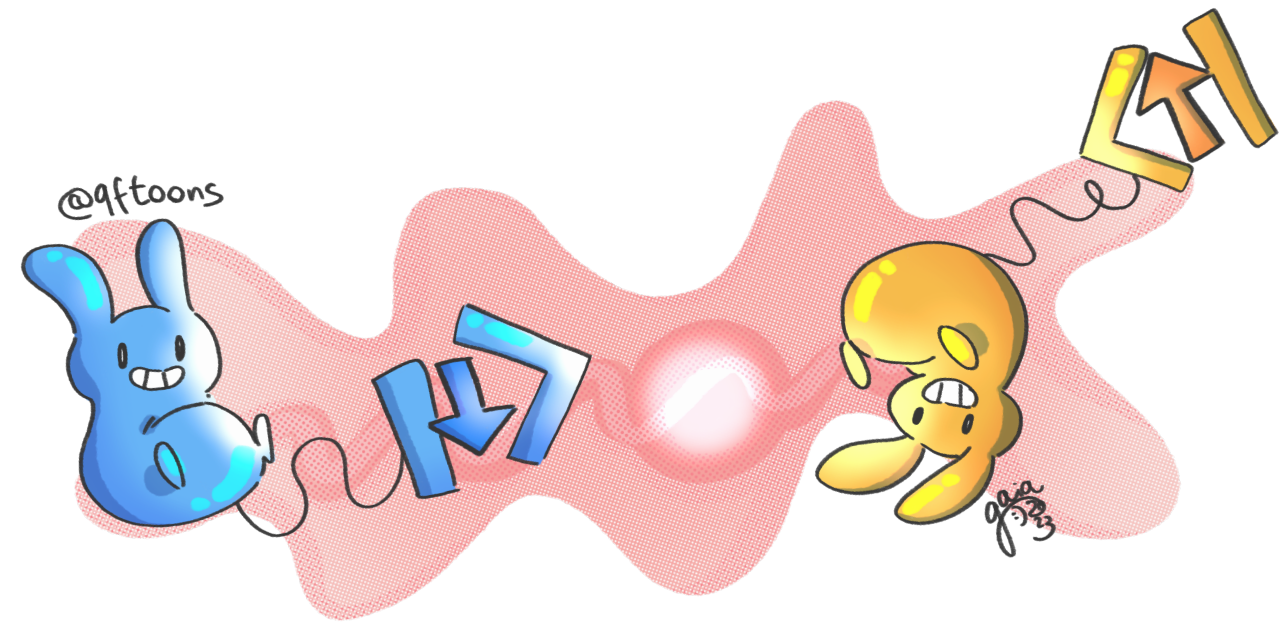


Entangled in Tops

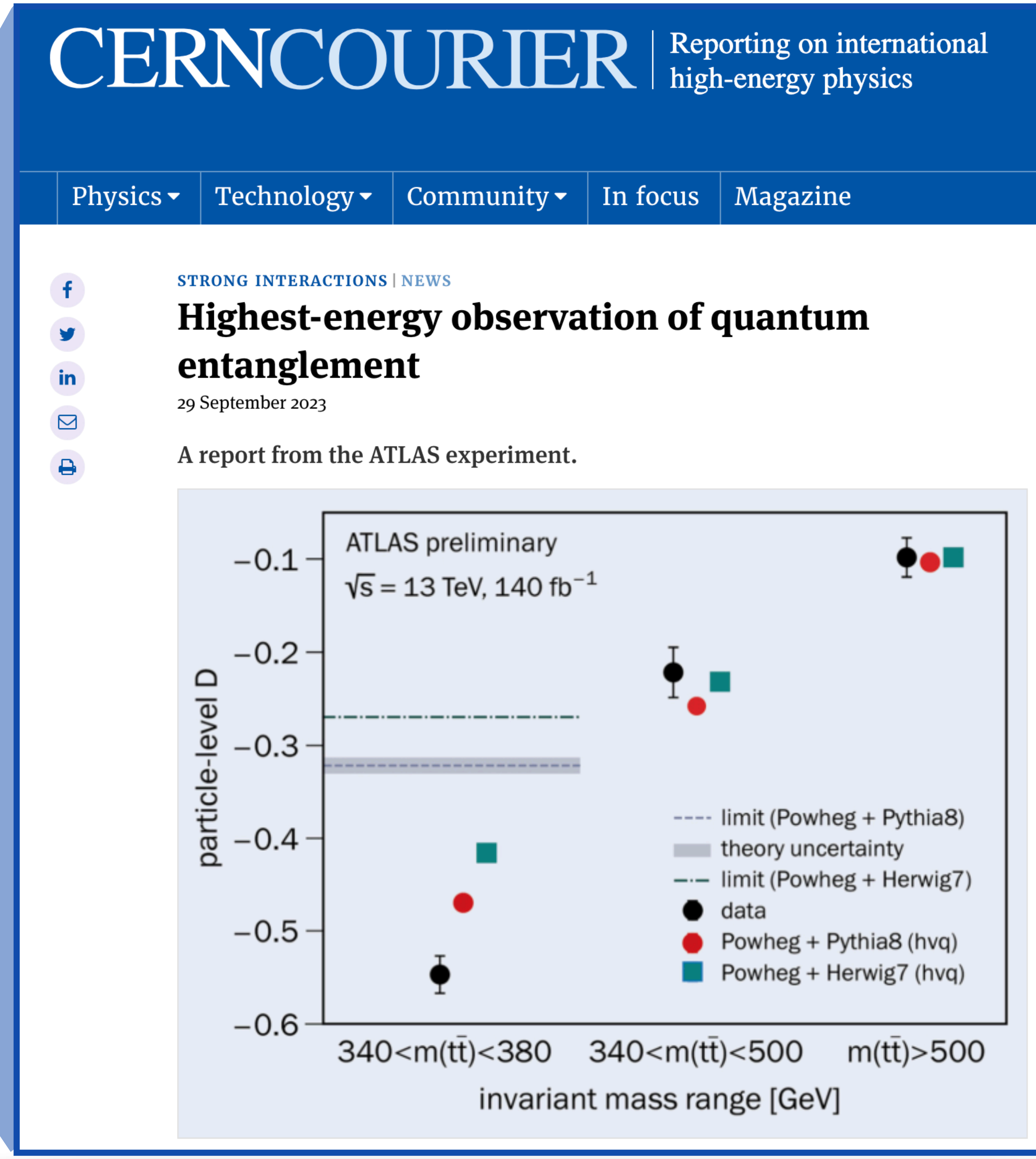
"How we turned ATLAS into the world's largest quantum information experiment"

Nello Bruscino INFN

Seminari INFN - 20/5/2024

ATLAS Result

arXiv:2311.07288 (submitted to Nature)



CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.

The Question

Can we turn LHC into the world's largest quantum information experiment?

Quantum Information (QI)

- pure or mixed quantum systems
- quantum entanglement (QE) and separability
- density operator

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

High Energy Physics (HEP)

- extreme energy scale, plenty of events
- variegated laboratory of QFT
- spin density matrix

$$\rho = \frac{I_4 + \sum_{i=1}^{3}\left(B_i^+\sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j=1}^{3} C_{ij}\sigma^i \otimes \sigma^j}{4}$$

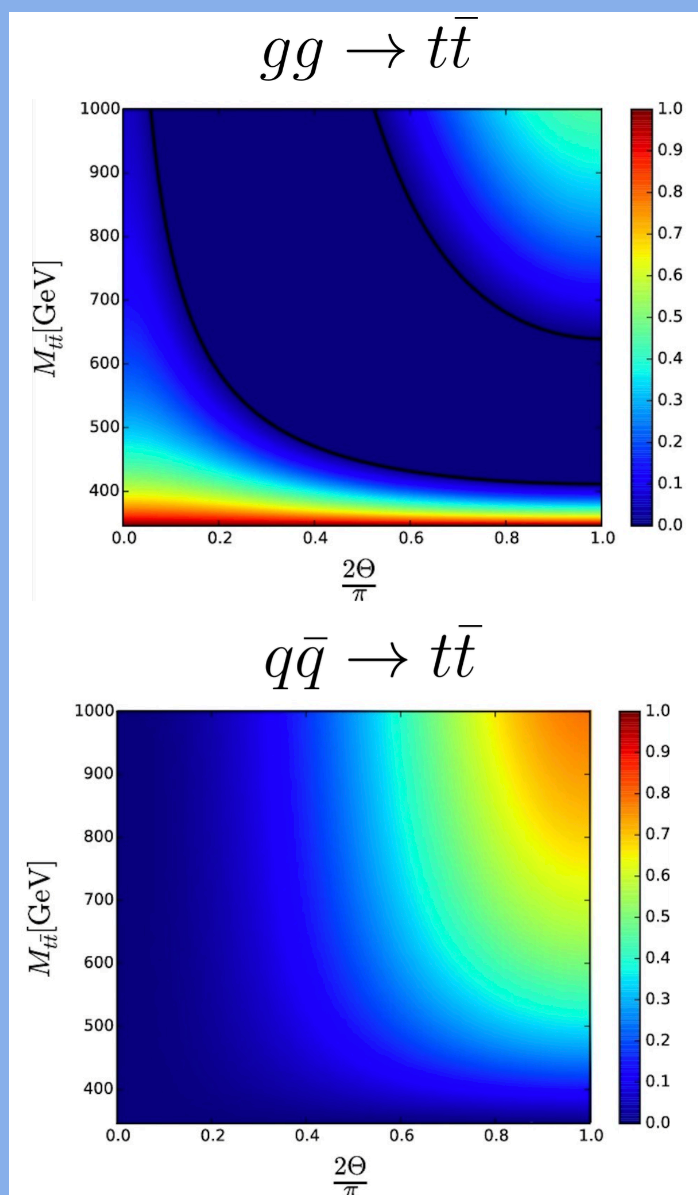
If density matrix "factorises", the state is not entangled

$$\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b$$

The Concepts

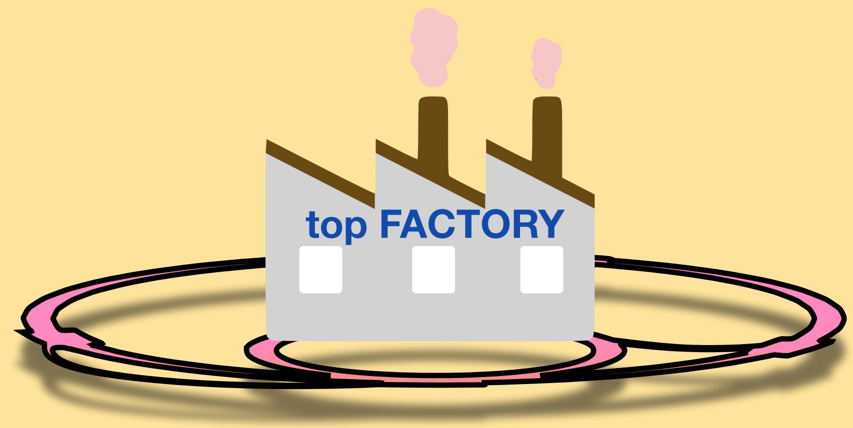
Concurrence

- this tells us where to look for entanglement! [Afik and de Nova, EPJP]



Why LHC?

- copious production at the LHC
- ≈750 $t\bar{t}$ pairs/minute (120M @140/fb)



Why top quarks?

-only "bare" quark

Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	<	$\frac{1}{\Gamma_t}$	<	$\frac{1}{\Lambda_{QCD}}$	<	$\frac{m_t}{\Lambda^2_{QCD}}$
~10^{-27} s		~10^{-25} s		~10^{-24} s		~10^{-21} s

QE Marker

QI: Peres-Horodecki criterion for two states to be entangled

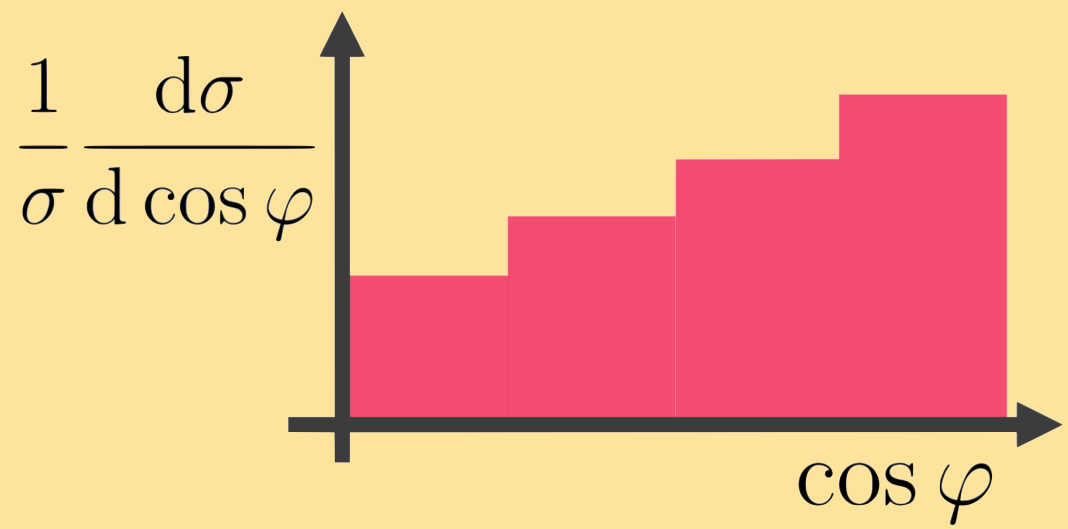
$$D = \frac{\mathrm{Tr}\,\mathbf{C}}{3} < -\frac{1}{3}$$

- C being the spin correlation matrix

HEP: entanglement marker

$$D = -3 < \cos\phi >$$

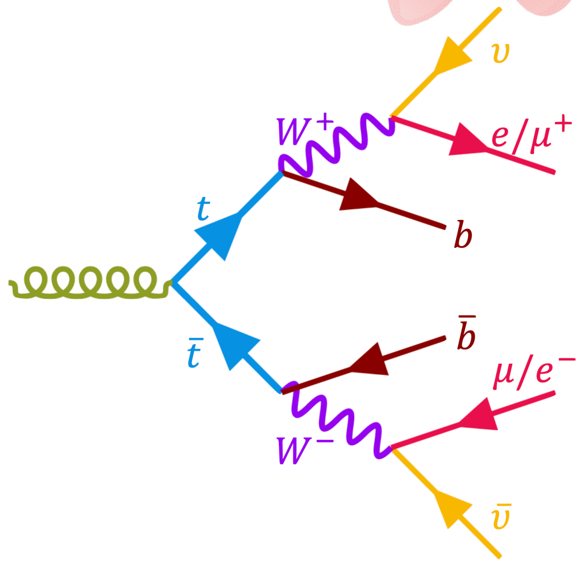
- $\cos\phi$ being the scalar product of lepton directions in their parent tops' frame

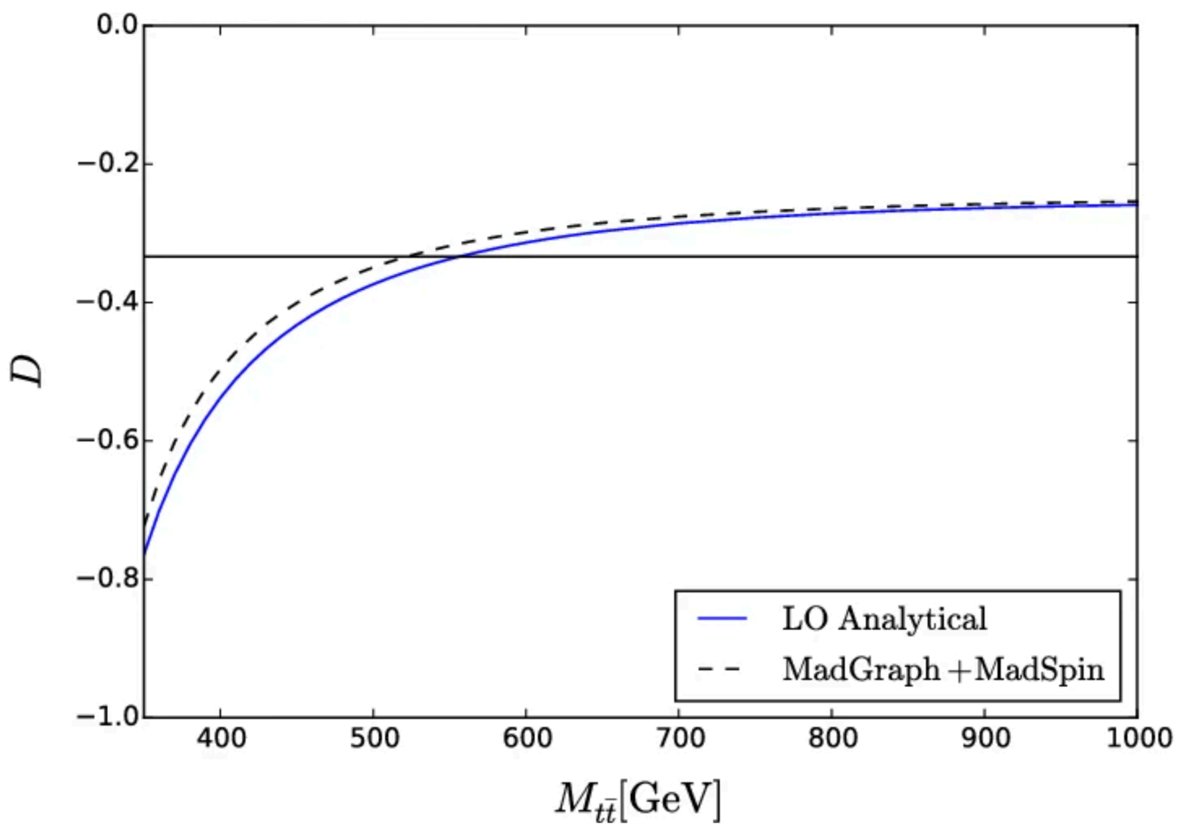


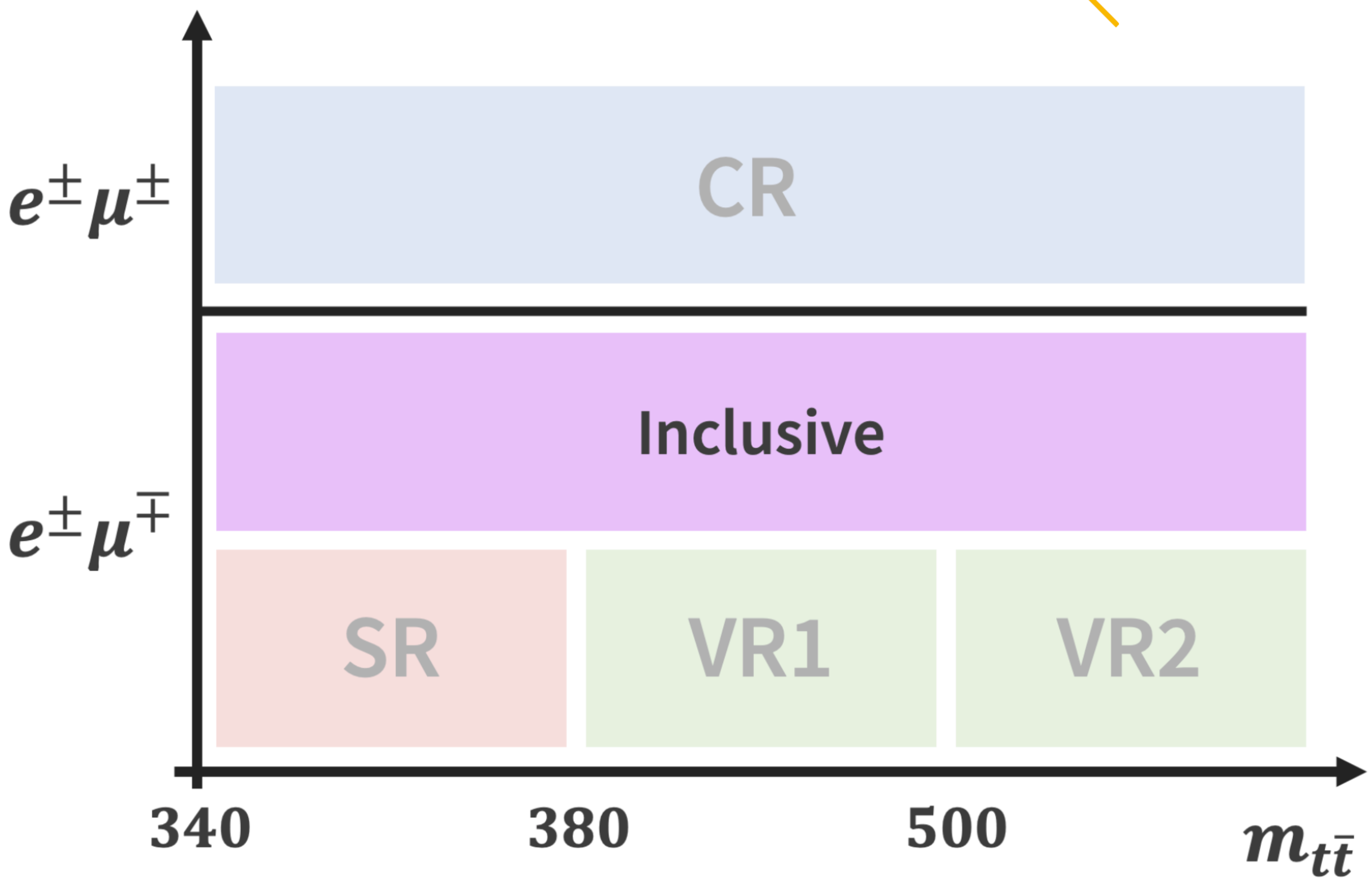
Analysis Strategy

Isolating signal maximally-sensitive to entanglement

- 1 electron and 1 muon
- 2 jets, of which at least 1 b-tagged jet (with “loose” 85% working point)







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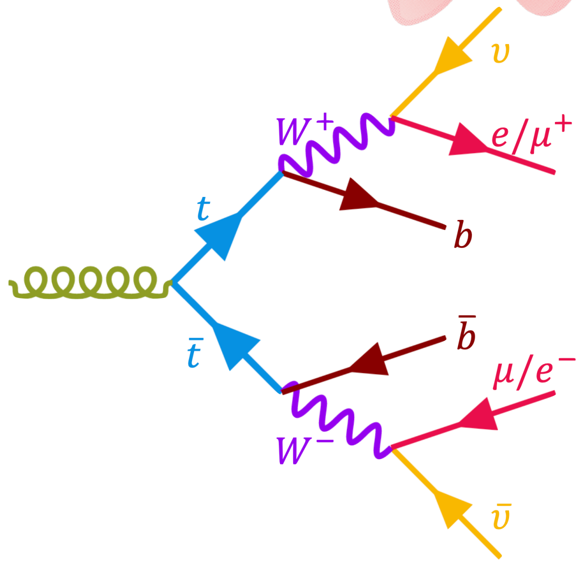

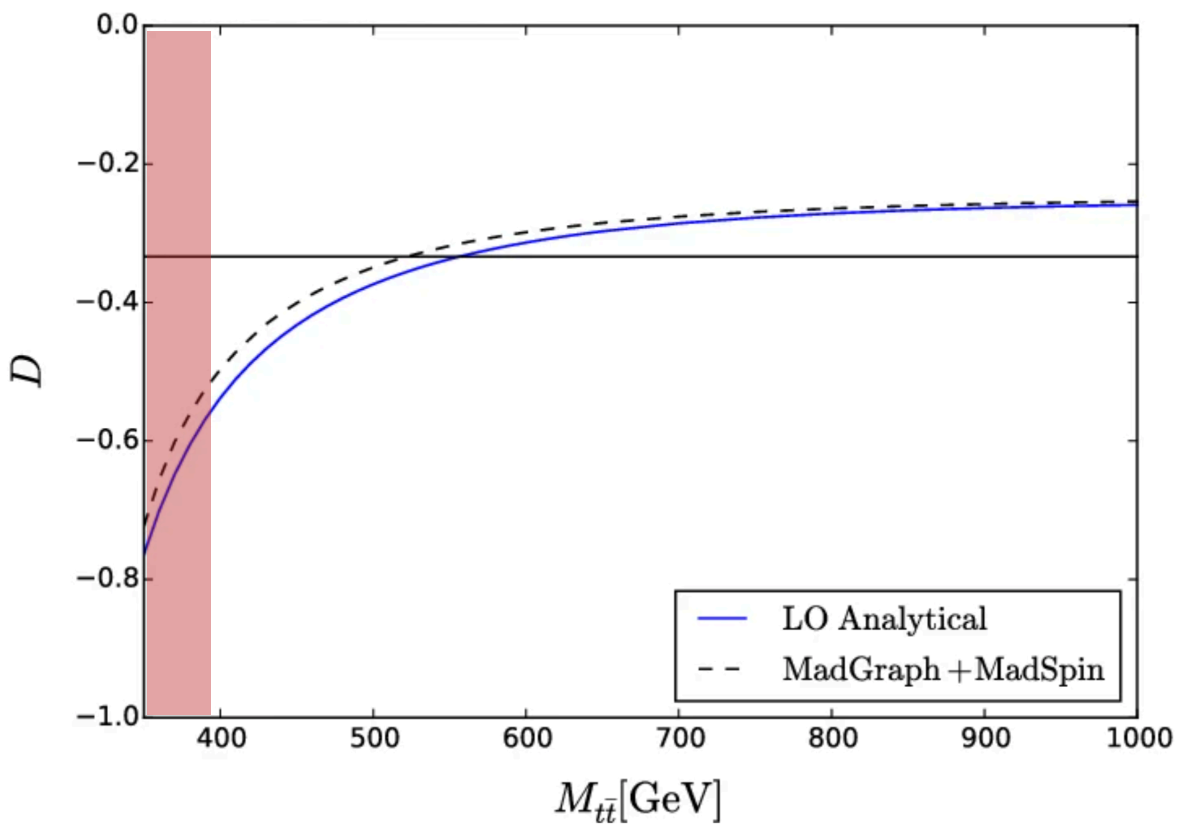

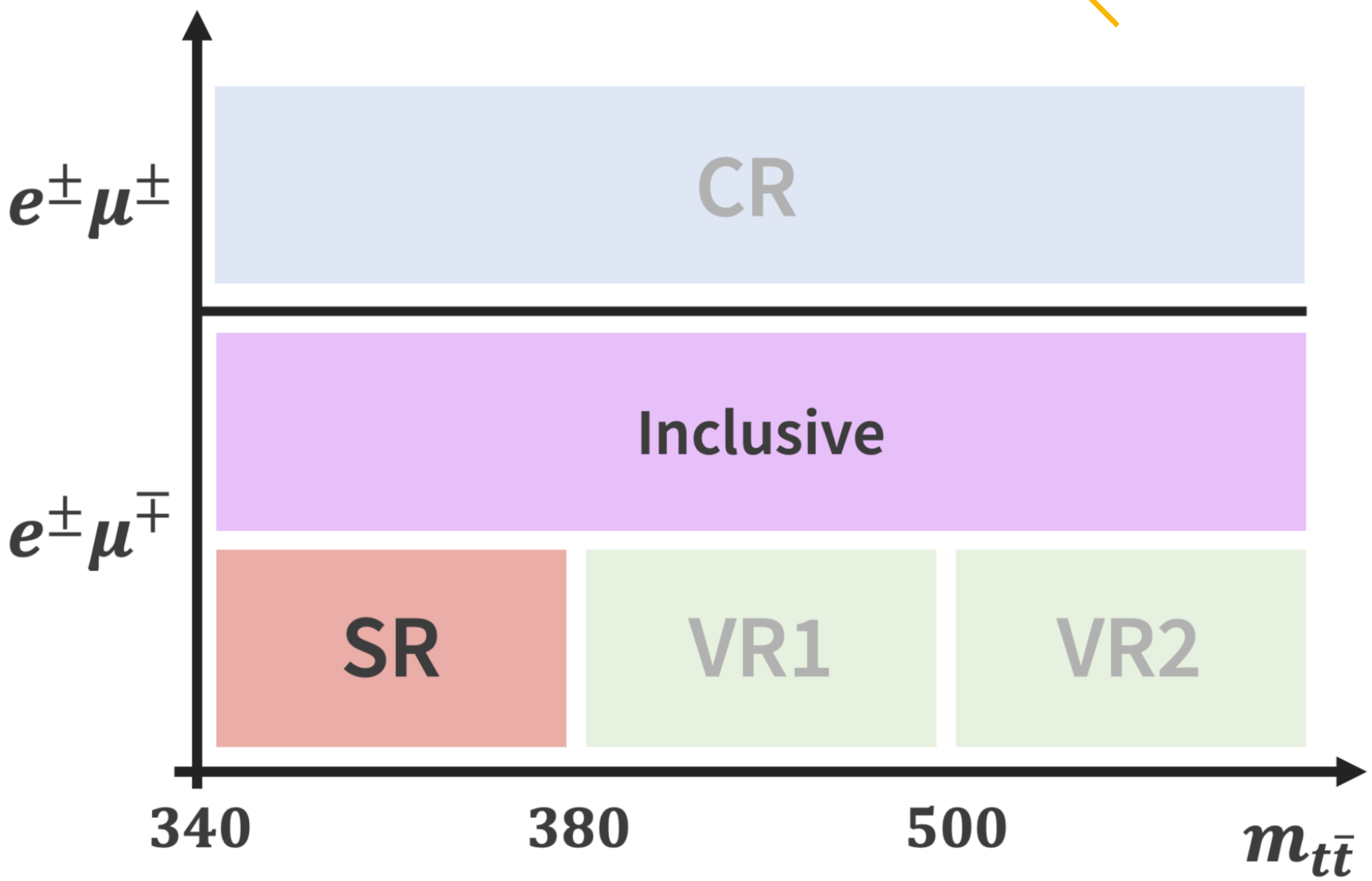

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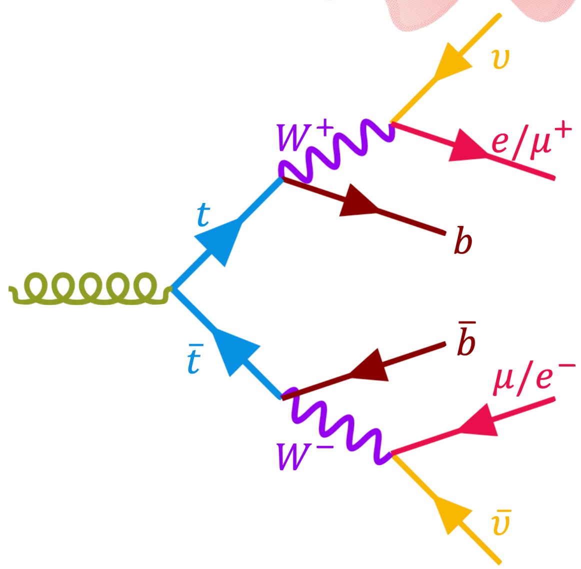

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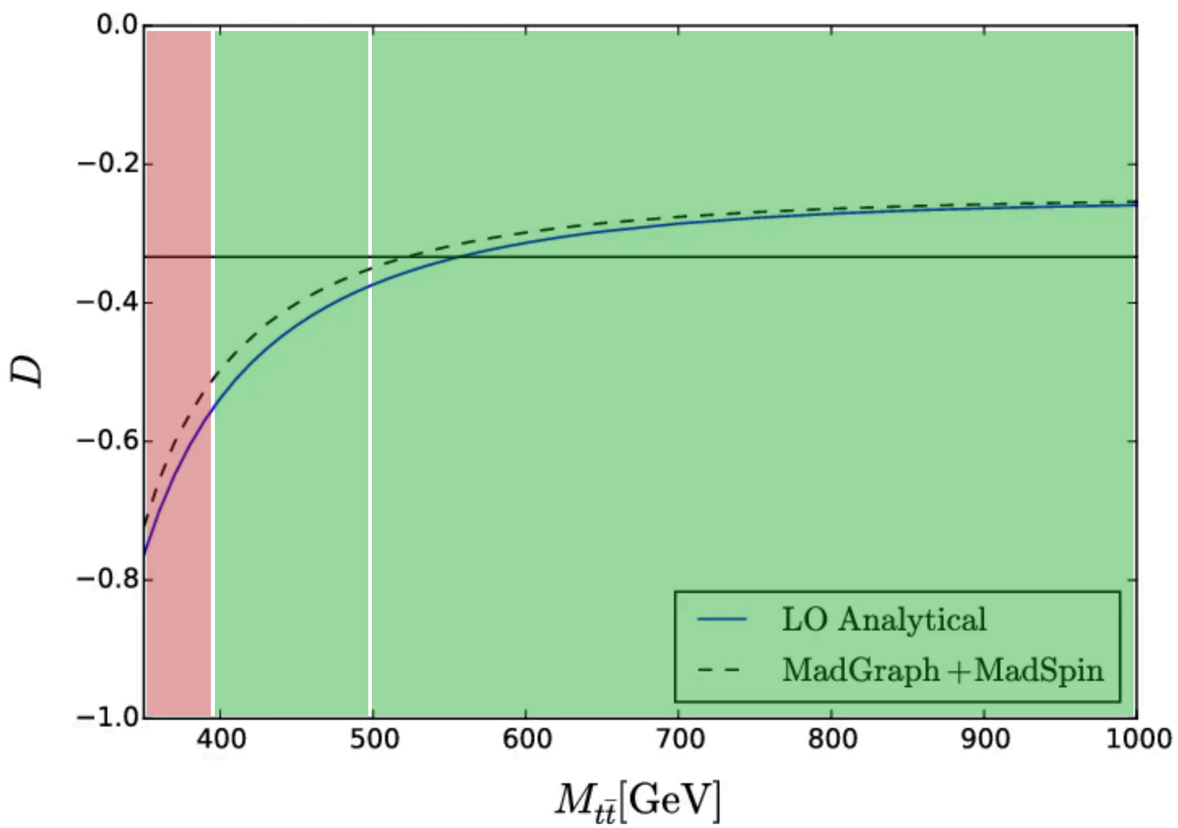

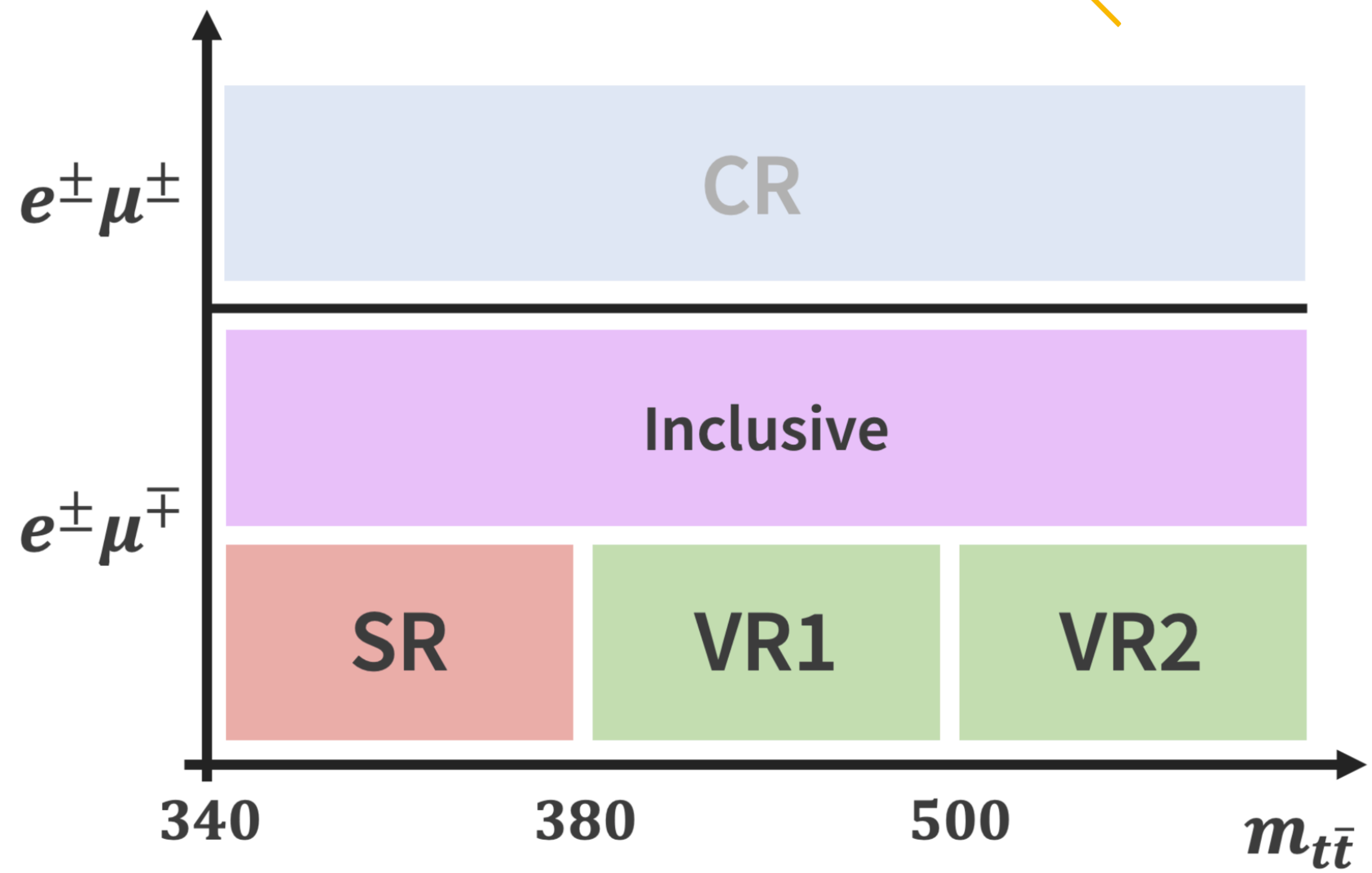

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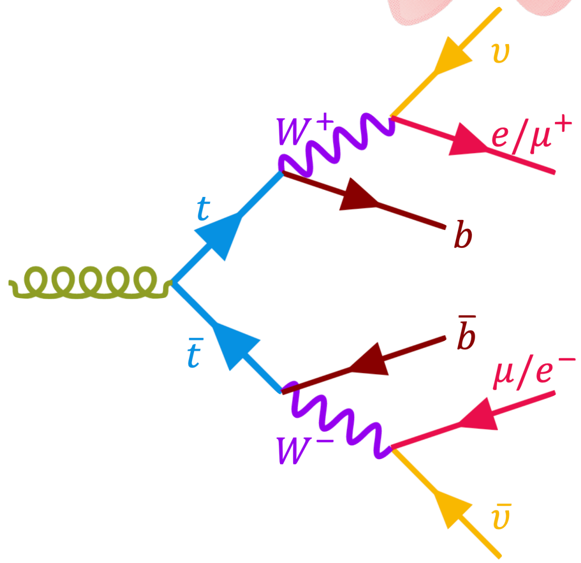
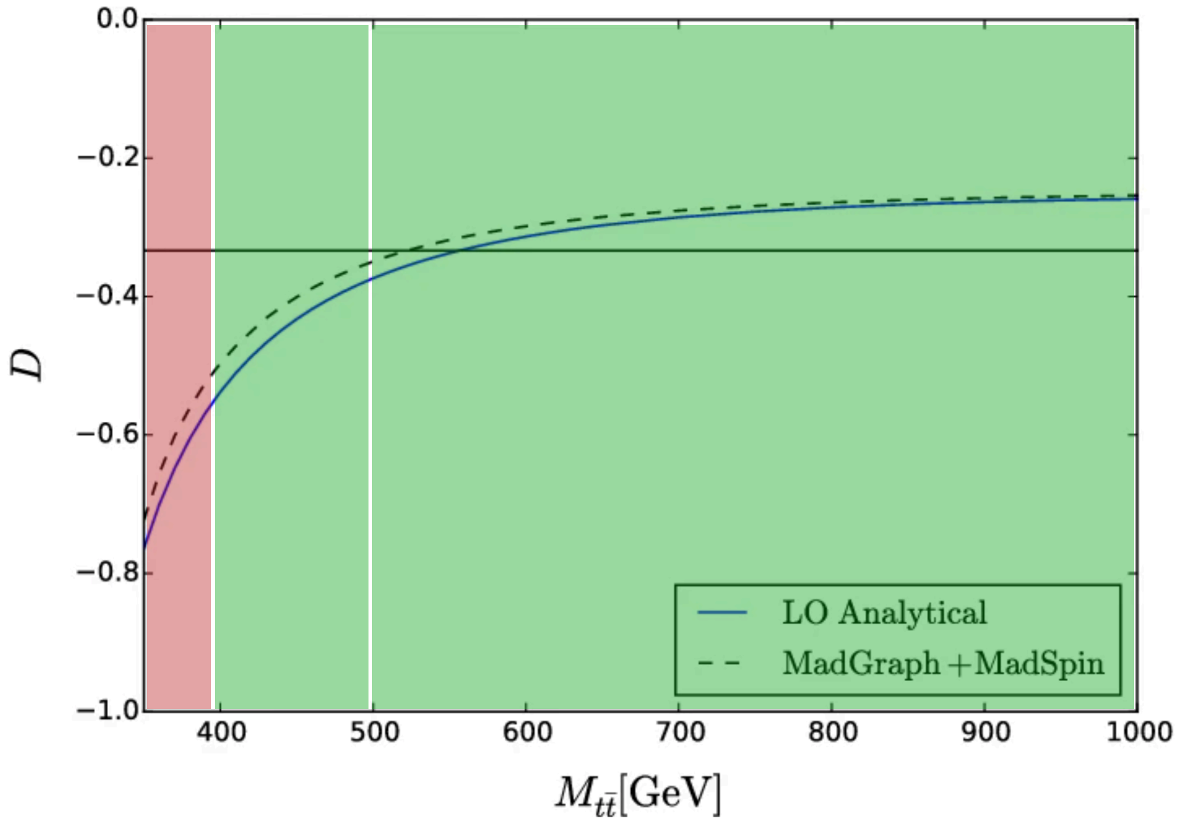
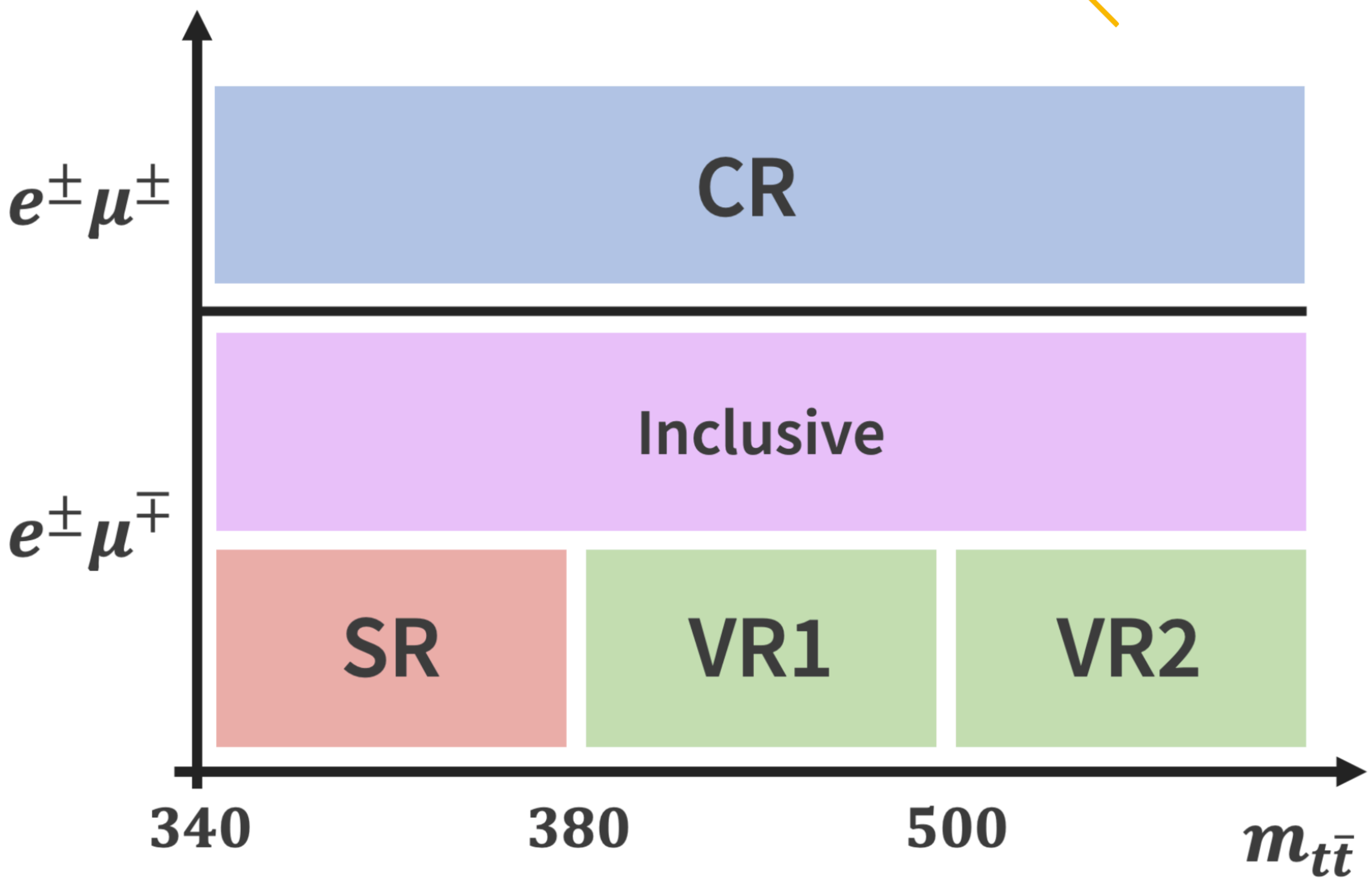
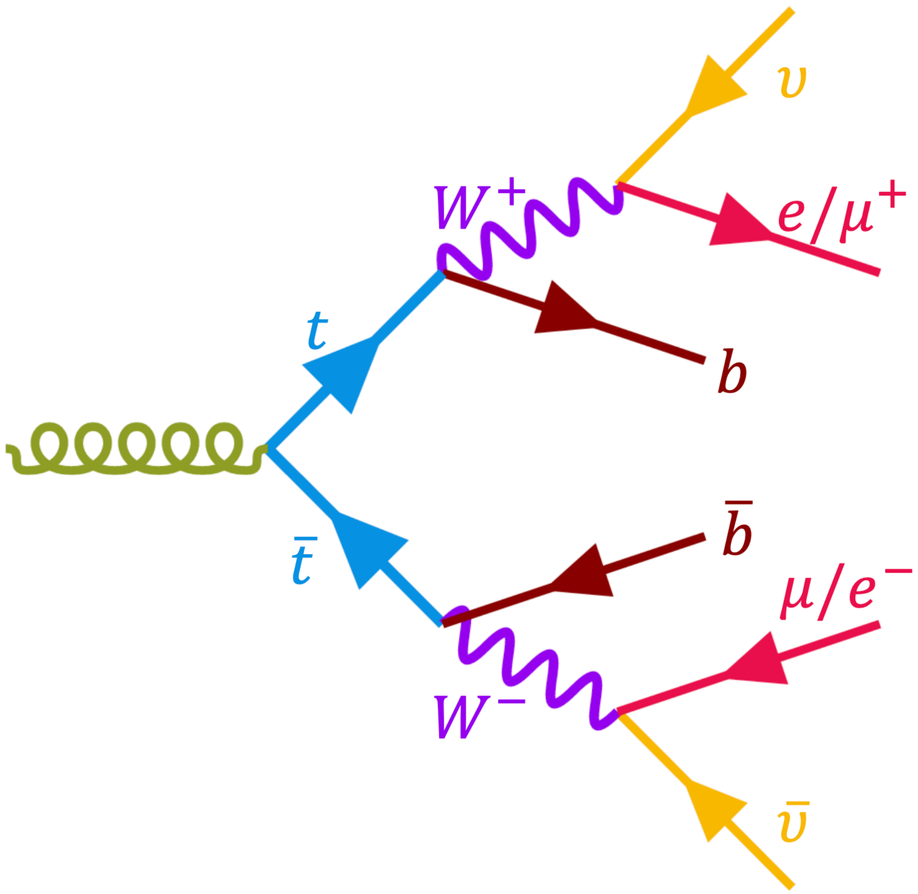




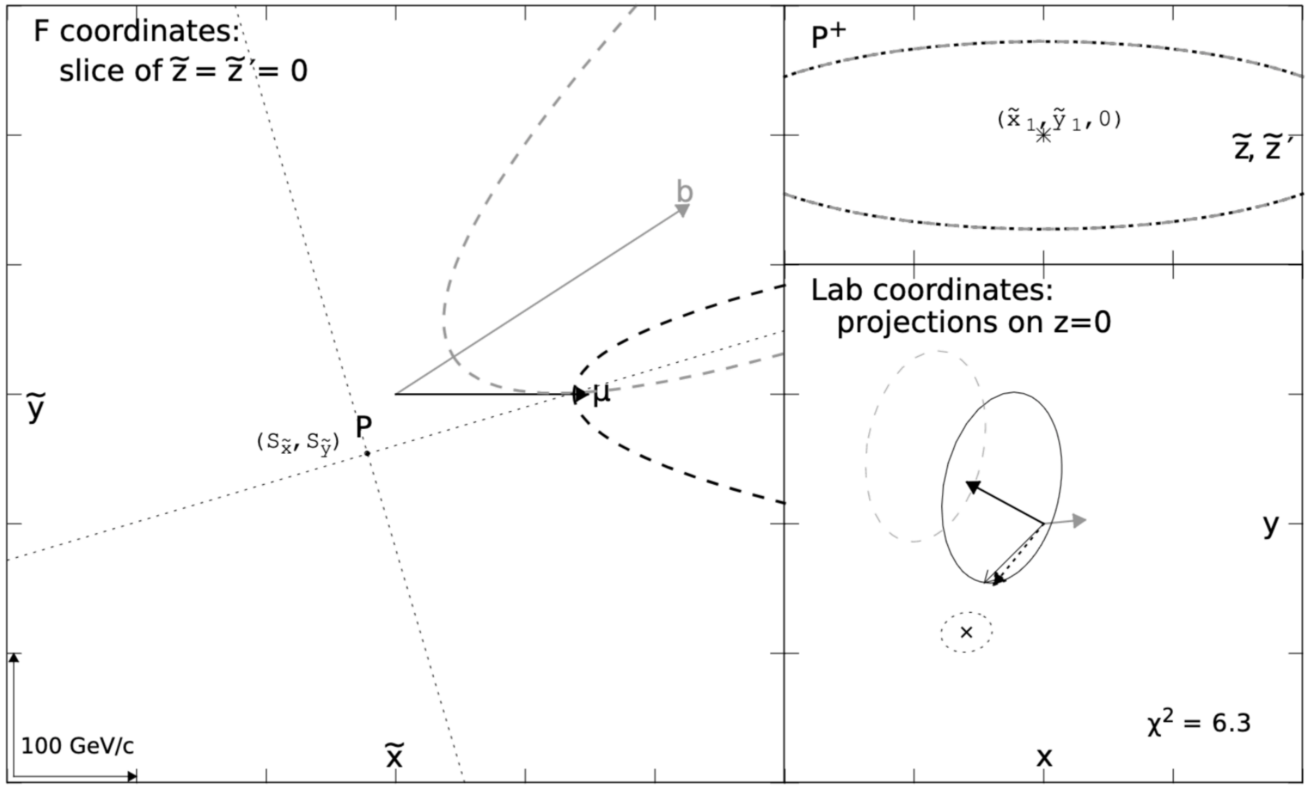


Di-leptonic Reconstruction



Primary reconstruction: Ellipse Method

- when Ellipse fails, alternative techniques:
  + NeutrinoWeighter
  + Simple kinematic matching



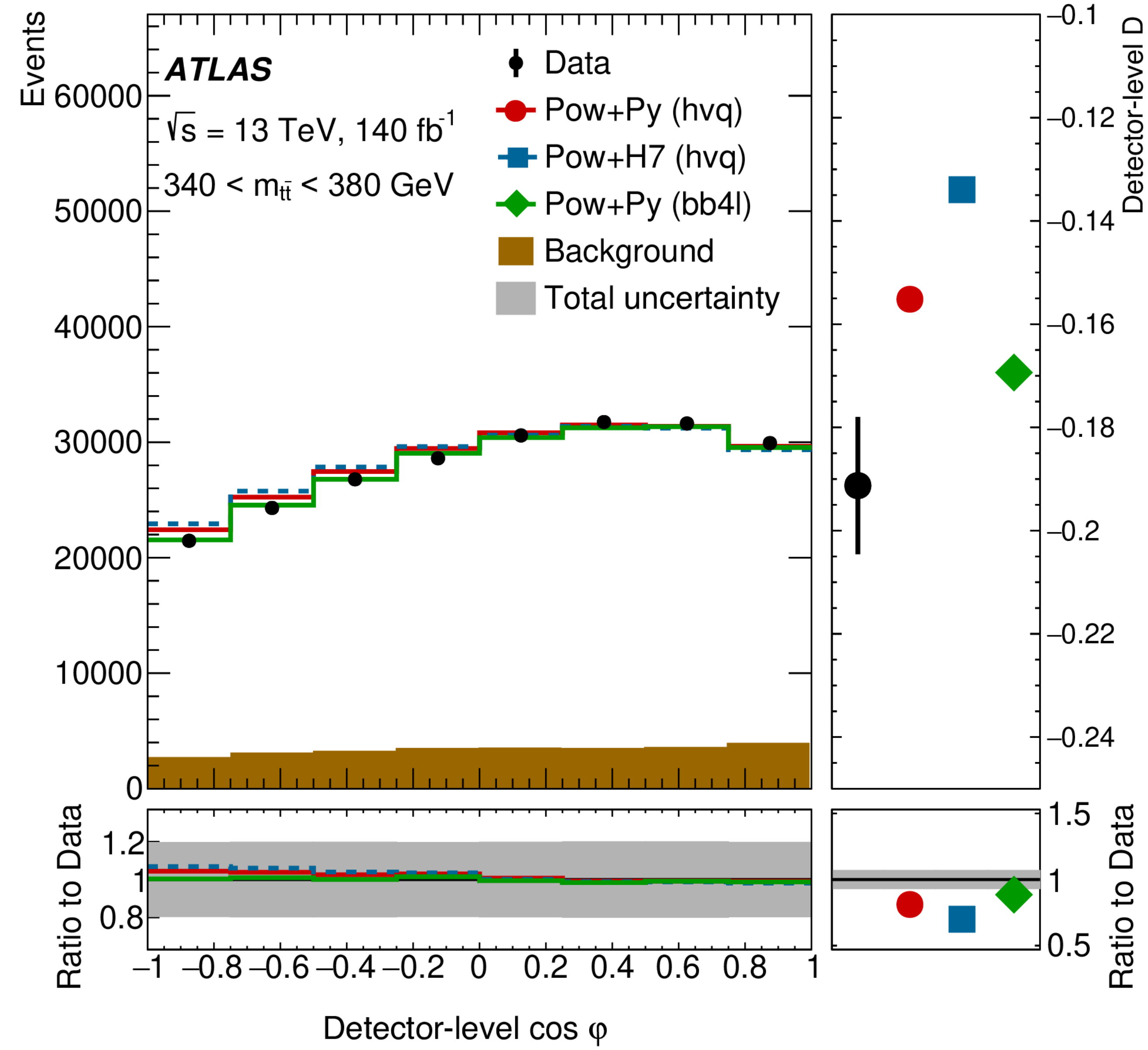
Signal and Backgrounds

Signal

- modelled using MC simulation
- various generators and showering algorithms considered:
  - + Powheg (hvq) + Pythia8
  - + Powheg (hvq) + Herwig7
  - + Powheg (bb4l) + Pythia8

Background

- estimated using simulation
- “fake” lepton prediction modified using a data-driven scale factor



Signal and Backgrounds

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- modelled us
- various gen
  algorithms (
    + **Powheg**
    + **Powheg**
    + **Powheg**

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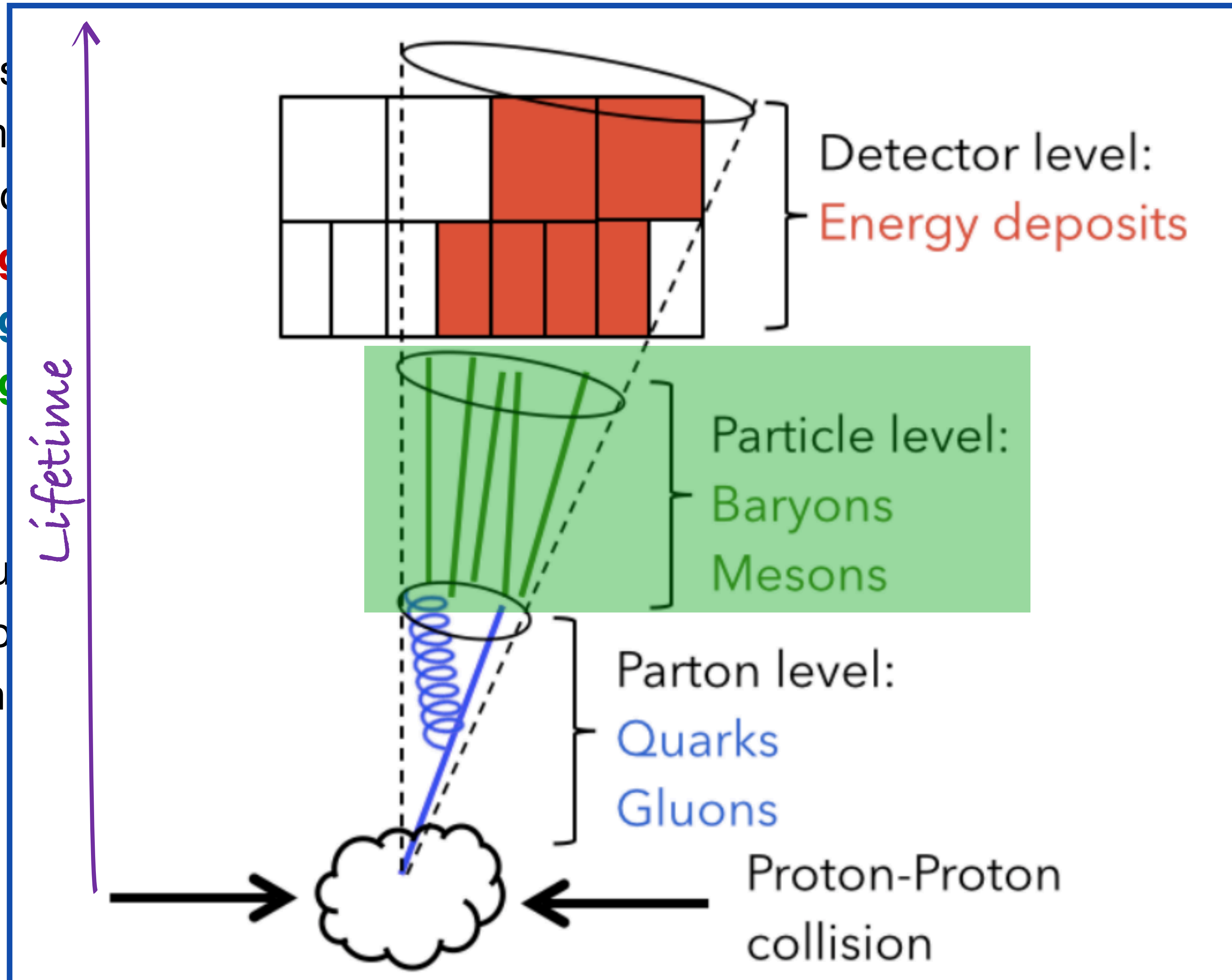
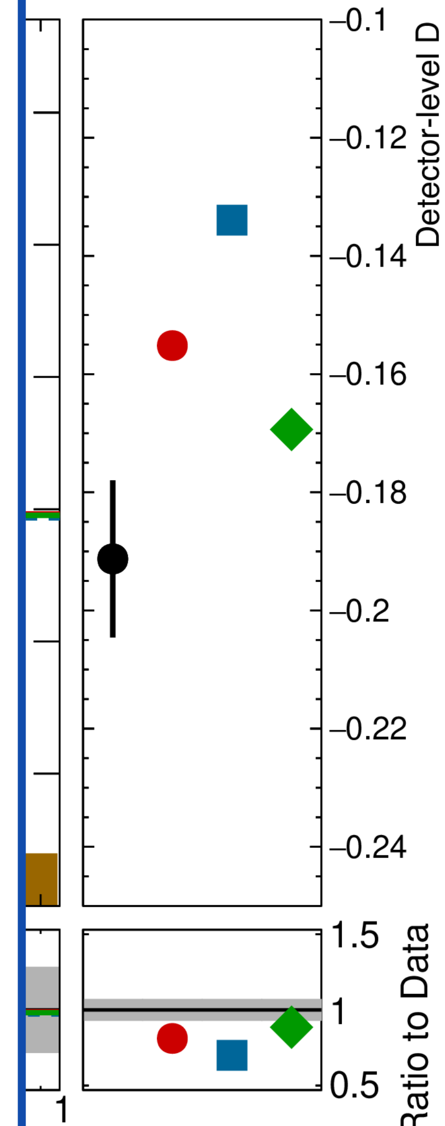
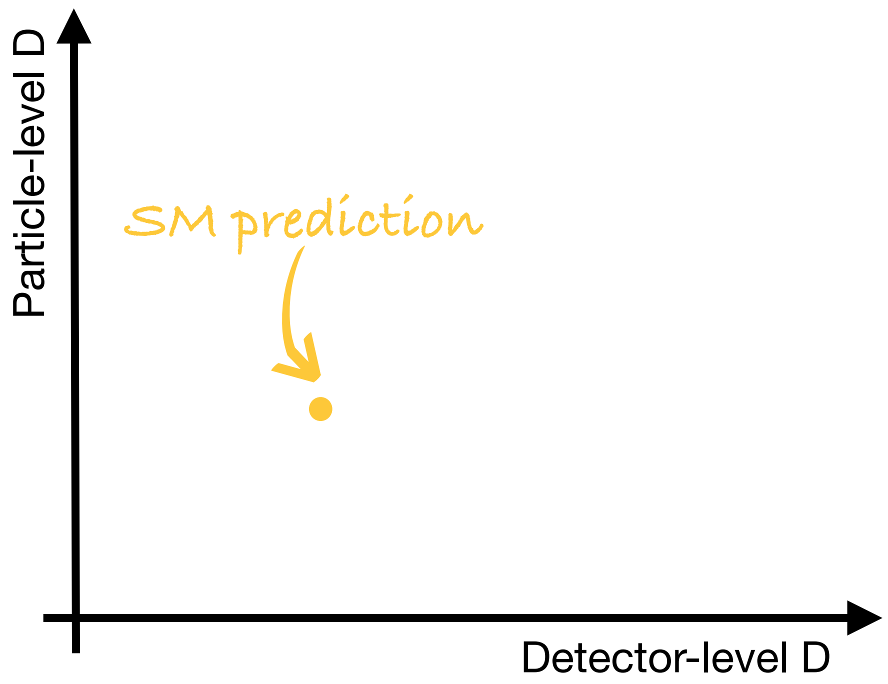


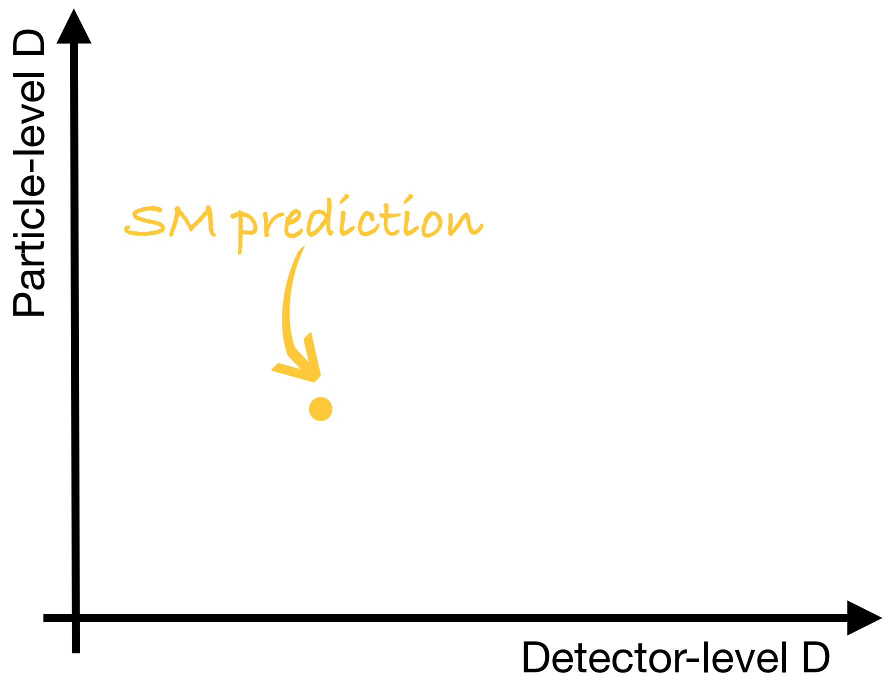


Calibration Curve



Calibration Curve

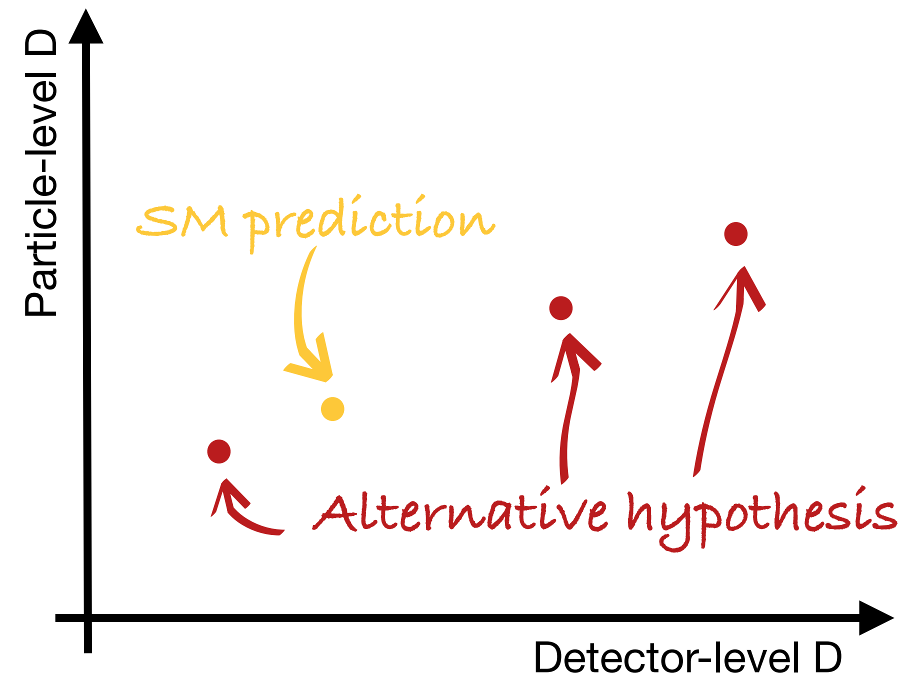
Parameterise variation in the detector effects on D



Calibration Curve

Parameterise variation in the detector effects on D

- different hypotheses of truth- and reco-D derived from simulation



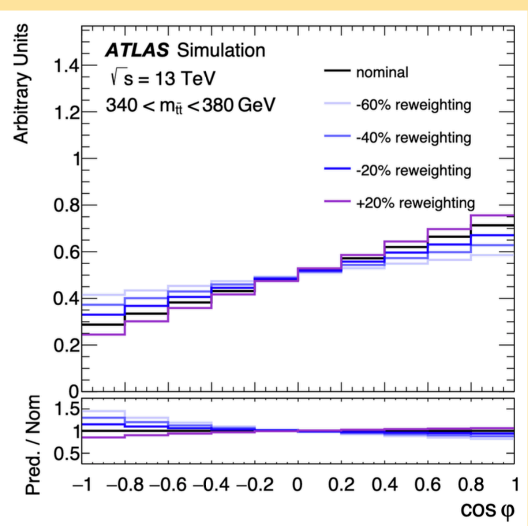
How to generate alternative hypotheses?

- apply a per-event re-weighting of the simulation

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

Choose such that distribution remains linear

scaling parameter



Calibration Curve

Parameterise variation in the detector effects on D

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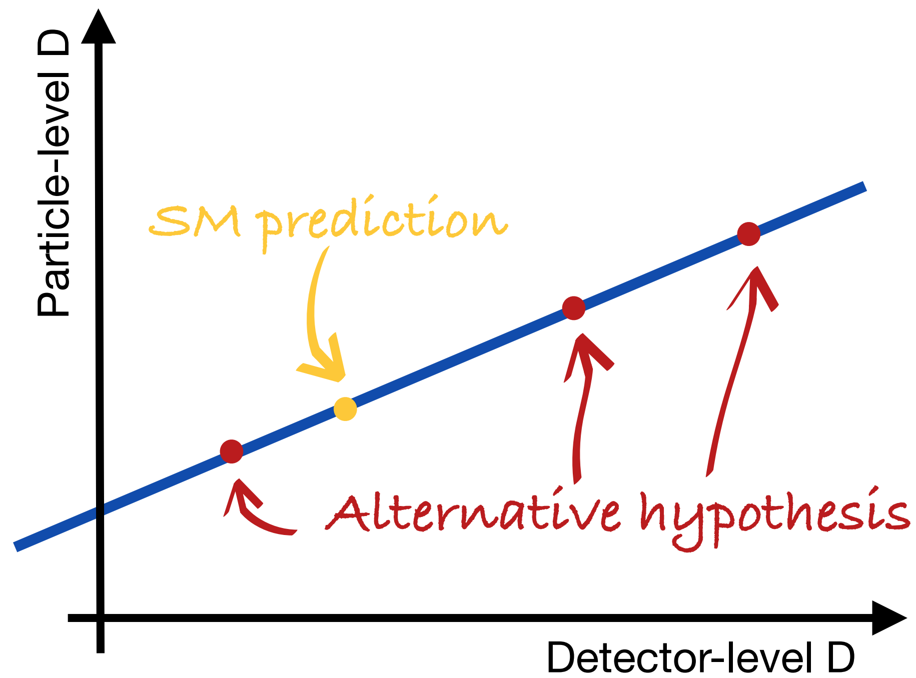
- Interpolate to give variation



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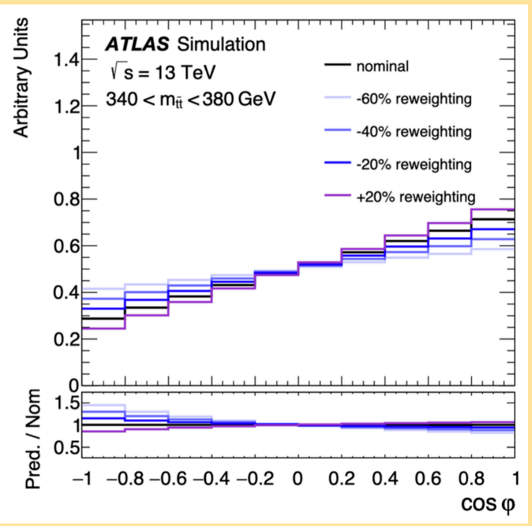

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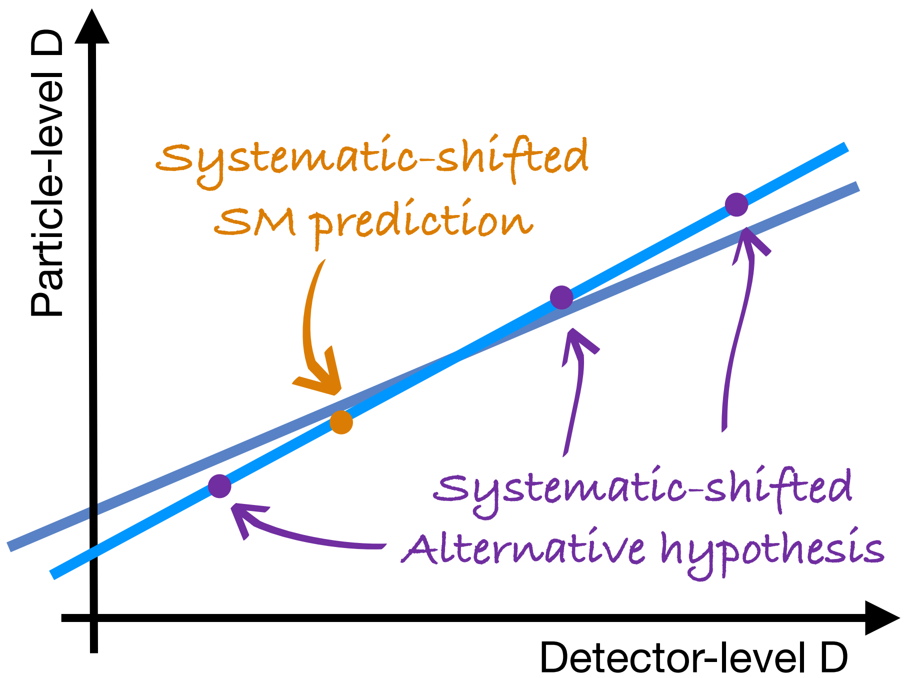
- Systematics build different calibration curves



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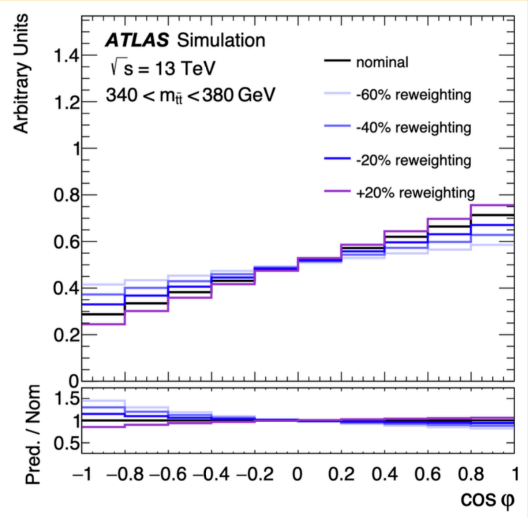

Calibration Curve

Parameterise variation in the detector effects on D

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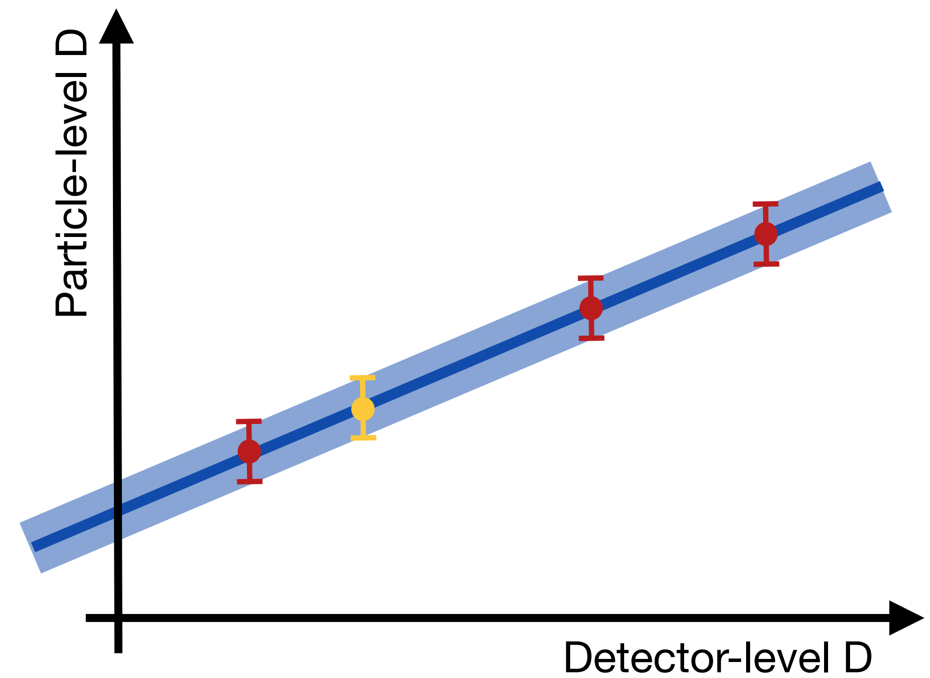
- Systematics build different calibration curves
- Combine all systematics to build nominal curve + uncertainty band
- Map a measured D to truth-level, with associated uncertainties



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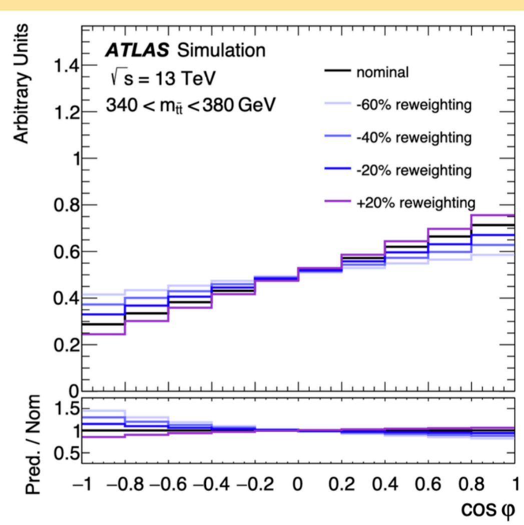

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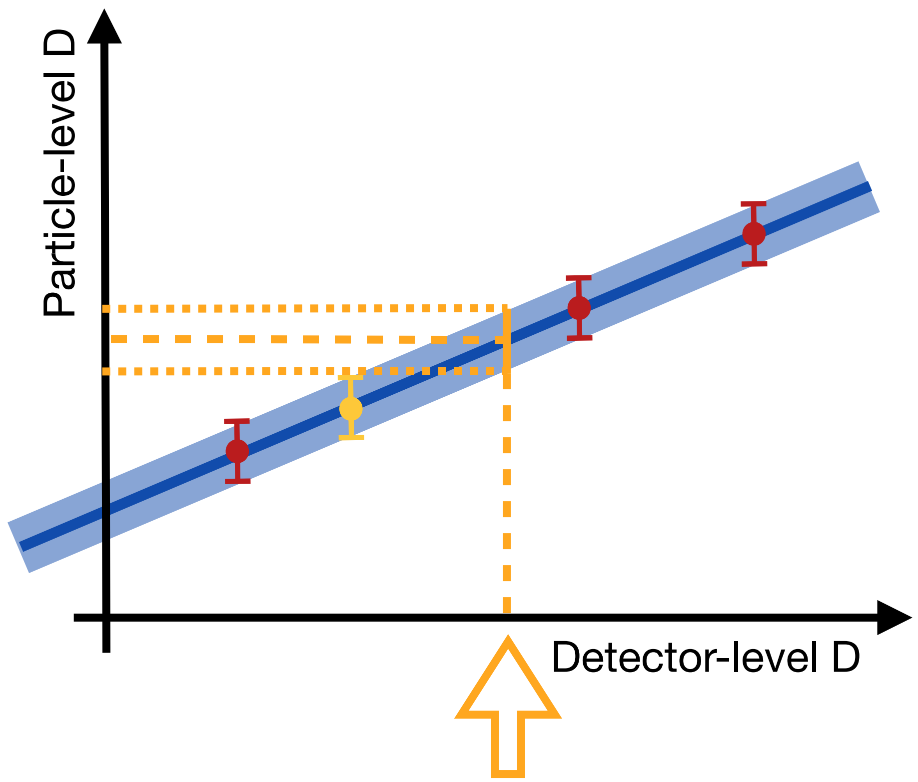

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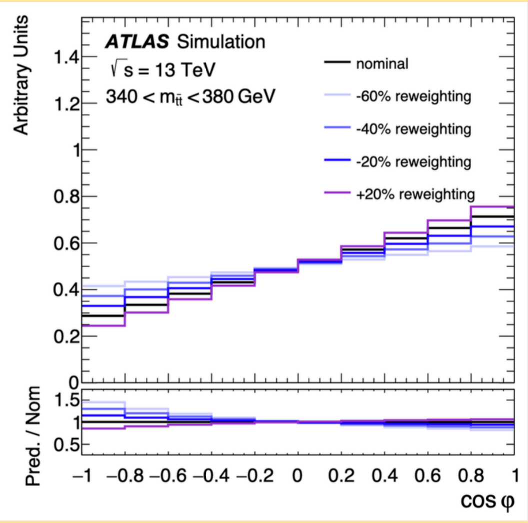
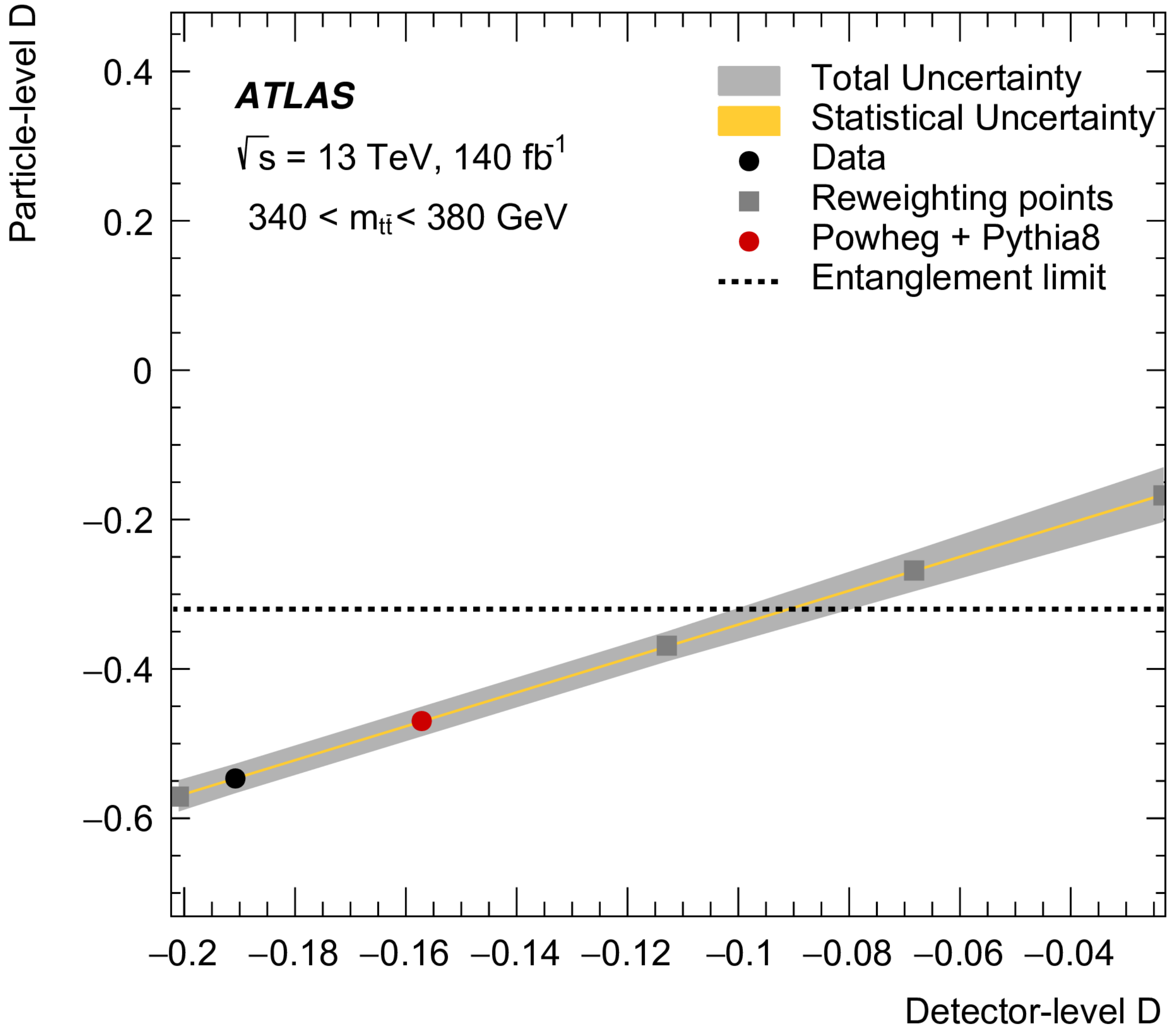


Calibration Curve

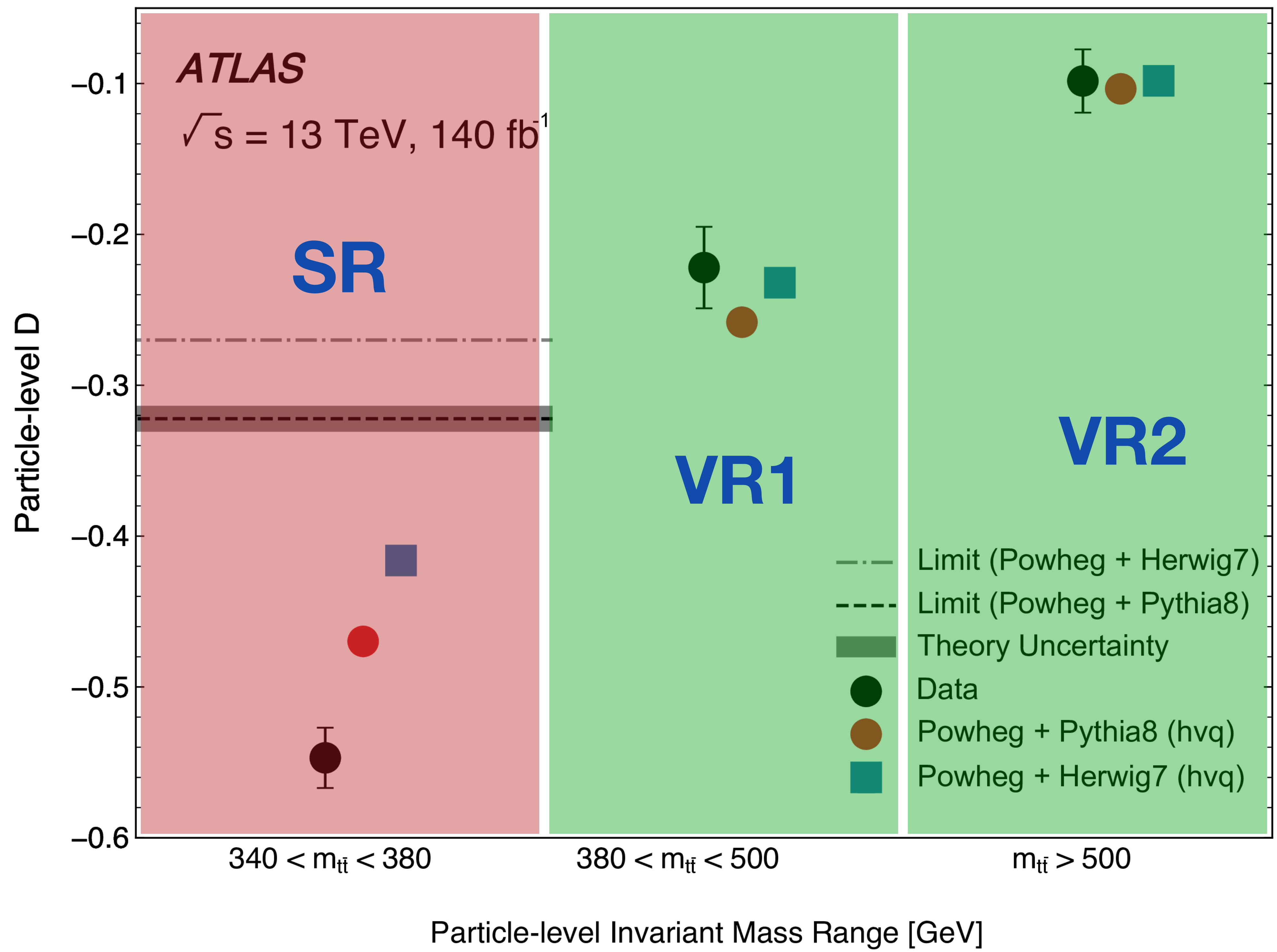
Correction to D in the signal region

- the entanglement limit (-1/3 at particle level) is roughly -0.09 at detector level

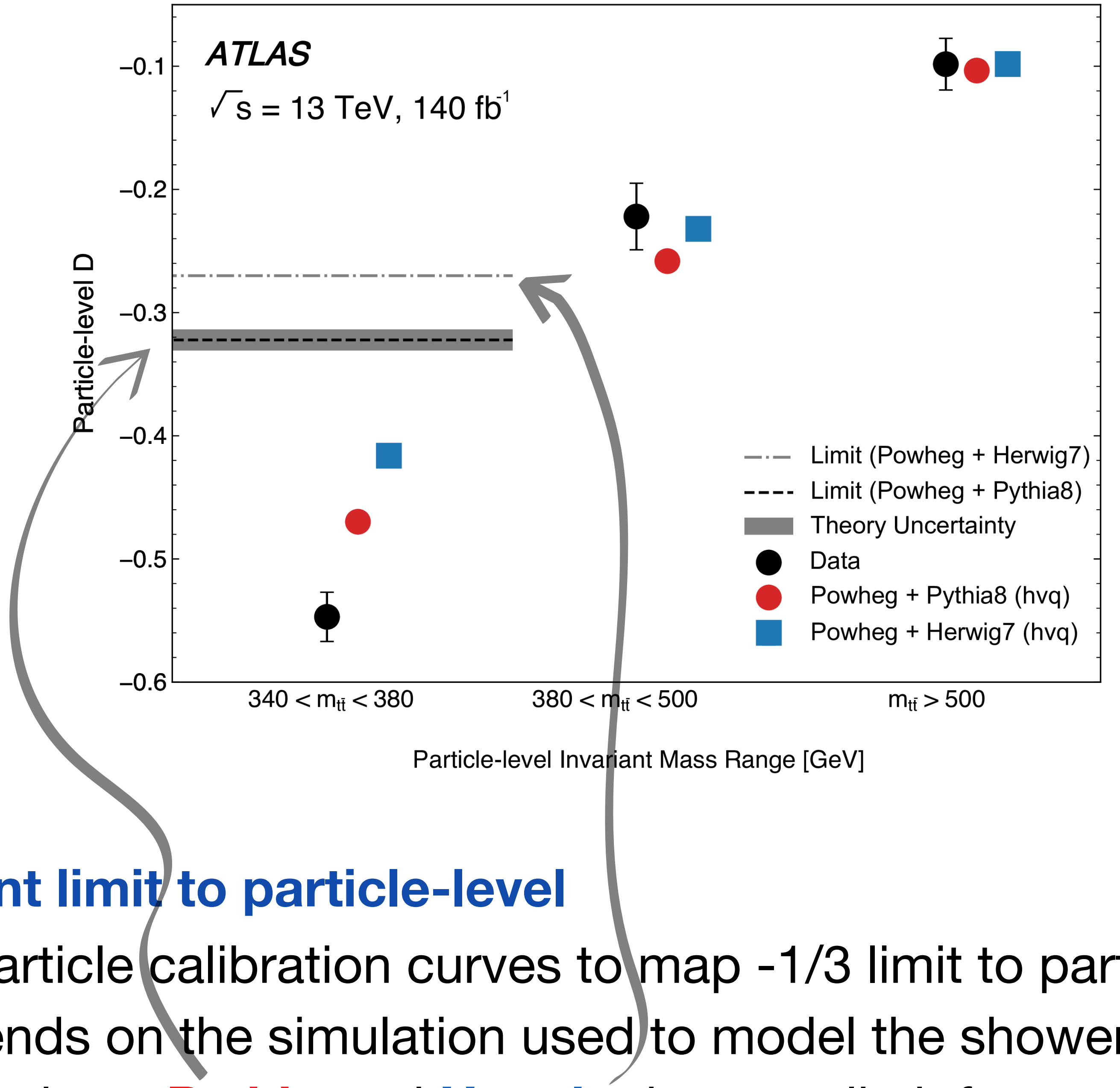


Result: QE Observation

The quantum entanglement measurement at particle-level



Particle-Level Entanglement Limits



Map the entanglement limit to particle-level

- We use parton → particle calibration curves to map -1/3 limit to particle-level
- This naturally depends on the simulation used to model the shower
- We have two predictions: **Pythia** and **Herwig**, hence a limit for each

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

Systematic Uncertainties

Signal modelling biggest limitation

Source of uncertainty	$\Delta D_{\text{observed}} (D = -0.547)$	ΔD [%]
Signal modeling	0.017	3.2
Electrons	0.002	0.4
Muons	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pile-up	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3
Backgrounds	0.010	1.8
Total statistical uncertainty	0.002	0.3
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Some background addition due to loose b-tagging WP

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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%

Some background addition due to loose b-tagging WP

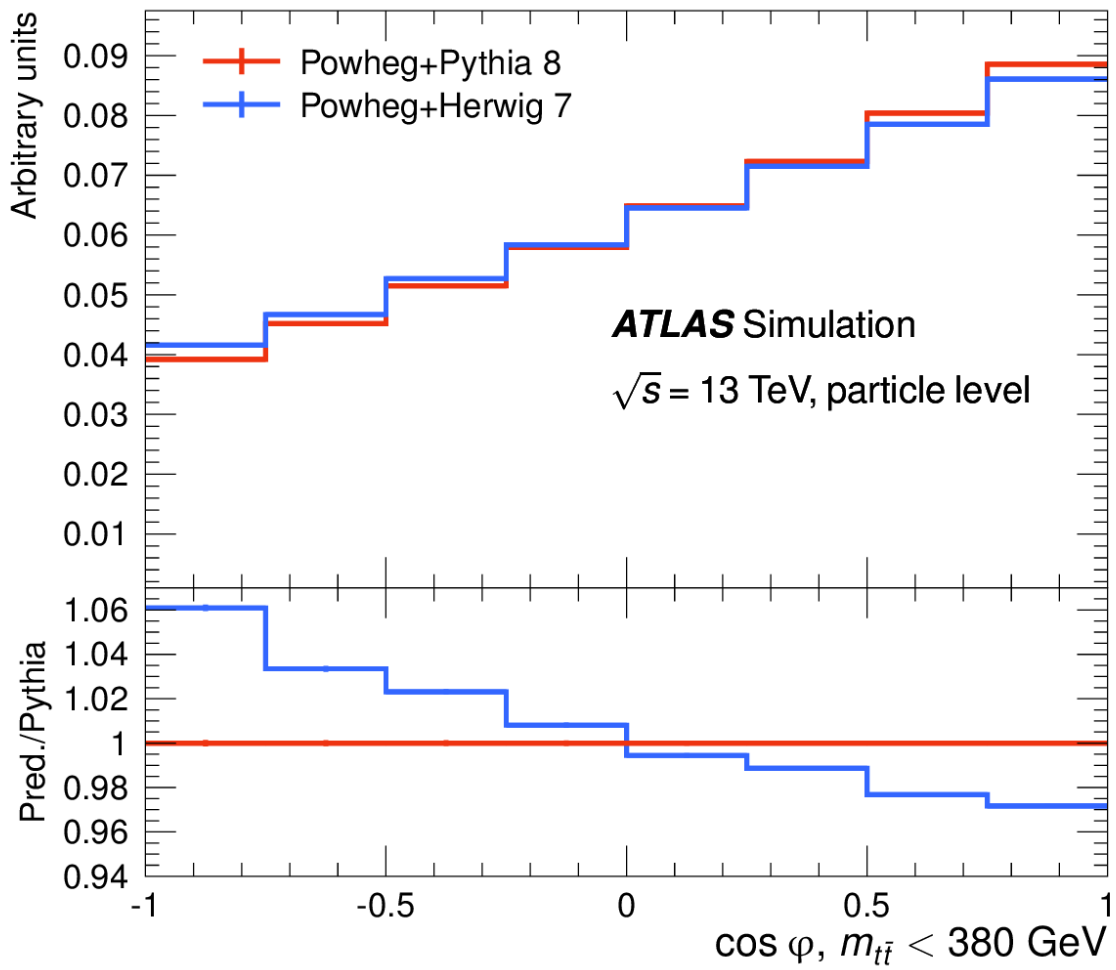
Showering uncertainty small because of correction to particle-level

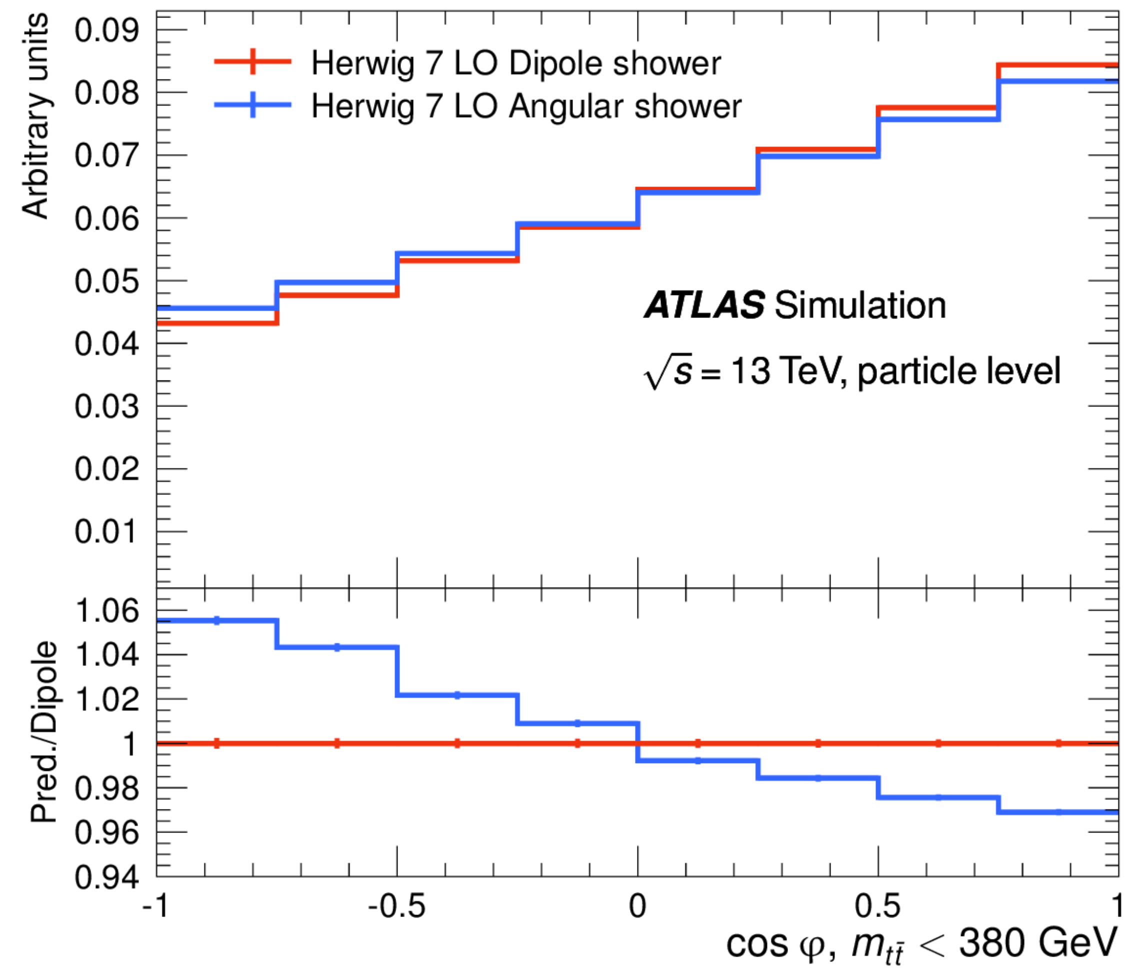
Difference between Pythia and MadSpin in handling top- quark decays

Q: Why Particle-Level?

A: Dipole- vs angular-ordered shower

- Ordering-parameter is seen to give large differences in particle-level distribution
- Correction to parton-level would induce extreme uncertainty

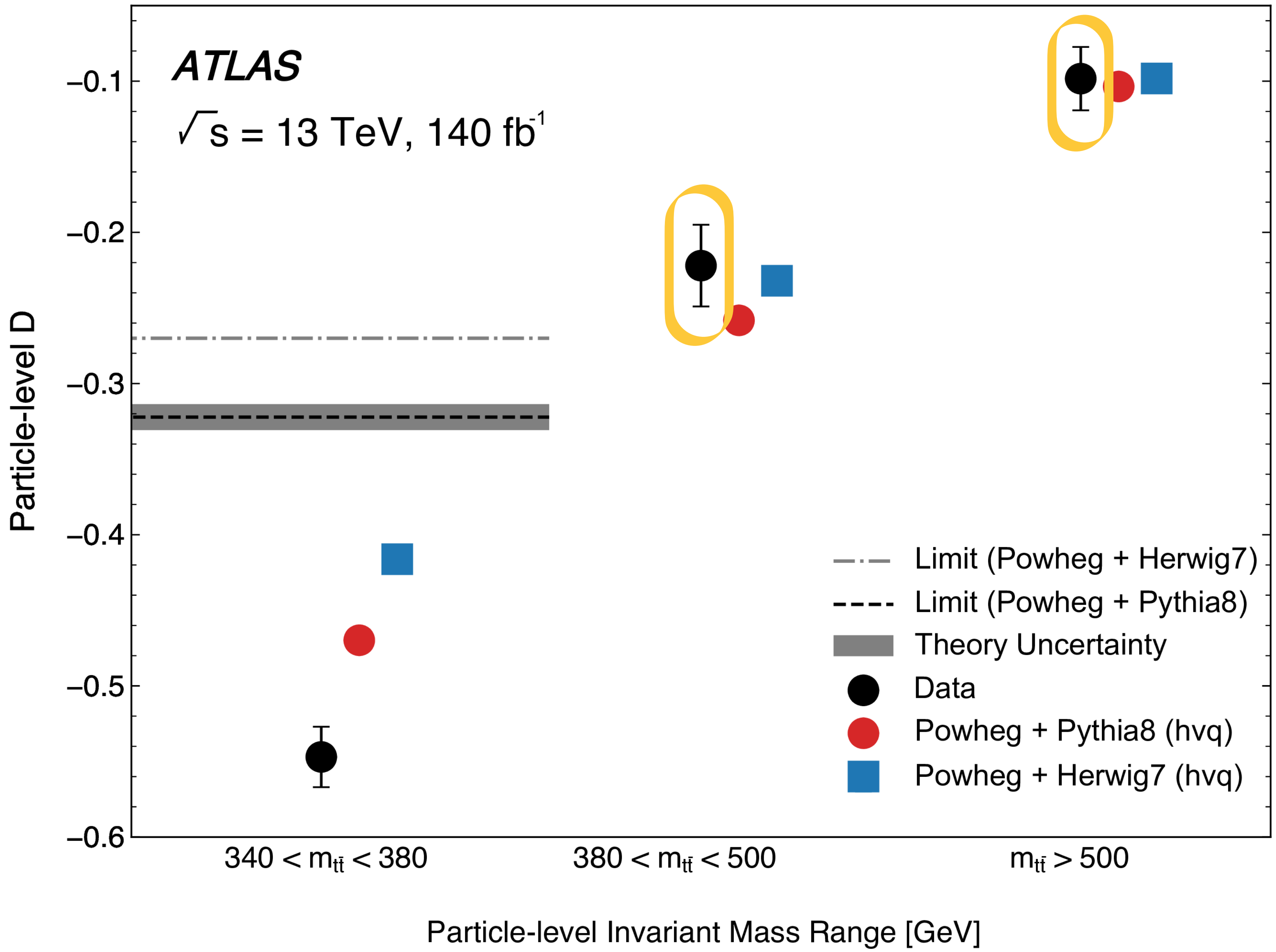




Q: How reliable is the Calibration Curve?

A: Very reliable!

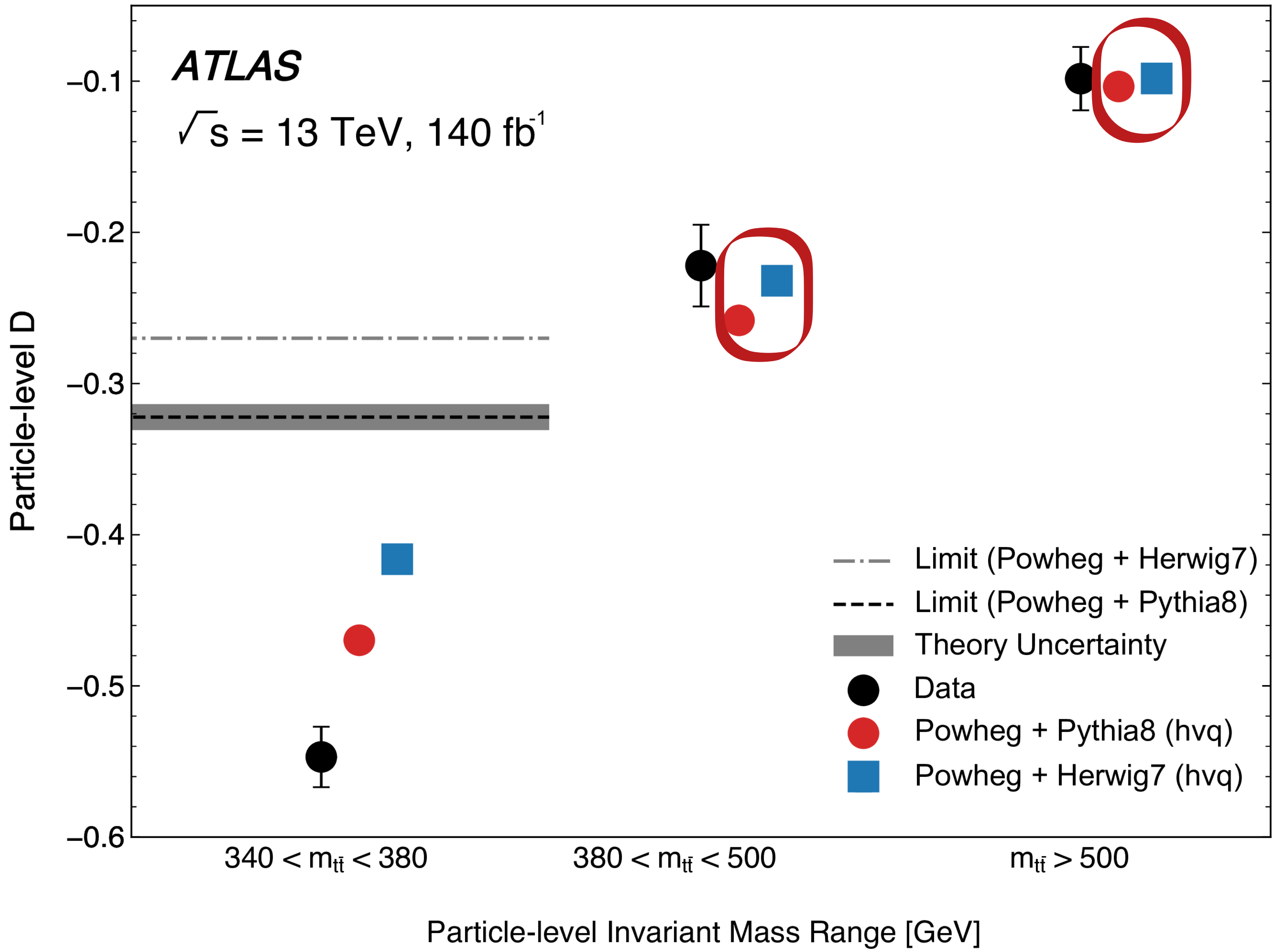
- the correction contains a full suite of uncertainties, like all ATLAS Top analyses
- we understand our detector response extremely well
- the detector responds the same way to Pythia and to Herwig simulation



Q: How reliable are our SM predictions?

A: Reliable but limited

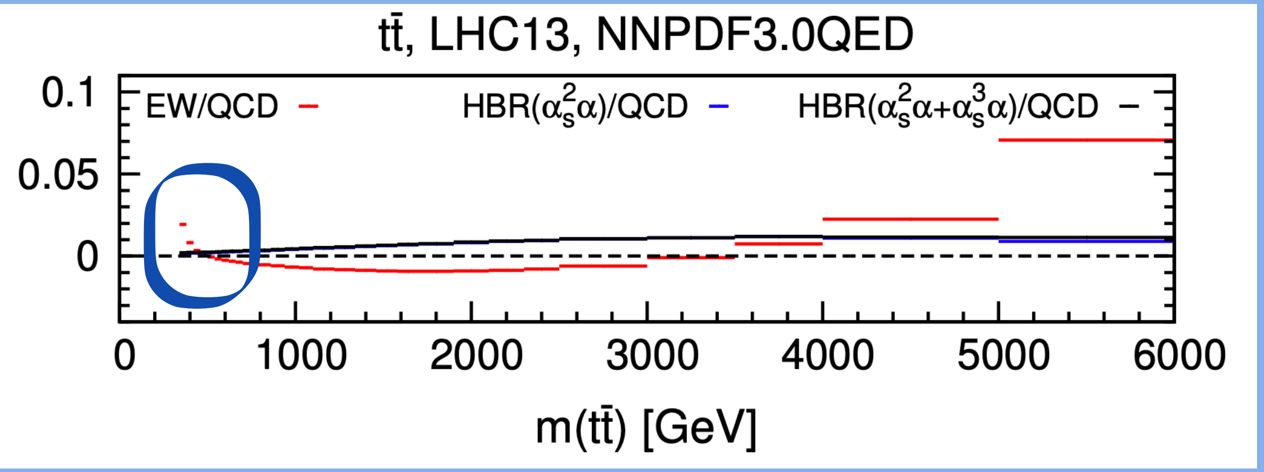
- derived from general-purpose MC event generators (powerful and widely used)
  - + lack full spin information in shower
  - + lack higher-order corrections to top quark decays
- a systematic model built around “bb4l” should be deployed by ATLAS in future



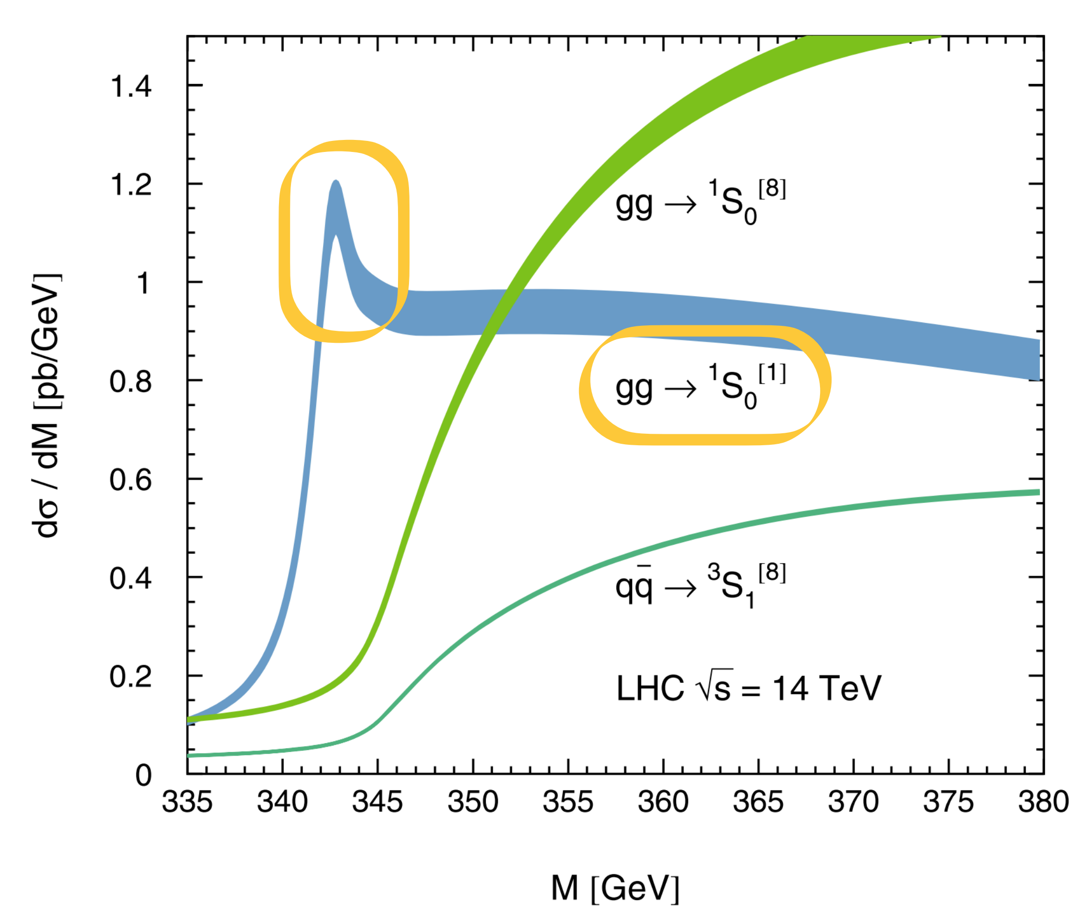
Q: Any missing Effects in Simulation?

Cross-section enhancement near threshold in both cases

NLO EW [ref. Czakon et al. 2017]



Bound state [ref. Kiyo et al. 2009]



- enhances spin singlet state so should increase level of entanglement

Conclusions

Measure separability of the density matrix of $t\bar{t}$

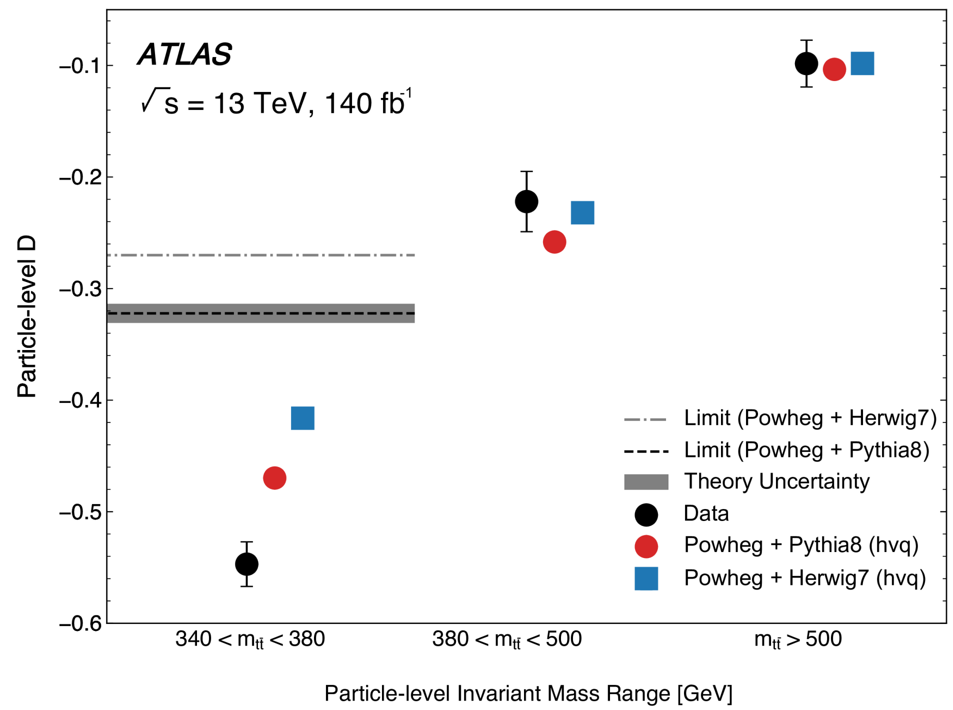
- concurrence and entanglement marker D

Determine D from angular distribution cosϕ

- standard di-leptonic channel and $t\bar{t}$ reconstruction techniques

Calibration curve to correct D to particle-level

- multiple hypothesis and full set of uncertainties



First observation of entanglement at the LHC!

Modelling remains a limitation

- improvements on the theoretical side are foreseen in the future analysis

This result propels forward the union of QI and HEP!

Thank you!

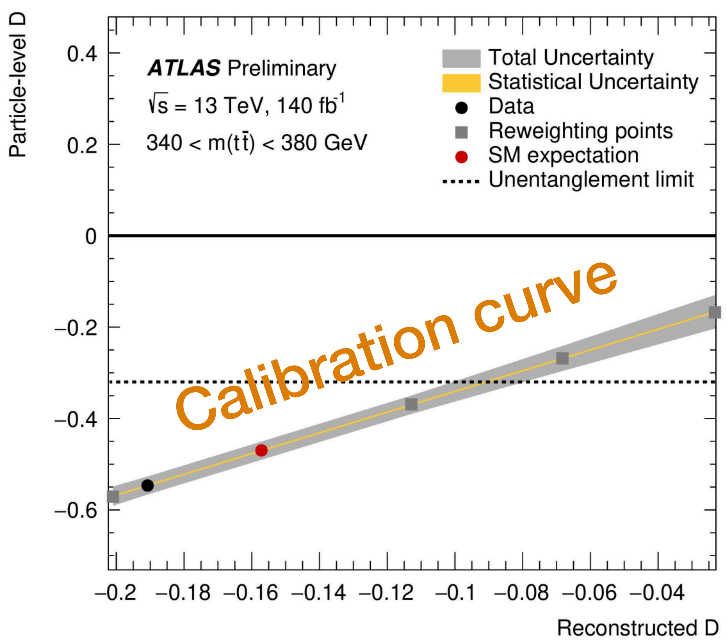
Spooky action at a distance is alive and well at the LHC!

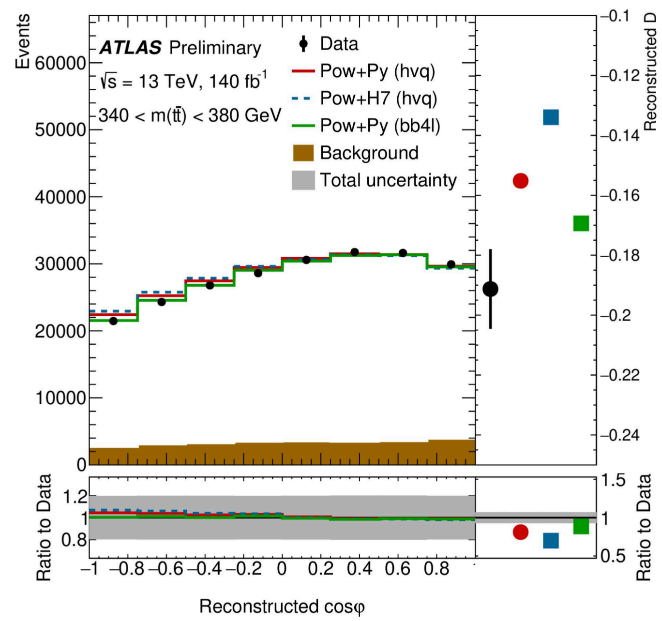
Auxiliary material

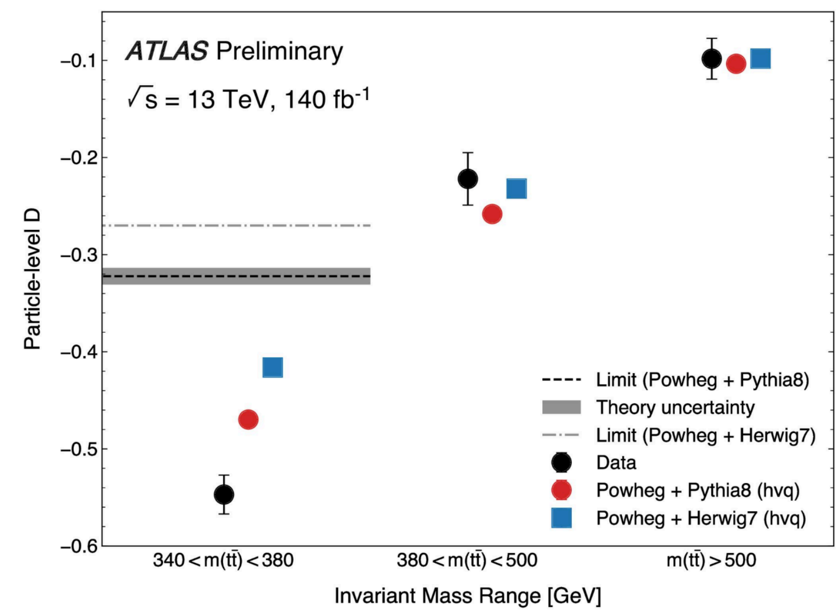
ATLAS Result: arXiv:2311.07288

ATLAS-CONF-2023-069 ATLAS Briefing CERN Courier article video (soon)

- presented at TOP2023







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$E_{\text{T}}^{\text{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
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Total systematic uncertainty	0.021	3.8	0.018	3.9
Total uncertainty	0.021	3.8	0.018	3.9

Some background addition due to loose b-tagging WP

Some personal thoughts

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

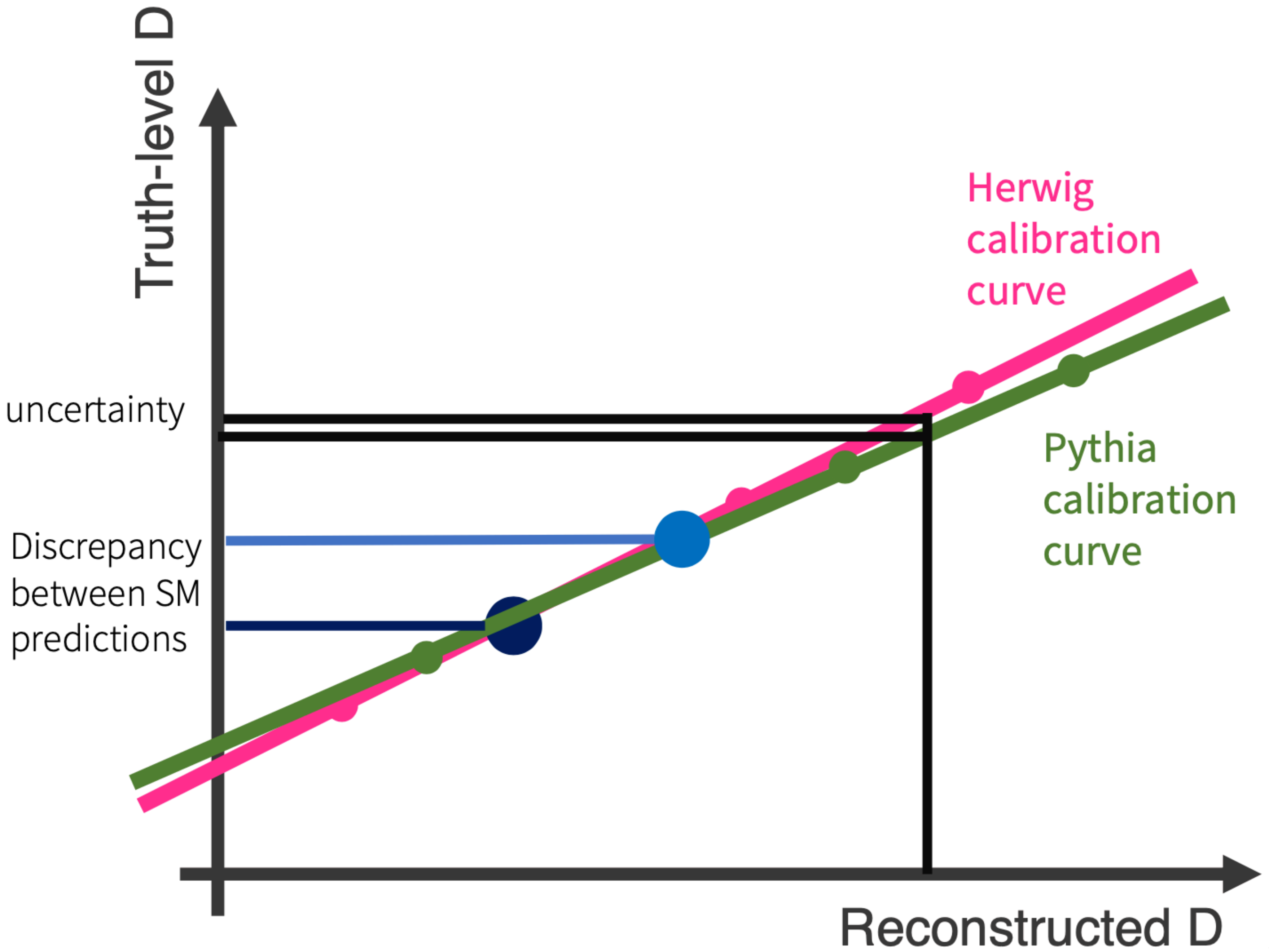
The accuracy of the simulation is limited because of:

- Discrepancies between predictions understood to arise from difference in parton showers
- Discrepancy between data and simulation thought to arise from missing effects

Lesson learnt:

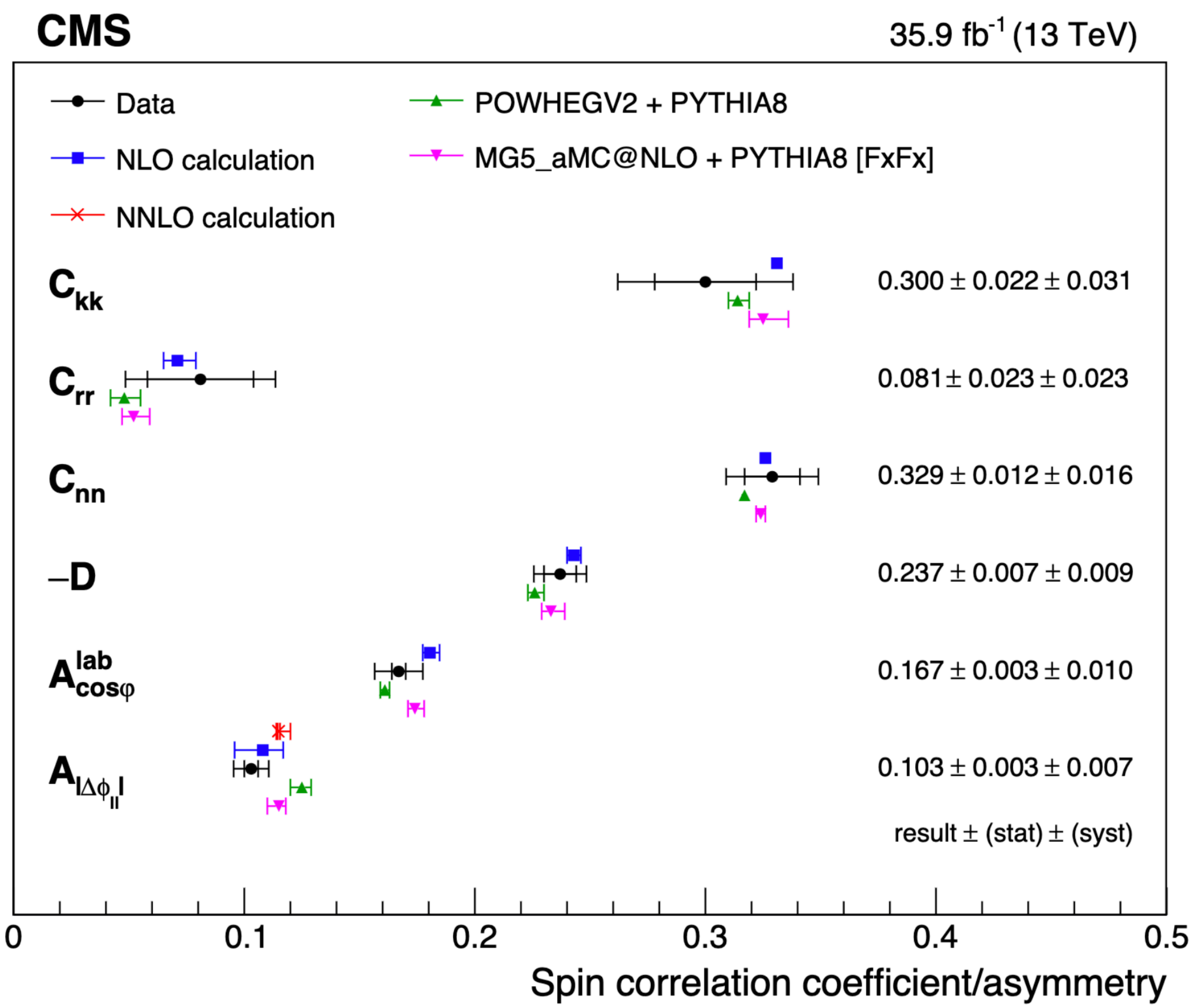
- many negligible issues are exacerbated by the narrow phase-space:
  + Resolution of top reconstruction not good enough.
  + Unfolding procedures biased.
  + Larger discrepancies in parton showers
  + Simulation lacks complete description
- we are essentially at the limit of what we can do in such a phase-space region

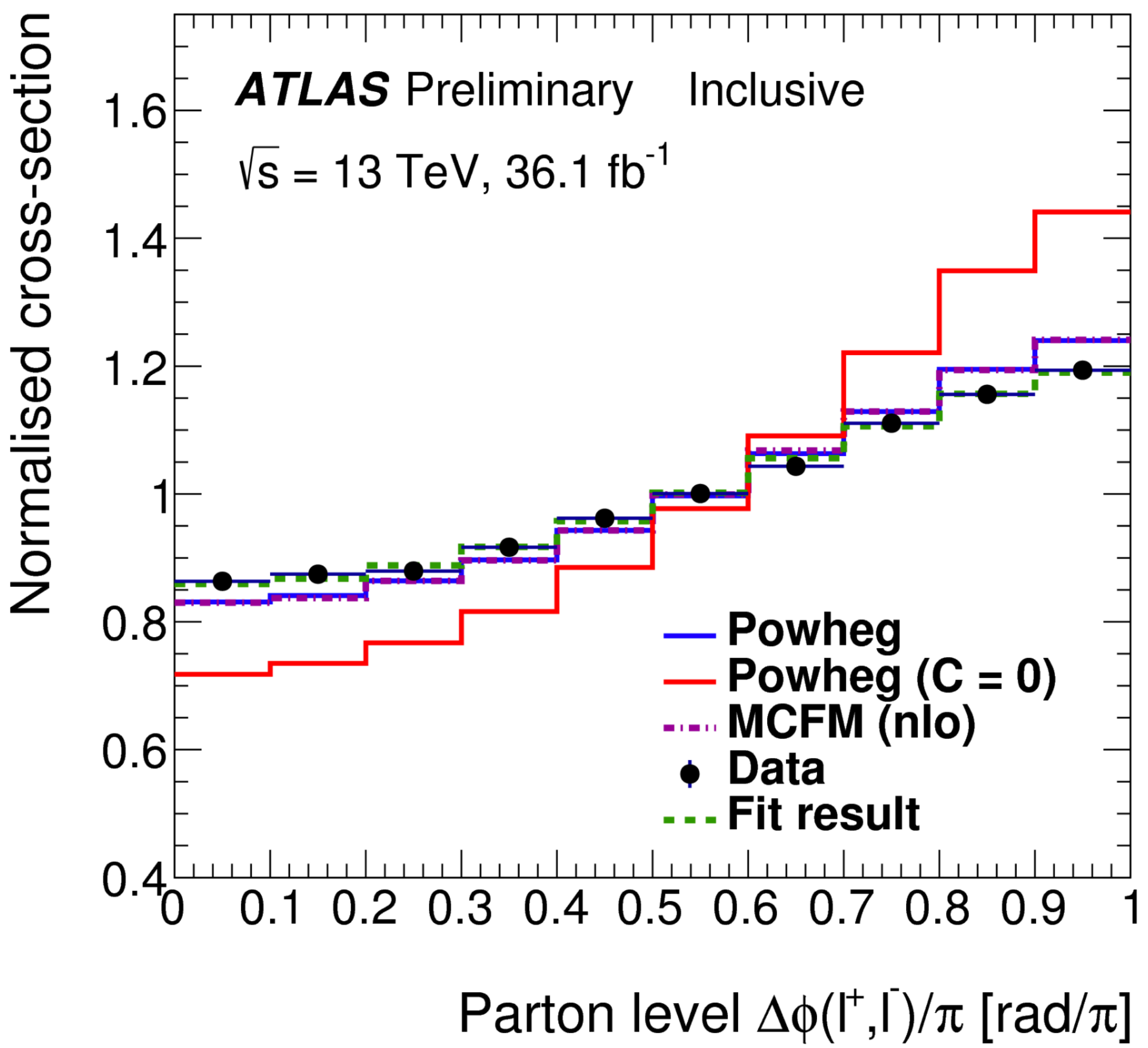
Large discrepancy, small uncertainty



Measurements of Spin Correlations

Many precision measurements of spin parameters in the past





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

View as an average spin correlation

Reweighting

Each event ascribed a weight through the expression:

$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot \chi \cdot \cos\phi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\phi}$$

where $D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$ **is fitted from simulation (differerent per MC generator)**

Parton→Particle→Detector

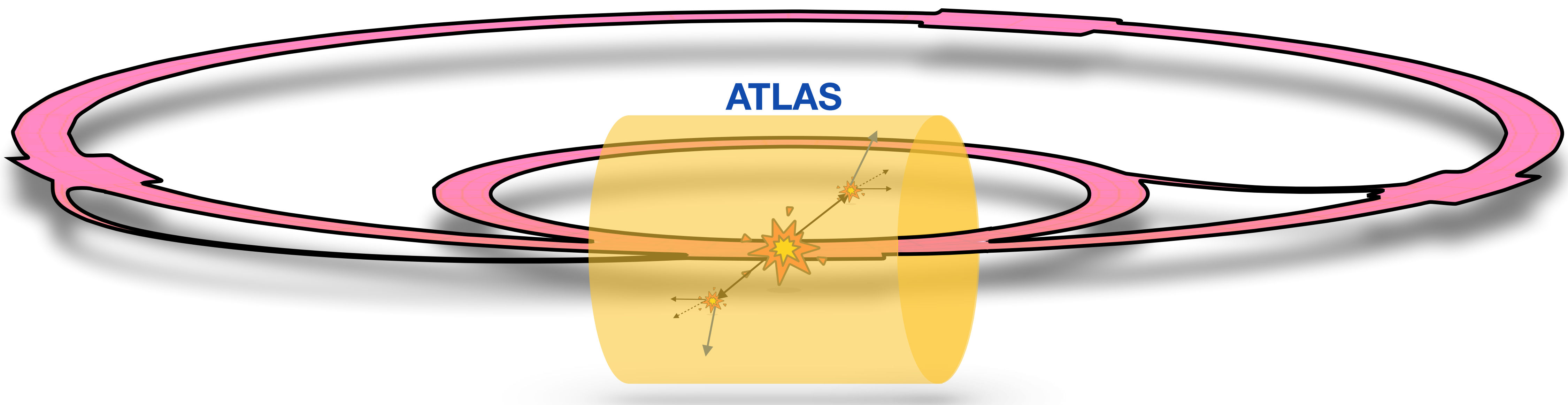
Parton-level objects taken directly from the MC history information (status code=1):

- Top quarks = partons that decay to a W boson and a b quark, whereas
- charged leptons = the immediate decay parton from the W boson from the top quark

Particle-level objects = simulated stable particles (mean lifetime > 30 ps) before reconstruction, but after hadronization within the η acceptance

- selection criteria closely as possible to detector-level objects
- Electrons, muons and neutrinos from the electroweak decay of a top quark
  + discarded if they arise from the decay of a hadron or a τ-lepton.
- Electrons and muons are “dressed” by summing their four-momenta with any prompt photons within $\Delta R = 0.1$; they must then lie within $\Delta R > 0.4$ from a jet to avoid being removed from the event
- leptons are required to have pT > 10 GeV and $|\eta| < 2.5$, and at least one with pT > 25 GeV
- jets are built by clustering all stable particles, using the anti-k algorithm with ΔR=0.4
- jets are tagged as containing b-hadrons if they have at least one ghost-matched b-hadron with pT > 5 GeV
- Jets are also required to have pT > 25 GeV and $|\eta| < 2.5$

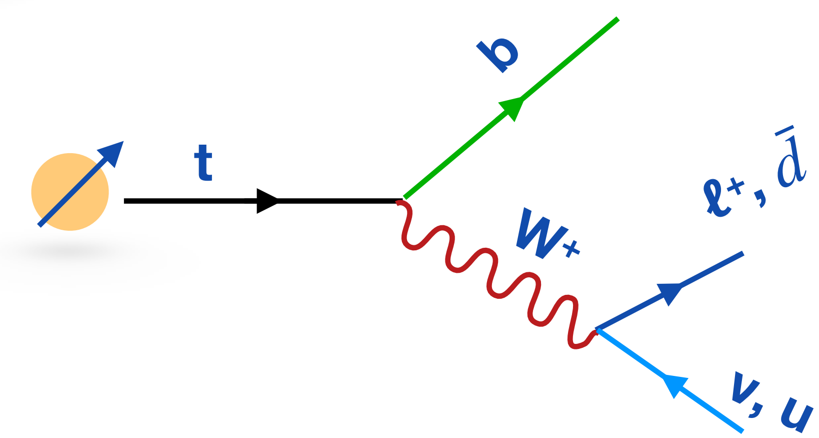
The Experiment



Dominant production gg → $t\bar{t}$ (90%)

$t\bar{t}$ events mostly produced at threshold (β≈0)

ℓ± as proxy of the spin ($\kappa_{\ell^+} \approx 1$)



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\chi_a} = \frac{1}{2}(1+\kappa_a\cos\chi_a)$$

$t\bar{t}$ cross-section:

t ($\bar{t}$) spin polarisation

spin-correlation matrix

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\ell}^+ - \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot C \cdot \hat{\ell}^-}{(4\pi)^2}$$

anti-lepton (lepton) direction
in the top (anti-top) rest frame

$t\bar{t}$ reconstruction

Ellipse method [doi:j.nima.2013.10.039]:

- a geometric T approach to analytically calculate the neutrino momenta
  - neutrino momentum found as a function of the 4-vectors of the associated bottom quark and charged lepton, the masses of the top quark and W boson, and a single parameter, which constrains it to an ellipse
  - the measured imbalance of momenta in the event reduces the solutions for neutrino momenta to a discrete set, in the cases of one or two top quarks decaying to leptons
- it yields at least one real solution in 85% of events
- If this method fails (e.g. the resultant solutions are all complex), the Neutrino Weighting method is used

Neutrino Weighting method:

- it assigns a weight to each possible solution by assessing the compatibility of the neutrino momenta and the p_T^{miss} in the event, after scanning possible values of the pseudorapidities of the neutrinos.
- If it fails, a simple pairing of each lepton with its closest b-tagged jet is used. If a second b-tagged jet is not present in the event, the leading (highest) pT untagged jet is used instead.