Experimental Prospects for Decoherence of Fermion Qubit Pairs from Radiation at Colliders

XL RSEF Physics Biennial

ETSI, University of Seville, Spain – July 20th-24th, 2026

Speaker: Guillermo Garcia-Mir

In collaboration with Jose Manuel Camacho, Marcel Vos, María Moreno Llácer (IFIC, CSIC-UV)

Many thanks to Rafael Aoude (Hamburg-DESY), Fabio Maltoni (Bologna/Louvain/CERN), Leonardo Satrioni, Valentin Durupt (Louvain)

Based on the paper arXiv:2604.16268.

Quantum entanglement

Is quantum mechanics complete with a probabilistic interpretation?

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

Quantum entanglement

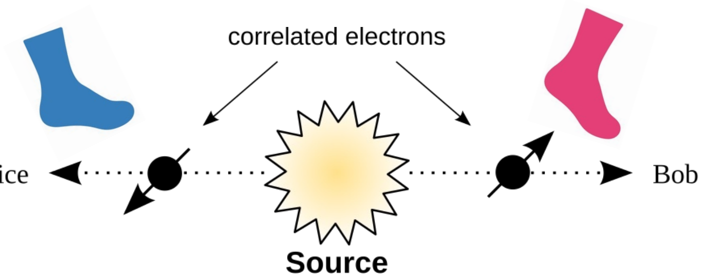
Is quantum mechanics complete with a probabilistic interpretation?

Niels Bohr, Werner Heisenberg, Albert Einstein

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

TWO-QUIBIT SYSTEM: Separable density matrix: $\rho = \sum_{ij} p_{ij} \rho_i^{(A)} \otimes \rho_j^{(B)}$

THE EPR THOUGHT EXPERIMENT:



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Singlet (S = 1) → Maximally entangled state ⇨ Alice and Bob observations are correlated

Quantum entanglement

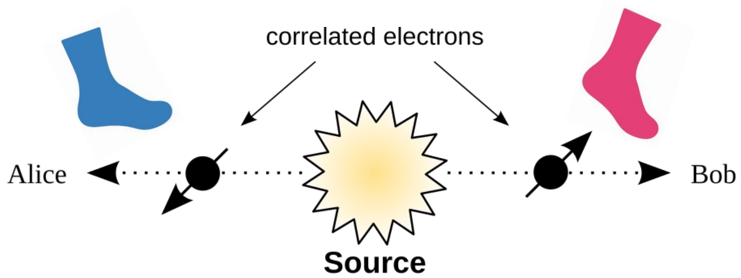
Is quantum mechanics complete with a probabilistic interpretation?

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

Niels Bohr, Werner Heisenberg, Albert Einstein

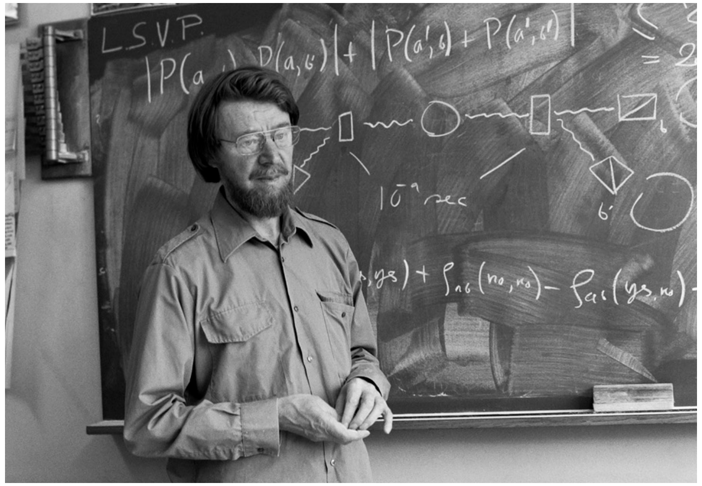
TWO-QUIBIT SYSTEM: Separable density matrix: $\rho = \sum_{ij} p_{ij} \rho_i^{(A)} \otimes \rho_j^{(B)}$

THE EPR THOUGHT EXPERIMENT:



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Singlet (S = 1) → Maximally entangled state ⇒ Alice and Bob observations are correlated



Jonh S. Bell at CERN, 1982

BELL TESTS: Classical maximum / Quantum maximum

CHSH inequality: $2 \leq |E(A_1, B_1) + E(A_1, B_2) + E(A_2, B_1) - E(A_2, B_2)| \leq 2\sqrt{2}$

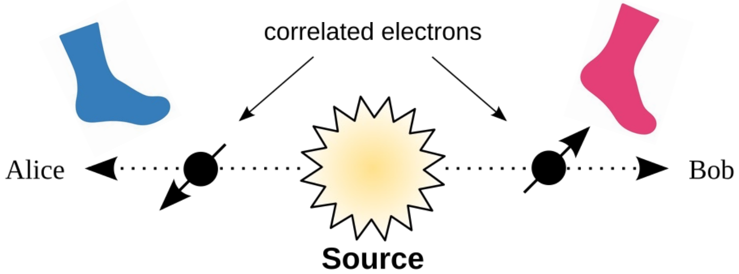
Quantum entanglement

Is quantum mechanics complete with a probabilistic interpretation?

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

TWO-QUIBIT SYSTEM: Separable density matrix: $\rho = \sum_{ij} p_{ij} \rho_i^{(A)} \otimes \rho_j^{(B)}$

THE EPR THOUGHT EXPERIMENT:



$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

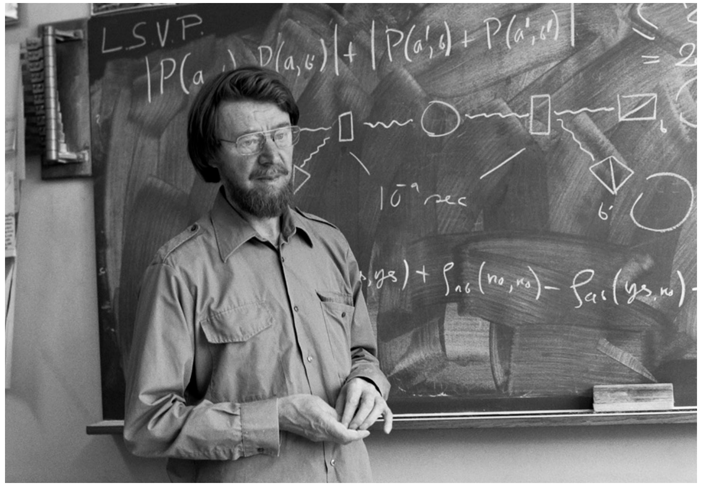
Singlet (S = 1) → Maximally entangled state ⇨ Alice and Bob observations are correlated

BELL TESTS: Classical maximum / Quantum maximum

CHSH inequality: $2 \leq \; |E(A_1, B_1) + E(A_1, B_2) + E(A_2, B_1) - E(A_2, B_2)| \; \leq 2\sqrt{2}$

Aspect’s experiment: First test of Bell’s inequaties → photons with distant detectors

Niels Bohr, Werner Heisenberg, Albert Einstein



Jonh S. Bell at CERN, 1982

Aspect, Clauser, Zeilinger, 2022 Nobel Prize

Quantum state tomography

How do we "*observe*" quantum mechanical systems in High Energy Physics?

1 ⟶ General two-qubit (spin ½) density matrix ρ:

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

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

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

References: W. Bernreuther et. al. (2015)

Quantum state tomography

How do we "*observe*" quantum mechanical systems in High Energy Physics?

1 ⟶ General two-qubit (spin ½) density matrix ρ:

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

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

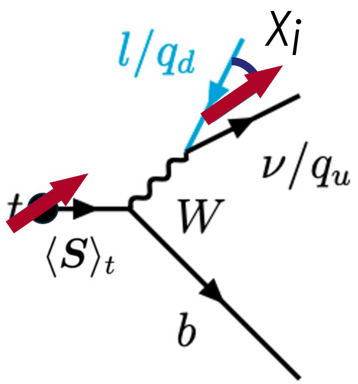
SPIN CORRELATION MATRIX $C_{ij} = \langle S_i S_j \rangle$

2 ⟶ Angular distribution for the decay width of the heavy fermions:

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

χ_i *: angle between i-th particle momentum and parent spin vector*

α : spin analysing power



- Daughter particle's momenta **correlated with the spin direction** of mother fermion.

- Strength of the correlation depends on the particle

α = 1

In $t\bar{t} \rightarrow$ (e/μ) or (d/s) quarks

In $\tau^+\tau^- \rightarrow \pi^\pm$.

References: W. Bernreuther et. al. (2015)

Quantum state tomography

How do we "*observe*" quantum mechanical systems in High Energy Physics?

1 ⟶ General two-qubit (spin ½) density matrix ρ:

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

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

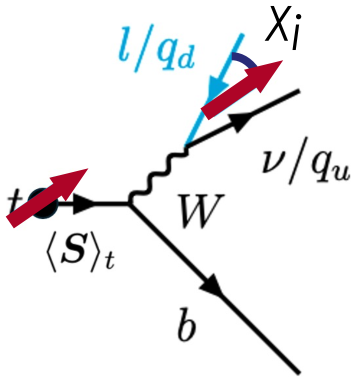
SPIN CORRELATION MATRIX $C_{ij} = \langle S_i S_j \rangle$

2 ⟶ Angular distribution for the decay width of the heavy fermions:

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

χ_i *: angle between i-th particle momentum and parent spin vector*

α : spin analysing power



3 ⟶ Normalized differential cross-section distribution:

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

$$B_i^a = \langle S_i \rangle^a = 3\,\frac{1}{\alpha}\,\langle \cos\theta_i^a \rangle \qquad C_{ij} = \langle S_i S_j \rangle = -9\,\frac{1}{\alpha_1 \alpha_2}\,\langle \cos\theta_i^a \cos\theta_j^b \rangle$$

- Daughter particle's momenta **correlated with the spin direction** of mother fermion.
- Strength of the correlation depends on the particle

$\alpha = 1$ In $t\bar{t} \to (e/\mu)$ or (d/s) quarks

In $\tau^+\tau^- \to \pi^\pm$.

References: W. Bernreuther et. al. (2015)

Quantum state tomography

How do we "*observe*" quantum mechanical systems in High Energy Physics?

1 ⟶ General two-qubit (spin ½) density matrix ρ:

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

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

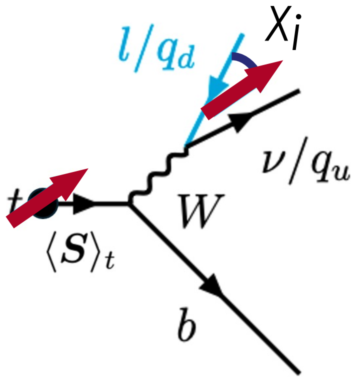
SPIN CORRELATION MATRIX $C_{ij} = \langle S_i S_j \rangle$

2 ⟶ Angular distribution for the decay width of the heavy fermions:

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

χ_i : angle between i-th particle momentum and parent spin vector

α : spin analysing power



3 ⟶ Normalized differential cross-section distribution:

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

$$B_i^a = \langle S_i \rangle^a = 3\,\frac{1}{\alpha}\,\langle \cos\theta_i^a \rangle \qquad C_{ij} = \langle S_i S_j \rangle = -9\,\frac{1}{\alpha_1 \alpha_2}\,\langle \cos\theta_i^a \cos\theta_j^b \rangle$$

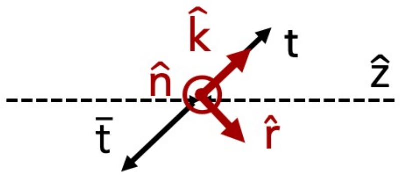
- Daughter particle's momenta **correlated with the spin direction** of mother fermion.
- Strength of the correlation depends on the particle

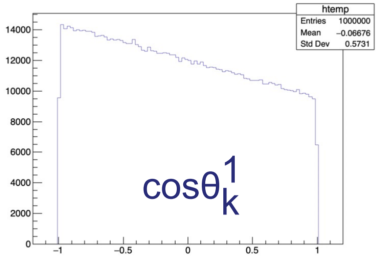
α = 1

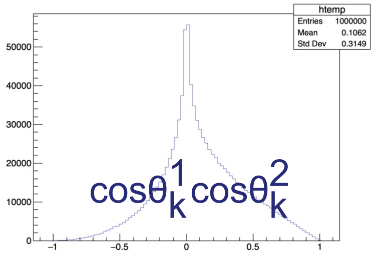
In $t\bar{t}$ ⟶ (e/μ) or (d/s) quarks

In $\tau^+\tau^-$ ⟶ $\pi^{\pm}$.

4 ⟶ The axis system chosen is the **helicity base:**



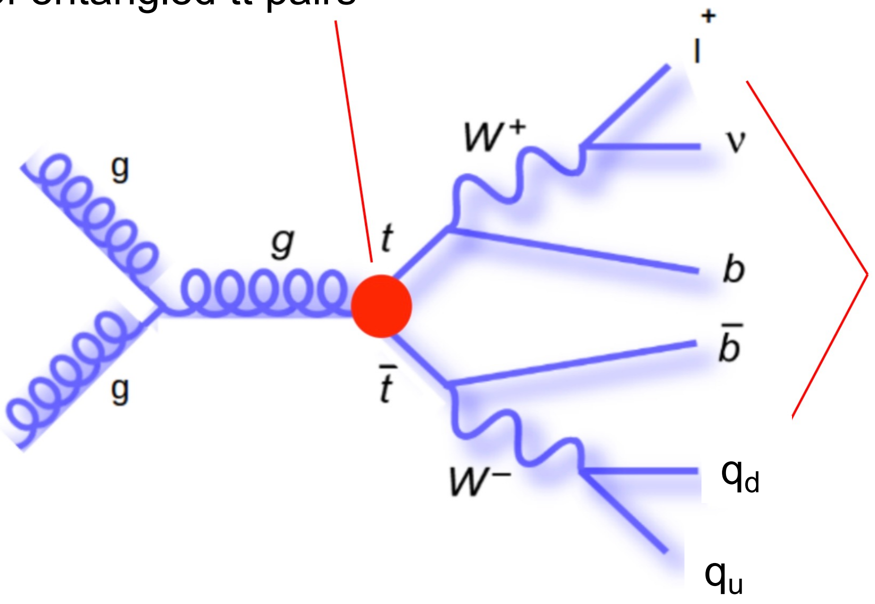




References: W. Bernreuther et. al. (2015)

The top quark as an instrument for QI tests at the LHC

Hard–scattering → Source of entangled $t\bar{t}$ pairs



Two-polarimeters from the top quark decay:

→ leptons or down-type quark

$\alpha = 1$

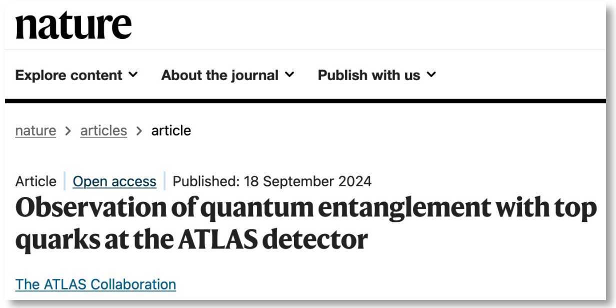
→ neutrinos or up-type quark

$\alpha = 0.4$

- ✦ Top quarks → Ideal measurment for quantum entanglement:
  - → Lifetime (~10^{-25} s) is shorter than:
    - → Spin decorrelation (~10^{-21} s)
    - → Hadronization (~10^{-24} s)

State of art of quantum entanglement observations at the LHC

- First **observation of quantum spin entanglement** in 2024 by ATLAS:
  - → $t\bar{t}$ pairs using a dilepton final state.
  - → Threshold region 340 GeV < m_{tt} < 380 GeV.



nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

nature > articles > article

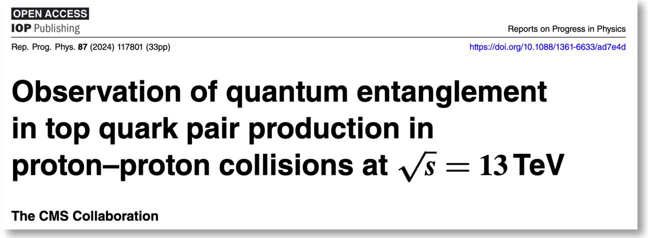
Article | Open access | Published: 18 September 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Nature volume 633, pages 542–547 (2024)

- First **observation of quantum spin entanglement** in 2024 by CMS:
  - → $t\bar{t}$ pairs using a dilepton final state.
  - → Threshold region 340 GeV < m_{tt} < 380 GeV.



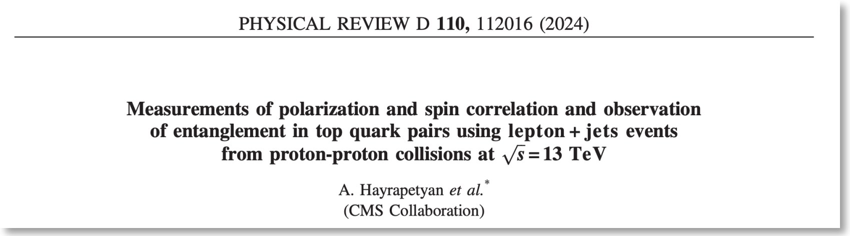
OPEN ACCESS
IOP Publishing — Reports on Progress in Physics
Rep. Prog. Phys. 87 (2024) 117801 (33pp) — https://doi.org/10.1088/1361-6633/ad7e4d

Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Rep. Prog. Phys. 87 117801

- Second **observation of quantum spin entanglement** in 2024 by CMS:
  - → $t\bar{t}$ pairs using a lepton+jets final state.
  - → Inclusive, in bins of m_{tt} and the top scattering angle.



PHYSICAL REVIEW D **110,** 112016 (2024)

Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton + jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.**
(CMS Collaboration)

Phys. Rev. D 110, 112016

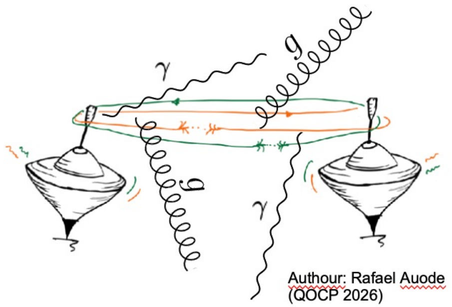
[1] https://doi.org/10.48550/arXiv.2504.07030

A step further: Quantum decoherence

How do the classical rules emerge from a fundamentally quantum world?

- ✦ **Fundamental puzzle** → What is a measurment → "*Measurement problem*"
  - ✦ Undestanting the wavefuntion collapse → connection between quantum and classical mechanical worlds
  - ✦ **Decoherence** → disturbance of "quantumness" from the interaction with enviroment → study the wavefuntion collapse by the progressive loss of entanglement.

A step further: Quantum decoherence



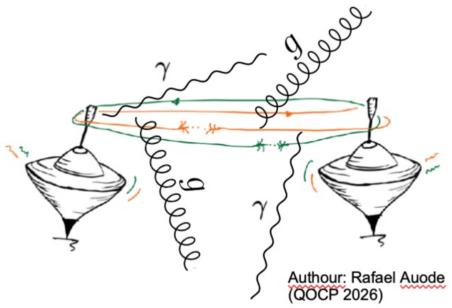
How do the classical rules emerge from a fundamentally quantum world?

- **Fundamental puzzle** → What is a measurment → "*Measurement problem*"
  - Undestanting the wavefuntion collapse → connection between quantum and classical mechanical worlds
  - **Decoherence** → disturbance of "quantumness" from the interaction with enviroment → study the wavefuntion collapse by the progressive loss of entanglement.
- **Proposal:** To model decoherence → introducing additional states (DOF) in our quantum systems.
  - Aoude et. al. (2025)[1] → Model environment interactions using **energetic radiation** —of gluons or photons—

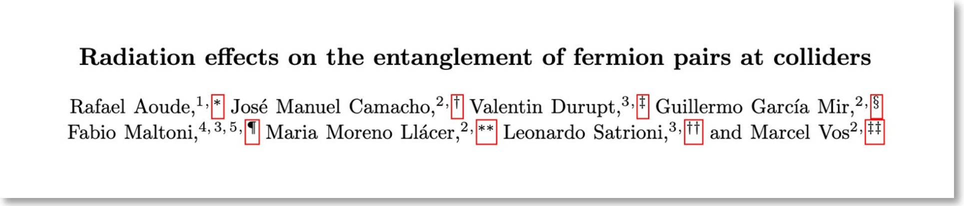
[1] https://doi.org/10.48550/arXiv.2504.07030

A step further: Quantum decoherence

How do the classical rules emerge from a fundamentally quantum world?



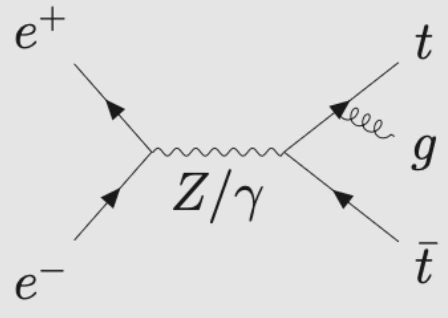
- **Fundamental puzzle** → What is a measurment → "*Measurement problem*"
  - Undestanting the wavefuntion collapse → connection between quantum and classical mechanical worlds
  - **Decoherence** → disturbance of "quantumness" from the interaction with enviroment → study the wavefuntion collapse by the progressive loss of entanglement.
- **Proposal:** To model decoherence → introducing additional states (DOF) in our quantum systems.
  - Aoude et. al. (2025)[1] → Model environment interactions using **energetic radiation** —of gluons or photons—
- **Experimantal study**: Prospects of the **effects of energetic final-state radiation (FSR)** in the **entanglement of heavy fermion pairs** in current and future colliders:
  - $t\bar{t}$ production at **LCF** and **LHC —Run 2 & HL-LHC—**
  - $\tau^+\tau^-$ production at **Belle II —recorded & target—** and **FCC-ee**.
  - Produce statistical significance for the experimental feasibility.


Radiation effects on the entanglement of fermion pairs 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,**] Leonardo Satrioni,[3,††] and Marcel Vos[2,‡‡]

[1] https://doi.org/10.48550/arXiv.2504.07030

Decoherence prospects for simulated $e^+e^- \rightarrow t\bar{t}+g$ events



Sample characteristics:

- ***Parton-level, leading order samples.***
- **Computation**: MadGraph5_aMC@NLO. J. Alwall et al., arXiv:1405.0301 [hep-ph]).
- **Decay mode:** $\mu^+\mu^-$ $(b\nu\bar{b}\bar{\nu})$

D & D_n MARKERS

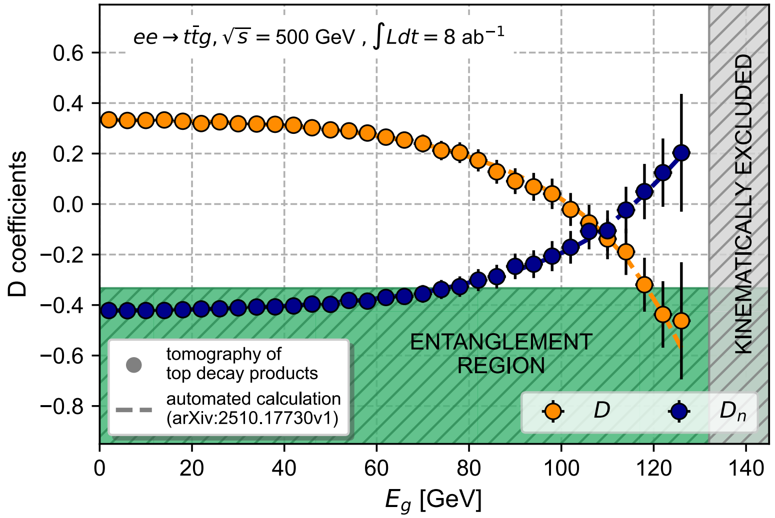
Provide with sufficient enough criteria for entanglement via linear expressions:

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

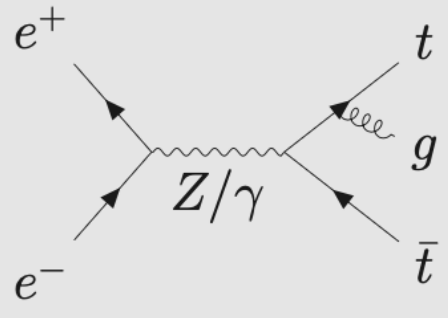
$$D_n = -\frac{1}{3}\left(C_{nn} - C_{rr} - C_{kk}\right)$$

ENTANGLEMENT:

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



Decoherence prospects for simulated $e^+e^- \to t\bar{t}+g$ events



Sample characteristics:

- ***Parton-level, leading order samples.***
- **Computation**: MadGraph5_aMC@NLO. J. Alwall et al., arXiv:1405.0301 [hep-ph]).
- **Decay mode:** $\mu^+\mu^-$ $(b\nu\bar{b}\bar{\nu})$

D & D_n MARKERS

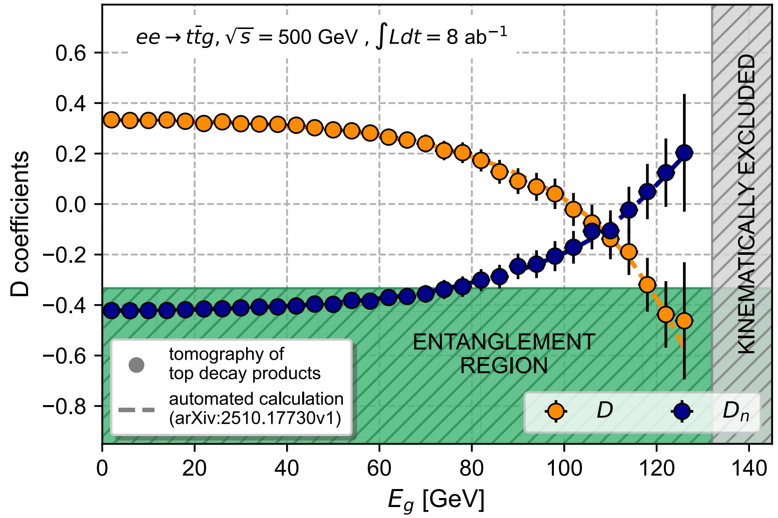
Provide with sufficient enough criteria for entanglement via linear expressions:

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

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

ENTANGLEMENT:

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



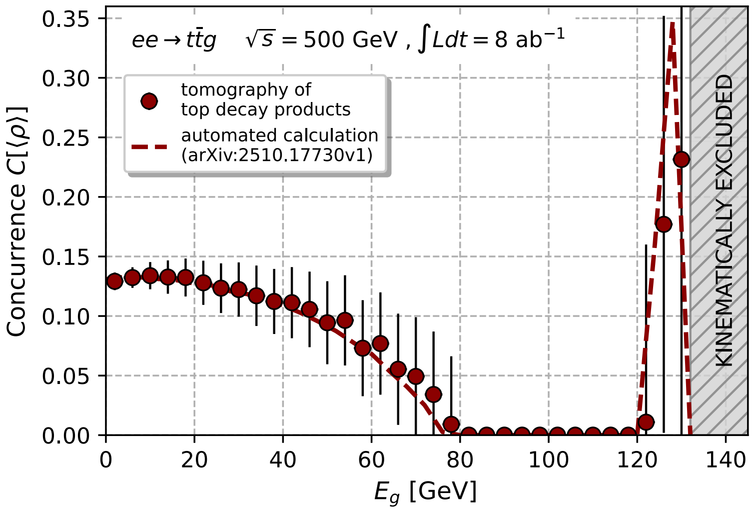
CONCURRENCE

Provides with a quantitative **non-linear** measurement of the degree of entanglement.

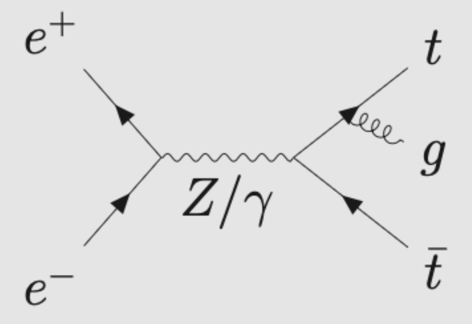
$$C\left[\langle\rho\rangle\right] = \max\left(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\right)$$

λ_i increasing eigenvalues of

$$R = \sqrt{\sqrt{\rho}\sigma_2 \otimes \sigma_2\rho^*\sigma_2 \otimes \sigma_2\sqrt{\rho}}$$



Decoherence prospects for simulated $e^+e^- \to t\bar{t}+g$ events



Sample characteristics:

- ***Parton-level, leading order samples.***
- **Computation**: MadGraph5_aMC@NLO. J. Alwall et al., arXiv:1405.0301 [hep-ph]).
- **Decay mode:** $\mu^+\mu^-$ $(b\nu\bar{b}\bar{\nu})$

Spin-spin transition! →

Modification from the **triplet** ($D_n <$ -1/3) to a **singlet** ($D <$ -1/3)

D & D_n MARKERS

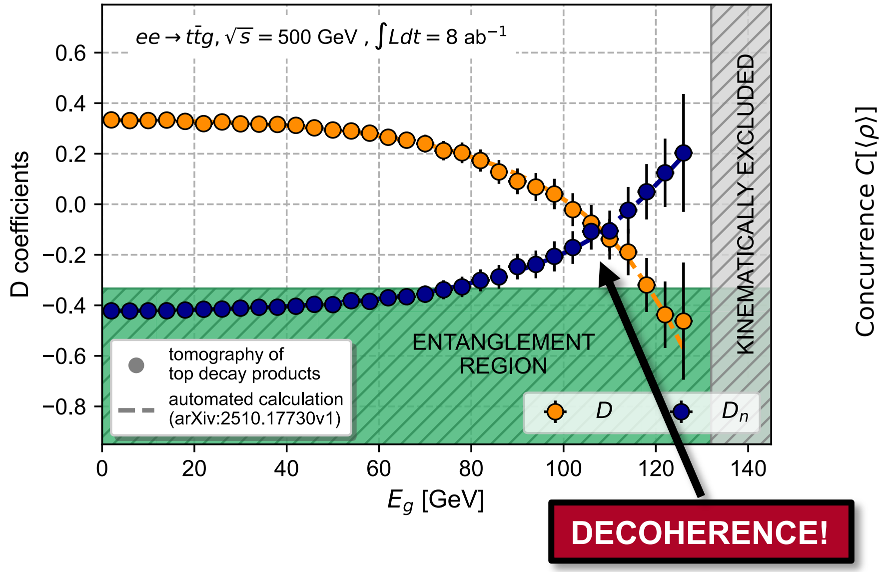
Provide with sufficient enough criteria for entanglement via linear expressions:

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

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

ENTANGLEMENT:

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



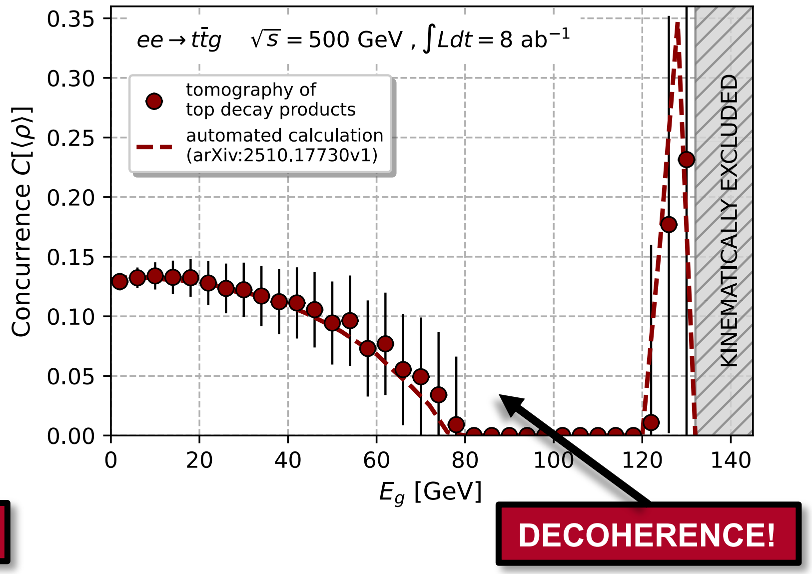
CONCURRENCE

Provides with a quantitative **non-linear** measurement of the degree of entanglement.

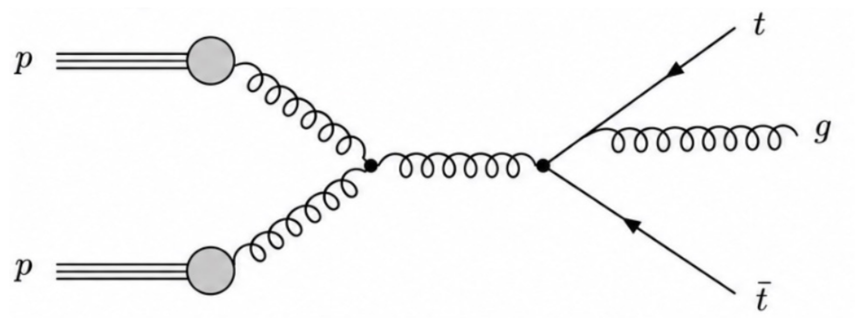
$$C\left[\langle\rho\rangle\right] = \max\left(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\right)$$

λ_i increasing eigenvalues of

$$R = \sqrt{\sqrt{\rho}\sigma_2 \otimes \sigma_2\rho^*\sigma_2 \otimes \sigma_2\sqrt{\rho}}$$



Quantum decoherence study at the ATLAS experiment



Decoherence study at LHC (Run 2) →

- Boosted (m_{tt} > 800 GeV) + Transverse regions ($|\cos\theta_t| < 0.4$)
- Semi-leptonic decay channel:
  - → Greater statistics + single neutrino MET
  - → Optimal hadronic polarimeter for the hadronic channel → $\alpha = 0.64$

Experimental approach:

- D_n can be retrived from **cos(ϕ)** distributions $D_n = 3\frac{\langle\cos\phi\rangle}{\alpha_1\alpha_2}$

  ϕ : angle of one polarimeter and the reflection of the other
- **cos(ϕ)** distributions are obtained for the inclusive sample and selecting p_T^{jet} > 150 GeV.
- D_n extracted from a profile-likelihood unblinding of the observable **cos(ϕ).**
- Previous iterations used detector-level jets; new results are being produced to make use of parton-level jets obtained from TOPQ7 new derivation formats.

Results:

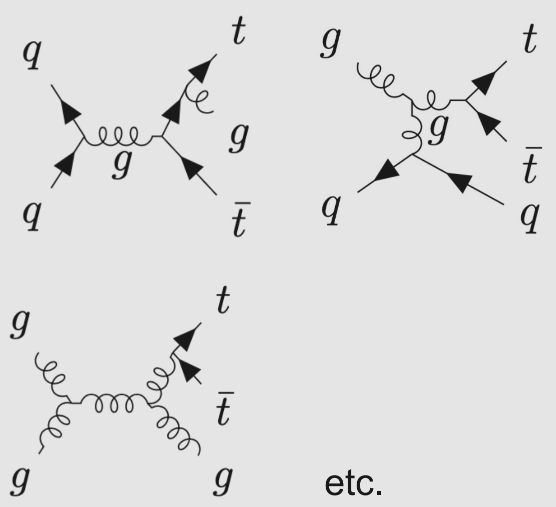
$D_n^{incl.} = -0.59$

$D_n^{pTj > 150\ GeV} = -0.38$

Significance = ~ 2σ

Decoherence prospects for simulated *pp* → $t\bar{t}$+*g* events

This processes may involve the radiation of quark and gluon jets:



etc.

Sample characteristics:

- ***Parton-level, leading order samples.***
- **Computation**: MadGraph5_aMC@NLO. J. Alwall et al., arXiv:1405.0301 [hep-ph]).
- **Decay mode:** $\mu^+\mu^-$ ($b\nu\bar{b}\bar{\nu}$)

FIDUCIAL REGION:

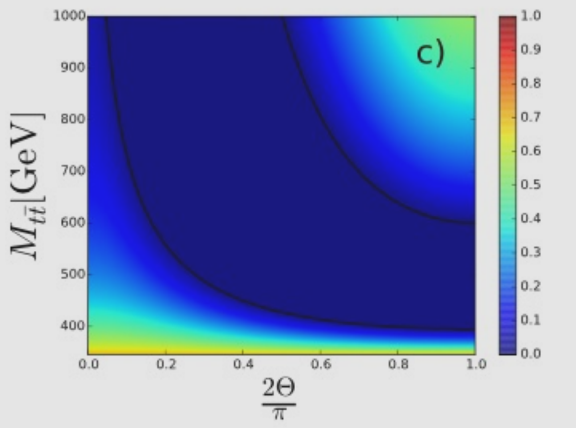
Restrict to the **fiducial region:**

- Isolate qq → $t\bar{t}$+jet topologies
- reduce contributions from ISR jets.

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

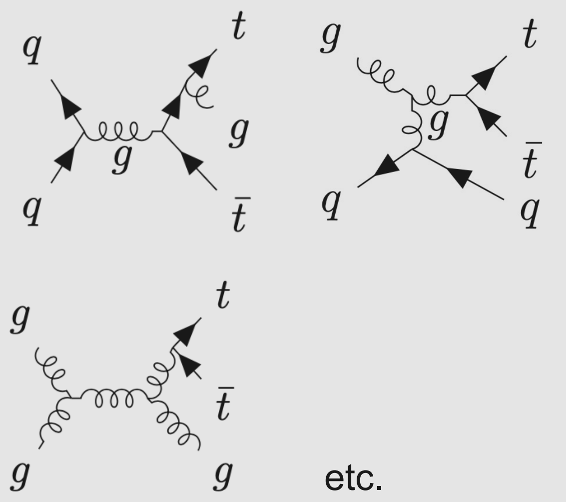
Concurrence as a function of m_{tt} and $\cos\Theta_t^{ttRF}$

Afik, Muñoz de Nova
Eur. Phys. J. Plus (2021) 136:907



Decoherence prospects for simulated $pp \to t\bar{t}+g$ events

This processes may involve the radiation of quark and gluon jets:



etc.

Sample characteristics:

- ***Parton-level, leading order samples.***
- **Computation**: MadGraph5_aMC@NLO. J. Alwall et al., arXiv:1405.0301 [hep-ph]).
- **Decay mode:** $\mu^+\mu^-$ ($b\nu\bar{b}\bar{\nu}$)

FIDUCIAL REGION:

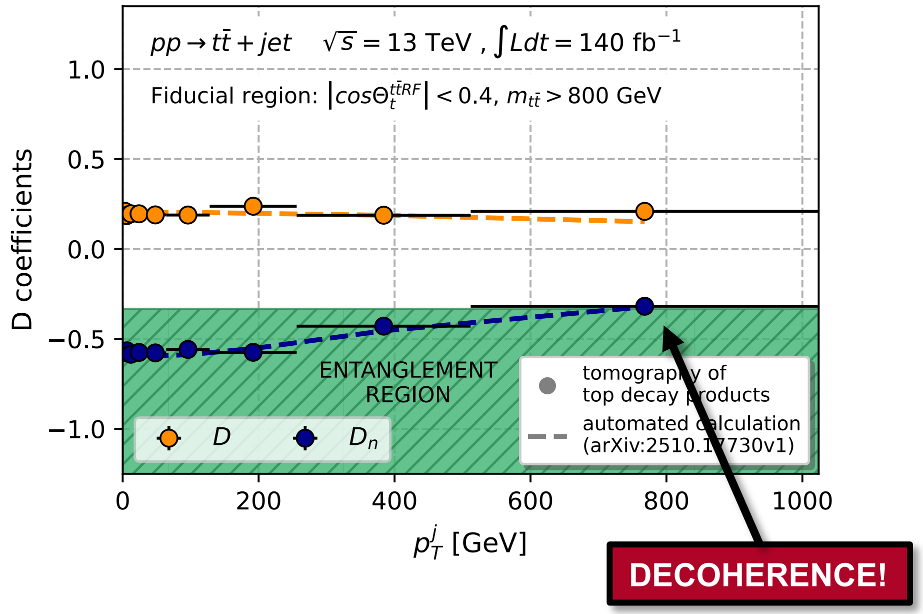
Restrict to the **fiducial region:**

- Isolate qq → $t\bar{t}$+jet topologies
- reduce contributions from ISR jets.

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

LHC Run 2 predictions

D MARKERS



Decoherence present above **250 GeV**. **Total separability** found above **500 GeV**.

Statistical significances for the observation of decoherence

A simple feasibility study separates the data set in two regions:

→ Inclusive region → establish entanglement of the fermion pair ($C_{inc} > 0$)

→ Exclusive region with FSR → establish decoherence ($C_{exc} < C_{inc}$)

Statistical significance

$$S = \frac{R - 1}{\sigma_R}$$

R → Decoherence quotient

1 → Null hypothesis.

σ_R → Statistical uncertainty

LHC:

Machine	$\sqrt{s}$ [TeV]	$C[\rho]_{t\bar{t}}$	$C[\rho]_{t\bar{t}+jet}$	$\boldsymbol{S = \frac{R-1}{\sigma_R}}$
LHC Run 2	13	0.310	0.118 (p_T^j>250GeV)	**4.0σ** dilep. / **11 σ** all ch.

(current operations)

Statistical significances for the observation of decoherence

A simple feasibility study separates the data set in two regions:

→ Inclusive region → establish entanglement of the fermion pair ($C_{inc} > 0$)

→ Exclusive region with FSR → establish decoherence ($C_{exc} < C_{inc}$)

Statistical significance

$$S = \frac{R - 1}{\sigma_R}$$

- R → Decoherence quotient
- 1 → Null hypothesis.
- σ_R → Statistical uncertainty

LHC:

Machine	$\sqrt{s}$ [TeV]	$C[\rho]_{t\bar{t}}$	$C[\rho]_{t\bar{t}+jet}$	$\mathcal{S} = \frac{R-1}{\sigma_R}$
LHC Run 2	13	0.310	0.118 (p_T^j>250GeV)	**4.0 σ** dilep. / **11 σ** all ch.
HL-LHC	14	0.431	0.096 (p_T^j>250GeV)	**12 σ** dilep. / **34 σ** all ch.

Linear Collider Facility

Machine	$\sqrt{s}$ [TeV]	$C[\rho]_{t\bar{t}}$	$C[\rho]_{t\bar{t}g}$	$\mathcal{S} = \frac{R-1}{\sigma_R}$
LCF	0.5	0.133	0.041 (p_T^g>30GeV)	**3.0 σ** dilep. / **8.2 σ** all ch.
linear e^+e^-	1.0	0.249	0.081 (p_T^g>120GeV)	**4.6 σ** dilep. / **13 σ** all ch.

(current operations)

Statistical significances for the observation of decoherence

A simple feasibility study separates the data set in two regions:

→ Inclusive region → establish entanglement of the fermion pair ($C_{inc} > 0$)

→ Exclusive region with FSR → establish decoherence ($C_{exc} < C_{inc}$)

Statistical significance

$$S = \frac{R - 1}{\sigma_R}$$

- R → Decoherence quotient
- 1 → Null hypothesis.
- σ_R → Statistical uncertainty

LHC:

Machine	$\sqrt{s}$ [TeV]	$C[\rho]_{t\bar{t}}$	$C[\rho]_{t\bar{t}+jet}$	$\mathcal{S} = \frac{R-1}{\sigma_R}$
LHC Run 2	13	0.310	0.118 ($p_T^j > 250 GeV$)	**4.0 σ** dilep. / **11 σ** all ch.
HL-LHC	14	0.431	0.096 ($p_T^j > 250 GeV$)	**12 σ** dilep. / **34 σ** all ch.

Linear Collider Facility

Machine	$\sqrt{s}$ [TeV]	$C[\rho]_{t\bar{t}}$	$C[\rho]_{t\bar{t}g}$	$\mathcal{S} = \frac{R-1}{\sigma_R}$
LCF linear e^+e^-	0.5	0.133	0.041 ($p_T^g > 30$GeV)	**3.0 σ** dilep. / **8.2 σ** all ch.
	1.0	0.249	0.081 ($p_T^g > 120$GeV)	**4.6 σ** dilep. / **13 σ** all ch.

Prospects $e^+e^- \to \tau^+\tau^-$

Machine	$\sqrt{s}[GeV]$	$C[\rho]_{\tau^+\tau^-}$	$C[\rho]_{\tau^+\tau^-\gamma}$	$\mathcal{S} = \frac{R-1}{\sigma_R}$
Belle II	10.58	0.727	0.235 ($p_T^\gamma > 2GeV$)	28σ 0.5 ab^{-1} / $\gg 5\sigma$ 50.0 ab^{-1}
FCC-ee	91.20	0.858	0.102 ($p_T^\gamma > 30GeV$)	16σ 0.1 ab^{-1} / $\gg 5\sigma$ 300 ab^{-1}

(current operations)

$\tau^+\tau^-\gamma$ production provides the **cleanest measurement of FSR** decoherence, in a single decay channel.

Conclusions

- Fermion pairs produced at colliders show a **significant loss of entanglement** when considering **gluon and photon FSR**.

- The current boosted $t\bar{t}$ lepton+jets analysis at ATLAS is expected to provided with the **first evidence of quantum decoherence** late 2026 or early 2027.

- The **observation of decoherence is already possible** at **Belle II**.

- The outlook is very promising for future e^+e^- accelerators, whether linear or circular:

    - The **target** data sets of Belle II, as well as the FCC-ee prospects, will allow a **precision differential measurement** of decoherence.

References

[1] Afik and Muñoz de la Nova. Eur. Phys. J. Plus 136, 907 (2021)

[2] ATLAS Collaboration. Nature 633, 542 (2024)

[3] CMS Collaboration. PRD 110, 112016 (2024)

[4] Aoude, Barr, Maltoni and Satrioni (arXiv.2504.07030)

[5] Bernreuther, Heislera and Sib. JHEP12(2015)026

[6] Alwall et al. arXiv:1405.0301

[7] Durupt, Maltoni and Mattelaera. arXiv:2510.17730v1

[8] Maltoni, Severi, Tentori and Vryonidou, JHEP 09 (2024) 001, [2404.08049].

[9] Ehatäht, Fabbrichesi , Marzola, and Veelken. Phys. Rev. D 109, 032005

[10] FCC collaboration. Eur. Phys. J. C 85, 1468 (2025).

[11] *H. Kragh (2002). Quantum generations*

[12] *W. H. Zurek (1025). Decoherence and Quantum Darwinism*

Based on the paper arXiv:2604.16268.

Contact information:

guillermo.garcia-mir@uv.es

jose.m.camacho@uv.es

marcel.vos@ific.uv.es

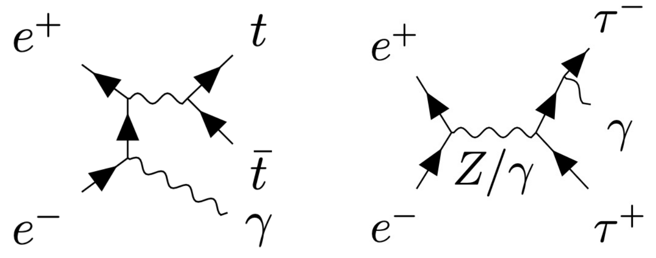
maria.moreno@ific.uv.es

The author's work is funded by regional government Generalitat Valenciana (Spain) through the predoctoral grant **CIACIF/2024/194.** This work is also supported by Spanish State Research Agency (AEI) grants PID2024-158190NB-C21 and PID2024-156321NB-I00.

BACK UP

Decoherence prospects for simulated $e^+e^- \to \tau^+\tau^- + \gamma$ events

This processes may involve the FSR and ISR:



We perform a tomography of hadronic **one-prong decays** (Fabbrichesi et. al.):

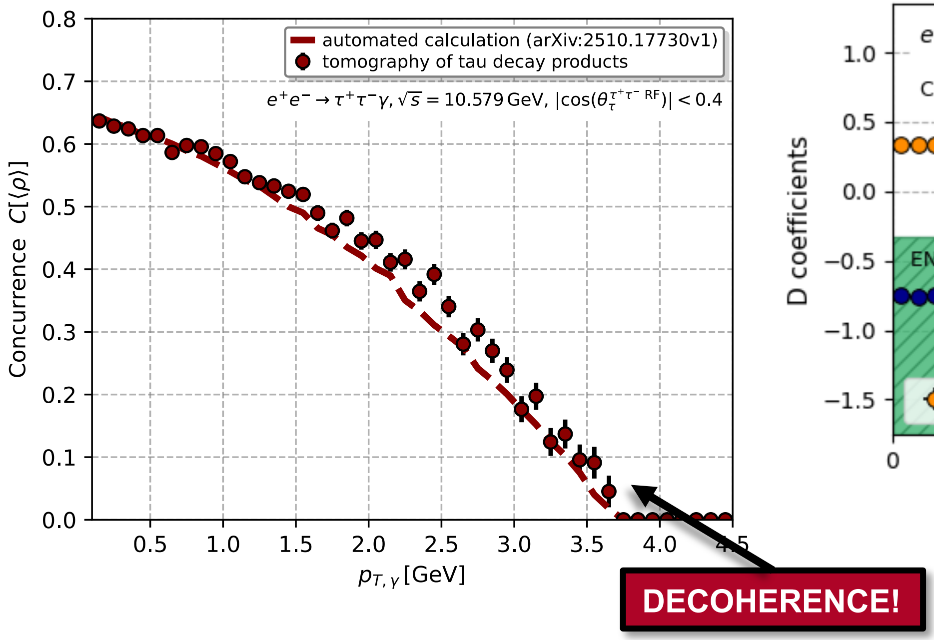
$\tau^\pm \to \pi^\pm \nu$

spin analysing power α = 1

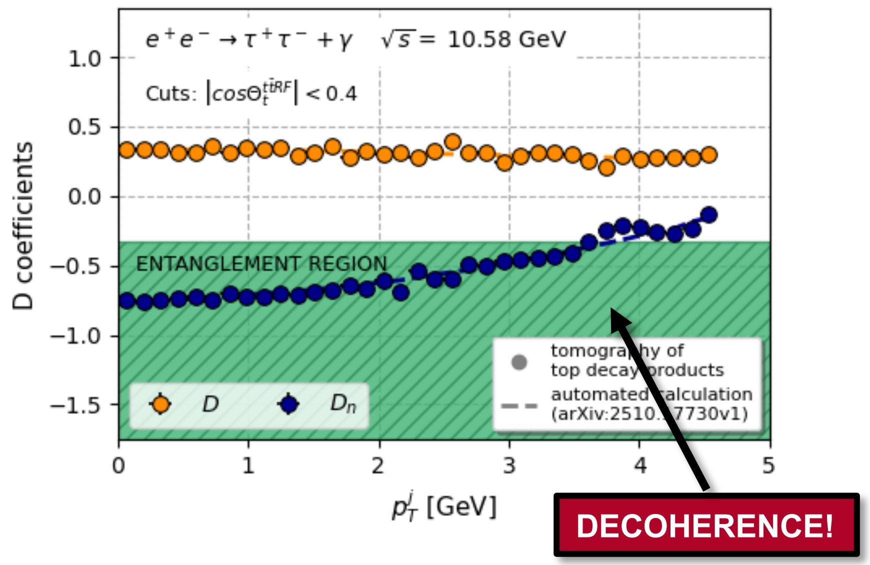
$$\left|cos(\Theta_\tau^{\tau^+\tau^- RF})\right| < 0.4$$

Restrict to central events to reduce contributions from ISR photons.

CONCURRENCE



D MARKERS



Example for Belle II experiment ($\sqrt{s}$ = 10.58 GeV).

Decoherence marked by the D_n marker

Total separability found above 500 GeV.