LA FISICA NELL'ERA POST HL-LHC: OSSERVABILI QUANTISTICI

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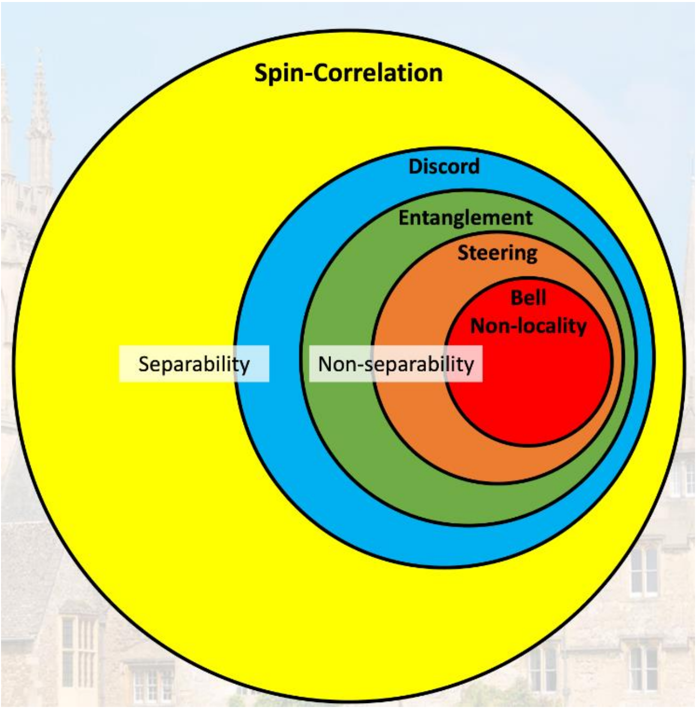
QUANTUM INFORMATION PRINCIPLES IN HEP



Credits Y. Afik (University of Chicago)

- Quantum field theory and special relativity are the foundation of the SM
  - Allow to formulate predictions for particle collisions.
- Only very recently measures that focus on the **quantum behaviour of elementary particles**
  - Field re-opened by a paper showing how to measure entanglement in tt in 2021.
- Many observables inspired by quantum information can be measured on particles produced at colliders:
  - Entanglement, Bell's inequality violation, Discord, Steering, Magic
- The quantum observables are measured with respect the spin of the particle (at ATLAS and CMS), but it is not the only option (e.g. flavour)
- This field is currently receiving increasing attention by the theoretical and experimental community (and funding)
  - Many proposal submitted
  - Many papers published (at the beginning of the year almost one per day in arxiv)

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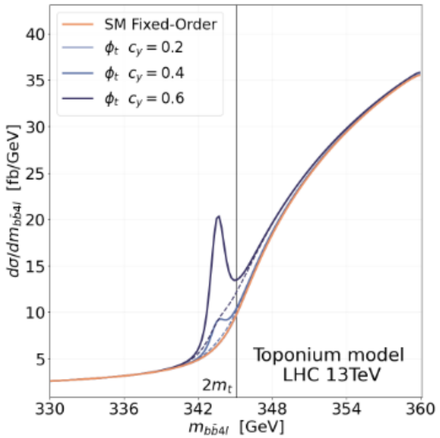

Cross-section

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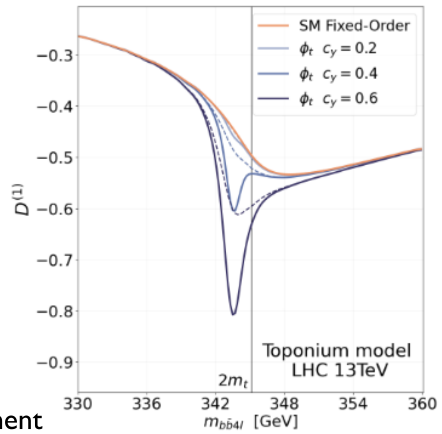
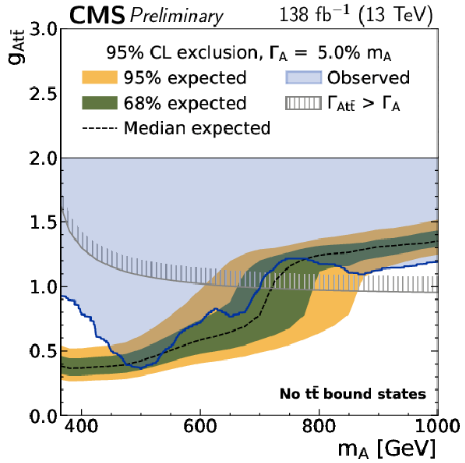


Entanglement marker



CMS-PAS-HIG-22-013

WHY IS IT INTERESTING?

- It is a new and **un-explored direction to search for new physics**
  - New physics modifies the quantum correlations among particles
  - Already exploited by CMS in a "discovery" of a new "particle" in the top-pair production at threshold
- Allow also to investigate a completely **new paradigm for physics beyond the SM**:
  - Can QM fail at very small distances?
- There is a nice **interplay with QI and Quantum Computing**:
  - The decoherence and collapse of the wave function are still not well understood→ can HEP help?

HOW TO PERFORM THIS KIND OF MEASUREMENTS?

- I will focus on the spin-based measurements: the ones currently investigated at ATLAS and CMS
- Two possible approaches:
  - Focus on one or few **entanglement/BIV markers**: a single observable that can say if the system is entangled or violate the Bell's inequalities (e.g. D or B)
  - Full **reconstruction of the spin density matrix** → allow to evaluate all the properties of the state

Both approaches need a partial or full **quantum tomography**:
- not possible to measure the spin per event at colliders
- spin measured as an average across similar states

Exploit the relation between the **spin of the parent particle** and the **direction of the decay product** in a weak decay
- The direction is in the **rest frame** of the parent particle

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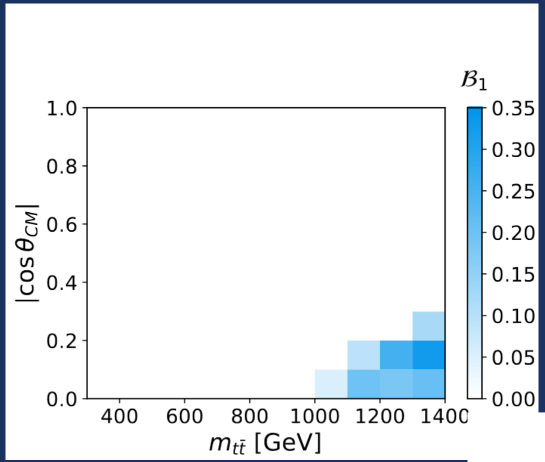
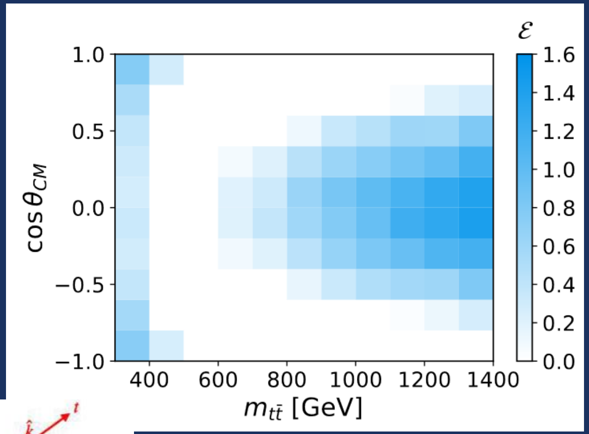
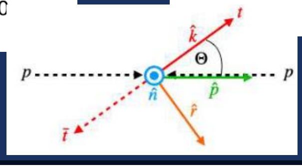
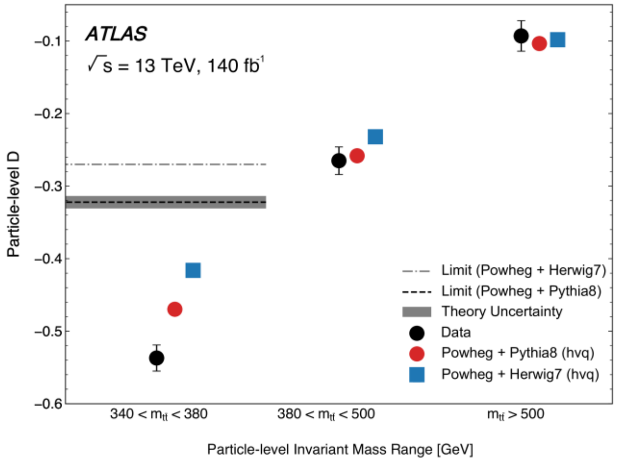
Need to restrict the phase space to observe entanglement or other quantum behaviour

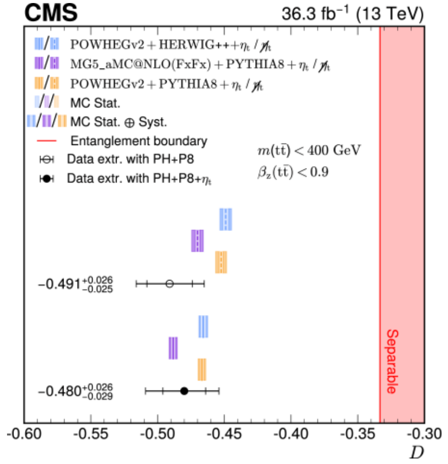




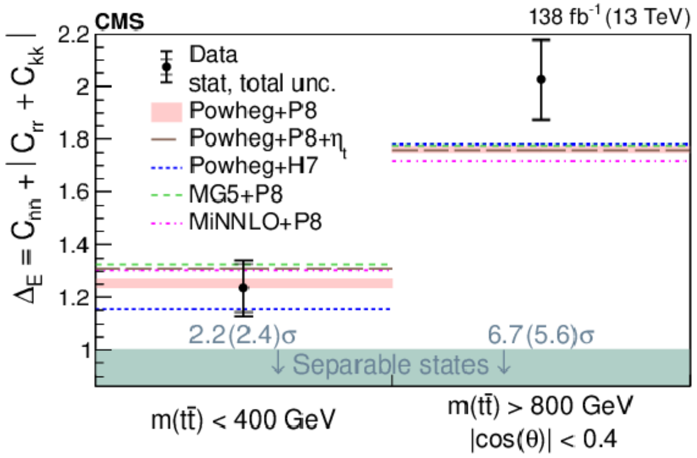




[Nature 633 (2024) 542]



[arXiv:2406.03976]



[arXiv:2409.11067]

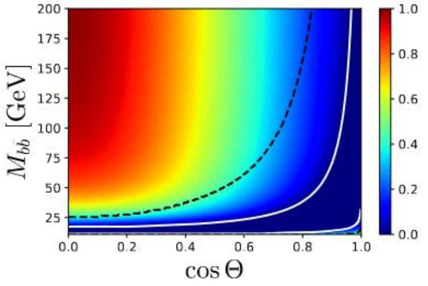
WHERE ARE WE NOW?

- For the moment just 3 experimental results presented:
  - All in top-quark pair final states
  - Observation of entanglement at threshold in ATLAS and CMS
    - First hint of discrepancy between the SM and the data
    - Large tension observed in a search in this region (also using this entanglement marker)
  - Observation of entanglement in the high mtt region in CMS (and full quantum tomography)
- ATLAS, CMS and Belle are working on other final states

WHAT CAN WE EXPECT BY THE END OF HL-LHC?

Several proposal exist for measurement at HL-LHC:

- Measurement of entanglement between two quark b from Z decay
  - Exploit the propagation of polarization to baryon final state
  - Reconstruct the b spin from the charged lepton in the Λ_b decay chain



arXiv:2406.04402

- Observation of entanglement and Bell's inequality violation in H→VV
  - Orthogonal final state compared to top-pair
  - Qutrit highly entangled across the whole phase space
  - Current main limitation is stat in ZZ final state and neutrino reconstruction in WW final state

- Measurement of entanglement in non-resonant di-boson final states
  - High potential for new physics constraints

- Measurement of the post-decay entanglement
  - Study the evolution of entanglement after the decay of one of the particles
  - Proposed in top pair production, between the top and the W
  - **In lepton colliders with polarised beams could also be possible to observe an increase in the entanglement compared to top-pair**

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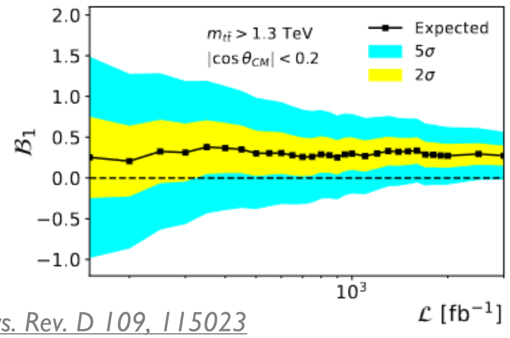
- Observation of BIV violation in top-pair production



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- Multibody entanglement:
  - Across multiple qubit in the final state
  - Between particles and the momentum of the system

- Several proposal based on mesons entanglement
  - Both in terms of flavour and spin
  - Flavour studies suggested to test different decoherence models

CURRENT LIMITING FACTORS

- The main limiting factor are:
  - **Reconstruction of the full state** due to the presence of neutrinos
    - Also deriving from the **un-known energy along z** in the initial state
  - **Statistical uncertainty**:
    - **overwhelming background** (both from other processes than combinatorial)
    - Select the **regions of the phase space** of maximal entanglement
  - **Theoretical uncertainties:**
    - PDF play an important role
    - Also top-quark decay, matching, scale uncertainties, IFSR
- **Many of these factors are eased in a lepton collider**
  - Several studies exist for lepton colliders, not much for future hadron colliders
  - Each study assumes a different lepton collider configuration: beam polarization and centre of mass energy

Entanglement

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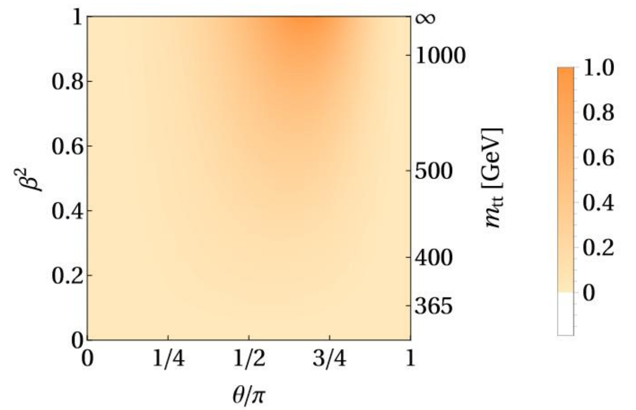
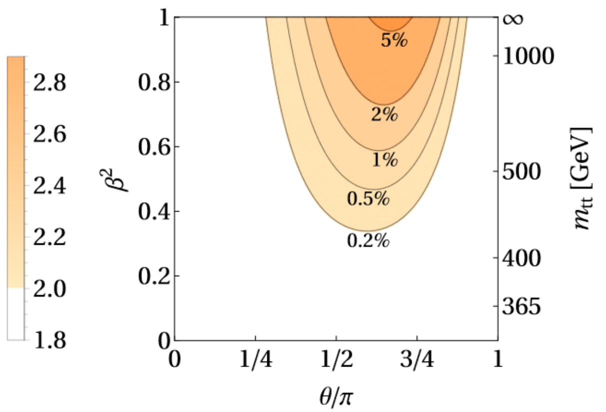


Assuming a cm energy > top-pair threshold

Bell's Inequality violation observation



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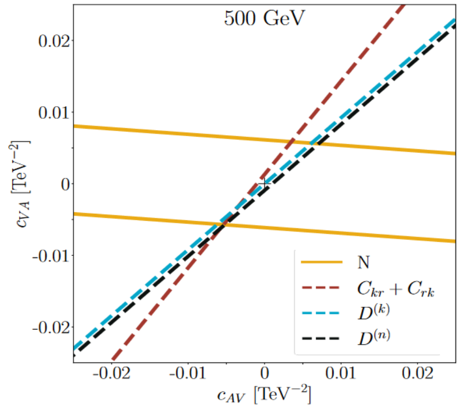
Limits on new physics



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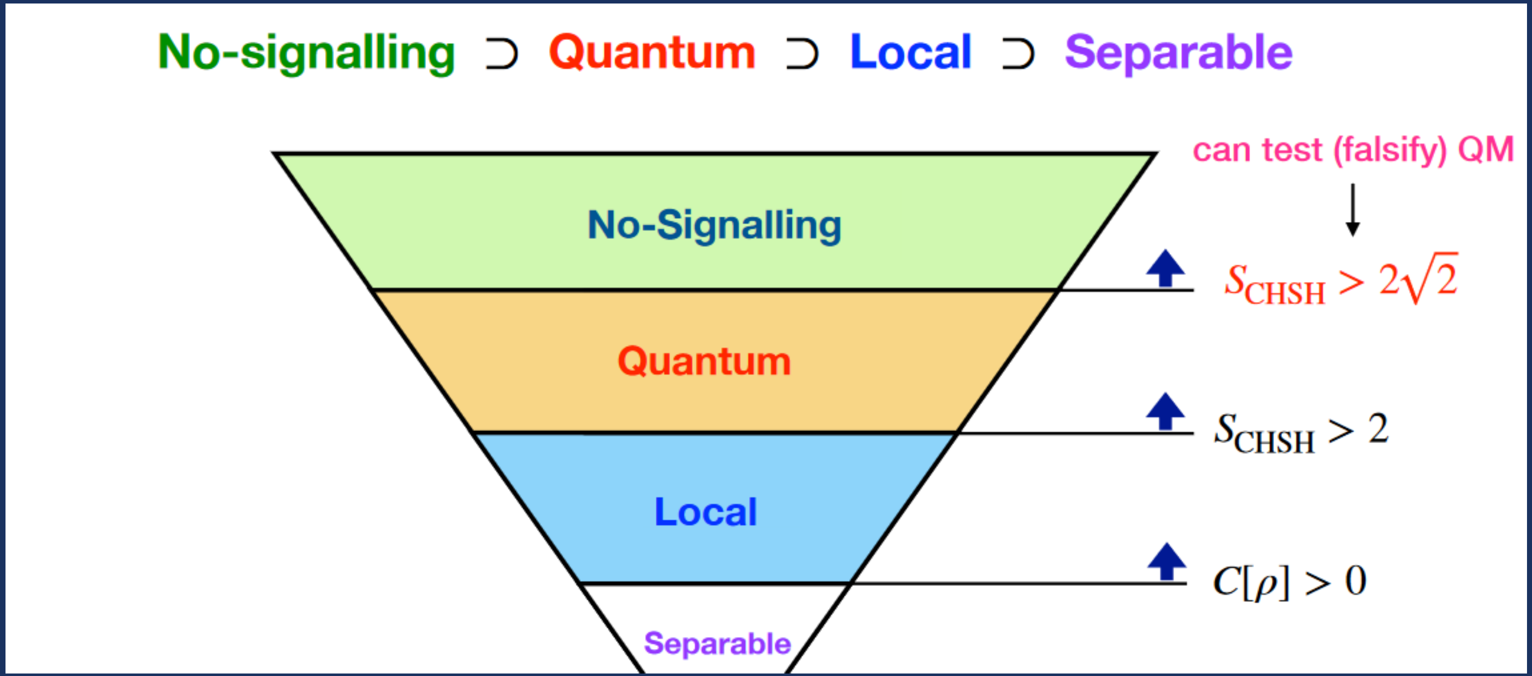
QUANTUM OBSERVABLES IN TOP PAIRS AT LEPTON COLLIDERS

- Different picture for quantum observables at lepton colliders
  - Entanglement and violation of Bell's inequality everywhere but by a small amount
  - Observation of Bell's inequality violation depends on the precision
  - Possible to combine multiple channels
- **The precise measurement of quantum observables provide highly orthogonal information in the search for new physics**
  - Shown using effective couplings to parametrise new physics
  - The change in number of events doesn't allow to discriminate among different couplings
  - Flat directions broken by quantum observables
  - True also for resonance searches

- Quantum mechanics set an upper bound to Bell's inequalities.
- This upper bound can be violated while maintaining causality → physics beyond QM
  - The very high energy/low distance can be the region where QM crumbles
- There are proposal coming out now on testing this aspect of QM using lepton colliders and top-pair final states (link to a seminar from K. Sakurai)
  - Experimental setup proposed to test this based on polarised lepton beams
  - Unconventional polarisation (not in the beam direction)

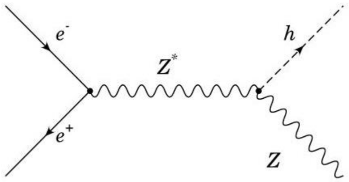


- True also for resonance searches

QUANTUM OBSERVABLES USING FINAL STATE WITH τ

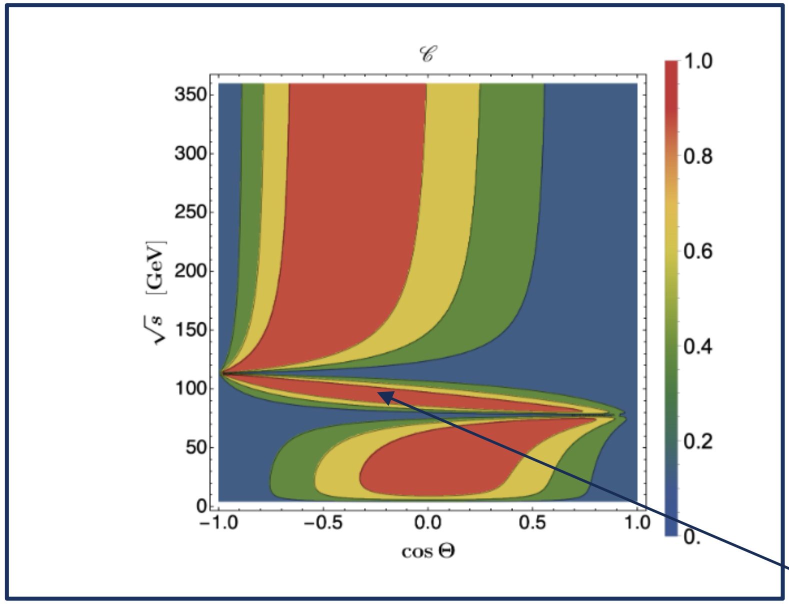
	ILC	FCC-ee
energy (GeV)	250	240
luminosity (ab^{-1})	3	5
beam resolution e^+ (%)	0.18	0.83×10^{-4}
beam resolution e^- (%)	0.27	0.83×10^{-4}
$\sigma(e^+e^- \to HZ)$ (fb)	240.1	240.3
# of signal ($\sigma \cdot \mathrm{BR} \cdot L \cdot \epsilon$)	385	663
# of background ($\sigma \cdot \mathrm{BR} \cdot L \cdot \epsilon$)	20	36

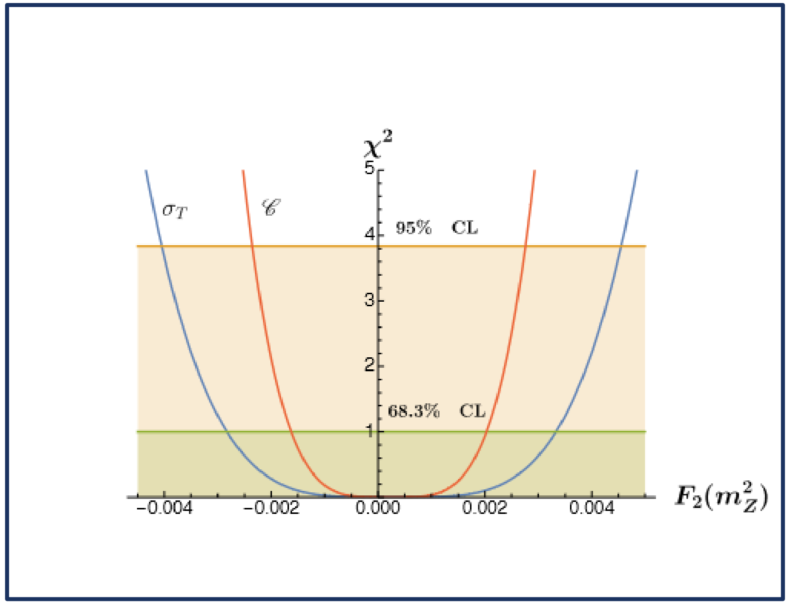
- The only lepton suitable for quantum tomography is the τ
  - The best channel is the semi-leptonic decay with a single pion
- The full final state including 1 or multiple τ is very hard to reconstruct at LHC
- The complete state $\ell^+\ell^- \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$ can be reconstructed with extreme precision at lepton colliders
  - Also exploits the τ decay vertex
  - Possibility to study in large details quantum observables and full quantum state
- Example of quantum observables measured in $H \to \tau\tau$
  - Quantum observable can be used to set model independent constraints on the CP-phase of the Higgs



	ILC	FCC-ee
Entanglement	$> 5\sigma$	$\gg 5\sigma$
Steerability	$\sim 4\sigma$	$\gg 5\sigma$
Bell-nonlocality	–	$\sim 3\sigma$
CP-phase δ ($\Delta\chi^2$)	$[-7.94°, 6.20°]$	$[-5.17°, 5.11°]$
CP-phase $\lvert\delta\rvert$ (A)	$< 7.9°$	$< 5.4°$

Z/ $\gamma \rightarrow \tau\tau$





- The level of entanglement and the region of maximal entanglement depends on the CM energy
  - FCC-ee 4 years data taking at the Z pole
  - Non aggressive uncertainty and resolution model
  - Bell's inequality violation can be observed with > 30 standard deviations
- The quantum observables can then be used to set limits to anomalous couplings
  - Can be more sensitive than the cross section
  - Lead to limits 1 order of magnitude stronger than current limits

CONCLUSIONS

- The study of quantum observables on particles created at colliders is a field that is receiving increasing attention from theoretical and experimental community
- It is a new direction in the search for new physics under multiple aspects:
    - Can be sensitive in direct searches, and directly allow to characterise the spin of the resonance
  - Provide orthogonal directions for EFT searches
  - Offer the opportunity to investigate physics beyond QM (not only beyond SM)
- These measurements require a precise reconstruction of the final state → there is a good potential at lepton colliders
  - Especially for final states including τ
- Few studies are already present for these observables in future colliders but given the quick development in this field much more are bound to come