Experimental prospects for quantum decoherence measurements at colliders

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Based on arXiv:2604.16268. Under review in Physical Review Letters

Overview

1. **INTRODUCTION:**
   - What is quantum entanglement? → Non-classical correlations in experimental measurements of composite systems.
2. **$t\bar{t}$ ENTANGLEMENT MEASUREMENTS AT THE LHC:**
   - How is entanglement experimentally observed? → Quantum tomography & the D markers.
   - The spin entanglement observation using $t\bar{t}$ pairs → ATLAS (2023) and CMS (2024).
3. **RADIATIONS EFFECTS ON ENTANGLED FERMIONS:**
   - Radiation emission as a source for decoherence in spin-entanglement fermion-pairs.
   - Defining new observables for studying entanglement and decoherence at colliders.
4. **QUANTUM DECOHERENCE PROSPECTS AT COLLIDERS:**
   - Prospects for the observation of quantum decoherence.
   - Opportunities for studying quantum observables differentially.

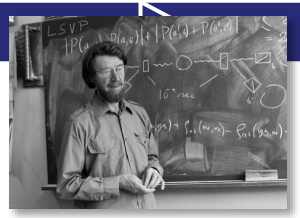
Quantum entanglement: experimental tests

"The quantum state of a particle cannot be described independently of the state of the other"

1935 EPR "paradox"



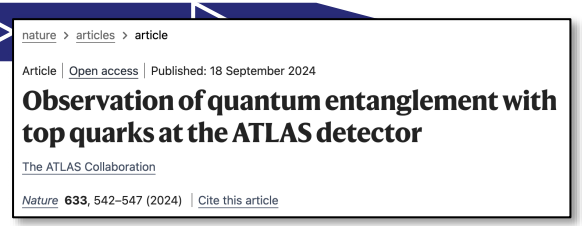
1964 Bell's theorem



1982



nature **2024**



QUANTUM ENTANGLEMENT ≡ NON-CLASICAL MEASUREMENT CORRELATIONS

1982 **Alain Aspect, Philippe Grangier, and Gérard Roger**

- Found quantum non-locality using polarized photon pairs:
- Experimental proof of QM over hidden variable theories

2024 **ATLAS and CMS**

- Highest energy observation of entanglement using top quark pairs
- Recently H → ZZ boson entanglement! (ATLAS Collaboration, PRL 137, 111804)

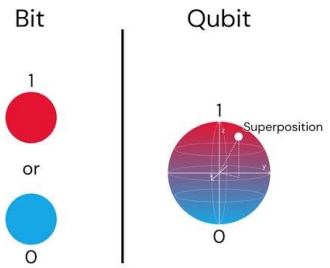
Belle II and other experiments

- Measurements of entanglement with K and B meson pairs

$t\bar{t}$ ENTANGLEMENT MEASUREMENTS AT THE LHC

Theoretical framework: The two-qubit system

A) Spin ½ particles as qubits:



- Qubit → QM generalization of the classical bit → Most simple quantum system $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- Spin of spin ½ particles → Most simple example of qubit in HEP $\rho = \frac{\mathbb{1}_4 + B^i \otimes \sigma_i}{2}$
- At colliders → Mixed states → Statistical combination of different pure states → density matrix $\hat{\rho} = \sum_{k=1}^{N} p_k |\psi_k\rangle\langle\psi_k|$

B) Composite systems and separability:

Separable = NO ENTANGLEMENT $\rho = \sum_i p_i \, \rho_A^i \otimes \rho_B^i$

Non-Separable = ENTANGLEMENT $\rho \neq \sum_i p_i \, \rho_A^i \otimes \rho_B^i$

Entanglement = Non-separability = Non-classical Correlations

C) General two-fermion pair spin density matrix

$$\rho = \frac{1}{4}\left[\mathbb{1}_4 + \sigma^i \otimes \mathbb{1}_2 \cdot B_i^1 + \mathbb{1}_2 \otimes \sigma^j \cdot B_j^2 + \sigma^i \otimes \sigma^j C_{ij}\right]$$

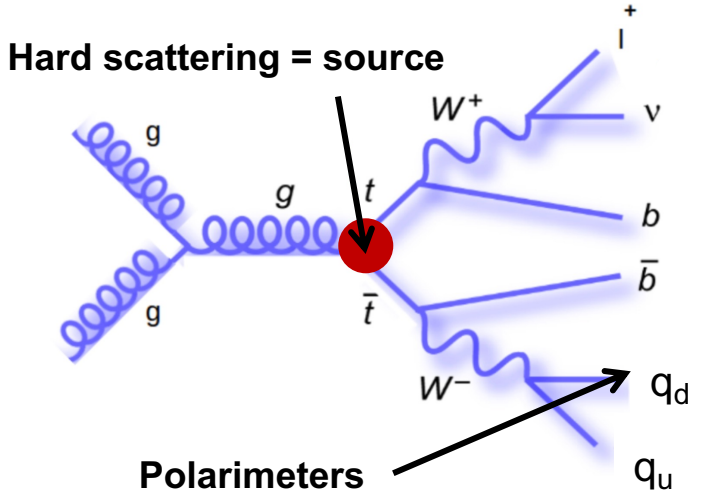
$B_i^a = \langle S_i \rangle^a$ **SPIN POLARIZATION VECTOR**

$C_{ij} = \langle S_i S_j \rangle$ **SPIN CORRELATION MATRIX**

- At colliders → **measure B and C** to reconstruct the spin density matrix

Top quark quantum tomography

- Top quark short **lifetime** (~10^{-25} s) is shorter than **decorrelation** (~10^{-21} s) and **hadronization** (~10^{-24} s) timescales:
  - All quantum information is passed to decay products



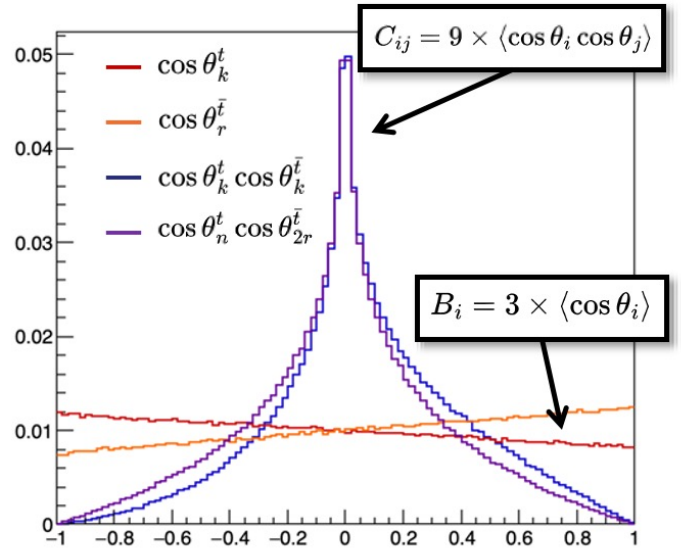
A) Reconstruction of the top quark spin information:

- **<u>Quantum state tomography</u>**:
  - Possible final states $t \to Wb \to l\nu b$ or $t \to Wb \to q_d q_u b$
  - Top quark spin vector is correlated with the daughter particle angular direction

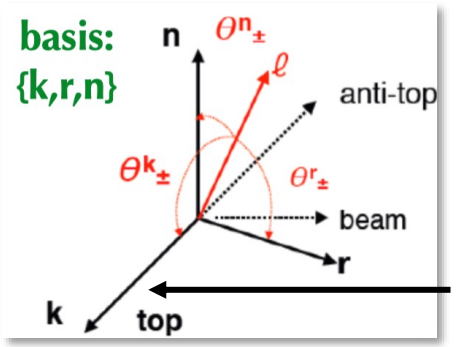
$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\chi_i} = (1 + \alpha_i \cos\chi_i)/2$$

- χ_i is the angle between a dauter particle momentum
- α_l is the spin analyzing power

  - Charged leptons and down-type quarks preserve the spin information perfectly (α = 1)



B) The helicity basis



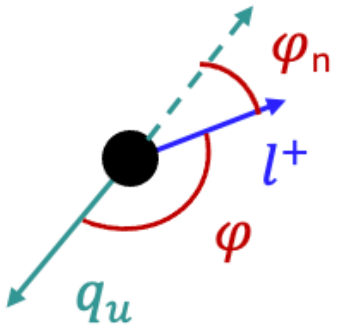
- Conventional basis in spin correlation studies.

Defined by the direction of fly of the top

Entanglement witnesses at the LHC events

The D markers (Afik, De Nova Eur. Phys. J. Plus **136**, 907)

- At the LHC → Avoid a full density matrix reconstruction → Entanglement can be proven just by using a single parameter
  - Build as a linear combination of the diagonal entries in the spin correlation matrix ***C.***
  - Defined as $D = -\frac{1}{3}\left(C_{nn} + C_{rr} + C_{kk}\right)$ $D_n = -\frac{1}{3}\left(C_{nn} - C_{rr} - C_{kk}\right)$
  - Peres-Horodecki entanglement criteria $D < -1/3$ or $D_n < -1/3$



Experimental reconstruction:

D
- Built from φ ≡ angle between two leptons or down-type jets measured in the parent top/antitop quark rest frames

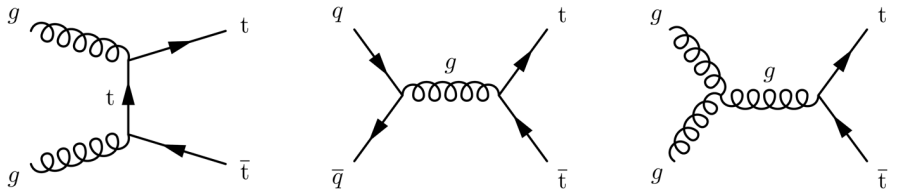
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1 - D\cos\varphi}{2} \qquad D = 3\frac{\langle\cos\varphi\rangle}{\alpha_1\alpha_2}$$

D_n
- Built from φ_n ≡ angle between the polarimeter of the top quark and the opposite direction of the polarimeter of the antitop quark.

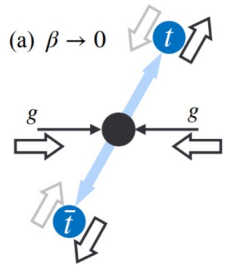
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_n} = \frac{1 - D_n\cos\varphi_n}{2} \qquad D_n = 3\frac{\langle\cos\varphi_n\rangle}{\alpha_1\alpha_2}$$

Entanglement of top quark pairs at the LHC

- $t\bar{t}$ production → two main production channels:
  - $gg \rightarrow t\bar{t}$
  - $q\bar{q} \rightarrow t\bar{t}$



- The SM predicts entanglement at:
  - Boosted —$M_{t\bar{t}} \gg 2\,m_t$ — and central —$|\cos\Phi| \lesssim 1/2$ — $t\bar{t}$ pair.
  - Production threshold — $M_{t\bar{t}} \simeq 2\,m_t$ — in gg fusion.

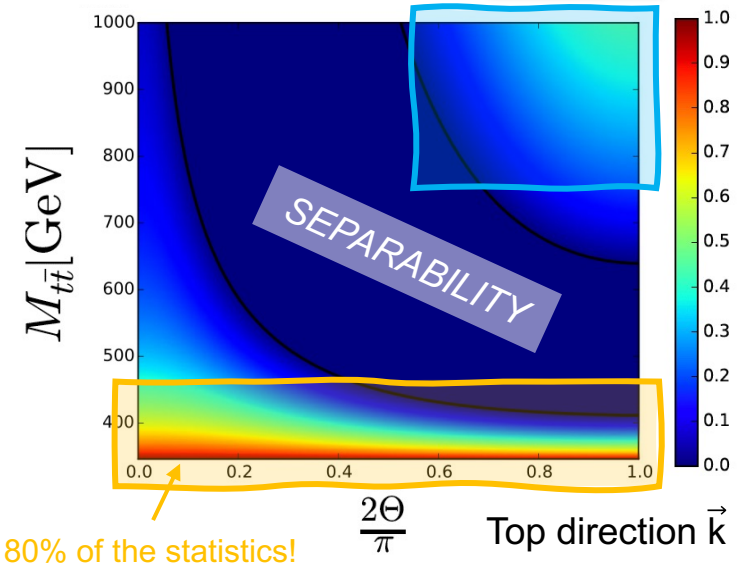


Spin-singlet states

- C_{rr} and $C_{kk} > 0$
- $D < -1/3$

D entanglement witness

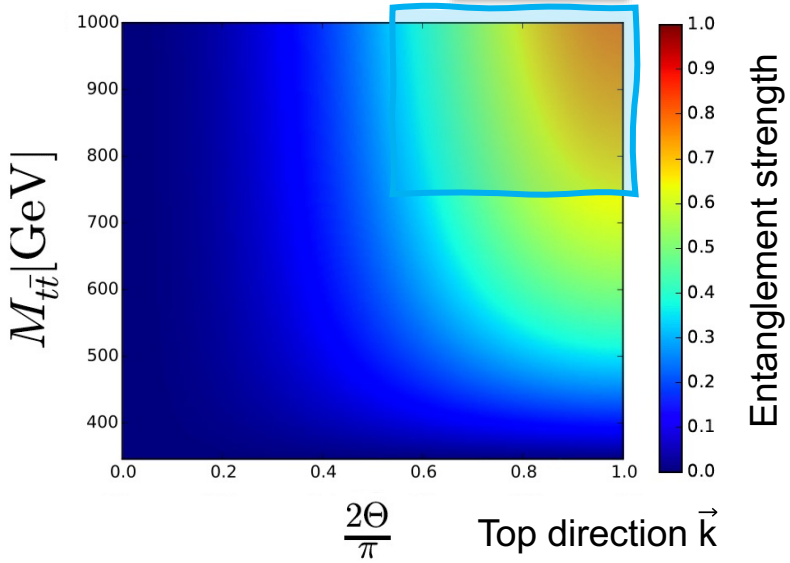
$gg \rightarrow t\bar{t}$

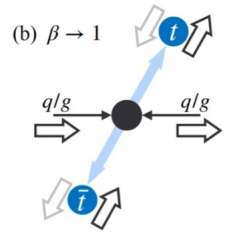


80% of the statistics!

Afik, De Nova Eur. Phys. J. Plus **136**, 907

$q\bar{q} \rightarrow t\bar{t}$





Spin-triplet states

- C_{rr} and $C_{kk} < 0$
- $D_n < -1/3$

D_n entanglement witness

- Measure D witnesses to understand the type of entanglement →

$D \equiv \rho_{singlet}$ $D_n \equiv \rho_{triplet}$

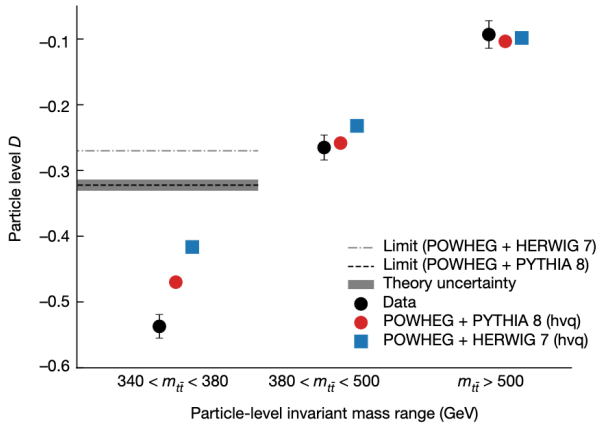
Quantum entanglement searches at the LHC

Observations of quantum entanglement in top quark pairs

- First observation of quantum spin entanglement in $t\bar{t}$ pairs:
  - ATLAS in 2023 (*Nature* **633**, 542–547, 2024) and CMS in 2024 (*Rep. Prog. Phys.* **87** 117801, 2024)
  - **Threshold production** region ($m_{tt} \lesssim 380$ GeV)
  - ***D* as the entanglement witness.**

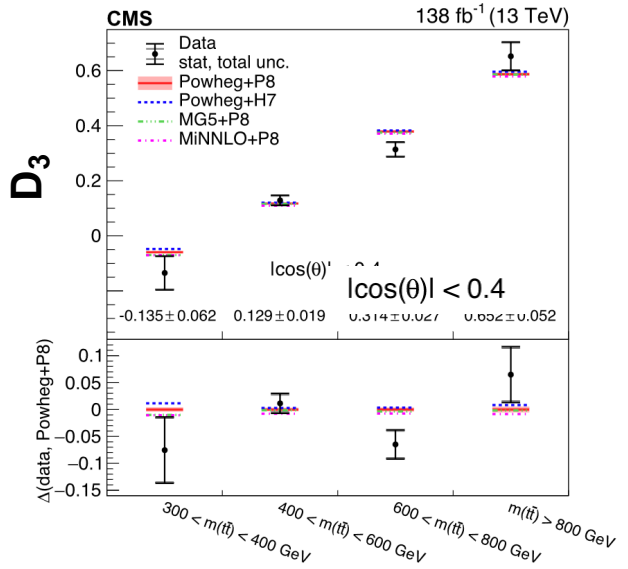
- First differential measurement of spin entanglement:
  - CMS in 2024 (PRD 110, 112016 (2024))
  - **Inclusive and binned** (m_{tt} and top scattering angle) **measurement**
  - **Both *D* and D_n as the entanglement witness**

ATLAS 2023 result



ATLAS Collaboration, *Nature* **633**, 542–547, 2024

CMS 2024 lepton+jets results



CMS Collaboration. PRD 110, 112016 (2024)

RADIATIONS EFFECTS ON ENTANGLED FERMIONS

The effects of radiation in entanglement measurements

Our work:

Experimental prospects for quantum decoherence measurements at colliders

Rafael Aoude,[1] José Manuel Camacho,[2] Valentin Durupt,[3] Guillermo García Mir,[2] Fabio Maltoni,[4,3,5] Maria Moreno Llácer,[2] Kazuki Sakurai,[6] Leonardo Satrioni,[3] and Marcel Vos[2]

(arXiv:2604.16268, under review by PRL)

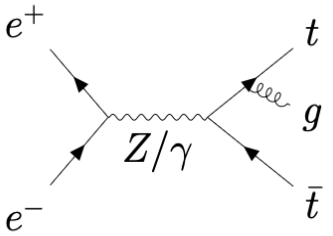
1. **Study → impact of radiation emission (FSR) in spin-entangled fermions:**
   - Theoretically → Radiation = System + environment interactions → Information leakage (Aoude, et. al.).
   - Phenomenologically → Radiation = Extra degrees of freedom in the final state.
2. **ORIGINAL RESULTS** - Parton-level two-fermion production + radiation in the final state**:**
   - Study quantum entanglement observables → **differentially with E_{rad}**
   - Calculate **significance for observation of decoherence**.

Studied processes

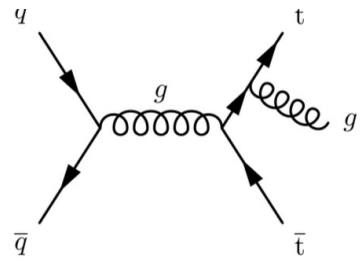
- **Parton-level simulations** with MadGraph5_aMC@NLO (10.1007/jhep07(2014)079) at LO:
  - 3 studied process: $e^+e^- \to t\bar{t} + g$, $pp \to t\bar{t} + j$ and $e^+e^- \to \tau^+\tau^- + \gamma$.
  - 2 sample categories: the **control sample ($f\bar{f}$ production)** and **radiative sample ($f\bar{f} + g$ *or* $f\bar{f} + \gamma$ production).**

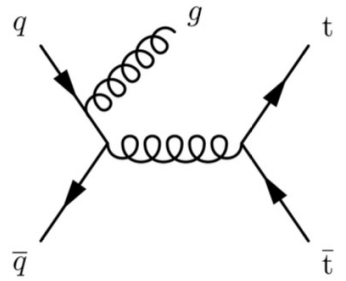
- **Topologies of radiative samples:**

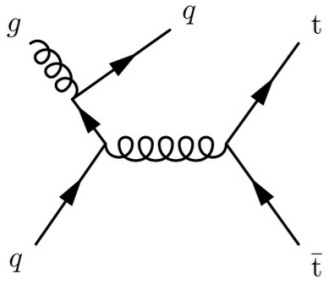
1.- $e^+e^- \to t\bar{t} + g$



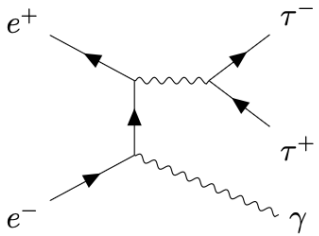
2.- $pp \to t\bar{t} + j$ ($j \equiv q, g$)

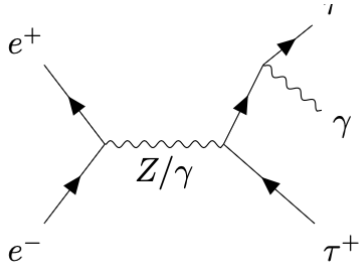






3.- $e^+e^- \to \tau^+\tau^- + \gamma$





Entanglement observables

From slide 10:

D & D_n MARKERS

$$D_n = -\tfrac{1}{3}\left(C_{nn} - C_{rr} - C_{kk}\right)$$ **Triplet density**

$$D = -\tfrac{1}{3}\left(C_{nn} + C_{rr} + C_{kk}\right)$$ **Singlet density**

Entanglement criteria

$$D < -1/3 \text{ or } D_n < -1/3$$

A) Concurrence C[ρ] $C(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$ λ_i increasing eigenvalues of $\sqrt{\sqrt{\rho}(\sigma_y \otimes \sigma_y)\rho^\star(\sigma_y \otimes \sigma_y)\sqrt{\rho}}$

- Quantitative measurement of the strength of entanglement.

minimum → $0 \leq \mathcal{C}(\rho) \leq 1$ → maximum

B) Purity η(⟨ρ⟩) $\gamma(\rho) \equiv \mathrm{Tr}\left[\langle\rho\rangle^2\right] \rightarrow \mu \equiv \frac{d}{d-1}\left(\gamma(\rho) - \frac{1}{d}\right) \underset{d=4}{=} \frac{4}{3}\left(\gamma(\rho) - \frac{1}{4}\right)$

- Quantitative measure of the pureness of the subsystem.

C) Quantum Discord $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{n}}\left[p_{\hat{n}} S(\rho_{\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}})\right]$ $S(\rho) \equiv -\mathrm{Tr}\left[\langle\rho\rangle \log(\langle\rho\rangle)\right]$

- Quantitative measure of the *non-classical mutual information* between subsystem A and B.

$$\rho_{\hat{n}} = \frac{\mathbb{1} + B^+_{\hat{n}} \cdot \vec{\sigma}}{2}, \quad B^+_{\hat{n}} = \frac{B^+ + C \cdot \hat{n}}{1 + \hat{n} \cdot B^-}, \quad p_{\hat{n}} = \frac{1 + \hat{n} \cdot B^-}{2}.$$

QUANTUM DECOHERENCE PROSPECTS AT COLLIDERS

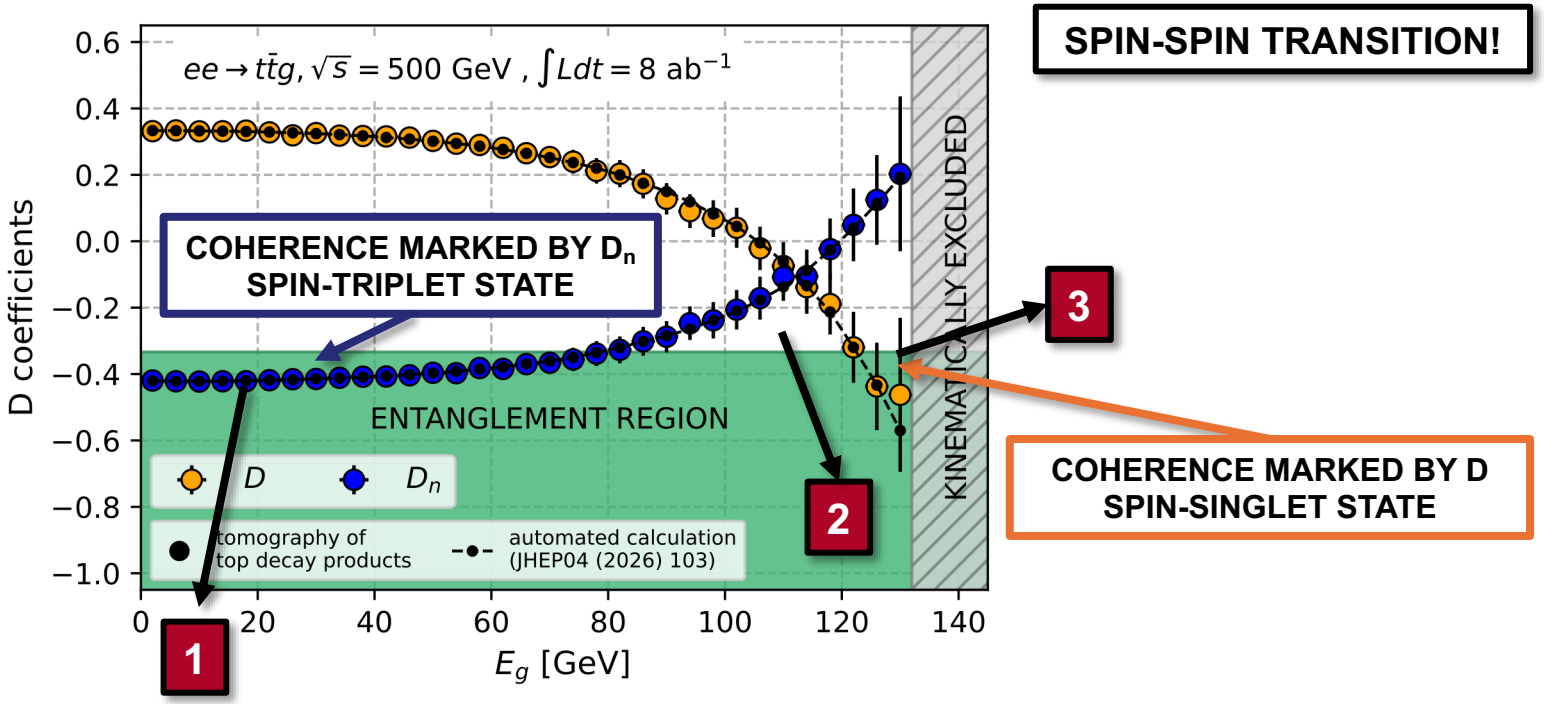
$e^+e^- \rightarrow t\bar{t}+g$: hard gluon emission decoherence

1. D markers : Evolution of D and D_n markers as a function the energy E_g of the radiated gluon.

$$D_n = -\tfrac{1}{3}\left(C_{nn} - C_{rr} - C_{kk}\right)$$

$$D = -\tfrac{1}{3}\left(C_{nn} + C_{rr} + C_{kk}\right)$$

$$D < -1/3 \text{ or } D_n < -1/3$$



1 Soft energy limit → D_n initially below -1/3:

- The top quarks are produced in a spin-triplet state.

2 E_g 80-120 GeV → All D_i marker above -1/3:

- The system is separable → No entanglement.

3 Hard energy limit → D cross -1/3 threshold:

- The top quarks are produced in a spin-singlet state

$e^+e^- \rightarrow t\bar{t}+g$: effects of hard gluon emission

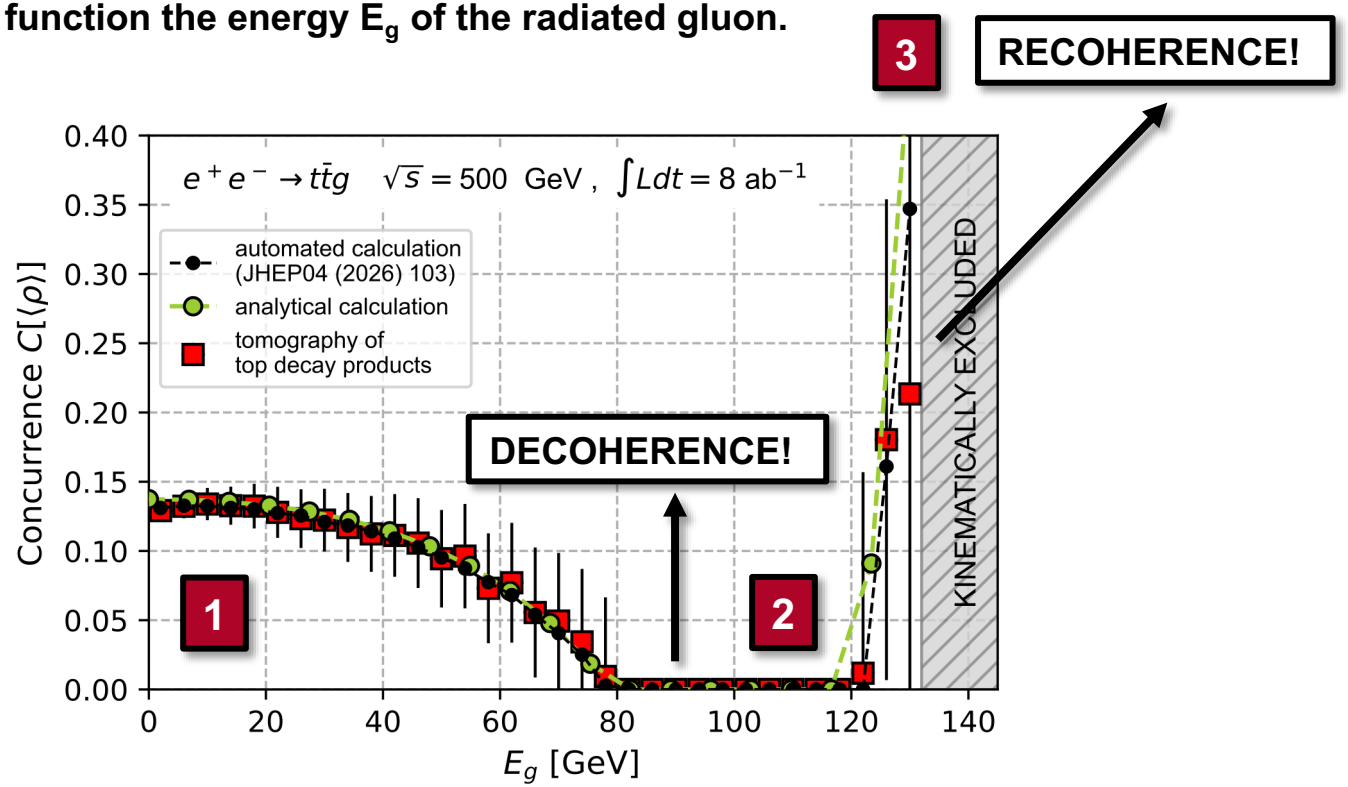
2. Concurrence C[ρ]: Evolution of C[ρ] as a function the energy E_g of the radiated gluon.

$$C(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$$

λ_i eigenvalues of $\sqrt{\sqrt{\rho}(\sigma_y \otimes \sigma_y)\rho^\star(\sigma_y \otimes \sigma_y)\sqrt{\rho}}$

$$0 \leq \mathcal{C}(\rho) \leq 1$$

separability



1 Soft energy limit → Entanglement is present:

- C[ρ] ($E_g \rightarrow 0$) ~ 0.13.

2 E_g 80-120 GeV → Total separability (C[ρ] = 0):

- C[ρ] drops abruptly with energetic radiation.

3 Hard energy limit → Strong entanglement:

- Concurrence increases at the kinematic endpoint (E_g ~ 130 GeV)
- **TOPONIUM? Work in progress**

$e^+e^- \to t\bar{t}+g$: effects of hard gluon emission

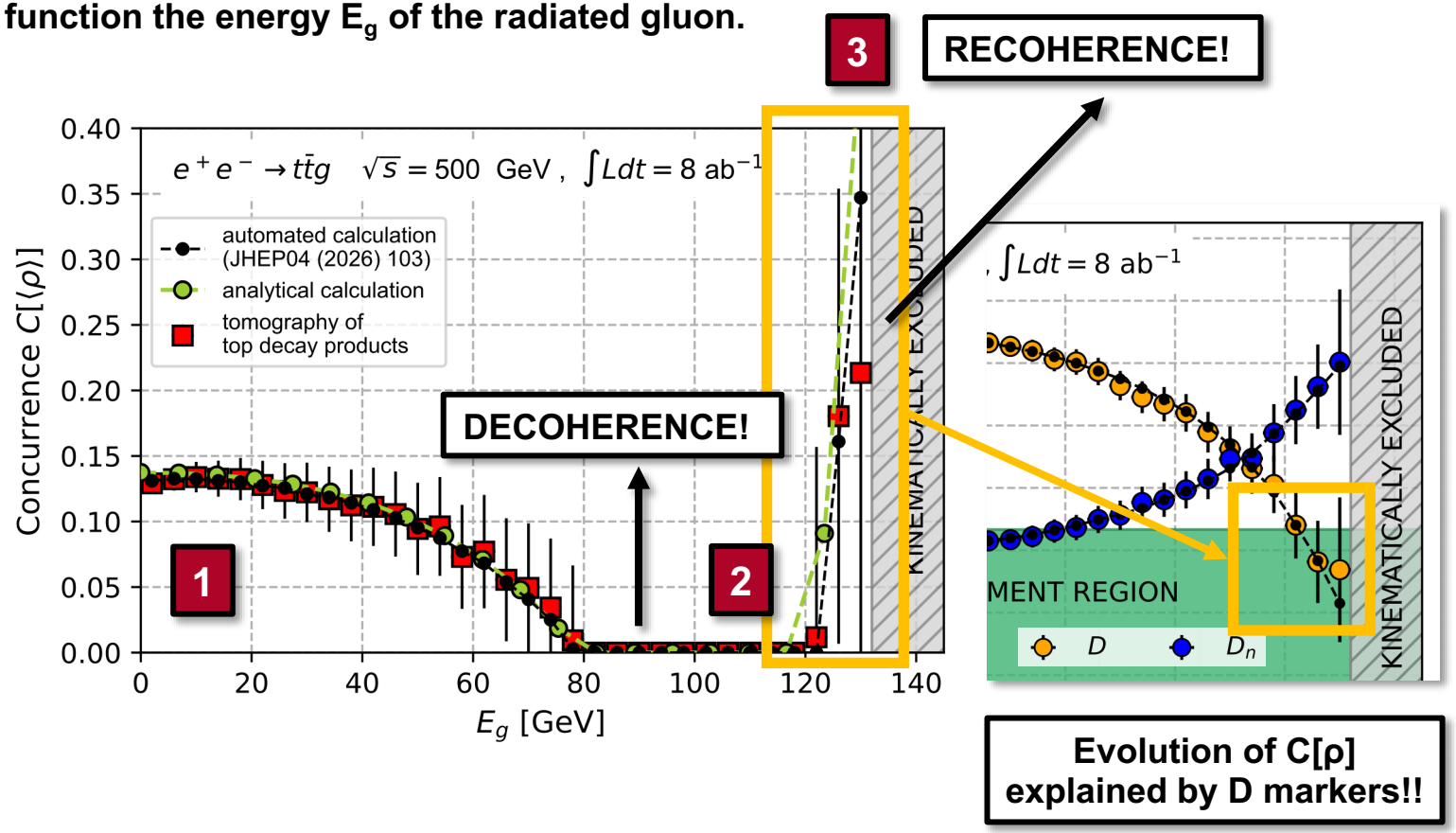
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separability

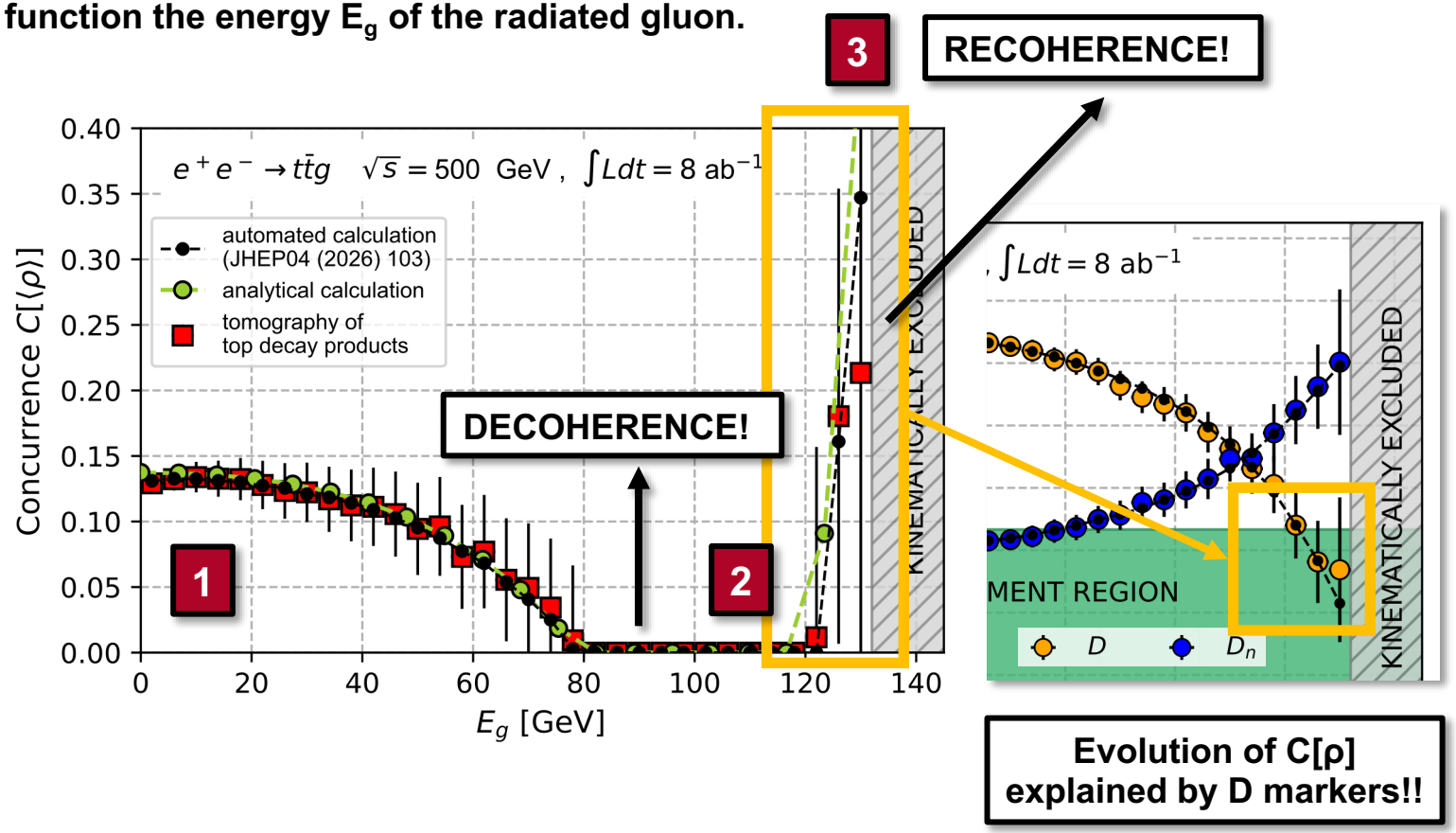
Use C[ρ] to measure decoherence!!

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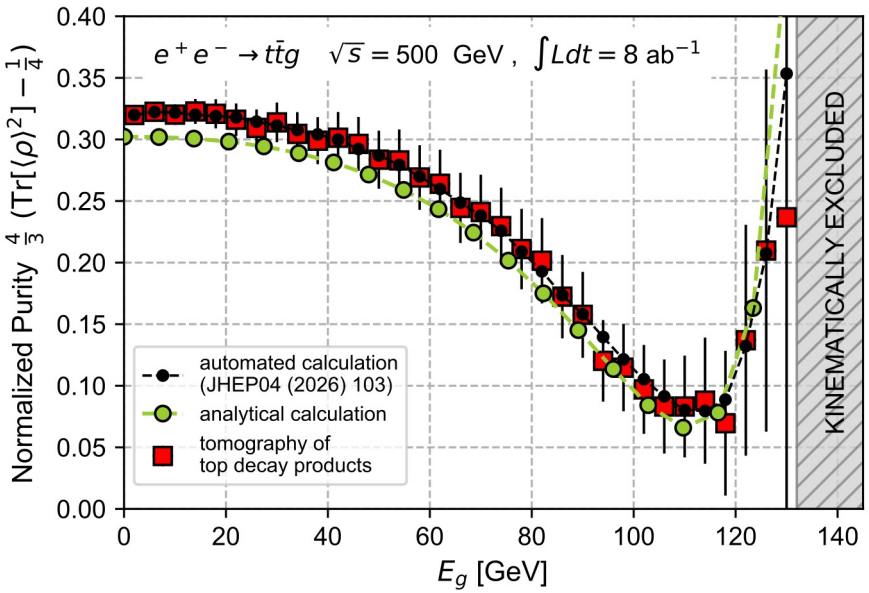
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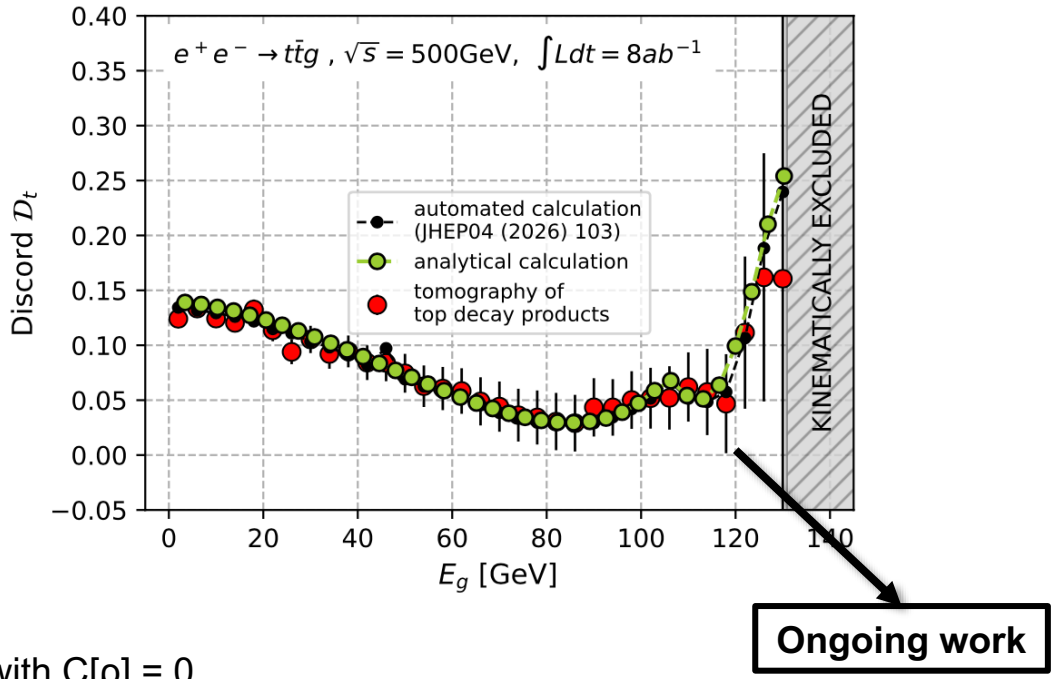
$e^+e^- \to t\bar{t}+g$ entanglement: effects of hard gluon emission

3. Purity and Discord: Further characterization of the sample

Normalized Purity



Quantum discord



- Maximum mixture (minimum purity) corresponding with C[ρ] = 0.
- Purity re-increases close to the kinematic end-point → Recover pureness.
- Similar trend seen for quantum discord.
  - Shape of the discord distribution → Still ongoing work.

pp → $t\bar{t}j$ for *LHC Run 2*: decoherence prospects

1. "Taming" the LHC effects:

1. Select boosted of threshold regions.
2. Initial state involve gluons and/or quarks.
3. There exist ISR jets.

- **The fiducial region:**

  Boosted and central $t\bar{t}$ pair production

$$m_{t\bar{t}} > 800 \text{ GeV} \qquad \left|\cos\Theta_t^{t\bar{t}RF}\right| < 0.4$$

BIAS FOR qq → $t\bar{t}j$ TOPOLOGY

RESULTS COMPARABLE WITH e^+e^- → $t\bar{t}$+g

$pp \to t\bar{t}j$ for *LHC Run 2*: decoherence prospects

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  Boosted and central $t\bar{t}$ pair production

$$m_{t\bar{t}} > 800 \text{ GeV} \qquad \left|\cos\Theta_t^{t\bar{t}RF}\right| < 0.4$$

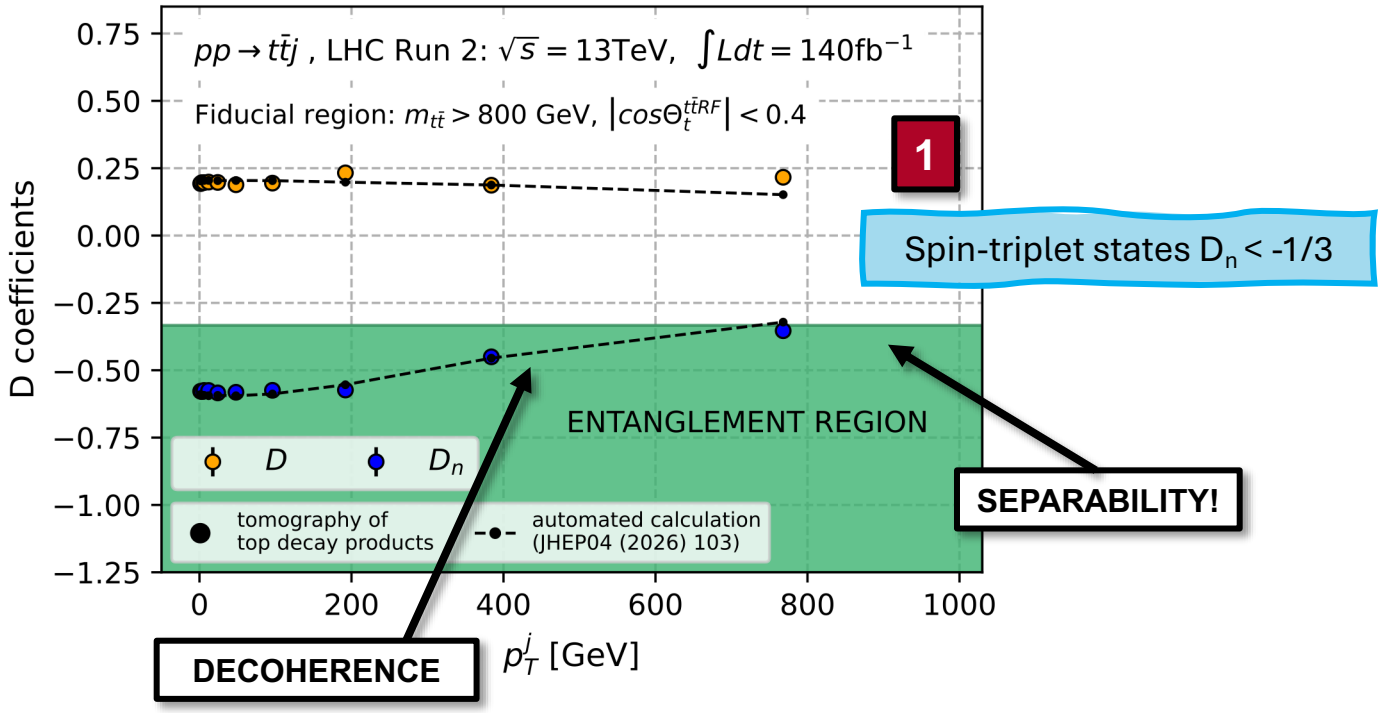
BIAS THE $qq \to t\bar{t}j$ TOPOLOGY

RESULTS COMPARABLE WITH $e^+e^- \to t\bar{t}+g$

2. D markers : Evolution of D and Dn with p_T^j of the adittional jet:

1 Evident decrease of D_n with p_T^j:

- Notable change in D_n beyond 250 GeV.
- Separability ($D_n > -1/3$) is reached around 500 GeV.



pp → tt̄j for *LHC Run 2*: decoherence prospects

1. Leading with LHC effects:

1. Select boosted of threshold regions.
2. Initial state involve gluons and/or quarks.
3. There exist ISR jets.

- **The fiducial region:**

  Boosted and central tt̄ pair production

$$m_{t\bar{t}} > 800\ \text{GeV} \qquad \left|\cos\Theta_t^{t\bar{t}RF}\right| < 0.4$$

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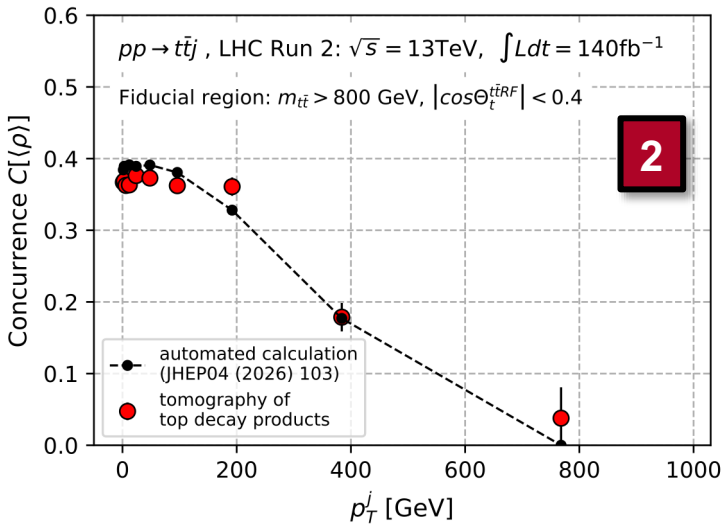
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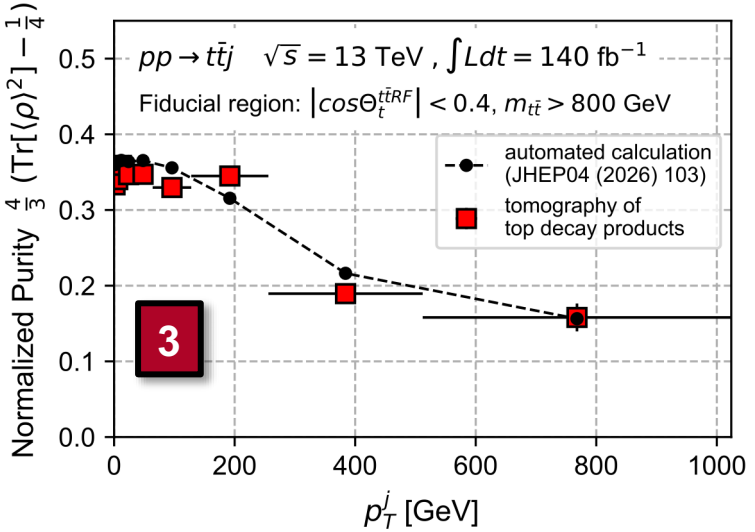
2 Clear decrease of the concurrence with p_T^j.

3 The mixture of the sample increases with p_T^j.

Concurrence C[ρ]



Normalized Purity



Observation of decoherence from $t\bar{t}$ production

A) Feasibility study:

- **Control sample** → Reference entanglement $C_{f\bar{f}}$ → from **inclusively** sample.
- **Radiation sample** → Decoherence entanglement $C_{f\bar{f}g/\gamma}$ → apply **exclusive** cut **minimum** p_T^j.

Statistical significance

$$R = \frac{C_{f\bar{f}g/\gamma}}{C_{f\bar{f}}} \qquad S = \left| \frac{1-R}{\sigma_R} \right|$$

$$\sigma_R = R\sqrt{\left(\frac{\sigma_{Cff}}{C_{ff}}\right)^2 + \left(\frac{\sigma_{Cffg/\gamma}}{C_{ffg/\gamma}}\right)^2}$$

B) Statistical significance results:

	C_{ff}	# *ttj* events in dilepton fs	$C_{ffg/\gamma}$	$R = C_{ff}/C_{ffg/\gamma}$	$S = \lvert 1 - R/\sigma_R \rvert$
e^+e^- 500 GeV	0.133 ± 0.005	$6.87 \cdot 10^3$ $p_T^g > 30$ GeV	0.041 ± 0.031 $p_T^g > 30$ GeV	0.31 ± 0.23	3 σ [8 σ all channels]
LHC Run 2 Fiducial region	0.405 ± 0.015	$2.81 \cdot 10^3$ $p_T^j > 250$ G	0.118 ± 0.049 $p_T^j > 250$ GeV	0.29 ± 0.12	6 σ [16 σ all channels]

Machine: i.e. LCF at CERN, $\mathcal{L}$ = 8000 fb^{-1}

RECORDED DATA ($\mathcal{L}$ = 140 fb^{-1})

- All uncertainties are for the dileptonic final state → Comparable statistics for *pp* and e^+e^-.
- Statistical siginificances for $\mathbf{e^+e^-}$ → **ttj** production:
  - Dilepton → suficient for evidence.
  - Hadronic polarimetry → enable observation.
- Potential for evidence/observation of decoherence at the LHC! → To be proven considering detector and systematic effects

$e^+e^- \to \tau^+\tau^-\gamma$ entanglement: effects of hard photon emission

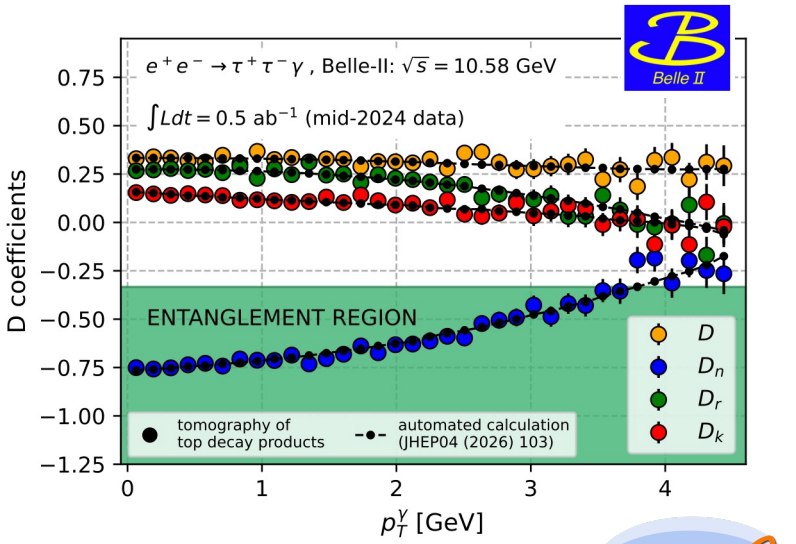
1. Leading with ISR:

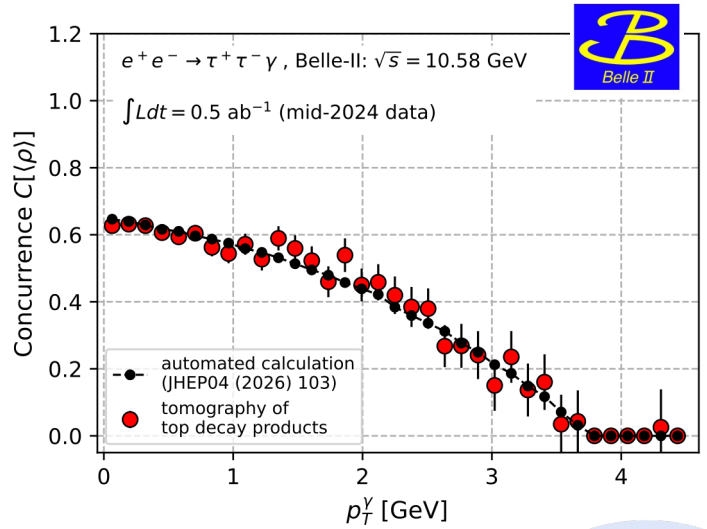
- **The fiducial region:** Only considering central $\tau^+\tau^-$ pair production $\left|cos(\Theta_{\tau}^{\tau^+\tau^- RF})\right| < 0.4$

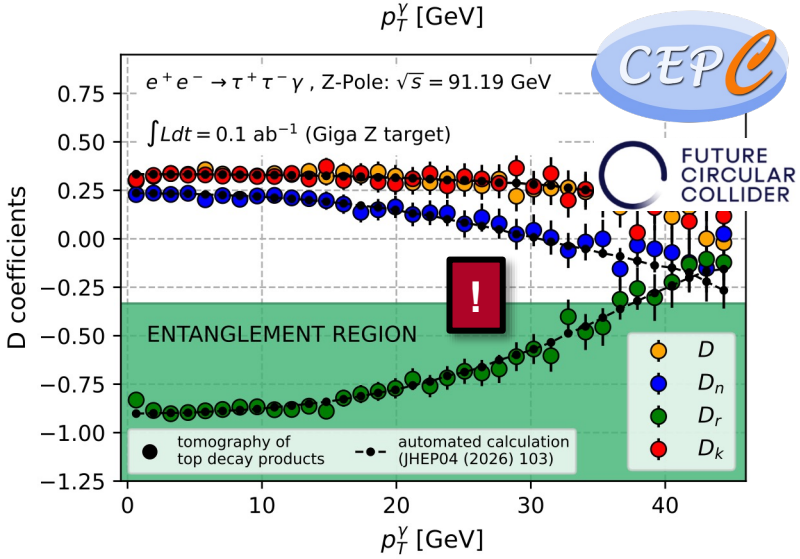
2. D markers and Concurrence

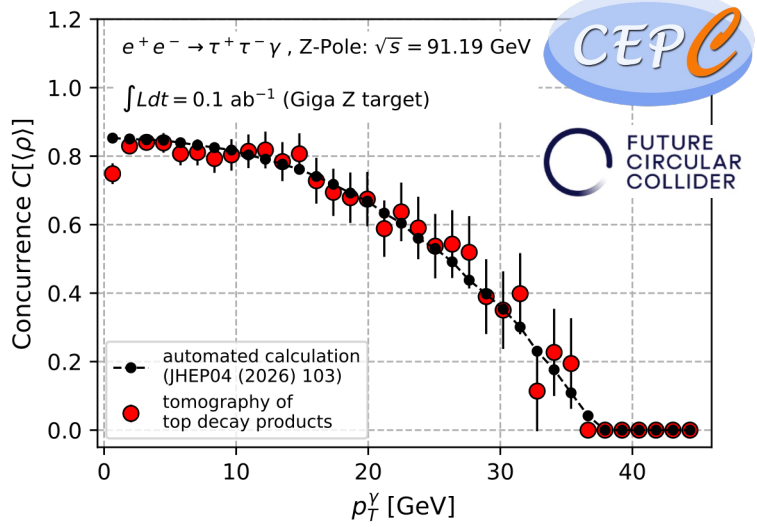
- Evident decrease of D_n with p_T^j:
  - Notable change in D_n beyond 3 GeV for Belle II.
  - Notable change in D_r beyond 30 GeV for FCC-ee Z-pole operation.
  - Total separability ($D_{n/r}$ > -1/3) is reached around 4 GeV or 40 GeV.
- Purity and discord also decrease with p_T^j.

! In Z-pole → D_r ?! → Process mediated by massive vector boson → On-going work.









$e^+e^- \to \tau^+\tau^-\gamma$ entanglement: effects of hard photon emission

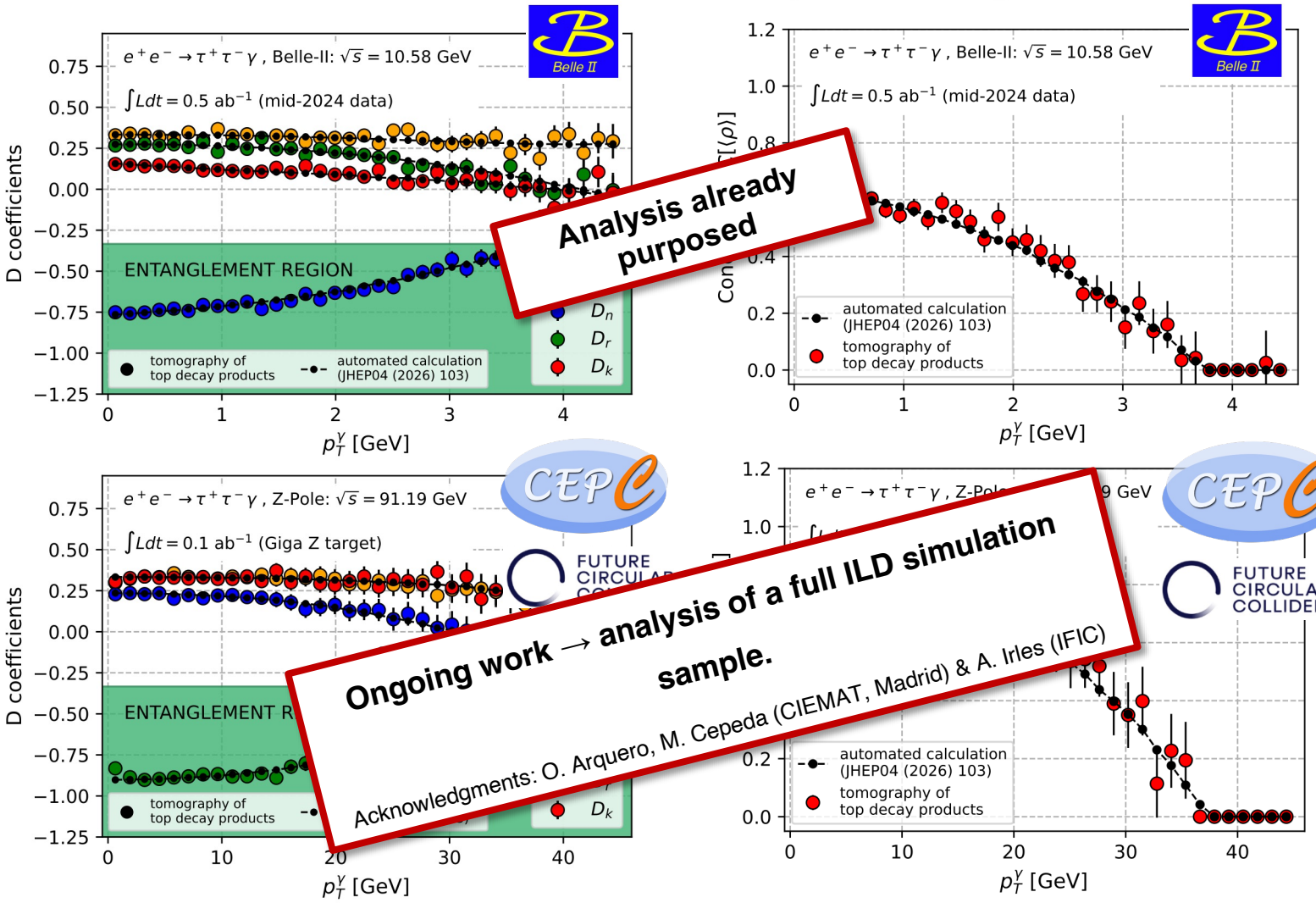
1. Leading with ISR:

- **The fiducial region:** Only considering central $\tau^+\tau^-$ pair production $\left|cos(\Theta_\tau^{\tau^+\tau^- RF})\right| < 0.4$

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- Evident decrease of D_n with p_T^j:
  - Notable change in D_n beyond 3 GeV for Belle II.
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! In Z-pole → D_r ?! → Process mediated by massive vector boson → On-going work.



Observation of decoherence from $\tau^+\tau^-$ production

A) Feasibility study:

- **Control sample** → Reference entanglement $C_{\tau^+\tau^-}$ → from **inclusively** sample.
- **Radiation sample** → Decoherence entanglement $C_{\tau^+\tau^-\gamma}$ → apply **exclusive** cut **minimum** p_T^{γ}.

Statistical significance

$$R = \frac{C_{\tau^+\tau^-}}{C_{\tau^+\tau^-\gamma}} \qquad S = \left| \frac{1 - R}{\sigma_R} \right|$$

$$\sigma_R = R \sqrt{\left(\frac{\sigma_{C_{\tau^+\tau^-}}}{C_{\tau^+\tau^-}}\right)^2 + \left(\frac{\sigma_{C_{\tau^+\tau^-\gamma}}}{C_{\tau^+\tau^-\gamma}}\right)^2}$$

B) Statistical significance results:

	$C_{\tau^+\tau^-}$	# $\tau^+\tau^-\gamma$ events in dilepton fs	$C_{\tau^+\tau^-\gamma}$	$R = C_{\tau^+\tau^-}/C_{\tau^+\tau^-\gamma}$	$S = \left\| 1 - R/\sigma_R \right\|$
Belle II (mid-2024) Fiducial regions	0.727 ± 0.002	$2.13 \cdot 10^4$	0.235 ± 0.017 $p_T^{\gamma} > 2$ GeV	0.323 ± 0.024	28 σ [280 σ target lumi]
e+e- Giga-Z Fiducial region	0.858 ± 0.003	$2.85 \cdot 10^3$	0.102 ± 0.047 $p_T^{\gamma} > 30$ GeV	0.119 ± 0.054	16 σ [860 σ Tera-Z]

RECORDED DATA UP TO MID-2024 ($\mathcal{L}$ = 0.5 ab^{-1})

TARGET DATA ($\mathcal{L}$ = 50 ab^{-1})

TARGET DATA ($\mathcal{L}$ = 0.1 & 500 ab^{-1})

- All uncertainties are for the single-prong final state.
- Statistical siginificances for $\tau^+\tau^-\gamma$ production → Cleanest measurement of FSR decoherence in a single decay measurement.
- Potential for studying quantum observables and decoherence differentiably.

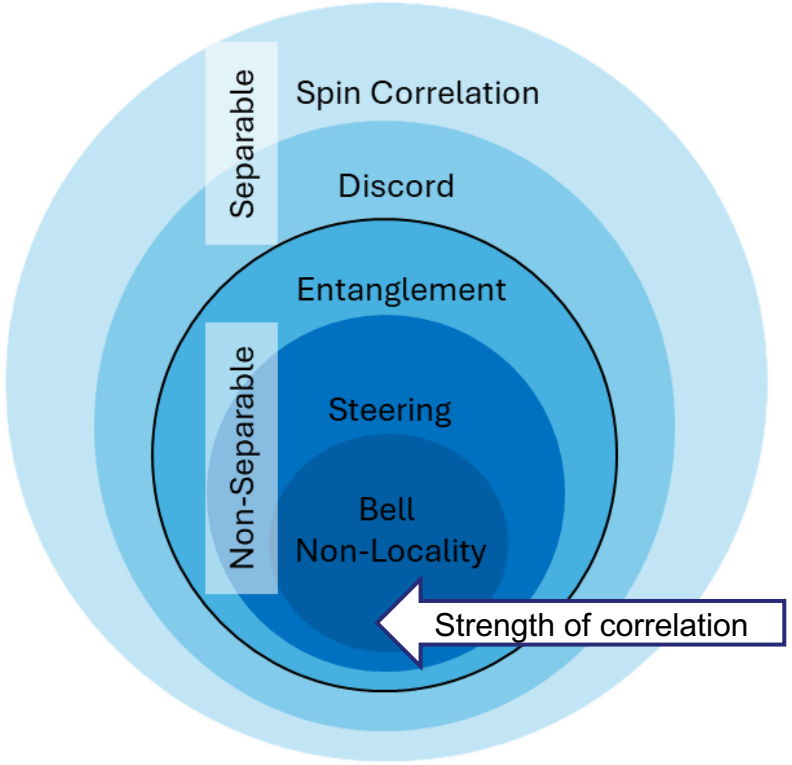
Conclusions

- The present study show the **observation of quantum decoherence** spin-entangled fermion pairs due to radiation emission effects, at current and future colliders.
- At the LHC → The observation of decoherence is already feasible.
  - The current boosted $t\bar{t}$ lepton+jets analysis at **ATLAS** is expected to provided with the **first evidence of quantum decoherence**.
- The outlook is very promising for $\tau^+\tau^-$ production:
  - **Current** data sets of Belle II enable observation.
  - Belle II and FCC-ee targets will allow a **precision differential measurement** of decoherence.
- Ongoing studies:
  - Realistic projection from full simulation and detector and systemac effects.
  - Tripartite entanglement.

Backup Slides

Quantum entanglement: experimental tests

"The quantum state of a particle cannot be described independently of the state of the other"



disclaimer!

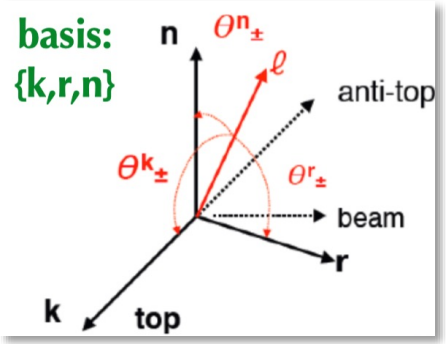
- Strick hierarchy for quantum correlations.
- HEP recorded events → quantum entanglement
- These correlations → weaker than non-locality tests.

Top spin measurements

C) Differential cross-section $t\bar{t}$ decay products

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}_1' \cdot \hat{\ell}_+ + \mathbf{B}_2' \cdot \hat{\ell}_- - \hat{\ell}_+ \cdot C' \cdot \hat{\ell}_-\right)$$

15 parameters: 3 vector + 3 vector + 3x3 matrix



D) Probing *B* and *C* individually

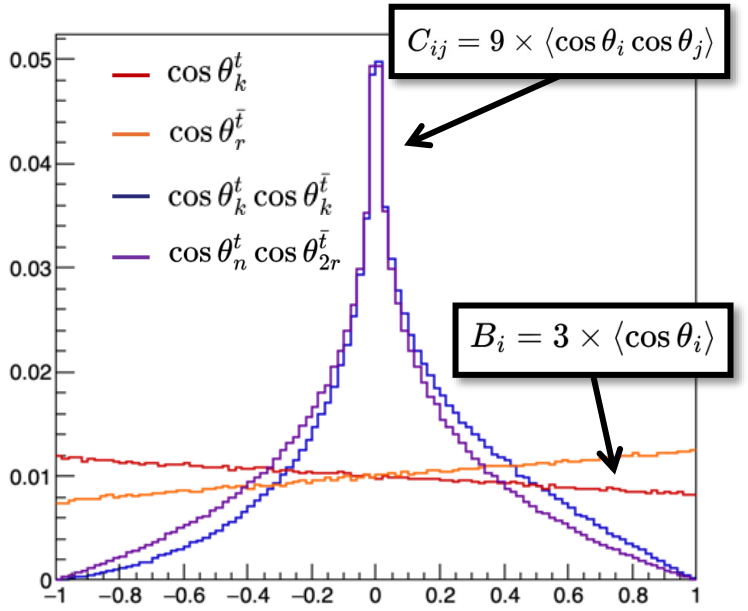
Top polarizations B:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1 + B_i \cos\theta_i}{2} \quad \rightarrow \quad B_i = 3 \times \langle \cos\theta_i \rangle$$

Top spin correlations C:

$$\frac{1}{\sigma}\frac{d\sigma}{dx_{ij}} = \frac{1 - C_{ij}x_{ij}}{2}\ln x_{ij} \quad \rightarrow \quad C_{ij} = 9 \times \langle \cos\theta_i \cos\theta_j \rangle$$

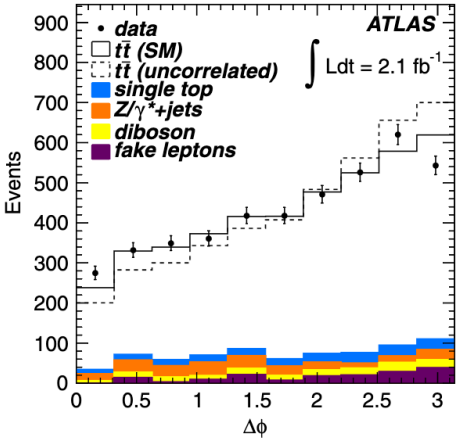
where $x_{ij} = \cos\theta_i^t \cos\theta_j^{\bar{t}}$



Spin correlations searches at the LHC

A) First measurement of top quark polarization and spin correlation

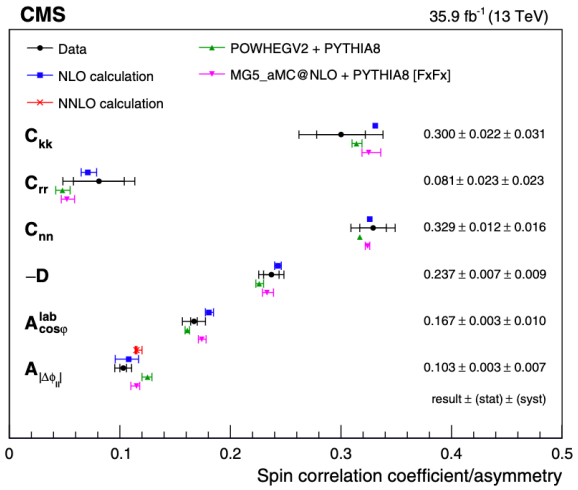
- Run 1 – 2011 data; $\mathcal{L}$ = 2.1 fb^{-1} (CMS)
- Using the dileptonic decay channel.
- Calculation of asymmetry of distributions:
  - $\Delta\phi_{l^+l^-}$ in the lab frame.



ATLAS Collaboration PRL 108, 212001 (2012)

B) Measurement of all spin density matrix coefficients

- Run 2 – 2016 data; $\mathcal{L}$ = 35.9 fb^{-1}
- Using the dileptonic decay channel.
- Calculation of all 15 $B_{1,2}$ and C coefficients in the helicity frame, using quantum tomography.
- Calculation of assymetry of distributions $\Delta\phi_{l^+l^-}$ and $\cos\Phi_{l^+l^-}$ in the lab frame.

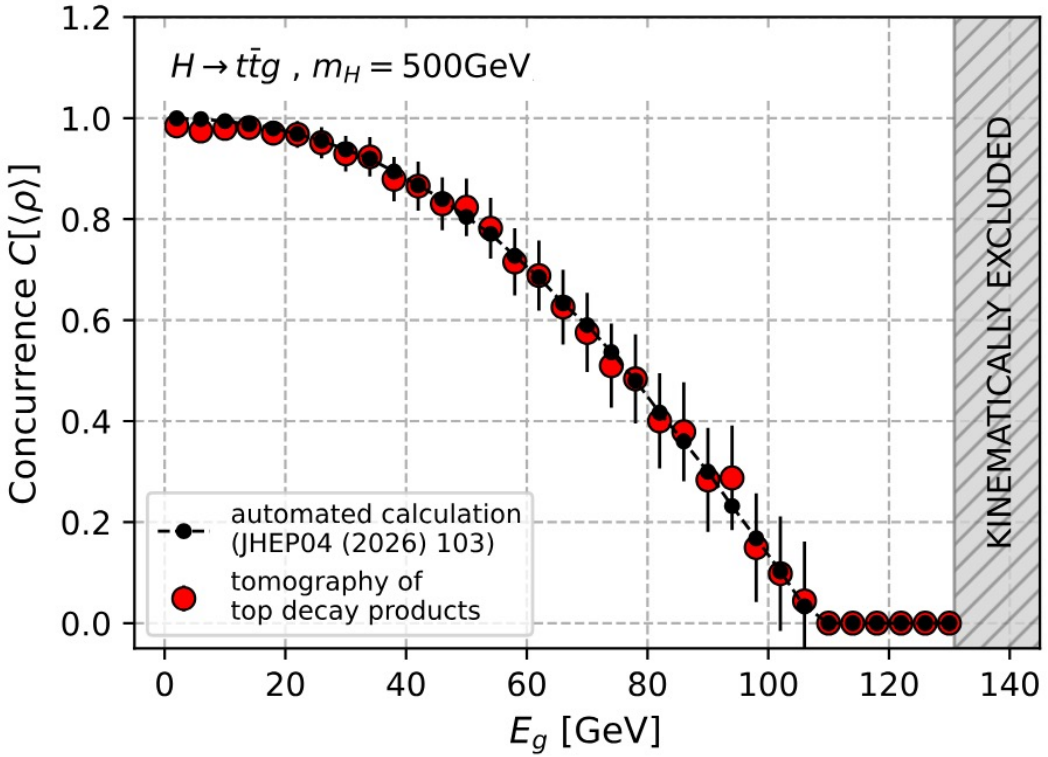


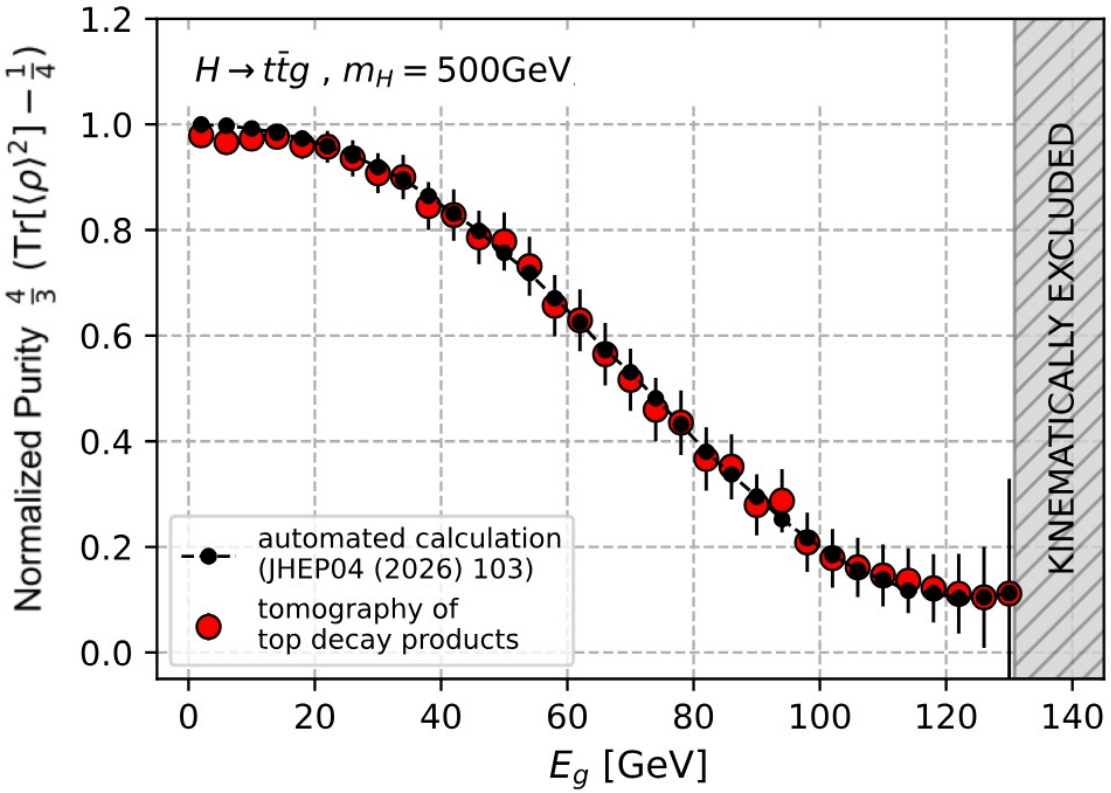
CMS Collaboration, PRD 100, 072002 (2019)

Effects of radiation emission in pure fermion-pair production

Fermion pair production from heavy scalar decay:

$S \rightarrow t\bar{t}$ + g (m_S = 500 GeV) → Concurrence and Norm. Purity:





$e^+e^- \rightarrow t\bar{t}+g$ emission decoherence at production threshold

$\sqrt{s}$ = 365 GeV

