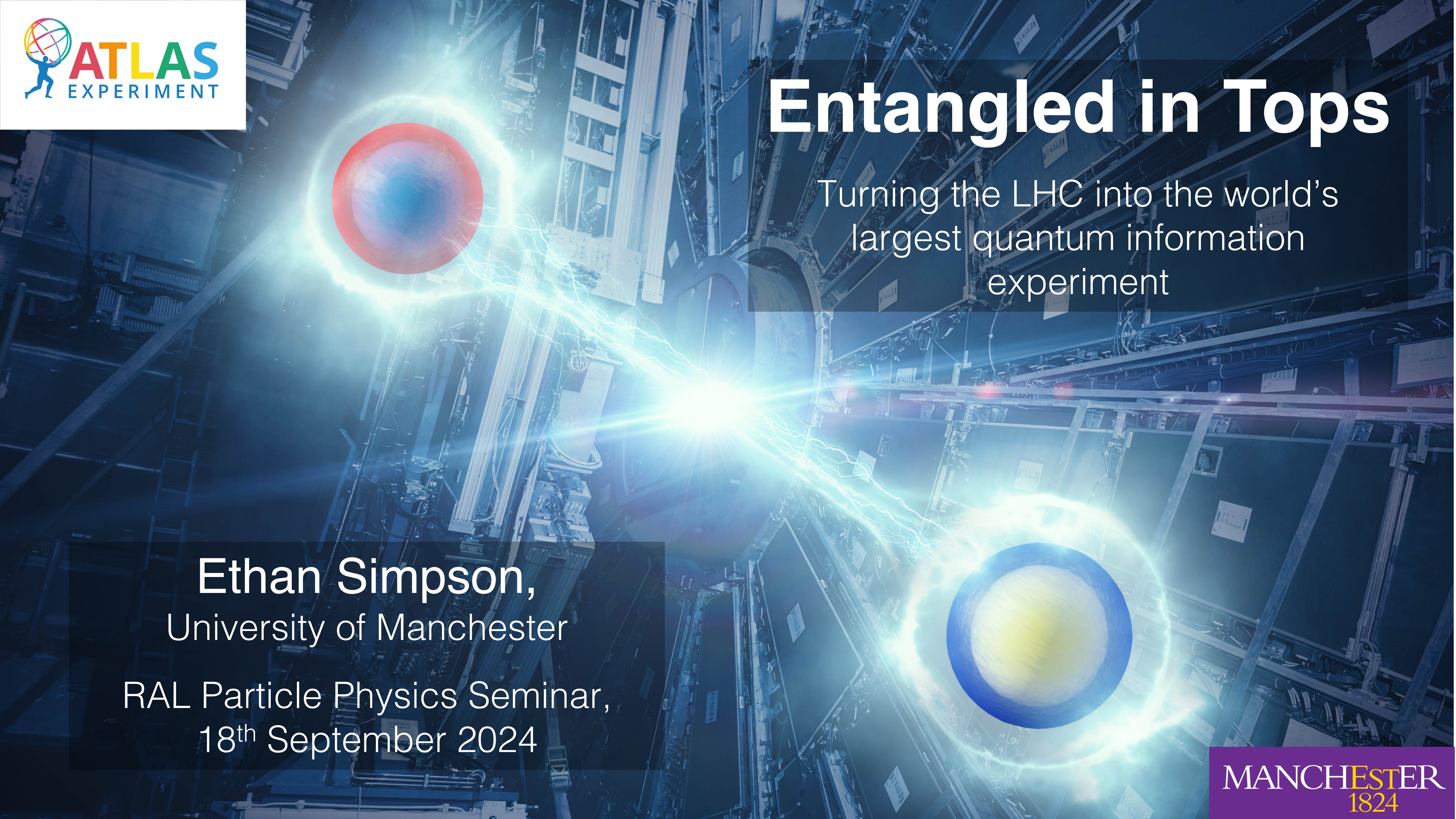


Entangled in Tops

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

Ethan Simpson,
University of Manchester

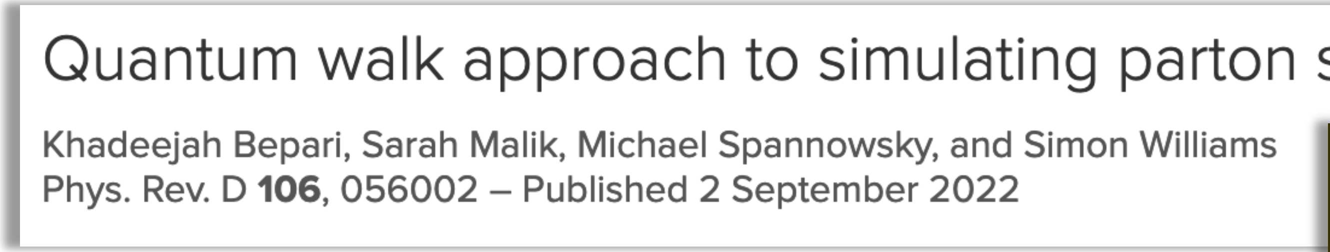
RAL Particle Physics Seminar,
18th September 2024

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

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

What about quantum computing?

Use quantum computers to improve HEP techniques

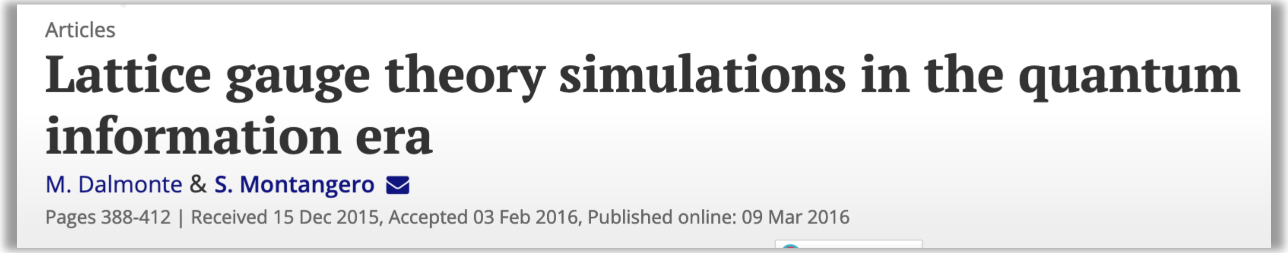


Quantum walk approach to simulating parton showers

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 integration of elementary particle processes

Gabriele Agliardi [a b] ✉, Michele Grossi [c] ✉, Mathieu Pellen [d] ✉, Enrico Prati [e f] ✉

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

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Phys. Rev. D **105**, 076012 – Published 19 April 2022

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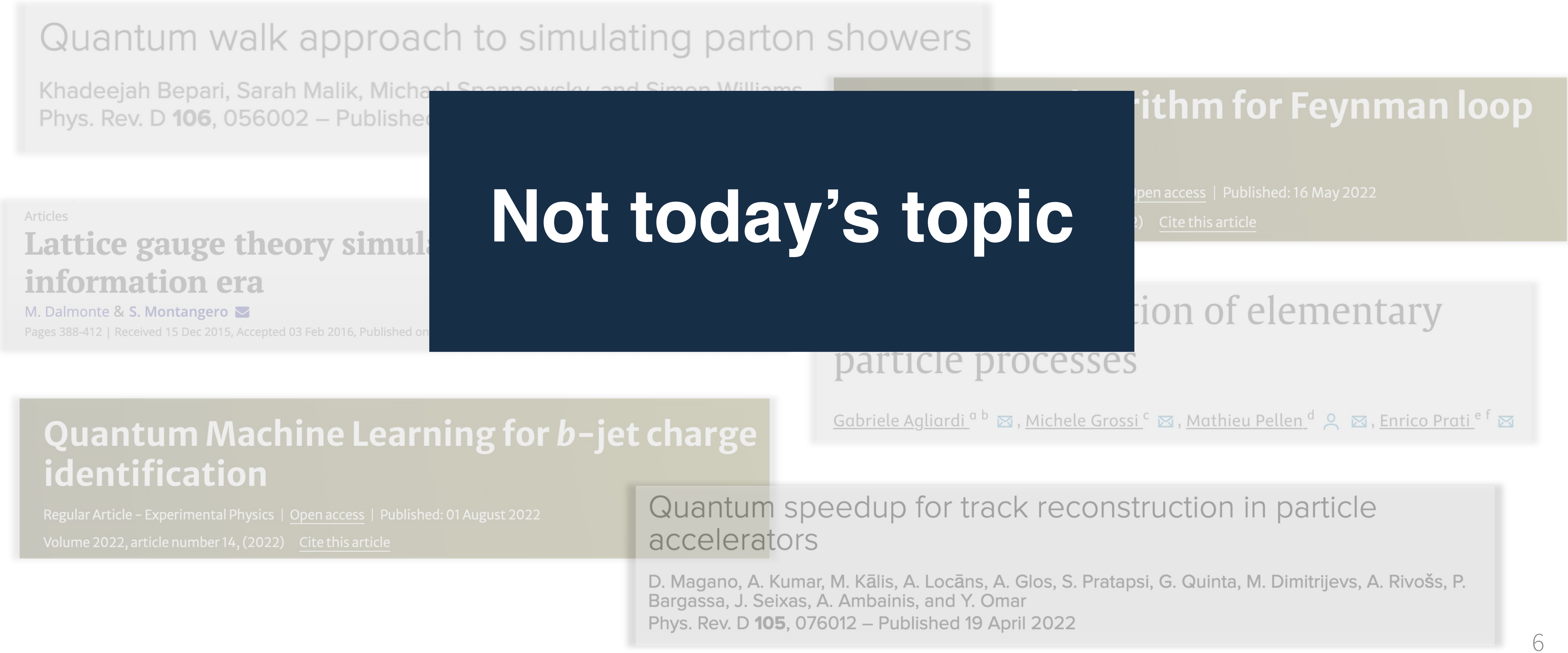

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Not today's topic

What about measuring
“quantum observables”

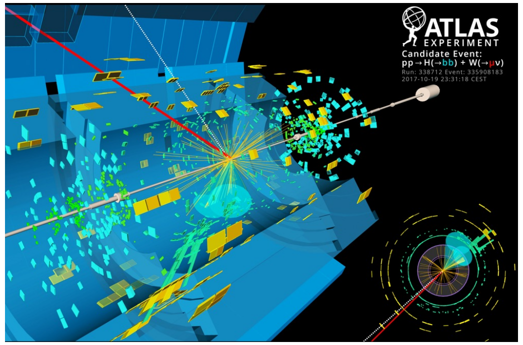
a.k.a

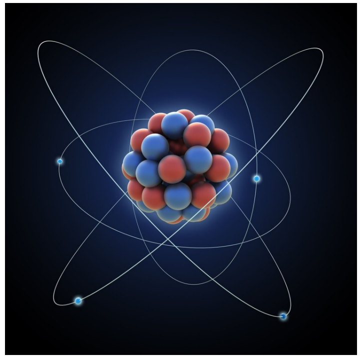
Testing QM in a new energy regime?

Why?

Why measure “quantum observables” at colliders?

Quantum at different length scales…





10^{-35} m

10^{-20} m

10^{-10} m

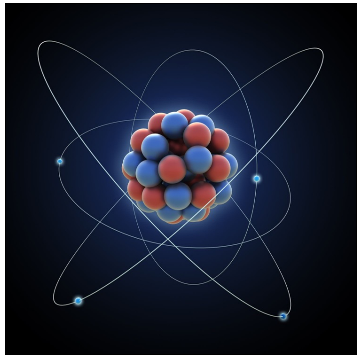
10^{-3} m

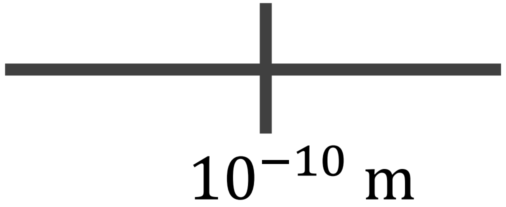
10^{0} m

Why?

Why measure "quantum observables" at colliders?

Quantum mechanics developed to describe physics at this length-scale





Why?

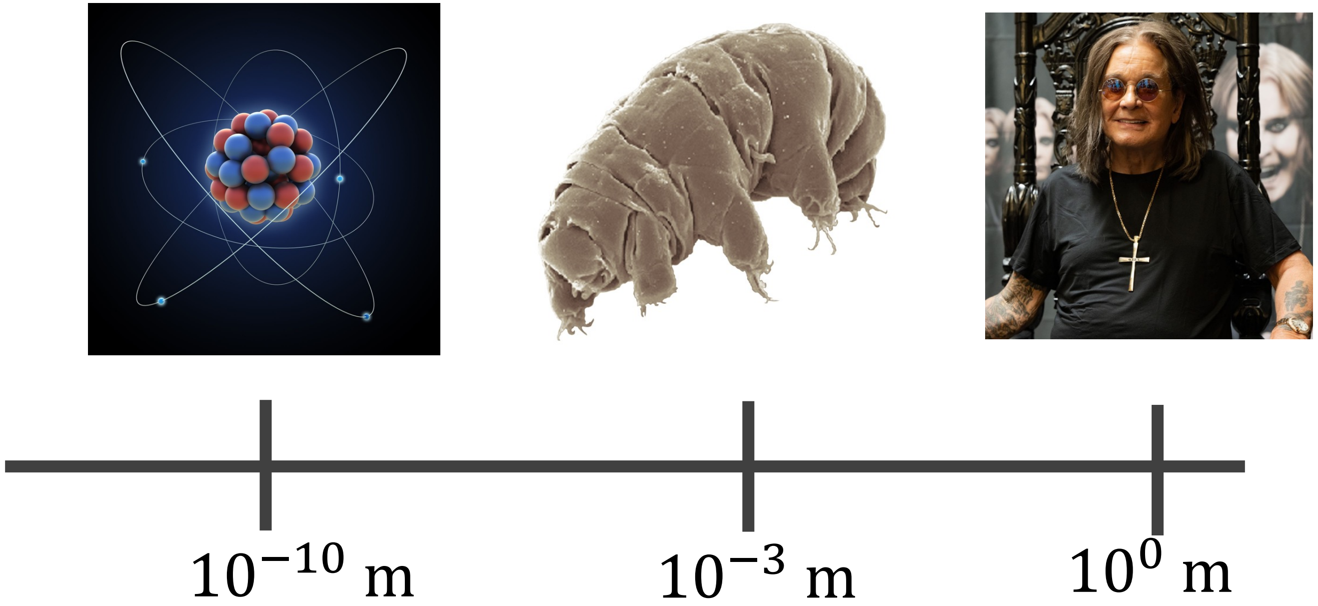
Why measure "quantum observables" at colliders?

QM phenomena at macroscopic scales:

- Quantum fluids
- Superconductivity

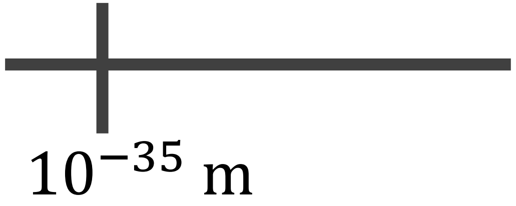
Harnessing QM:

- Quantum computing



Why?

Why measure "quantum observables" at colliders?



"It from qubit"…

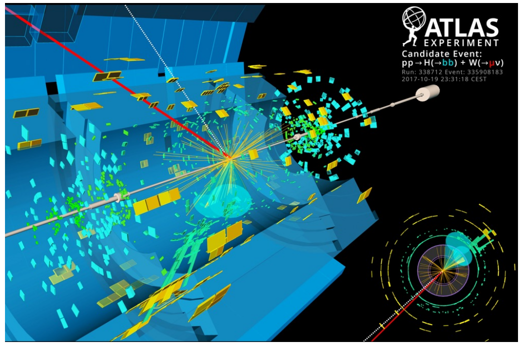
- What is the information-theoretic structure of QFTs?
- Is spacetime an emergent property of quantum entanglement?

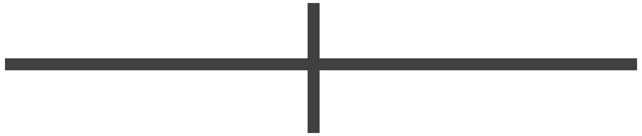
Further reading:

- Simons Collaboration on Quantum Fields, Gravity and Information
- Spacetime from Entanglement

Why?

Why measure “quantum observables” at colliders?





10^{-20} m

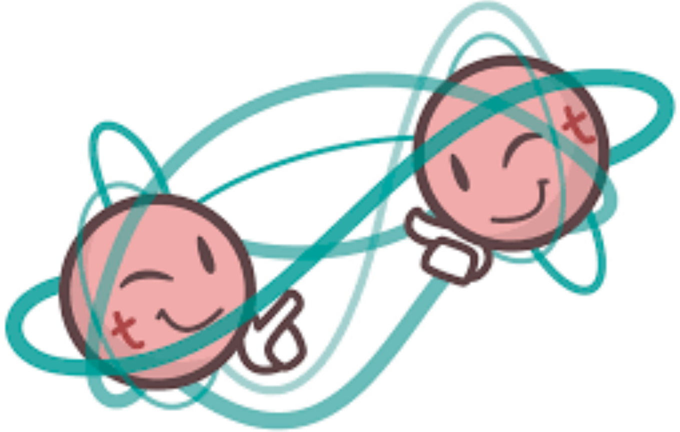
- Does QM look different in QFT regime?
- Test “beyond QM”…
- There’s more to life than (not) finding New Physics
- Can quantum observables help us look for New Physics?

Quantum Entanglement

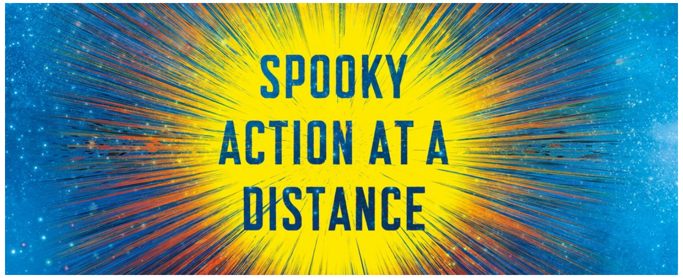
“the most characteristic trait of QM”

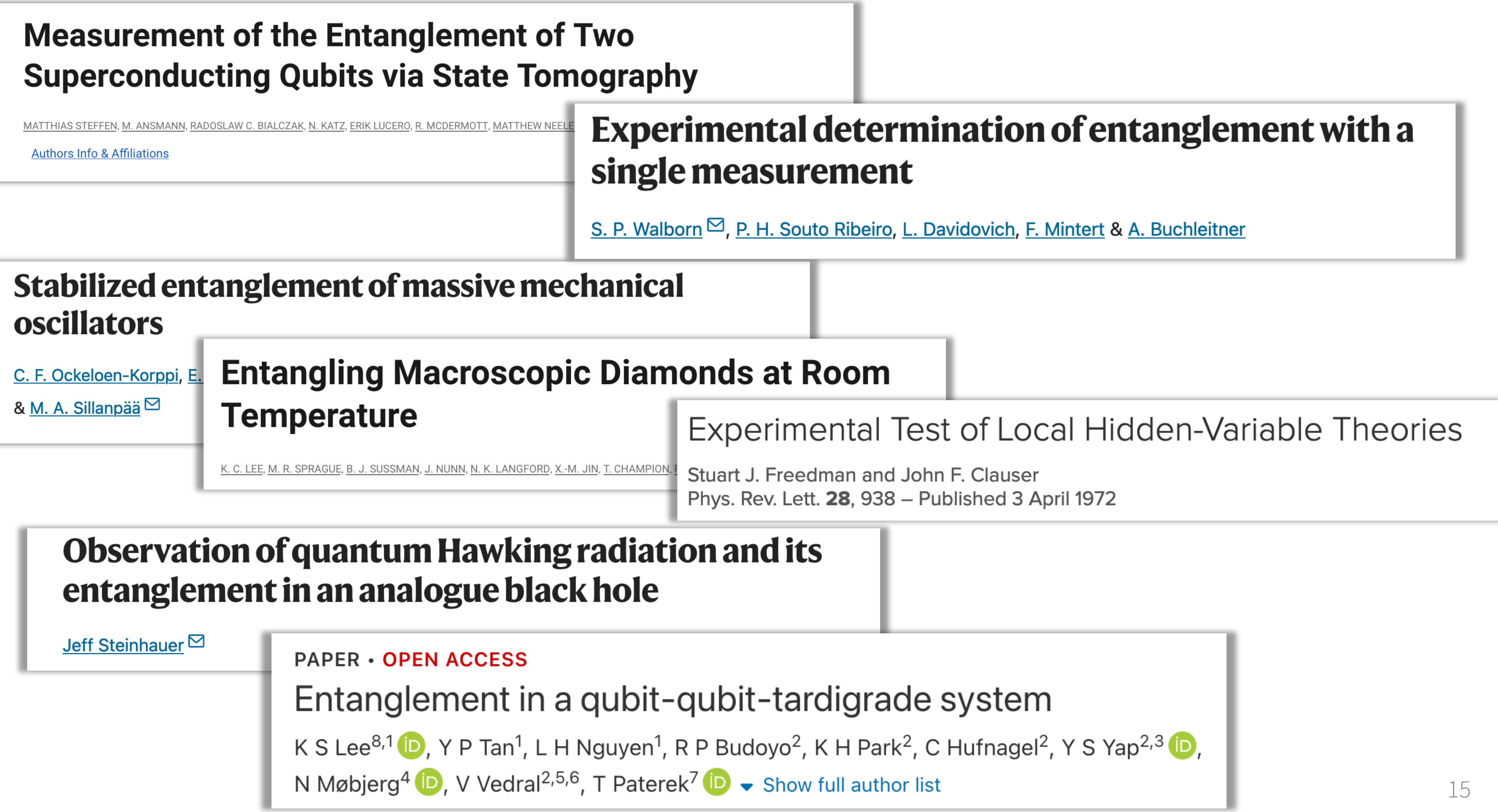
Quantum Entanglement

- 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. Ockeleon-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,

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 Tan[1], L H Nguyen[1], R P Budoyo[2], K H Park[2], C Hufnagel[2], Y S Yap[2,3], N Møbjerg[4], V Vedral[2,5,6], T Paterek[7]

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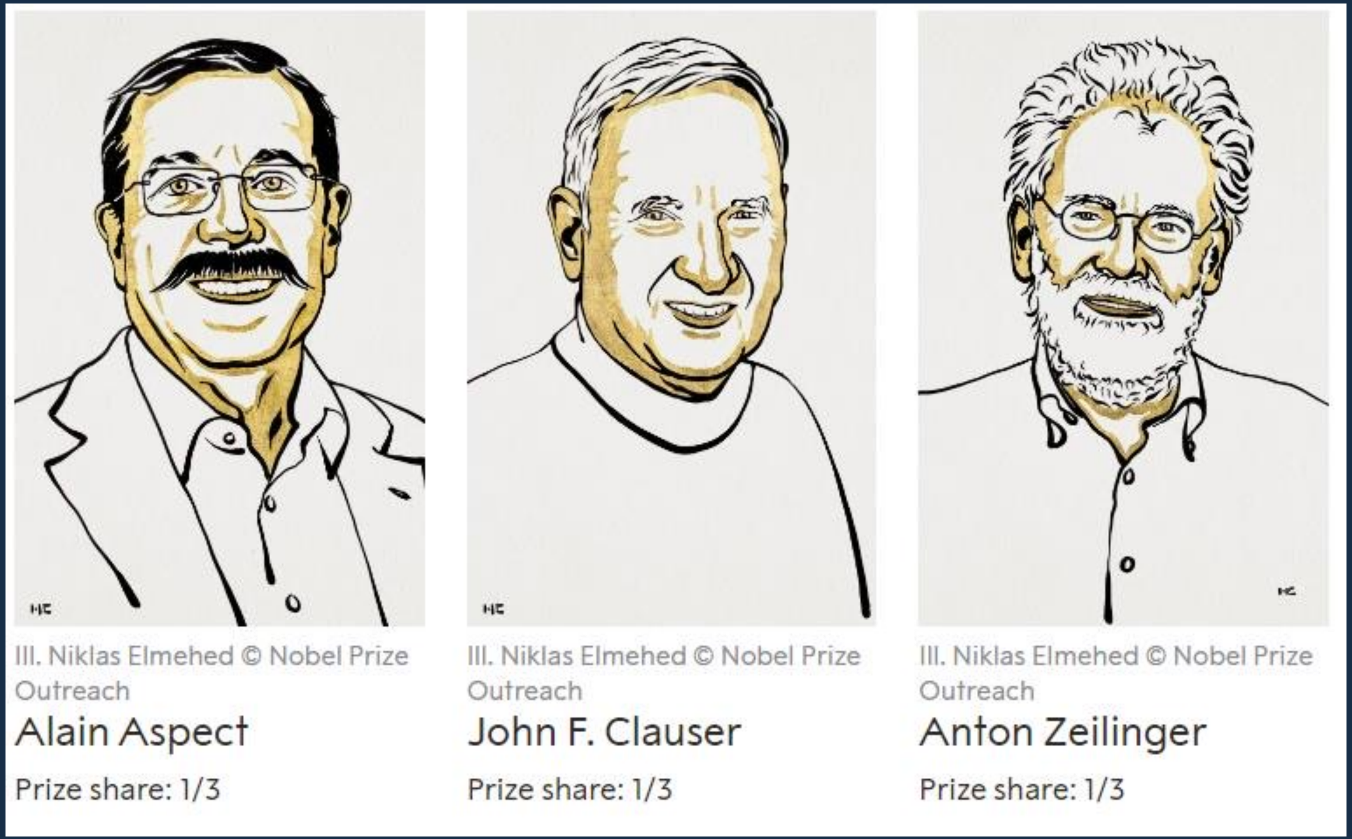
2022 Nobel Prize



Ill. Niklas Elmehed © Nobel Prize Outreach

Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

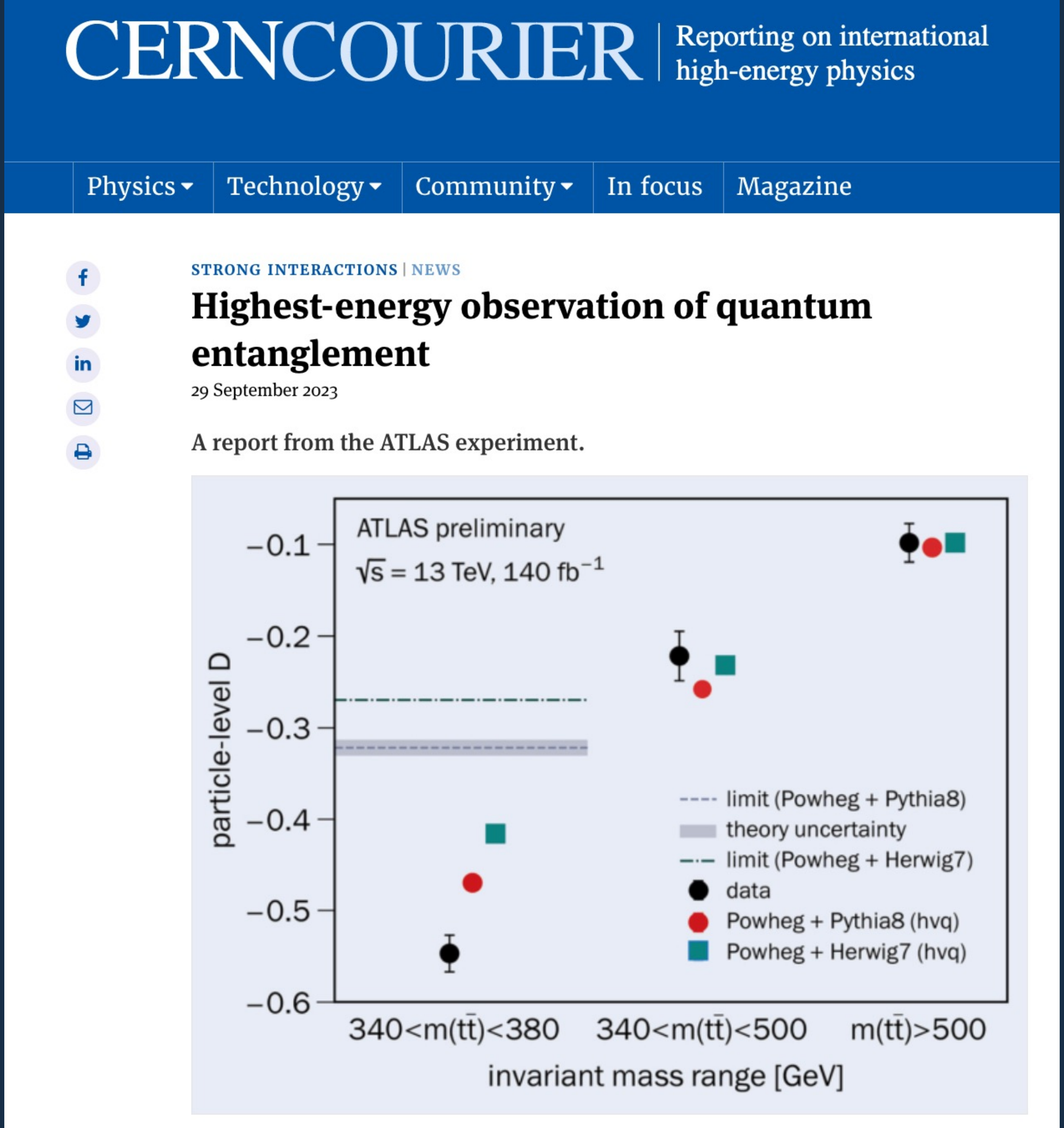
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

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



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STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

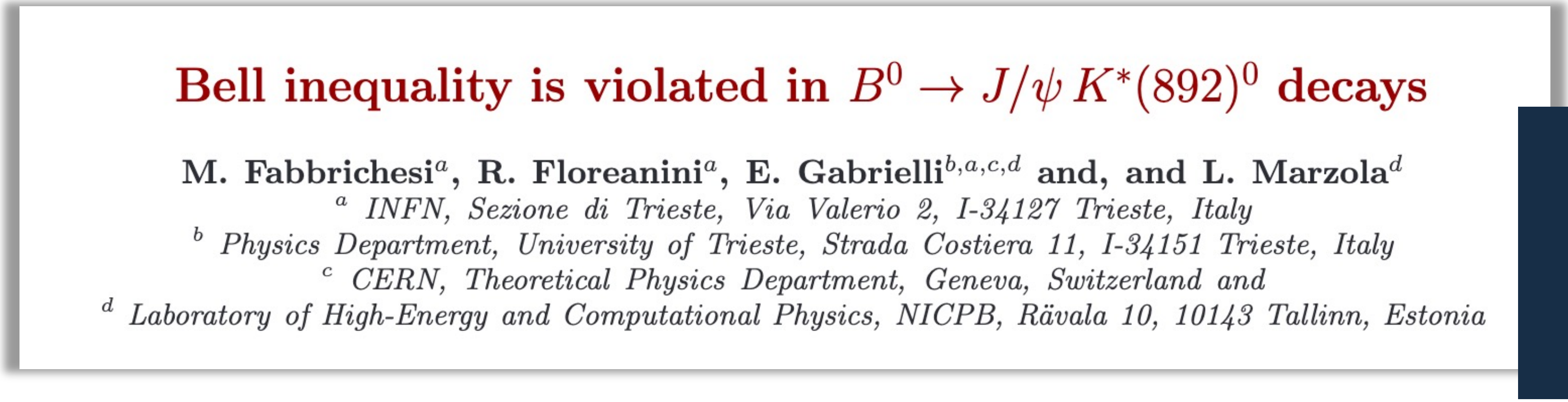
A report from the ATLAS experiment.

Entanglement in HEP

Measurement of EPR-type flavour entanglement in Upsilon(4S)->B0 B0bar decays

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

Flavour entanglement
(2007)



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

M. Fabbrichesi[a], **R. Floreanini**[a], **E. Gabrielli**[b,a,c,d] **and, 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, Rävala 10, 10143 Tallinn, Estonia*

Polarisation
entanglement
(2023)

Entanglement in HEP

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

ATLAS Collaboration

Dileptonic top pairs
(2023)

Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s}$ = 13 TeV

CMS Collaboration

Dileptonic top pairs
(2024)

CMS-PAS-TOP-23-007

Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events from pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$

CMS Collaboration

Lepton + jets top pairs
(2024)

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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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

Strategy

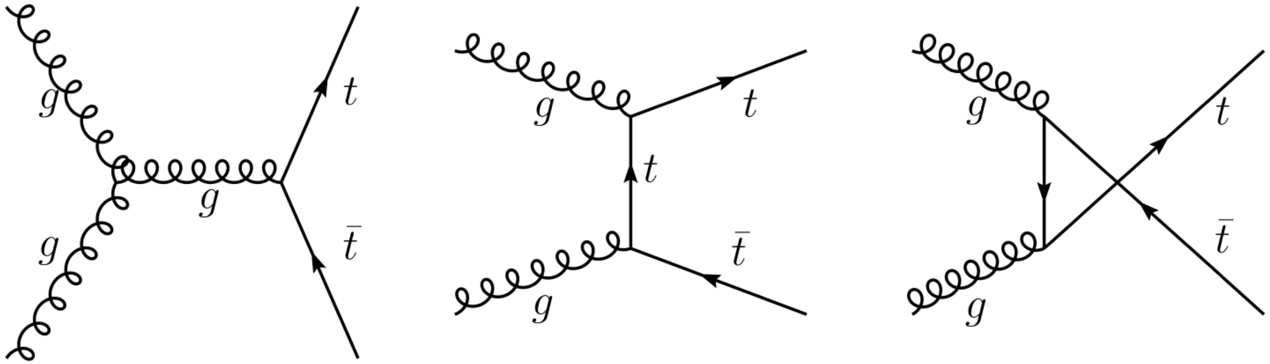
1. Define a mathematical (QM) description of $t\bar{t}$ production
2. Condense description down into a single entanglement marker
3. Measure an angular observable in $t\bar{t}$ data
4. Extract the entanglement marker from this angular distribution
5. Compare the measured value to a no-entanglement limit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

The Top Quark

The Top Quark

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

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



1. Spin-1/2 qubit
2. Decays weakly, quickly

$t\bar{t}$ production

In terms of density matrices

$$\sigma_{t\bar{t}} \propto \mathrm{Tr}\left[\underbrace{\Gamma_{\bar{t}\to\bar{b}f\,f}}_{\text{Decay}} \times \underbrace{\mathrm{R}_{gg\to t\bar{t}}}_{\text{Production}} \times \underbrace{\Gamma_{t\to bf\,f}}_{\text{Decay}}\right]$$

$t\bar{t}$ production

In terms of density matrices

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

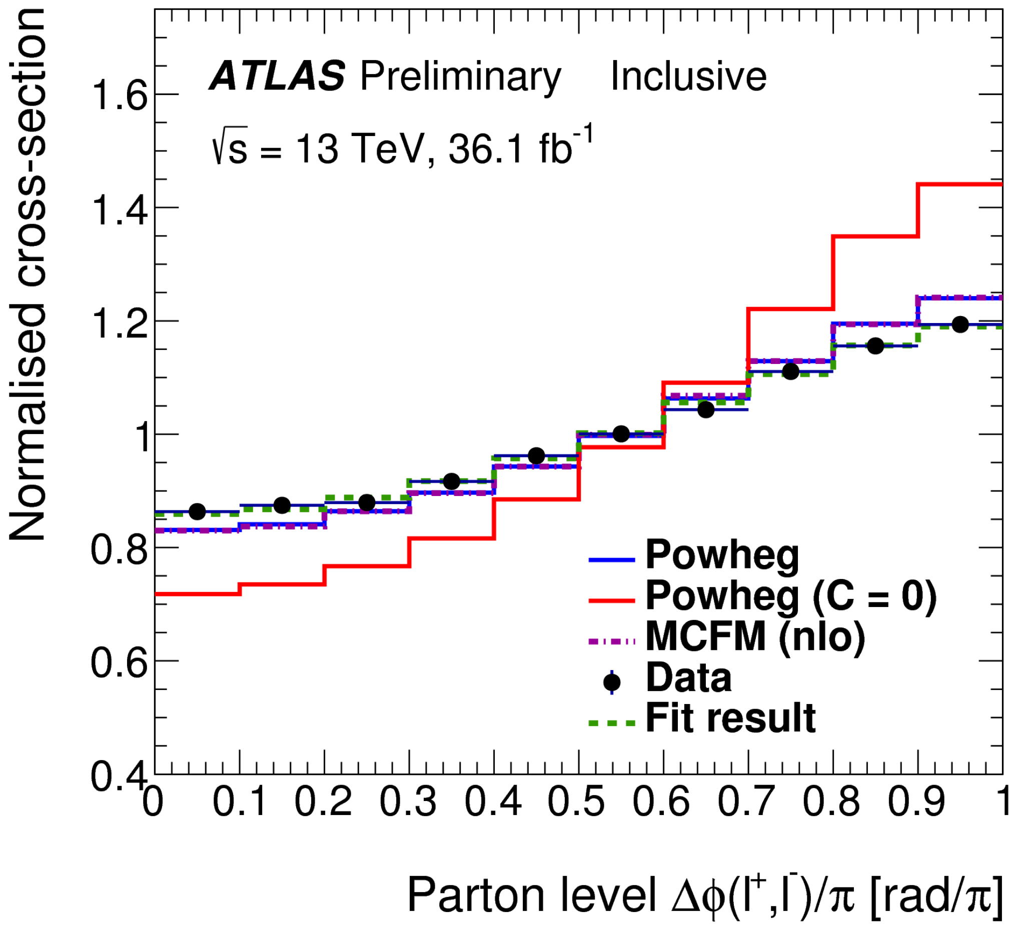
$$\mathrm{R} = A + \sum_i \left(\underbrace{B_i^+}\sigma^i + \underbrace{B_i^-}\bar{\sigma}^i\right) + \sum_{i,j} \underbrace{C_{ij}}_{\substack{\text{Correlations} \\ \text{(between tops' spins)}}}\sigma^i\bar{\sigma}^j$$

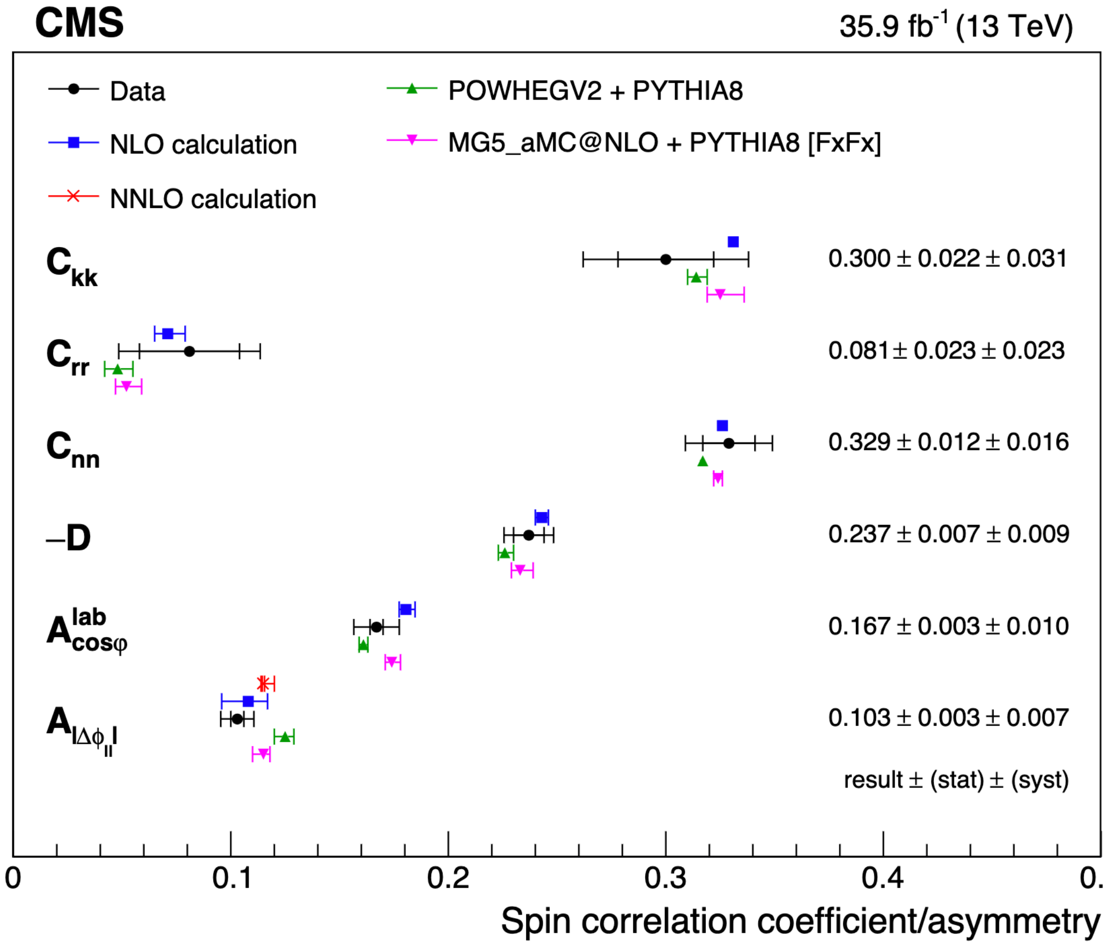
Polarisations

(of individual tops)

Spin correlation measurements

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





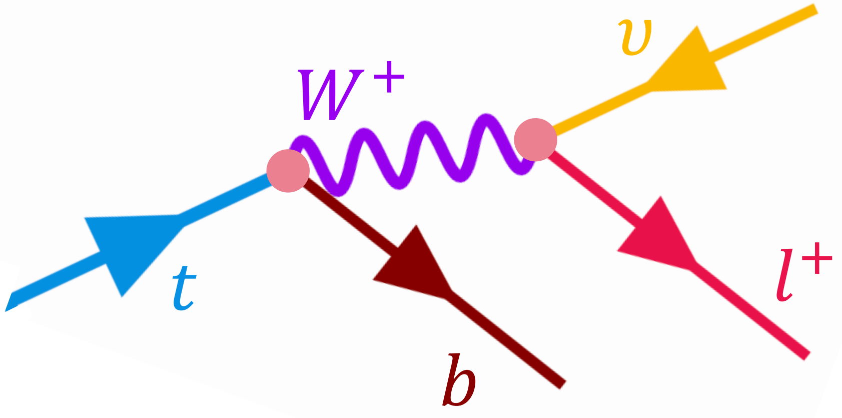
Accessing Top Spin

Decays so quickly, spin information retained

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

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

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

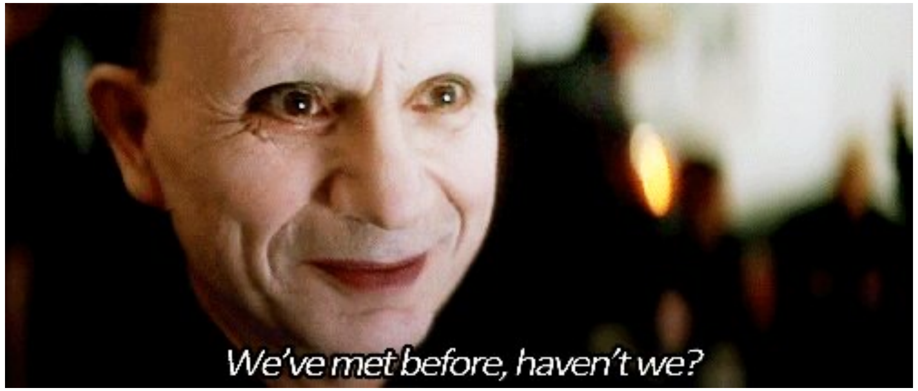
Old Friend

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

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

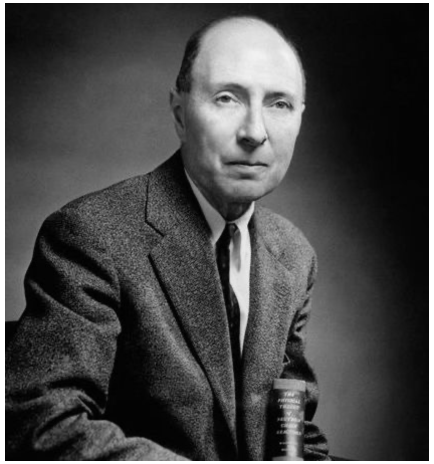
Polarisations
(of individual tops)

Correlations
(between tops' spins)



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

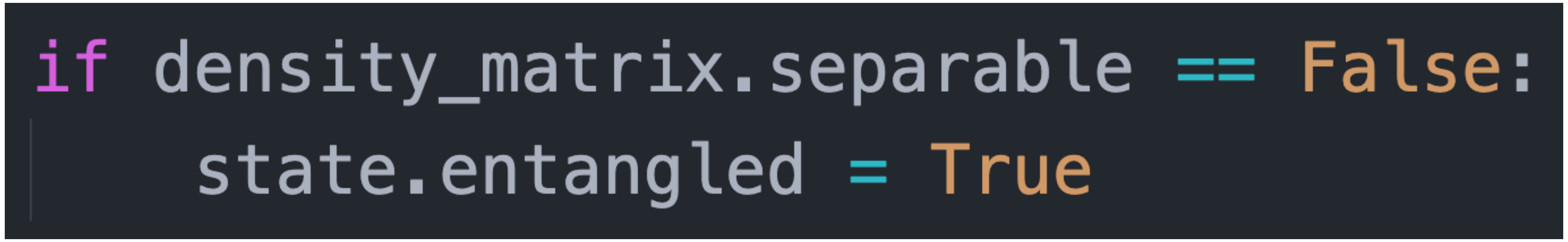
("The unreasonable effectiveness of mathematics" - Wigner)



Entanglement

Is the density matrix factorisable?

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

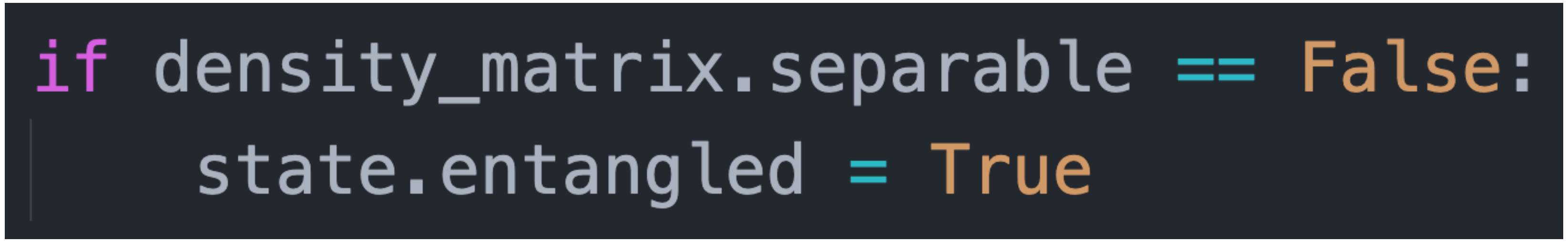


```
if density_matrix.separable == False:
    state.entangled = True
```

Entanglement

Is the density matrix factorisable?

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



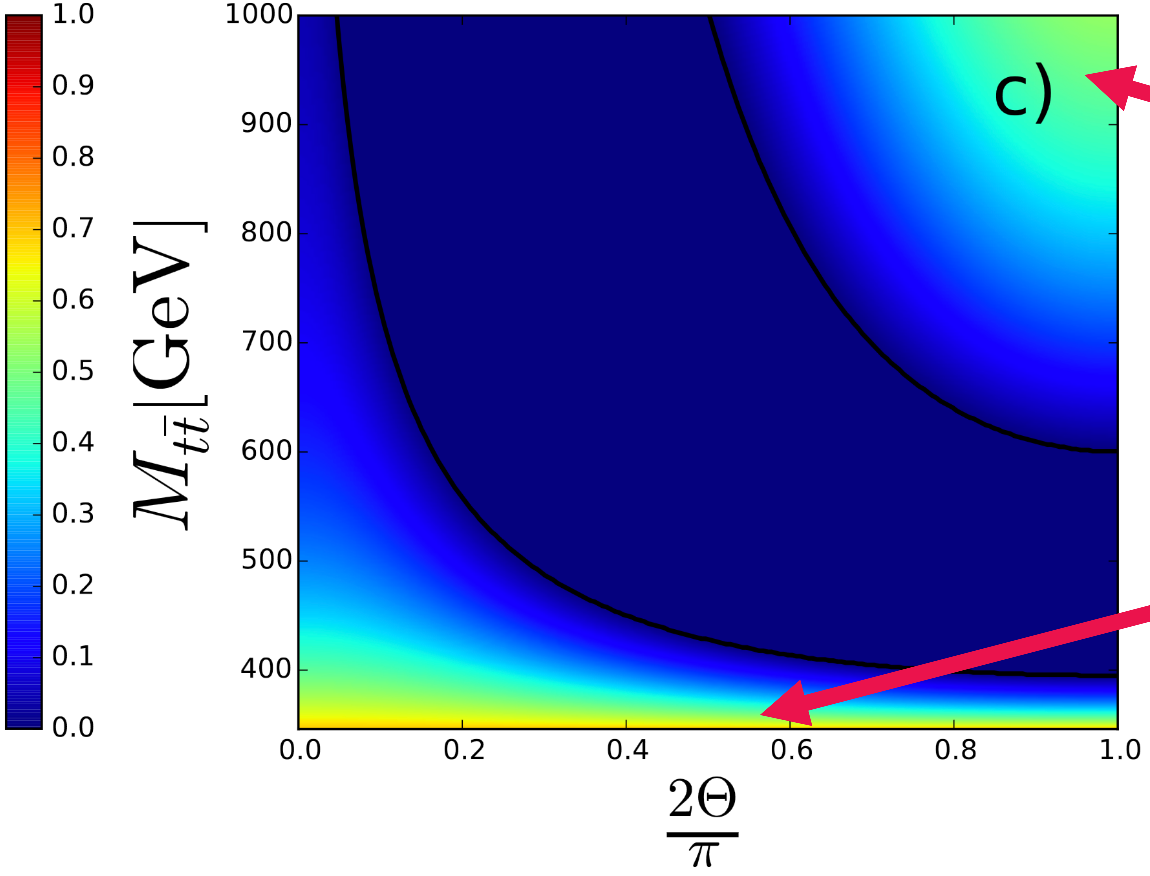
```
if density_matrix.separable == False:
    state.entangled = True
```

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

Concurrence

A measure of how entangled

(Related to the eigenvalues of the density matrix)

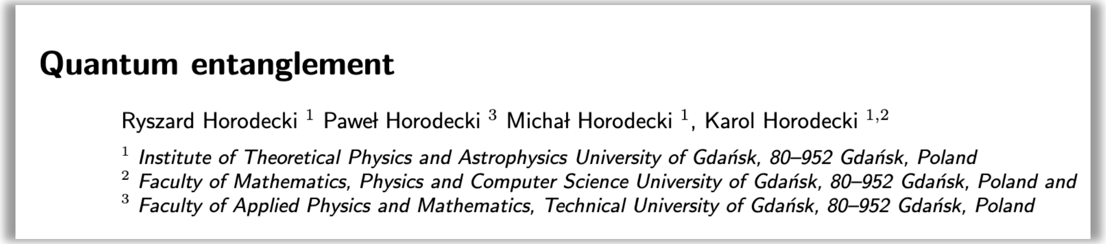


- Low statistics
- Larger jet uncertainties
- Driven by subdominant qq

- 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

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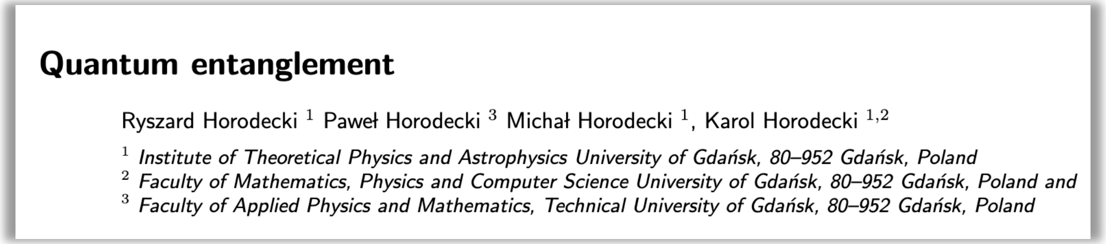

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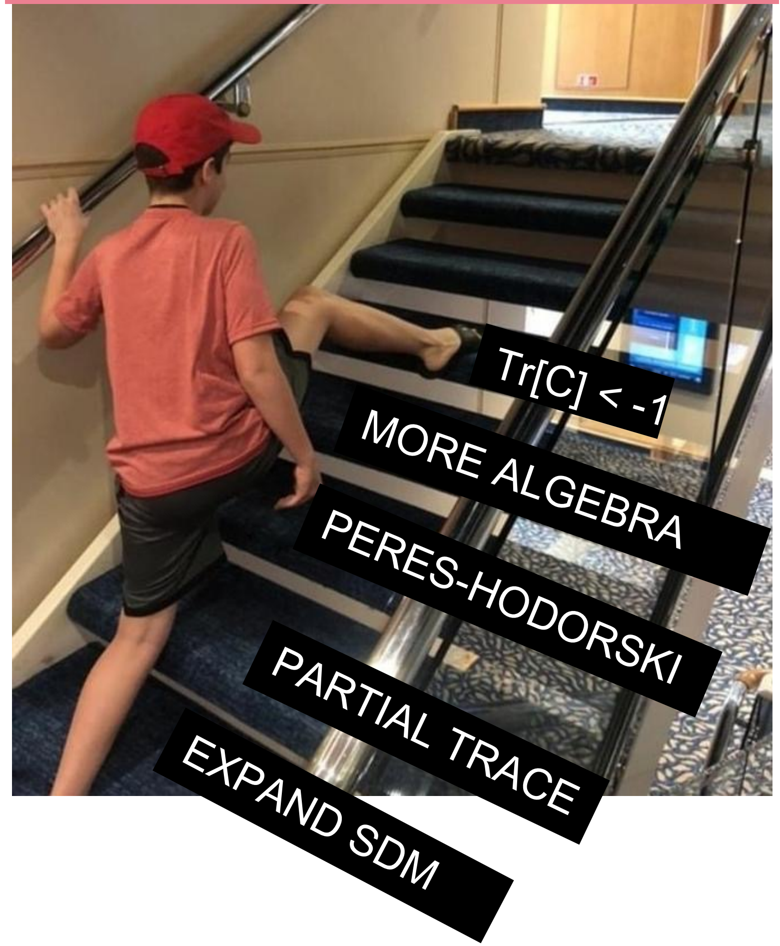
[1] Institute of Theoretical Physics and Astrophysics University of Gdańsk, 80–952 Gdańsk, Poland
[2] Faculty of Mathematics, Physics and Computer Science University of Gdańsk, 80–952 Gdańsk, Poland and
[3] Faculty of Applied Physics and Mathematics, Technical University of Gdańsk, 80–952 Gdańsk, Poland

Much linear algebra…



Perform linear algebra operations transpose one of the subsystems

Partial transpose

$$\rho \to \rho^{T_2}$$

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

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?

$$\Delta_{\mathrm{E}} = C_{nn} + |C_{rr} + C_{kk}| > 1$$

Spin correlations we can measure!

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

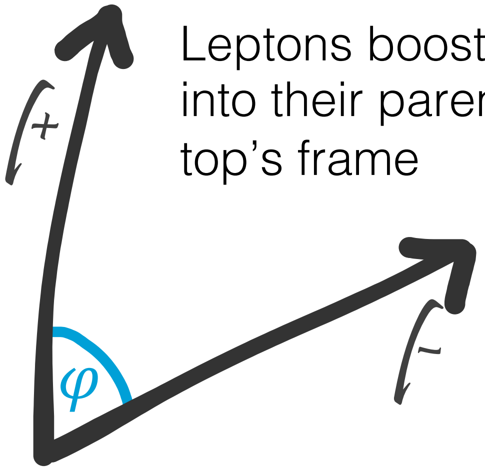
Peres-Horodecki

Accessing experimentally

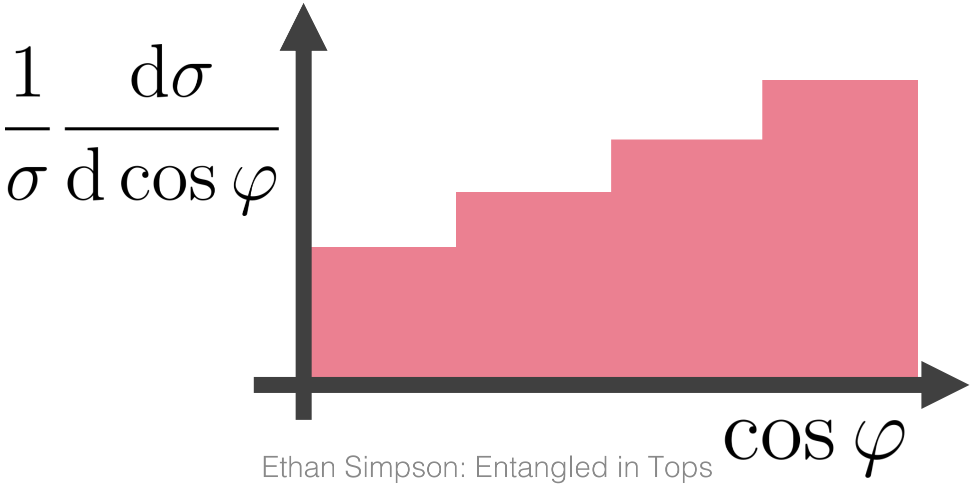
$$D = \frac{1}{3}\left(C_{11} + C_{22} + C_{33}\right)$$

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

D can be extracted from a single angular distribution:



Leptons boosted into their parent top's frame



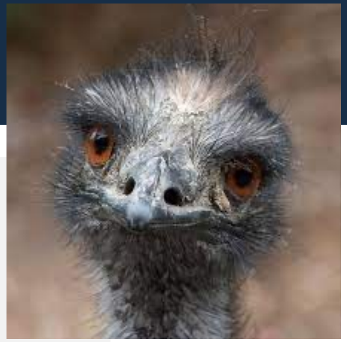
$$D = -3\langle\cos\varphi\rangle$$

Summary

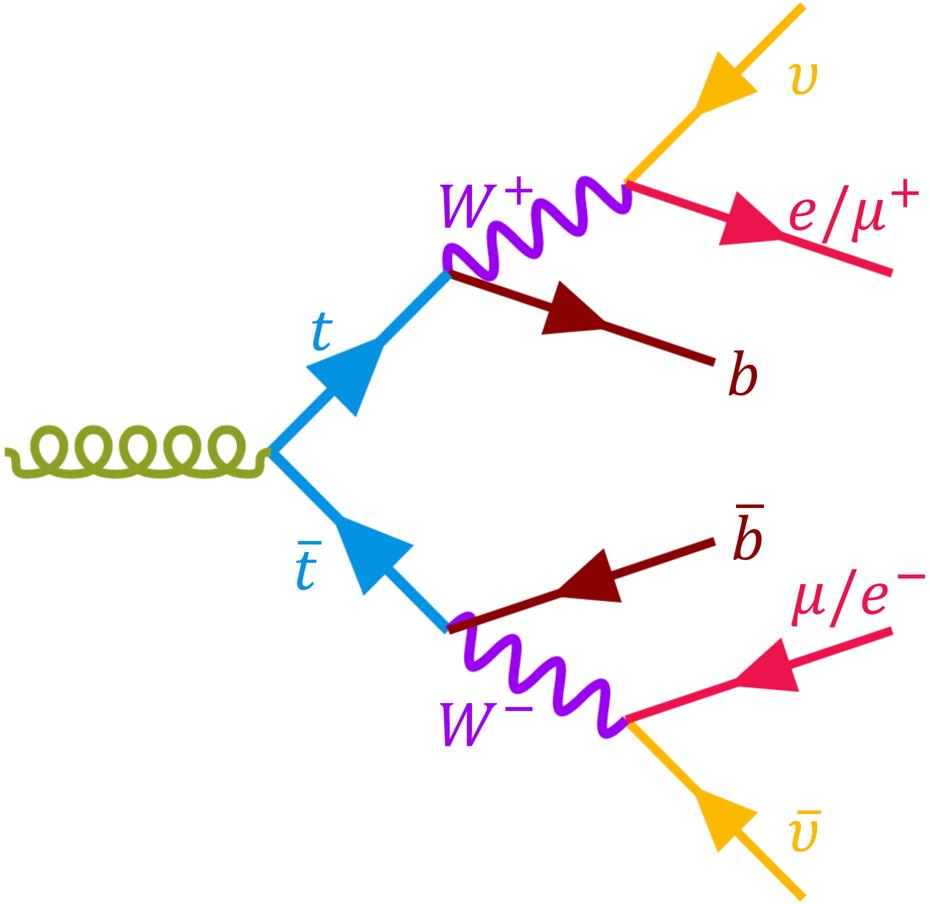
- $t\bar{t}$ production is described by a density matrix.
- Entanglement is non-separability of the density matrix
- Measure entanglement through one angular observable, D.

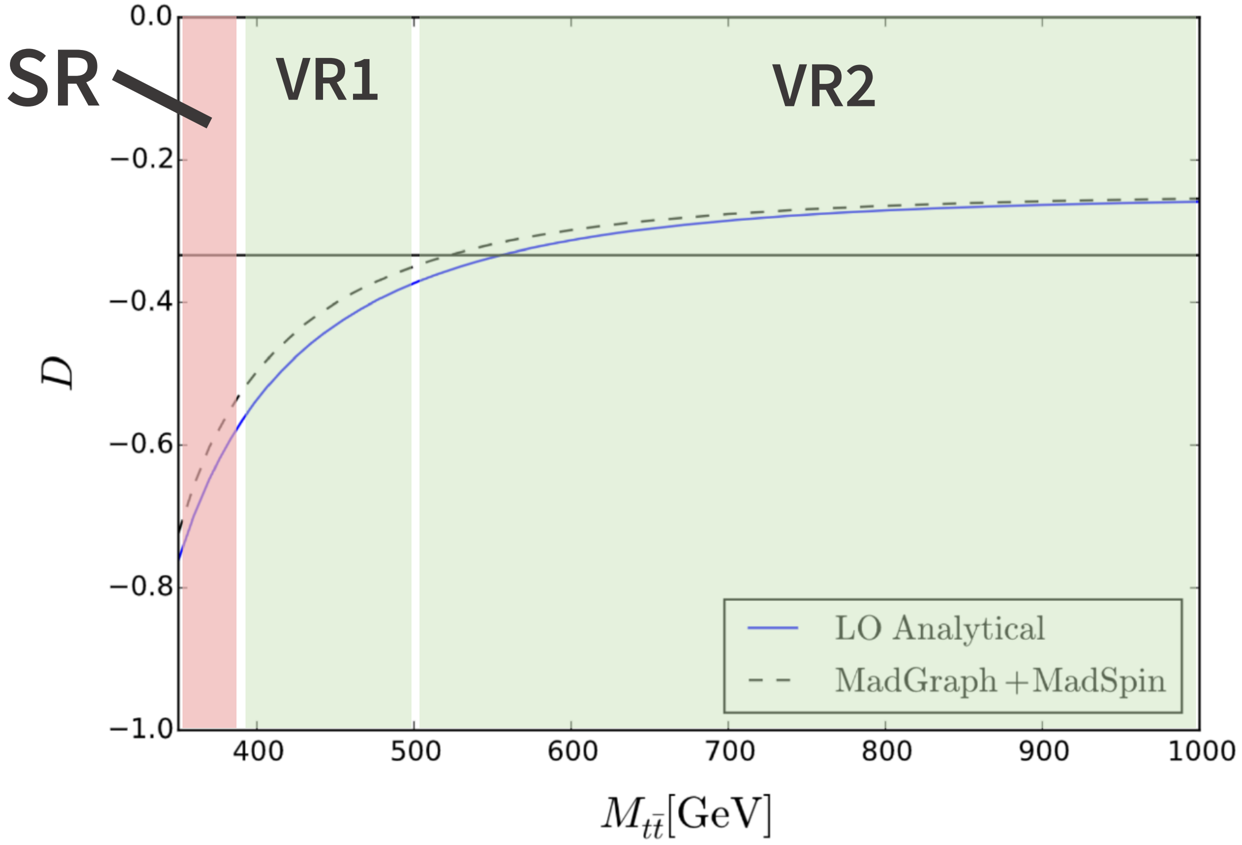
ATLAS Measurement

Selections



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





Signal / Background

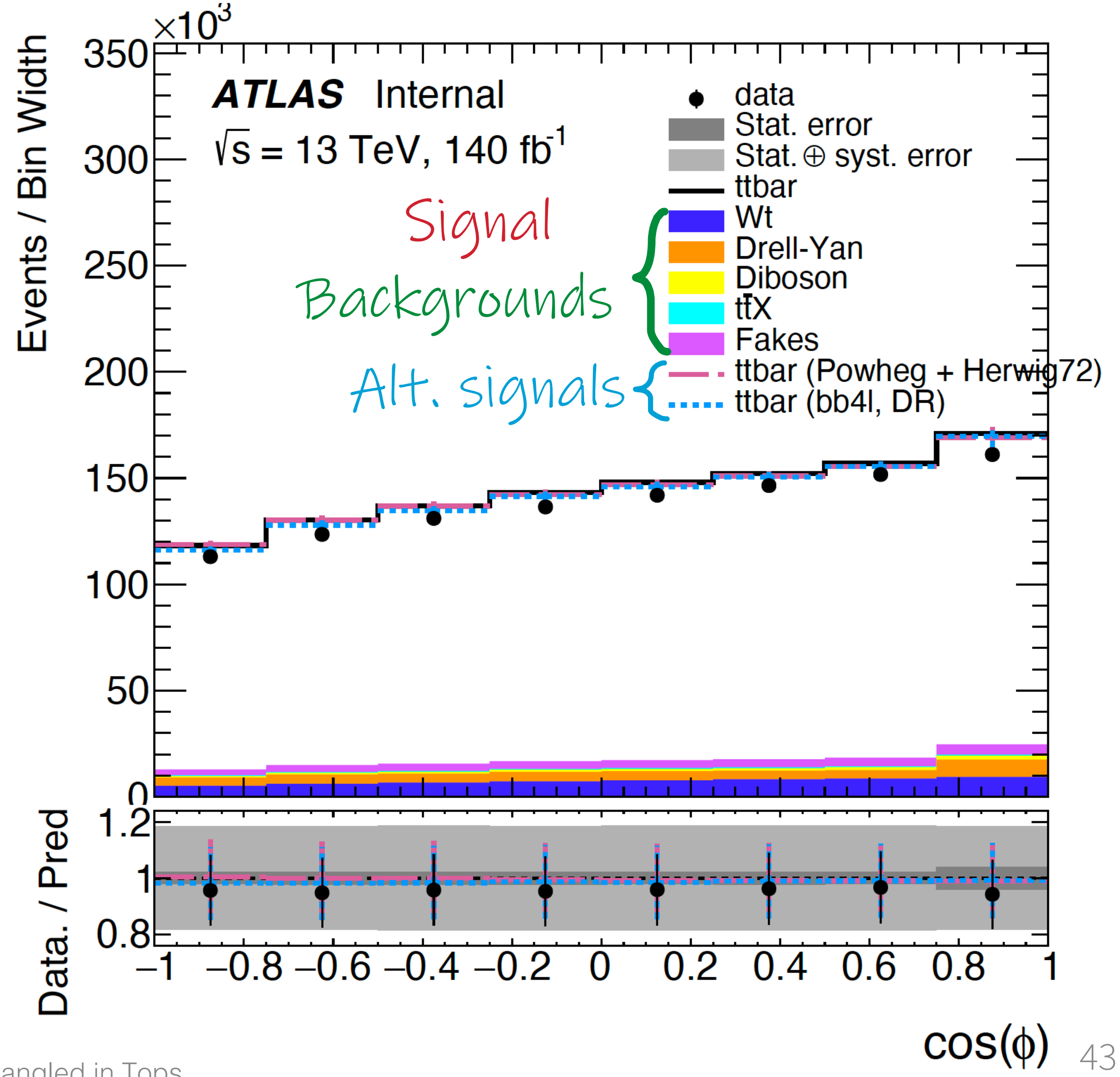
Signal

Modelled using MC simulation:

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

Background

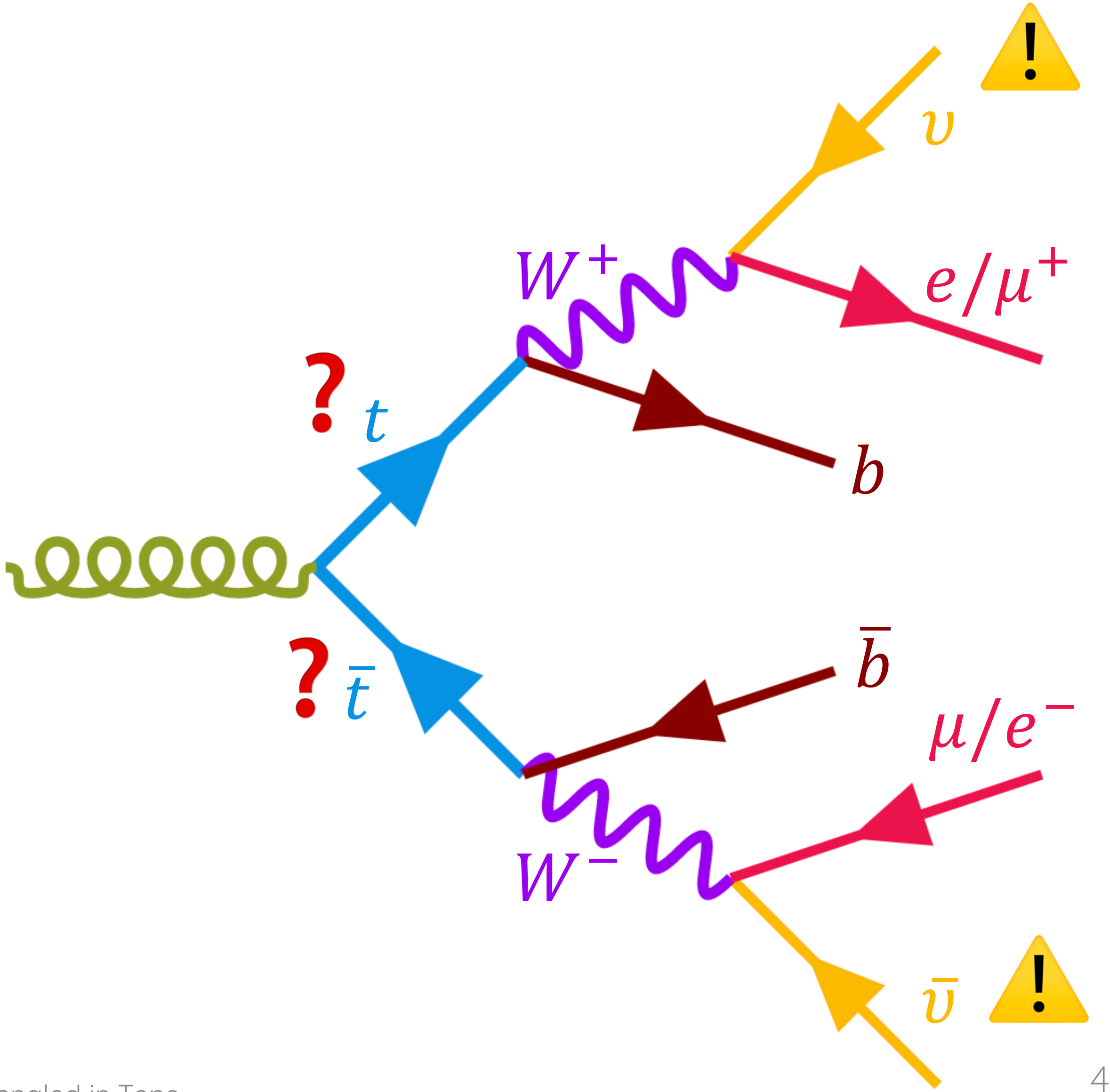
- Backgrounds are estimated using simulation.
- Fake lepton prediction modified using a data-driven scale factor.



Dileptonic Reconstruction

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

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



Dileptonic Reconstruction

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

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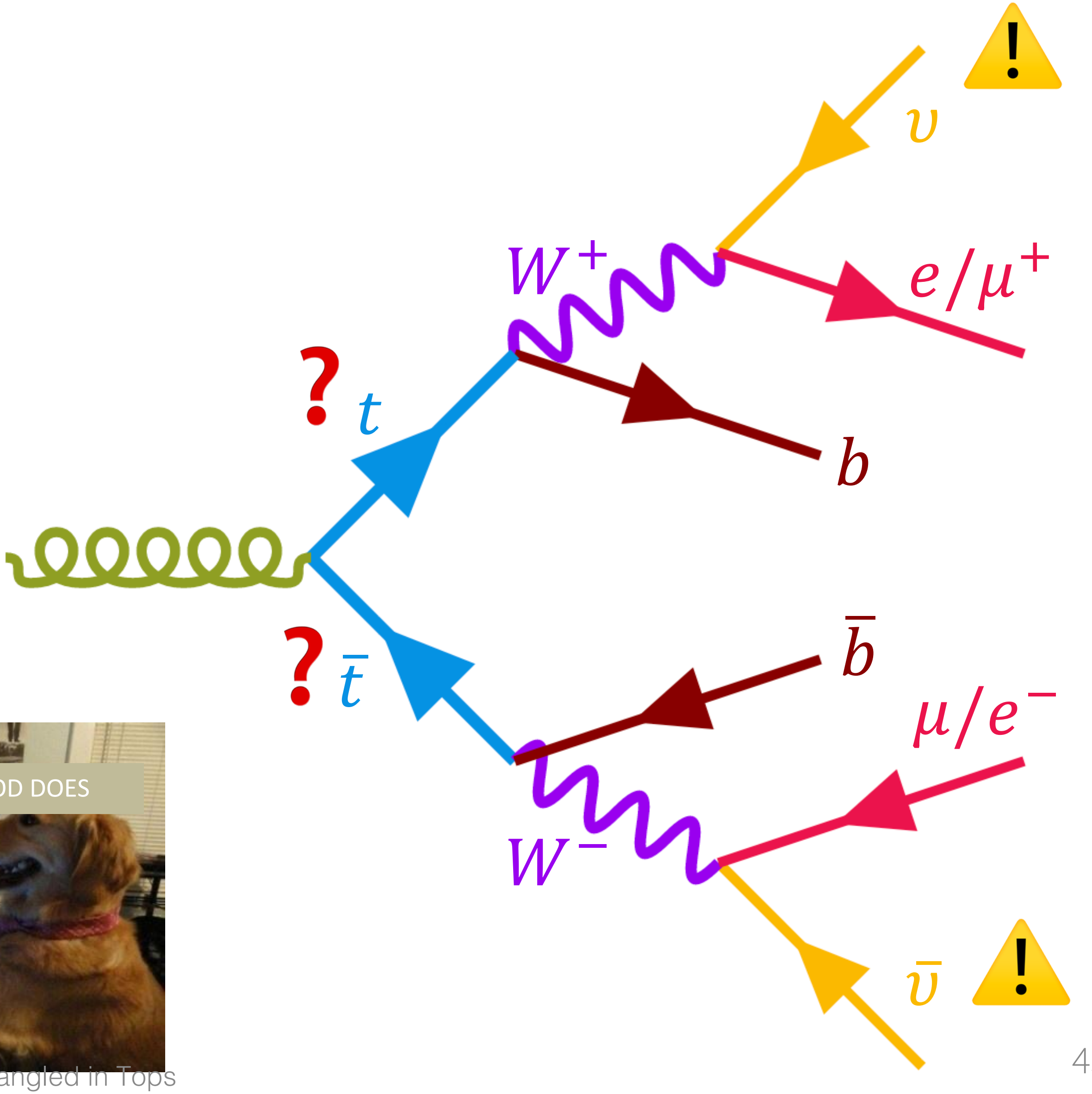
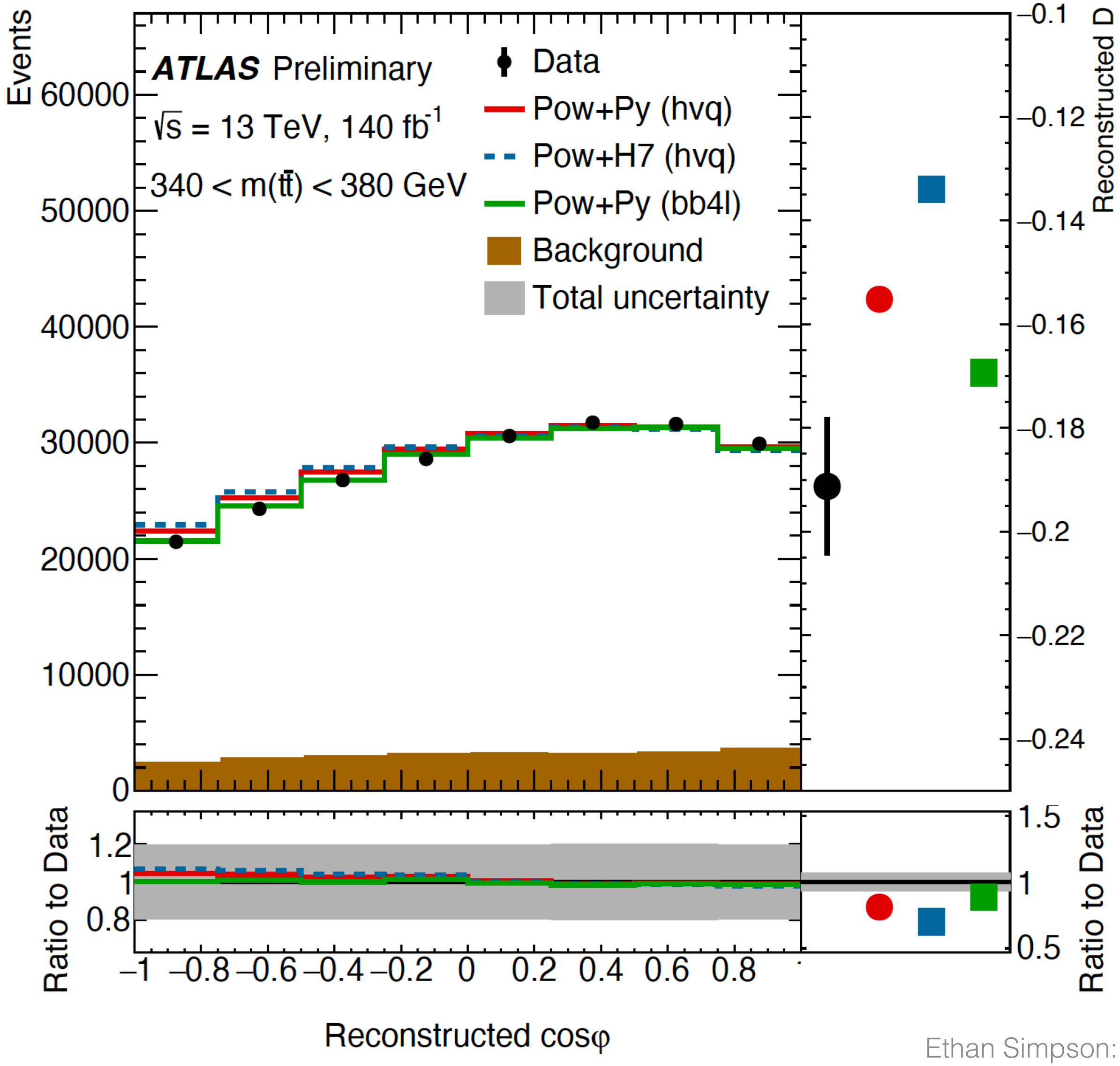


Primary technique: Ellipse Method

Alternative techniques:

- NeutrinoWeighter
- Simple kinematic matching

Data-Simulation Comparison



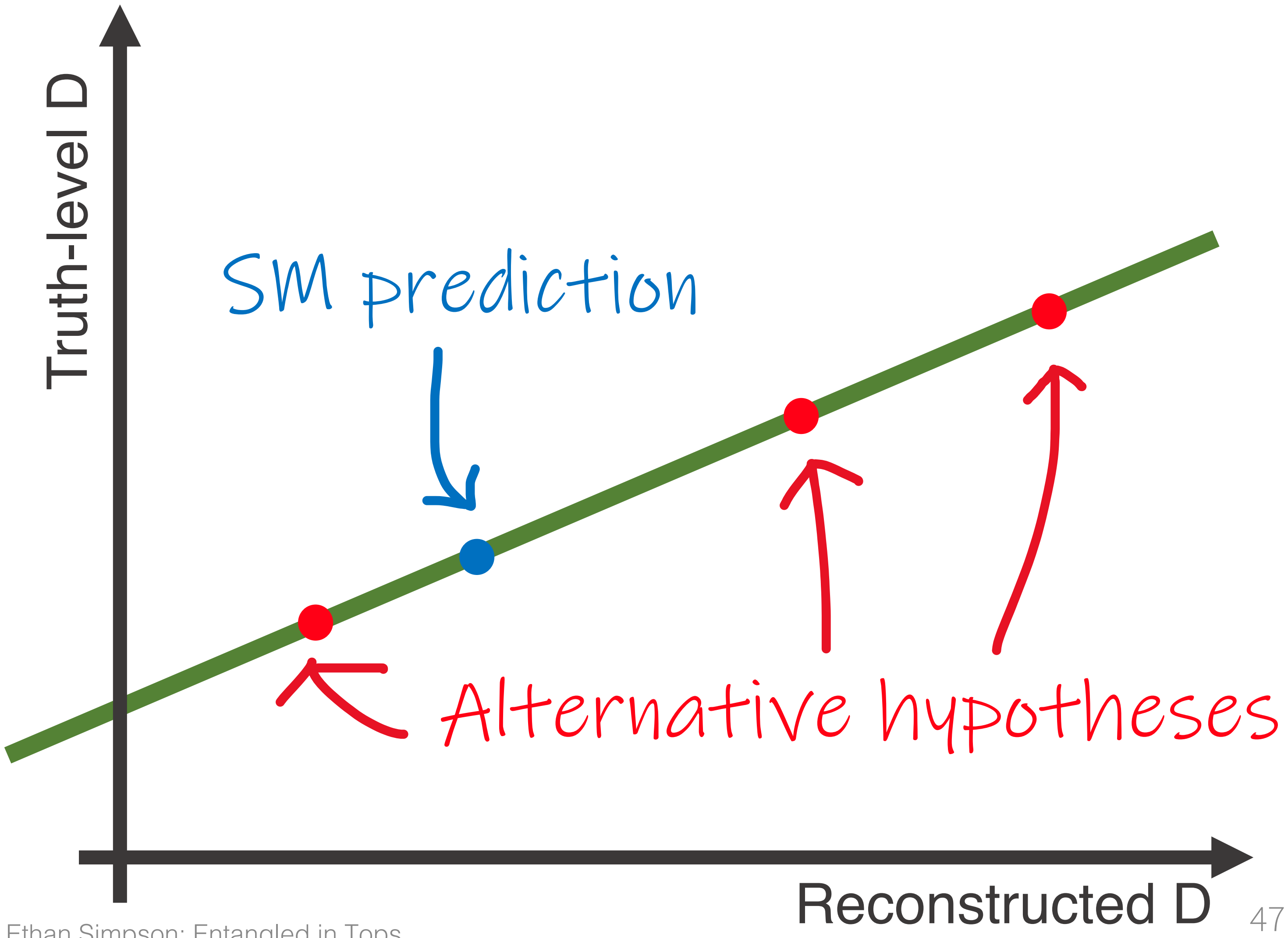
- Distortion from detector effects (resolution, acceptance)
- The agreement is decent for the distribution.
- Tension in the mean.

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

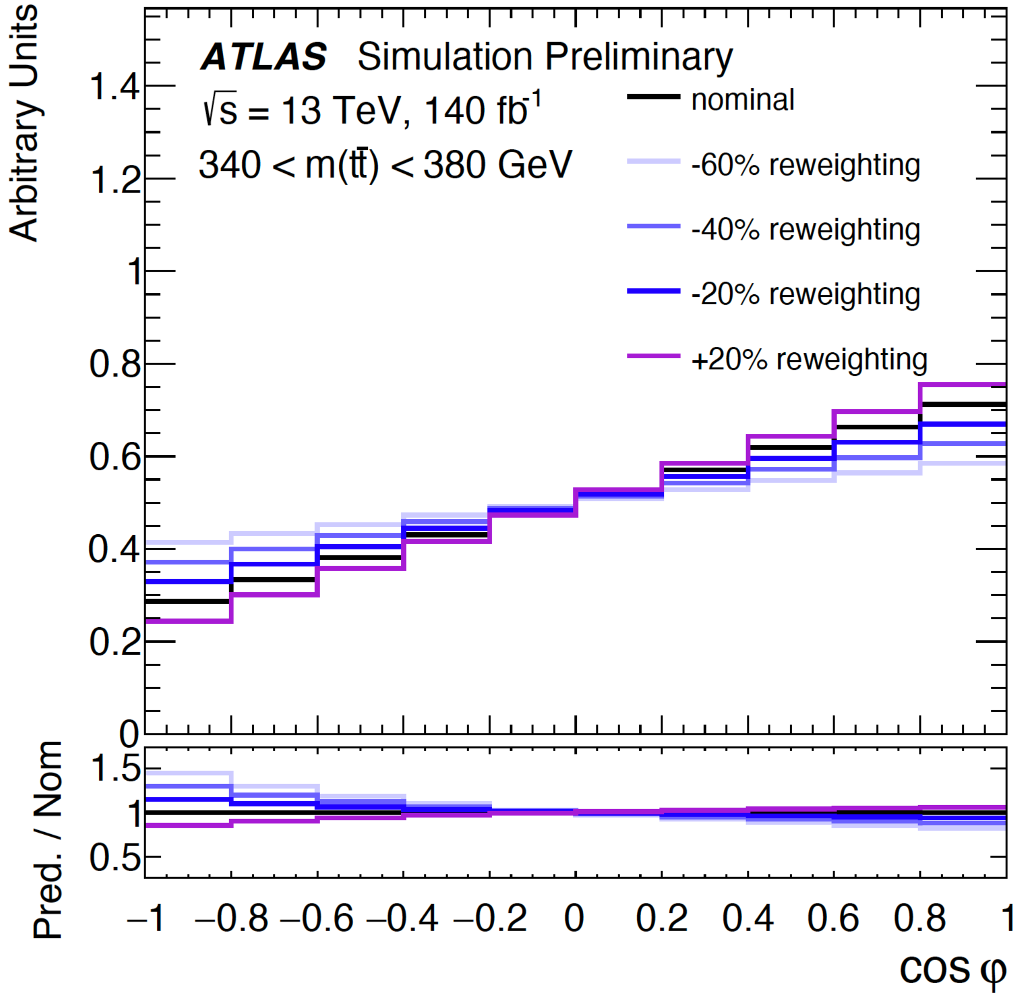
Generate alternative hypotheses

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

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

Choose such that
distribution <u>remains linear</u>

Scaling parameter

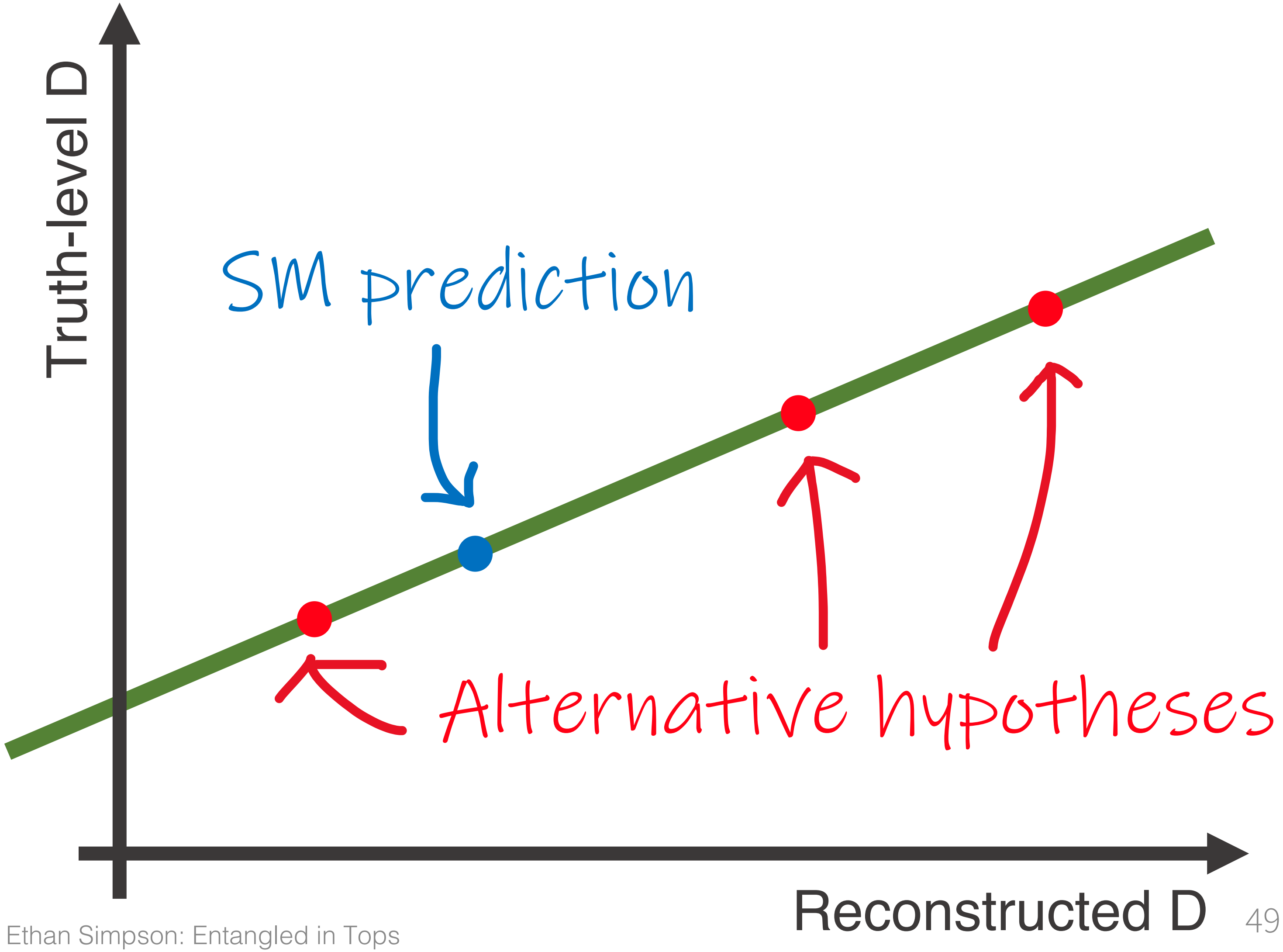


Calibration Curve

Parameterise variation in D

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

Interpolate to give variation.



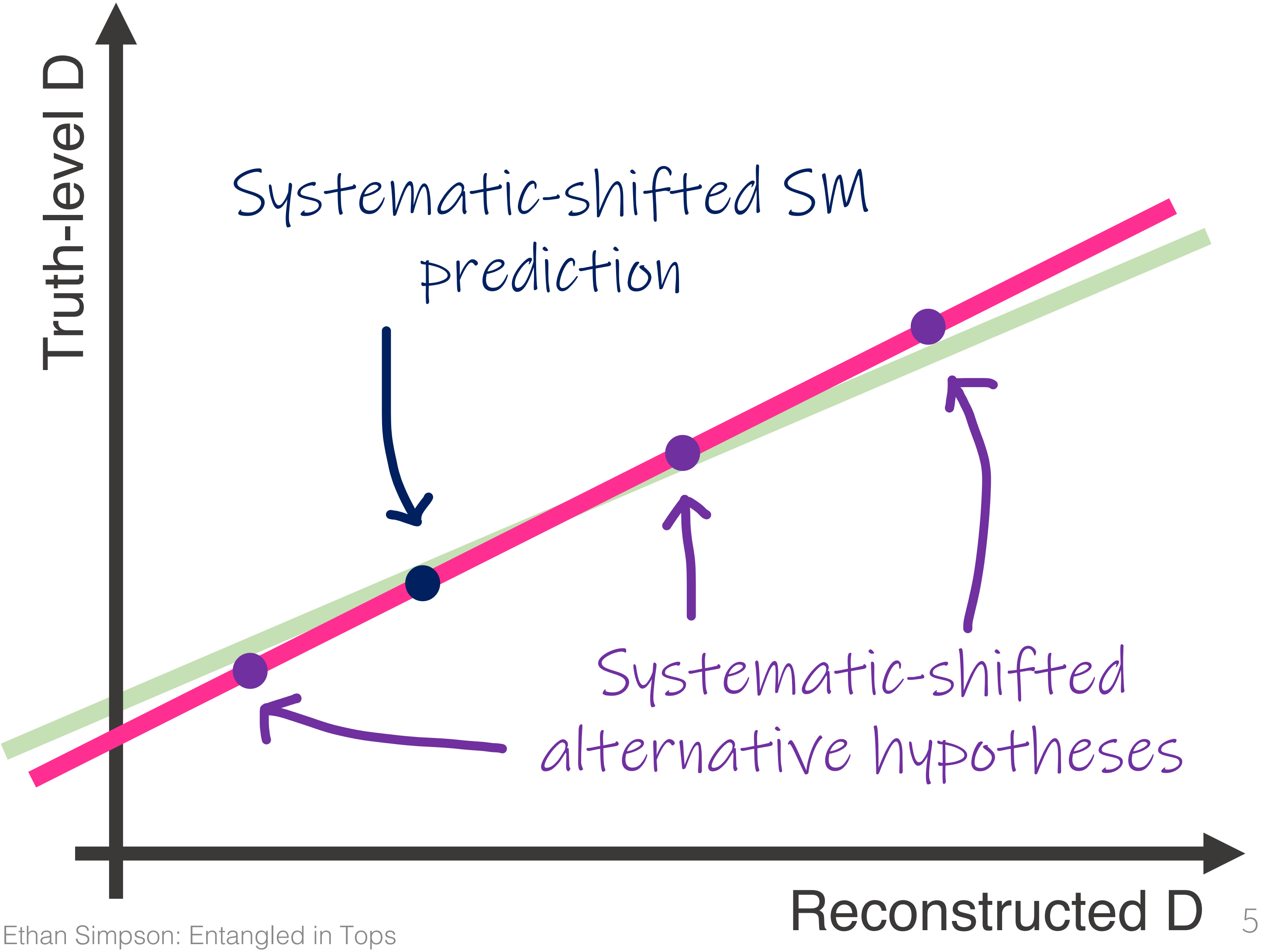
Calibration Curve

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

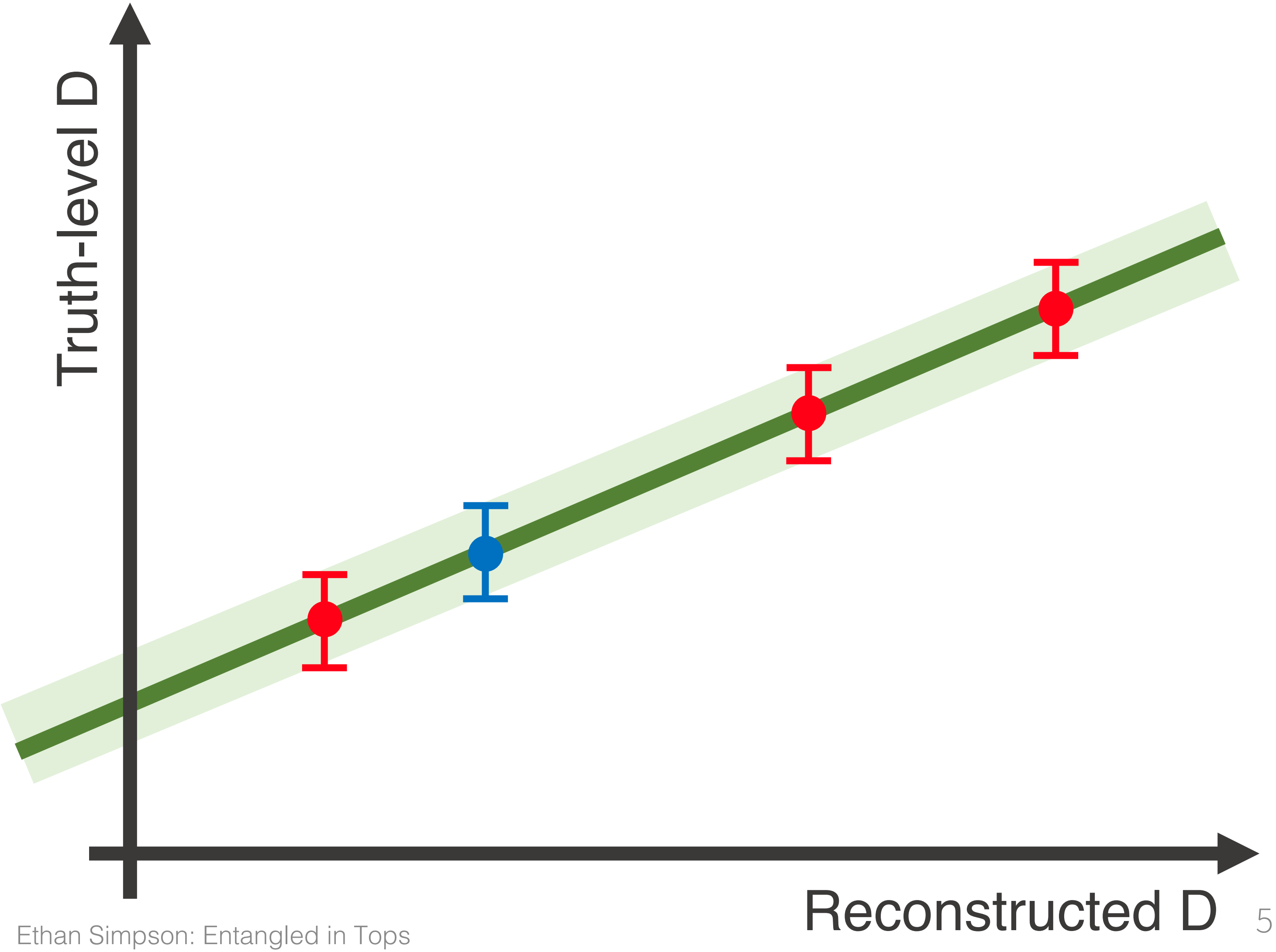
Parameterise variation in D

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

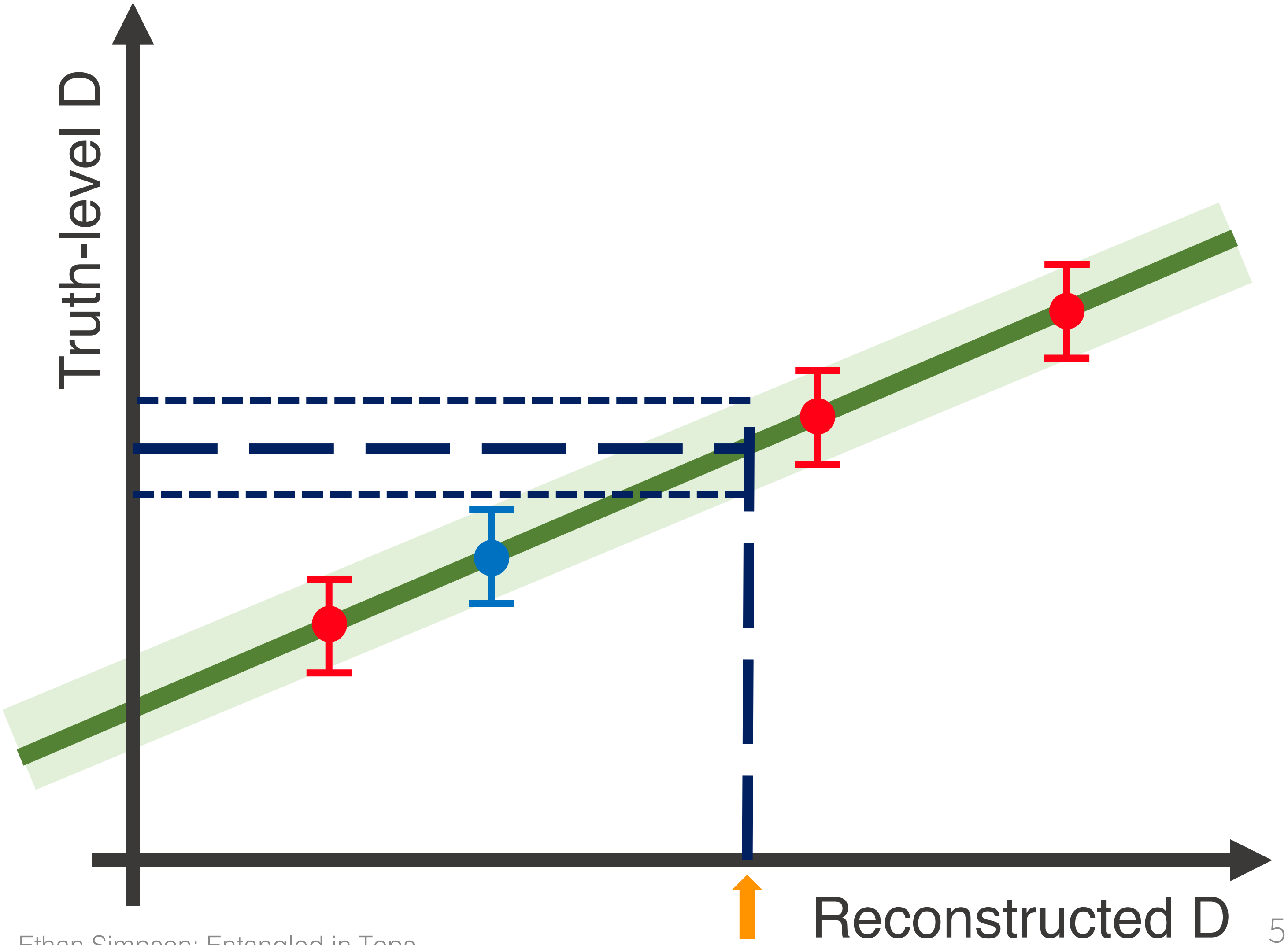
Different hypotheses of truth- and reco-D, derived from simulation.

Interpolate to give variation.

Systematics build different calibration curves.

Combine all systematics to build nominal curve + uncertainty band.

Map measured D to truth.

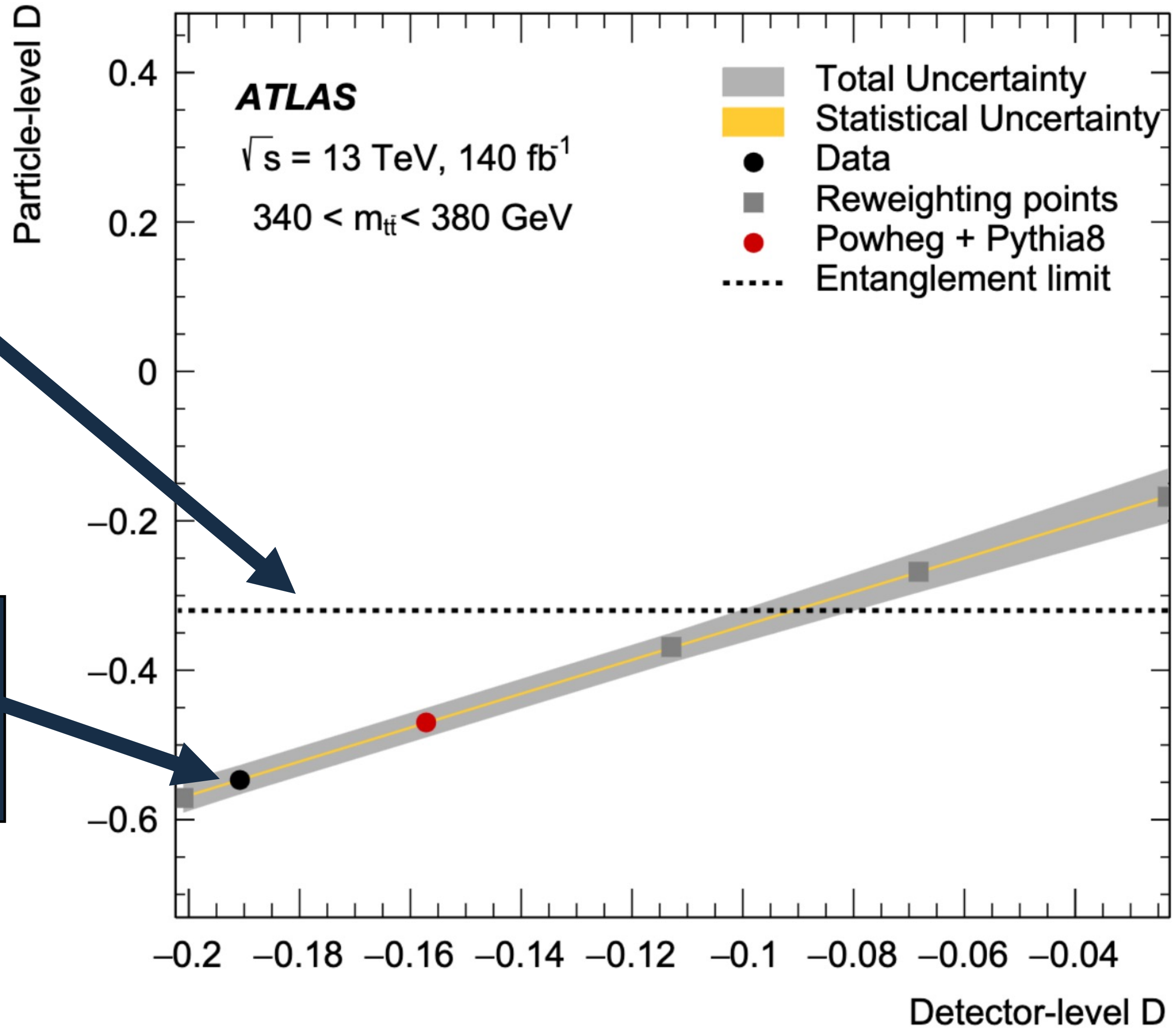


Results

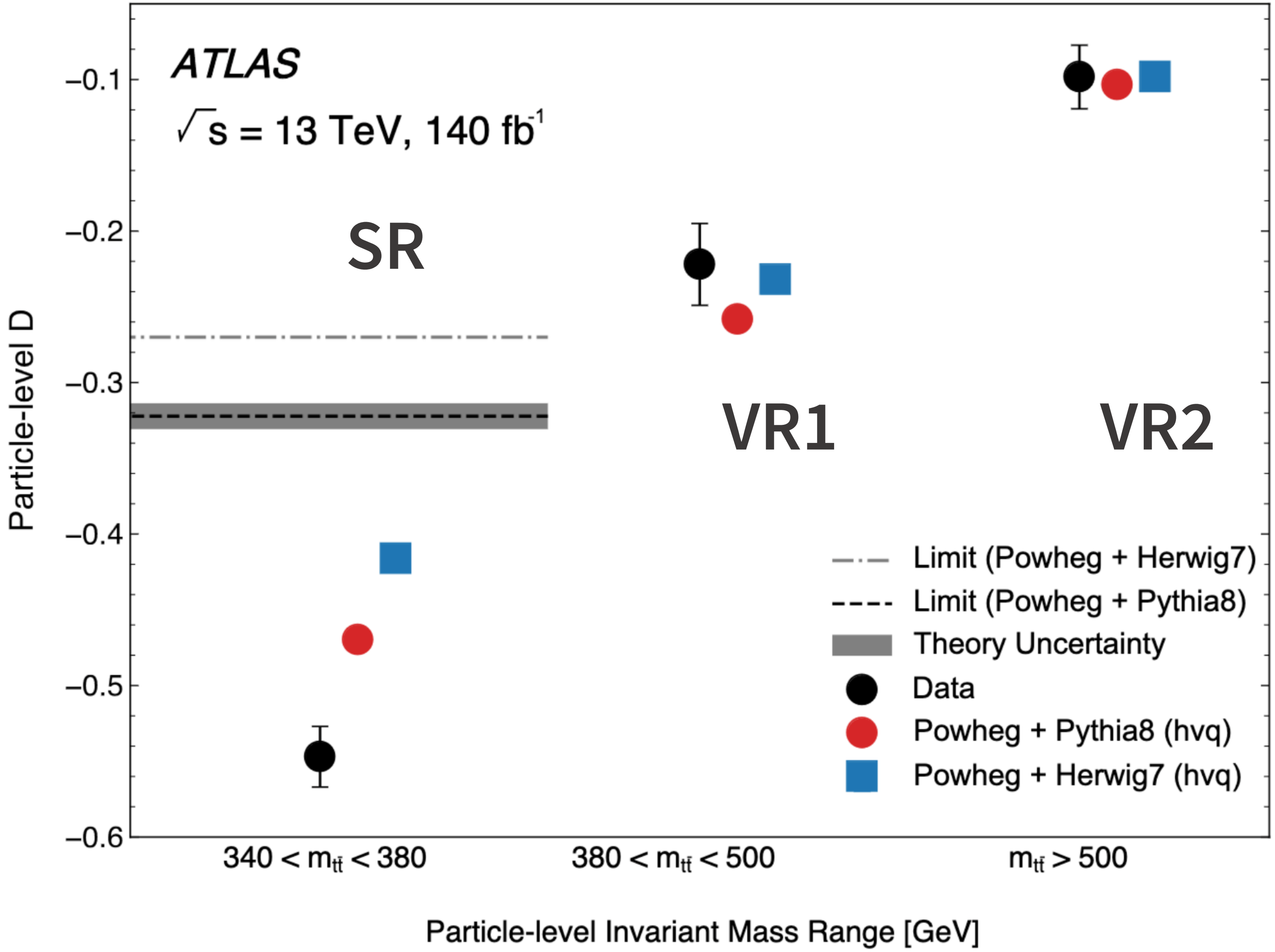
Calibration Curve

No-entanglement limit

Higher level of entanglement than predicted in simulation

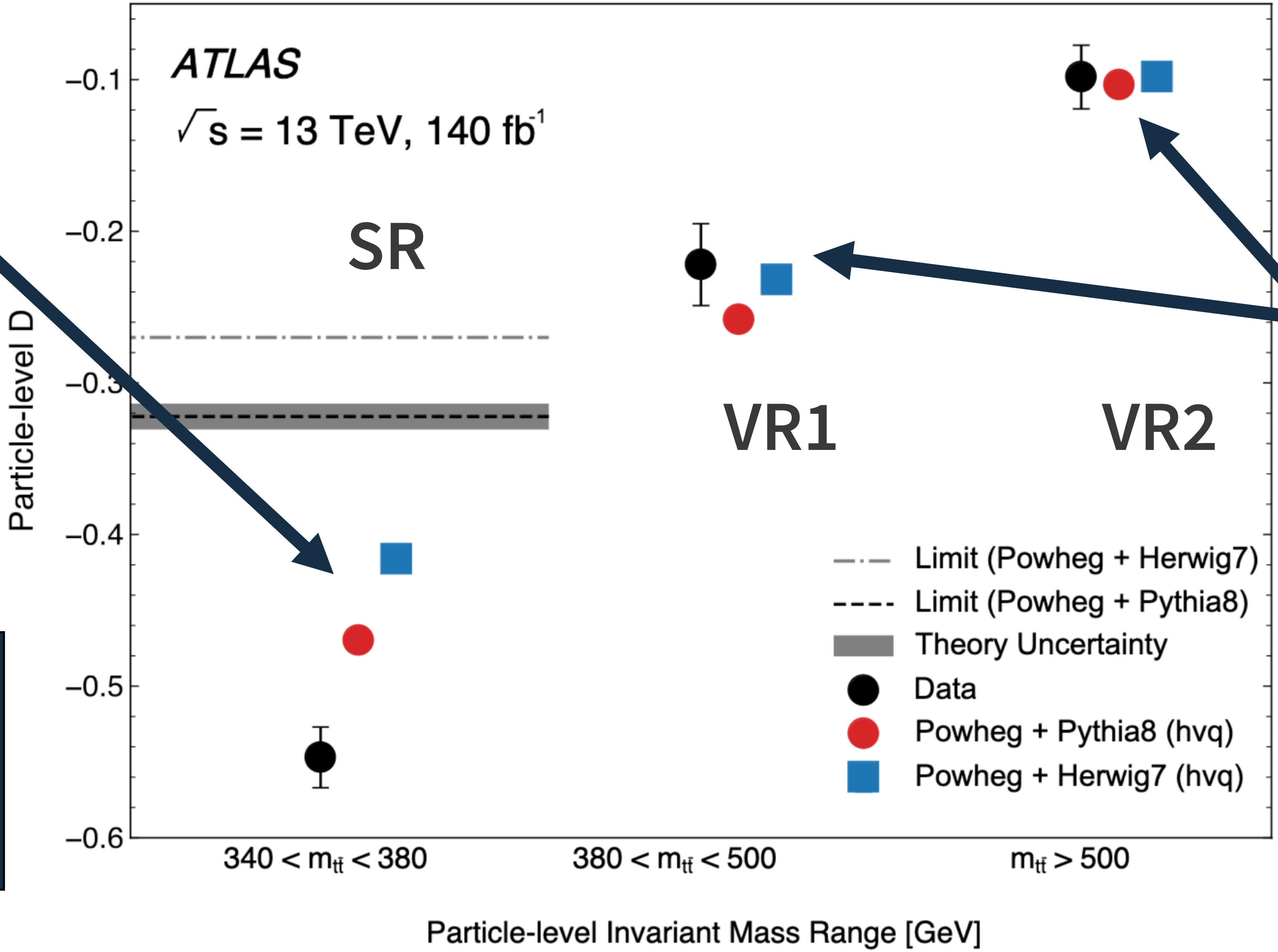


Results



ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
SR
VR1
VR2
Particle-level D
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
$340 < m_{t\bar{t}} < 380$
$380 < m_{t\bar{t}} < 500$
$m_{t\bar{t}} > 500$
Particle-level Invariant Mass Range [GeV]
Limit (Powheg + Herwig7)
Limit (Powheg + Pythia8)
Theory Uncertainty
Data
Powheg + Pythia8 (hvq)
Powheg + Herwig7 (hvq)

Results



Simulation predictions do not agree

Agreement in VRs

Predictions underestimate data

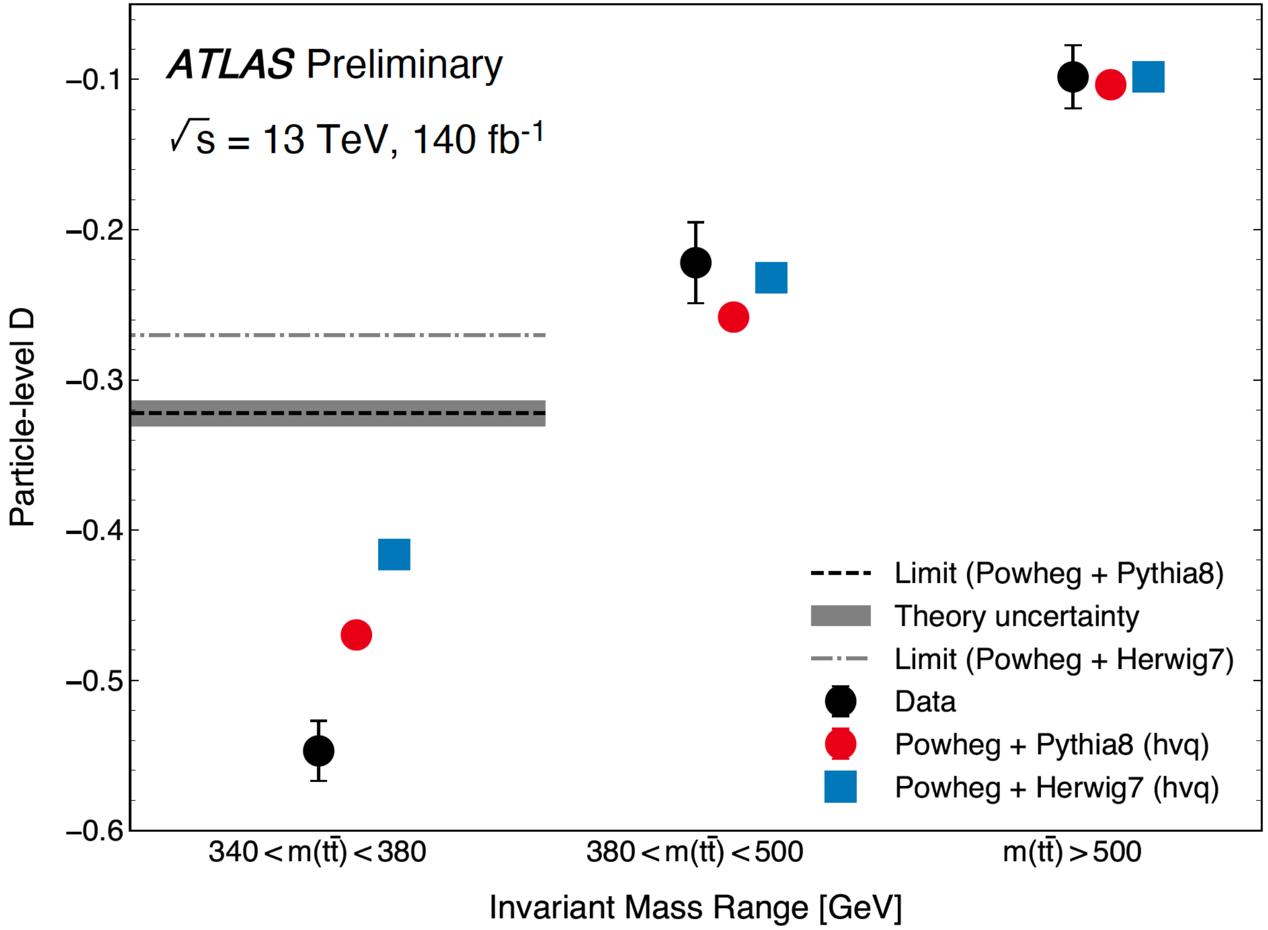
Results

Mapping limit to particle-level

Map entanglement limit using parton→particle calibration curves.

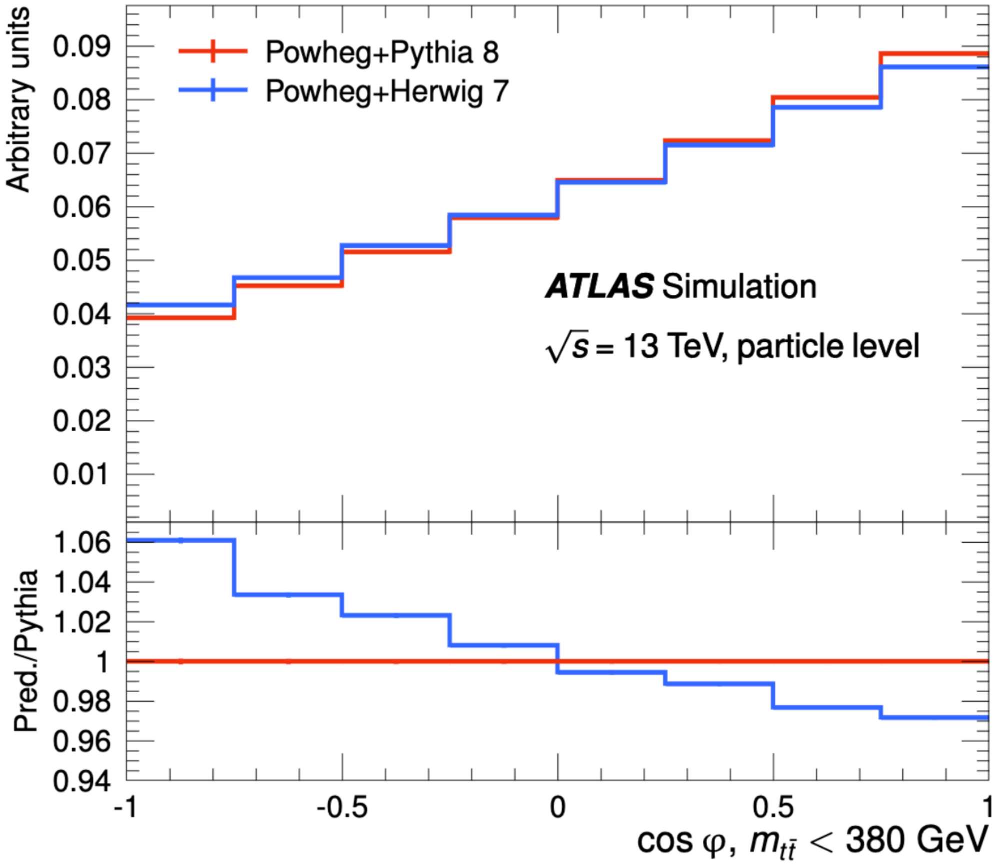
We derive a separate mapping for both Pythia and Herwig parton showers.

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

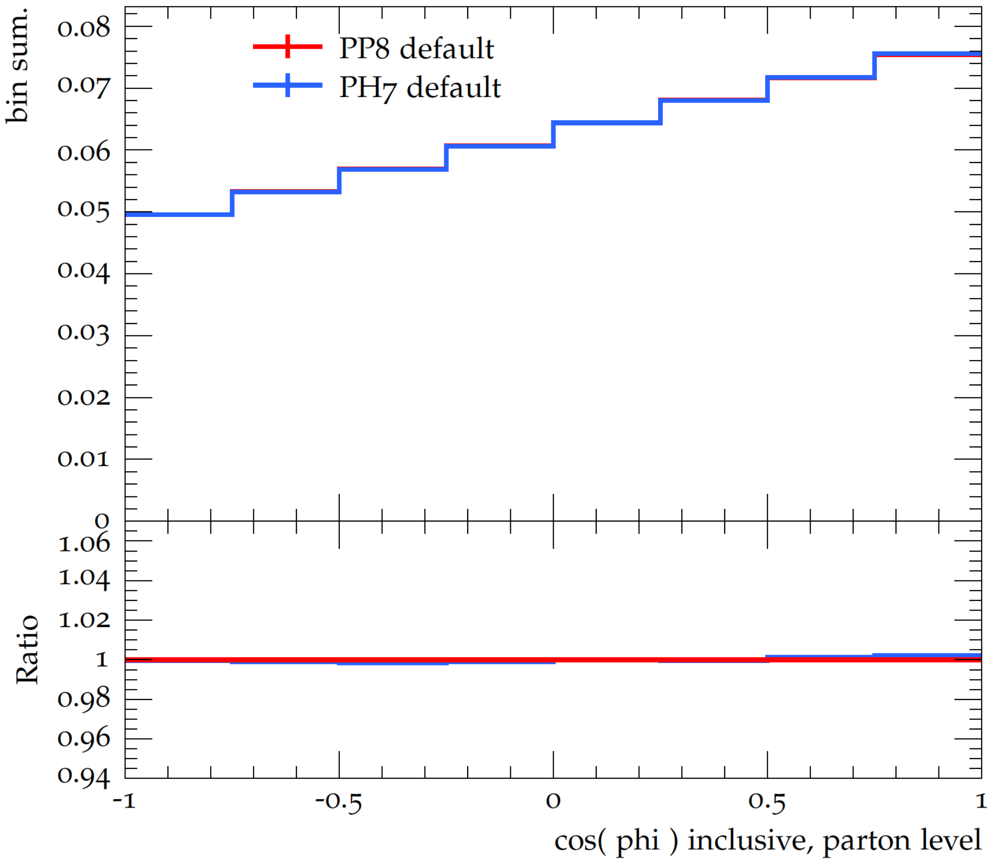


Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



Large difference at particle-level

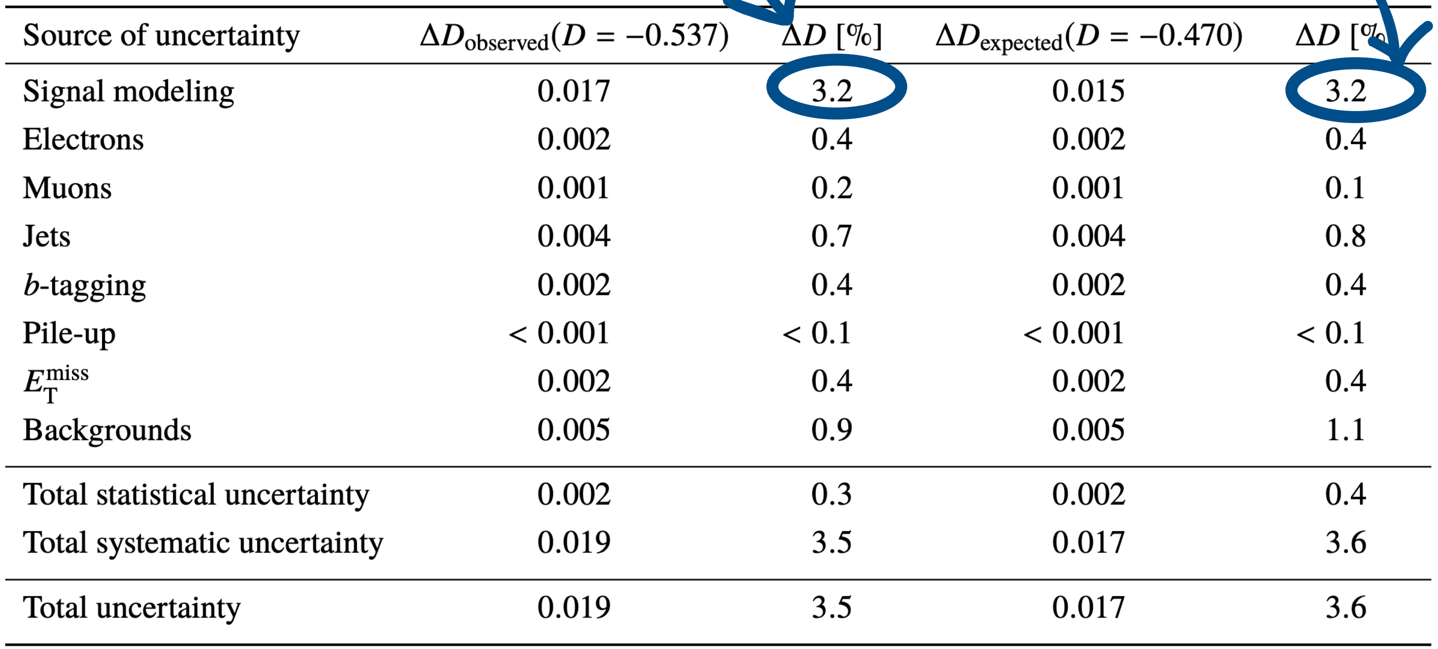


No difference at parton-level

Systematic Uncertainties

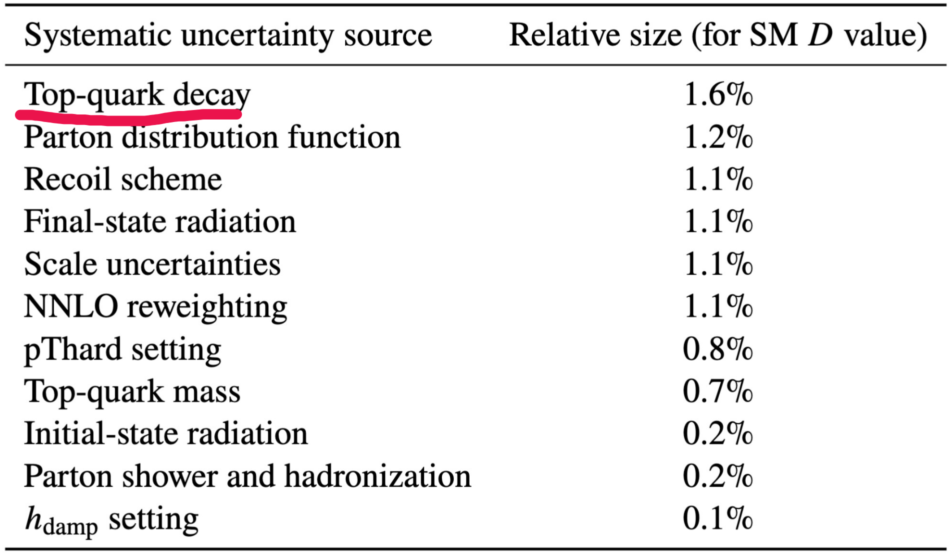
Modelling dominates, like in other precision top-quark measurements

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
$E_{\text{T}}^{\text{miss}}$	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

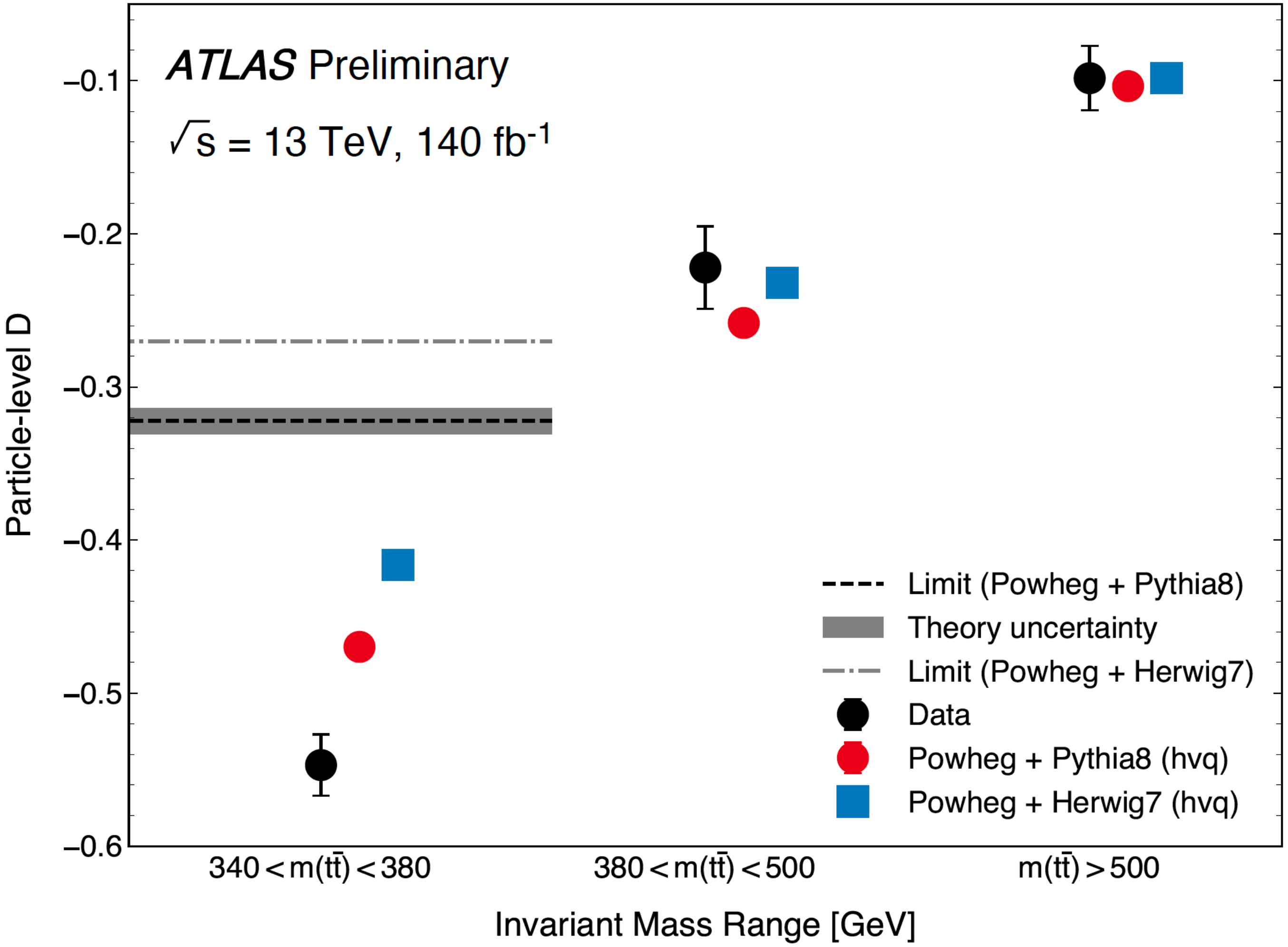
Propagation of spin information



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

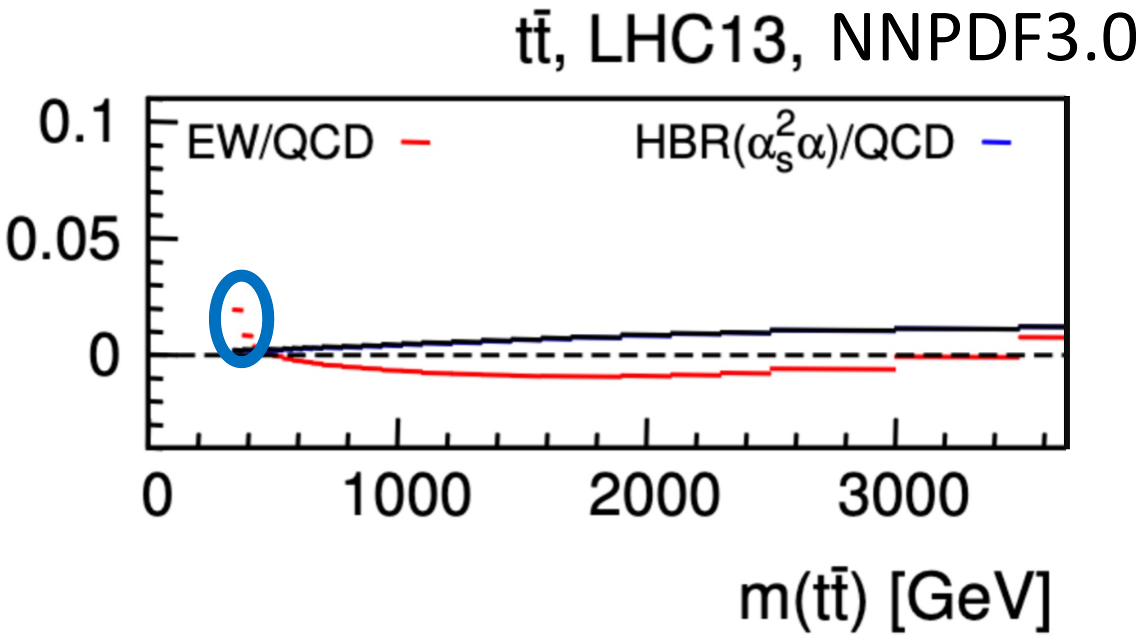
Derived from general-purpose MC event generators (powerful and widely used).

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

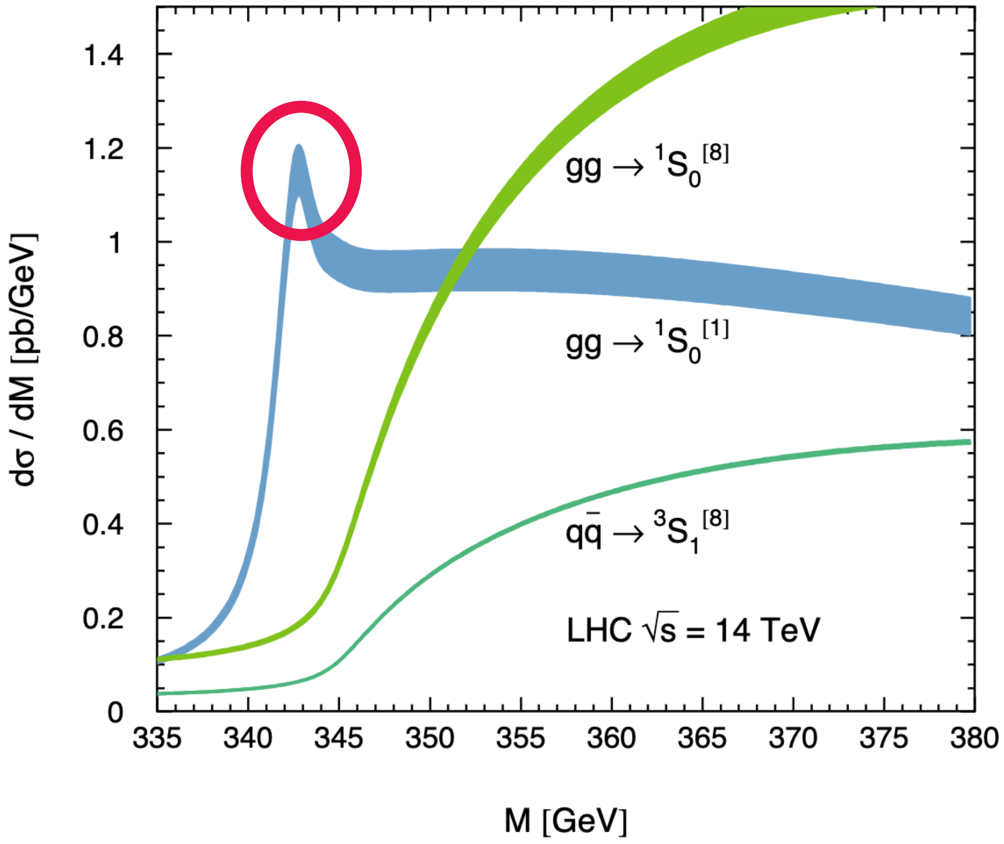
Future: build systematic model built around something like *bb4l*

Sources of mis-modelling

NLO EW



Bound state

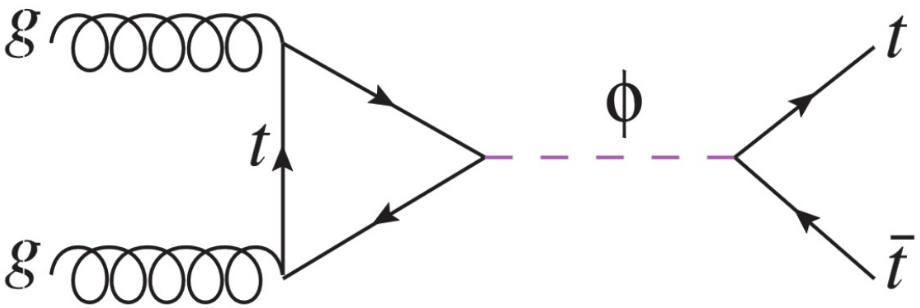


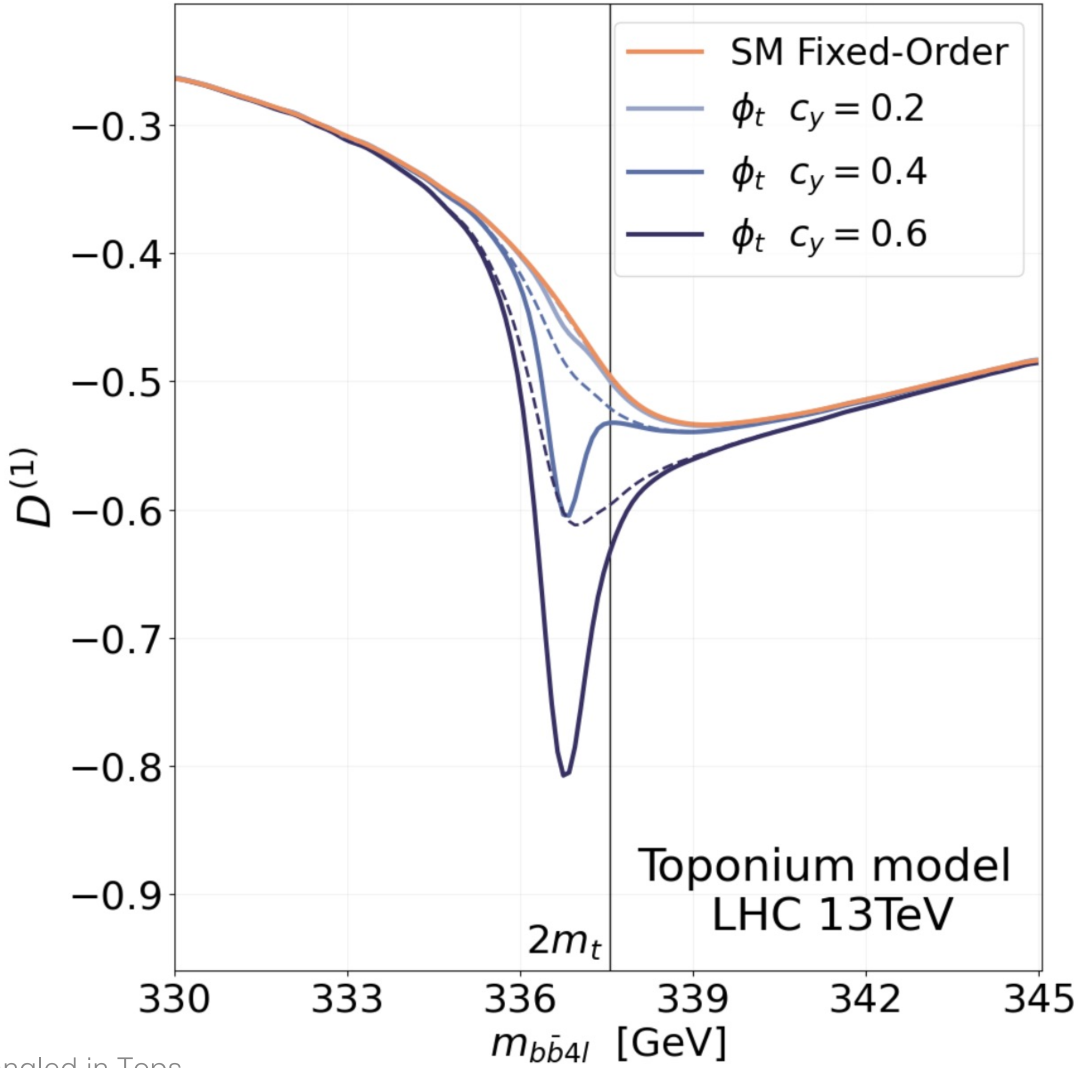
Cross-section enhancement near threshold in both cases.

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.

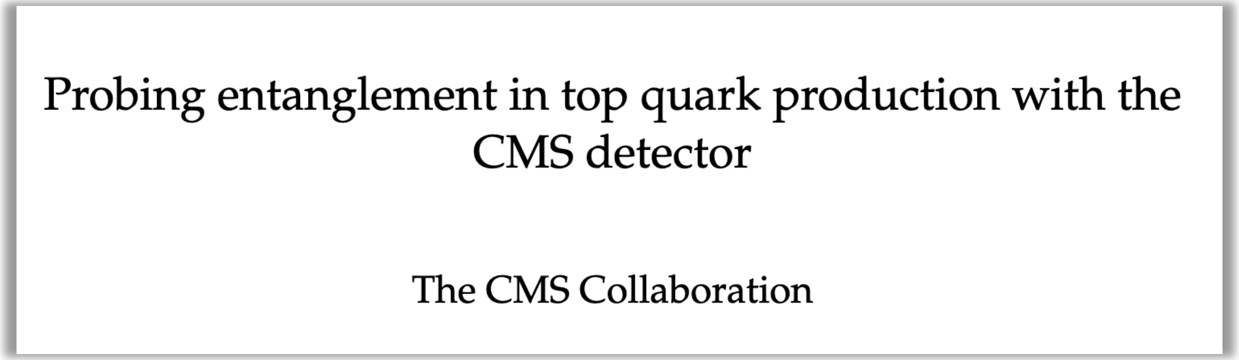
CMS Measurements

CMS has two measurements of entanglement

In the dilepton channel,
re-observe entanglement at threshold

In the lepton+jets channel, observe
entanglement at high mass

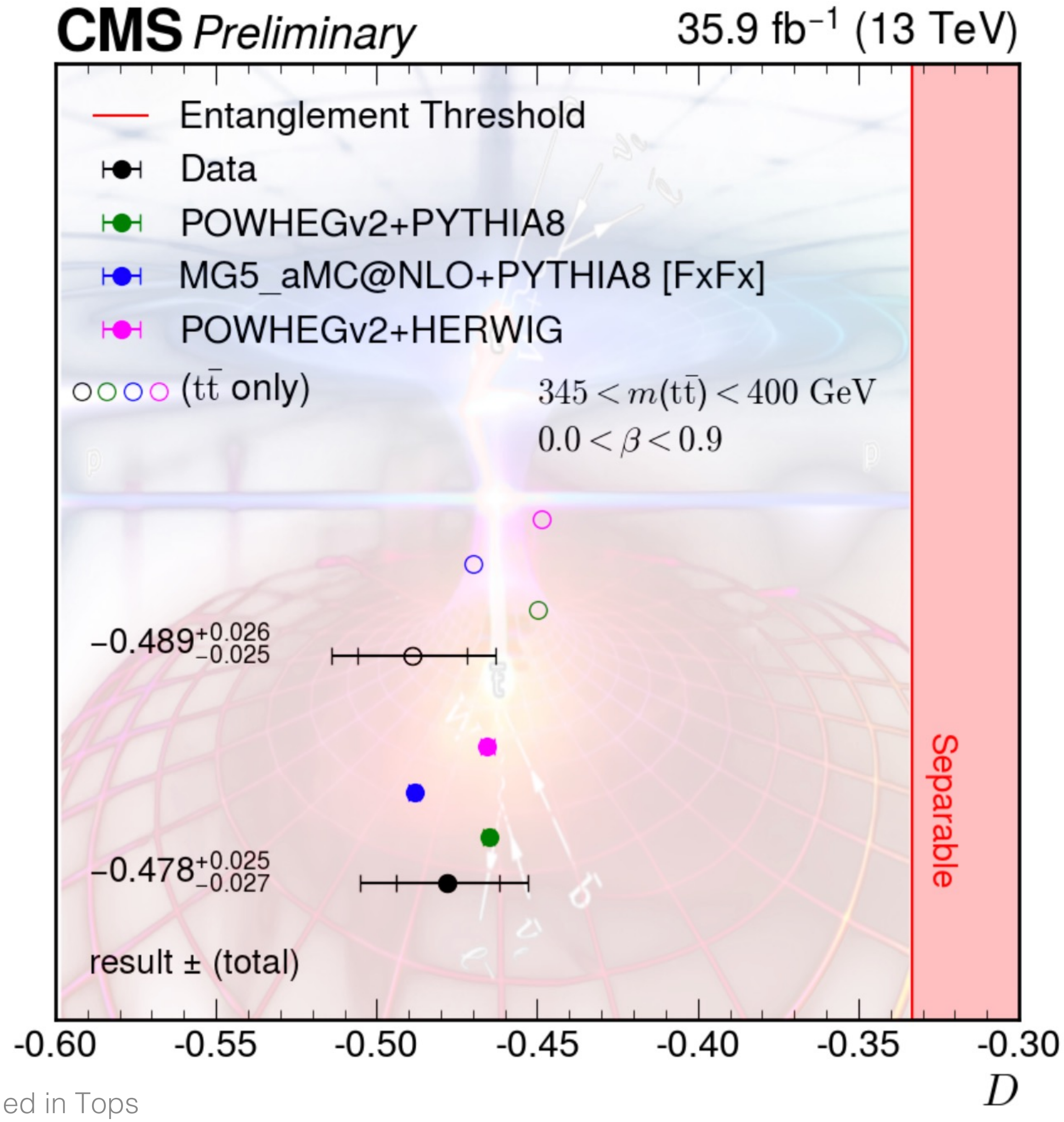
Dilepton Measurement



Probing entanglement in top quark production with the CMS detector

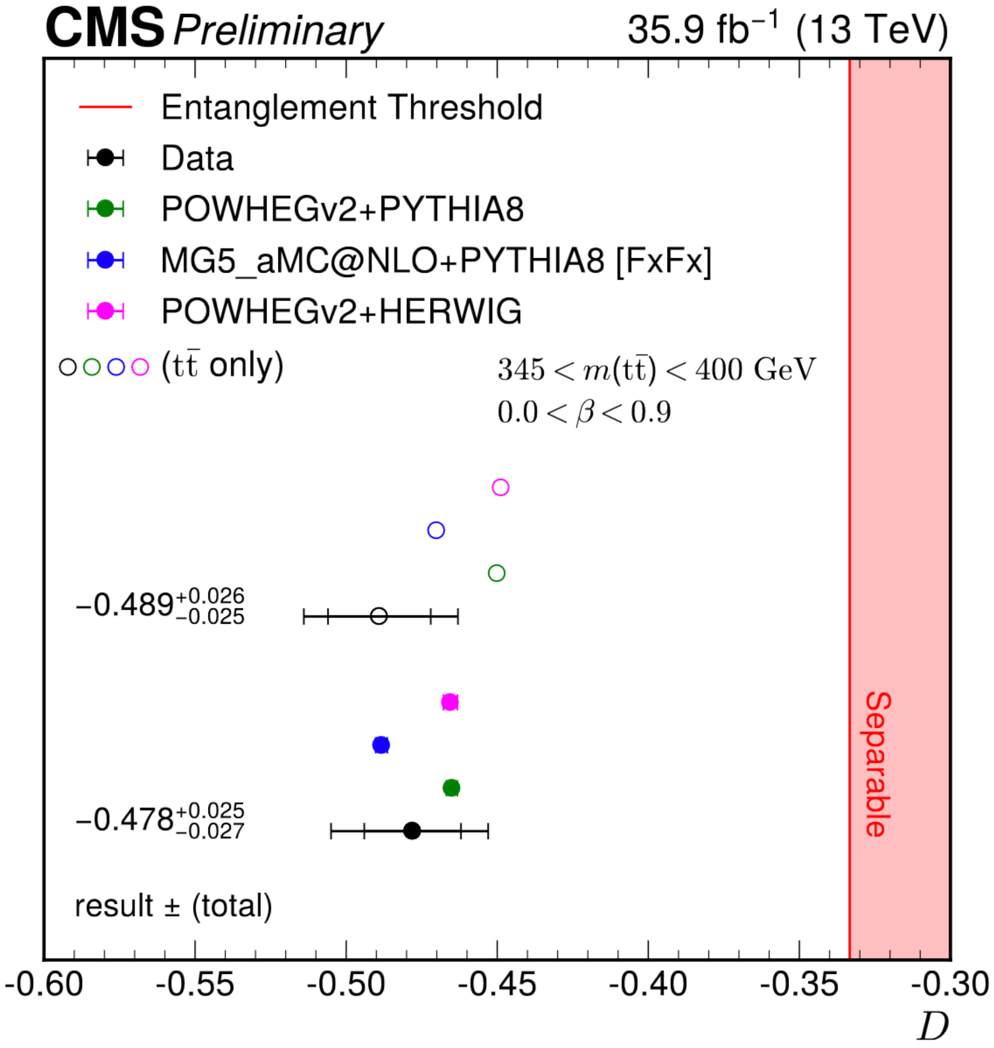
The CMS Collaboration

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



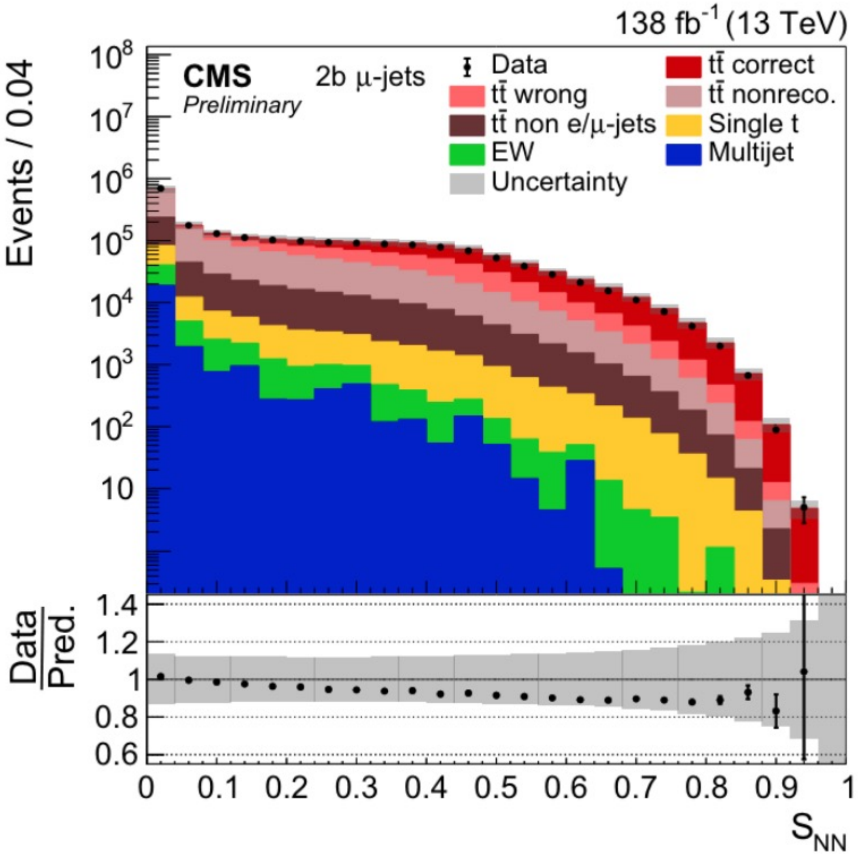
Dilepton Toponium

- 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…



Single-lepton Method

- Uses a DNN to reconstruct the top quarks

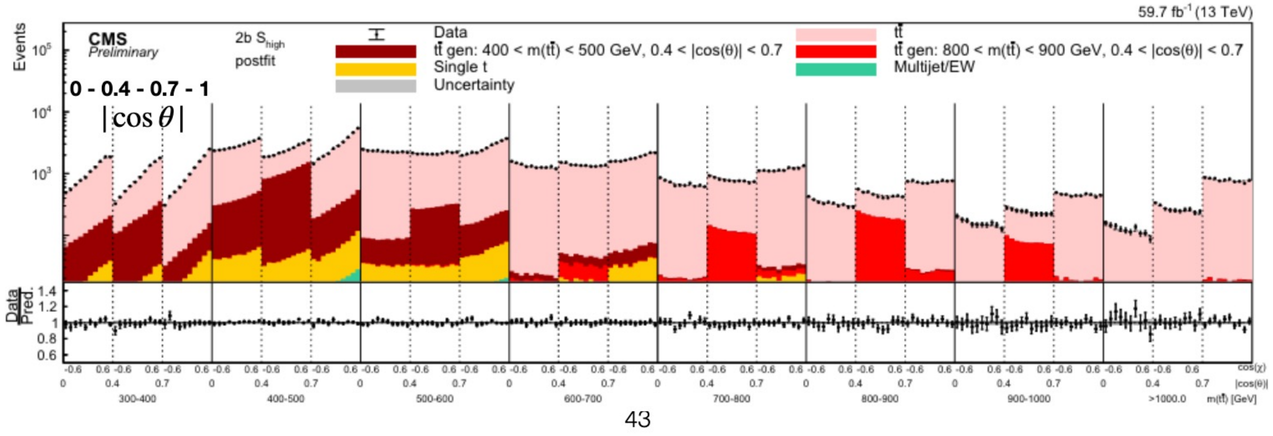


- Simultaneous binned likelihood fit to extract all spin parameters

- Reweight MC templates to reco-level

$$\Sigma_{\text{tot}} = \Sigma_0 + \sum_{m=1}^{15} Q_{\text{m}}\Sigma_m.$$

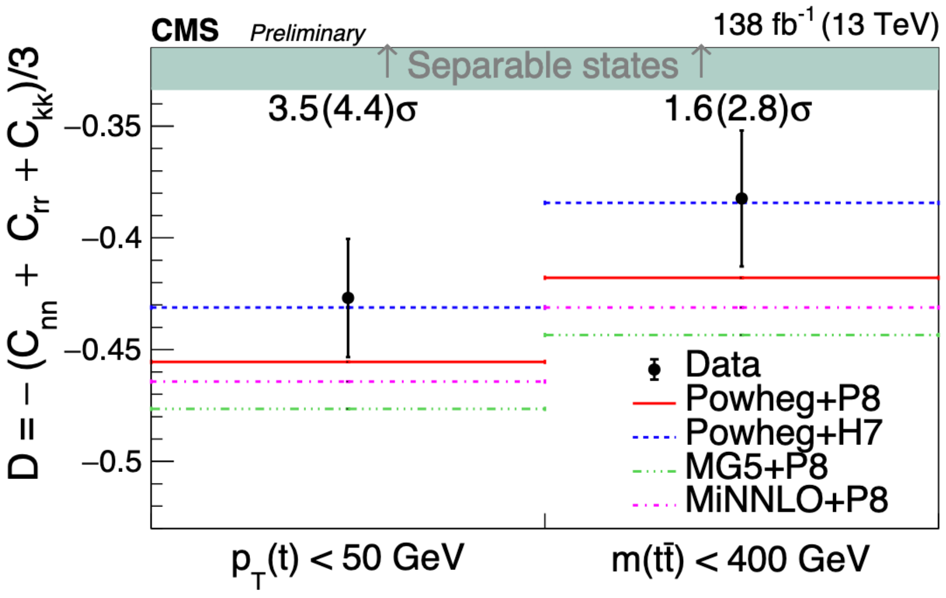
Postfit



Single-lepton Results

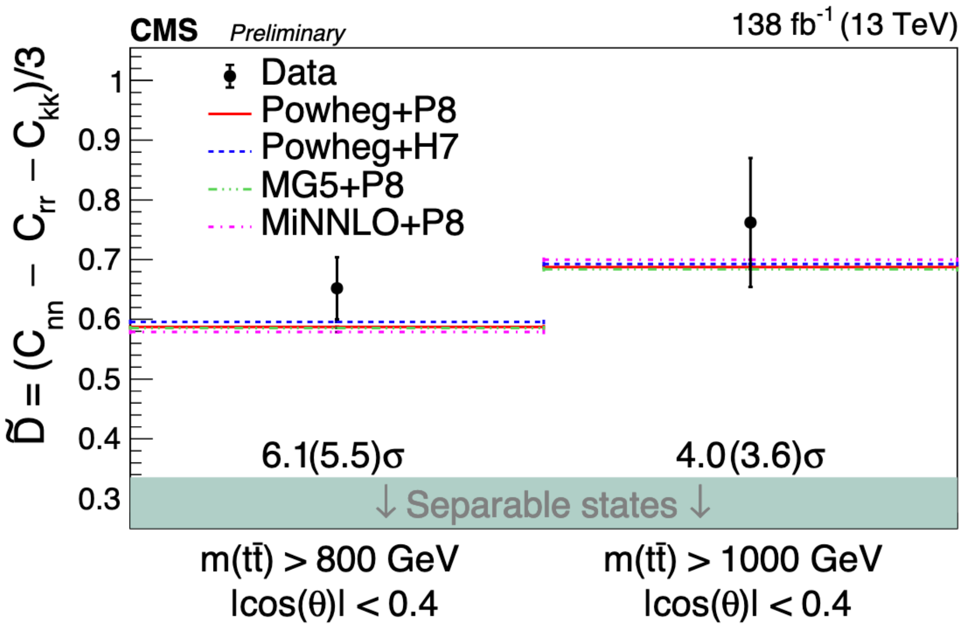
Threshold

Not enough significance for evidence



High-mass

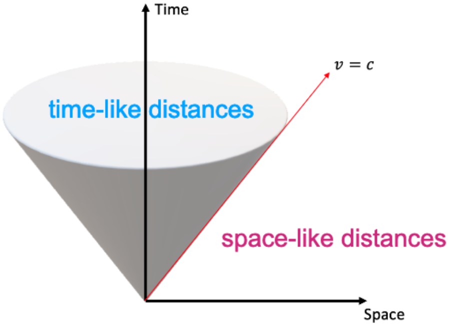
First observation



Single-lepton Space- vs time-like separated

Excluding classical explanation

- **Fraction of events with space-like separation increases with $m_{t\bar{t}}$**



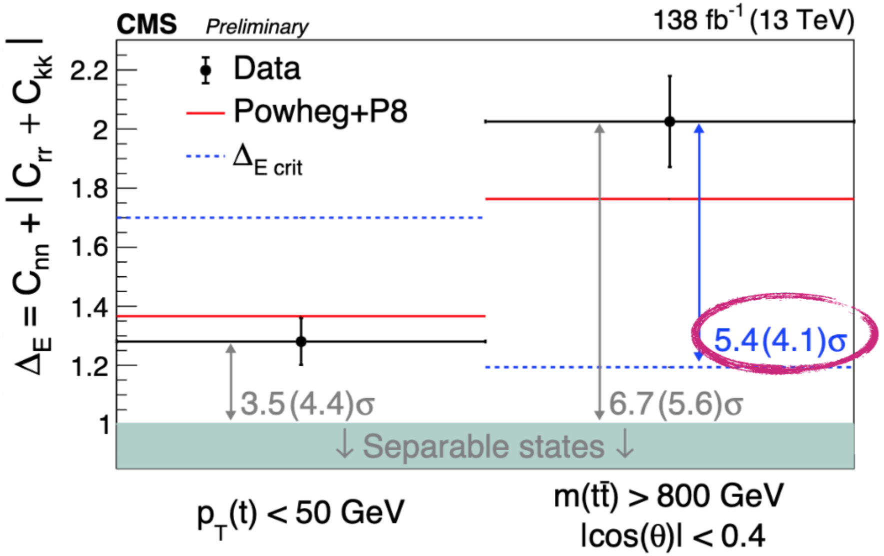
- What is the maximum value of Δ_E that can still be explained by non-quantum communication ($v \leq c$)?
  - time-like separated events: ΔE max = 3 (C_{ii} = 1)
  - space-like separated events: ΔE sep = 1

- The **boundary of critical entanglement** ($\Delta_{E\ critical}$) is defined for a given fraction f of space-like separated events as:

$$\Delta_{\mathrm{E\,crit}} = f\Delta_{\mathrm{E\ sep}} + (1-f)\Delta_{\mathrm{E\ max}}$$

Observed Δ_E exceeds $\Delta_{E\ critical}$ by >5 σ

→ level of observed entanglement cannot be explained by classical exchange of information between the two particles !



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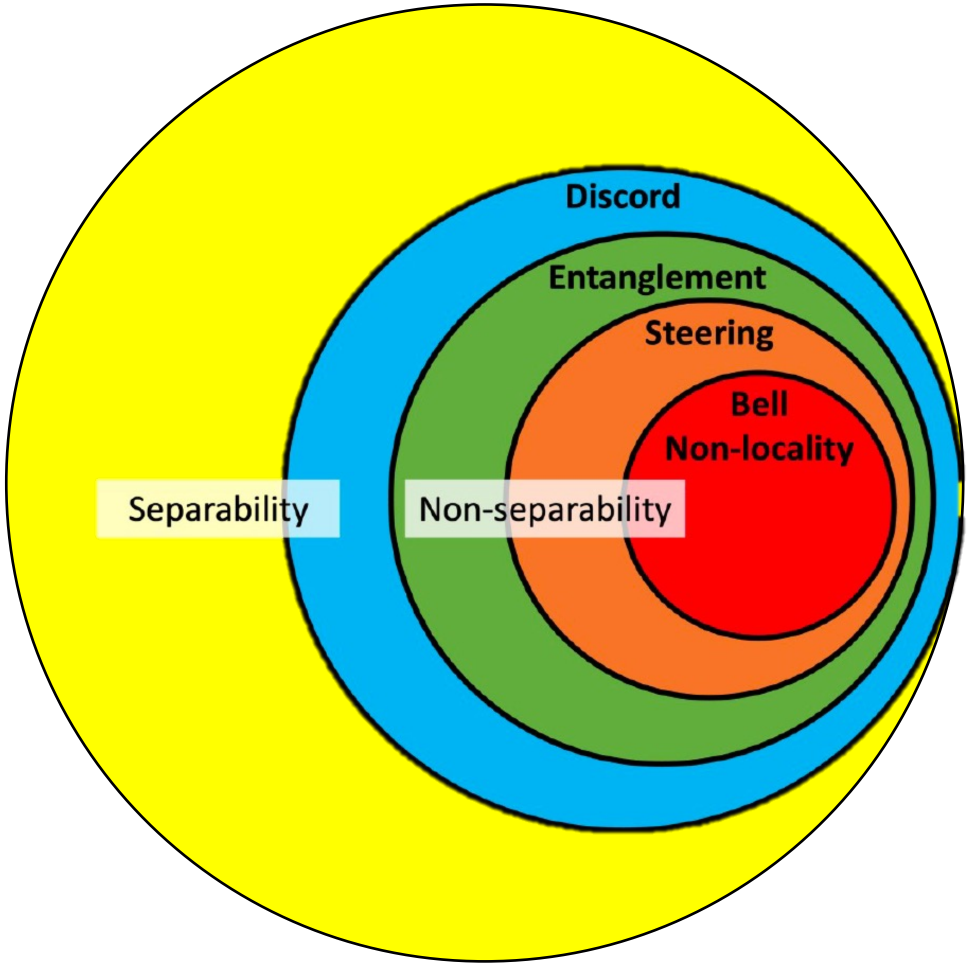
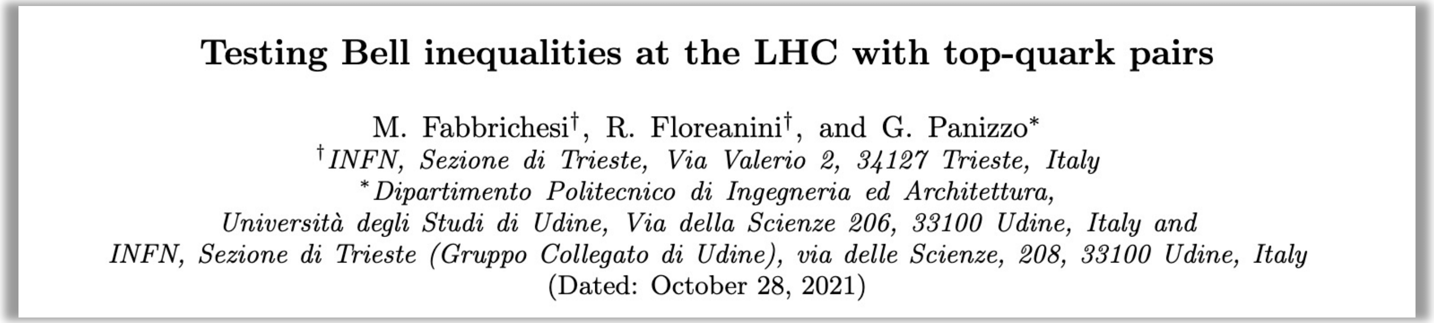
Postscript

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

ClaudioSeveri[1,a], Cristian Degli Esposti Boschi[3,4,b] , Fabio Maltoni[2,4,5,c], Maximiliano Sioli[2,4,d]
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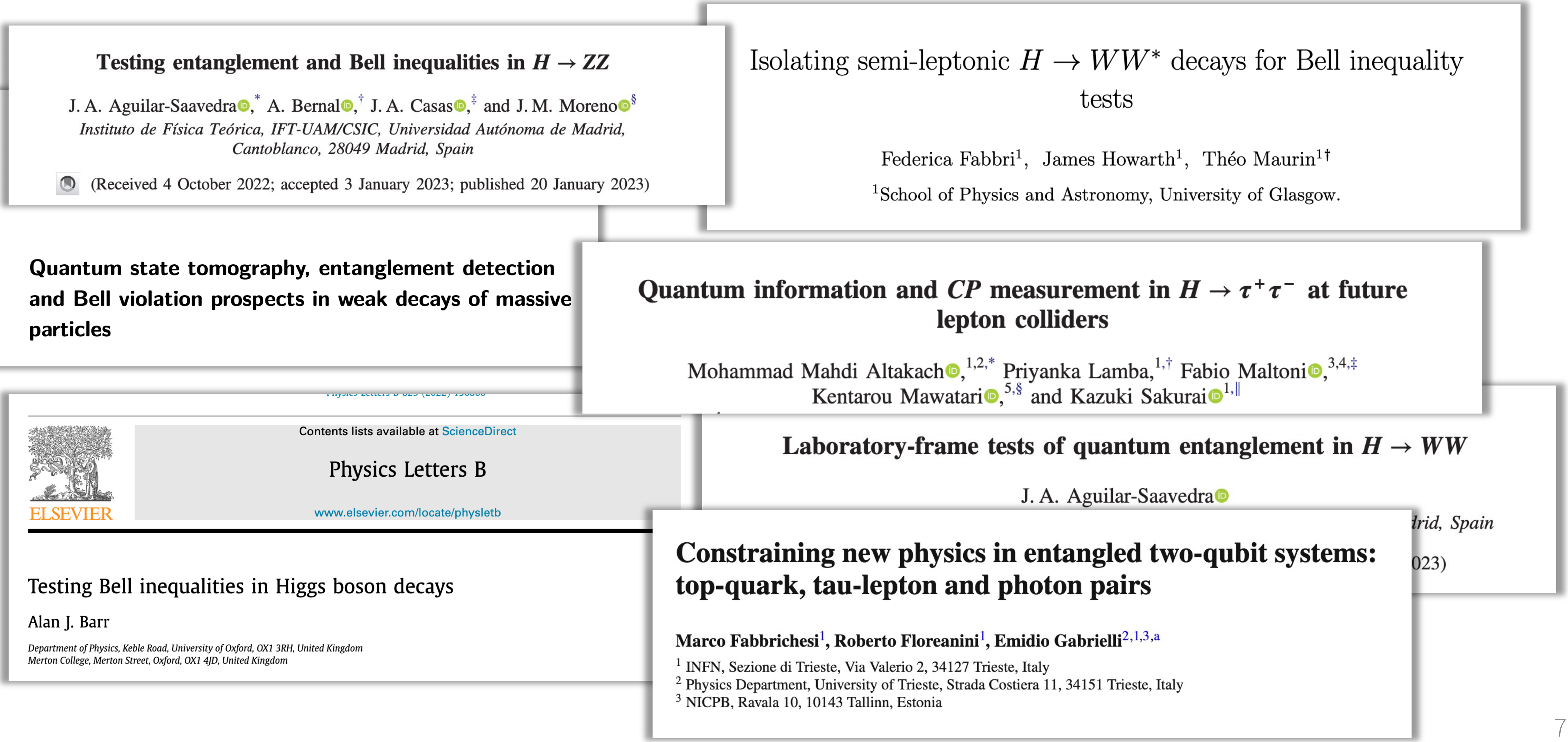
[5] Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-la-Neuve, Belgium

Beyond Top Quarks



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

J. A. Aguilar-Saavedra,[*] A. Bernal,[†] J. A. Casas,[‡] and J. M. Moreno[§]
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Cantoblanco, 28049 Madrid, Spain

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

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

Federica Fabbri[1], James Howarth[1], Théo Maurin[1†]
[1]School 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 $H \to \tau^+\tau^-$ at future lepton colliders

Mohammad Mahdi Altakach,[1,2,*] Priyanka Lamba,[1,†] Fabio Maltoni,[3,4,‡]
Kentarou Mawatari,[5,§] and Kazuki Sakurai[1,‖]

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Testing Bell inequalities in Higgs boson decays

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Merton College, Merton Street, Oxford, OX1 4JD, United Kingdom

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

J. A. Aguilar-Saavedra
drid, Spain
023)

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

Marco Fabbrichesi[1], Roberto Floreanini[1], Emidio Gabrielli[2,1,3,a]
[1] INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy
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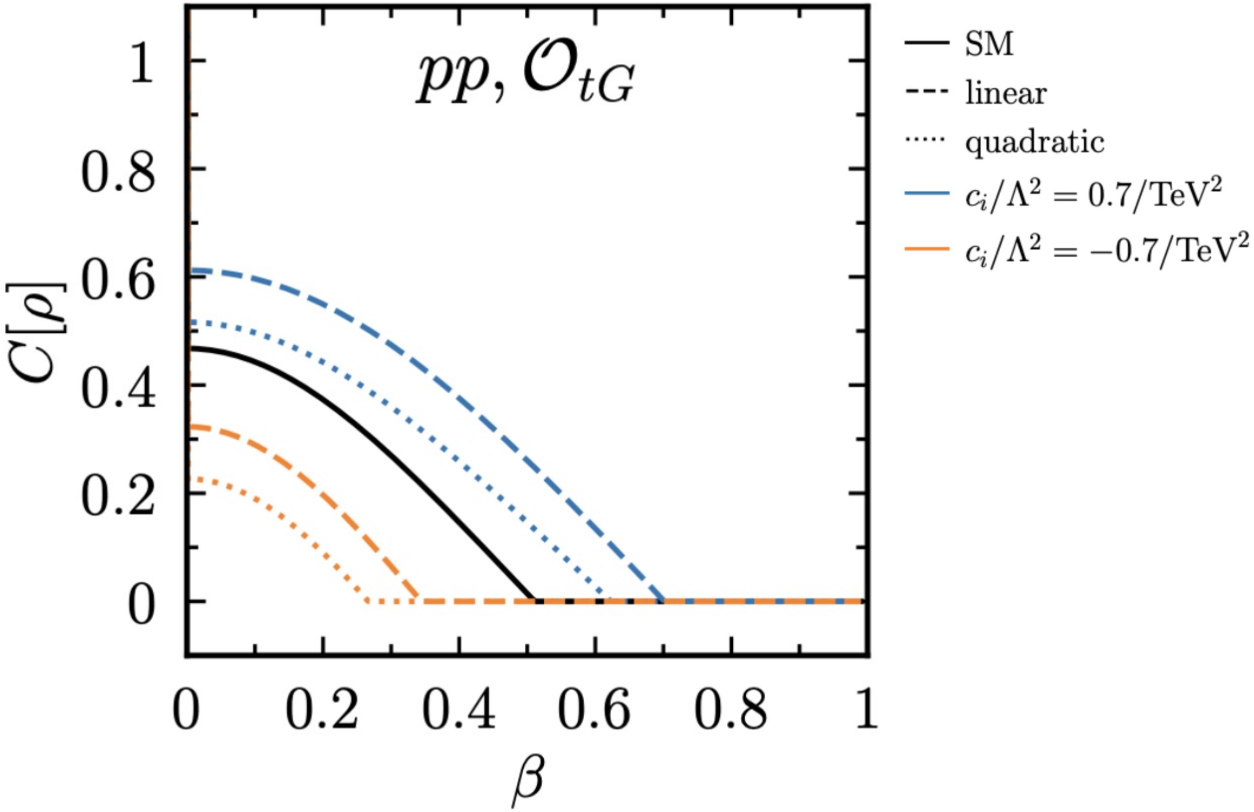
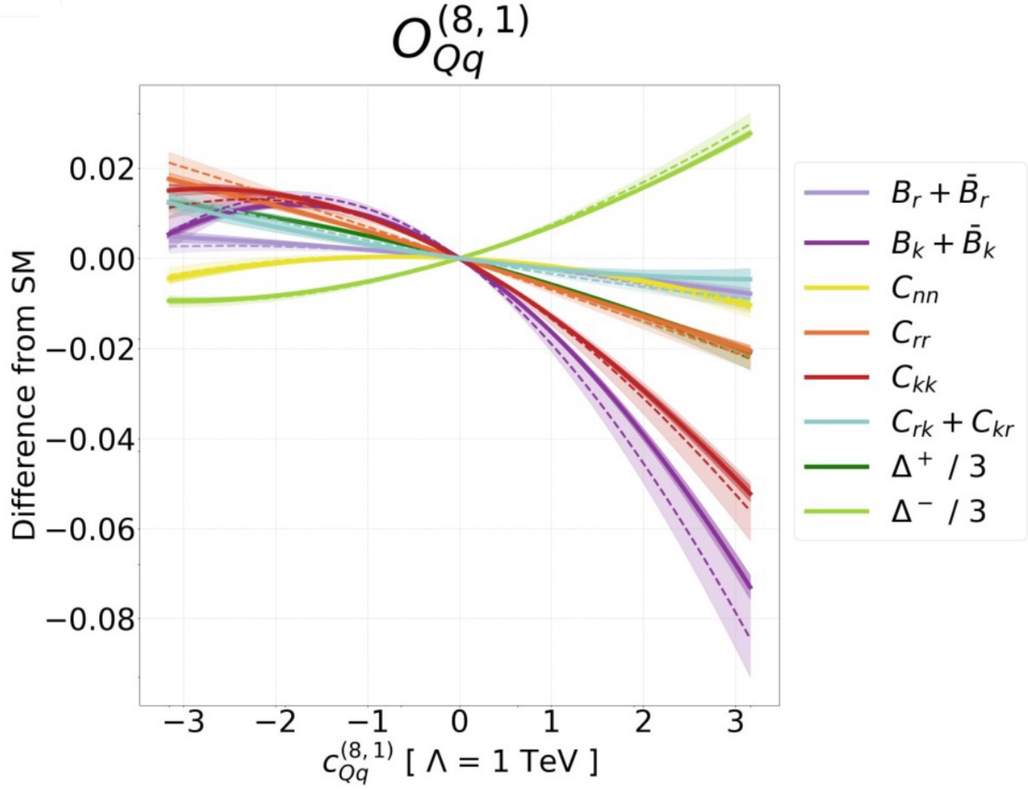
[3] NICPB, Ravala 10, 10143 Tallinn, Estonia

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](2307.06991)

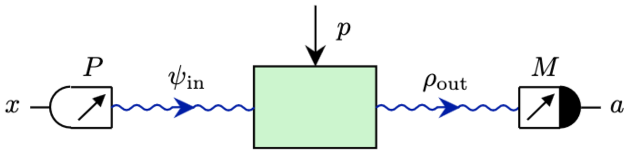
[2308.07412](2308.07412)

Electrons before and after they notice the detector

Beyond Quantum Mechanics?

General Probabilistic Theories

Objective Collapse Models

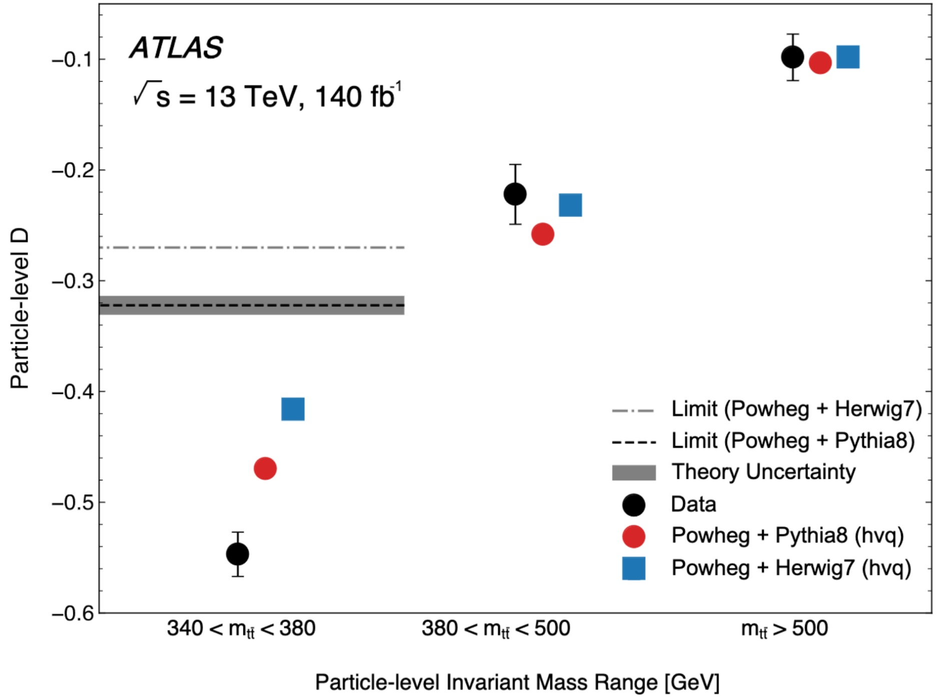


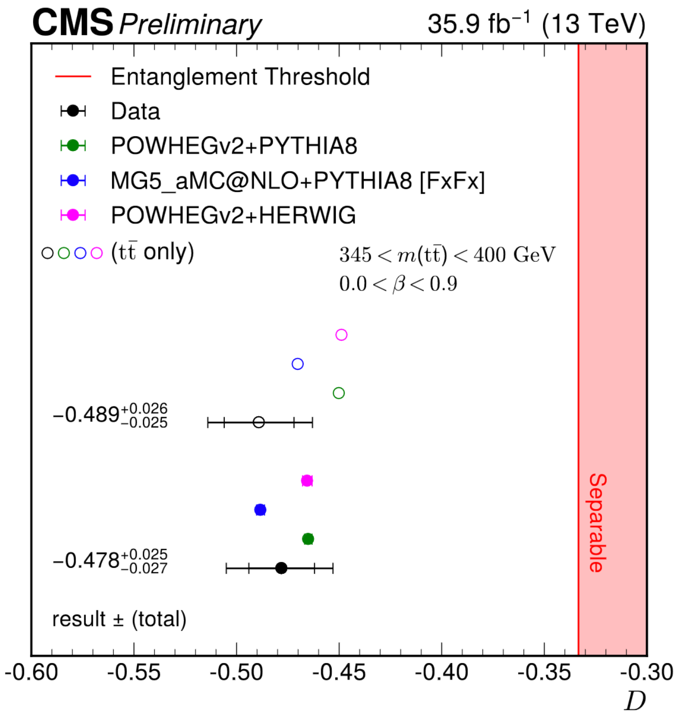
Q-data Tests

Conclusions

First observation of entanglement at LHC

First observation of entanglement between free quarks





Conclusions

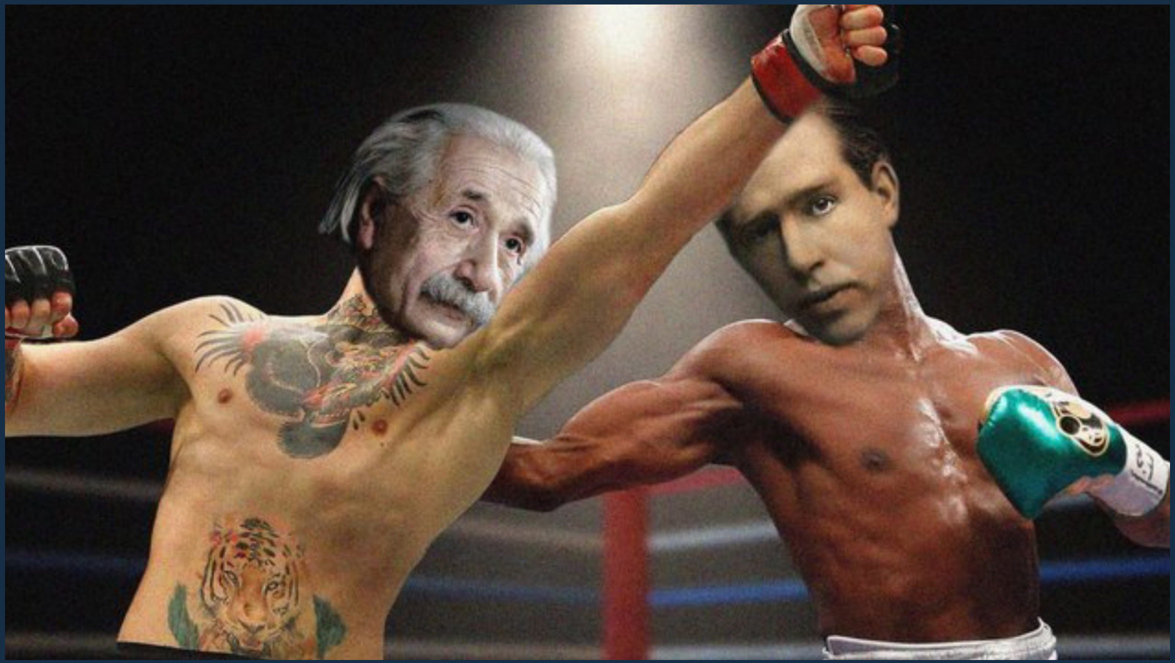
First observation of entanglement at LHC

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!



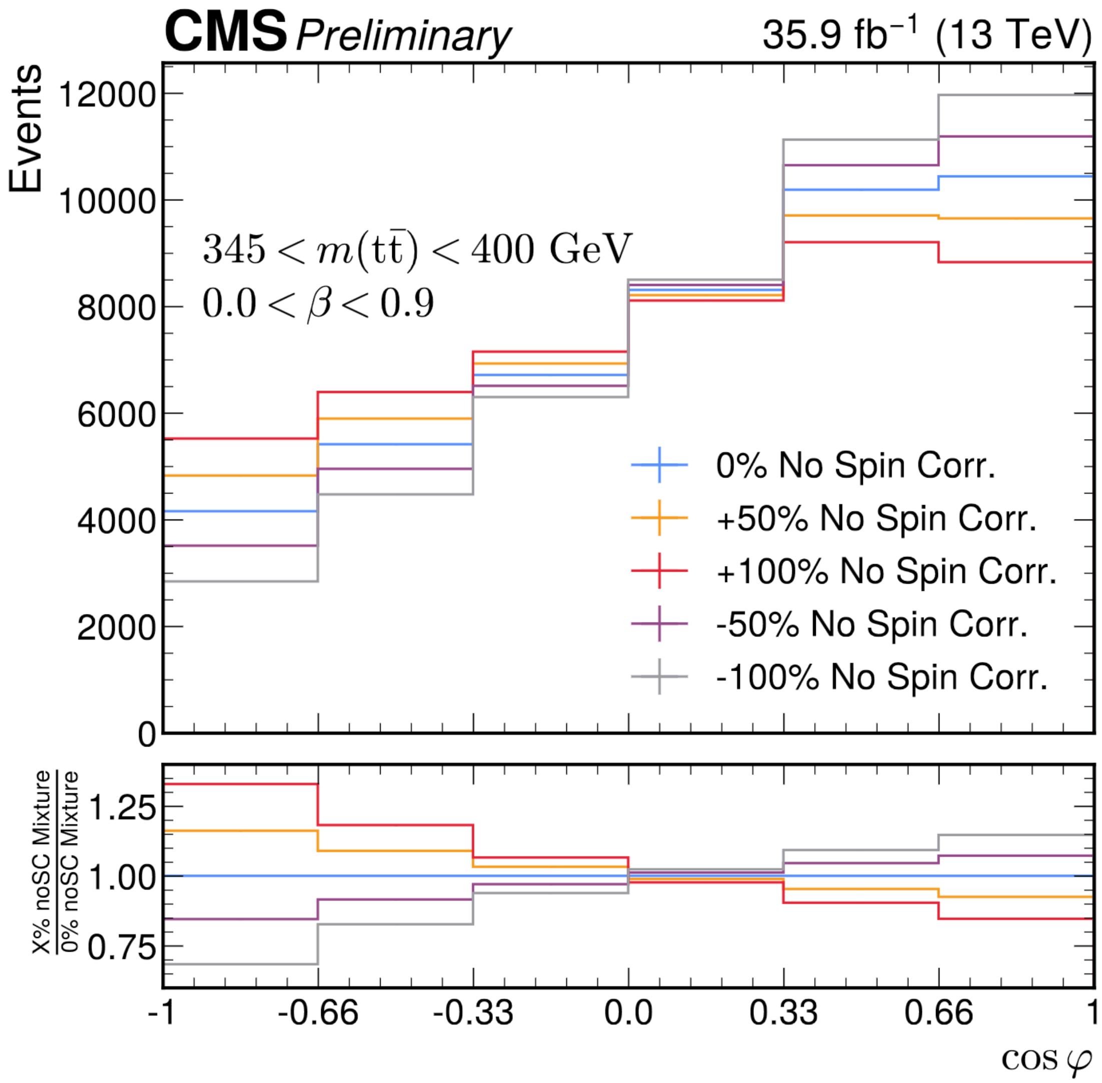
Auxiliary Materials

Dilepton Alternative Entanglement Hypotheses

- Generate simulation with no spin correlations

- Weighted combination of “spin-on” and “spin-off” samples yields changes in D

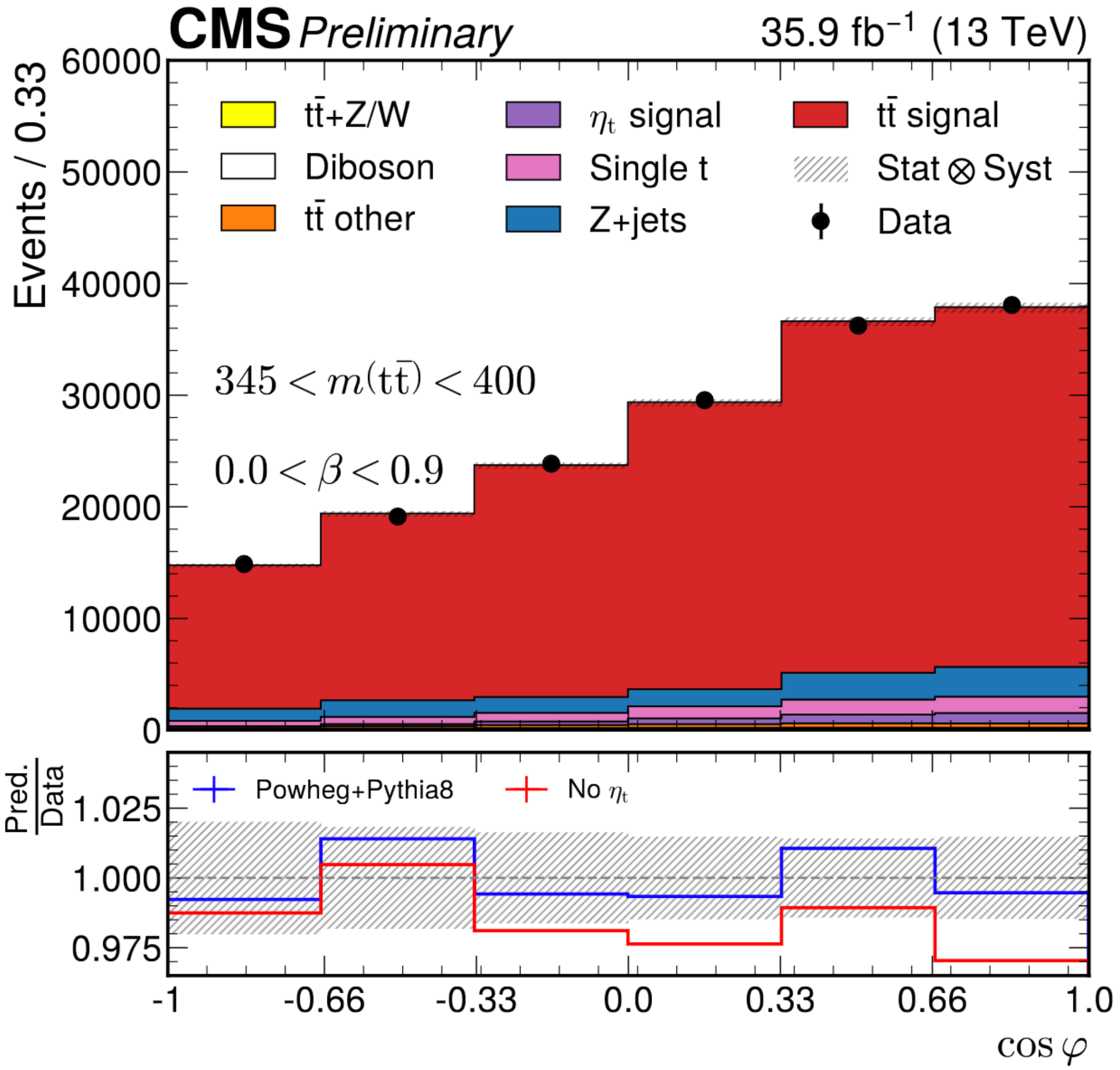
(ATLAS used MC reweighting)



Dilepton Entanglement Marker

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

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



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

A Lesson

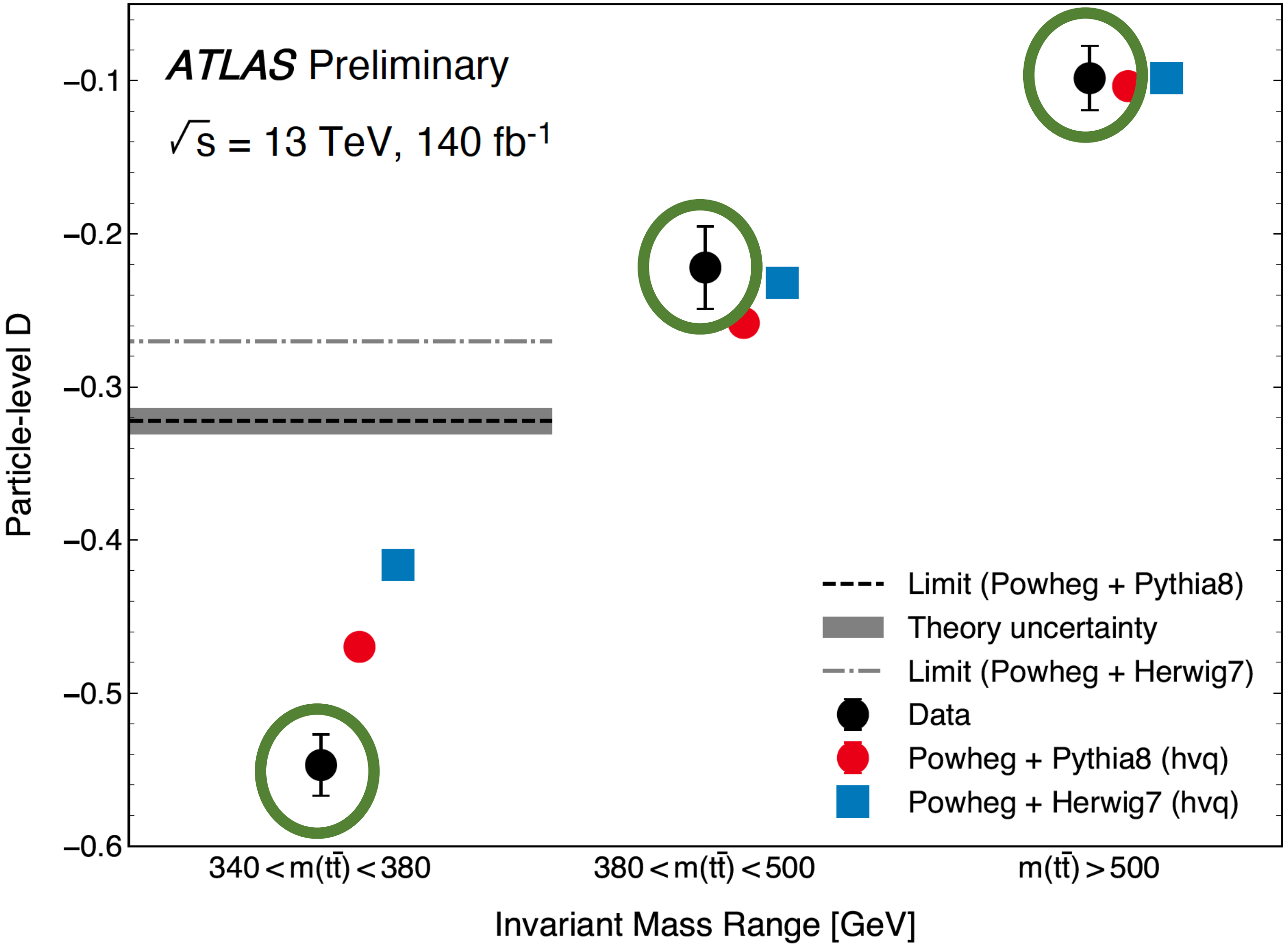
Many issues are exacerbated by the narrow phase-space:

- 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 ✓

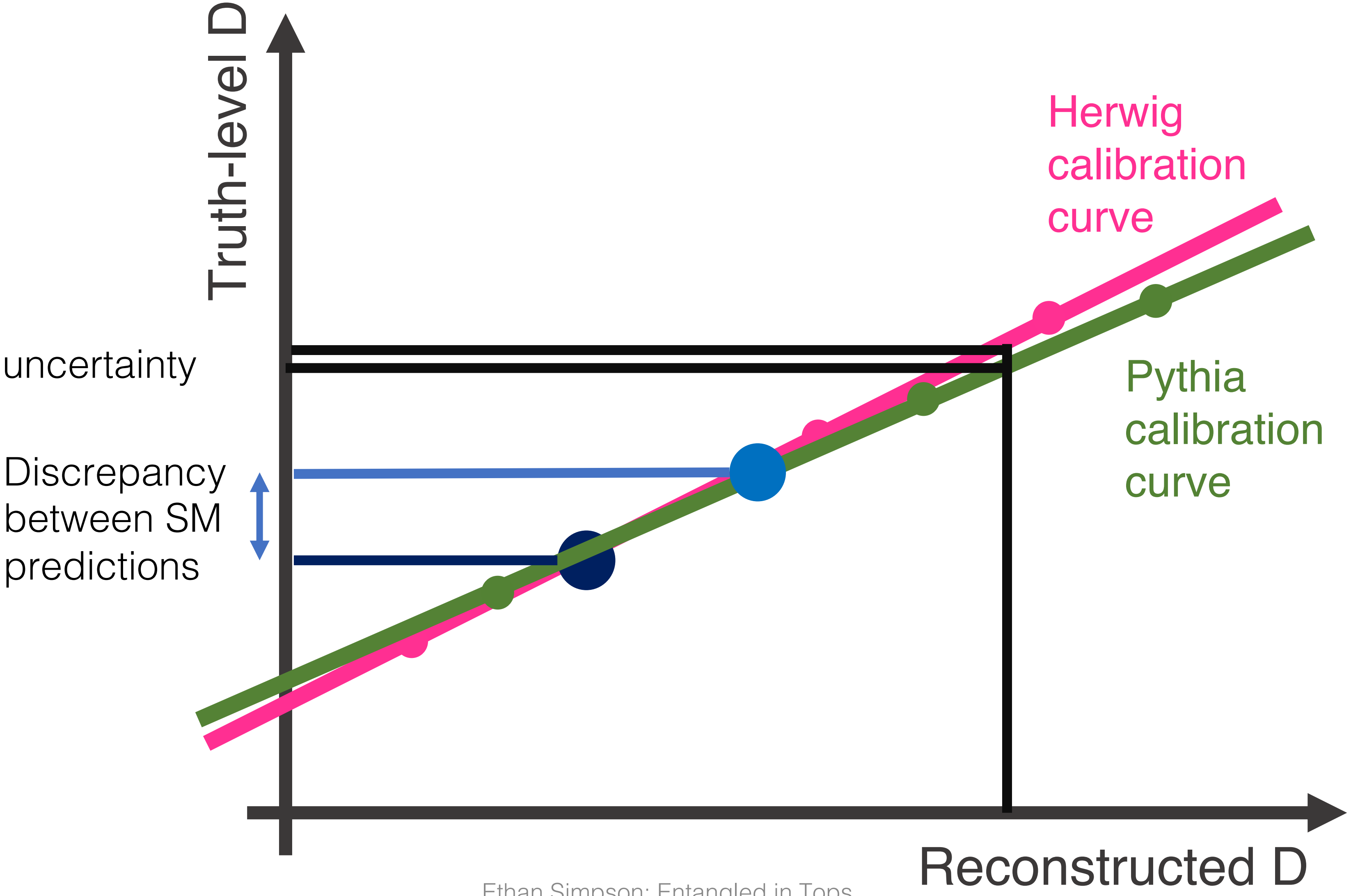
The correction contains a full suite of uncertainties, like all ATLAS Top analyses.

We understand our detector response extremely well.

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

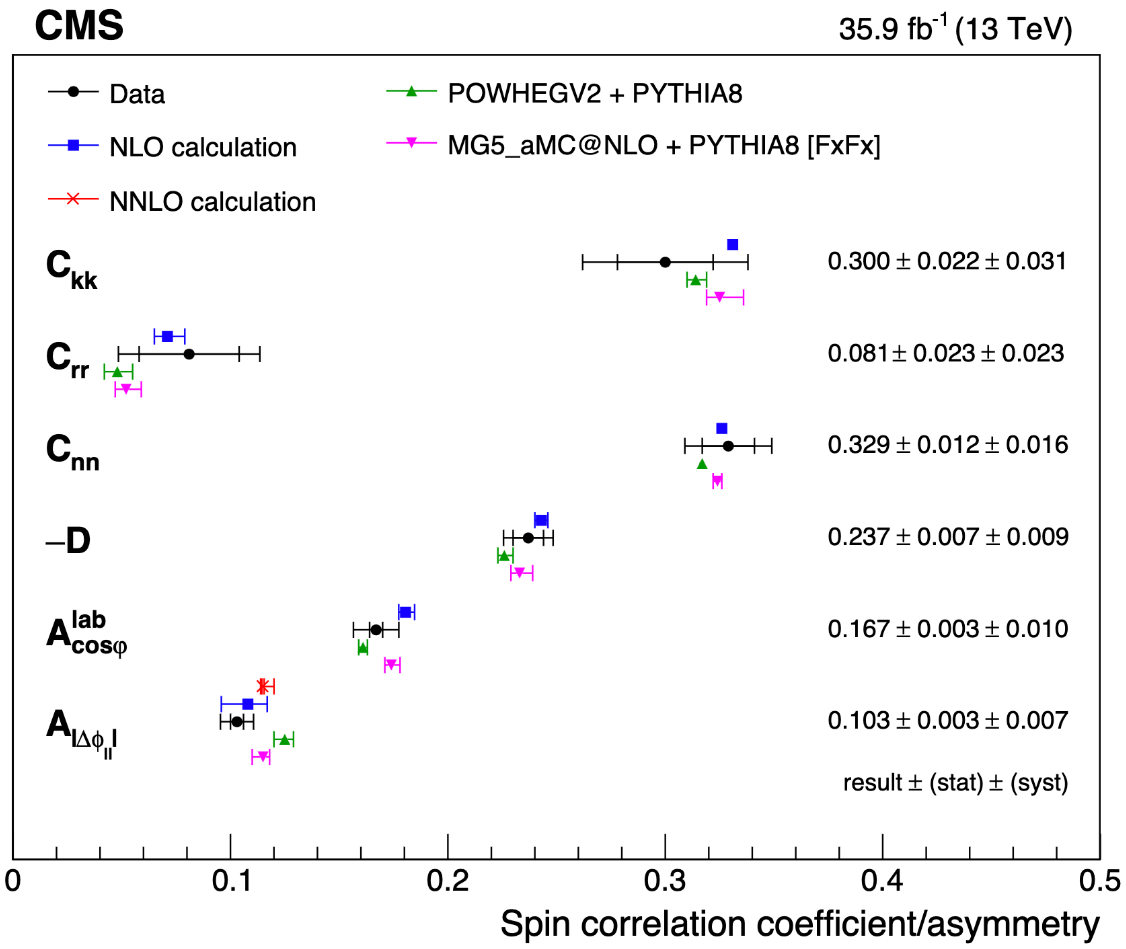
Common Questions

How reliable is the calibration curve method?



Measurements of Spin Correlations

Many precision measurements of spin parameters in the past



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

View as an average spin correlation

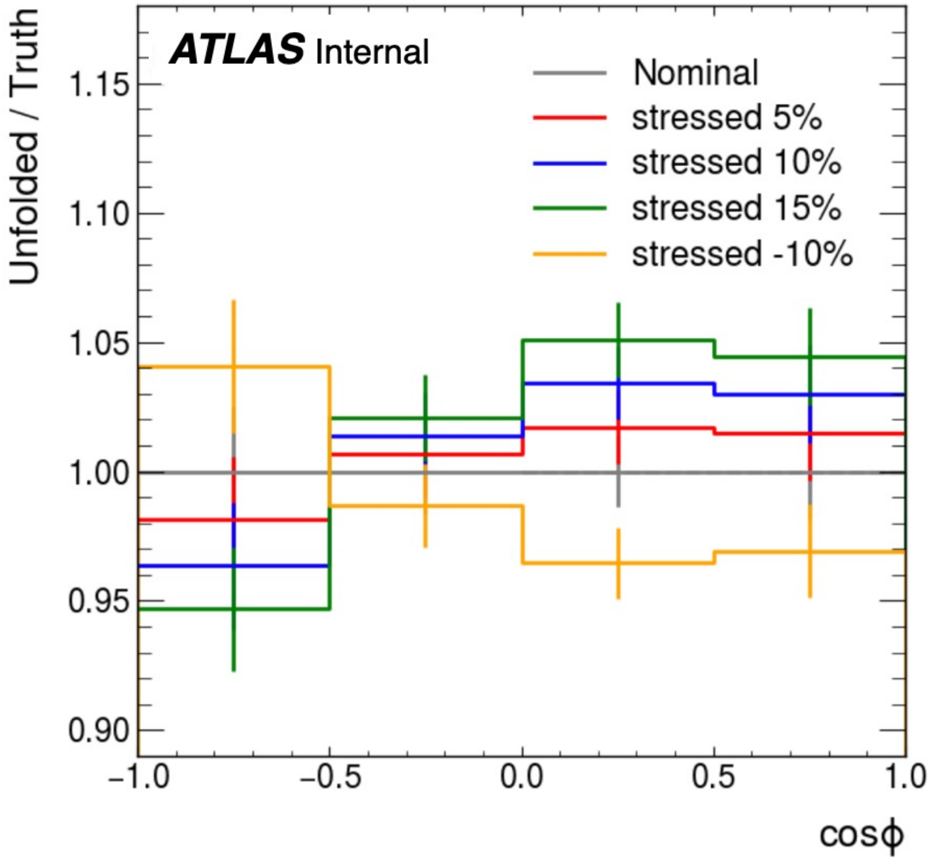
Unfolding

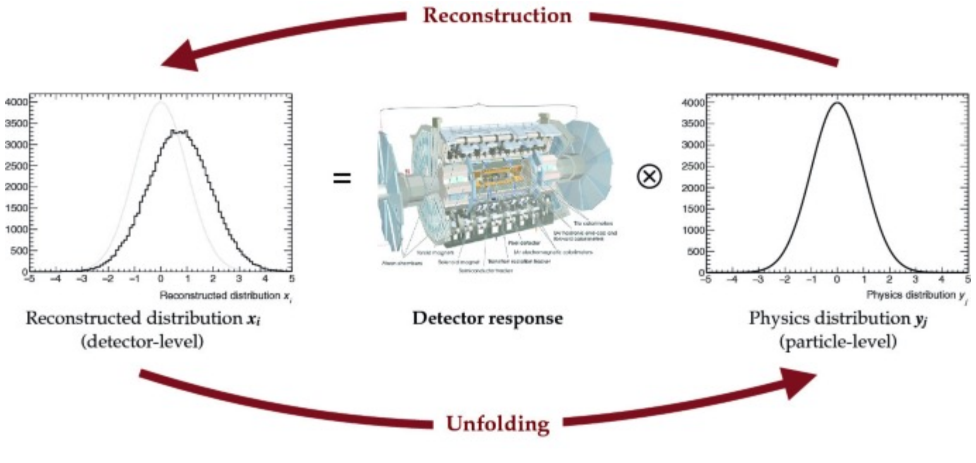
Correct detector effects back to underlying truth

For comparison to predictions and other experimental results.

Many techniques available: tried Iterative Bayesian Unfolding

Must check procedure for bias…





Unfolding Efforts

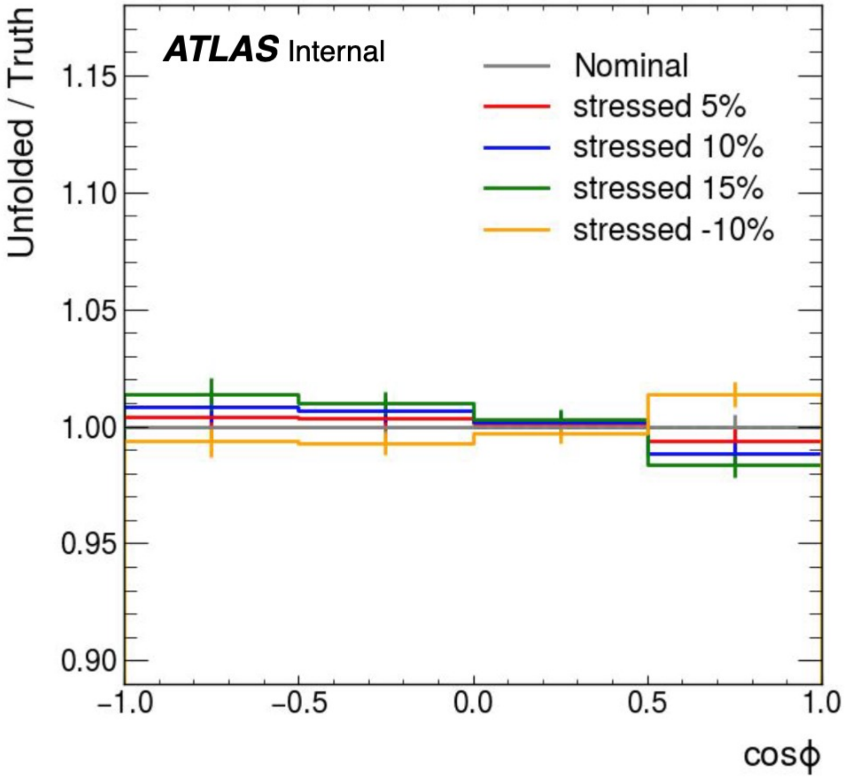
Parameterise variation in the detector effects on D.

Alter the slope of the cos-phi distribution

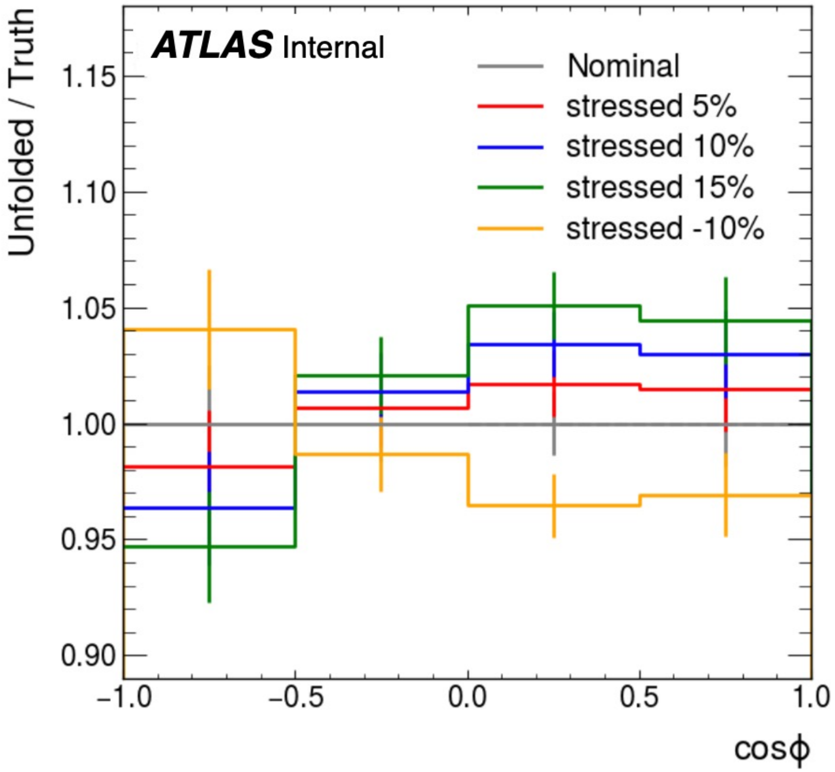
Unfold the distorted result

Compare unfolded to truth

Inclusive

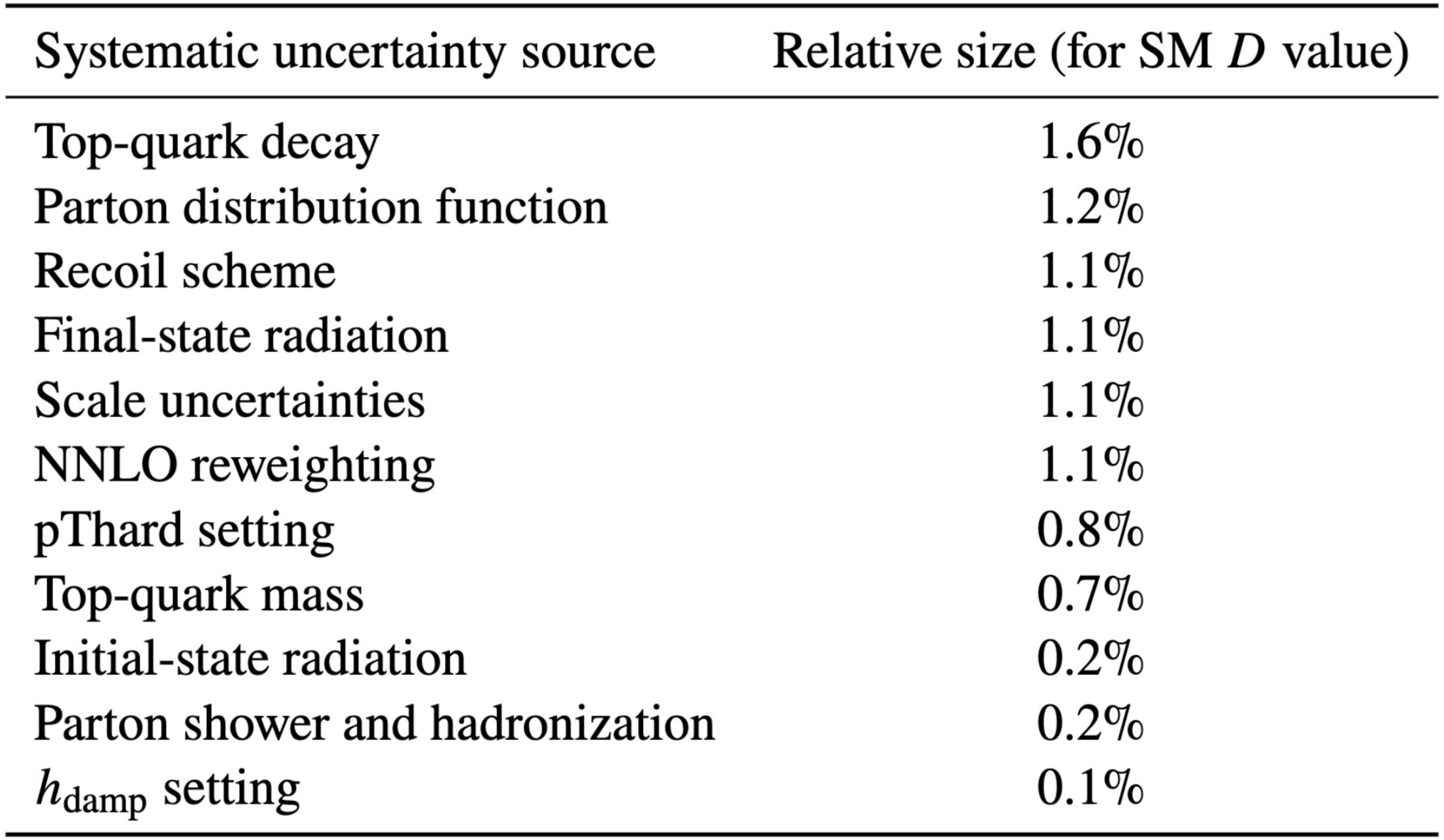


Signal Region



Modelling Uncertainties

tt modelling near threshold has large impact on precision.

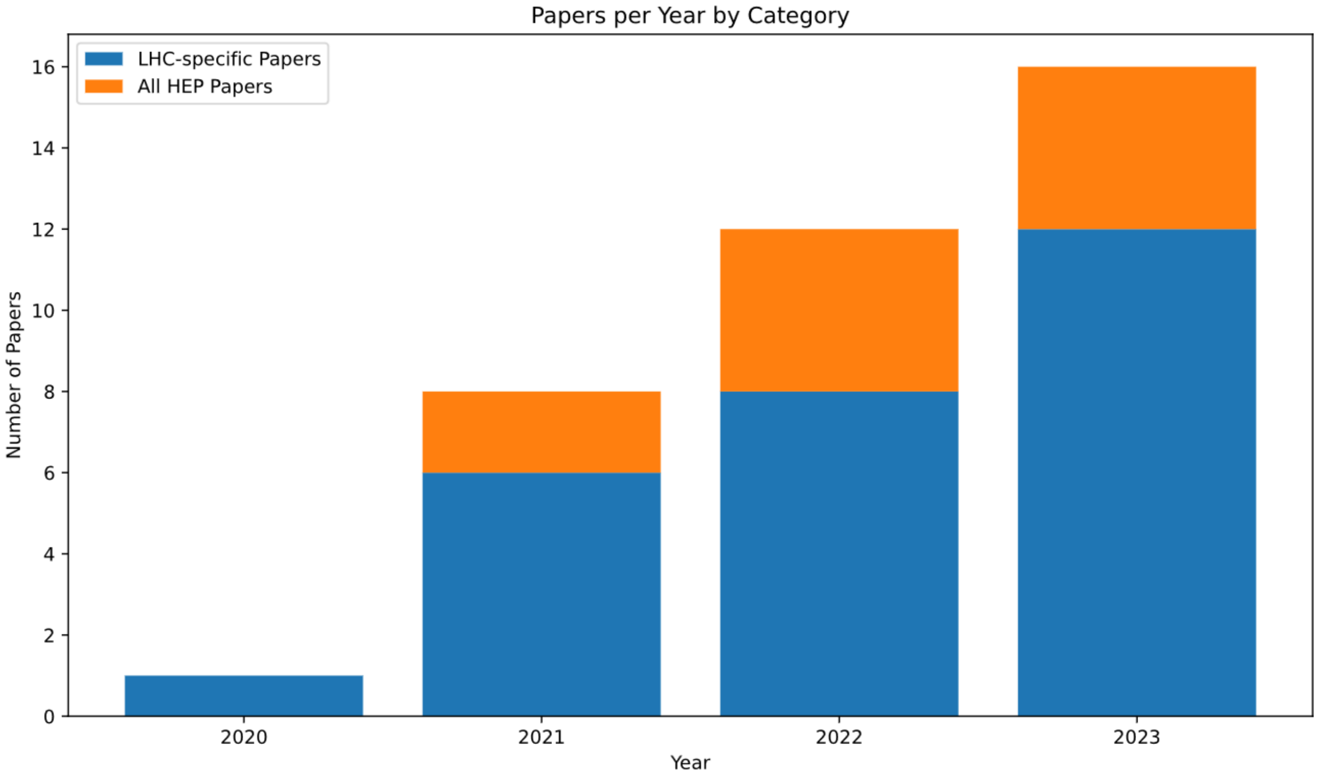


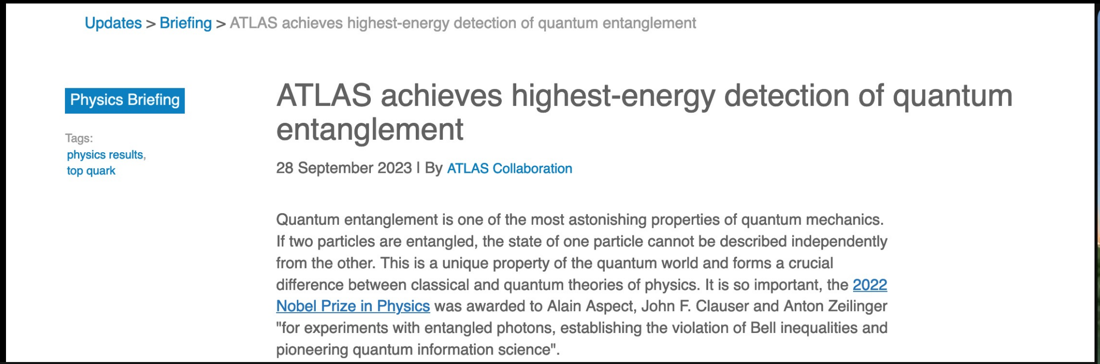
Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization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

How heavy-resonance decays and spin correlations are treated

Small because correction to particle-level.

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



Updates > Briefing > ATLAS achieves highest-energy detection of quantum entanglement

ATLAS achieves highest-energy detection of quantum entanglement

28 September 2023 | By ATLAS Collaboration

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".

Physics

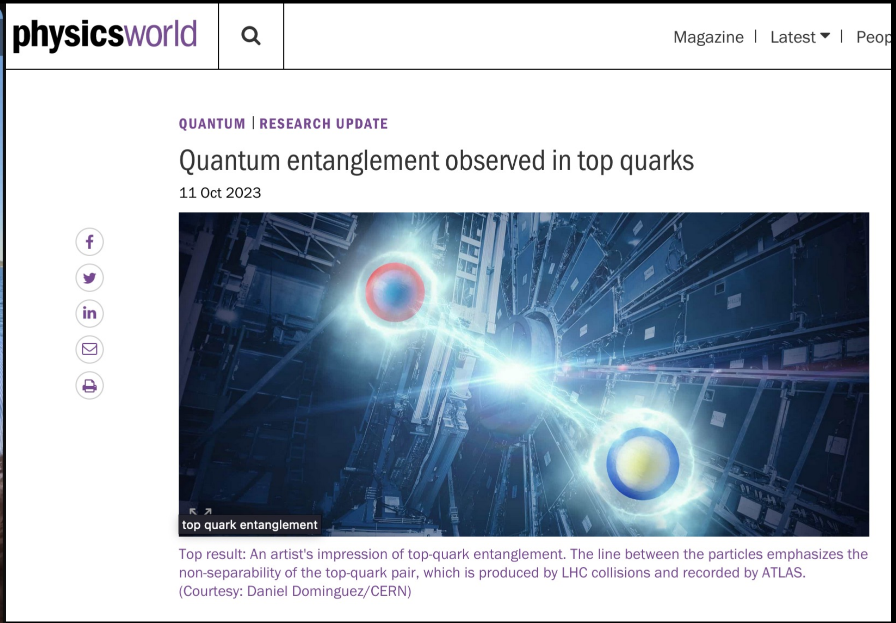
Large Hadron Collider turned into world's biggest quantum experiment

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

By Alex Wilkins

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

@ParticleCl

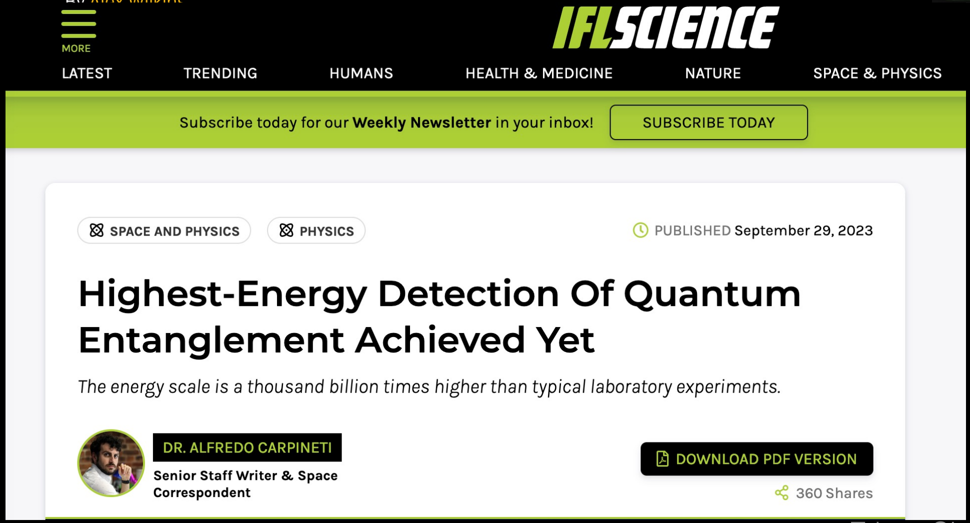


QUANTUM | RESEARCH UPDATE

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)

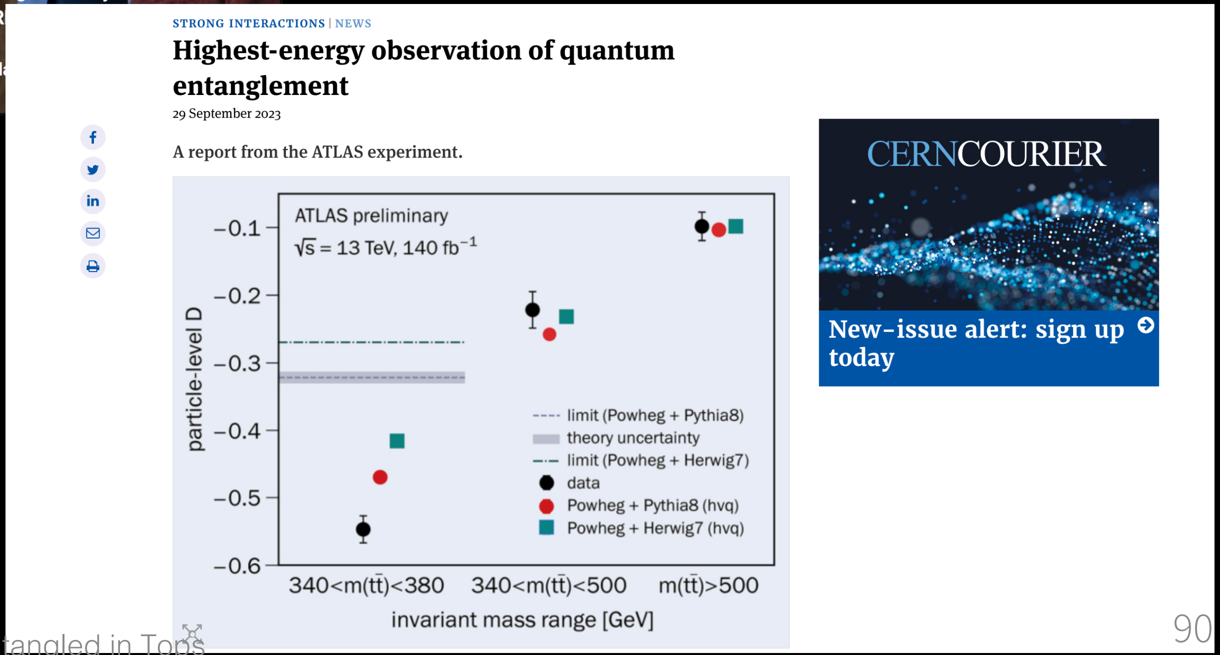


PUBLISHED September 29, 2023

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



STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

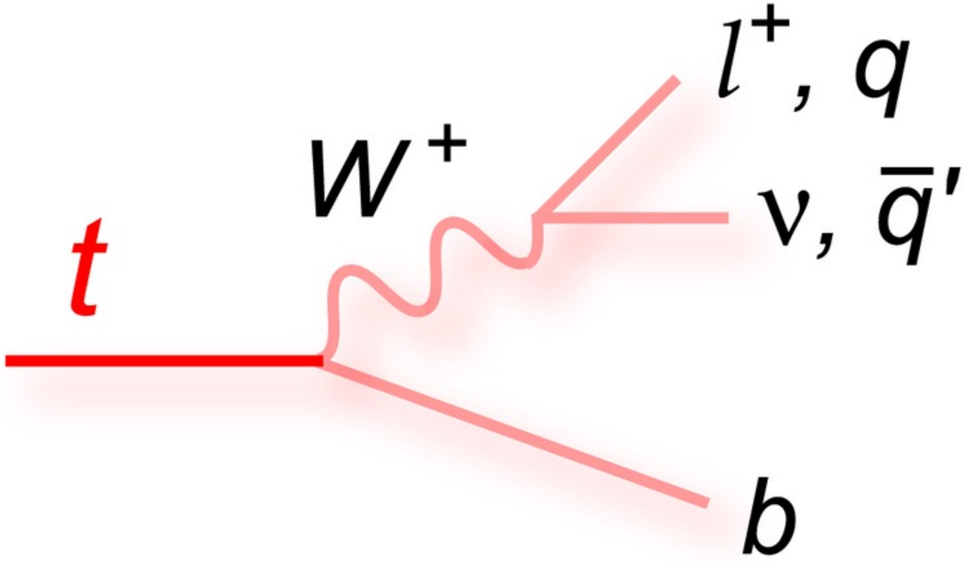
29 September 2023

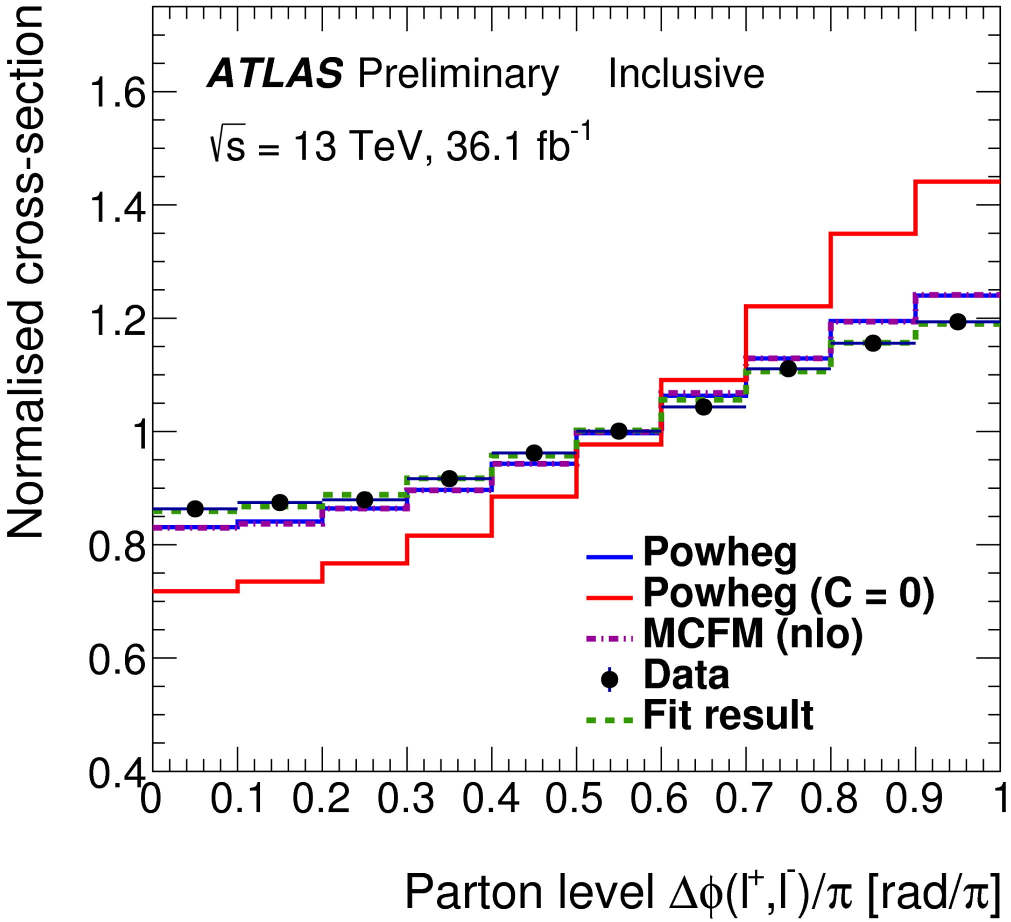
A report from the ATLAS experiment.

Angular Observables

Measure spin parameters through angular observables.

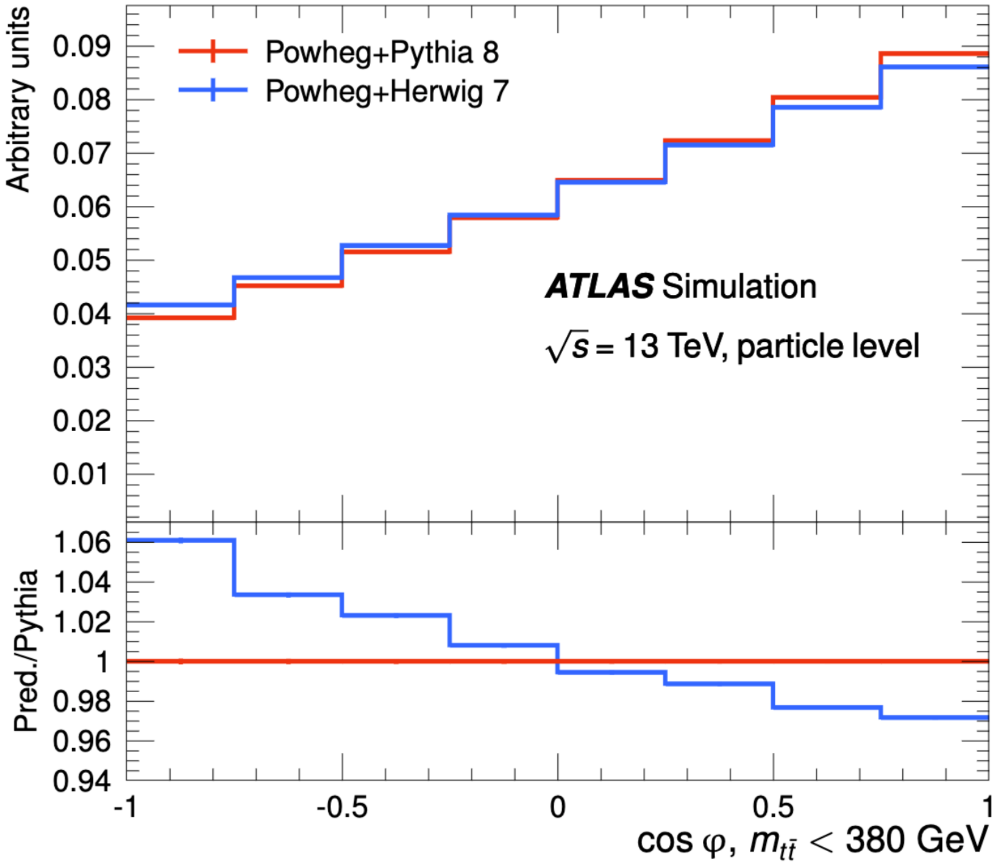
- Top spins determine W helicities.
- W helicities correlate with decay product directions



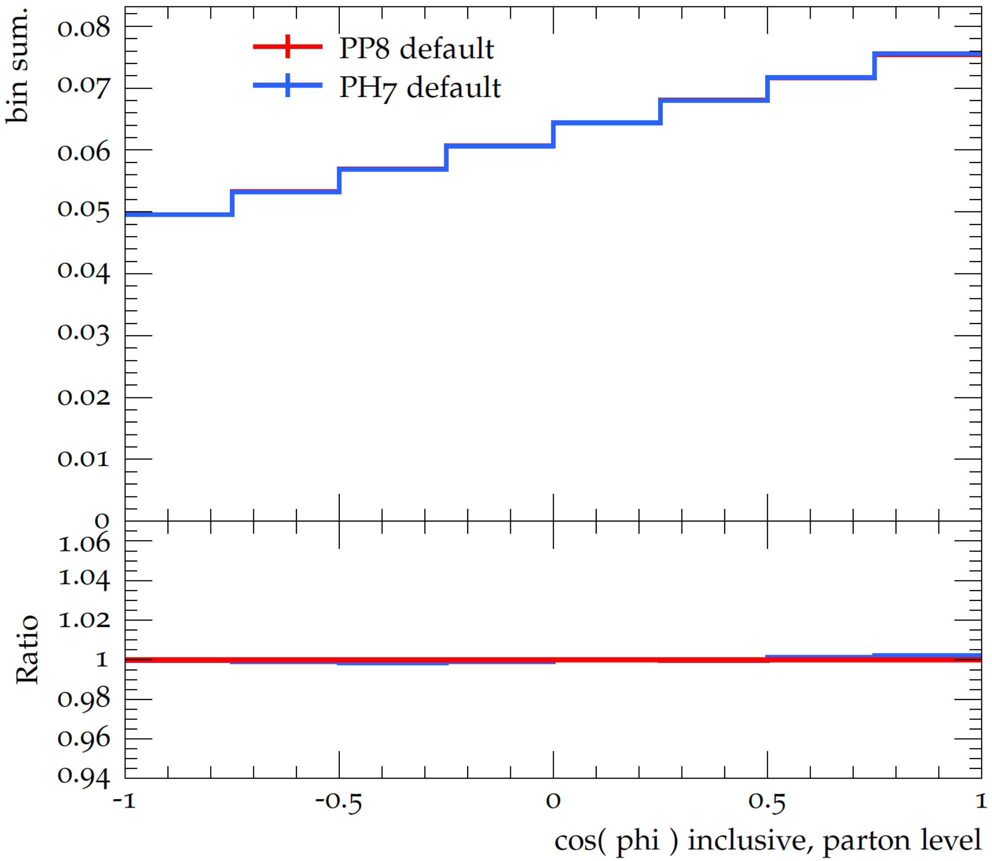


Why Particle-Level?

Extrapolation to parton-level incurs huge parton shower uncertainty



Large difference at particle-level



No difference at parton-level

Why Particle-Level?

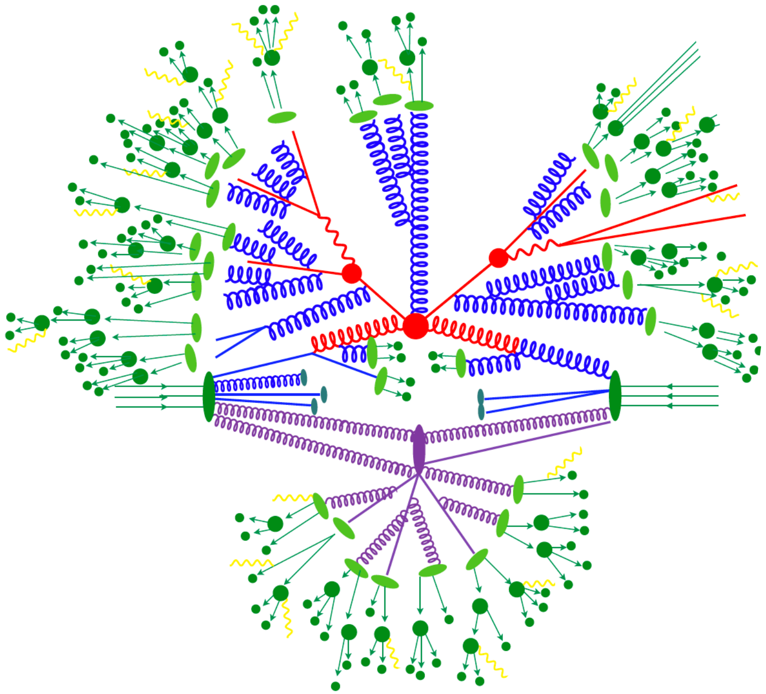
Extrapolation to parton-level incurs huge parton shower uncertainty

Large differenc

on-level

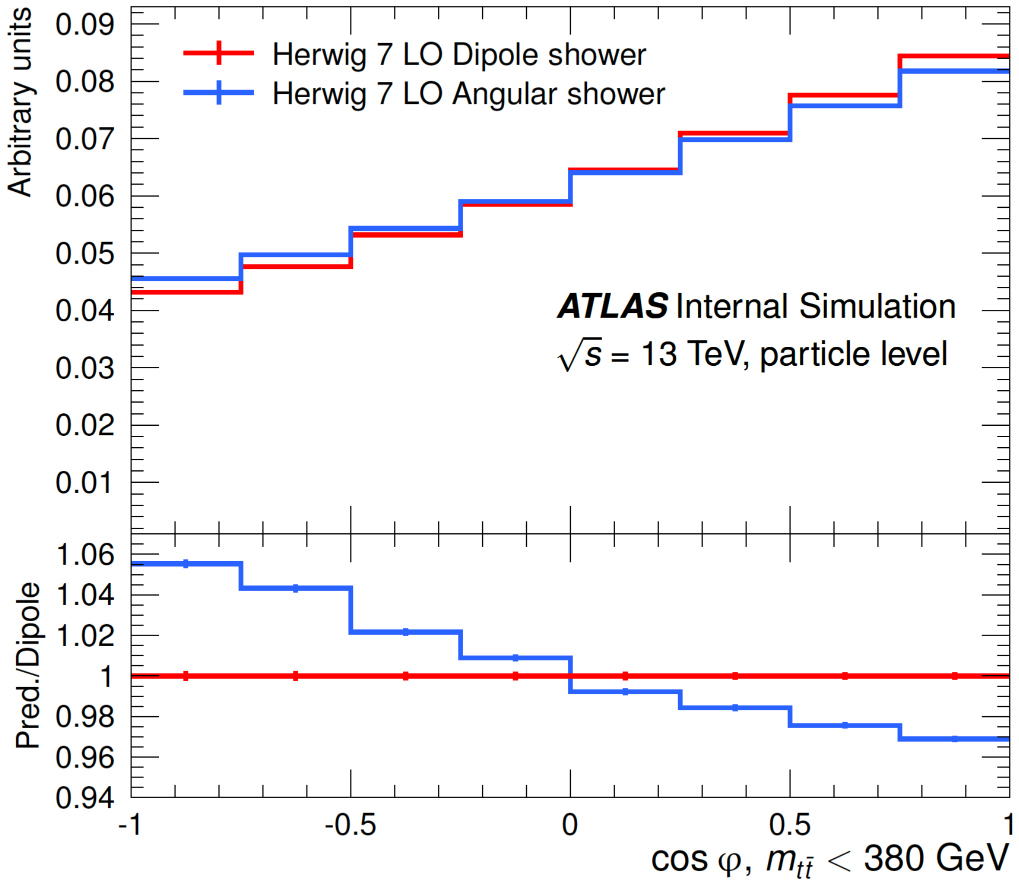
Problems with the shower

A parton shower models QCD radiation from hard partons



Evolves by stepping through some <u>ordering parameter.</u>

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?

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

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

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.