MSCA CUP J33C23001080006

QUANTUM TESTS AT LHC

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OUTLINE

- Limiting aspects of Quantum Tests at LHC
- ATLAS result on entanglement in top-pair final state
- CMS result on entanglement in top-pair final state
- Future developments
- What does it mean Bell's Inequality Violation

LIMITING ASPECTS - I

- We cannot measure the spin of the particles produced at LHC per event
- We need to use quantum tomography
  - Relate the direction of the decay product to the spin of the parent particle
    - Not all particles are the same → each particle has a certain spin analysing power
- Optimal frame for measuring the angles is usually defined in the CofM rest frame
  - Need to reconstruct the whole final state

Pion in the 1 prong decay

Charged lepton or down type quark

All particle have the same spin analysing power, important to keep consistency!

Neutrino…

LIMITING ASPECTS - II

Charged Leptons

- The leptons are the easier particles to reconstruct
- They are often produced in association with neutrinos
- Multiple neutrinos in the final state make impossible to fully reconstruct the final state

Jets

- Much less neutrinos!
- Worst resolution compared to leptons
- Hard to understand the original quark flavour
  - Up and down type quark usually have opposite sign analysing power. Mixing them significantly decreases the sensitivity of the measurement
  - Limited analysis power compared to leptons → larger uncertainty

Statistics

- These are all measurement all based on averages across similar events
- This is a limiting factor for some processes (H)
- The largest entanglement could be in very limited regions of the phase space

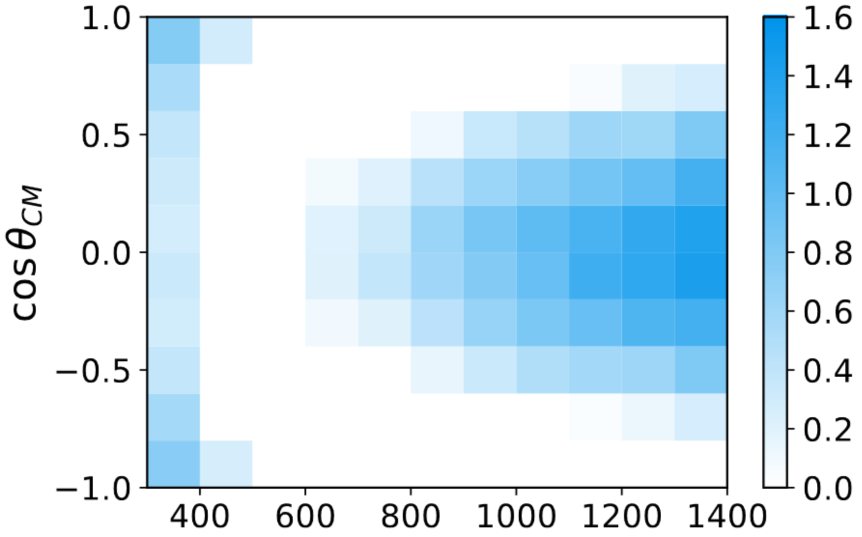
Resolution

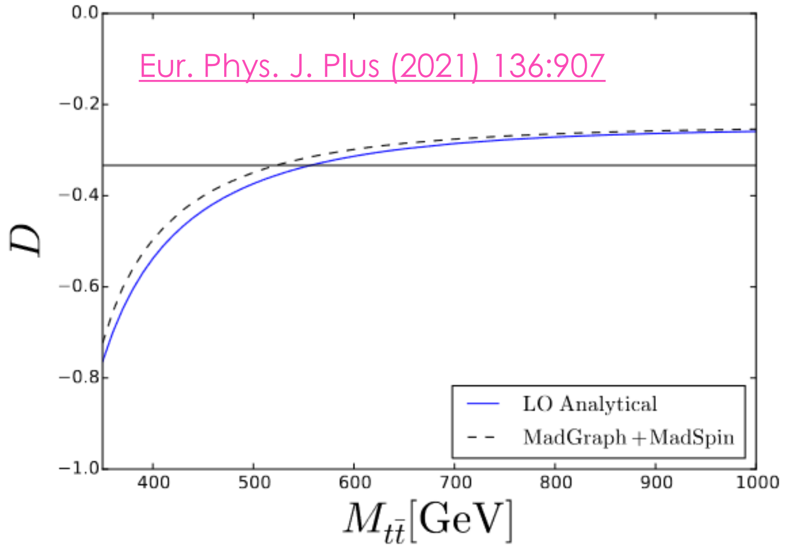
- The observables are highly affected by many aspects of detector reconstruction and event evolution.

ENTANGLEMENT IN TOP-QUARK PAIRS

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

PRD 109.115023





ENTANGLEMENT IN TOP PAIRS

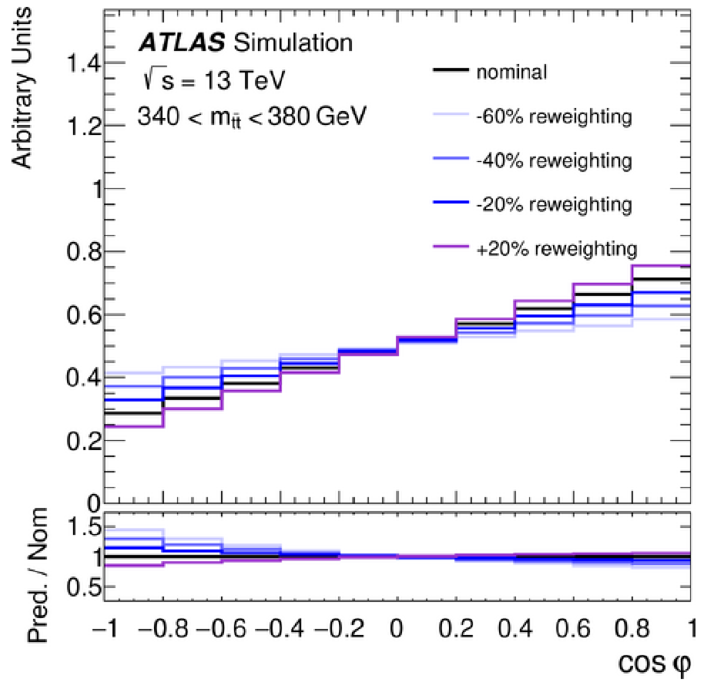
- The top-quarks are interpreted as qubit:

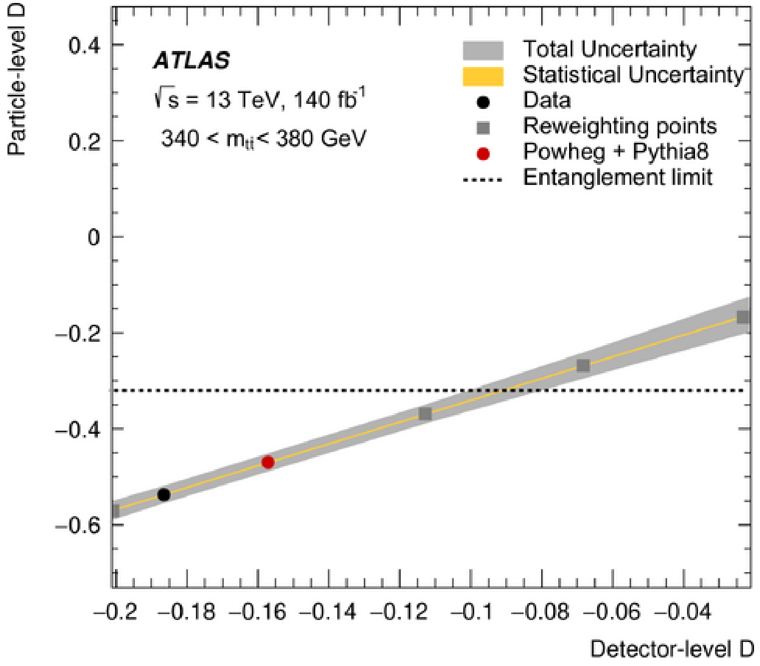
$$\rho = \frac{1}{4}\left[\mathbf{1}\otimes\mathbf{1} + B_i\sigma_i \otimes \mathbf{1} + \overline{B}_i \mathbf{1}\otimes\sigma_i + C_{ij}\sigma_i\otimes\sigma_j\right]$$

- The entanglement can be extracted from the elements of the spin density matrix or directly from a single observable
  - $D = \frac{3<\cos(\varphi_{ab})>}{\alpha_a\alpha_b}$ or $\frac{2}{\alpha_a\alpha_b}\,\frac{N(\cos(\varphi_{ab})>0)-N(\cos(\varphi_{ab})<0)}{N}$
  - φ is the angle between the two leptons in the parent rest frame
  - D < -1/3 entanglement limit
- The top quark pairs are generally produced not entangled
  - Entangled in a limited region of the phase space: at threshold and at really high mass.
  - Measurement of the entanglement need to target these regions

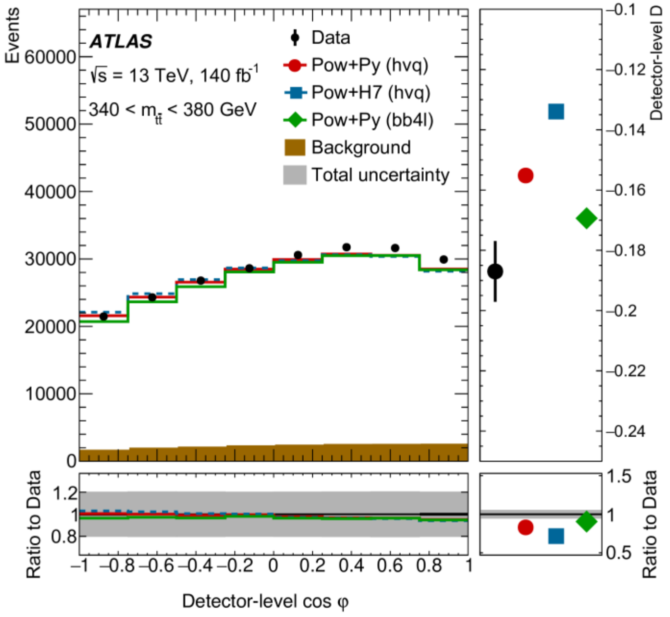
ATLAS MEASUREMENT

ANALYSIS STRATEGY



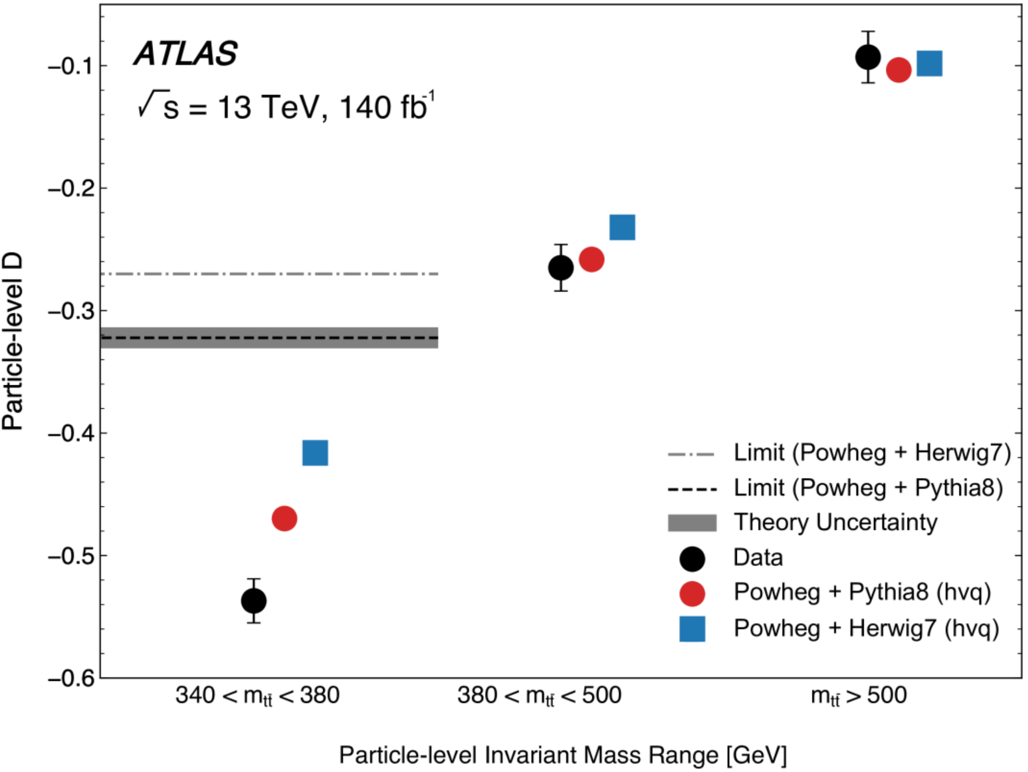


- Select events in the dilepton final state
  - Reconstruct the full final state imposing the W and top-quark mass constraints
  - Include all Run2 events
- Measure D in the threshold region
- Extract D at particle level to reduce the dependence on modelling uncertainties
  - Fiducial region defined on stable objects
  - Calibrate D using tilted templates
- Large difference between detector and particle level
  - Even larger going to parton



Nature 633 (2024) 542

RESULTS



- Observed entanglement between top-quarks
  - Larger observed entanglement compared to expected
  - Disagreement only in the region very close to threshold
- Dominant uncertainties from modelling
  - Large difference in the particle level entanglement limit between Herwig7 and Pythia8

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

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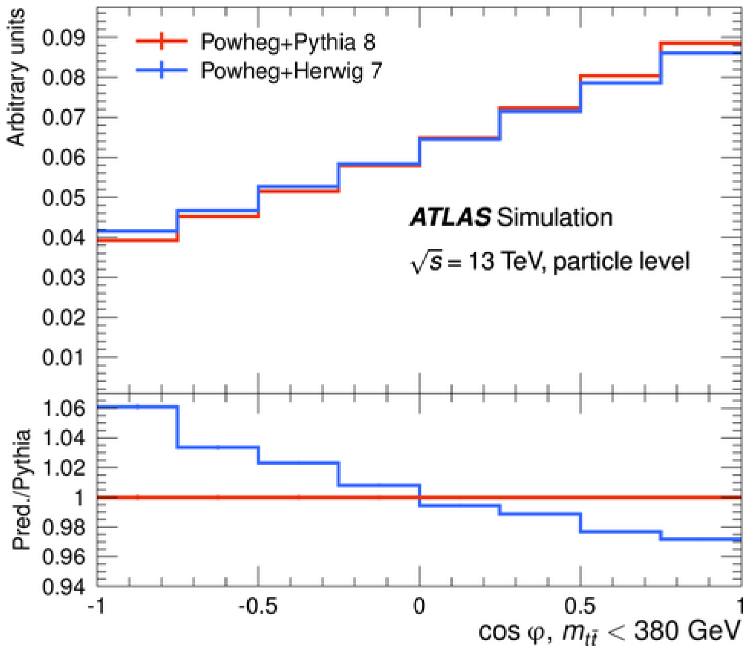
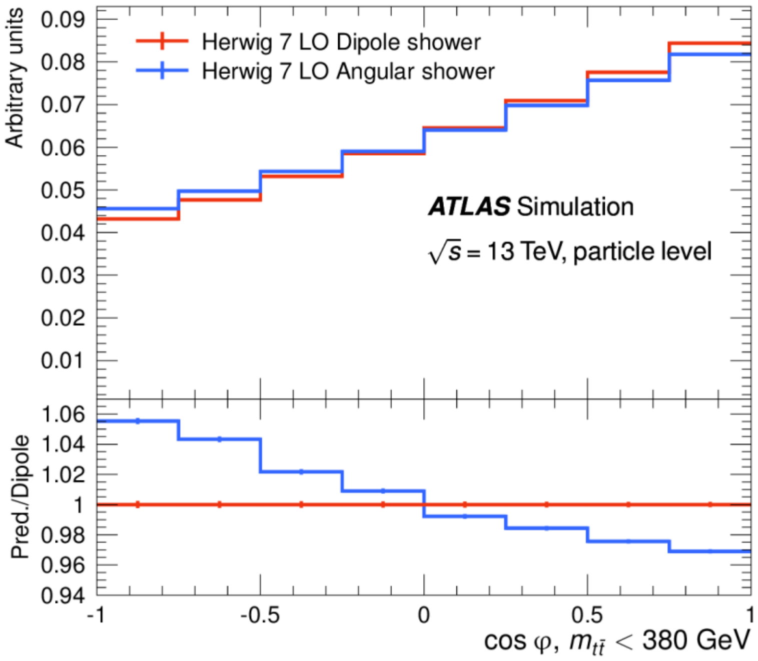
MODELLING

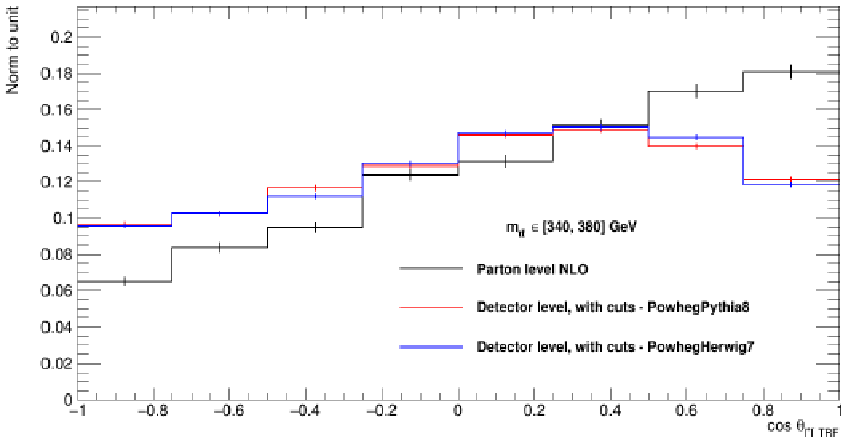
- Analysis strategy dictated by the large difference between pythia and Herwig
  - Large difference in the entanglement threshold
  - Seems related to the ordering in the showering





B. D. Gonzaléz, F. Fabbri, M. M. Llácer, M. Vos

EFFECT OF THE RECONSTRUCTION



CUT SELECTION	$p_T(jet)$(GeV)	p_T(l)(GeV)	$\eta_{jet,l}$
BASE	>25	>27	$-2.5 < \eta_{jet,l} < 2.5$
p_T(l)	>25	>10	$-2.5 < \eta_{jet,l} < 2.5$
No η cut	>25	>27	-
CARDS SELECTION			
BASE	Default ATLAS Delphes Cards		
B-tag	light-jet mistagging rate c-jet mistagging rate b-tagging efficiency		Decreased ~50% Decreased ~75% Increased ~10%
Jet reso	Jet resolution		Increased ~50%
NEUTRINO SELECTION			
BASE	MET + neutrino weighting method		
Real ν + WM	Real ν summed + neutrino weighting method		
Real ν	Real ν		

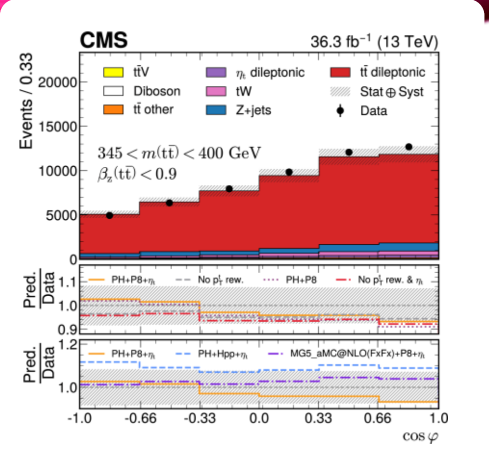
- External study to investigate which aspect of the reconstruction and selection has the largest impact on the observables
  - Base: baseline dilepton selection
  - Detector level: Delphes ATLAS card
- Neutrino reconstruction has certainly a large impact on the result
- Ongoing studies presented in Oxford 10/2024 M. Moreno Llácer

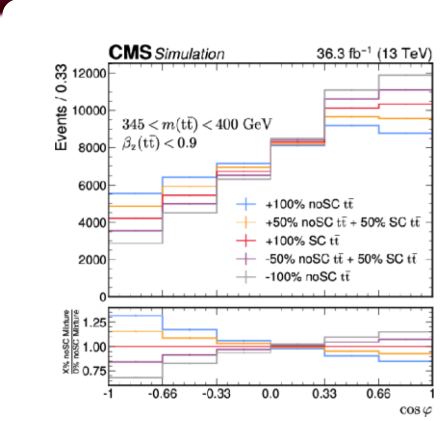
Observable	PARTON LEVEL		RECONSTRUCTION LEVEL						
	No cuts	Base	Base	$p_t(l)$	No η cut	B-tag	Jet reso	Real ν + WM	Real ν
C_{kk}	-0.342	-0.43	-0.087	-0.001	-0.087	-0.088	-0.087	-0.082	-0.285
C_{rr}	-0.029	-0.04	-0.130	-0.119	-0.131	-0.131	-0.130	-0.110	-0.027
C_{nn}	-0.329	-0.39	-0.331	-0.335	-0.331	-0.328	-0.314	-0.313	-0.399
D	-0.233	-0.287	-0.183	-0.151	-0.183	-0.182	-0.177	-0.168	-0.237
D_3	-0.014	-0.029	0.038	0.072	0.038	0.036	0.034	0.040	0.029

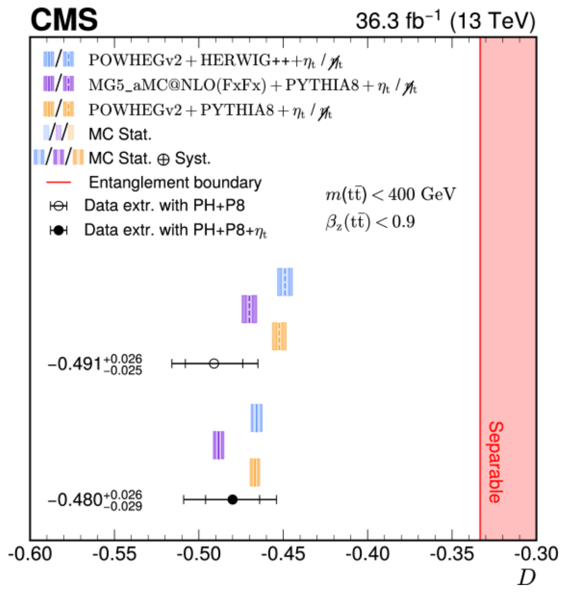
CMS MEASUREMENTS

Rep. Prog. Phys. 87 (2024) 117801

DILEPTON RESULT



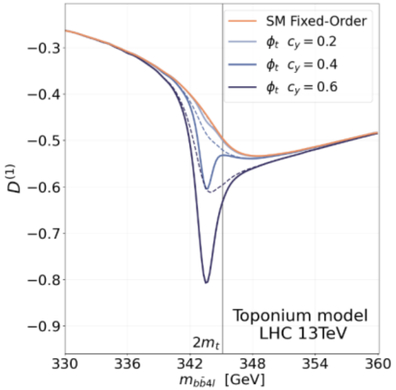


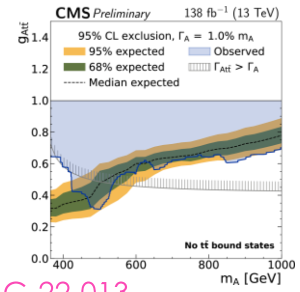


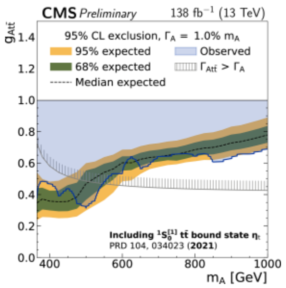
- Investigate the threshold region for top-pair production in dilepton channel
  - Full final state reconstruction with kinematic fit
- Extract the result at parton level using a profile likelihood fit
  - Template built by mixing together SM events and events with no spin correlations
- Two different results one including and one excluding toponium
  - Including this new “bound state” improves the agreement

TOPONIUM?

10.1007/JHEP03(2024)099







HIG-22-013

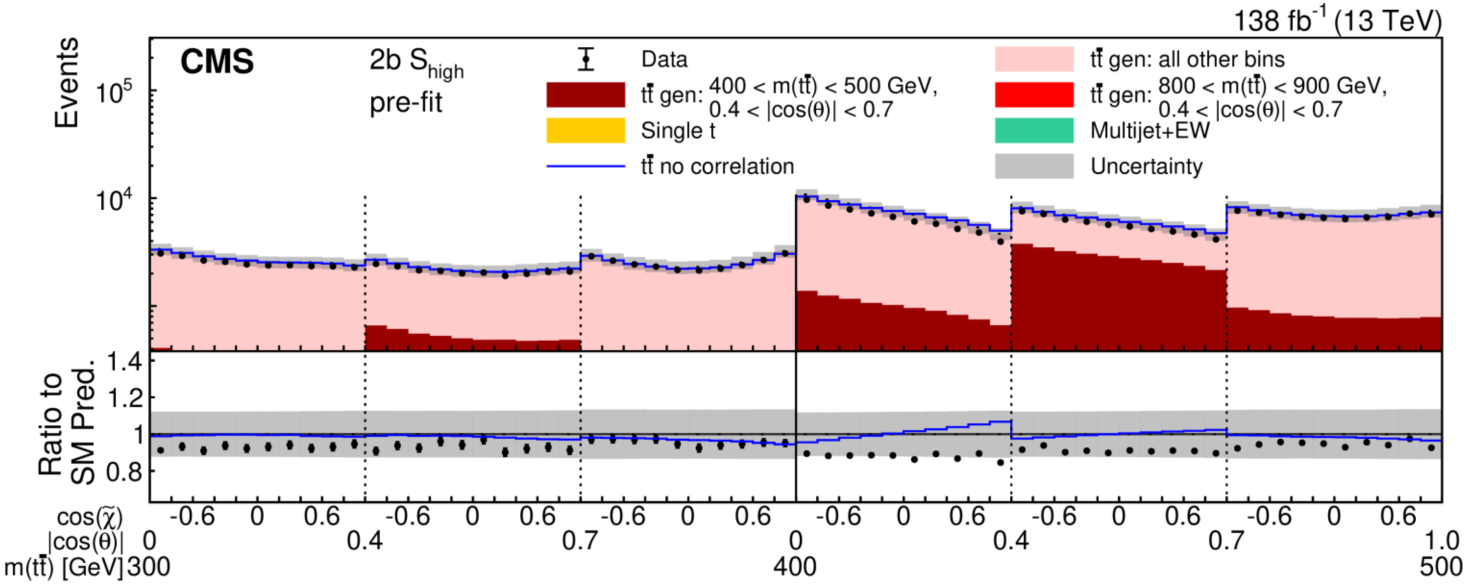
- Pseudo-bound state enhancing the cross section in the color singlet gg→$\bar{t}t$ at threshold
  - Similar to a resonance
  - Includes an octet component that is currently not simulated in existing effective models
  - Predicted by the SM, not included in “standard”MC simulation
  - Should highly increase the entanglement at threshold
- Both ATLAS and CMS results show a tension that would be eased by adding this state in the simulations
- CMS recently published a search for a scalar/pseudo-scalar at low m($\bar{t}t$) using both m($\bar{t}t$) and observables related to entanglement
  - Large tension observed at low m($\bar{t}t$)
  - Significantly reduced when including the effective toponium model

ENTANGLEMENT IN THE HIGH MASS REGION

TOP-23-007 (PRD)

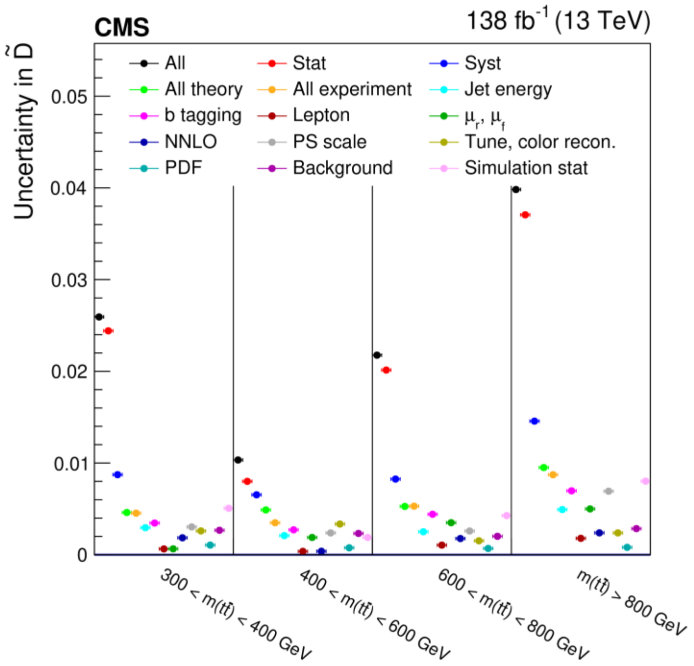
$$\Sigma_{\text{tot}}(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}) = \frac{d^4\sigma}{d\phi_p \, d\cos(\theta_p) \, d\phi_{\bar{p}} \, d\cos(\theta_{\bar{p}})}$$
$$= \sigma_{\text{norm}} \left(1 + \kappa \mathbf{P} \cdot \mathbf{\Omega} + \bar{\kappa} \bar{\mathbf{P}} \cdot \bar{\mathbf{\Omega}} - \kappa\bar{\kappa} \mathbf{\Omega} \cdot (\mathbf{C} \bar{\mathbf{\Omega}})\right)$$

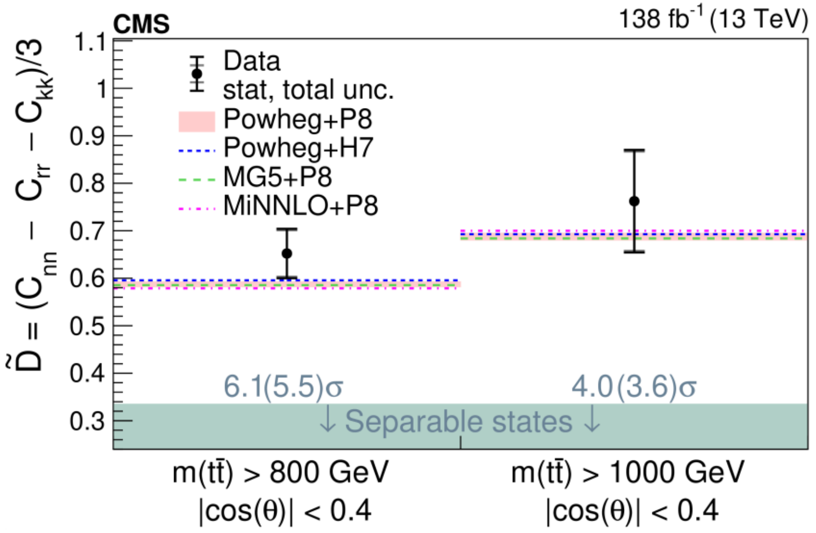
- CMS also performed a measurement in the l+jets channel
  - ML approach to reconstruct the events
  - Identify the down type jet originating by the W decay
- Profile likelihood fit to 3D observables: m($t\bar{t}$), top production angle and the angle sensitive to the polarimeters
- Template built changing directly the spin density matrix coefficients



TOP-23-007 (PRD)

RESULTS





- Good agreement between the results and the SM
- Observed entanglement also in the boosted region
- Extract all components of the spin density matrix in bins of m$(t\bar{t})$
  - Could be interesting for limit on new physics
- Statistically limited in the high mass regions
  - The number of events with 4 jets in the final state reduces drastically in the high mass region

FUTURE DEVELOPMENT

Very personal view on the near future

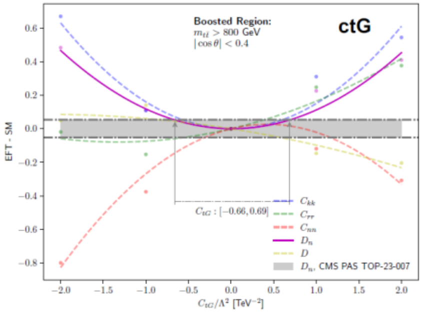
There are tons of extremely cool ideas on what to do with LHC data:

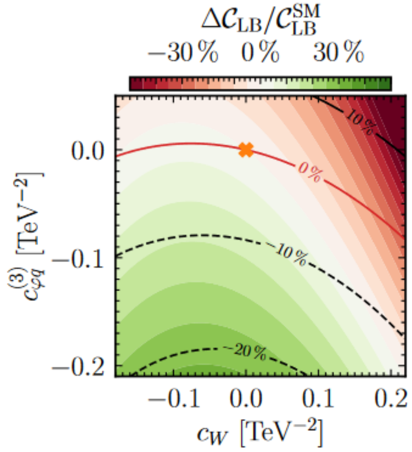
- Steering & Discord10.1103/PhysRevLett.130.221801
- Entanglement post decay (tW) arXiv:2307.06991
- Entanglement between b-quarks : 2406.04402
- Lab-frame entanglement test in H→WW https://arxiv.org/abs/2209.14033
- Measure magic
- Identical particle interference effects https://arxiv.org/abs/2411.13464

$$X = X_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}\sum_i C_i X_i^{(1)}}_{\text{Linear Terms}} + \underbrace{\frac{1}{\Lambda^4}\sum_{ij} C_i C_j X_{ij}^{(2)}}_{\text{Quadratic Terms}} + \mathcal{O}(\Lambda^{-4})$$

LIMIT ON NEW PHYSICS

- According to pheno studies the quantum information inspired observables should increase the sensitivity to new physics
  - Direct and indirect searches
- Recent attempt to include them in the global EFT fit
  - The observables appear to be sensitive to the EFC couplings
  - Not "the most sensitive"
- Still to investigate the ability to break blind directions
- [Ongoing studies presented in Oxford 10/2024 M. Moreno Llácer]





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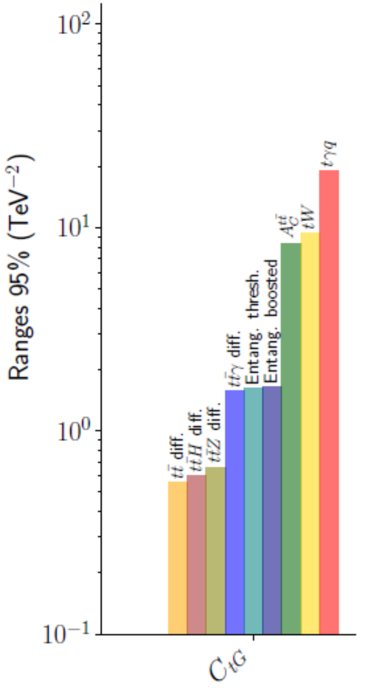
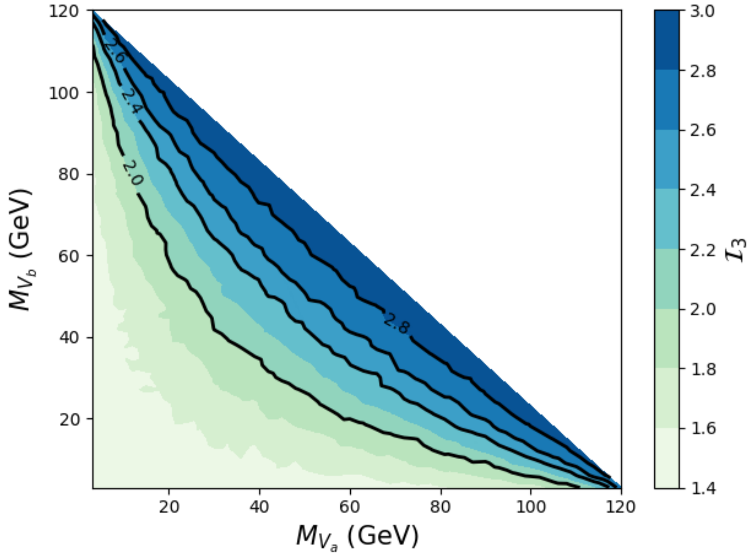
Linear+Quad.



MEASUREMENT IN H



- Several phenomenology studies on the measurement on entanglement and BIV in H→VV
- The V bosons are treated as qutrits

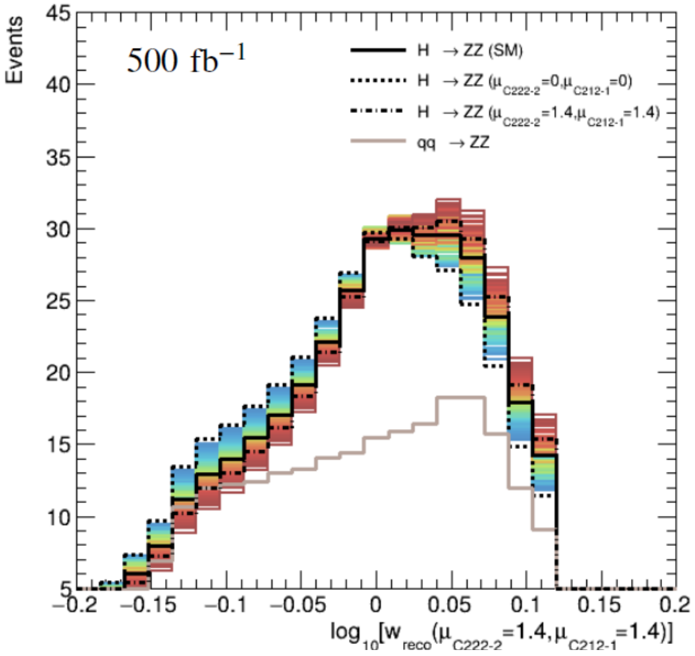
$$\rho = \frac{1}{9}\left[\mathbb{1}_3 \otimes \mathbb{1}_3 + A^1_{LM}\ T^L_M \otimes \mathbb{1}_3 + A^2_{LM}\ \mathbb{1}_3 \otimes T^L_M + C_{L_1M_1L_2M_2}\ T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right]$$

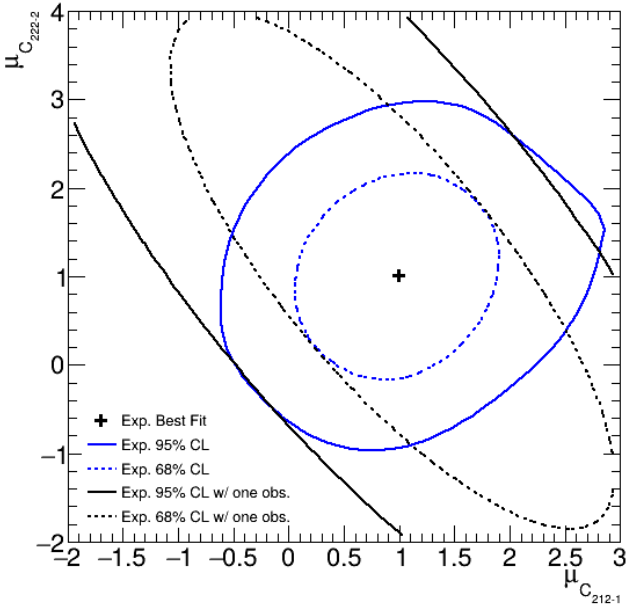
$$\rho_{\rm LO} = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & a_+a_+^* & \cdot & a_+a_0^* & \cdot & a_+a_-^* & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & a_0a_+^* & \cdot & a_0a_0^* & \cdot & a_0a_-^* & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & a_-a_+^* & \cdot & a_-a_0^* & \cdot & a_-a_-^* & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix}$$

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(1-\sqrt{2}A^1_{2,0}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

- The presence of the scalar parent highly simplify the matrix
  - Limited number of helicity configurations
  - Non zero off-diagonal term means state superposition → entanglement
  - Otherwise more complicated condition
- Bosons are created entangled almost across the whole phase-space
  - They should violate the Bell's inequality in a very large region of the phase space ($I_3 > 2$)

MEASUREMENT IN H->ZZ*





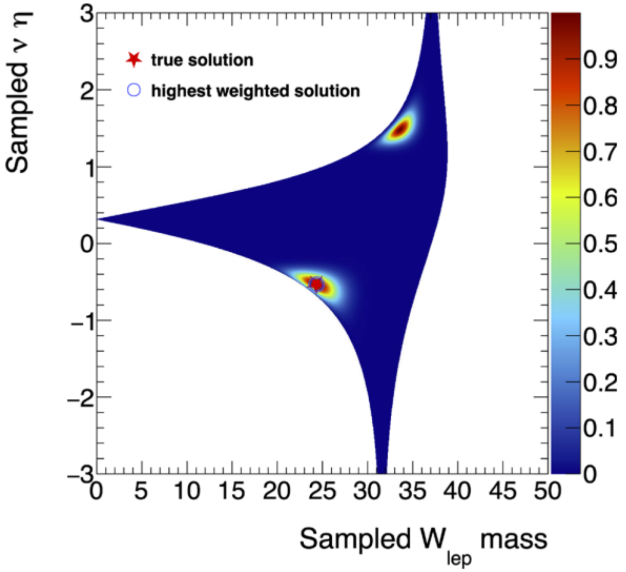
- Suggested strategy similar to tt l+jets
  - Template built changing the A and C elements of the spin density matrix

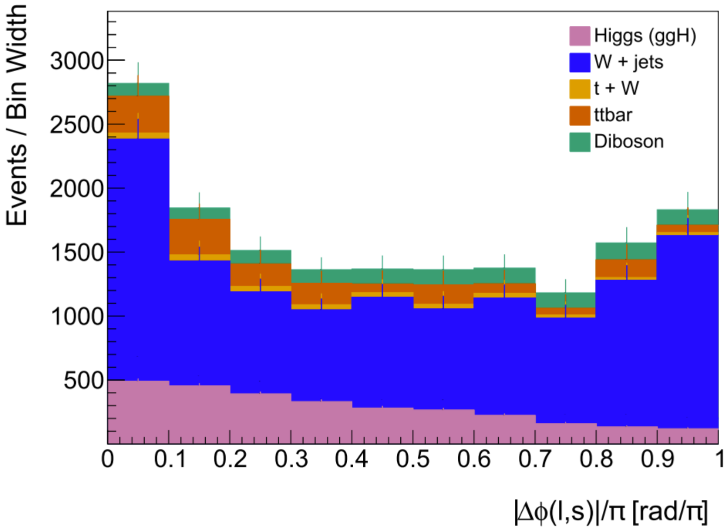
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\Big[1 + A^1_{LM}B_L Y^M_L(\theta_1,\varphi_1) + A^2_{LM}B_L Y^M_L(\theta_2,\varphi_2) + C_{L_1M_1L_2M_2}B_{L_1}B_{L_2}Y^{M_1}_{L_1}(\theta_1,\varphi_1)Y^{M_2}_{L_2}(\theta_2,\varphi_2)\Big] ,$$

  - Observable obtained with the directions of the negative lepton in the parent rest frame ($\varphi_1, \theta_1, \varphi_2, \theta_2$)
- Based on LO simulation passed through DELPHES
  - Most "accurate" emulation of a realistic workflow
- Separable hypothesis discarded at 2 sigma level
  - Still very limited sensitivity to the spin density matrix observables
- Study presented by M. Jukarova in Oxford, 10/2024

MEASUREMENT IN H→WW*

- The final state with two leptons has 2 neutrinos
  - Given that one W is off-shell the system is under constrained
- Try to exploit the H→WW*→lnucs final state
  - Polarimeter ?
    - The c-tagging allows to identify the flavour of the quark used as polarimeter (down type)
  - S/B separation?
    - The c-tagging reduces the W+jets background
    - Dedicated reconstruction algorithm assuming Higgs mass
- This final state can be exploited at HL to observe BIV violation in





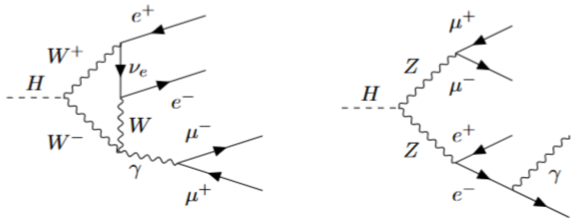
Luminosity [fb^{-1}]	$\langle \mathcal{B}^{zx}_{\text{CGLMP}} \rangle$ (idealised)	Significance (idealised)
139	2.45 ± 0.25 (0.18)	1.8 (2.5)
300	2.45 ± 0.17 (0.12)	2.65 (3.75)
3000	2.45 ± 0.05 (0.04)	9.0 (11.25)

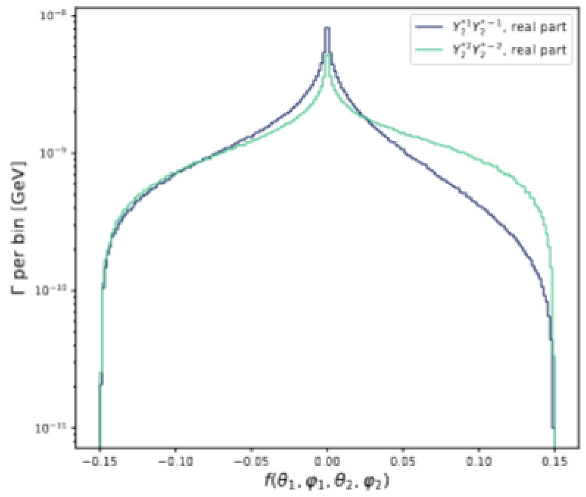
ELECTROWEAK CORRECTIONS

- NLO EW corrections add many diagrams to $H \to \ell^+\ell^-\ell^+\ell^-$
- The data will behave accordingly to NLO EW or new-physics
  - First NLO corrections to these observables: Grossi, Pellicciolì, Vicini
- Many works assume NLO EW corrections is few %
- The approach to estimate the effect of the correction is based on the tomography:
  - Evaluate the corrections on the angular distributions
    - Treat the NLO EW corrections are data
  - the element of the spin density matrix are linear combinations of the A and C coefficients
  - The very simple structure of the spin density matrix results in many relations between the coefficients

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} Y_L^{*M}(\Omega_j)\, d\Omega_a d\Omega_b = \frac{B_L^j}{4\pi} A_{LM}^j \quad j = a, b$$

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} Y_{L_1}^{*M_1}(\Omega_a) Y_{L_2}^{*M_2}(\Omega_b)\, d\Omega_a d\Omega_b = \frac{B_{L_1}^a B_{L_2}^b}{(4\pi)^2} C_{L_1 M_1 L_2 M_2}$$





ELECTROWEAK CORRECTIONS

- Changes in the coefficients break these relations
  - Modify the form of the spin density matrix
- The entanglement condition is not valid anymore for this matrix
  - More generic qutrit-qutrit entanglement condition?

LO

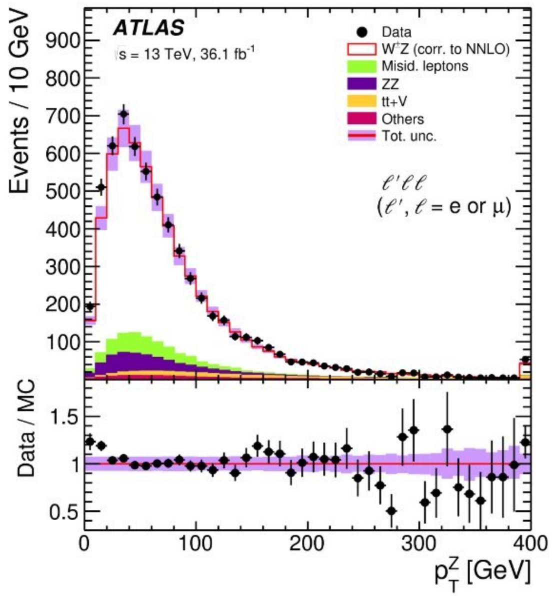
$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.195 & 0 & -0.313 & 0 & 0.194 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.313 & 0 & 0.6121 & 0 & -0.313 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.194 & 0 & -0.313 & 0 & 0.195 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

NLO

$$\begin{pmatrix} 0.099 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.004 & 0 & 0.131 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.111 & 0 & -0.183 & 0 & 0.189 & 0 & 0 \\ 0 & 0.131 & 0 & -0.009 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.183 & 0 & 0.591 & 0 & -0.183 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.009 & 0 & 0.131 & 0 \\ 0 & 0 & 0.189 & 0 & -0.183 & 0 & 0.110 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0 & 0.131 & 0 & 0.004 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.099 \end{pmatrix}$$

MEASURING ENTANGLEMENT IN WZ

- Non resonant diboson final state have also been proposed to study entanglement at colliders
  - Generic qutrit pair→ the entanglement can only be estimated as a lower bound on the concurrence (c^2_{MB})
- WZ final state has intermediate cross-section compared to WW and ZZ, a single neutrino and a clean final state
- In addition, it is the only process that is expected to be slightly entangled (on average) in the inclusive phase space
- Sensitive to new physics effects



Process	c^2_{MB}
$pp \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	-0.147
$H(125) \to WW^{(*)} \to \ell^+\nu_\ell \ell^-\bar{\nu}_\ell$	0.973
$H(200) \to WW \to \ell^+\nu_\ell \tau^-(30)\bar{\nu}_\tau$	0.946
$pp \to ZZ \to e^+e^-\mu^+\mu^-$	-0.21
$H(125) \to ZZ^{(*)} \to e^+e^-\mu^+\mu^-$	0.53
$pp \to W^+Z \to e^+\nu_e\mu^+\mu^-$	0.10

MEASURING ENTANGLEMENT IN WZ

- c_{MB}^2 has to be determined through a combination of all 80 coefficients of the spin density matrix
  - Each can be determined through quantum tomography
- Ongoing feasibility study considering:
  - Realistic statistical method and uncertainty
  - Realistic selection and reconstruction
  - Smearing of the missing energy
- Ongoing work: *N. Forti, F. Fabbri, F. Maltoni*

$$\rho = \frac{1}{9} I_9 + \frac{1}{3} \sum_{i=1}^{8} a_i \lambda_i \otimes I_3 + \frac{1}{3} \sum_{j=1}^{8} b_j I_3 \otimes \lambda_j + \sum_{i=1}^{8} \sum_{j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j$$

W boson

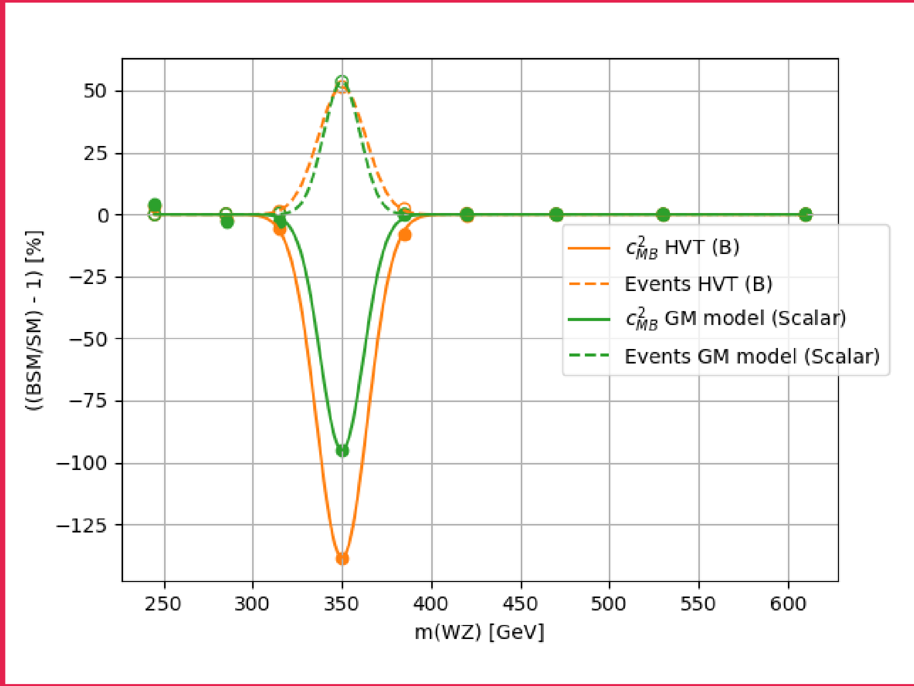
Z boson

Correlation

- Entanglement across the whole phase space not possible to observe before HL
  $${c_{MB}}^2 = 0.046 \pm 0.031$$
- Identified regions of the phase space where evidence of entanglement could be reached prior to the end of Run3

MEASURING ENTANGLEMENT IN WZ

- Measuring the
  generic qutrit s
  the lower boun
  - Combinatio
    spin density
  - Can be dete
    tomography
- Ongoing feasib
  - Realistic stat
    uncertainty
  - Realistic sele
  - Smearing of



Good sensitivity to new physics.

$\sum^{8}_{j=1} c_{ij} \lambda_i \otimes \lambda_j$

Correlation

hole phase
rve before HL

e where
t could be
f Run3

BELL INEQUALITY VIOLATION AT LHC

Several proposal to measure the bell inequality violation at LHC

- This means define a Bell operator acting on the spin density matrix

The spin density matrix is currently derived based on momentum measurement

- Connection between spin and direction assumes the quantum mechanics
- Momentum are commuting variables

It is always possibles to design a local hidden variable theory that reproduces the momenta distributions (10.1016/0370-2693(92)90071-B)

So the current ~large consensus is it is not a real Bell test (testing locality)

- It is still interesting to identify the most correlated regions of the phase space
- The assumption is tomography, after that the approach is valid
- We have a new set of observable to search for new physics

CONCLUSIONS

- Lot of interest at LHC in measure quantum information inspired observables
  - Started with top-pair production where both ATLAS and CMS observed entanglement
  - Ongoing studies also in other channels to keep up with the several interesting proposals from phenomenology studies
- New set of variables introduced seems quite effective in search for new physics
  - Direct searches (e.g. CMS measurement)
  - Indirect searches (EFT)
- Proposals to investigate physics beyond QM, not only beyond SM
- Workshop at GGI on this topic on the 7th – 10th of April
  - Small workshop with ~60 people
  - Subscription will open next week
  - https://www.ggi.infn.it/showevent.pl?id=525