Entanglement measurements at the LHC

LHC Precision Program (Benasque), 02/10/2023

Baptiste Ravina

Prelude: top quark spin correlations

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

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

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

→ **correlations are observable!**

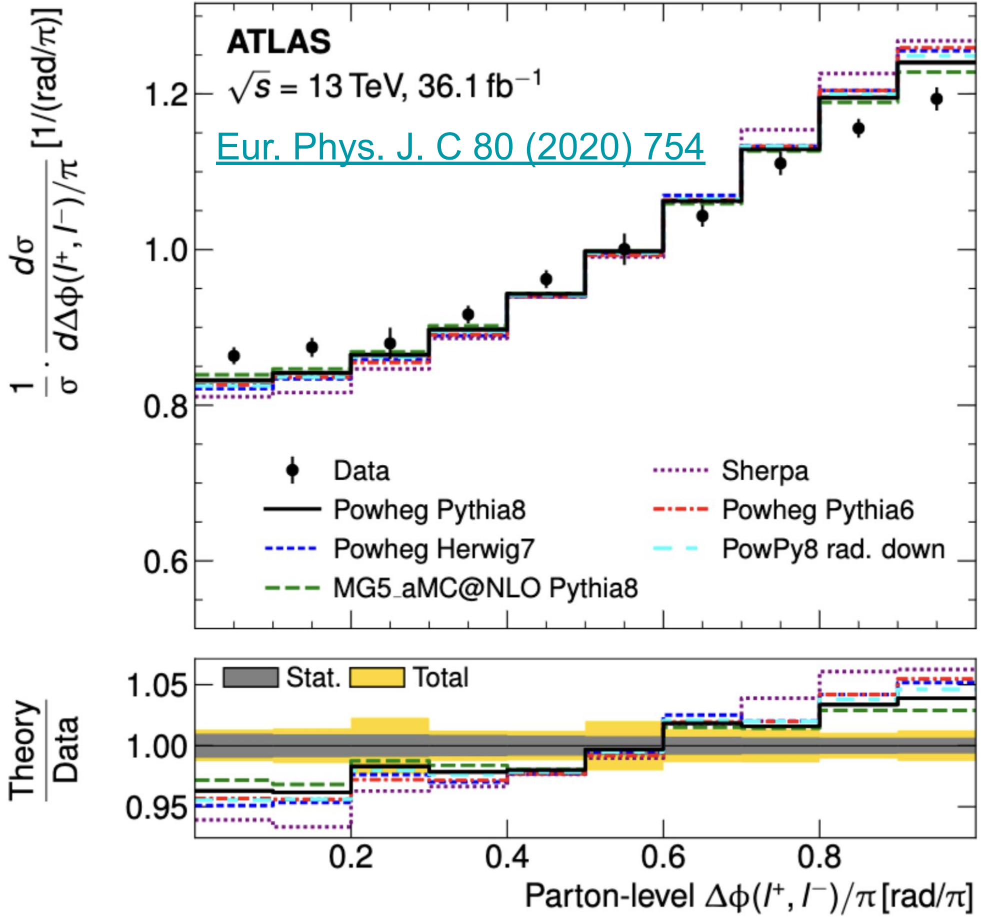
	b	l	d/s	u/c
α_i(LO)	-0.41	1	1	-0.31
α_i(NLO)	-0.39	~ 1	0.97	-0.32

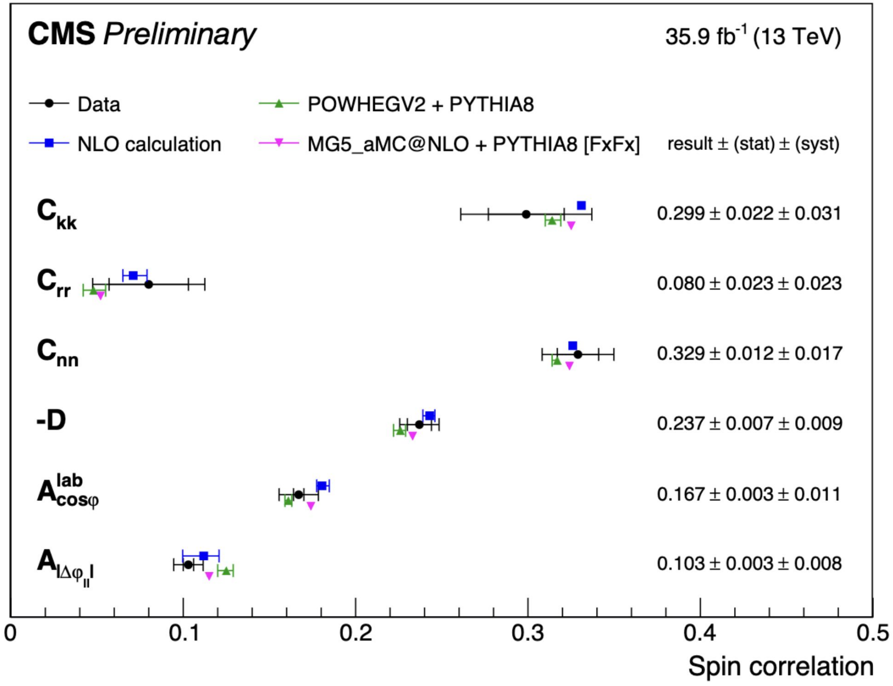
Typical analysis:

- rely on dilepton final state (maximal spin analysing power α)
- unfold angular distributions to access polarisation (B) and correlation (C) coefficients
- observable Δϕ(l,l) is also very sensitive to spin correlations already at detector-level

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

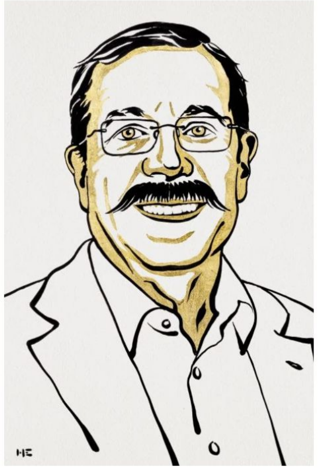
State-of-the-art in 2020...





Phys. Rev. D 100 (2019) 072002

As you may have heard…



Ill. Niklas Elmehed © Nobel Prize Outreach

Alain Aspect

Prize share: 1/3

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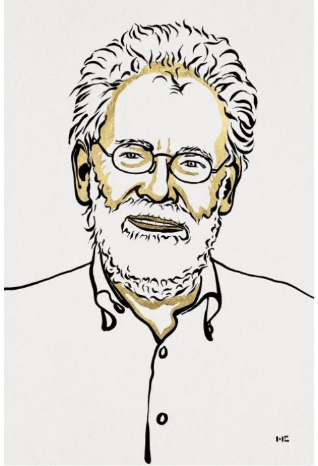
John F. Clauser

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

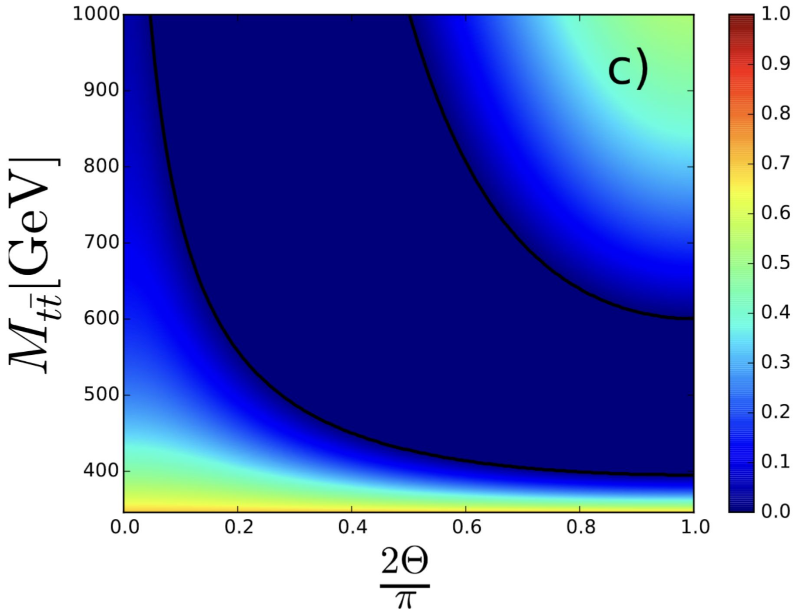
Prize share: 1/3

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"

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**"

$$\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b, \quad \sum_n p_n = 1, \; p_n \geq 0$$ *definition of a separable state*

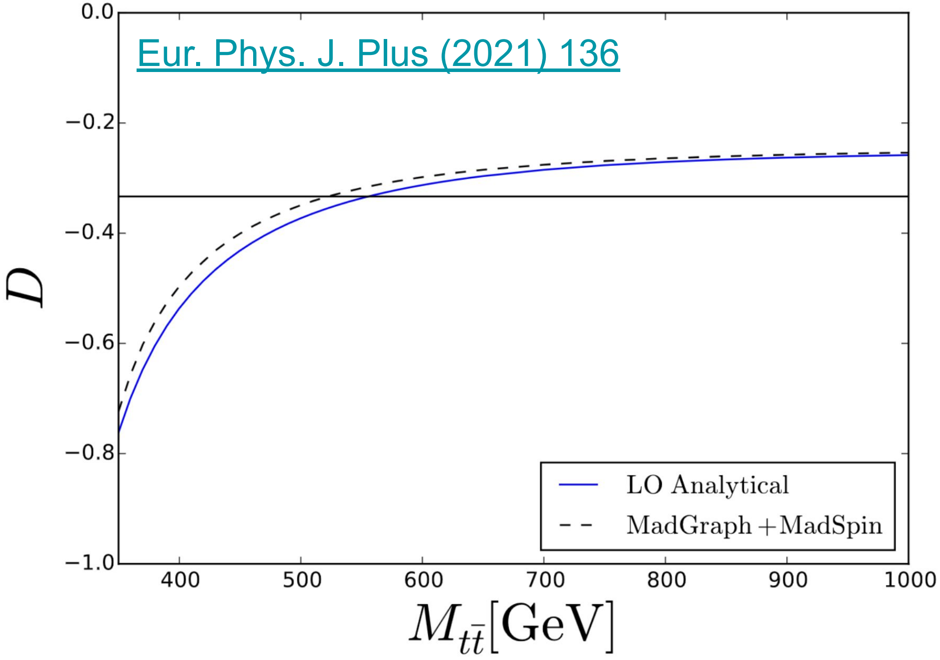


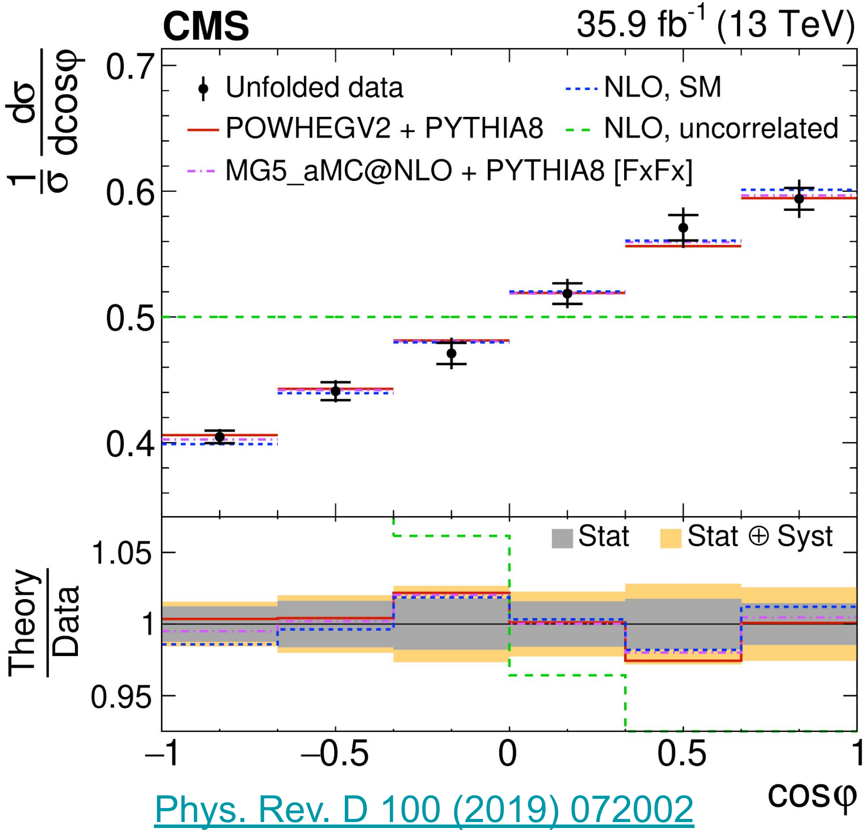
$$\mathrm{Tr}\,[\mathbb{C}] < -1$$ *Peres-Horodecki criterion*

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

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

So… did CMS observe quantum entanglement ?





Phys. Rev. D 100 (2019) 072002

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

The brand-new ATLAS result

Quantum entanglement in dilepton ttbar

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

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

	b	l	d/s	u/c
α_i(LO)	-0.41	1	1	-0.31
α_i(NLO)	-0.39	~ 1	0.97	-0.32

Maximal spin analysing power of the leptons

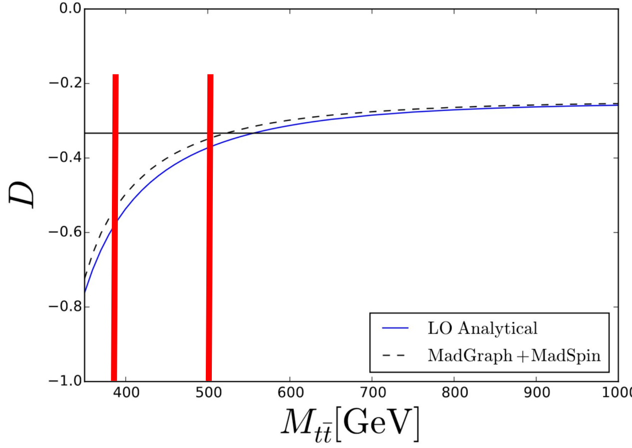
Need to reconstruct the full ttbar system (2 neutrinos)

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

→ mixture of methods to improve efficiency

Then partition events into three selections:

- **340<M_{tt}<380: entanglement signal region**
- 380<M_{tt}<500: validation region (dilution+mis-reconstruction)
- **500<M_{tt}: no-entanglement** control region



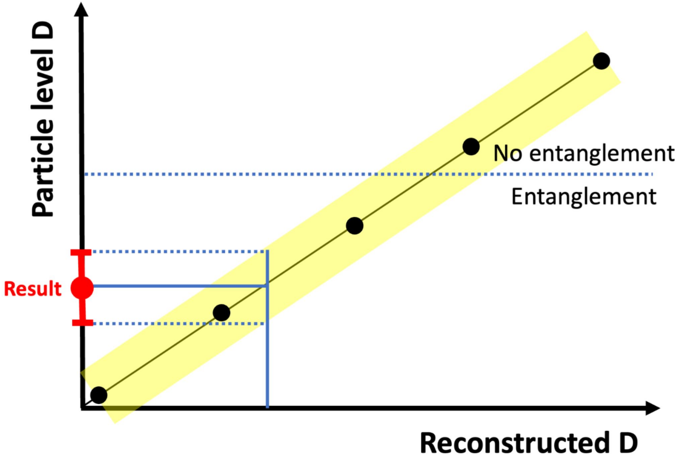
Analysis procedure

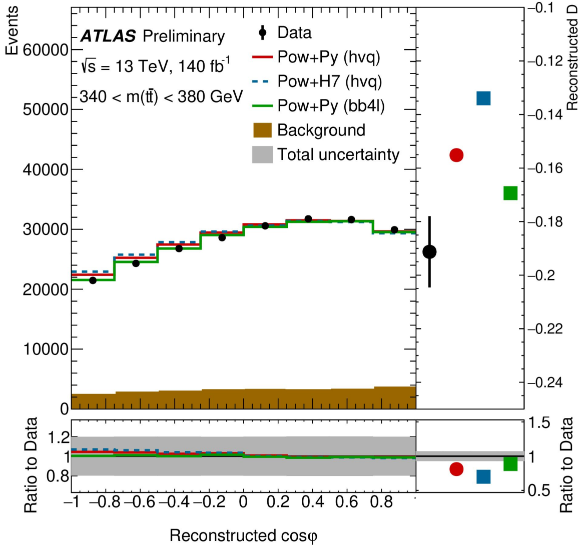
"Calibration curve" method: use the nominal MC to map the detector-level D value (average of distribution) to the fiducial particle-level D.

Systematics are propagated with their own curves, quadratic envelope.

→ Build the curve by sampling different D values.

State-of-the-art MC: Powheg Box Res (bb4l), comes with full NLO spin correlations and off-shell/interference effects





A closer look at uncertainties

"Backgrounds": mostly $Z \rightarrow \tau\tau$, from which we get two leptons that escape the Zee/μμ cuts and lead to a flat cos(φ) distribution (spin information from taus is lost)

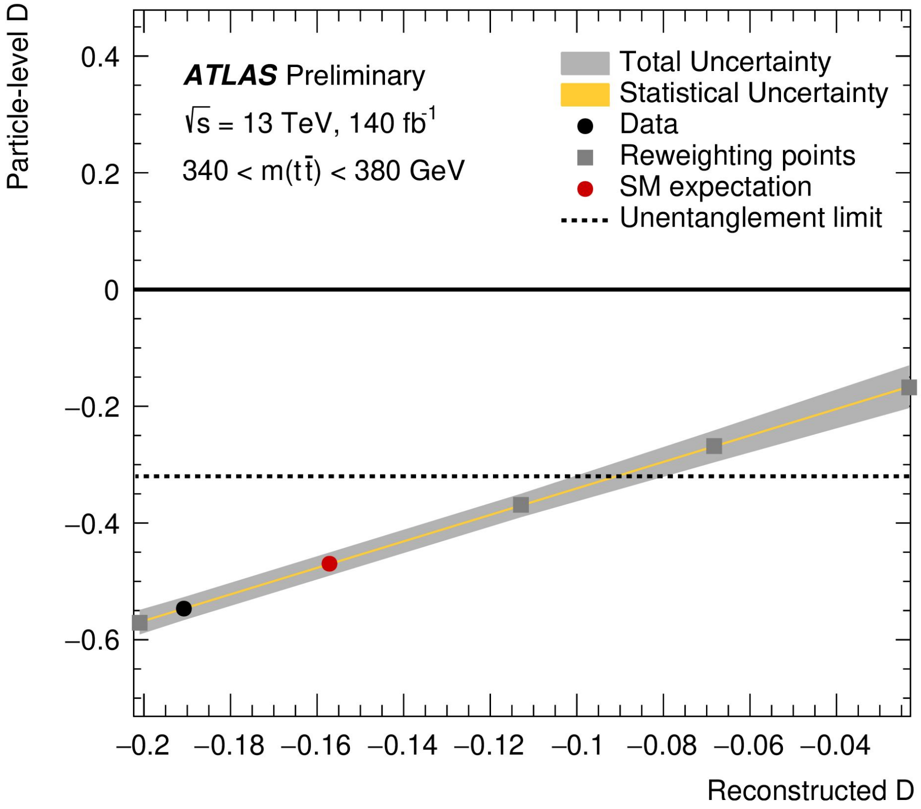
Calibrate to fiducial particle-level to avoid "arbitrarily large" parton shower uncertainty (Pythia vs Herwig) : full details in the CONF.

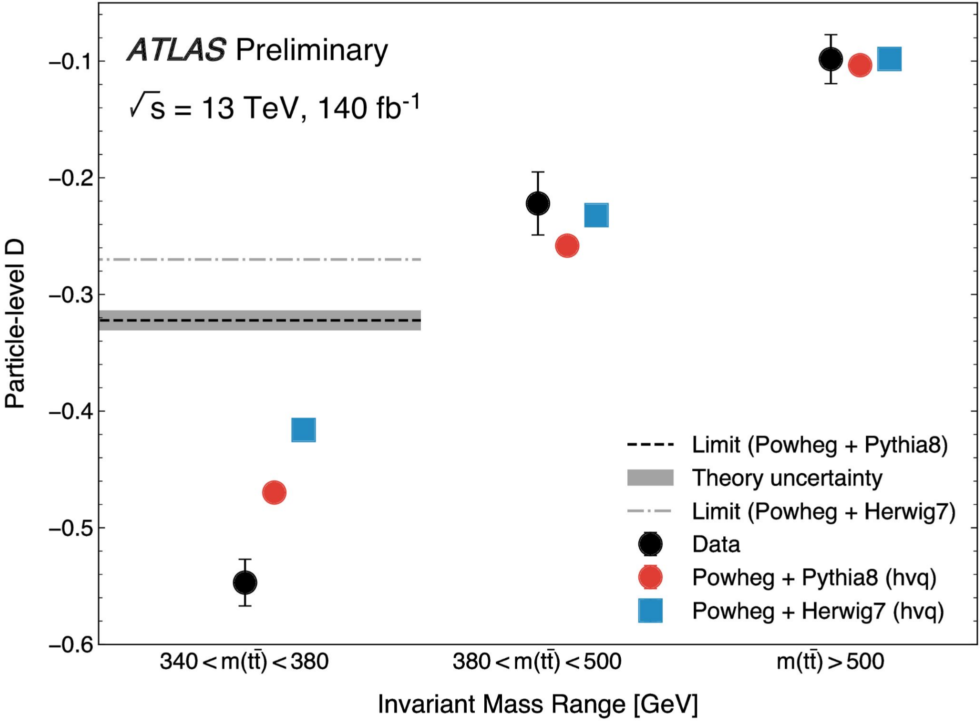
We believe it boils down to the p_T-ordered shower used in Pythia versus angular-ordered shower in Herwig

Systematic source	$\Delta D_{\text{particle}} (D = -0.470)$	ΔD (%)
Signal Modelling	0.017	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.3
Backgrounds	0.010	1.8
Stat.	0.002	0.3
Syst.	0.021	3.8
Total	0.021	3.8

Leading Systematics	Relatvie Size [D = SM (−0.47)]
Top-quark decay	1.6 %
$Z \rightarrow \tau\tau$ Cross-section	1.5 %
Recoil To Top	1.1 %
Final State Radiation	1.1 %
Scale Uncertainties	1.1 %
NNLO Reweighting	1.1 %
Parton Distribution Function (5)	0.8 %
pThard1 Setting	0.8 %
Top-quark Mass	0.7 %
Single Top Quark Wt Cross-section	0.4 %

Observation of quantum entanglement in dilepton ttbar





non-relativistic QCD effects close to threshold, not included in MC generators

$$D = -0.547 \pm 0.002\ [\text{stat.}] \pm 0.020\ [\text{syst.}]\ (-0.470 \pm 0.002\ [\text{stat.}] \pm 0.017\ [\text{syst.}])$$

Observation of quantum entanglement in dilepton ttbar

ATLAS CONF Note

ATLAS-CONF-2023-069

28th September 2023

Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

We report the highest-energy observation of entanglement so far in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a centre-of-mass energy of $\sqrt{s}$ = 13 TeV and an integrated luminosity of 140 fb^{-1}. Spin entanglement is detected from the measurement of a single observable D, inferred by the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured on a narrow interval around the top-quark–antitop-quark production threshold, where the entanglement detection is expected to be significant. The entanglement observable is measured in a fiducial phase-space with stable particles. The entanglement witness is measured to be $D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The large spread in predictions from several mainstream event generators indicates that modelling this property is challenging. The predictions depend in particular on the parton-shower algorithm used. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks, and the observation of entanglement at the highest energy to date.

effects close to threshold, not ...erators

$D = -0.547 \pm 0.00$ ... [stat.] $\pm$ 0.017 [syst.])

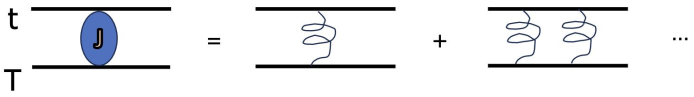
Last week was the TOP'2023 conference

- First public presentation of the ATLAS results
- We were *eagerly awaiting* a similar set of results from CMS!
  - *rumours* that it would be a repeat of the previous full spin density matrix measurement, but now also differential in M(ttbar)
  - would include the quantum entanglement observable (perhaps a bit more?)
  - maybe an interpretation in terms of toponium production at threshold?
  - ultimately the results were not approved in time by the CMS Collaboration 😢

- Instead of presenting the CMS results, I will therefore briefly highlight a few other topics:
  - **what's going on at threshold?**
  - can we **confirm this "slight excess of entanglement"** without CMS?
  - **what else can be achieved** with Run 3 at the LHC / what needs HL-LHC?

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 arXiv:2102.11281 → **toponium**
    - but apparently not working properly? anyone else wants to volunteer a model?
  - A number of calculations available, most recently Ju et al. arXiv:2004.03088
    - pure parton-level calculation (stable tops), resums leading-power and next-to-leading-power calculations and matches to NNLO differential ttbar



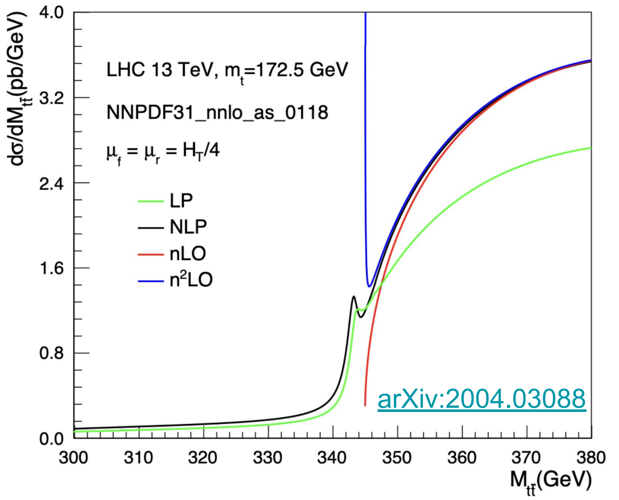
from A. Mitov

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): $J \sim \frac{\alpha_s/\beta}{e^{\pi\frac{\alpha_s}{\beta}}-1} = 1+\frac{\alpha_s}{\beta}+\dots$



A possible and conceptually “simple” cross-check

- We can repeat the measurement in the lepton+jets channel!
  - already used in the ATLAS Run 1 spin correlation measurement Phys. Rev. D 90 (2014) 112016

- There we need to rely on the down-type quark from the W boson
  - target $W \rightarrow cs$ final states (50%) with charm-tagging
  - combinatorics get better with recent machine learning developments
- More backgrounds, but easier reconstruction
- Could also throw in the b-jets…

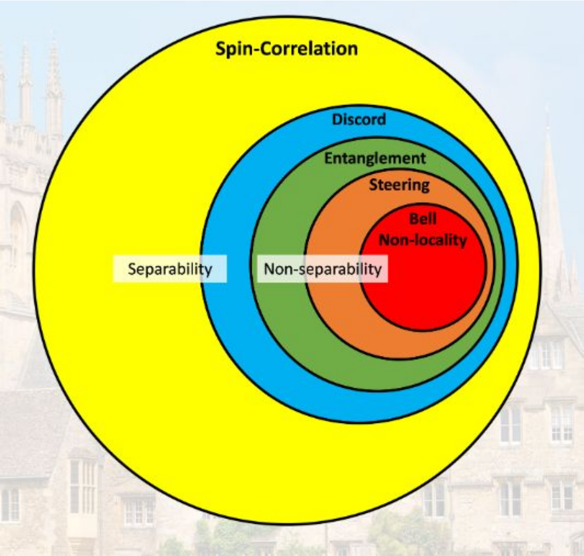
	b	l	d/s	u/c
α_i(LO)	-0.41	1	1	-0.31
α_i(NLO)	-0.39	~ 1	0.97	-0.32

The landscape of quantum information at the LHC

Quantum tops beyond entanglement

Follow-up papers by the same authors formulate additional quantum information theory concepts in term of ttbar production at the LHC:

- **Quantum Discord** measures the departure of the information entropy from classical theory
- **Quantum Steering** measures the non-local effect of one measurement on the outcome of the other
- both are usually very hard to measure, given the need to repeat experiments over large samples of spin directions → the LHC gives us millions of randomly sampled directions "for free"!
- both are **asymmetric** quantities → new tests of CP violation in the strong sector!



In general, want to perform quantum tomography
= reconstruct the full spin density matrix

Improved tests of entanglement with tops

- A new **general marker** of quantum entanglement has been proposed
  - in the **threshold** region, exactly what is being done now (D=Tr[C]/3)
  - in the **boosted** region, would need slightly different angular distribution
  - at threshold, additional cut on the ttbar velocity β can reduce the qq contamination
  - both approaches can increase the statistical sensitivity by ~20%
- Similarly, we can **simplify tests** of Bell's inequality violation
  - sufficient to know the 3 spin correlation coefficients, but better done in the beam basis
  - alternatively, could measure a simple asymmetry

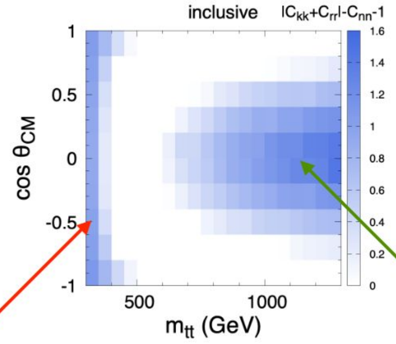
$$E \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

spin correlations

	Threshold $\not\beta$	Threshold β	Boosted
Individual	0.021 ± 0.053	0.119 ± 0.074	0.218 ± 0.141
Direct	0.027 ± 0.035	0.121 ± 0.045	0.208 ± 0.125

asymmetry

cut on β



Threshold region,
$E = -(C_{kk} + C_{rr} + C_{nn}) - 1 > 0$

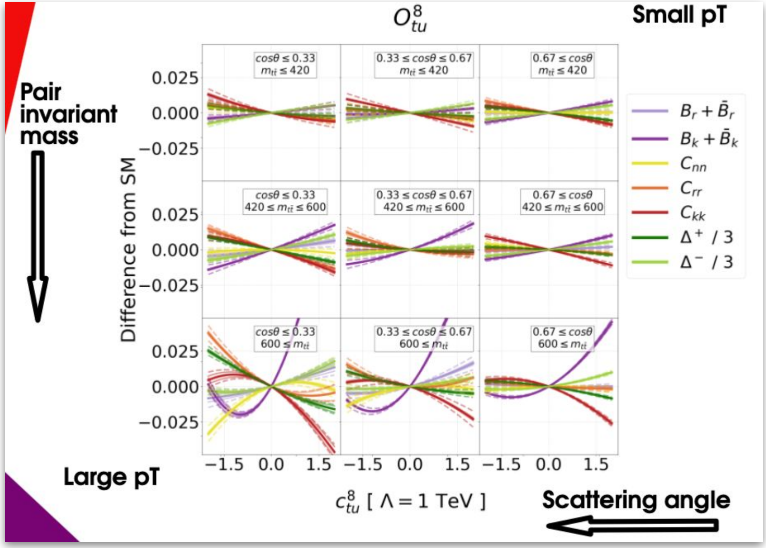
Boosted region,
$E = C_{kk} + C_{rr} - C_{nn} - 1 > 0$

Quantum entanglement in the SMEFT

- The 15 components of the ttbar spin density matrix can constrain SMEFT operators affecting top production
  - entanglement and Bell observables are also sensitive
  - in the dilepton channel, all $O(1/\Lambda^2)$ effects in the top decay cancel out (to less than permille level)
  - best predictions are currently at NLO QCD with approximate-NLO spin effects: this is not something we can match with our MC, **better to unfold the data**
- 4-quark operators need NLO calculations
  - projections of CMS-like analysis to full Run 2+3 give competitive constraints wrt. to current **full global fits to top LHC data**

negligible EFT in top decays!

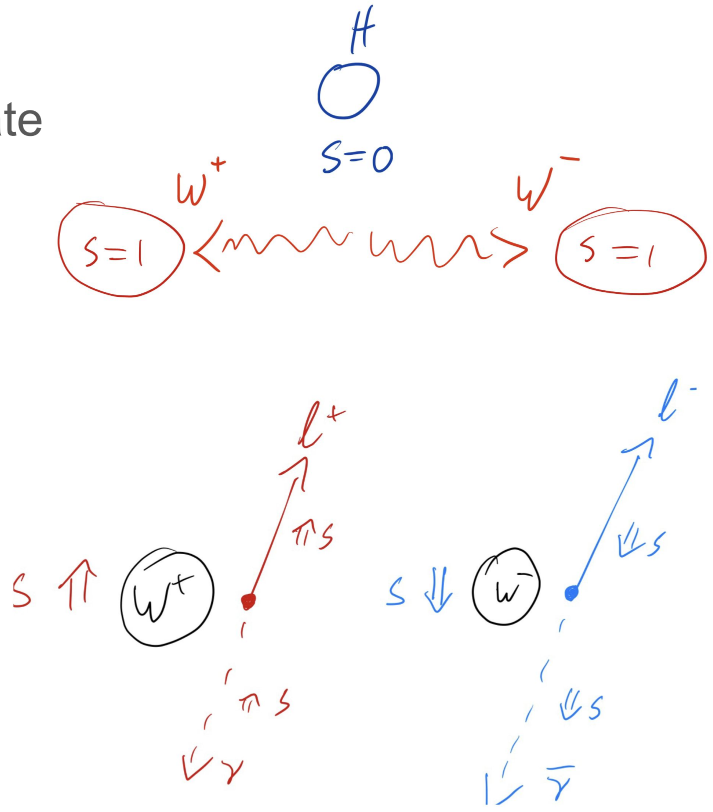
$$\alpha_\ell = 1 - \frac{c^2_{uW,33} v^4}{\Lambda^4} \frac{4(2m_t^6 + 3m_t^4 m_W^2 - 6m_t^2 m_W^4 + m_W^6 + 12 m_t^4 m_W^2 \log m_W/m_t)}{(m_W^2 - m_t^2)^2 (m_t^2 + 2m_W^2)}$$



Quantum state tomography with weak decays

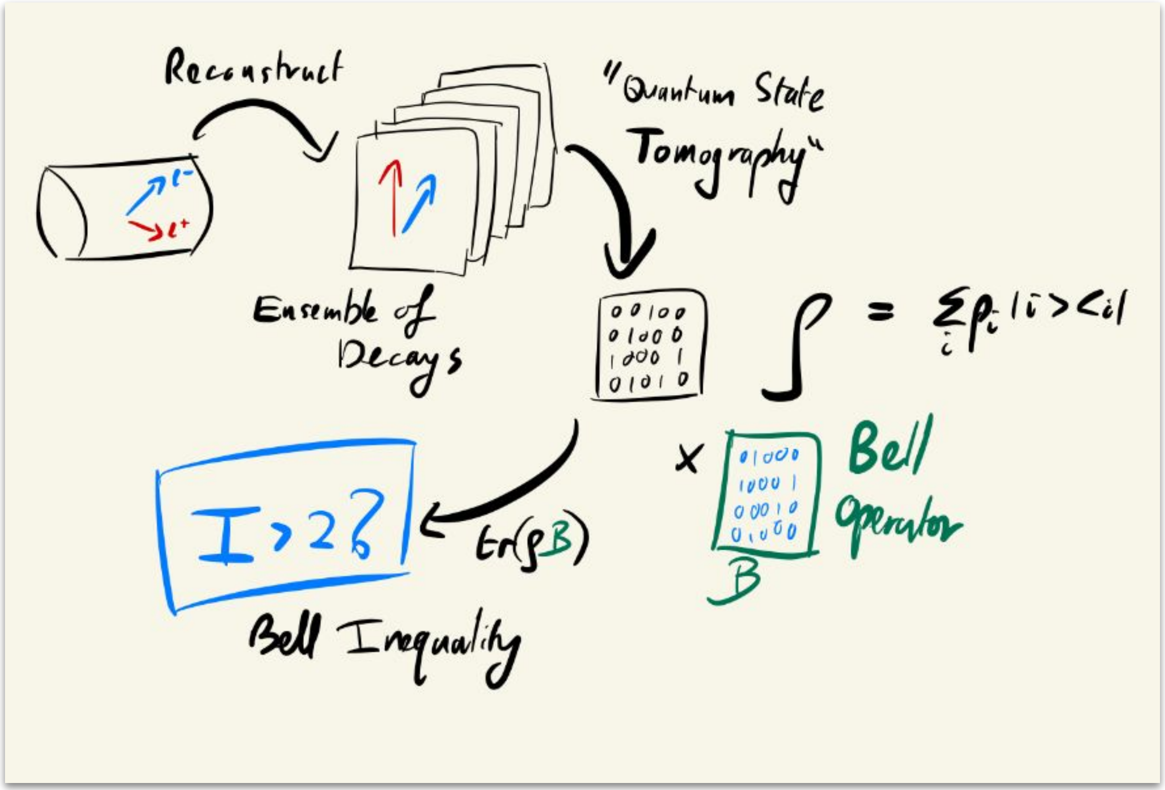
“Decaying W bosons are their own polarimeters”

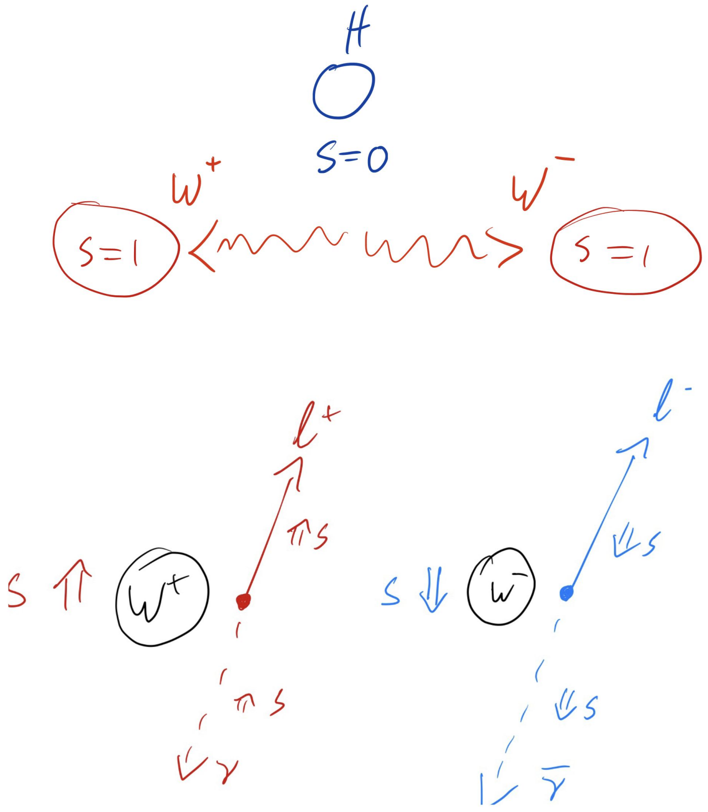
- HWW* provides a near-maximally entangled state
  - spin density matrix has 80 real parameters
  - can be uniquely determined from angular distributions
  - violation of Bell’s inequality for a pair of qutrits can be probed from “only” 10 such distributions
- Sensitivity estimate in the lνlν final state range from 1σ to 5σ
  - but neglects backgrounds and assumes 10 GeV resolution on neutrino reconstruction… unrealistic?



Quantum state tomography with weak decays

"Decaying W bosons are their own polarimeters"





Quantum tomography of diboson systems

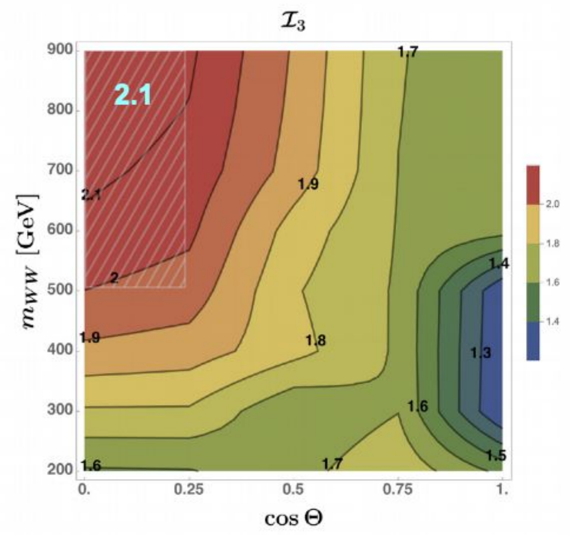
Formalism can be extended to all massive diboson final states: HWW*, HZZ*, WW, WZ, ZZ

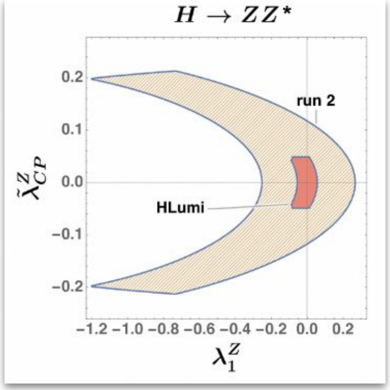
pp→VV infeasible at the HL-LHC: have to "wait" for FCC/muon colliders

Expect HWW* to be systematically dominated, but HZZ* gets better with stats

- Bell's inequality violation at most 1sigma for HWW*
- 1.3σ for HZZ* in Run 2, 5.6σ at HL-LHC
- but once again the "experimental scenarios" are likely too idealised

HZZ* could further be used to **drive constraints** on anomalous couplings → stronger than cross section alone!





Entanglement and Bell's inequalities in HZZ*

We can exploit further the symmetries of the ZZ final state, to **avoid** having to study the full 80-parameter spin density matrix

→ **entanglement marker** narrowed down to 2 doubly-differential observables

Observing entanglement becomes equivalent to observing an asymmetry in either!

Highlights the relevance of mass cuts

We are looking to show C≠0 and I_3>2

Experimental projections compatible with other theory predictions, slightly more realistic scenario due to 4 lepton final state…

- **LHC Run 2+3**

	min m_{Z_2} 0	10 GeV	20 GeV	30 GeV
N	450	418	312	129
$C_{2,1,2,-1}$	-0.98 ± 0.31	-0.97 ± 0.33	-1.05 ± 0.38	-1.06 ± 0.61
$C_{2,2,2,-2}$	0.60 ± 0.37	0.64 ± 0.38	0.74 ± 0.43	0.82 ± 0.63
I_3	2.66 ± 0.46	2.67 ± 0.49	2.82 ± 0.57	2.88 ± 0.89

Table 1: Values $C_{2,1,2,-1}$, $C_{2,2,2,-2}$ and I_3 obtained from 1000 pseudo experiments with $L = 300$ fb^{-1}.

- **HL-LHC**

	min m_{Z_2} 0	10 GeV	20 GeV	30 GeV
N	4500	4180	3120	1290
$C_{2,1,2,-1}$	-0.95 ± 0.10	-1.00 ± 0.10	-1.04 ± 0.12	-1.04 ± 0.19
$C_{2,2,2,-2}$	0.60 ± 0.12	0.64 ± 0.12	0.74 ± 0.14	0.83 ± 0.20
I_3	2.63 ± 0.15	2.71 ± 0.16	2.81 ± 0.18	2.84 ± 0.28

Table 2: Same as Table 1, for $L = 3$ ab^{-1}.

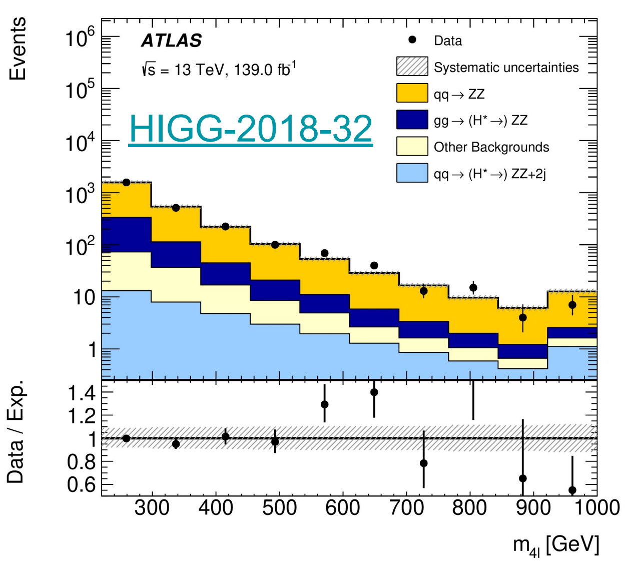
A twist on polarisations: H*ZZ (not a typo!)

ATLAS recently proposed a new analysis strategy to search for high-mass off-shell Higgs bosons in the 4 lepton final state → 2 on-shell Z bosons!

Allows to use another **entanglement "trick"**: entanglement marker can be recast as binary test between observing only longitudinal polarisations of the Z bosons (**separable**) or both transverse and longitudinal (**entangled**).

Can be done with lab-frame observables (very clean) and existing Monte Carlo techniques (well defined polarisations)

In practice: completely stat dominated all the way up to HL-LHC (see ATLAS-internal study)

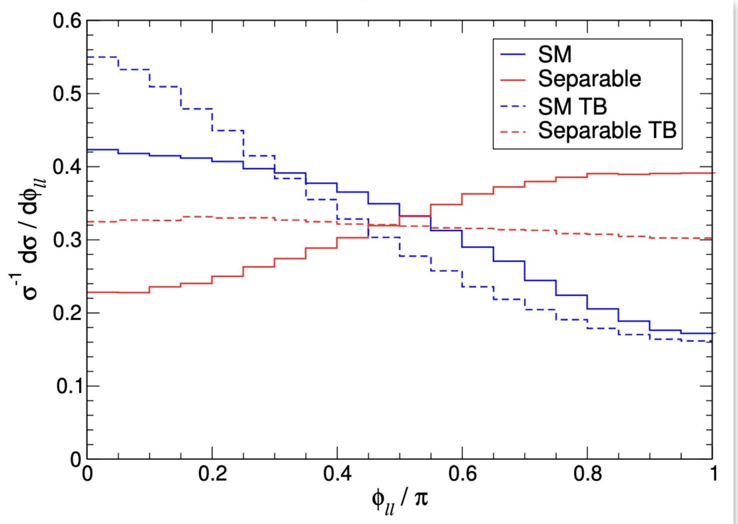


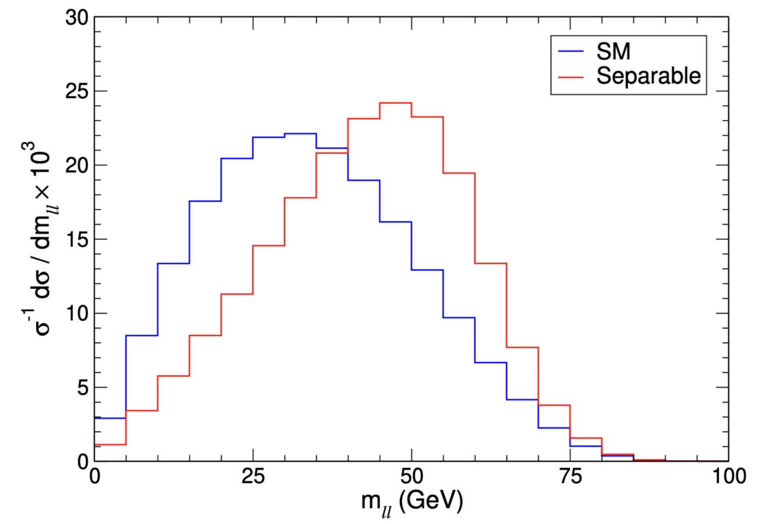
Resampling polarisations in HWW*

The “**trick**” is saved in the H-onshell/W-offshell regime by the assumption that the W decays to massless particles: OK for e/μ, not for taus (but we don’t want to look at taus anyway)

Rely on the **“CAR” method** (*custom angle replacement*) to resample existing HWW* MC samples according to new PDFs where we change the W polarisations

→ currently under study for application within ATLAS



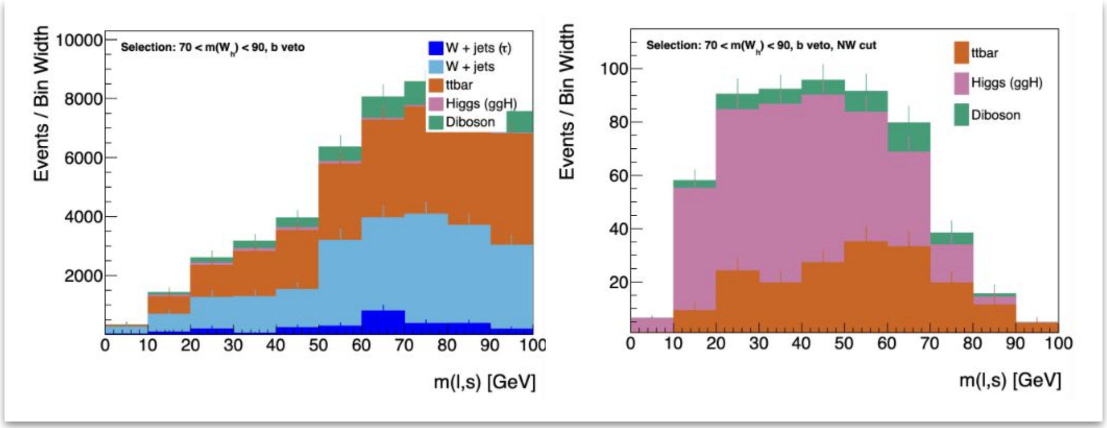


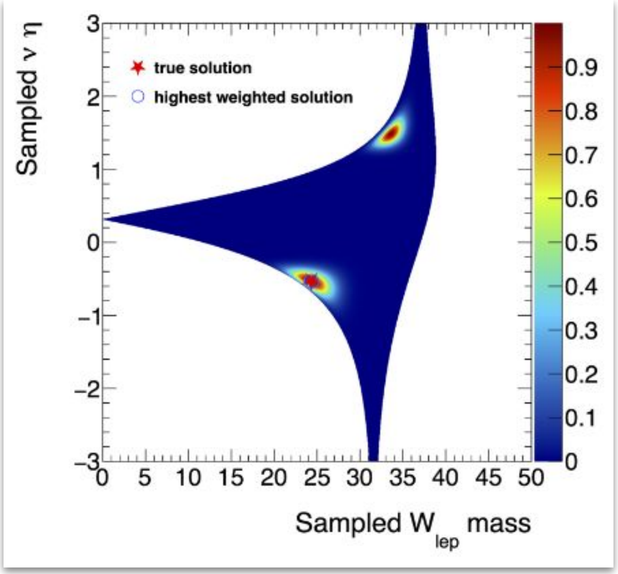
Accessing entanglement in semi-leptonic HWW*

Dileptonic WW: clean observables at detector-level, but very hard to reconstruct the full Higgs system to measure the spin density matrix.

Semileptonic WW was so far too messy (large SM backgrounds)
→ new technique inspired from top reconstruction helps!

- exploit charm tagging to reconstruct on-shell W→cs
- off-shell W*→lν reconstructed with Neutrino Weighting
- both reconstructions can be used to suppress backgrounds:
  opens up a practical new final state for Higgs physics!
- but Bell's inequality violation will still take time (2σ until HL-LHC)





Wrapping it up

Multiple final states to look at:

- ttbar, HWW*, HZZ* ($\tau\tau$ and VV also received attention, but not nearly as promising)
- multi-lepton final states are “easier”, but we benefit from tackling complicated reconstruction problems (semileptonic HWW, dileptonic ttbar/HWW, off-shell bosons…)

The ultimate goal is to **measure the full spin density matrices** (in several bases and differentially in the invariant mass of the system)

- can also target observation of entanglement by using dedicated observables (few caveats of SM-like assumptions)
- Bell’s inequality violation very challenging
- **quantum discord** could be measured “properly” for the first time…

First observation of quantum entanglement in quarks and at relativistic energies!

We are eagerly awaiting any announcement from CMS…

A new subfield emerges: **quantum information at the LHC**

Backup

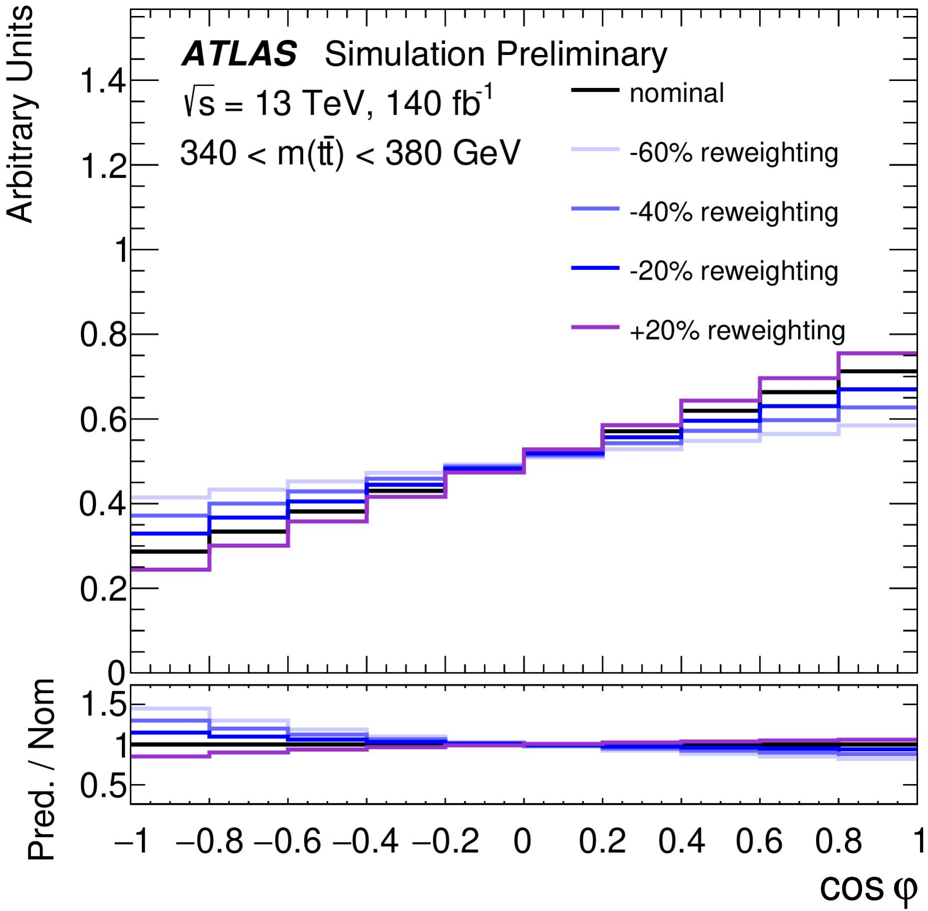
The reweighting method

- 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(ttbar)

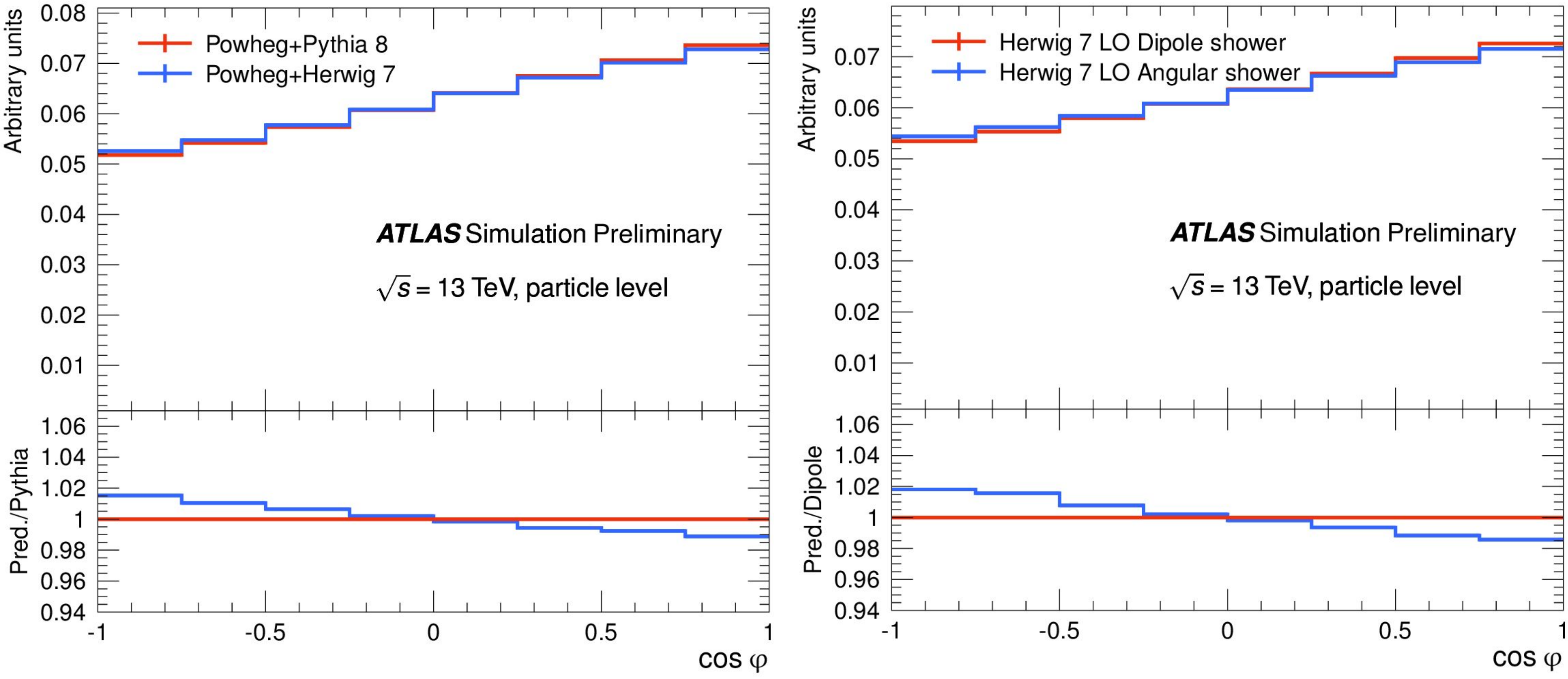
$$D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

- Then reweight each event as

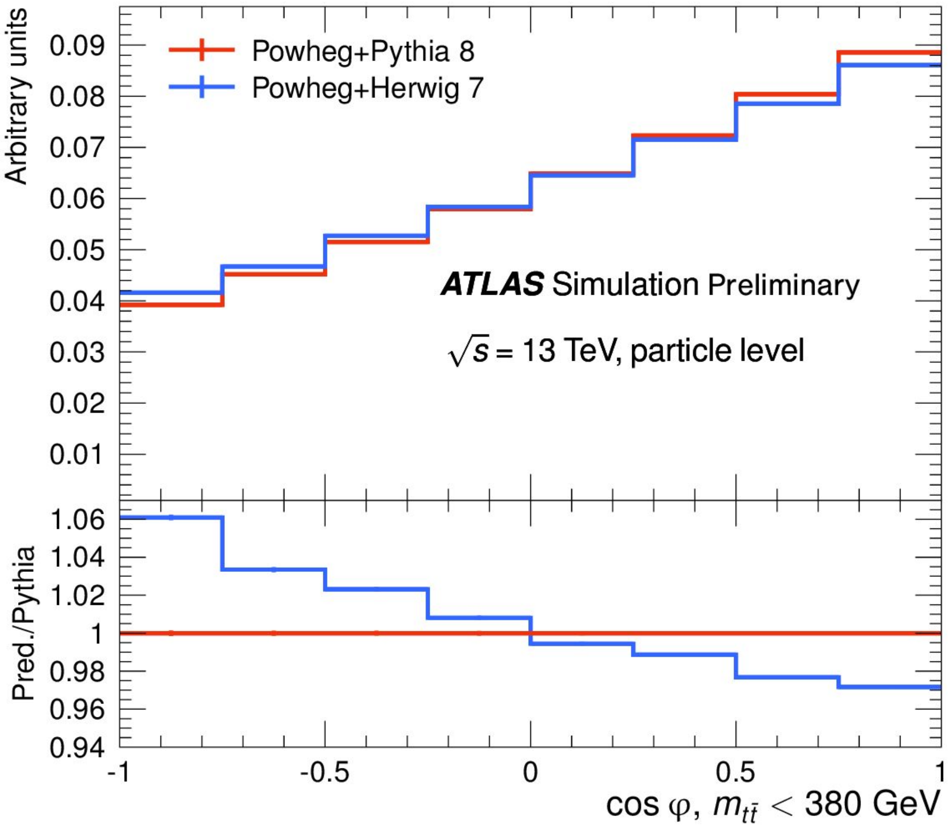
$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot X \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$$

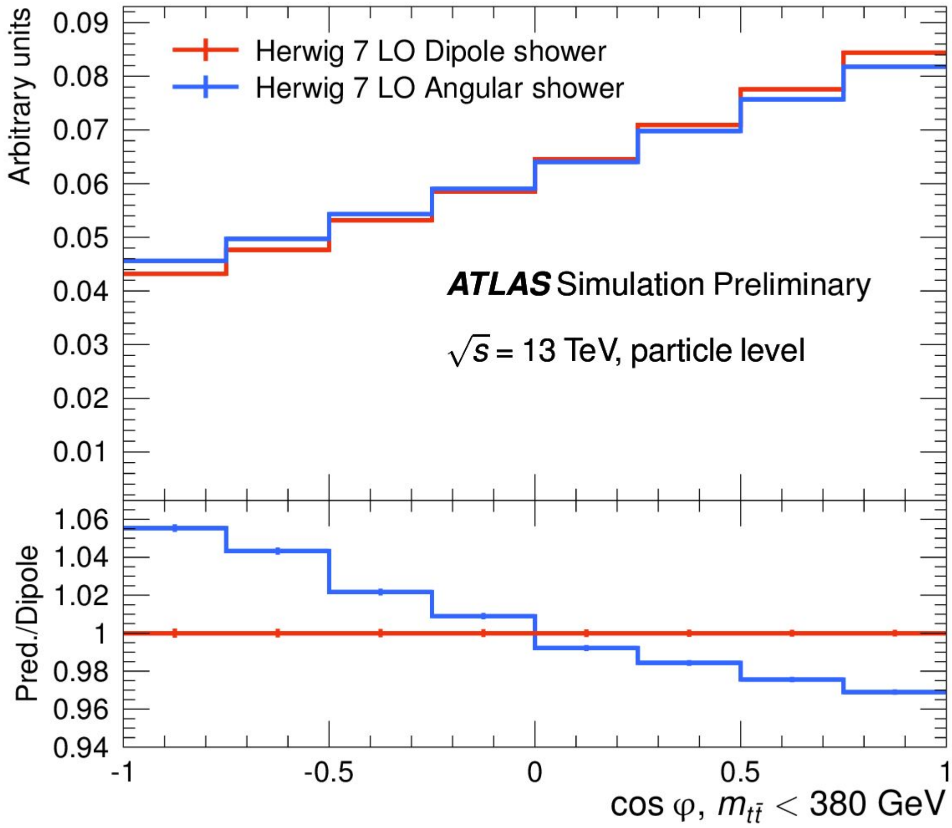


The problem with shower ordering (inclusive)

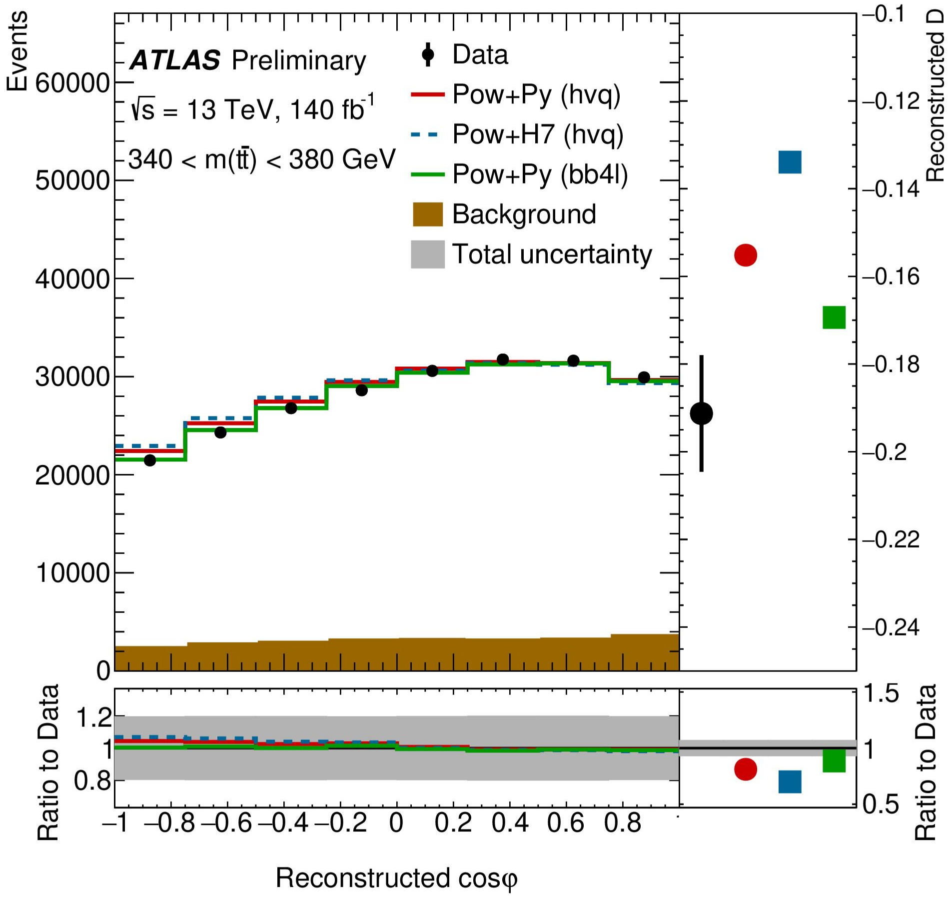


The problem with shower ordering (signal region)

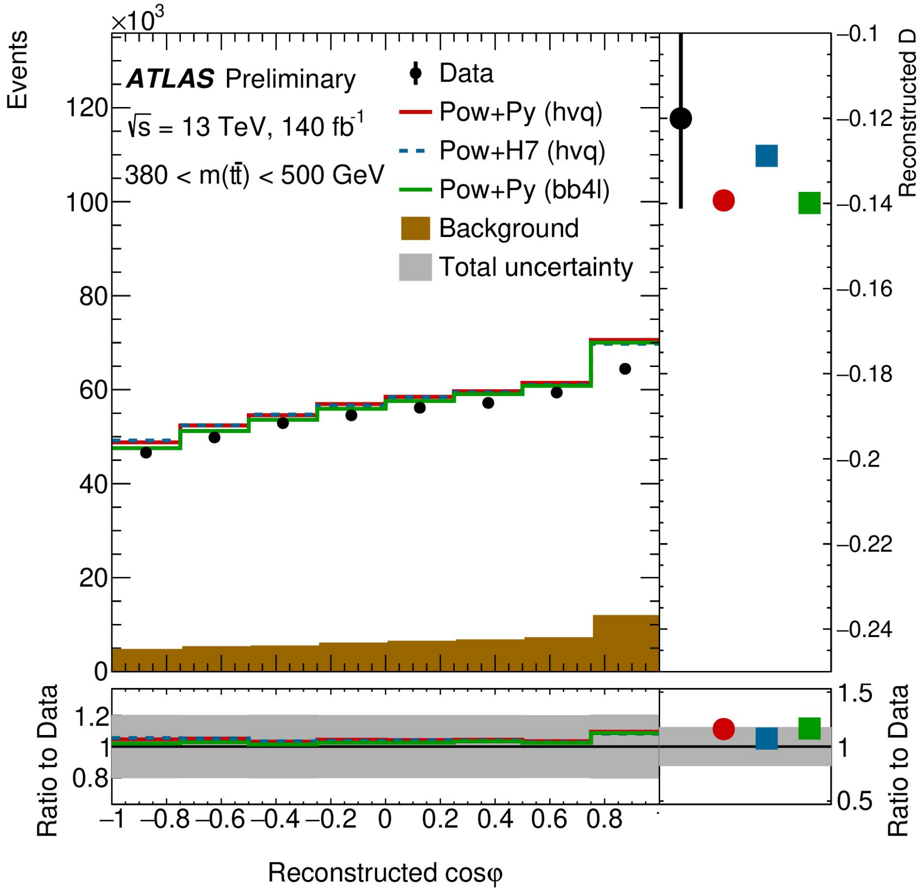


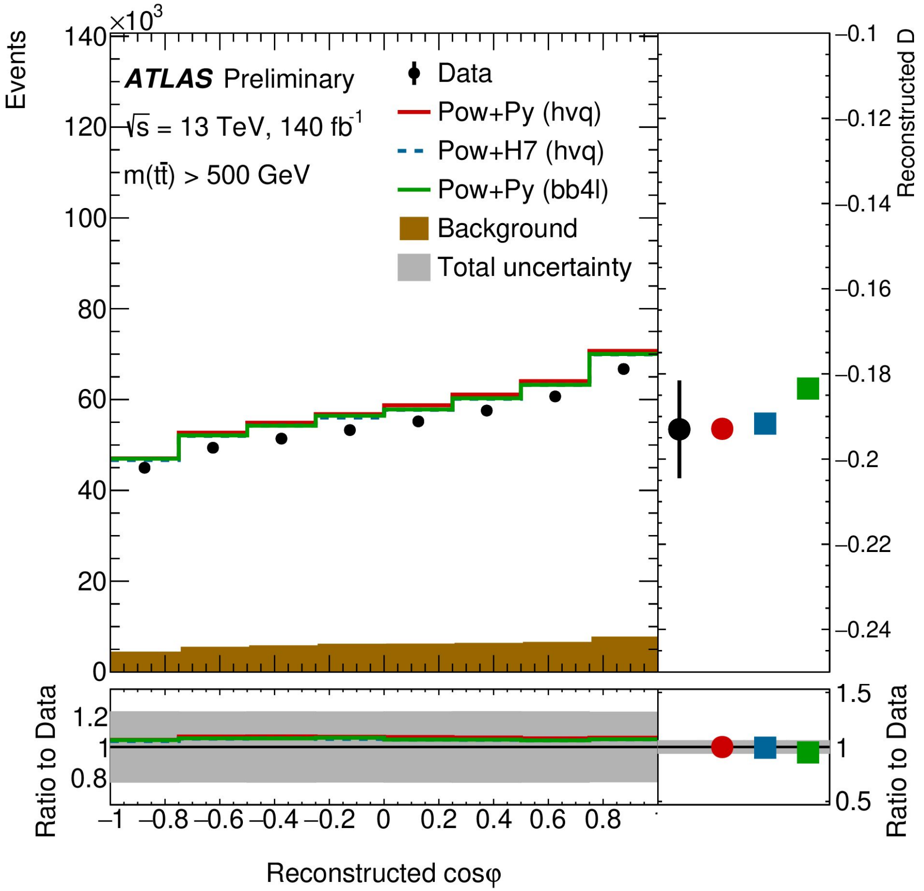


Data / MC agreement in the entanglement region



Data / MC agreement outside the entanglement region





Quantum entanglement in di-tau systems

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