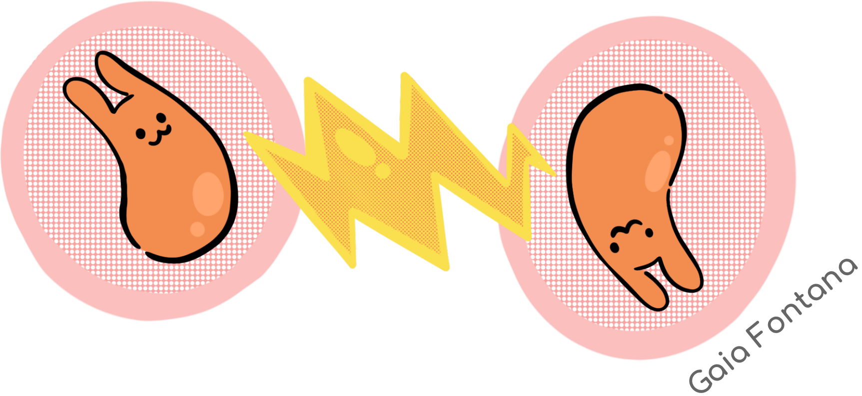
Entanglement in top production



Claudio Severi
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Entanglement?

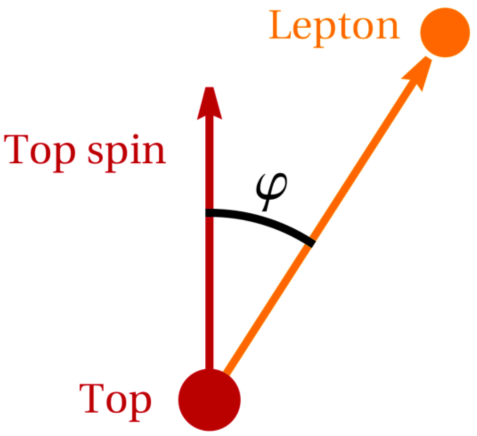
The exceptional performance of the collider and of the detectors now opens new possibilities.

One is the observation of entanglement between tops, accessed experimentally through spin correlations.

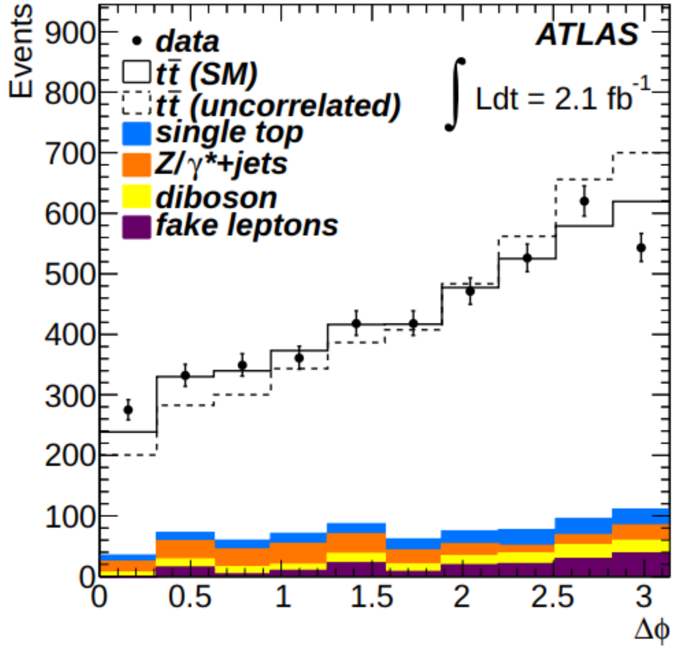
The spin quantum state is transferred to decay products:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1+\alpha_a B_i \cos\theta_i}{2}$$

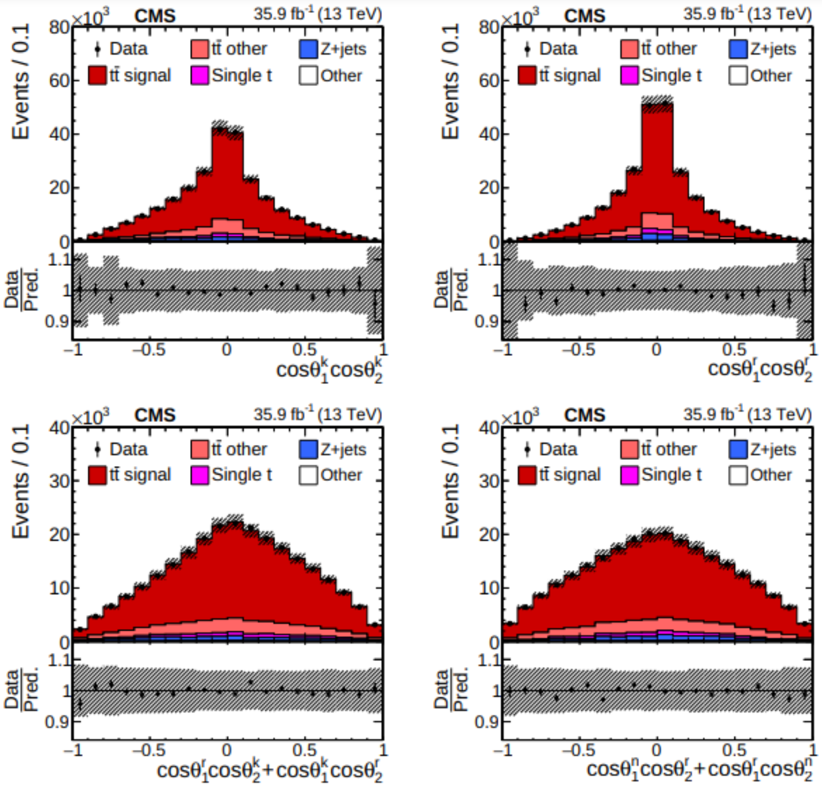
$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_i\cos\bar{\theta}_j)} = -\frac{1+C_{ij}\alpha_a\alpha_b\,\cos\theta_i\cos\bar{\theta}_j}{2}\log\left|\,\cos\theta_i\cos\bar{\theta}_j\,\right|$$



Spin correlations in tt were observed in 2012, the density matrix has been measured in 2019 with early Run2 data.



Phys.Rev.Lett. 108 (2012) 212001



Phys.Rev.D 100 (2019) 7, 072002

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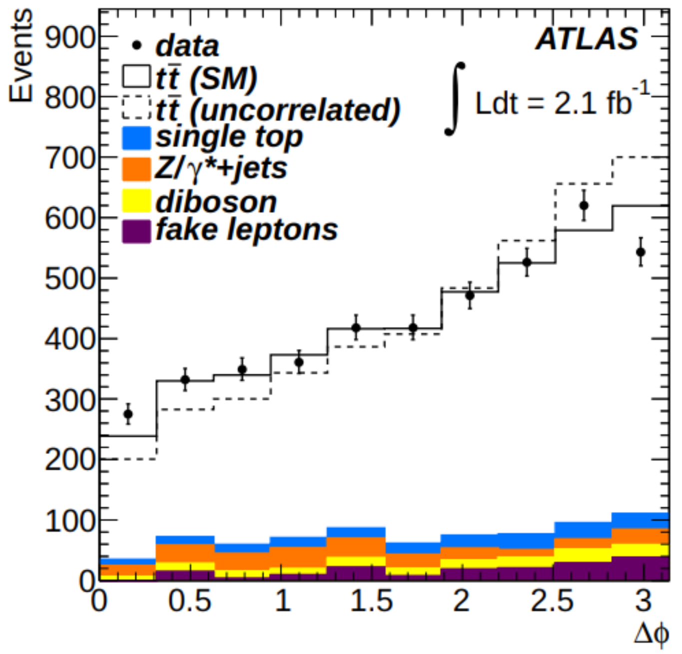

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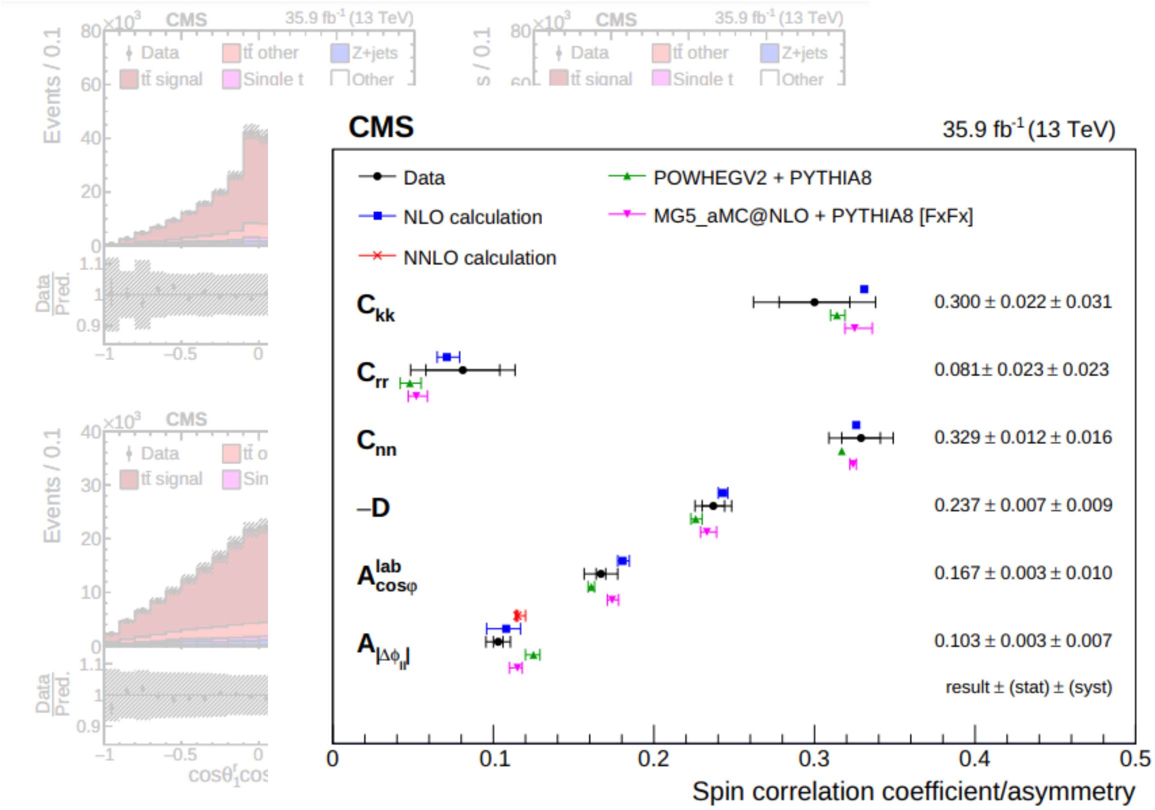

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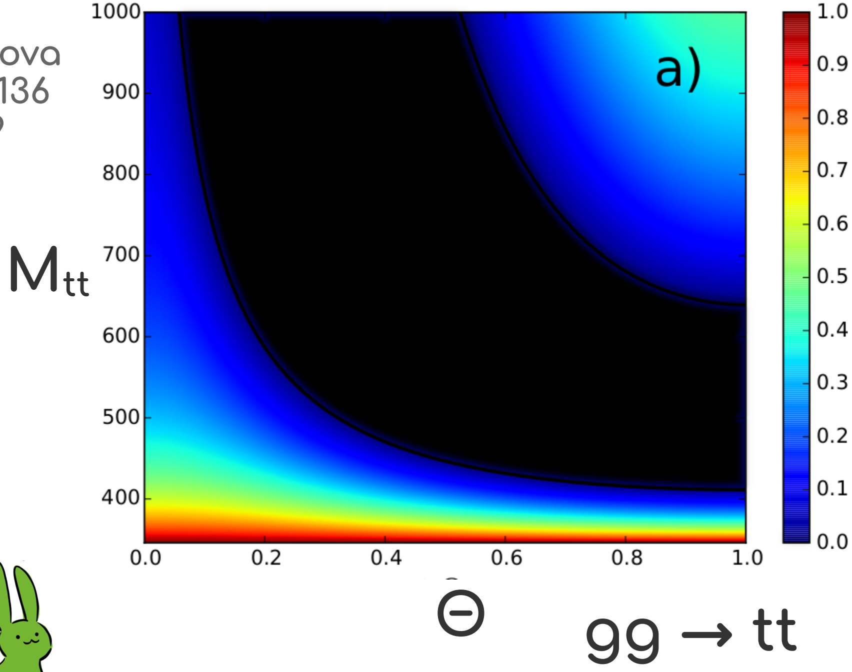
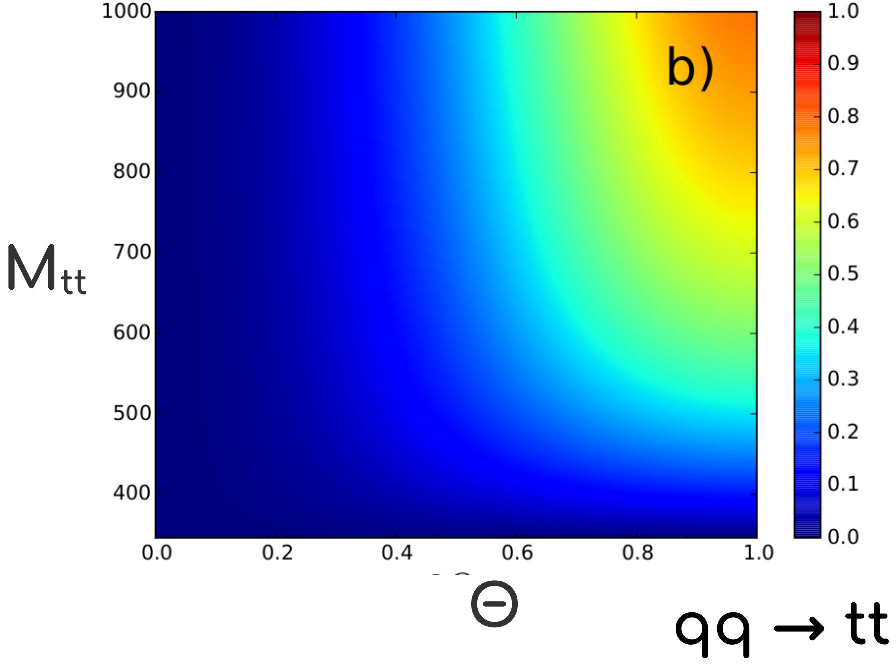
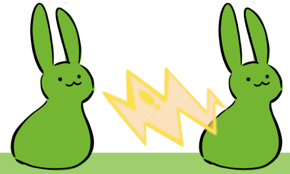
Simulations show that top pairs are sometimes produced in an entangled state, spin correlations can be used as a witness. Entanglement depends on kinematics and production channel:

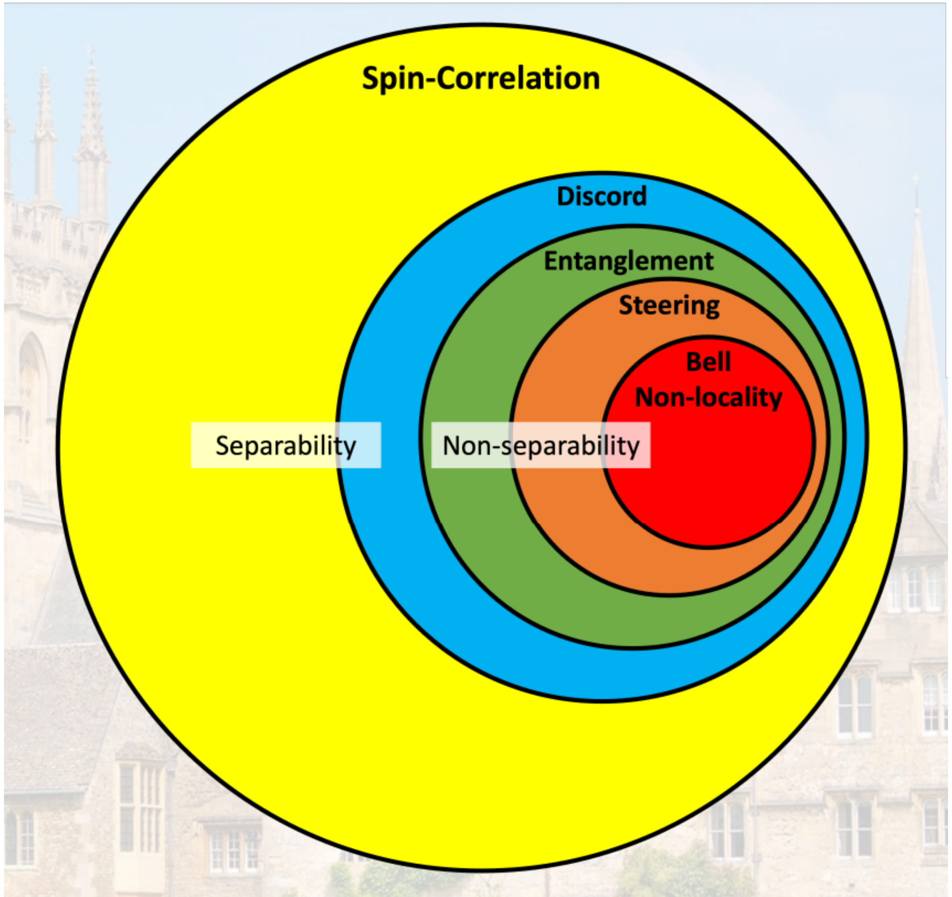
Afik, De Nova EPJ.Plus 136 (2021) 9







Quantum observables



Many more "quantum" observables exist, like concurrence, discord and steering.

The strongest signal of non classical behaviour is a violation of Bell inequalities.

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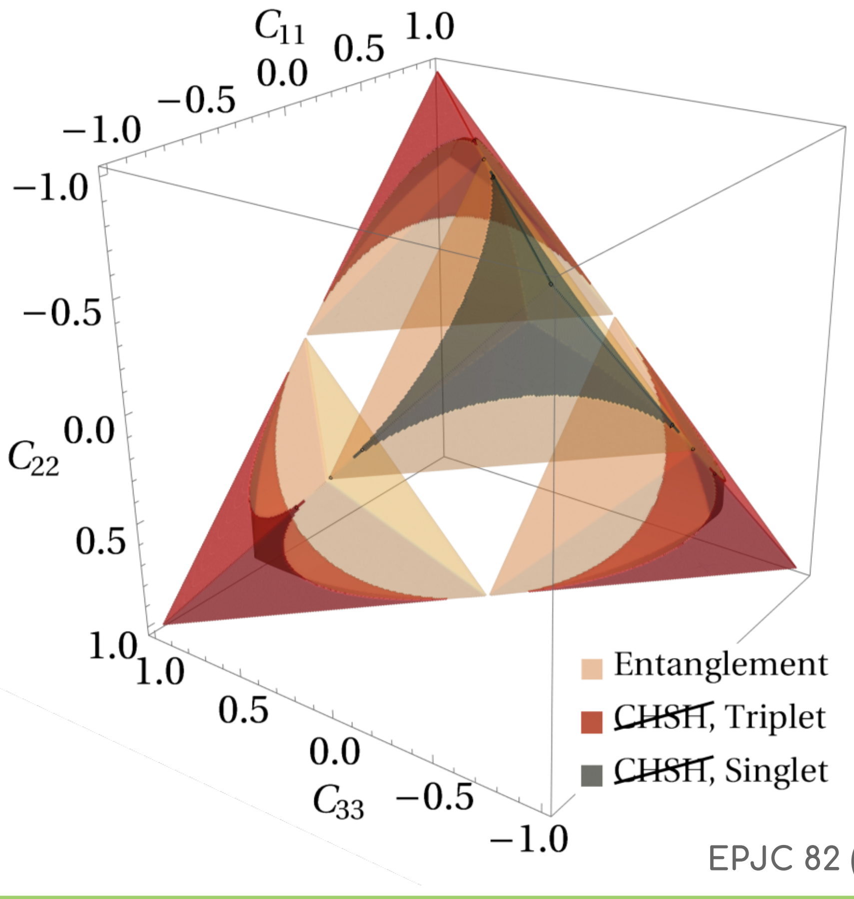
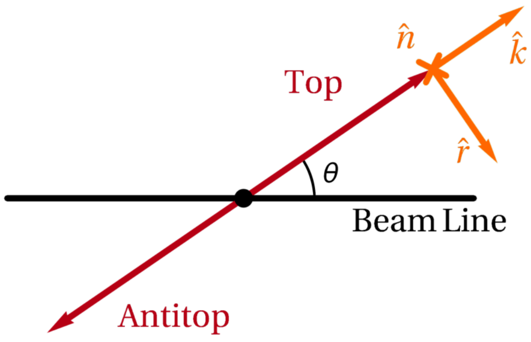
Beyond entanglement

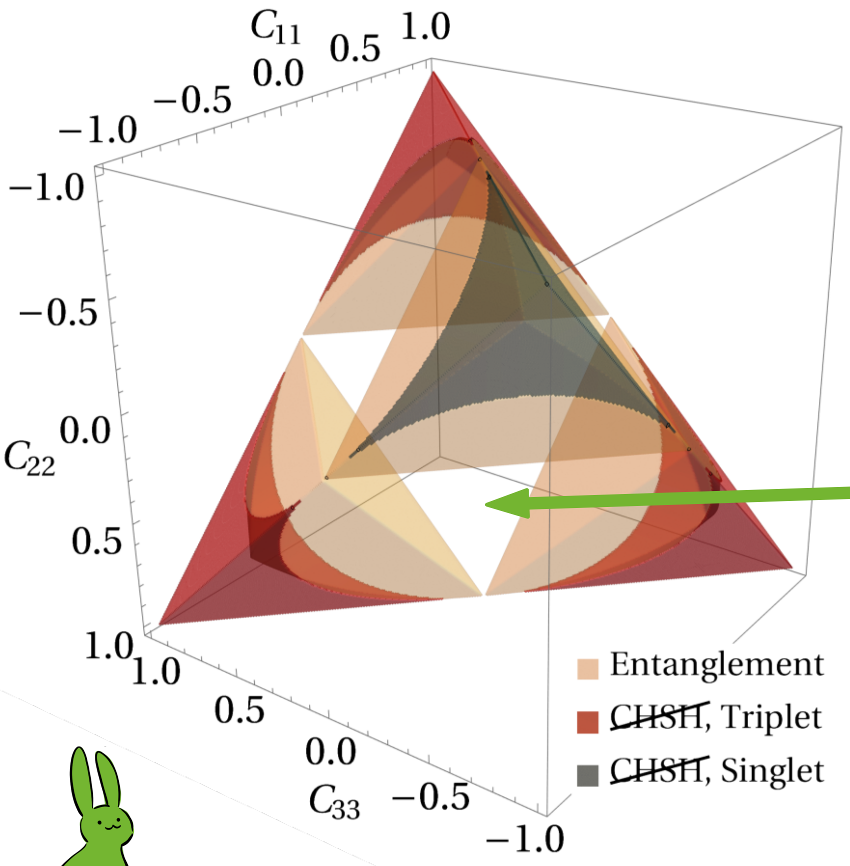


When a quantum state is entangled enough, it violates Bell Inequalities.



EPJC 82 (2022) 4, 285

Beyond entanglement



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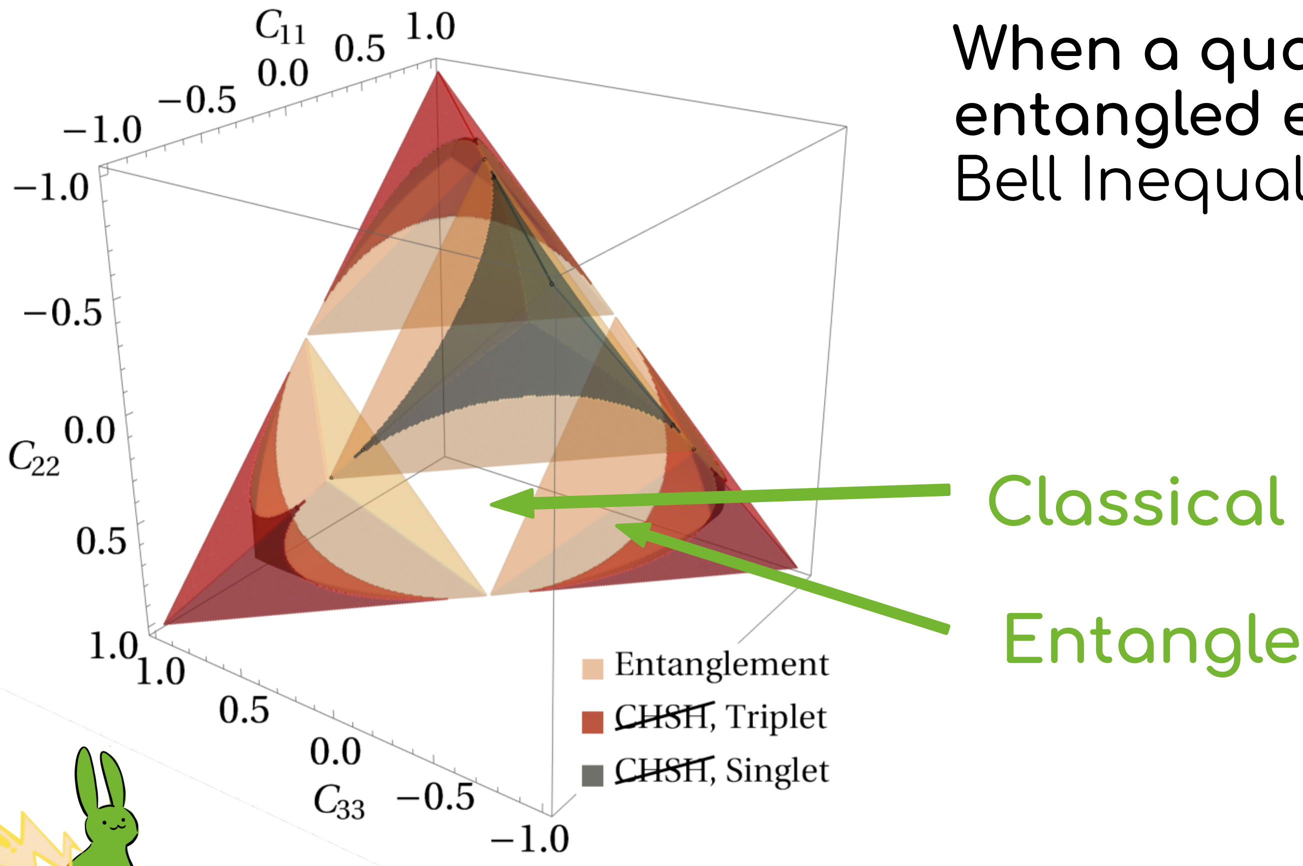
Classical

Beyond entanglement



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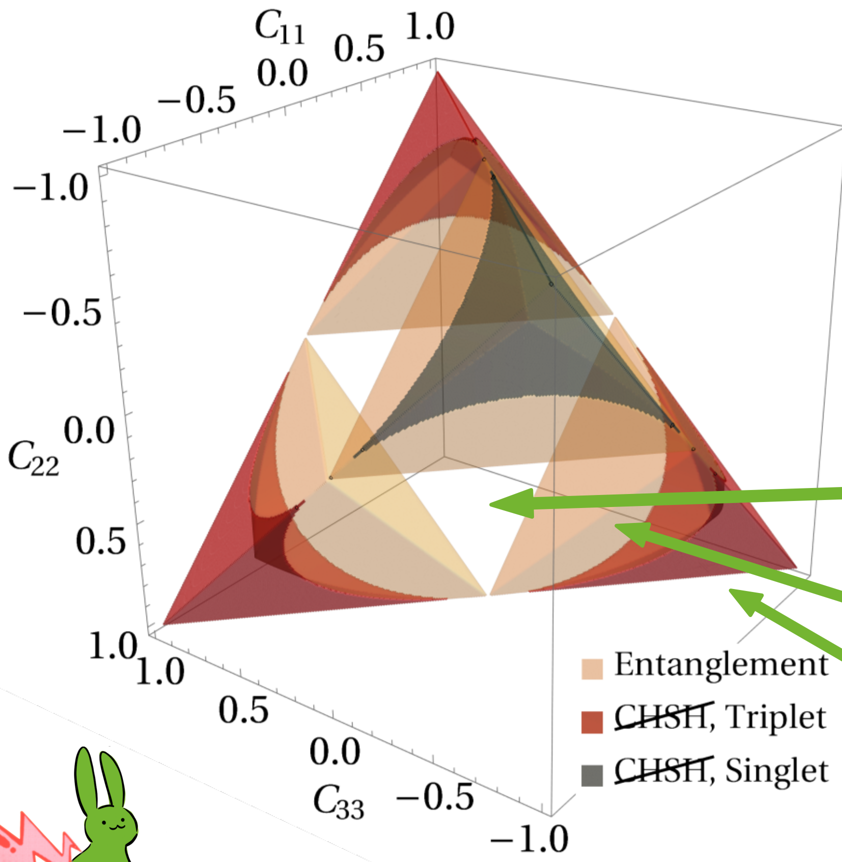
Beyond entanglement

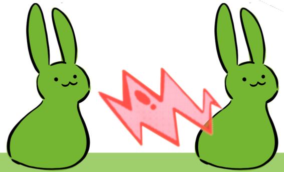


When a quantum state is entangled enough, it violates Bell Inequalities.

Classical

Entangled, not Bell violating

Entangled, Bell violating



Bell inequalities

At parton level, tops violate Bell inequalities in extreme regions of phase space.

Bell inequalities

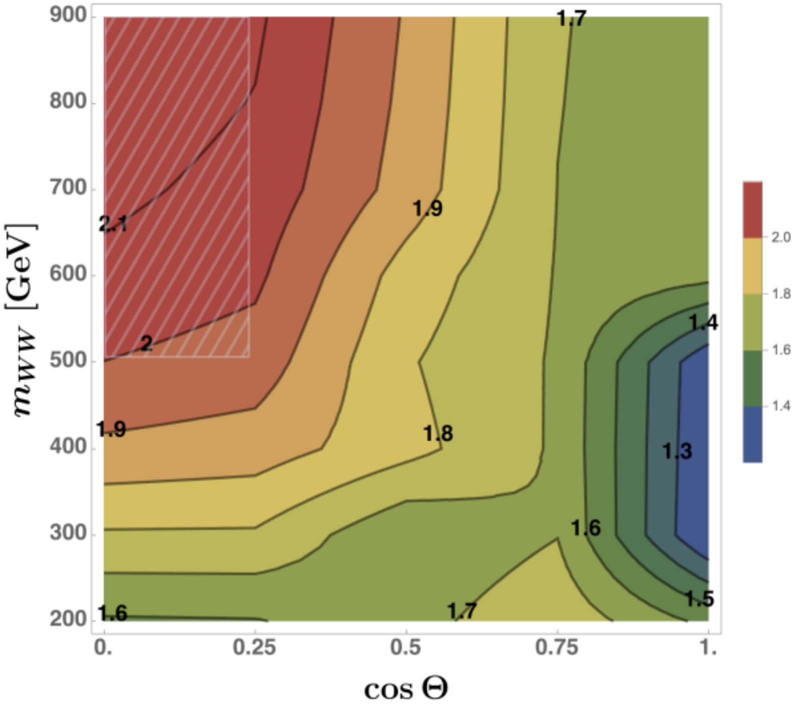
At parton level, tops violate Bell inequalities in extreme regions of phase space.

Simulations show that observing a Bell violation at the LHC will be very challenging.

New ideas are needed, **to improve event selection or to improve event reconstruction.**

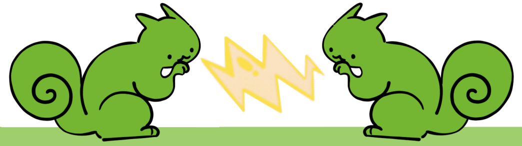
Beyond tt

Top pairs are not the only option for quantum observables at the TeV scale: studies exist for **ττ**, H→WW, H→ZZ.



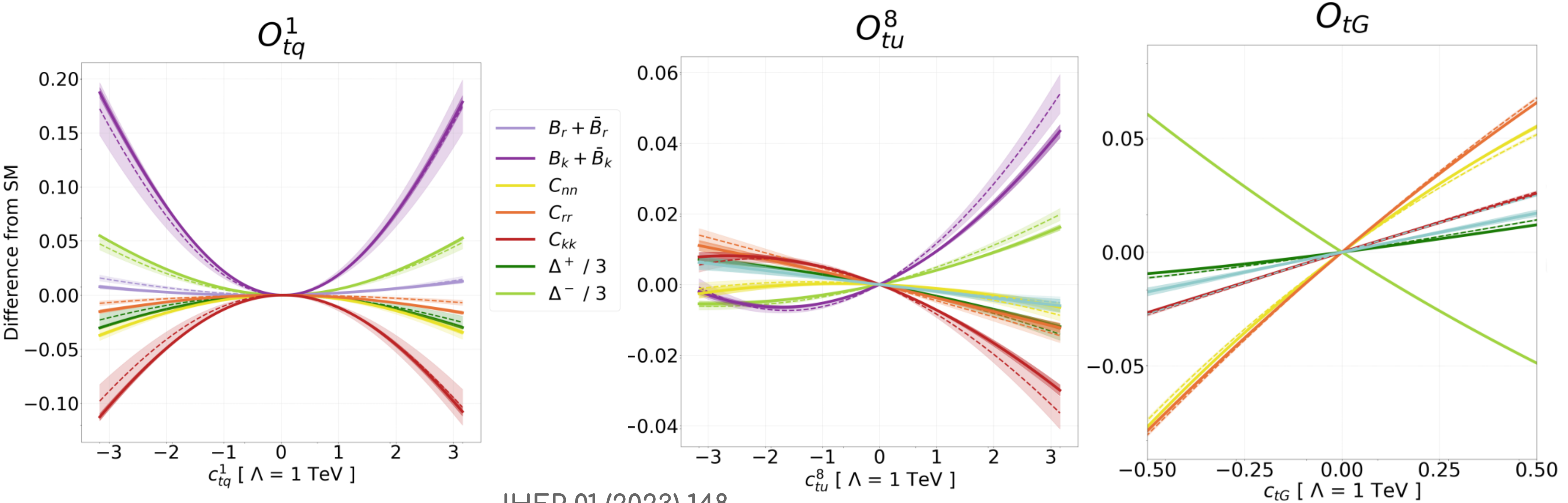
Sensitivity depends on systematic uncertainty, which we can't predict.

The best channel may not be tt.



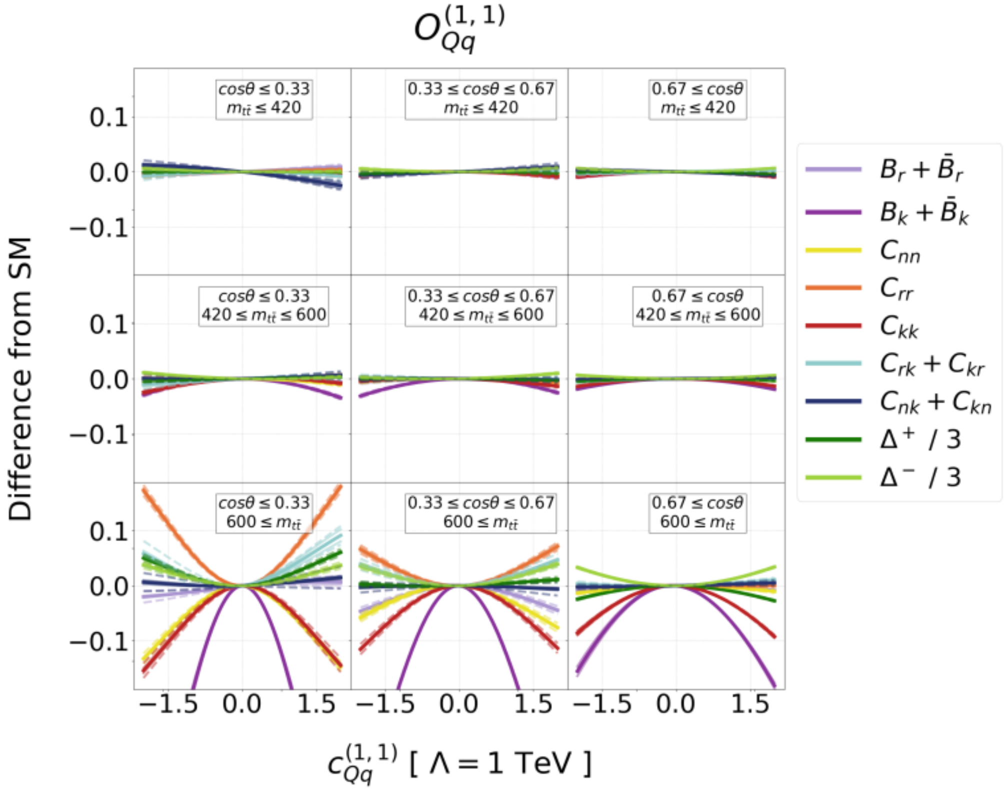
Entanglement for BSM searches

BSM physics affects the amount of entanglement, with new and intricate patterns:



JHEP 01 (2023) 148

The structure of spin correlations in phase space makes a differential measurement ~ 10x more effective than an inclusive one.



Quantum observables and spin correlations in general will yield remarkable improvements to BSM searches and SMEFT global fits.

Conclusions

Quantum properties seem to be accessible at the LHC, at the unprecedented TeV scale.

Top pairs are a good candidate for the observation of entanglement, and maybe more.

Quantum observables will also prove very effective in discovering/constraining new physics.