Quantum observables for New Physics

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TOP2024, Saint Malo

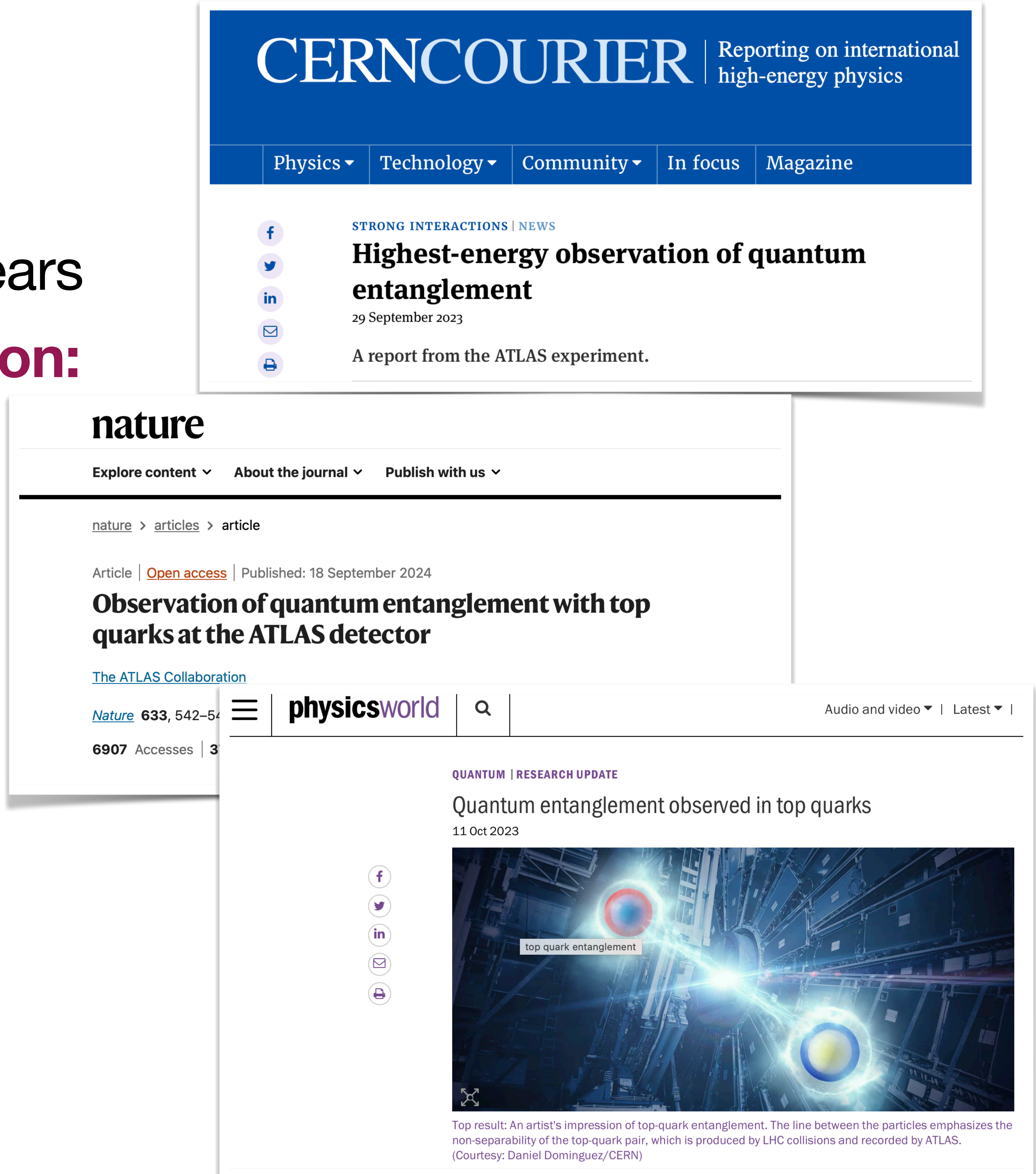
23/9/24

Introduction

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

Measurement of entanglement in top pair production:

Thursday afternoon session!



Why is this interesting?

Quantum mechanics at the TeV scale!

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

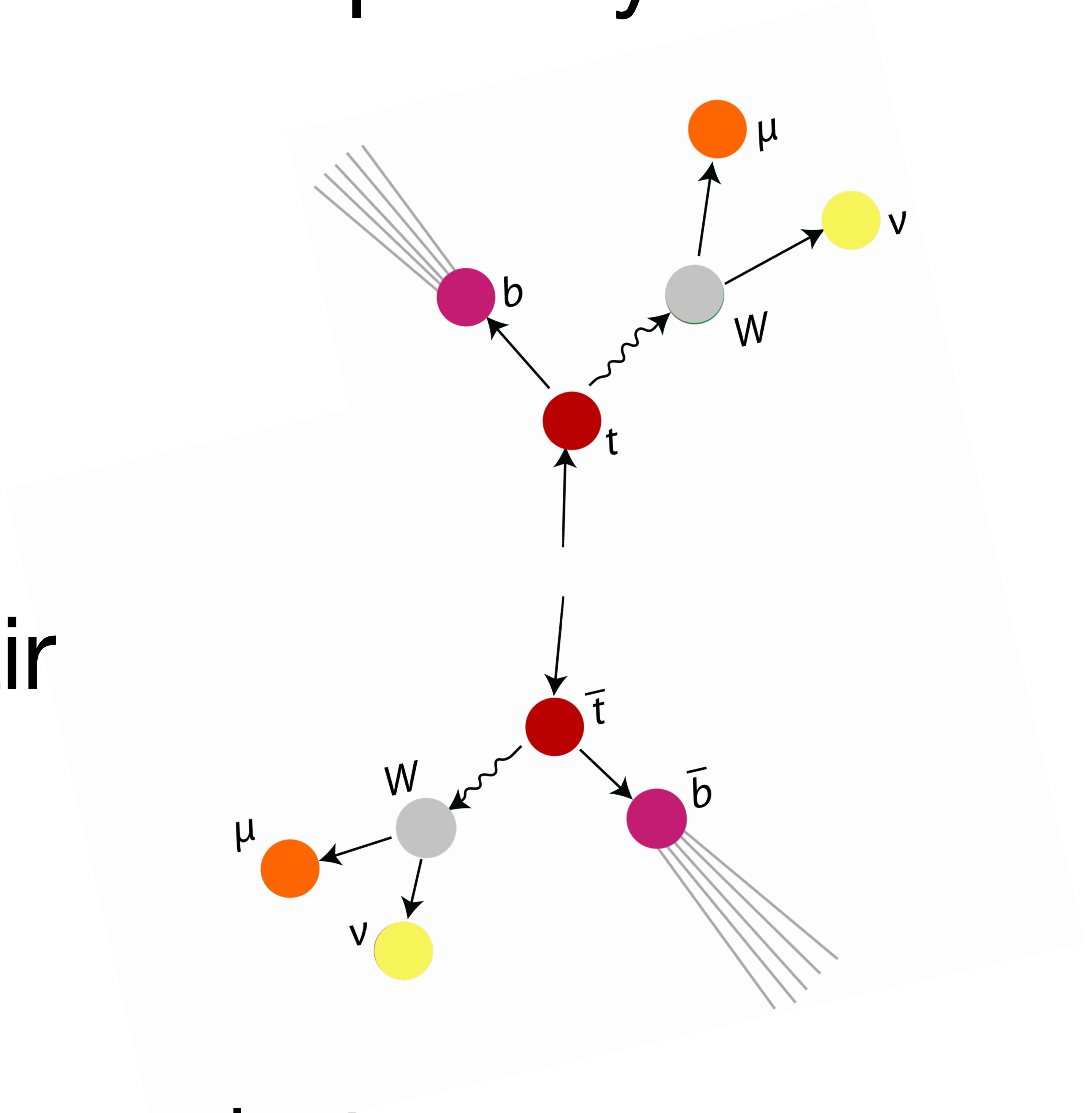
New insights and information about new physics

Spin density matrix

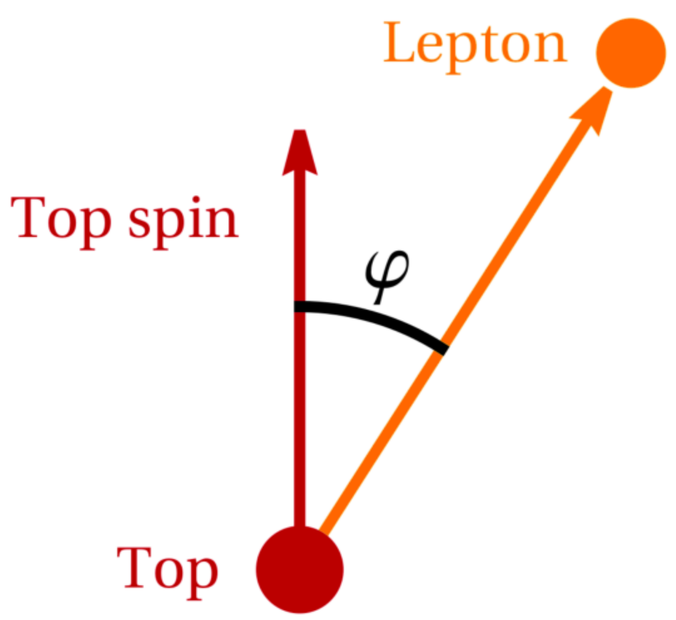
Tops produced in pairs have their spins S_i, S_j correlated: a two-qubit system

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

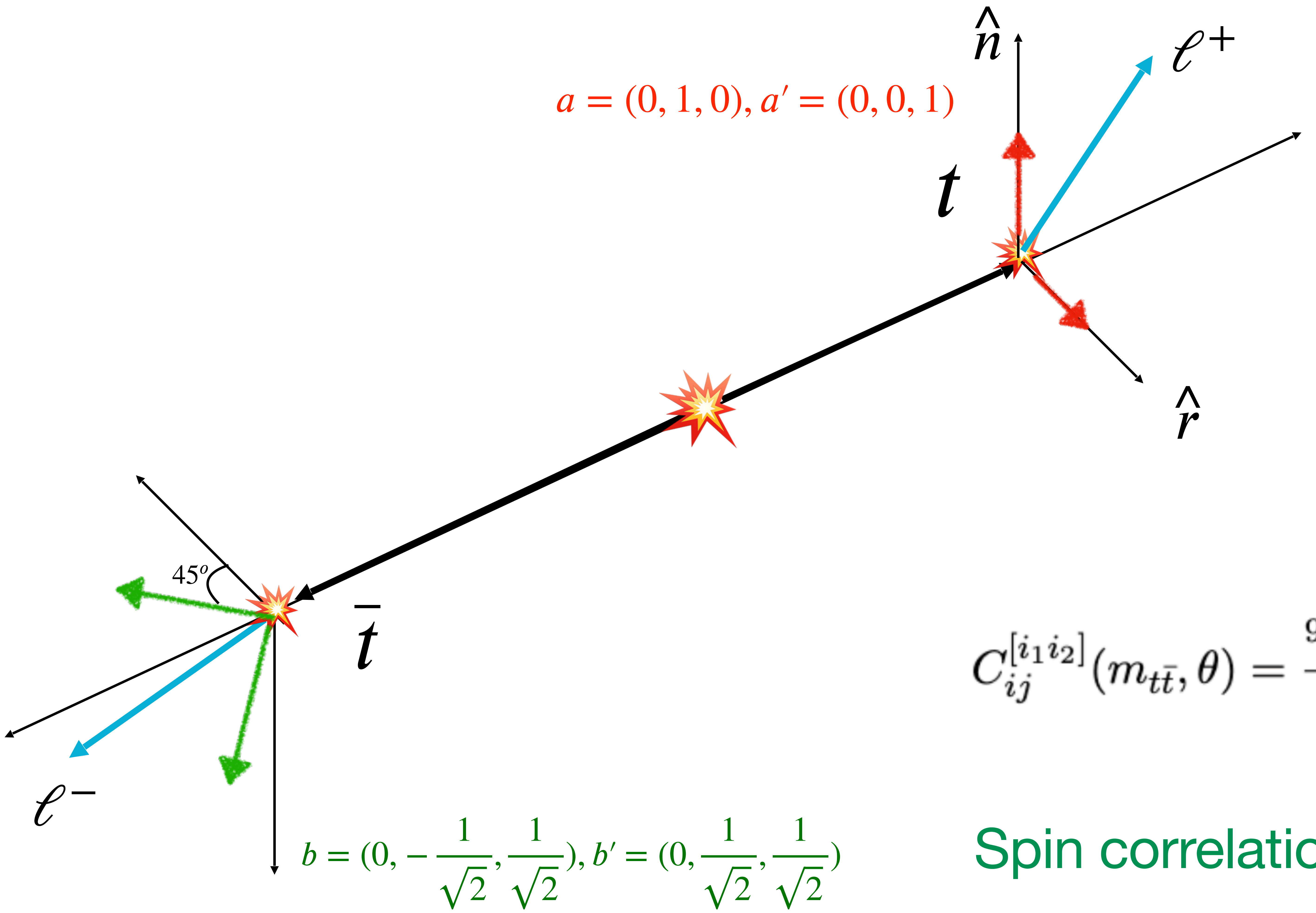


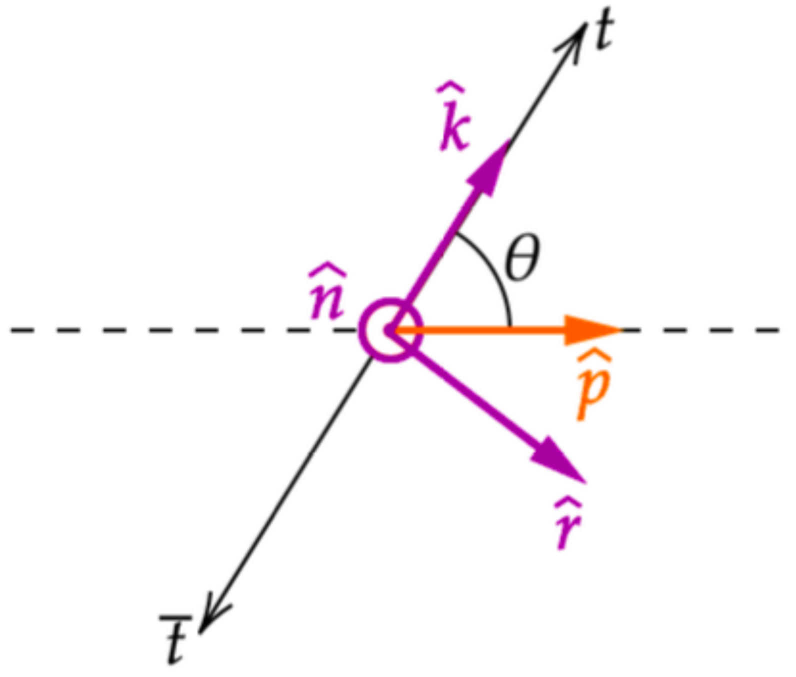
$$\langle S_i\rangle = B_i,\quad \langle \bar{S}_i\rangle = \bar{B}_j,\quad \langle S_i\bar{S}_j\rangle = C_{ij}$$

Extracted by measuring angular distributions of decay products

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

Kinematics





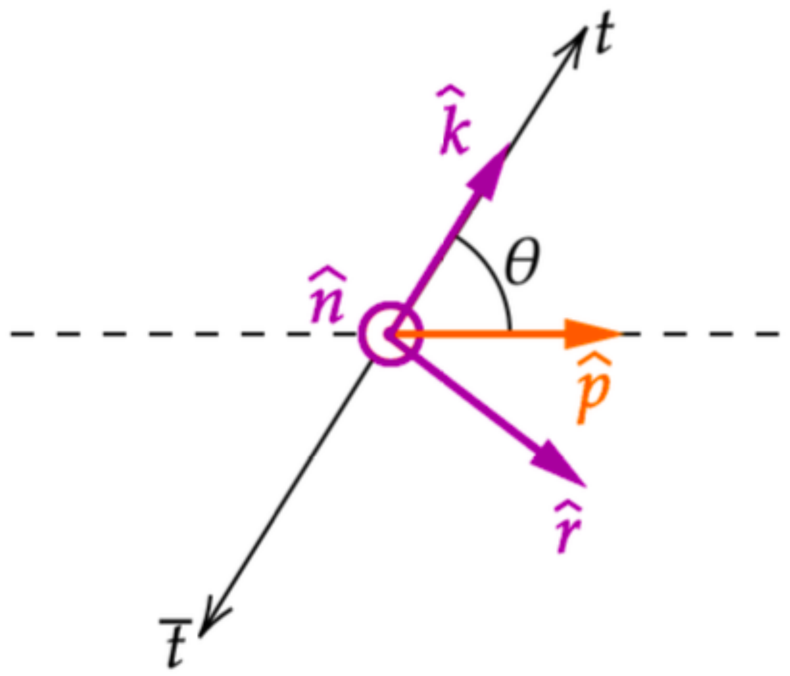
$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

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

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

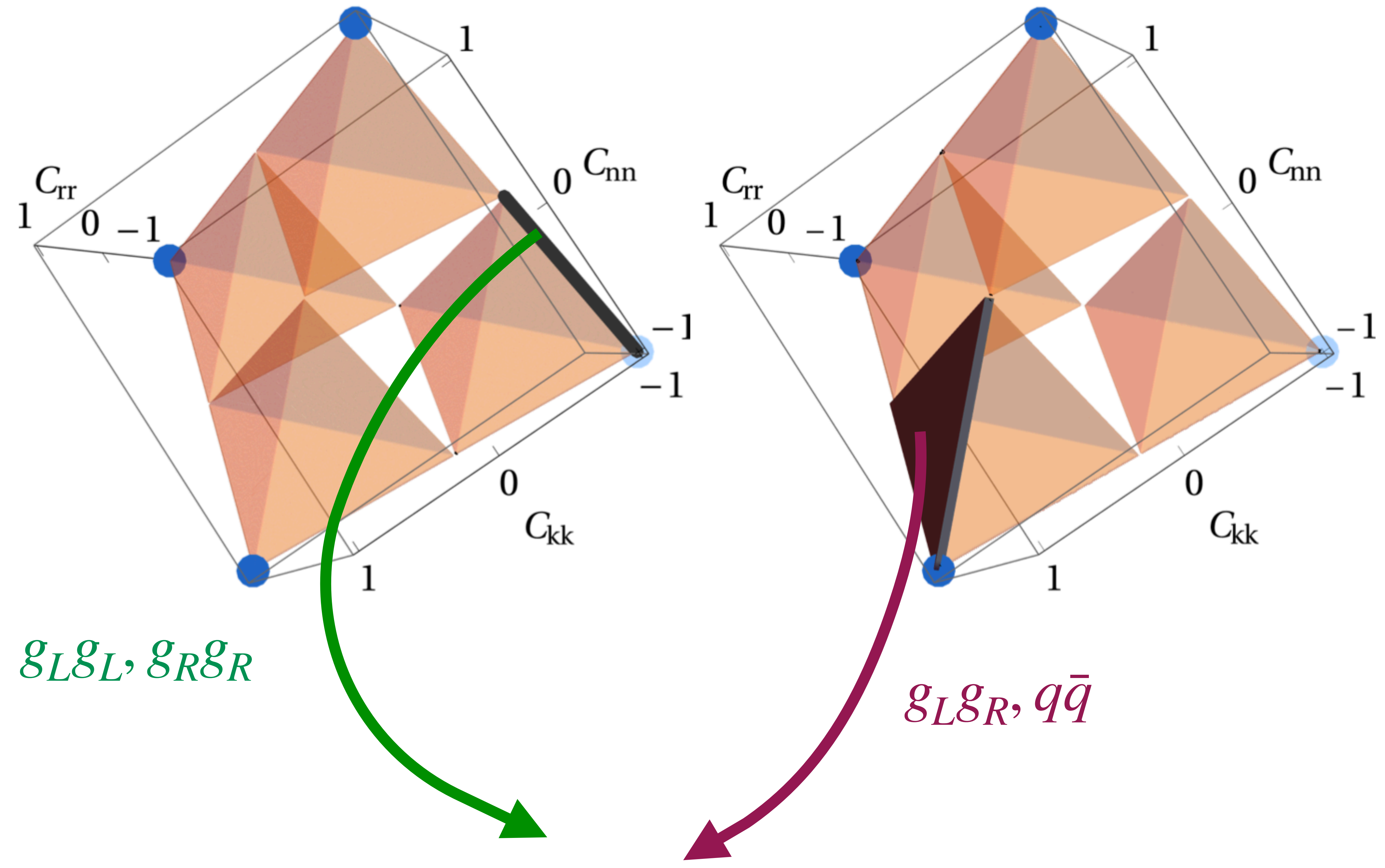
$$D_{\min} < -1/3$$

for a proof see arXiv:2003.02280

Necessary and sufficient condition for entanglement

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

When are tops entangled?



reachable entangled states

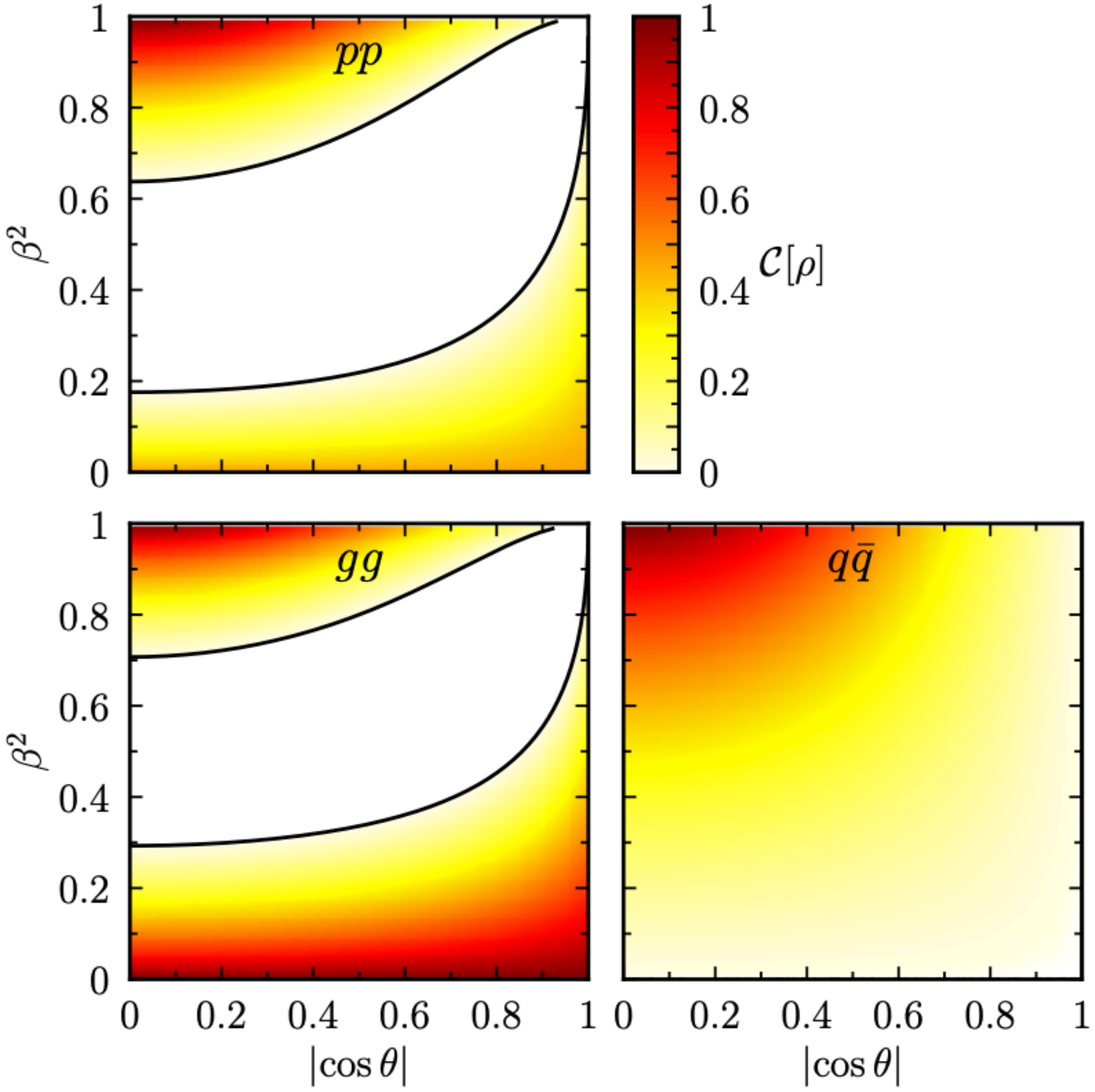
Consider top pair production in pp collisions
Which spin states can be reached?

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

White regions: no entanglement (C<0)

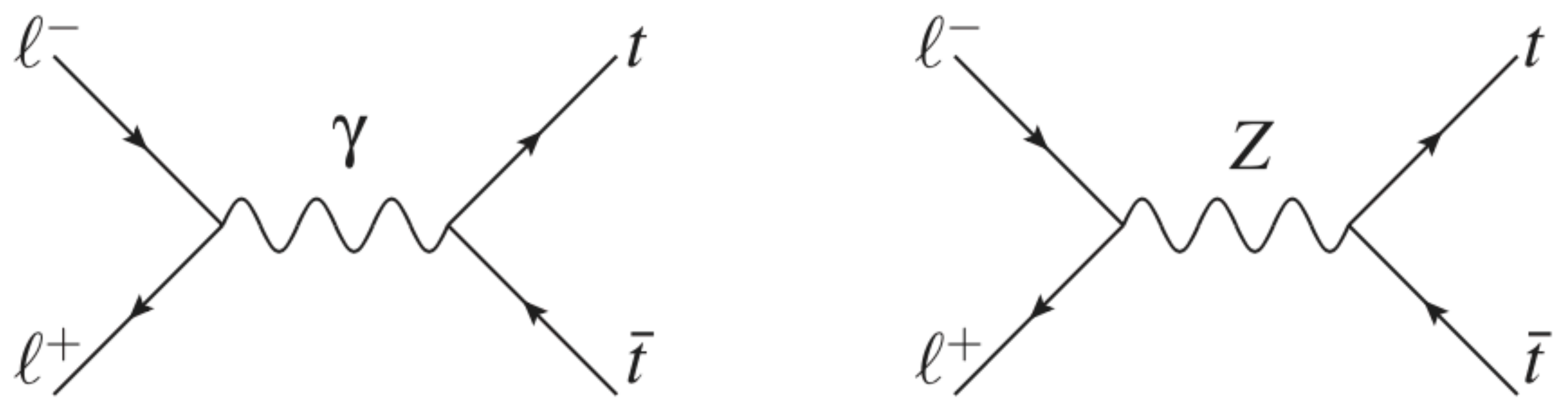
Maximal entanglement regions

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

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

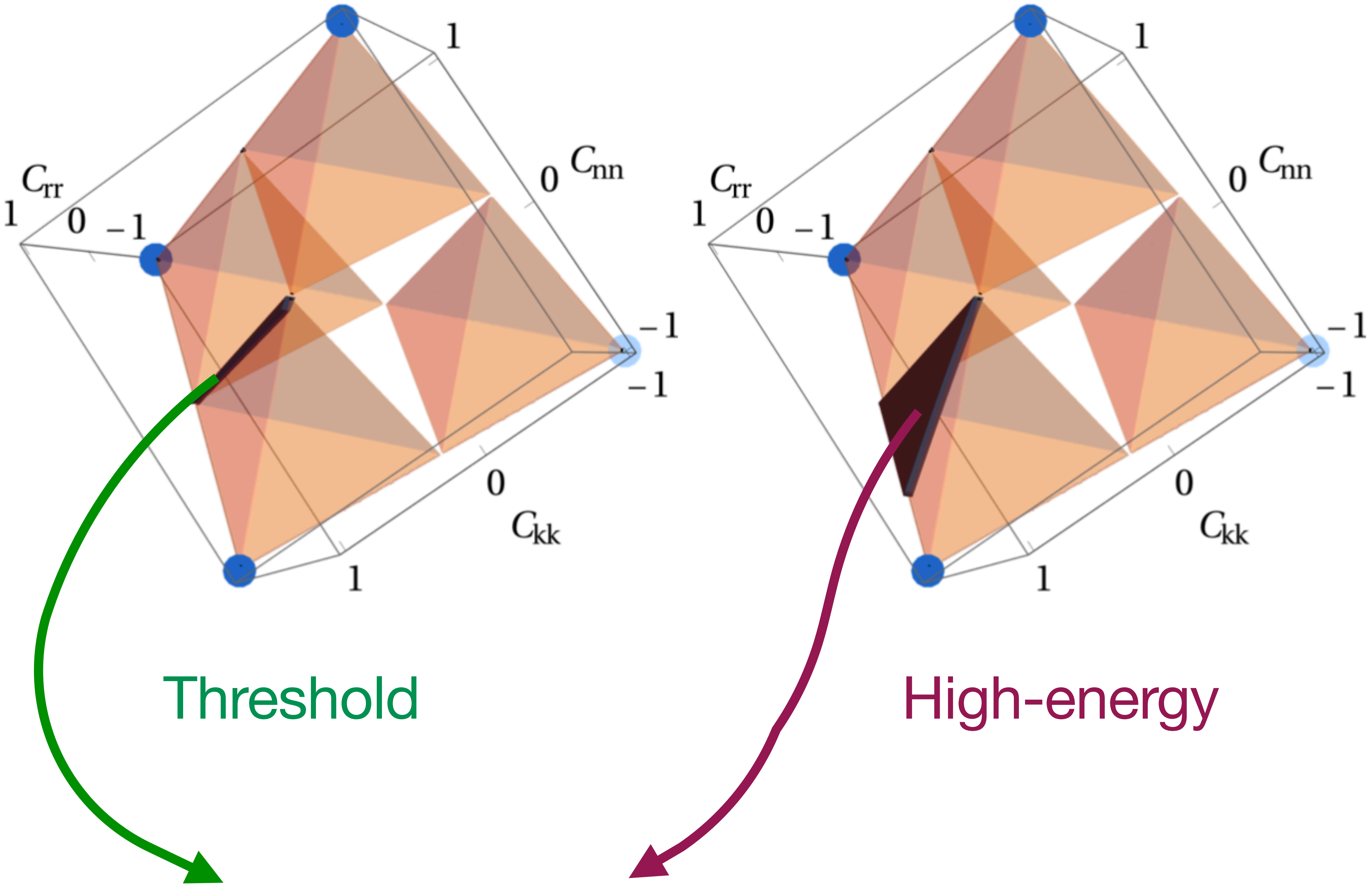
C. Severi, C. Boschi, F. Maltoni, M. Sioli : 2110.10112

Tops in lepton colliders



$$1/3\,\mathrm{Tr}\,[\mathcal{C}] = D^{(1)} = +\frac{1}{3},$$

Spin-1 exchange
Spin triplet state



reachable entangled states

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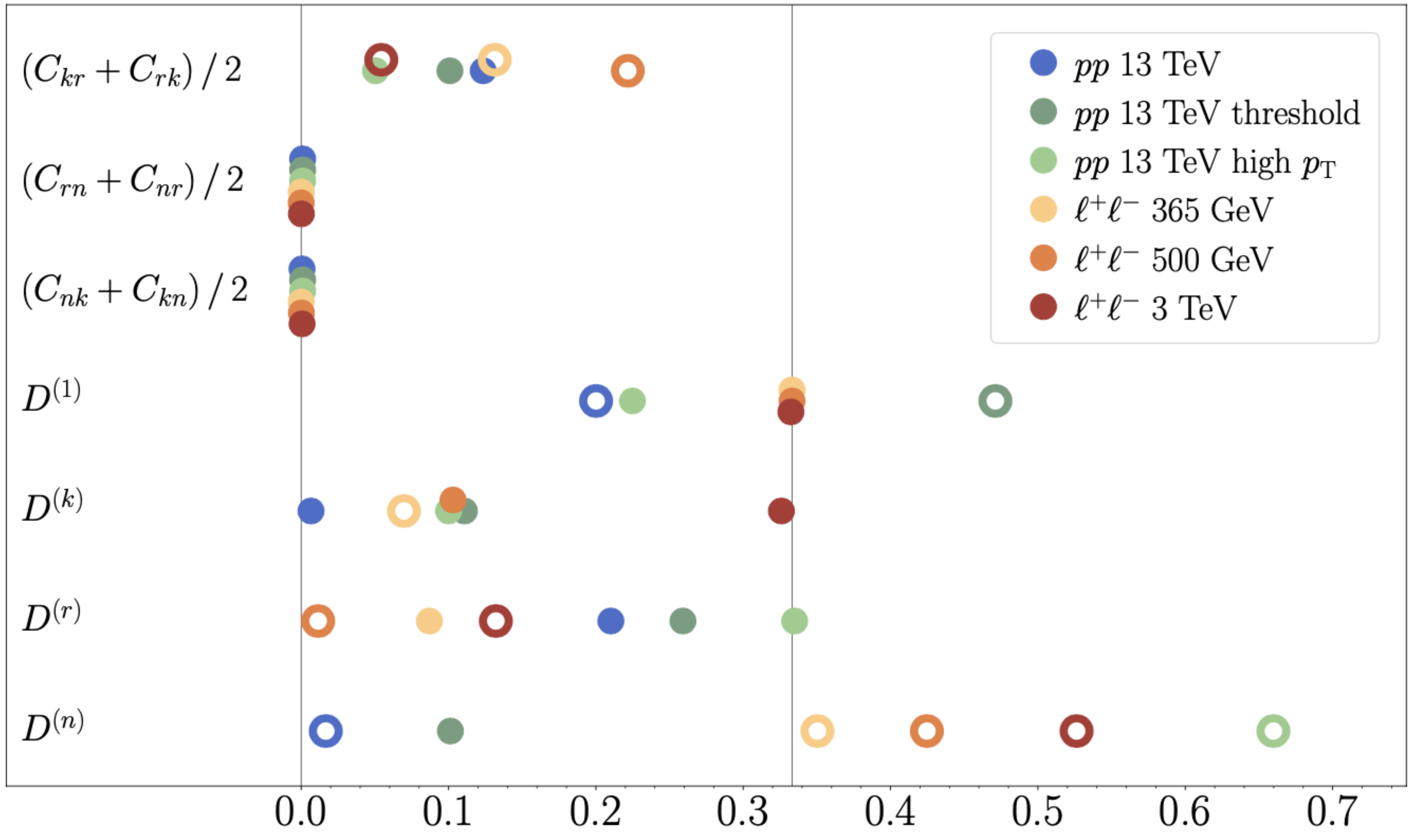
Lepton vs pp collisions



- Spin Triplet state $D^{(1)} = +1/3$
- 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

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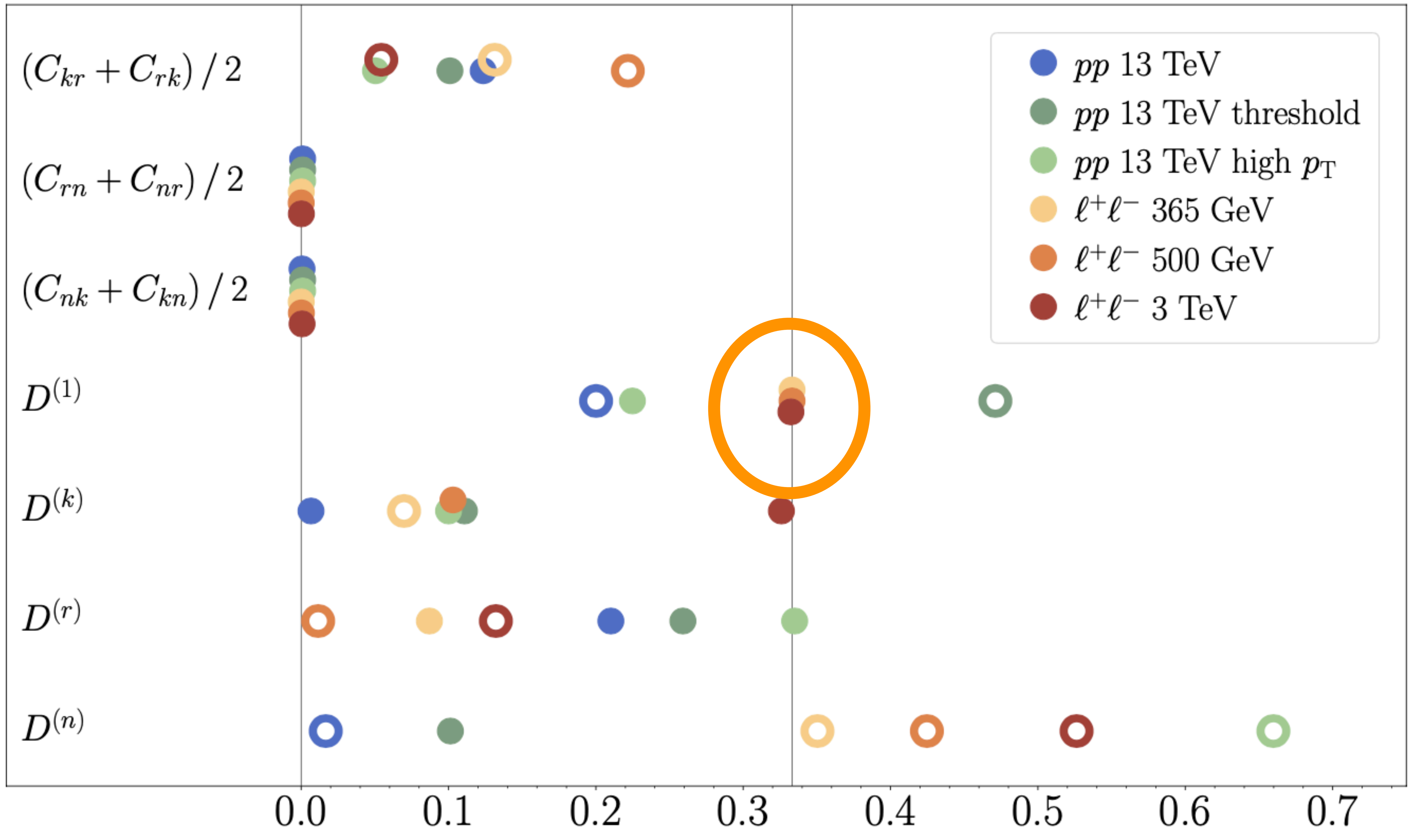

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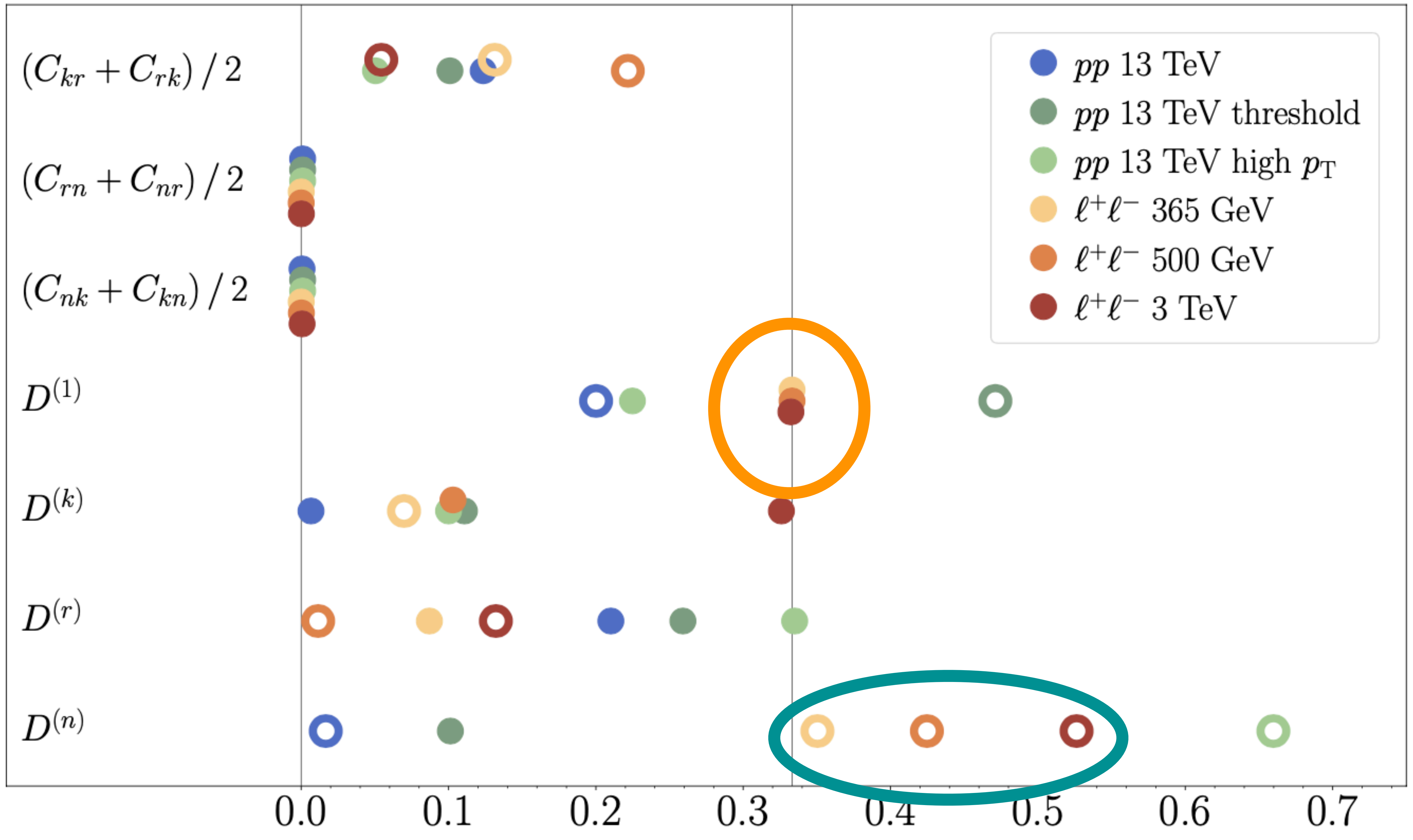

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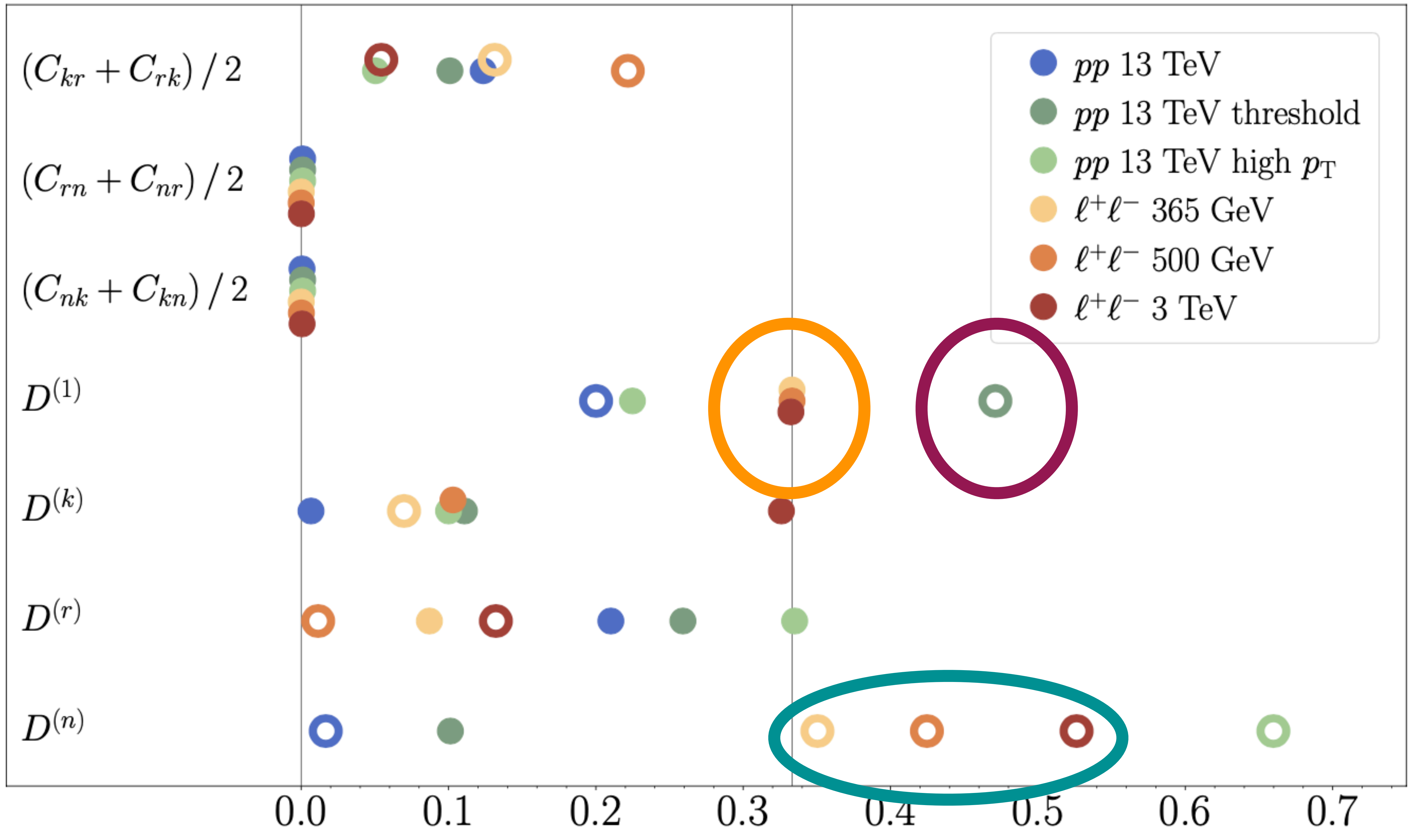

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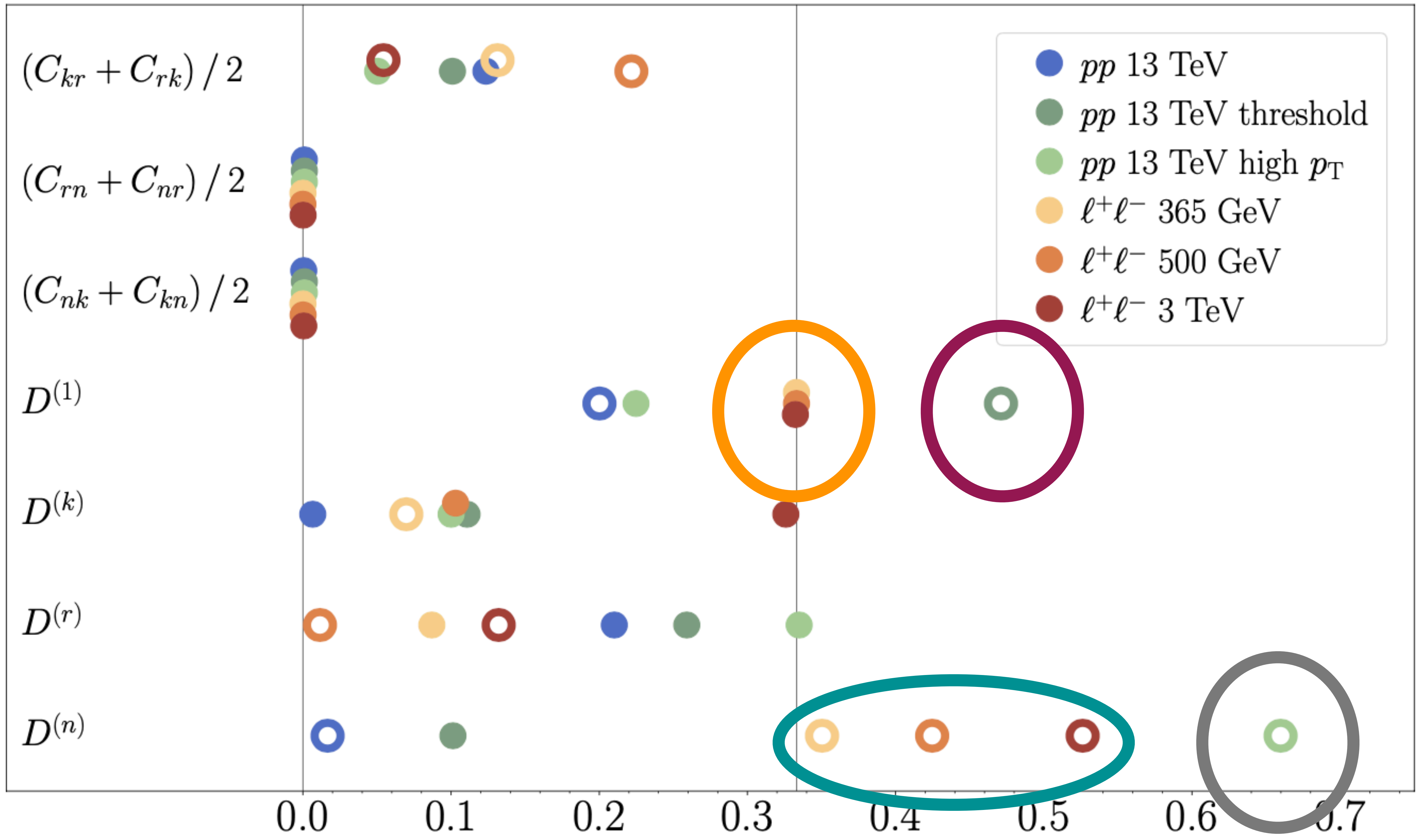

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C. Severi, F.Maltoni, S. Tentori, EV: 2404.08049

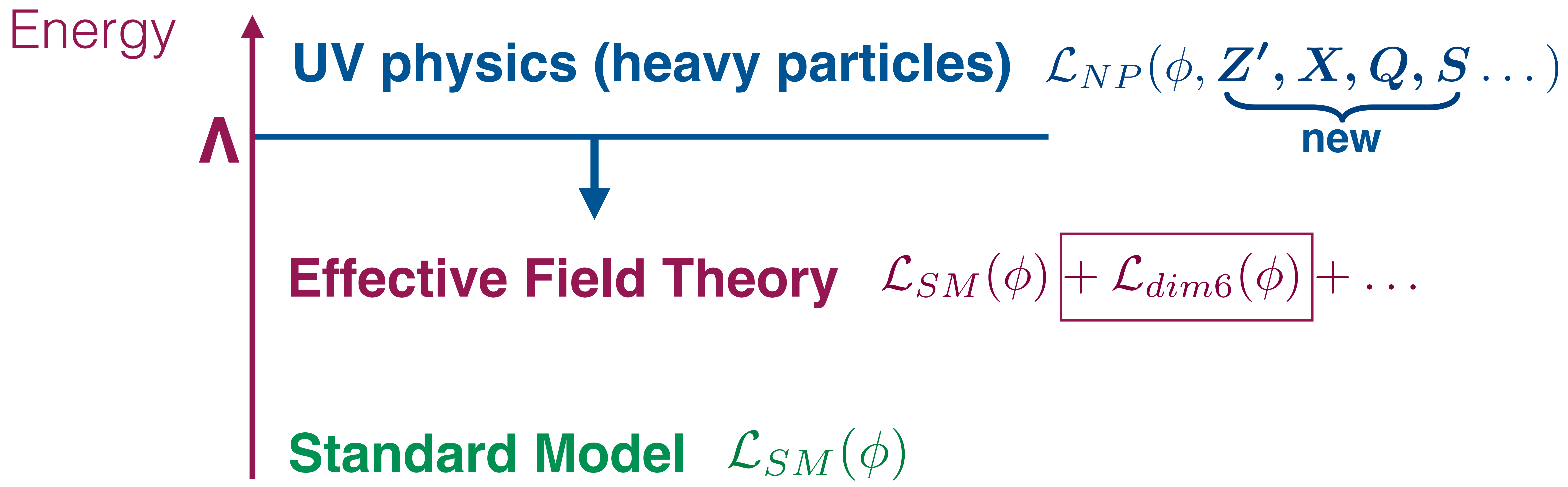
Using QI for new physics

First quantum observable measurements are here

Can they tell us anything interesting/new?

- SMEFT
- Resonances

Effective Field Theory



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

SMEFT basics

BSM? → New Interactions of SM particles

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

59(3045) operators at dim-6:

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884

dim-6: 59 operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

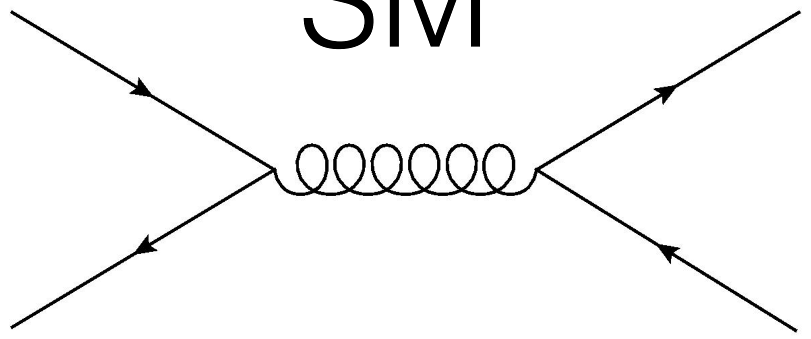
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

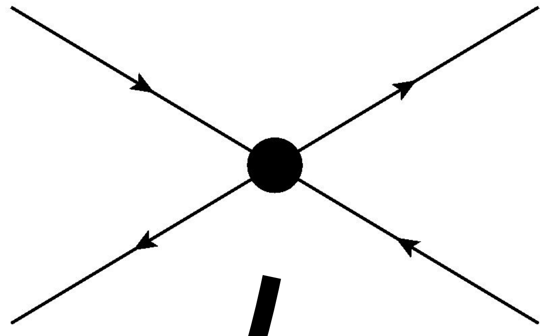
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

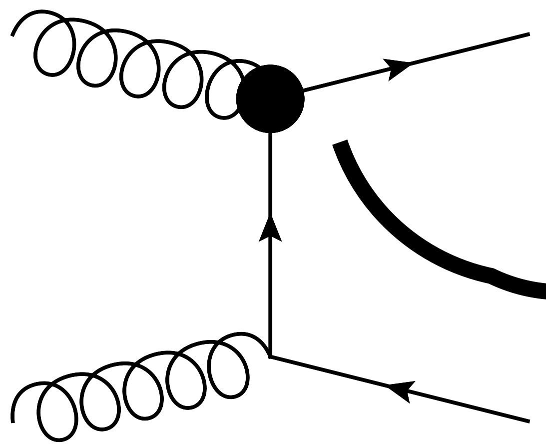
EFT in top pair production

SM





EFT



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

Chromomagnetic dipole operator

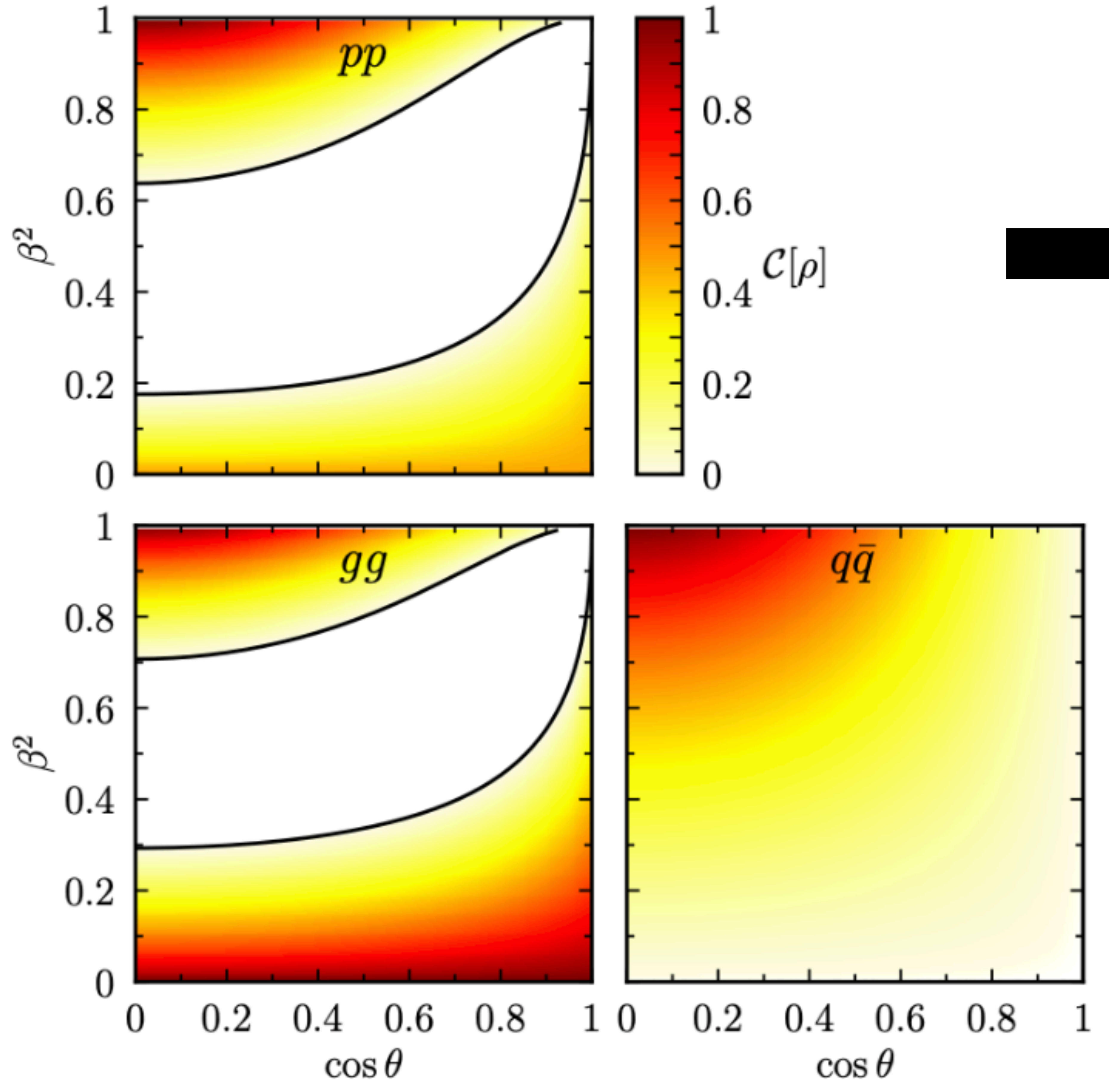
4-fermion operators

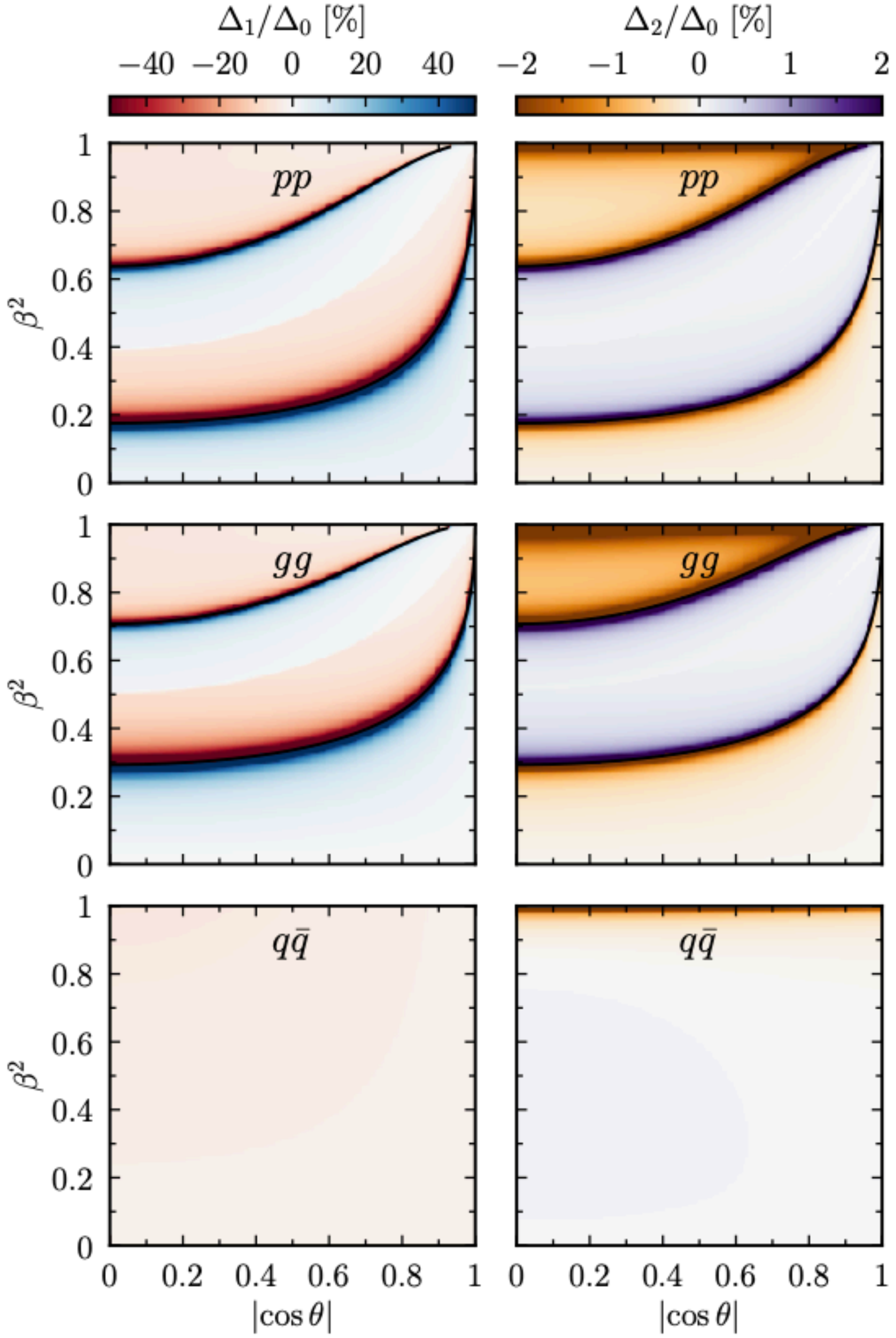
Octets	Singlets
$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$	$O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$
$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A\tau^I Q)(\bar{q}_i\gamma^\mu T^A\tau^I q_i)$	$O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu\tau^I Q)(\bar{q}_i\gamma^\mu\tau^I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

Different chiralities and colour structures

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

SMEFT in top pair production





Linear Quadratic

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

Chromomagnetic dipole operator

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

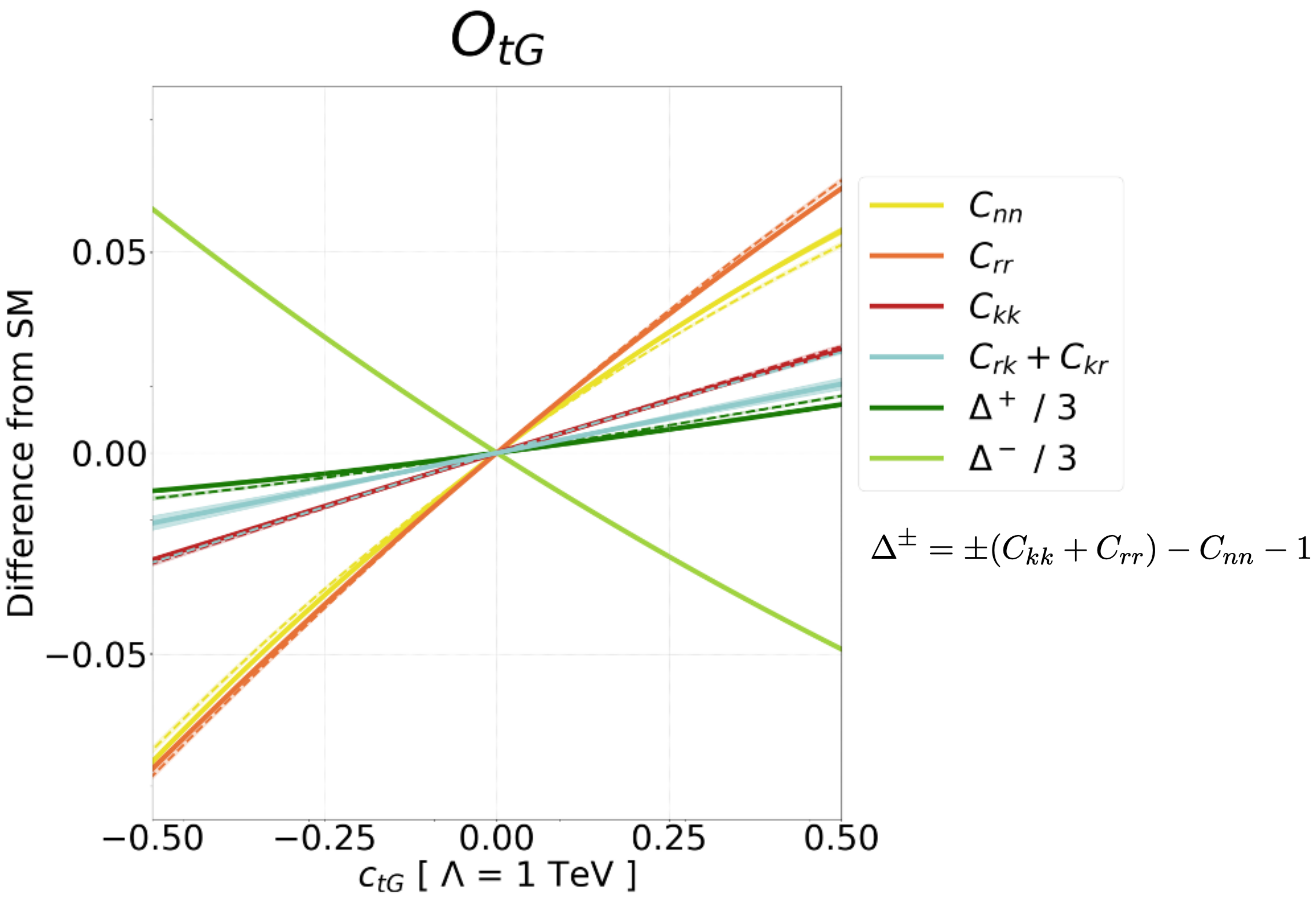
Δ_0 SM

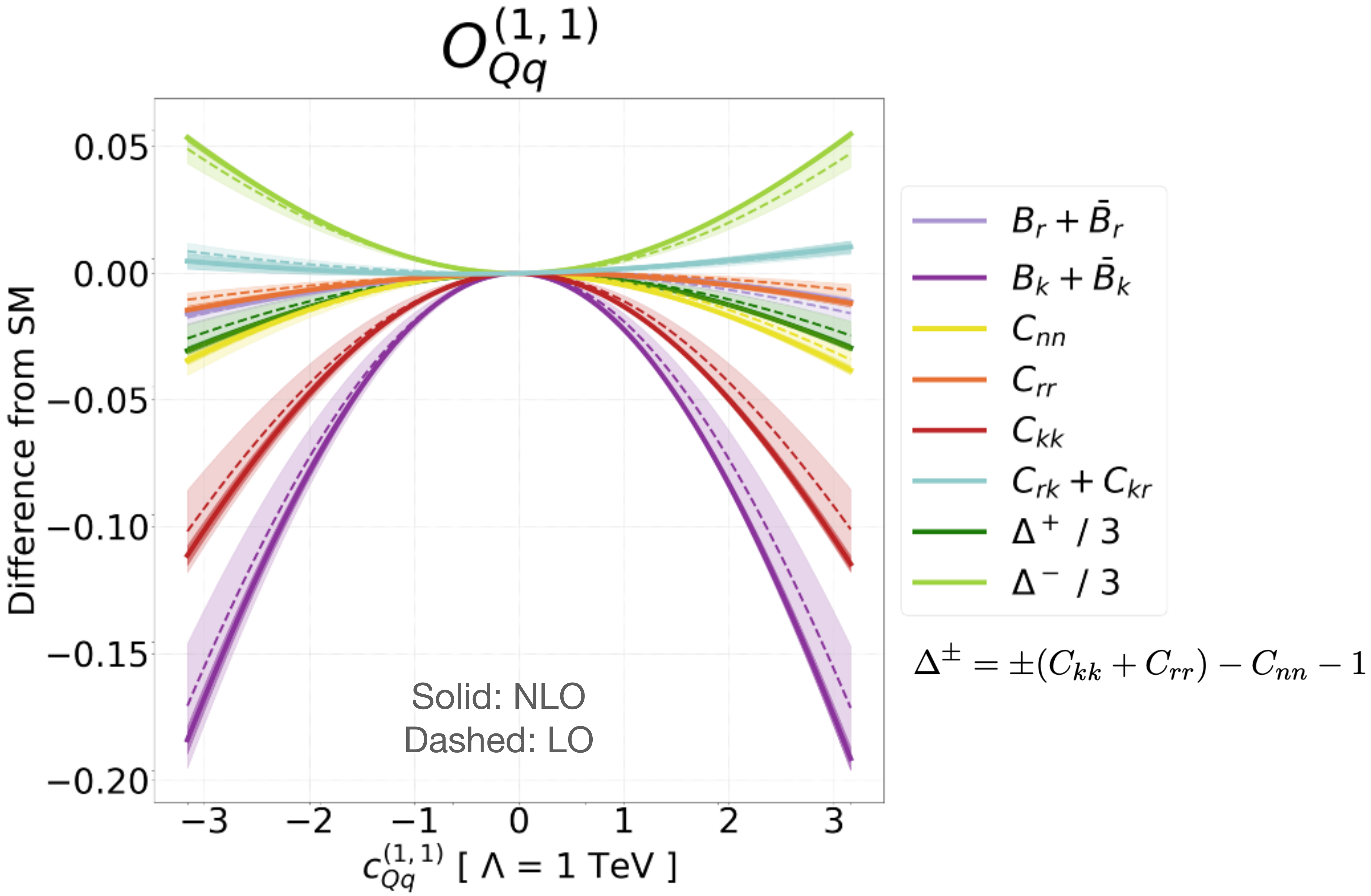
$$\Delta_1 \equiv \Delta - \Delta_0 \quad \mathcal{O}(\Lambda^{-2})$$

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

Aoude, Madge, Maltoni, Mantani arXiv:2203.05619

SMEFT impact on entanglement markers



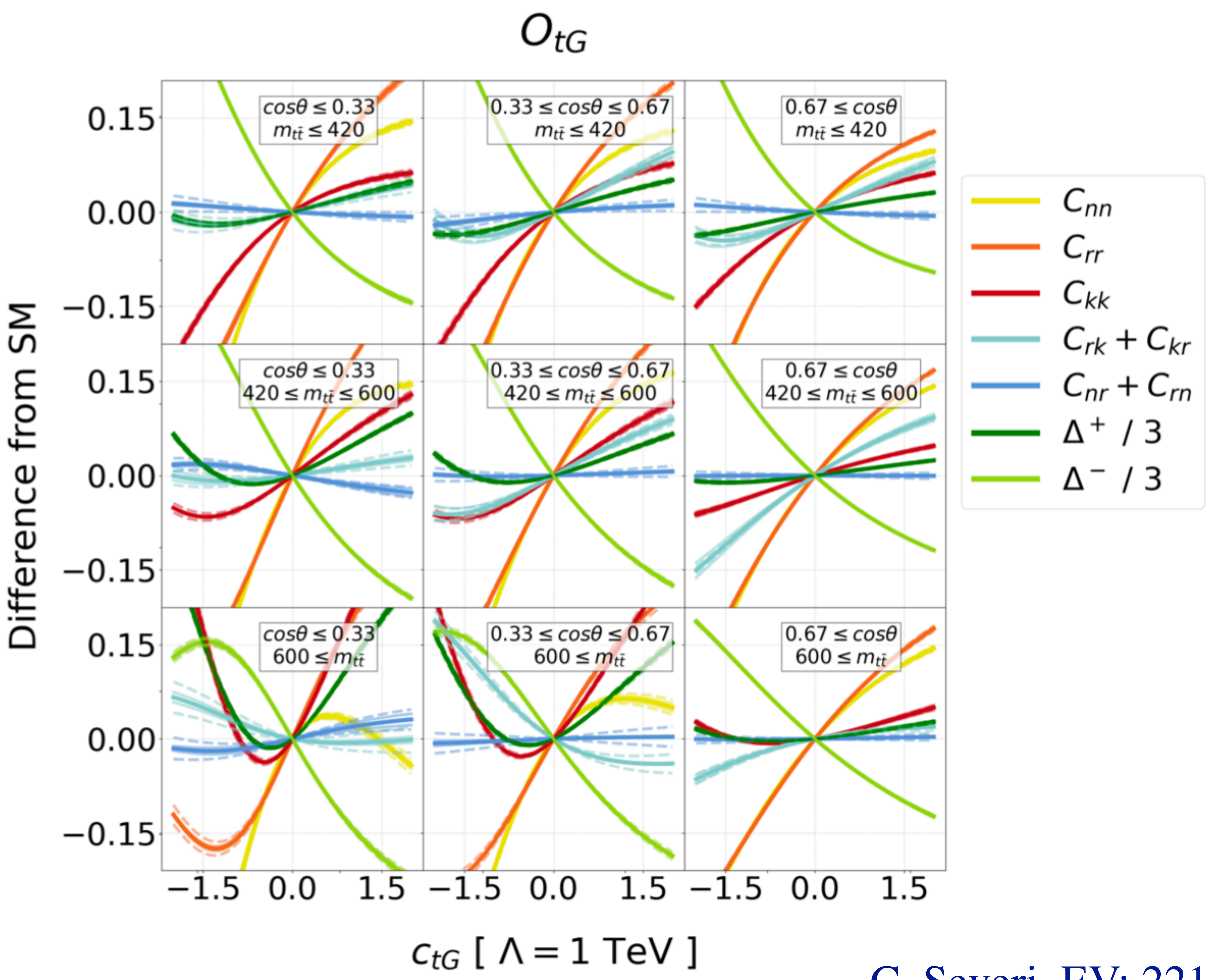


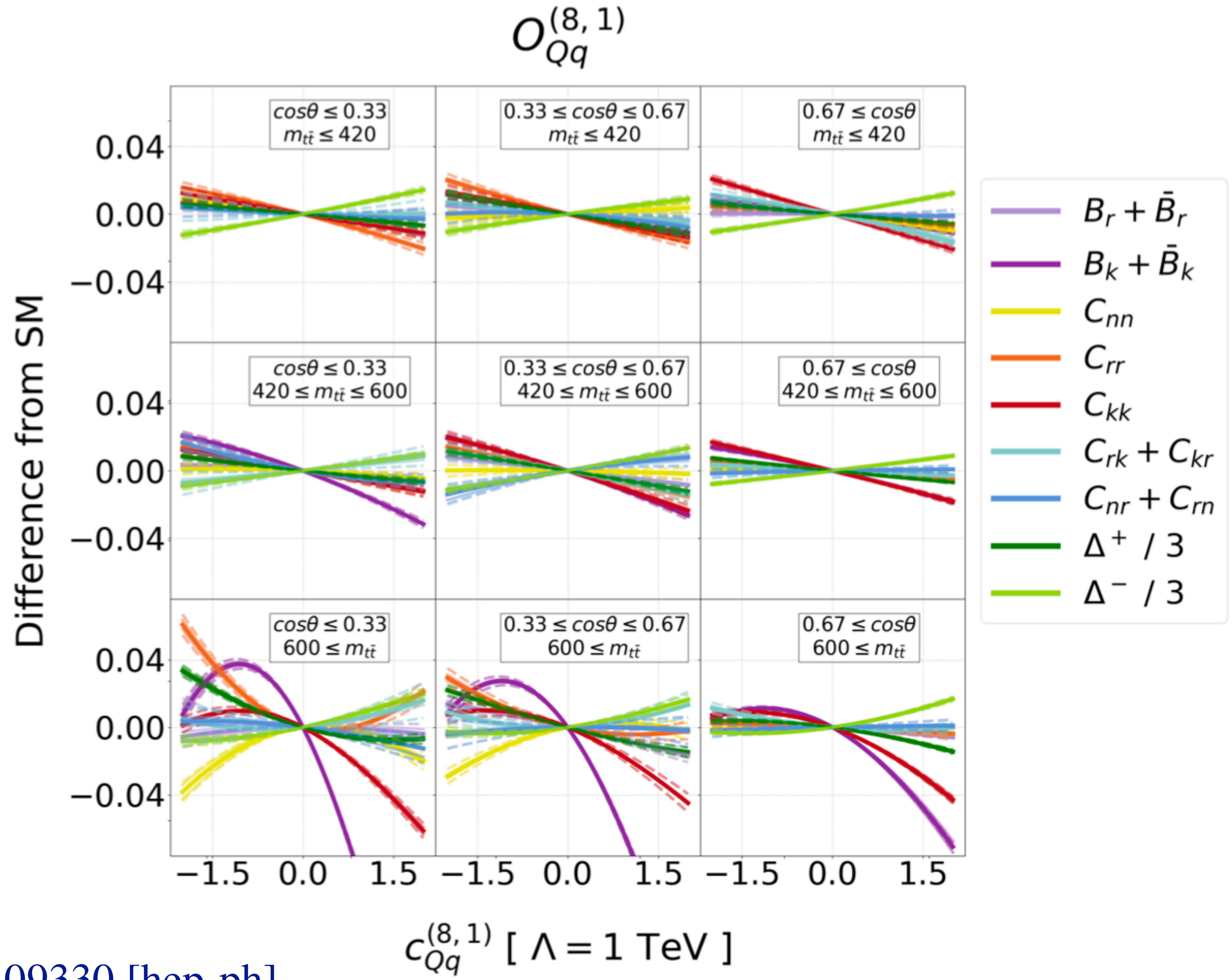
C. Severi, EV: 2210.09330 [hep-ph]

Quantum entanglement markers modified by SMEFT operators

Results available also with QCD corrections

Differential results



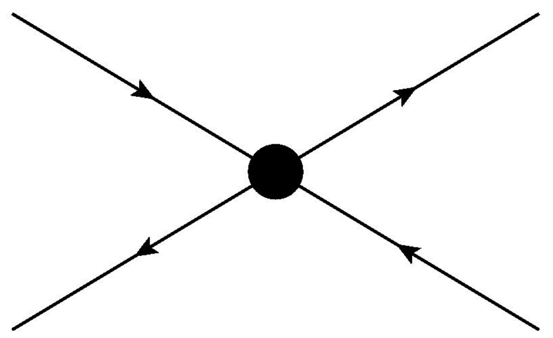


C. Severi, EV: 2210.09330 [hep-ph]

At differential level bigger impact of EFT for high energy tails

SMEFT in lepton colliders

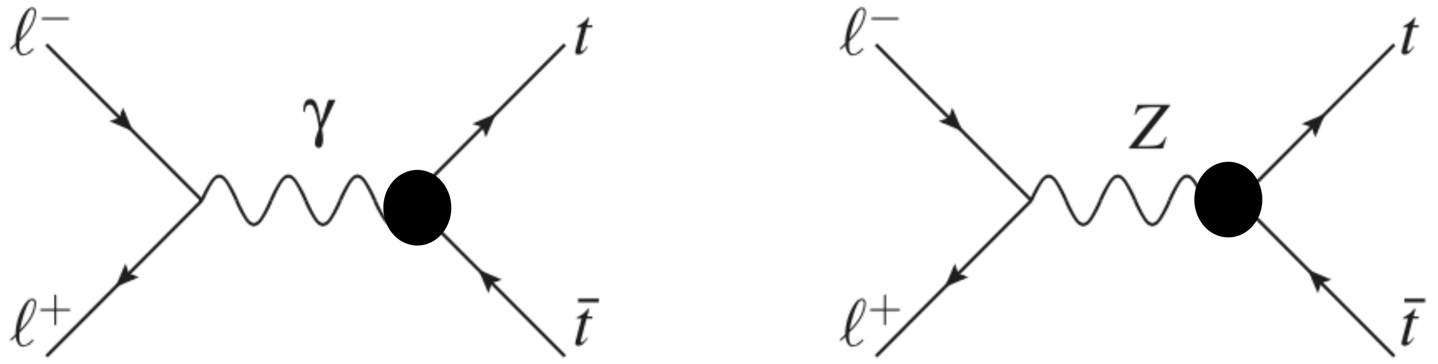
$$\mathcal{O}_{Q\ell}^{(1)} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{\ell}_L \gamma_\mu \ell_L),$$
$$\mathcal{O}_{Q\ell}^{(3)} = (\bar{Q}_L \gamma^\mu \sigma_I Q_L)(\bar{\ell}_L \gamma_\mu \sigma^I \ell_L),$$
$$\mathcal{O}_{Qe} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{\ell}_R \gamma_\mu \ell_R),$$
$$\mathcal{O}_{t\ell}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



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



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

dipole operators

Degrees of freedom

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

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

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

Structure of spin correlations within SMEFT

Degeneracy between possible structures arising from SM and EFT

$$
\left.
\begin{aligned}
A^{[0]} &= F^{[0]} \left(\beta^2 c_\theta^2 - \beta^2 + 2\right) \\
A^{[1]} &= 2\, F^{[1]}\, c_\theta \\
A^{[2]} &= F^{[2]} \left(1 + c_\theta^2\right)
\end{aligned}
\right\} \text{SM}
$$

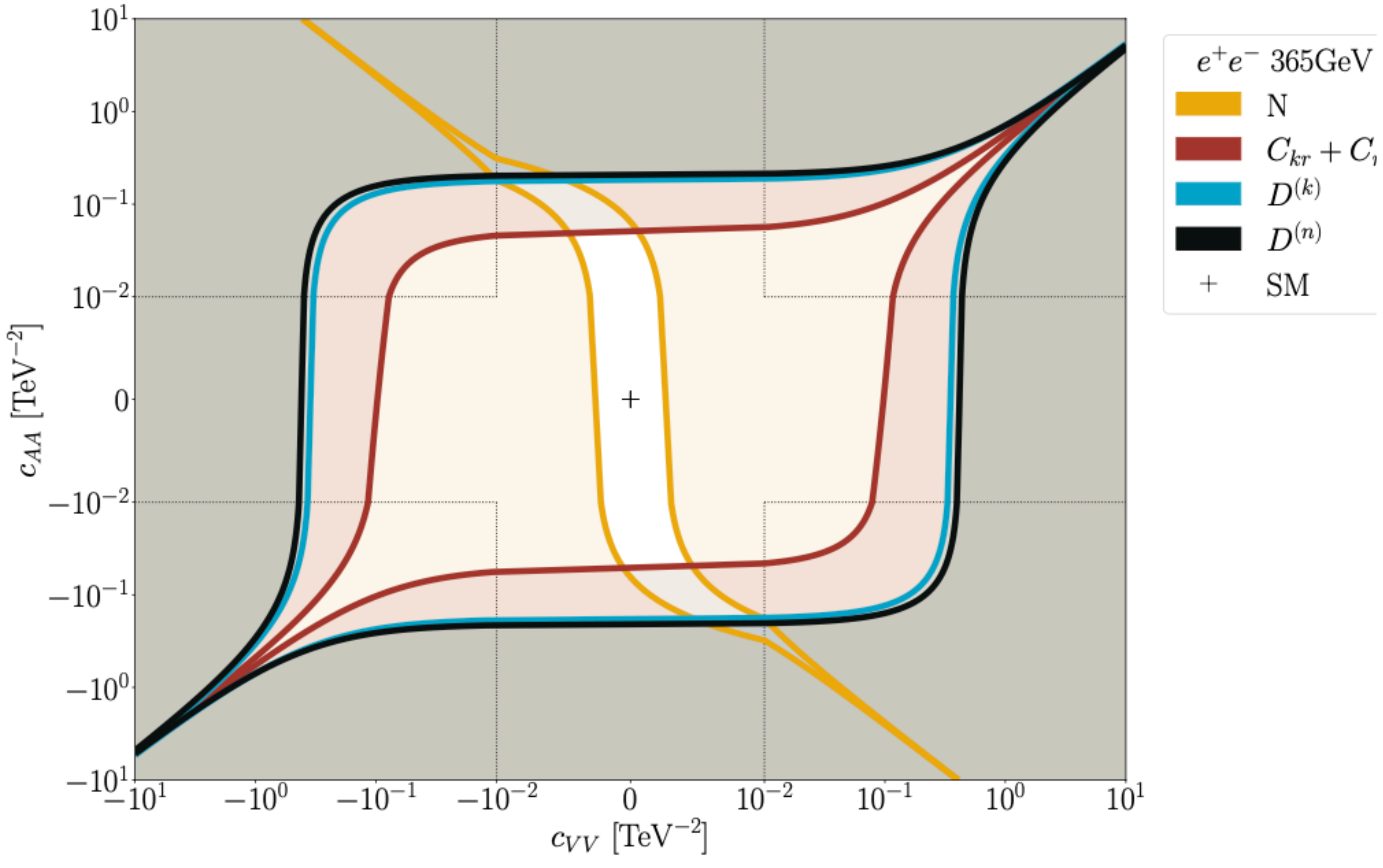
$$
\left.
\begin{aligned}
A^{[6,0,\mathrm{D}]} &= F^{[6,0,\mathrm{D}]} \\
A^{[6,1,\mathrm{D}]} &= F^{[6,1,\mathrm{D}]}\, c_\theta \\
A^{[8,\mathrm{DD}]} &= F^{[8,\mathrm{DD}]} \left(-\beta^2 c_\theta^2 - \beta^2 + 2\right)
\end{aligned}
\right\} \text{BSM}
$$

		$\mathcal{M}_1$		
		$Q_\mathrm{t},\ g_\mathrm{Vt},$ $c_\mathrm{VV},\ c_\mathrm{VA},\ c_{\phi\mathrm{V}}$	$g_\mathrm{At},$ $c_\mathrm{AV},\ c_\mathrm{AA},\ c_{\phi\mathrm{A}}$	$c_{\mathrm{t}Z},\ c_{\mathrm{t}\gamma}$
$\mathcal{M}_2$	$Q_\mathrm{t},\ g_\mathrm{Vt}$ $c_\mathrm{VV},\ c_\mathrm{VA},\ c_{\phi\mathrm{V}}$	$A^{[0]}$	$A^{[1]}$	$A^{[6,0,D]}$
	g_At $c_\mathrm{AV},\ c_\mathrm{AA},\ c_{\phi\mathrm{A}}$	$A^{[1]}$	$A^{[2]}$	$A^{[6,1,D]}$
	$c_{\mathrm{t}Z},\ c_{\mathrm{t}\gamma}$	$A^{[6,0,D]}$	$A^{[6,1,D]}$	$A^{[8,\mathrm{DD}]}$

New structures related to dipole operators, the rest gives linear combinations of pre-existing structures

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

Breaking degeneracies with Quantum Obs



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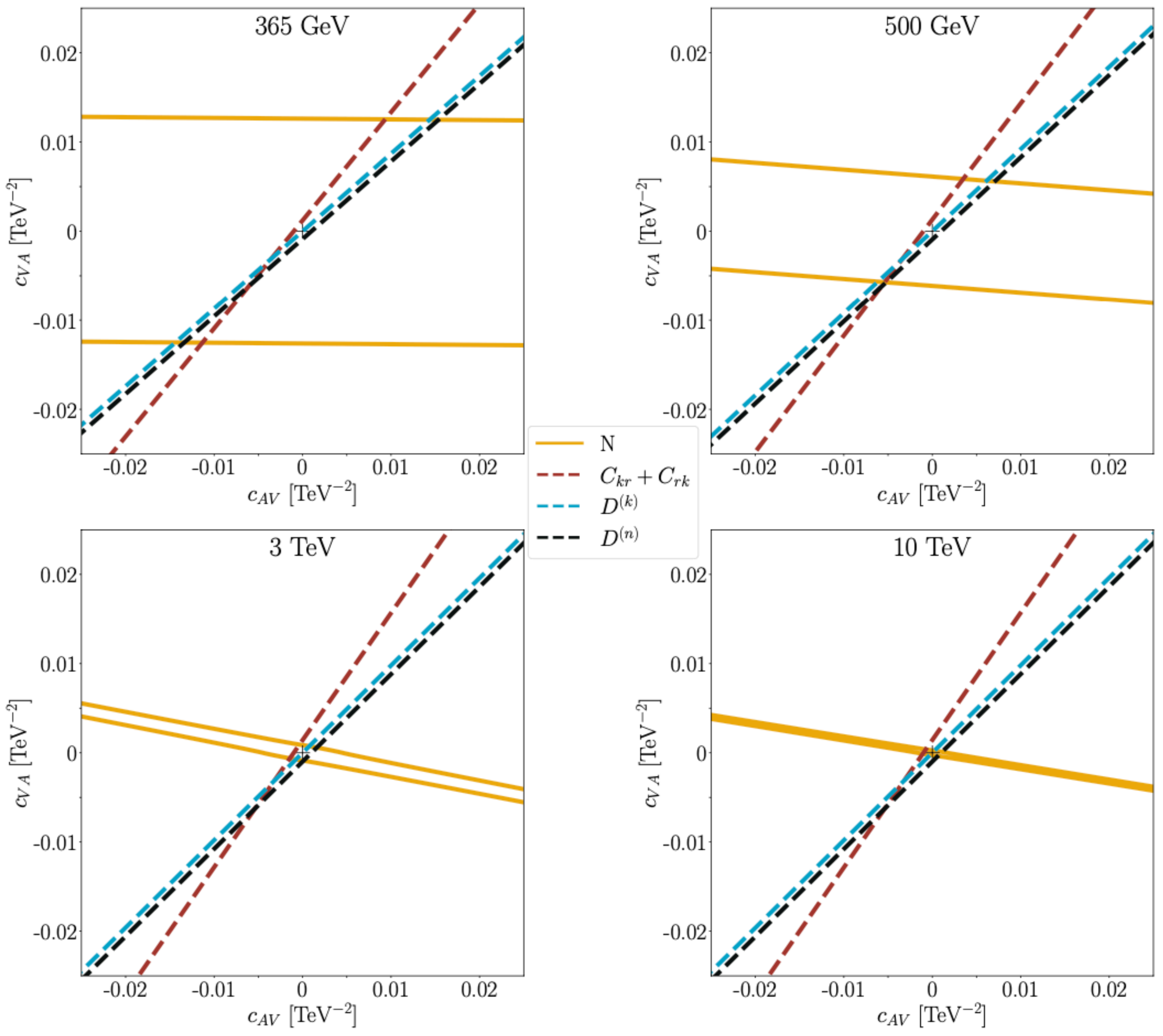


Spin correlation observables probe different linear combinations of Wilson coefficients

➡ Breaking degeneracies

SMEFT summary

New interactions modify both conventional and quantum observables

Dimension-6 operators can modify the degree of entanglement between top quarks

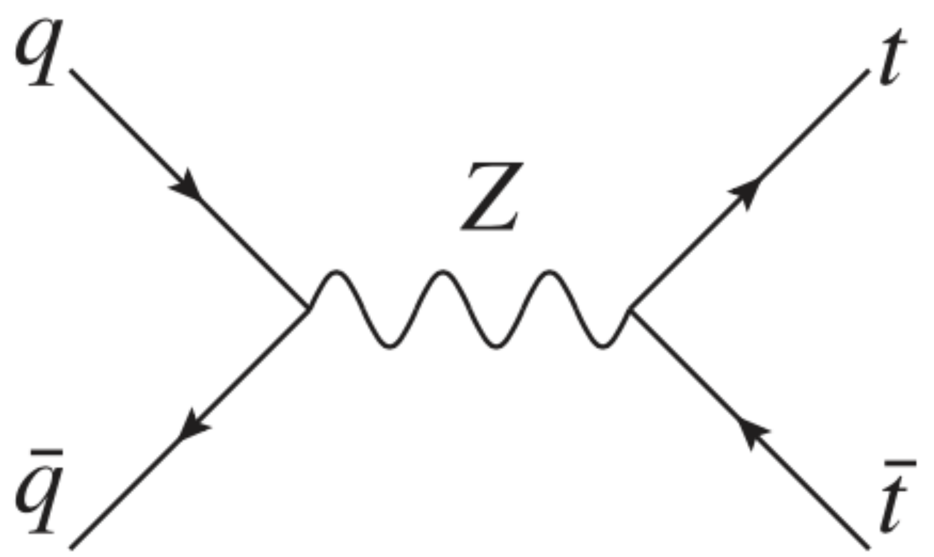
SMEFT introduce new structures, thus probing new linear combinations between coefficients

QI observables can break degeneracies between operators when combined with standard observables

➡ New sensitivity

New particle searches

Vector resonances



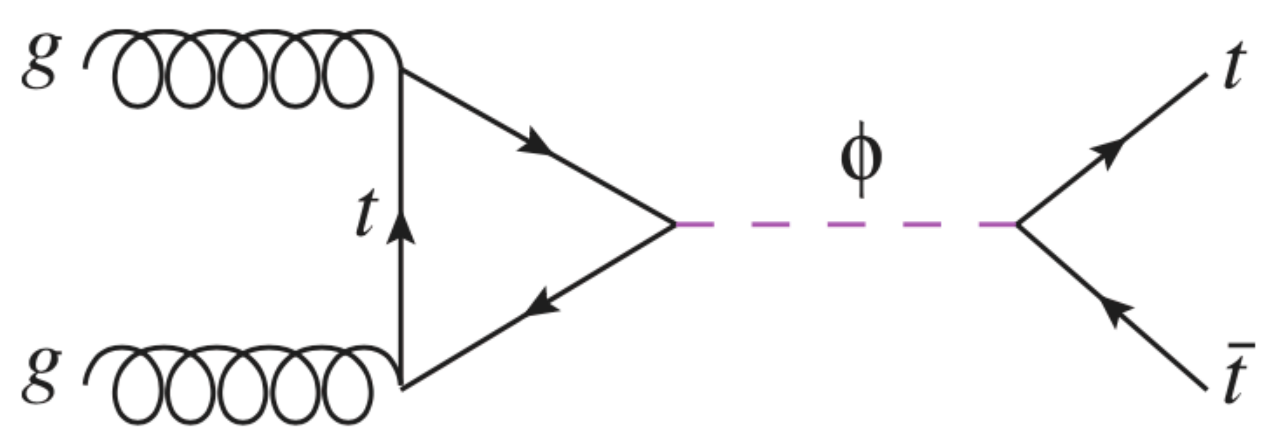
Spin-1 exchange: spin-triplet state as in the SM

$$1/3\,\mathrm{Tr}\,[\mathcal{C}] = D^{(1)} = +\frac{1}{3}$$

$$\beta \to 1 \qquad C_{kk} = 1, \qquad C_{rr} = -C_{nn}$$

Similar to QCD background

Scalar resonances



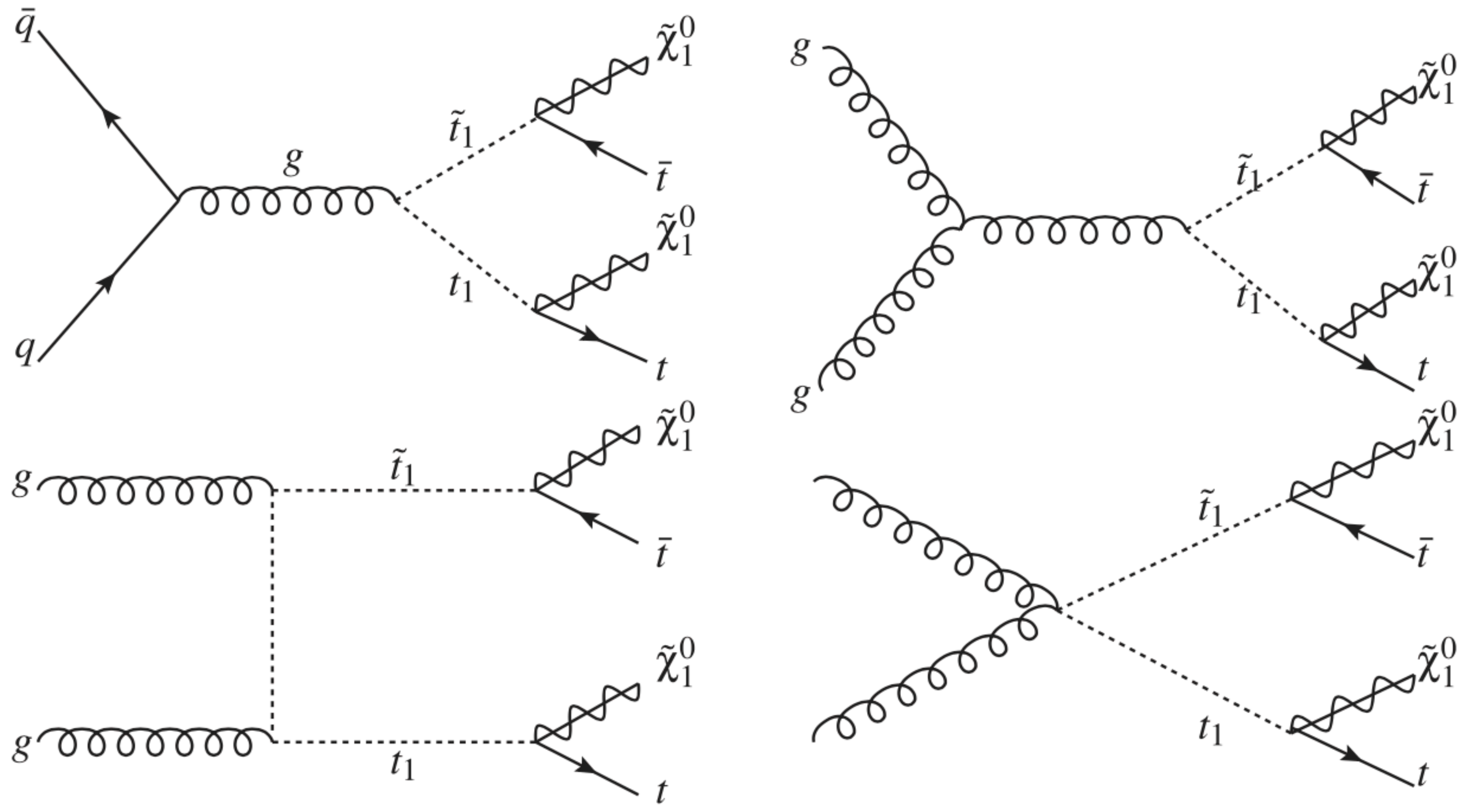
$$\mathcal{C}^{[gg,\phi]}\big|_{\alpha=0} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \mathcal{C}^{[gg,\phi]}\big|_{\alpha=\pi/2} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

Scalar: Pure triplet

Pseudoscalar: Pure singlet

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

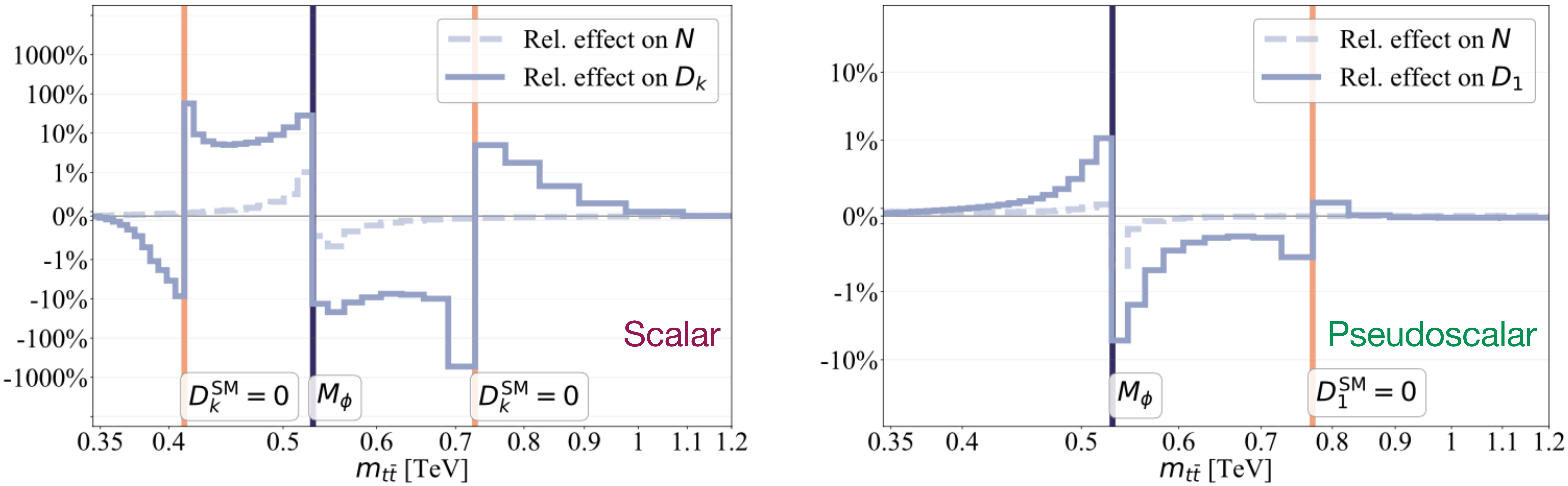
Stops



$$\mathcal{C}^{[\mathrm{SUSY}]} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Diluted Spin Correlations

New scalars and their impact on QI observables



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

Relative effect on Quantum observables is significantly larger:

100% vs 1%

Sensitivity analysis

How can we check if the Quantum observables help?

Simulate:

$$p\,p \to t\,\bar{t} \to b\,\bar{b}\,\ell^+\,\ell^-\,\nu_\ell\,\bar{\nu}_\ell.$$

Compare different observables:

- Event rate
- $D^{(1)}, D^{(k)}, D^{(r)}, D^{(n)}$
- $\Delta\eta = |\eta_{\ell^+} - \eta_{\ell^-}|, \Delta\phi = |\phi_{\ell^+} - \phi_{\ell^-}|$
- $\cos\varphi = p_{\ell^+} \cdot p_{\ell^-}$

Observable	Systematic unc.	Statistical unc.
$m_{t\bar{t}}$	30 GeV	
$dN/dm_{t\bar{t}}$	$0.03 \cdot N$	$\sqrt{N}$
$d(\cos\varphi)/dm_{t\bar{t}}$	0.010	$0.5/\sqrt{N}$
$d(\Delta\eta)//dm_{t\bar{t}}$	0.010	$3/\sqrt{N}$
$d(\Delta\phi)/dm_{t\bar{t}}$	0.010	$2.5/\sqrt{N}$
$dD^{(1)}/dm_{t\bar{t}}$	0.015	$0.75/\sqrt{N}$
$dD^{(k,r,n)}/dm_{t\bar{t}}$	0.025	$0.75/\sqrt{N}$

Uncertainties motivated by existing measurements

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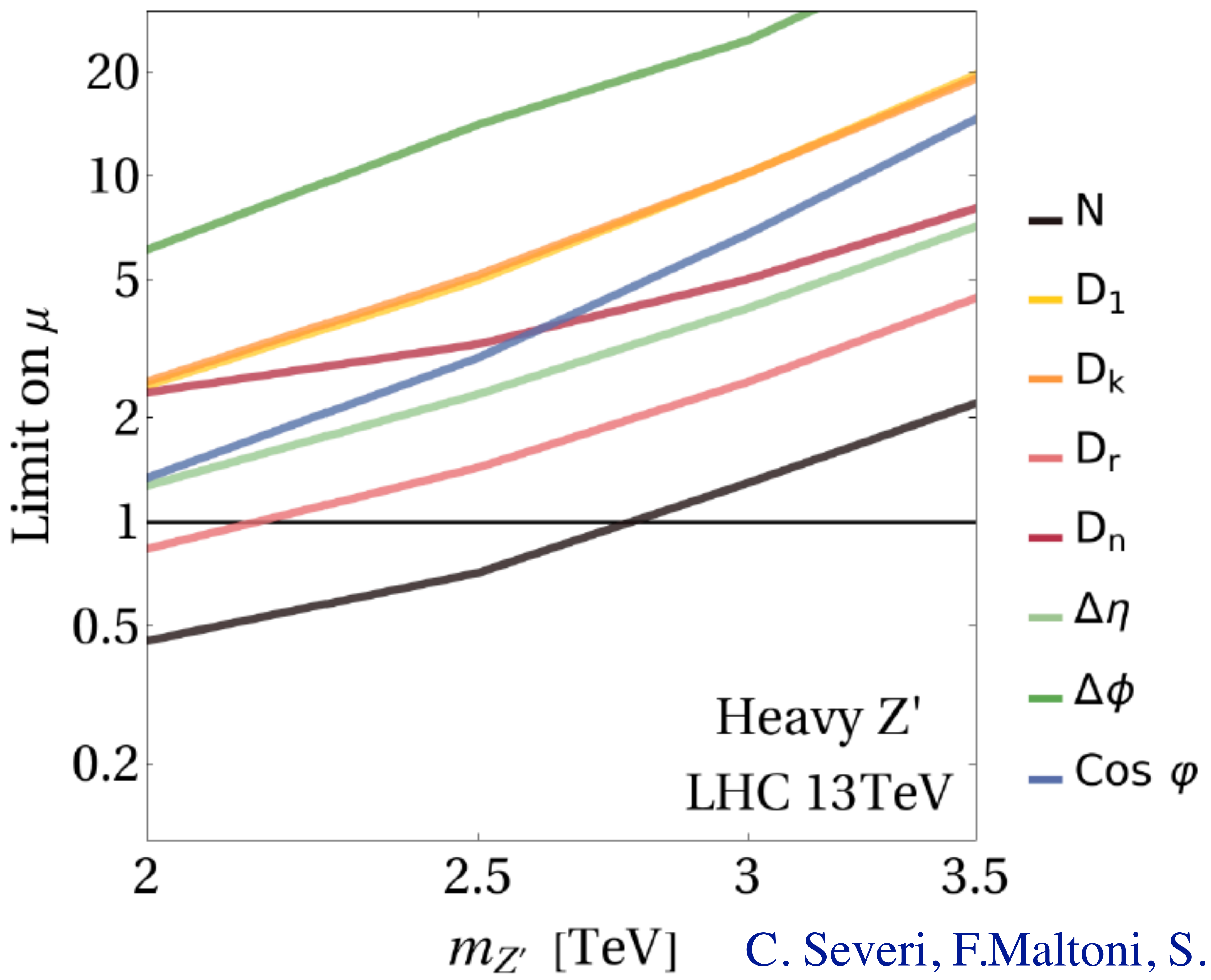
Resonances: Vector and SUSY



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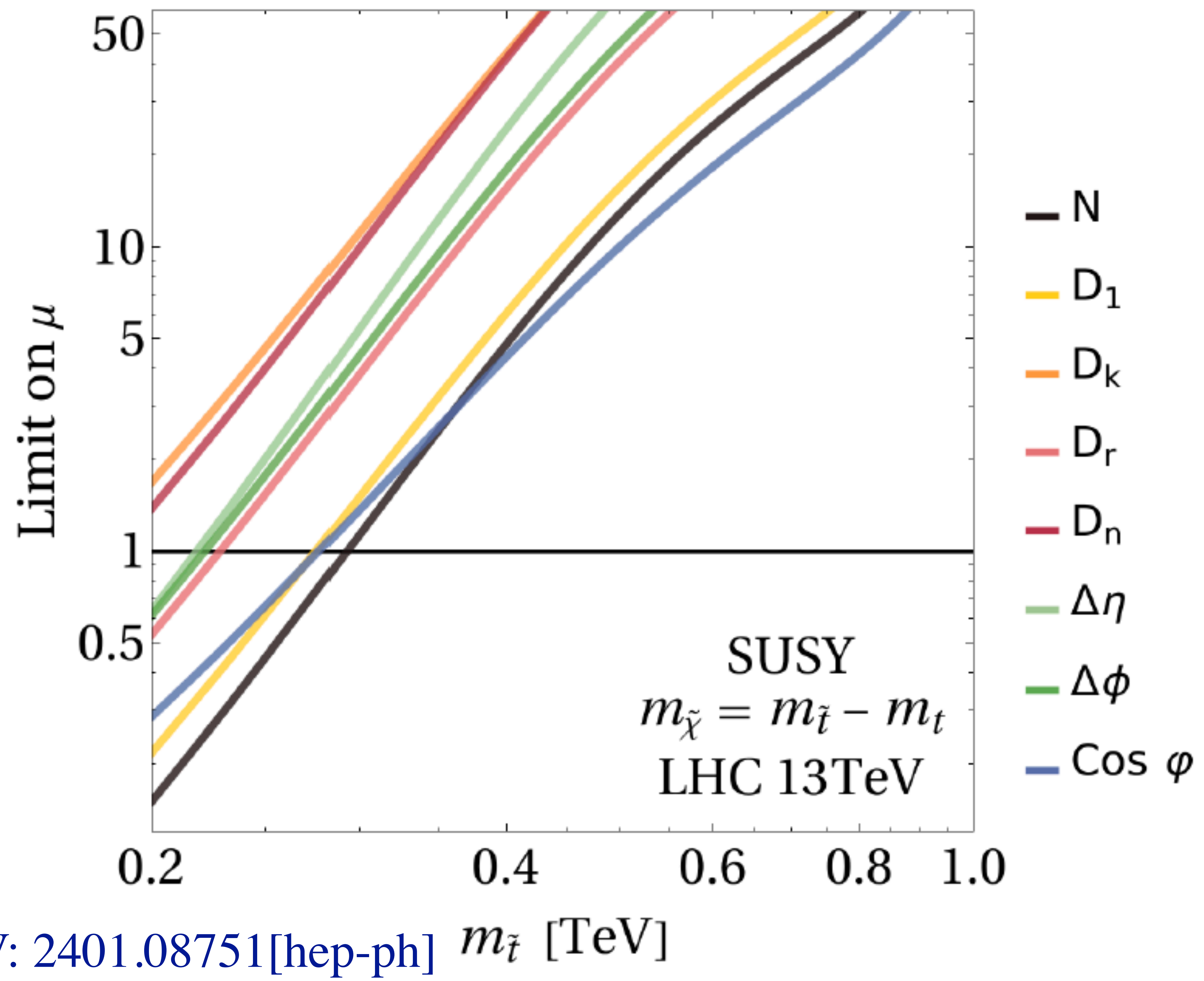
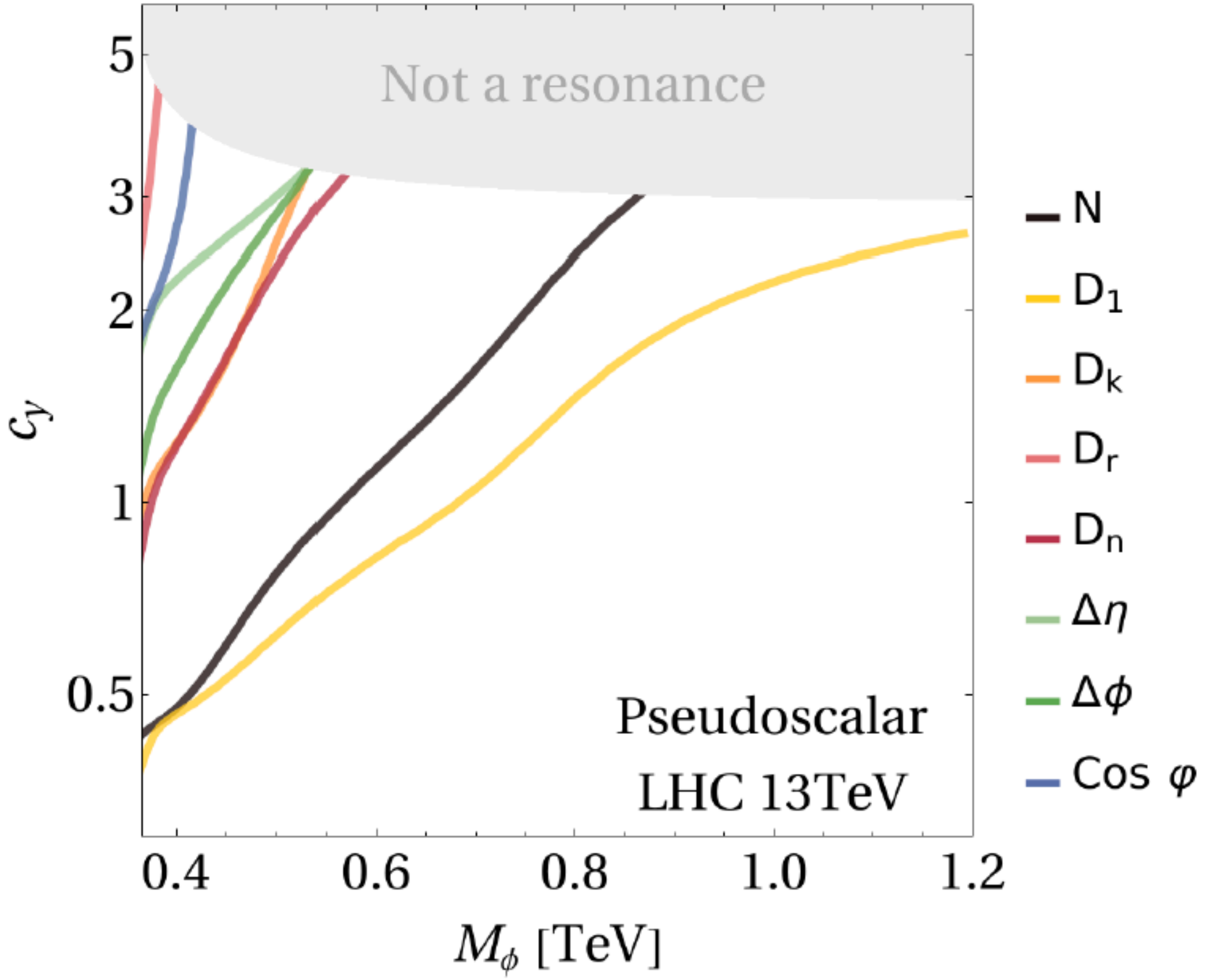
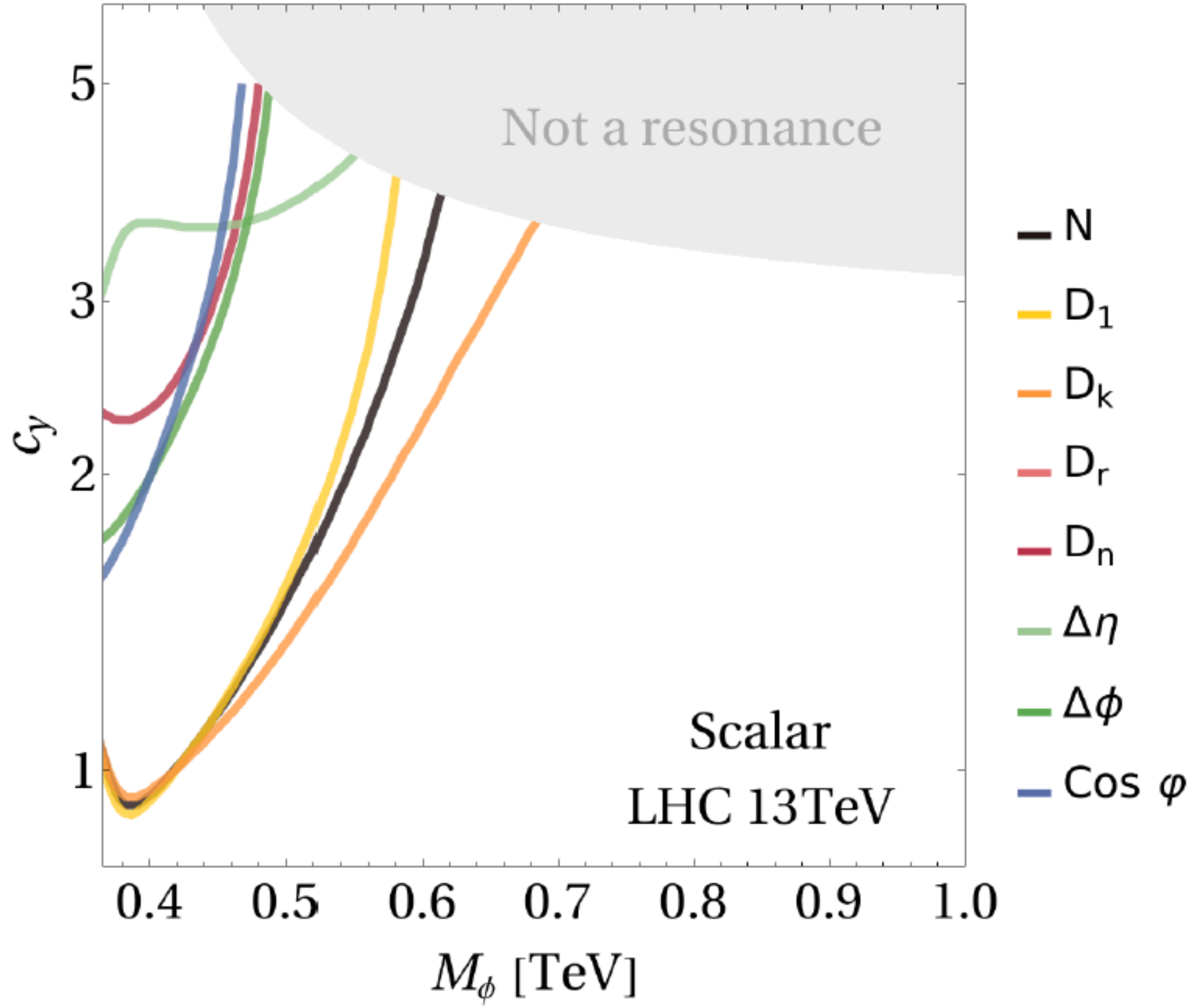


Less constraining than rate information

Similar to rate information

(Pseudo)Scalar resonances





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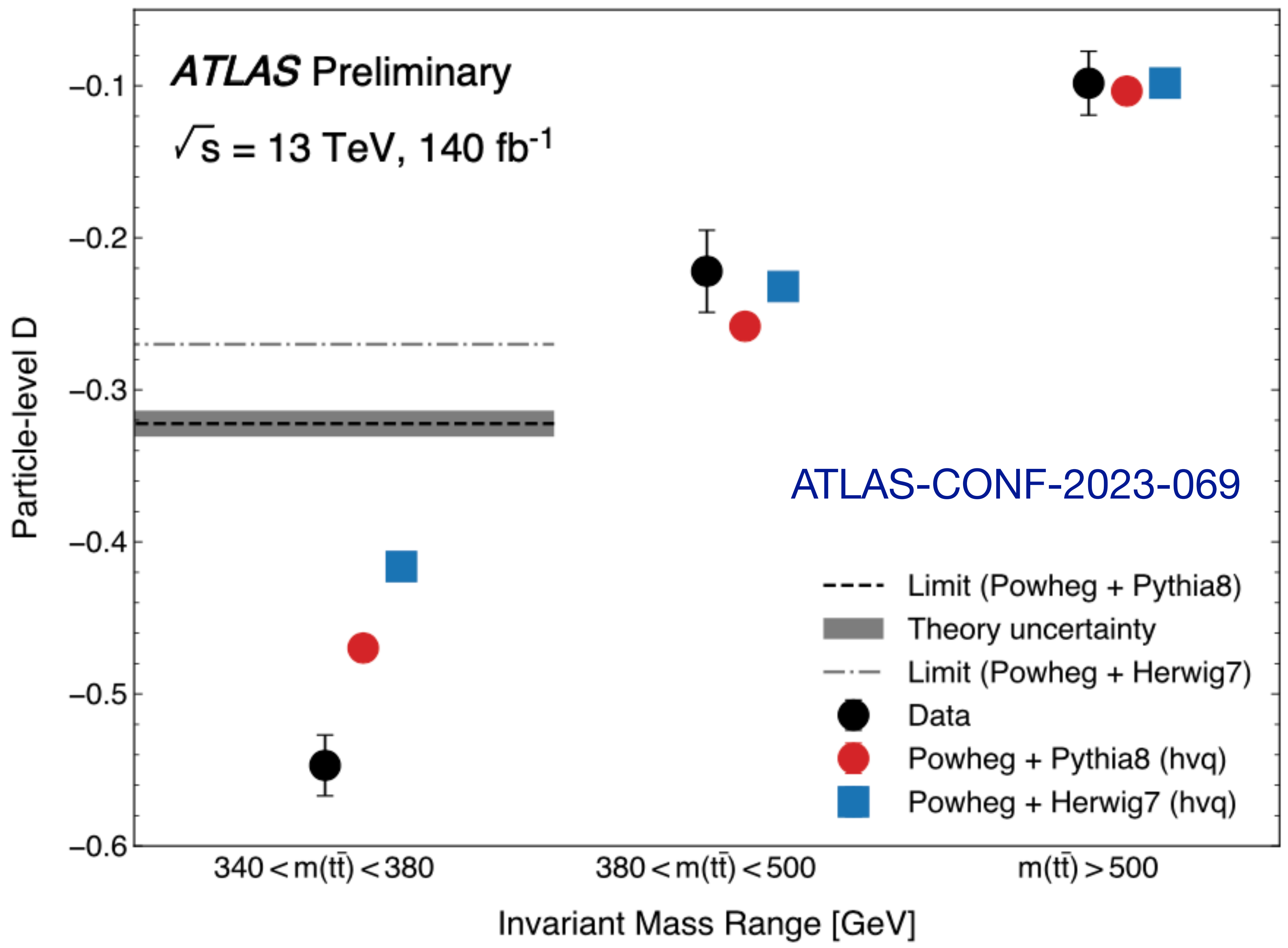
Conclusions

- 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
- QI observables are not only fun but can also help to probe new physics: both EFT and new particles

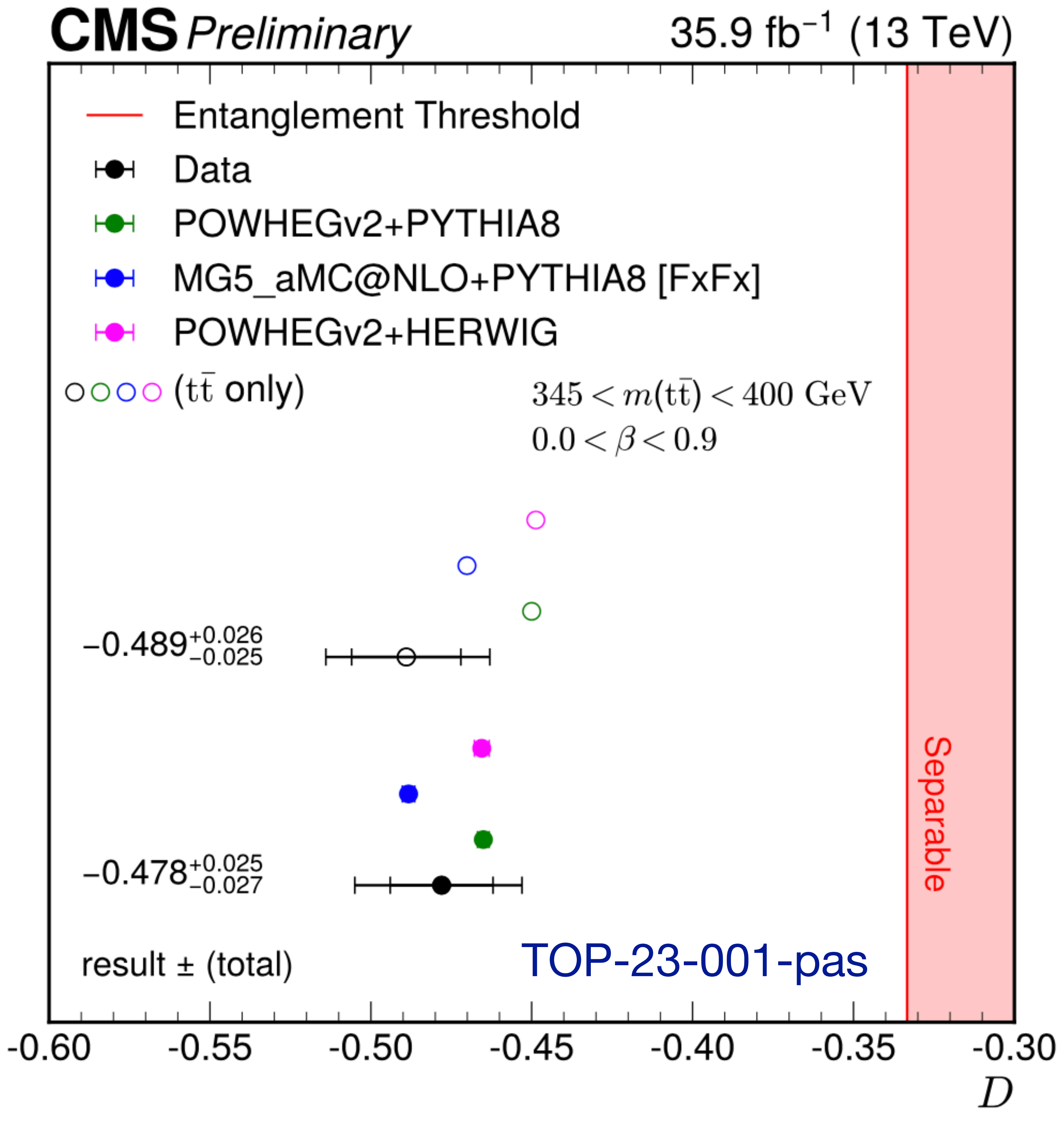
Thank you for your attention

Backup

First measurements

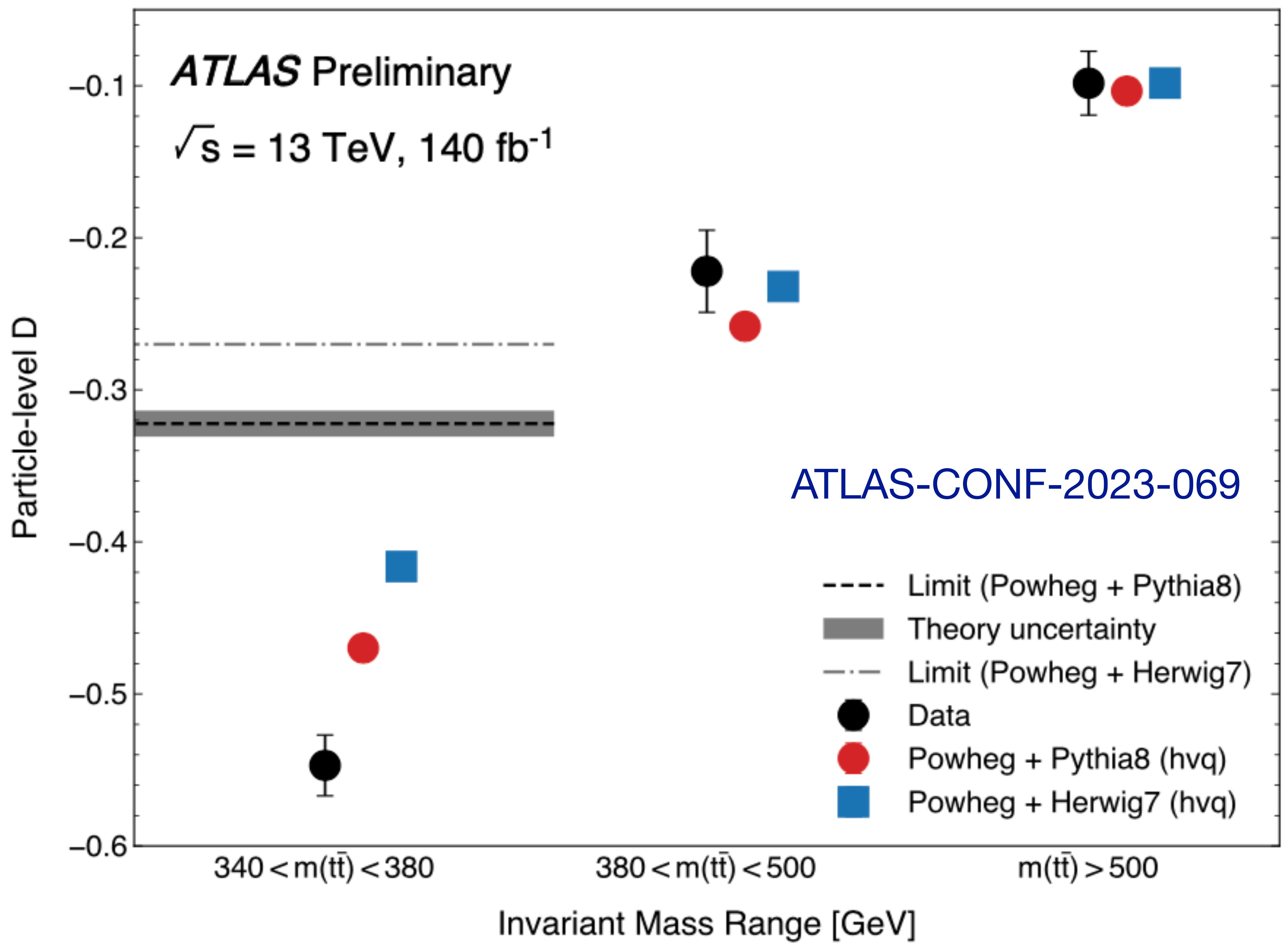


Entanglement observation by ATLAS



Entanglement observation by CMS

First measurements



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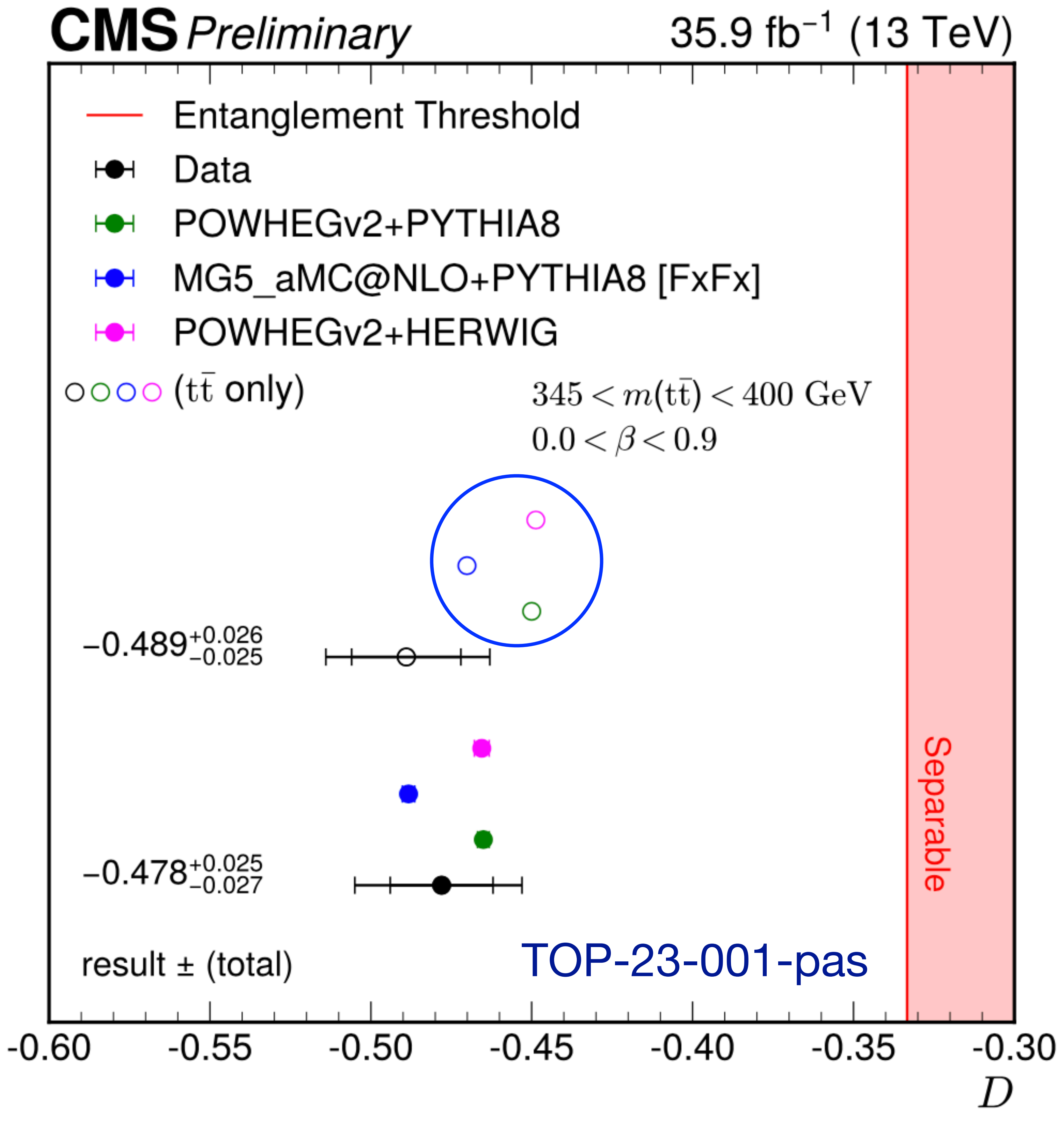

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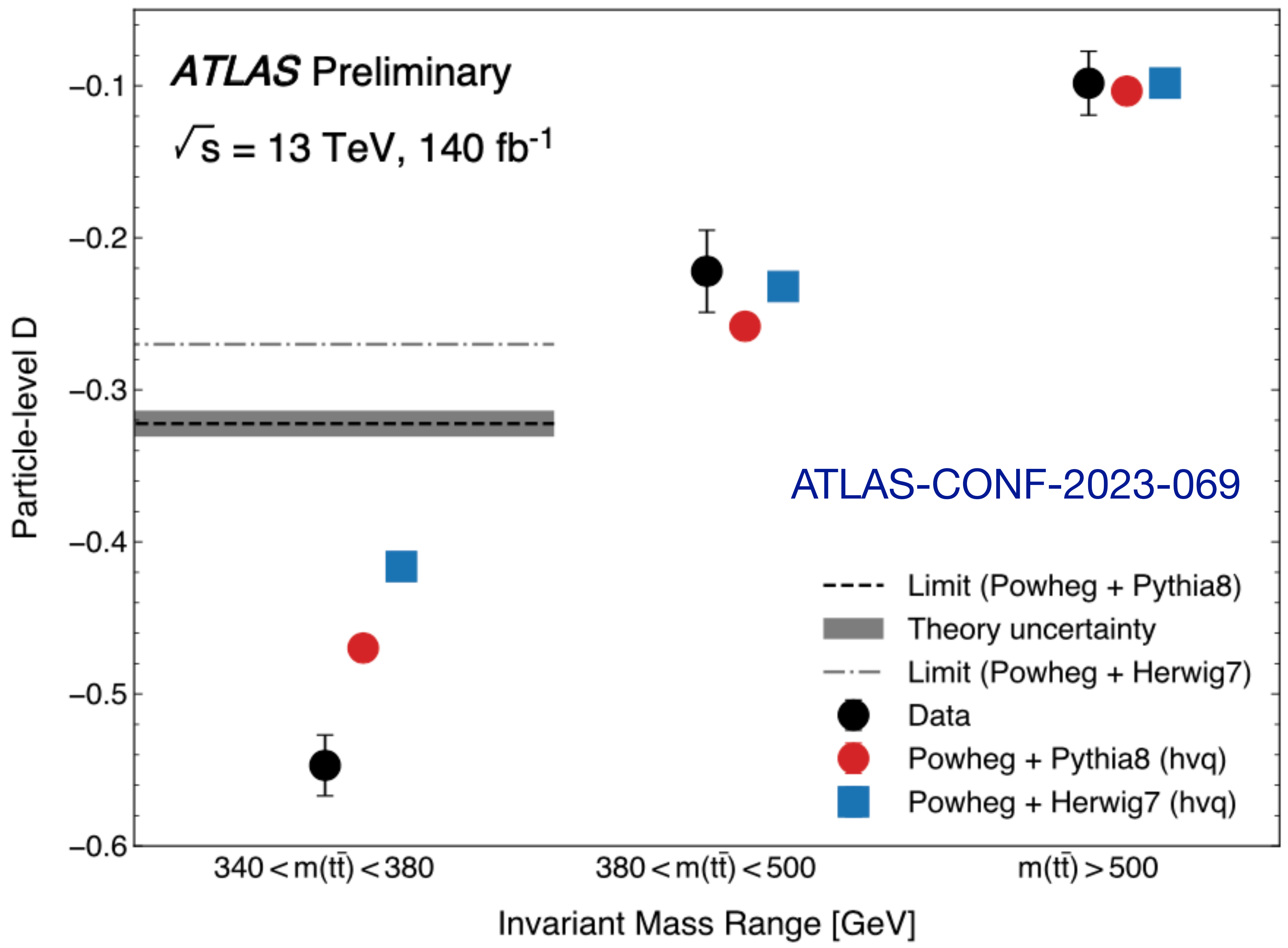

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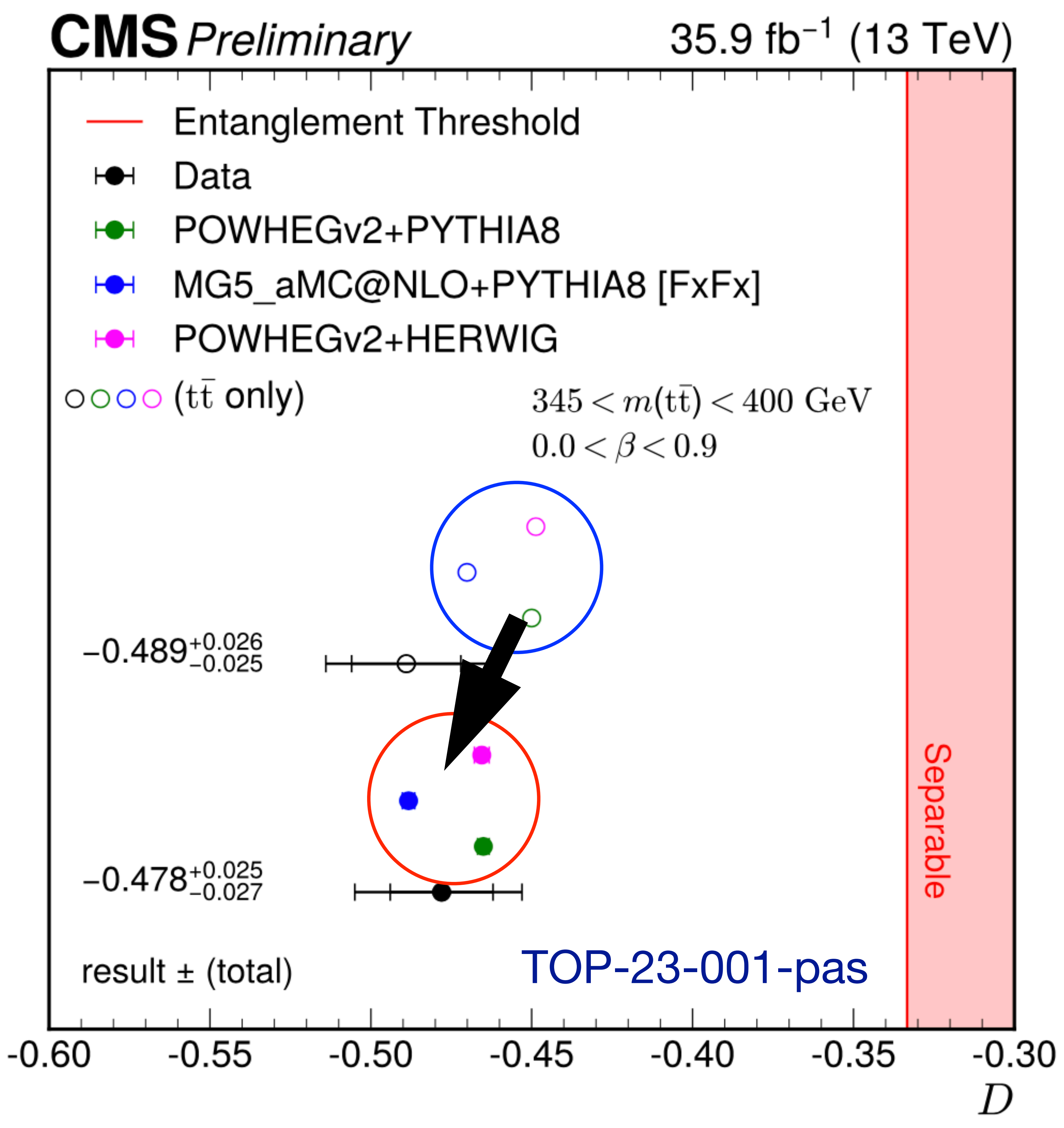
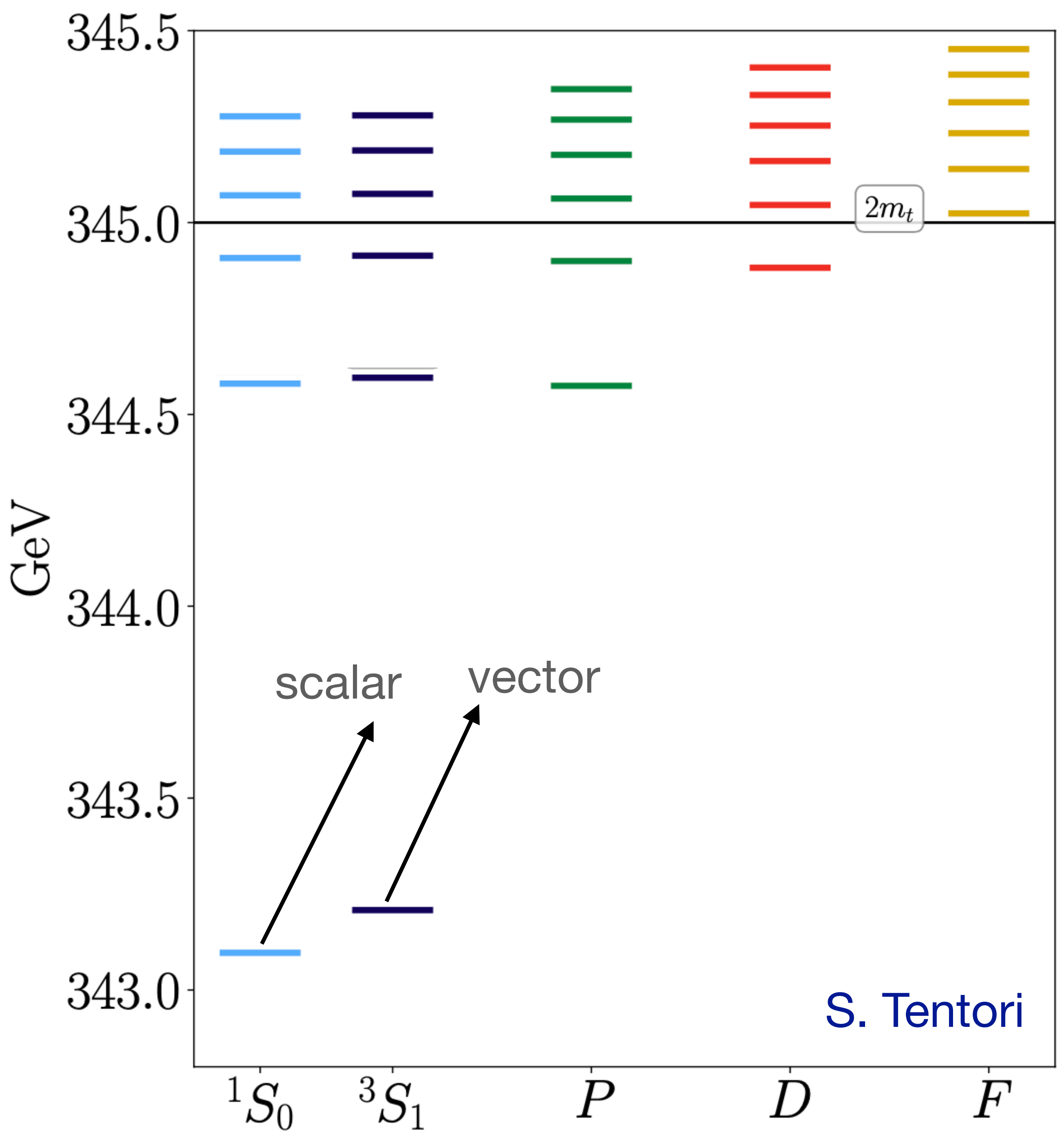


Entanglement observation by CMS

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^-



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

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

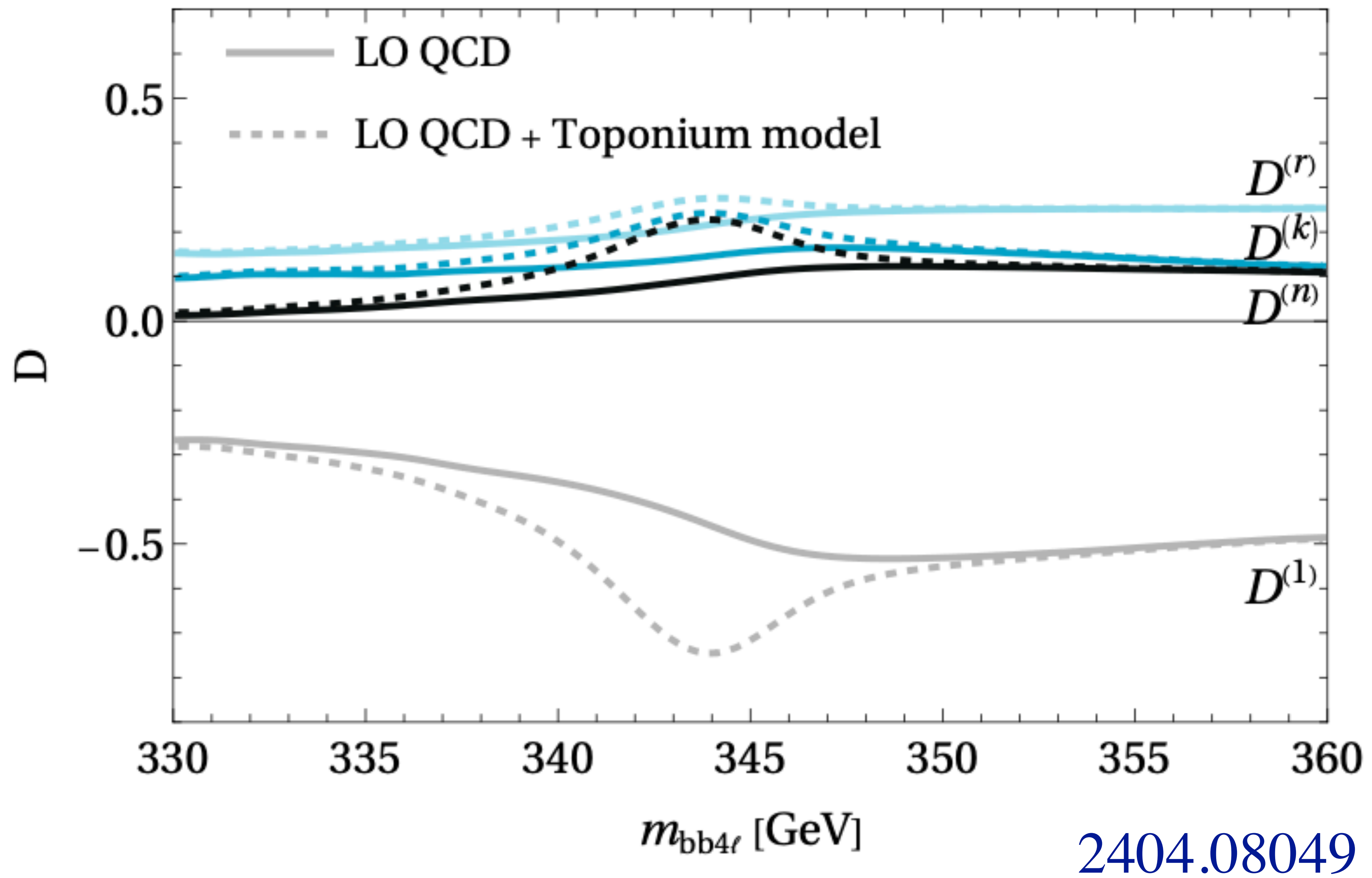
Toponium modelling

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

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

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



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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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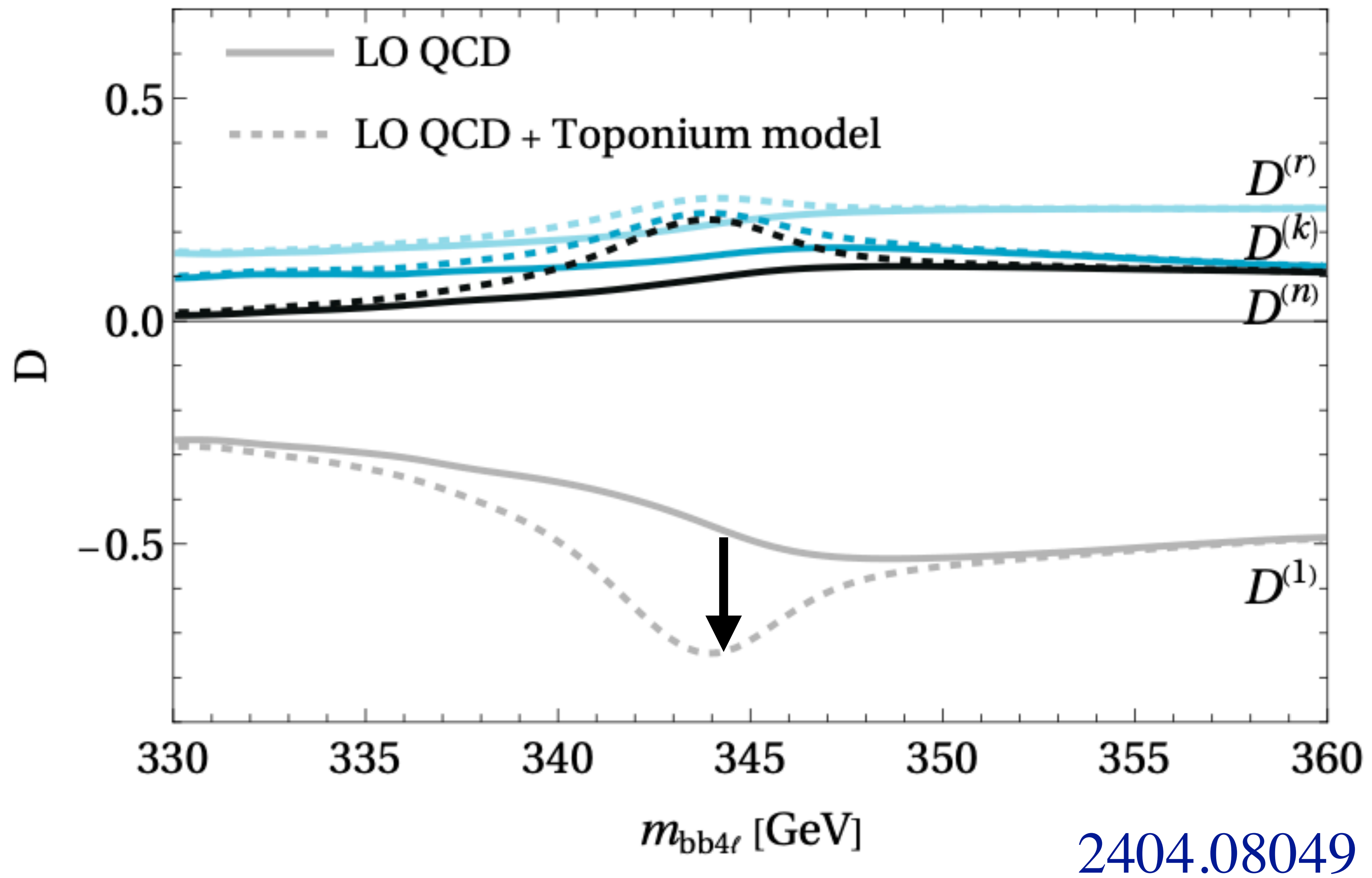

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