# Quantum observables in top quark physics

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# Introduction

Big interest in the community in the past 5 years

**Quantum entanglement in top pair production at the LHC**

Why is this interesting?

Quantum Information at colliders!

What can we learn in particle physics using QI?

New insights about SM physics and perhaps information about new physics

I will talk about top quarks but other systems explored

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STRONG INTERACTIONS | NEWS

**Highest-energy observation of quantum entanglement**

29 September 2023

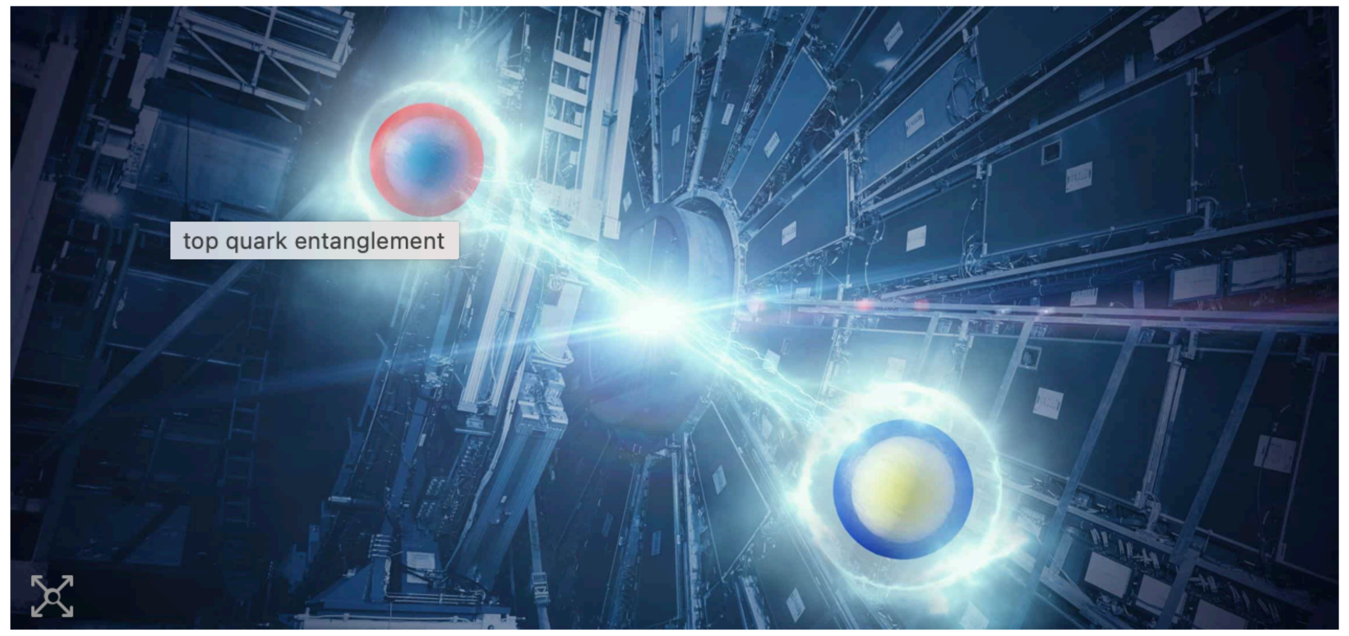
A report from the ATLAS experiment.

physicsworld | Audio and video ▾ | Latest ▾ |

QUANTUM | RESEARCH UPDATE

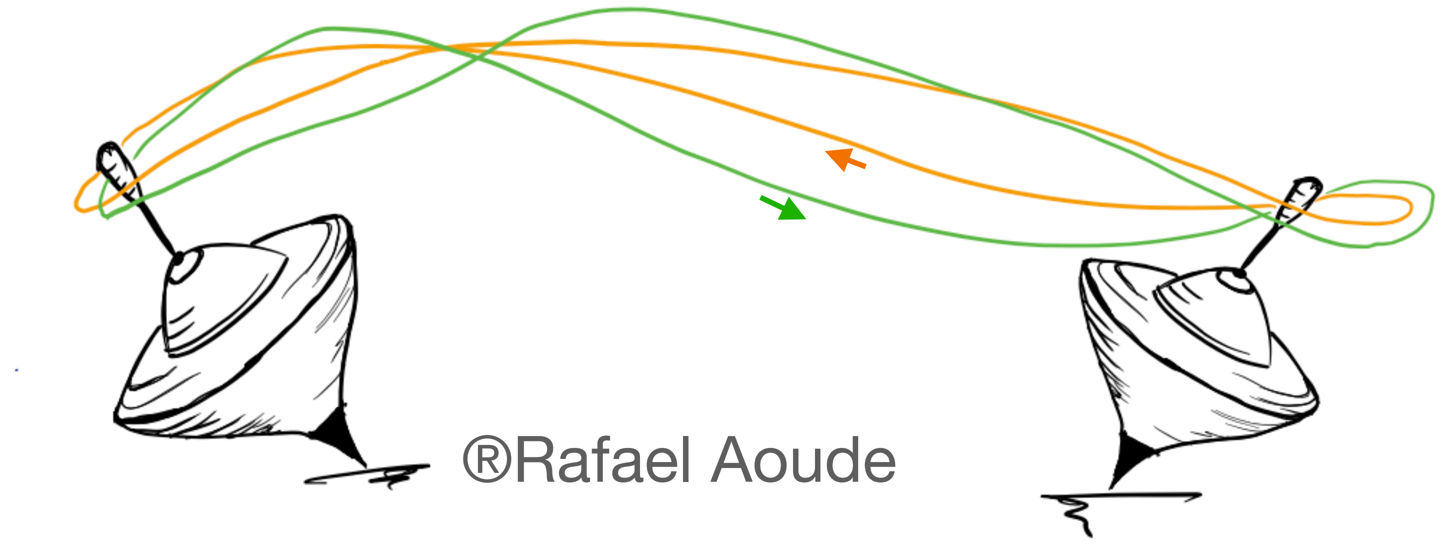
Quantum entanglement observed in top quarks

11 Oct 2023




Top result: An artist's impression of top-quark entanglement. The line between the particles emphasizes the non-separability of the top-quark pair, which is produced by LHC collisions and recorded by ATLAS. (Courtesy: Daniel Dominguez/CERN)

# Quantum tops @ LHC and beyond




Y. Afik and JRM de Nova: 2003.02280

Y. Afik and JRM de Nova: 2203.05582

C. Severi, EV: 2210.09330

Y. Afik and JRM de Nova: 2209.03969

M. Fabbrichesi, R. Floreanini. G. Panizzo: 2102.11883

C. Severi, C. Boschi, F. Maltoni, M. Sioli : 2110.10112

J.A. Aguilar-Saavedra, J.A. Casas: 2205.00542

R. Aoude, E. Madge, F. Maltoni, L. Mantani: 2203.05619

Z. Dong, D. Gonçalves, K. Kong, A. Navarro: 2305.07075

J.A. Aguilar-Saavedra : 2307.06991

T. Han, M. Low, TA Wu: 2310.17696

J.A. Aguilar-Saavedra, J.A. Casas: 2401.06854

C. Severi, F. Maltoni, S. Tentori, EV: 2401.08751

C. Severi, F. Maltoni, S. Tentori, EV: 2404.08049

C. White, M. White: 2406.07321

K. Cheng,T. Han, M. Low: 2407.01672

Z. Dong, D. Gonçalves, K. Kong, A. Larkoski, A. Navarro: 2407.07147

R. Aoude, H. Banks, C. White and M. White: 2505.12522

M. Altakach, P. Lambda, F. Maltoni, K. Sakurai: 2601.09558

Y.C. Guo, T. Han, M. Low, Y. Su: 2602.02719

Y. Afik et al. : 2602.15115

L. Antozzi et al. : 2602.23426

See also a review: A. Barr, M. Fabbrichesi, R. Floreanini, E. Gabrielli, L. Marzola arXiv: 2402.07972

# Density matrix

## Density matrix : pure versus mixed states

Any quantum state is described by a density matrix

Its properties are different for pure and mixed states

| Pure | Generic (mixed) |
|---|---|
| $\rho = \lvert\psi\rangle\langle\psi\rvert$ | $\rho = \sum_j p_j \lvert\psi_j\rangle\langle\psi_j\rvert \quad (\sum_j p_j = 1,\ p_j \geq 0)$ |

$$\langle A \rangle = \mathrm{Tr}[A\rho]$$

$$\rho^\dagger = \rho \qquad \langle\phi\lvert\rho\rvert\phi\rangle \geq 0 \qquad \mathrm{Tr}[\rho] = 1$$

| Pure | Generic (mixed) |
|---|---|
| $\mathrm{Tr}[\rho^2] = 1 \quad \rho = \rho^2$ | $\mathrm{Tr}[\rho^2] < 1 \quad \rho \neq \rho^2$ |

# Density matrix

## Composite systems

| | | |
|---|---|---|
| Pure state | $\vert\psi\rangle = \vert a\rangle \otimes \vert b\rangle$ | $\vert\psi\rangle = \sum_{ij} p_{ij} \vert a_i\rangle \otimes \vert b_j\rangle \quad p_{ij} \in \mathbb{C}, \sum_{ij} p_{ij} p^*_{ij} = 1$ <br> $\vert a_i\rangle, \vert b_j\rangle$ orthonormal bases |
| | Separable | Non-separable: Entangled State |
| Mixed state | $\rho = \sum_i p_i\, \rho^i_A \otimes \rho^i_B$ <br> $p_i \geq 0, \sum_i p_i = 1$ | $\rho \neq \sum_i p_i\, \rho^i_A \otimes \rho^i_B$ |

All quantum observables are based on this matrix

# Entanglement

For a state to be separable: $|\Psi\rangle = |\Psi_A\rangle|\Psi_B\rangle$ $\rho = \sum_n p_n \rho_n^A \otimes \rho_n^B, \ \sum_n p_n = 1$

A non-separable state is entangled

How do we check for entanglement? Peres-Horodecki criterion

Peres, Phys. Rev. Lett. 77, 1413 (1996)
Horodecki, Physics Letters A 232, 333 (1997)

E.g. for a two-qubit system, such as the top-anti-top spins, we can use the concurrence

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

with $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$ eigenvalues of

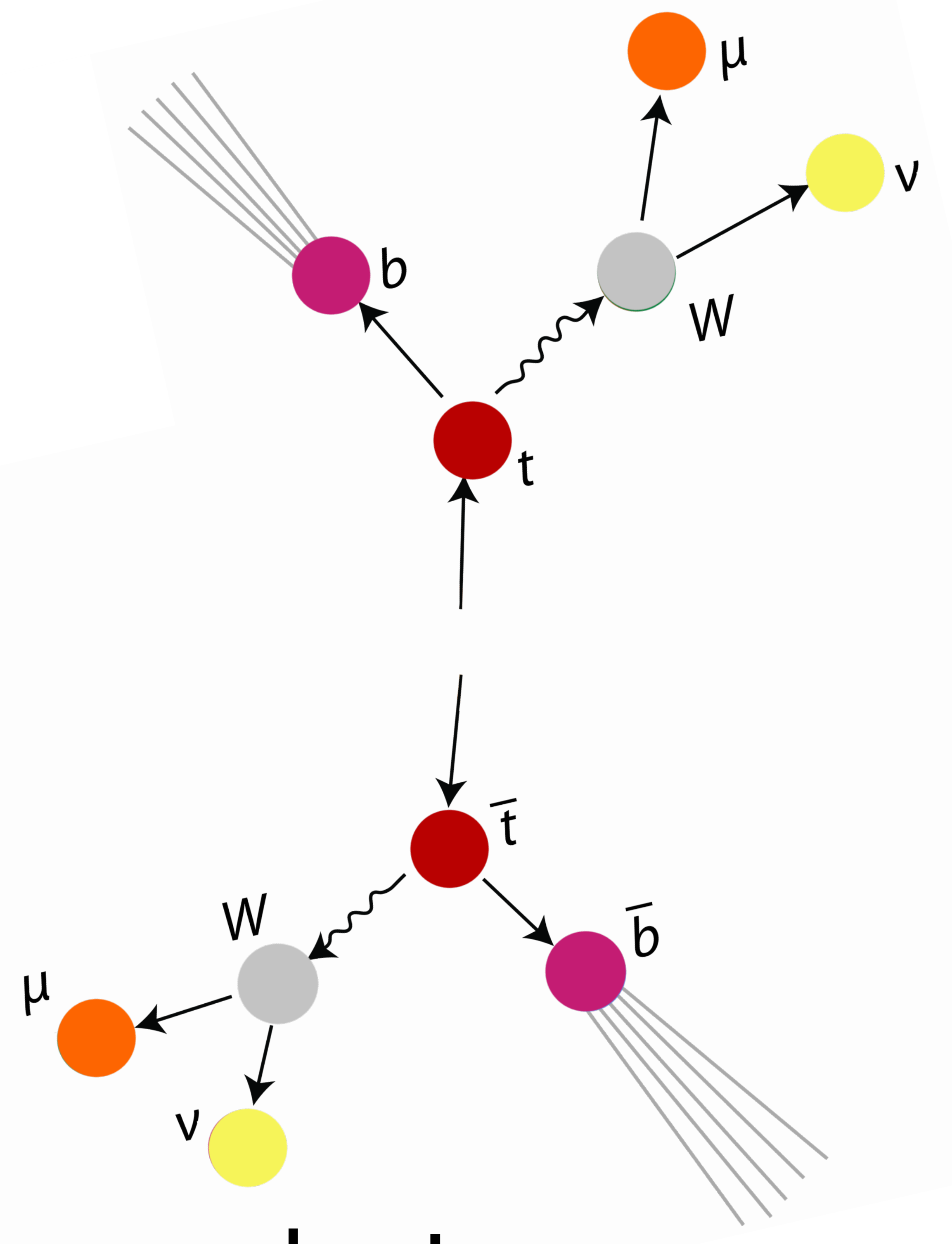
$$\sqrt{\sqrt{\rho}\,(\sigma_y \otimes \sigma_y)\rho^\star(\sigma_y \otimes \sigma_y)\,\sqrt{\rho}}$$

for a proof see Afik and de Nova arXiv:2003.02280

$C > 0$ means the system is entangled

# Spin density matrix of the top pair

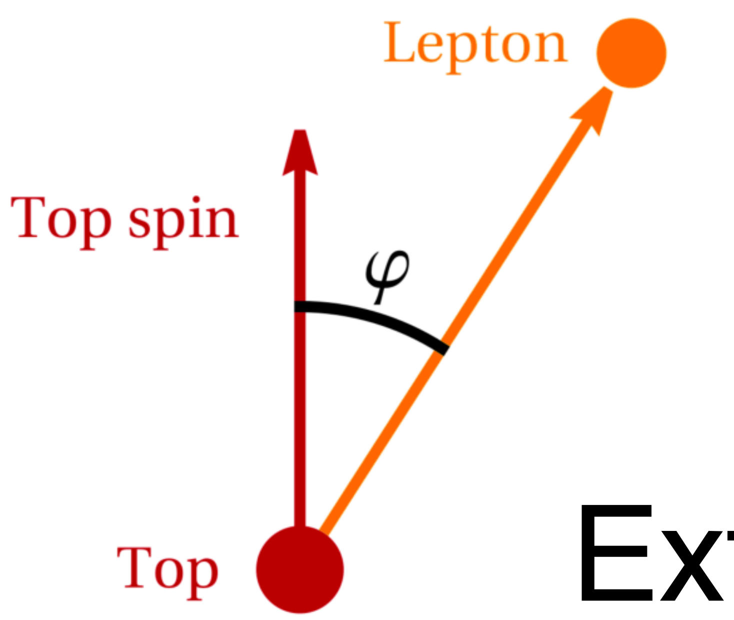
Tops produced in pairs have their spins $S_i$, $S_j$ correlated: a two-qubit system




Spin density matrix:

$$\rho = \frac{1}{4}\left(\mathbb{1} \otimes \mathbb{1} + \sum_{i=1}^{3} B_i\, \sigma_i \otimes \mathbb{1} + \sum_{j=1}^{3} \bar{B}_j\, \mathbb{1} \otimes \sigma_j + \sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij}\, \sigma_i \otimes \sigma_j\right)$$

15 parameters describe the quantum state of the top pair

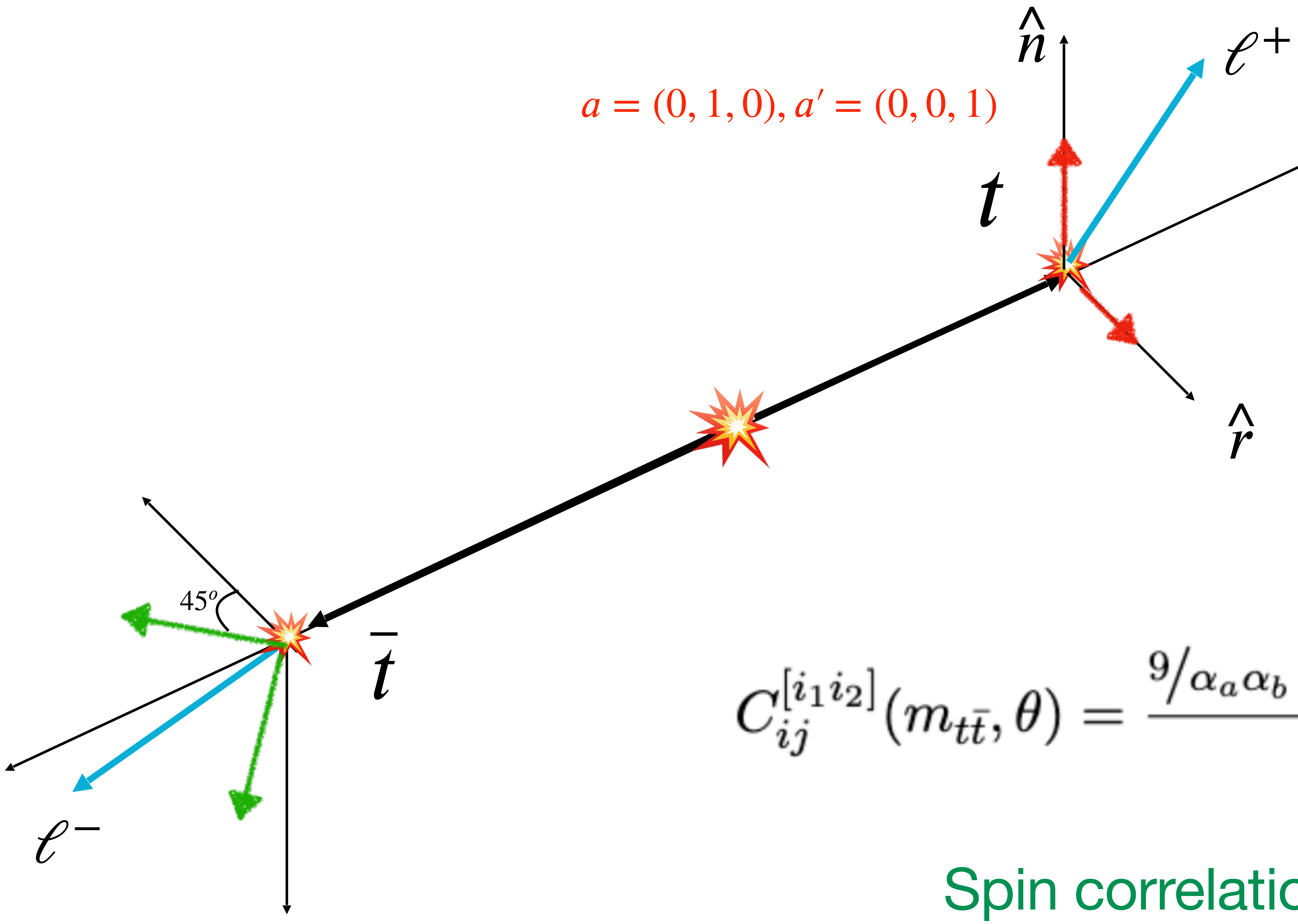



$$\langle S_i \rangle = B_i, \quad \langle \bar{S}_j \rangle = \bar{B}_j, \quad \langle S_i \bar{S}_j \rangle = C_{ij}$$

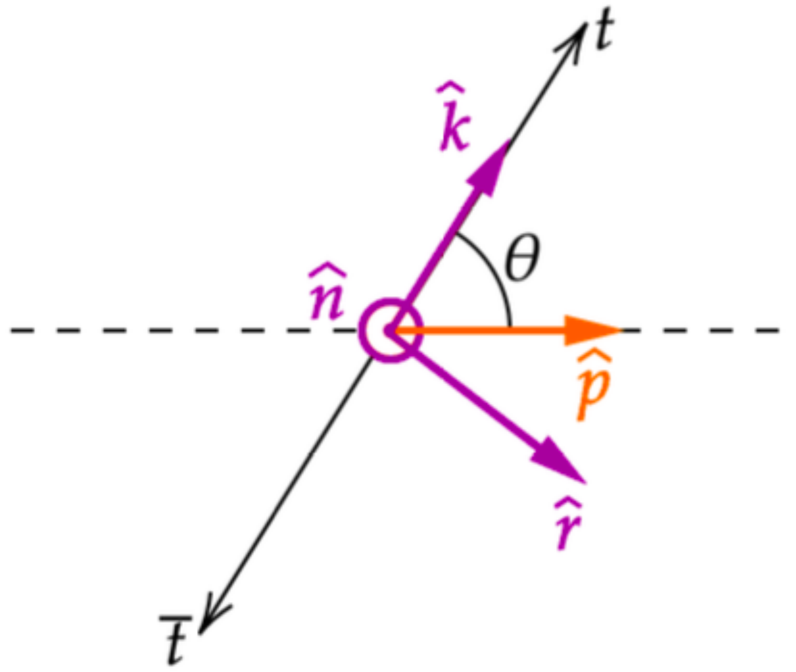
Extracted by measuring angular distributions of decay products

Quantum tomography is extraction of 15 parameters: 6 polarisations and 9 correlations

# Kinematics




$b = (0, -\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}), b' = (0, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$



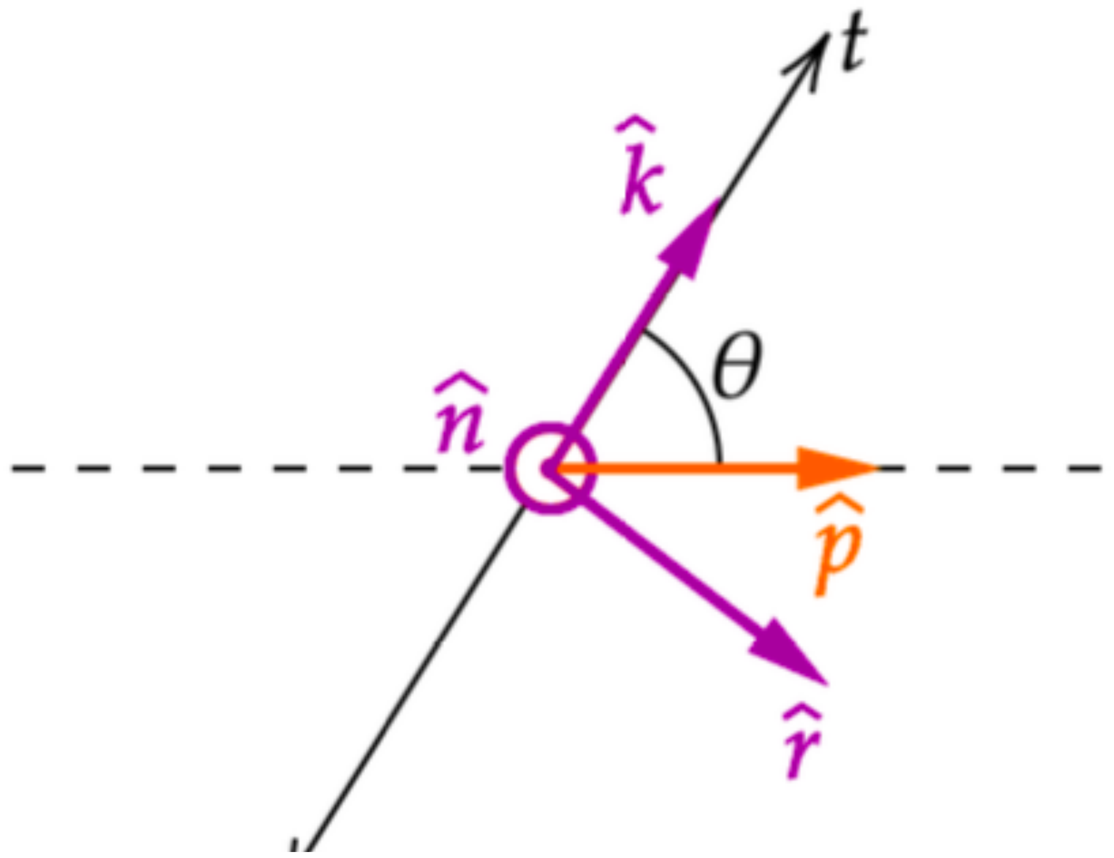

$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p}\times\hat{k}}{\sin\theta}$$

Helicity basis

$$C_{ij}^{[i_1 i_2]}(m_{t\bar{t}}, \theta) = \frac{9/\alpha_a\alpha_b \int \cos\theta_{ai}\cos\theta_{bj}\,|\mathcal{M}_{i_1 i_2 \to t\bar{t} \to a\,b\,X}|^2\, d\pi}{\int |\mathcal{M}_{i_1 i_2 \to t\bar{t} \to a\,b\,X}|^2\, d\pi}$$

Spin correlation coefficients are averages of angles

# From spin correlations to entanglement




$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p}\times\hat{k}}{\sin\theta}$$

$$D^{(1)} = 1/3(+C_{kk} + C_{rr} + C_{nn}),$$
$$D^{(k)} = 1/3(+C_{kk} - C_{rr} - C_{nn}),$$
$$D^{(r)} = 1/3(-C_{kk} + C_{rr} - C_{nn}),$$
$$D^{(n)} = 1/3(-C_{kk} - C_{rr} + C_{nn}).$$

$$D_{\min} \equiv \min\{D^{(1)}, D^{(k)}, D^{(r)}, D^{(n)}\}$$

Entanglement markers, from the Peres-Horodecki criterion

$$D_{\min} < -1/3$$

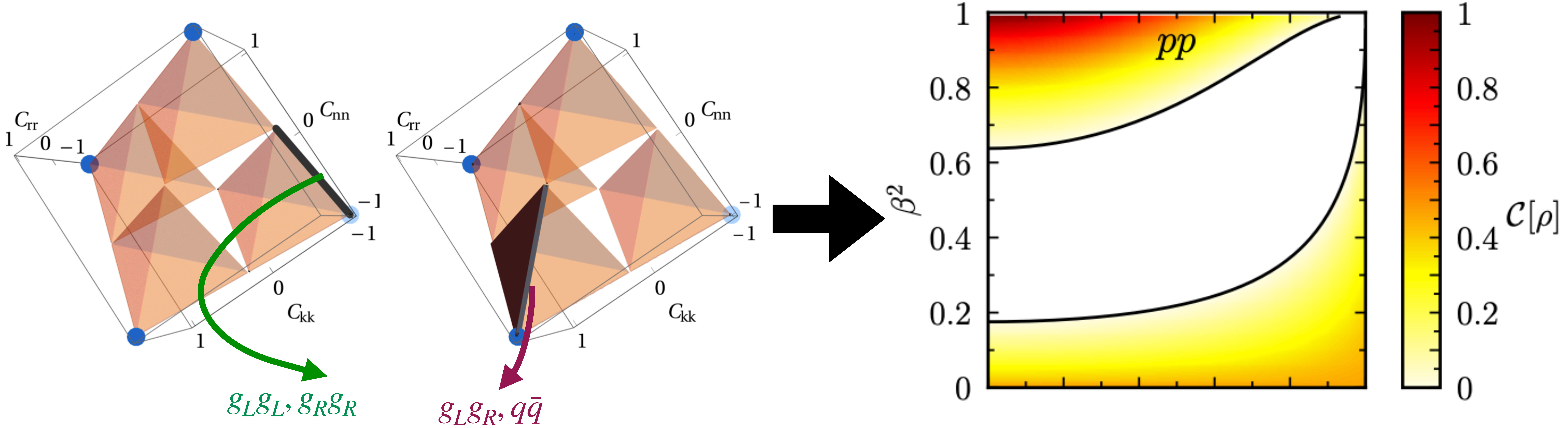
for a proof see Afik and de Nova arXiv:2003.02280

Necessary and sufficient condition for entanglement

$$C = \frac{1}{2}\max\left(0, -1 - 3D_{\min}\right) > 0$$

# When are top spins entangled?

## Reachable entangled states in pp collisions




R. Aoude, E. Madge, F. Maltoni, L. Mantani: 2203.05619

Threshold:

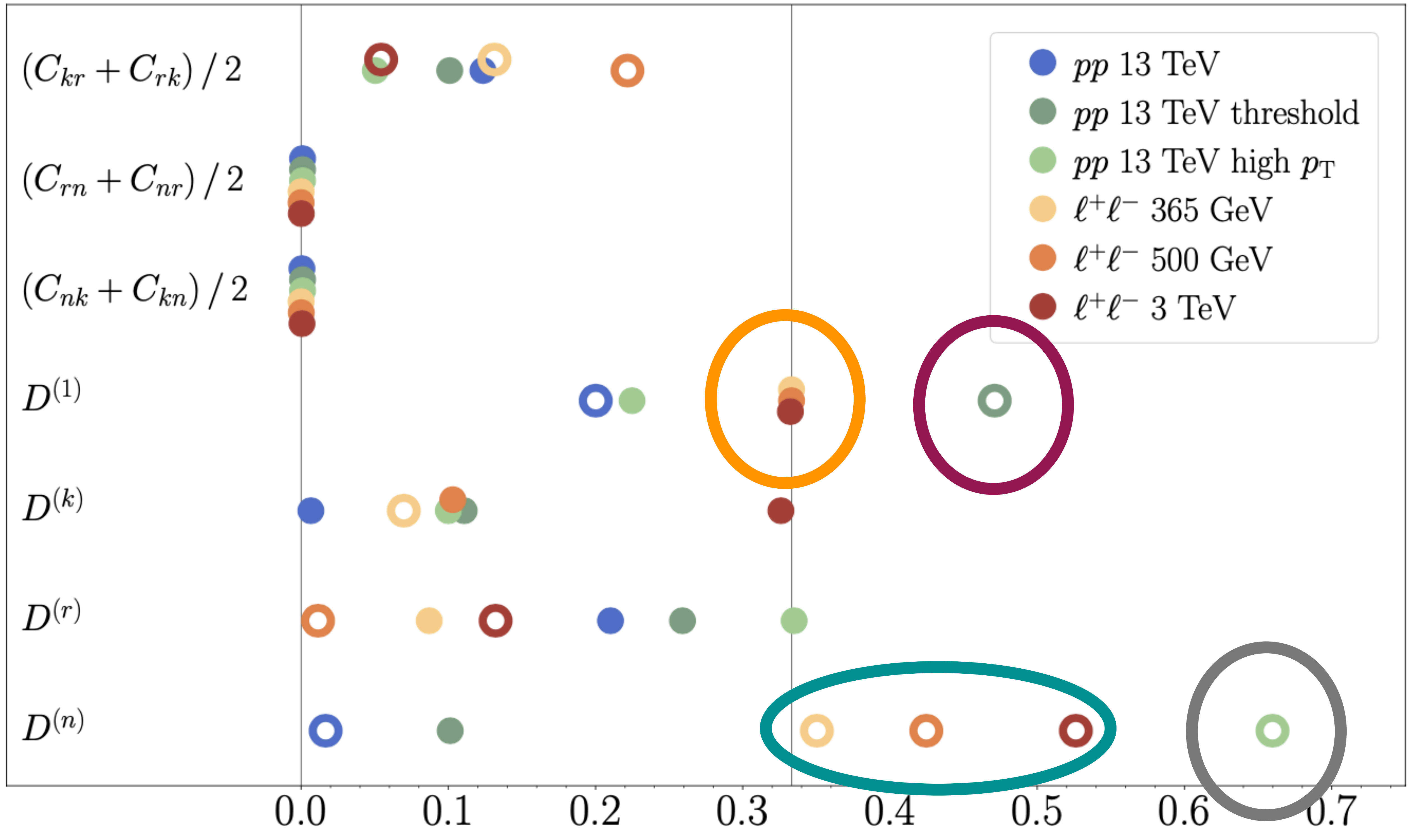
- entangled singlet state: same helicity gluons

Boosted:

- entangled triplet state: qqbar pairs and opposite helicity gluons

Maltoni, Severi, Tentori, EV arXiv:2404.08049

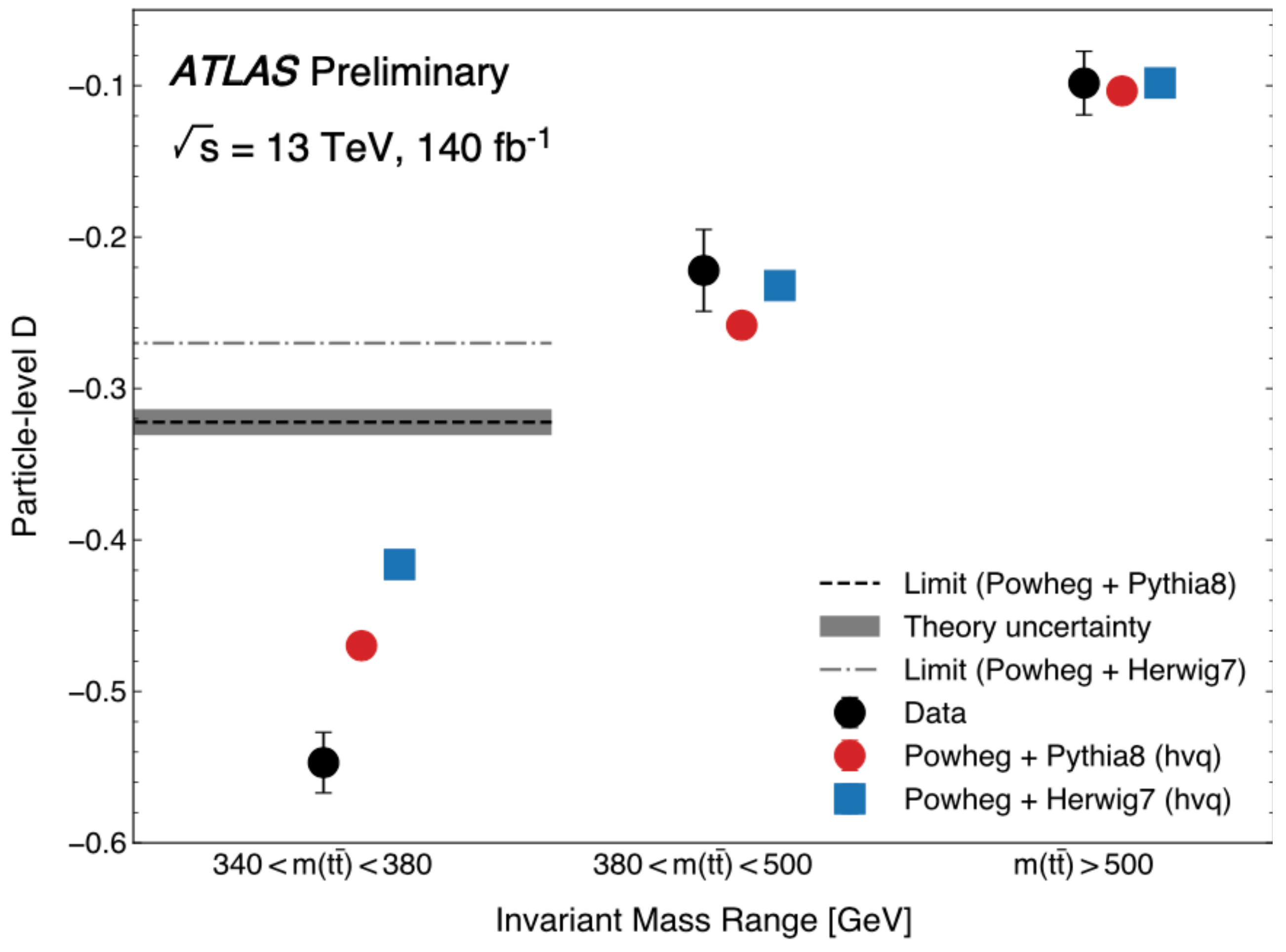
# Lepton vs pp collisions



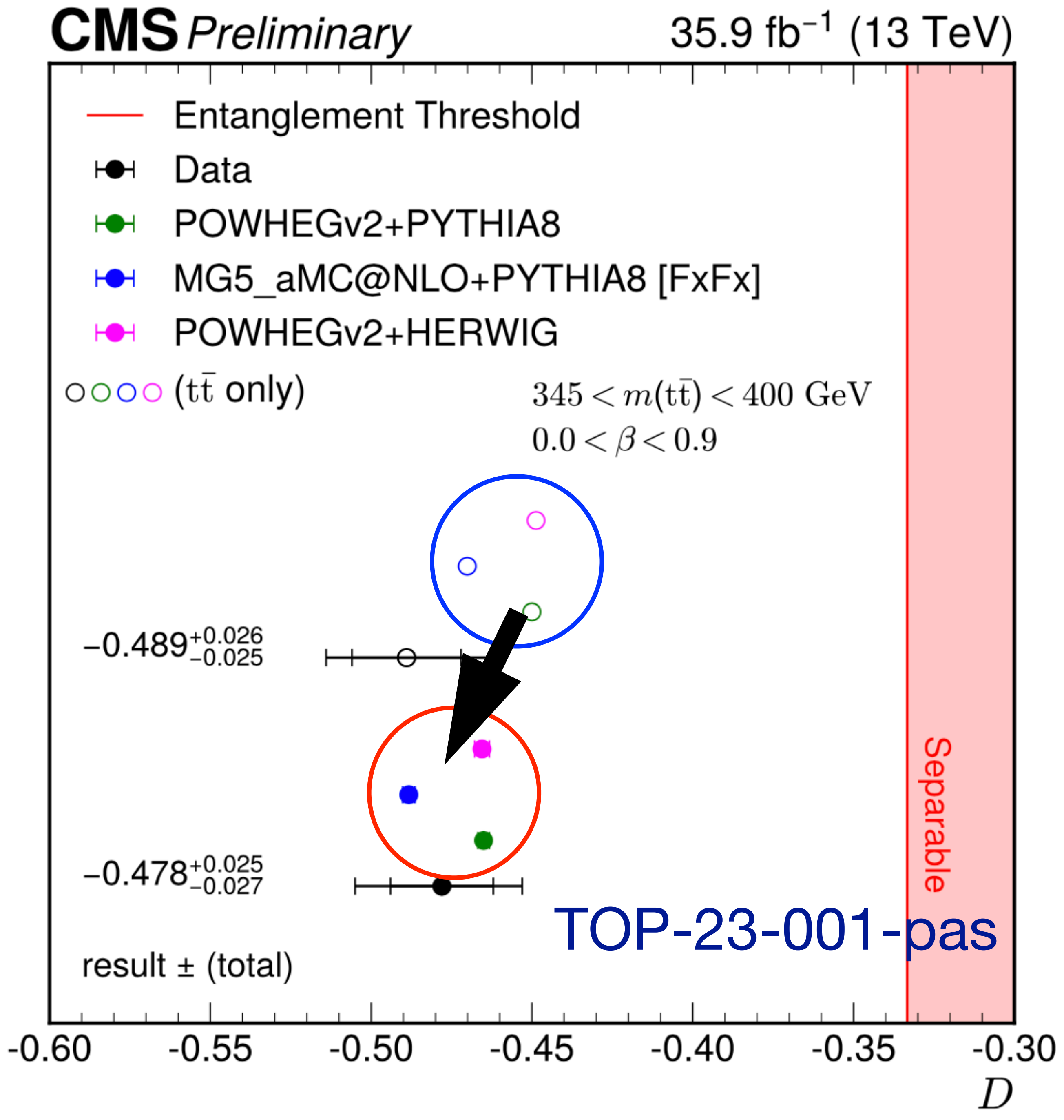

Maltoni, Severi, Tentori, EV arXiv:2404.08049

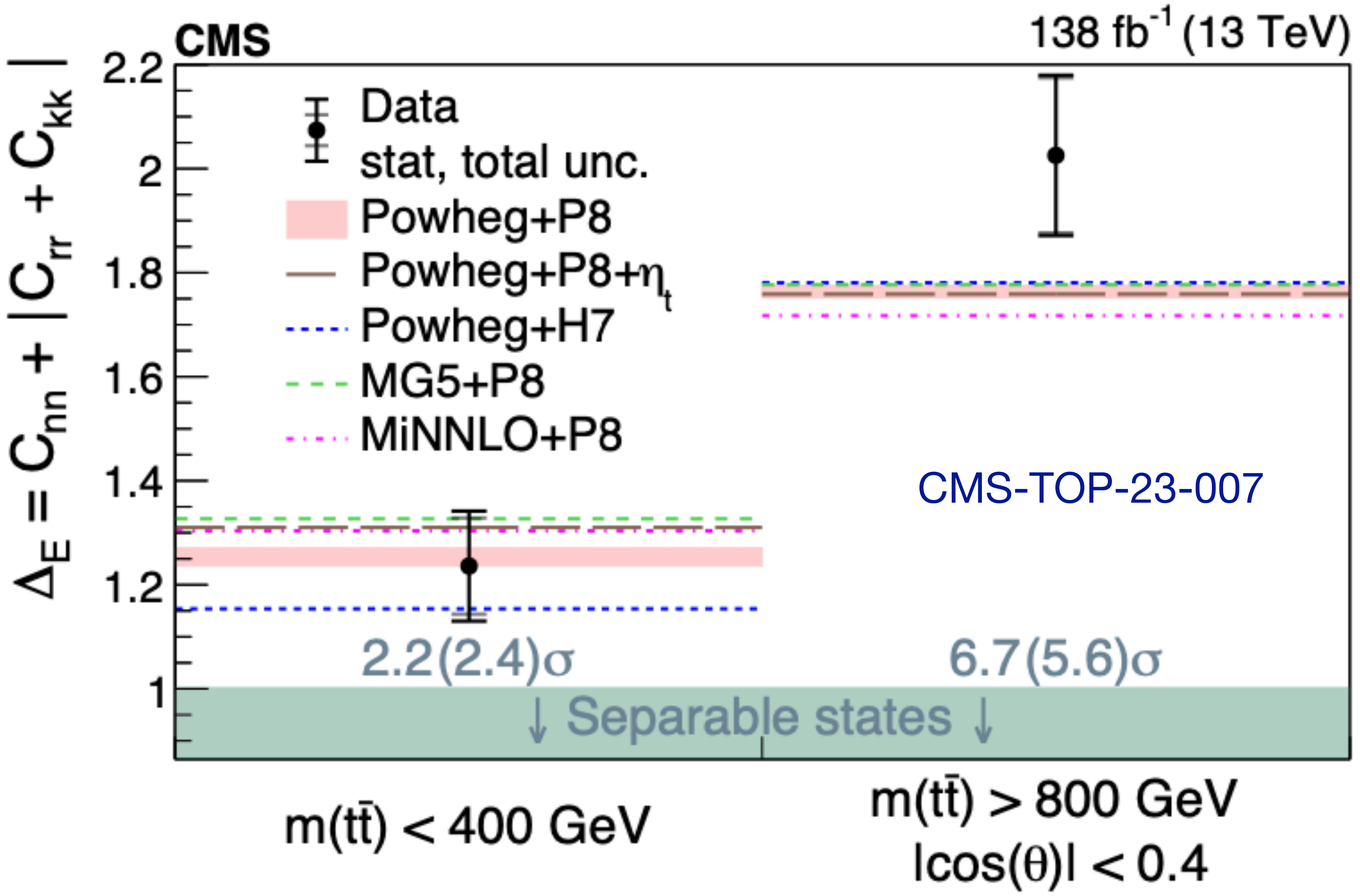
- Spin Triplet state $D^{(1)} = +1/3$ for lepton collisions
- Entanglement through $D^{(n)}$ for lepton colliders
- Entanglement through $D^{(1)}$ for LHC at threshold
- Entanglement through $D^{(n)}$ for LHC at high transverse momentum

# First measurements




ATLAS-CONF-2023-069




Entanglement observation at threshold by ATLAS and CMS

Entanglement observation at high energy by CMS

# What is next?

What happens to quantum observables if there is new physics?

How do the properties change for different final states?

What other observables can we study, can they tell us something new?

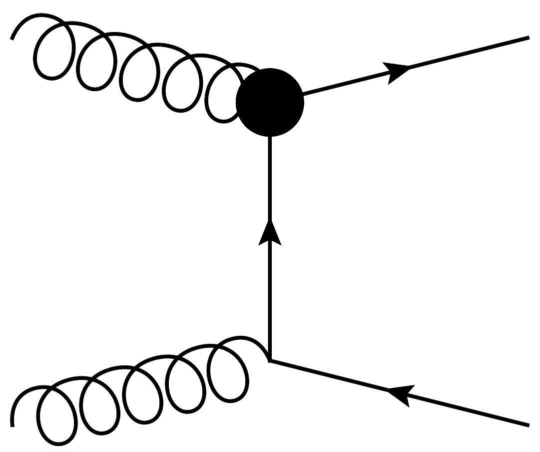
**New processes, new observables, new physics**

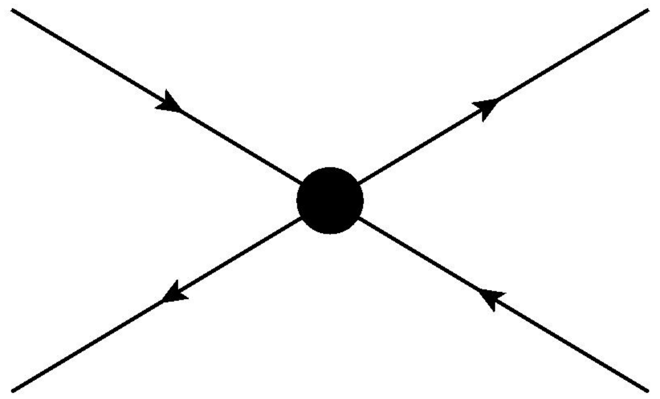
# Using QI observables for new physics

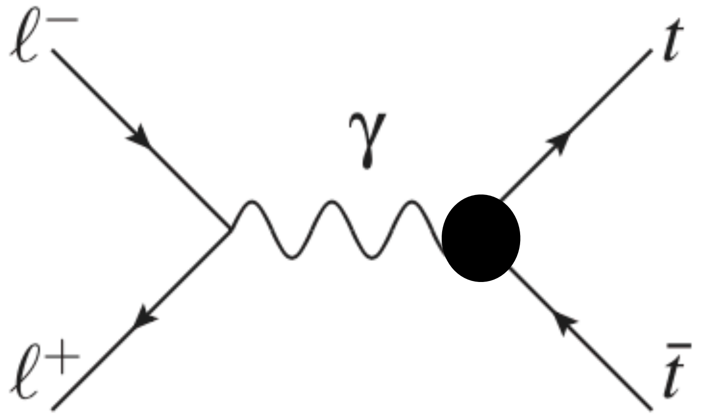
## Can they tell us anything interesting?

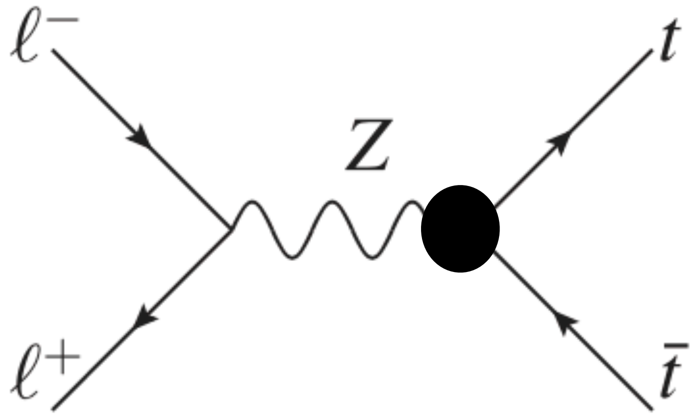
SMEFT → New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

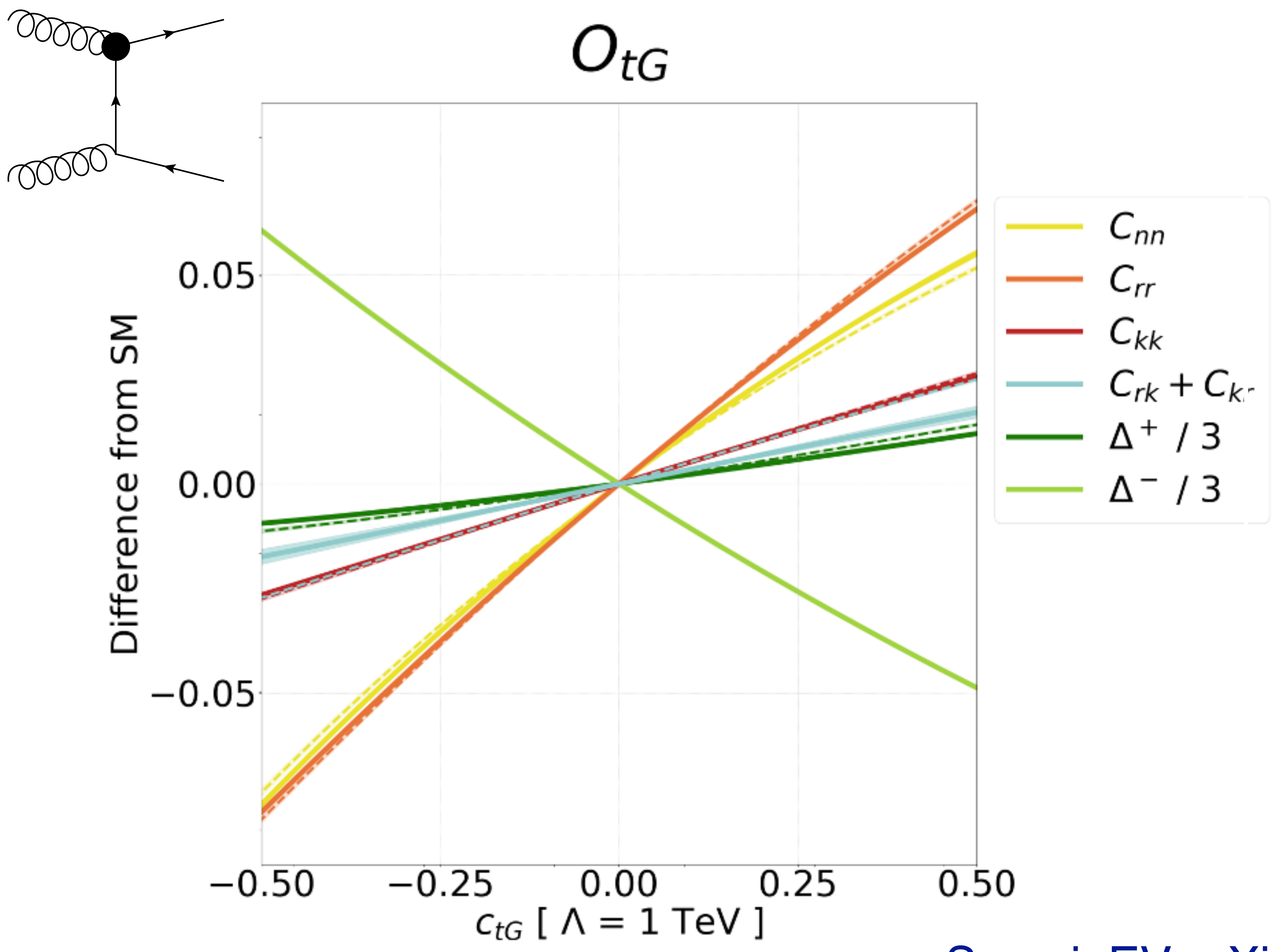


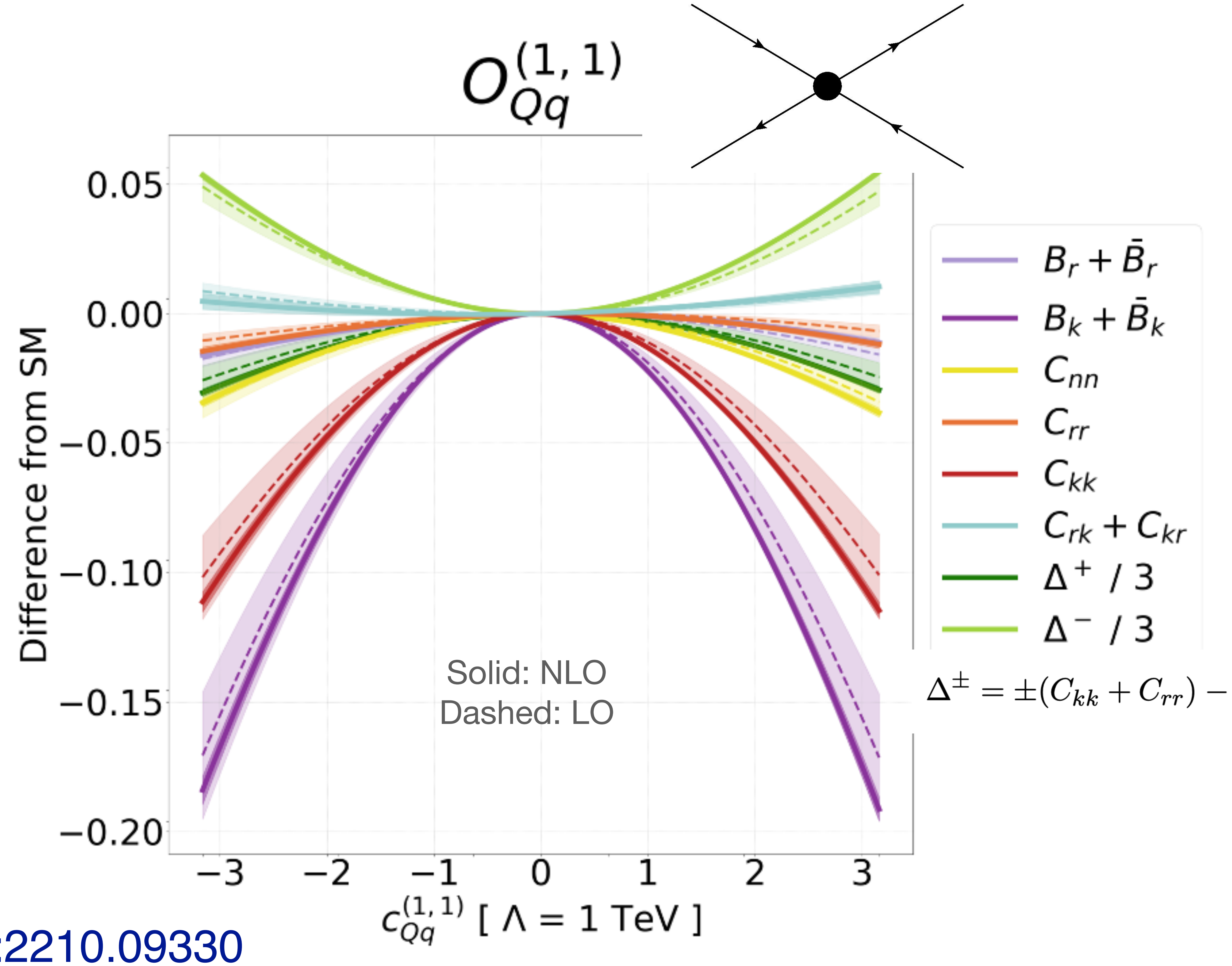




# Entanglement markers in the SMEFT



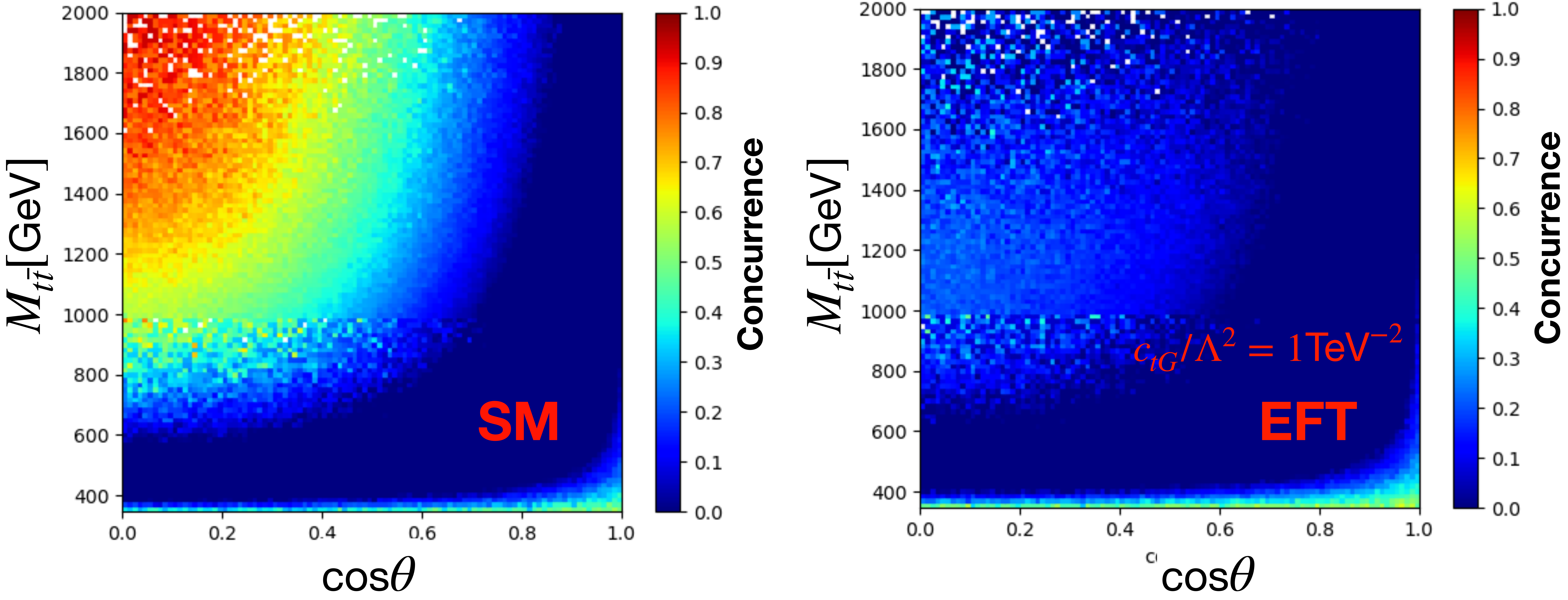

$\Delta^{\pm} = \pm(C_{kk} + C_{rr}) - C_{nn} - 1$

Severi, EV arXiv:2210.09330

Quantum entanglement markers modified by SMEFT operators

Results available also with QCD corrections

# Differential results for $pp \to t\bar{t}$



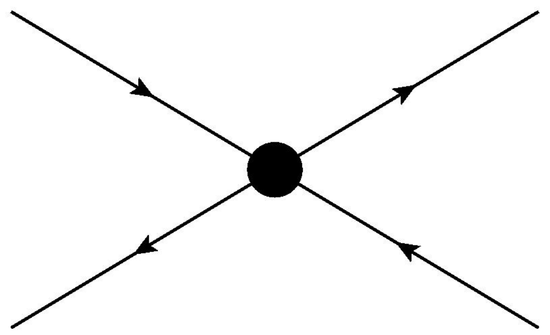

Sengupta, EV in preparation
Based on implementation of
Durupt, Maltoni, Mattelaer 2510.17730

Degree of entanglement changes mostly in the high-pT region

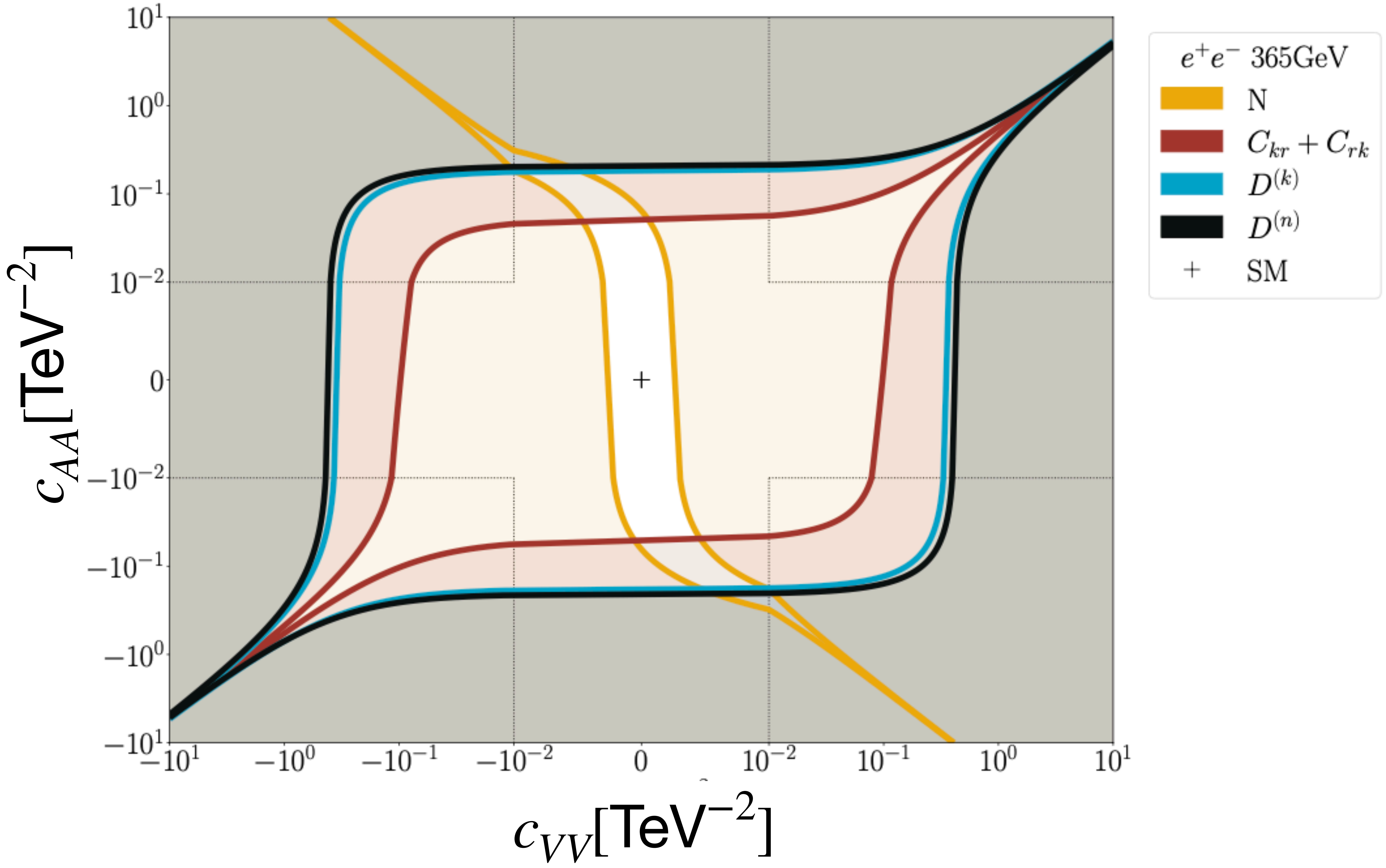
# Breaking degeneracies with Quantum Obs

**Example:** $e^+e^- \to t\bar{t}$

$$\mathcal{O}_{Q\ell}^{(1)} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{\ell}_L\gamma_\mu \ell_L),$$
$$\mathcal{O}_{Q\ell}^{(3)} = (\bar{Q}_L\gamma^\mu \sigma_I Q_L)(\bar{\ell}_L\gamma_\mu \sigma^I \ell_L),$$
$$\mathcal{O}_{Qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{\ell}_R\gamma_\mu \ell_R),$$
$$\mathcal{O}_{t\ell} = (\bar{t}_R\gamma^\mu t_R)(\bar{\ell}_L\gamma_\mu \ell_L),$$
$$\mathcal{O}_{te} = (\bar{t}_R\gamma^\mu t_R)(\bar{\ell}_R\gamma_\mu \ell_R).$$



$$c_{\mathrm{VV}} = \frac{1}{4}\left(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} + c_{Qe}\right)$$
$$c_{\mathrm{AA}} = \frac{1}{4}\left(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} - c_{Qe}\right)$$




Maltoni, Severi, Tentori, EV arXiv:2404.08049

Spin correlation observables probe different linear combinations of Wilson coefficients

➡ Breaking degeneracies

# New observables: Purity

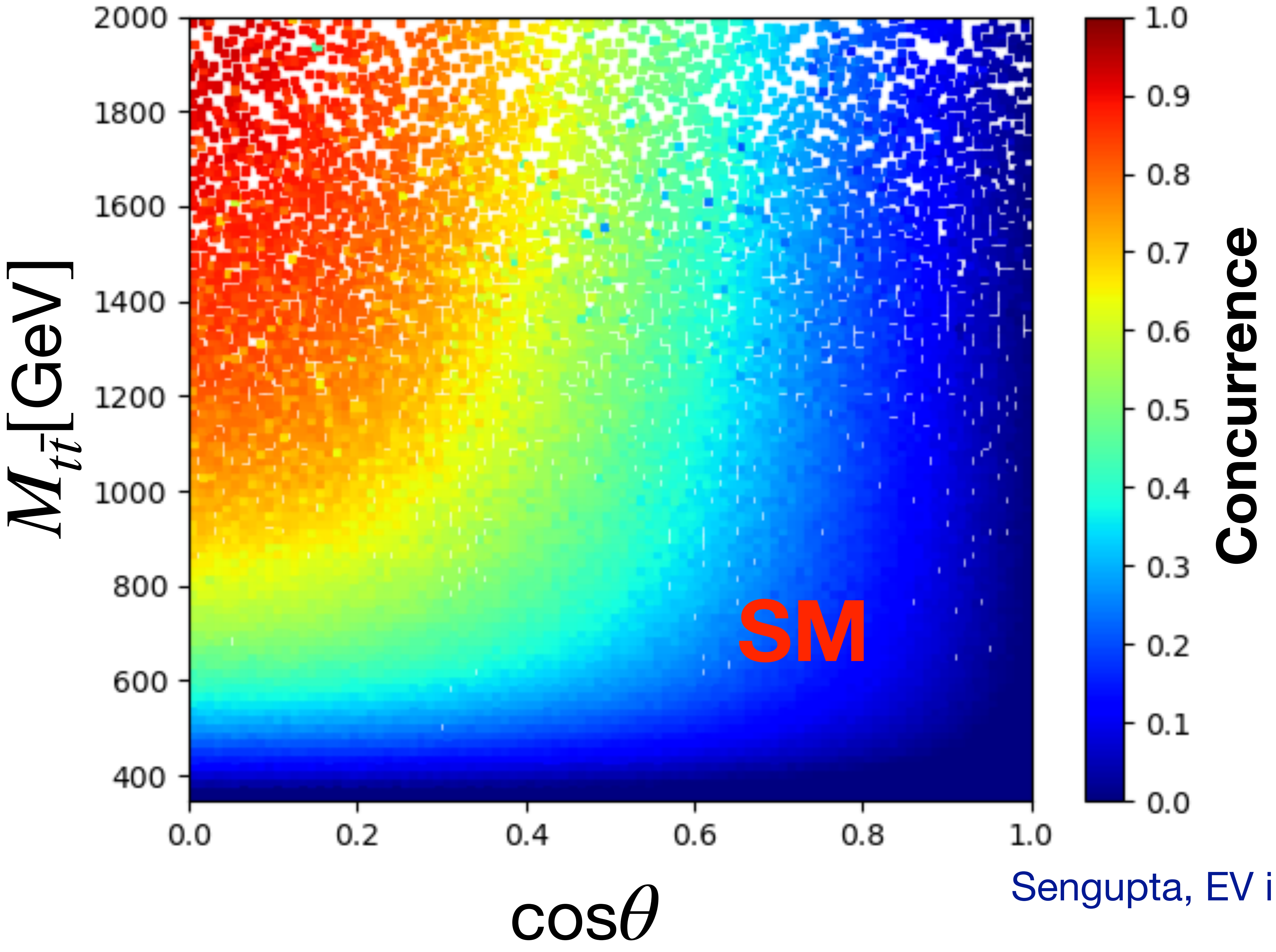
## Pure or mixed?


Sengupta, EV in preparation
Durupt, Maltoni, Mattelaer 2510.17730

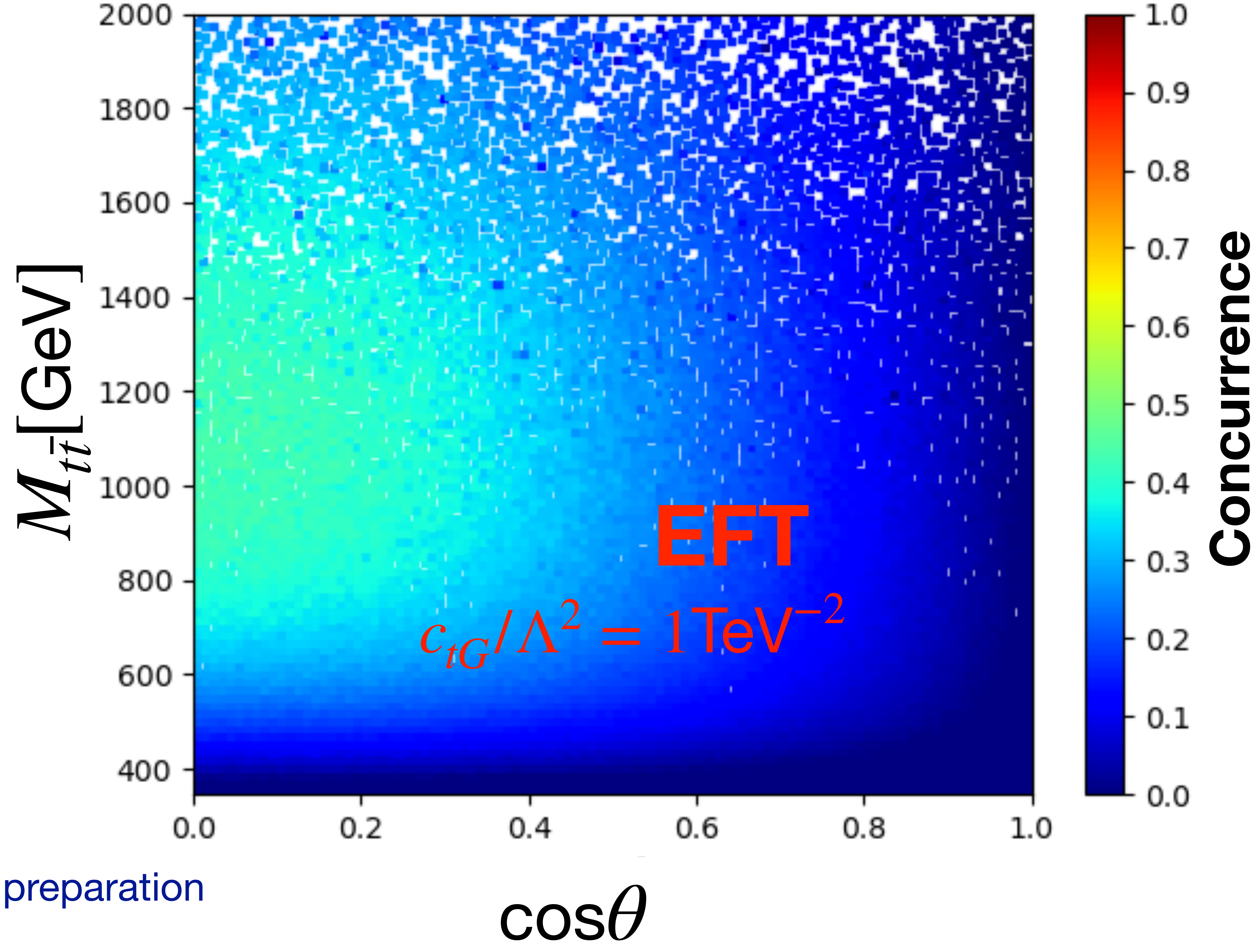
Quantum observables: Additional handles in separating processes

# Top Associated Production

## ttW: SM vs EFT




Sengupta, EV in preparation




Quantum observables: Additional handles in probing new interactions

# Conclusions

- Top pairs are an ideal testing ground for quantum information observables
- Different entanglement patterns for lepton and hadron colliders
- New physics introduces new structures, and change quantum observables
- Quantum observables can break degeneracies between operators when combined with standard observables

# Thank you for your attention