Finalizing the paper draft

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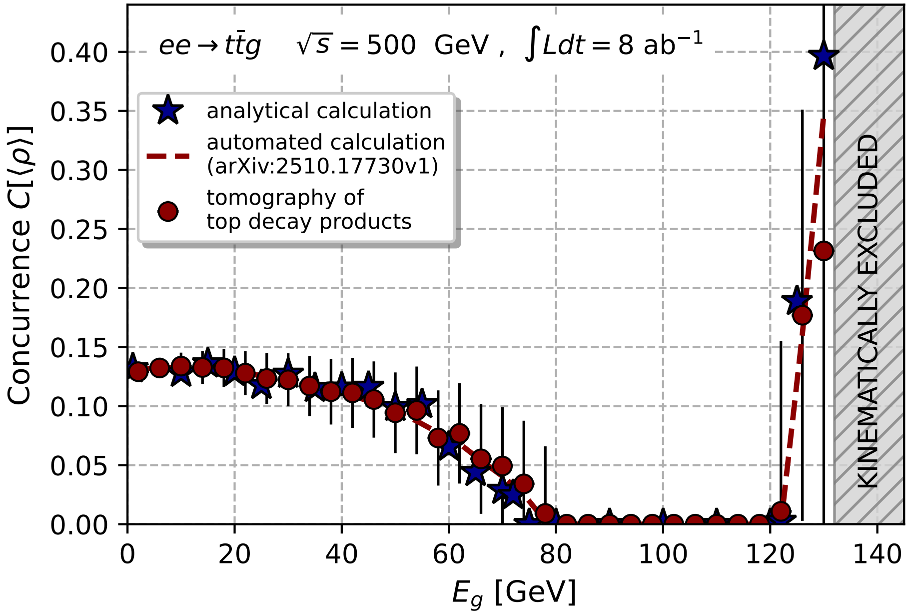
Decoherence meeting, june 22nd 2026

ArXiv:2604.16268

Our preprint presents a **new opportunity to study decoherence** at colliders
- SM predictions from analytical and automated calculations and tomography
- Several two-fermion processes with Final State Radiation
- Experimental prospects for observation of decoherence

New figure 2 includes analytical prediction for e+e- → Z/γ^* → ttg

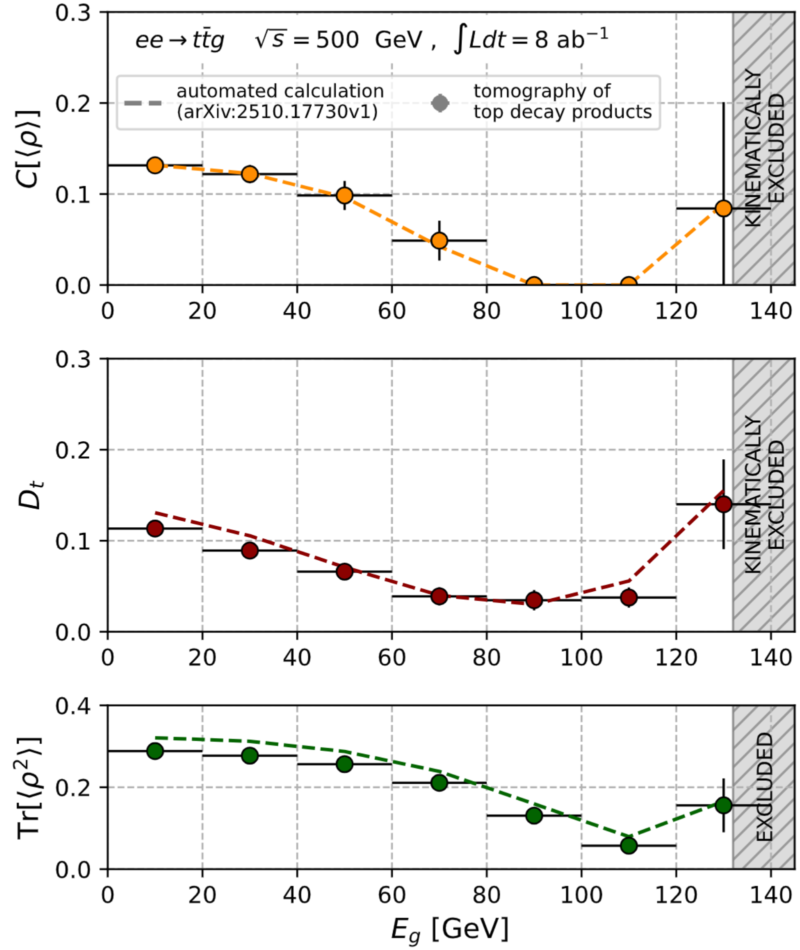


Understanding our paper: is it decoherence?

Clearly, the ttbar quantum system looses entanglement; already for low pT FSR, but most dramatic at high pT

Coherence + discord – intended to quantify the degree of quantumness of the system – show a similar (but not identical) trend

The purity of the quantum system decreases – the quantum superposition turns into a classical mixture



Add the observations on the tripartite system: entanglement is transferred to ttbar-gluon system for S→ttg decay, lost in additional d.o.f. for e+e- → ttg (see: Kazuki)

Title proposal: “quantum decoherence can be observed at collider experiments”

More tri-partite entanglement

Tripartite Entanglement in $e^+e^- \to t\bar{t}Z$

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Abstract: Multipartite entanglement is a uniquely quantum form of correlation that captures collective properties of a composite quantum state beyond those encoded in its bipartite subsystems. We investigate this phenomenon in the process $e^+e^- \to t\bar{t}Z$ at a future lepton collider, where the final state spins span the tripartite Hilbert space $\mathcal{H} = \mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \mathbb{C}^3$. Starting from the Standard Model helicity amplitudes, we reconstruct the full 12×12 spin density matrix and characterise its entanglement structure through one-to-one negativities, one-to-other negativities, and the genuine multipartite negativity, evaluated at three increasingly inclusive levels of phase space integration. Pairwise entanglement is generally suppressed relative to the collective (one-to-other) and the genuine multipartite entanglement, and all measures decrease as more kinematic information is integrated out. Assuming quantum tomography in the fully leptonic decay channel at $\sqrt{s} = 1$ TeV, we find that collective entanglement should be accessible at a realistic high-luminosity polarised lepton collider. By contrast, certifying genuine multipartite entanglement is more challenging, with only limited sensitivity projected for a specific polarisation benchmark within the expected ILC luminosity. The study establishes $e^+e^- \to t\bar{t}Z$ as an attractive laboratory for probing multipartite entanglement in high-energy collisions and provides a general mixed state framework that applies to any tripartite spin system.

arXiv:2606.11296v2 [hep-ph] 16 Jun 2026

Congratulations, Kazuki!

We should discuss the relevance of this paper for our draft, and add a reference.

Work on paper draft – theory intro

The introduction of the calculation has attracted some comments from Kazuki and Juan Ramon… It's also somewhat lengthy for a letter that does not develop the calculation itself further, just presents results

unnormalized spin-density matrix $\boldsymbol{R}_{\mathrm{LO}}$ is

$$\boldsymbol{R}_{\mathrm{LO}} = \sum_{\text{in dof}} |\mathcal{M}_0\rangle\langle\mathcal{M}_0| \,, \tag{1}$$

where $\mathcal{M}_0$ is the tree-level amplitude, the ket carries the $t\bar{t}$ spin indices, and we sum over the initial-state degrees of freedom. At a center-of-mass energy of 500 GeV, the top quarks are relativistic and the concurrence is about 0.13, with only a mild dependence on the beam polarization [42–44]. The concurrence increases further with increasing center-of-mass energy.

We now consider corrections to this tree-level picture. If one of the top quarks emits a gluon before decaying, as shown in Fig. 1, the entanglement of the $t\bar{t}$ spin system is modified.

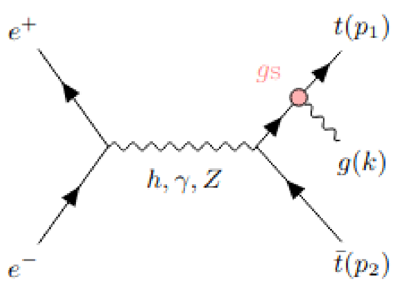


FIG. 1: Real emission contribution to $e^+e^- \to t\bar{t}g$

entanglement depends on the emitted radiation, we introduce the following differential density matrix:

$$\mathrm{d}\boldsymbol{\rho} = \frac{1}{\mathrm{tr}[\boldsymbol{R}]}\left[\left(\boldsymbol{R}_{\mathrm{LO}} + \boldsymbol{R}_{\mathrm{NLO}}^{\mathrm{virt.}}\right)\mathrm{d}\Phi_2 + \boldsymbol{R}_{\mathrm{NLO}}^{\mathrm{real}}\mathrm{d}\Phi_3\right] . \tag{5}$$

The quantity defined above is infrared-safe and remains a density matrix for the $t\bar{t}$ spin subsystem, differential in the radiation phase space. To probe how the entanglement depends on the emitted-gluon energy, we construct an energy-binned density matrix by integrating over the gluon direction at fixed E_g. The concurrence is then computed from this binned density matrix, for $E_g > 0$

$$\frac{\mathrm{d}C[\langle\boldsymbol{\rho}\rangle]}{\mathrm{d}E_g} = \frac{1}{w(E_g)} C\left[\int \mathrm{d}\Omega_g\, w(E_g, \Omega_g)\boldsymbol{\rho}_{t\bar{t}}\right] , \tag{6}$$

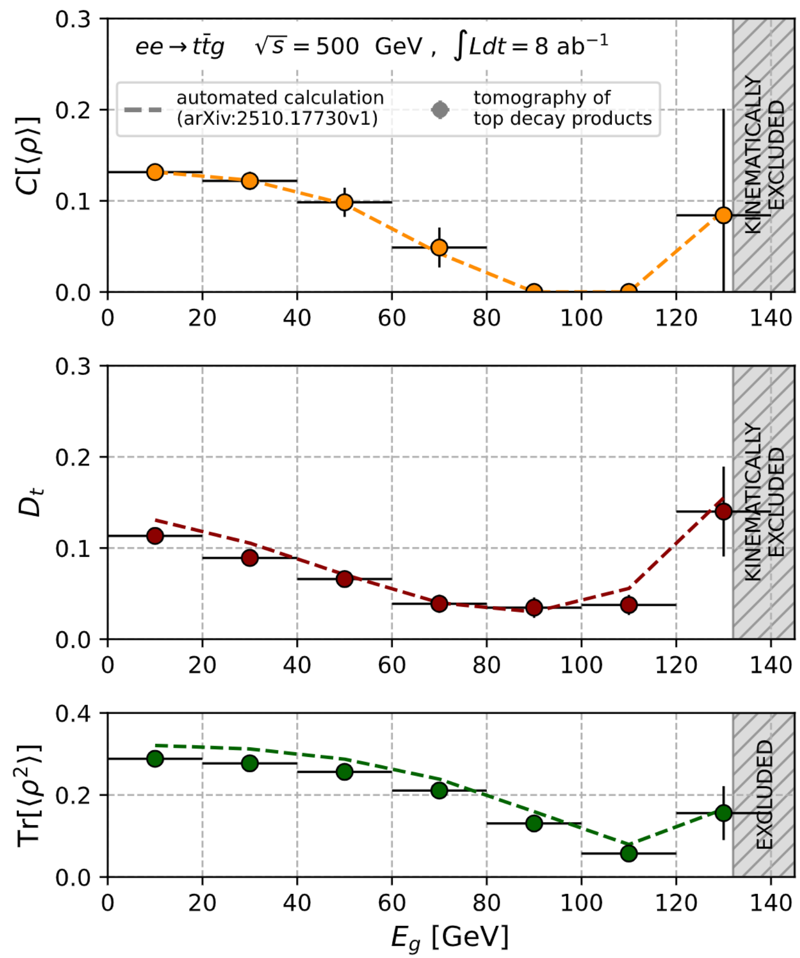
[KS] I think we should improve this equation. (i) The argument of $C[\bullet]$ is not normalised, which is awkward (but not wrong since $C[\lambda\rho] = \lambda C[\rho]$). (ii) The LHS and RHS have different dimensions. where $w(E_g) = \mathrm{d}\sigma/\mathrm{d}E_g$, $w(E_g, \Omega_g) = \mathrm{d}\sigma/(\mathrm{d}\Omega_g\,\mathrm{d}E_g)$, and $\boldsymbol{\rho}_{t\bar{t}}$ is Eq. (5) integrated over the phase space variables of the $t\bar{t}$ pair. This definition is inclusive in the sense that the integration over the unresolved gluon kinematics is performed before evaluating the concurrence.

Work on paper draft

This figure: good agreement between analytical, automatic and tomography results for concurrence

This figure: discord minimization remains mysterious → confirmed by and under investigatation with Martin White and Ondrej Penc (ATLAS)

This figure: slight discrepancy in purity traced back to imaginary parts of density matrix rho and one of the polarizations (see: Guillermo)



Experimental progress: ATLAS + Belle 2

Maria, Davide, Katinka, Guillermo, M.V.) are part of the ATLAS boosted l+jets entanglement analysis with Federica Fabbri, Frederic Deliot, Yoav Afik, and others.

The scope of the run 2 + partial run 3 analysis includes:
--- confirmation of entanglement in boosted l+jets analysis
--- full spin correlation matrix and unfolded angular distributions
--- decoherence analysis: a measurement of D3 vs. pT(jet)

We're in the approval pipeline, now, with an Editorial Board.

Realistic target: TOP26 (October) or Moriond 2027?

We've had a few meetings with the FCCee tau physics and ILD physics groups

I'll arrange for a meeting with Belle 2 groups (Max Planck in Munich, Rome) once our paper is submitted

Conferences

TOP26 is in Turkey!
https://indico.cern.ch/event/1643686/
Registration is open!

Maria Moreno accepted a talk on our paper at the conference