Observation of quantum entanglement in top quark pairs at ATLAS

LHCP, 05/06/2024

Baptiste Ravina on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

Prelude: top quark spin correlations

The top quark has a mean lifetime ~5x10^{-25}s << 1/Λ_{QCD} ~10^{-23}s

→ **spin information is correlated and transferred** to decay products

BR(t→Wb) ~100% + weak interaction is maximally parity-violating

→ **correlations are observable!**

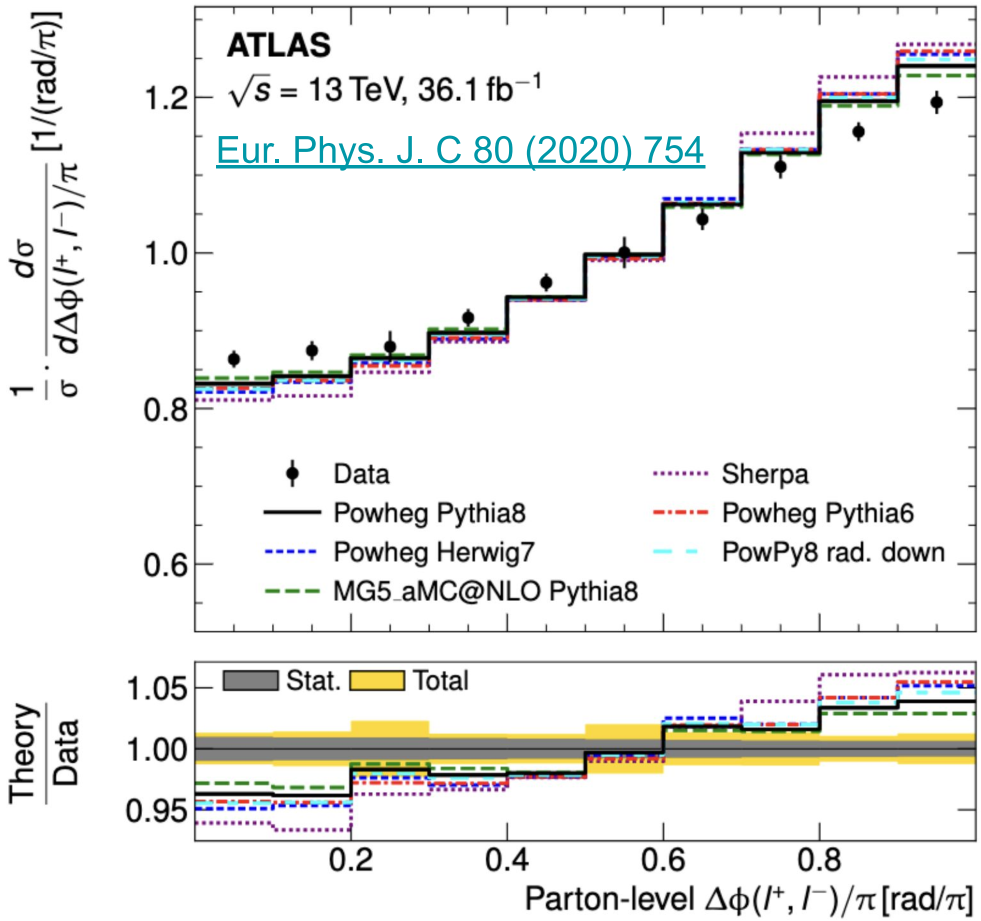
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

top polarisations + spin correlations

= full spin density matrix

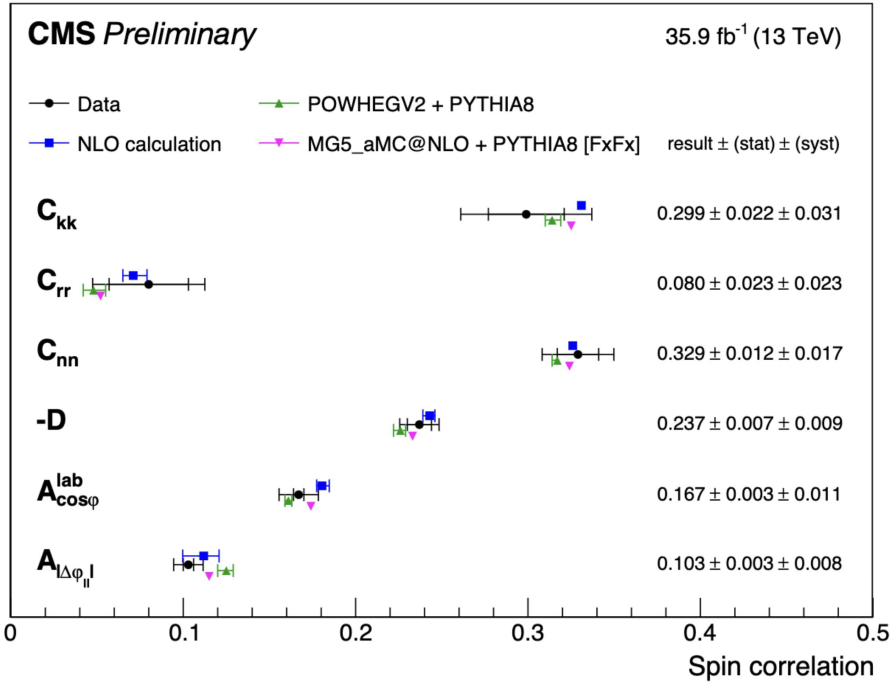
$\alpha_1 = \alpha_2 = 1$ (maximal) for leptons

State-of-the-art in 2020...



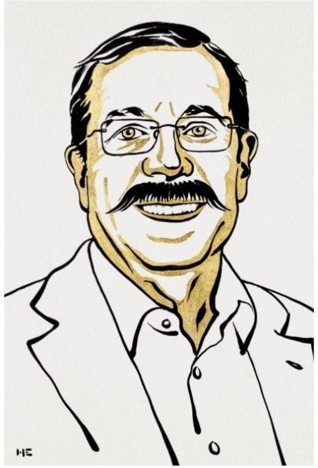
Eur. Phys. J. C 80 (2020) 754

Spin correlations in $t\bar{t}$ are well-established



Phys. Rev. D 100 (2019) 072002

As you may have heard...



Ill. Niklas Elmehed © Nobel Prize Outreach

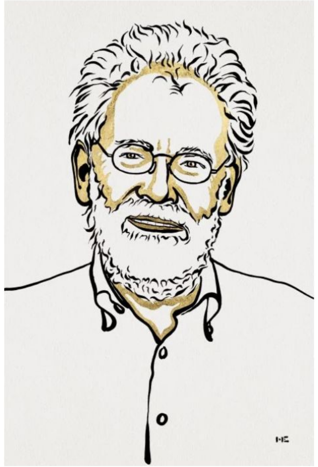
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

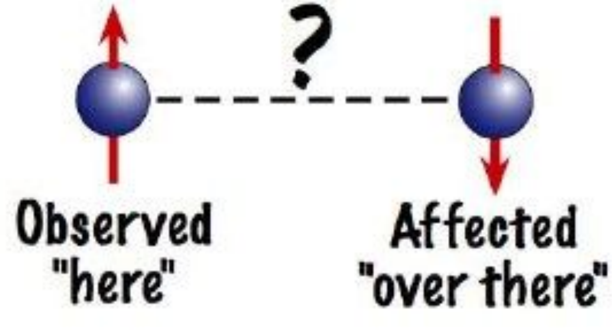


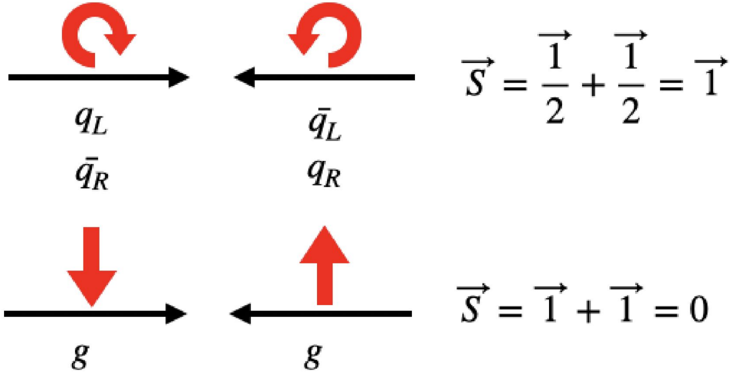
Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly 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"





gg→tt̄: spin-singlet state at threshold

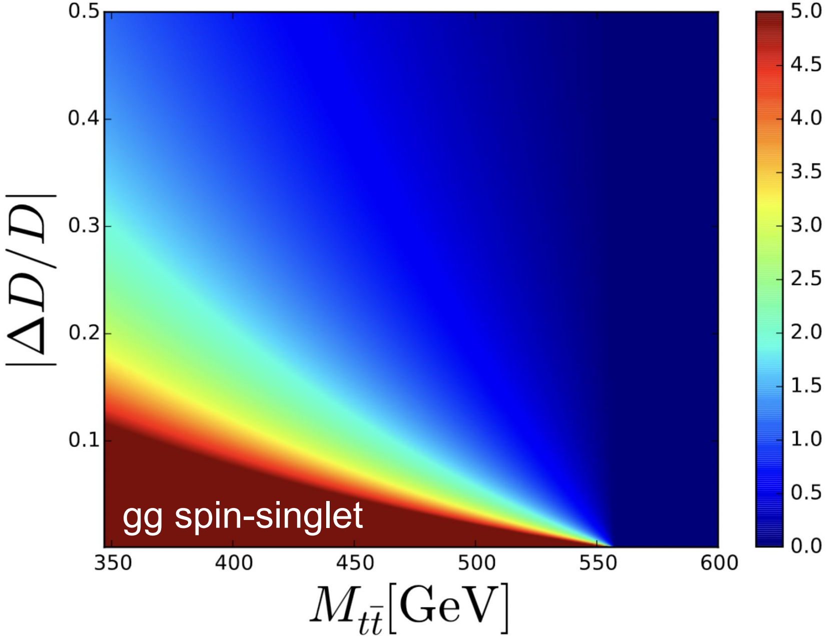
Quantum tops beyond (classical) spin correlations

Eur. Phys. J. Plus (2021) 136 (March 2020) → first analysis of top quark pair production *from the quantum information point of view*: “**bipartite qubit system**”

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\, \mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\, \mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\, \mathbb{C}\, \hat{\ell}_2\right)$$

0 0

QCD is CP-even: zero polarisations at LO!



$$\mathrm{Tr}\,[\mathbb{C}] < -1$$ *Peres-Horodecki criterion*

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$ *a simple observable*

$$D = \frac{\mathrm{Tr}\,[\mathbb{C}]}{3} \Rightarrow D < -\frac{1}{3}$$ *a quantum entanglement marker!*

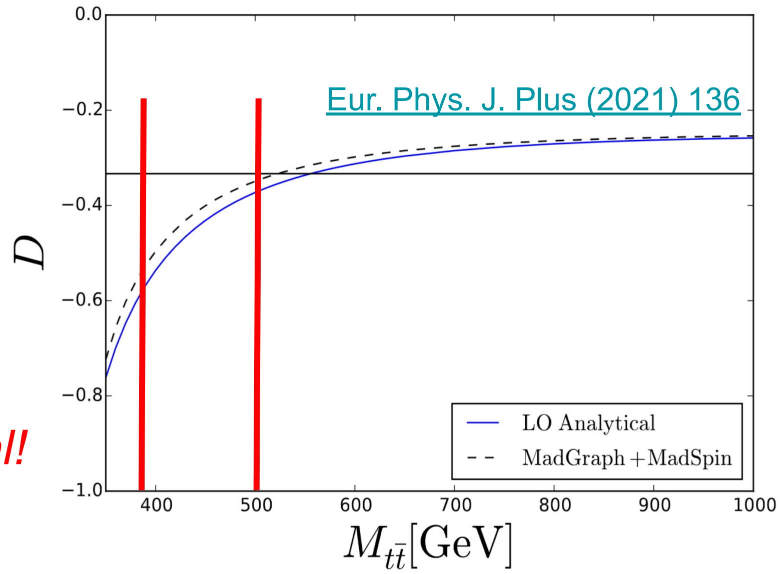
Quantum entanglement in dileptonic $t\bar{t}$

Dilepton eμ final state is very clean (90% purity) and at the end of Run 2 we have about a million events after preselection.

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

- Boost the leptons in their parent top's rest frame
- Measure **D = -3<cos(φ)>**
- Then partition events into three selections:
  - **340<M_{tt}<380: entanglement signal region**
  - 380<M_{tt}<500: validation region (dilution from mis-reconstruction)
  - **500<M_{tt}: no-entanglement** validation region

The mass cuts are crucial!

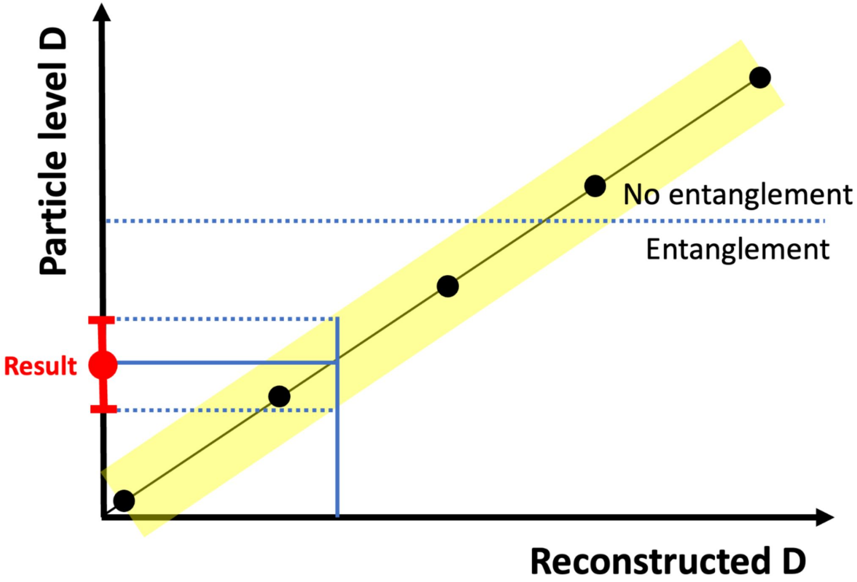


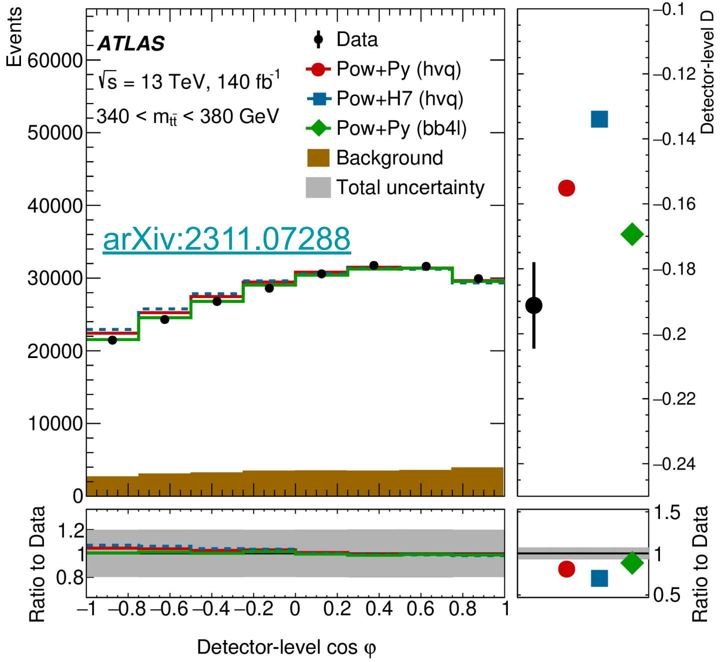
Analysis procedure

“Calibration curve” method: use the nominal MC to map the detector-level D value (average of distribution) to the fiducial particle-level D.

Systematics are propagated with their own curves, quadratic envelope.

→ Build the curve by sampling different D values.





A closer look at uncertainties

“Backgrounds”: mostly $Z \rightarrow \tau\tau$, which leads to a flat cos(φ) distribution

(spin information from taus is lost)

Calibrating to fiducial particle-level reduces the parton shower uncertainty (Pythia vs Herwig)

→ full details in the paper.

Signal modelling:

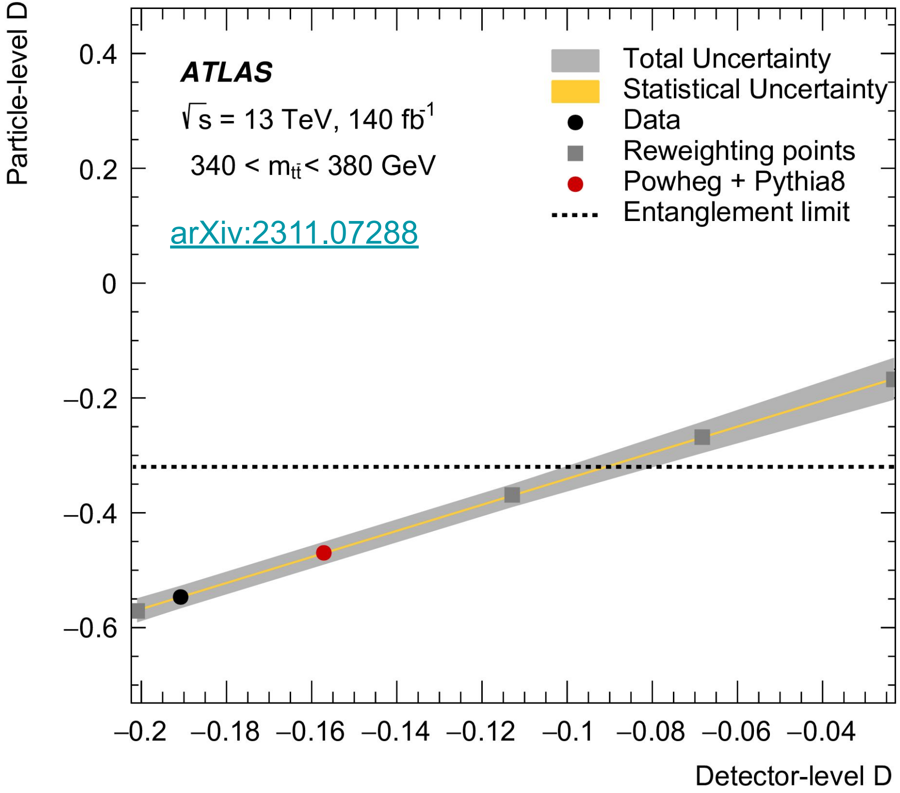
by far the largest contribution

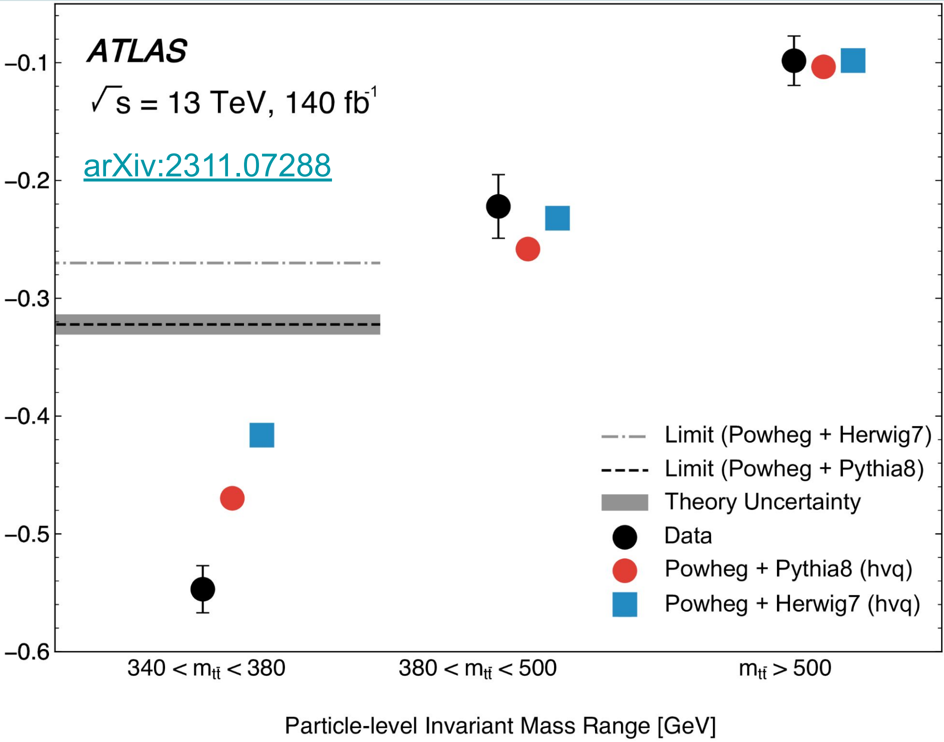
arXiv:2311.07288

Source of uncertainty	$\Delta D_{\text{expected}}$ ($D = -0.470$)	ΔD [%]
Signal modeling	0.015	3.2
Electrons	0.002	0.4
Muons	0.001	0.1
Jets	0.004	0.8
b-tagging	0.002	0.4
Pile-up	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.4
Backgrounds	0.009	1.8
Total statistical uncertainty	0.002	0.4
Total systematic uncertainty	0.018	3.9
Total uncertainty	0.018	3.9

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%

Observation of quantum entanglement in dileptonic $t\bar{t}$



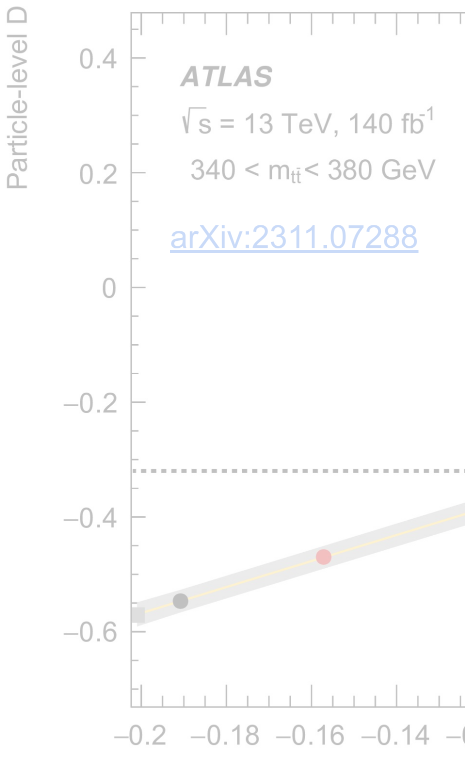


non-relativistic QCD effects close to threshold, not included in MC generators → would only affect predictions, not calibration

expected: D = -0.470 ± 0.002 (stat.) ± 0.018 (syst.)

D = -0.547 ± 0.002 (stat.) ± 0.021 (syst.)

Observation of quantum entanglement in dilepton $t\bar{t}$



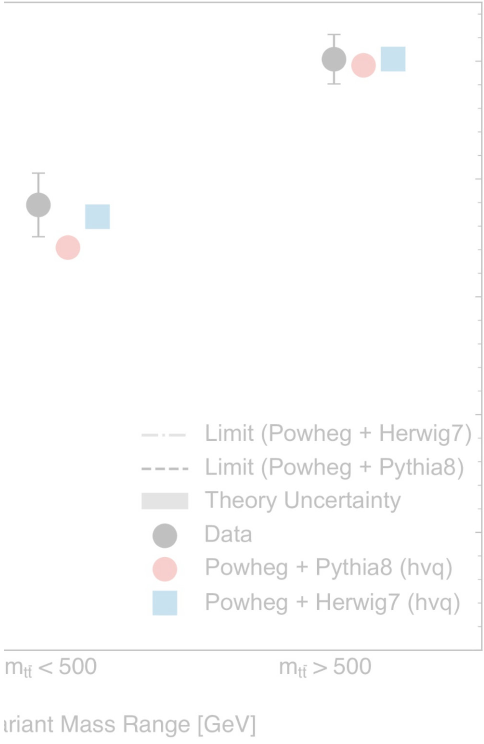
Submitted to: Nature

CERN-EP-2023-230
November 20, 2023

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

The ATLAS Collaboration

We report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a center-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes both the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement to date.



se to threshold, not included in
fect predictions, not calibration

expected: D = -0.470 ± 0.002 (st

at.) ± 0.020 (syst.)

Conclusions

- **Observation of quantum entanglement in top quark pairs by ATLAS**

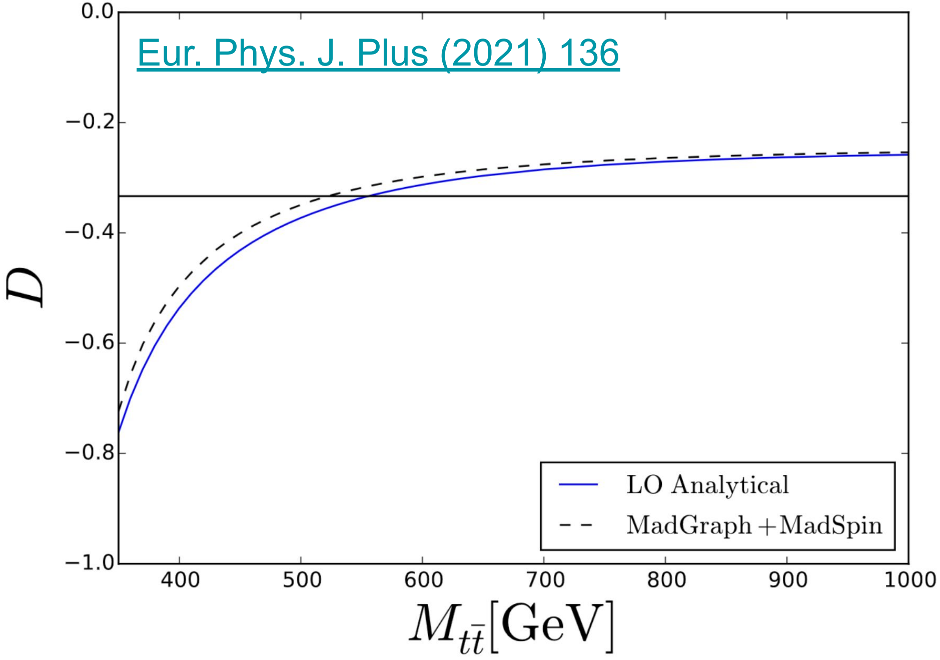
- Paves the way for future measurements of quantum information at the LHC
  - highest energies, quarks, large statistics… → **interesting for the QI community**
  - angular measurements binned in $M(t\bar{t})$ are a powerful tool for BSM searches → **interesting for the HEP community**

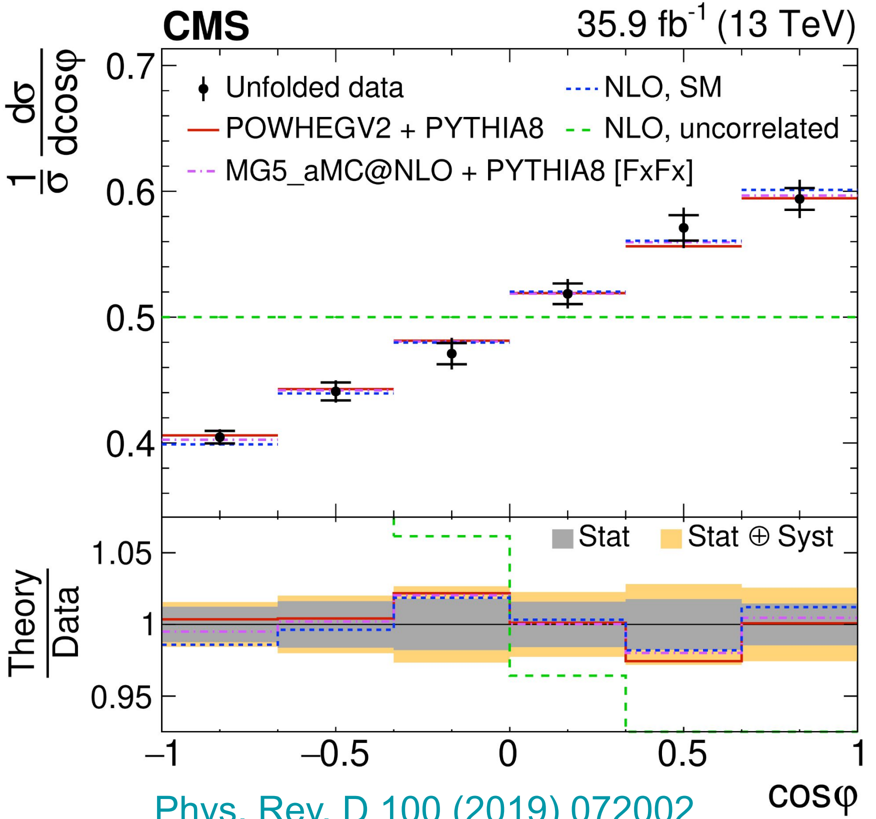
- Simple but **robust measurement** that already highlights the importance of precise top quark modelling near pair production threshold
  - improvements related to parton shower and "toponium" effects will carry over to other key measurements! (top mass, width, properties…)

Thank you!

👉 ATLAS Briefing
👉 CERN Courier

The 2019 CMS measurement



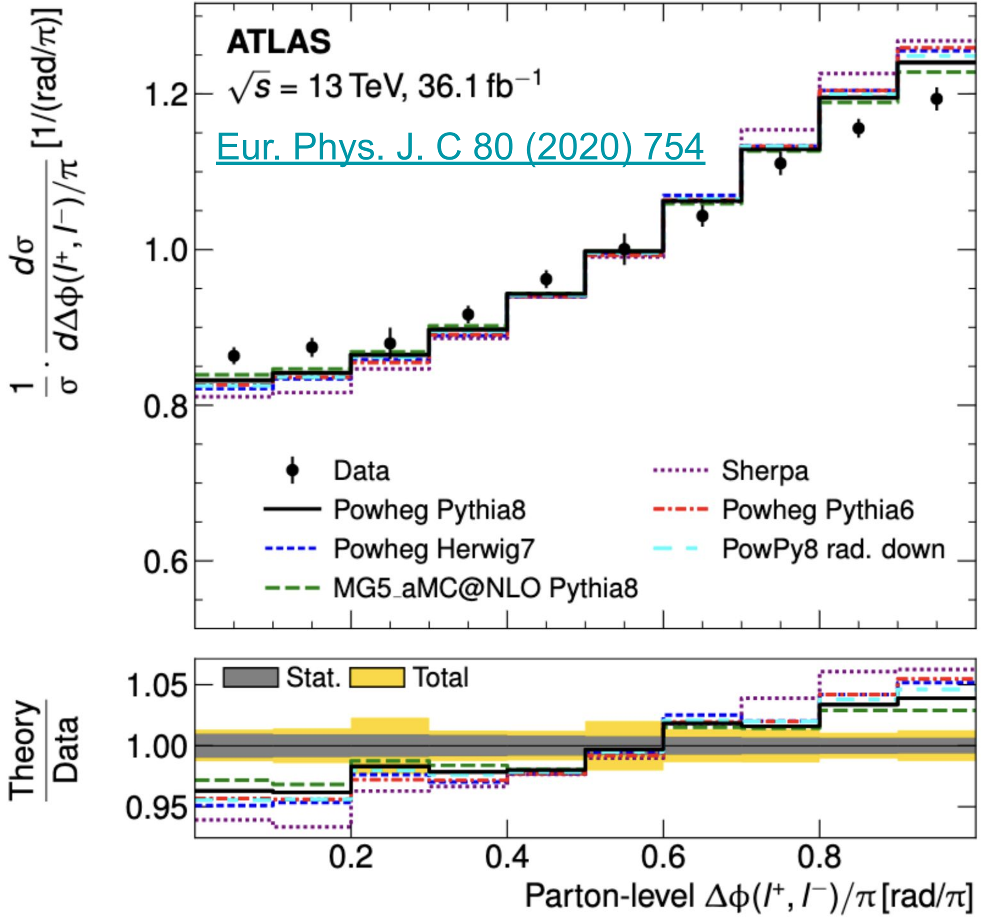


Phys. Rev. D 100 (2019) 072002

CMS measured $D = -0.237 \pm 0.011 > -\frac{1}{3}$

inclusively → need to go differential in M(tt̄)

Spin correlations at NNLO



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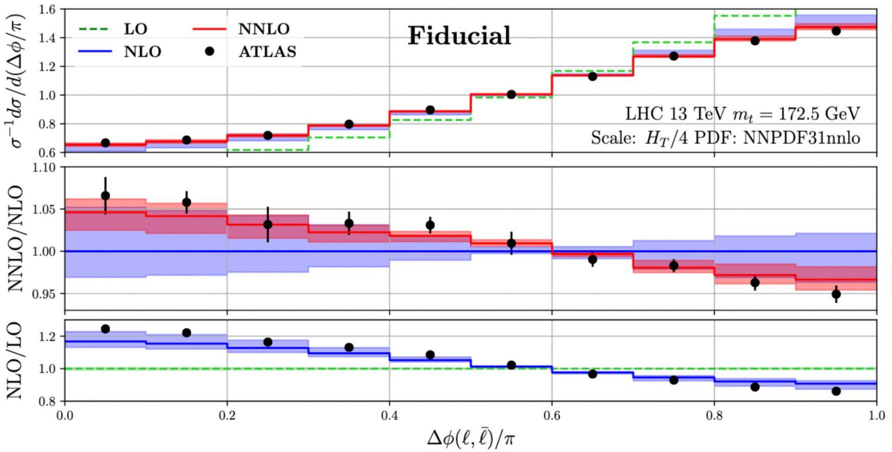
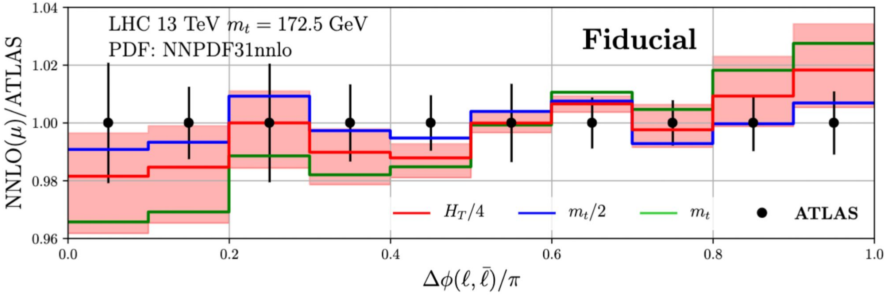
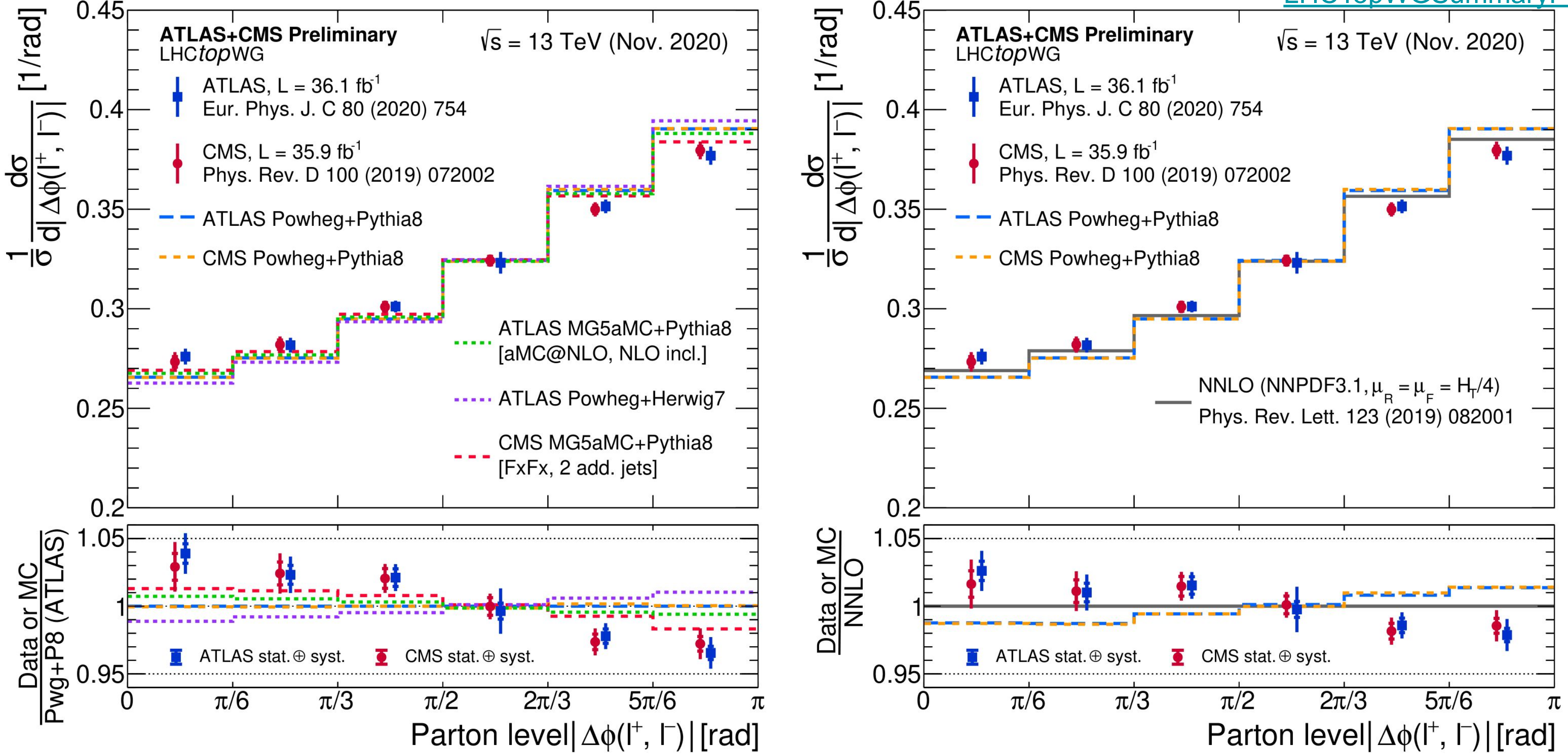
arXiv:1901.05407





Spin correlations: ATLAS and CMS

LHCTopWGSummaryPlots



Event selection

- 1 electron and 1 muon (opposite charges)
- single lepton triggers
- leptons' p_T>25–28 GeV
- at least 2 jets with p_T>25 GeV
- at least 1 b-tagged jet (at 85% b-tagging efficiency)

arXiv:2311.07288

Process	Inclusive	340 – 380 GeV	380 – 500 GeV	> 500 GeV
$t\bar{t}$	1030000 ± 40000	202000 ± 8000	408000 ± 16000	417000 ± 17000
tW	59800 ± 1100	10330 ± 200	23800 ± 500	25700 ± 500
Z+jets	38000 ± 4000	9300 ± 400	19000 ± 4000	9730 ± 270
$WW/WZ/ZZ$	9140 ± 340	1320 ± 50	3280 ± 120	4540 ± 170
$t\bar{t}X$	2959 ± 6	437.7 ± 2.1	1080.1 ± 3.4	1441 ± 4
fakes	17700 ± 8900	3600 ± 1900	7100 ± 3800	7000 ± 3700
Expectation	1150000 ± 40000	227000 ± 8000	462000 ± 17000	466000 ± 17000
Data	1105403	225056	441196	439151
data/MC	0.96 ± 0.03	0.99 ± 0.04	0.95 ± 0.04	0.94 ± 0.04

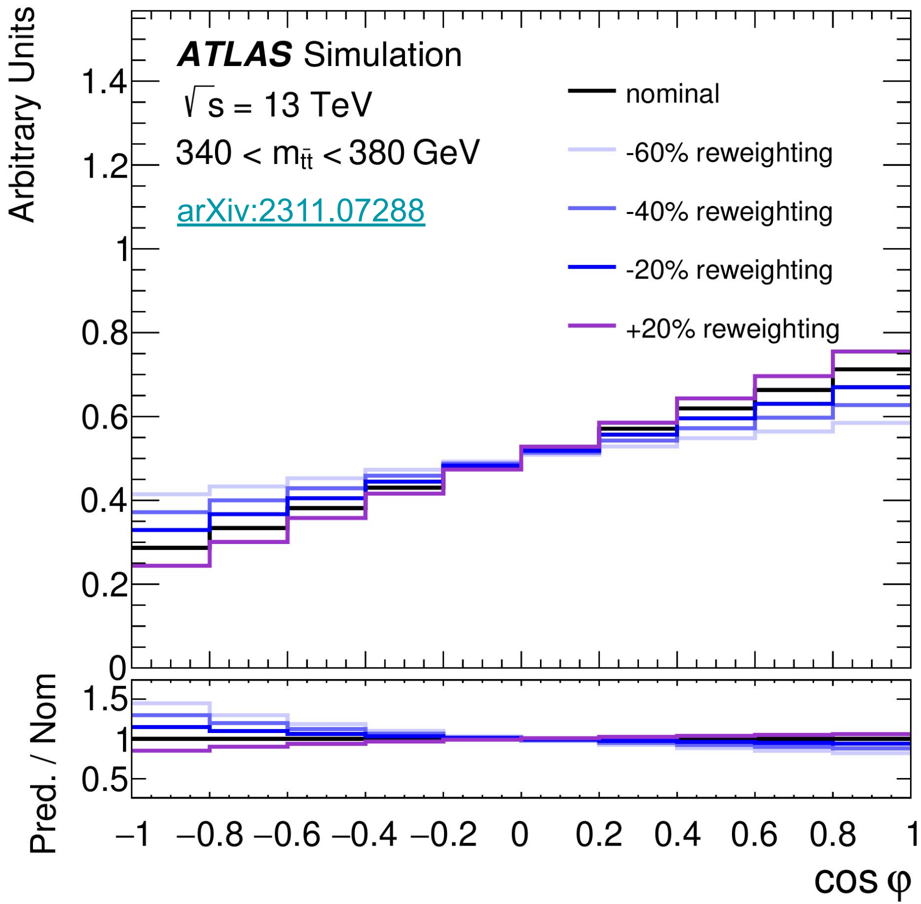
The reweighting method

- We have no handle on the "amount of entanglement" in the generators, but we know exact functional forms at parton-level → can reweight D
- Fit a 3rd order polynomial to extract the dependence on M(tt̄)

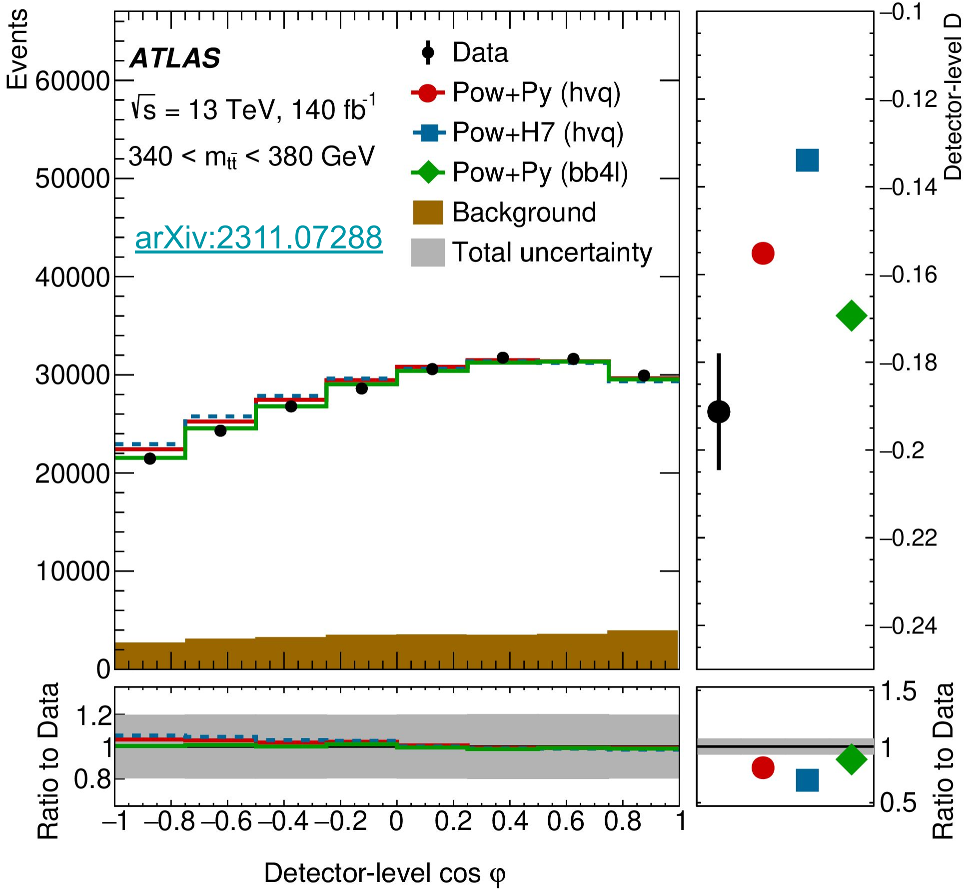
$$D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

- Then reweight each event as

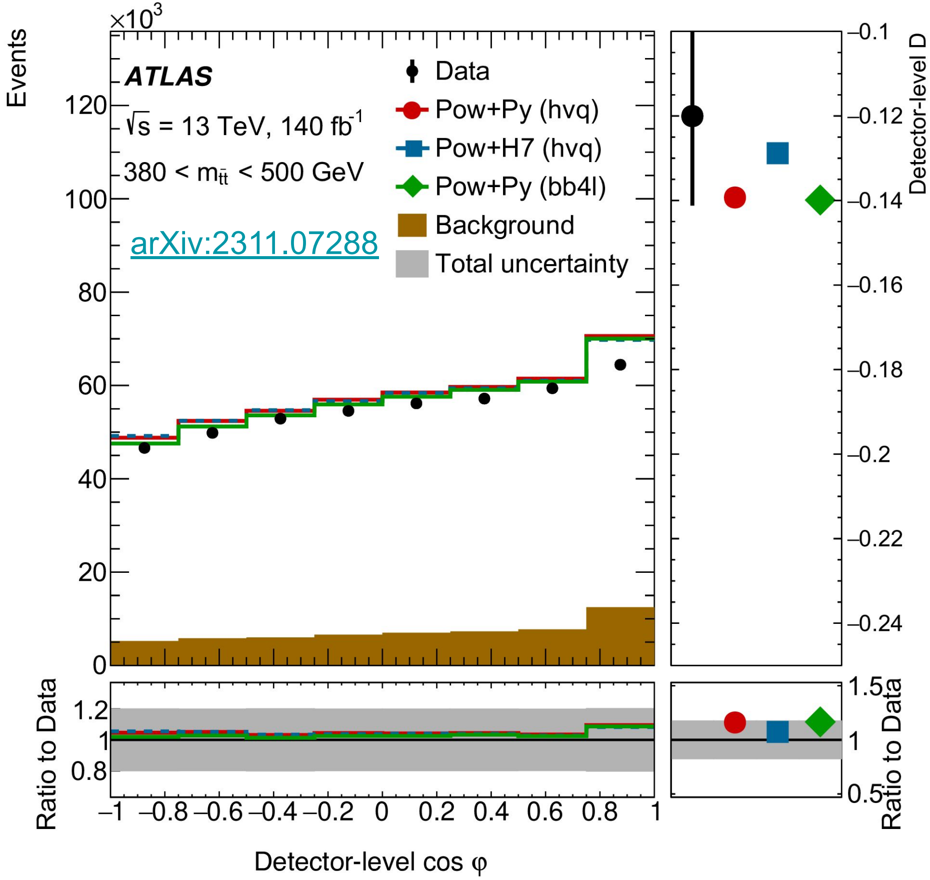
$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$$

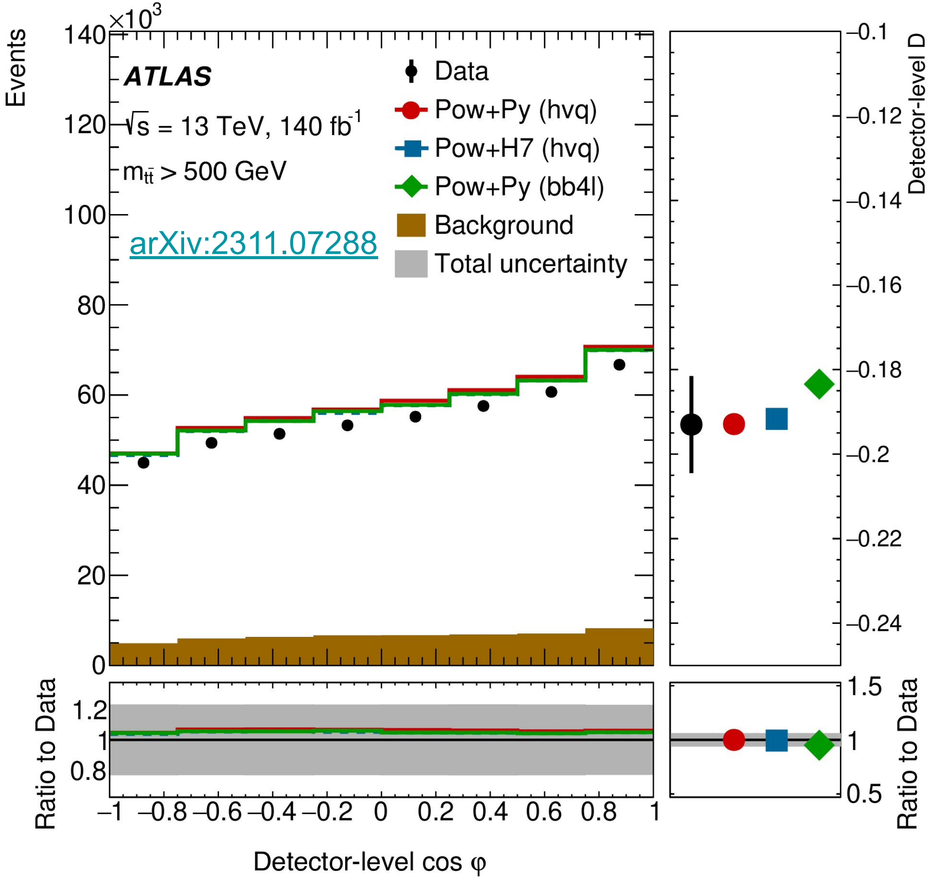


Data / MC in the signal region

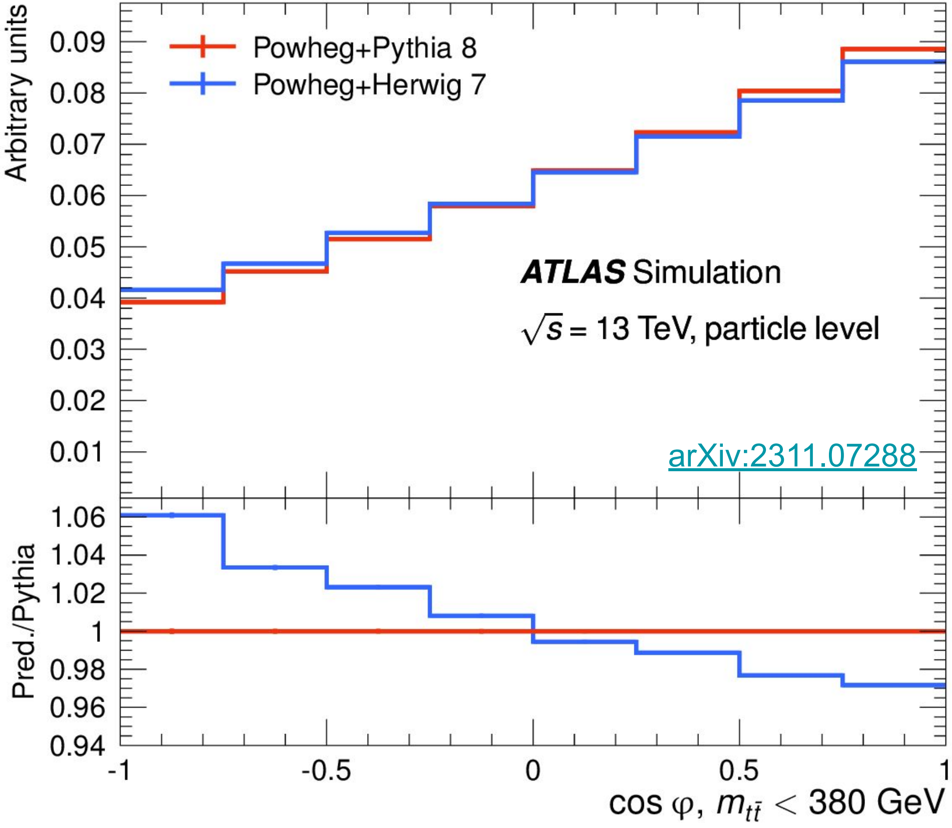


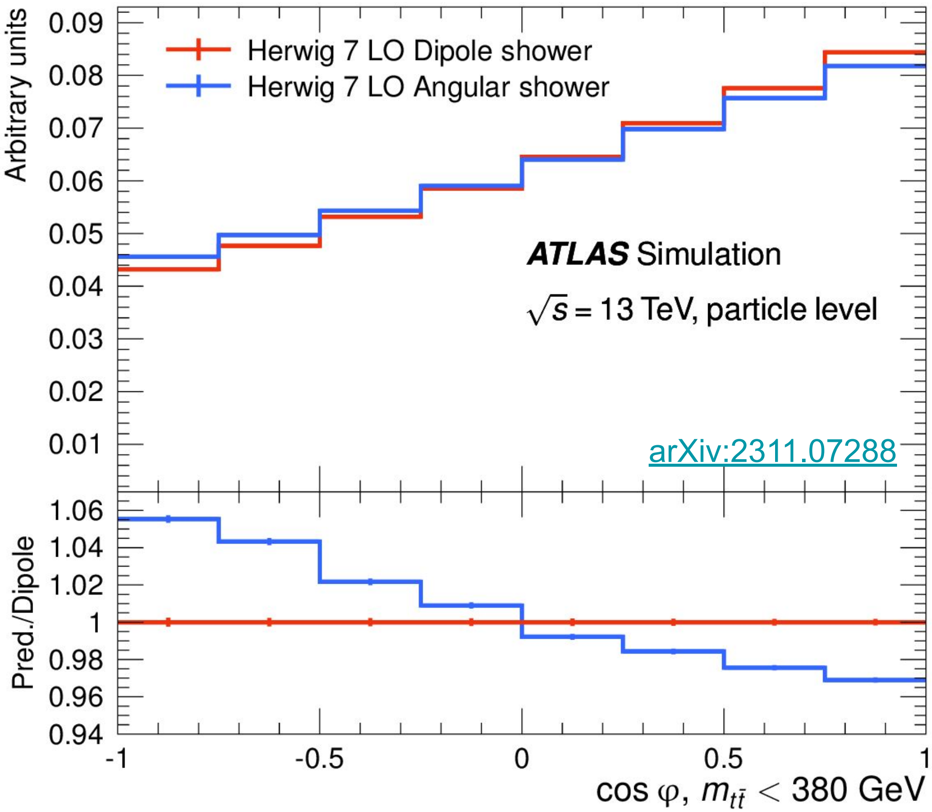
Data / MC outside the signal region





Investigations of parton shower effects

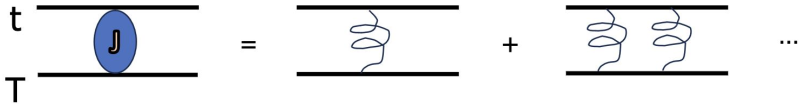




Differences appear in the parton→particle level transition,
and seem to largely match the Dipole vs Angular ordering schemes

At threshold: need input from the theorists

- Our MC generators don't include the necessary non-perturbative effects – how do we get around that?
    - Fuks et al. implemented a BSM Lagrangian in MadGraph → **toponium**
    - A number of calculations available, most recently Ju et al.
        - pure parton-level calculation (stable tops), resums leading-power and next-to-leading-power calculations and matches to NNLO differential $t\bar{t}$



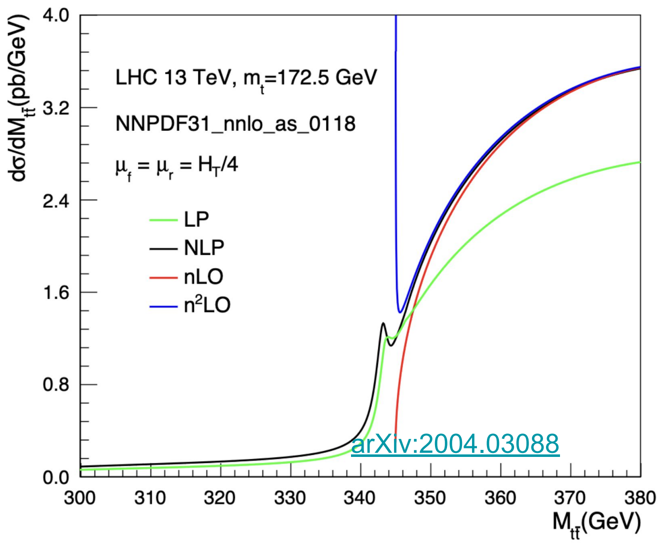
from A. Mitov

We can sum up:

leading power (LP) $\left(\frac{\alpha_s}{\beta}\right)^n$

next to leading power (NLP) $\alpha_s \left(\frac{\alpha_s}{\beta}\right)^n$

This results in a complicated function (Sommerfeld factor): $J \sim \frac{\alpha_s/\beta}{e^{\pi\frac{\alpha_s}{\beta}} - 1} = 1 + \frac{\alpha_s}{\beta} + \ldots$



Separable and entangled states

Example: top pair production

J.A. Aguilar Saavedra

q_L q_L[-bar] → t t-bar gives a spin configuration $|\leftarrow\rangle \otimes |\leftarrow\rangle$[in the q_L direction]

This is obviously not entangled.

q_R q_R[-bar] → t t-bar gives a spin configuration $|\rightarrow\rangle \otimes |\rightarrow\rangle$

Not entangled either.

g g → t t-bar at threshold gives $\frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle)$

This one is entangled.

Mixed states in top pair production

qq → t t-bar is 50% of the time q_L q_L and 50% of the time q_R q_R

Then, we have 50% of the time $|\leftarrow\rangle \otimes |\leftarrow\rangle$ and 50% $|\rightarrow\rangle \otimes |\rightarrow\rangle$

Obviously, in qq → t t-bar we do have t t-bar spin correlations. But not entanglement!

General bipartite qubit system

$$\rho = \frac{1}{4}\left(\mathbb{1}\otimes\mathbb{1} + \sum_i (B_i^+\sigma_i\otimes\mathbb{1} + B_i^-\mathbb{1}\otimes\sigma_i) + \sum_{ij} C_{ij}\sigma_i\otimes\sigma_j\right)$$

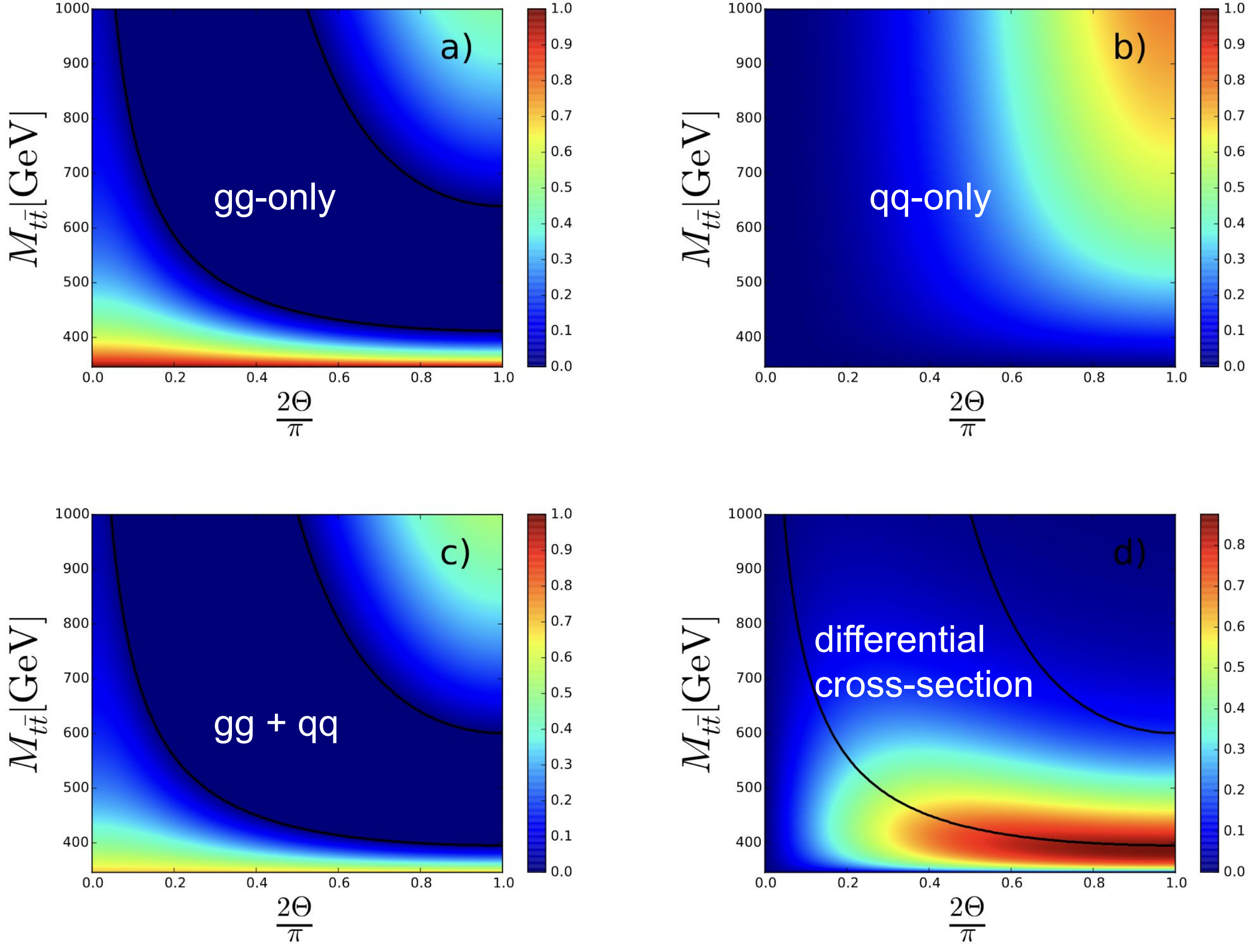
$$\rho = \frac{1}{4}\begin{bmatrix} 1+B_3^++B_3^-+C_{33} & B_1^-+C_{31}-i(B_2^-+C_{32}) & B_1^++C_{13}-i(B_2^++C_{23}) & C_{11}-C_{22}-i(C_{12}+C_{21}) \\ B_1^-+C_{31}+i(B_2^-+C_{32}) & 1+B_3^+-B_3^--C_{33} & C_{11}+C_{22}+i(C_{12}-C_{21}) & B_1^+-C_{13}-i(B_2^+-C_{23}) \\ B_1^++C_{13}+i(B_2^++C_{23})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

$$\rho^{T_2} = \frac{1}{4}\begin{bmatrix} 1+B_3^++B_3^-+C_{33} & B_1^-+C_{31}+i(B_2^-+C_{32}) & B_1^++C_{13}-i(B_2^++C_{23}) & C_{11}+C_{22}+i(C_{12}-C_{21}) \\ B_1^-+C_{31}-i(B_2^-+C_{32}) & 1+B_3^+-B_3^--C_{33} & C_{11}-C_{22}-i(C_{12}+C_{21}) & B_1^+-C_{13}-i(B_2^+-C_{23}) \\ B_1^++C_{13}+i(B_2^++C_{23}) & C_{11}-C_{22}+i(C_{12}+C_{21}) & 1-B_3^++B_3^--C_{33} & B_1^--C_{31}+i(B_2^--C_{32}) \\ C_{11}+C_{22}-i(C_{12}-C_{21}) & B_1^+-C_{13}+i(B_2^+-C_{23}) & B_1^--C_{31}-i(B_2^--C_{32}) & 1-B_3^+-B_3^-+C_{33} \end{bmatrix}$$

Peres-Horodecki: if ρ^{T2} has at least one negative eigenvalue, the state is entangled

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1+\alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1+\alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2+\alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

Production phase-space



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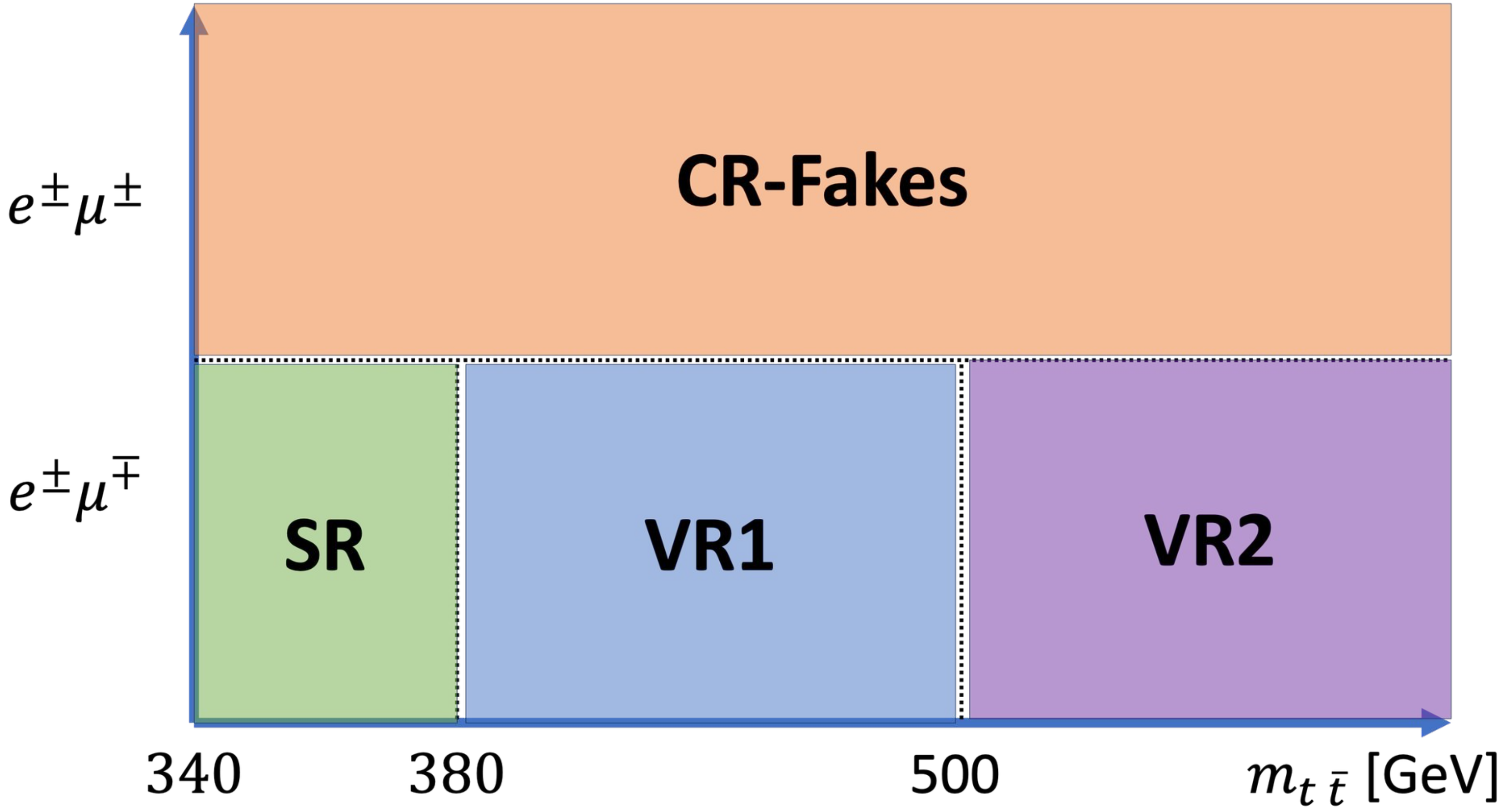
z-axis: concurrence C[ρ]

$$C[\rho] \equiv \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4) \quad (4)$$

where λ_i are the eigenvalues, ordered in decreasing magnitude, of the matrix $\mathcal{C}(\rho) = \sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$, with $\tilde{\rho} = (\sigma_2 \otimes \sigma_2)\ \rho^*\ (\sigma_2 \otimes \sigma_2)$ and ρ^* the complex conjugate of the density matrix in the usual spin basis of σ_3. The concurrence satisfies $0 \leq C[\rho] \leq 1$, with a quantum state being entangled if and only if $C[\rho] > 0$. Therefore, states satisfying $C[\rho] = 1$ are maximally entangled. We refer

C[ρ] > 0 ⇔ entanglement

Dileptonic $t\bar{t}$ selection



Reconstruction for the dilepton entanglement result

the detector. Several methods are available to reconstruct the top quarks from the detector level charged leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. The main method used in this work is the Ellipse method [70], which is a geometric approach to analytically calculate the neutrino momenta. Approximately 85% of events are successfully reconstructed by this method. If this method fails, the Neutrino Weighting method [71], which assigns a weight to each possible solution by the compatibility between the neutrino momenta and the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event, after scanning possible values of the pseudo-rapidities of the neutrinos, is used. If both methods fail,

arXiv:2311.07288