Quantum information at the LHC

Harvard LPPC Seminar, 29/11/2023

Baptiste Ravina

Outline of the seminar

I want to show you the recent ATLAS **observation of quantum entanglement** in **top quark pair production**:

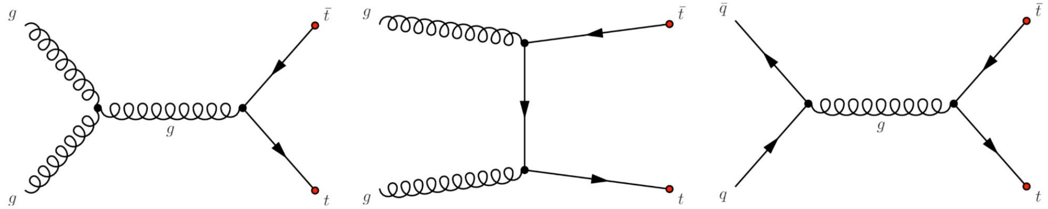
- introduce the top quark
- what has been done historically (spin correlations)
- moving to quantum entanglement
- discussing the experimental results

Then I will give an overview of **what else is possible** in terms of **quantum information at the LHC**:

- prospects for Higgs physics
- beyond entanglement: Bell's inequalities

Starting with top quark physics...

Fundamentals of top quark physics



- Most massive fundamental particle in the SM

→ its Mass / Yukawa is a free parameter: need to measure it

- Mean lifetime ~5x10^{-25}s << 1/Λ_{QCD} ~10^{-23}s

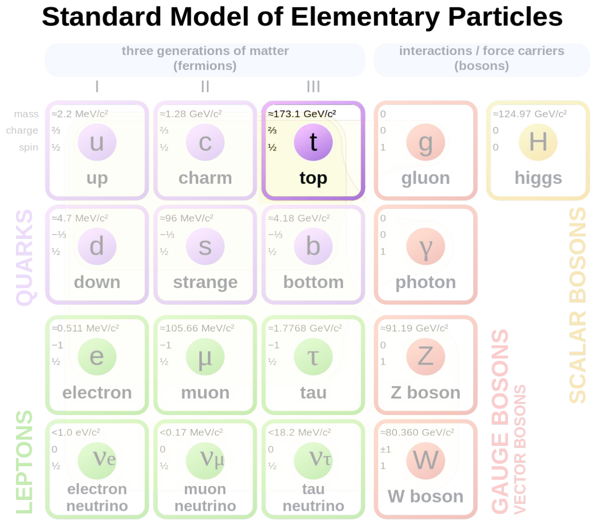
→ the only “bare quark”

- BR(t→Wb) ~ 100%

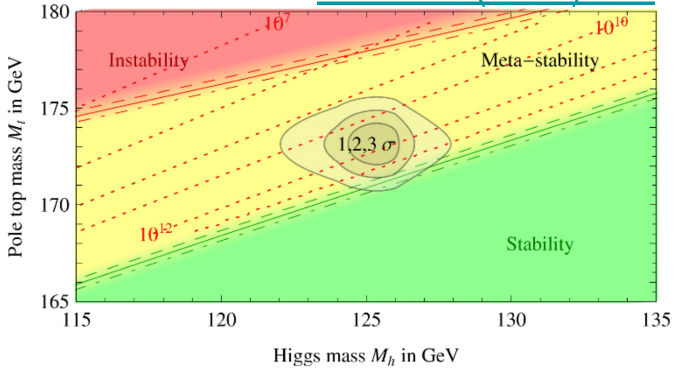
→ unique experimental signature

- Abundant production at the LHC, O(100M) pairs

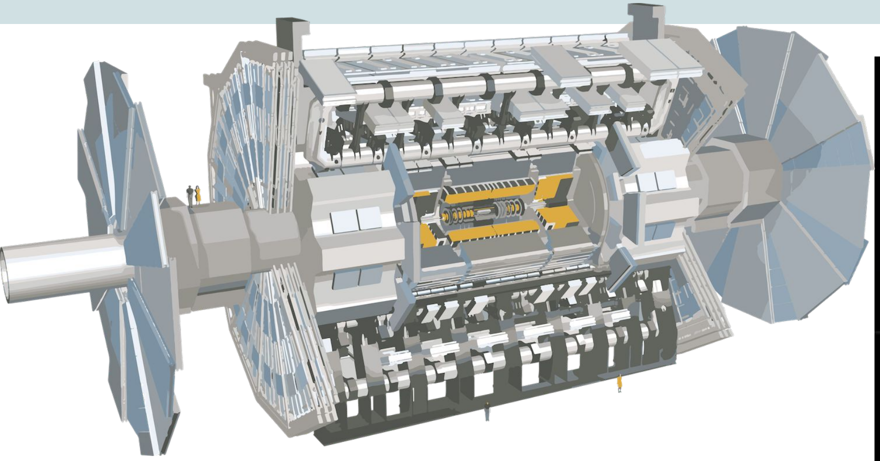
→ **“standard candle”**, very useful for calibrations

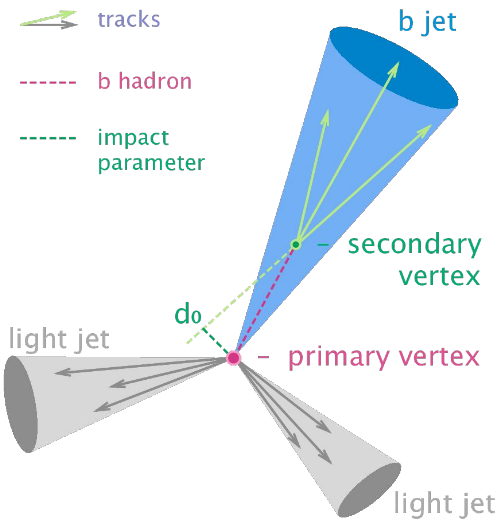


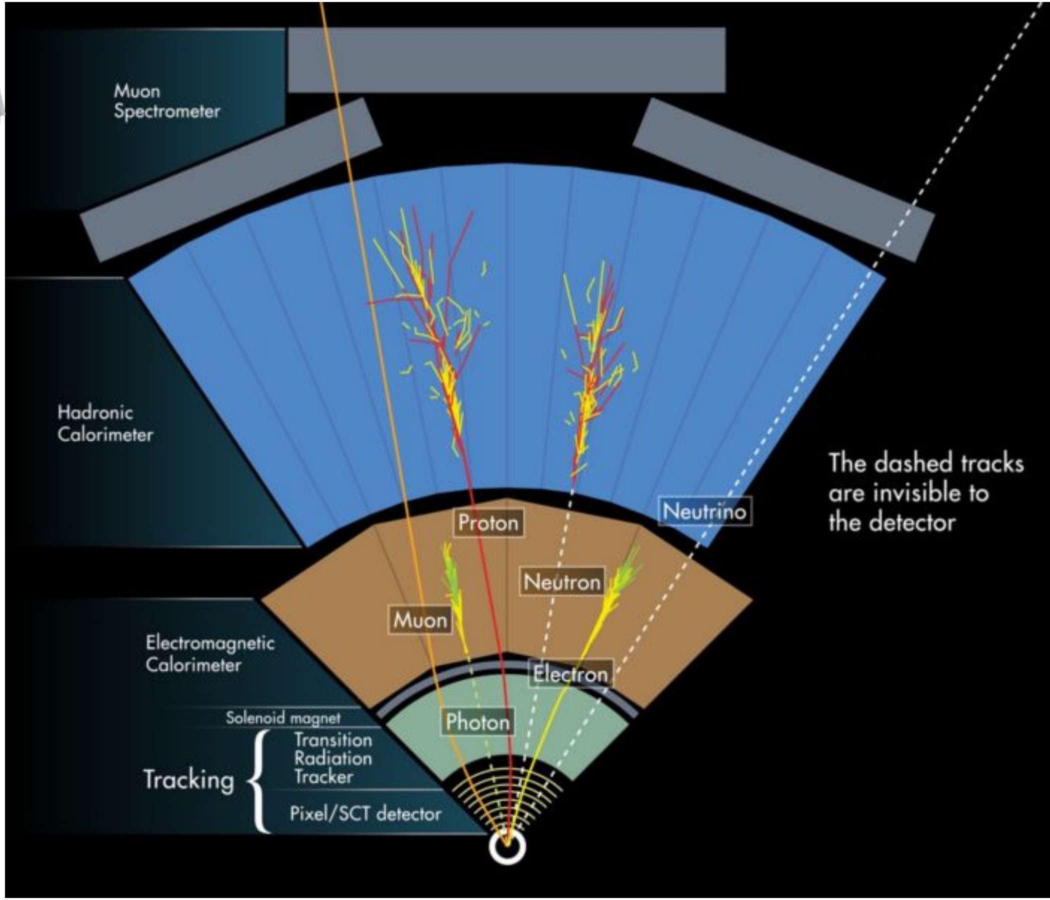
JHEP 08 (2012) 098



Particle identification at ATLAS in one slide







A long way to the top…

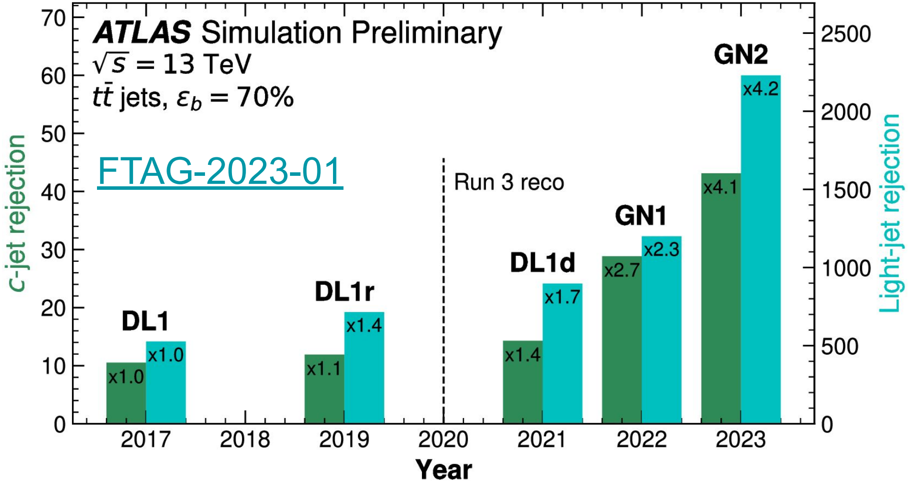
👉 CMS results
👉 ATLAS results

28 years of top quark physics!

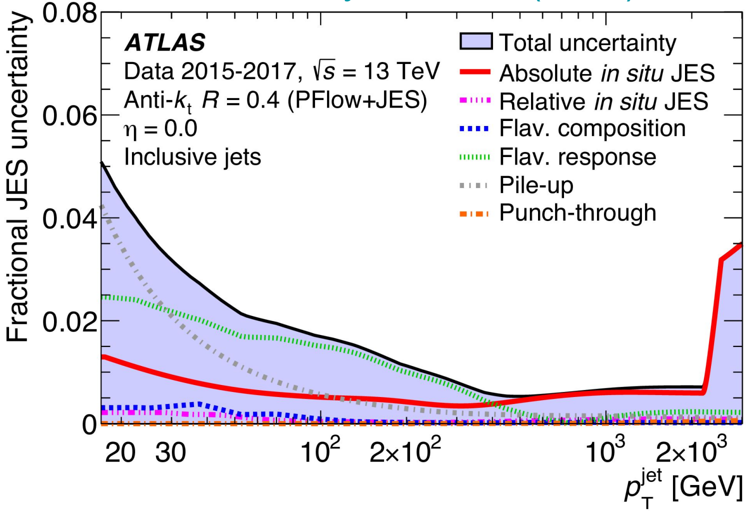
Ever more precise measurements enabled by excellent collider and detector performance

Benefit from all areas of Combined Performance:

- jets & missing energy
- flavour tagging
- lepton ID & isolation
- luminosity
- …



Eur. Phys. J. C 81 (2021) 689

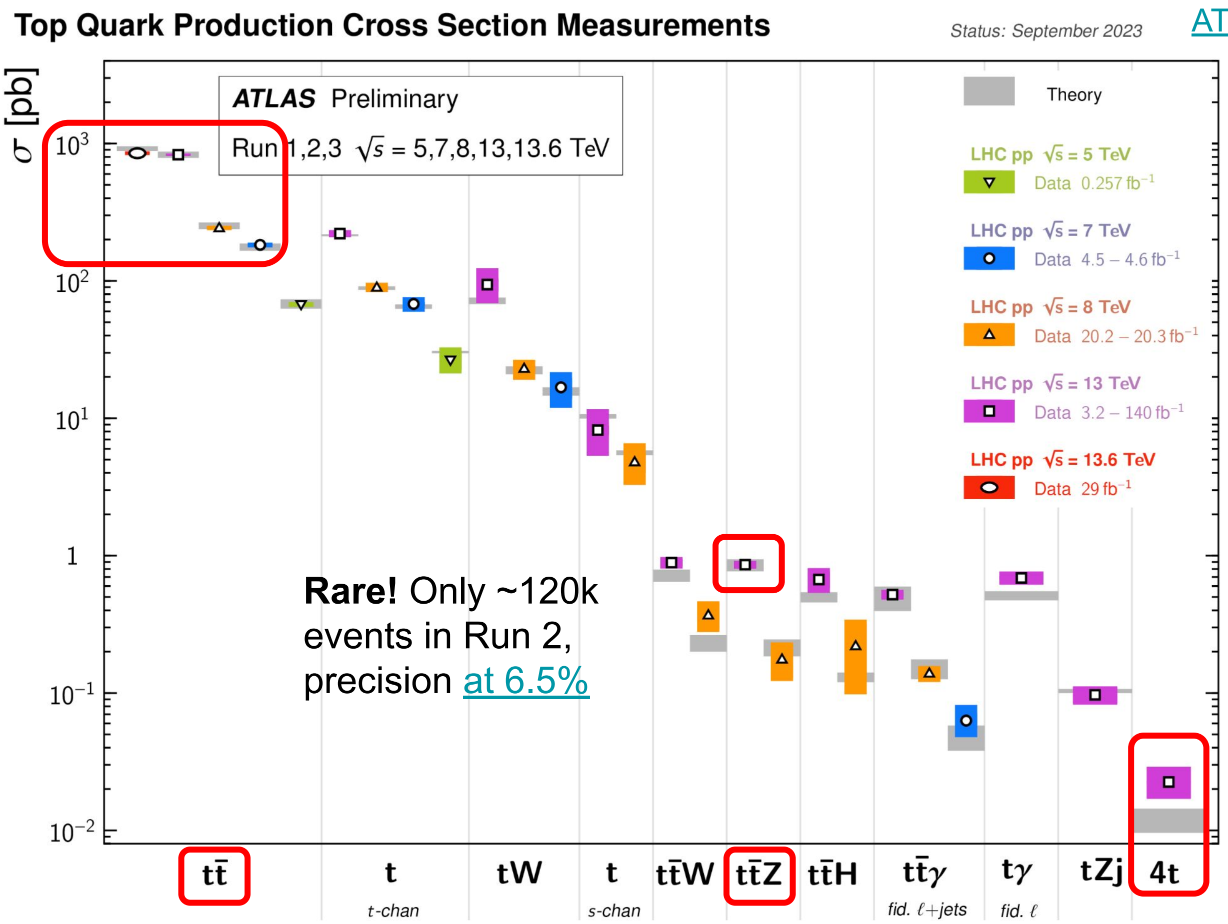


The range of top quark physics

ATL-PHYS-PUB-2023-028

Abundant production!

O(100M) events in Run 2
Precision down to [1.8%](1.8%)



Rare! Only ~120k events in Run 2, precision [at 6.5%](at 6.5%)

Extremely challenging!
Only ~3k events, precision [~25%](~25%)

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

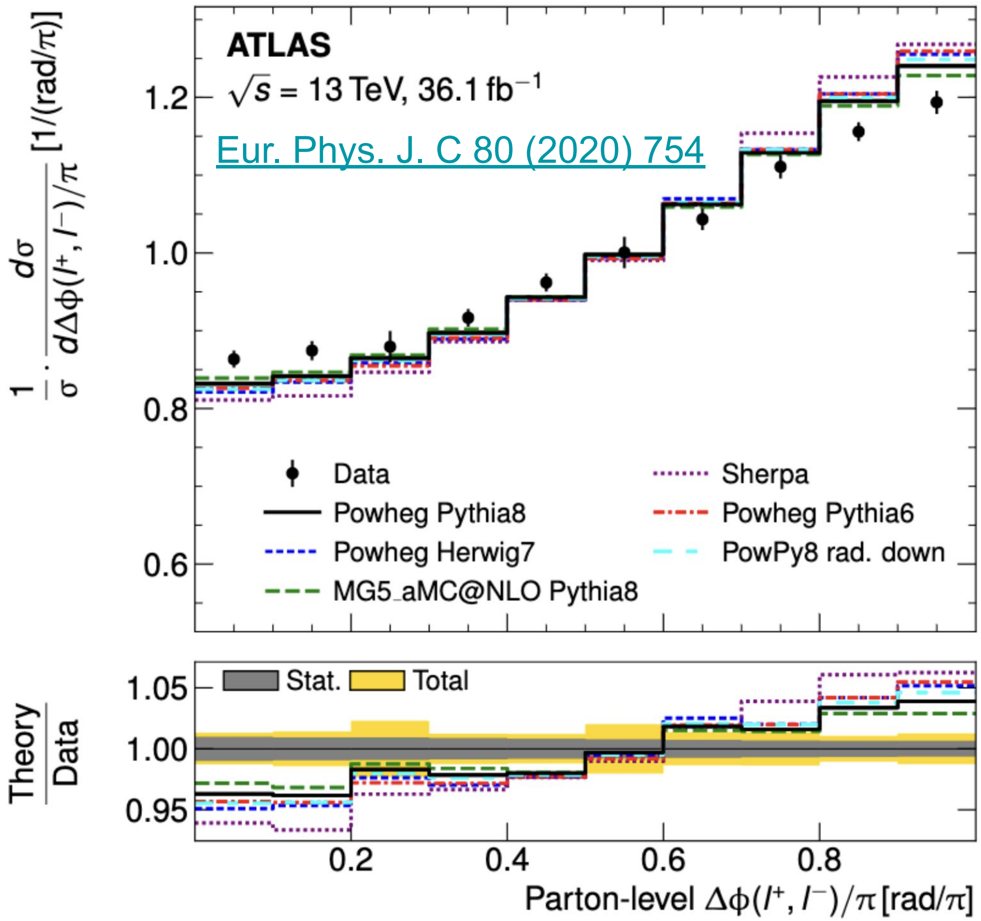
→ **correlations are observable!**

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

top polarisations + spin correlations

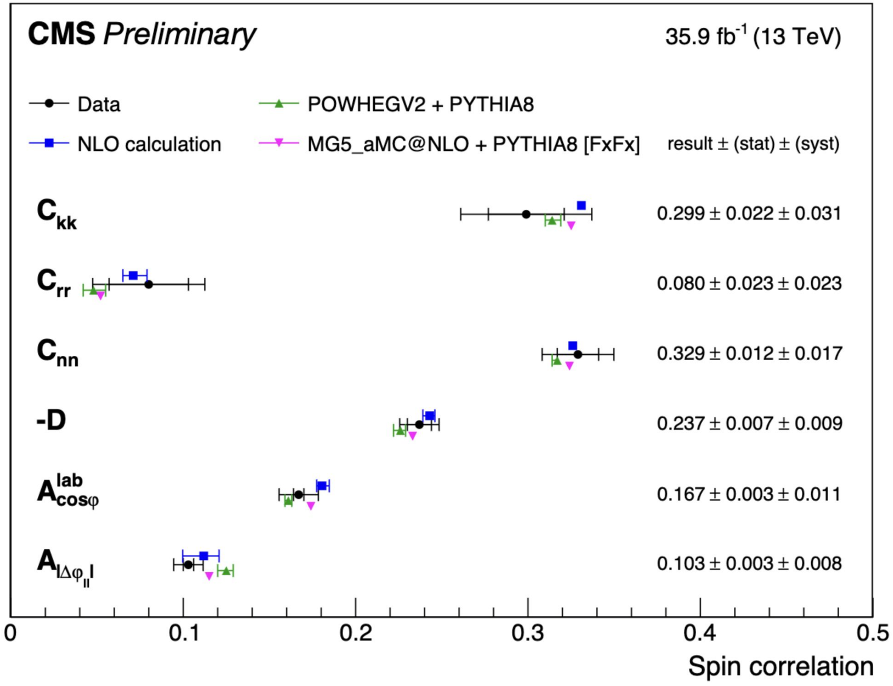
= full spin density matrix

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



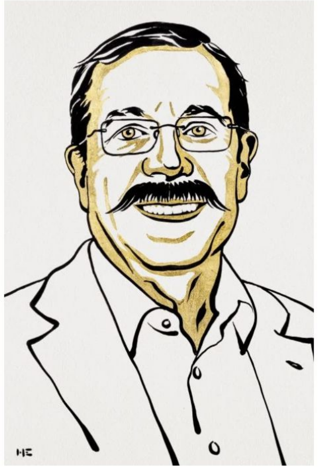
Eur. Phys. J. C 80 (2020) 754

Spin correlations in ttbar are well-established



Phys. Rev. D 100 (2019) 072002

As you may have heard…



Ill. Niklas Elmehed © Nobel Prize Outreach

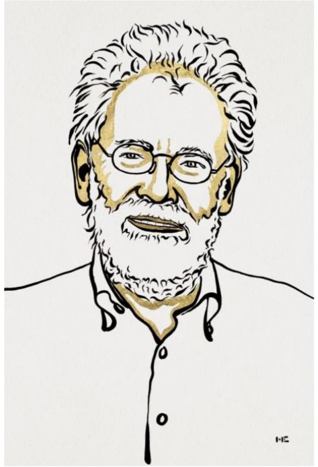
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

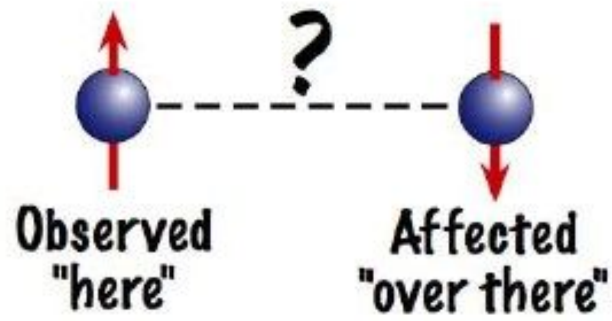


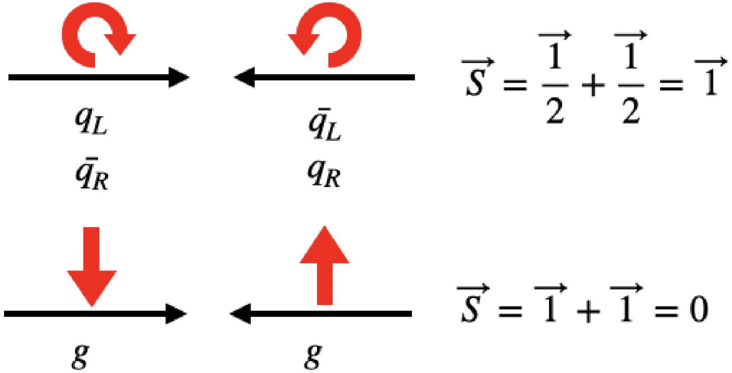
Ill. Niklas Elmehed © Nobel Prize Outreach

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"





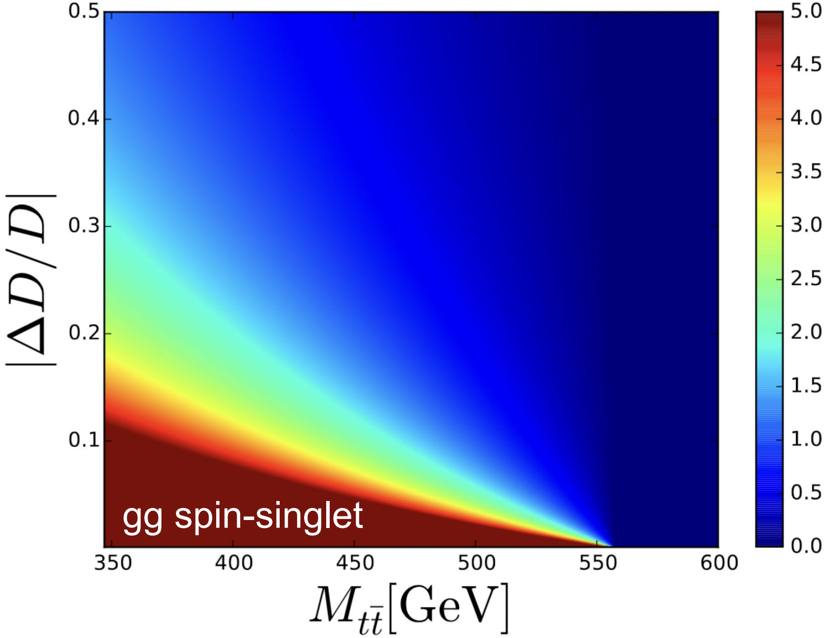
gg→ttbar: spin-singlet state at threshold

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**"

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

($\mathbf{B}_1 \to 0$, $\mathbf{B}_2 \to 0$)

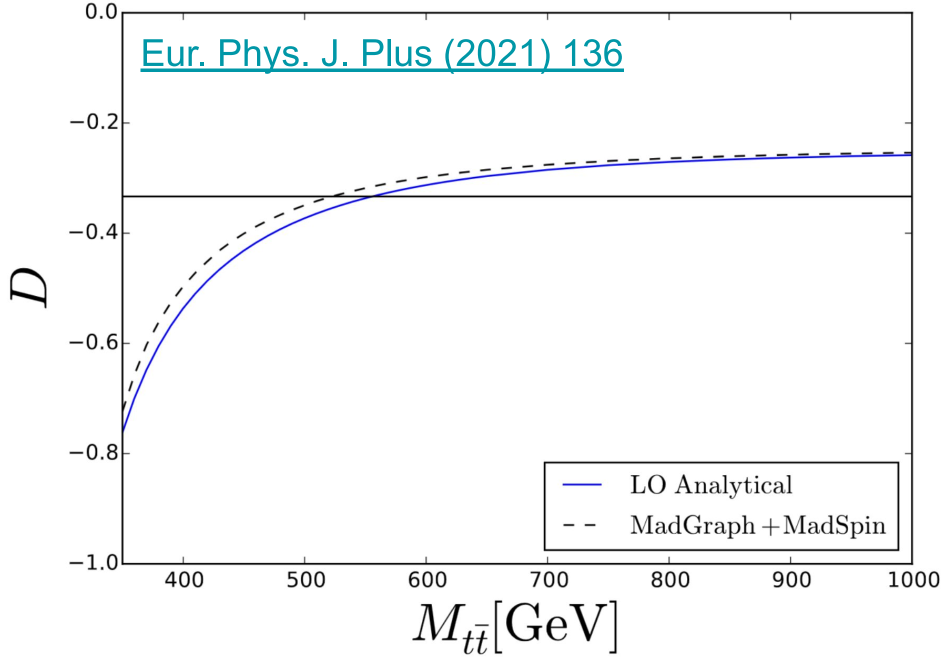


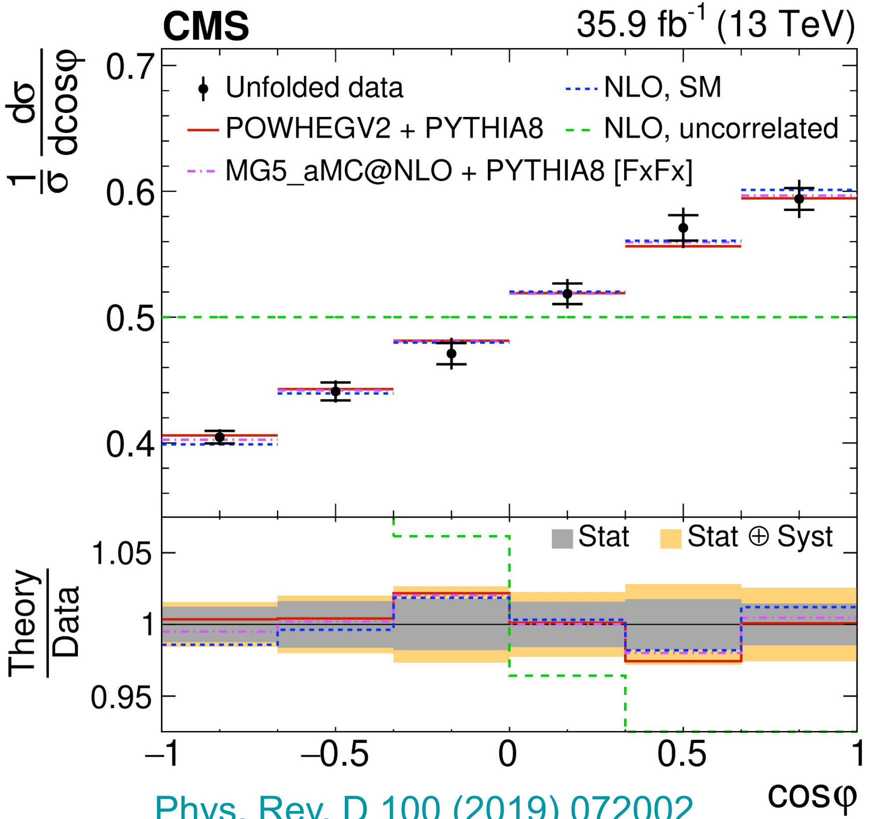
$$\mathrm{Tr}\,[\mathbb{C}] < -1$$ *Peres-Horodecki criterion*

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

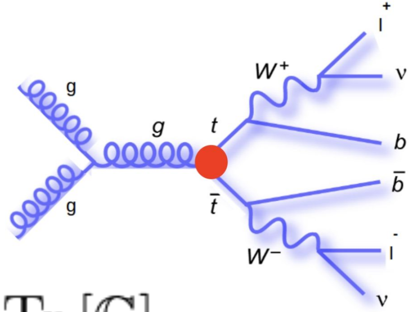
CMS measured $D = -0.237 \pm 0.011 > -\frac{1}{3}$

inclusively → need to go differential in M(ttbar)

The brand-new ATLAS result

Quantum entanglement in dilepton ttbar

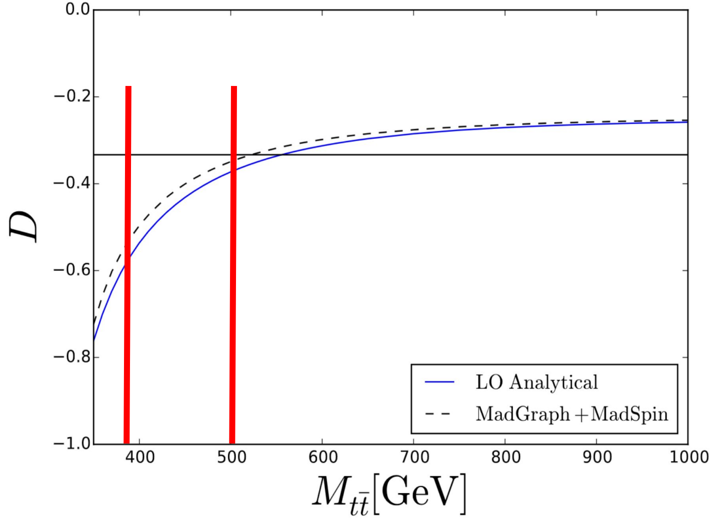
Dilepton eμ final state is very clean (90% purity) and at the end of Run 2 we have about a million events after preselection.



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

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



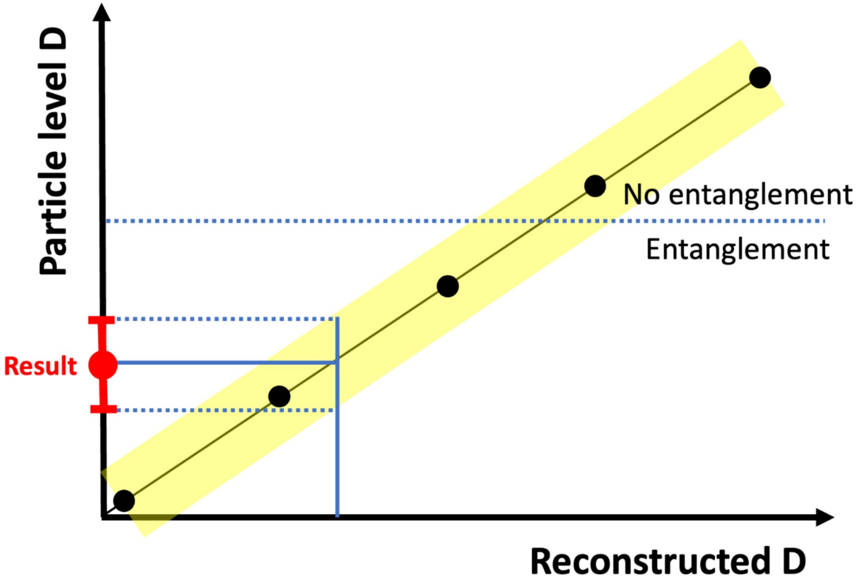
The mass cuts are crucial!

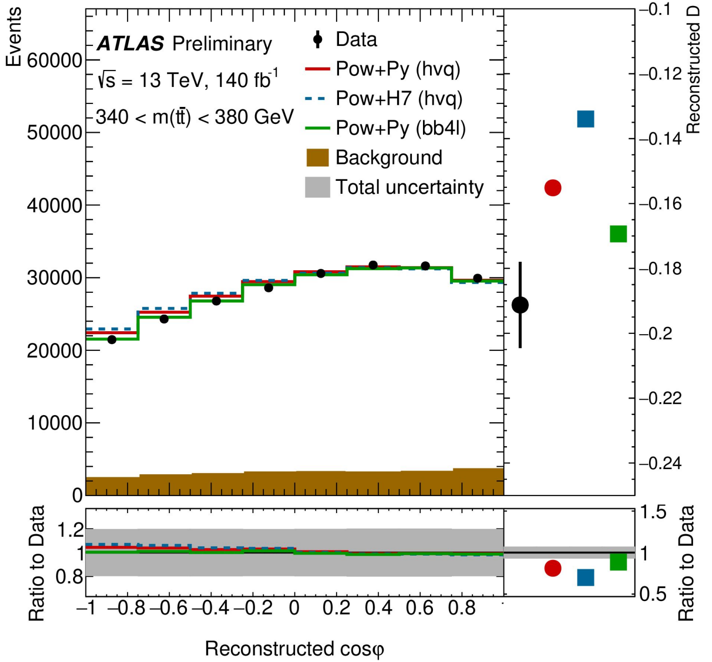
Analysis procedure

“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)

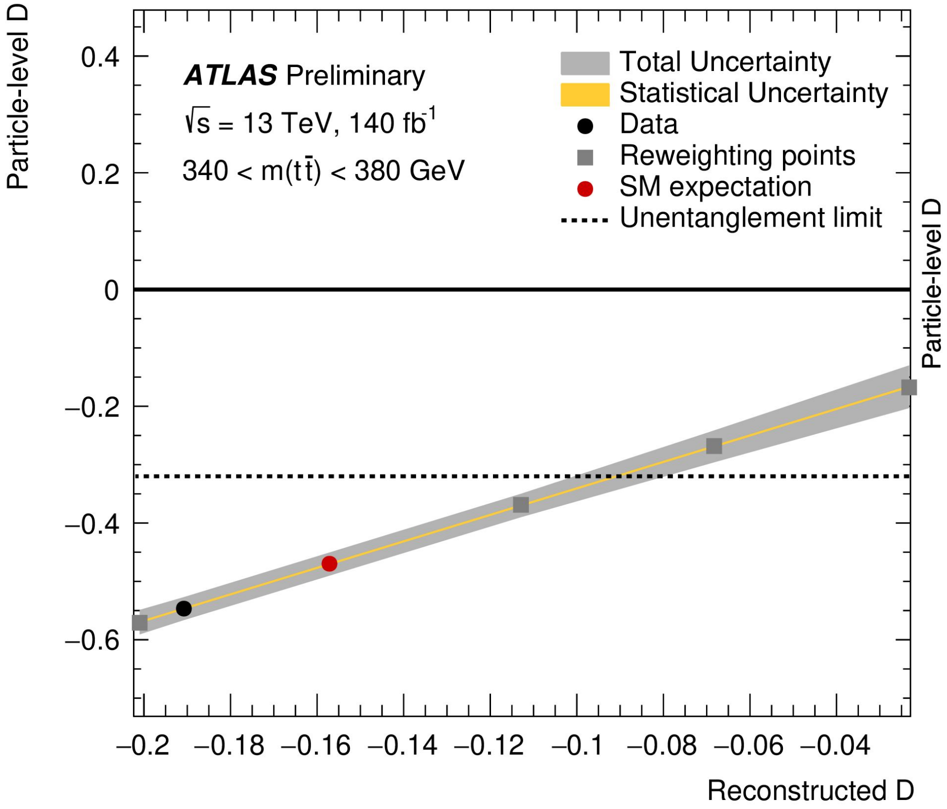
Calibrating to fiducial particle-level reduces the parton shower uncertainty (Pythia vs Herwig) : full details in the CONF.

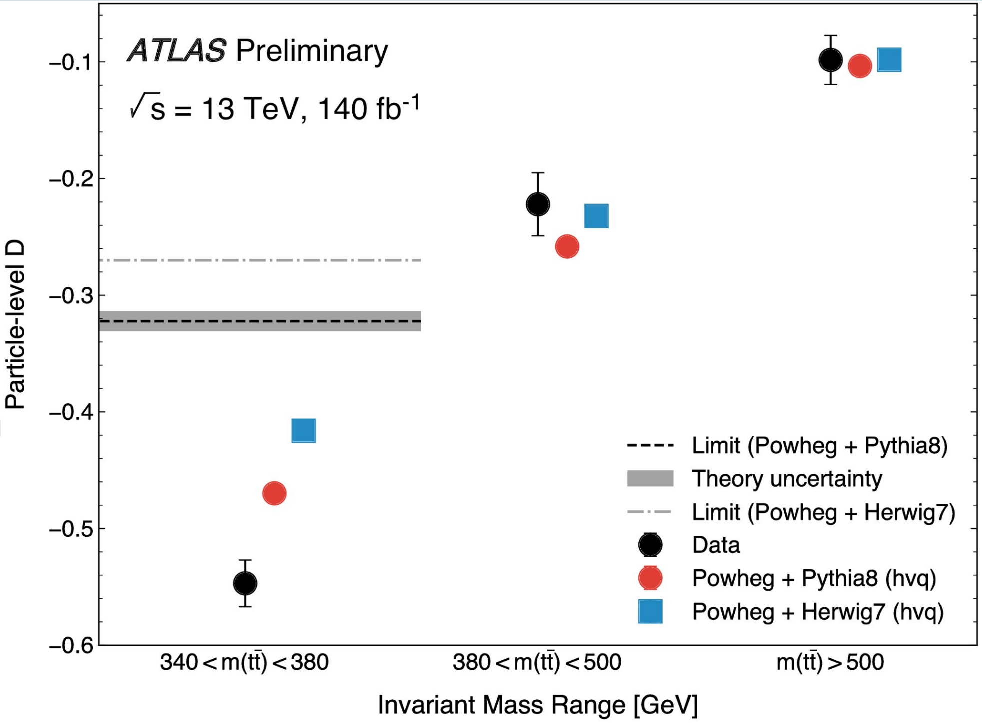
Signal modelling: by far the largest contribution

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
$E_{\text{T}}^{\text{miss}}$	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 → would only affect predictions, not calibration

expected: D = -0.470 ± 0.002 (stat.) ± 0.017 (syst.)

D = -0.547 ± 0.002 (stat.) ± 0.020 (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.) $\pm$ 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.] ± 0.017 [syst.])

SIGNIFICANT interest from the **THEORY** community

[Submitted on 10 Mar 2022 (v1), last revised 20 Sep 2022 (this version, v2)]

Quantum information with top quarks in QCD

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks represent unique high-energy systems since their spin correlations can be ... high-energy colliders. We present here the general framework of the quantum state of ... energy collider. We argue that, in general, the total quantum state that can be probed i... rise to a mixed state. We compute the quantum state of a $t\bar{t}$ pair produced from the m... different regions of phase space. We show that any realistic hadronic production of a $t\bar{t}$ ... experimentally relevant cases of proton–proton and proton–antiproton collisions, perfo... energy of the collisions. We provide experimental observables for entanglement and C... single observable, which in the case of entanglement represents the violation of a Cauc... pair proposed in the literature to more general quantum states, and for any production... form of violation of Bell's theorem, necessarily containing a number of loopholes.

Comments: 36 pages, 10 figures, 1 table. Accepted version of the manuscript
Subjects: Quantum Physics (quant-ph); High Energy Physics – Phenomenology (hep-ph); High...
Cite as: arXiv:2203.05582 [quant-ph]
(or arXiv:2203.05582v2 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2203.05582
Journal reference: Quantum 6, 820 (2022)
Related DOI: https://doi.org/10.22331/q-2022-09-29-820

[Submitted on 8 Sep 2022]

Quantum discord and steering in top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks have been recently shown to be a promising system to study quantum information problems at the hi... discuss topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture o... discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a se... statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord ca... ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional setups. In ... discord and steering can provide witnesses of new physics beyond the Standard Model.

Comments: 6 pages, 3 figures
Subjects: Quantum Physics (quant-ph); High Energy Physics – Experiment (hep-ex); High Energy Physics – Phenomenology (hep-p...
Cite as: arXiv:2209.03969 [quant-ph]
(or arXiv:2209.03969v1 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2209.03969

[Submitted on 4 Mar 2020 (v1), last revised 6 Sep 2021 (this version, v3)]

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top-antitop-quark pairs at the LHC, representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with high statistical significance, using the current data recorded during Run 2 at the LHC. In addition, we develop a simple protocol for the quantum tomography of the top-antitop pair. This experimental te... experimental te...

Comments: 15...
Subjects: Qu...
Cite as: ar...
Journal reference: Eu...
Related DOI: ht...

[Submitted on 28 Sep 2022 (v1), last revised 11 Oct 2022 (this version, v2)]

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

Rachel Ashby-Pickering, Alan J. Barr, Agnieszka Wierzchucka

A rather general method for determining the spin density matrix of a multi-particle system from angular decay data is presented. The method is based on a Bloch parameterisation of the d-dimensional generalised Gell-Mann representation of ρ and exploits the associated Wigner- and Weyl-transforms on the sphere. Each parameter of a (possibly multipartite) ... spin density matrix can can b... non-projective decays are des... Monte Carlo simulations of pp... $H \to ZZ^*$. Measurements are...

Comments: v2: additional references...
Subjects: Quantum Physics (quan...

[Submitted on 10 Mar 2022 (v1), last revised 30 Aug 2022 (this version, v2)]

Quantum SMEFT tomography: top quark pair production at the LHC

Rafael Aoude, Eric Madge, Fabio Maltoni, Luca Mantani

Quantum information observables, such as entanglement measures, provide a powerful way to characterize the properties of quantum states. We propose to use them ... structure of fundamental interactions and to search for new physics at high energy. Inspired by recent proposals to measure entanglement of top quark pairs produced ... we examine how higher-dimensional operators in the framework of the SMEFT modify the Standard Model expectations. We explore two regions of interest in the phas... the Standard Model produces maximally entangled states: at threshold and in the high-energy limit. We unveil a non-trivial pattern of effects, which depend on the init... partons, $q\bar{q}$ or gg, on whether only linear or up to quadratic SMEFT contributions are included, and on the phase space region. In general, we find that higher-dimensi... lower the entanglement predicted in the Standard Model.

[Submitted on 2 Jun 2021 (v1), last revised 26 Jul 2022 (this version, v4)]

Testing Bell inequalities in Higgs boson decays

Alan Barr

Higgs boson decays produce... of the $W^{\pm}$ pair may be recon... determined. Numerical simul... near-maximally violated. Exp... controlled then statistically s...

Comments: Sign corrections t...
Subjects: High Energy Phy...
Cite as: arXiv:2106.01377...
(or arXiv:2106.01...
https://doi.org/1...
Journal reference: Physics Letters B ...
Related DOI: https://doi.org/1...

[Submitted on 28 Sep 2022]

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

J. A. Aguilar-Saavedra

Quantum entanglement between ... frame observables that only invol... be used to observe the quantum ... dimensional) angular distribution...

Comments: LaTeX 6 pages
Subjects: High Energy Physics – ...
Report number: IFT-UAM/CSIC-22-119
Cite as: arXiv:2209.14033 [hep-...
(or arXiv:2209.14033v1 ...
https://doi.org/10.4855...

[Submitted on 27 Sep 2022]

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

J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno

We discuss quantum entanglement and violation of Bell inequalities in the $H \to ZZ$ decay, in particular when the two Z–bosons decay into light leptons. Although such pr... implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally-entangled" system, which makes it very promising to check these... phenomena at high energy. In this paper we devise a novel framework to extract from $H \to ZZ$ data all significant information related to this goal, in particular spin correl... observables. In this context we derive sufficient and necessary conditions for entanglement in terms of only two parameters. Likewise, we obtain a sufficient and improved... for the violation of Bell-type inequalities. The numerical analysis shows that with a luminosity of $L = 300\text{fb}^{-1}$ entanglement can be probed at $> 3\sigma$ level. For $L = 3\text{ab}^{-1}$ (H... entanglement can be probed beyond the 5σ level, while the sensitivity to a violation of the Bell inequalities is at the 4.5σ level

...heory (hep-th); Quantum Physics (quant-ph)

[Submitted on 1 May 2022 (v1), last revised 1 Aug 2022 (this version, v2)]

Improved tests of entanglement and Bell inequalities with LHC tops

J. A. Aguilar-Saavedra, J. A. Casas

We discuss quantum entanglement in top pair production at the LHC. Near the $t\bar{t}$ threshold, entanglement observa... subprocesses, which is achieved by a simple cut on the velocity of the $t\bar{t}$ system in the laboratory frame. Furtherm... combinations of $t\bar{t}$ spin correlation coefficients involved in the measurement of entanglement and Bell inequalities... 7 for Bell inequalities near threshold...

[Submitted on 19 Oct 2021 (v1), last revised 25 Mar 2022 (this version, v2)]

Quantum tops at the LHC: from entanglement to Bell inequalities

Claudio Severi, Cristian Degli Esposti Boschi, Fabio Maltoni, Maximiliano Sioli

We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable fo... measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglem... only very high-p_T events are sensitive to a vio... different unfolding methods and independent... he high luminosity LHC run.

[Submitted on 24 Aug 2022]

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

Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli

The measurement of quantum entanglement can provide a new and most sensitive probe to physics beyond the Standard Model. We use the concurrence of the top-quark pairs spin states produced at colliders to constrain the magnetic dipole term in the coupling between top quark and gluons, that of τ-lepton pairs spin states to bound contact interactions an... that of τ-lepton pairs or two photons spin states from the decay of the Higgs boson to try distinguishing between CP-even and odd couplings. These four examples show the power of the new approach as well as its limitations. We show that differences in the entanglement in the top-quark and τ-lepton pairs production cross sections can provide constraints better than those previously estimated from total cross sections or classical correlations. Instead, the final states in the decays of the Higgs boson remain maximally entangled even in the presence of CP-odd couplings and cannot be used to set bounds on new physics. We discuss the violation of Bell inequalities featured in all four processes and find that the decays of the Higgs boson into τ-lepton pairs or two photons constitute the best instances to observe such violations.

Comments: 31 pages, 16 Figures
Subjects: High Energy Physics – Phenomenology (hep-ph); High Energy Physics – Experiment (hep-ex)
Cite as: arXiv:2208.11723 [hep-ph]
(or arXiv:2208.11723v1 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2208.11723

[Submitted on 23 Feb 2021 (v1), last revised 27 Oct 2021 (this version, v2)]

Testing Bell inequalities at the LHC with top-quark pairs

M. Fabbrichesi, R. Floreanini, G. Panizzo

Entanglement between the spins of top-quark pairs produced at a collider can be used to test a (generalized) Bell inequality at energies never explored so far. We show how the measurement of a single observable can provide a test of the violation of the Bell inequality at the 98% CL with the data already collected at the Large Hadron Collider and at the 99.99% CL with the higher luminosity of the next run.

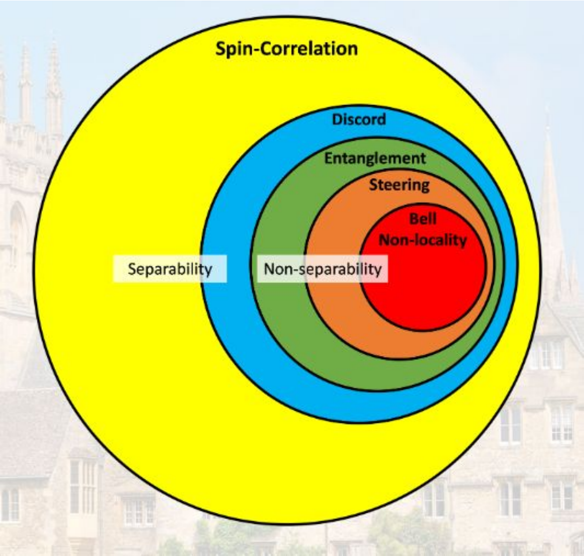
Comments: 4 pages, 1 figure
Subjects: High Energy Physics – Phenomenology (hep-ph); High Energy Physics – Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 [hep-ph]
(or arXiv:2102.11883v2 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2102.11883
Journal reference: Phys.Rev.Lett. 127 (2021) 16, 161801
Related DOI: https://doi.org/10.1103/PhysRevLett.127.161801

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

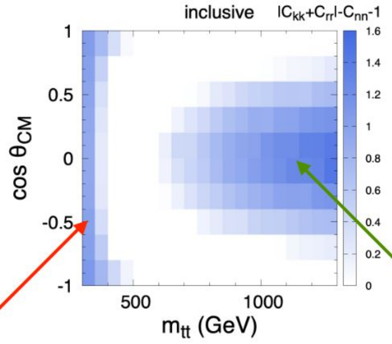
spin correlations

	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

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



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

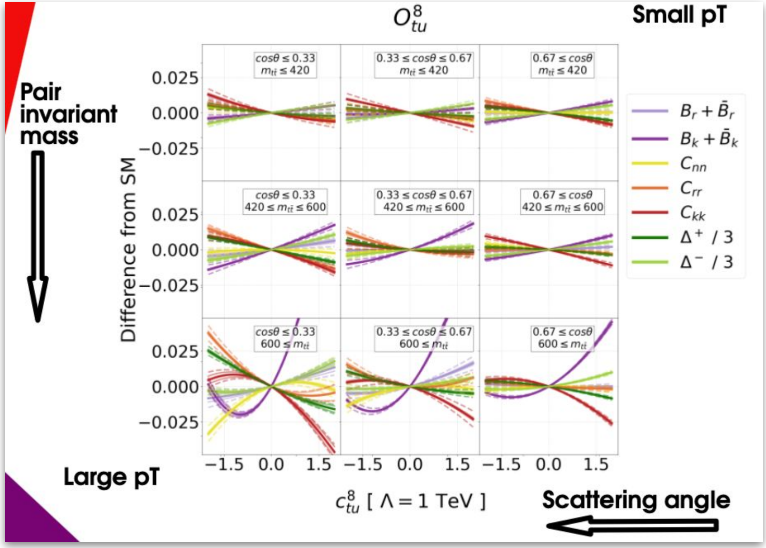
Boosted region,
$$E = C_{kk} + C_{rr} - C_{nn} - 1 > 0$$

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!

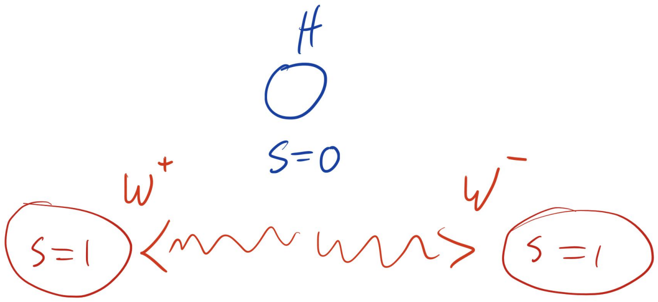
$$\alpha_\ell = 1 - \frac{c^2_{uW,33} v^4}{\Lambda^4} \frac{4(2m_t^6 + 3m_t^4 m_W^2 - 6m_t^2 m_W^4 + m_W^6 + 12 m_t^4 m_W^2 \log m_W/m_t)}{(m_W^2 - m_t^2)^2 (m_t^2 + 2m_W^2)}$$

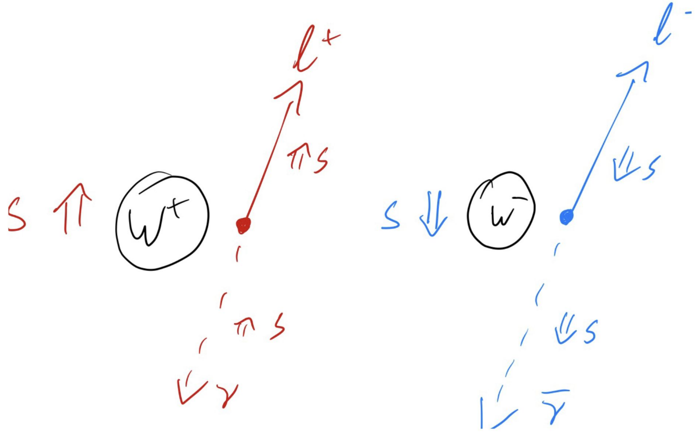


Quantum state tomography with weak decays

“Decaying W bosons are their own polarimeters”

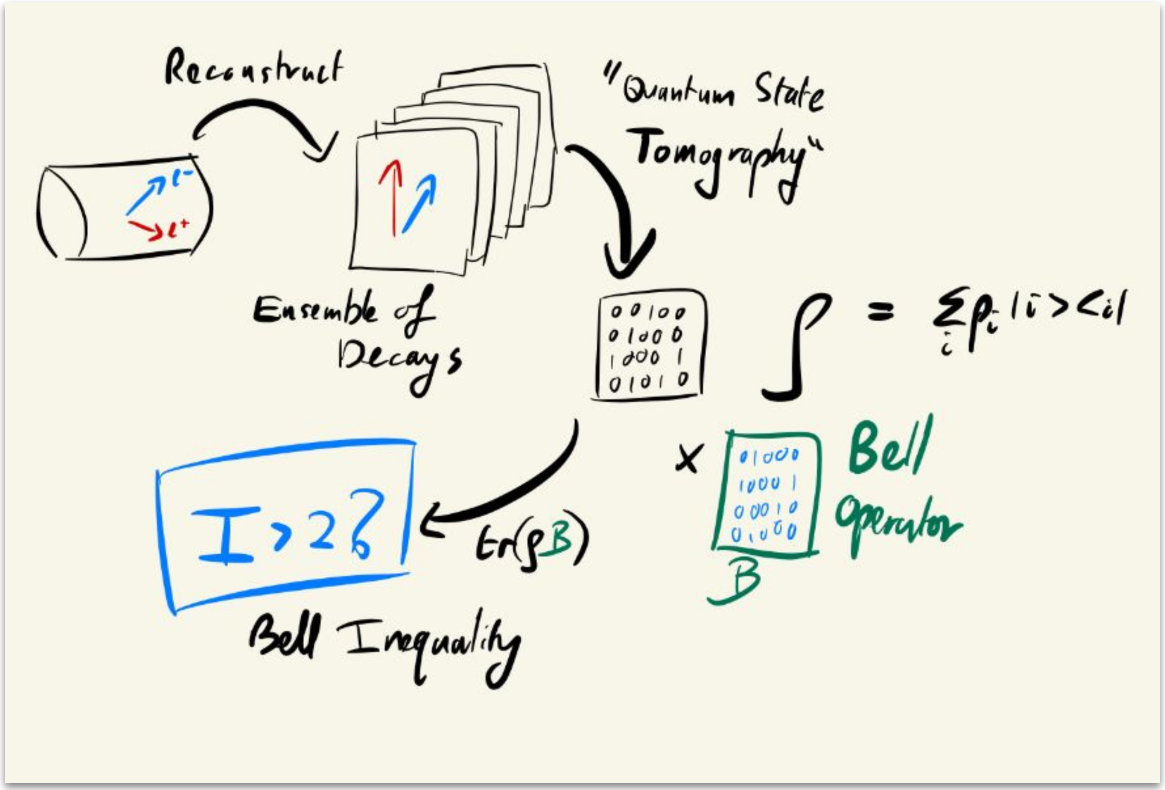
- HWW* provides a near-maximally entangled state
  - spin density matrix has 80 real parameters
  - can be uniquely determined from angular distributions
  - violation of Bell’s inequality for a pair of qutrits can be probed from “only” 10 such distributions
- Sensitivity estimate in the lνlν final state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

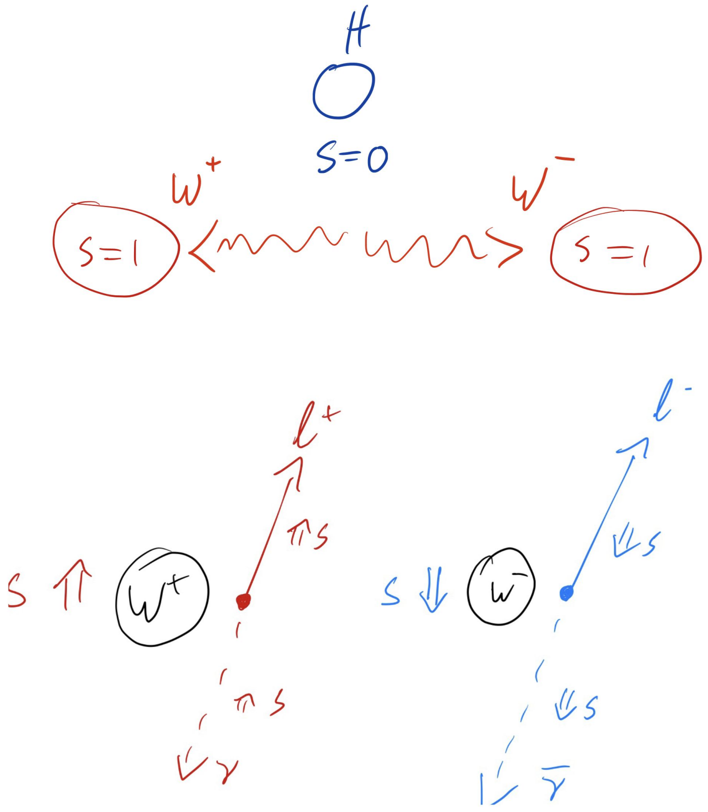




Quantum state tomography with weak decays

“Decaying W bosons are their own polarimeters”





Quantum tomography of diboson systems

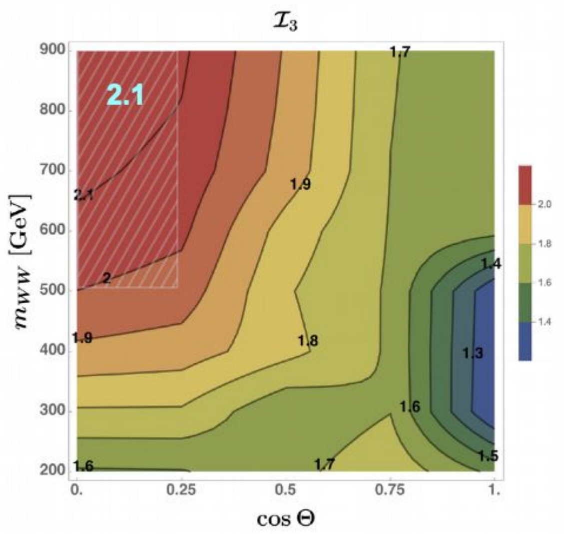
Formalism can be extended to all massive diboson final states: HWW*, HZZ*, WW, WZ, ZZ

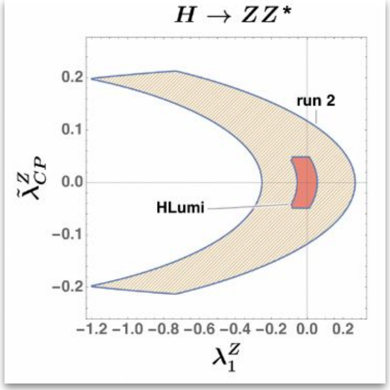
pp→VV infeasible at the HL-LHC: have to "wait" for FCC/muon colliders

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}.

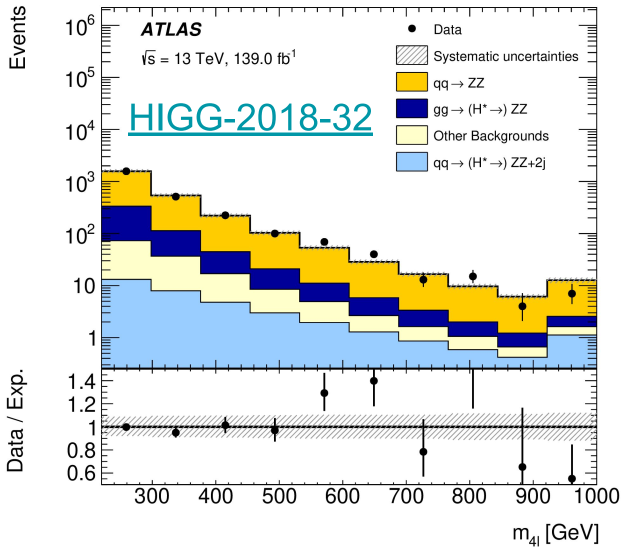
A twist on polarisations: H*ZZ (not a typo!)

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

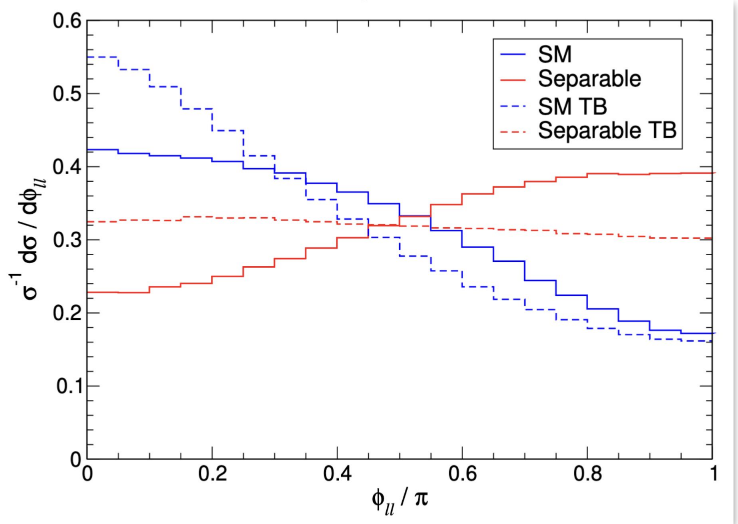


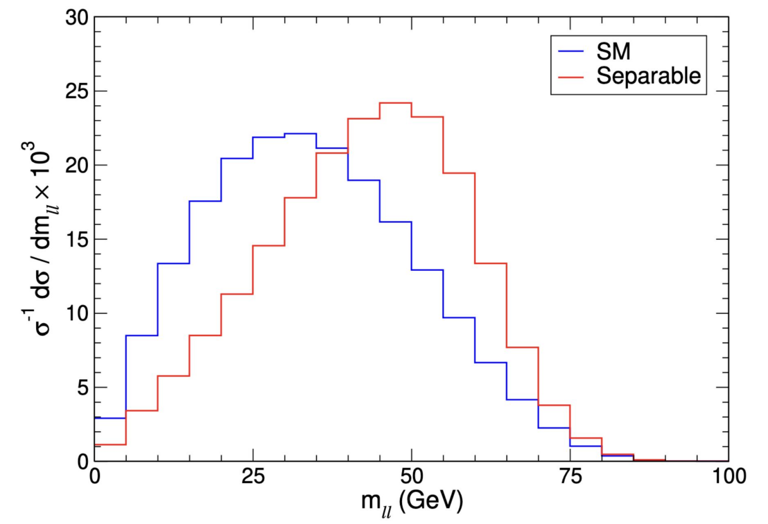
Resampling polarisations in HWW*

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



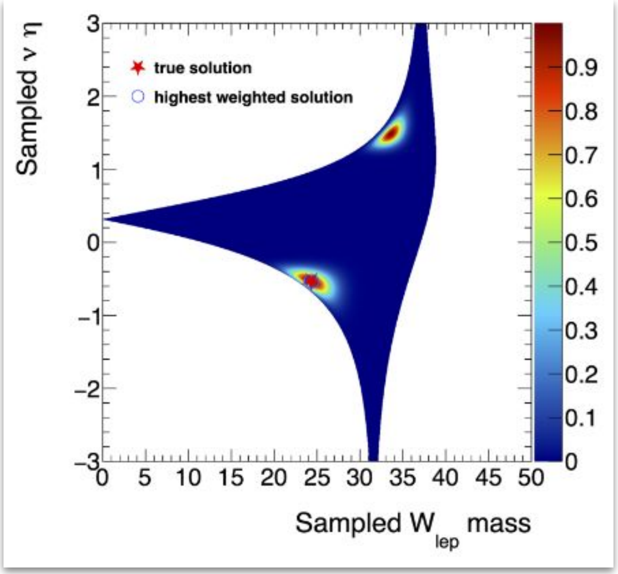


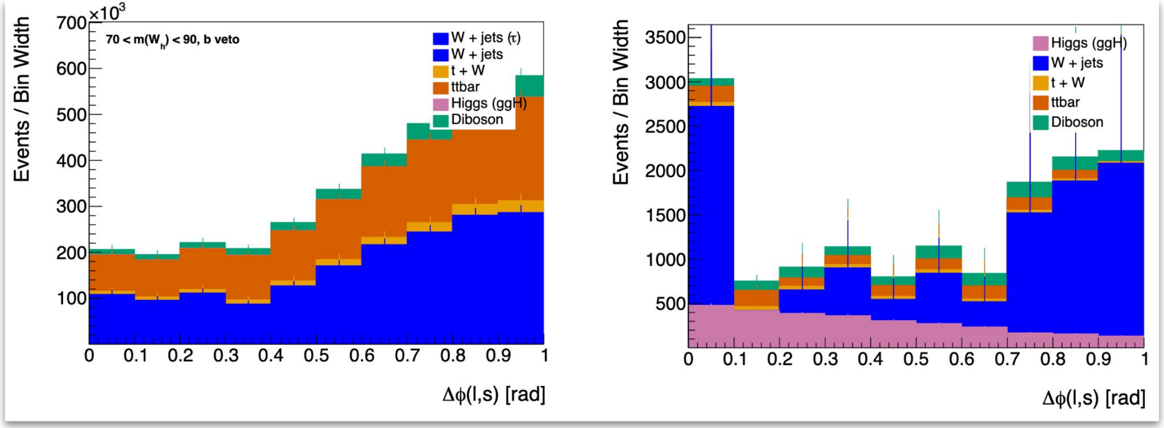
Accessing entanglement in semi-leptonic HWW*

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*→lv 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 (2sigma at 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 resonances…)
- qubits vs qutrits, two- and three-particle entanglement, decays…

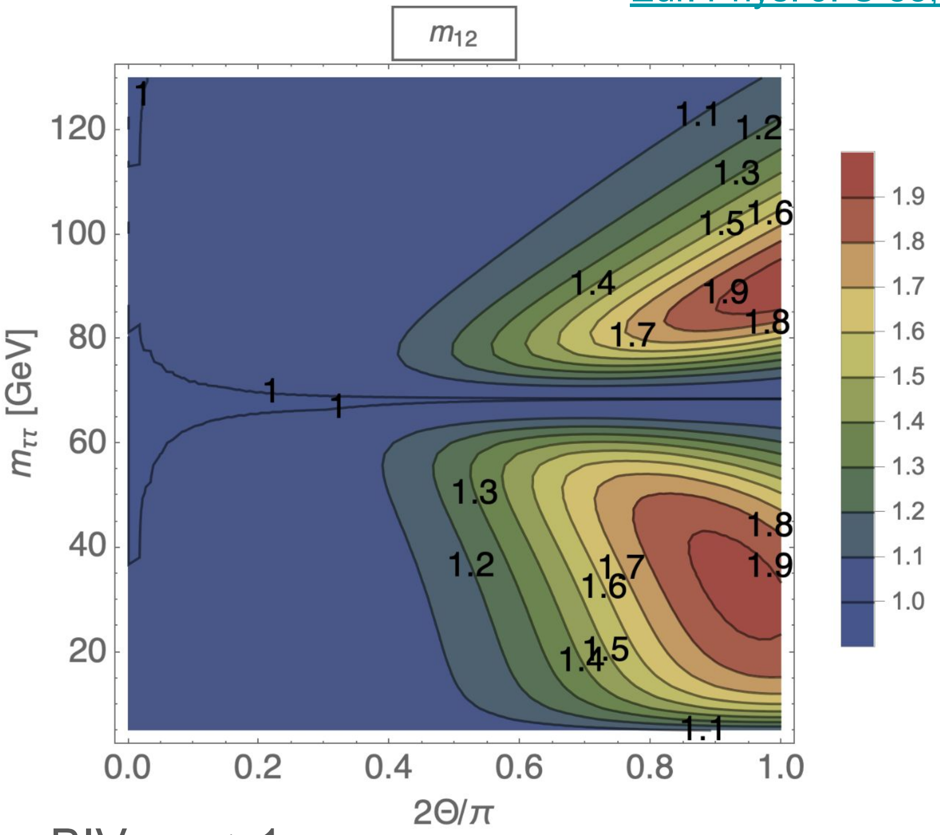
The ultimate goal is to **measure the full spin density matrices** (in several bases and differentially in the invariant mass of the system)

- 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…

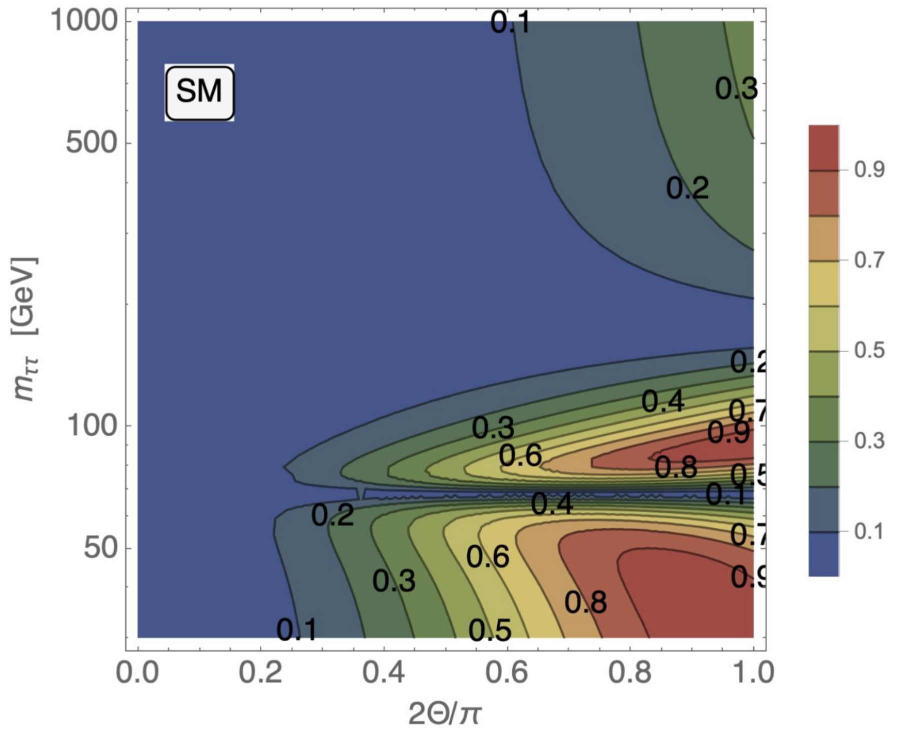
Backup

Quantum entanglement in di-tau systems

[Eur. Phys. J. C 83, 162 (2023)]

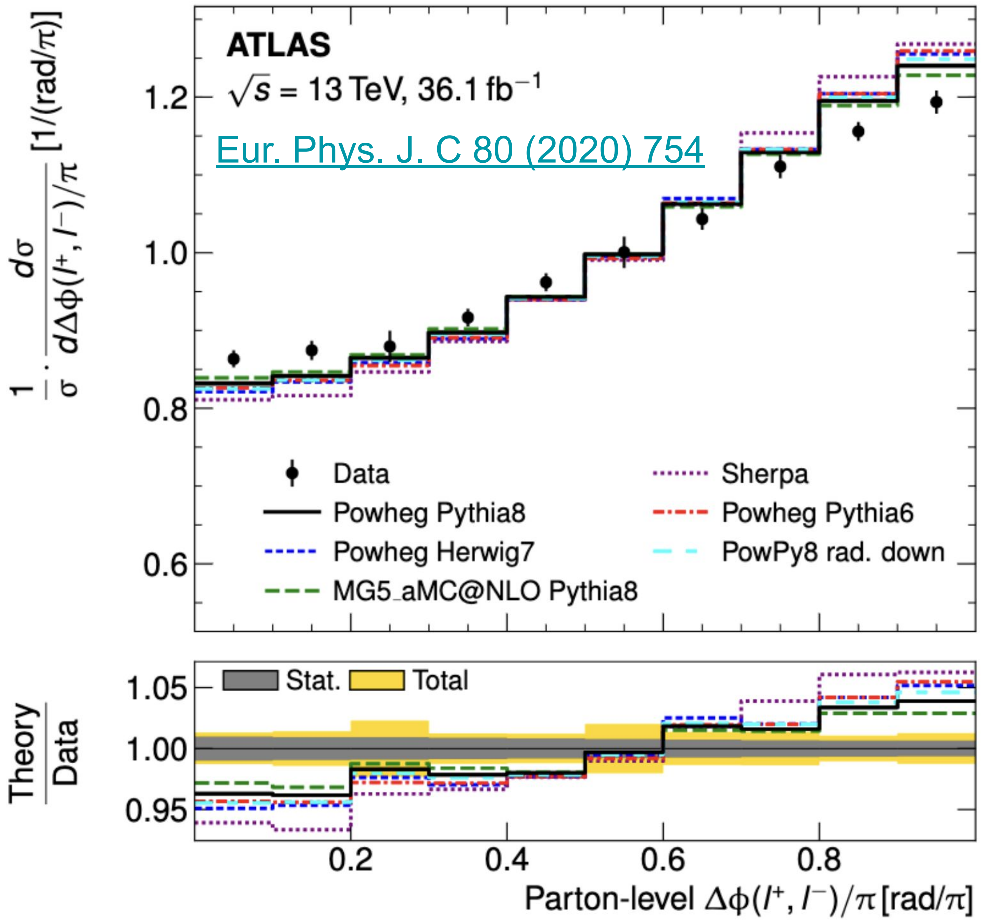


BIV: m_{12}>1

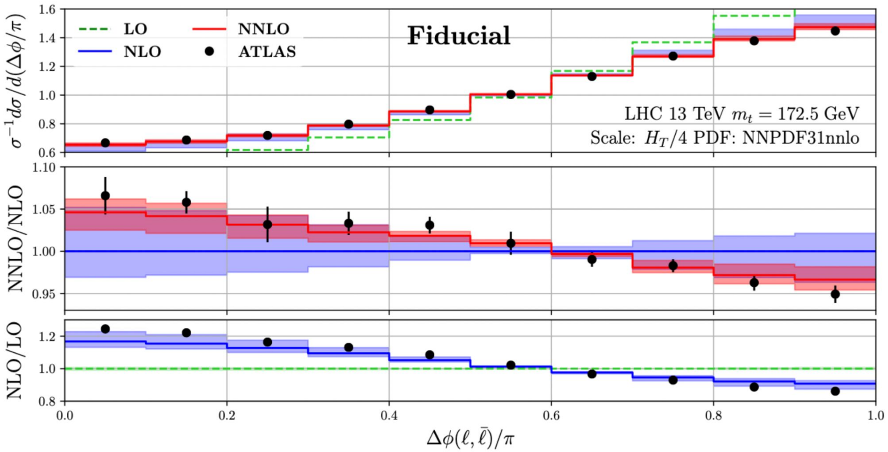


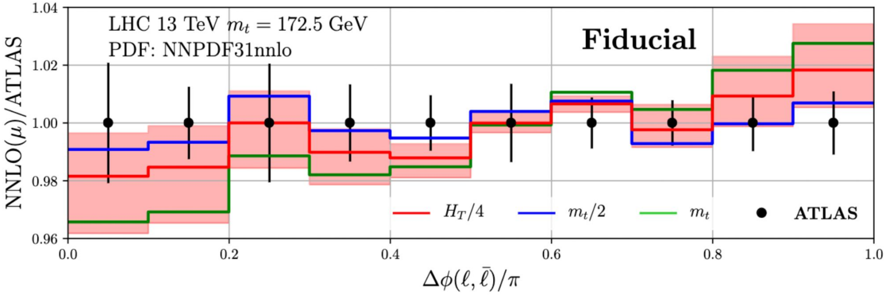
QE: C>0

Spin correlations at NNLO



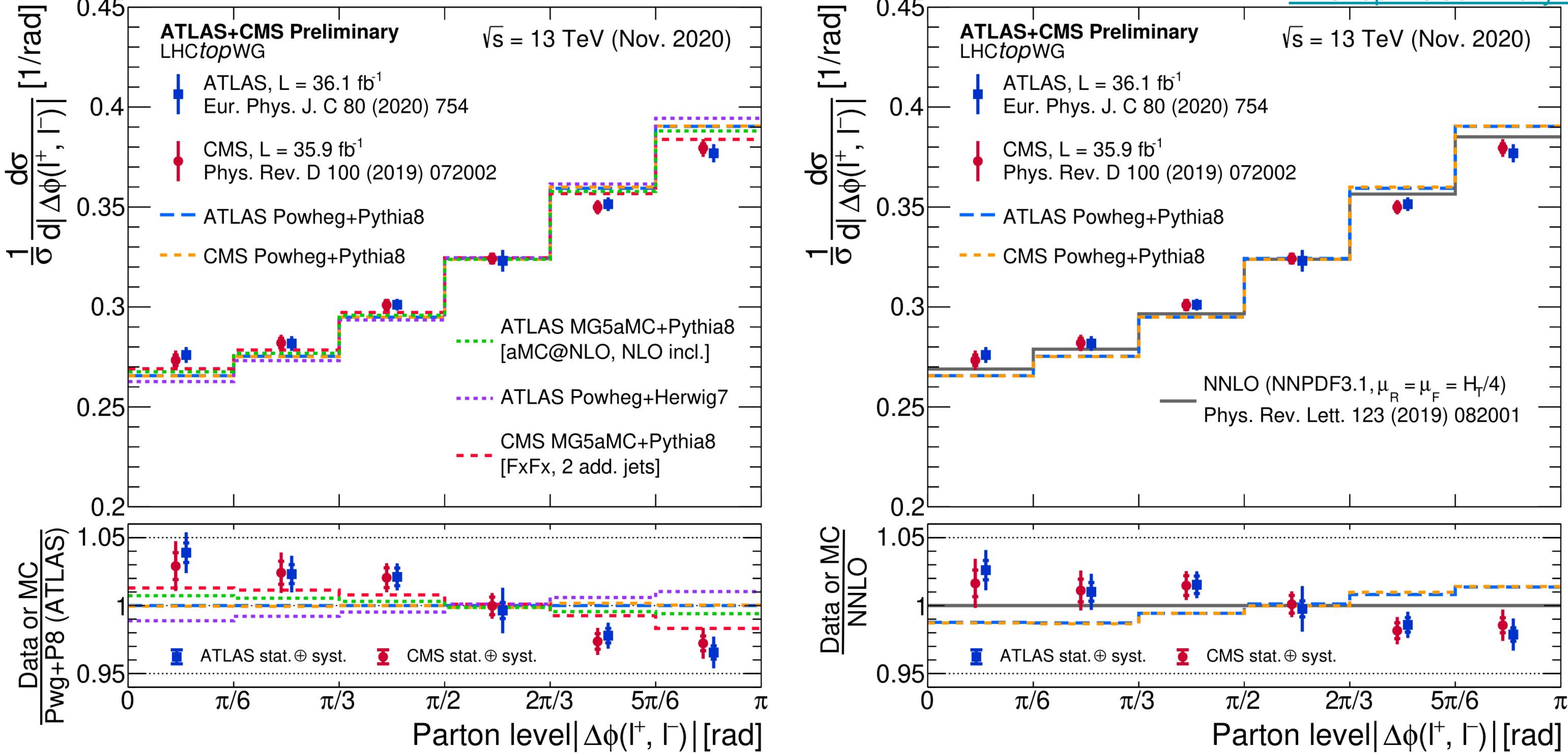
arXiv:1901.05407





Spin correlations: ATLAS and CMS

LHCTopWGSummaryPlots



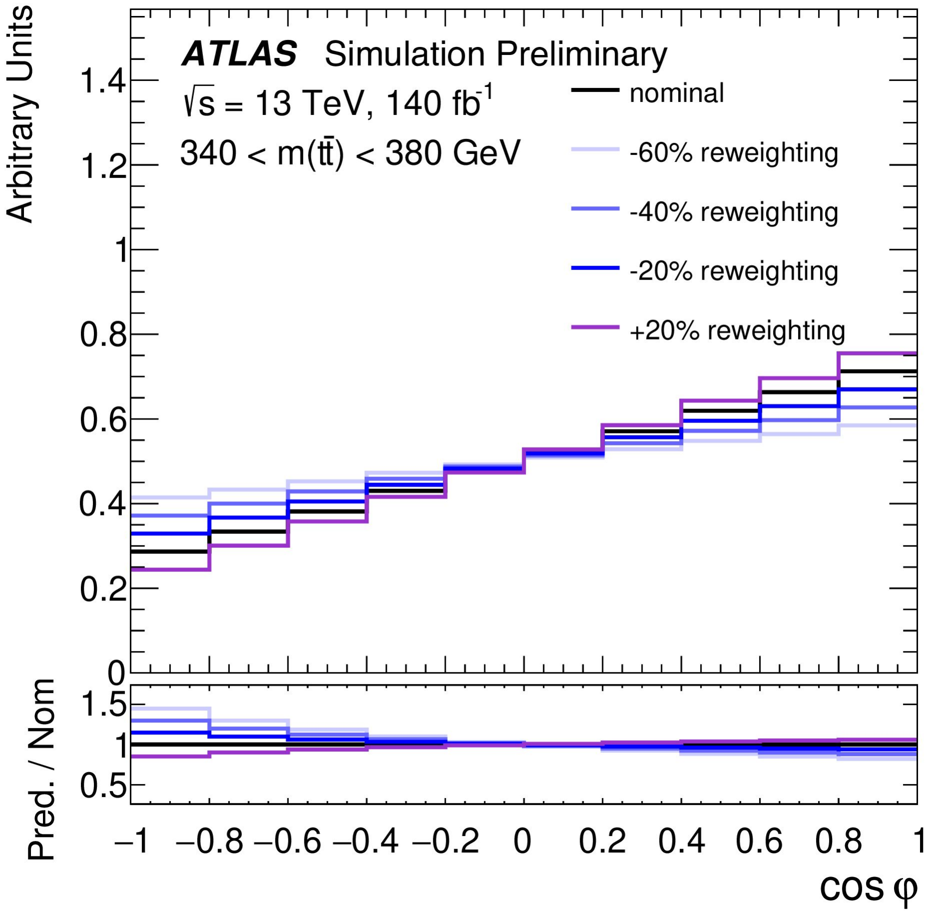
The reweighting method

- 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)

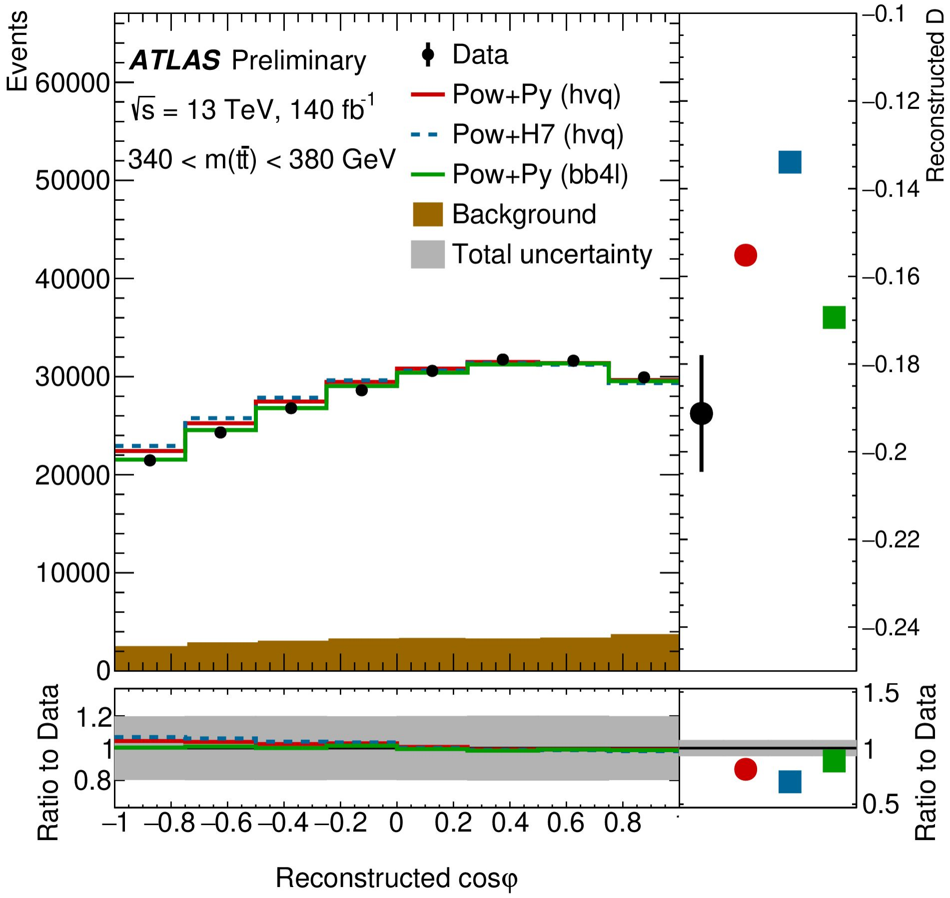
$$D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

- Then reweight each event as

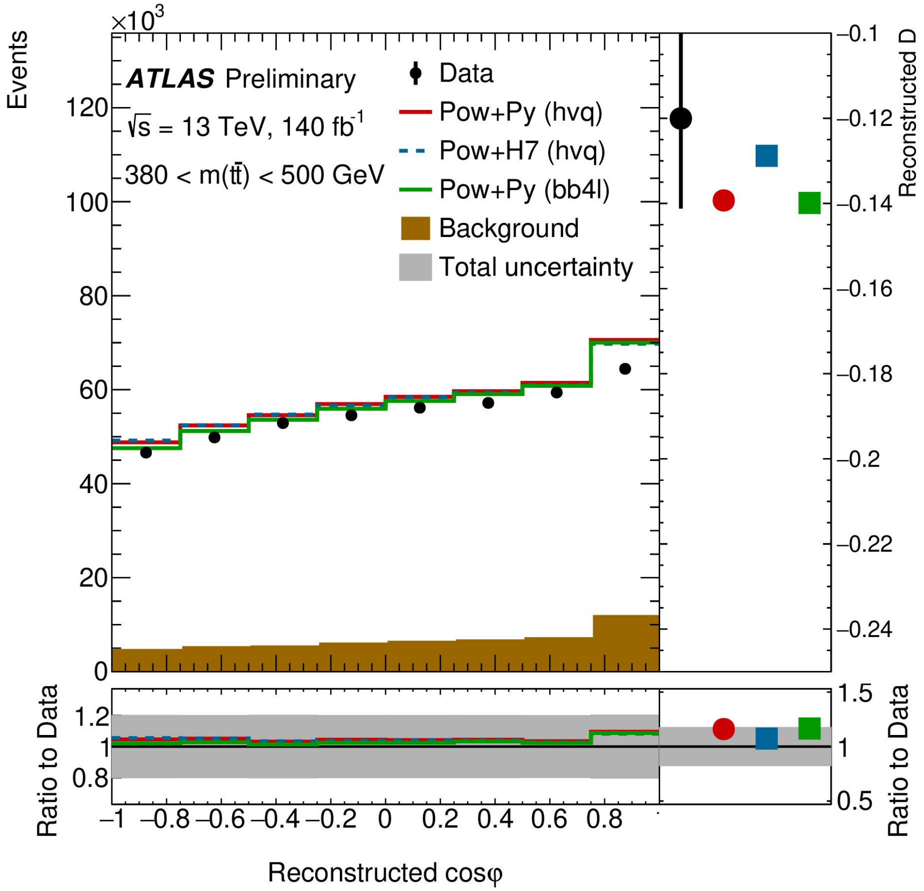
$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$$

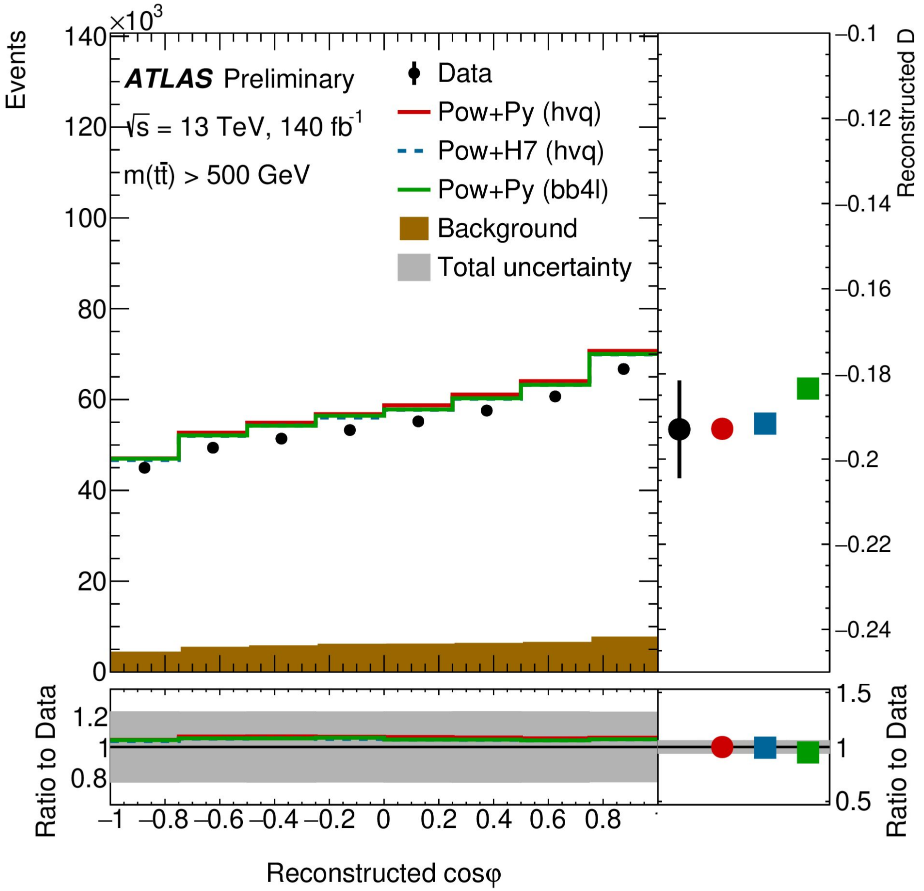


Data / MC in the signal region

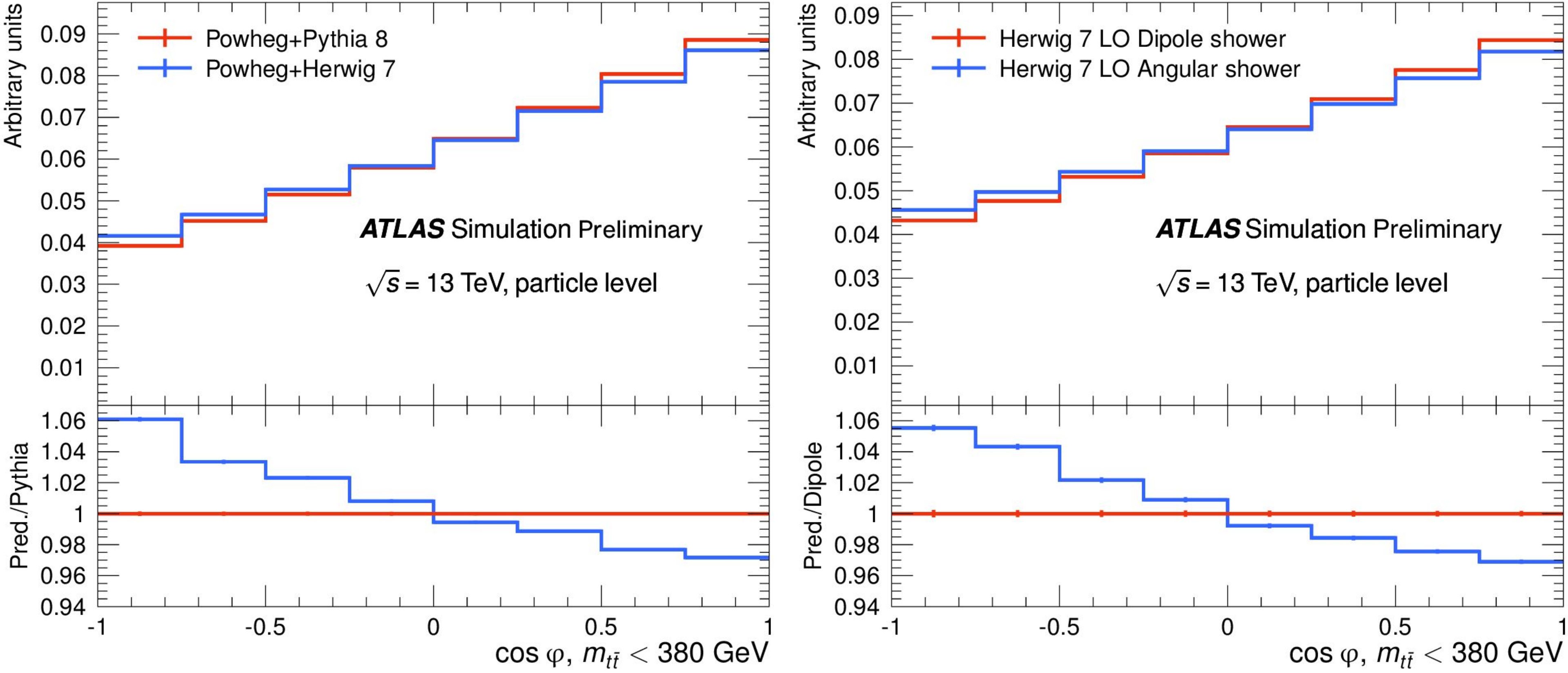


Data / MC outside the signal region





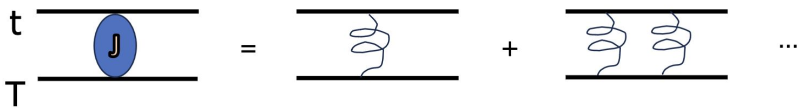
Investigations of parton shower effects



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 ttbar



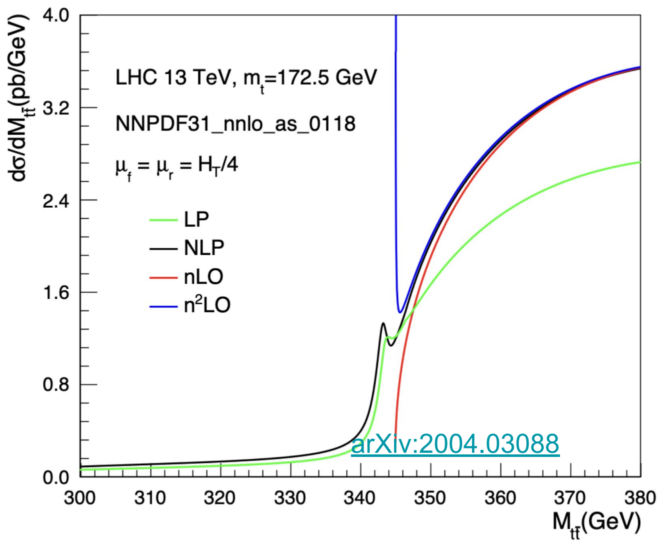
from A. Mitov

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



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

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

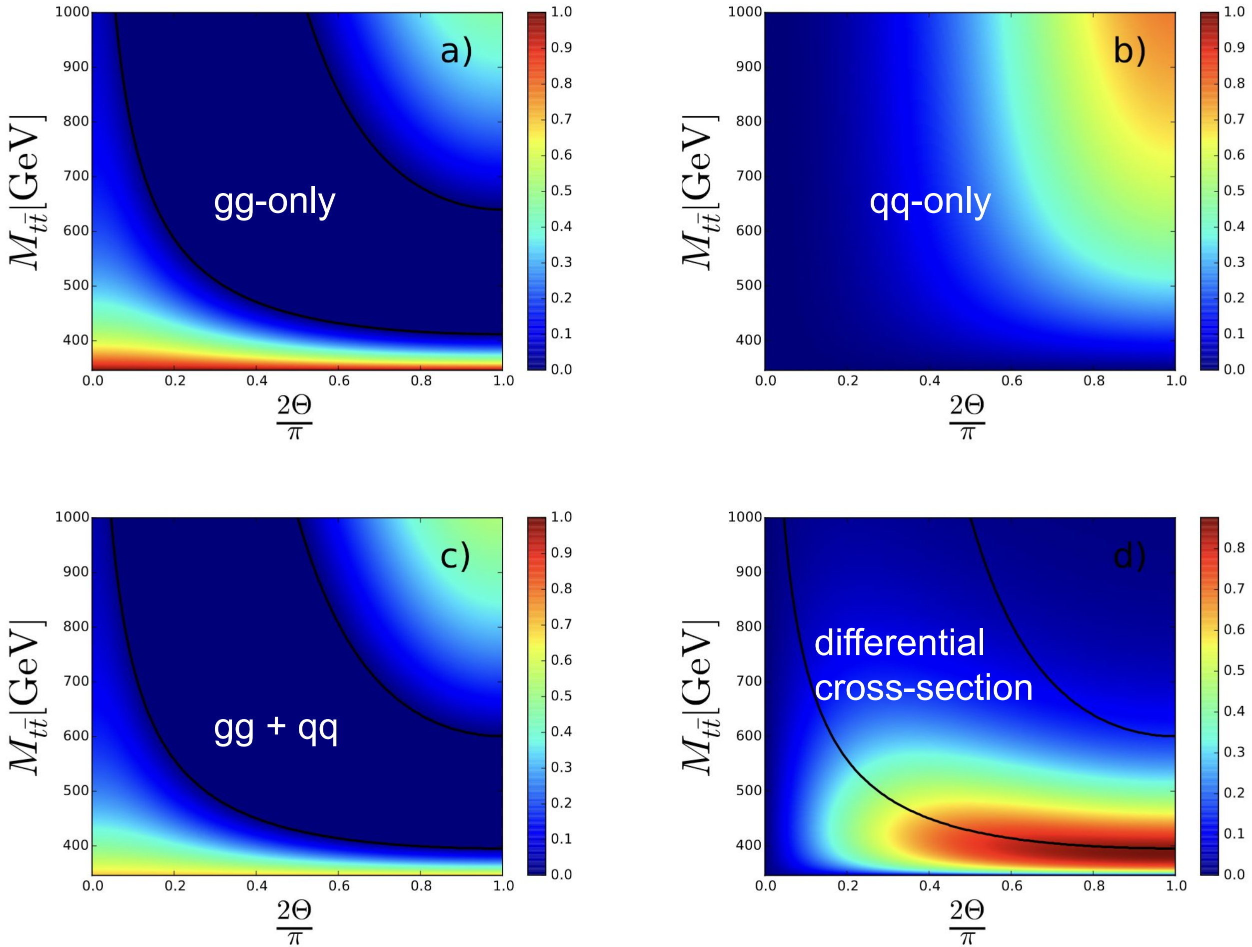
$$\rho = \frac{1}{4}\begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} - i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} - C_{22} - i(C_{12} + C_{21}) \\ B_1^- + C_{31} + i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) & B_1^+ - C_{13} - i(B_2^+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

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

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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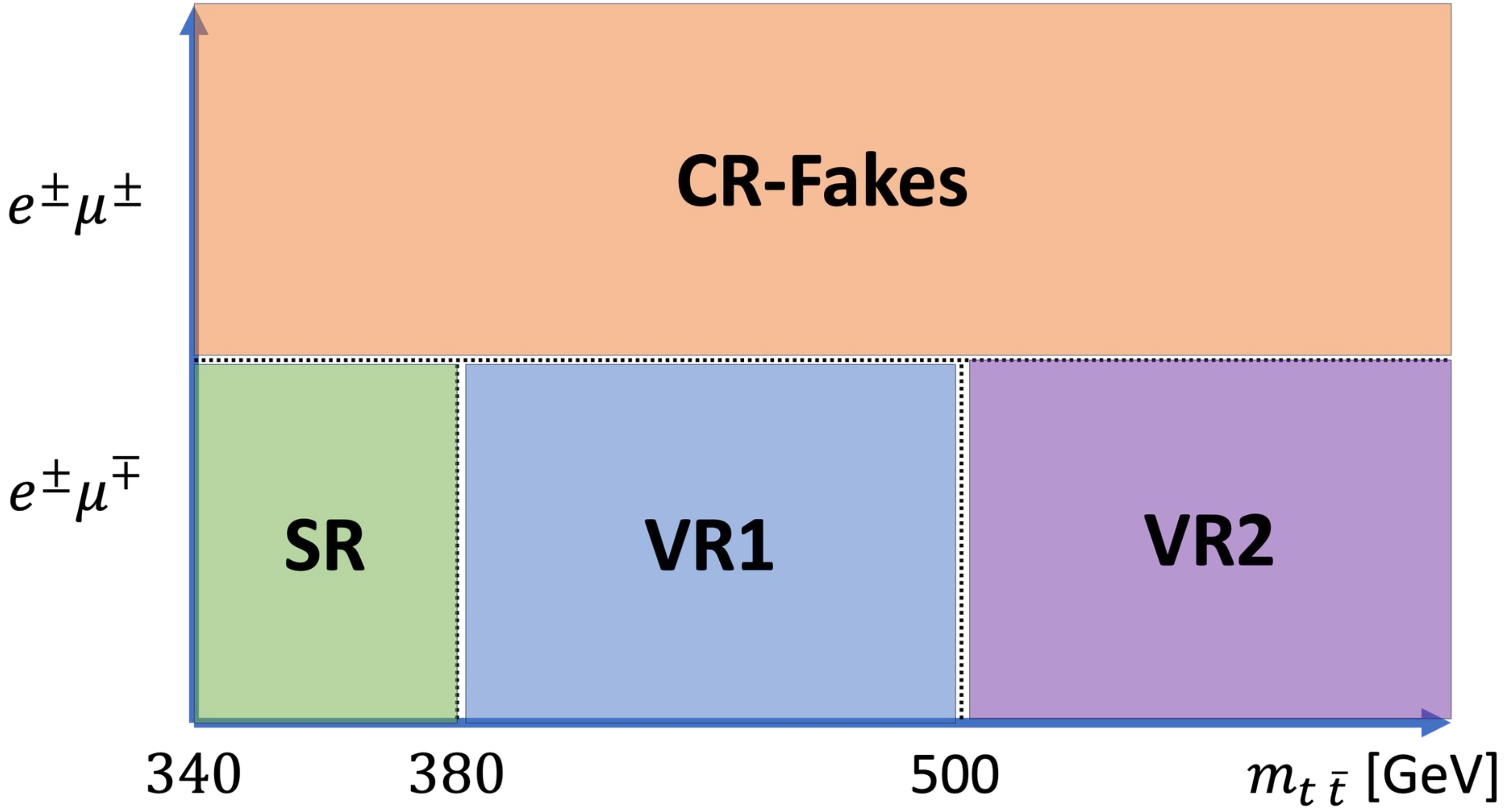
z-axis: concurrence C[ρ]

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

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

Dilepton ttbar selection



Post-decay three-particle entanglement

☑ Novel entanglement tests that were not possible before.

J.A. Aguilar Saavedra

What is genuinely new in particle physics with respect to experiments with electrons and photons? Particle decay.*

- Post-decay entanglement: JAAS 2307.06991

A and B entangled
$A \to A_1 A_2$
→
A_1, A_2 and B entangled
A_1 and B entangled

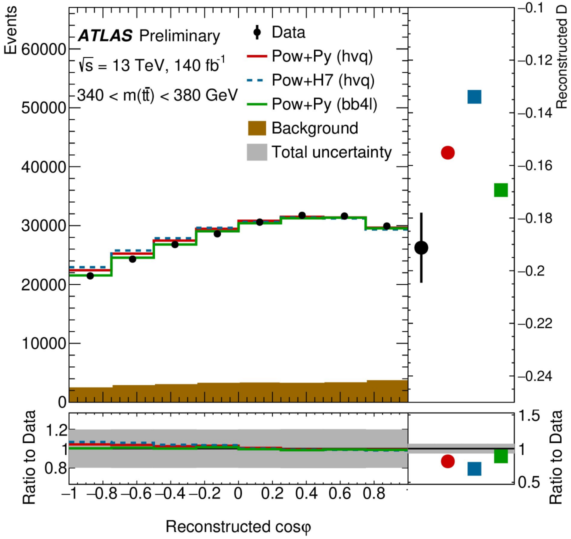
- Entanglement and post-selection: JAAS 2308.07412

A and B entangled
$A \to A_1 A_2$
Measurement on B
(time ↓)
→
$\asymp$ spin selection on A,
which already has decayed

* J. Bernabéu, talk at 7th Red LHC workshop, Madrid, May 10-12 2023

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,



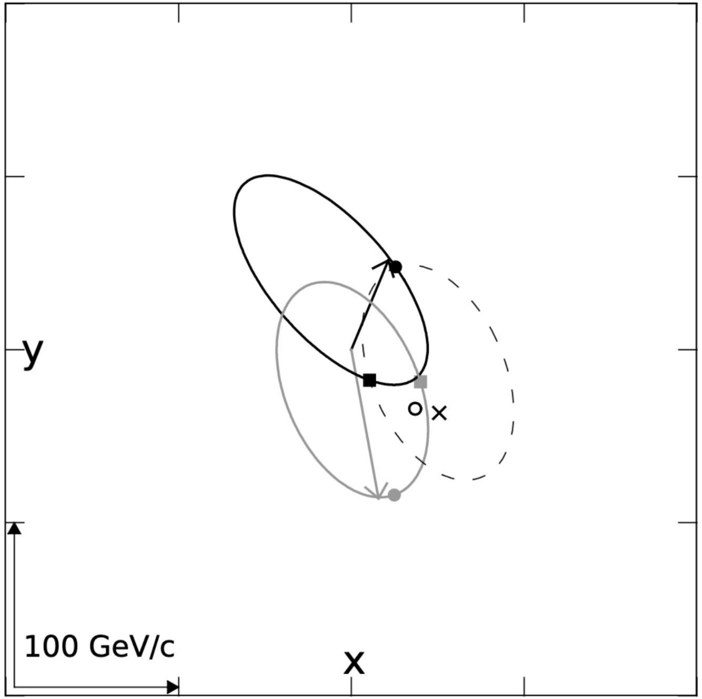
ATLAS-CONF-2023-069

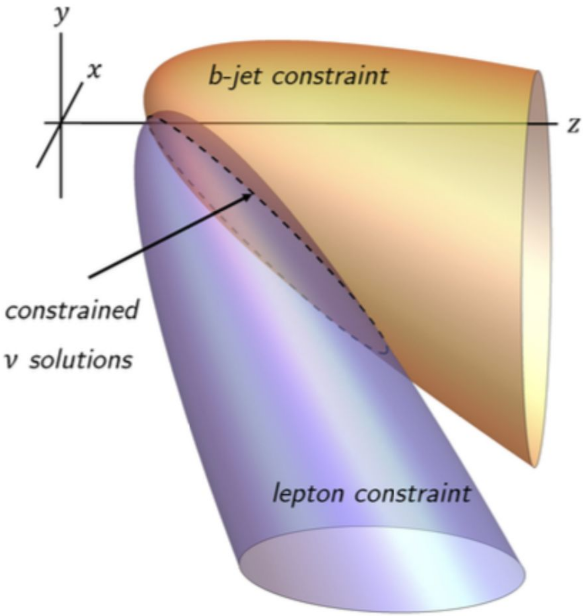
The Ellipses method

Nucl. Instrum. Meth. A 736 (2014) 169

Assume: everything is on-shell AND neutrinos are the source of the missing E_T

→ neutrino momenta are **geometrically** constrained to an ellipse





The Neutrino Weighting method

Phys. Rev. Lett. 80 (1998) 2063

- Dates back to D0 (1997), they measured m_{top} = 172.0 ± 7.5 GeV
- LHC Run 1 combination (2023) measured m_{top} = 172.52 ± 0.33 GeV
- **Don't assume** that the missing E_T comes from the neutrinos
  - instead **scan (η_1,η_2)** and for each pair extract (p_{x1},p_{y1}) and (p_{x2},p_{y2}) from the mass constraints
  - then compare to missing E_T and extract a weight

$$w = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right)\cdot\exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right)$$

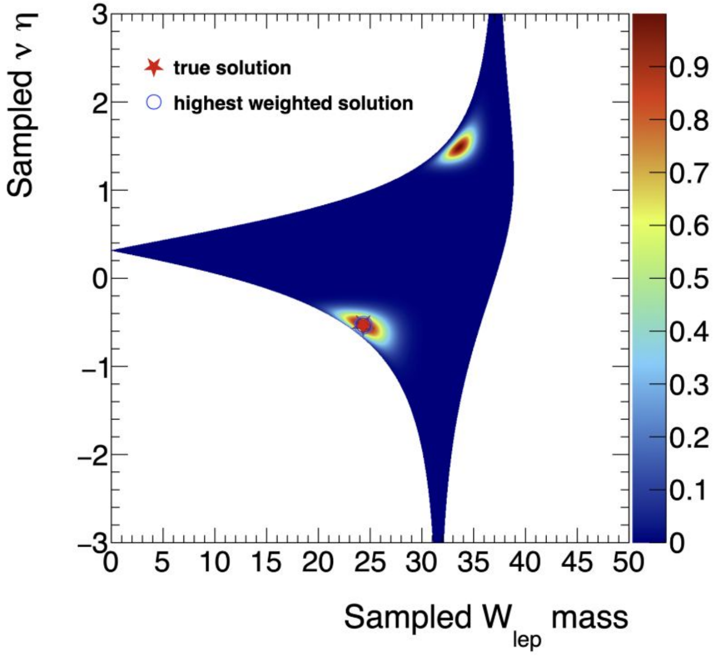
- Still have to check the b-jet assignments, possible dependence on m_{top}, smearing in case there are no solutions, …

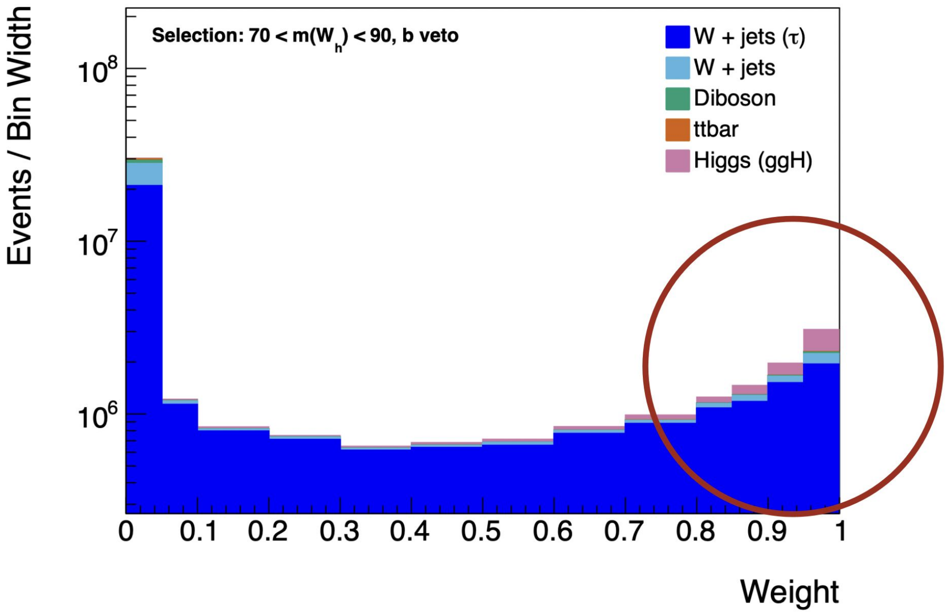
  → **very CPU-expensive!**

Aside: Neutrino Weighter with a twist

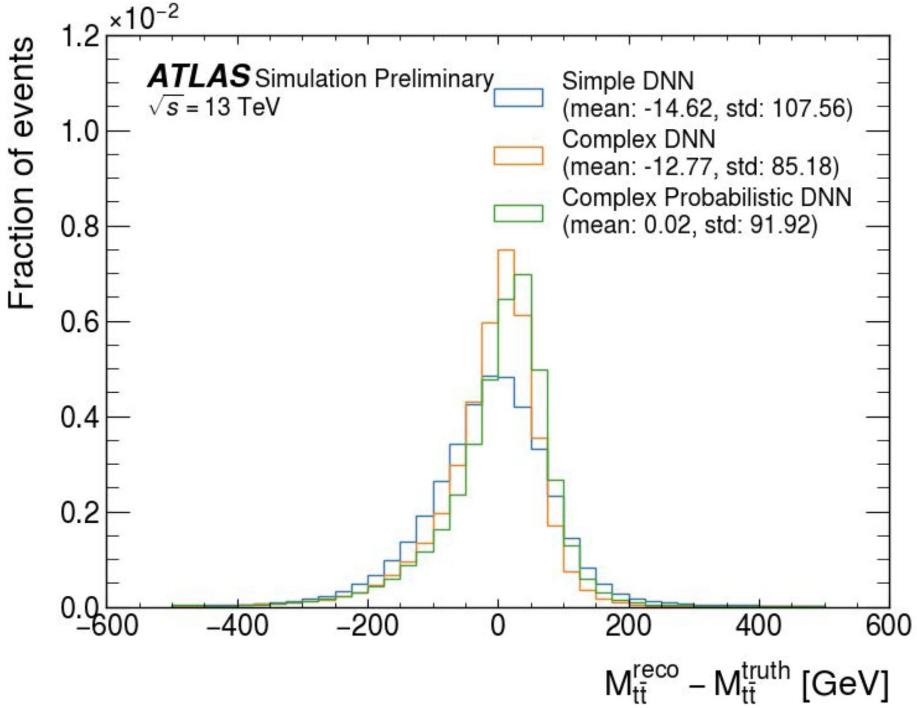
See Theo Maurin's talk

- **We reconstruct many Higgs each event under different assumptions of m_{W^*} and η_ν.**





“Can we throw machine learning at it?”



Simple → **Complex**: add more inputs and more layers, get *improvement in resolution*.
DNN → **Probabilistic DNN**: get an estimate of the aleatoric uncertainty, *remove the bias*.

Reconstructing the two neutrinos’ 4-vectors is the hard part…

But maybe this is not always the goal?
For instance, we could regress m(ttbar) directly:

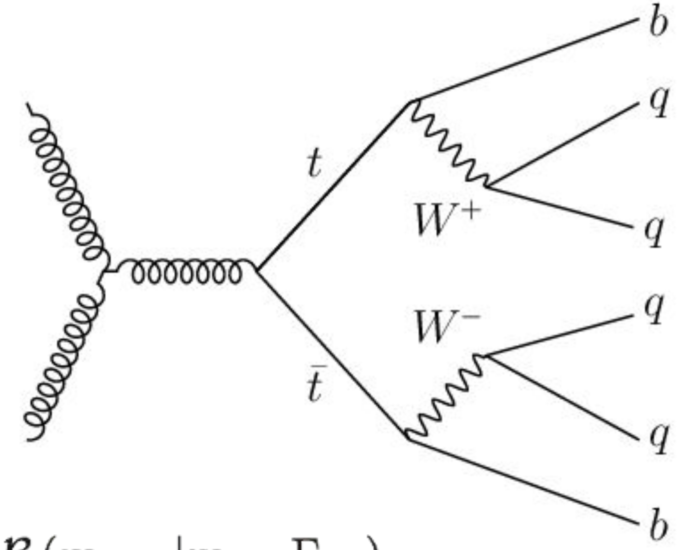
- Z’→ttbar resonance searches?
- dependence of m(ttbar) on top Yukawa?
- reducing the amount of dilution in QE/BIV measurements?

All-hadronic ttbar: should be easy, right?

All decay products are visible jets → **completely avoid the problems** associated with neutrinos!

But now have to deal with combinatorics…

$$\chi^2 = \frac{(m_{b_1q_1q_2} - m_t)^2}{\sigma_t^2} + \frac{(m_{b_2q_3q_4} - m_t)^2}{\sigma_t^2} + \frac{(m_{q_1q_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{q_3q_4} - m_W)^2}{\sigma_W^2},$$



$$\mathcal{L} = \mathcal{B}\left(m_{q_1q_2q_3}|m_t,\Gamma_t\right)\cdot\mathcal{B}\left(m_{q_1q_2}|m_W,\Gamma_W\right)\cdot \mathcal{B}\left(m_{q_4q_5q_6}|m_t,\Gamma_t\right)\cdot\mathcal{B}\left(m_{q_4q_5}|m_W,\Gamma_W\right)\cdot \prod_{i=1}^{6} W_{\text{jet}}\left(E_{\text{jet},i}^{\text{meas}}|E_{\text{jet},i}\right)$$

Suffer from CPU cost of permutations

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Machine learning instead of combinatorics: SPA-Net

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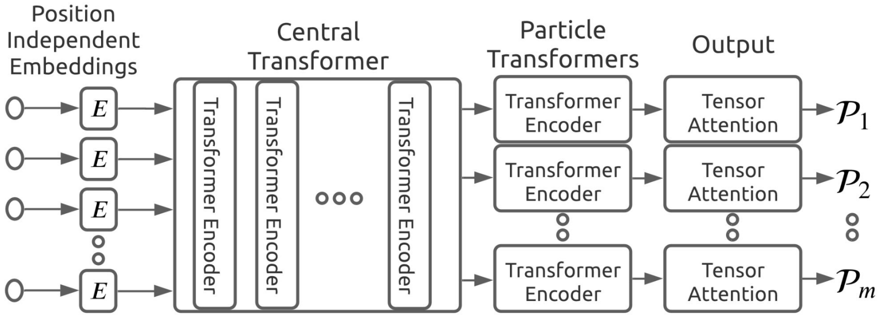
Symmetry-**P**reserving **A**ttention **Net**work

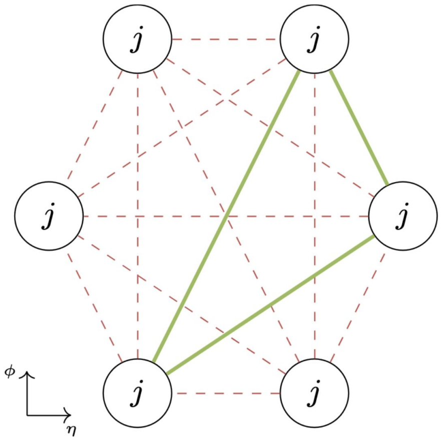


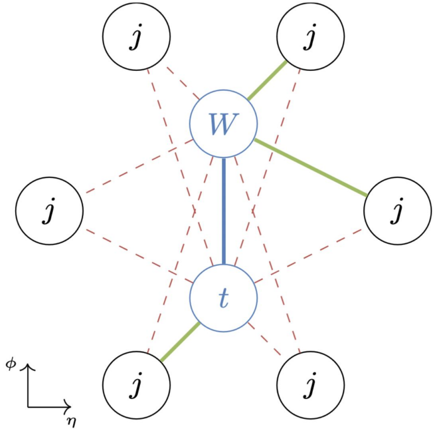
Transformer-Encoder: state-of-the-art from Natural Language Processing
→ relate the input jets to each other in the latent space

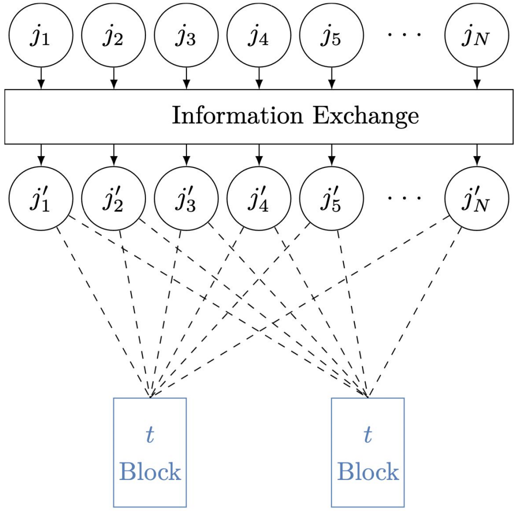
Tensor attention: impose symmetries of the topology
W ~ qq / top ~ bqq

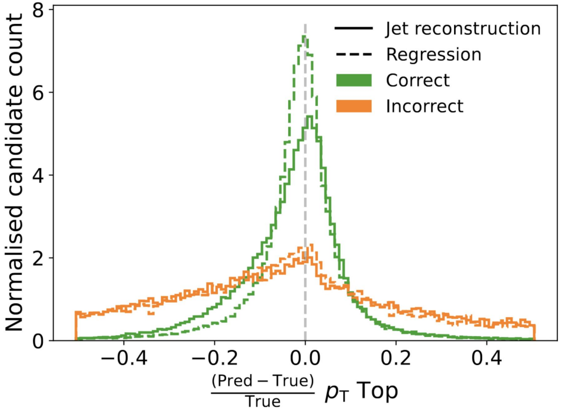
	N_{jets}	Event Fraction	SPA-NET Efficiency Event	SPA-NET Efficiency Top Quark	χ^2 Efficiency Event	χ^2 Efficiency Top Quark
All Events	== 6	0.245	0.643	0.696	0.424	0.484
	== 7	0.282	0.601	0.667	0.389	0.460
	≥ 8	0.320	0.528	0.613	0.309	0.384
	Inclusive	**0.848**	**0.586**	**0.653**	**0.392**	**0.457**
Complete Events	== 6	0.074	0.803	0.837	0.593	0.643
	== 7	0.105	0.667	0.754	0.413	0.530
	≥ 8	0.145	0.521	0.662	0.253	0.410
	Inclusive	**0.325**	**0.633**	**0.732**	**0.456**	**0.552**

Injecting yet more physics into the machine: Topographs









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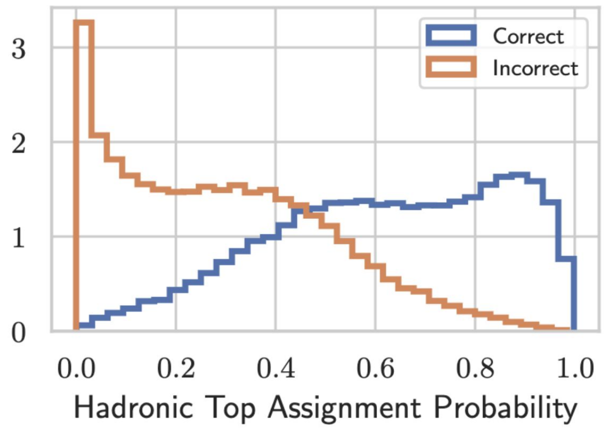
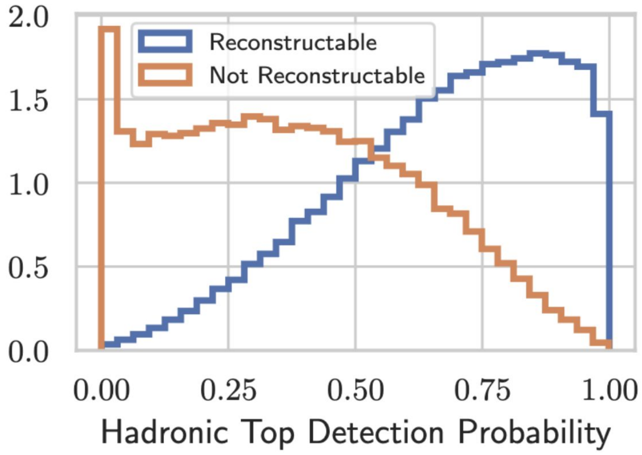
Physically motivated representation of the inputs: **graph**
→ inject intermediate resonances and specify the allowed connections

- Edge regression: find best assignments
- Node regression: predict the kinematics of the resonances
- Performs as well as SPA-Net

	6j 2b	6j >=2b	7j 2b	7j >=2b	>=6j 2b	>=6j >=2b
Best Spanet [%]	81.58	79.60	65.09	63.09	68.95	66.20
Best Topograph [%]	81.44	79.53	64.91	62.81	68.86	66.24

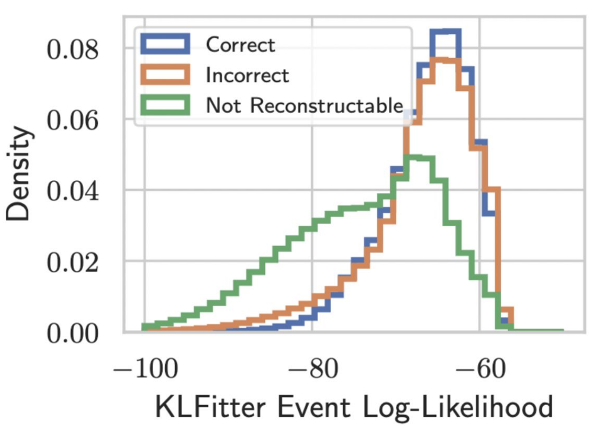
From reconstruction to classification

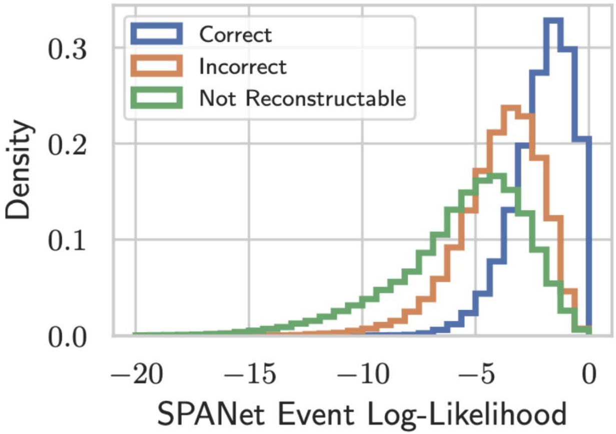


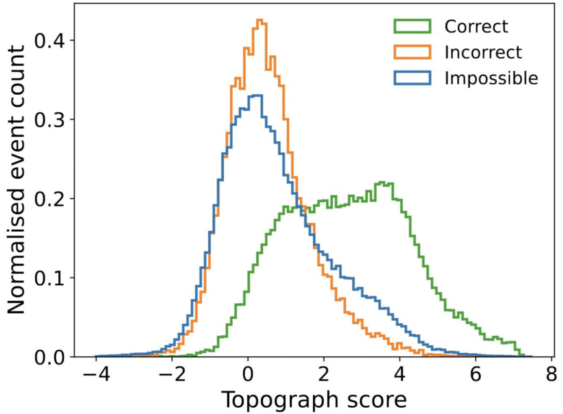


Could select only those events that are **well-reconstructed**:

- signal vs background?
- unfolding?
- modelling uncertainties?







A middle ground? ttbar → lepton+jets

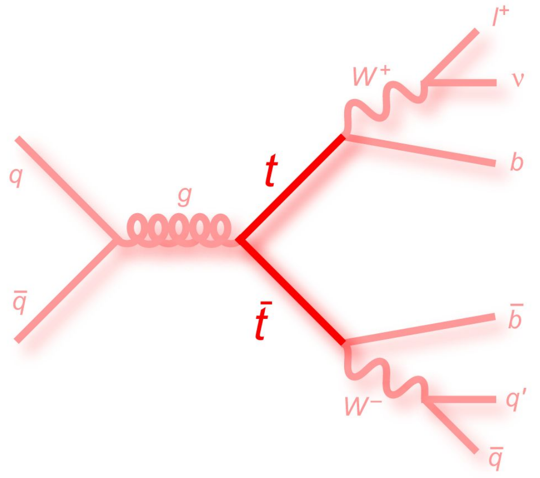
Final state with a single neutrino: can be **fully determined from one mass constraint** (on-shell W) → analytical solution(s)

$$p_z^\nu = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a},$$

$$a = (p_z^\ell)^2 - (E^\ell)^2,$$
$$b = \alpha p_z^\ell,$$
$$c = \frac{\alpha^2}{4} - (E^\ell)^2 (p_\mathrm{T}^\nu)^2,$$
$$\alpha = m_W^2 - m_\ell^2 + 2(p_x^\ell p_x^\nu + p_y^\ell p_y^\nu).$$

Is this useful for spin correlation and quantum information studies?

→ Yes! the d-quark from the W decay has α_{spin}~1



Conditional neutrino regression: ν-flows

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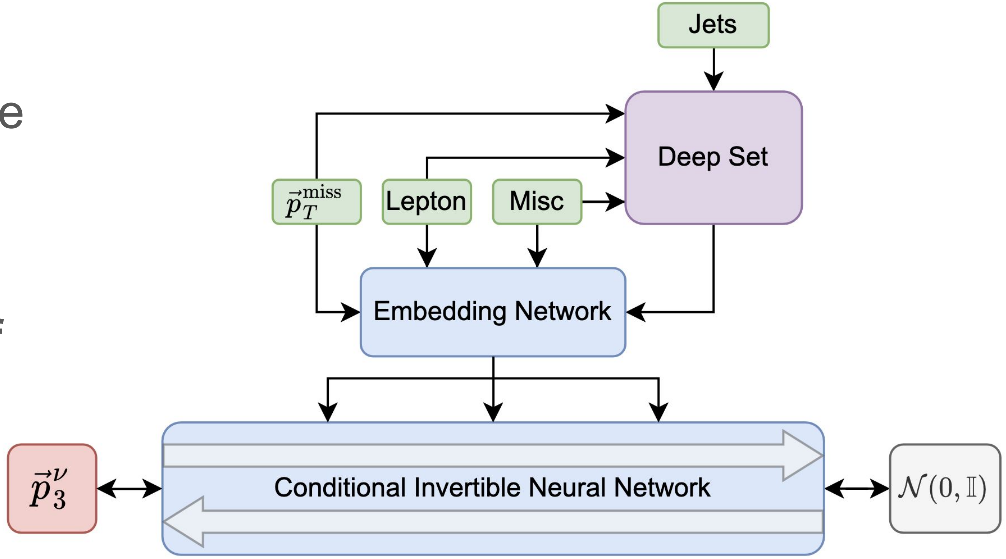
1. Embed your input particles in some way
2. **Train a mapping of the Normal distribution to the kinematics of the neutrinos**
3. Learn what the likelihood of the neutrino kinematics based on the rest of the event
   → no assumption of on-shell W's, perfect reconstruction etc.



Conditional neutrino regression: ν-flows

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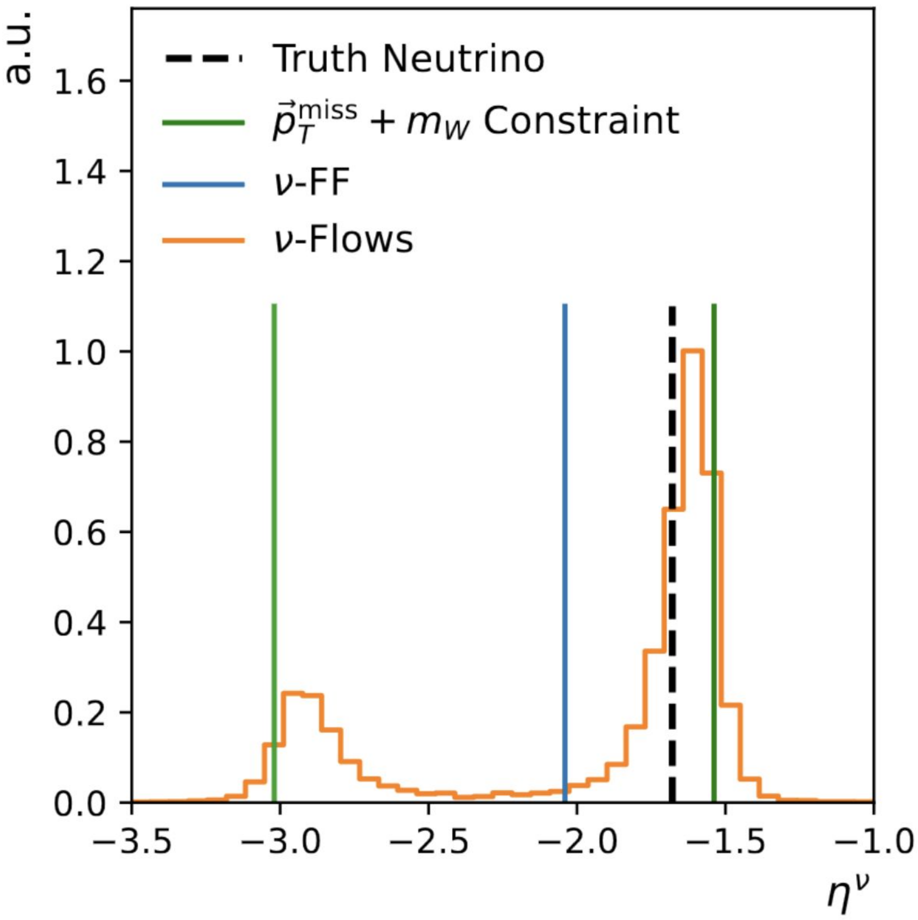
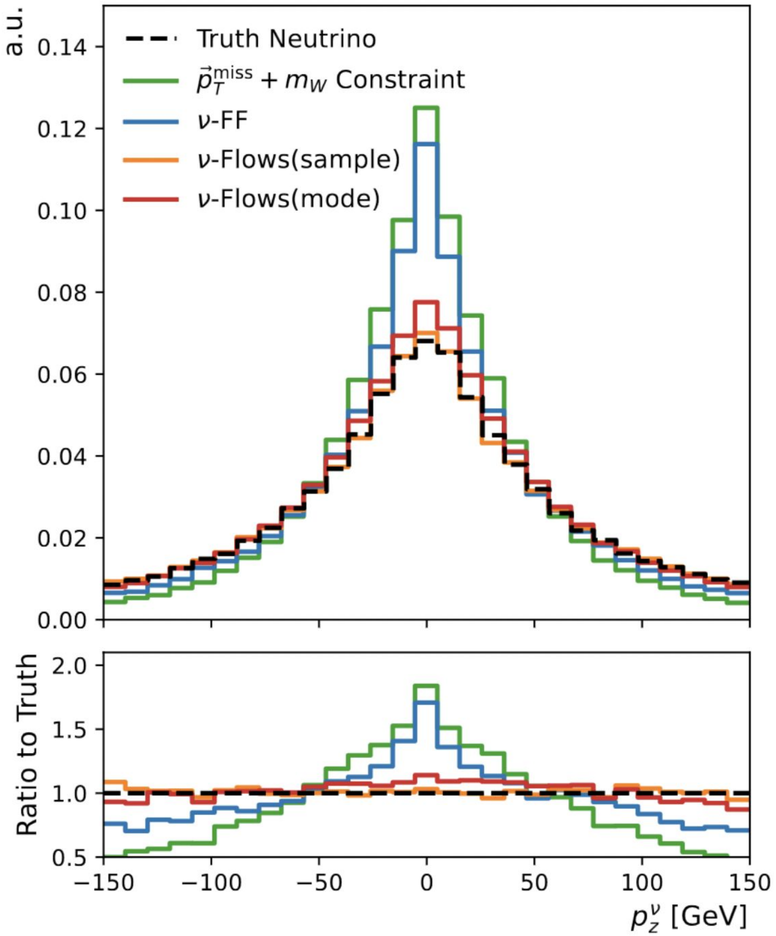
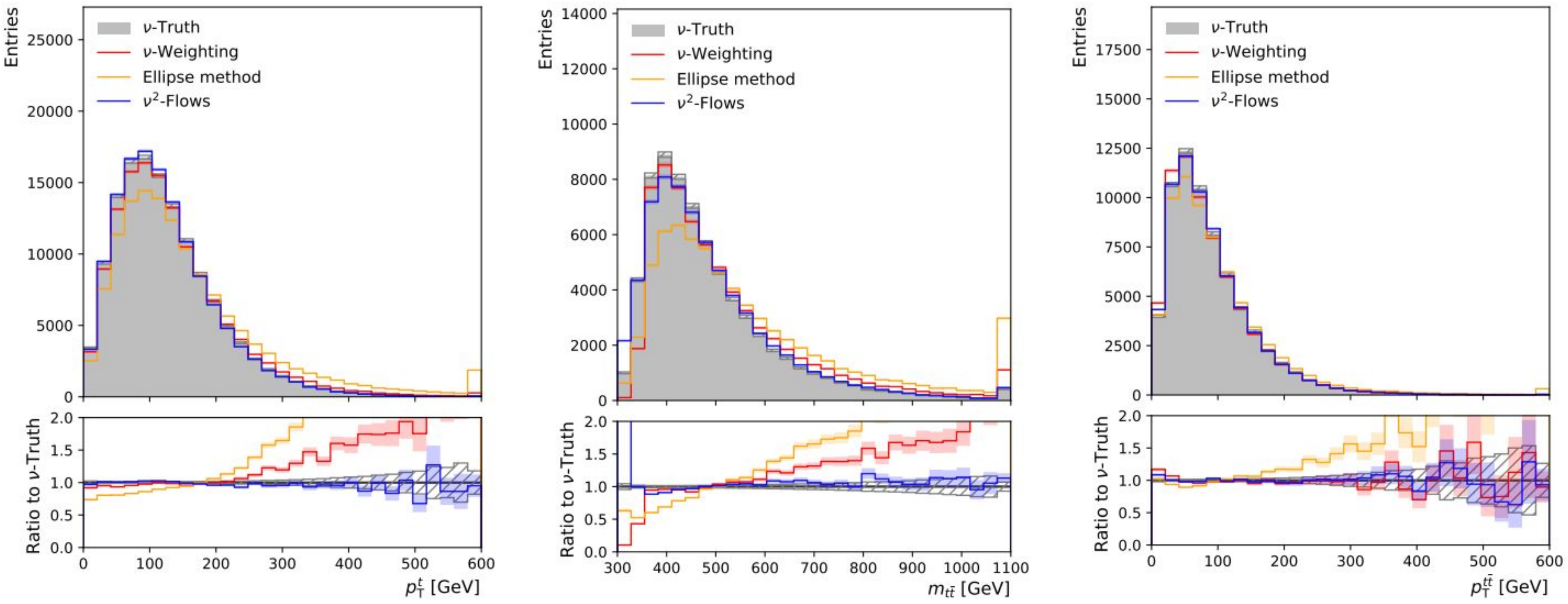




More neutrinos! ν^2-flows

arXiv:2307.02405



More neutrinos! ν^2-flows

arXiv:2307.02405