Quantum tops at colliders

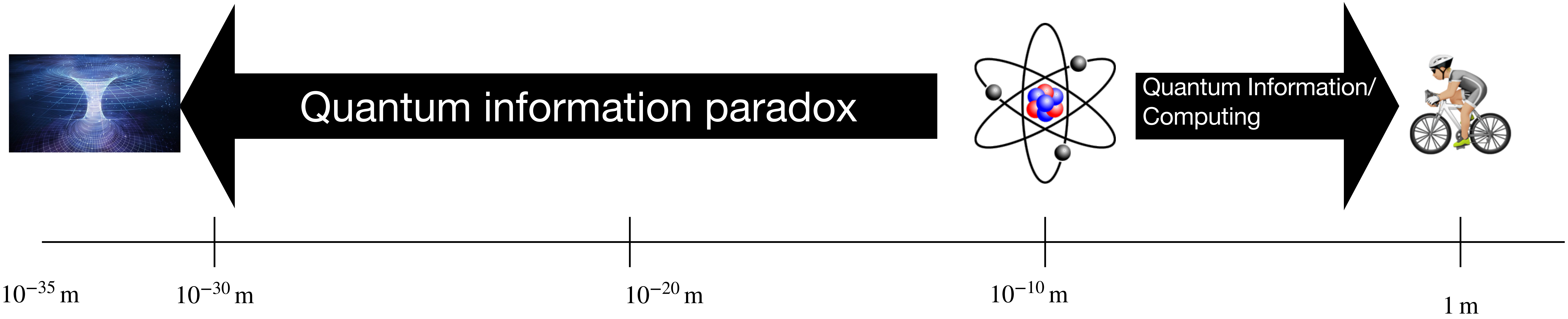
Eleni Vryonidou

Be.HEP Solstice meeting

Leuven, 21/6/24

Quantum world

Bridging different scales



adapted from F. Maltoni

Quantum world

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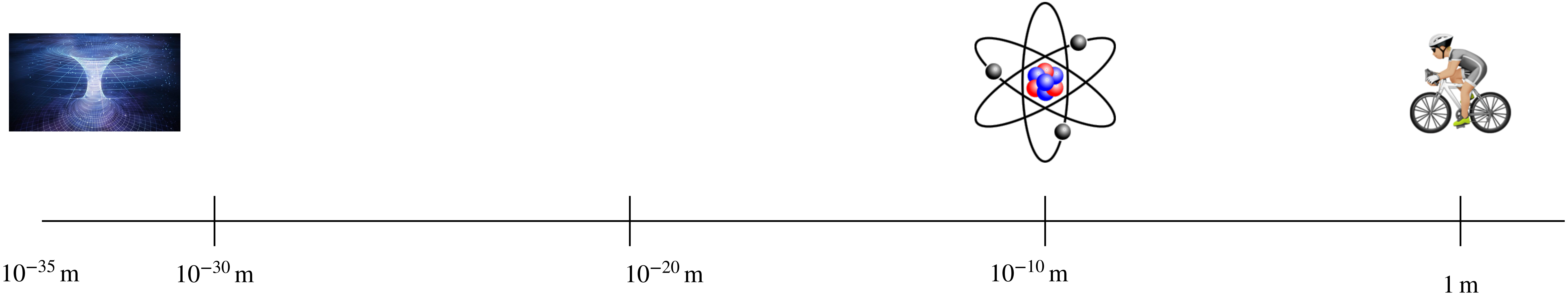

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Quantum world

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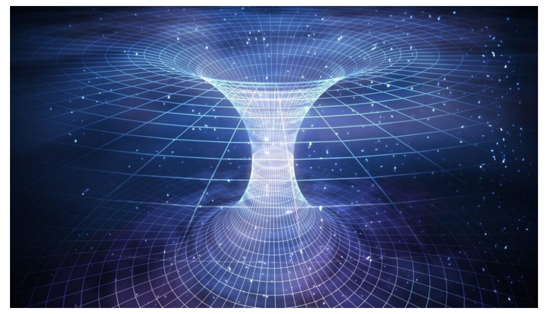
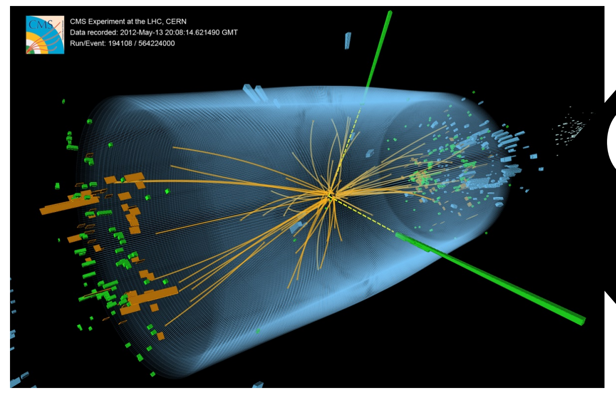
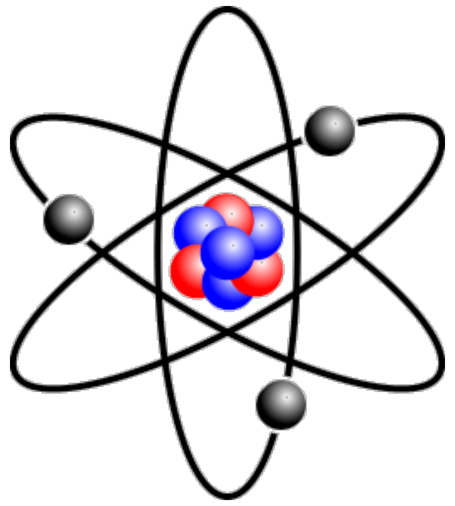




Quantum observables
at colliders



10^{-35} m — 10^{-30} m — 10^{-20} m — 10^{-10} m — 1 m

adapted from F. Maltoni

Introduction

Big interest in the theory community in the past 3-4 years

Measurement of entanglement in top pair production: Next talk!!

Why is this interesting?

Quantum mechanics at the TeV scale!

What can we learn in particle physics using QM/QI?

New insights and information about new physics

CERNCOURIER | Reporting on international high-energy physics

Physics | Technology | Community | In focus | Magazine

STRONG INTERACTIONS | NEWS

Highest-energy observation of quantum entanglement

29 September 2023

A report from the ATLAS experiment.

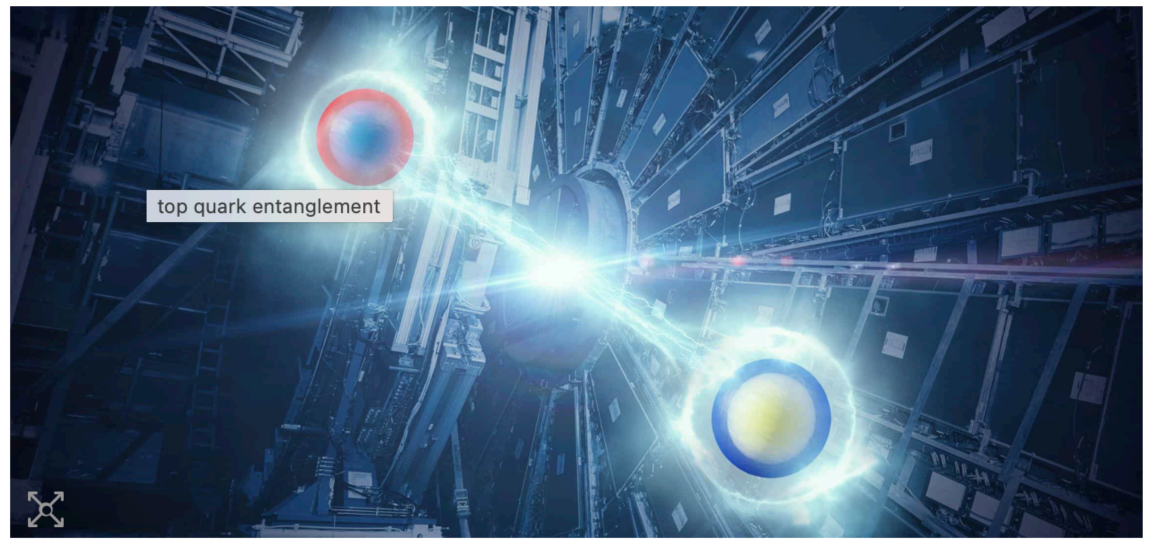
physicsworld

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)

Outline

- Quantum Mechanics basics
- Top quarks and their spins
- Quantum Tops in high—energy colliders
- Entanglement measurement and threshold effects
- Quantum observables for New Physics
- Conclusions

Density matrix

Pure versus mixed states in composite systems

Any quantum state is described by a density matrix

Product pure state	Generic state (entangled)
$\vert\psi\rangle = \vert a\rangle \otimes \vert b\rangle$	$\vert\psi\rangle = \sum_{ij} p_{ij} \vert a_i\rangle \otimes \vert b_j\rangle \qquad p_{ij} \in \mathbb{C}\,, \sum_{ij} p_{ij} p_{ij}^* = 1$ $\vert a_i\rangle, \vert b_j\rangle$ orthonormal bases

Separable	Non-separable (generic)
$\rho = \sum_i p_i\, \rho_A^i \otimes \rho_B^i$ $p_i \geq 0\,, \sum_i p_i = 1$	$\rho = \sum_{ijkl} p_{ij} p_{kl}^* \vert a_i\rangle \otimes \vert b_j\rangle\langle a_k\vert \otimes \langle b_l\vert = \sum_{ijkl} p_{ij} p_{kl}^* \vert a_i\rangle\langle a_k\vert \otimes \vert b_j\rangle\langle b_l\vert$ $\rho_A = \mathrm{Tr}_B\left[\rho\right] = \sum_{ijl} p_{ij} p_{kj}^* \vert a_i\rangle\langle a_k\vert$ $\rho_B = \mathrm{Tr}_A\left[\rho\right] = \sum_{ijl} p_{ij} p_{il}^* \vert b_j\rangle\langle b_l\vert$

The properties are different for pure and mixed states

Entanglement

For a bipartite system: $\mathscr{H} = \mathscr{H}_A \otimes \mathscr{H}_B$

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

A non-separable state is entangled

How do we check for entanglement: Peres-Horodecki criterion

A necessary criterion for separability of a mixed state of A and B:

$$\rho = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle \otimes |b_j\rangle\langle a_k| \otimes \langle b_l| \qquad \rho^{T_B} = (I \otimes T)[\rho] = \sum_{ijkl} p_{il} p_{kj}^* |a_i\rangle\langle a_k| \otimes |b_j\rangle\langle b_l|$$

The partial transpose wrt B

If ρ is separable then all the eigenvalues of ρ^{T_B} are non-negative.

In other words, if ρ^{T_B} has a negative eigenvalue, ρ is guaranteed to be entangled.

Concurrence

Take an entangled pure state between the two subsystems A and B.

$$\mathscr{H} = \mathscr{H}_A \otimes \mathscr{H}_B$$

The concurrence $C_{A|B}$ is defined as

$$0 \leq C^2_{A|B} = 2(1 - \mathrm{Tr}[\rho_A^2]) = C^2_{B|A} \leq 1$$

For mixed states, we use different entanglement witnesses and measures.

E.g. for a two-qubit system:

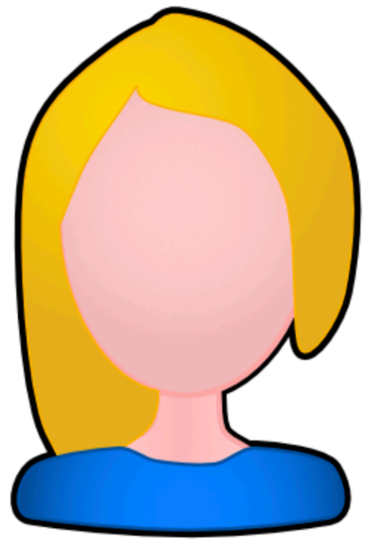
$$C = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$$

with $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$ eigenvalues of $\sqrt{\sqrt{\rho}\,(\sigma_y \otimes \sigma_y)\rho^\star(\sigma_y \otimes \sigma_y)\,\sqrt{\rho}}$

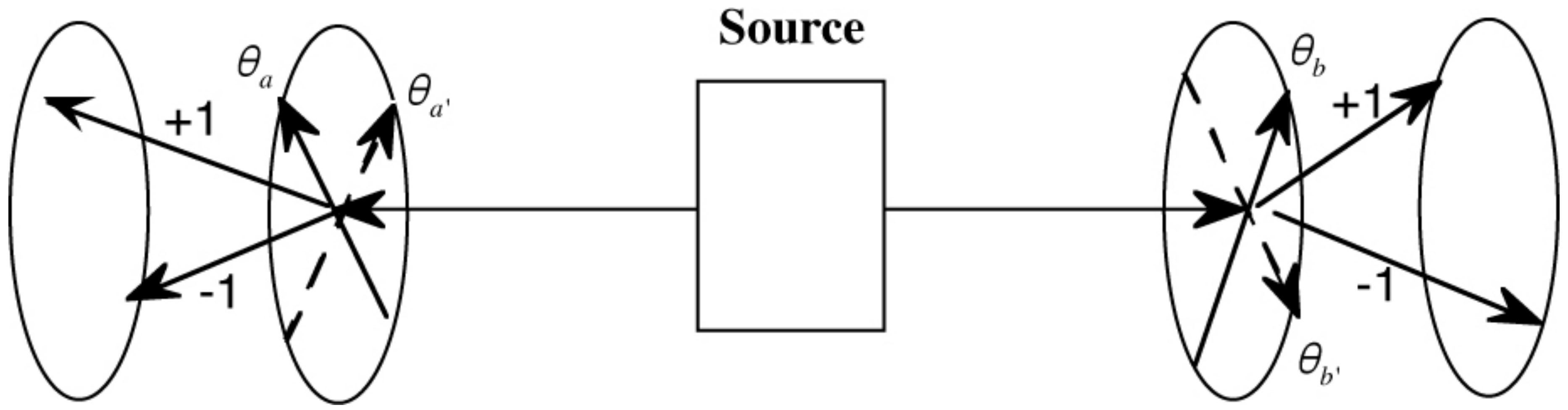
Bell inequalities

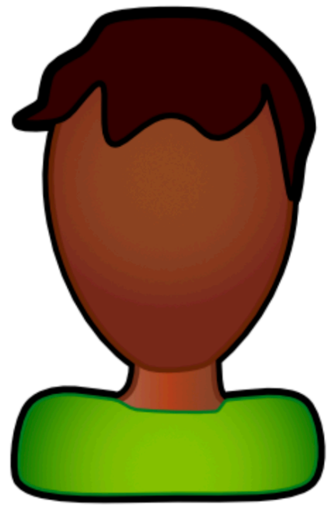
Clauser-Horne-Shimony-Holt (CSHS) inequality

Bell locality means (classically):



Alice





Bob

$$E(AB) + E(AB') + E(A'B) - E(A'B') \leq 2$$

Violation of Bell Inequalities means non-locality

In Quantum mechanics:

$$E(AB) + E(AB') + E(A'B) - E(A'B') = 2\sqrt{2}$$

Violating Bell locality

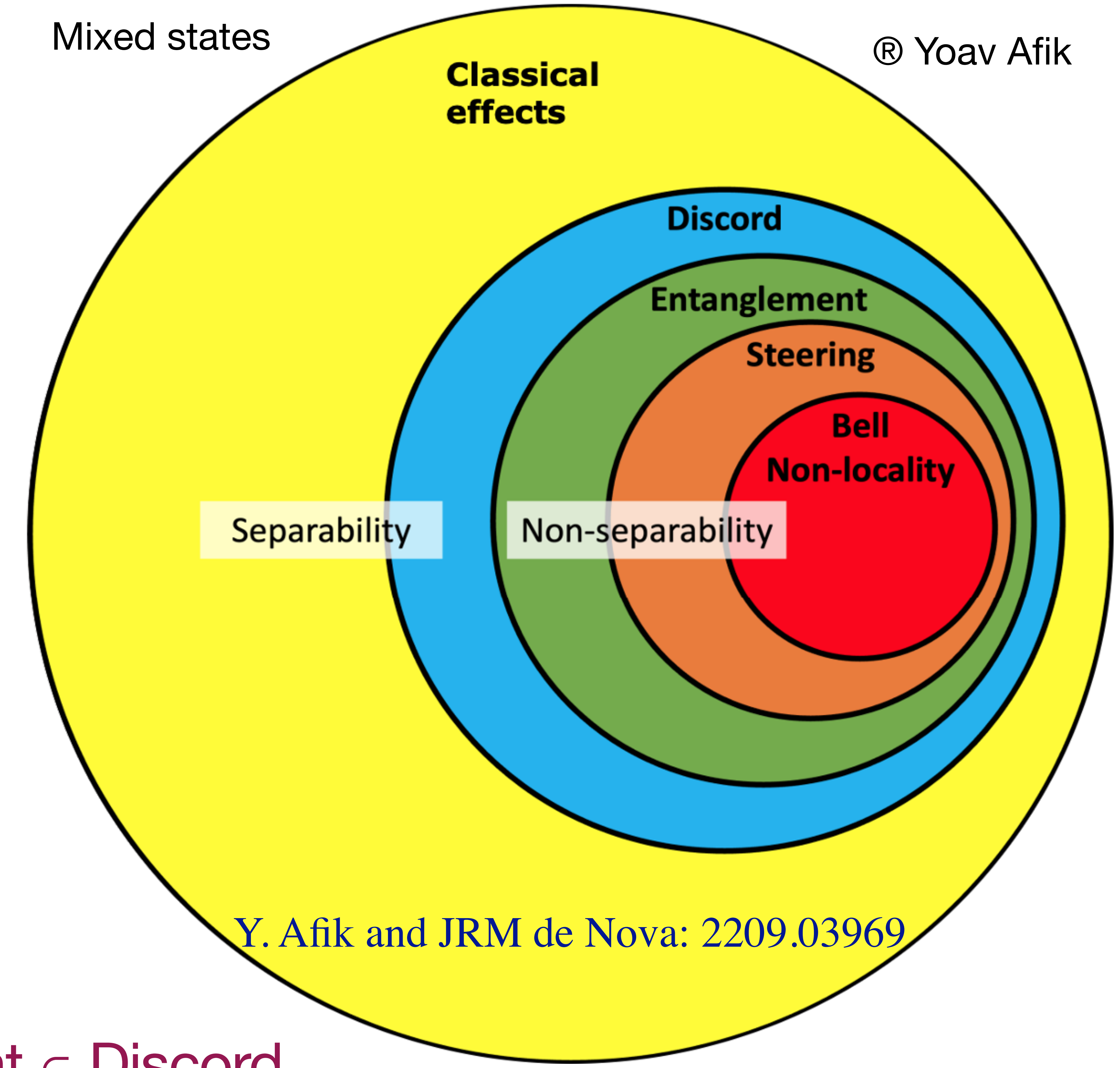
Different levels of correlations

Entanglement: difference between separable and non-separable states.

Quantum discord is an asymmetric measure of nonclassical correlations between two subsystems of a system, based on the difference between two different quantum definitions of mutual information.

Quantum steering differs from entanglement for mixed states and it is also asymmetric.

Bell non-locality needs a strong quantum correlation. For pure states it just amounts to entanglement again.



Bell Non-locality ⊂ Steering ⊂ Entanglement ⊂ Discord

Top quark

Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs

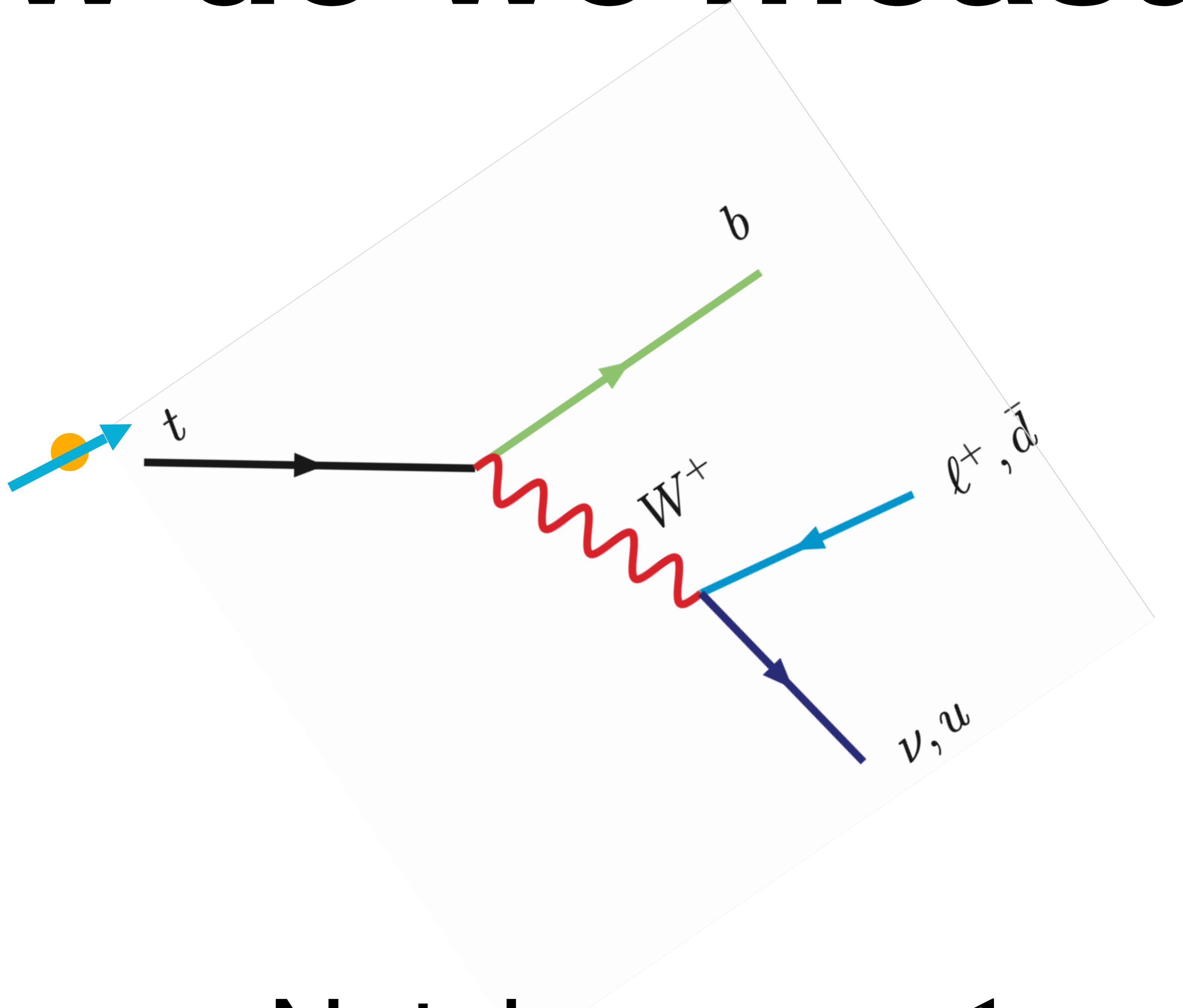
2. Portal to new physics: e.g. EWSB, composite Higgs

3. LHC is a top factory: precise access to top properties through a lot of production channels, see Didar's talk

4. Weak decays before hadronisation

5. **Top spins in pair production: a 2-qubit system!**

How do we measure the spins?



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_X} = \frac{1+\alpha_X\cos\theta_X}{2}$$

$\alpha_\ell = 1$ Spin analysing power

Noteby: $\alpha_d = 1, \alpha_u = -0.3, \alpha_b = -0.4, \alpha_W = 0.4$

The direction of the charged lepton is 100% correlated with the top quark spin

Allows to reconstruct the top spin by measuring the angular distribution of the lepton

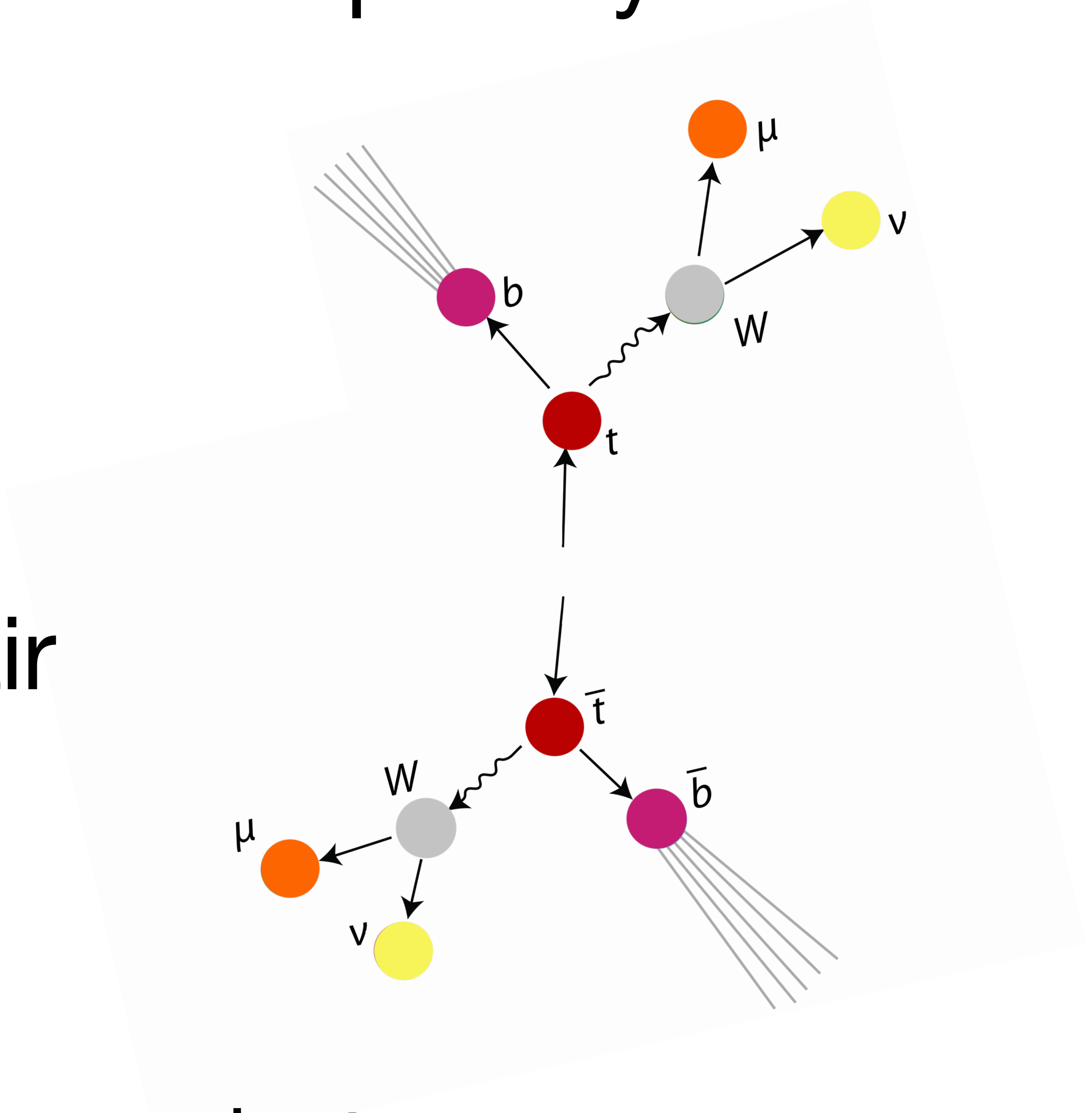
Basis of all spin correlation/entanglement measurements in tops

Spin density matrix

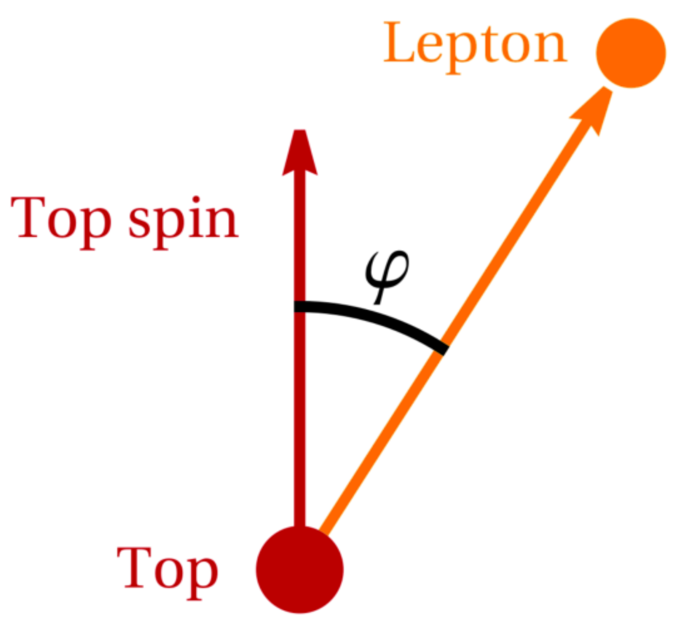
Tops produced in pairs have their spins S_i, S_j correlated: a two-qubit system

Spin density matrix:

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



15 parameters describe the quantum state of the top pair

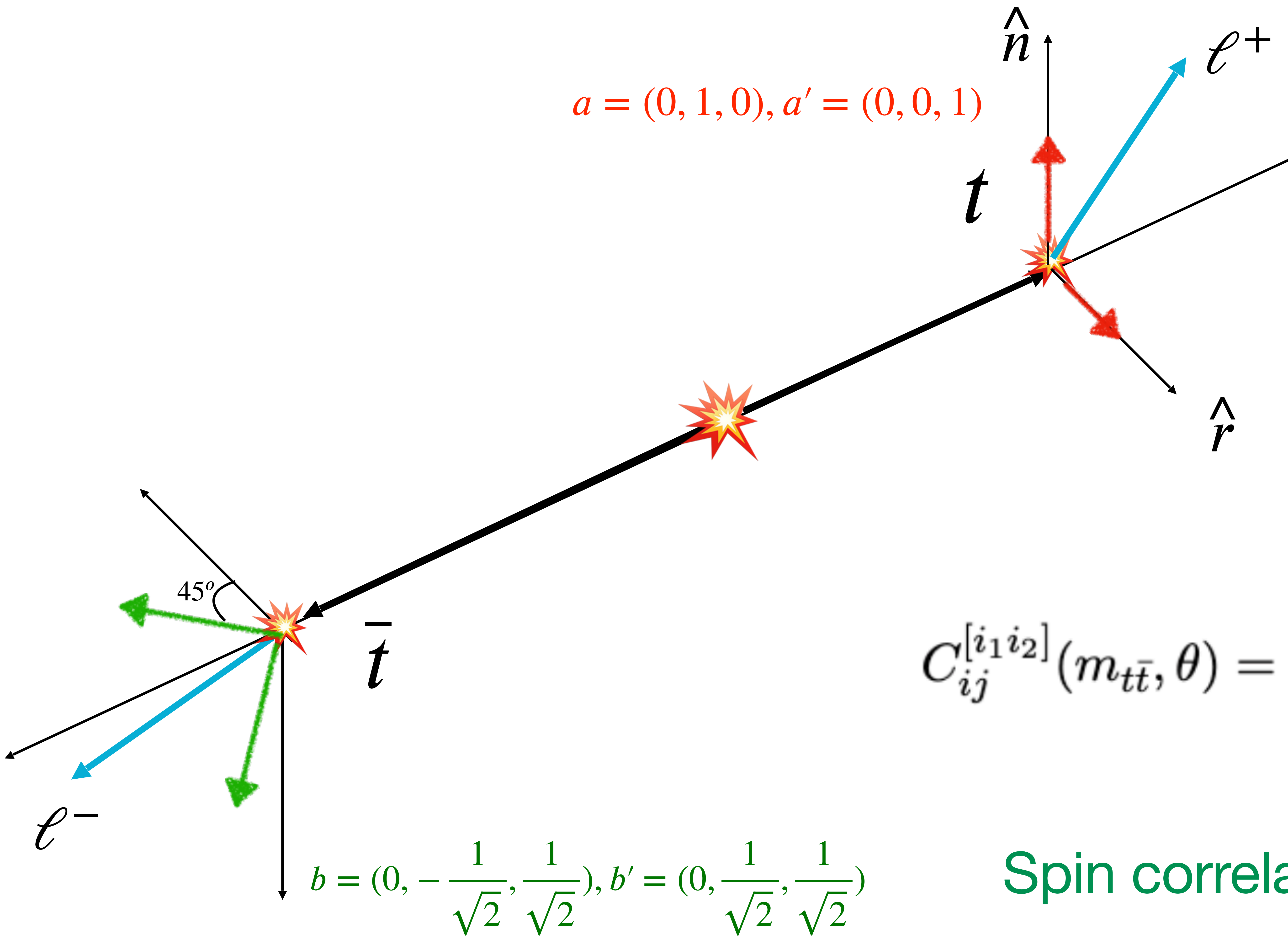


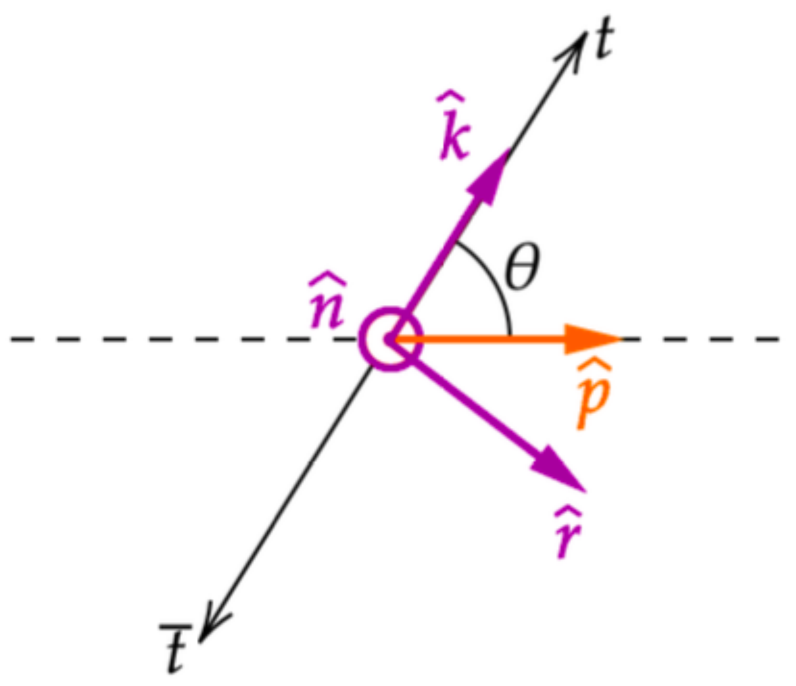
$$\langle S_i \rangle = B_i, \quad \langle \bar{S}_i \rangle = \bar{B}_j, \quad \langle S_i \bar{S}_j \rangle = C_{ij}$$

Extracted by measuring angular distributions of decay products

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

Kinematics





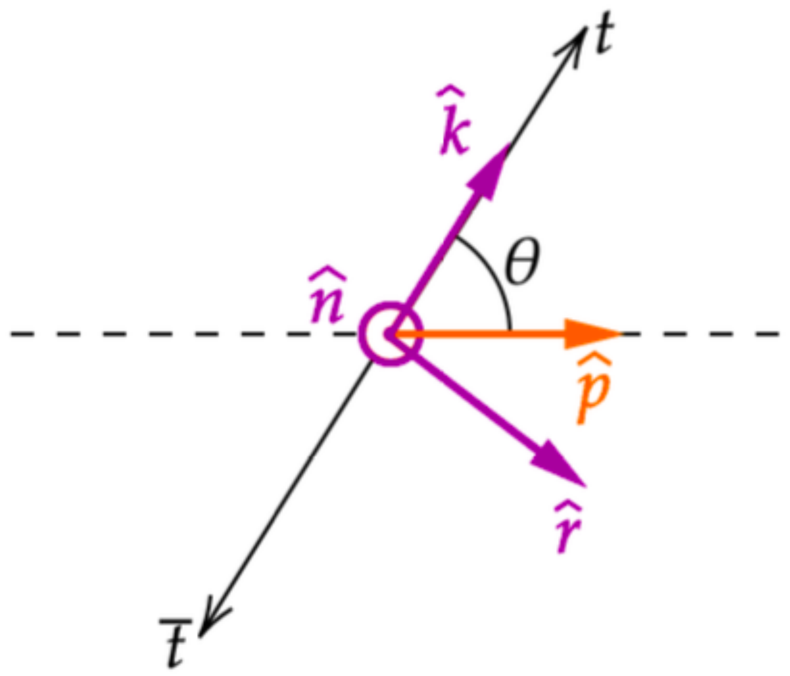
$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

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

Spin correlations to entanglement



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

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

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

Entanglement markers, from the Peres-Horodecki criterion

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

for a proof see arXiv:2003.02280

Necessary and sufficient condition for entanglement

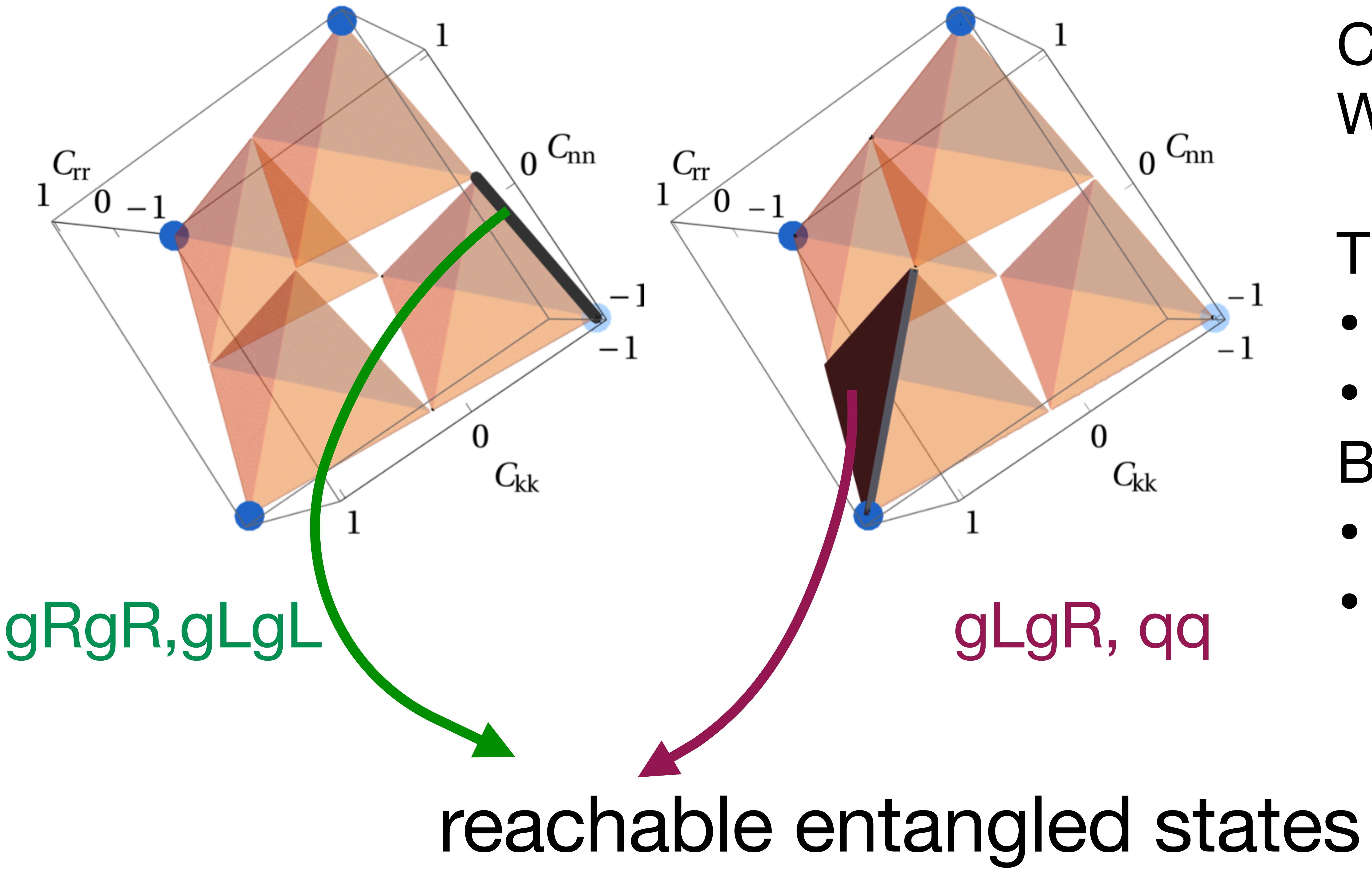
$$C = \frac{1}{2}\max\left(0, -1 - 3D_{\text{min}}\right) > 0$$

$$\mathcal{C}^{(\text{singlet})} = \begin{pmatrix} -\eta & 0 & 0 \\ 0 & -\eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}, \qquad \mathcal{C}^{(\text{triplet})} = \begin{pmatrix} \eta & 0 & 0 \\ 0 & \eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}, \qquad 0 < \eta \leq 1$$

$$D^{(1)} = -\eta \qquad\qquad D^{(i)} = -\eta$$

$$\eta > \frac{1}{3} \implies \text{entanglement},$$
$$\eta > \frac{1}{\sqrt{2}} \implies \text{Bell inequality violation}$$
$$\eta = 1 \implies \text{pure state.}$$

When are tops entangled?



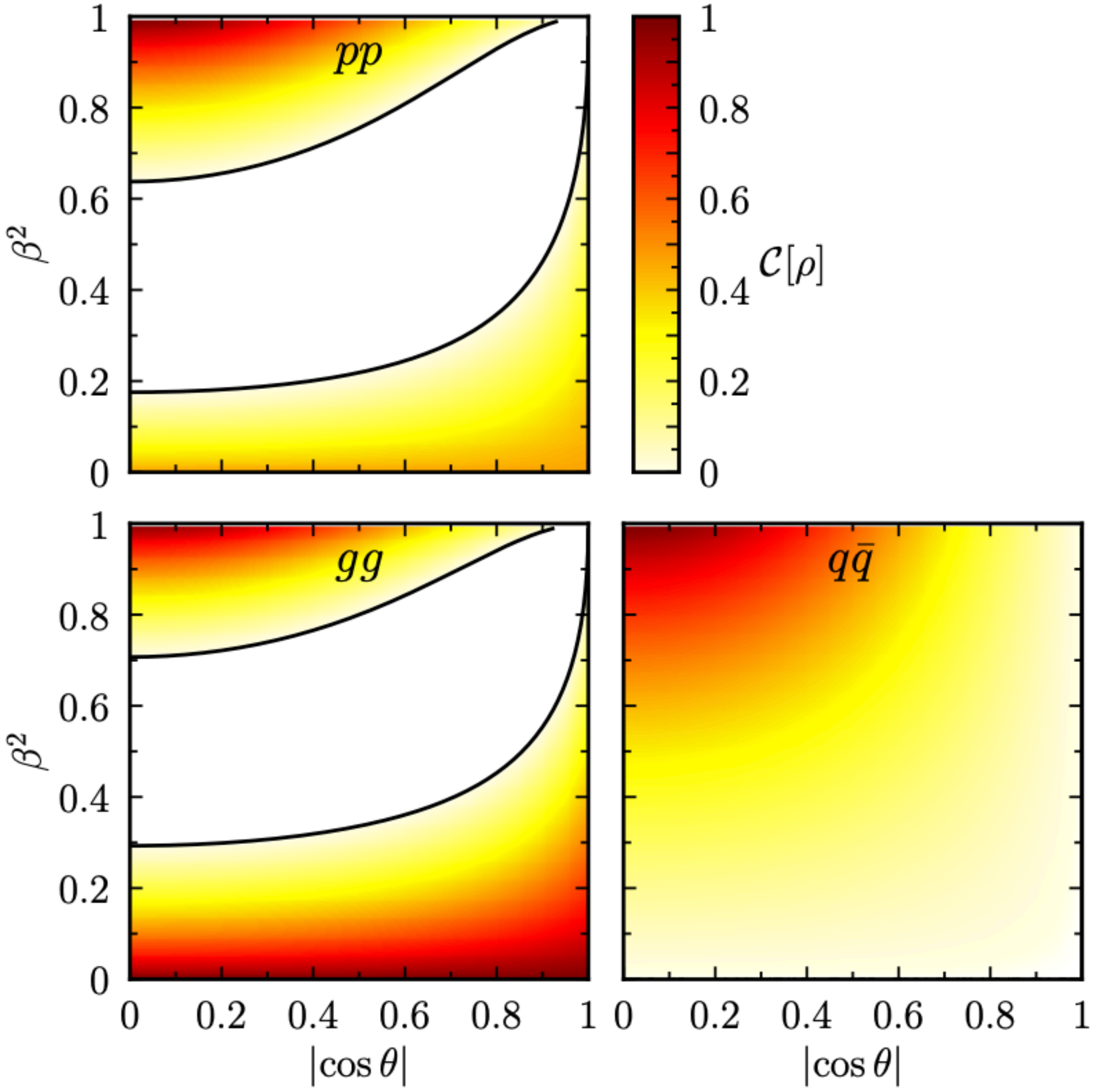
Consider top pair production in pp collisions
Which spin states can be reached?

Threshold:
- entangled singlet state
- from same helicity gluons

Boosted:
- entangled triplet state
- for qqbar pairs and opposite helicity gluons

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

Entanglement in the SM



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

White regions: no entanglement (C<0)

Maximal entanglement regions

At threshold: $\beta^2 = 0, \forall\theta$

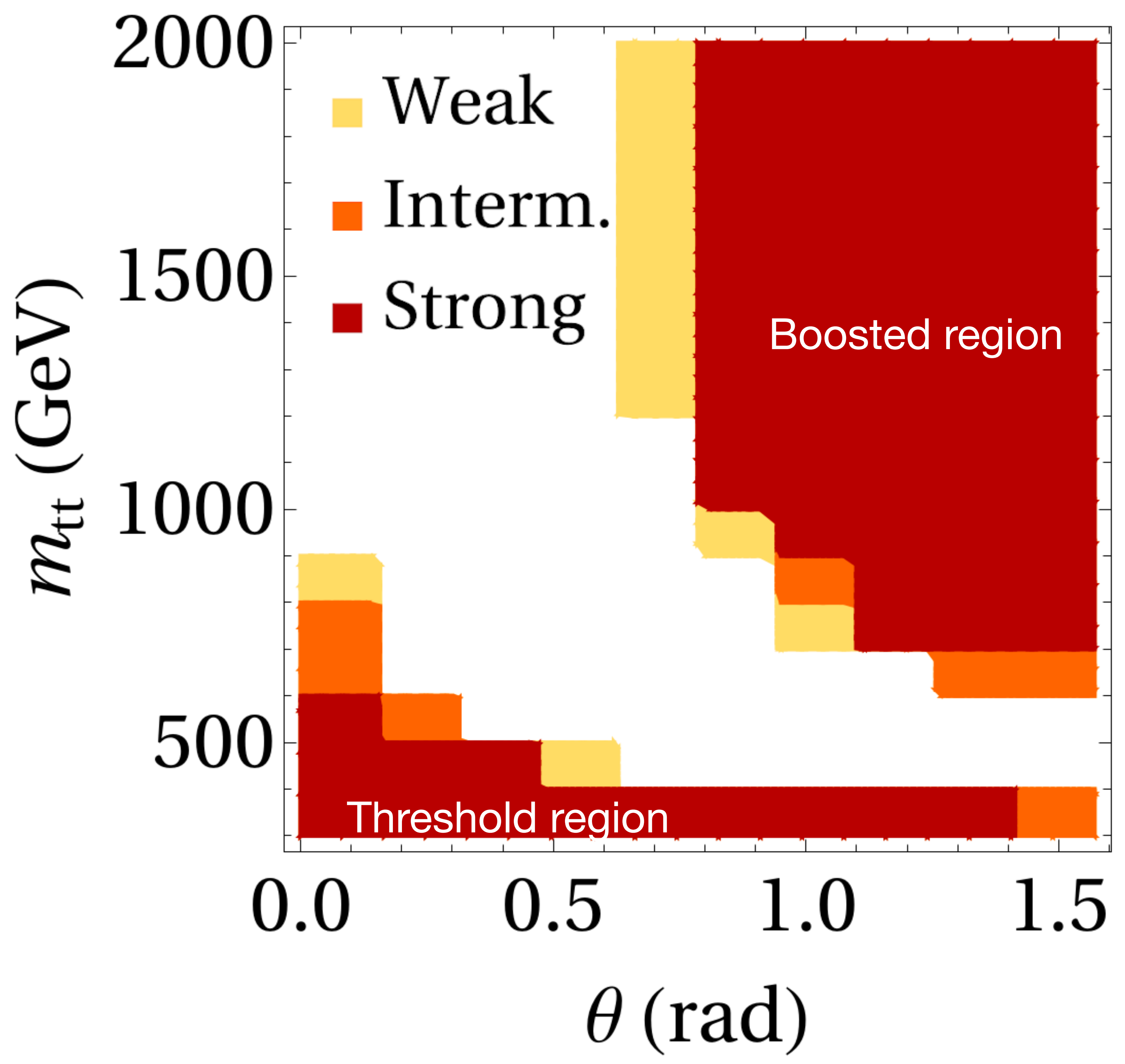
High-Energy: $\beta^2 \to 1, \cos\theta = 0$

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

Entanglement in top pair production

Can we see this experimentally?

Region	Selection	Cross section	$\lvert C_{kk}+C_{rr}\rvert - C_{nn}$ Reconstructed	$\lvert C_{kk}+C_{rr}\rvert - C_{nn}$ Significance for > 1
Threshold	Weak	14 pb	1.31 ± 0.02	$\gg 5\sigma$
	Intermediate	12 pb	1.34 ± 0.02	$\gg 5\sigma$
	Strong	10 pb	1.38 ± 0.02	$\gg 5\sigma$
High-p_T	Weak	1.9 pb	1.32 ± 0.07	5σ
	Intermediate	1.5 pb	1.36 ± 0.08	4σ
	Strong	1.0 pb	1.42 ± 0.13	3σ



Entanglement observable at the LHC

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

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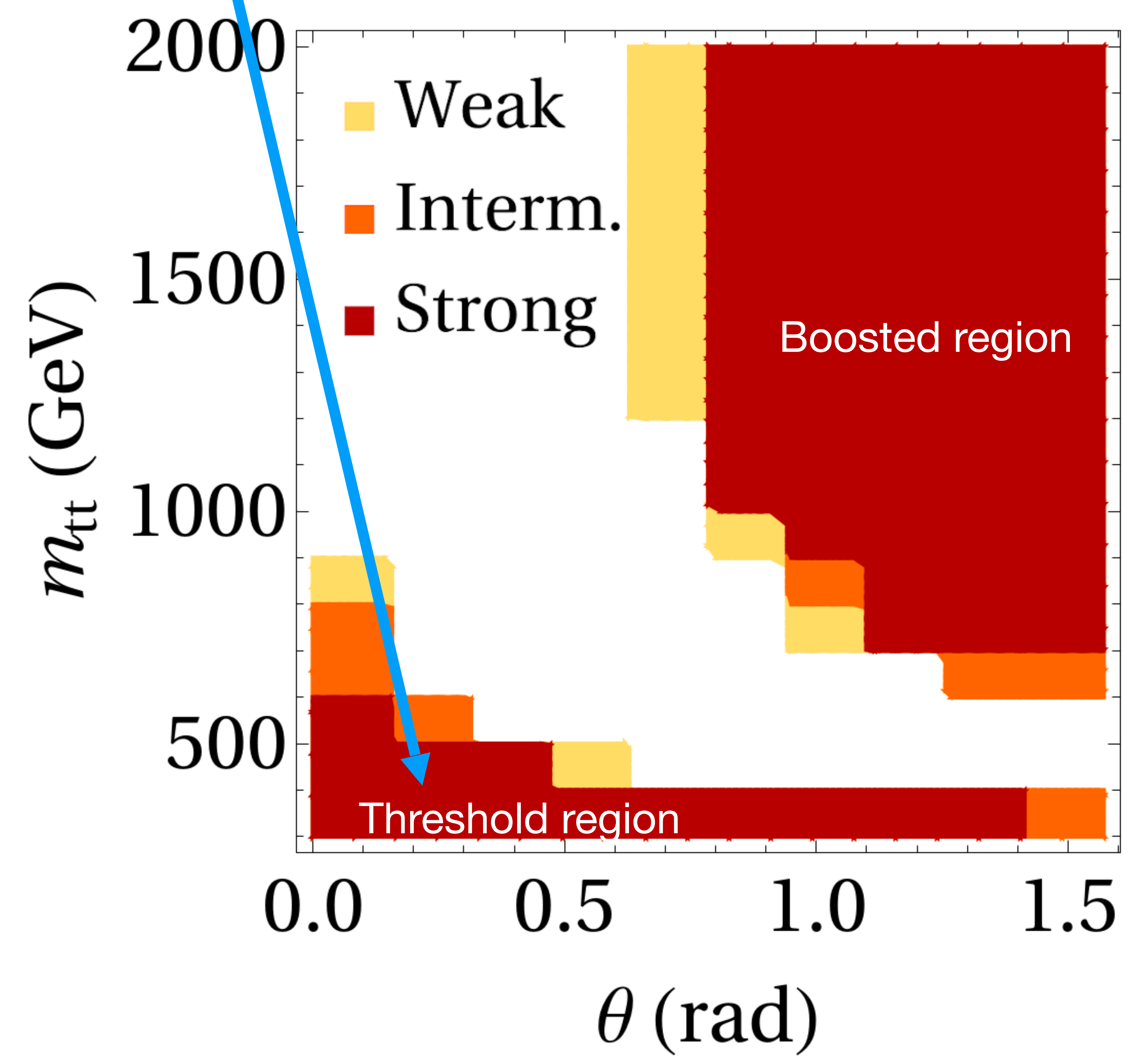
C. Severi, C. Boschi, F. Maltoni, M. Sioli : 2110.10112

$-C_{kk} - C_{rr} - C_{nn} > 1$



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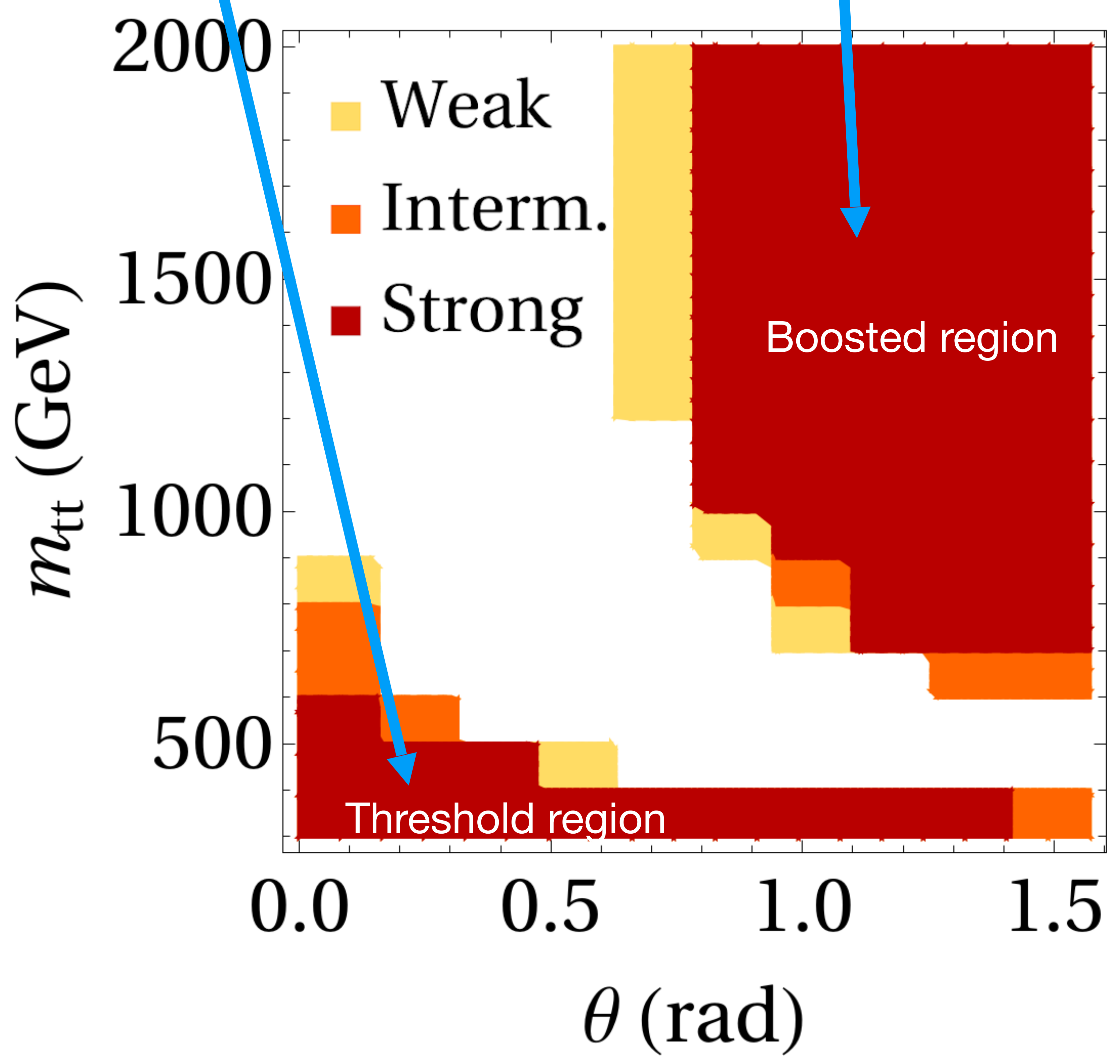
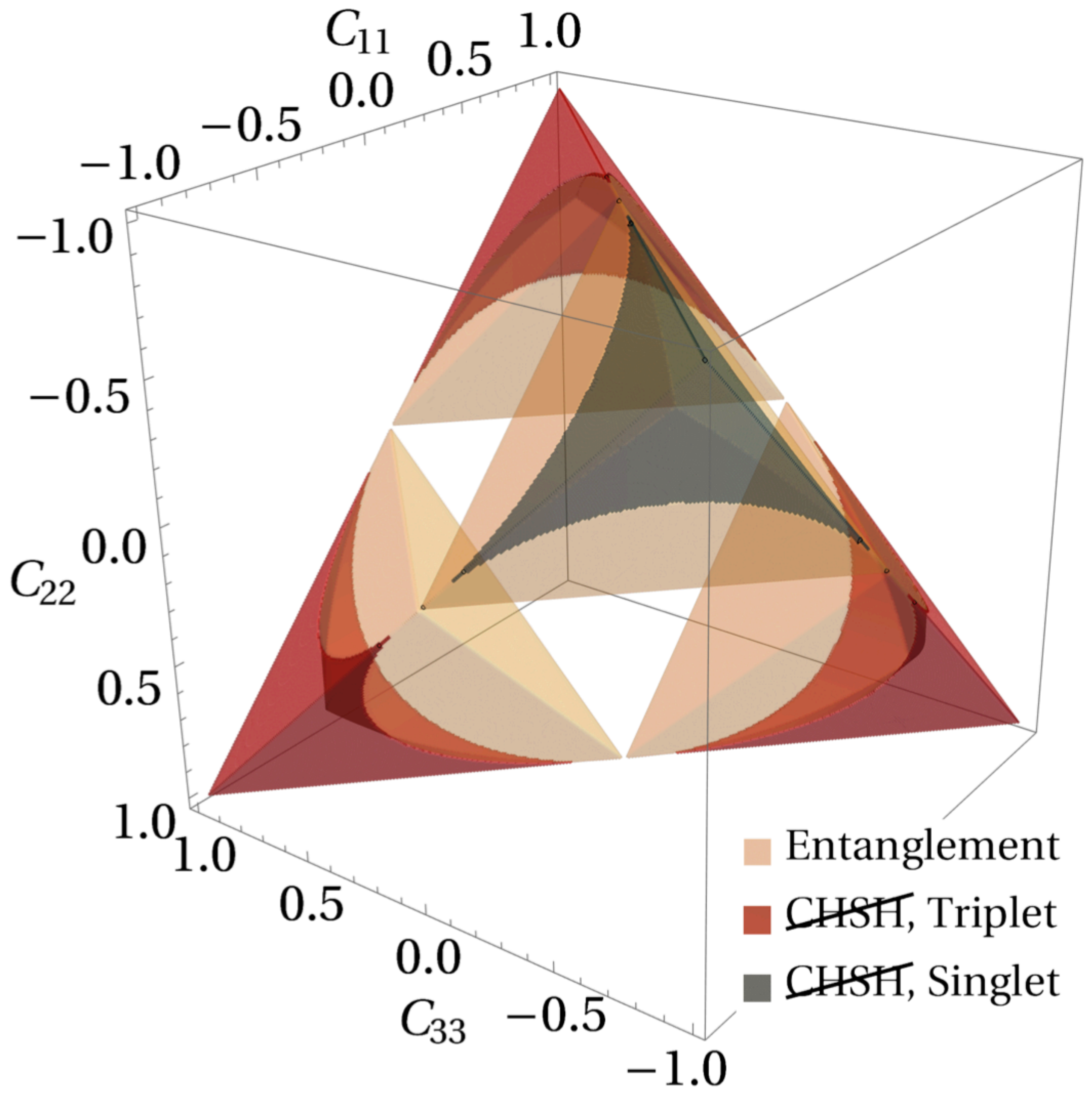
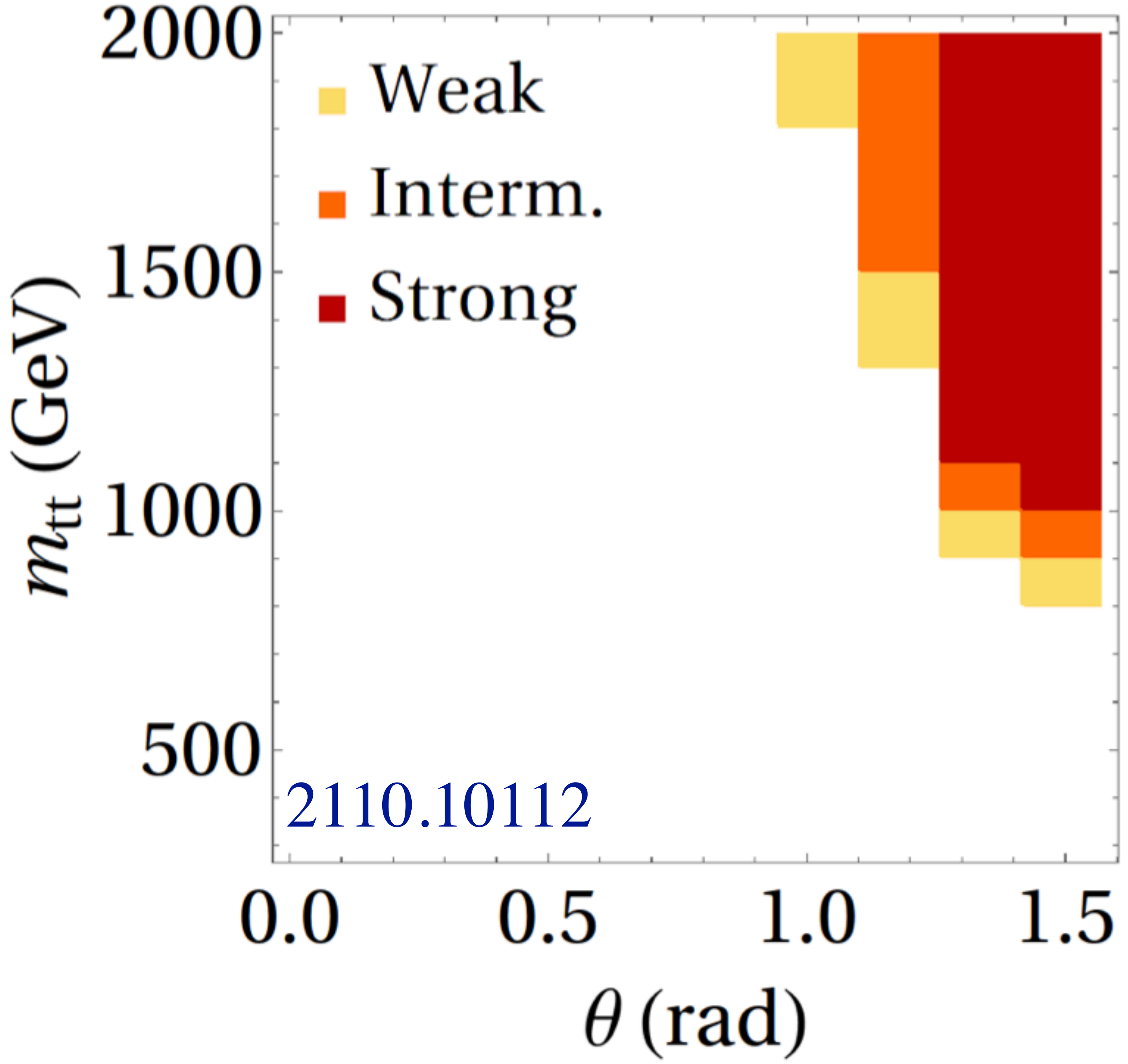
$C_{kk} + C_{rr} - C_{nn} > 1$

$-C_{kk} - C_{rr} - C_{nn} > 1$



How about Bell inequalities?





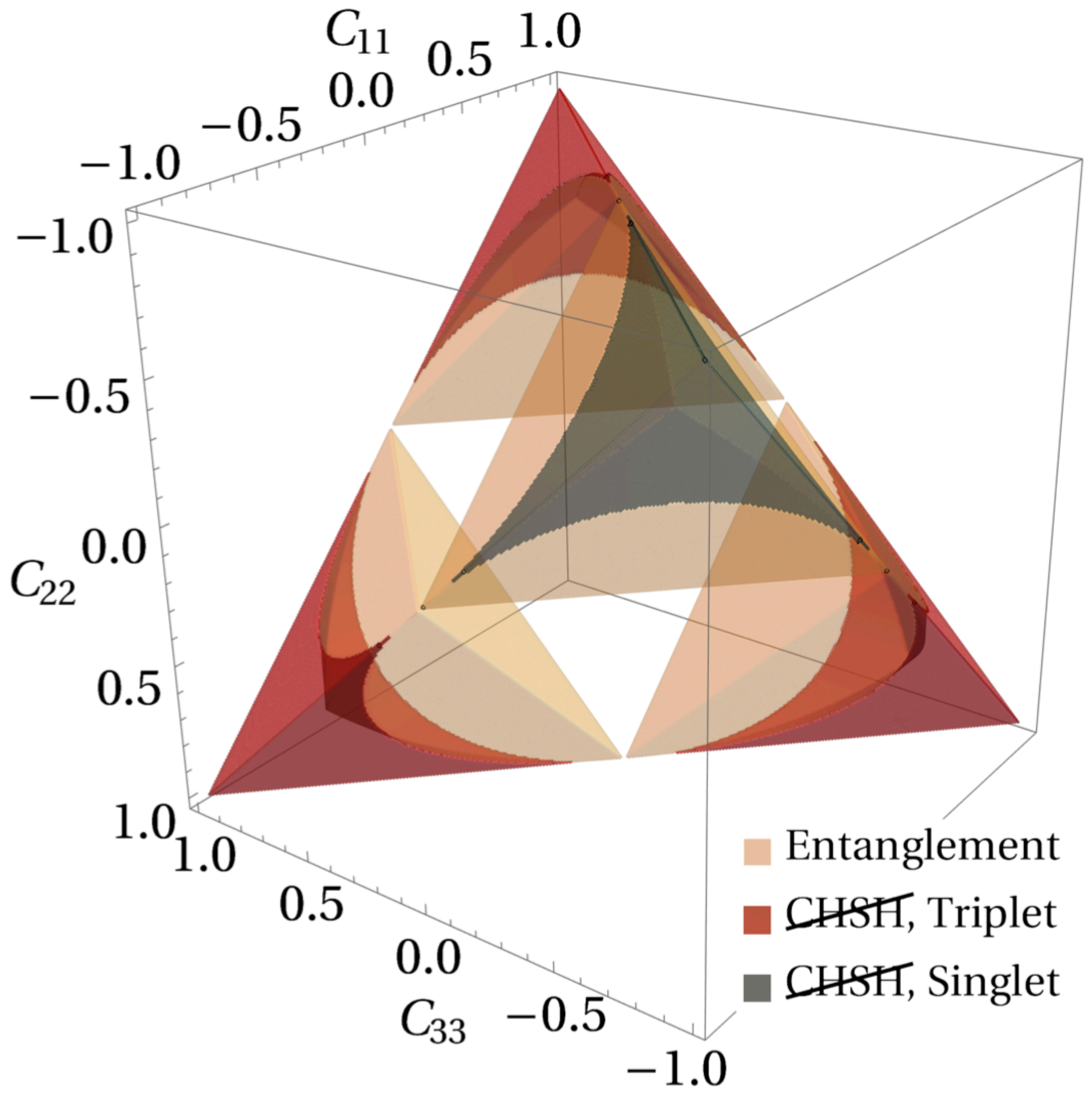
CHSH $$\left|\sum_{ij} C_{ij}\left(a_i b_j - a_i b'_j + a'_i b_j + a'_i b'_j\right)\right| \leq 2$$

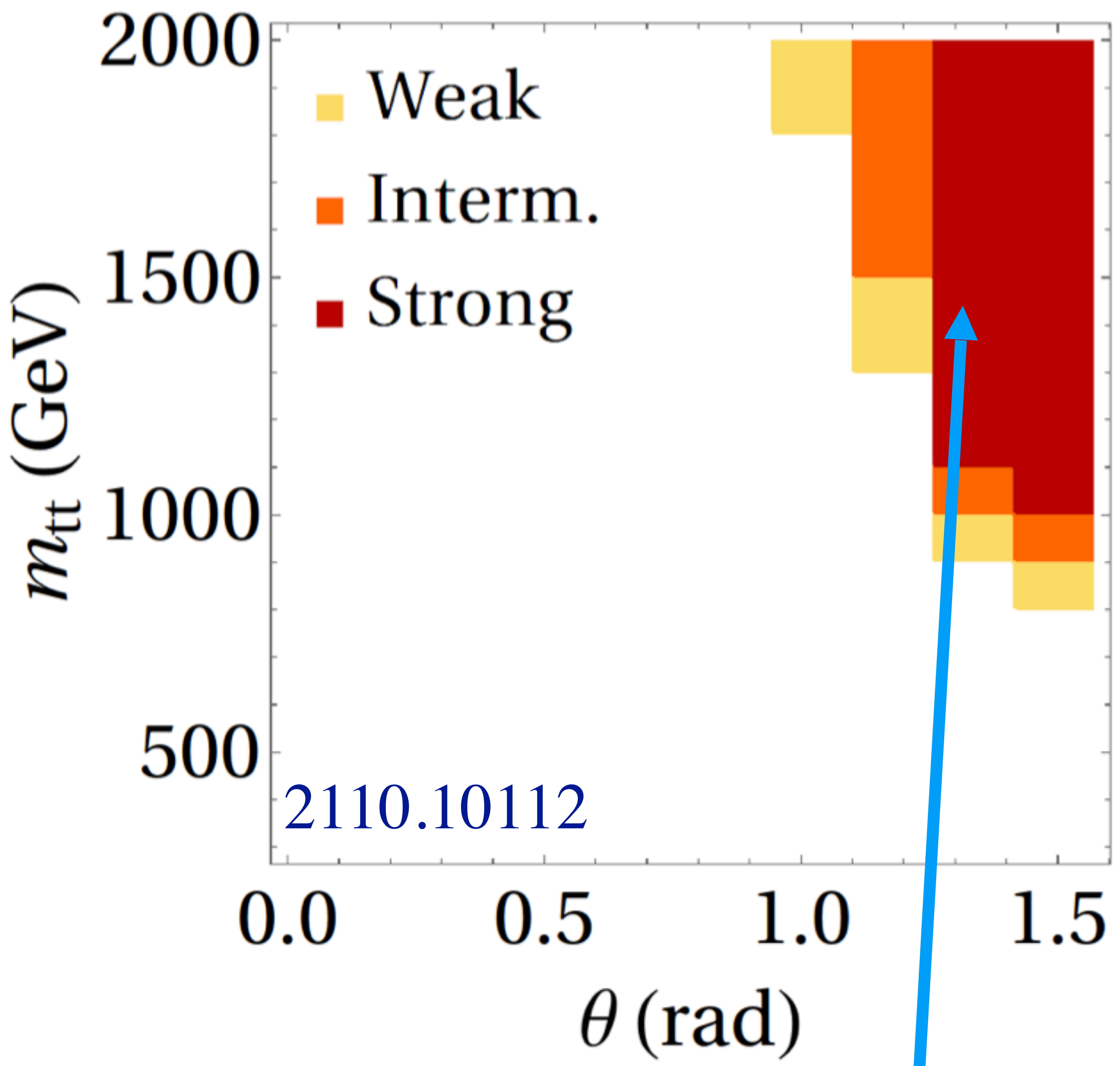
$$\max_{a\,a'\,b\,b'}\left|\sum_{ij} C_{ij}\left(a_i b_j - a_i b'_j + a'_i b_j + a'_i b'_j\right)\right| = 2\sqrt{\lambda + \lambda'},$$

two largest eigenvalues of $C^T C$

Much harder to see Bell inequalities violation

How about Bell inequalities?





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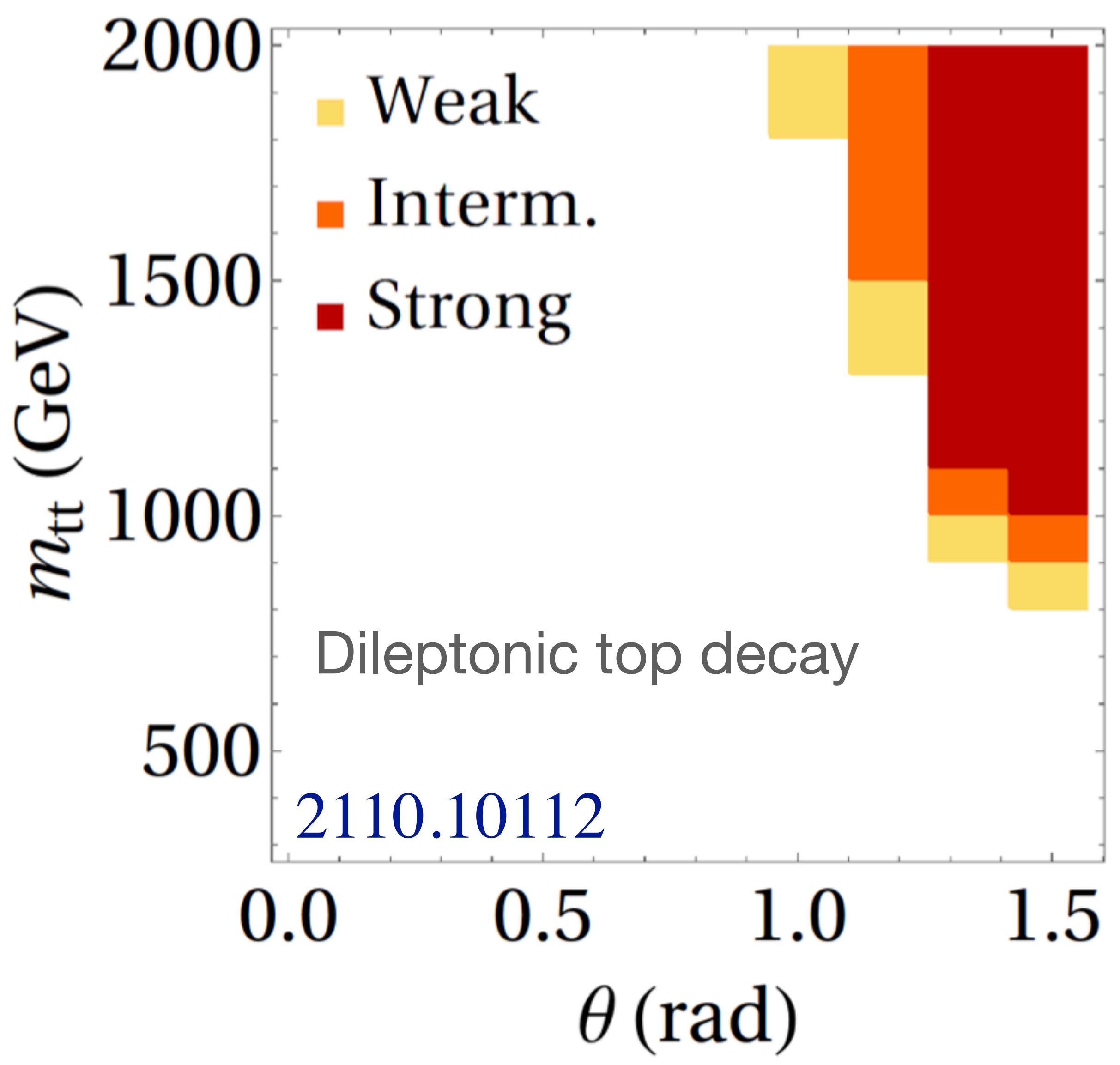
two largest eigenvalues of $C^T C$

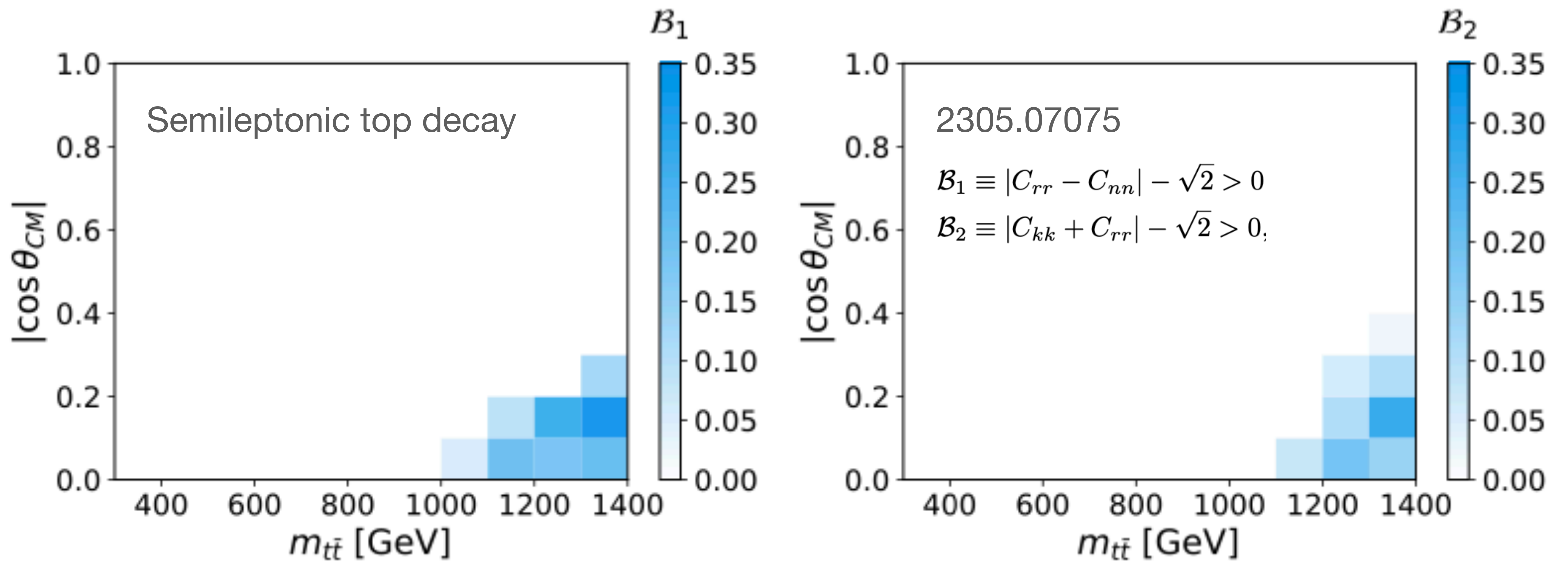
$$\sqrt{2}\,\left|-C_{rr} + C_{nn}\right| > 2$$

Much harder to see Bell inequalities violation

Bell-inequalities



High-p_T Selection	Cross section	Significance for > 2 w/ 3 ab^{-1}
Weak	0.58 pb	83% CL
Intermediate	0.31 pb	81% CL
Strong	0.17 pb	66% CL



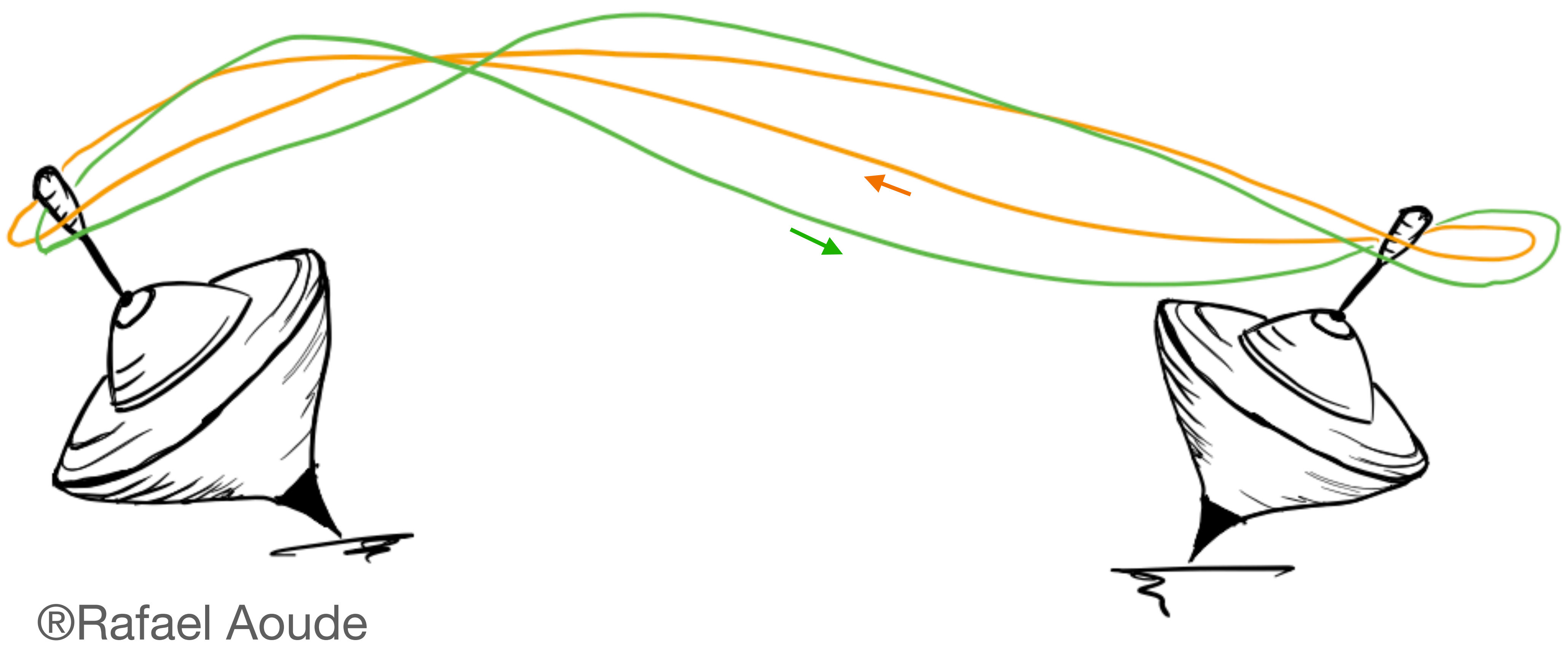
Indicator	Parton-level	Unfolded	Significance ($\mathcal{L} = 3$ ab^{-1})
$\mathcal{B}_1$	0.267 ± 0.023	0.274 ± 0.057	4.8
$\mathcal{B}_2$	0.204 ± 0.023	0.272 ± 0.058	4.7

Better statistics, use of boosted top tagging
Use of optimal hadronic direction

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

More challenging to observe

Quantum tops @ LHC



®Rafael Aoude

Y. Afik and JRM de Nova: 2003.02280 [quant-ph]

M. Fabbrichesi, R. Floreanini. G. Panizzo: 2102.11883 [hep-ph]

C. Severi, C. Boschi, F.Maltoni, M. Sioli : 2110.10112 [hep-ph]

Y. Afik and JRM de Nova: 2203.05582 [quant-ph]

R. Aoude, E. Madge, F.Maltoni , L. Mantani: 2203.05619 [hep-ph]

J.A. Aguilar-Saavedra, J.A. Casas: 2205.00542 [hep-ph]

Y. Afik and JRM de Nova: 2209.03969 [quant-ph]

C. Severi, EV: 2210.09330 [hep-ph]

Z. Dong, D. Gonçalves, K. Kong, A. Navarro: 2305.07075 [hep-ph]

J.A. Aguilar-Saavedra : 2307.06991 [hep-ph]

T. Han, M. Low, TA Wu: 2310.17696 [hep-ph]

J.A. Aguilar-Saavedra, J.A. Casas: 2401.06854 [hep-ph]

C. Severi, F.Maltoni, S. Tentori, EV: 2401.08751[hep-ph]

C. Severi, F.Maltoni, S. Tentori, EV: 2404.08049[hep-ph]

Many other papers on VV, H→VV, $\tau^+\tau^-$, tW,...

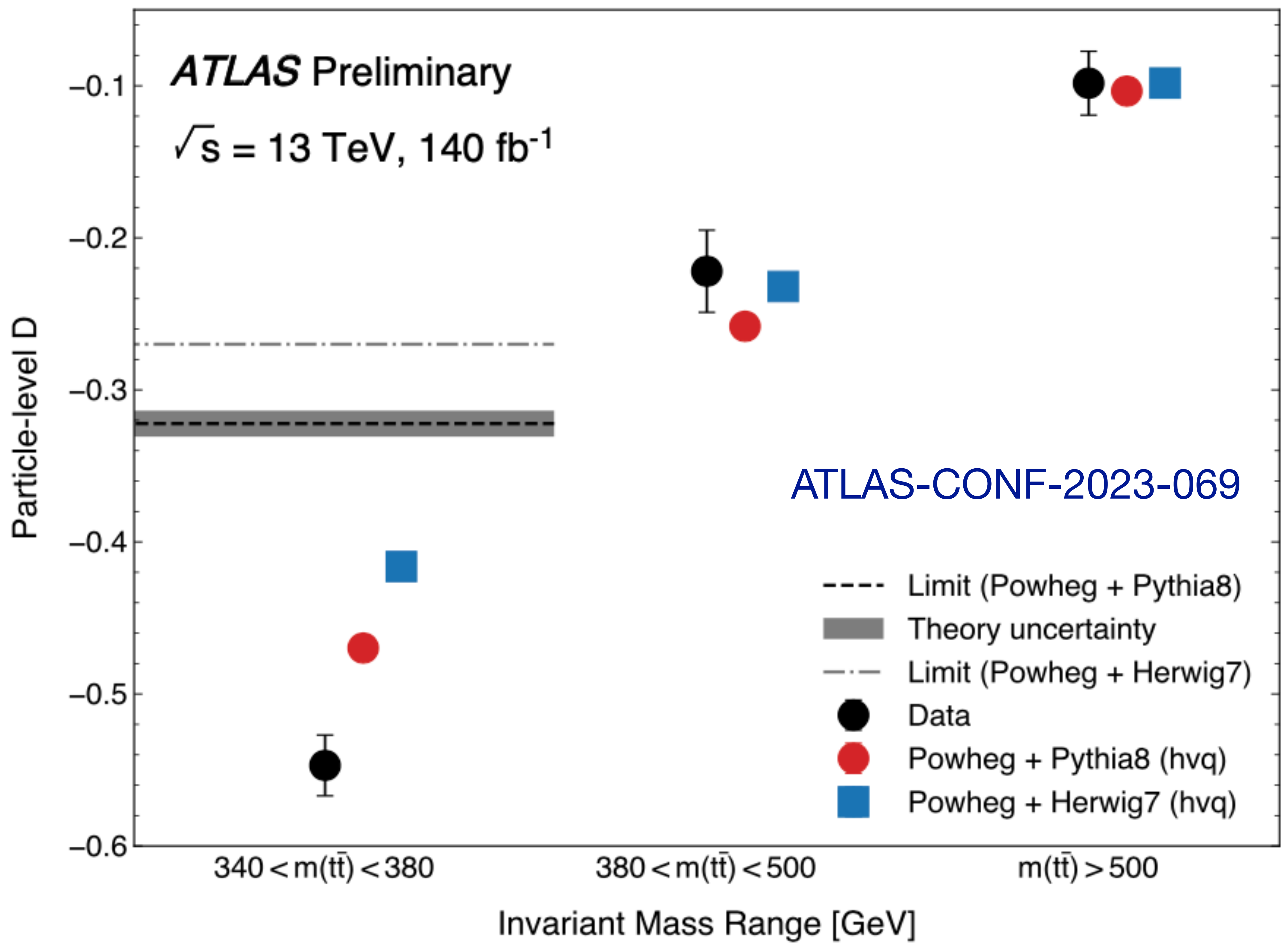
See also a review: A. Barr, Fabbrichesi, Floreanini, Gabrielli, Marzola arXiv: 2402.07972

Summary so far

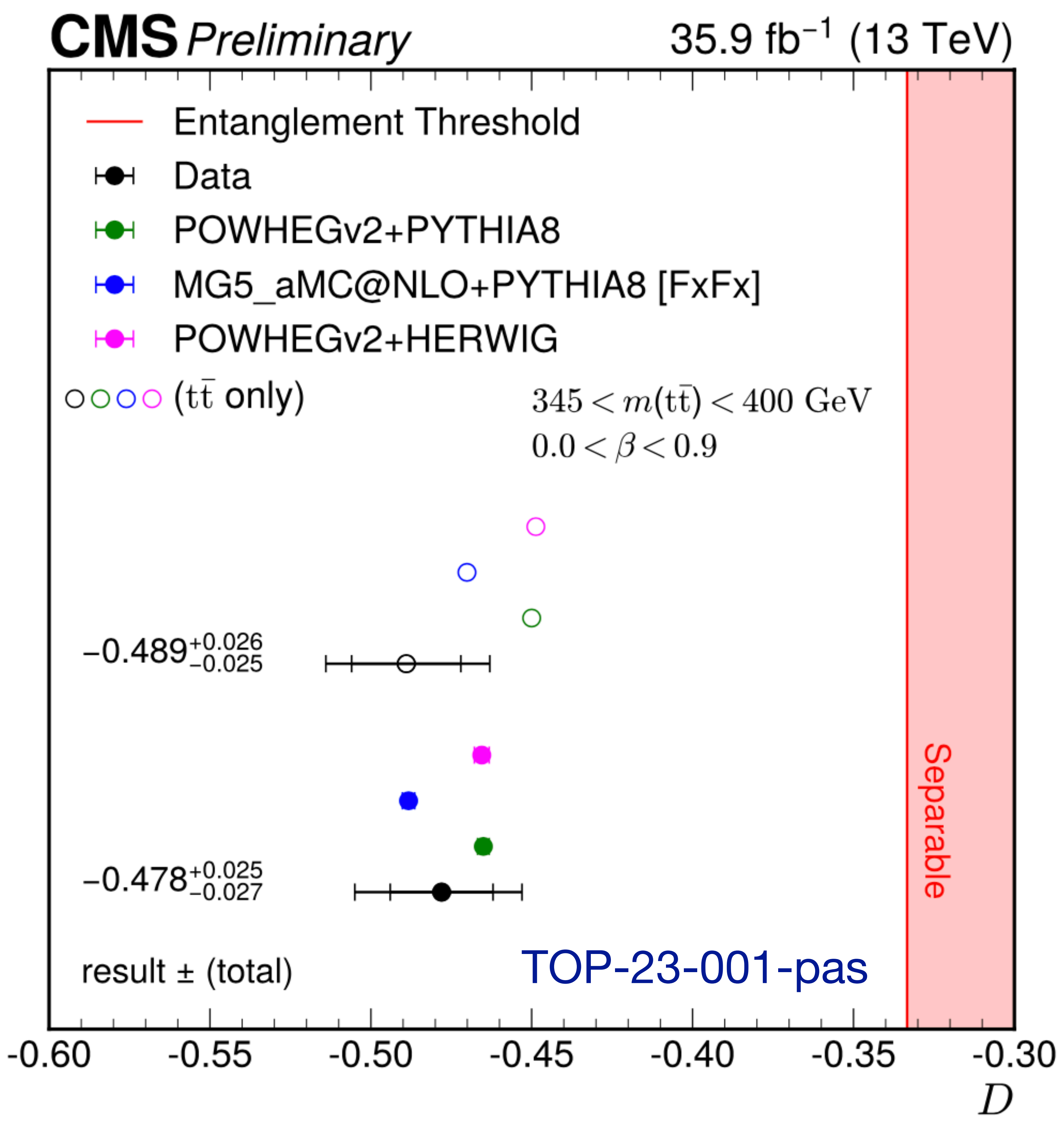
- Principles of quantum mechanics applied to top quarks pairs:
  a 2-qubit system
- Different degrees of correlations from classical to Bell inequality violation
- Correlations depend on the production mode and hence kinematic regions
- Prospects for quantum measurements explored by phenomenologists

How about experimentally?

First measurements

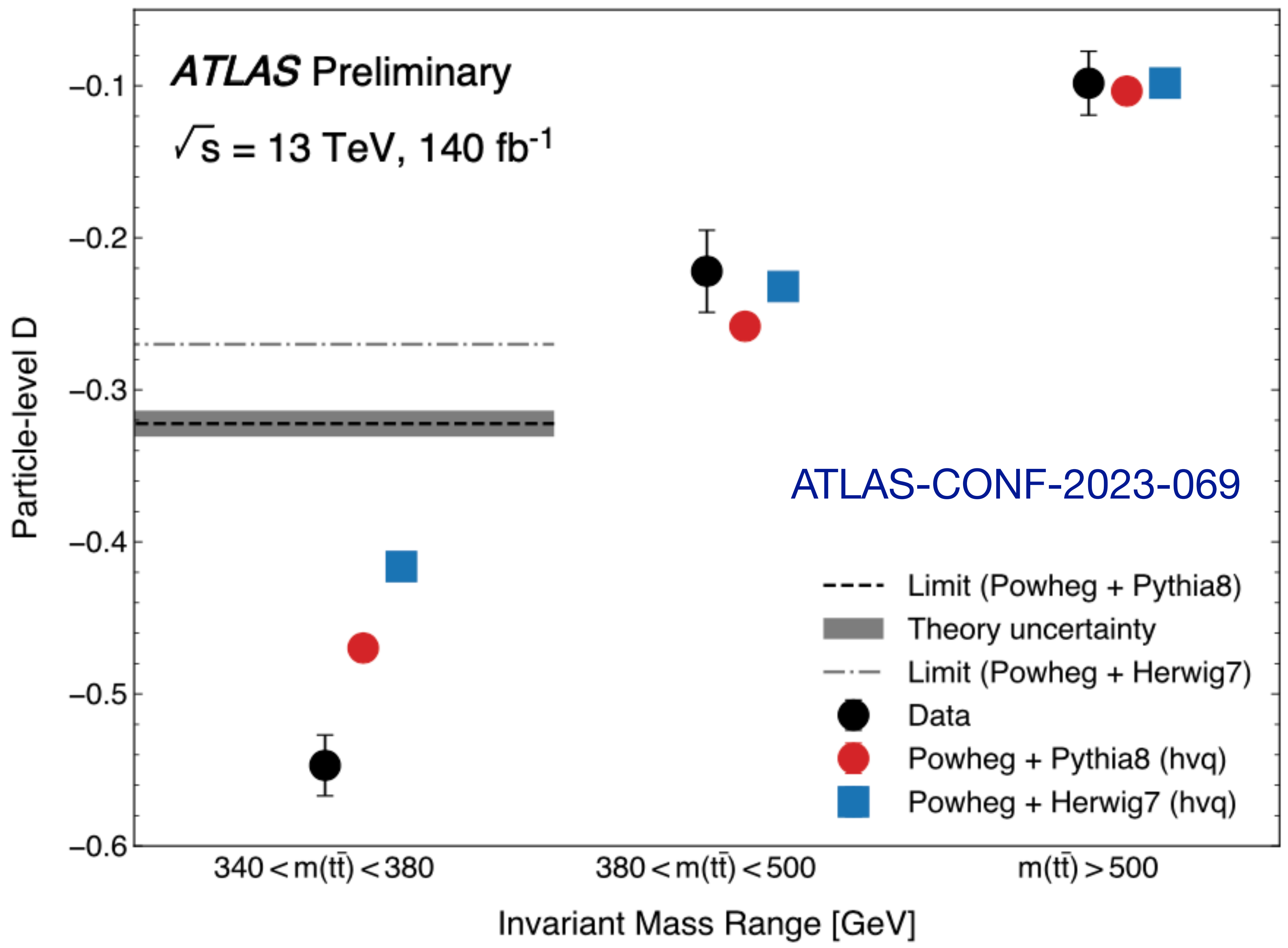


Entanglement observation by ATLAS

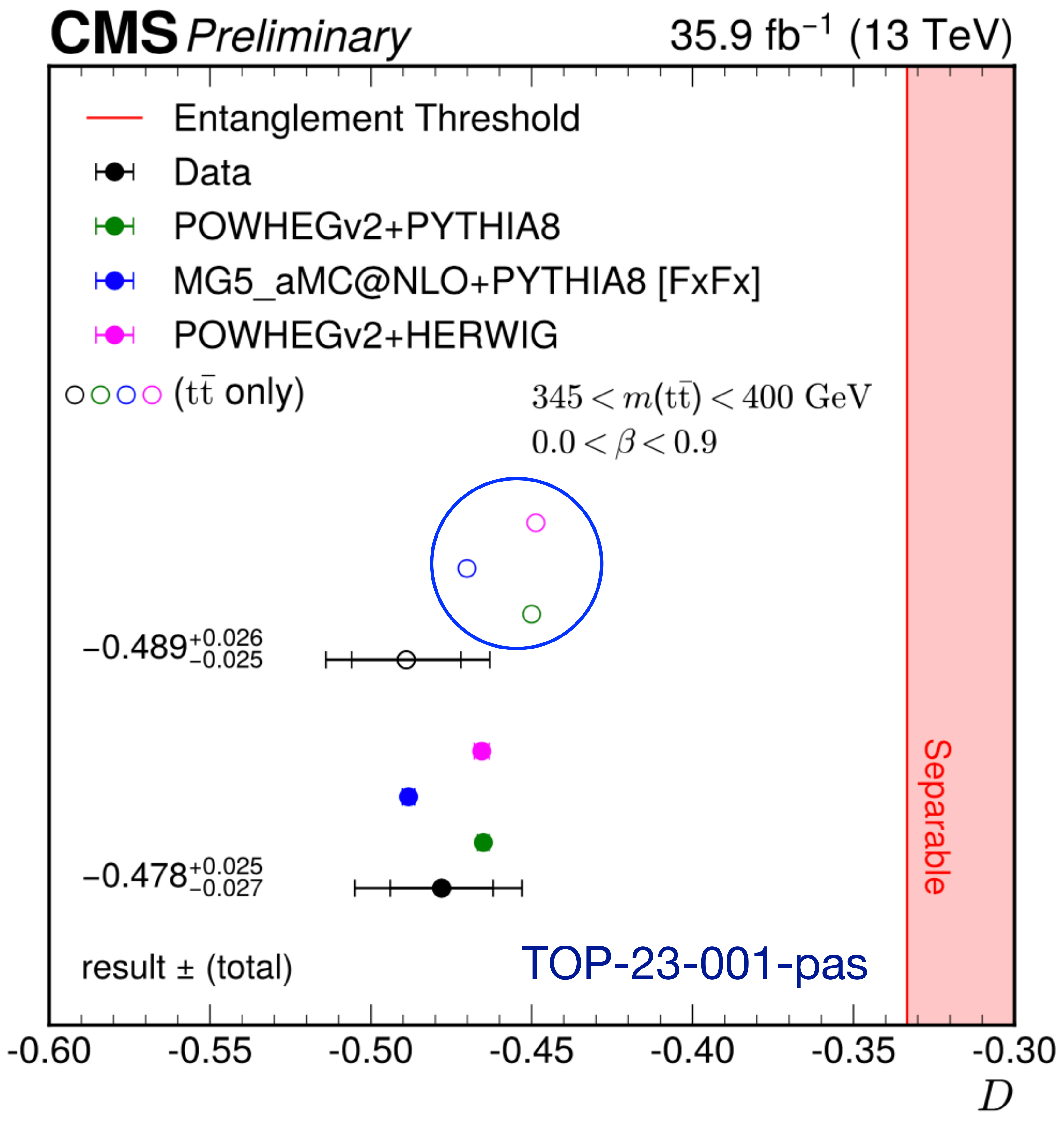


Entanglement observation by CMS

First measurements

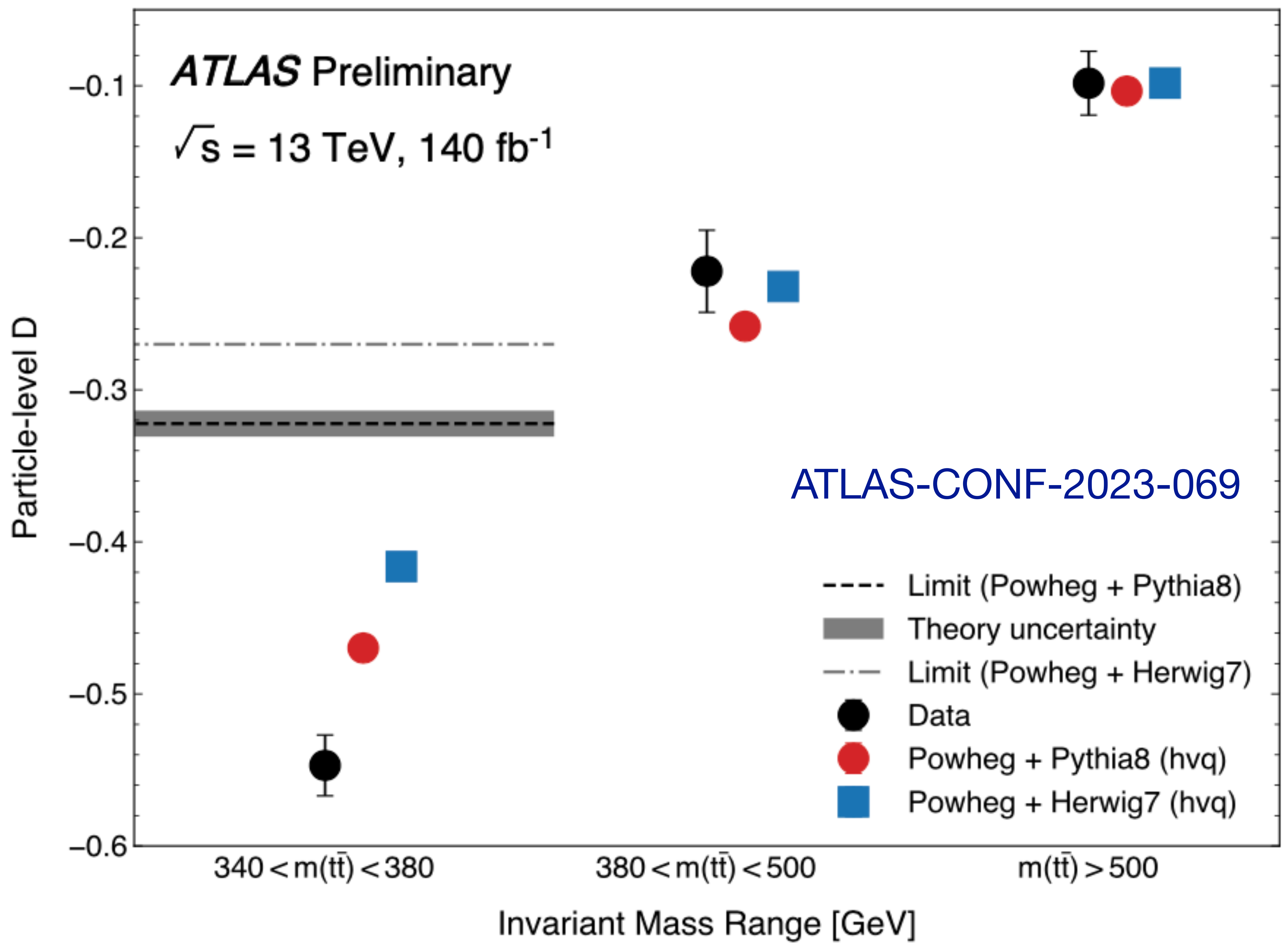


Entanglement observation by ATLAS

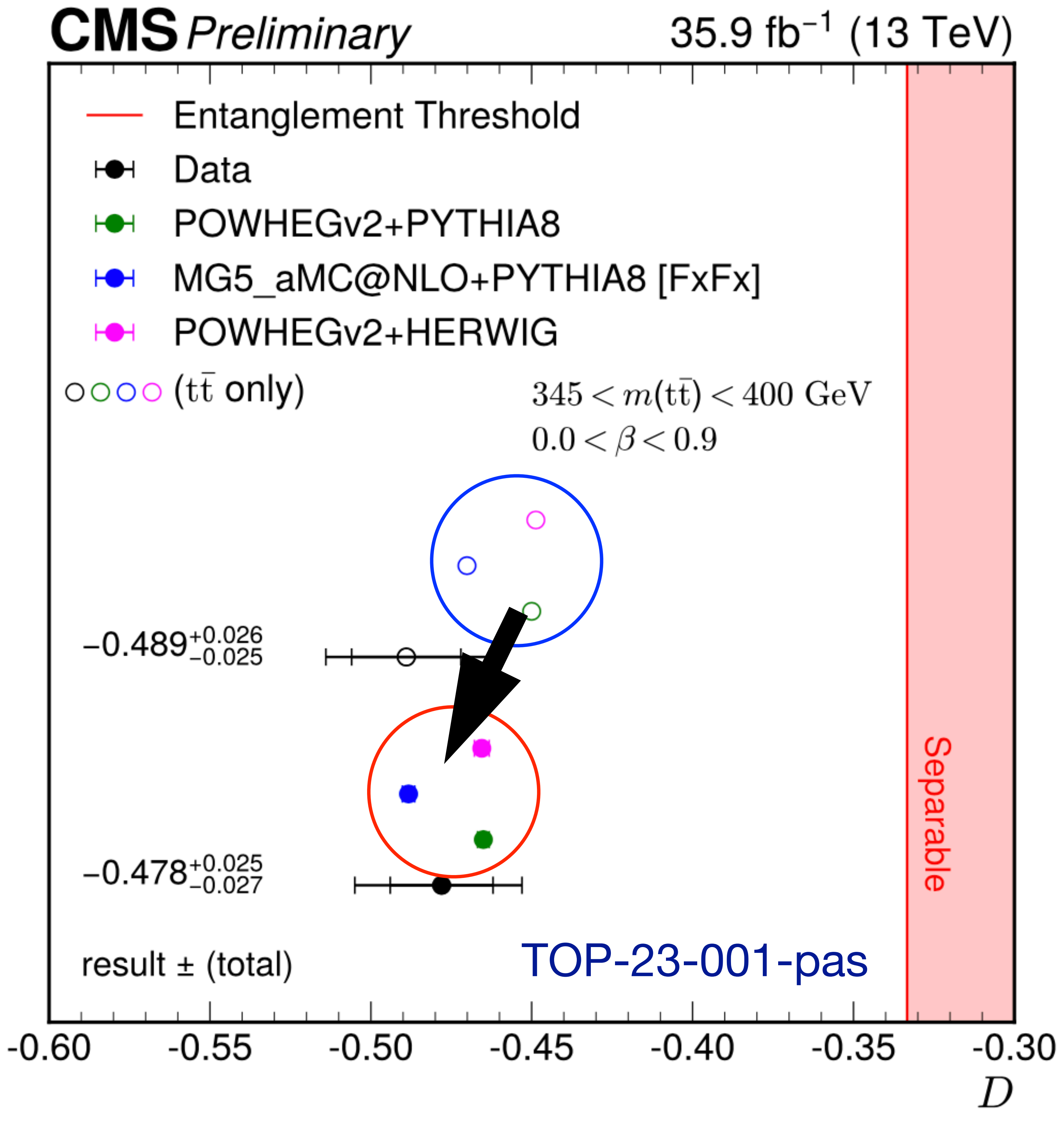


Entanglement observation by CMS

First measurements



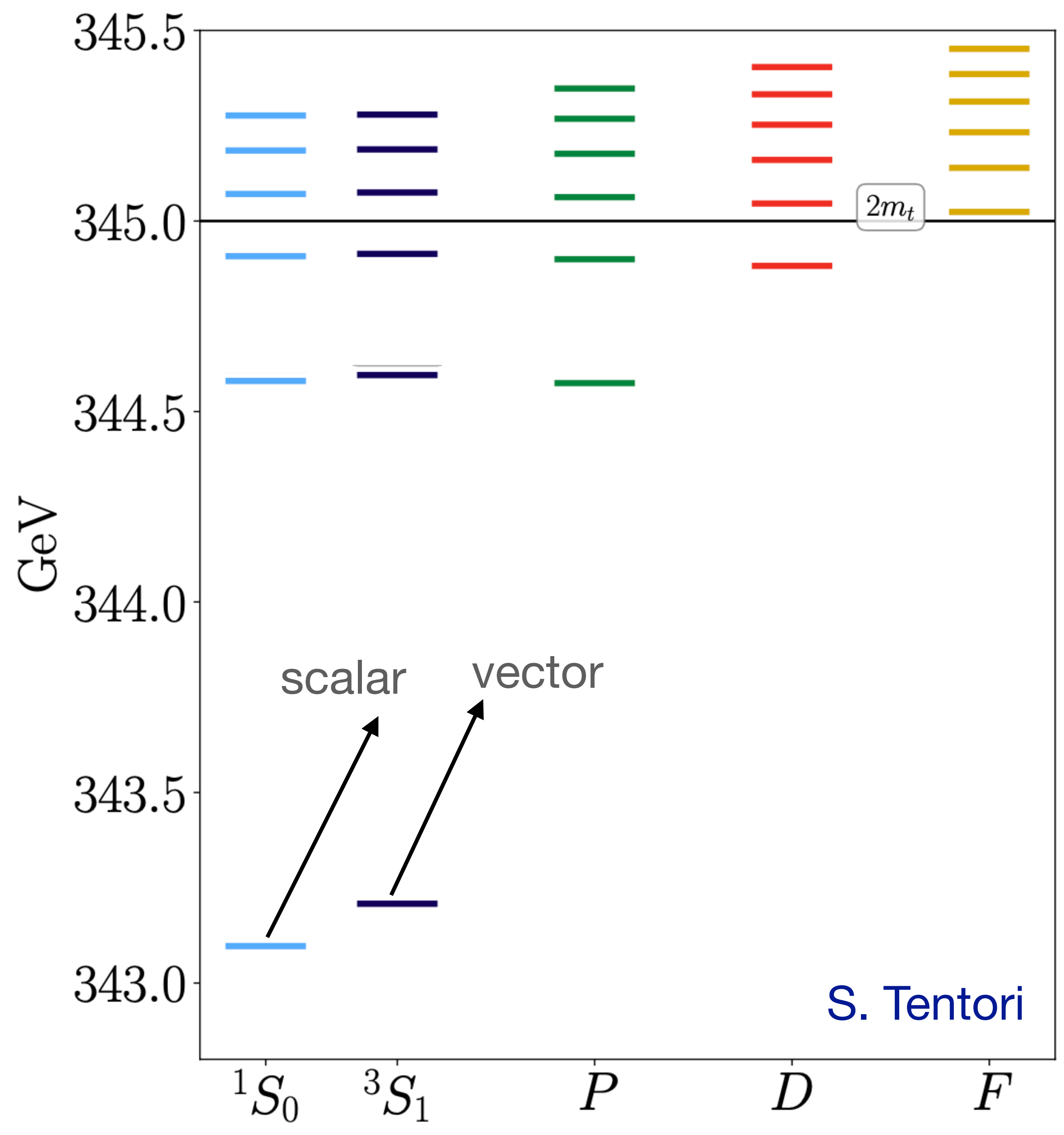
Entanglement observation by ATLAS



Entanglement observation by CMS

Toponium

- Quasi-Bound State of top and antitop
- Energy states obtained by solving Schrödinger equation with QCD potential
- Described by NRQCD
- Ground state n=1 S-wave
- Spin-singlet vs spin-triplet depending on production mode
  - spin singlet for pp and spin triplet for e^+e^-



$$\left[(E + i\Gamma_t) - \left(\frac{\boldsymbol{\nabla}^2}{m_t} + V(\boldsymbol{r})\right)\right] G(\boldsymbol{r}, E + i\Gamma_t) = \delta^{(3)}(\boldsymbol{r})$$

$$V_{\rm QCD}(r,\mu_B) = C^{[\rm col]}\,\frac{\alpha_s(\mu_B)}{r}\left[1 + \frac{\alpha_s}{4\pi}\left(2\,\beta_0 \log(e^{\gamma}\mu_B\, r) + \frac{31}{9}C_A - \frac{10}{9}n_f\right) + \mathcal{O}(\alpha_s^2)\right]$$

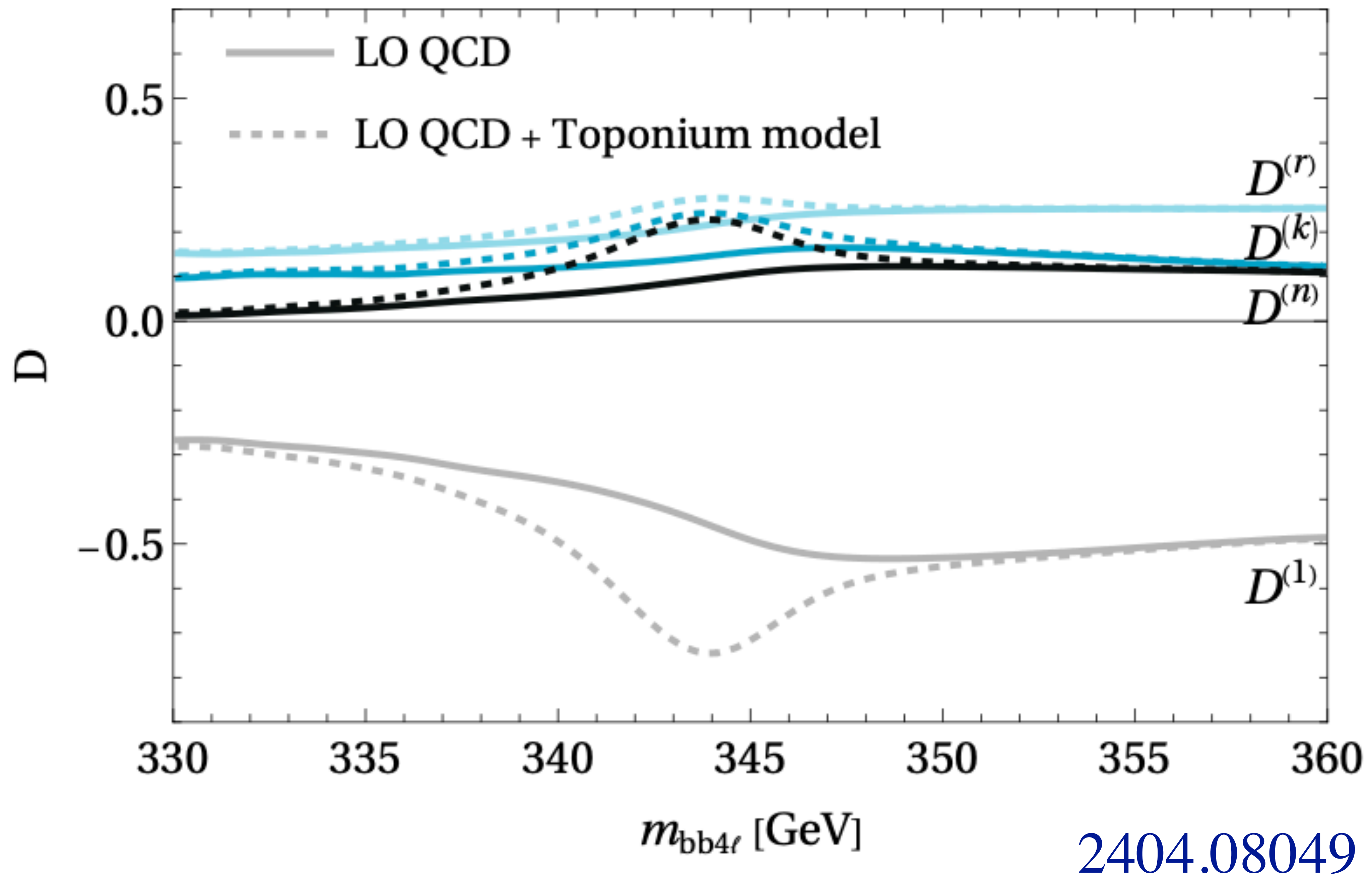
Toponium modelling

We can approximate the impact in the Monte Carlo by introducing a toy model with a resonance

- vector resonance for lepton collisions
- psedoscalar resonance for proton collisions

$$m_\psi = m_\eta \simeq 2m_t - 2\,\text{GeV}, \quad \text{and} \quad \Gamma_\psi = \Gamma_\eta \simeq 2\,\Gamma_t$$

Peak of resonance fitted to match the results obtained by the resummed computation
CMS toponym simulation based on: Fuks et al. 2102.11281



2404.08049

Significant impact on entanglement markers, hence improvement of measurement agreement with theory
Pseudoscalar resonance leads to different spin correlations compared to QCD

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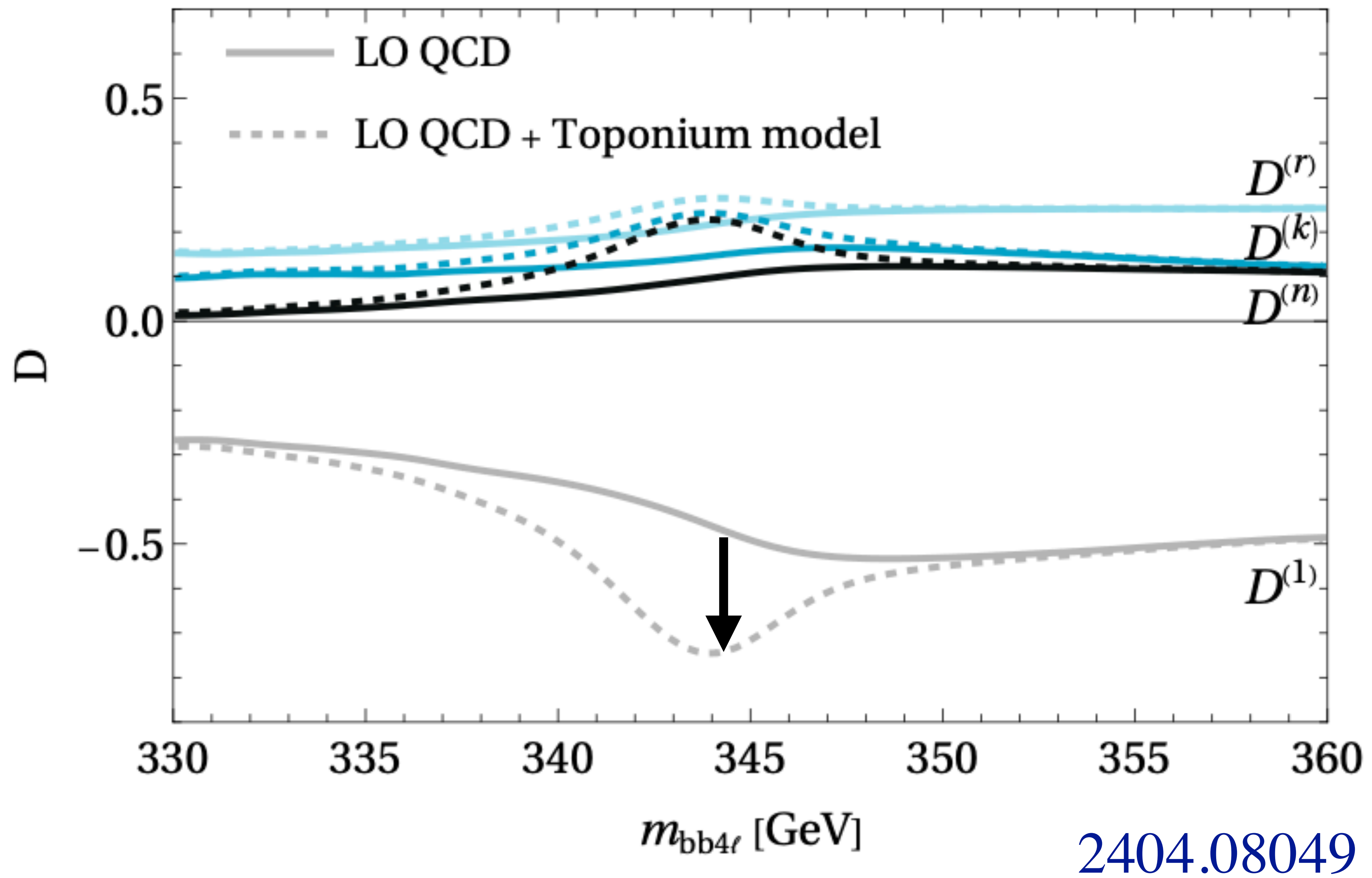

2404.08049

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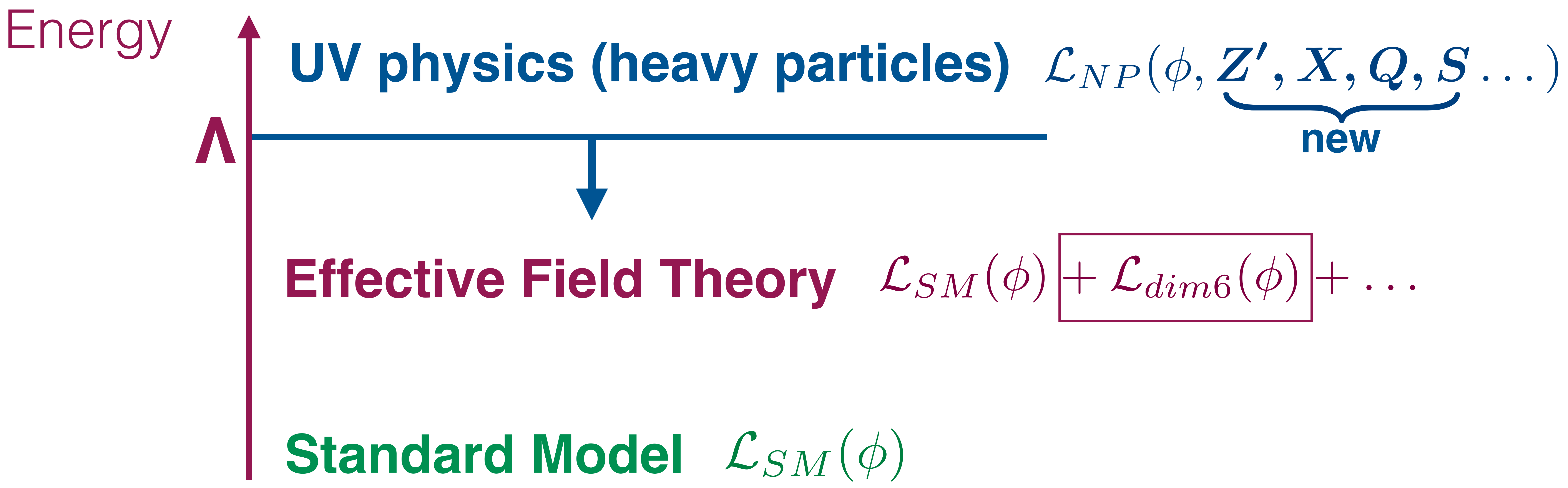
Pseudoscalar resonance leads to different spin correlations compared to QCD

Using QI for new physics

First quantum observable measurements are here
Can they tell us anything interesting/new?

- Effective Field Theory
- Resonances

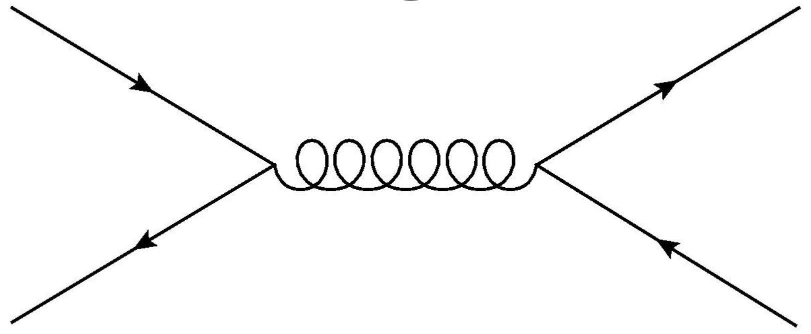
Effective Field Theory



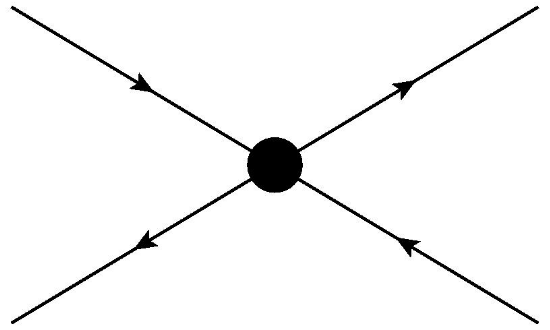
Effective Field Theory reveals high energy physics through precise measurements at low energy.

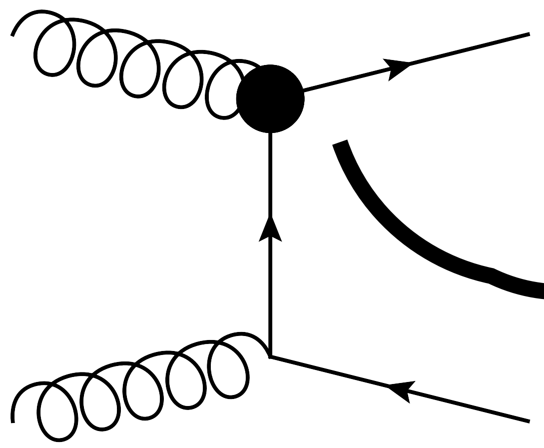
EFT in top pair production

SM



EFT





$\mathcal{O}_{tG}$ $\quad ig_S\left(\bar{Q}\tau^{\mu\nu}T_A\, t\right)\tilde{\varphi}\, G^A_{\mu\nu}$

Chromomagnetic dipole operator

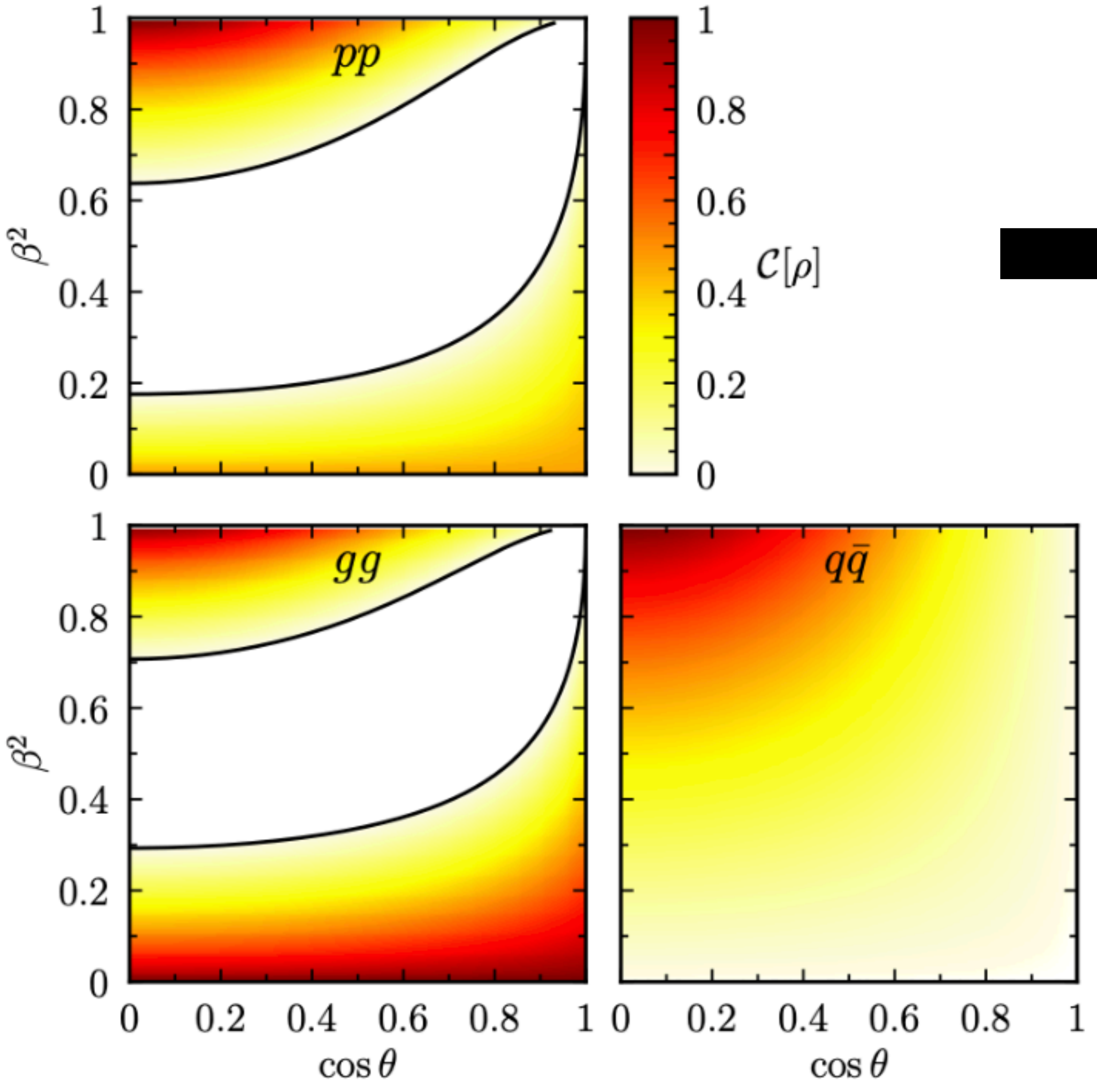
4-fermion operators

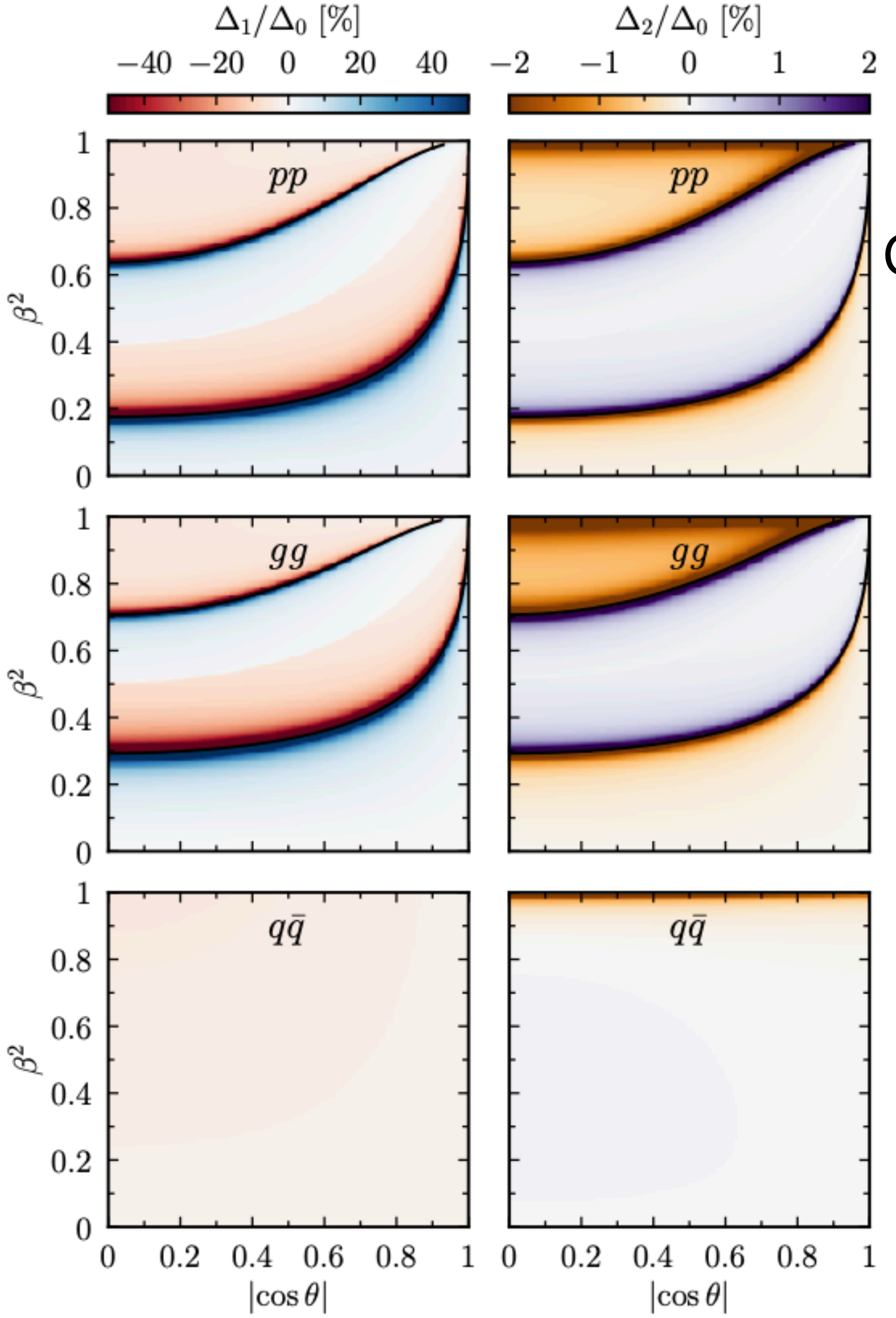
Octets	Singlets
$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$	$O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$
$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A\tau^I Q)(\bar{q}_i\gamma^\mu T^A\tau^I q_i)$	$O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu\tau^I q_i)$
$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i)$	$O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$
$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i)$	$O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)$;
$O^{8}_{Qu} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i)$	$O^{1}_{Qu} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$
$O^{8}_{Qd} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i)$	$O^{1}_{Qd} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$
$O^{8}_{tq} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$	$O^{1}_{tq} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)$;

Different chiralities and colour structures

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

SMEFT in top pair production





Linear Quadratic

$\mathcal{O}_{tG}$ $\quad ig_S\left(\bar{Q}\tau^{\mu\nu}T_A t\right)\tilde{\varphi}\,G^A_{\mu\nu}$

Chromomagnetic dipole operator

$$\Delta = -C_{nn} + |C_{kk} + C_{rr}| - 1 > 0$$

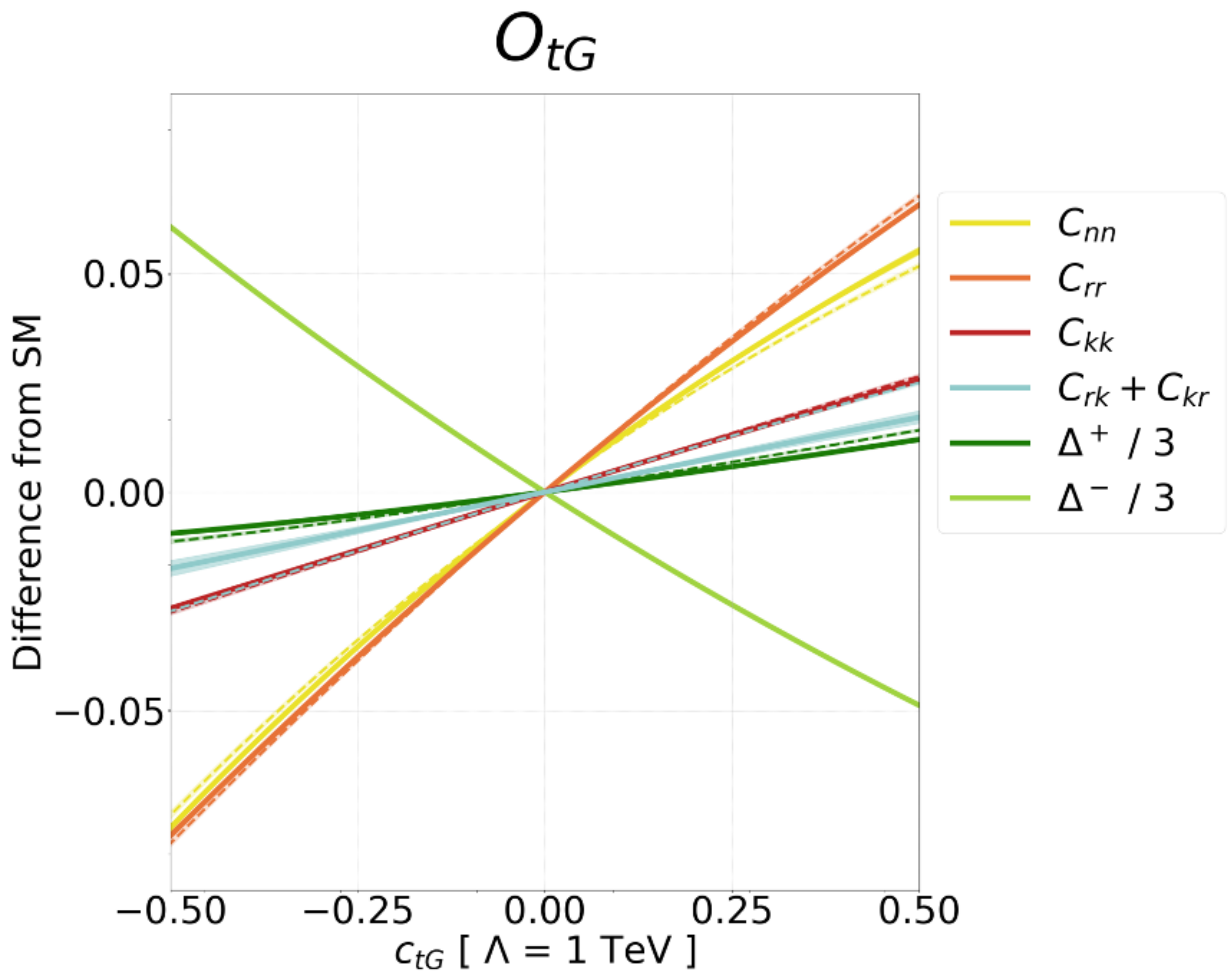
Δ_0 SM

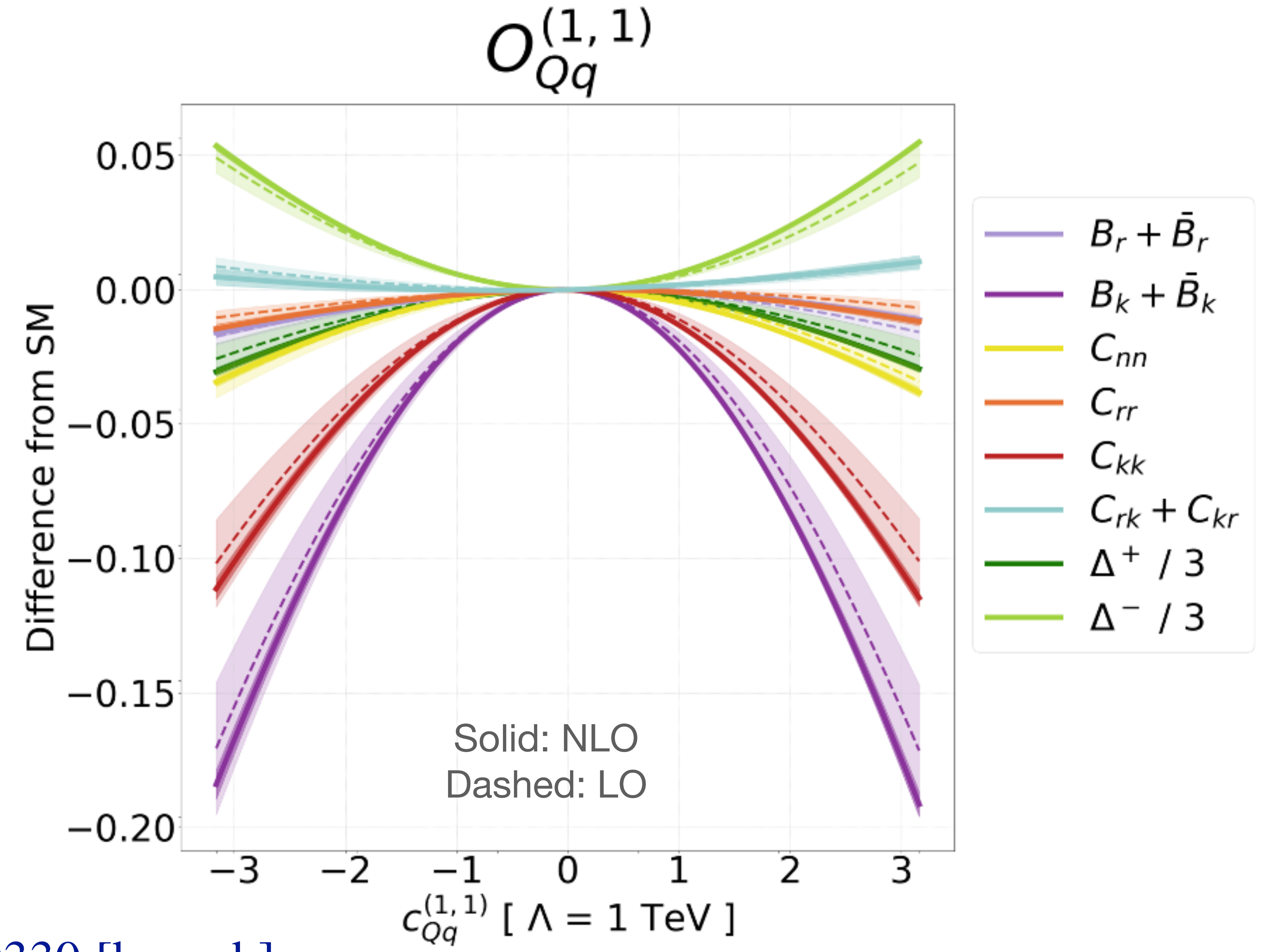
$$\Delta_1 \equiv \Delta - \Delta_0 \quad \mathcal{O}(\Lambda^{-2})$$

$$\Delta_2 \equiv \Delta - \Delta_1 - \Delta_0 \quad \mathcal{O}(\Lambda^{-4})$$

Aoude, Madge, Maltoni, Mantani arXiv:2203.05619

SMEFT impact on entanglement markers



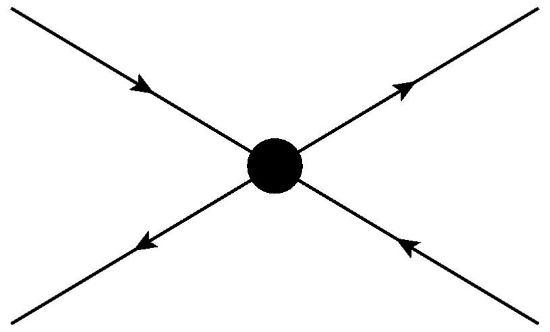


C. Severi, EV: 2210.09330 [hep-ph]

Quantum entanglement markers modified by SMEFT operators

SMEFT in lepton colliders

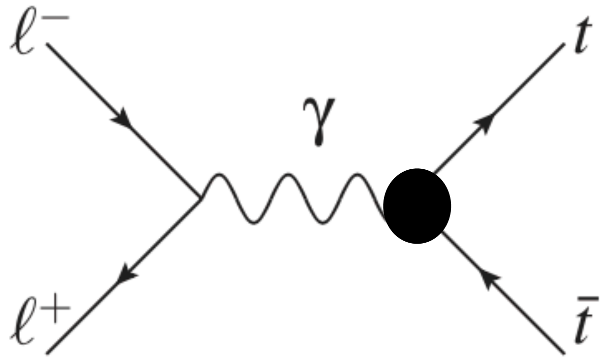
$$\mathcal{O}_{Q\ell}^{(1)} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{\ell}_L\gamma_\mu\ell_L),$$
$$\mathcal{O}_{Q\ell}^{(3)} = (\bar{Q}_L\gamma^\mu\sigma_I Q_L)(\bar{\ell}_L\gamma_\mu\sigma^I\ell_L),$$
$$\mathcal{O}_{Qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{\ell}_R\gamma_\mu\ell_R),$$
$$\mathcal{O}_{t\ell} = (\bar{t}_R\gamma^\mu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

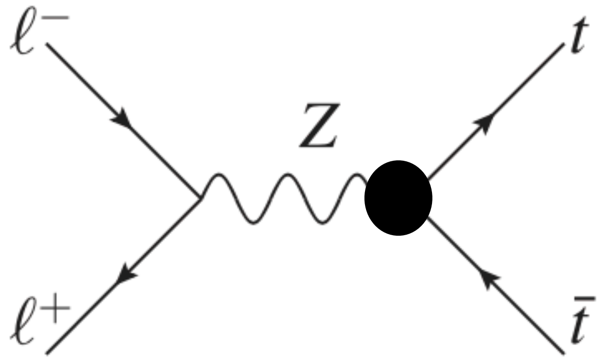


4-fermion operators

$$\mathcal{O}_{\phi Q}^{(1)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}_L\gamma^\mu Q_L),$$
$$\mathcal{O}_{\phi Q}^{(3)} = i(\phi^\dagger \overleftrightarrow{D}_{\mu I} \phi)(\bar{Q}_L\gamma^\mu\sigma^I Q_L),$$
$$\mathcal{O}_{\phi t} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}_R\gamma^\mu t_R),$$

current operators





$$\mathcal{O}_{tW} = (\bar{Q}_L\gamma^{\mu\nu}\sigma_I t_R)\,\tilde{\phi}\,W^I_{\mu\nu},$$
$$\mathcal{O}_{tB} = (\bar{Q}_L\gamma^{\mu\nu} t_R)\,\tilde{\phi}\,B_{\mu\nu}.$$

dipole operators

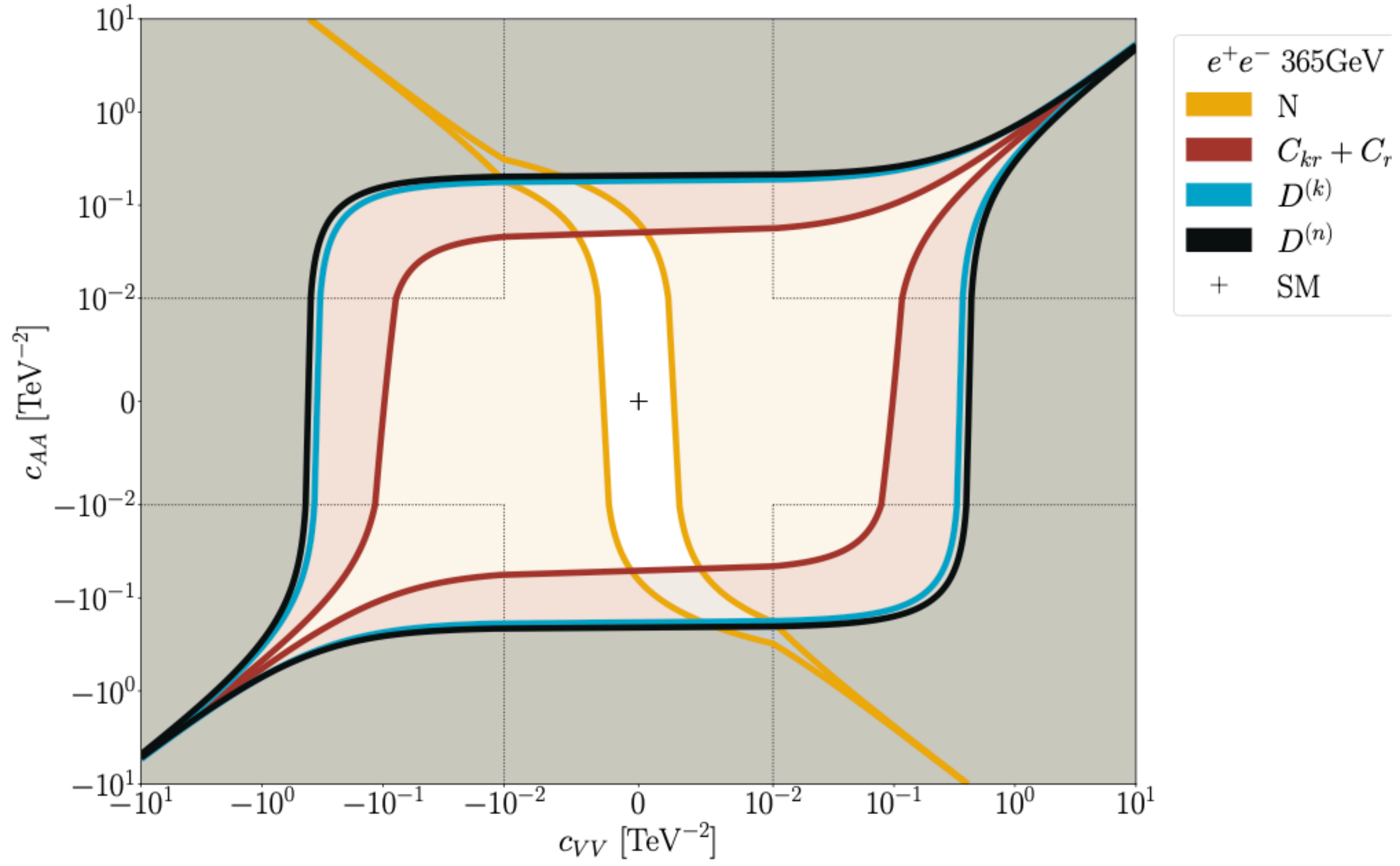
Degrees of freedom

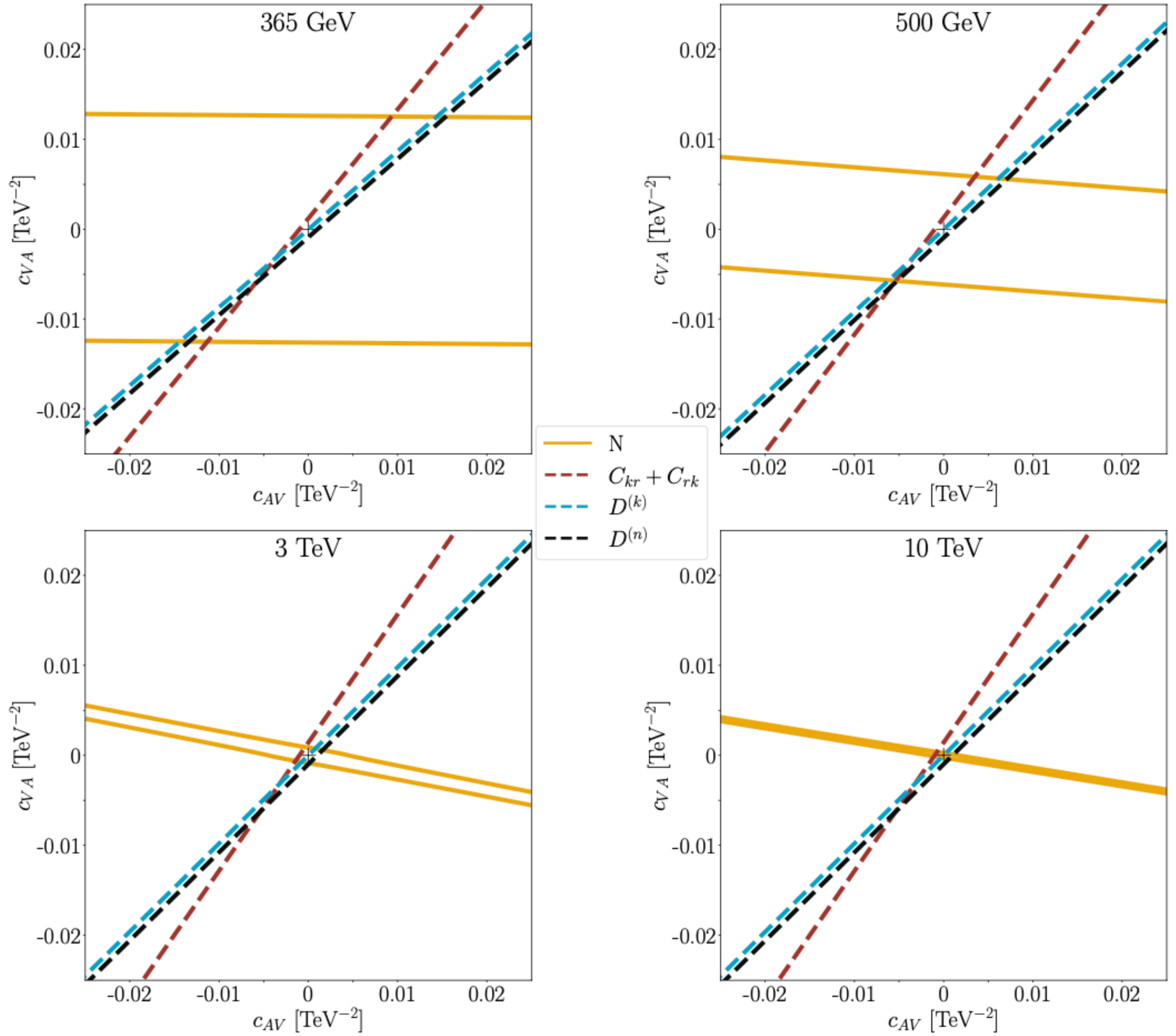
$$c_{Q\ell}^{(3)} + c_{Q\ell}^{(1)},$$
$$c_{\rm VV} = \frac{1}{4}\big(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} + c_{Qe}\big),$$
$$c_{\rm AV} = \frac{1}{4}\big(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} - c_{Qe}\big),$$
$$c_{\rm VA} = \frac{1}{4}\big(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} + c_{Qe}\big),$$
$$c_{\rm AA} = \frac{1}{4}\big(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} - c_{Qe}\big).$$

$$c_{\phi Q}^{(3)} + c_{\phi Q}^{(1)},$$
$$c_{\phi \rm V} = \frac{1}{2}\big(c_{\phi t} + c_{\phi Q}^{(1)} - c_{\phi Q}^{(3)}\big),$$
$$c_{\phi \rm A} = \frac{1}{2}\big(c_{\phi t} - c_{\phi Q}^{(1)} + c_{\phi Q}^{(3)}\big).$$

$$c_{tZ} = c_{\rm W}\, c_{tW} - s_{\rm W}\, c_{tB},$$
$$c_{t\gamma} = s_{\rm W} c_{tW} + c_{\rm W} c_{tB},$$

Breaking degeneracies with Quantum Obs



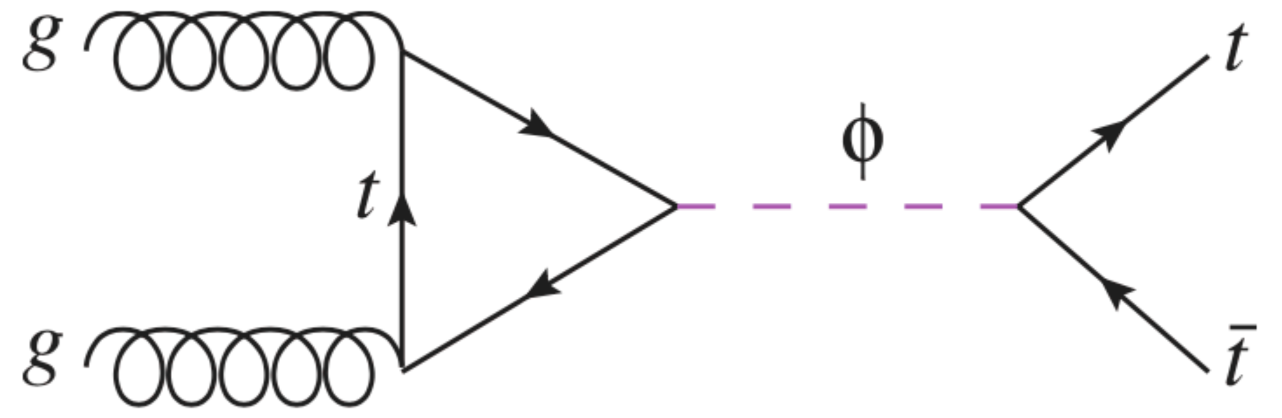


Spin correlation observables probe different linear combinations of Wilson coefficients

➡ Breaking degeneracies

New particle searches

Example: Scalar resonances

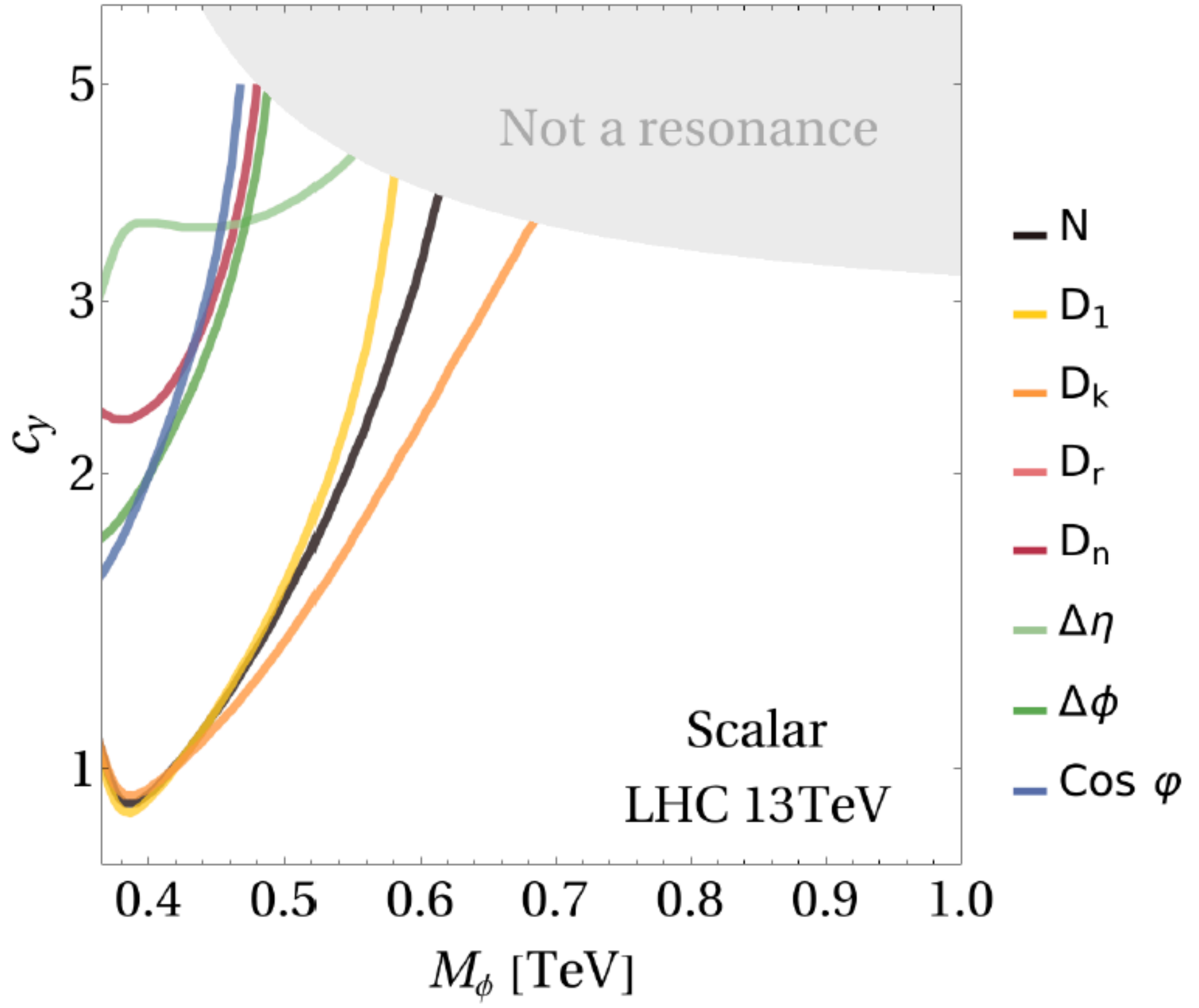


$$\mathcal{C}^{[gg,\phi]}\big|_{\alpha=0} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \mathcal{C}^{[gg,\phi]}\big|_{\alpha=\pi/2} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Scalar: Pure triplet

Pseudoscalar: Pure singlet

Also true for the interference with the SM (pure state → projector)



More constraining than rate information

Conclusions

- A new era of quantum observables at colliders is here
- Ideas and methods of QM adjusted to high energy physics
- First measurements, and lots of studies already here
- Top pairs an ideal testing ground, different degrees of correlations can be observed
- Quantum observables are not only fun but can also help to probe new physics

Thank you for your attention