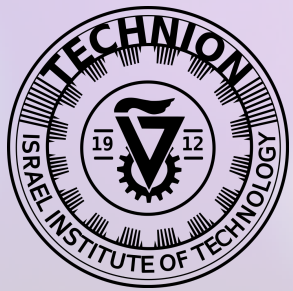
Quantum Information and Entanglement with Top Quarks at the LHC

BOOST 2020

Based on: 2003.02280

Y. Afik, J. R. M. De Nova

20.07.2020

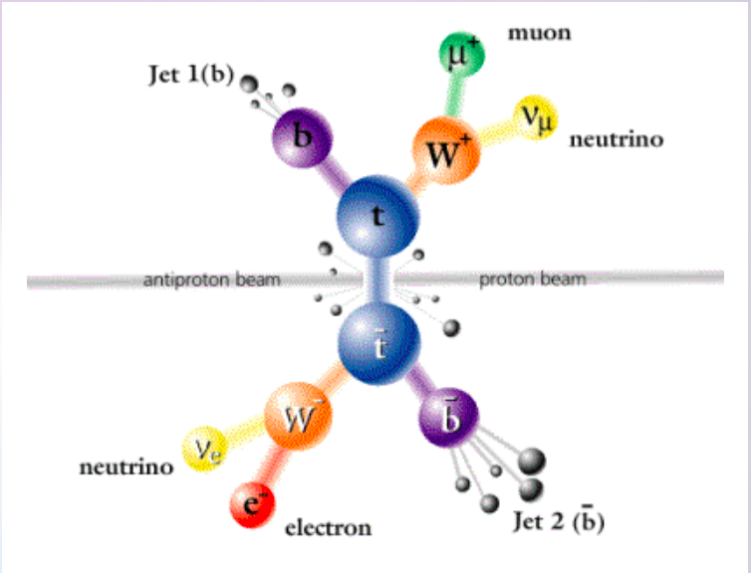


Motivation

- The SM is a quantum field theory: special relativity and QM.
- Fundamental properties of QM can be tested via the SM.
- Entanglement is one of the most genuine features of QM.
- First study of entanglement between a pair of quarks.
- Quantum tomography: reconstruction of the full quantum state of the $t\bar{t}$ pair.
- Quantum information into HEP.

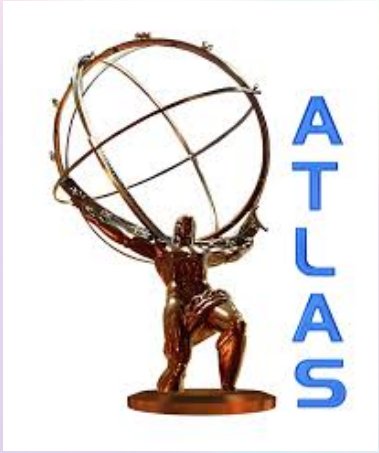
Top-Quark

- **General:**
  - Hadronisation: $\sim 10^{-23}$s.
  - Spin-decorrelation: $\sim 10^{-21}$s.
- **Top quark:**
  - Lifetime: $\sim 10^{-25}$s.
- Spin information $\rightarrow$ decay products.
- Spin-correlations between a pair of top-quarks can be measured.
- Considering leptonic decays.

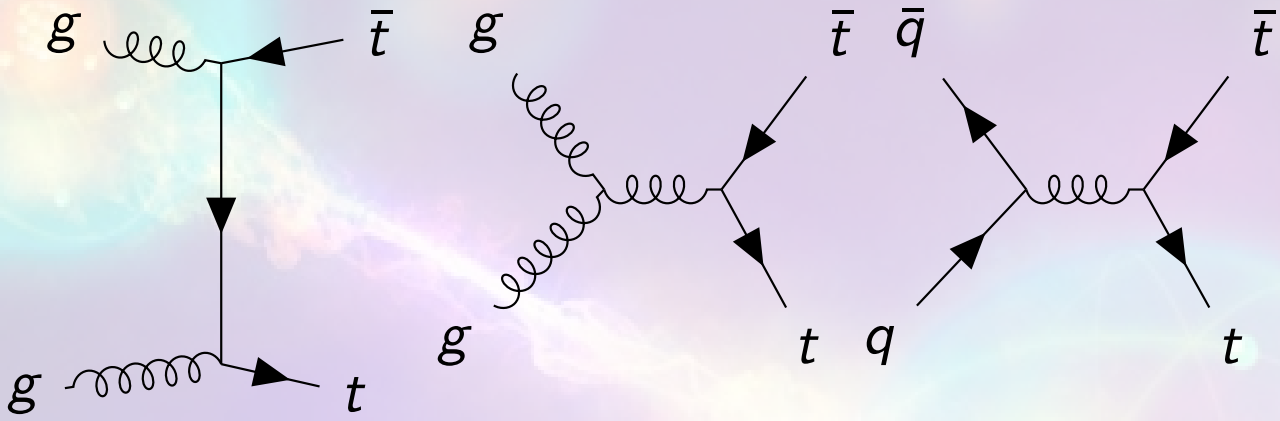


Spin-Correlations between Top-Quark Pairs

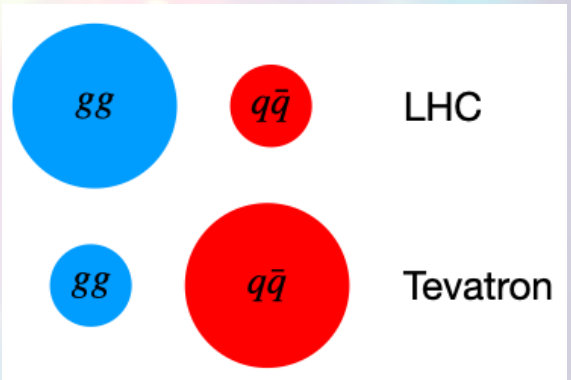
- Studied extensively theoreticaly.
- Measured by the D0, CDF, ATLAS and CMS collaborations.
- No link between spin-correlations and quantum entanglement so far.
- Note! **Spin-Correlations $\neq$ Quantum Entanglement!** However, Quantum Entanglement $\subset$ Spin-Correlations.



LO Analytical Calculation

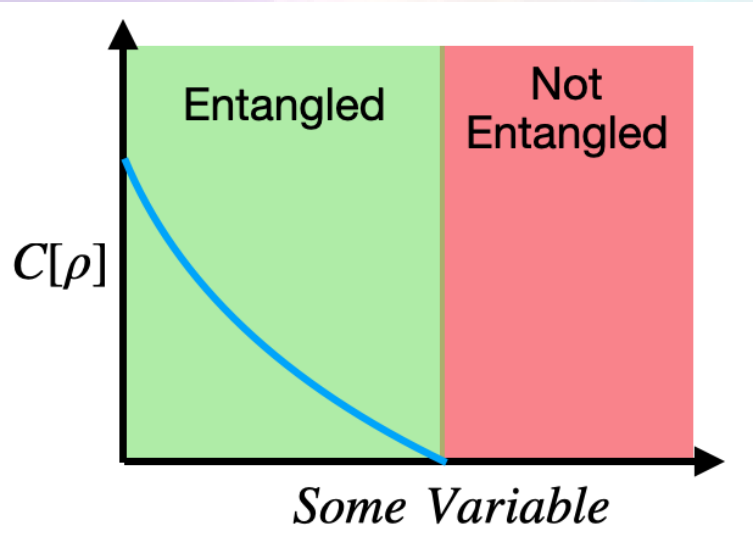


- Analytical calculation at LO.
- The total quantum state:
  $\rho(M_{t\bar{t}}) \equiv \int_{2m_t}^{M_{t\bar{t}}} \mathrm{d}M \int \mathrm{d}\Omega \; p(M,\hat{k})\rho(M,\hat{k})$



Entanglement Criterion

- **Concurrence** $C[\rho]$: Quantitative measurement of entanglement.
- $0 \leq C[\rho] \leq 1$, $C[\rho] \neq 0$ iff the state is entangled.
- Here, $C[\rho] = \max(\Delta, 0)/2$. Entanglement equivalent to $\Delta > 0$.
- $D = \frac{\mathrm{tr}[\mathbf{C}]}{3} = -\frac{1+\Delta}{3}$ provides an experimental entanglement marker.



Measurable Entanglement Marker

- Plots are shown with integration only for $[2m_t, M_{t\bar{t}}]$.
- In particular: $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$ where φ is the angle between the lepton directions in each one of the parent top and antitop rest frames.
- The condition $\Delta > 0$ translates into $D < -1/3$.

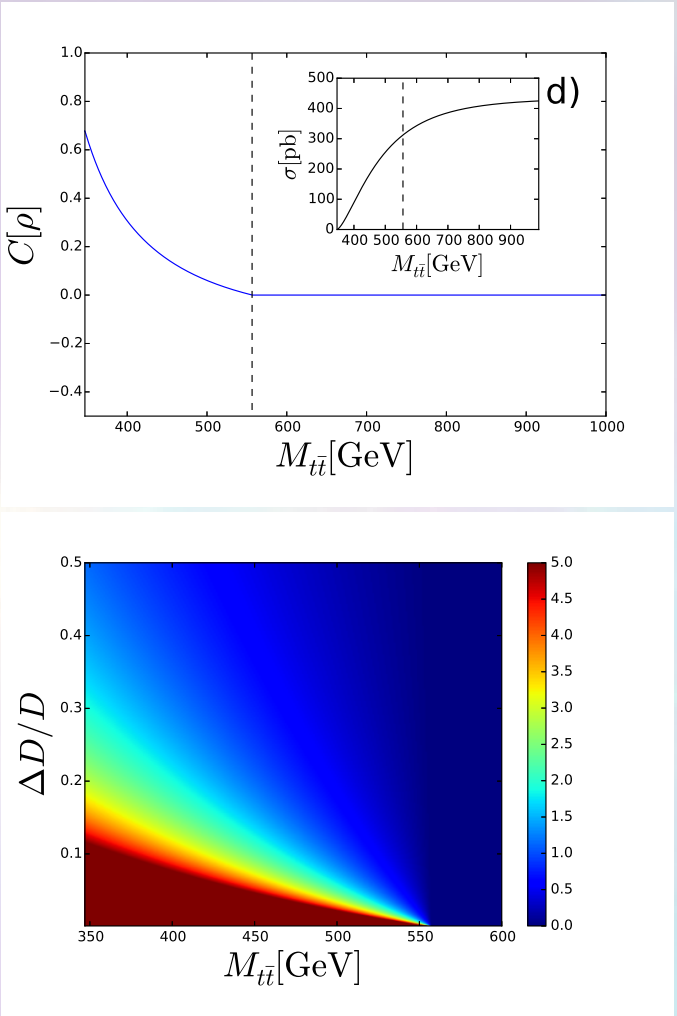


Figure: Up: concurrence; botton: Statistical deviation from the null hypothesis ($D = -1/3$).

Quantum Tomography

- Quantum tomography=Reconstruction of the quantum state of the system.
- Only need to measure 4 parameters (transverse and longitudinal spin correlations and the longitudinal polarizations).
- Test theoretical predictions for the $t\bar{t}$ quantum state.

Summary

- First study of entanglement between quarks.
- Quantum information study in a relativistic system.
- Although the calculation is analytical at LO, the conclusion still holds at higher orders.
- Quantum tomography: new platform to test new theories and new physics effects.
- Interdisciplinary measurement: propagate quantum information physics into HEP.

Summary

- First study of entanglement between quarks.
- Quantum information study in a relativistic system.
- Although the calculation is analytical at LO, the conclusion still holds at higher orders.
- Quantum tomography: new platform to test new theories and new physics effects.
- Interdisciplinary measurement: propagate quantum information physics into HEP.
- **Can be detected at the LHC with currently recorded data!**

Thank You

For further discussions, we'll be available at this **zoom link**, 20.07.2020 (Monday) at 17:00.