# *Opportunities of Quantum Entanglement at Colliders*

**Quantum Technologies for Fundamental Physics: Global Networks**

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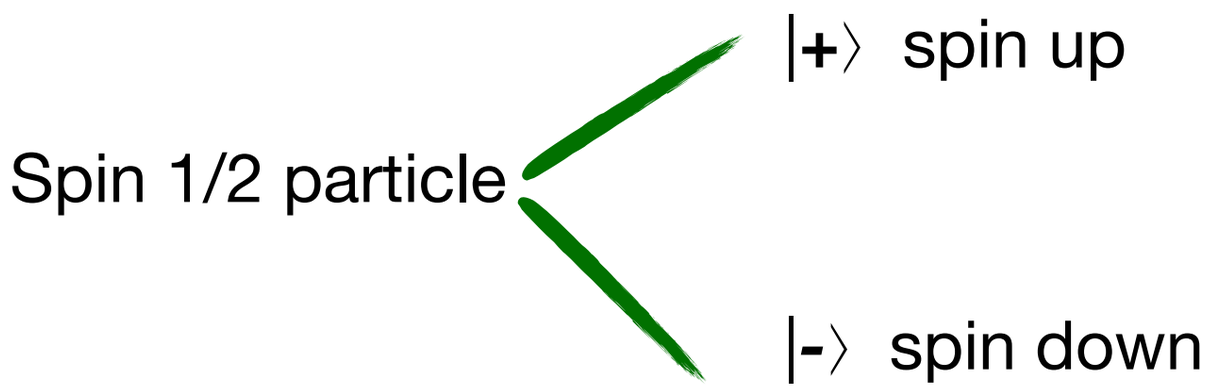
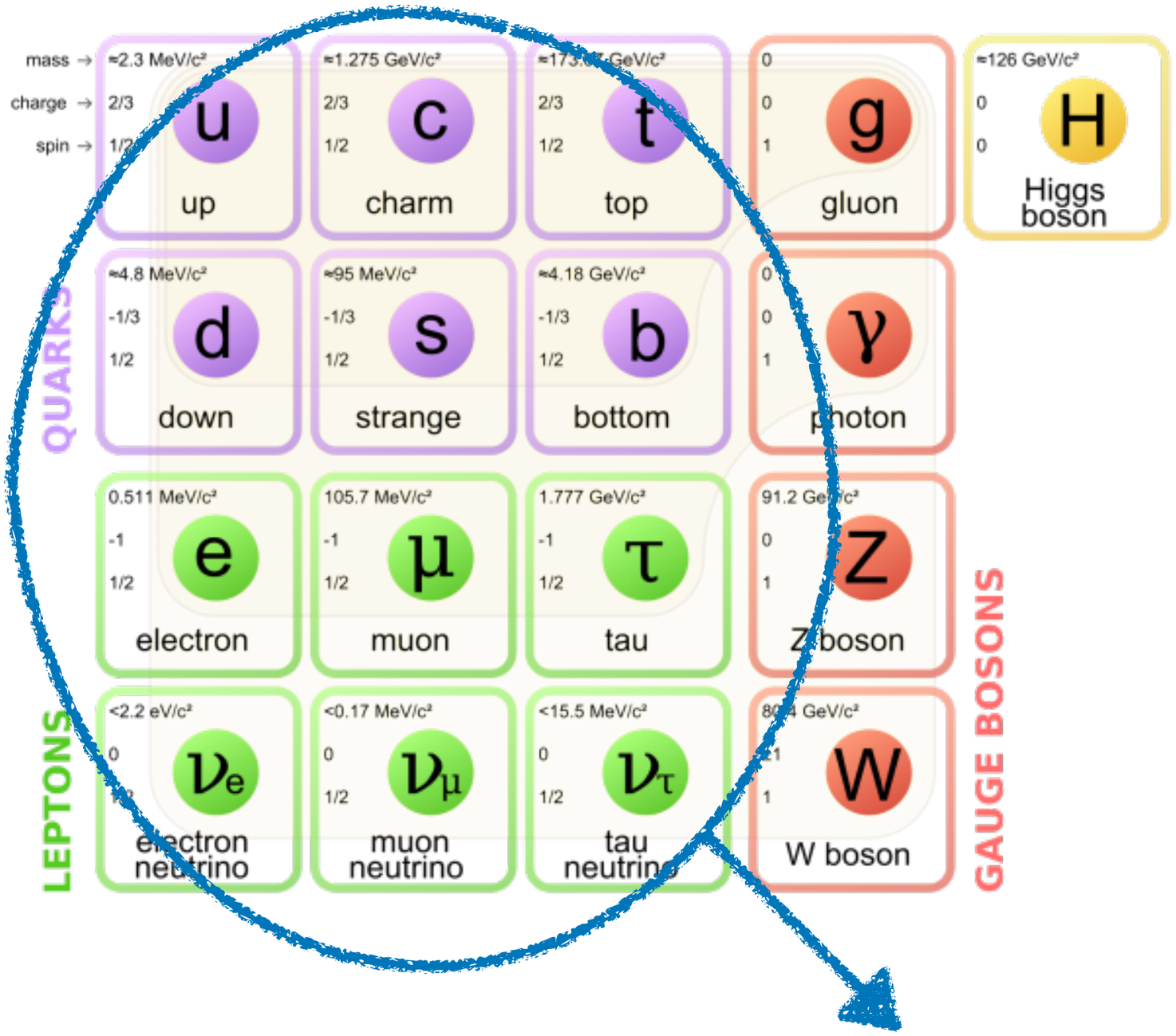
- A qubit is a quantum system with two different states: |**+**〉 and |**-**〉




- Two spin 1/2 particles form a two qubit system → Entanglement

- The spin quantum state is described by the density matrix: $\rho$

- A density matrix $\rho$ is an operator with positive eigenvalues.




Quarks and leptons are spin 1/2 particles

- A process with two fermions in the final state is a two qubit system.

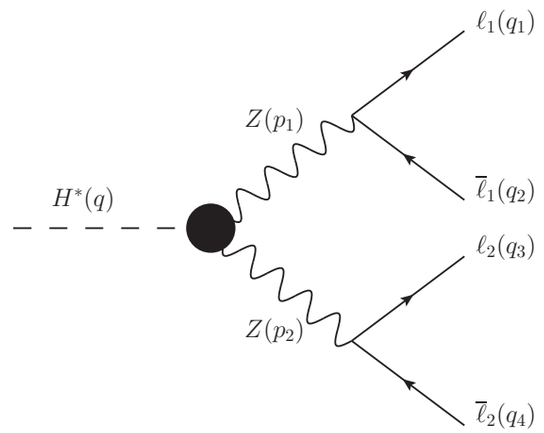
- In collider physics, we observe

$$\sigma \sim \mathscr{M}\mathscr{M}^{\dagger} dR \,.$$

Amplitude

Computed from Feynman diagrams

Space phase



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Any matrix product of this form has positive eigenvalues

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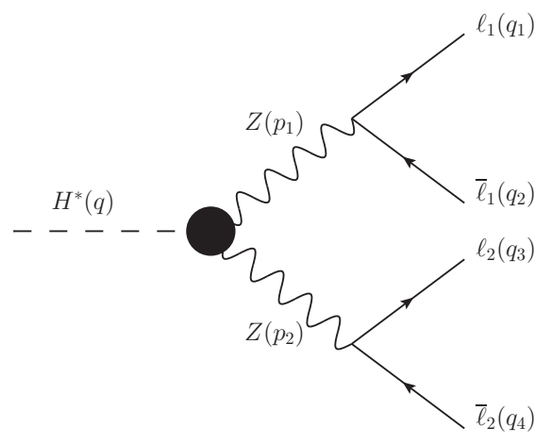

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$\mathscr{M}\mathscr{M}^\dagger$ is a density matrix $\rho$

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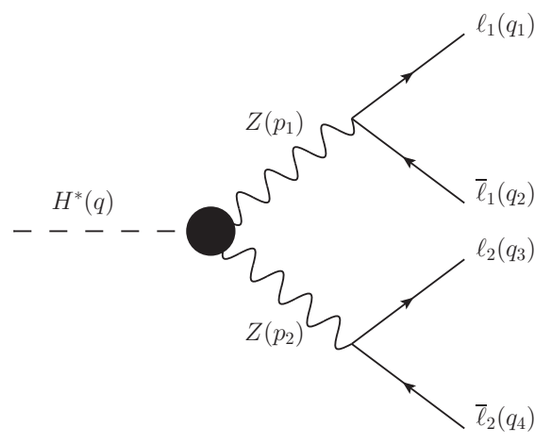
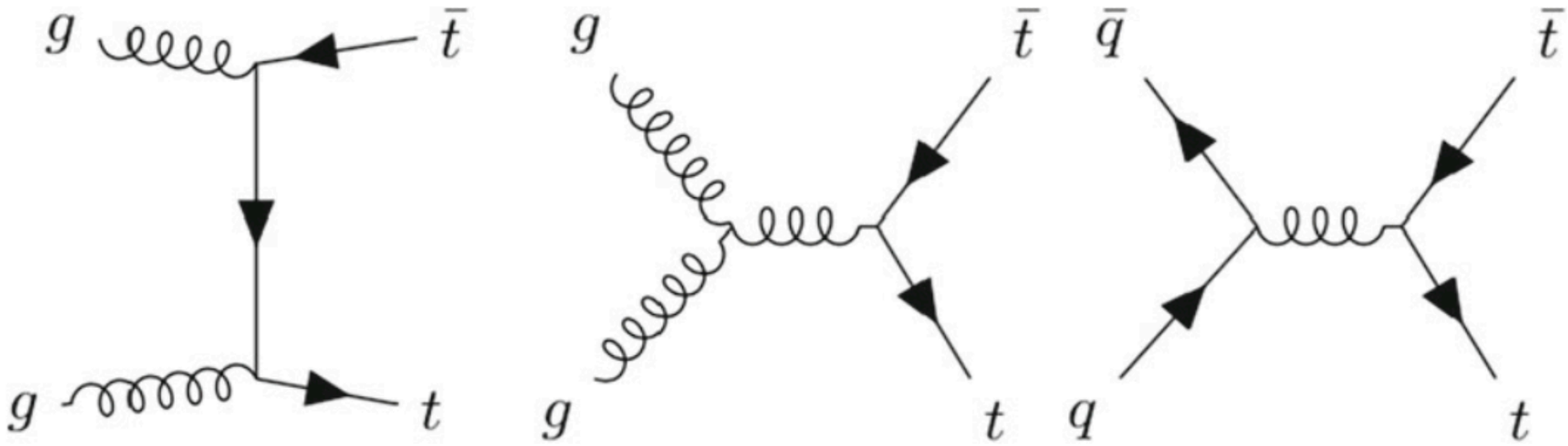


# Example: $t\bar{t}$ production

Afik, Y. & de Nova, J. R. M. Entanglement and quantum tomography with top quarks at the LHC. Eur. Phys. J. Plus 136, 907 (2021).




- The top quarks are not observed at the final state.

$$A \to \bar{t}t \to W^{-}\bar{b}W^{+}b \to (\ell\nu_{\ell})\bar{b}(\bar{\ell}\nu_{\bar{\ell}})b\,.$$

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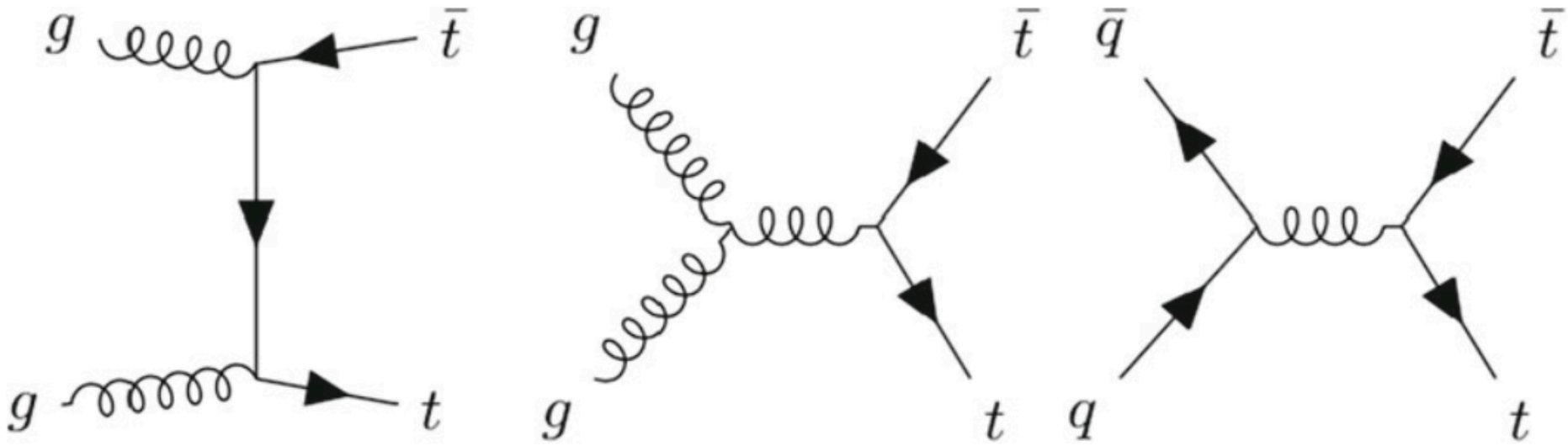


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The normalized cross-section is

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

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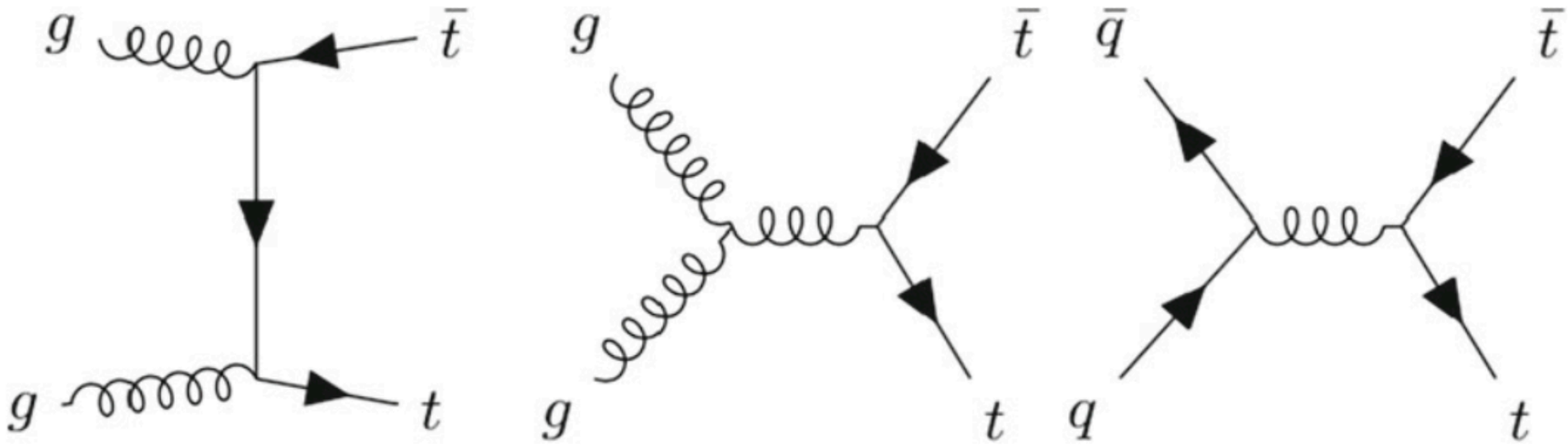


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Lepton and antilepton direction in the rest frame of their corresponding parent top quark

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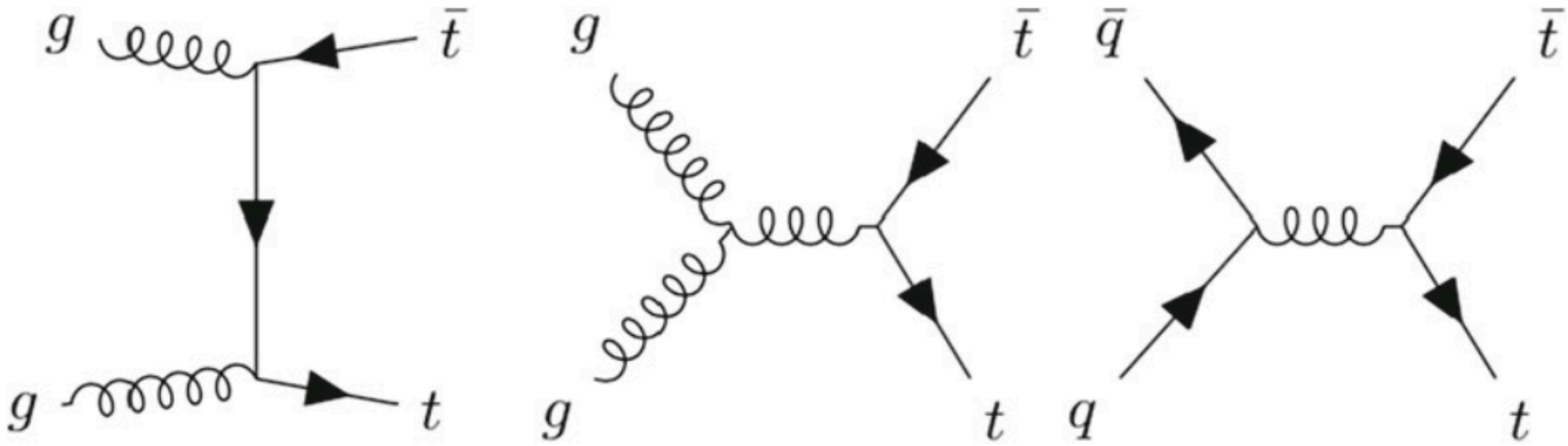


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$C$: $\bar{t}t$ spin correlation matrix

# Example: $t\bar{t}$ production

- It is convenient to define an entanglement marker

$$D = tr[C]/3 = -3\langle \cos \Phi \rangle$$

$\langle \cos \Phi \rangle$ is the average value of the cosine of the angle between the charged lepton directions and their parent top quark.

**Article**

## Observation of quantum entanglement with top quarks at the ATLAS detector

https://doi.org/10.1038/s41586-024-07824-z

Received: 14 November 2023

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The ATLAS Collaboration*✉

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced

# Example: $t\bar{t}$ production

- It is convenient to define an entanglement marker

$\langle \cos \Phi$ ...en
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**Conclusion: To study quantum entanglement at colliders we have to compute the spin correlation matrix and measure it.**

Articl...

**Ob... top...**

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# Quantum tomography

J.C. Martens, J.P. Ralston, J.D. Tapia Takaki, Quantum tomography for collider physics: illustrations with lepton-pair production. Eur. Phys. J. C 78(1), 5 (2018)

- According to the Martens-Ralston-Tapia approach for $e^+e^- \to Z \to \mu^+\mu^-$:

$$d\sigma = tr[\rho^{probe}(k,k')\rho(X)]dR,$$

where

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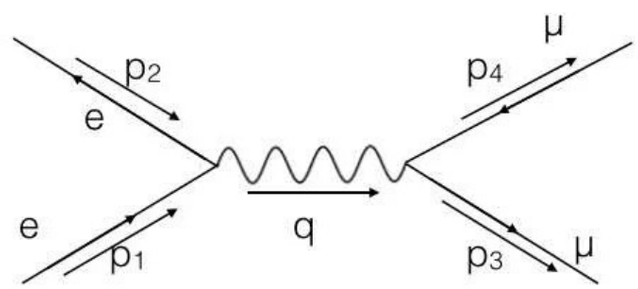
Analogous to classical Feynman Diagram calculation



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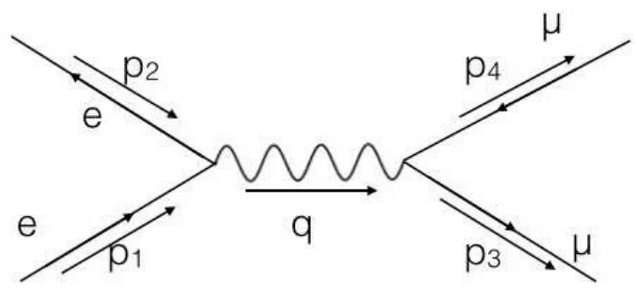
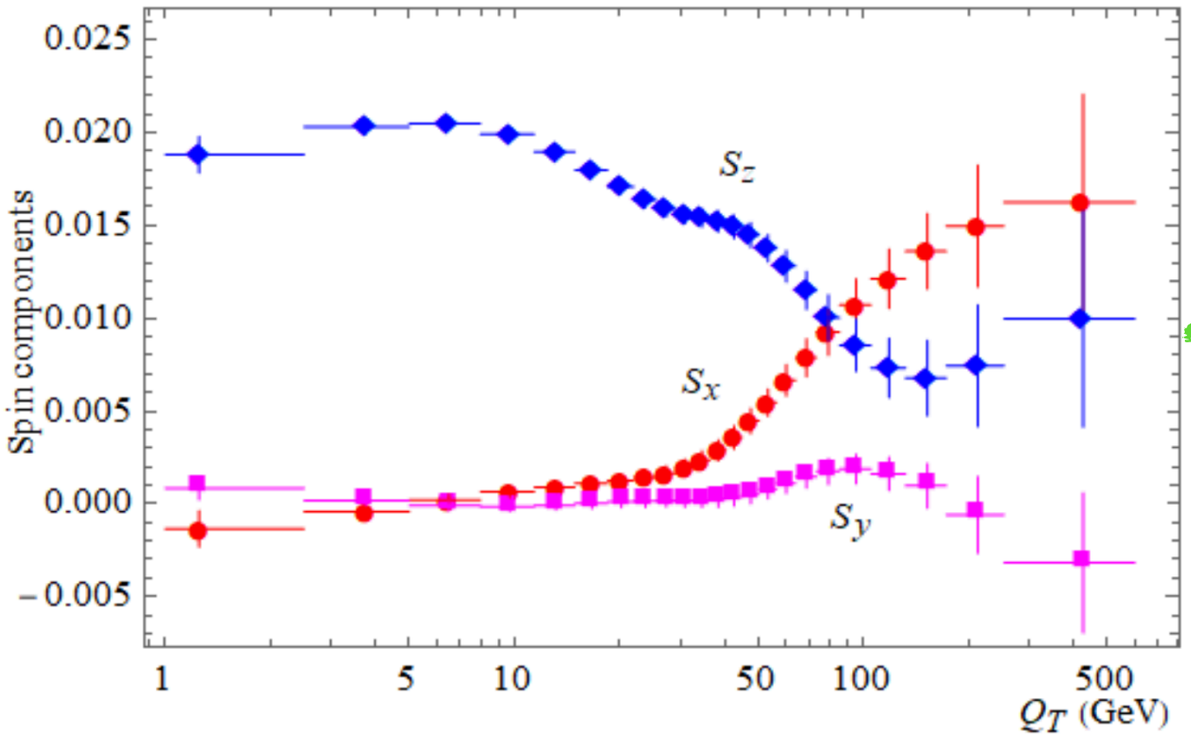
**The M-R-T approach can be extended to any process**

Analogous to classical Feynman Diagram calculation

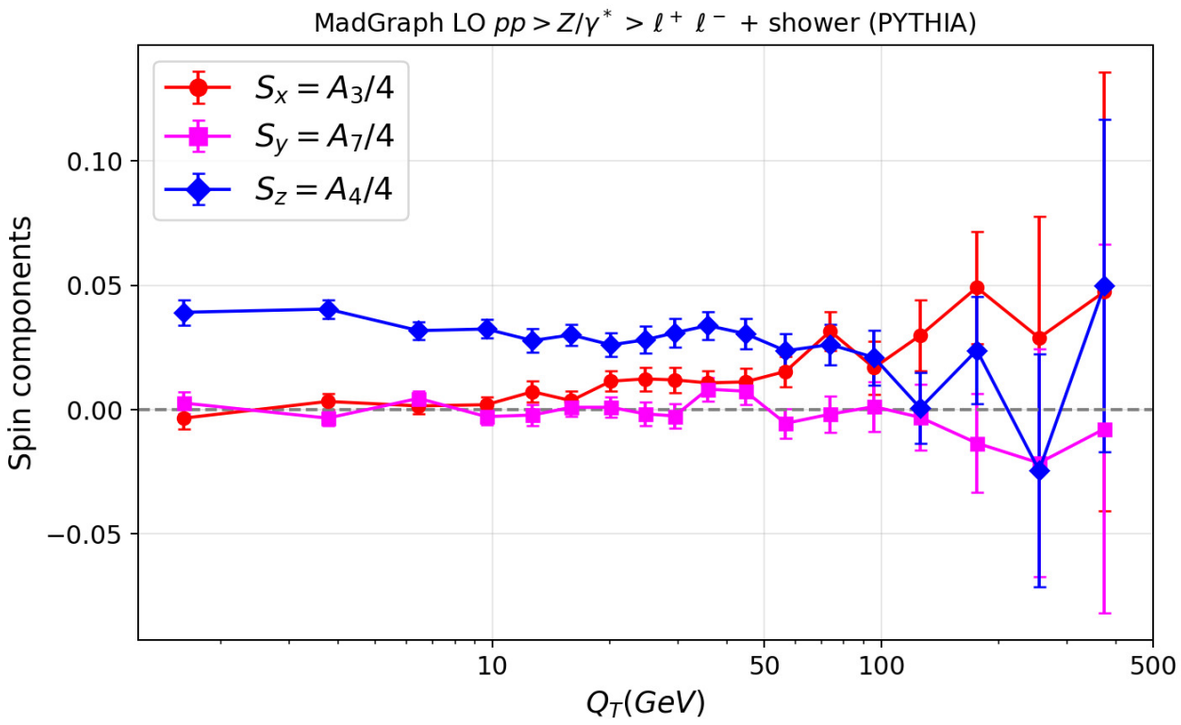


# Quantum tomography in MC

arXiv:2605.03254




Obtained from LHC data



Jadihel

MC simulation in Madgraph

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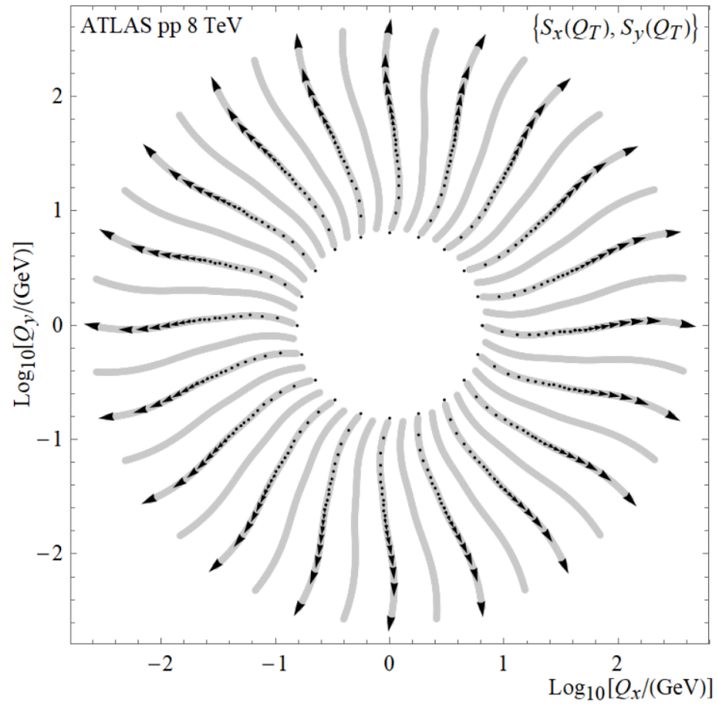


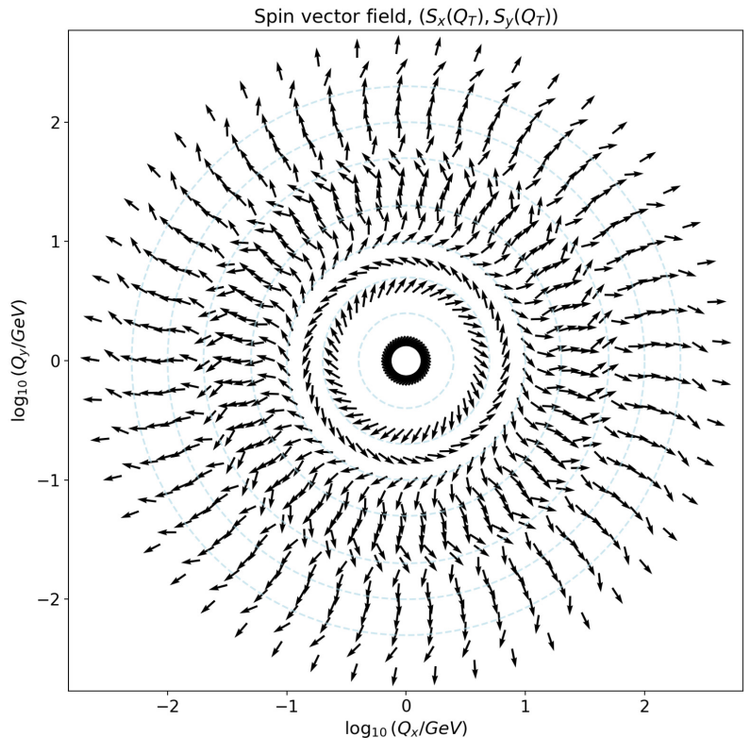


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# Conclusions

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- Quantum entanglement and quantum tomography are hot topics in collider physics!

# ¡Gracias!

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