MEASUREMENT OF QUANTUM INFORMATION INSPIRED OBSERVABLES AT COLLIDERS

F. FABBRI

MSCA CUP J33C23001080006

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

INFN BOLOGNA

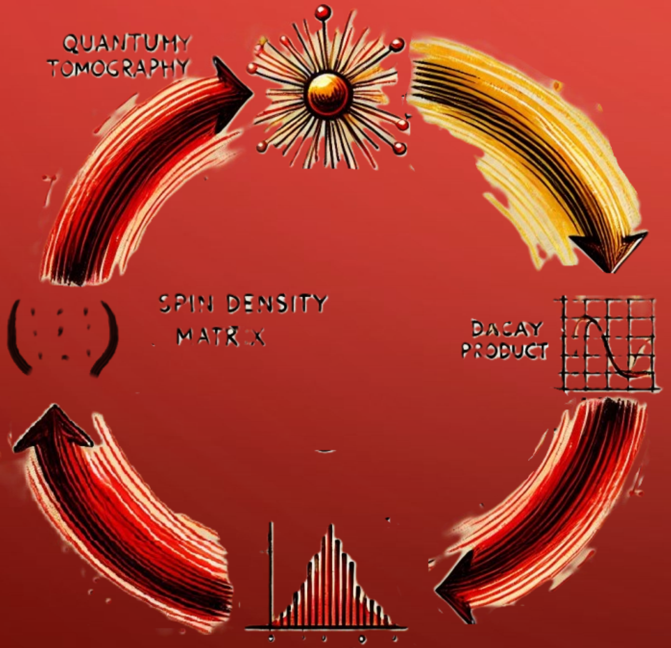
QUANTUM INFORMATION PRINCIPLES IN HEP

- Quantum field theory is the foundation of the SM
  - **But** till recently no dedicated observables to test the quantum behaviour of the particles measured at colliders
- Several quantities, defined in the context of quantum information, can be studied also at LHC
  - **entanglement,** Bell's inequality violation, steering, discord, magic
- We need to perform this study with respect to a quantum property of a particle:
  - **Spin** is the most common at ATLAS, CMS
  - Flavour is being investigate at Belle-II
- This field is currently growing very fast mixing together experimental particle physics, phenomenology and quantum information expert:
  - Which final state/process?
  - How to actually perform the measurement?
  - What is the correct interpretation?
  - Which variable to measure?
  - How to exploit this field to increase our knowledge in particle physics
  - How to exploit this field to increase our knowledge in quantum information

HOW TO PERFORM THE MEASUREMENTS?

- Consider the spin of the particles as the representation of a qudit
- Unfortunately, we can not directly measure the spin of the particles produced in each collision at LHC
- What we do well is measure lepton and jet direction and energy/momentum

QUANTUM TOMOGRAPHY!!



- Exploit the connection between parent particle spin and decay particle direction
  - Due to characteristic of weak interaction
- Measuring the decay product direction we can reconstruct the **spin density matrix**
  - Averaging on all events
- The directions are usually measured in the center of mass frame
- The relation between the parent spin and direction is proportional to the spin analysing power

LIMITATIONS OF THESE MEASUREMENTS

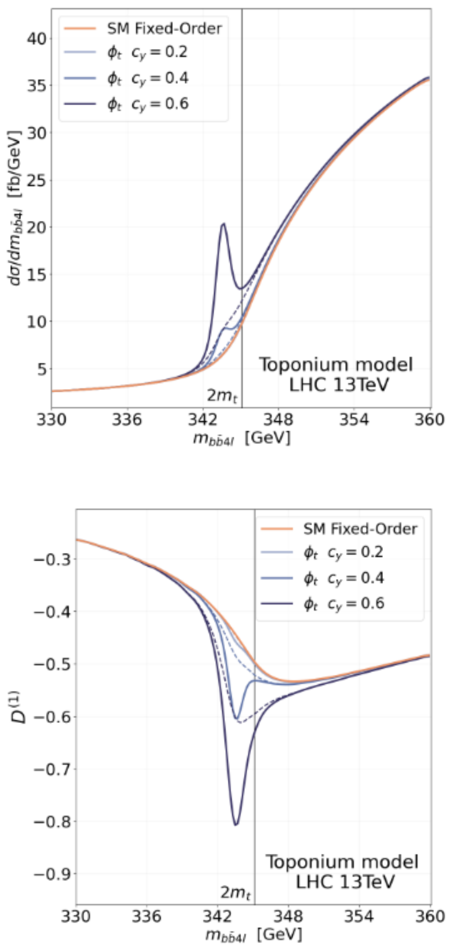
Experimental

- The directions of the decay products needs to be measured in the parent particle rest frame
  - The whole final state needs to be reconstructed, highly challenging in presence of multiple neutrinos (not reconstructed by ATLAS/CMS)
  - All aspect of the detector and the showering and hadronization enter in the final observable
- Not all decay product have the same spin analysing power
  - Depend on the process and particle flavour
  - Difficult to assign the correct spin analysing power to the jets
- The **entanglement** can be in limited regions of the phase space
  - Even for processes with high cross section the statistic may be an issue

Theoretical

- What is the impact of higher orders on the prediction of these kind of observables
- Understanding the limitation of tomography approach: the assumptions, the reference frame used

RELEVANCE OF THESE MEASUREMENTS



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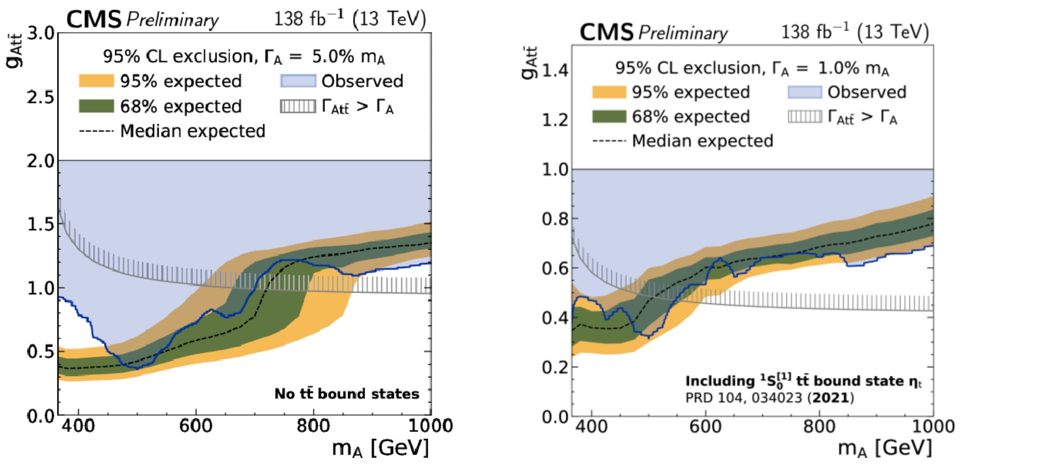
- These measurements probe some aspect of the particle interaction still not tested
    - Spin correlations were measured before but the entanglement
- These are new observables sensitive to new physics effects
    - Direct searches
    - Indirect searches
- They also provide a new direction to test beyond quantum mechanics
    - There are few theories that goes beyond QM, not only beyond SM, and these observable may be a way to test them (at the highest possible energy)
- There is a strong interplay with QI and quantum computing: special framework to study
    - Decoherence
    - Impact of interaction and decay on quantum correlations

INTERACTION WITH NEW PHYSICS



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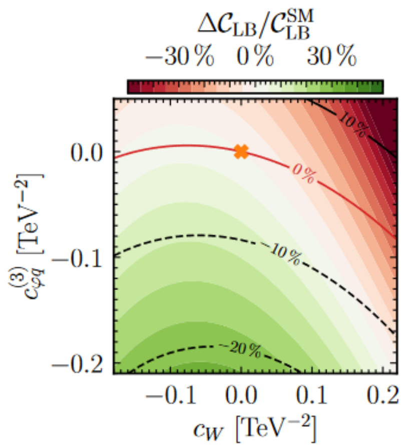

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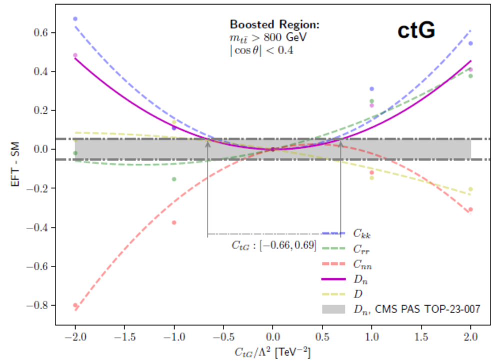


Belén D. González
Erasmus internship

- A new particle or bound state changes the entanglement between particles
  - The entanglement provide a new direction to investigate
  - Combined with mass can provide very good sensitivity to processes otherwise impossible to observe
  - Very large hint of toponium presence
- For indirect searches can be used to put limits to the coefficients of the new operators
  - Can disentangle two operators that have very similar effects on cross section

ACTIVITIES IN BOLOGNA

People

- ATLAS group: F. Fabbri, M. Sioli, M. Romano, N. Forti
- Pheno group: F. Maltoni, M. Sioli, O. Miniati, D. Pagani, P. Lamba, M. Del Gratta (student)

Active grant:

- MSCA QUANTUMLHC “Exploring quantum observables at the LHC”
- Bando a cascata: “Exploring the foundations of quantum information in particle physics“
- Section of other grant to explore the connection with new physics searches

Activities:

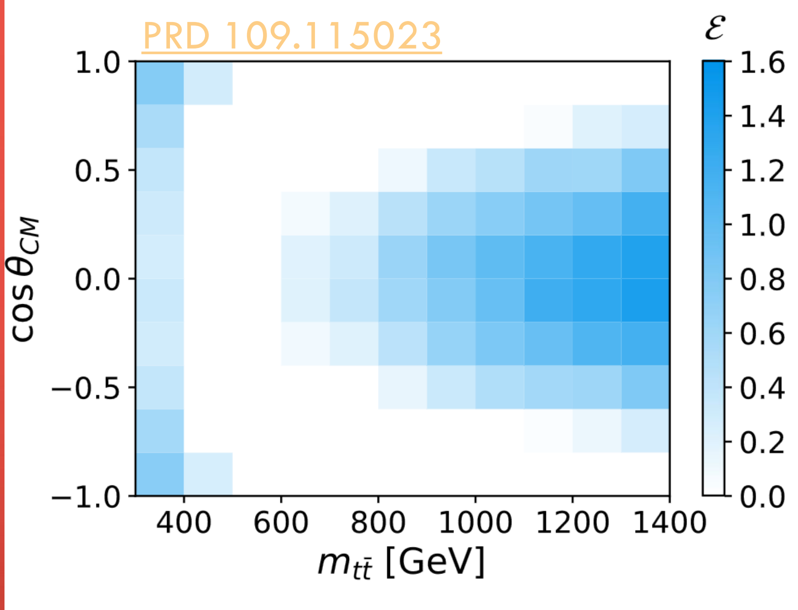
- Quantum correlation between the top-quarks in ATLAS
- Quantum correlations between bosons originated from Higgs decay at LHC
- Quantum correlation in diboson final states at LHC

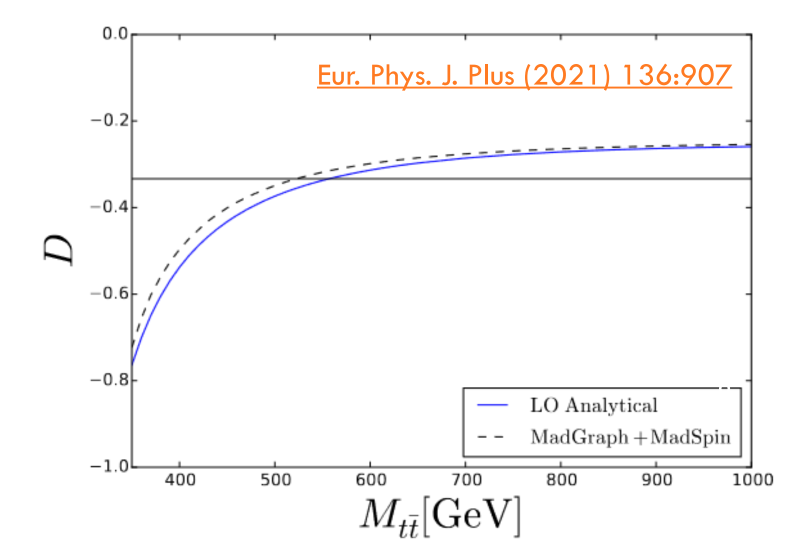
ENTANGLEMENT IN TOP PAIR FINAL STATES

- The top-quarks are interpreted as qubit:

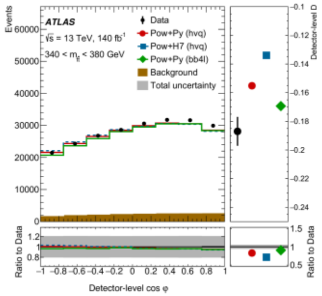
$$\rho = \frac{1}{4}\left[\mathbf{1}\otimes\mathbf{1} + B_i\sigma_i\otimes\mathbf{1} + \overline{B}_i\mathbf{1}\otimes\sigma_i + C_{ij}\sigma_i\otimes\sigma_j\right]$$

- The entanglement can be extracted measuring all the elements of the spin density matrix or from a single observable
  - $D = \frac{3\langle\cos(\varphi_{ab})\rangle}{\alpha_a\alpha_b}$ where φ_{ab} are the angles between the decay products in the parent top rest frame
  - $\alpha_a\alpha_b$ is the spin analysing power and is 1/-1 for leptons or down type quarks
  - D < -1/3 at threshold corresponds to entanglement
- Quark tops are generally not entangled, only at threshold and in the boosted region

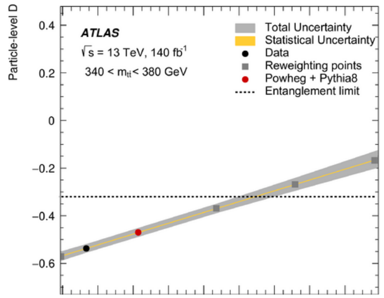




OBSERVATION OF ENTANGLEMENT IN TOP PAIR FINAL STATES



Nature 633 (2024) 542



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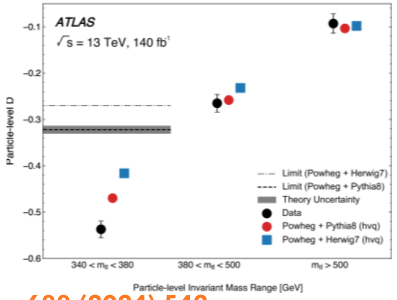
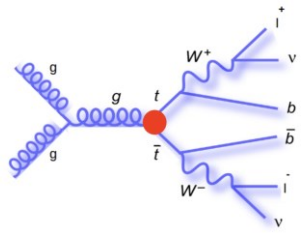


Nature 633 (2024) 542

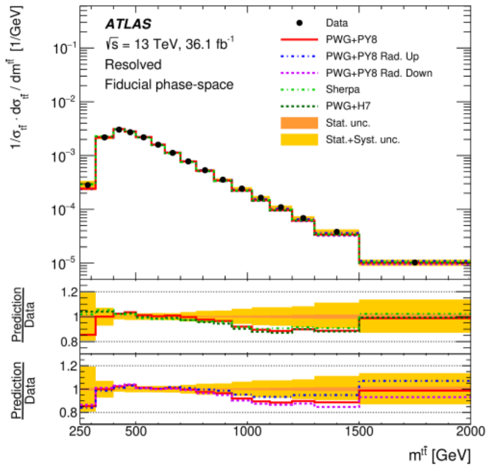
- The dilepton final state has been used to observe the entanglement between top quarks at threshold
  - First challenge: fully reconstruct the final state with 2 neutrinos
  - Second challenge: perform the measurement in a very small region
- Strategy: measure $\cos(\varphi_{ab})$ and remove the detector effects to find D
  - third challenge: very large modelling uncertainties had to be mitigated with the strategy



- Results:
  - Observed entangled between top quarks
  - Dominant uncertainty originates by top-quark pair modelling
  - Very large differences in how different generators simulate this observable at threshold
  - Tension between the SM and the observed D
    - Could be the new "particle" I mentioned earlier

BELL INEQUALITY VIOLATION?

- The entanglement is a necessary but not sufficient condition for Bell inequality violation
- Bell's inequality violation only occur in the high mass region: region of maximal entanglement
  - Where the number of events significantly drops
  - the dilepton channel may not be the best one: ~80% less events compared to the l+jets channel
- In the l+jets channel we need to find a way to identify the jet flavour on the hadronic side
  - Down type quarks have the maximum spin analysing power
    - We can exploit W→cs channel and use the c-tagging to identify the down type quark
  - We can combine the jets coming from the W decay
    - Lower spin analysing power
- CMS already observed the entanglement in the ~high mass region and the measurement is dominated by statistical uncertainty
  - Further improvements are needed to observe the bell inequality violation in this



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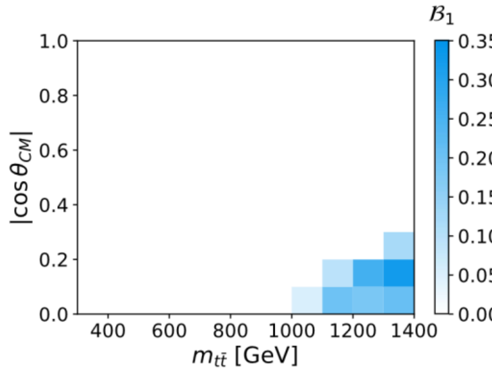
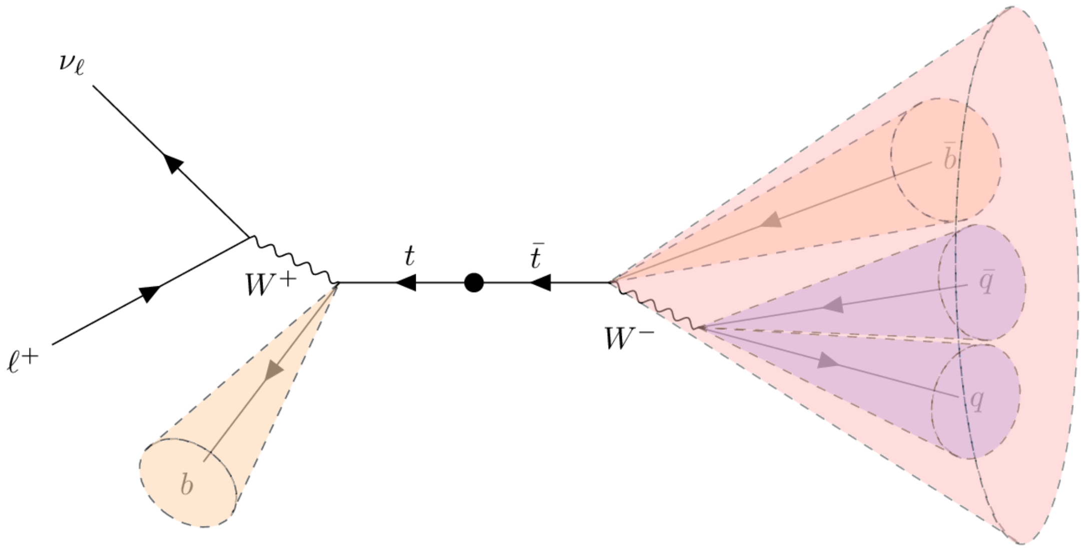
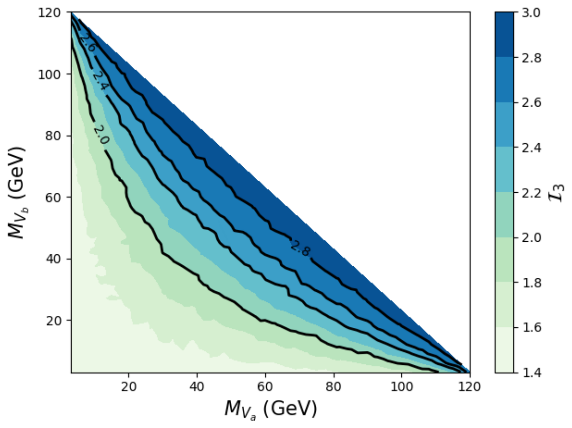
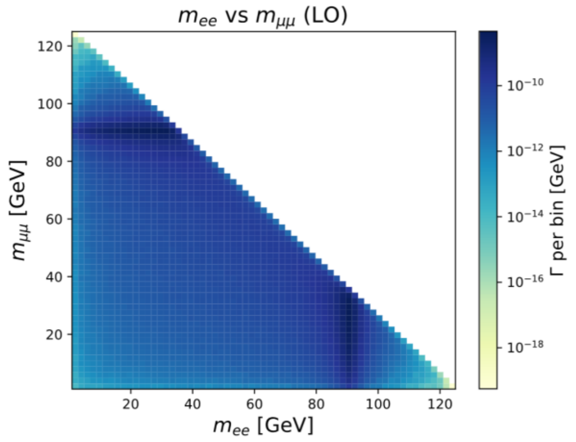


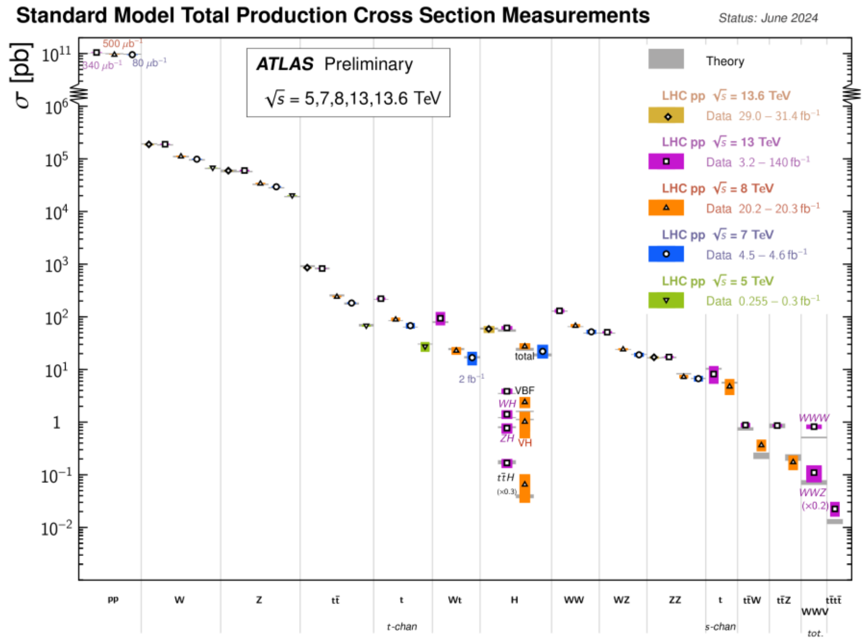


ENTANGLEMENT IN HIGGS FINAL STATES

- The spin of the vector bosons originating from the Higgs decay can be interpreted as qutrit
  - This is possible even if one (or both) the two bosons are off-shell
- They originated from a scalar
  - The spin density matrix is much simpler compared to a generic pair of qutrit
  - They are entangled across almost the whole phase space
- Bell's inequality are also violated across the whole phase space
- The cross section for the production of this final state is very limited and there are large backgrounds
  - Orthogonal situation compared to top quark pairs



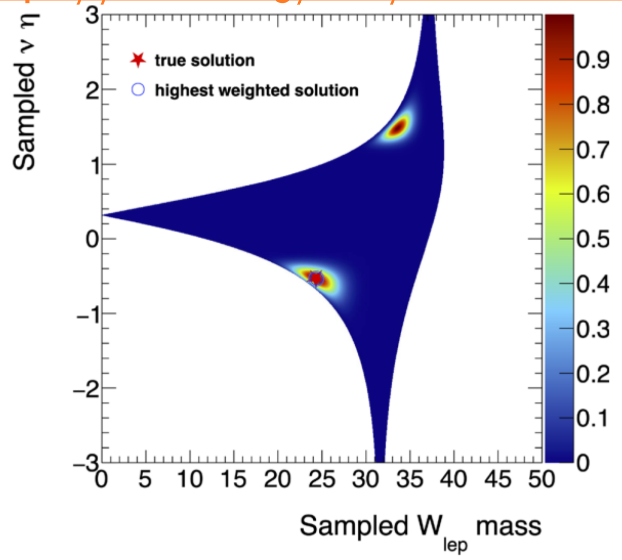


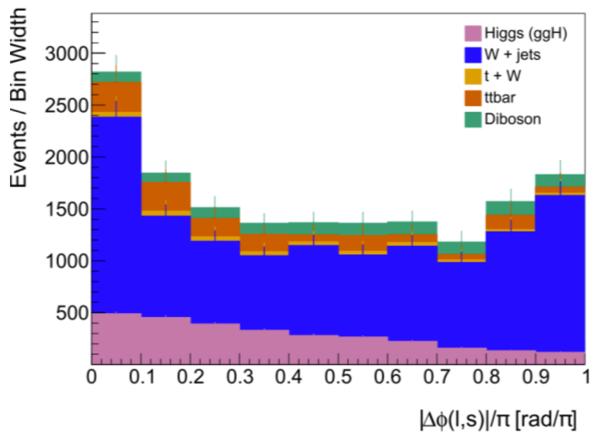


ENTANGLEMENT IN H→WW*

- The final state with two W bosons has a larger branching ratio compared to the ZZ final state
- The fully leptonic final state has 2 neutrinos
  - Under-constrained system
- The other possibility Is to exploit the semi-leptonic final state
  - One W decaying to two jets
  - Never observed at LHC due to the over-whelming W+jets background
- The channel H→W*W→lnucs has a small BR but:
  - The charm jet can be used to reduce the background and reconstruct the spin on the hadronic side
  - The leptonically decaying off-shell W can be used trigger the event
  - Reconstruction technique applied to the full event can be used to reject background
  - Measure a weight that quantifies the reconstruction performance

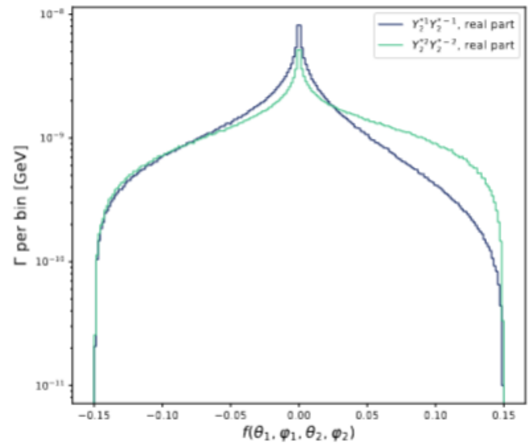
https://arxiv.org/abs/2307.13783

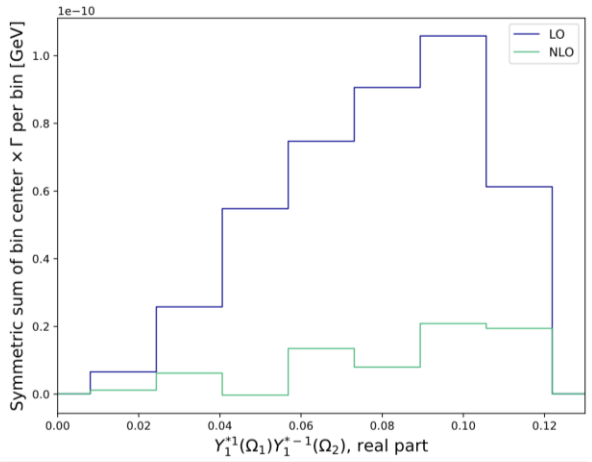


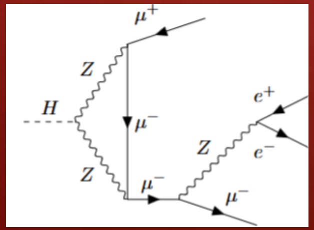


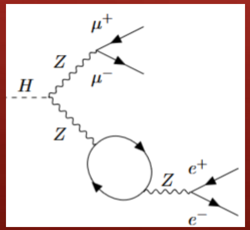
ENTANGLEMENT IN H→ZZ*

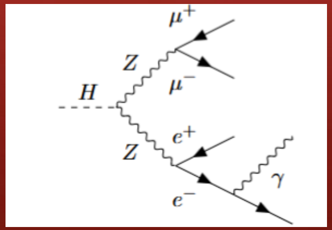
- The H→ZZ* channel has a small BR but a very clean final state with no neutrinos
  - Could be the first channel attempted by ATLAS and CMS to measure entanglement
- The spin density matrix, and consequent entanglement and Bell inequality violation can be measured at LHC using a tomography approach
  - Measure angular quantities that are then proportional to the element of the spin density matrix
- At colliders we will actually measure $H \rightarrow \ell^+\ell^-\ell^+\ell^-$
  - This is much more complicated that the simple H→ZZ* situation
- What is the impact on the observables
- We started looking to the effects on angular distributions
  - We observed a very large effect on some of the angular distributions
  - The impact on some regions can be very large, while limited in other regions





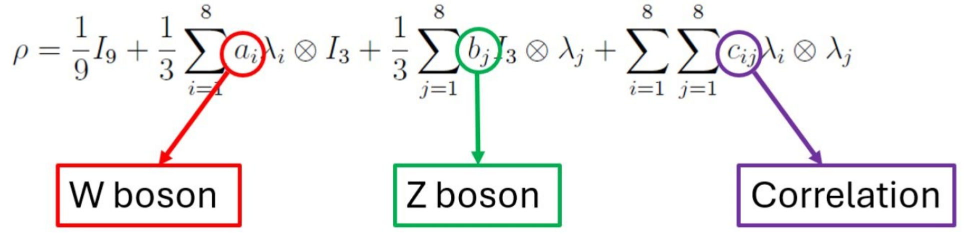


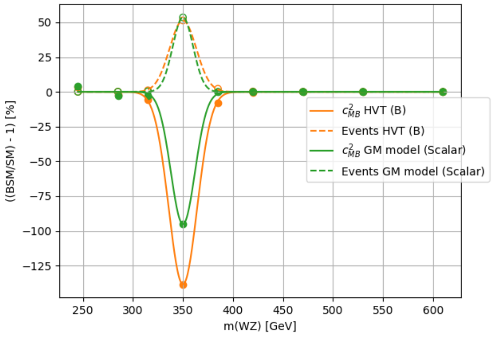


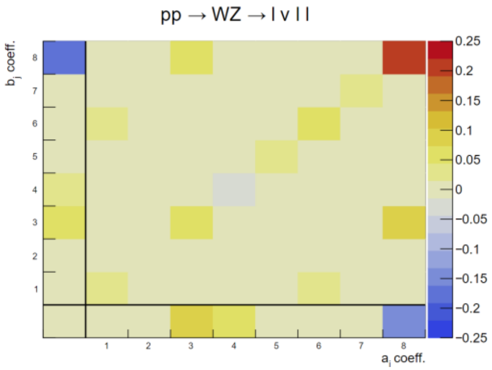


ENTANGLEMENT IN WZ FINAL STATES

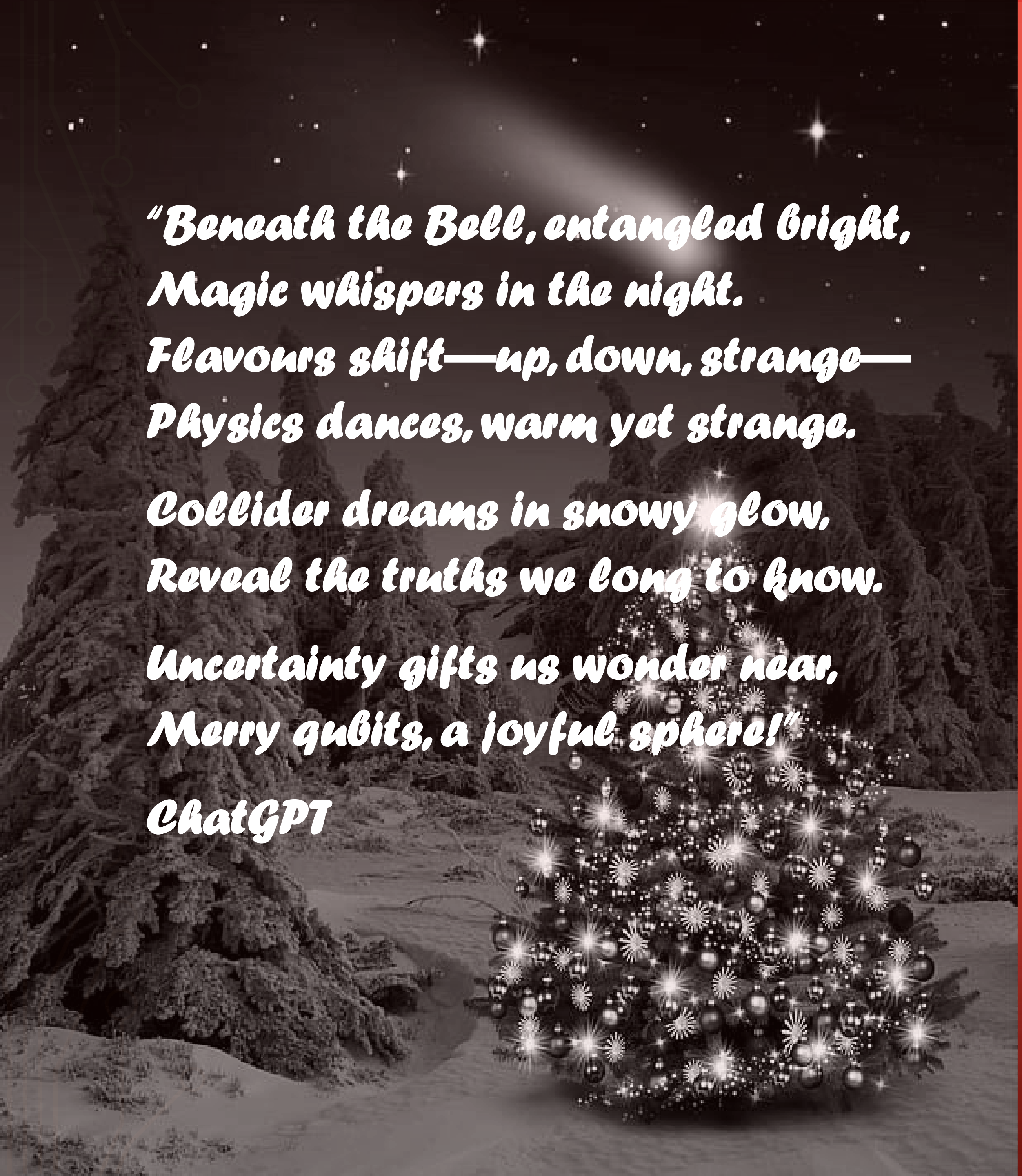
$$\rho = \frac{1}{9} I_9 + \frac{1}{3}\sum_{i=1}^{8} a_i \lambda_i \otimes I_3 + \frac{1}{3}\sum_{j=1}^{8} b_j I_3 \otimes \lambda_j + \sum_{i=1}^{8}\sum_{j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j$$







- Non resonant diboson final state can be used to study the entanglement
- More complicated than Higgs final state → no symmetries to simplify the spin density matrix
- Among the possibilities (WW,WZ,ZZ)
  - WZ has an intermediate cross-section but a single neutrino in the final state for the clean fully leptonically final state
  - It is the only one that is expected to be (inclusively) slightely entangled across the whole final state
  - It is highly sensitive to the triple gauge coupling
- The measurement of the entanglement requires the reconstruction of all 80 coefficients of the spin density matrix
  - And the correction of the detector effects on them, that can be highly significant
- Preliminary results suggest that:
  - The reconstruction of the neutrino is an essential aspect of the measurement
  - There are region of the phase space where it will be possible to observe the entanglement at HL-LHC
  - The spin density matrix coefficients are highly sensitive to new physics effects



CONCLUSIONS

- The measurement of quantum information inspired observables at LHC is a very active area
  - New theoretical and experimental studies presented almost daily
  - Several activities presented in top-pair and diboson final states
- In Bologna there is a growing group of people working on this
  - INFN & UNIBO
  - Experimental and phenomenology
  - Several funding from Italy and Europe
- Organising a dedicated international workshop at GGI in Florence in April
  - **“Quantum Observables for Collider Physics 2025”**
  - Financed by INFN and MSCA
  - https://www.ggi.infn.it/showevent.pl?id=525