)

Articles

Lattice gauge theory simulations in the quantum information era

M. Dalmonte & S. Montangero 

Pages 388-412 | Received 15 Dec 2015, Accepted 03 Feb 2016, Published online: 09 Mar 2016

Quantum Machine Learning for b -jet charge identification

Regular Article – Experimental Physics | [Open access](#) | Published: 01 August 2022

Volume 2022, article number 14, (2022) [Cite this article](#)

Quantum integration of elementary particle processes

[Gabriele Agliardi](#)^{a b} , [Michele Grossi](#)^c , [Mathieu Pellen](#)^d  , [Enrico Prati](#)^{e f} 

Quantum speedup for track reconstruction in particle accelerators

D. Magano, A. Kumar, M. Kālis, A. Locāns, A. Glos, S. Pratapsi, G. Quinta, M. Dimitrijevs, A. Rivošs, P. Bargassa, J. Seixas, A. Ambainis, and Y. Omar
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Not today's topic

Production of elementary

particle processes

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What about measuring
“quantum observables”

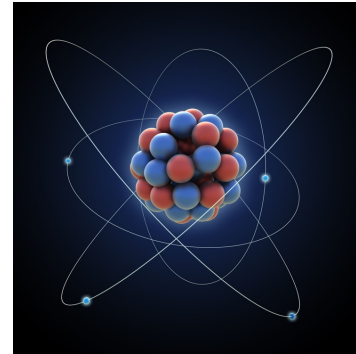
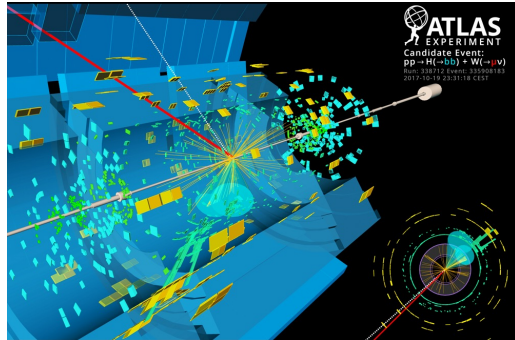
a.k.a

Testing QM in a new energy
regime?

Why?

Why measure “quantum observables” at colliders?

Quantum at different length scales...



10^{-35} m

10^{-20} m

10^{-10} m

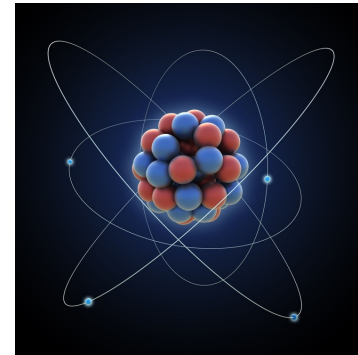
10^{-3} m

10^0 m

Why?

Why measure “quantum observables” at colliders?

Quantum mechanics
developed to describe
physics at this
length-scale



10^{-10} m

Why?

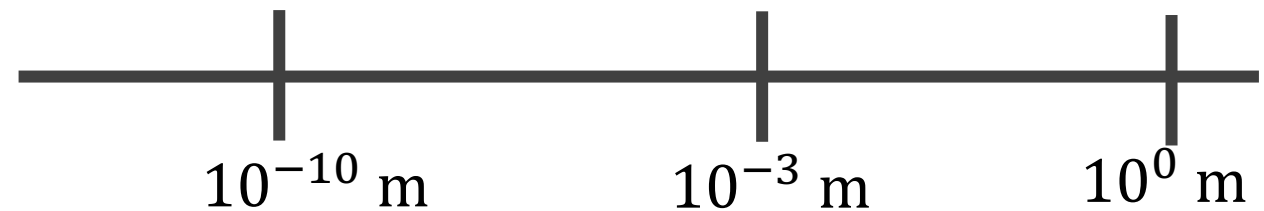
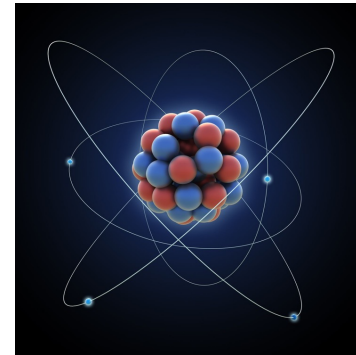
Why measure “quantum observables” at colliders?

QM phenomena at macroscopic scales:

- Quantum fluids
- Superconductivity

Harnessing QM:

- Quantum computing



Why?

Why measure “quantum observables” at colliders?



10^{-35} m

“It from qubit”...

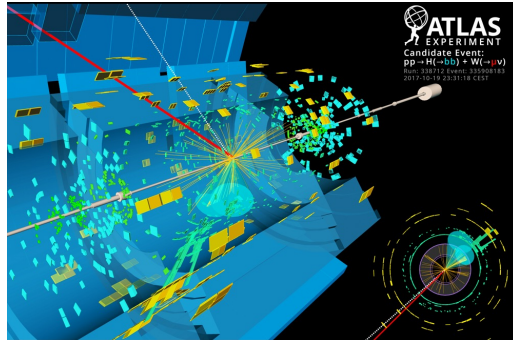
- What is the information-theoretic structure of QFTs?
- Is spacetime an emergent property of quantum entanglement?

Further reading:

- [Simons Collaboration on Quantum Fields, Gravity and Information](#)
- [Spacetime from Entanglement](#)

Why?

Why measure “quantum observables” at colliders?



10^{-20} m

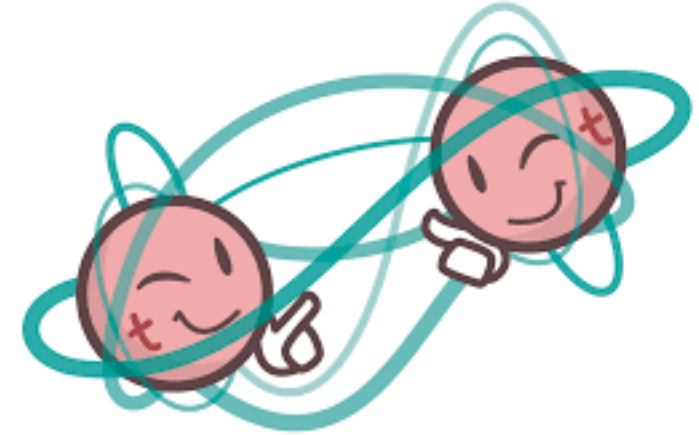
- Does QM look different in QFT regime?
- Test “beyond QM” ...
- There’s more to life than (not) finding New Physics
- Can quantum observables help us look for New Physics?

Quantum Entanglement

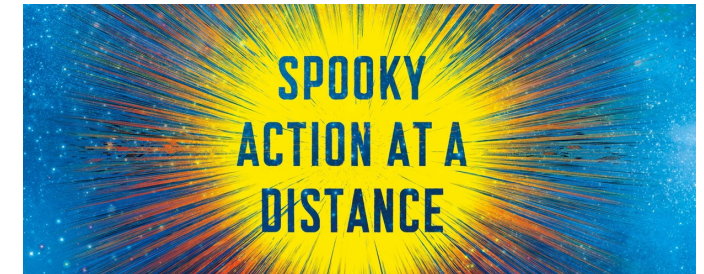
“the most characteristic trait of QM”

Quantum Entanglement

- **Correlations** between quantum numbers.
- **Shared** internal degrees of freedom



You cannot write down a description of one particle without describing the other...



Measurement of the Entanglement of Two Superconducting Qubits via State Tomography

MATTHIAS STEFFEN, M. ANSMANN, RADOSLAW C. BIALCZAK, N. KATZ, ERIK LUCERO, R. MCDERMOTT, MATTHEW NEELE

[Authors Info & Affiliations](#)

Experimental determination of entanglement with a single measurement

[S. P. Walborn](#) , [P. H. Souto Ribeiro](#), [L. Davidovich](#), [F. Mintert](#) & [A. Buchleitner](#)

Stabilized entanglement of massive mechanical oscillators

[C. F. Ockeloen-Korppi](#), [E.](#)
& [M. A. Sillanpää](#) 

Entangling Macroscopic Diamonds at Room Temperature

K. C. LEE, M. R. SPRAGUE, B. J. SUSSMAN, J. NUNN, N. K. LANGFORD, X.-M. JIN, T. CHAMPION, F.

Experimental Test of Local Hidden-Variable Theories





Stuart J. Freedman and John F. Clauser
Phys. Rev. Lett. **28**, 938 – Published 3 April 1972

Observation of quantum Hawking radiation and its entanglement in an analogue black hole

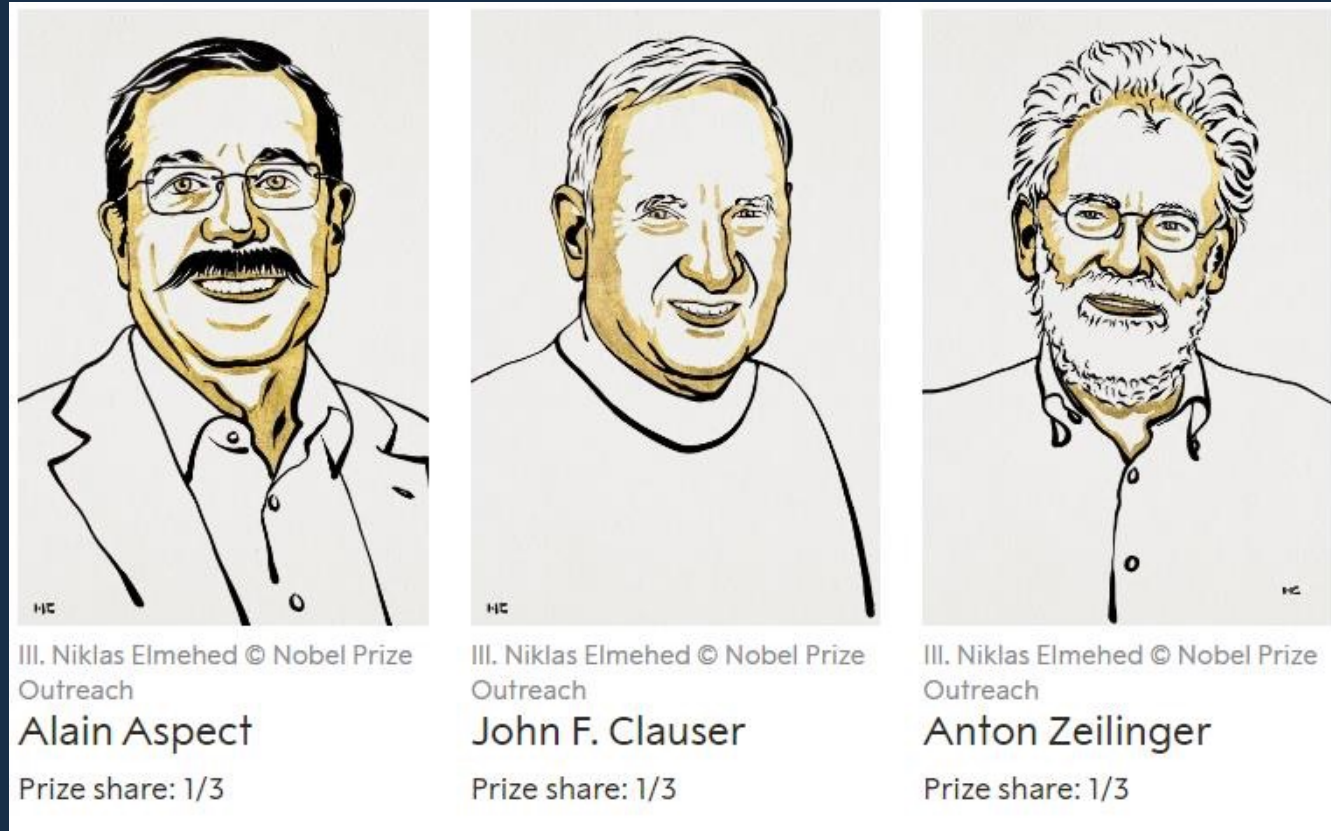
[Jeff Steinhauer](#) 

PAPER • **OPEN ACCESS**

Entanglement in a qubit-qubit-tardigrade system

K S Lee^{8,1} , Y P Tan¹, L H Nguyen¹, R P Budoyo², K H Park², C Hufnagel², Y S Yap^{2,3} ,
N Møbjerg⁴ , V Vedral^{2,5,6}, T Paterek⁷  [Show full author list](#)

2022 Nobel Prize



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

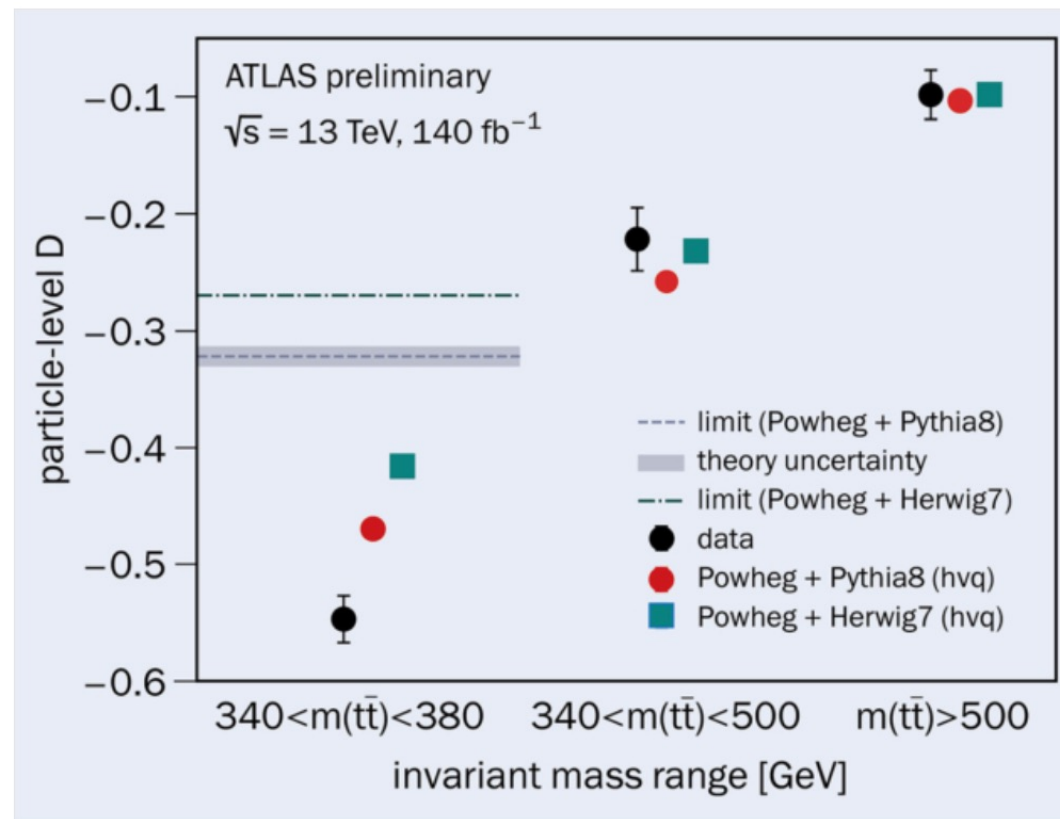


STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.



Entanglement in HEP

Measurement of EPR-type flavour entanglement in $Upsilon(4S) \rightarrow B^0 B^0_{\text{bar}}$ decays

A. Go, A. Bay, et al. (for the Belle Collaboration)

Flavour entanglement
(2007)

Bell inequality is violated in $B^0 \rightarrow J/\psi K^*(892)^0$ decays

M. Fabbrichesi^a, R. Floreanini^a, E. Gabrielli^{b,a,c,d} and L. Marzola^d

^a INFN, Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy

^b Physics Department, University of Trieste, Strada Costiera 11, I-34151 Trieste, Italy

^c CERN, Theoretical Physics Department, Geneva, Switzerland and

^d Laboratory of High-Energy and Computational Physics, NICPB, R vala 10, 10143 Tallinn, Estonia

Polarisation
entanglement
(2023)

Observation of quantum entanglement in top-quark pairs using the ATLAS detector

ATLAS Collaboration

Spin entanglement
(2023)

Strategy

1. Define a mathematical (QM) description of $t\bar{t}$ production
2. Condense description down into a single **entanglement marker**

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3. Measure an **angular observable** in $t\bar{t}$ data
4. Extract the entanglement marker from this angular distribution

Strategy

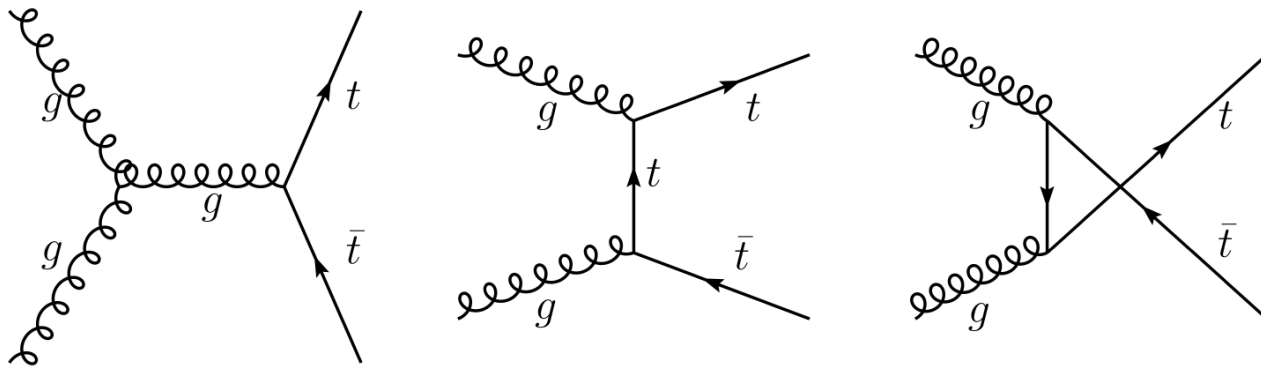
1. Define a mathematical (QM) description of $t\bar{t}$ production
2. Condense description down into a single **entanglement marker**
3. Measure an **angular observable** in $t\bar{t}$ data
4. Extract the entanglement marker from this angular distribution
5. Compare the measured value to a **no-entanglement limit**
6. Defend against claims this is “spin correlation window dressing”

Aside: The Top Quark

The Top Quark

We have produced **tens of millions** of top quarks at the LHC.

Tops have several **unique properties** which make them useful for quantum information studies.



$t\bar{t}$ production

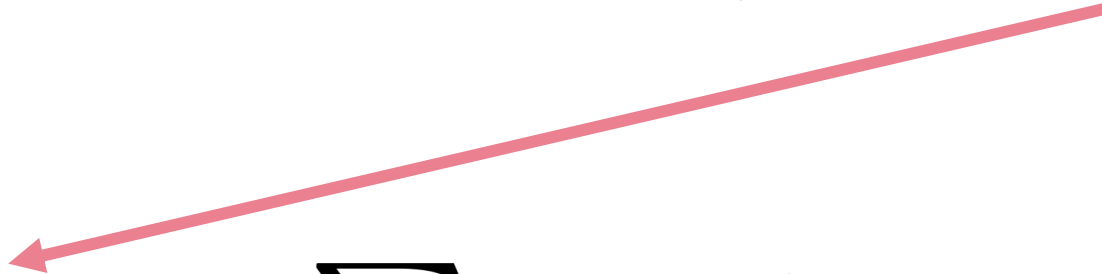
In terms of density matrices

$$\sigma_{t\bar{t}} \propto \text{Tr} \left[\underbrace{\Gamma_{\bar{t} \rightarrow \bar{b} f f}}_{\text{Decay}} \times \underbrace{R_{gg \rightarrow t\bar{t}}}_{\text{Production}} \times \underbrace{\Gamma_{t \rightarrow b f f}}_{\text{Decay}} \right]$$

$t\bar{t}$ production

In terms of **density matrices**

$$\sigma_{t\bar{t}} \propto \text{Tr} \left[\underbrace{\Gamma_{\bar{t} \rightarrow \bar{b} f f}}_{\text{Decay}} \times \underbrace{R_{gg \rightarrow t\bar{t}}}_{\text{Production}} \times \underbrace{\Gamma_{t \rightarrow b f f}}_{\text{Decay}} \right]$$

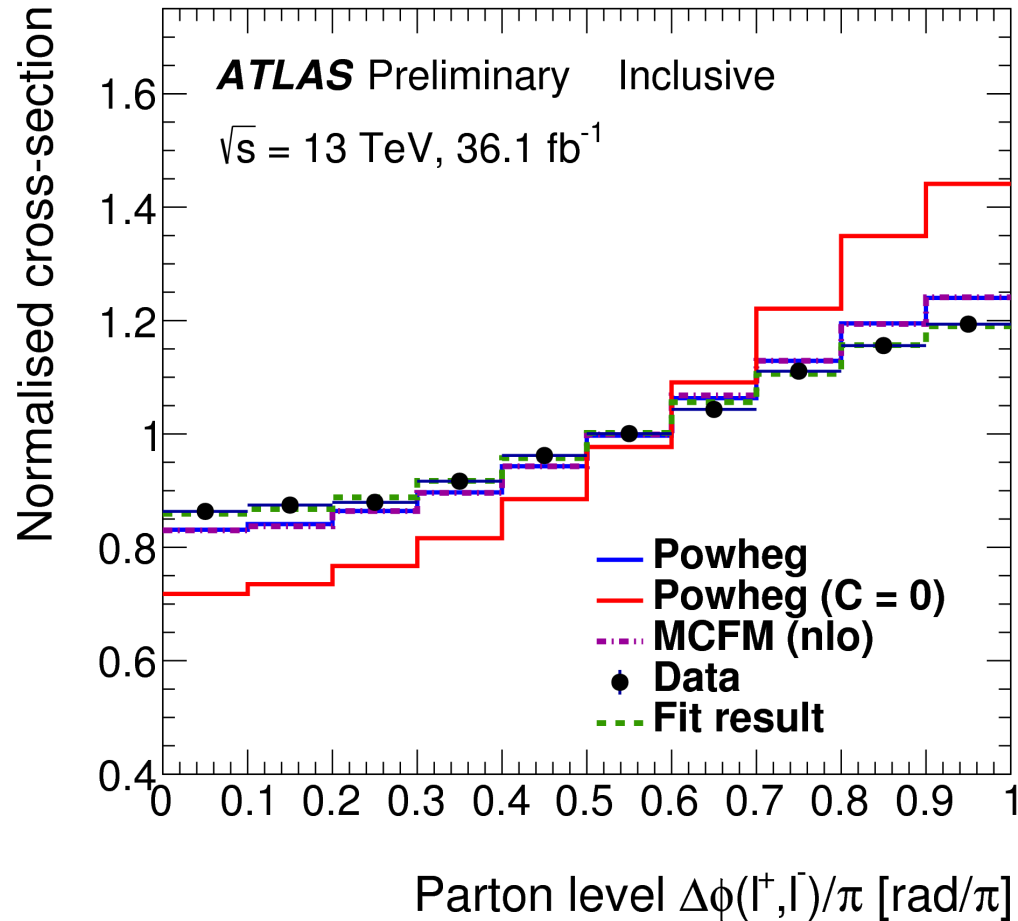

$$R = A + \sum_i \left(\underbrace{B_i^+}_{\text{Polarisations}} \sigma^i + \underbrace{B_i^-}_{\text{Polarisations}} \bar{\sigma}^i \right) + \sum_{i,j} \underbrace{C_{ij}}_{\text{Correlations}} \sigma^i \bar{\sigma}^j$$

(of individual tops)

(between tops' spins)

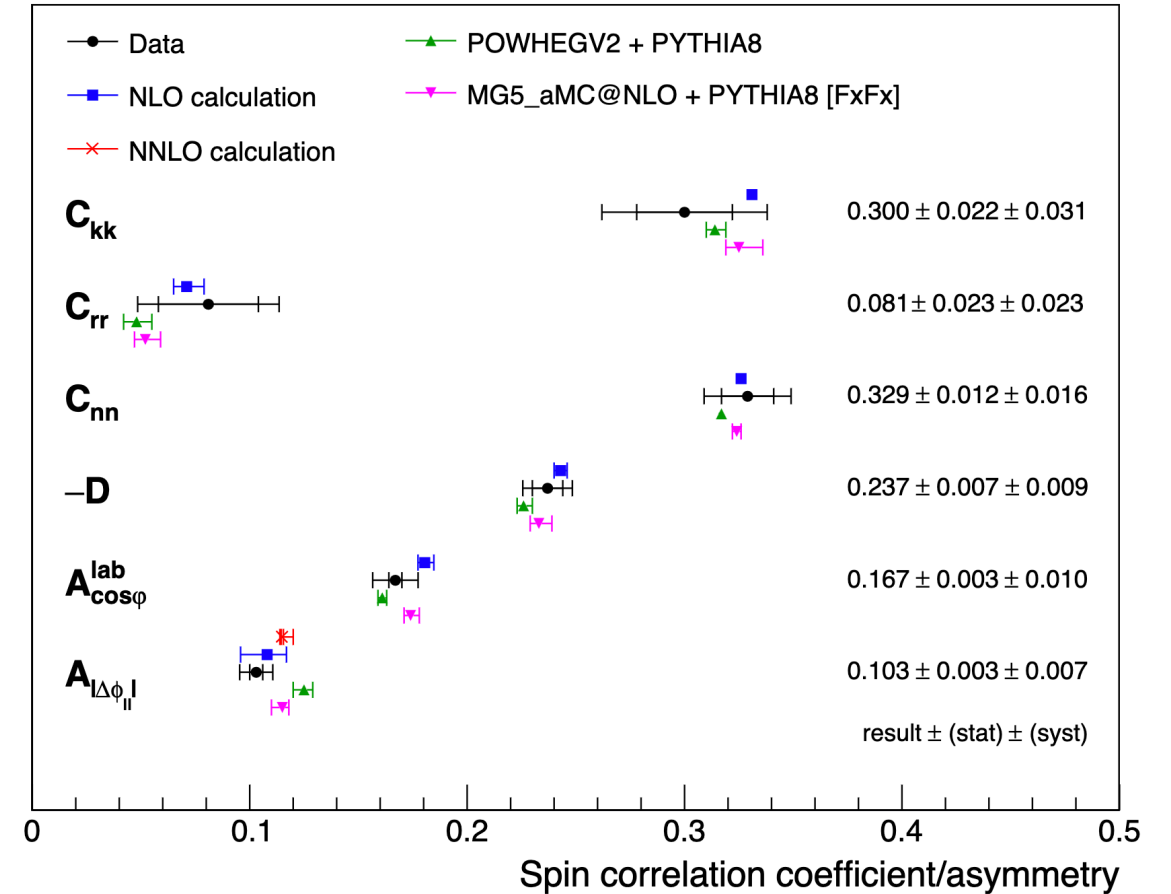
Spin correlation measurements

History of $t\bar{t}$ spin measurements at the LHC



CMS

35.9 fb^{-1} (13 TeV)



Accessing Top Spin

Decays so quickly, spin information retained

Production

$$\frac{1}{m(t)} \sim 10^{-27} \text{ s}$$

\ll

Lifetime

$$\frac{1}{\Gamma(t)} \sim 10^{-25} \text{ s}$$

\ll

Hadronisation

$$\frac{1}{\Lambda_{QCD}} \sim 10^{-24} \text{ s}$$

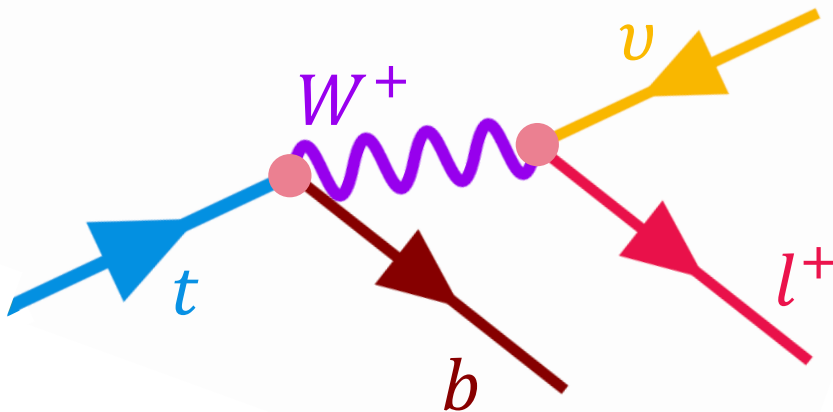
\ll

Spin decorr.

$$\frac{m(t)}{\Lambda_{QCD}} \sim 10^{-22} \text{ s}$$

Weak decay does something magic...

The spin information of the quark...



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



QI Theory

Quantum States

Pure quantum system:
vector in a Hilbert space

$$|\Psi\rangle = \sum_n \alpha_n |\phi_n\rangle$$

Mixed quantum system:
density operator in Hilbert space

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



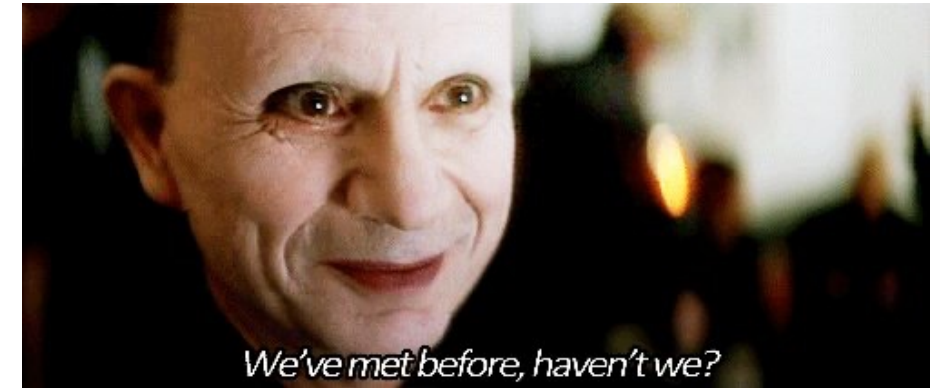
Old Friend

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

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

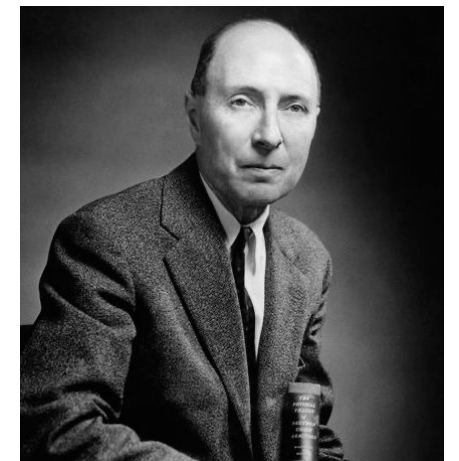
(of individual tops)

(between tops' spins)



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

(“The unreasonable effectiveness of mathematics” - Wigner)



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
```



Entanglement

Is the density matrix **factorisable**?

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

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if density_matrix.separable == False:  
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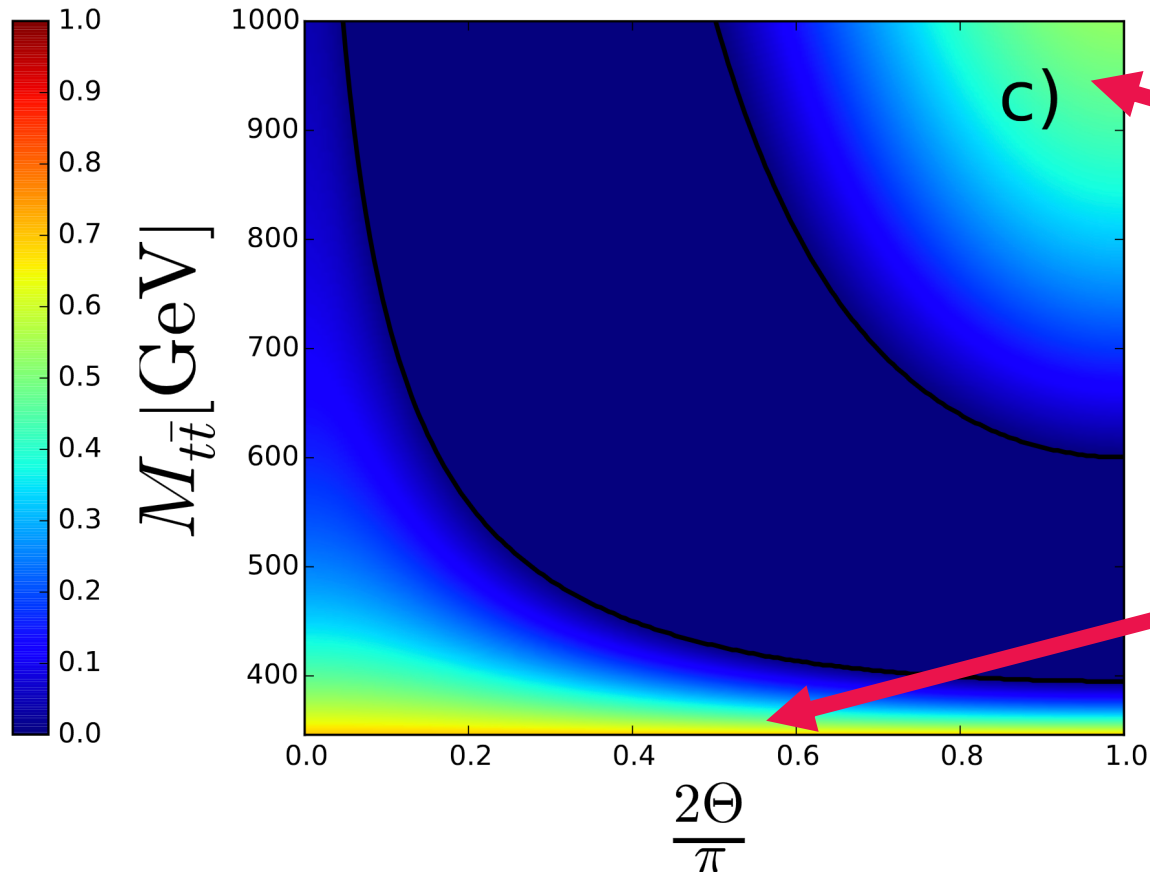


Quantum Separability Problem: Determining whether an arbitrary density matrix is separable is in general NP-hard [[arXiv:0303055](https://arxiv.org/abs/0303055)].

Concurrence

A 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

Alternative entanglement definition

Quantum entanglement

Ryszard Horodecki ¹ Paweł Horodecki ³ Michał Horodecki ¹, Karol Horodecki ^{1,2}

¹ Institute of Theoretical Physics and Astrophysics University of Gdańsk, 80-952 Gdańsk, Poland

² Faculty of Mathematics, Physics and Computer Science University of Gdańsk, 80-952 Gdańsk, Poland and

³ Faculty of Applied Physics and Mathematics, Technical University of Gdańsk, 80-952 Gdańsk, Poland



Peres-Horodecki

Alternative entanglement definition

Quantum entanglement

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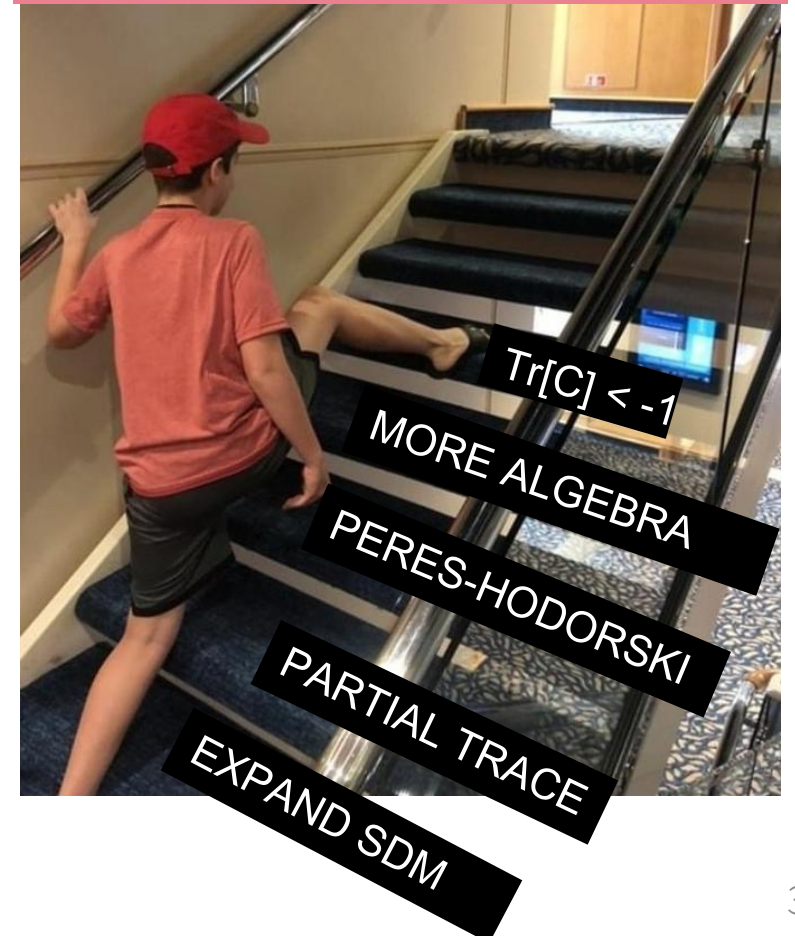
Perform linear algebra operations to trace out one of the sub-systems

Partial trace

$$\rho \rightarrow \rho^t$$

Do we still have a density matrix after this operation?
If so, state is **not** entangled...

Much linear algebra...



Peres-Horodecki

A measure of **how entangled?**



$$\rho = \frac{1}{4} \begin{bmatrix} 1 + B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} - i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} - C_{22} - i(C_{12} + C_{21}) \\ B_1^- + C_{31} + i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) & B_1^+ - C_{13} - i(B_2^+ - C_{23}) \\ B_1^+ + C_{13} + i(B_2^+ + C_{23}) & C_{11} + C_{22} + i(C_{21} - C_{12}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} - i(B_2^- - C_{32}) \\ C_{11} - C_{22} + i(C_{21} + C_{12}) & B_1^+ - C_{13} + i(B_2^+ - C_{23}) & B_1^- - C_{31} + i(B_2^- - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

is separable?

$$(C_{11} + C_{22} + C_{33}) < -1$$

Spin correlations we can measure!

Peres-Horodecki

Accessing *experimentally*

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

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

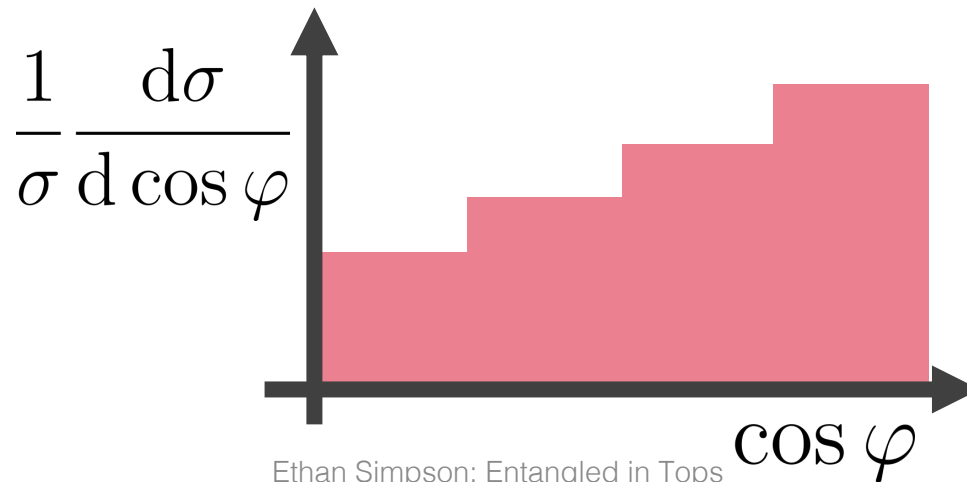
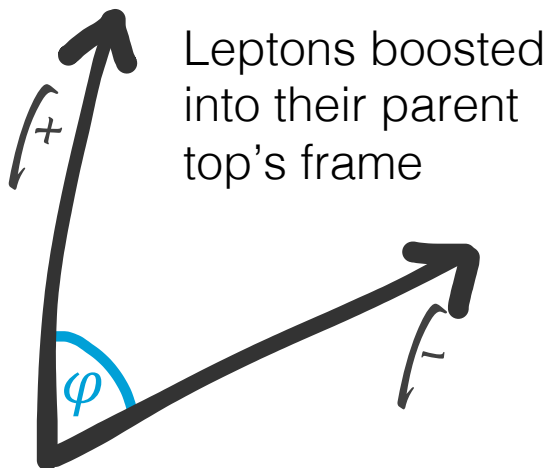
Peres-Horodecki

Accessing **experimentally**

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

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

D can be extracted from a single angular distribution:



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

Summary

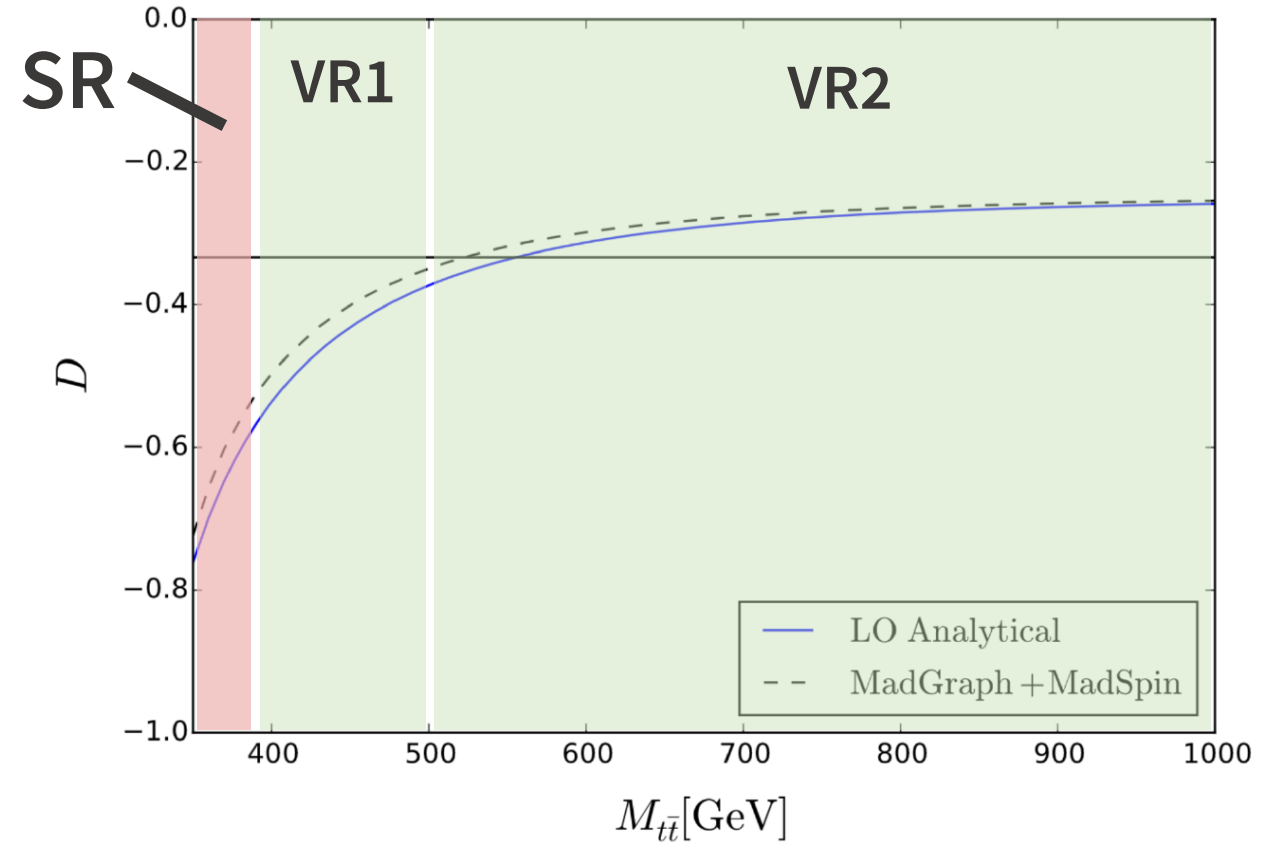
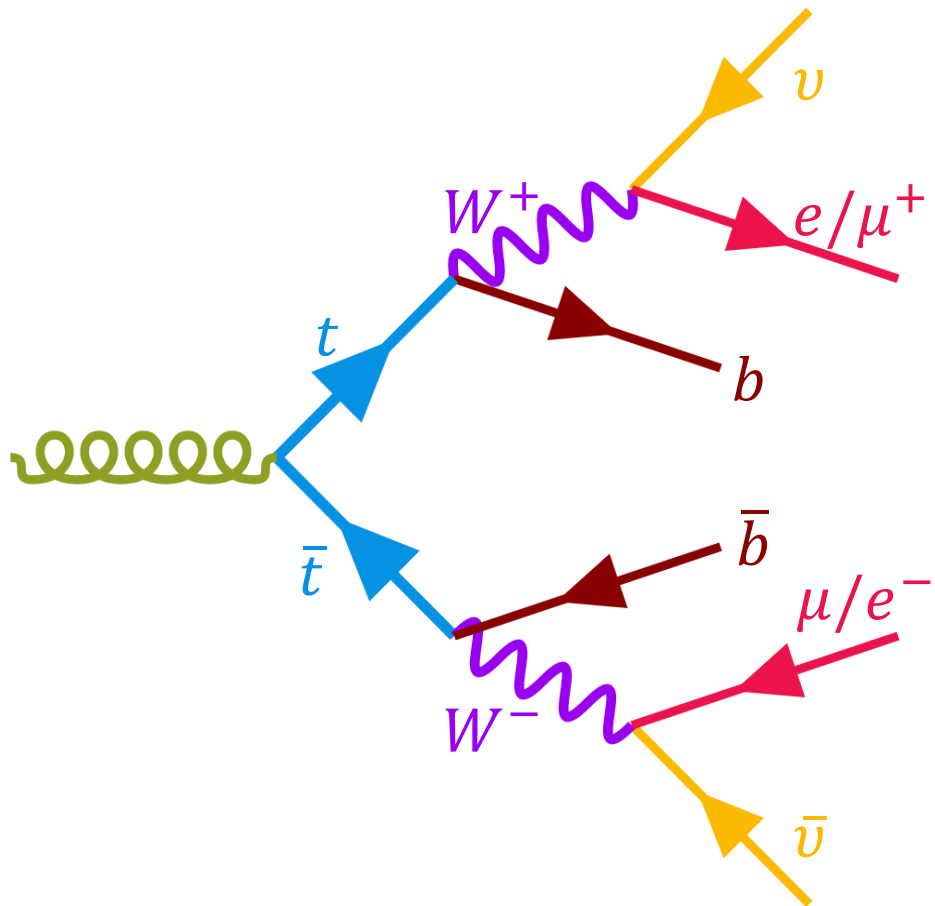
- $t\bar{t}$ production is described by a **density matrix**.
- **Entanglement** is **non-separability** of the density matrix
- Measure entanglement through one **angular observable, D** .

ATLAS Measurement

Selections



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



Signal / Background

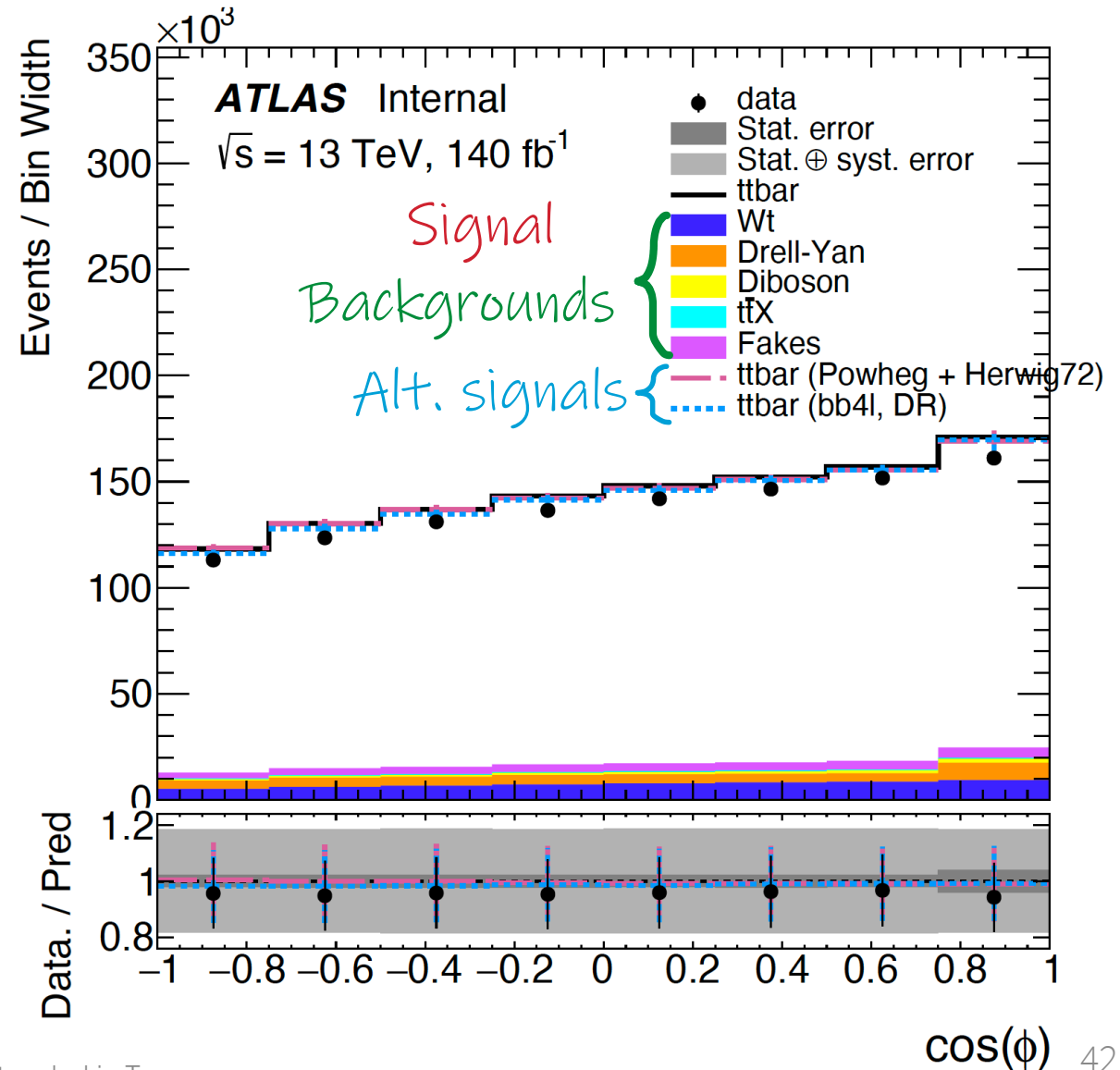
Signal

Modelled using MC simulation:

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

Background

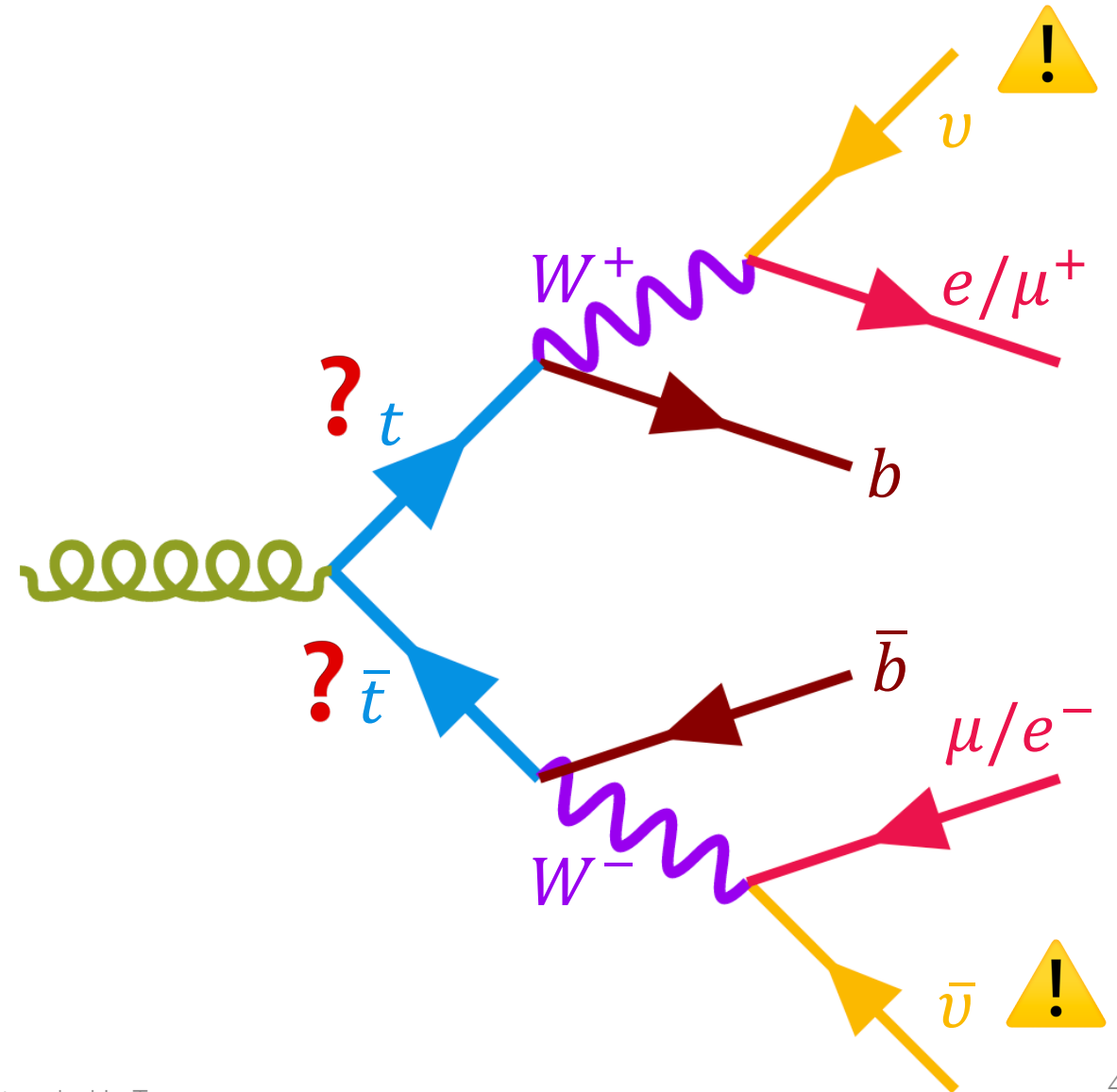
- Backgrounds are estimated using simulation.
- Fake lepton prediction modified using a data-driven scale factor.



Dileptonic Reconstruction

$$t = b + e/\mu^+ + \nu$$

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



Dileptonic Reconstruction

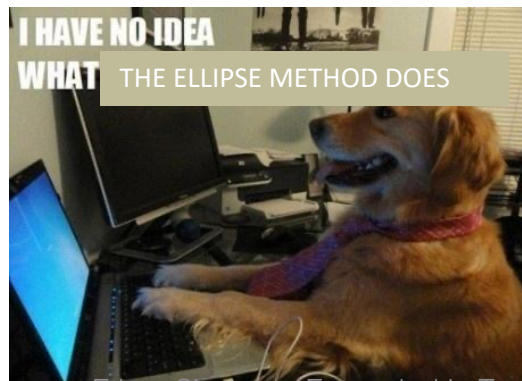
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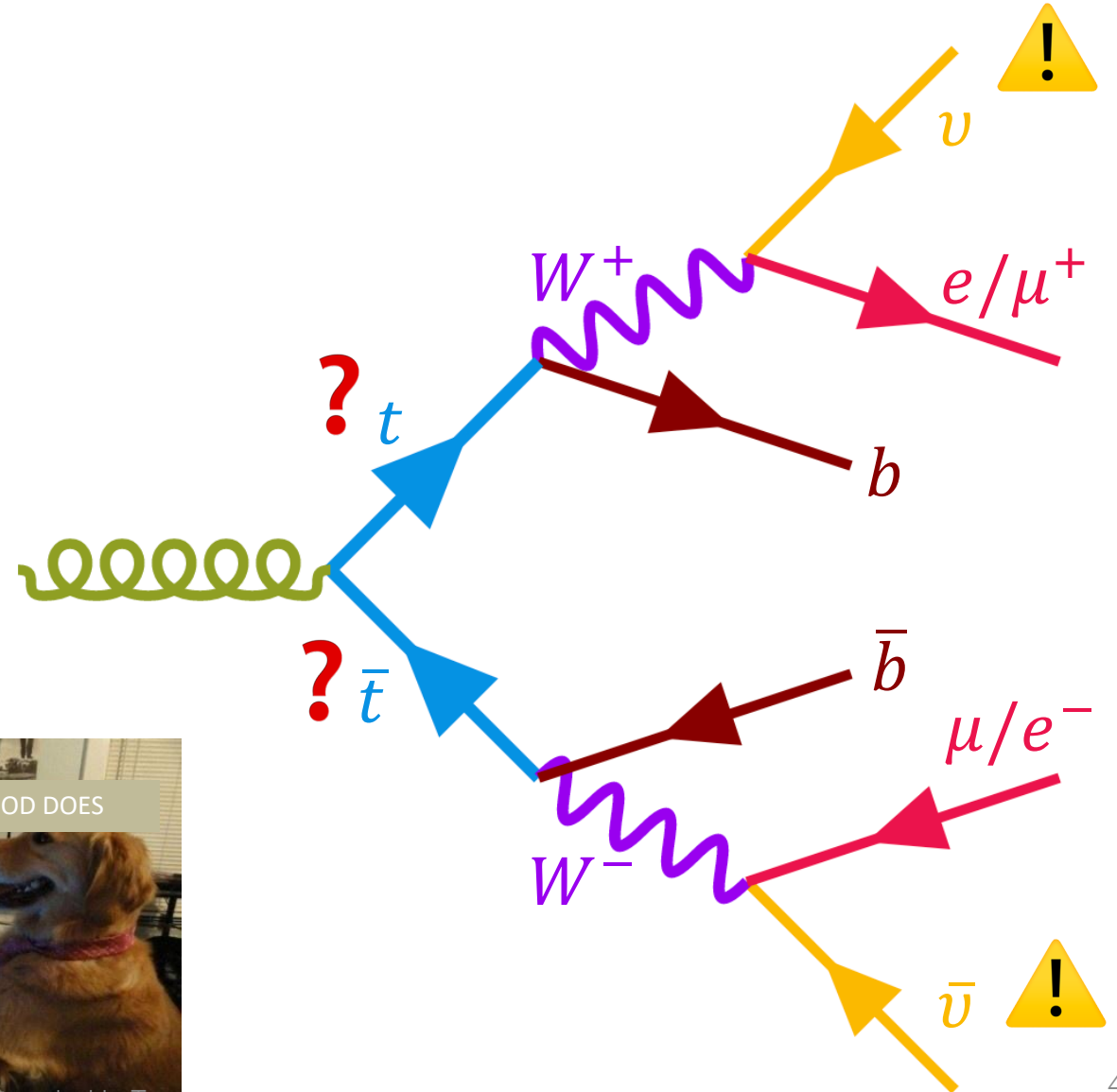
Primary technique: Ellipse Method

Alternative techniques:

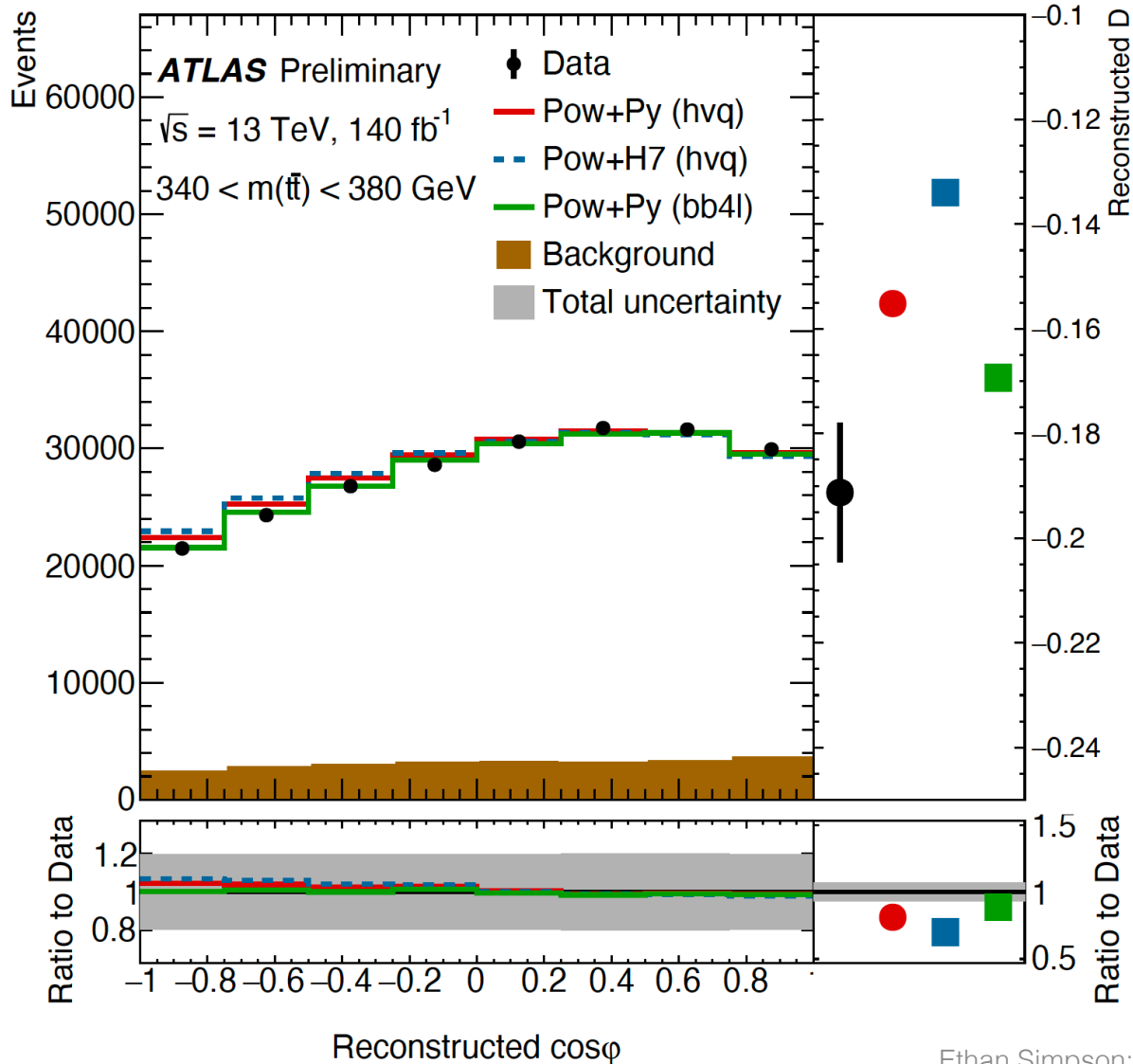
- NeutrinoWeighter
- Simple kinematic matching



Ethan Simpson: Entangled in Tops



Data-Simulation Comparison



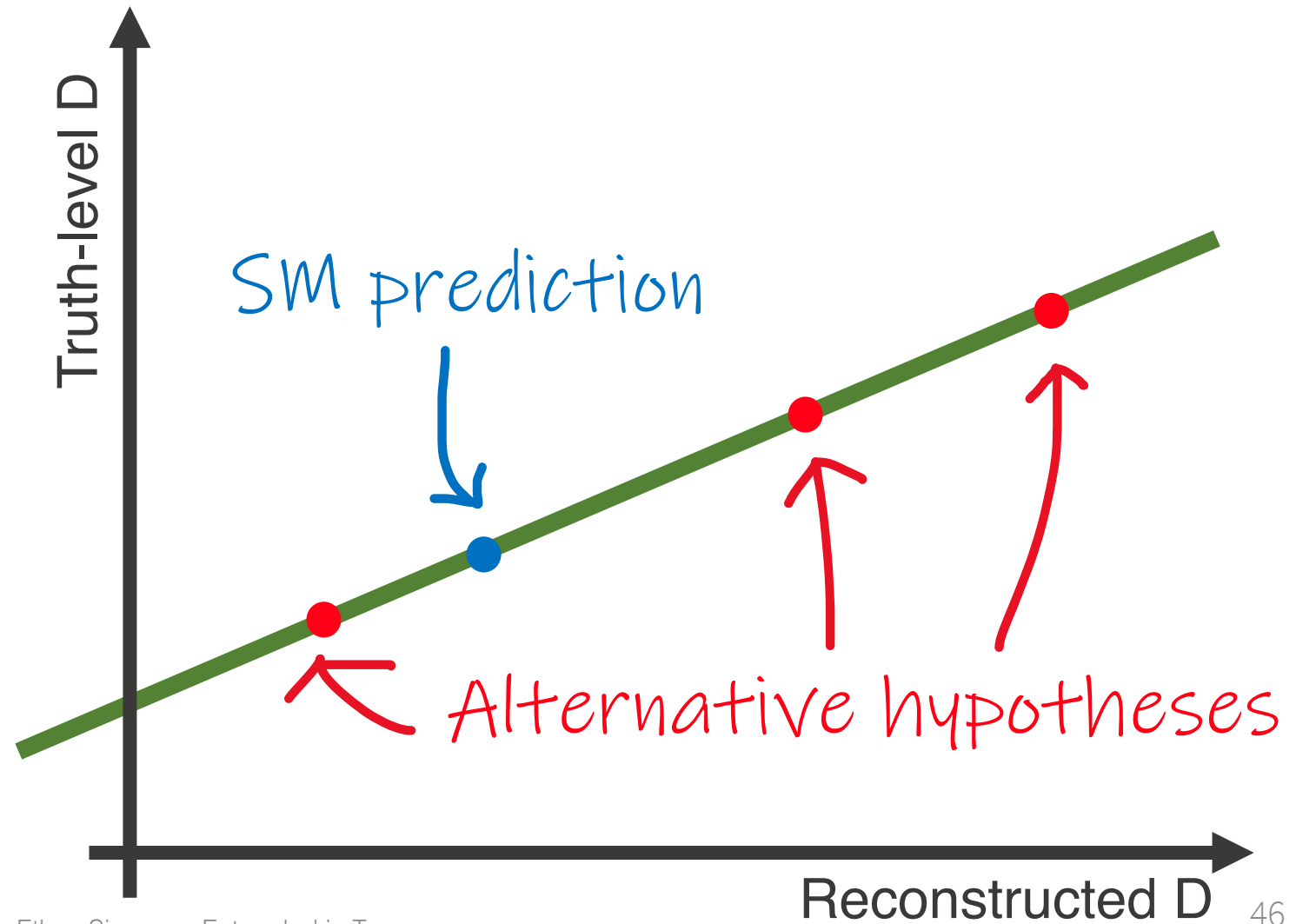
- Distortion from **detector effects** (resolution, acceptance)
- The agreement is decent for the distribution.
- **Tension in the mean.**

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**

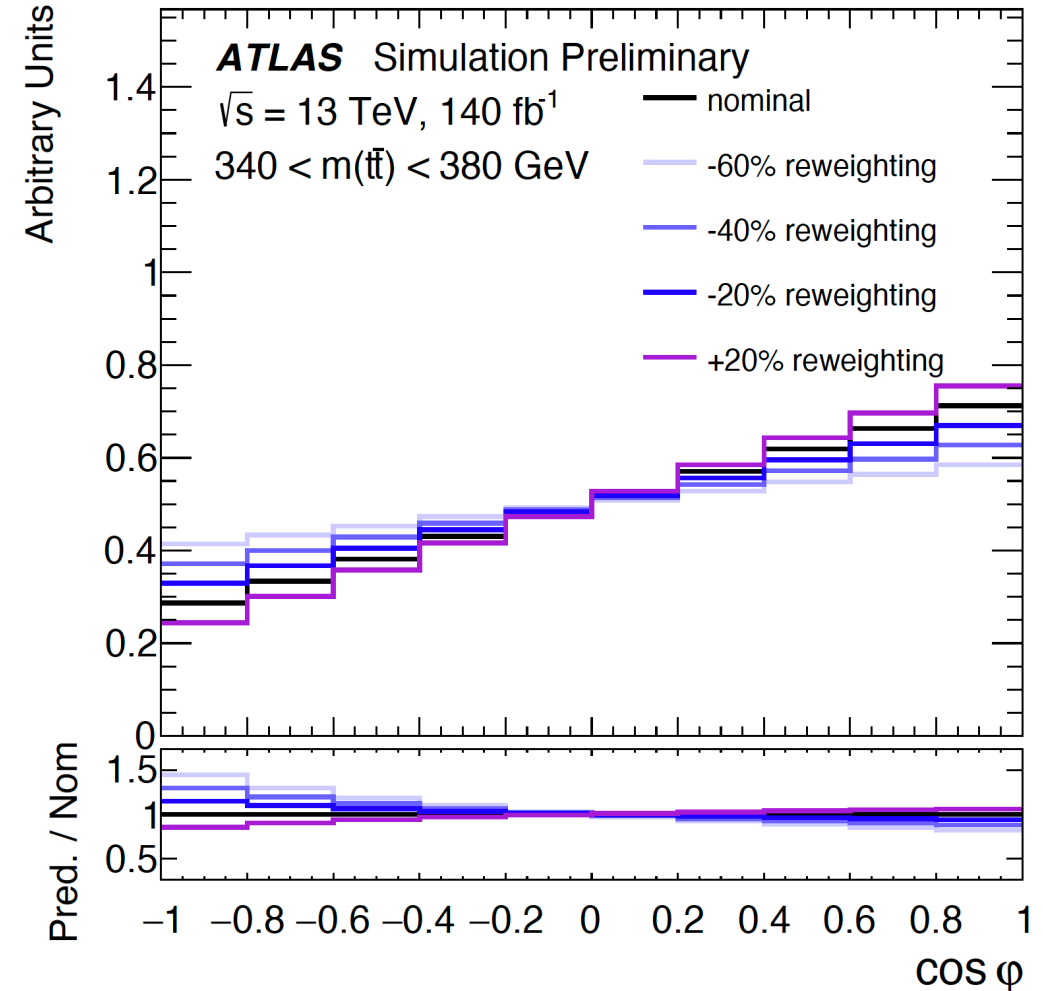


Apply a per-event **re-weighting** of the simulation!

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

Choose such that distribution remains linear

Scaling parameter

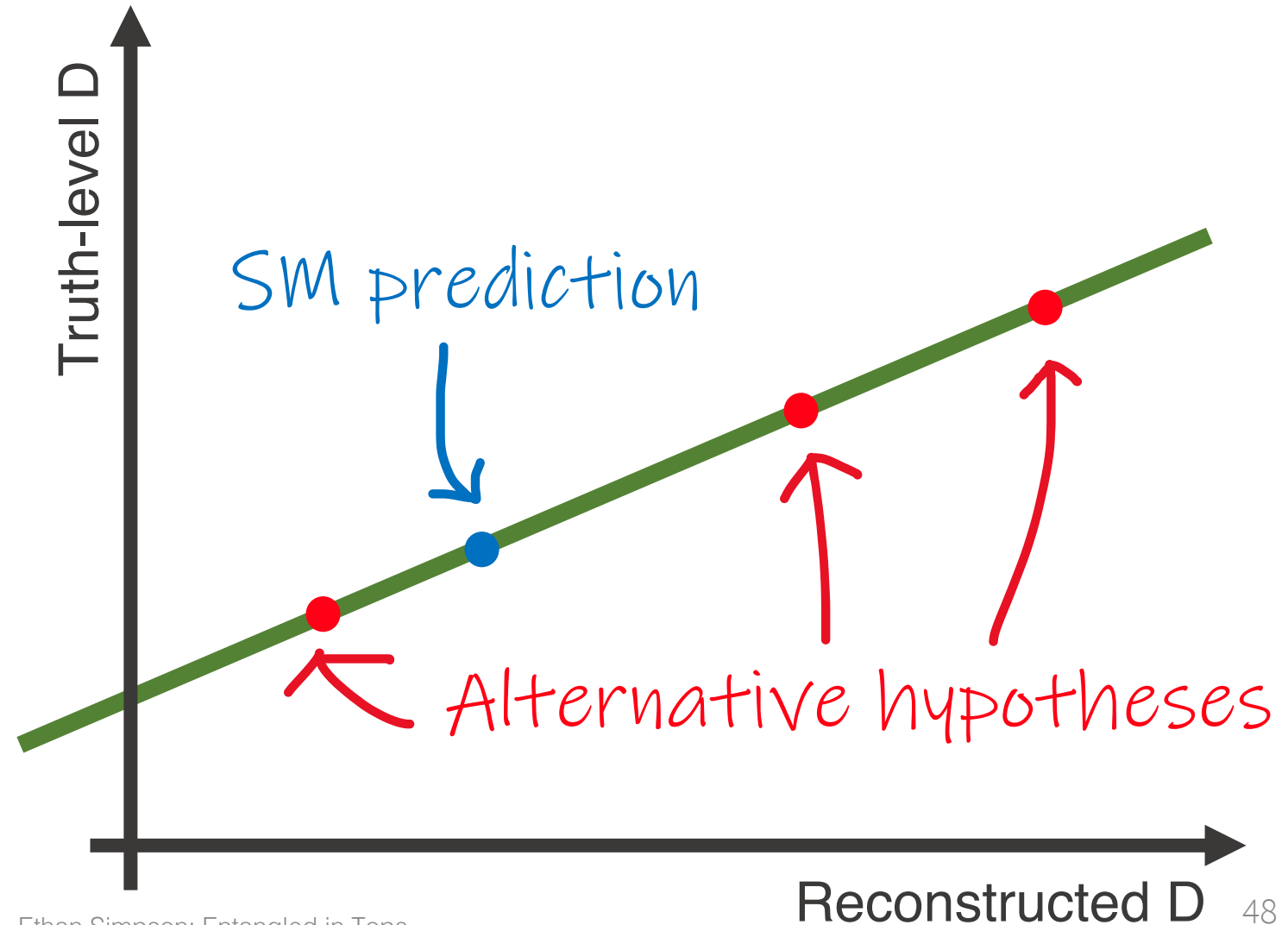


Calibration Curve

Parameterise variation in D

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

Interpolate to give variation.



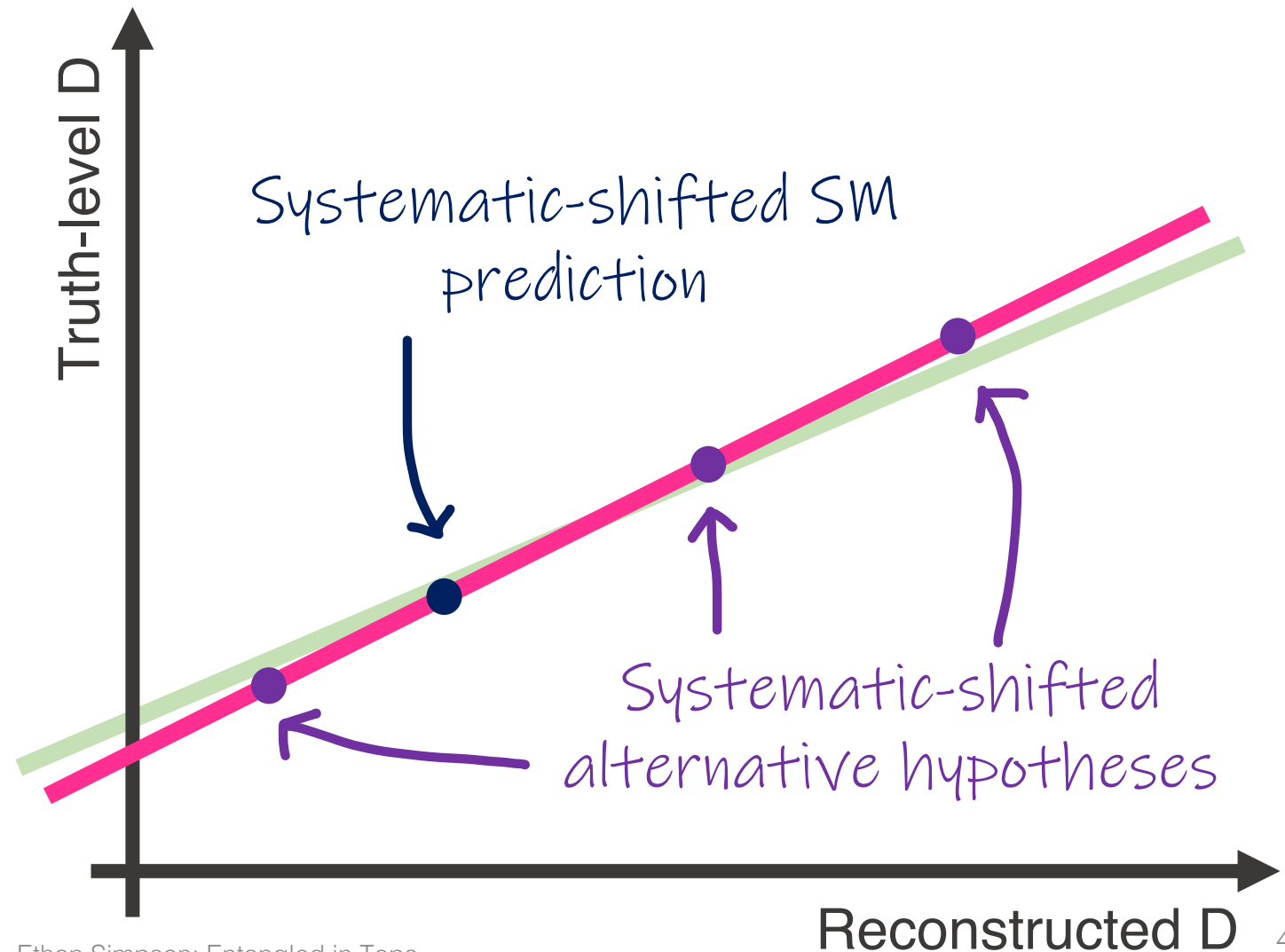
Calibration Curve

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

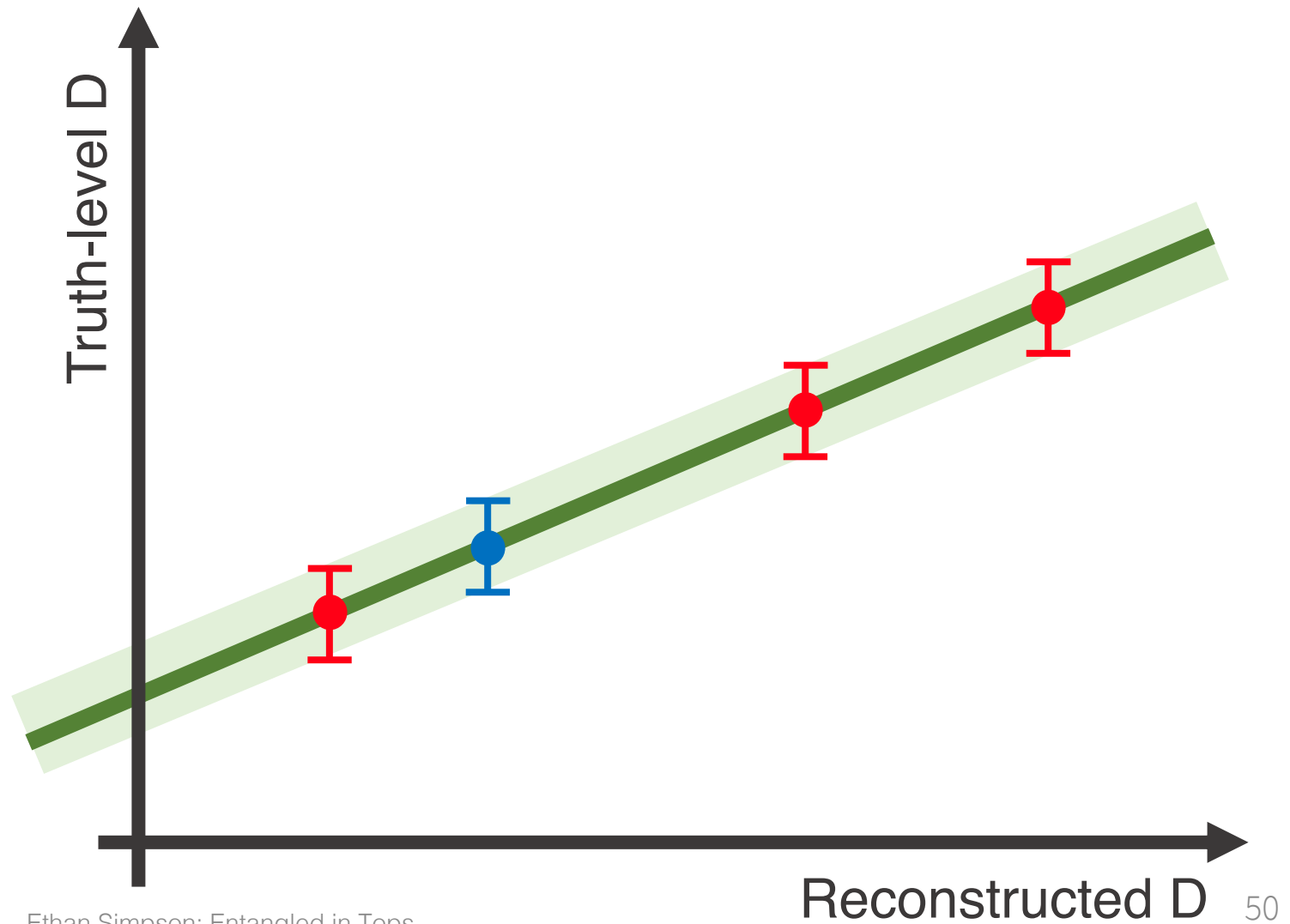
Parameterise variation in D

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.



Calibration Curve

Parameterise variation in D

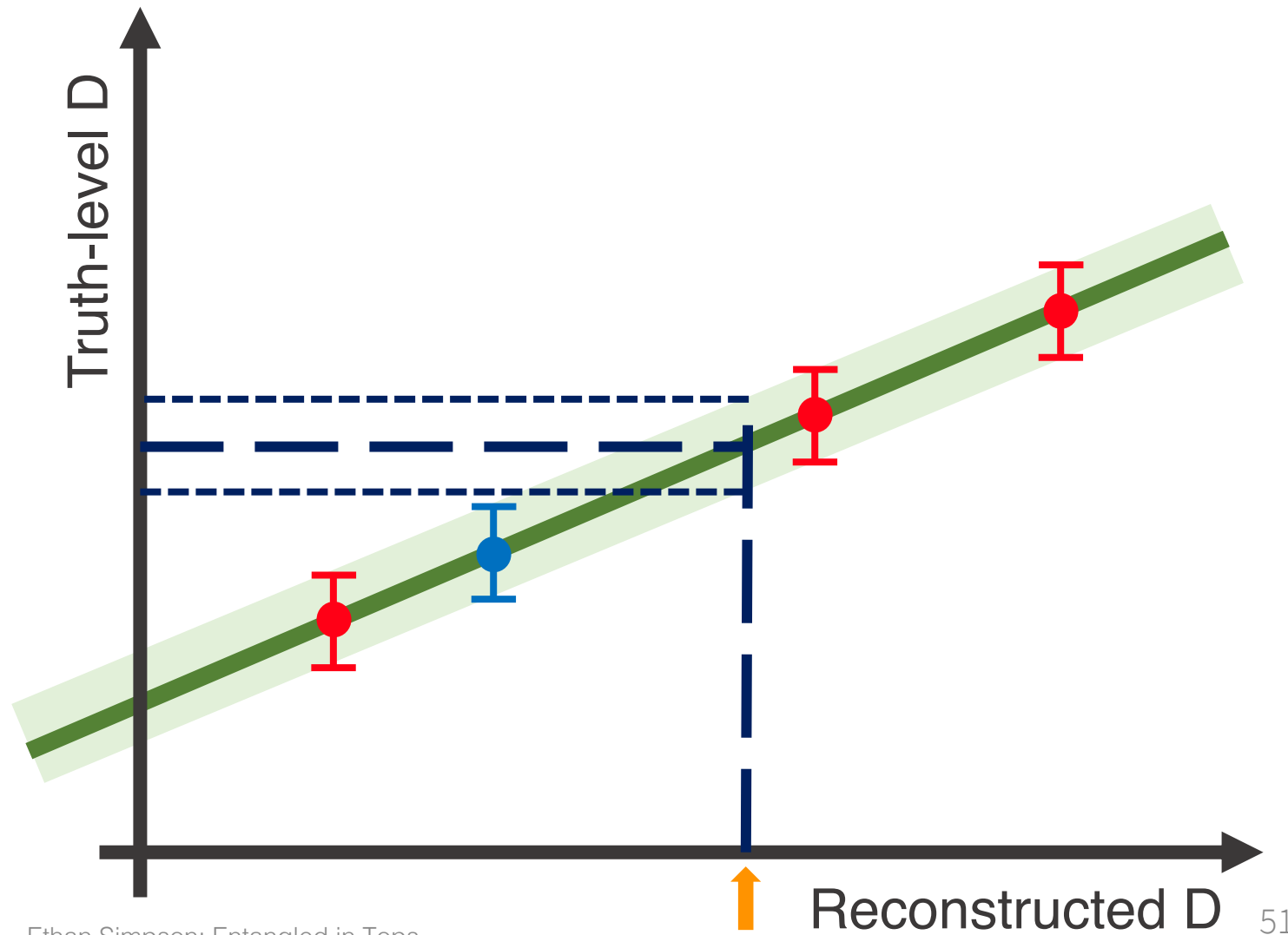
Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.

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Combine all systematics to build nominal curve + uncertainty band.

Map measured D to truth.

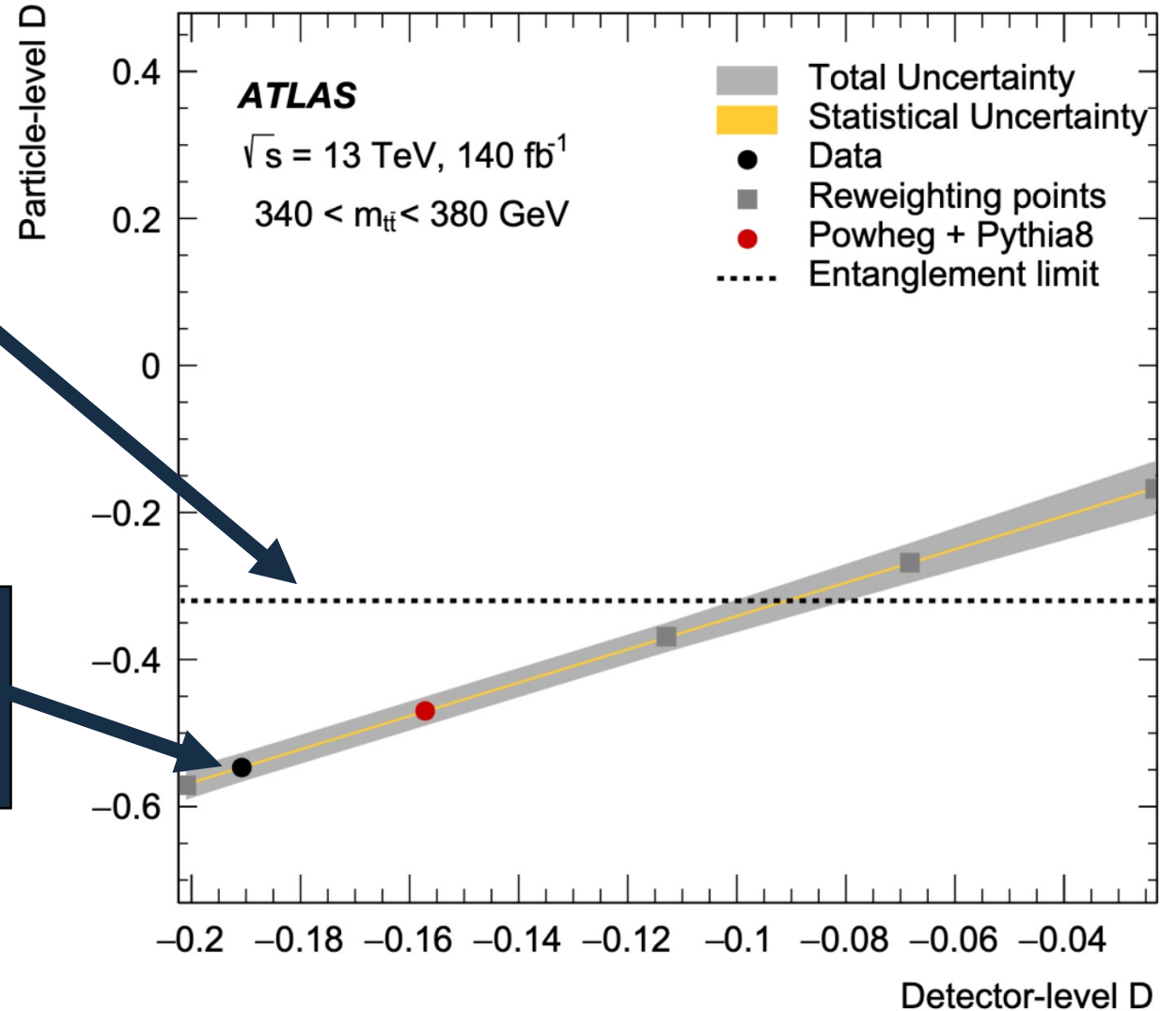


Results

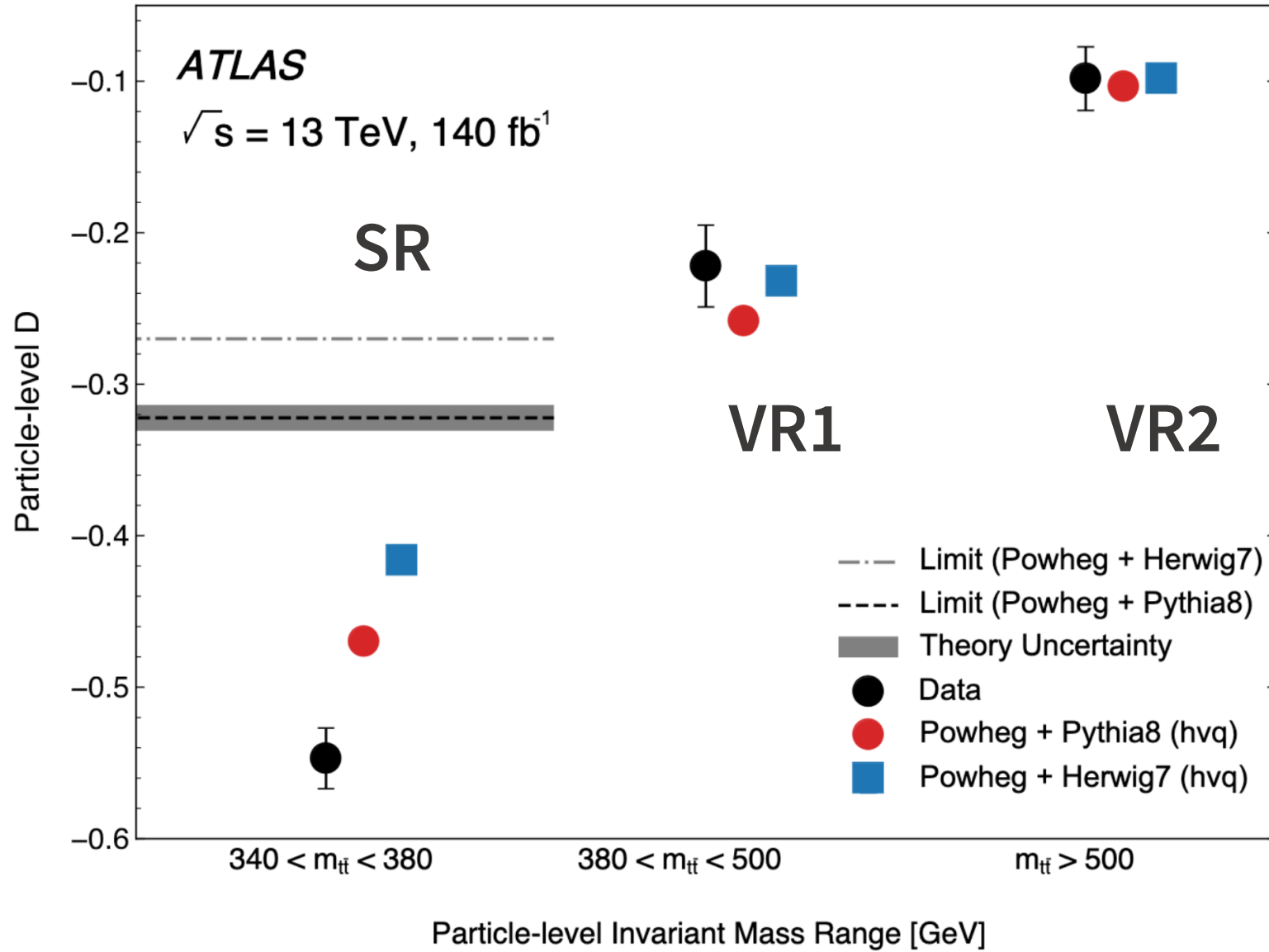
Calibration Curve

No-entanglement limit

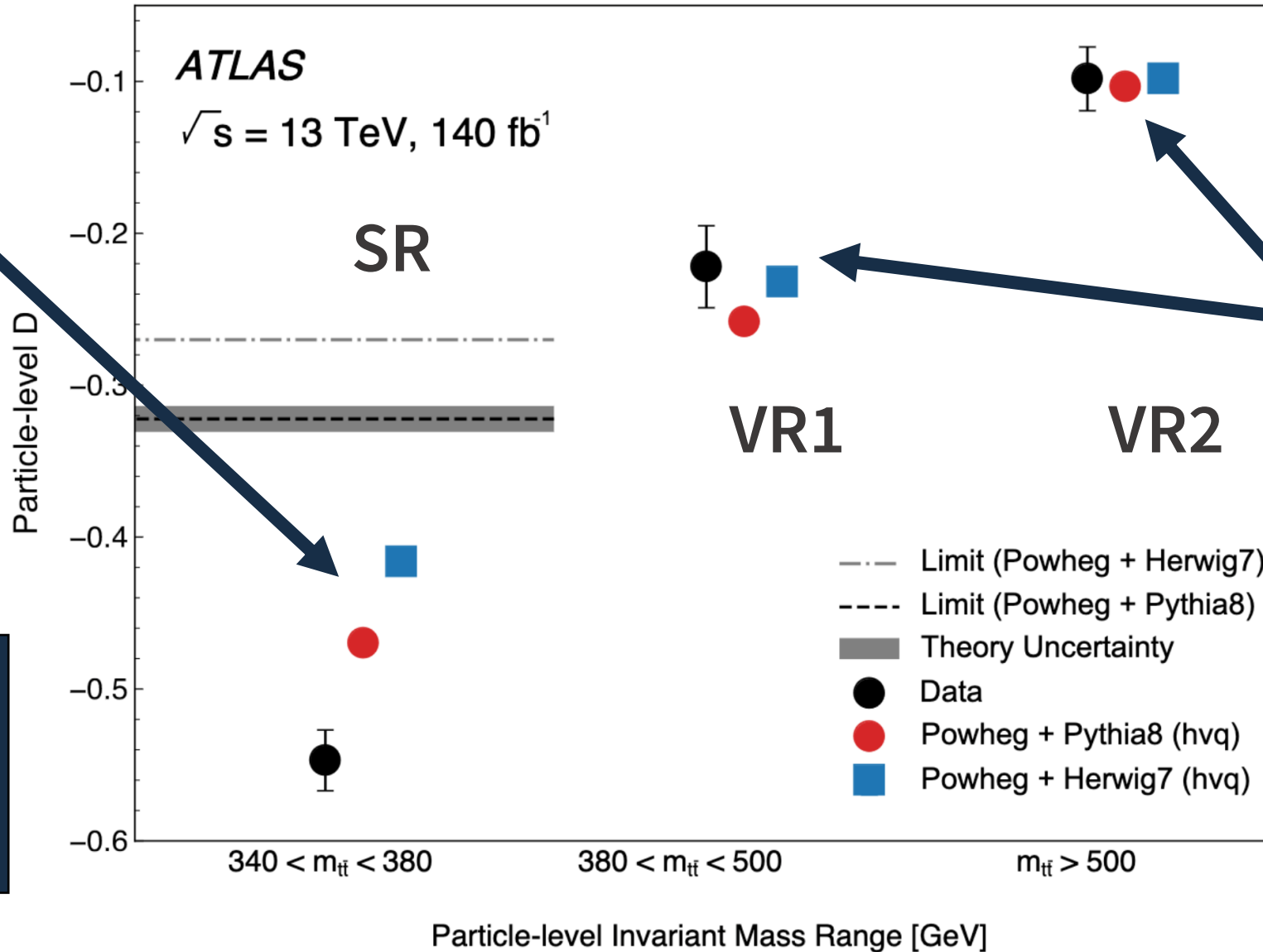
Higher level of entanglement than predicted in simulation



Results



Results



Simulation predictions do not agree

Predictions underestimate data

Agreement in VRs

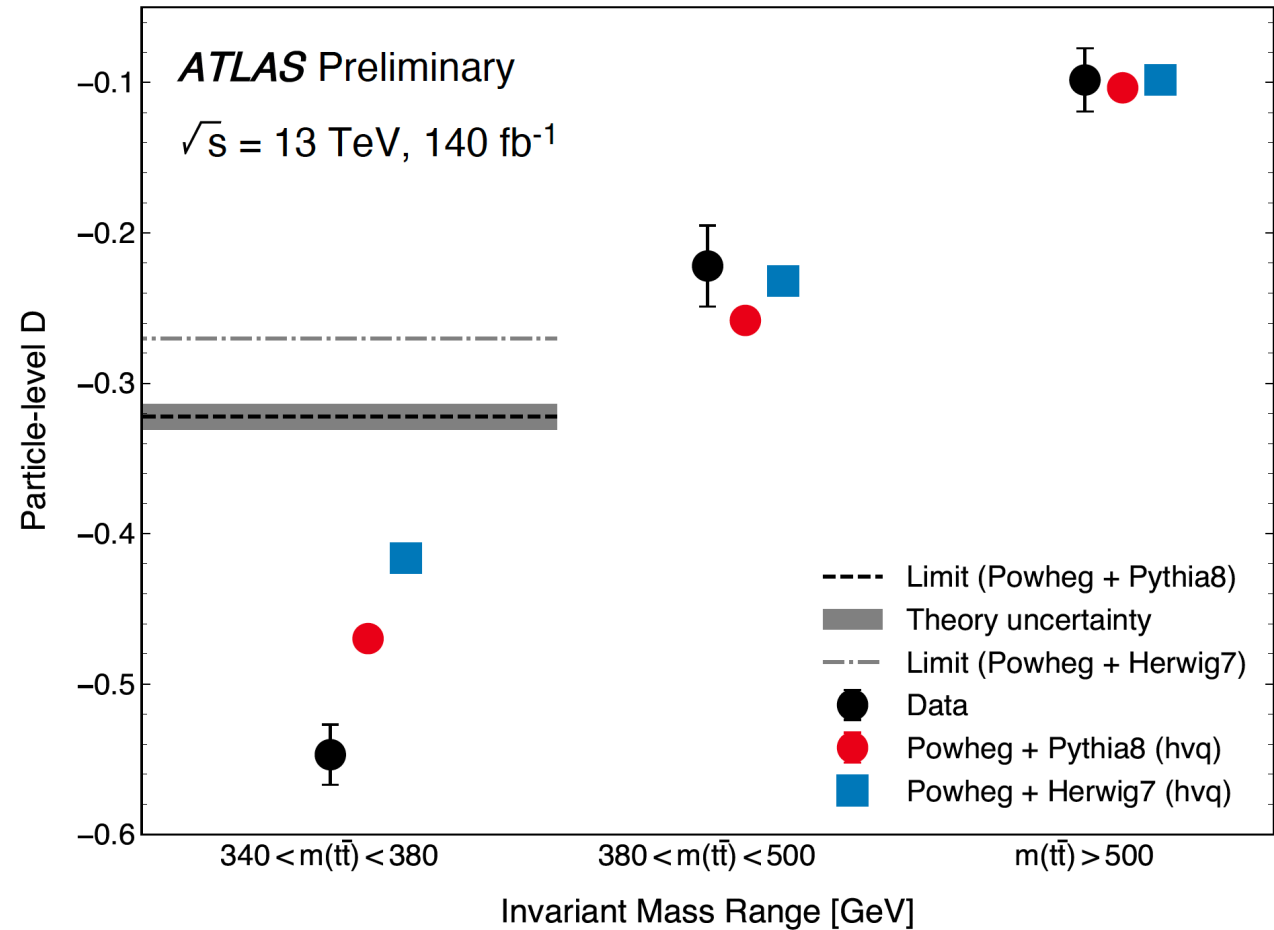
Results

Mapping **limit** to **particle-level**

Map entanglement limit using **parton**→**particle** calibration curves.

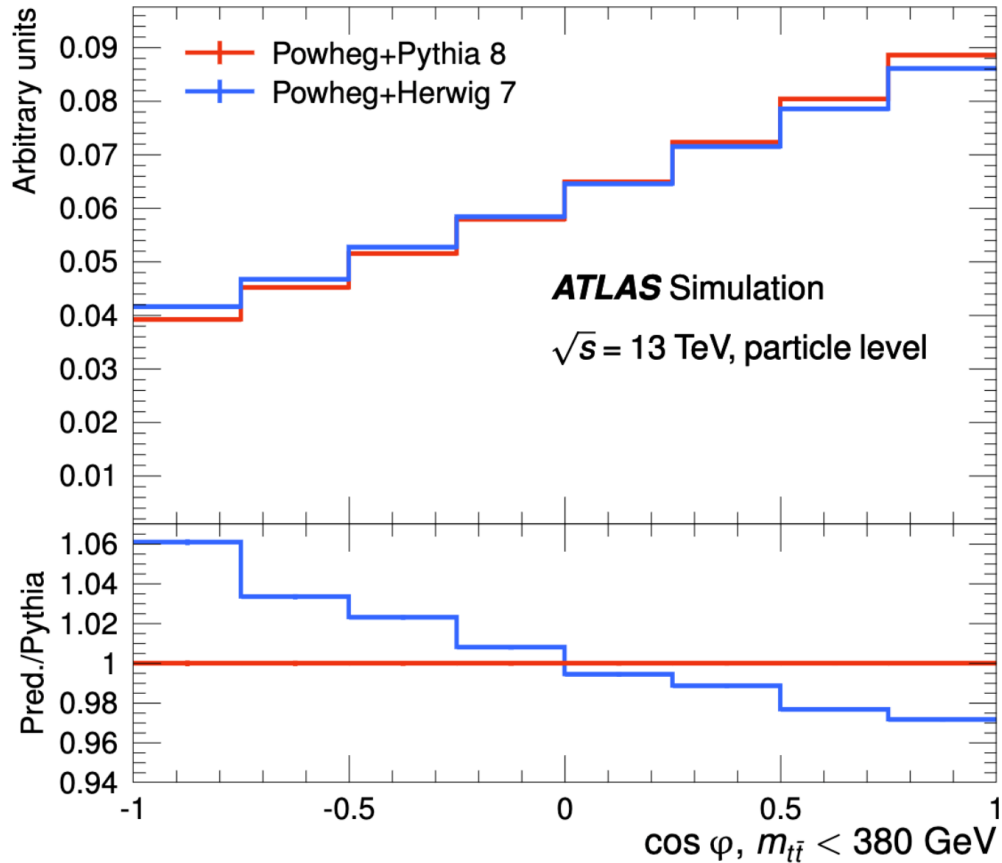
We derive a separate mapping for both Pythia and Herwig parton showers.

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

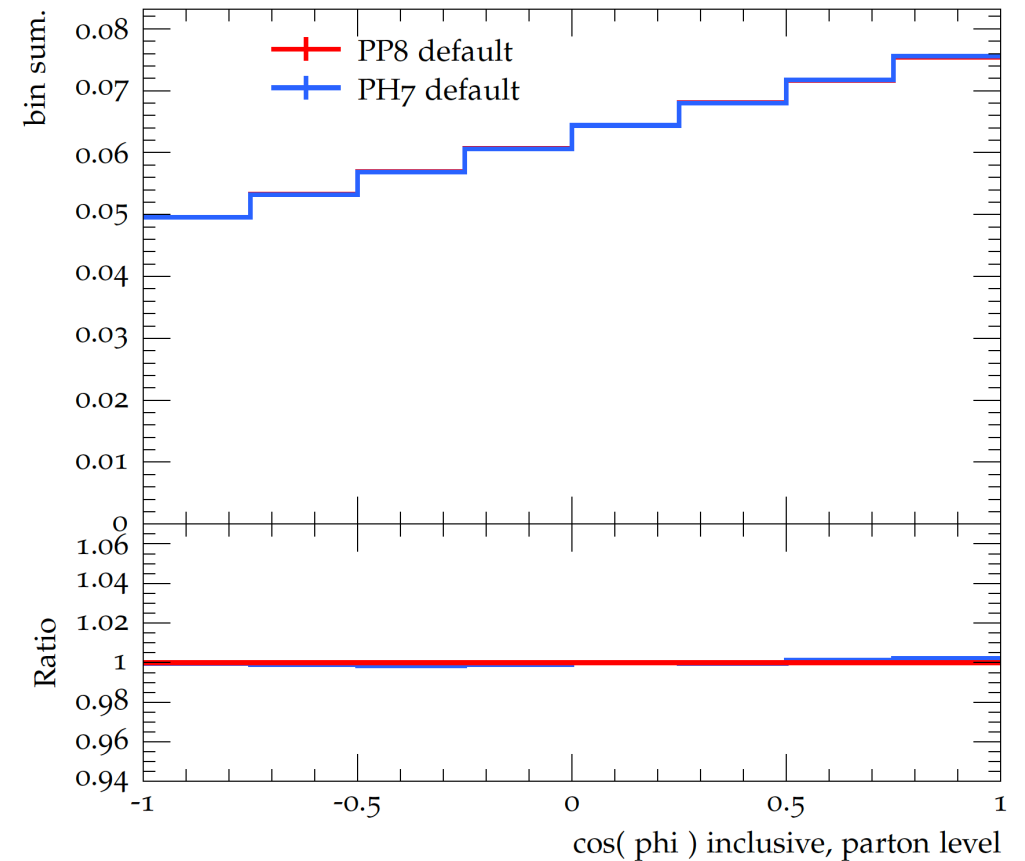


Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



Large difference at particle-level



No difference at parton-level

Systematic Uncertainties

Modelling dominates, like in other precision top-quark measurements

Signal modelling biggest limitation

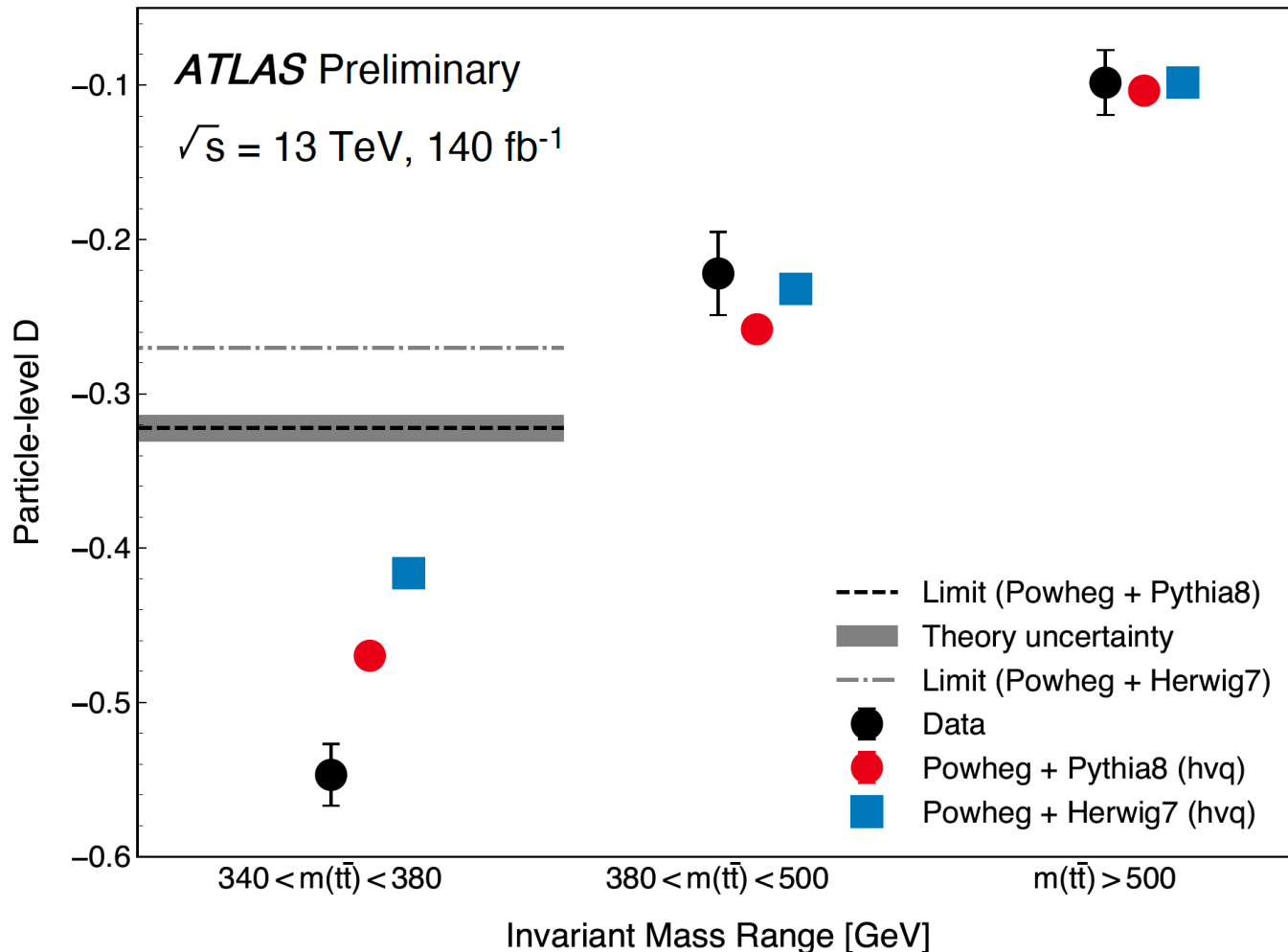
Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b -tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1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

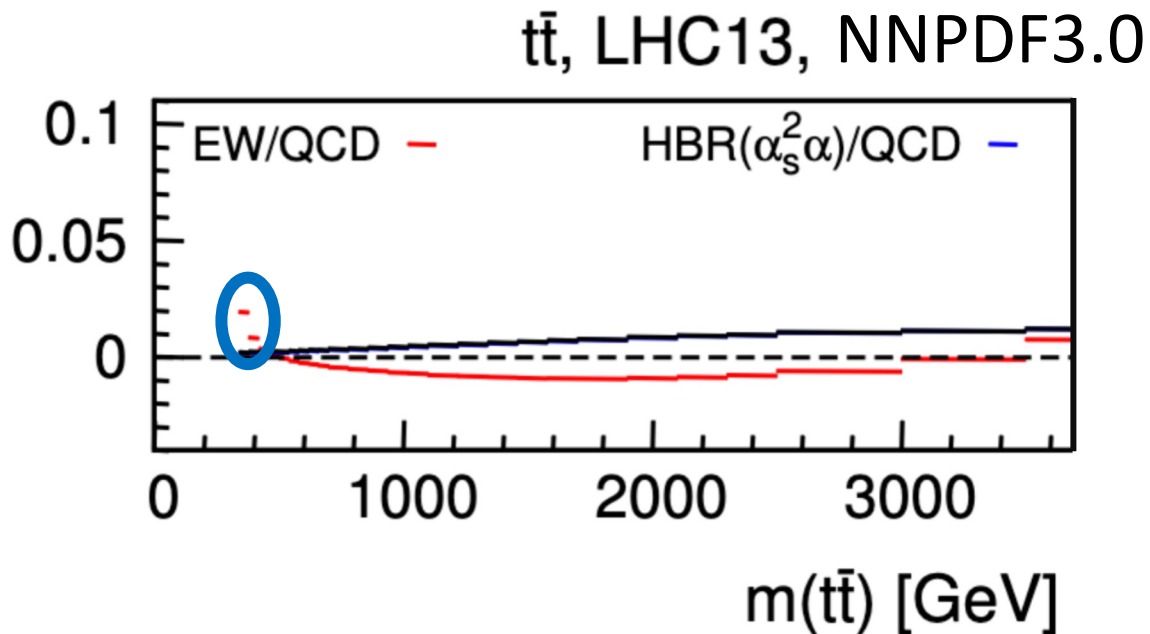
Derived from general-purpose MC event generators (powerful and widely used).

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

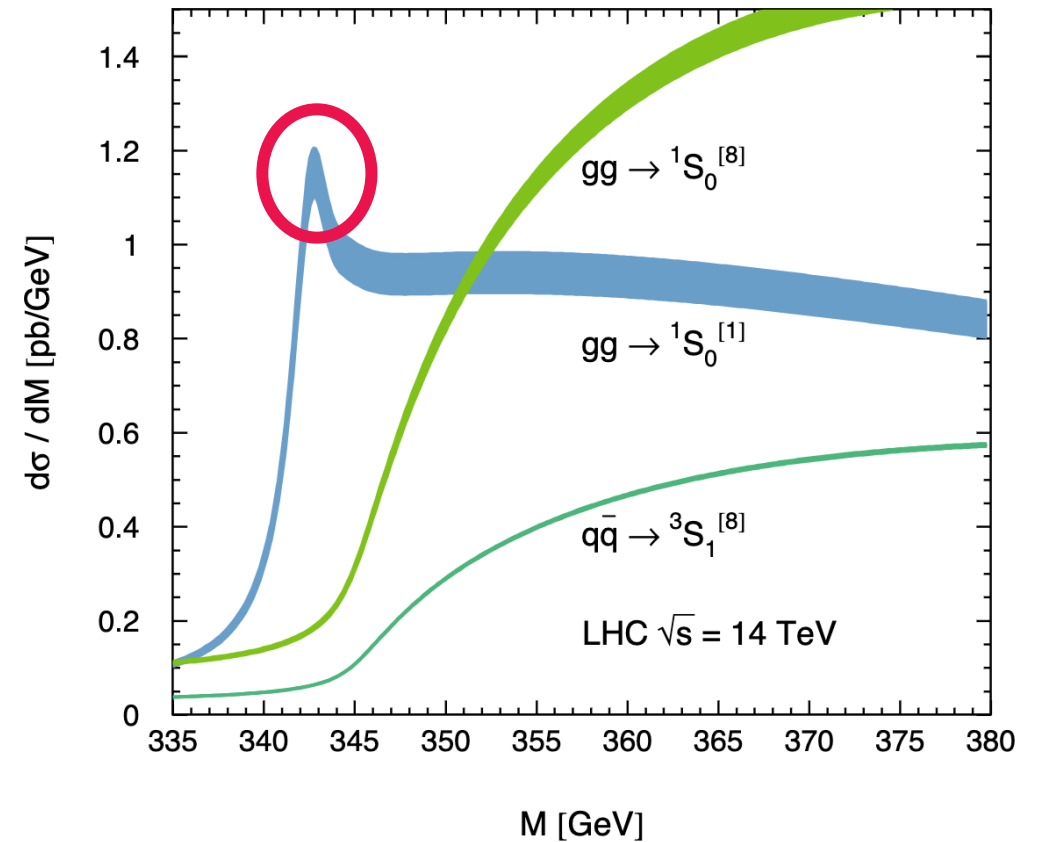
Future: build systematic model built around something like *bb4l*

Sources of mis-modelling

NLO EW



Bound state

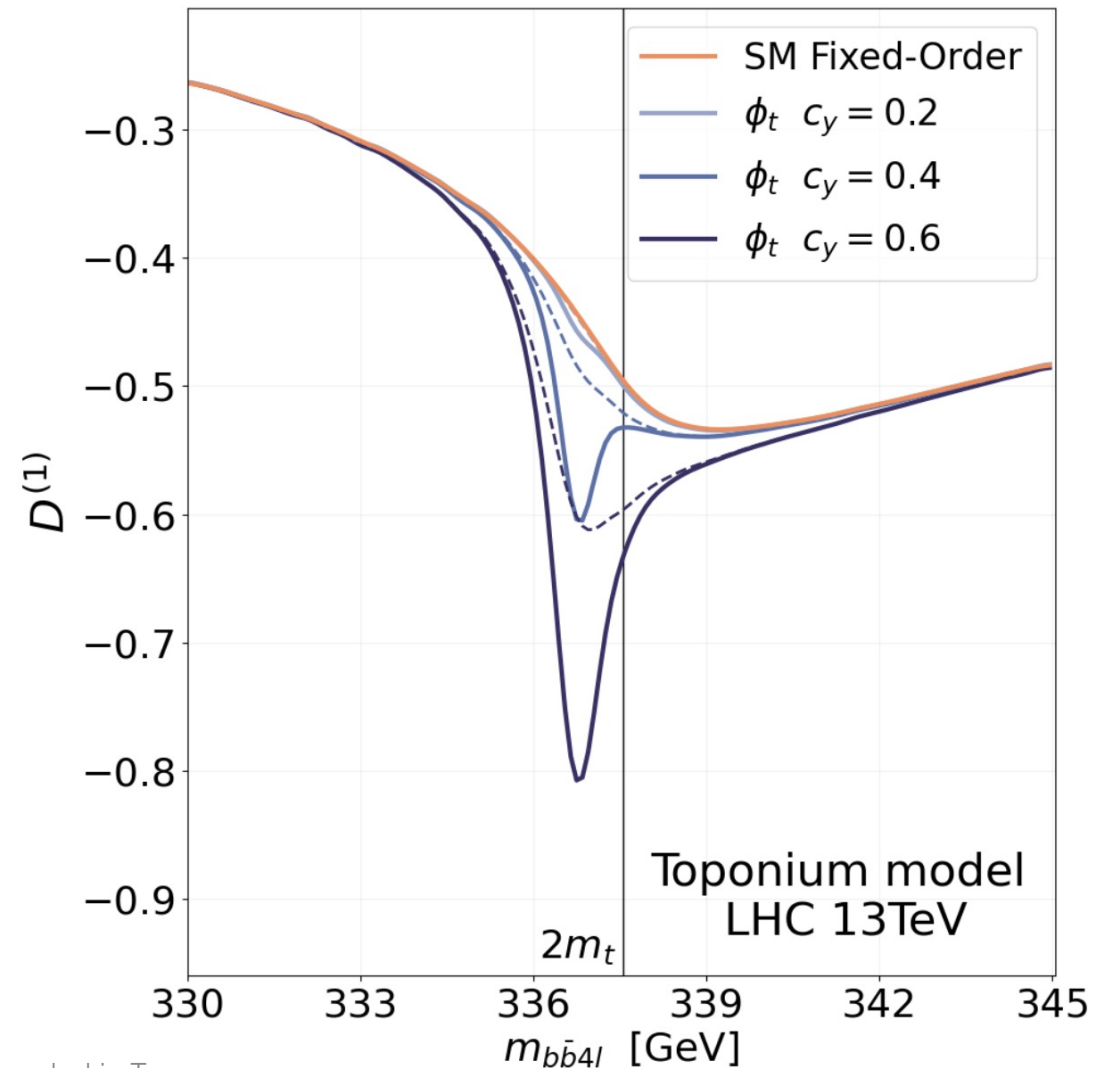
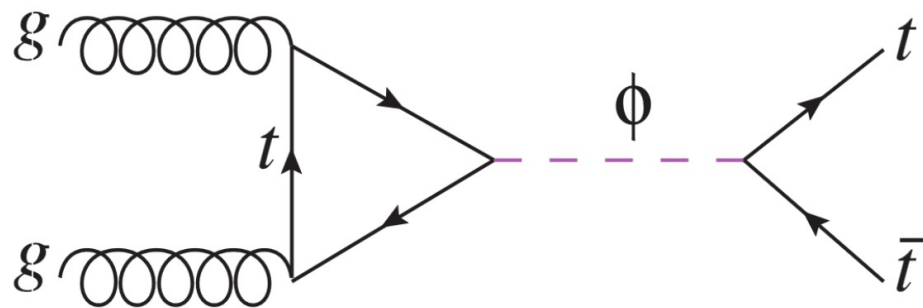


Cross-section enhancement near threshold in both cases.

Bound States

Simple **toponium** model

2401.08751 consider a **bound pseudo-scalar** decaying to an on-shell top-quark pair

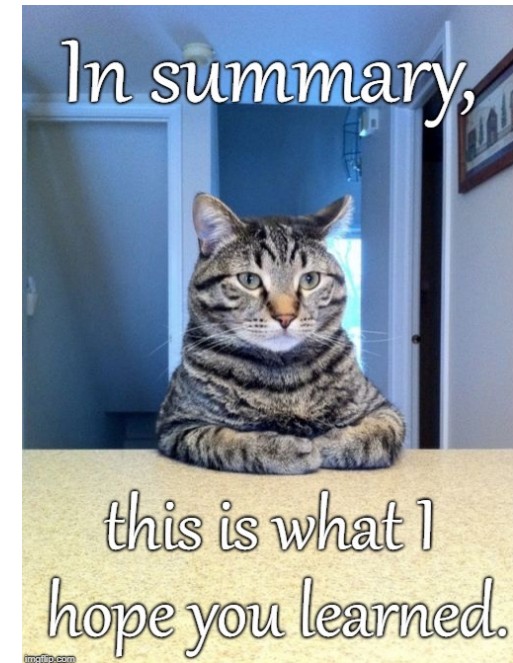


Summary of Arguments

The **precision** 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.



CMS Measurement

**The CMS measurement follows
the same basic strategy**

**Also achieves observation of
entanglement**

**The CMS measurement follows
the same basic strategy**

**Also achieves **observation of
entanglement****

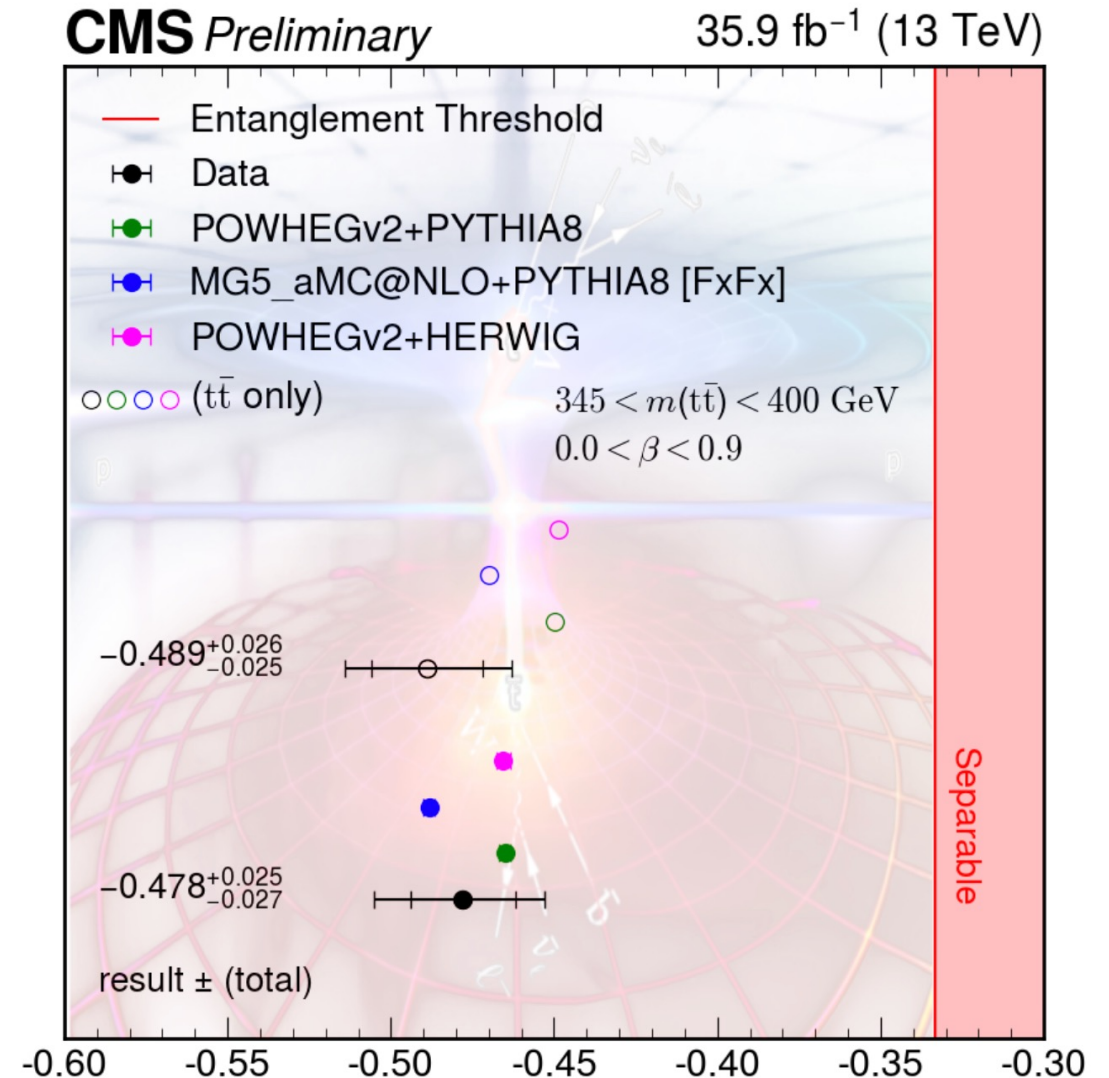
Many **differences** between ATLAS measurement
make direct **comparison challenging**
(see [LHC Top WG Comparison](#))

Key Points

Probing entanglement in top quark production with the CMS detector

The CMS Collaboration

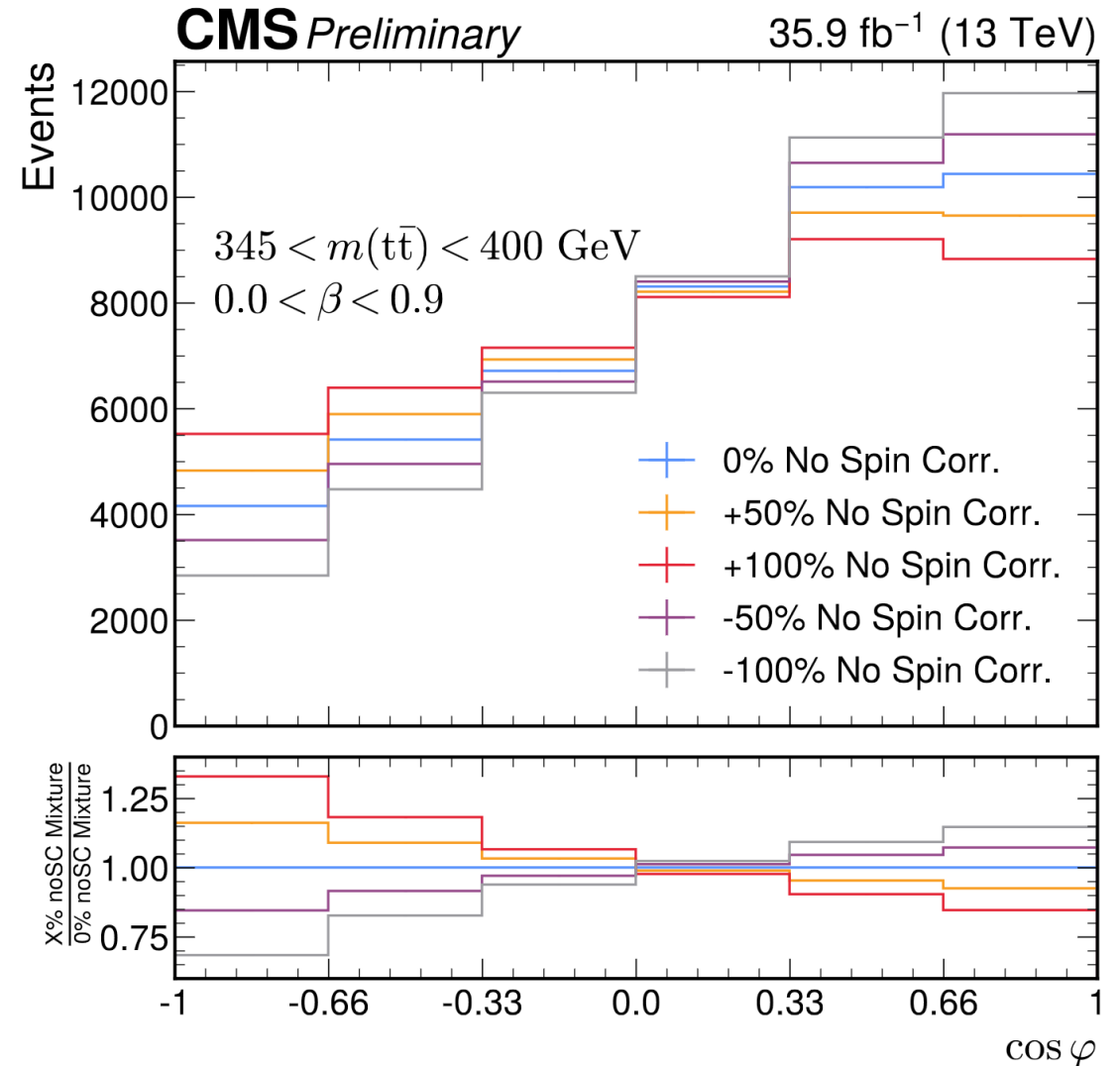
- Only use 2016 data
- Use all OS dilepton channels
- Invariant mass window [345, 400] GeV
- Additional kinematic cuts to target gg-fusion



Alternative Entanglement Hypotheses

- Generate simulation with no spin correlations
- Weighted combination of “spin-on” and “spin-off” samples yields changes in D

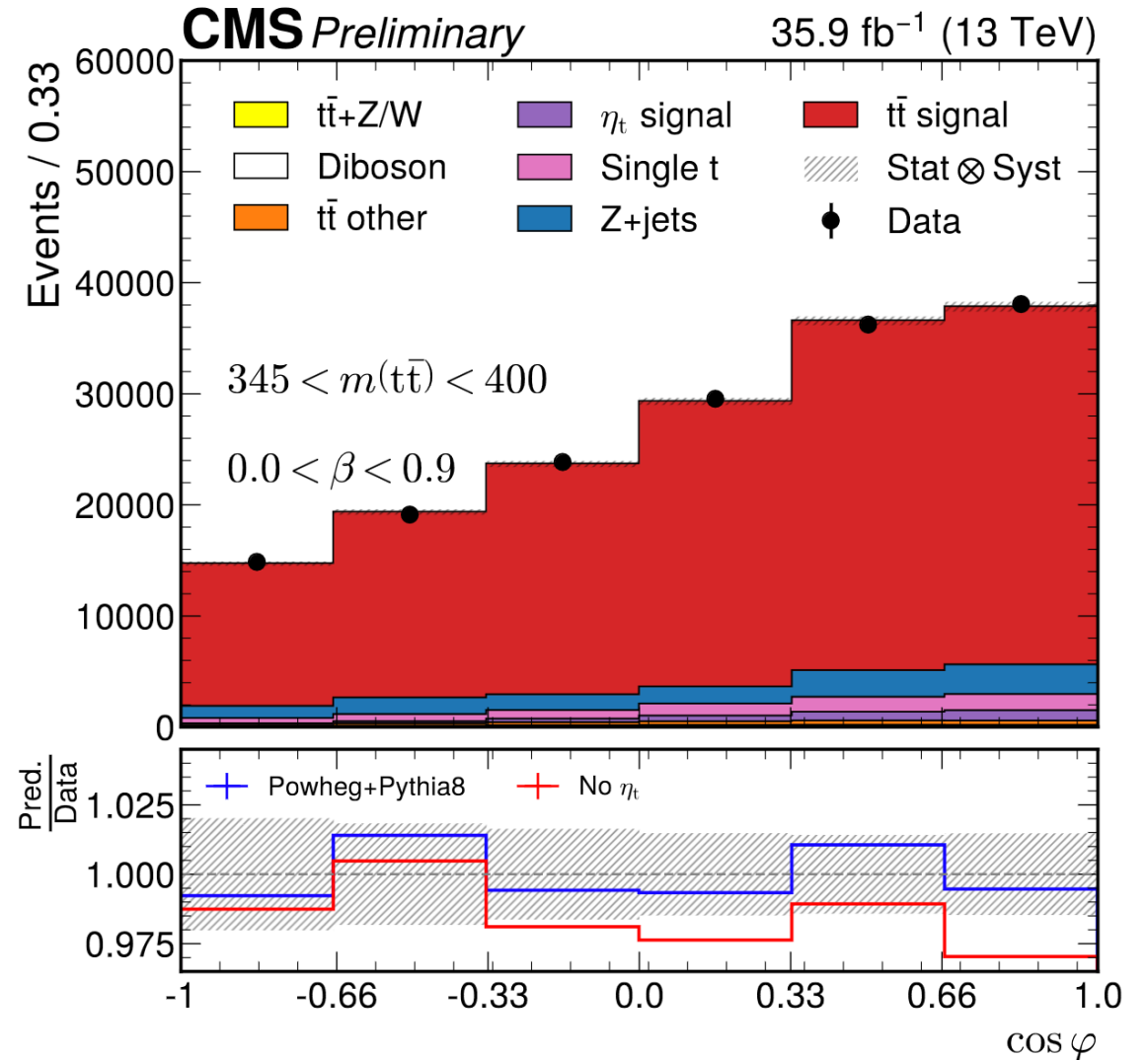
(ATLAS used MC reweighting)



Extraction of D

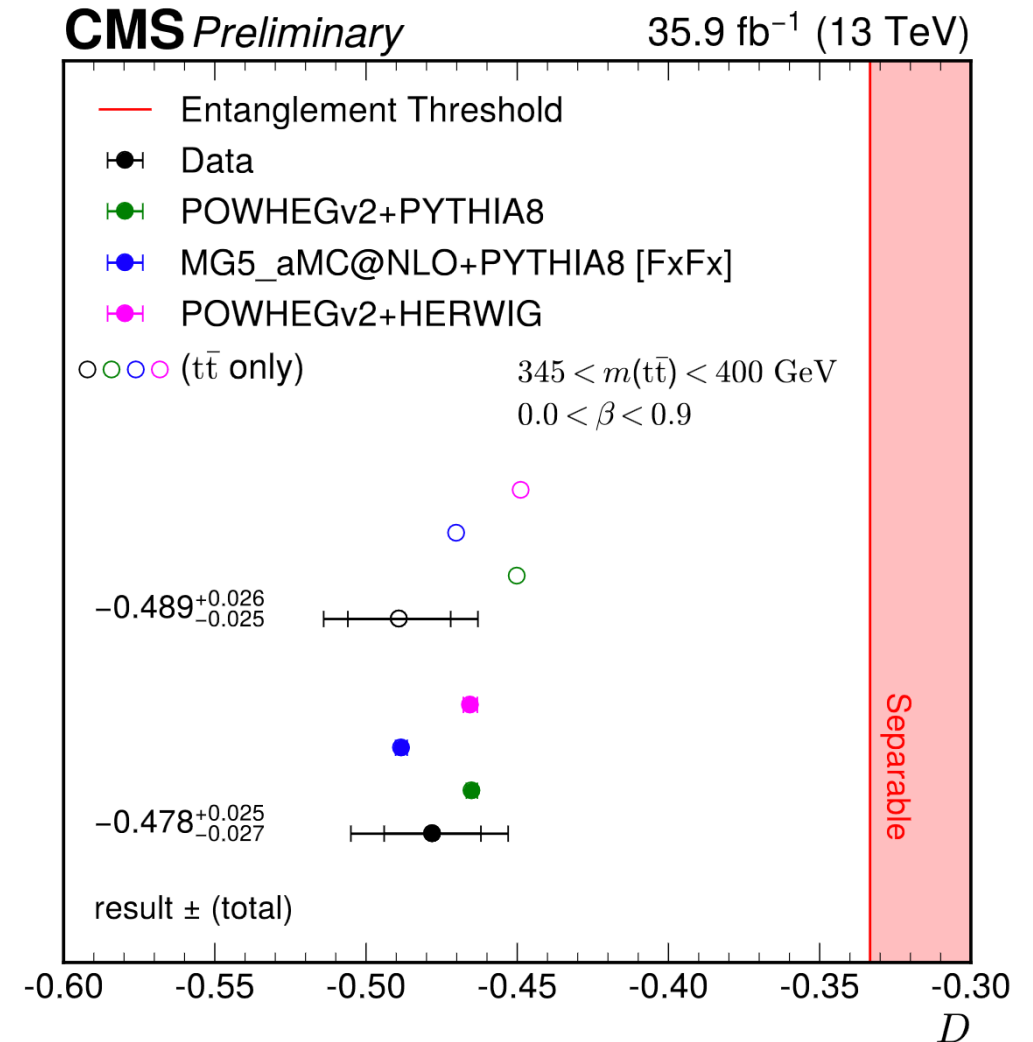
- Employ binned template profile likelihood fit
- Based on MC templates
- D at parton-level

(ATLAS corrected to particle-level using a calibration curve)



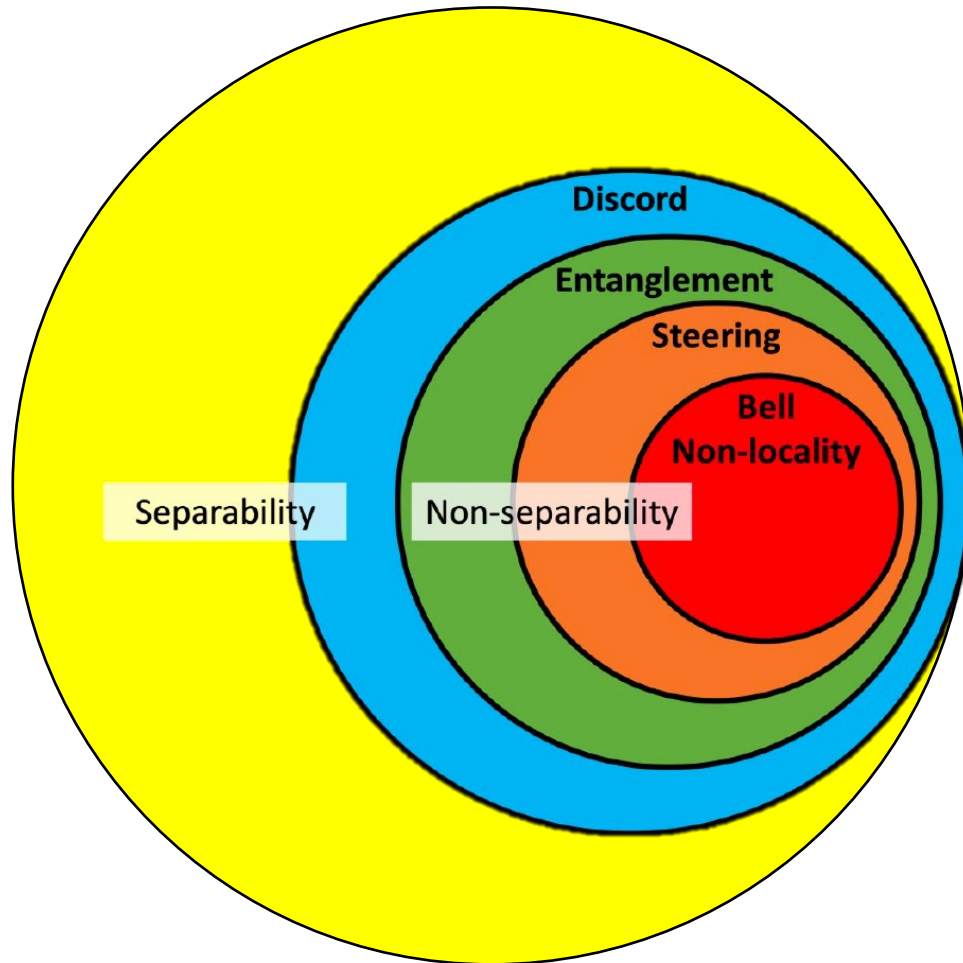
Results with “Toponium”

- Include a model of toponium bound-state in the simulation
- Data-MC tension reduced when toponium effects included
- Superior bound-state modelling should appear soon...



Postscript

Beyond Entanglement



Bell-type tests in $t\bar{t}$ production, using special observables

Testing Bell inequalities at the LHC with top-quark pairs

M. Fabbrichesi[†], R. Floreanini[†], and G. Panizzo^{*}

[†]INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy

^{*}Dipartimento Politecnico di Ingegneria ed Architettura,

Università degli Studi di Udine, Via della Scienze 206, 33100 Udine, Italy and

INFN, Sezione di Trieste (Gruppo Collegato di Udine), via delle Scienze, 208, 33100 Udine, Italy

(Dated: October 28, 2021)

Quantum tops at the LHC: from entanglement to Bell inequalities

Claudio Severi^{1,a}, Cristian Degli Esposti Boschi^{3,4,b}, Fabio Maltoni^{2,4,5,c}, Maximiliano Sioli^{2,4,d}

¹ Department of Physics and Astronomy, University of Manchester, Manchester, UK

² Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, Bologna, Italy

³ CNR-IMM, Sezione di Bologna, via Gobetti 101, 40129 Bologna, Italy


⁴ INFN, Sezione di Bologna, via Irnerio 46, Bologna, Italy

⁵ Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-la-Neuve, Belgium

Beyond Top Quarks

Testing entanglement and Bell inequalities in $H \rightarrow ZZ$

J. A. Aguilar-Saavedra^{✉,*}, A. Bernal^{✉,†}, J. A. Casas^{✉,‡}, and J. M. Moreno^{✉,§}
Instituto de Física Teórica, IFT-UAM/CSIC, Universidad Autónoma de Madrid,
Cantoblanco, 28049 Madrid, Spain

 (Received 4 October 2022; accepted 3 January 2023; published 20 January 2023)

Isolating semi-leptonic $H \rightarrow WW^*$ decays for Bell inequality tests

Federica Fabbri¹, James Howarth¹, Théo Maurin^{1†}
¹School of Physics and Astronomy, University of Glasgow.

Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles

Quantum information and CP measurement in $H \rightarrow \tau^+ \tau^-$ at future lepton colliders

Mohammad Mahdi Altakach^{✉,1,2,*}, Priyanka Lamba^{1,†}, Fabio Maltoni^{✉,3,4,‡},
Kentaro Mawatari^{✉,5,§} and Kazuki Sakurai^{✉,1,||}

Laboratory-frame tests of quantum entanglement in $H \rightarrow WW$

J. A. Aguilar-Saavedra[✉]

Constraining new physics in entangled two-qubit systems: top-quark, tau-lepton and photon pairs

Marco Fabbrichesi¹, Roberto Floreanini¹, Emidio Gabrielli^{2,1,3,a}

¹ INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy

² Physics Department, University of Trieste, Strada Costiera 11, 34151 Trieste, Italy

³ NICPB, Ravala 10, 10143 Tallinn, Estonia



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Testing Bell inequalities in Higgs boson decays

Alan J. Barr

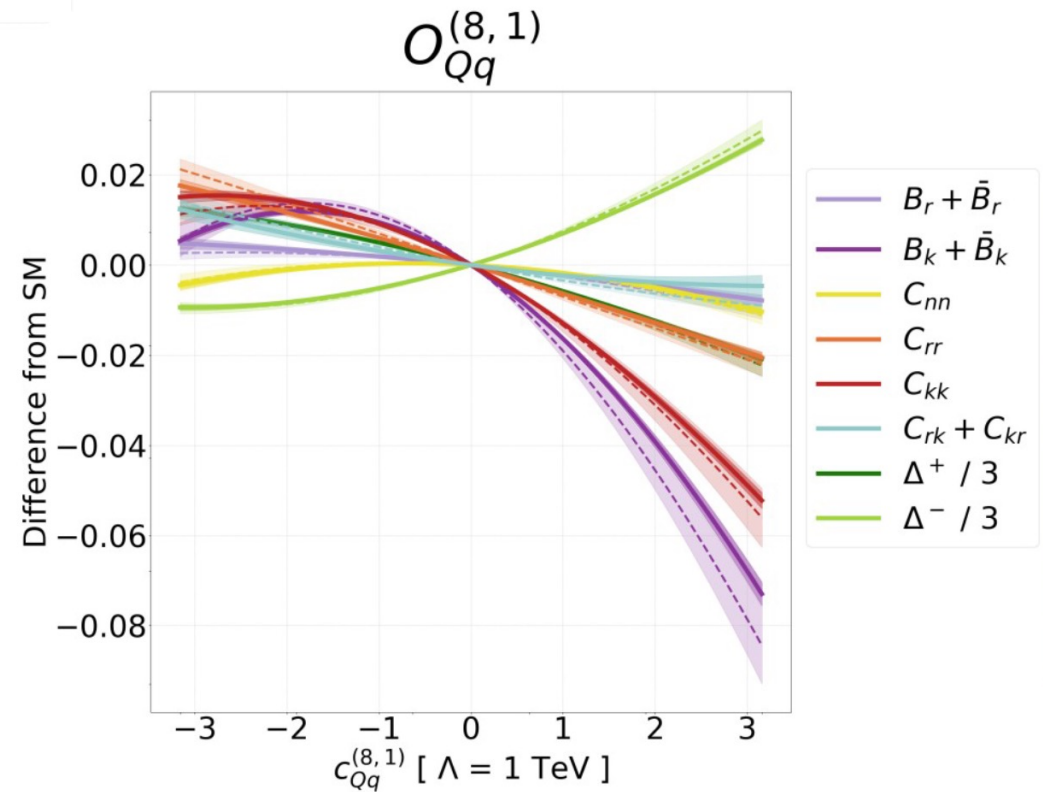
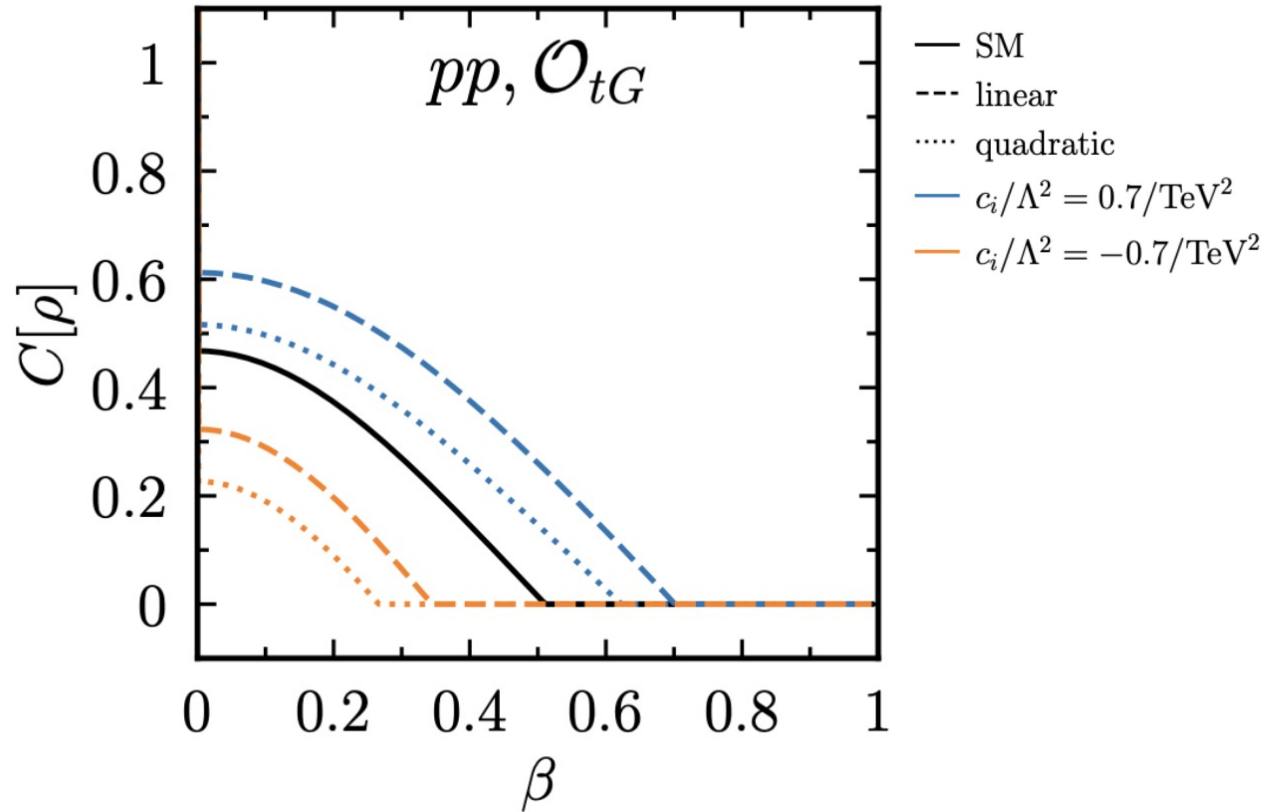
Department of Physics, Keble Road, University of Oxford, OX1 3RH, United Kingdom
Merton College, Merton Street, Oxford, OX1 4JD, United Kingdom

Madrid, Spain

(2023)

QI 4 BSM

QI observables can probe and constrain New Physics



SMEFT operators alter amount of entanglement, not nature of entanglement.

Exotica

Post-decay entanglement?
Decoherence?

[2307.06991](#)

[2308.07412](#)

Electrons before and after they
notice the detector

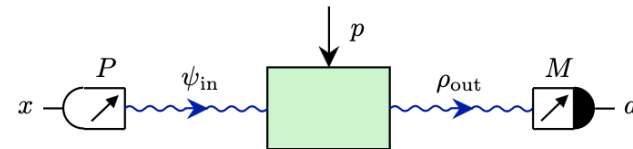


Beyond Quantum Mechanics?

[General Probabilistic Theories](#)

[Objective Collapse Models](#)

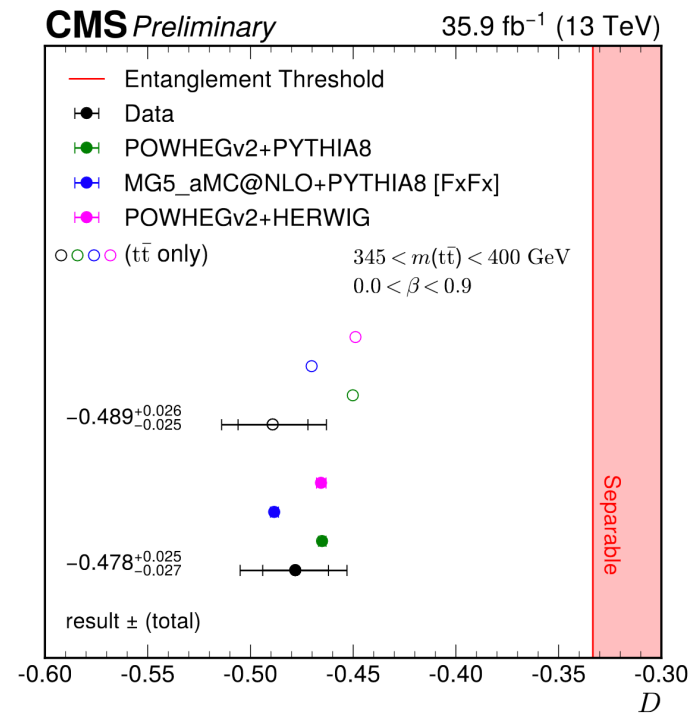
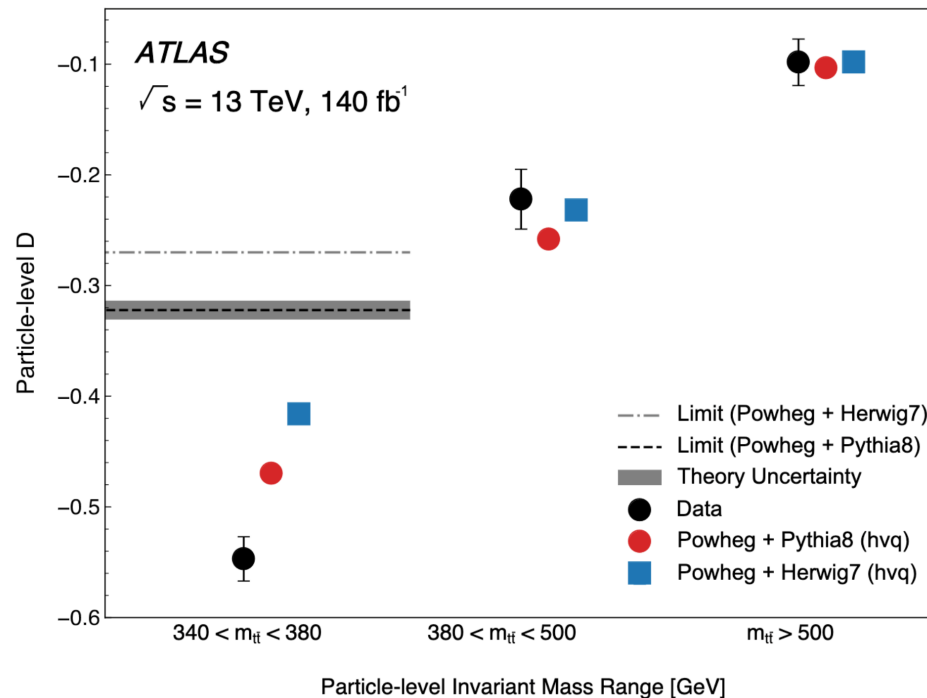
[Q-data Tests](#)



Conclusions

First observation of **entanglement** at LHC

First observation of **entanglement** between free quarks



Conclusions

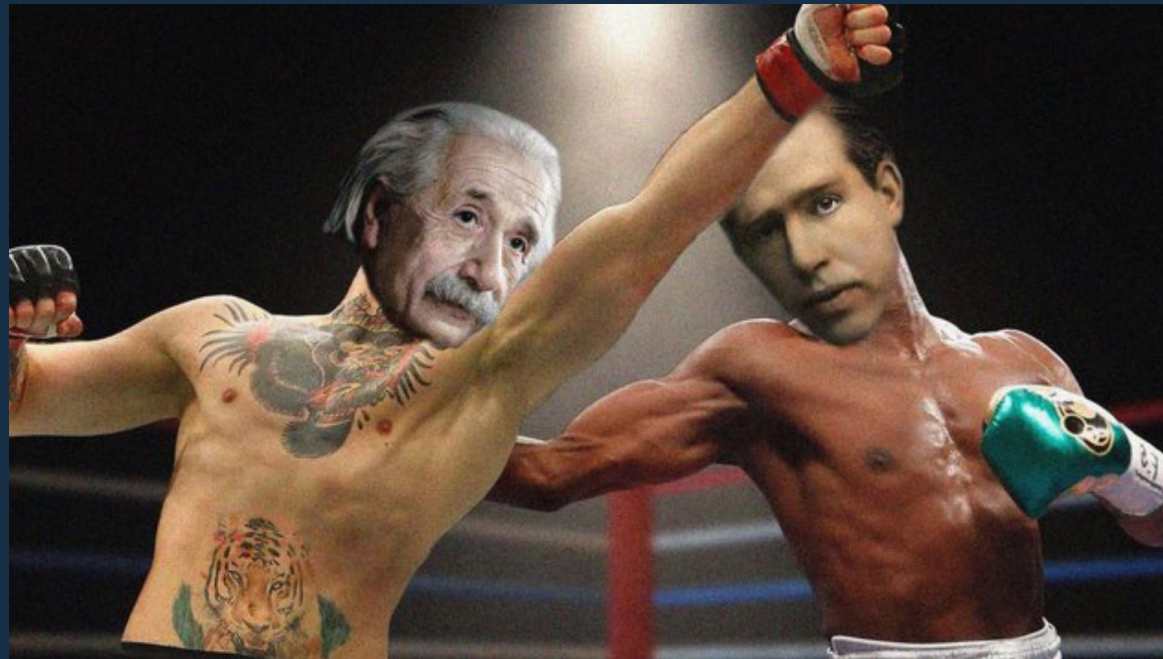
First observation of **entanglement** at **LHC**

First observation of **entanglement** between **free quarks**

- Separability of density matrix: measure through marker D .
- Extract D from angular distribution: standard di-leptonic techniques.
- Motivates improvements to modelling tools

Thank You

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



Auxiliary Materials

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.

Experimental highlights

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

WRONG!



A Lesson

Many 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

At the limit of what we can do in such a tight phase-space region?



Common Questions

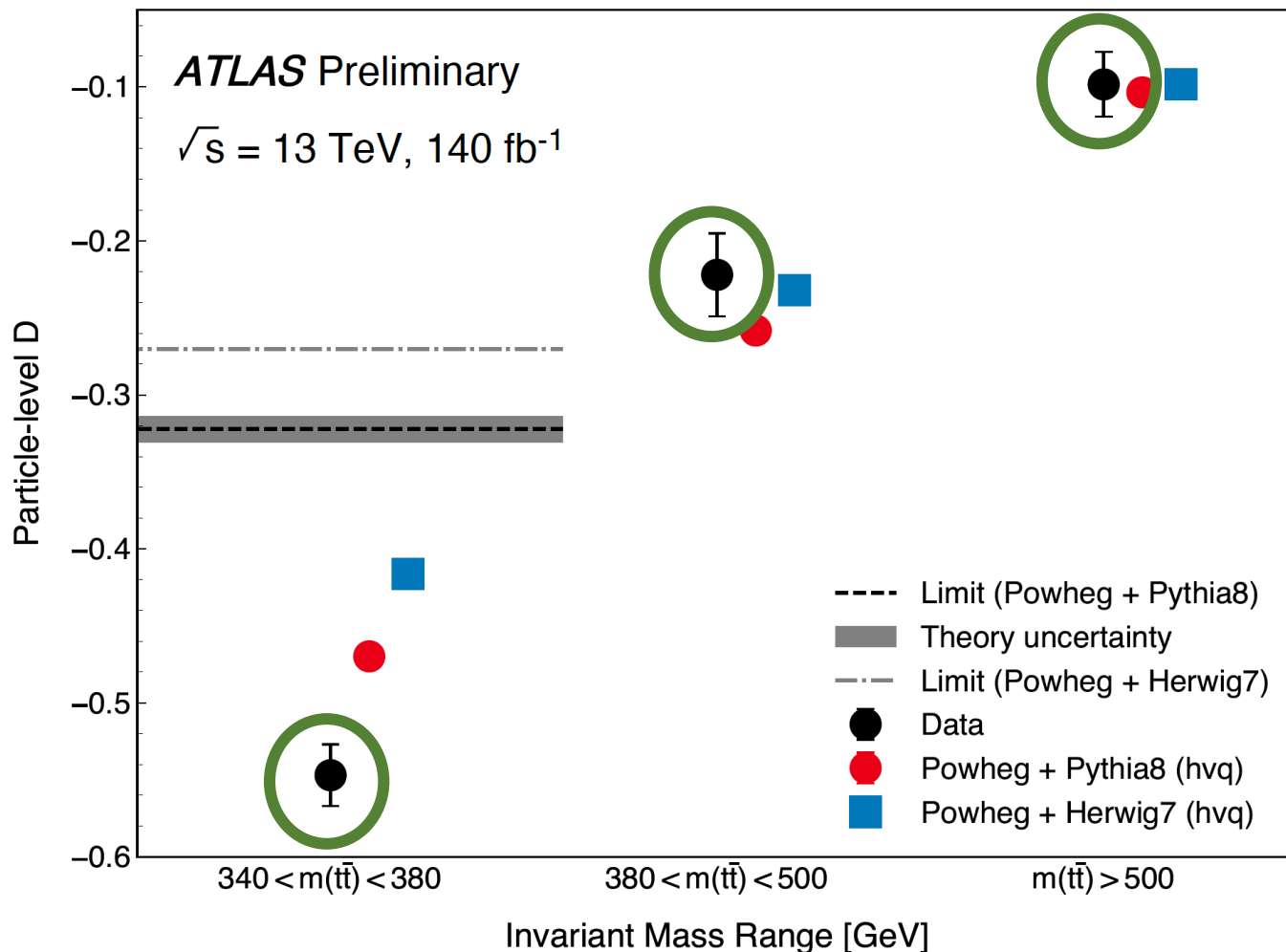
How **reliable** is the **calibration curve** method?

Very reliable ✓

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

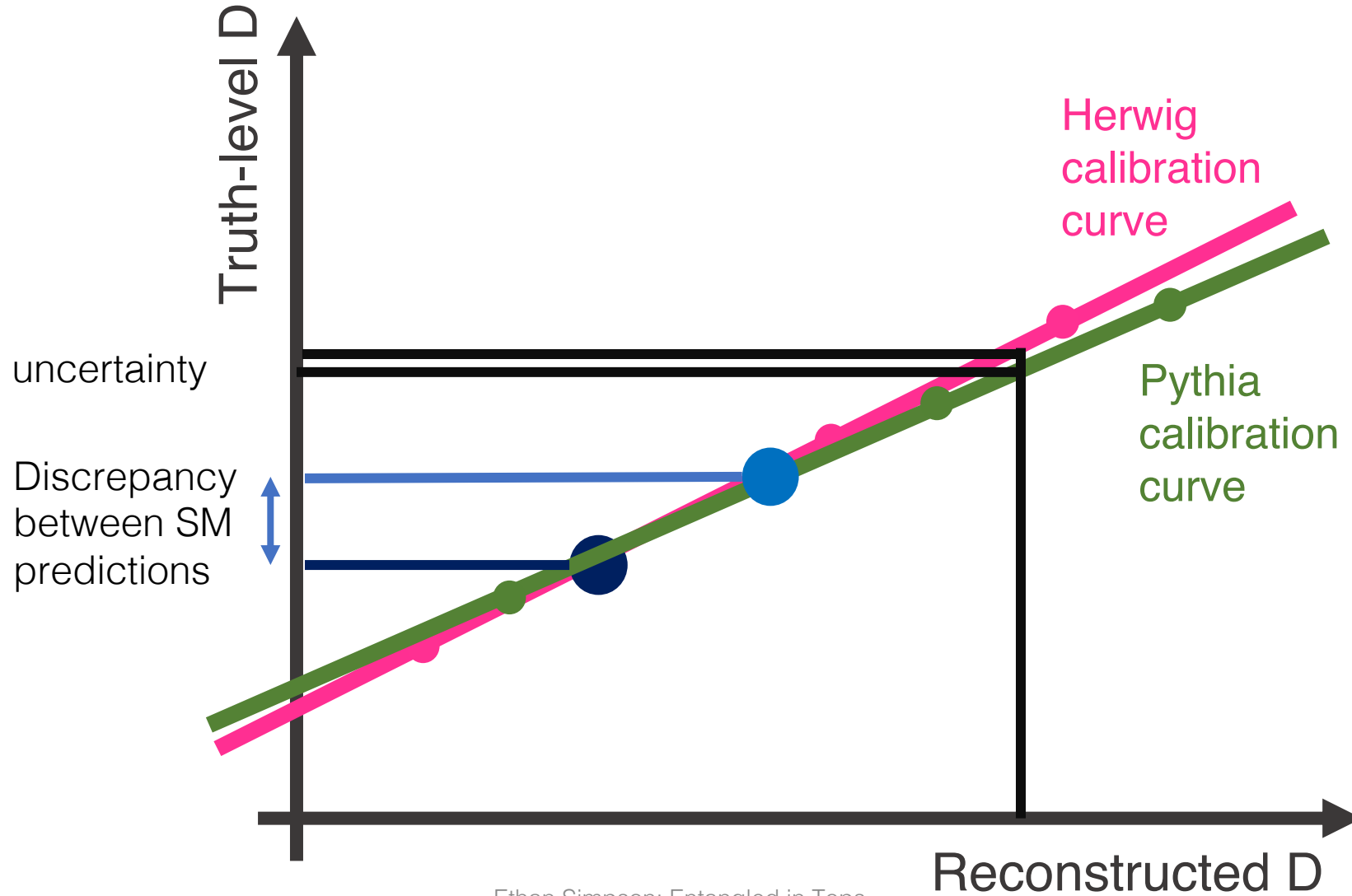
We understand our detector response extremely well.

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



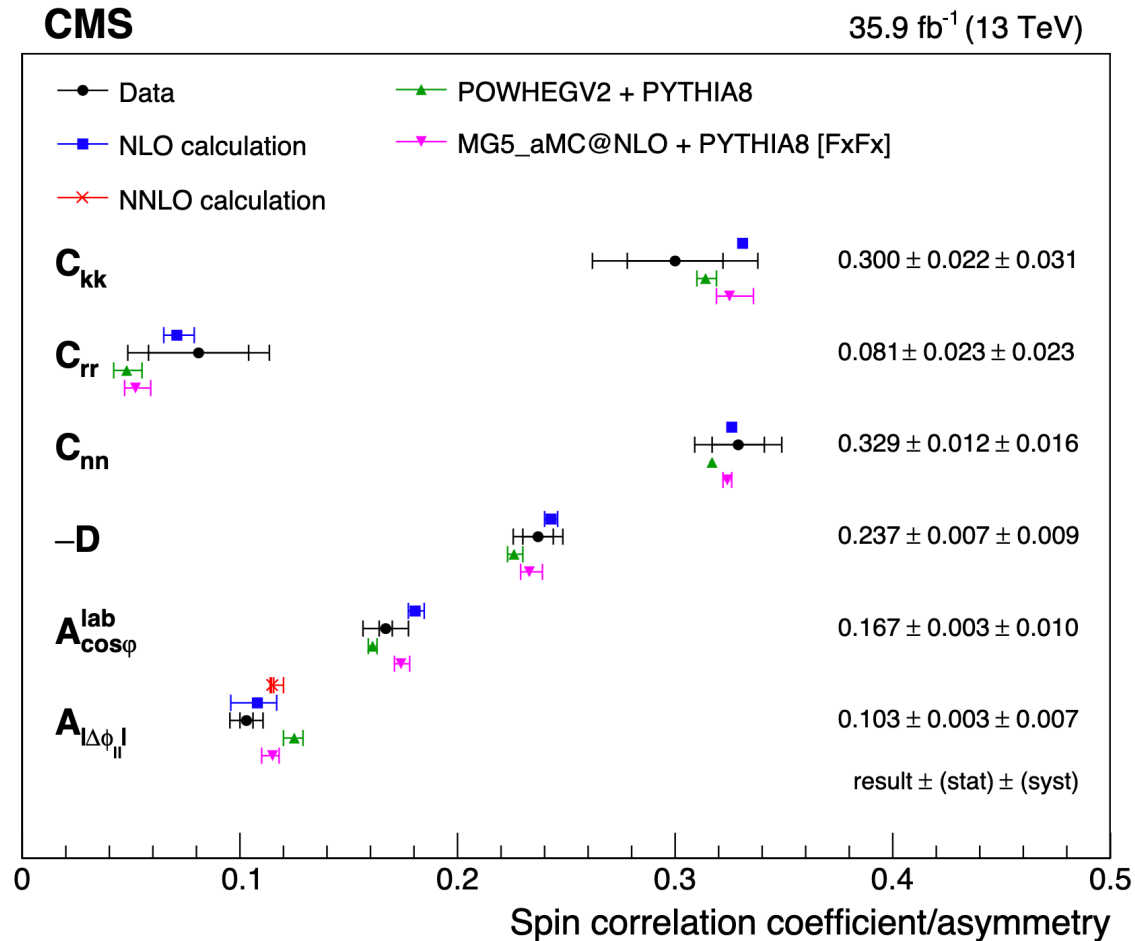
Common Questions

How **reliable** is the **calibration curve** method?



Measurements of Spin Correlations

Many precision measurements of spin parameters in the past



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

View as an average spin correlation

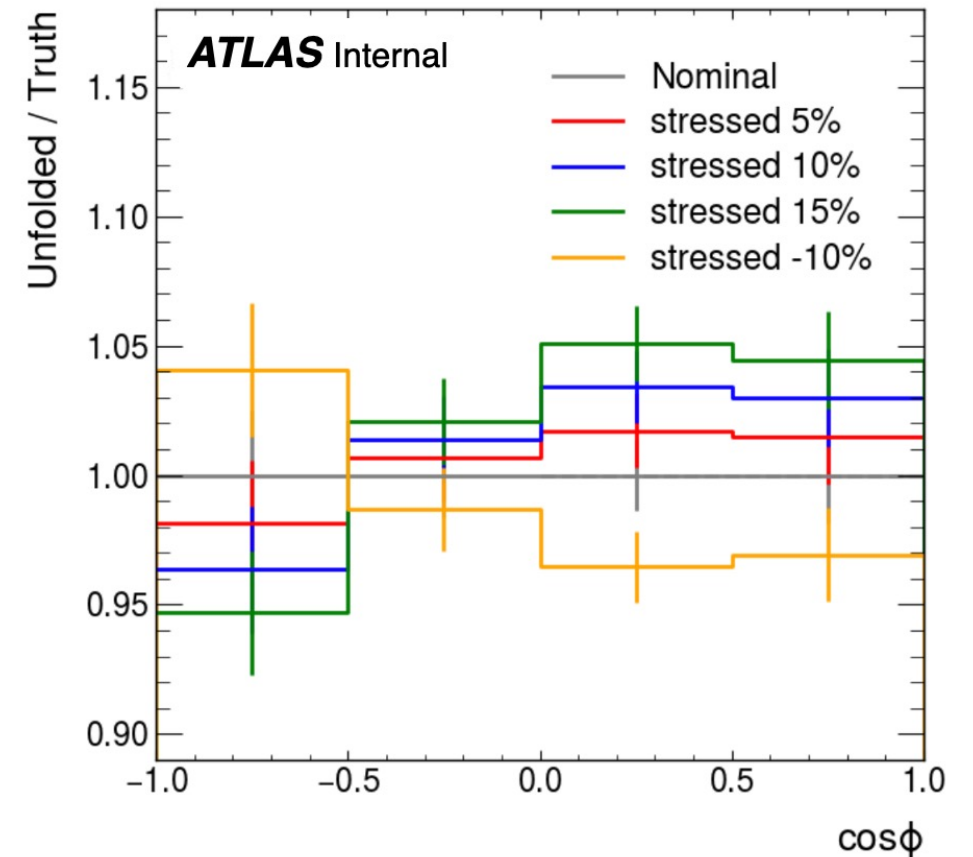
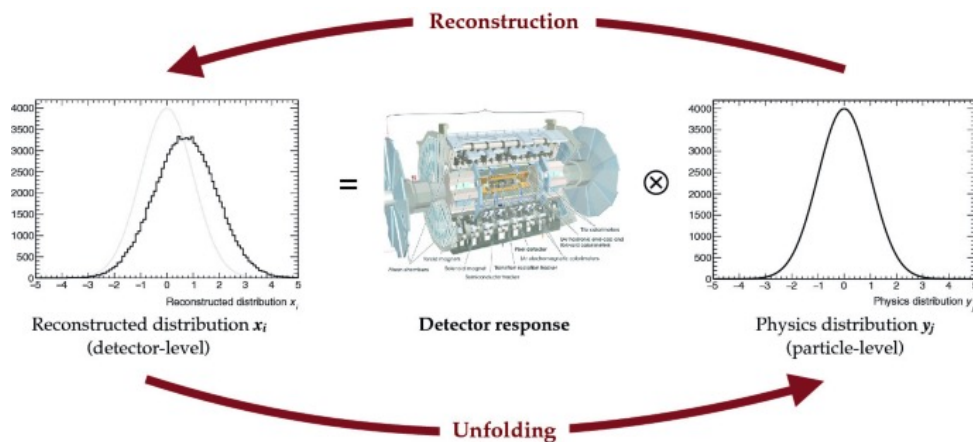
Unfolding

Correct detector effects back to underlying truth

For comparison to predictions and other experimental results.

Many techniques available: tried Iterative Bayesian Unfolding

Must check procedure for bias...



Unfolding Efforts

Parameterise variation in the detector effects on D.

Alter the slope of the $\cos\phi$ distribution

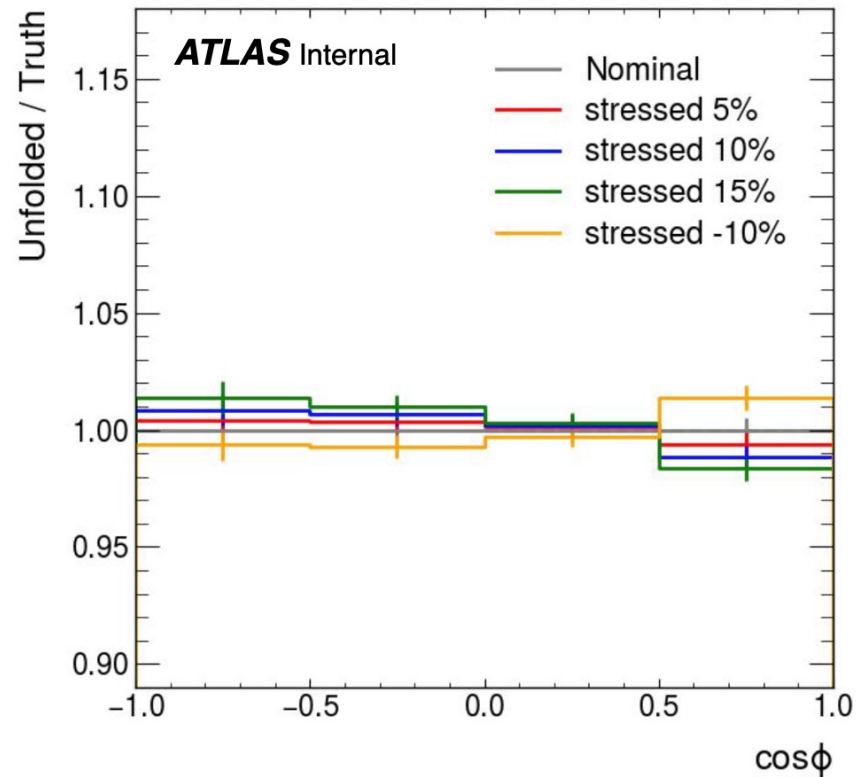


Unfold the distorted result

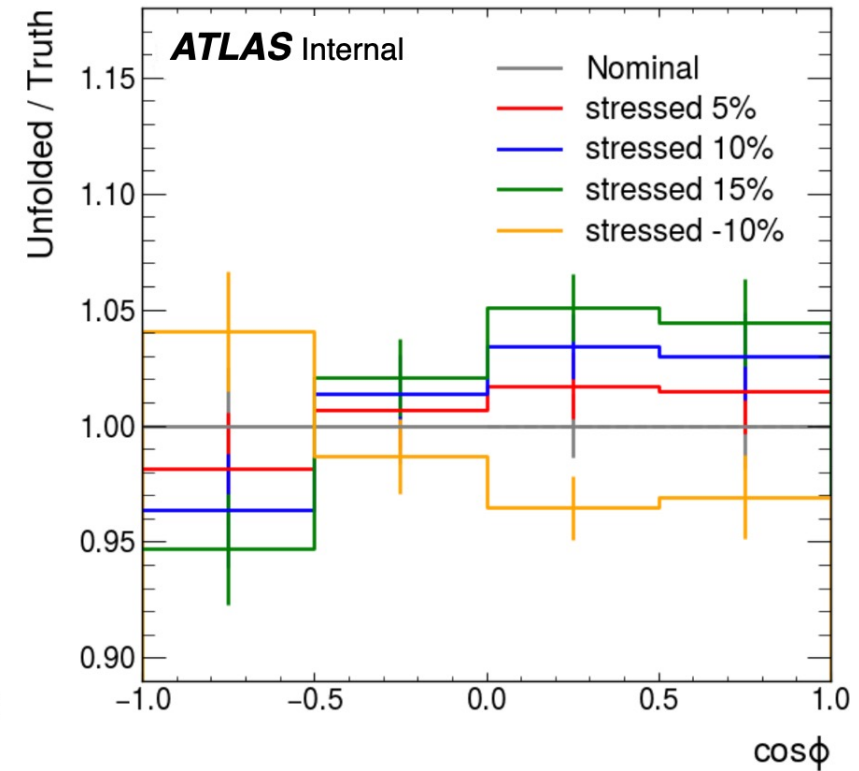


Compare unfolded to truth

Inclusive



Signal Region



Modelling Uncertainties

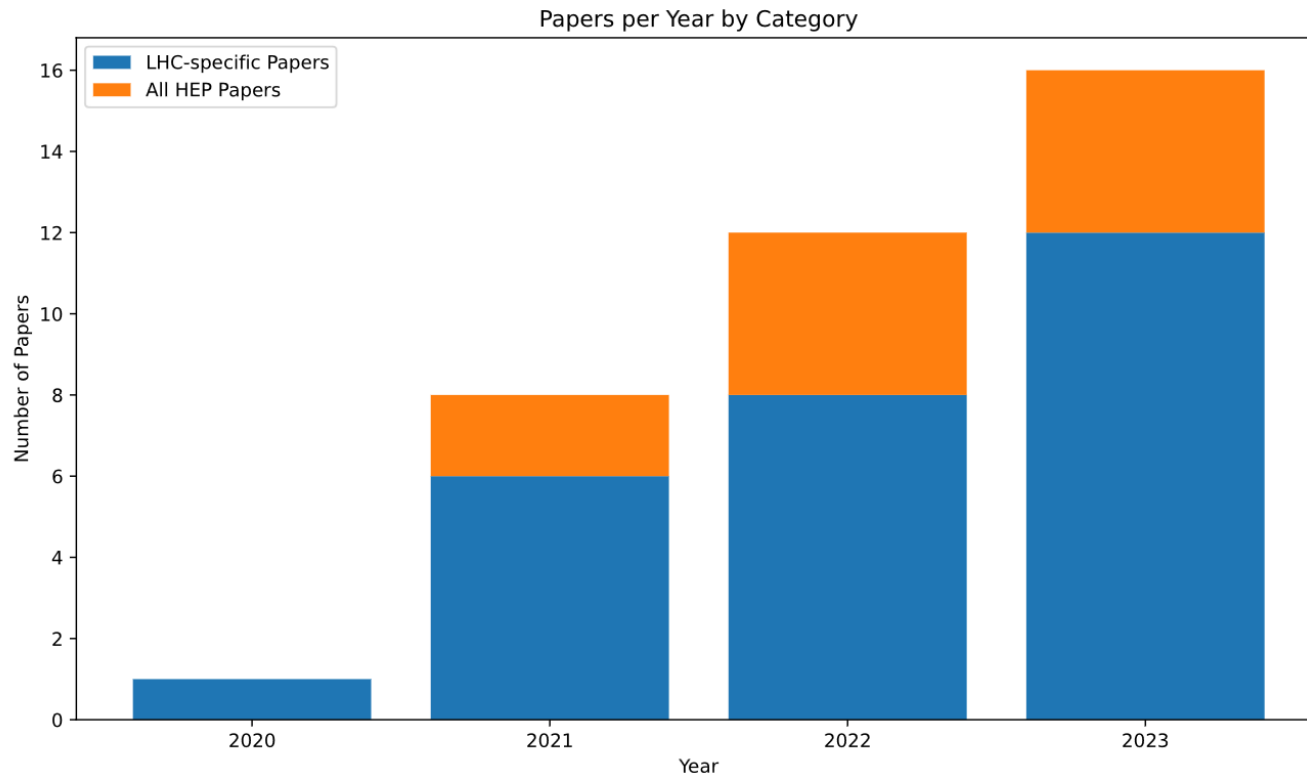
$t\bar{t}$ modelling near threshold has large impact on precision.

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%
$p_{T\text{hard}}$ setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

How heavy-resonance decays and spin correlations are treated

Small because correction to particle-level.

QI-HEP Hype



Physics Briefing

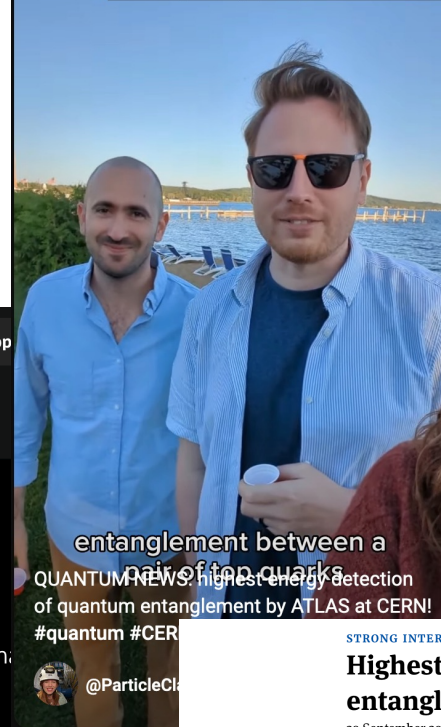
ATLAS achieves highest-energy detection of quantum entanglement

28 September 2023 | By ATLAS Collaboration

Tags: physics results, top quark

Quantum entanglement is one of the most astonishing properties of quantum mechanics. If two particles are entangled, the state of one particle cannot be described independently from the other. This is a unique property of the quantum world and forms a crucial difference between classical and quantum theories of physics. It is so important, the [2022 Nobel Prize in Physics](#) was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

discovered entanglement between a pair of top quarks



entanglement between a pair of top quarks

QUANTUM NEWS: highest energy detection of quantum entanglement by ATLAS at CERN!

#quantum #CERN

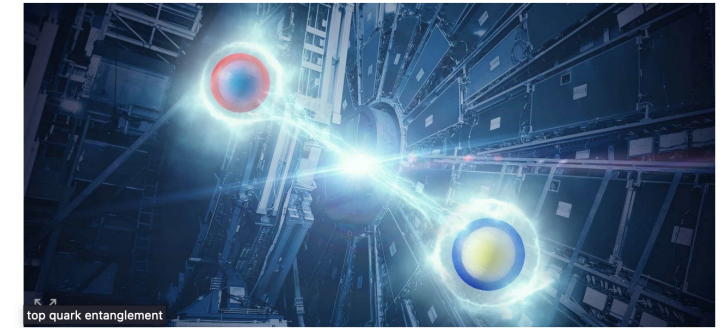
@ParticleCl



QUANTUM | RESEARCH UPDATE

Quantum entanglement observed in top quarks

11 Oct 2023



Top result: An artist's impression of top-quark entanglement. The line between the particles emphasizes the non-separability of the top-quark pair, which is produced by LHC collisions and recorded by ATLAS. (Courtesy: Daniel Dominguez/CERN)

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Large Hadron Collider turned into world's biggest quantum experiment

Physicists have used the famous particle smasher to investigate the strange phenomenon of quantum entanglement at far higher energies than ever before

By Alex Wilkins



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PUBLISHED September 29, 2023

Highest-Energy Detection Of Quantum Entanglement Achieved Yet

The energy scale is a thousand billion times higher than typical laboratory experiments.



DR. ALFREDO CARPINETI

Senior Staff Writer & Space Correspondent

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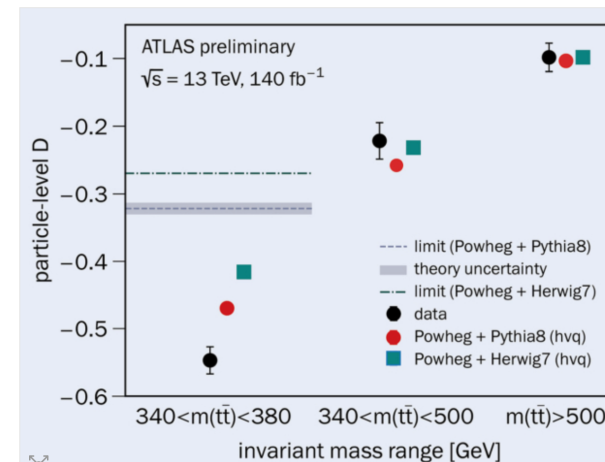
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STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.



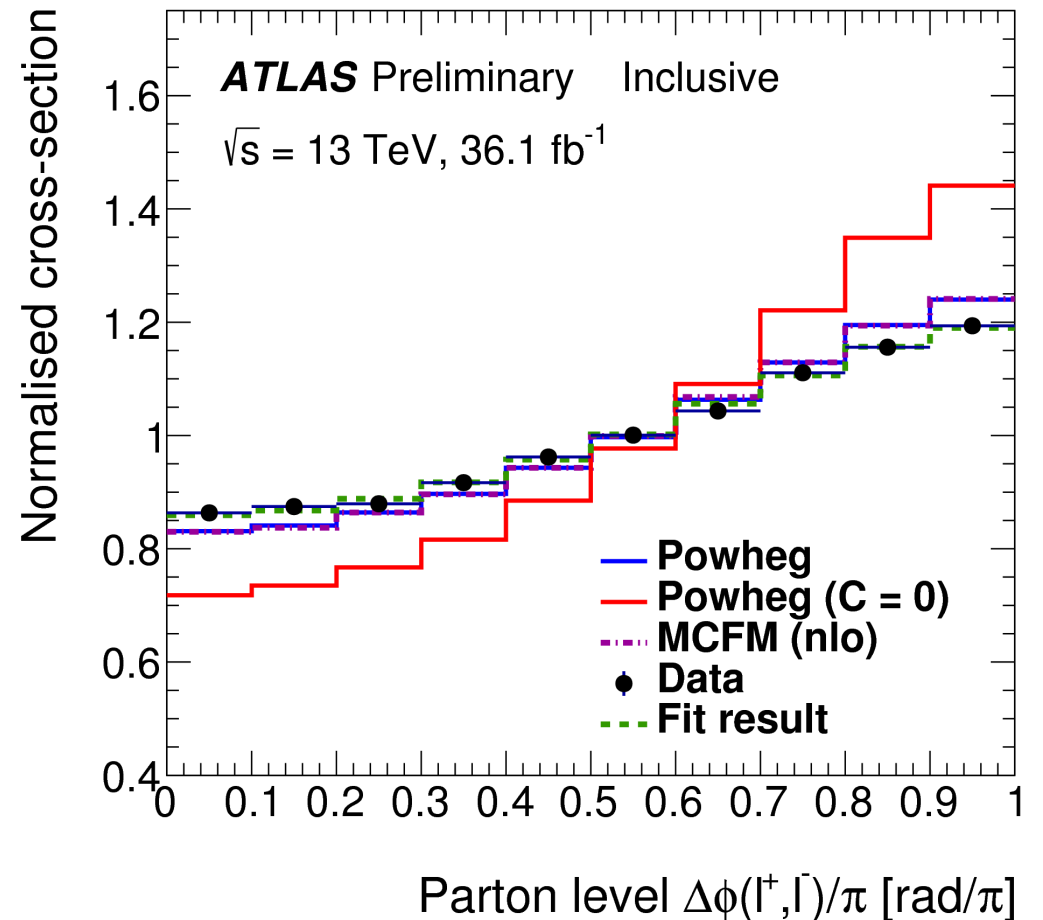
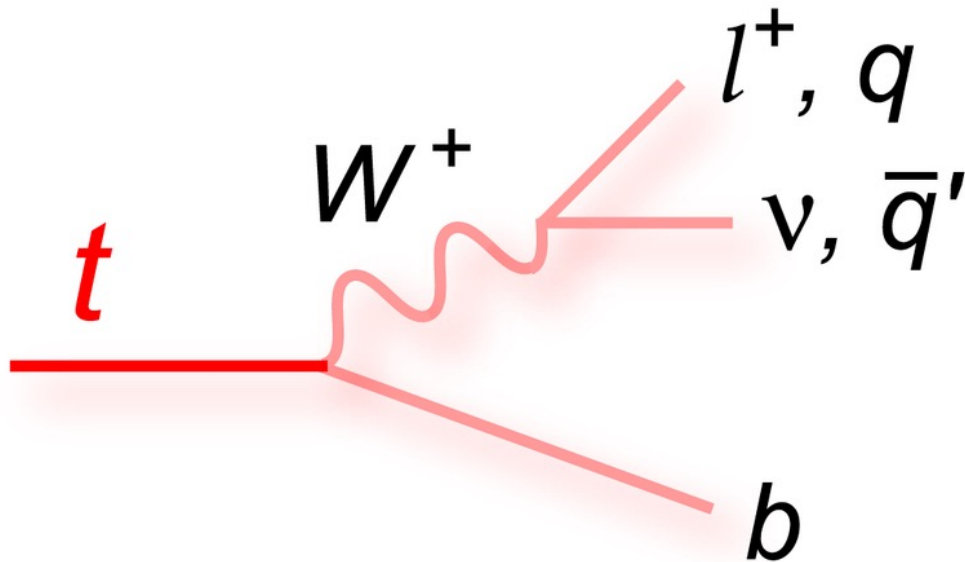
CERN COURIER

New-issue alert: sign up today

Angular Observables

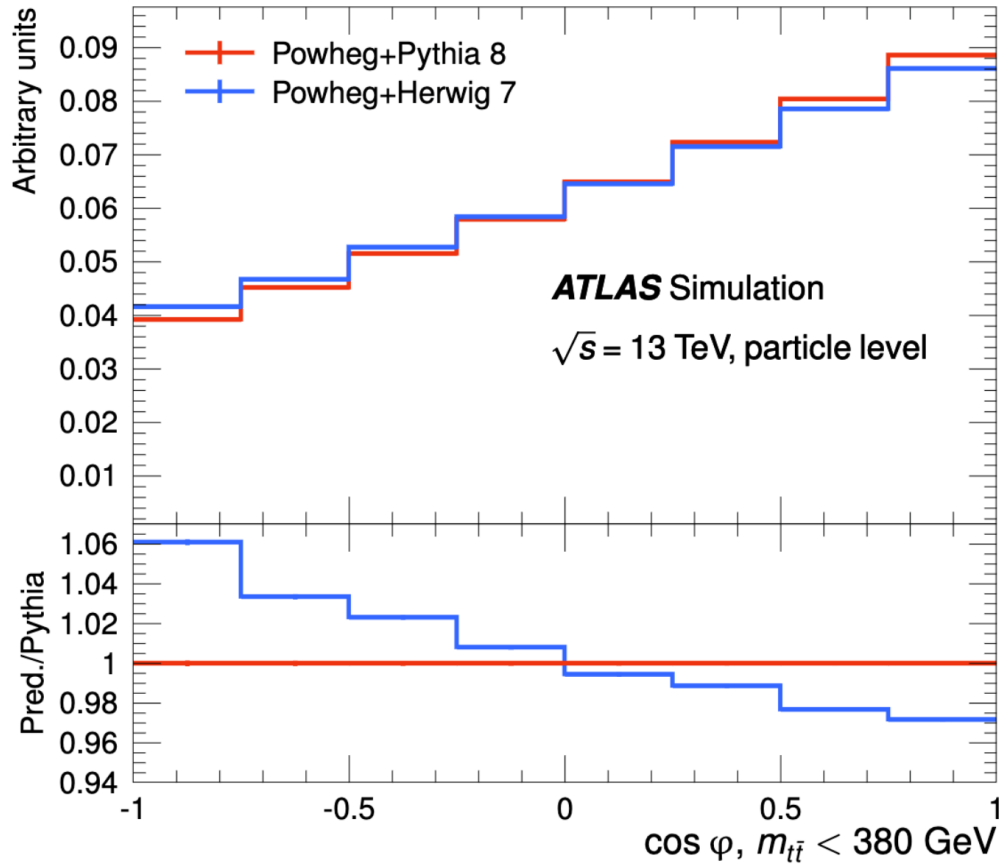
Measure spin parameters through angular observables.

- Top spins determine W helicities.
- W helicities correlate with decay product directions

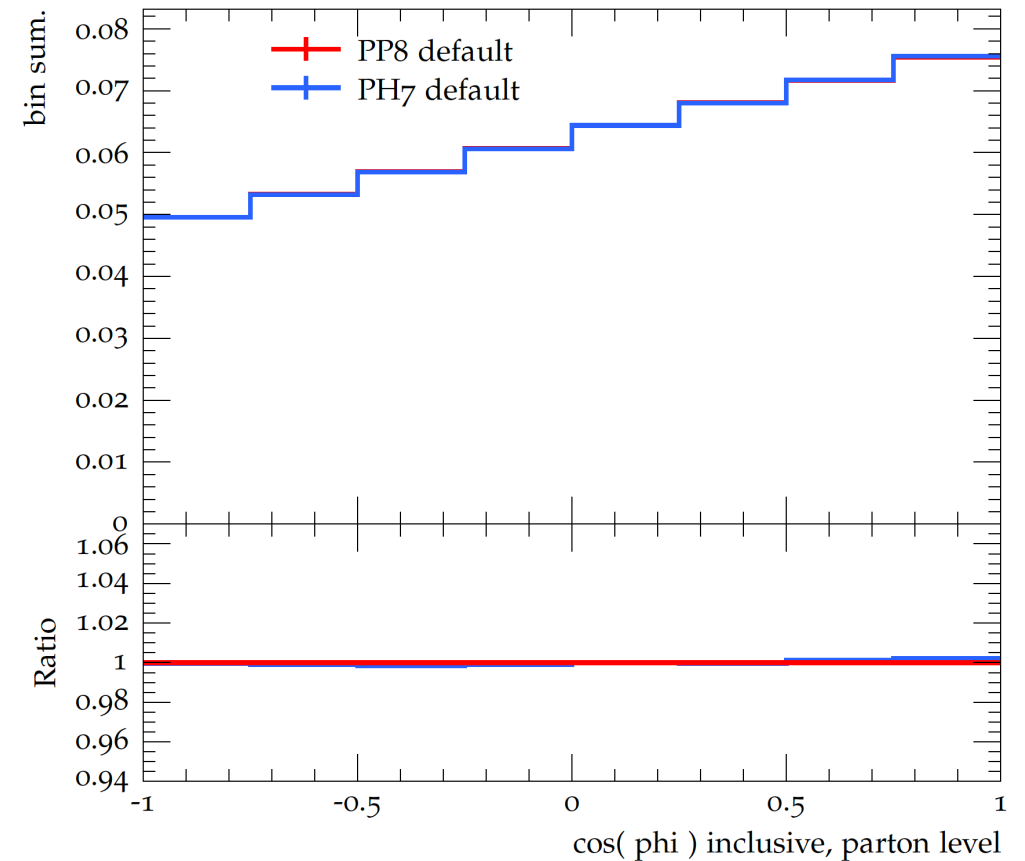


Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



Large difference at particle-level



No difference at parton-level

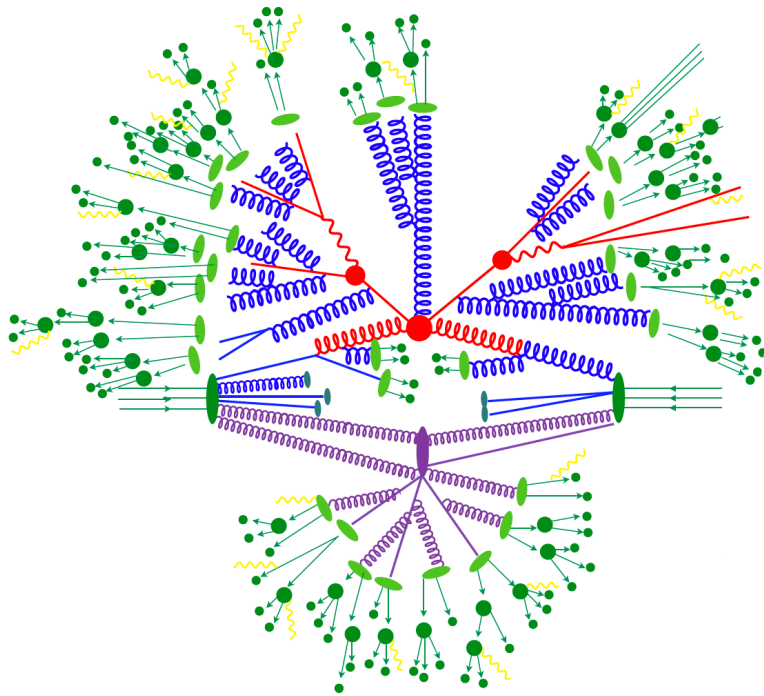
Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



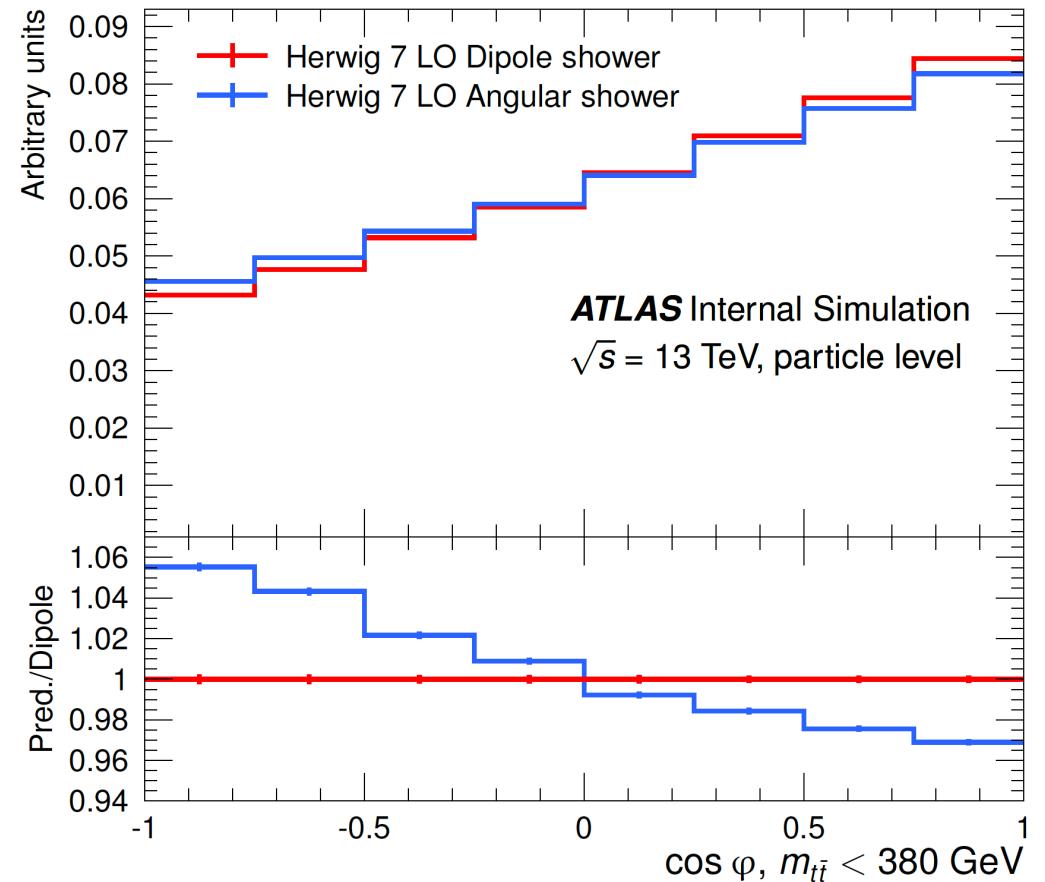
Problems with the shower

A parton shower models QCD radiation from hard partons



Evolves by stepping through some ordering parameter.

Dipole-ordered vs angular-ordered



Top Quark Production

In general, the spin information can be accessed through the decay products of tops

Two factors come to our aid:

- The short lifetime of the top reduces probability that other effects will wash out spin information.
- The chiral structure of the weak interaction mean constrains the helicities of the decay products, eventually leading to a correlation between the flight of the decay products and the initial spin information.

“New Physics” in HEP-QI

- In this context, we have to be slightly careful about what new physics is e.g. *Is new physics affecting the quantum state?*
- Can we test “beyond-quantum” theories e.g. general probabilistic theories: seek deviations from unitarity and linearity. Apparently so, Bell-type tests probe these things.
- EFTs not necessarily probing this.
- Is EFT just changing spin correlations. This does amount to changing entanglement?

$$w = \frac{1 - K \cdot D(m_{t\bar{t}}) \cos \varphi}{1 - D(m_{t\bar{t}}) \cos \varphi}.$$

$$D(m_{t\bar{t}}) = \sum_{i=0}^3 \frac{a_i}{m_{t\bar{t}}^i},$$

Werner States

- Werner states can exhibit entanglement (non-separability) but no Bell nonlocality.
- Werner states have the minimum amount of quantum uncertainty.
- To test Bell nonlocality, need to do a Bell test.
- This whole study assumes that the states are quantum, in the Bell nonlocal sense.