Probing new physics through entanglement

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Uppsala, Sweden

"Heart of Quantum Mechanics"

"There is a troubling weirdness about QM. Perhaps its weirdest feature is entanglement, the need to describe even systems that extend over macroscopic distances in ways that are inconsistent with classical ideas."

- Weinberg

Quantum superposition

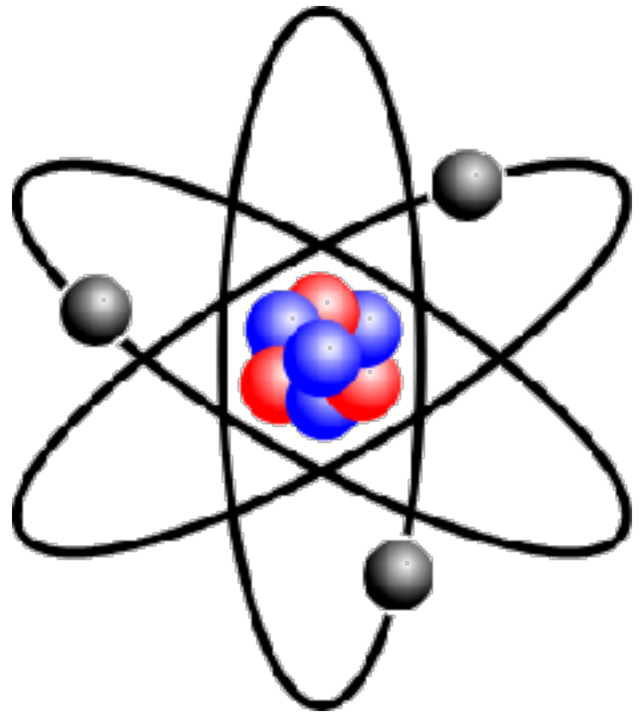
$|\psi\rangle = \frac{1}{\sqrt{2}}|$  $\rangle + \frac{1}{\sqrt{2}}|$  $\rangle$

Entanglement

$$|\psi_{\mathrm{ab}}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \neq |\psi_{\mathrm{a}}\rangle \otimes |\psi_{\mathrm{b}}\rangle$$

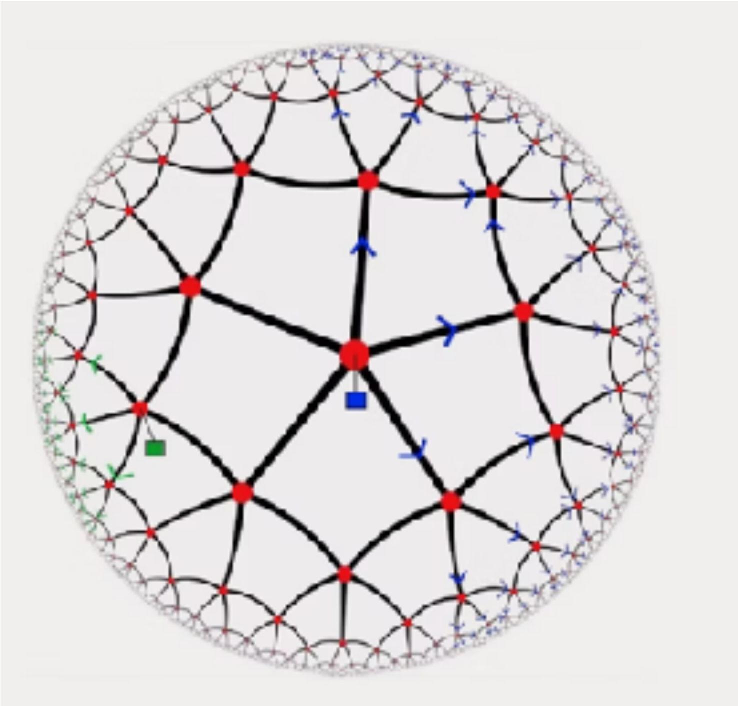
Borders of the Quantum World: Energy/distance scales

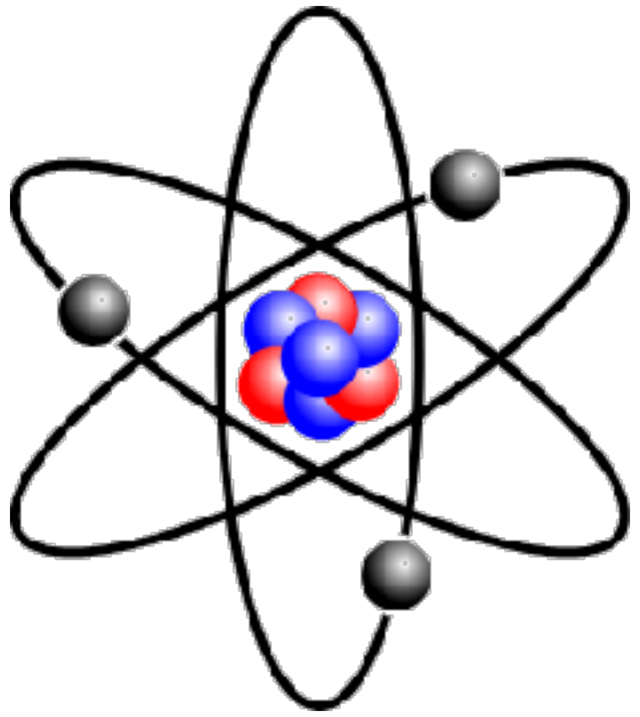
Quantum computers
Quantum devices,..



Borders of the Quantum World: Energy/distance scales

It from Qubit

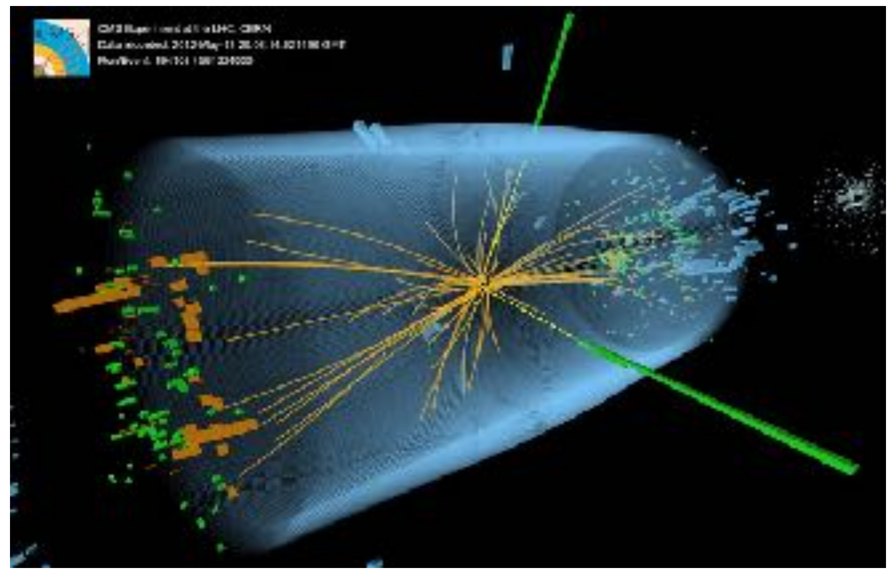


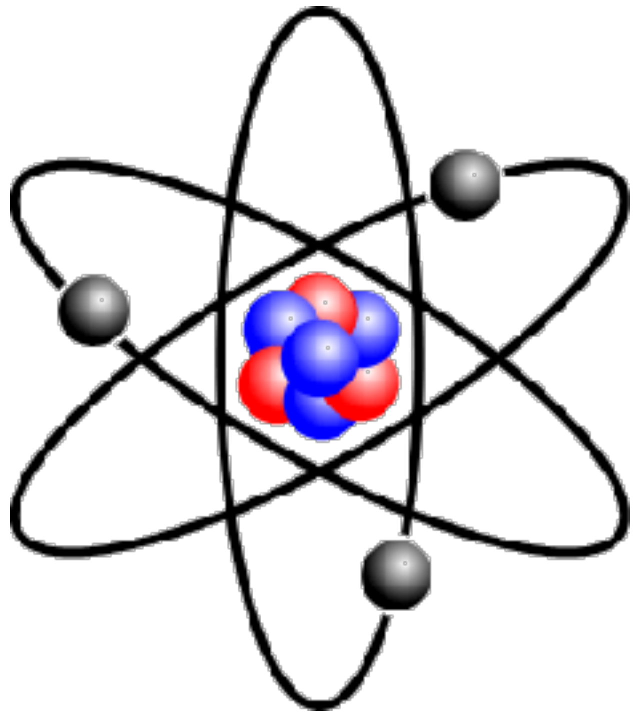


$10^{-35}\mathrm{m}$ $10^{-20}\mathrm{m}$ $10^{-10}\mathrm{m}$ $1\mathrm{m}$

Borders of the Quantum World: Energy/distance scales

LHC





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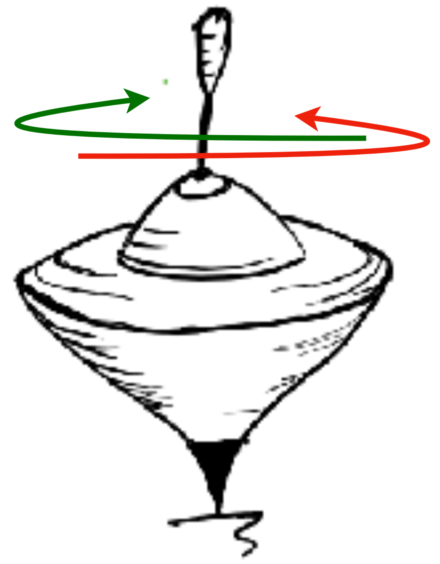
Back to the basics…   entanglement in spin space

One qubit



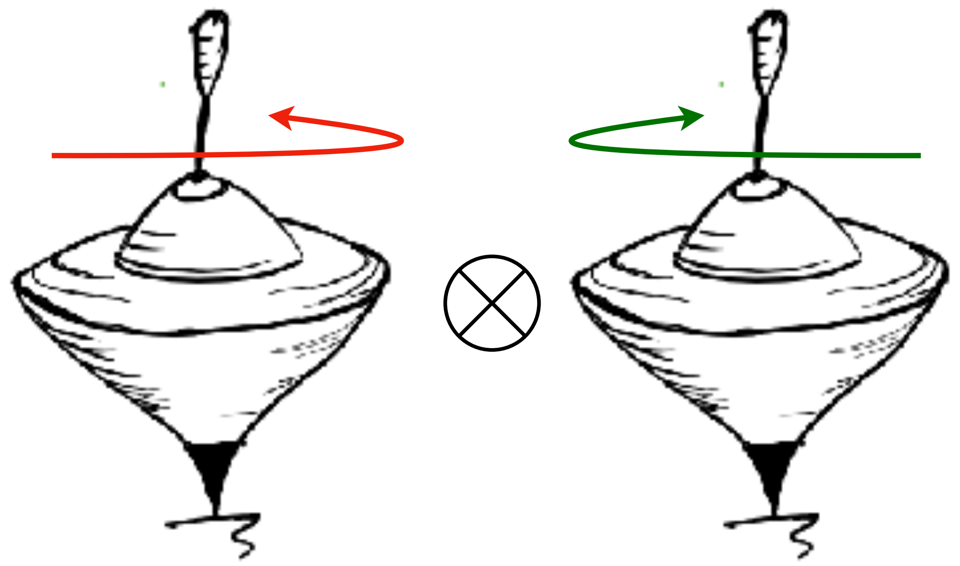
$$|\psi\rangle = c_1|\uparrow\rangle + c_2|\downarrow\rangle = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

Density matrix: $\rho_{\text{pure}} = |\psi\rangle\langle\psi| \longrightarrow \rho_{\text{mixed}} = \sum_i p_i |\psi_i\rangle\langle\psi_i|$

Gen. decomposition (identity and Pauli's) $\rho = \frac{1}{2}\left(\mathbb{1}_2 + a_i\sigma^i\right)$

Back to the basics… entanglement in spin space

Two qubit

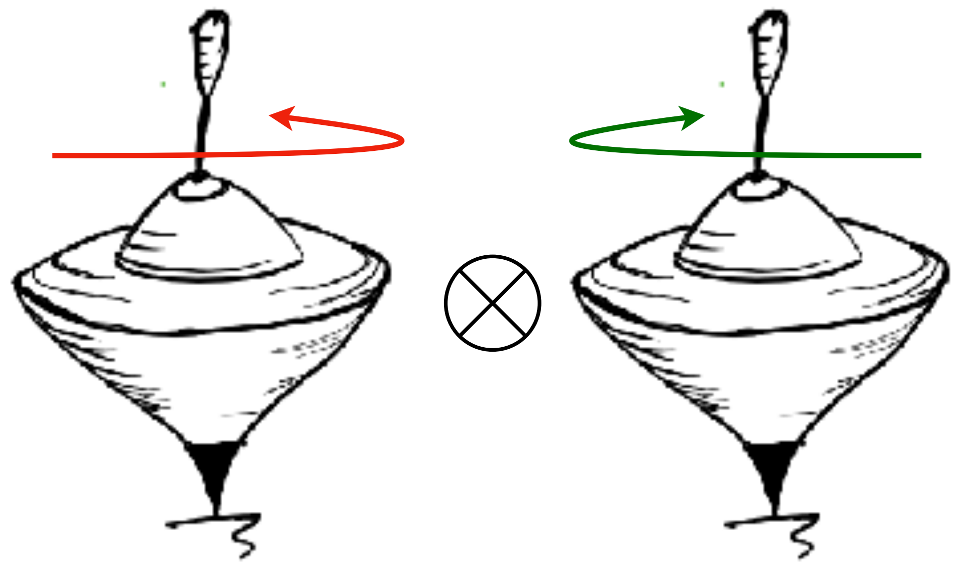


$$|\psi_{\rm ab}\rangle = c_1|\uparrow\uparrow\rangle + c_2|\uparrow\downarrow\rangle + c_3|\downarrow\uparrow\rangle + c_4|\downarrow\downarrow\rangle \; = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix}$$

Density matrix is 4x4

$$\rho = \frac{\mathbb{1}_2 \otimes \mathbb{1}_2 + B_i^+ \sigma^i \otimes \mathbb{1}_2 + B_i^- \mathbb{1}_2 \otimes \sigma^i + C_{ij}\, \sigma^i \otimes \sigma^j}{4}.$$

Back to the basics… entanglement in spin space

Two qubit 

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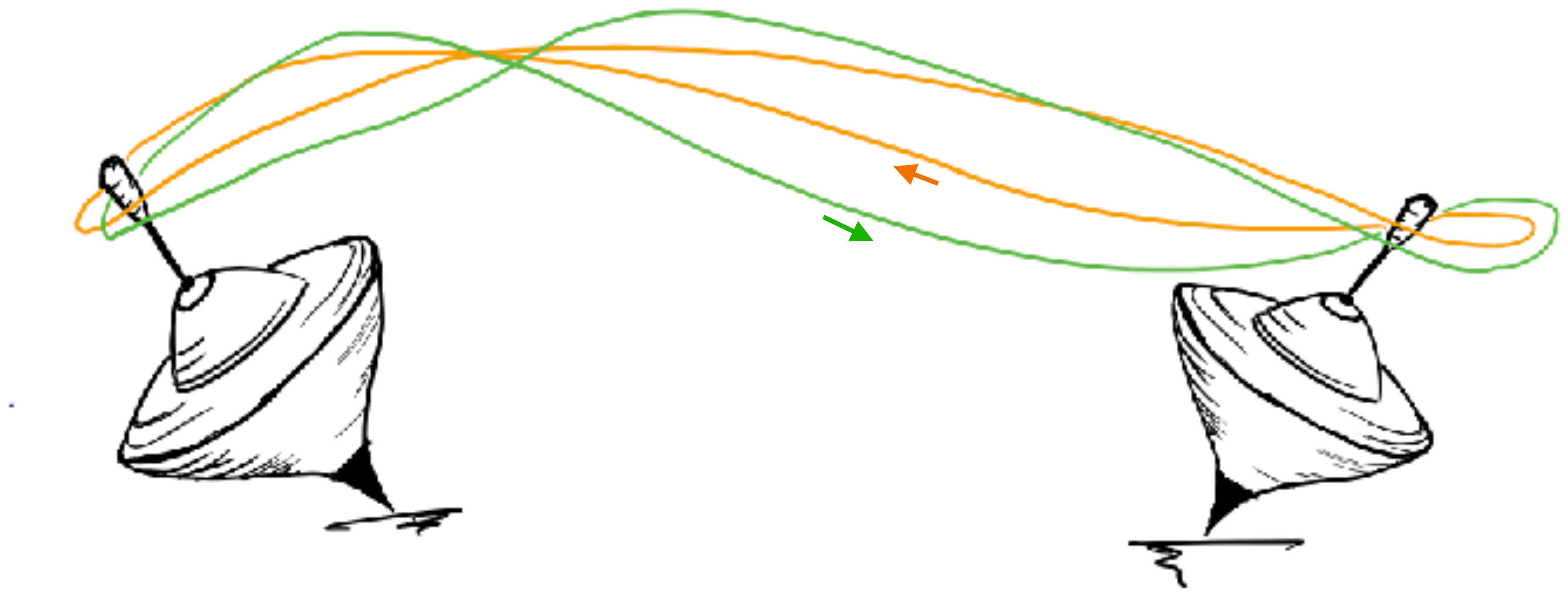
Entanglement



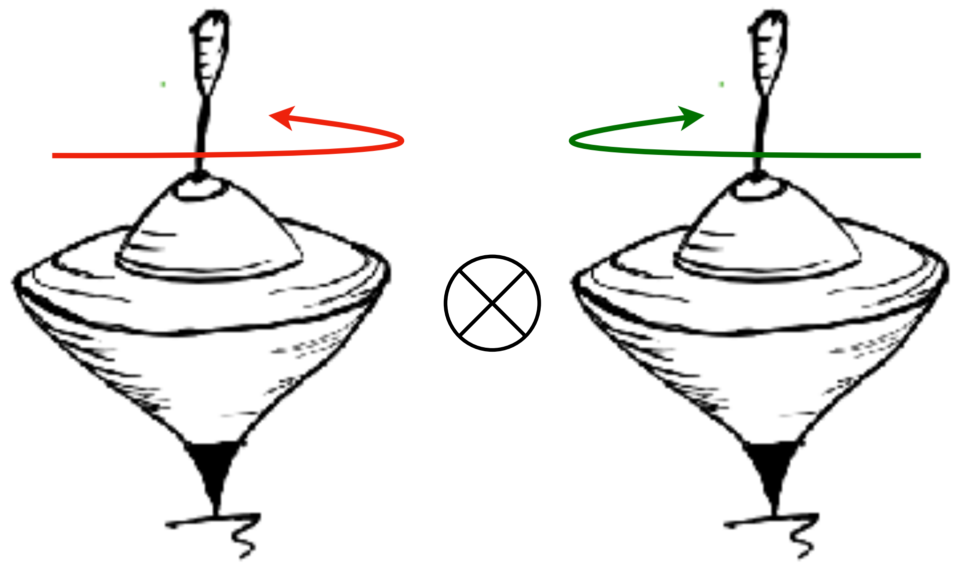
Given a bipartite system $\mathcal{H}_{\rm ab} = \mathcal{H}_{\rm a} \otimes \mathcal{H}_{\rm b}$

Can you write $|\psi_{\rm ab}\rangle = |\psi_{\rm a}\rangle \otimes |\psi_{\rm b}\rangle$?

No? Then it is entangled.

Back to the basics… entanglement in spin space

Two qubit



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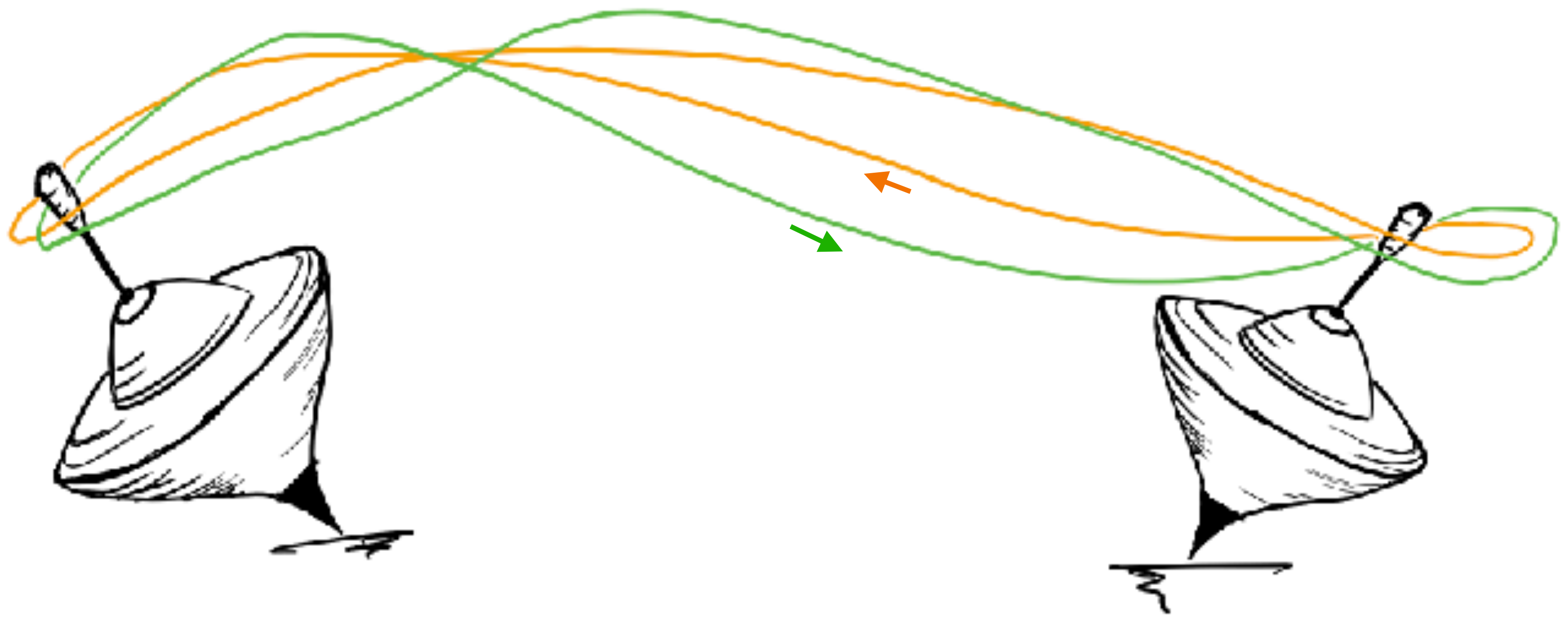
Entanglement



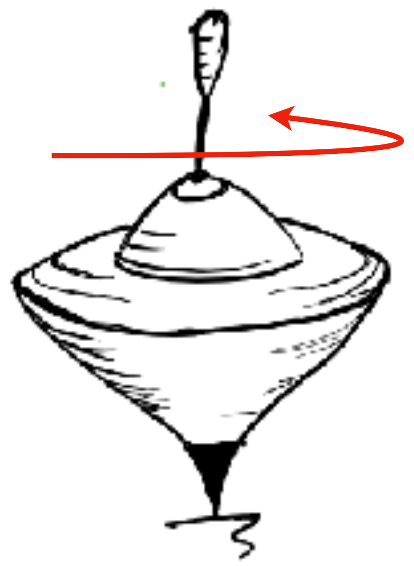
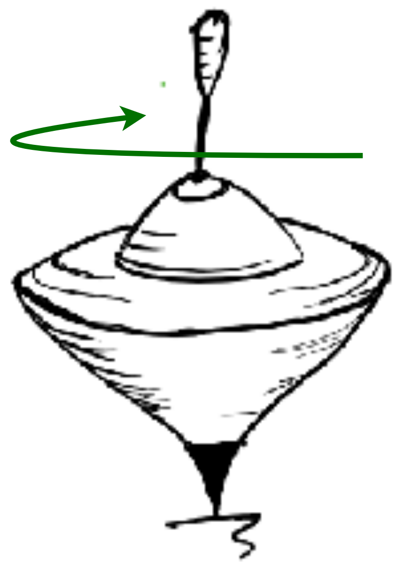
Peres-Horodecki Criterion:

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

Concurrence (max =1):

$$C[\rho] = \max(\Delta/2, 0)$$

Back to the basics… entanglement in spin space

Two qubit  $\otimes$  $$|\psi_{\rm ab}\rangle = c_1|\uparrow\uparrow\rangle + c_2|\uparrow\downarrow\rangle + c_3|\downarrow\uparrow\rangle + c_4|\downarrow\downarrow\rangle \; = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix}$$

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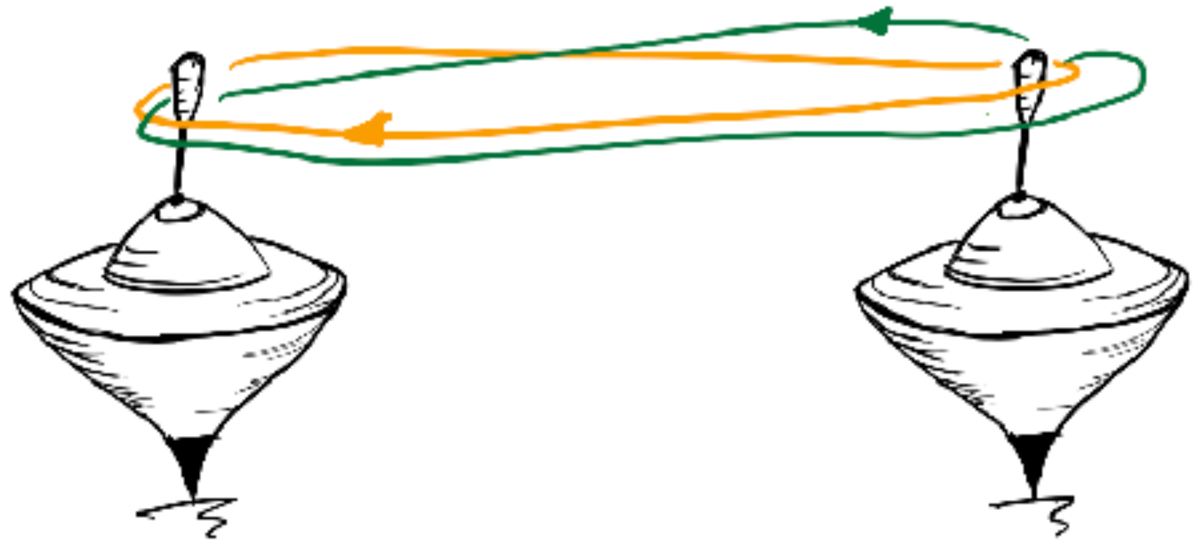
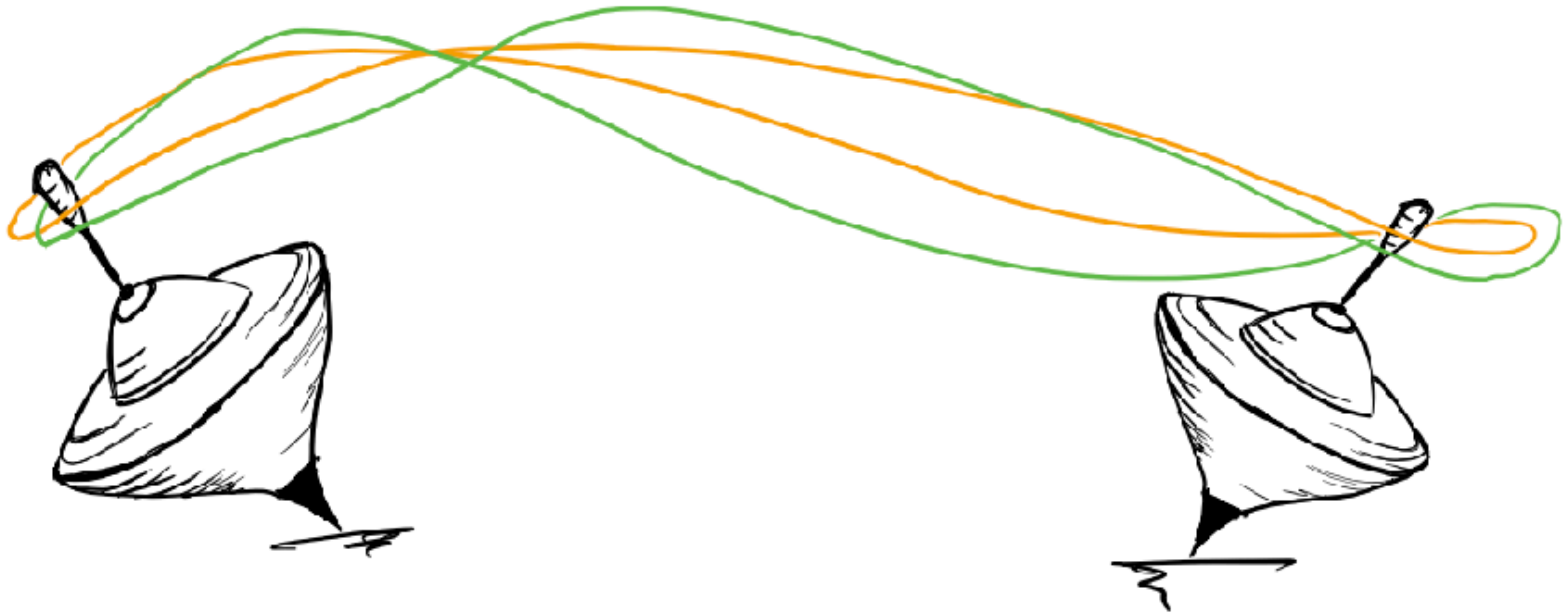


Maximally entangled states (e.g Bell states):

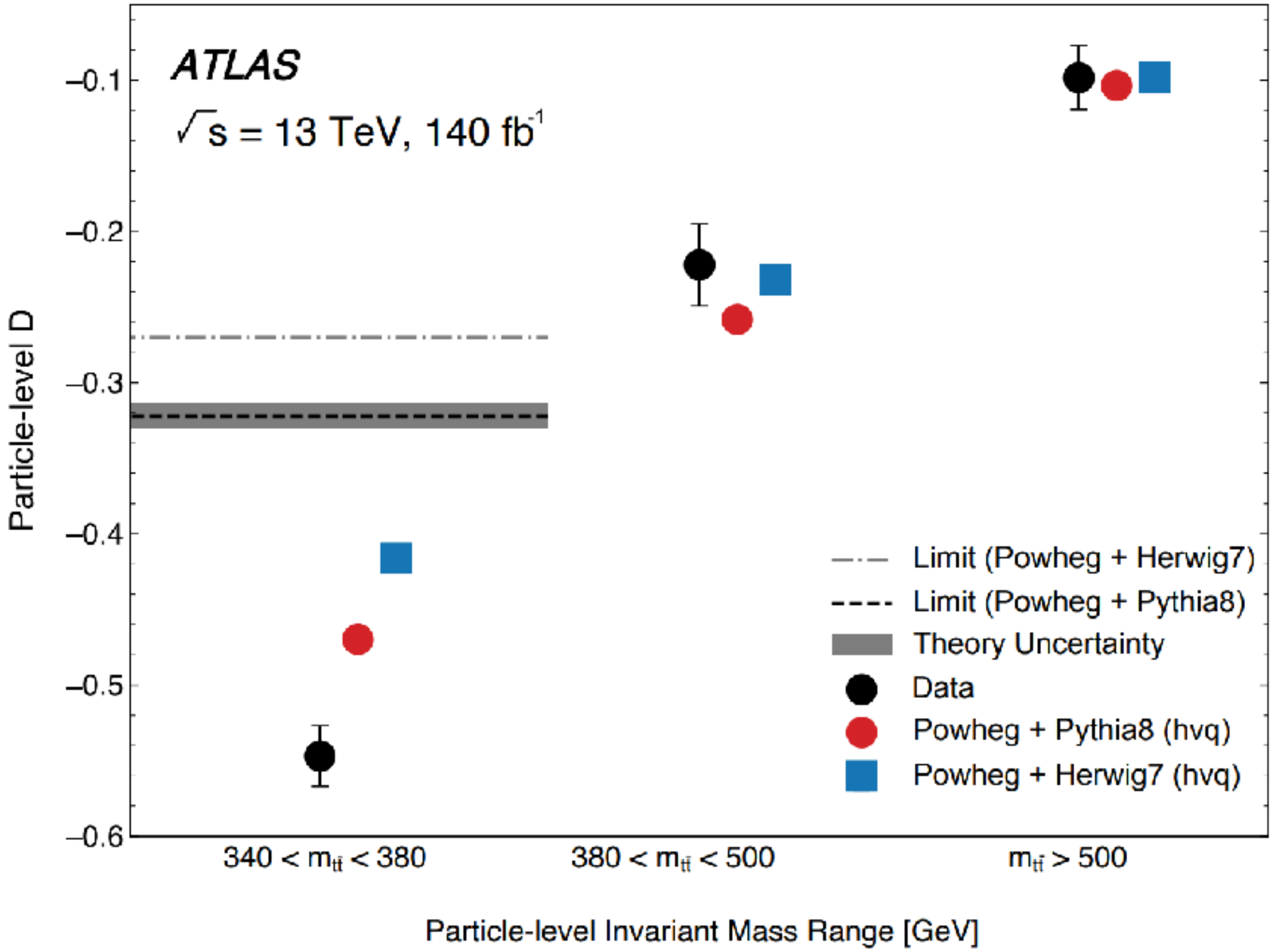
$$|\Phi^\pm\rangle = \frac{|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle}{\sqrt{2}} \quad \text{or} \quad |\Psi^\pm\rangle = \frac{|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle}{\sqrt{2}}$$

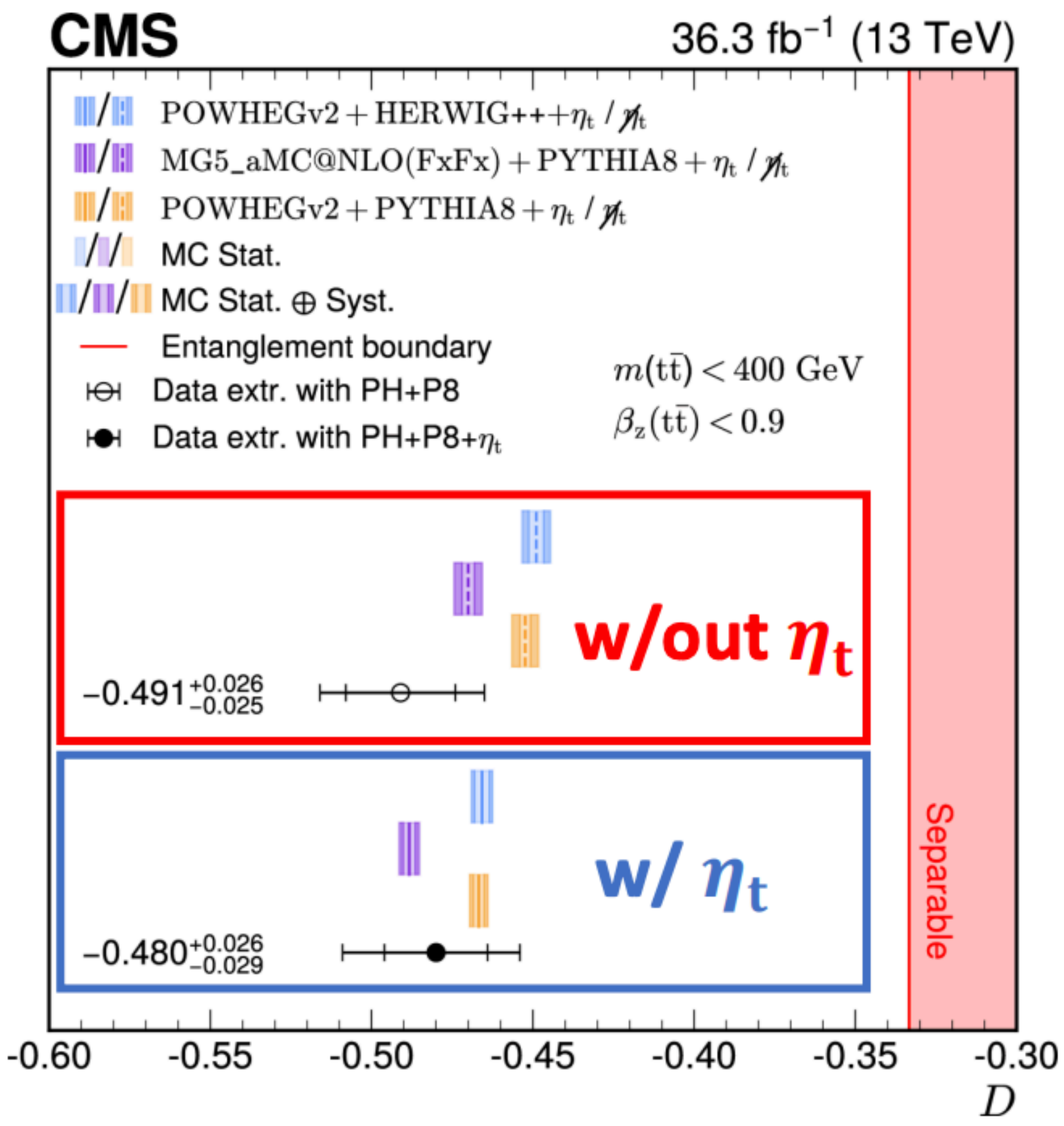
Measures: $\Delta = 2$ $\quad C[\rho] = 1$

Top-pair entanglement



ATLAS and CMS observed!

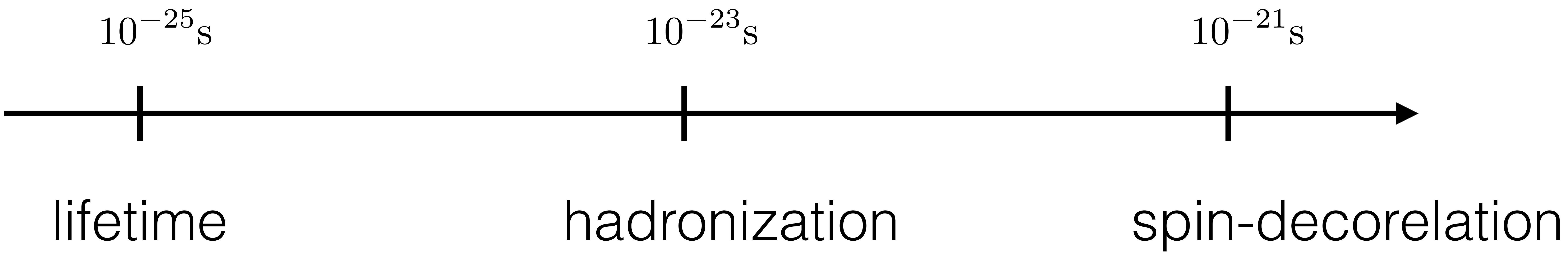




$D < -1/3 \longleftrightarrow$ entangled

Why top quarks?

- it is very heavy (172.5 GeV ~ mass of Rhenium nucleus)

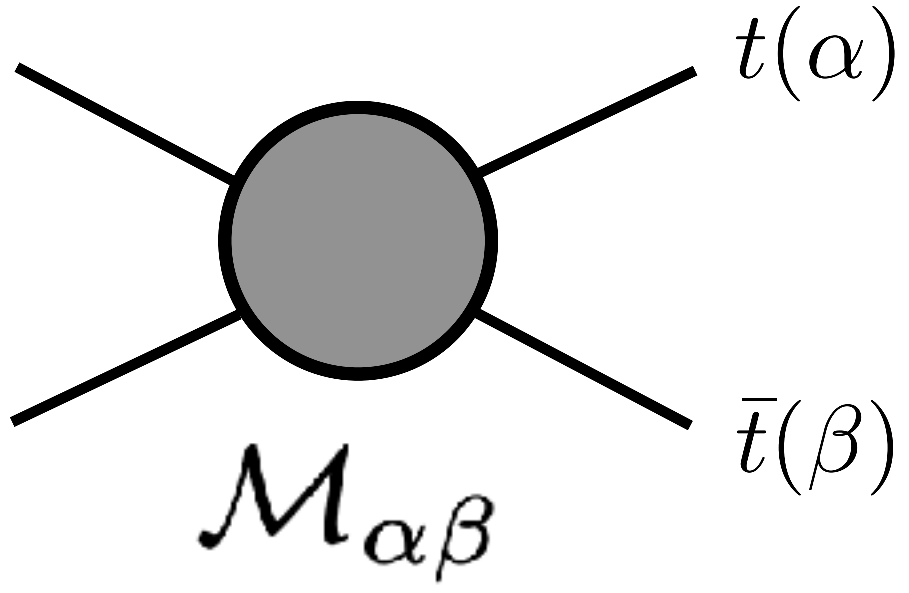


- allows to efficiently reconstruct the spin from decay products
- top spin correlations vastly studied (both in theo and exp):

  D0 and CDF at Tevatron and ATLAS and CMS at LHC

- Observation of entanglement by ATLAS and CMS

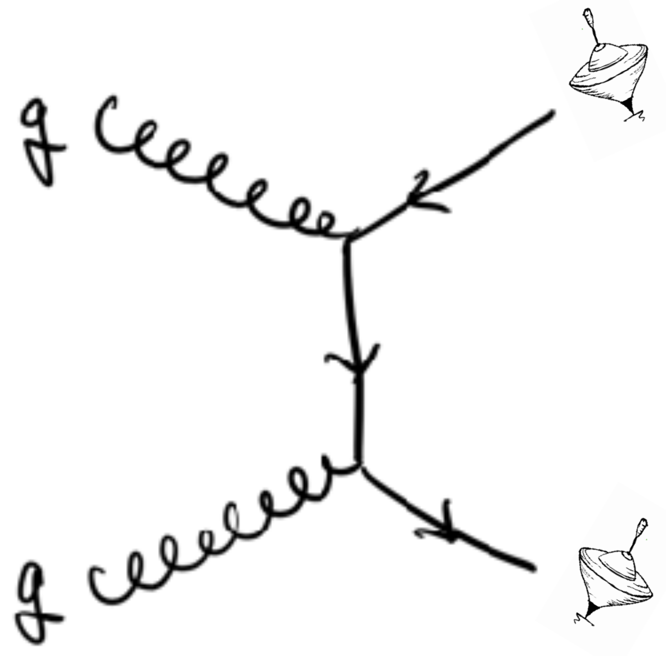
How to construct the spin density matrix?

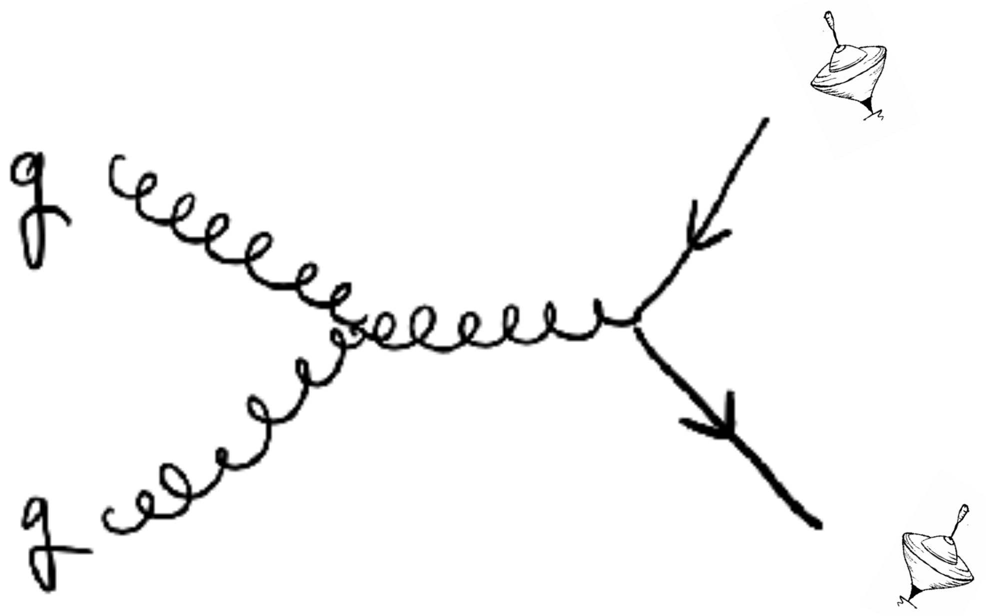


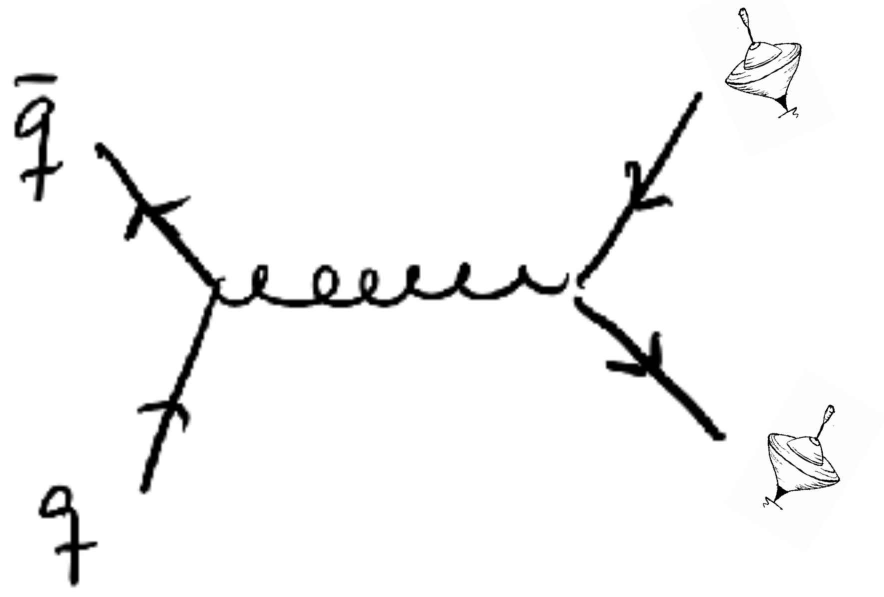
$$R^I_{(\alpha_1\beta_1)(\alpha_2\beta_2)} \sim \sum_{\text{color spin}} \mathcal{M}^*_{\alpha_2\beta_2}\mathcal{M}_{\alpha_1\beta_1}$$

4x4 matrix

SM:







Mixed state of qq and gg initiated channels, weighted by the luminosity functions

$$R(\hat{s}, \boldsymbol{k}) = \sum_I L^I(\hat{s}) R^I(\hat{s}, \boldsymbol{k})$$

Spin production density matrix

Fano decomposition: (spanned by tensor prod. of Pauli and Identity)

$$R = \tilde{A}\,\mathbb{1}_2 \otimes \mathbb{1}_2 + \tilde{B}_i^+\,\sigma^i \otimes \mathbb{1}_2 + \tilde{B}_i^-\,\mathbb{1}_2 \otimes \sigma^i + \tilde{C}_{ij}\,\sigma^i \otimes \sigma^j\,.$$

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Cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega \mathrm{d}\hat{s}} = \frac{\alpha_s^2 \beta}{\hat{s}^2} \tilde{A}\,(\hat{s}, \boldsymbol{k})$$

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Degree of top and anti-top polarisation (zero for P-inv interactions)

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Spin-correlations NB: Spin-Correlations $\supseteq$ Entanglement

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Degree of top and anti-top polarisation (zero for P-inv interactions)

Spin-correlations NB: Spin-Correlations $\supseteq$ Entanglement

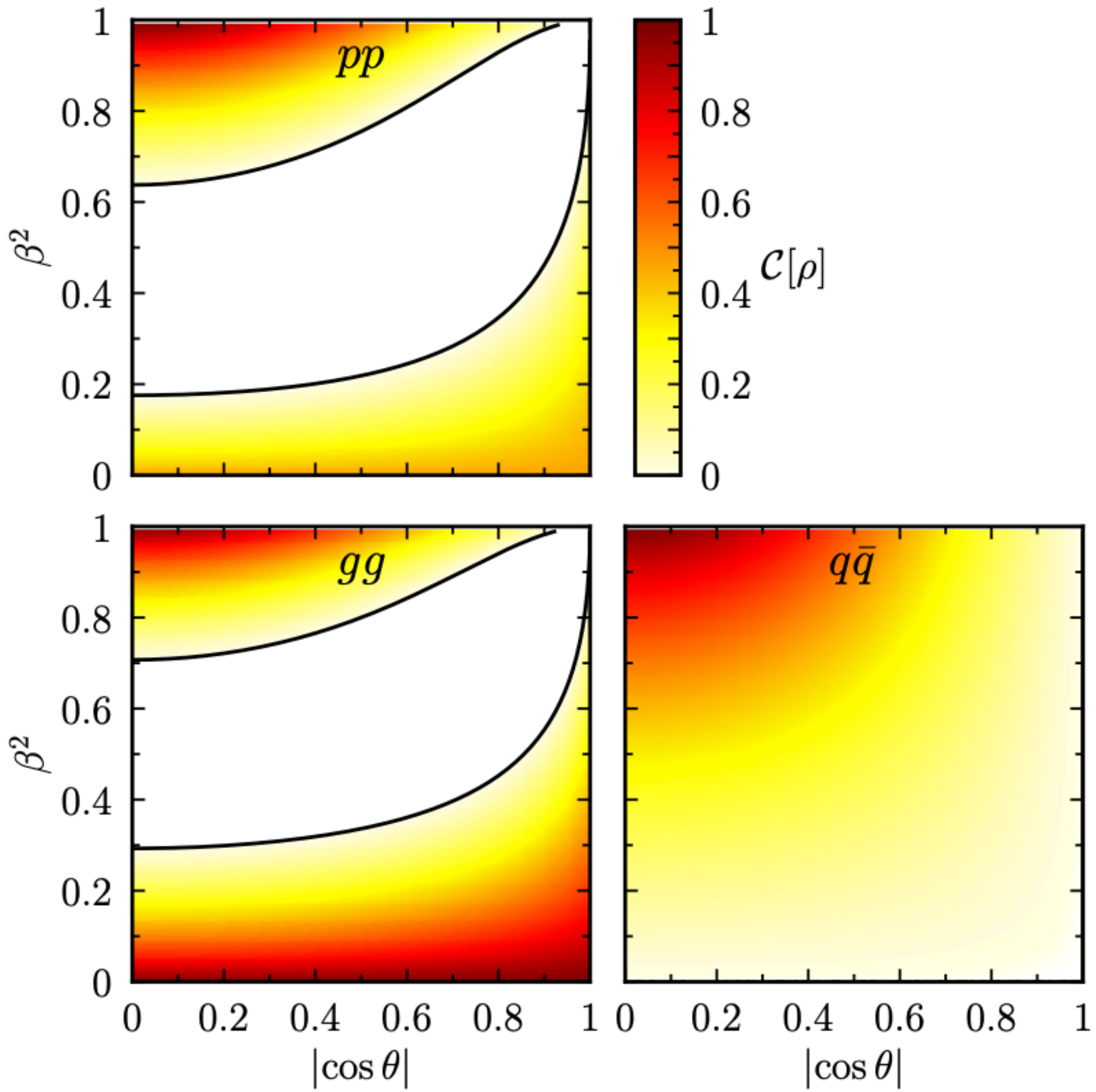
Normalize the state as

$$\rho = R/\mathrm{tr}(R)$$

$$\rho = \frac{\mathbb{1}_2 \otimes \mathbb{1}_2 + B_i^+ \sigma^i \otimes \mathbb{1}_2 + B_i^- \mathbb{1}_2 \otimes \sigma^i + C_{ij}\, \sigma^i \otimes \sigma^j}{4}.$$

What's the story for the SM?

[Afik and de Nova, 21']



Two-to-two scattering: 2 d.o.f

velocity and angle of the top

$$\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}} \qquad \cos\theta$$

White regions: zero-entanglement

Maximal entanglement points/regions

- At threshold: $\beta^2 = 0, \forall\theta$
- high-E: $\beta^2 \to 1, \cos\theta = 0$

Experimental detection (Quantum tomography)

Top quark cannot be measured directly

Spin information is directly transmitted to decay products $t \to W^+ + b$

$(W^+ \to \ell^+ + \nu \text{ or } \bar{d} + u)$

Lepton direction is totally correlated to the top spin

D-coefficient: $D = \frac{\mathrm{tr}[\mathbf{C}]}{3}$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

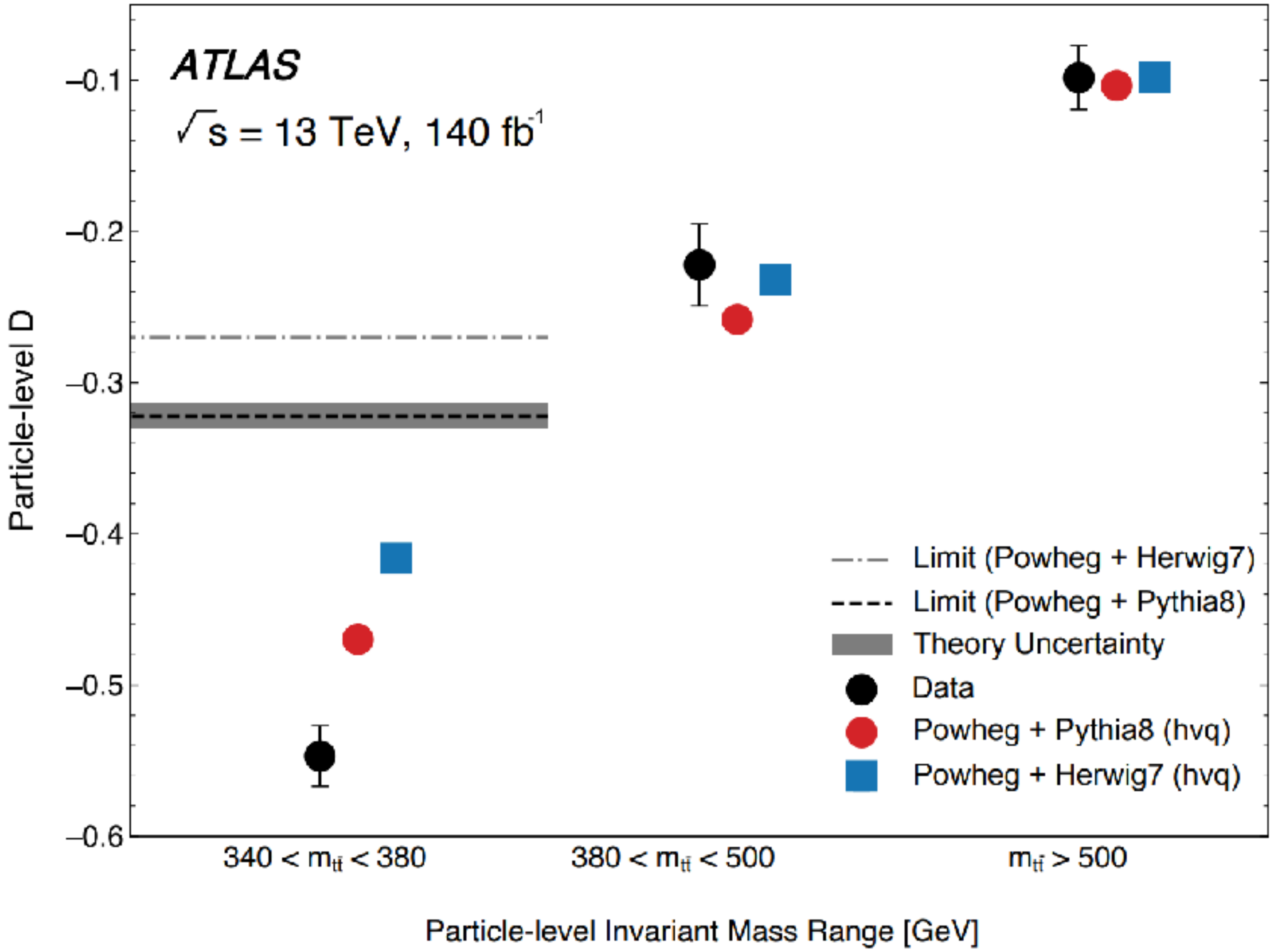
φ angle between leptons in each parent direction rest frames

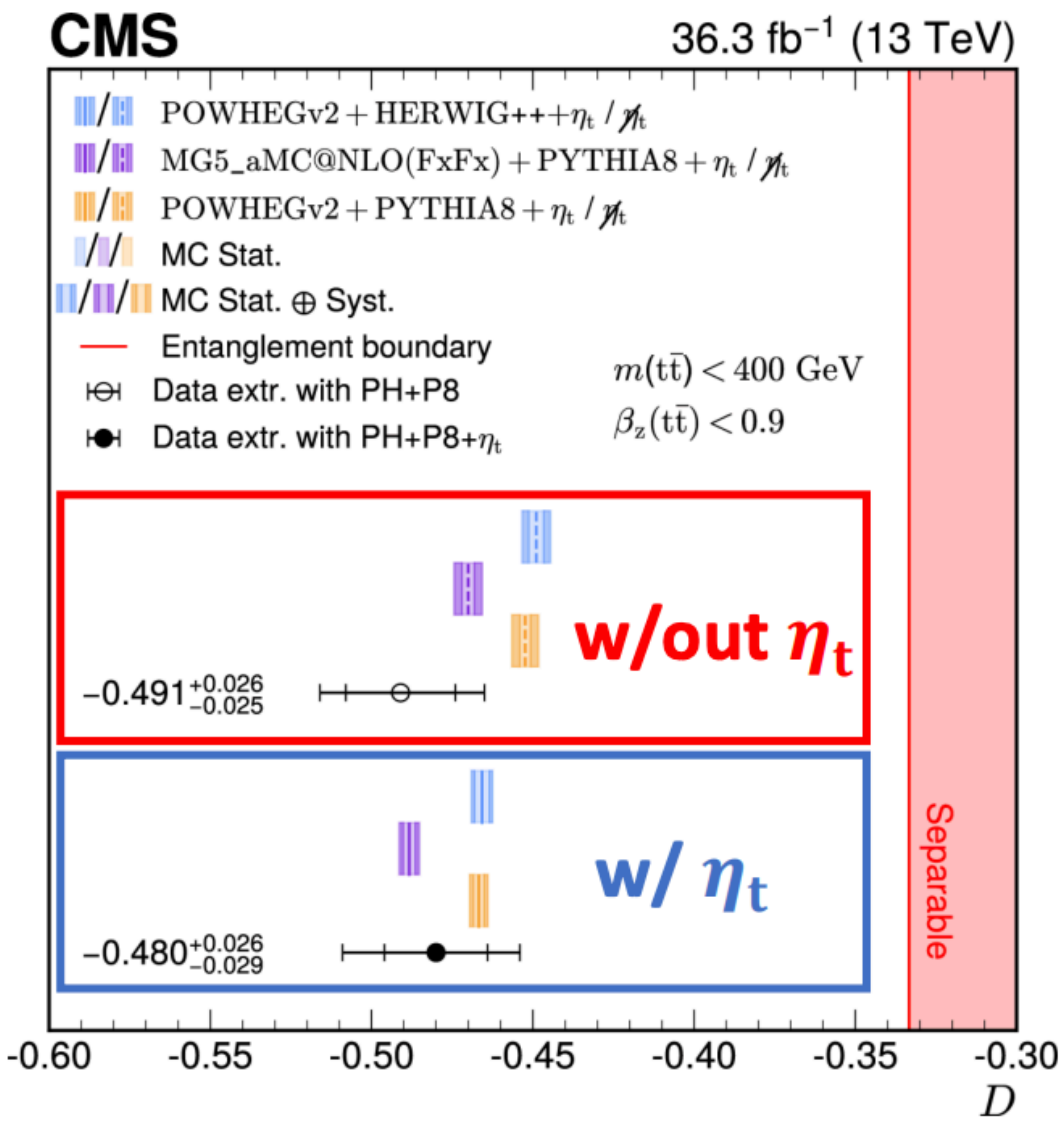
$C[\rho] = \max(1 - 3D, 0)/2$ ⟶ entangled if $D < -1/3$

ATLAS and CMS measurement

*η_t topponium modelling

At threshold $\beta^2 \sim 0$





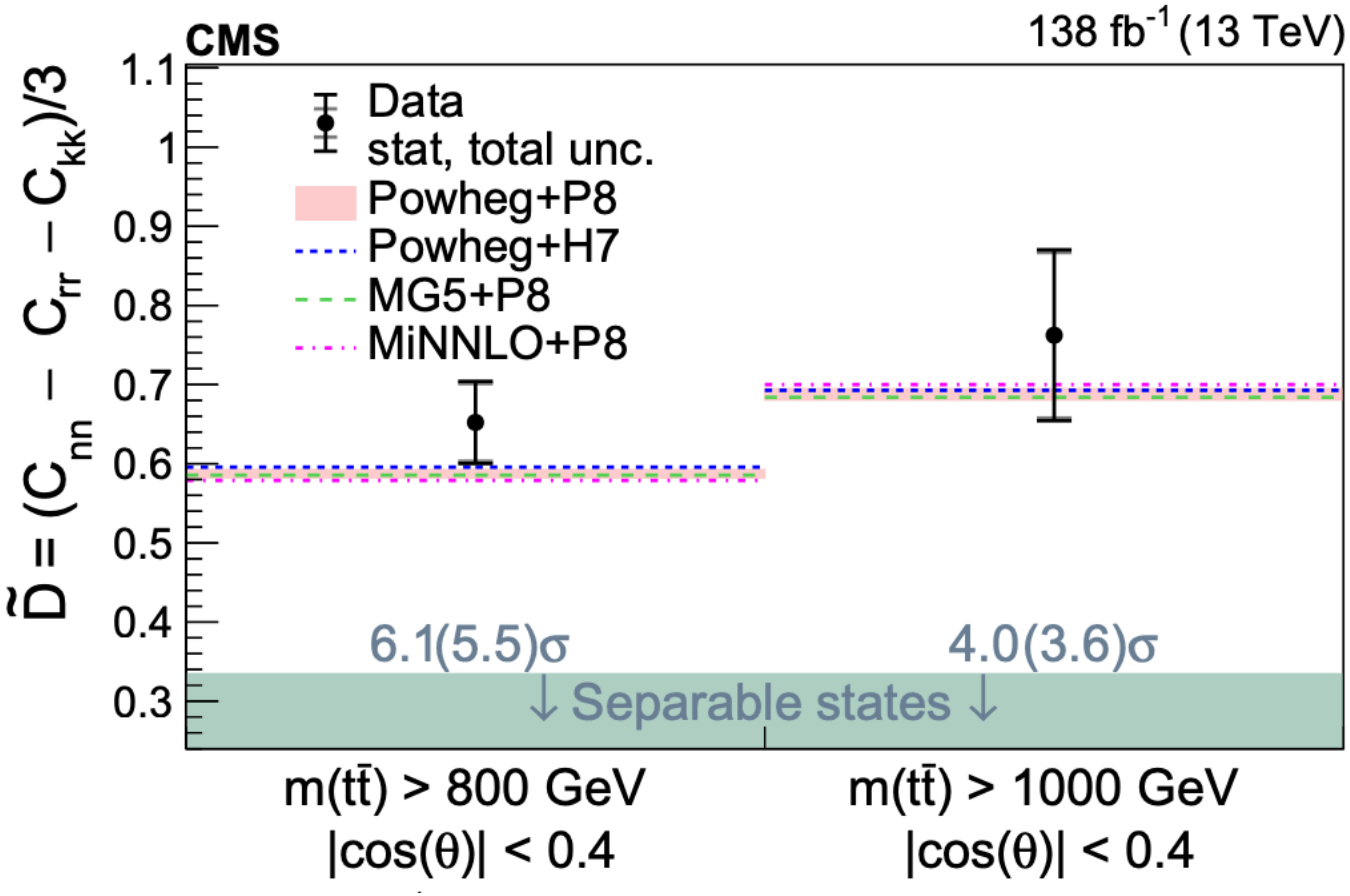
[Nature 633, 542-547 (2024)]

[Rep. Prog. Phys. 86 (2024) 117801]

$D < -1/3 \longleftrightarrow$ entangled

Also observed at high invariant mass by CMS

maximal at $\beta^2 \to 1, \cos\theta = 0$



[Rep. Prog. Phys. 86 (2024) 117801]

SMEFT

SM Effective Field Theory

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 10']

[Aguilar-Saavedra et. al, 18']

[SMEFTatNLO: Degrande et. al, 20']

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i$$

$\mathcal{L}_{\mathrm{UV}}$

Λ

LO-QCD in ttbar prod.

+4F operators

$$\mathcal{O}_{Qq}^{(8,1)}, \mathcal{O}_{Qq}^{(8,3)}, \mathcal{O}_{tu}^{(8)}, \mathcal{O}_{td}^{(8)}, \mathcal{O}_{Qu}^{(8)}, \mathcal{O}_{Qd}^{(8)}, \mathcal{O}_{tq}^{(8)}$$

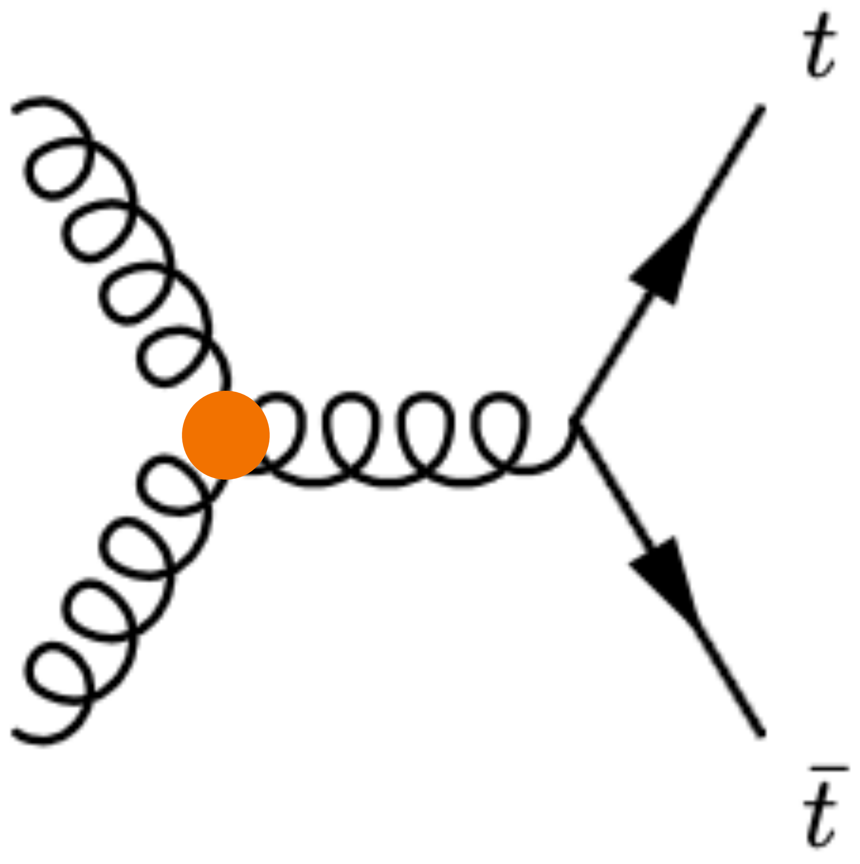
$$\mathcal{O}_G = g_s f^{ABC} G_\nu^{A,\mu} G_\rho^{B,\nu} G_\mu^{C,\rho}$$

$\mathcal{L}_{\mathrm{SMEFT}}$

$$\mathcal{O}_{\varphi G} = \left(\varphi^\dagger \varphi - \frac{v^2}{2}\right) G_A^{\mu\nu} G_{\mu\nu}^A$$

$$\mathcal{O}_{tG} = g_s (\bar{Q} \sigma^{\mu\nu} T^A\, t) \tilde{\varphi} G_{\mu\nu}^A + \mathrm{h.c.}$$

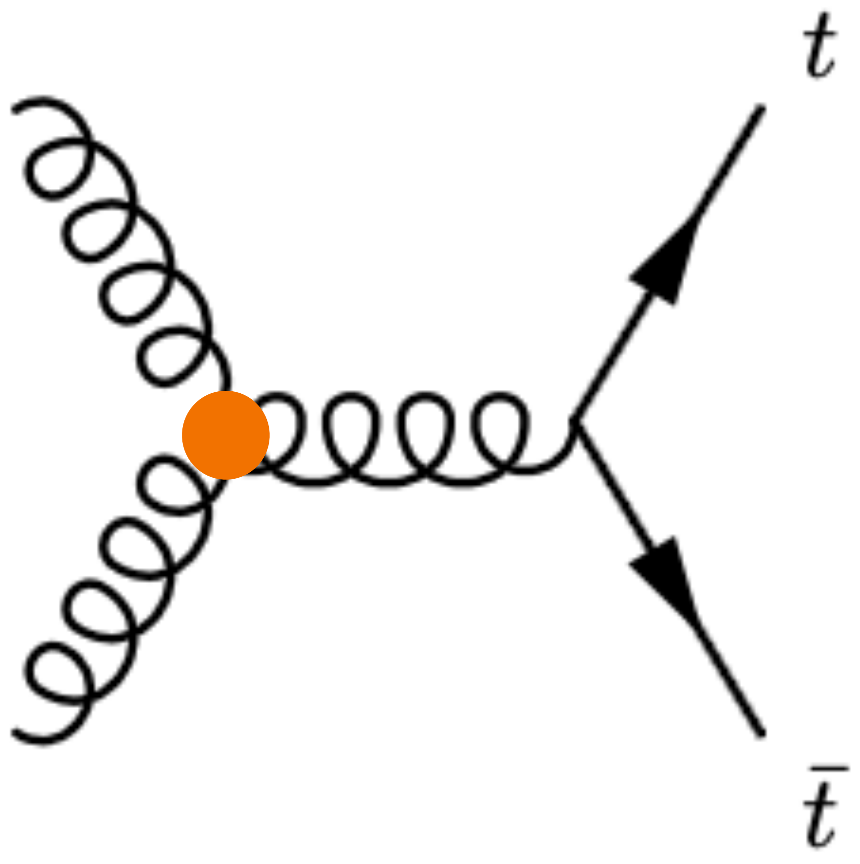
Top pair within SMEFT

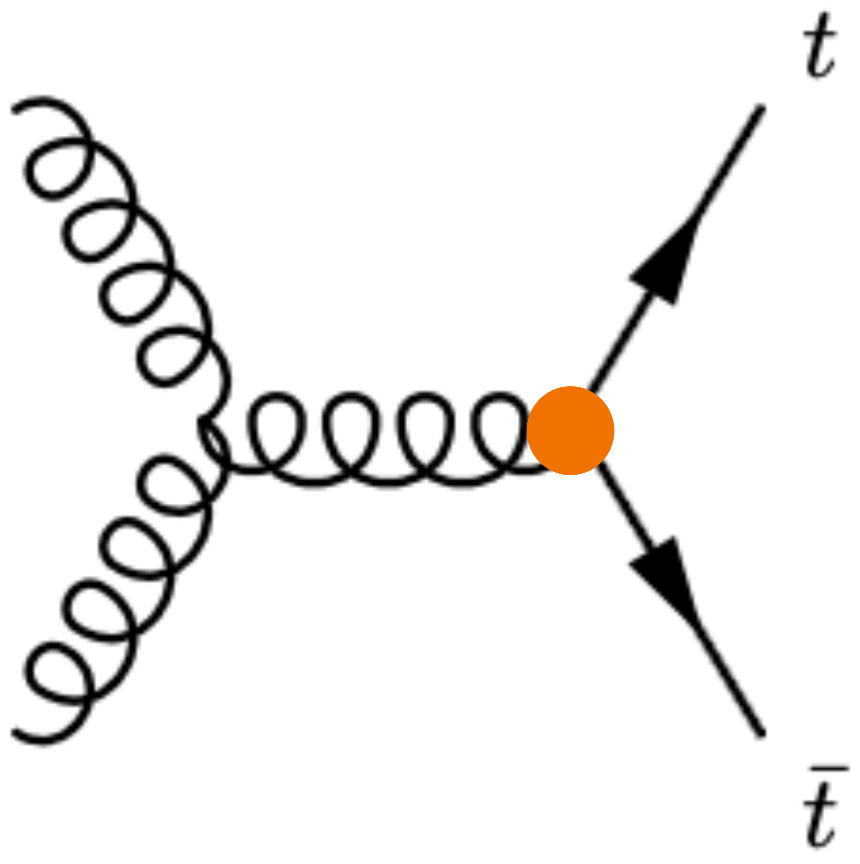


SM: $-\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu}$

EFT: $f^{ABC}G^{A,\mu}_{\nu}G^{B,\nu}_{\rho}G^{C,\rho}_{\mu}$

Top pair within SMEFT

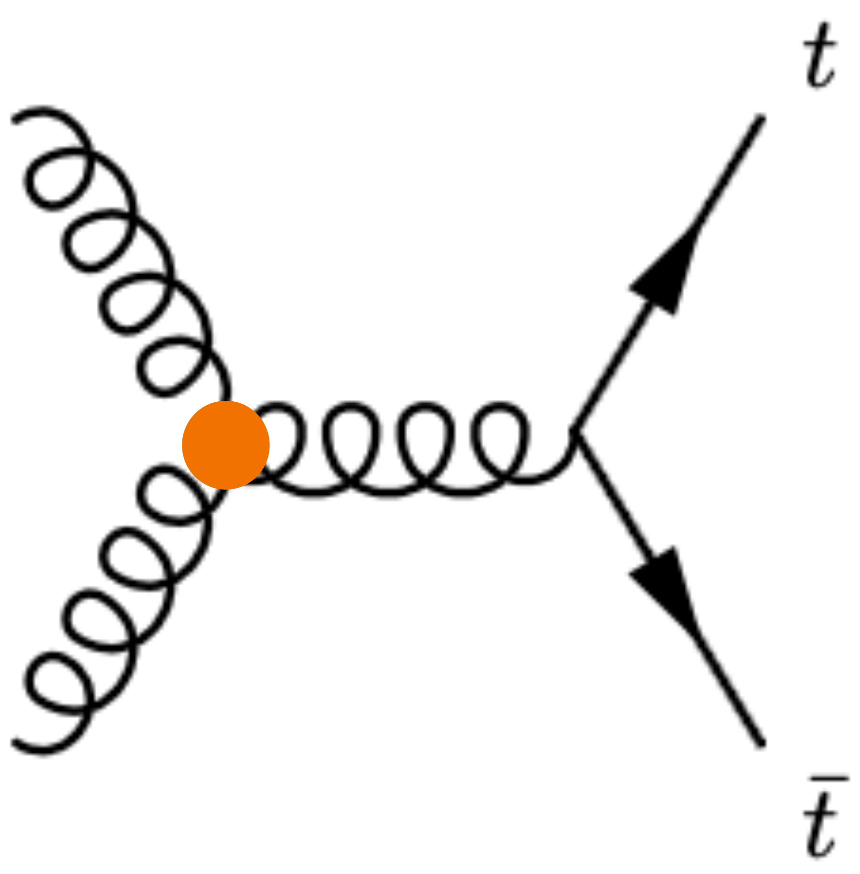


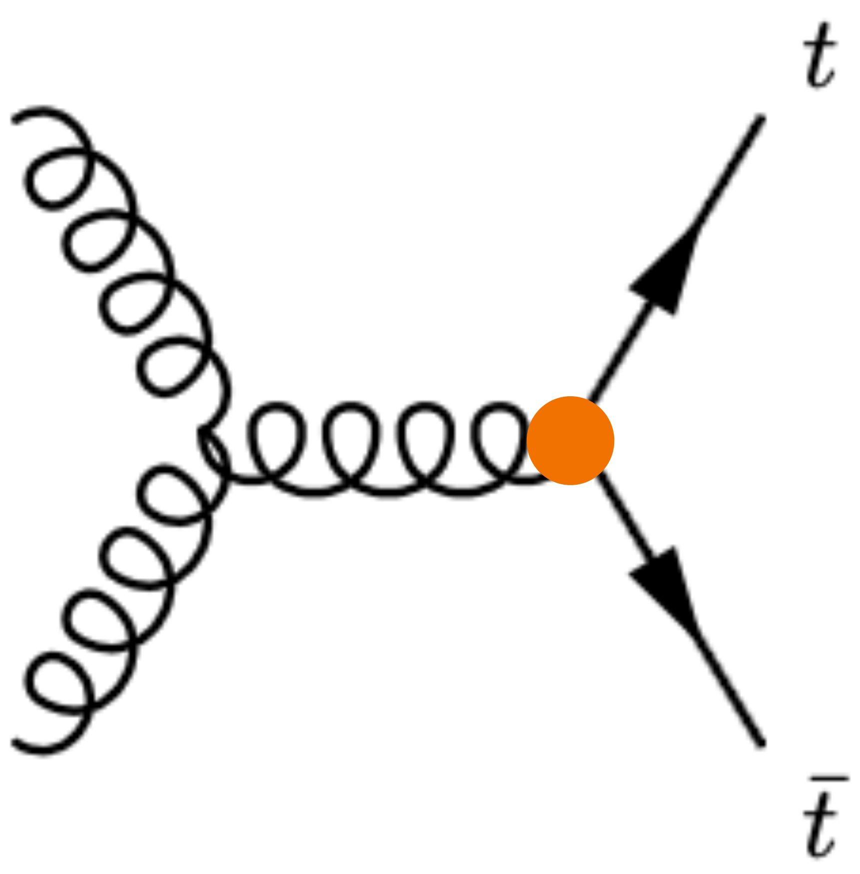


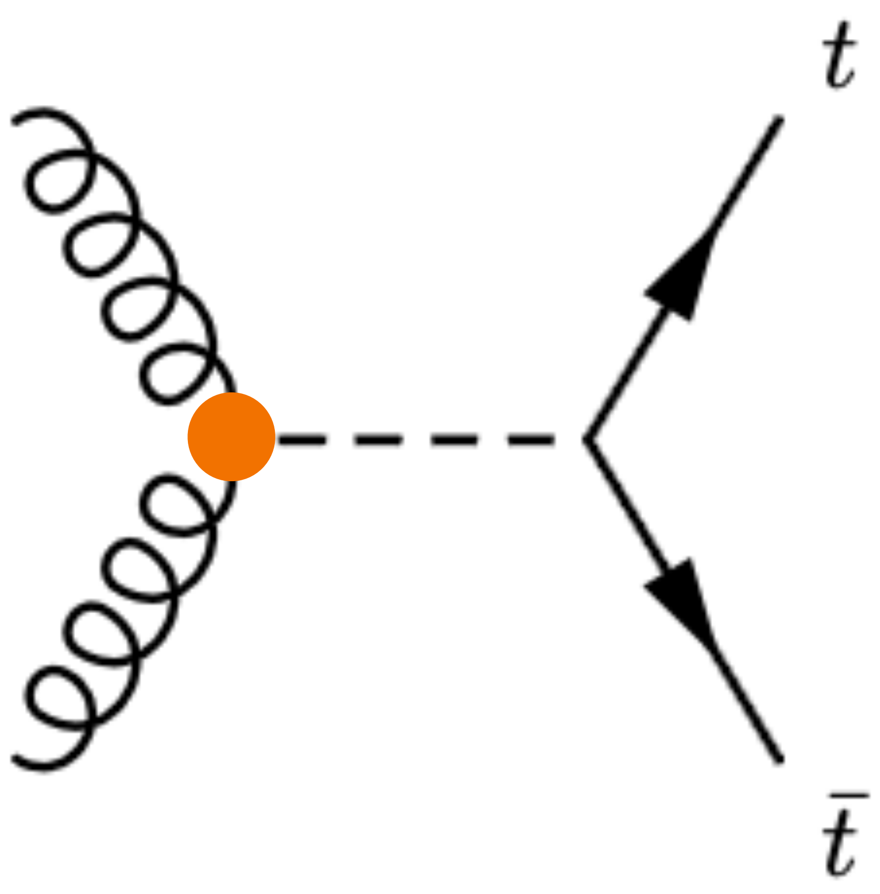
SM: $\bar{t}\gamma^{\mu}t$

EFT: $\bar{t}\sigma^{\mu\nu}t$

Top pair within SMEFT



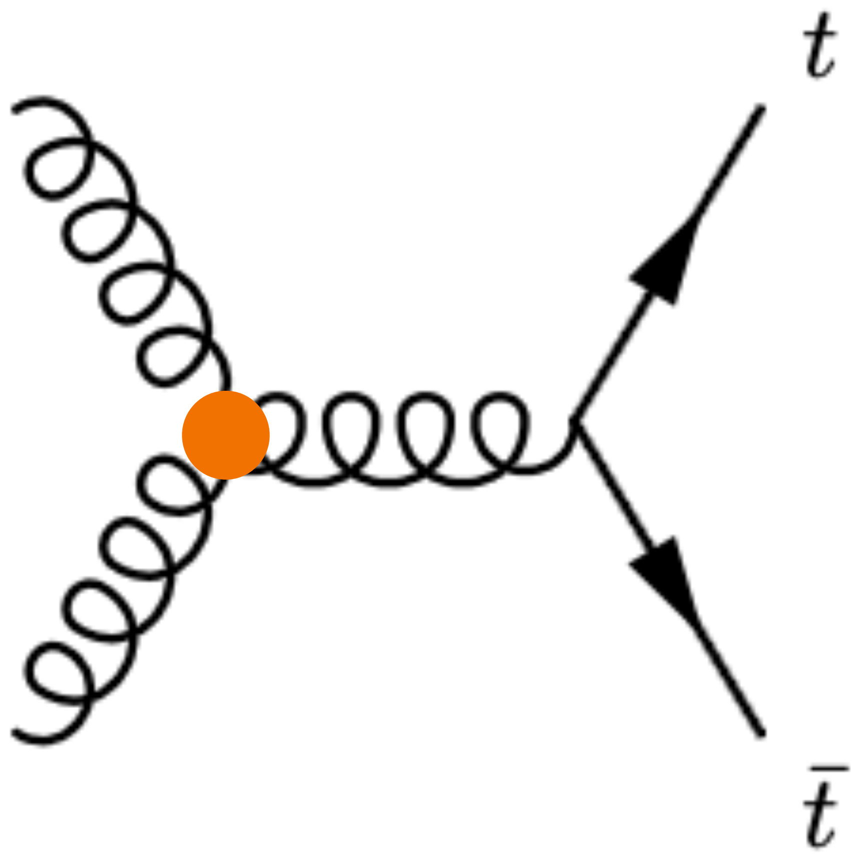




~~SM~~

EFT: $\varphi G_A^{\mu\nu} G^A_{\mu\nu}$

Top pair within SMEFT



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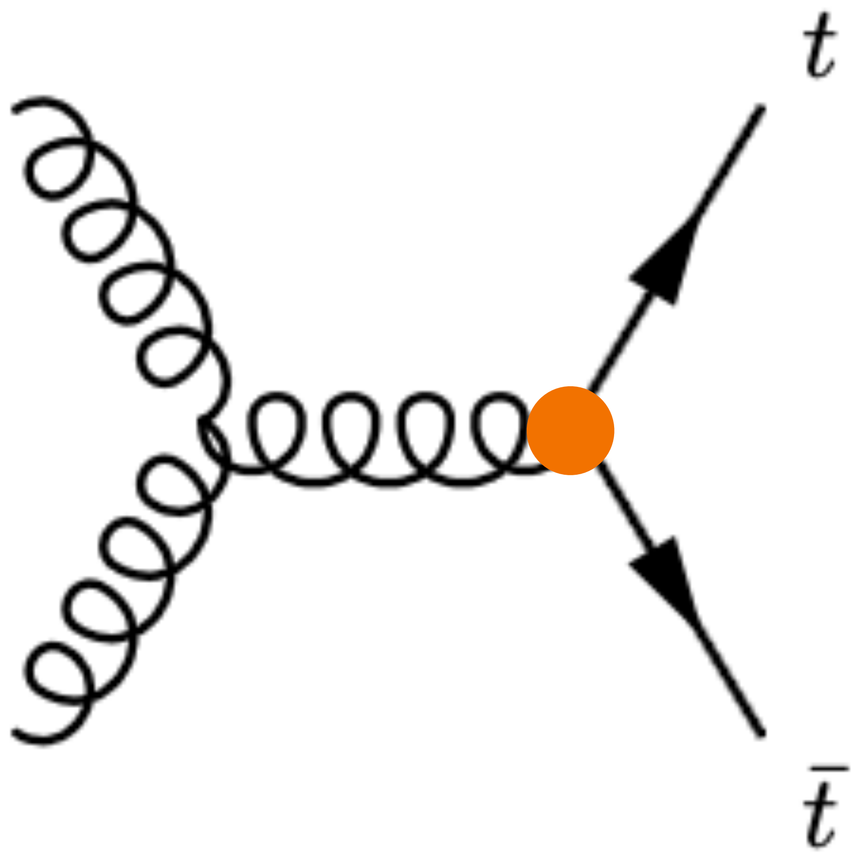

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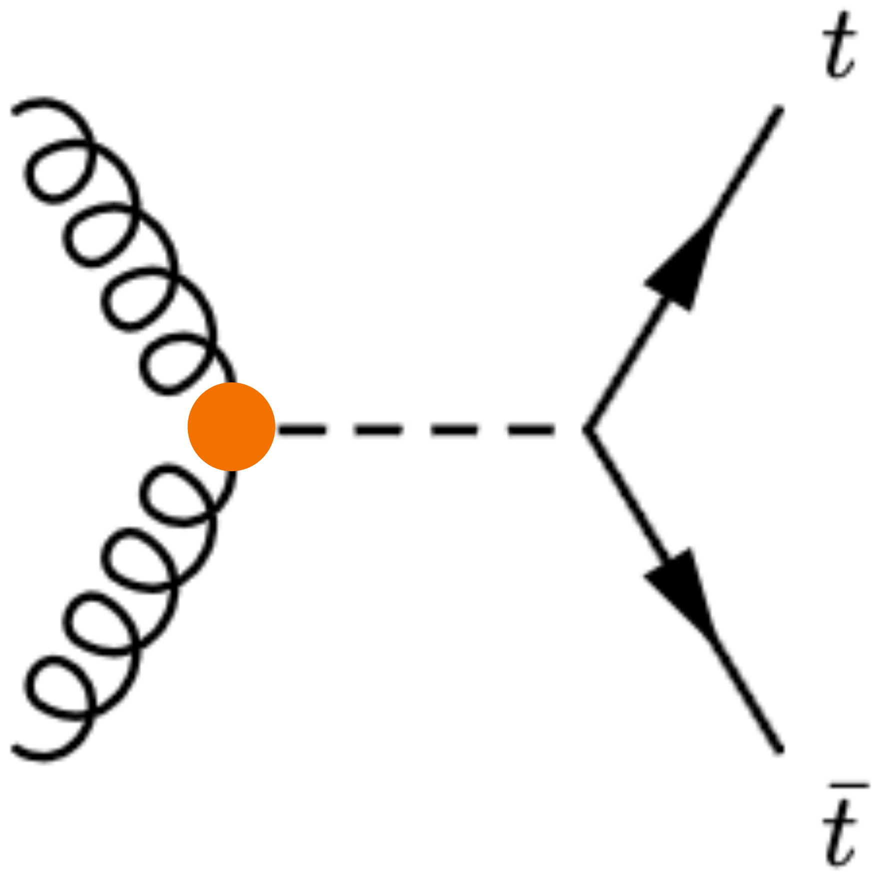

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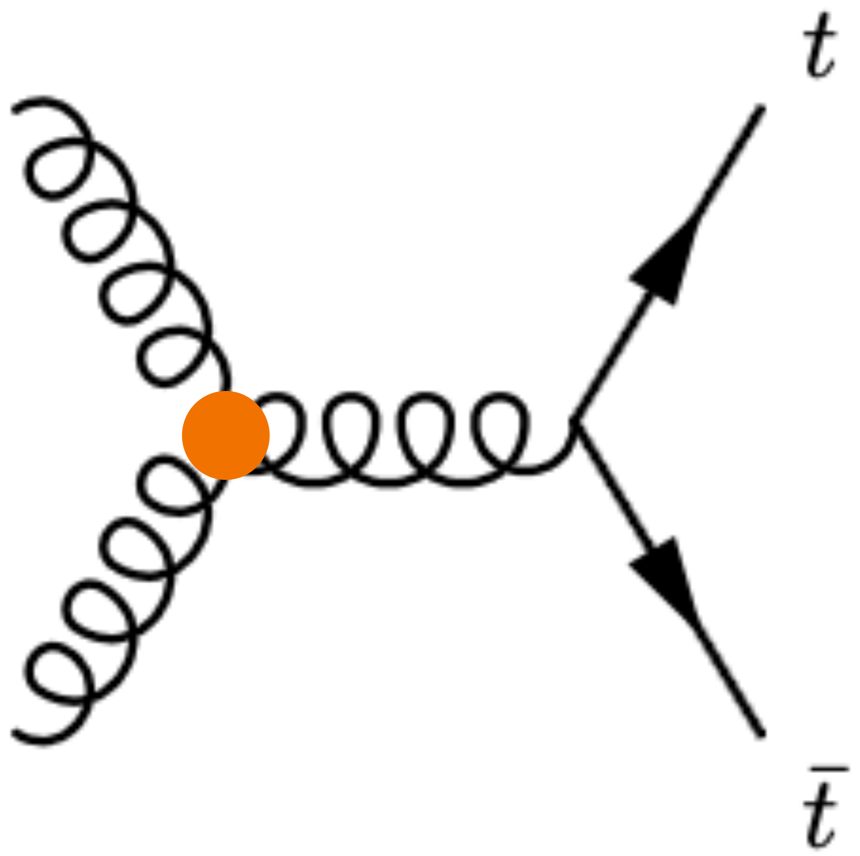

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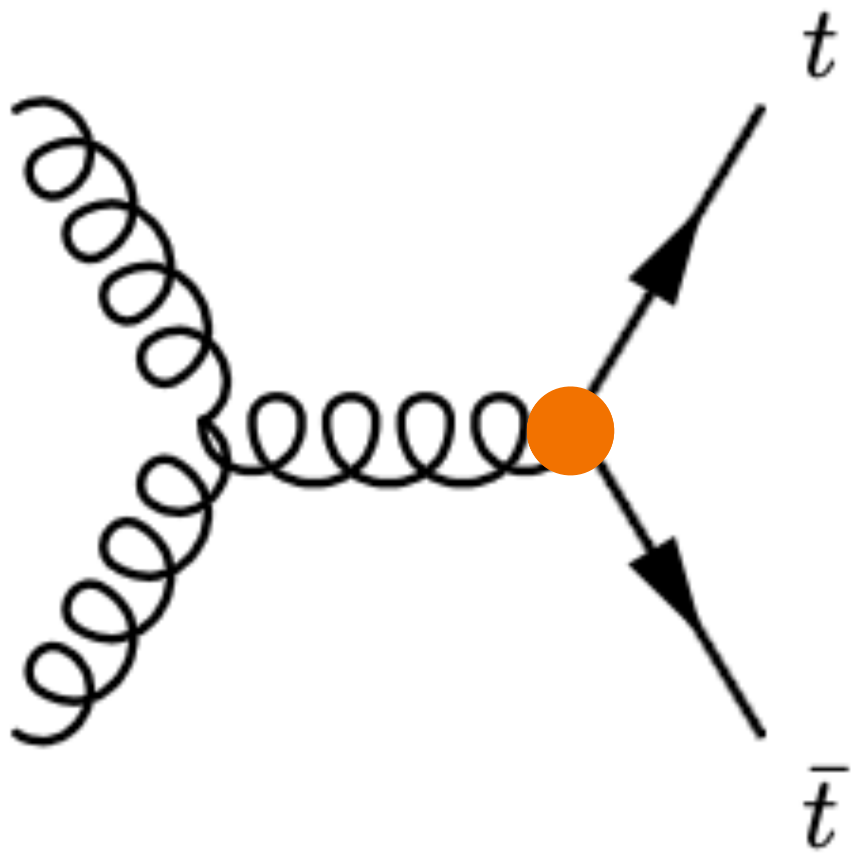

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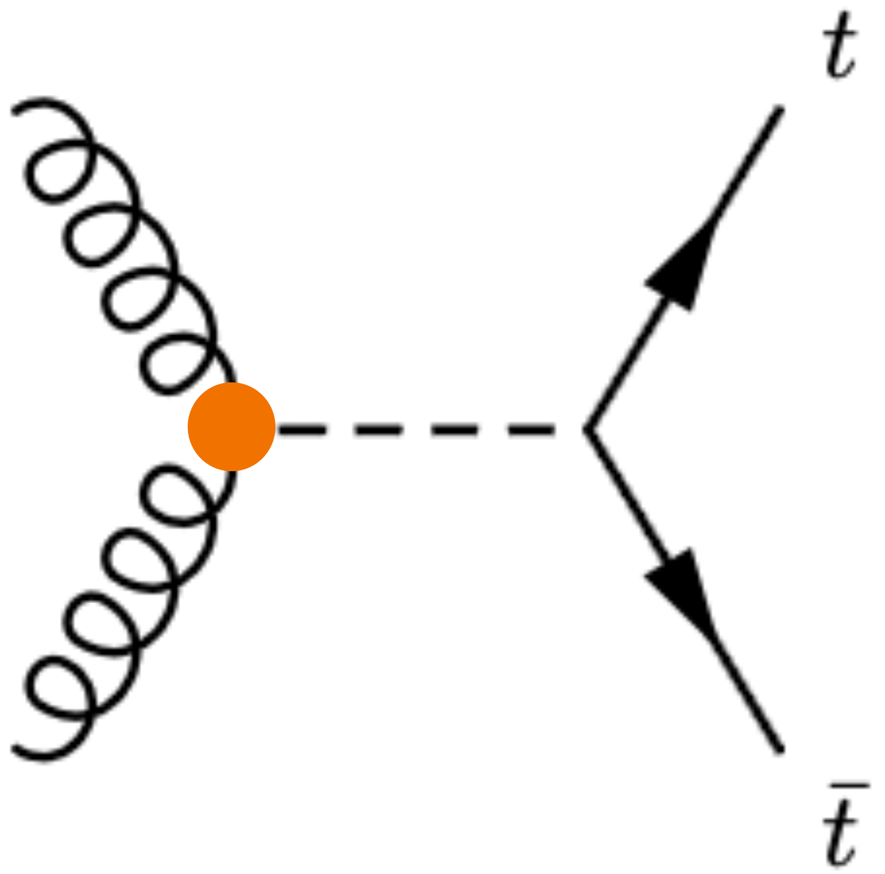

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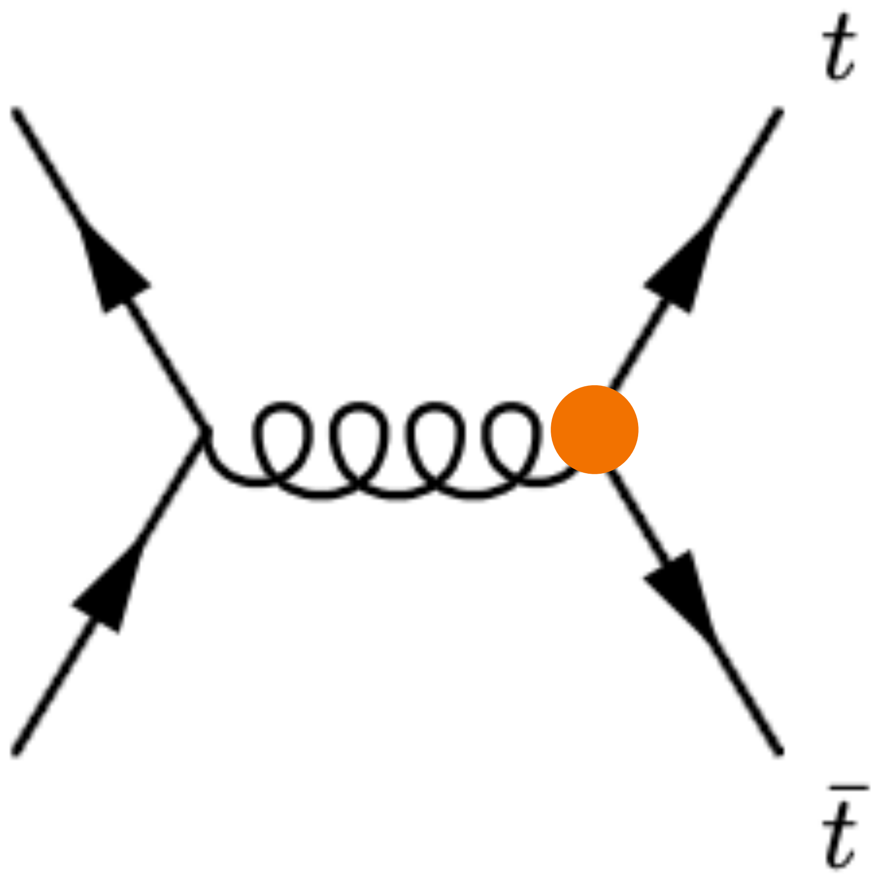

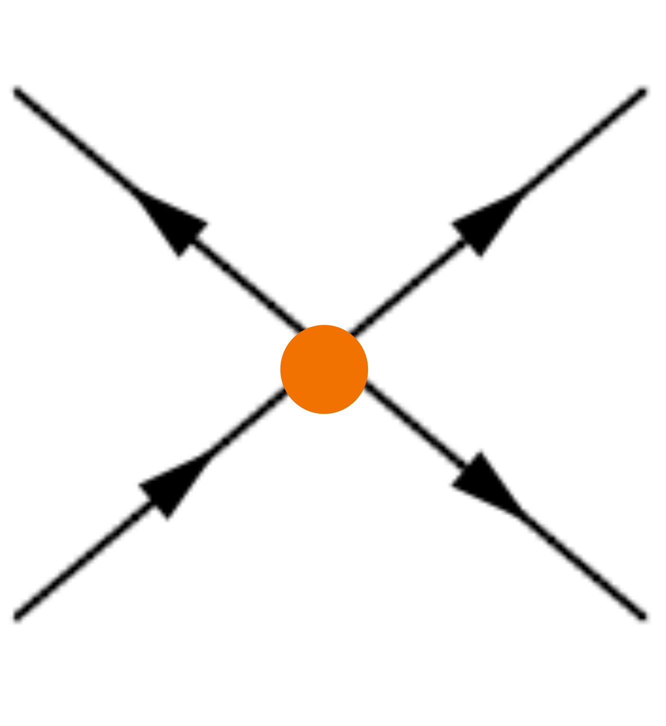

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Four-fermion op.

SMEFT averaged concurrence

[Aoude, Madge, Maltoni, Mantani, 22']

Average over the solid angle

$$\bar{R} = (4\pi)^{-1} \int \mathrm{d}\Omega \, R(\hat{s}, \boldsymbol{k})$$

⟶ Only function of energy (top velocity) β

SMEFT averaged concurrence

[Aoude, Madge, Maltoni, Mantani, 22']

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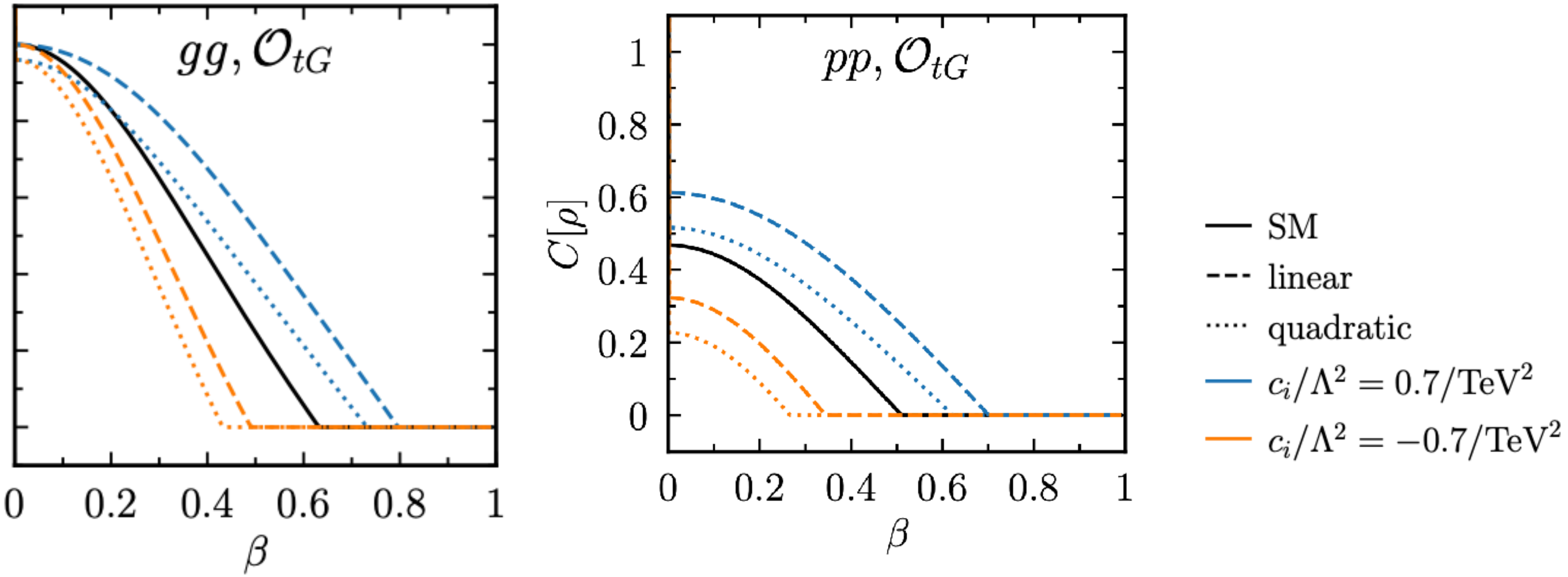
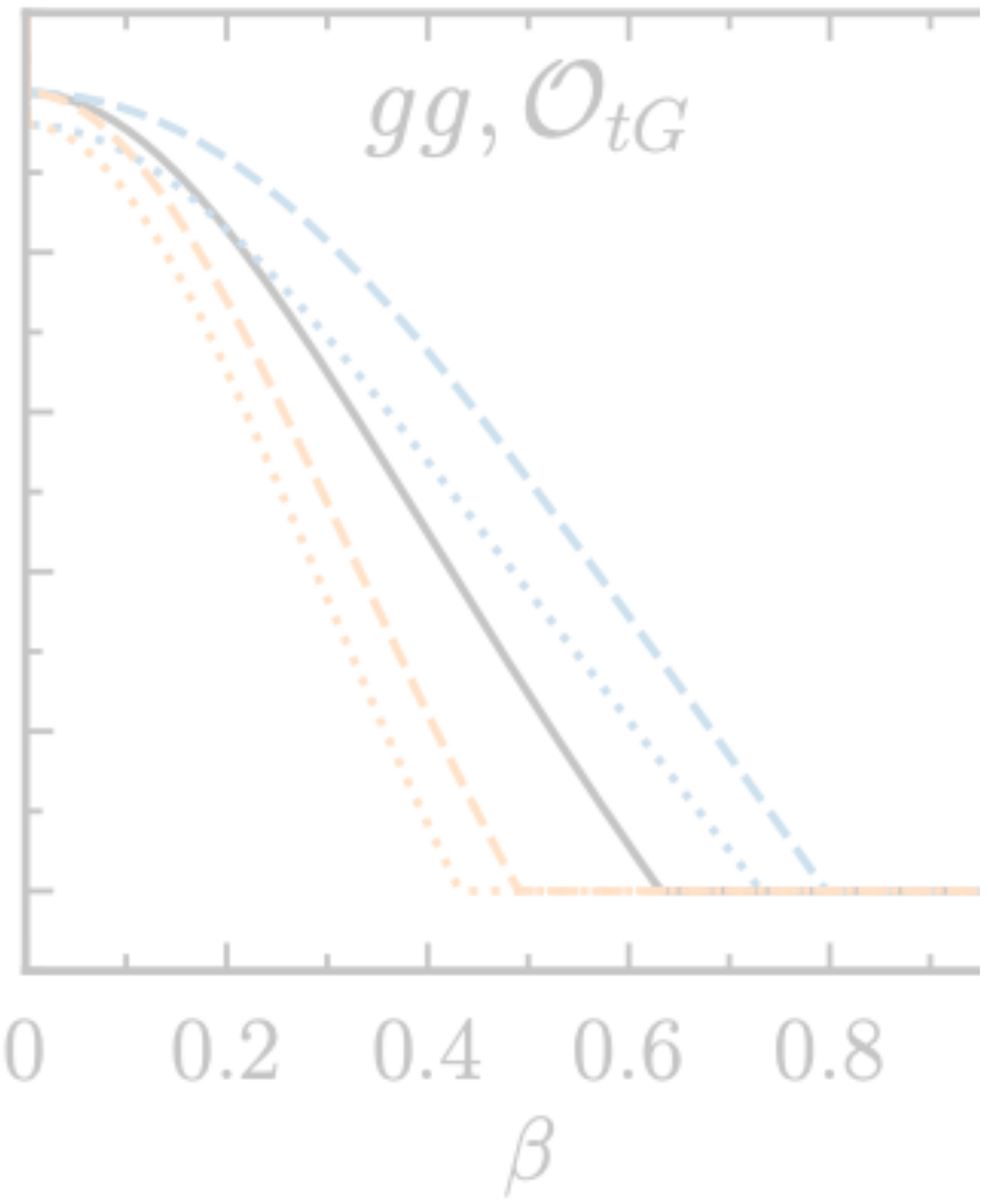
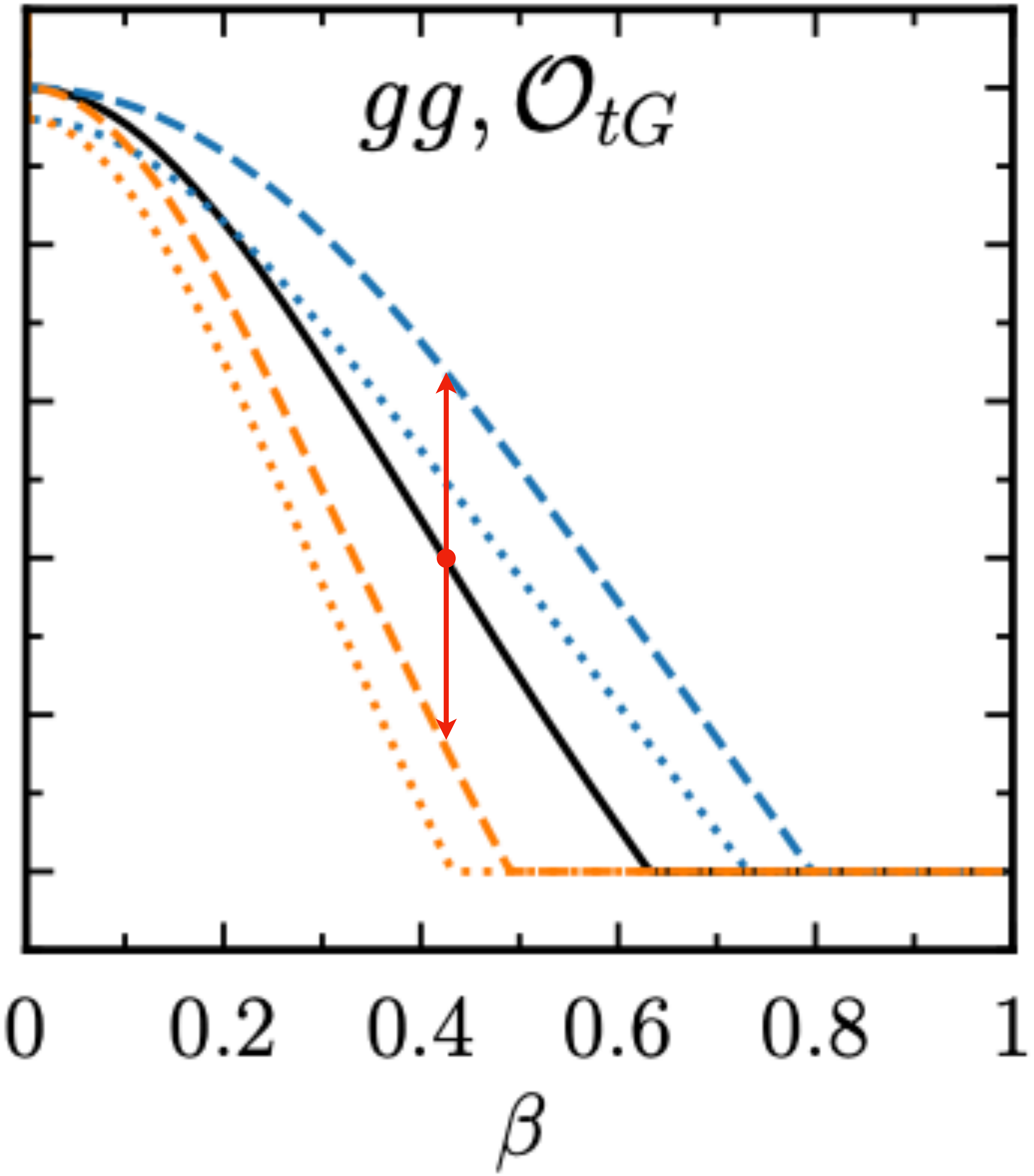


SMEFT averaged concurrence

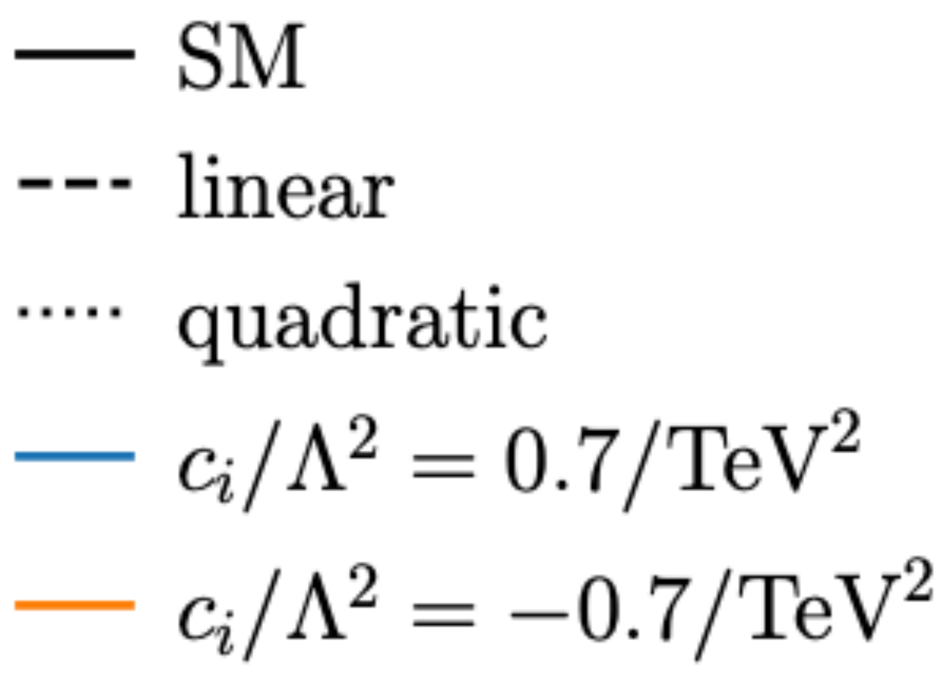
Average over the so

$$\bar{R} = (4\pi)^{-1} \int$$





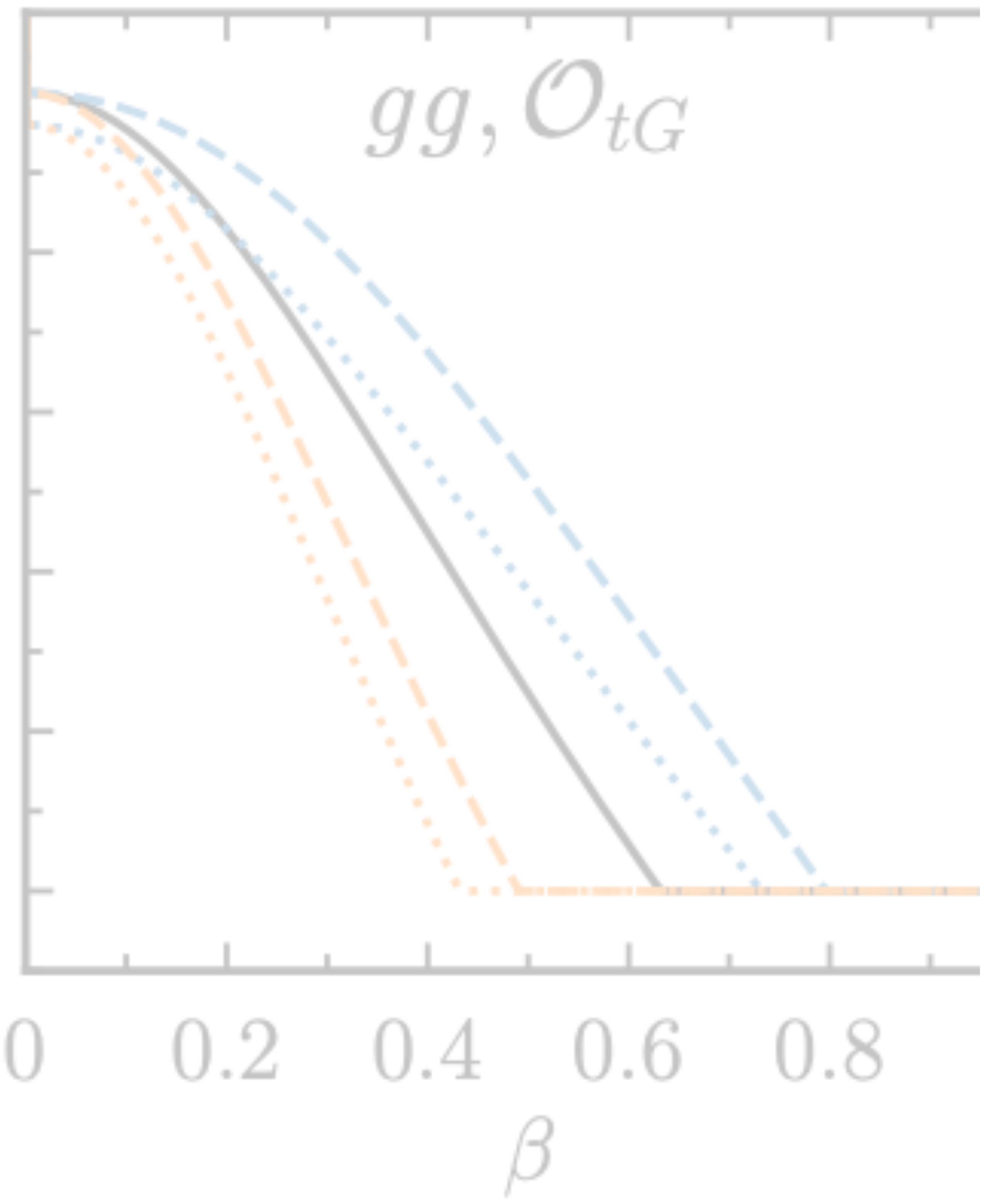
linear depends on the sign

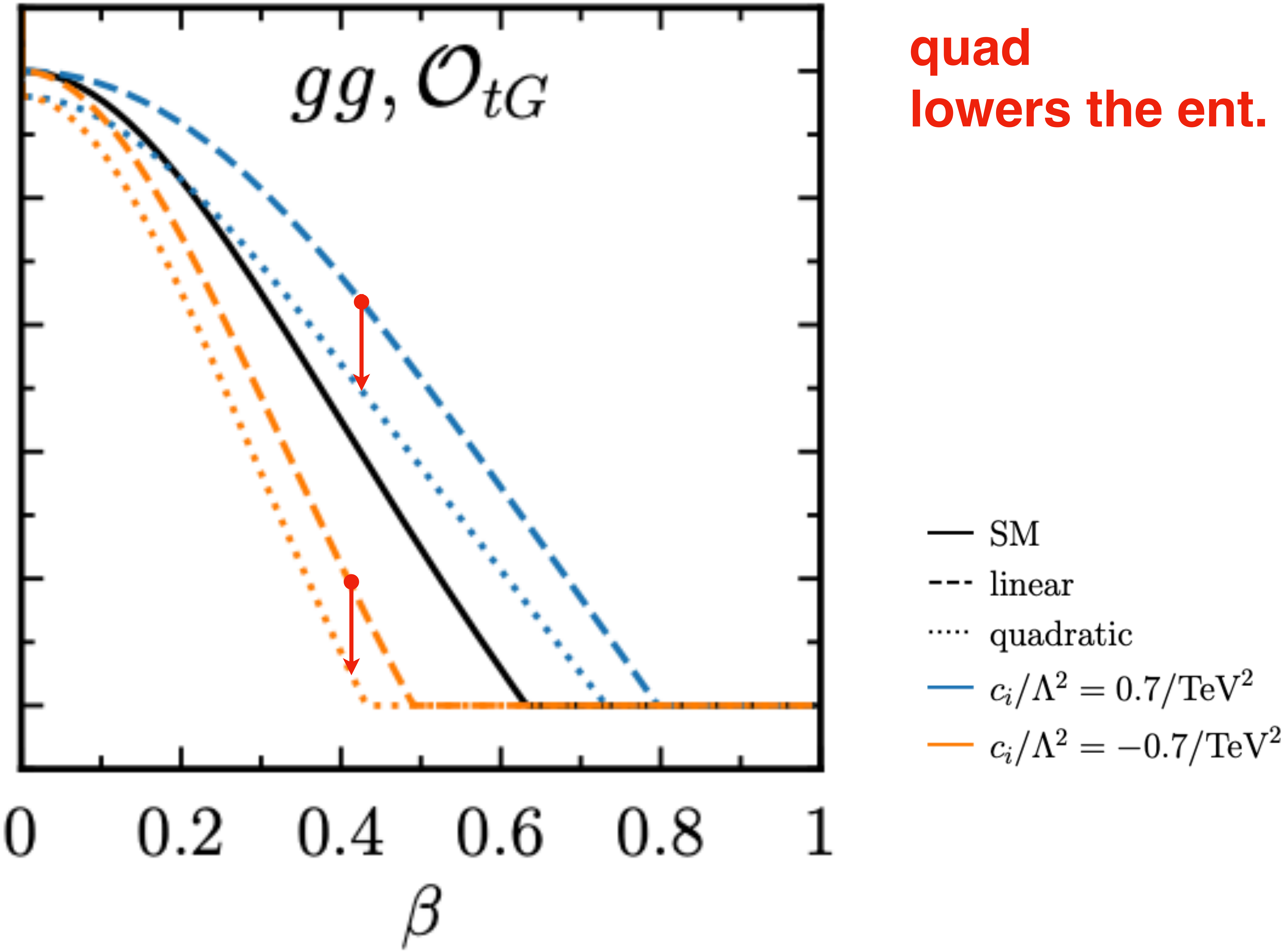


SMEFT averaged concurrence

Average over the so

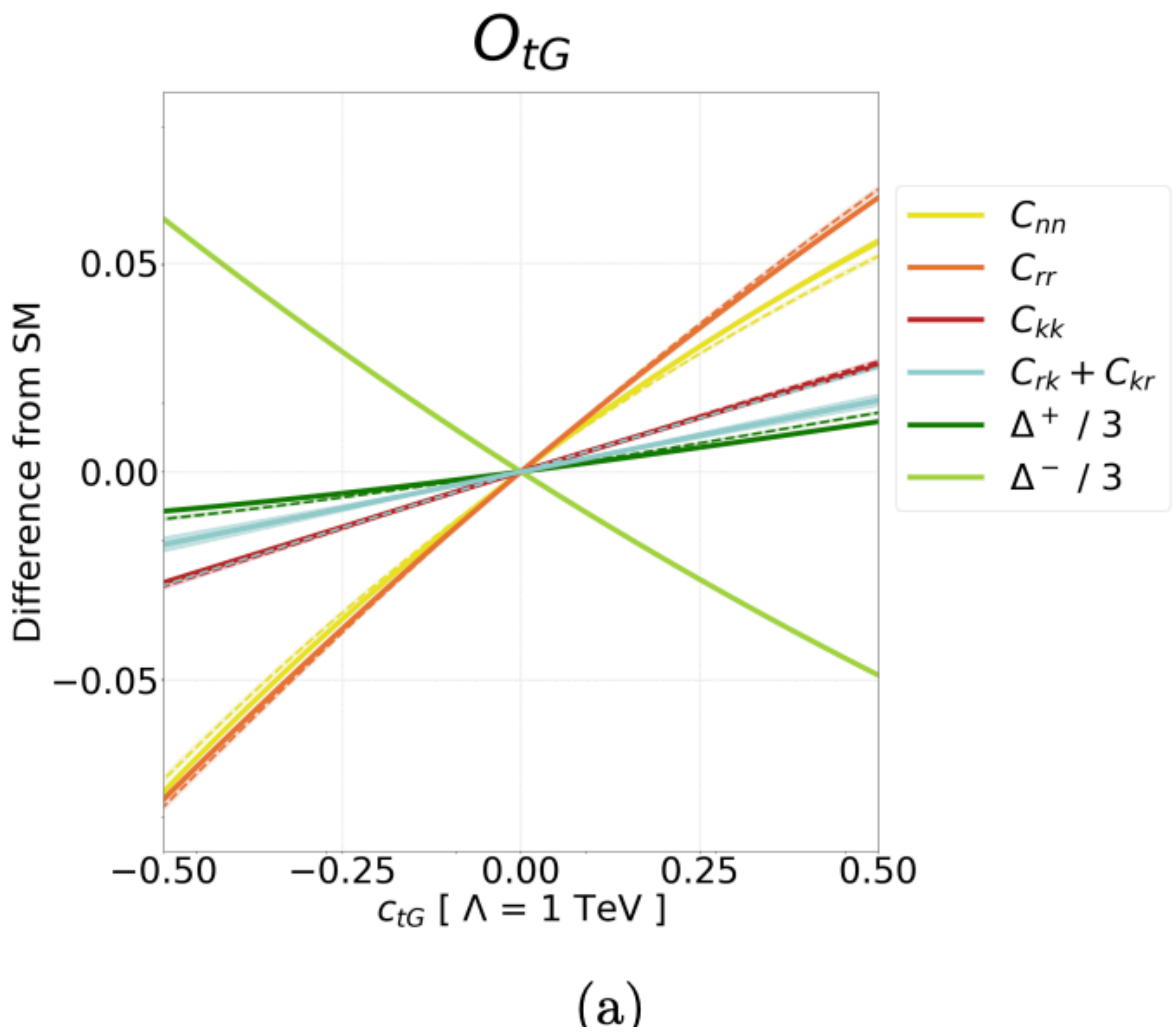
$$\bar{R} = (4\pi)^{-1} \int$$





NLO QCD SMEFT and resonant new physics

[Severi, Vryonidou 22']



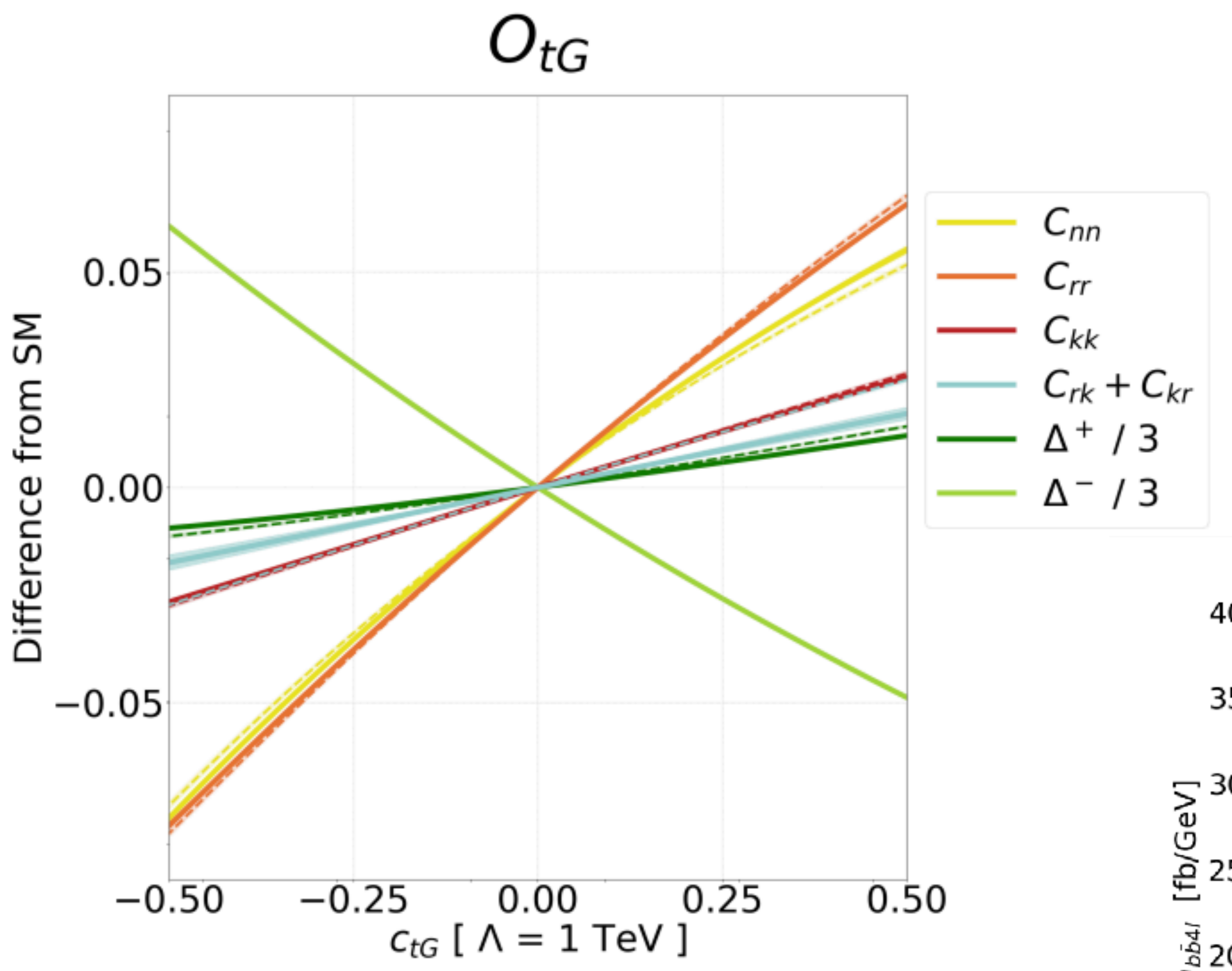
$$D \equiv (\Delta^- + 1)/3.$$

LO (dashed)
NLO (solid)

NLO QCD SMEFT and resonant new physics

[Severi, Vryonidou 22']

[Maltoni, Severi, Tentori, Vryonidou 24']

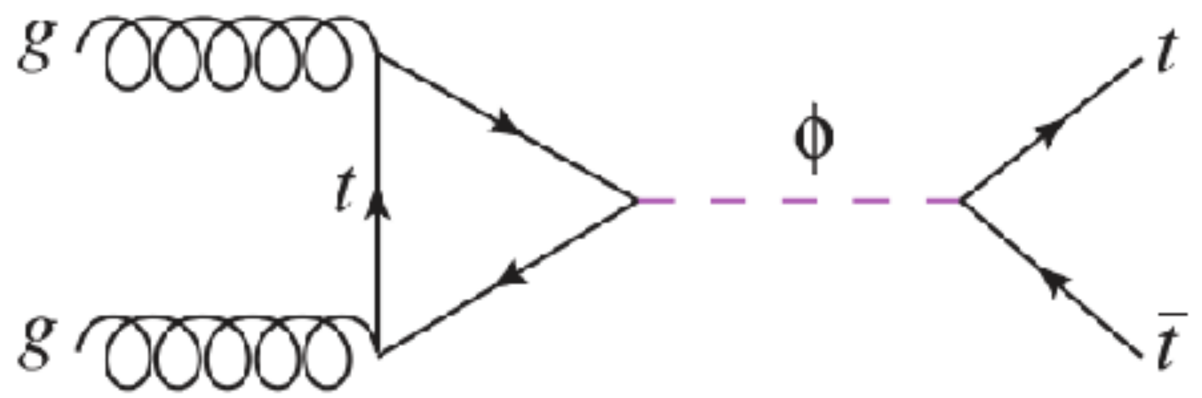


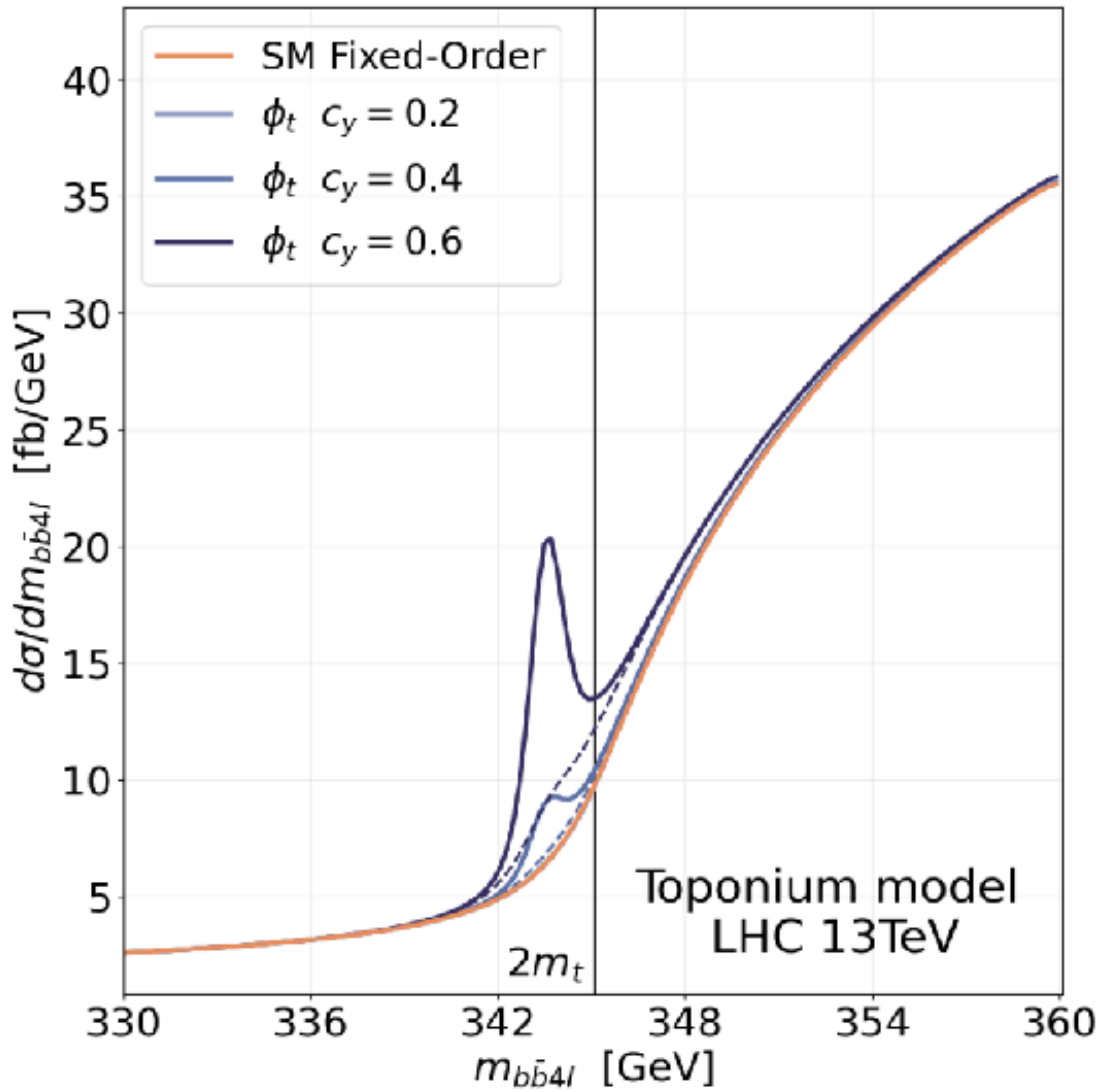
(a)

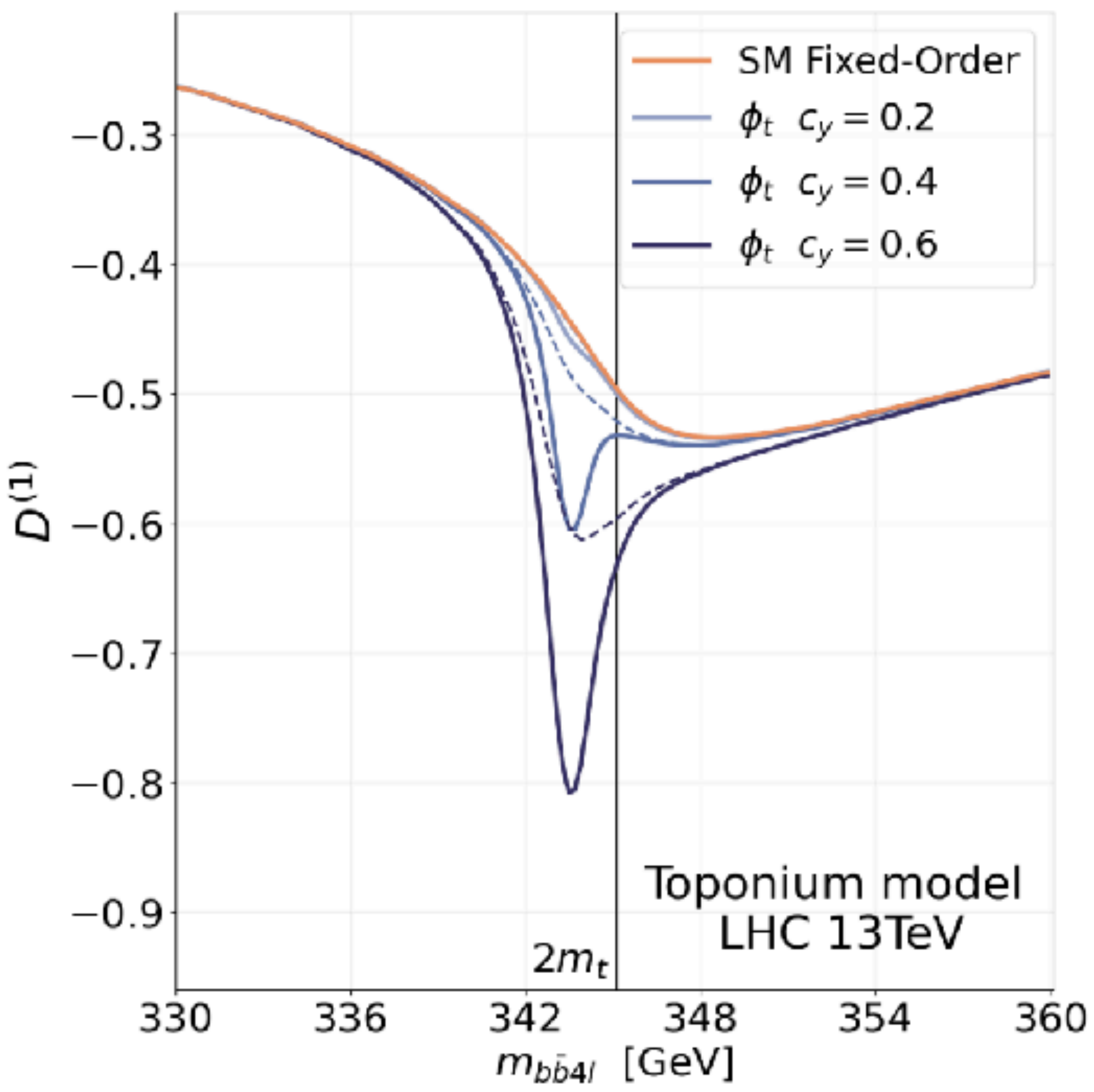
$$D \equiv (\Delta^- + 1)/3.$$

LO (dashed)
NLO (solid)

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\phi(\partial^2 + M_\phi^2)\phi + c_y\,\frac{y_t}{\sqrt{2}}\,\phi\,\bar{t}\,(\cos\alpha + i\gamma^5\sin\alpha)\,t.$$







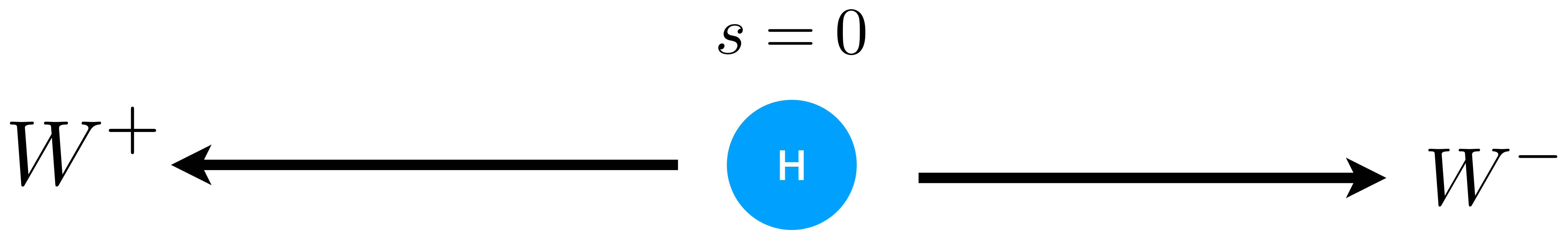
Many many questions

- Threshold bound state effects (topponium)
- Better observables ?
- Can we test beyond QM ?
- Can we test Bell inequalities ?
- What happens at higher-orders? NNLO QCD? EW?
- Actually, Bell inequalities were proposed a while back [Abel, Dittmar, Dreiner ’92] [Dittmar, Dreiner ’96]
- and many more…

but…

We are in the Higgs 2024 conference.

Entanglement in Higgs decay?



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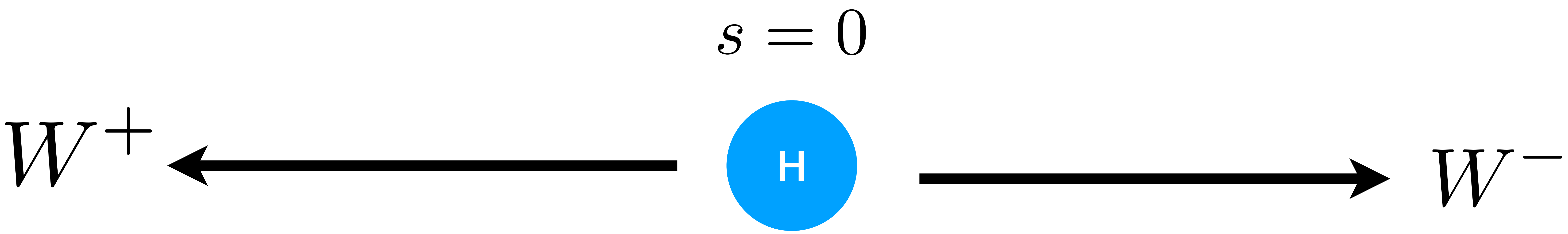
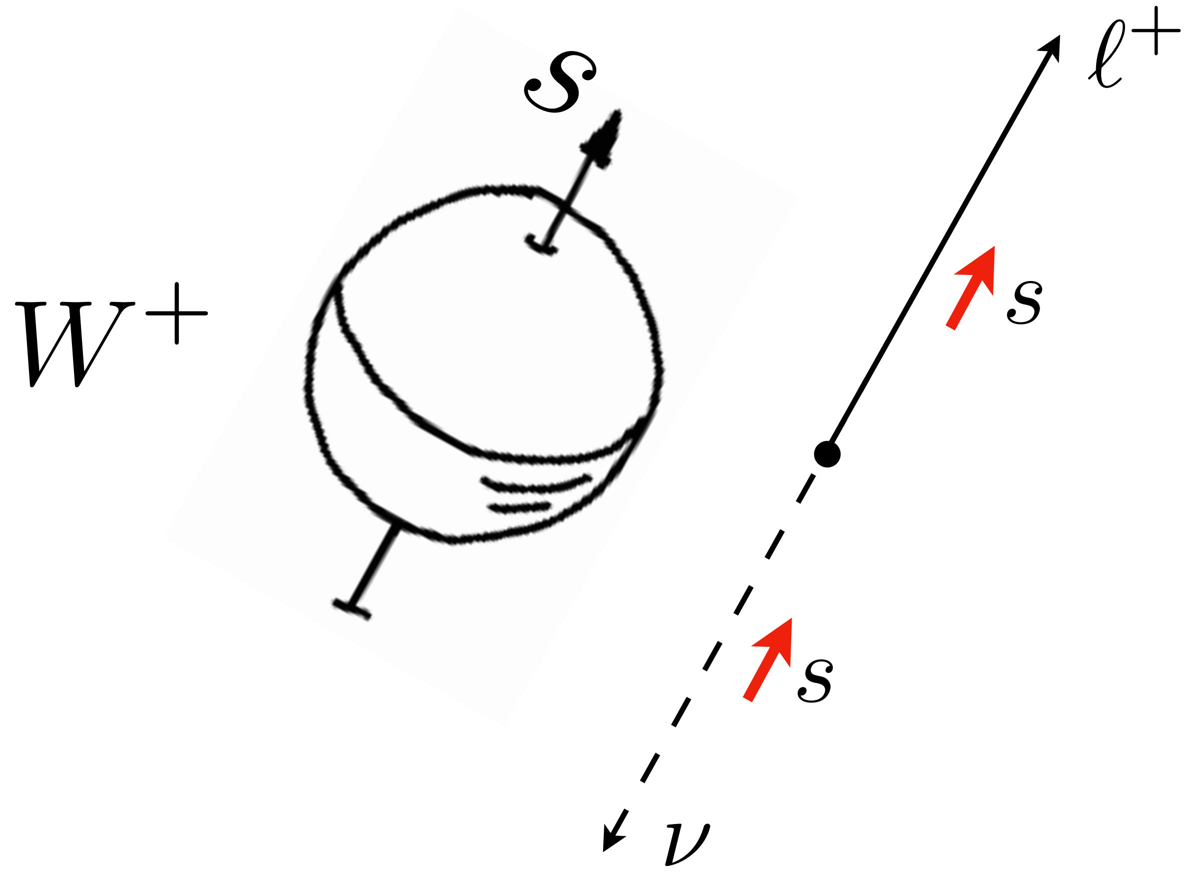
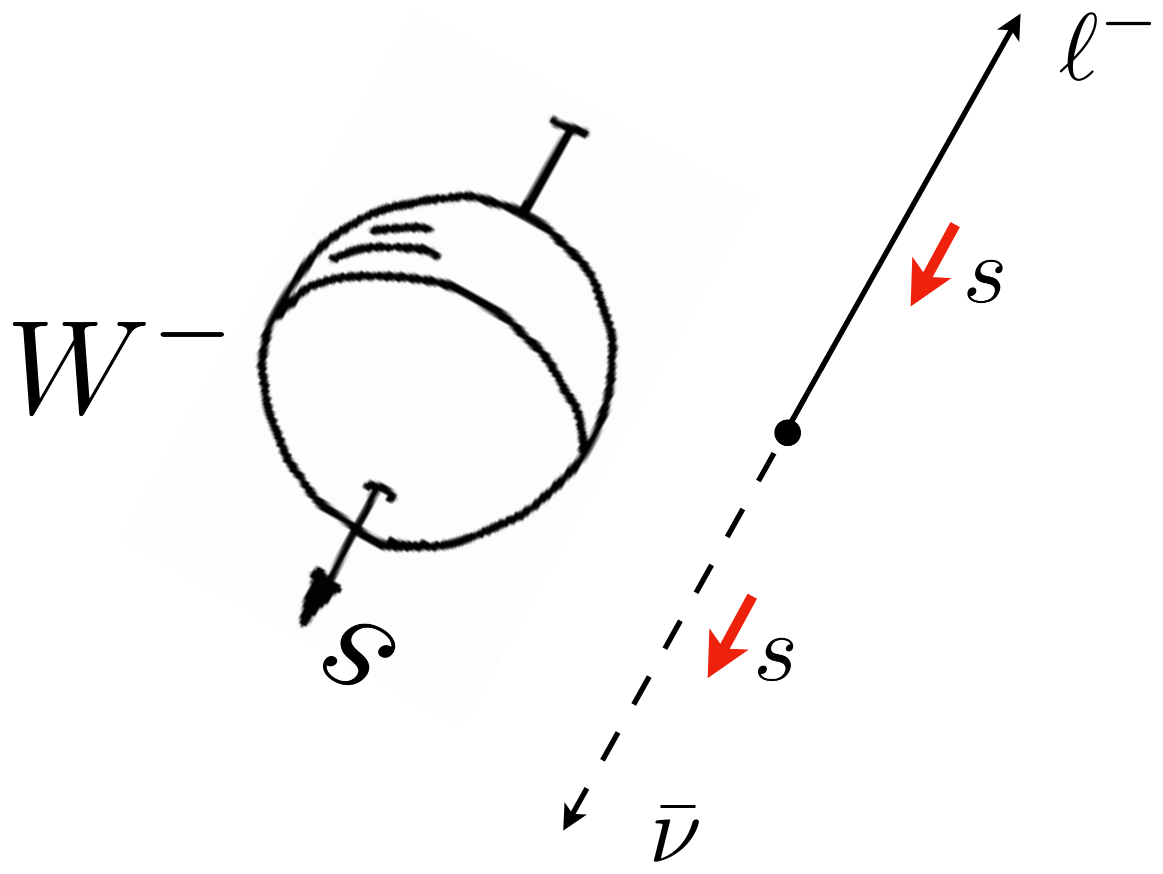


W acts as its own polarimeter: It decays along the axis of the emitted lepton





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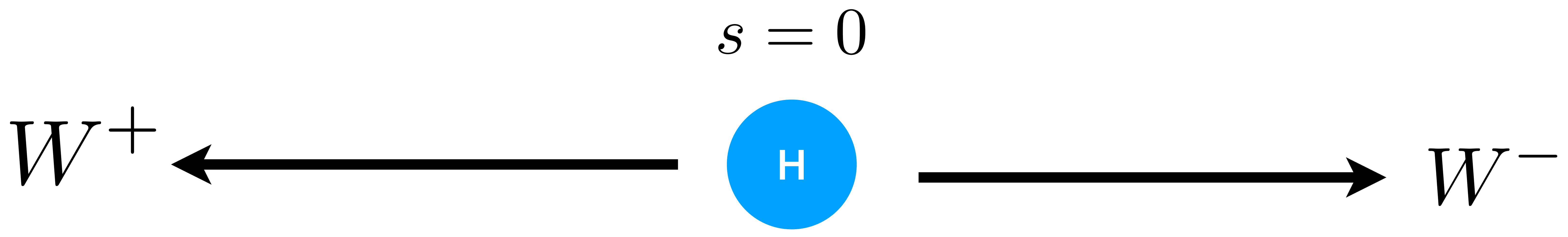
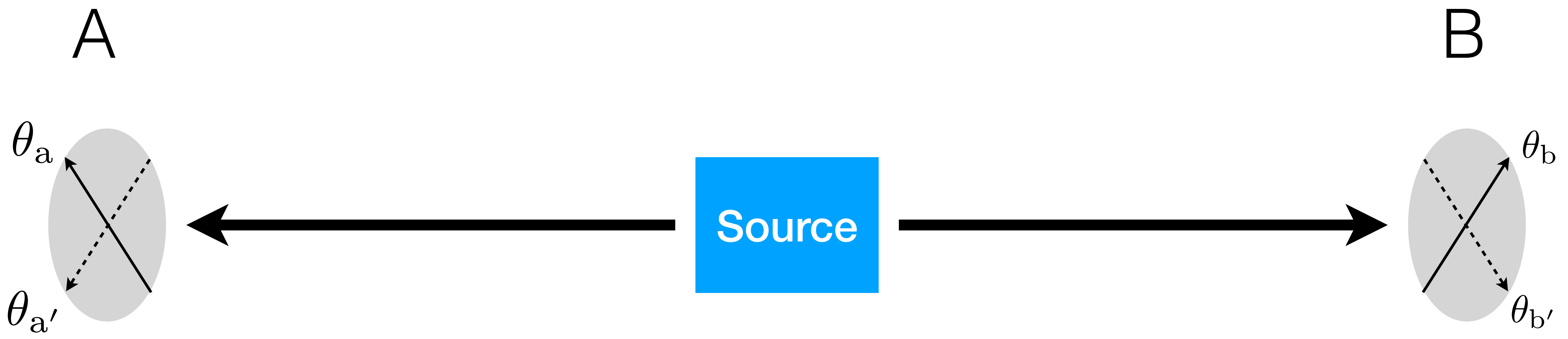


Bell-type experiment!



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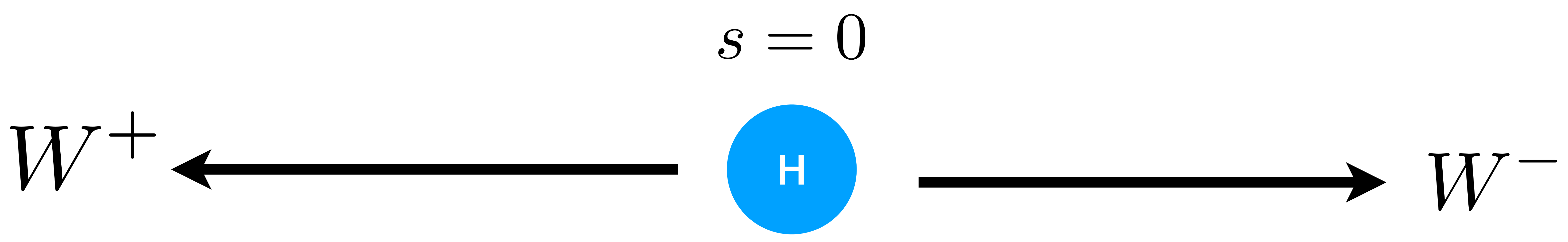
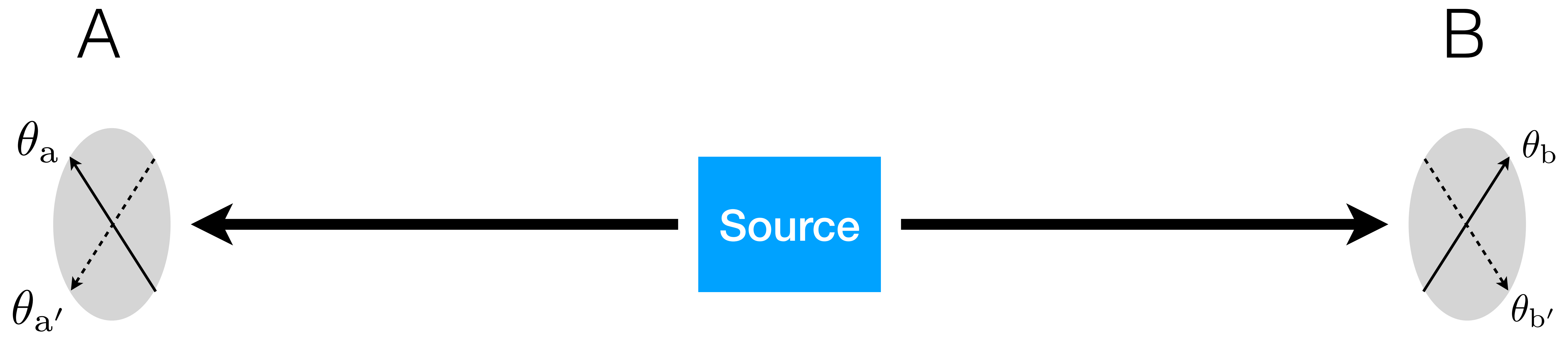


Bell-type experiment!



But the W has 3 polarisations. It is not a qubit anymore: **Qutrit**!

Qutrits

[Ashby-Pickering, Barr, Wierzchuca, '22]

Massive spin-1 boson (W,Z): $|V\rangle = c_+|V_+\rangle + c_0|V_L\rangle + c_-|V_-\rangle = \begin{pmatrix} c_+ \\ c_0 \\ c_- \end{pmatrix}$

Single Qutrit: (3x3) $\rho = \frac{1}{3}\mathbb{I} + \sum_{i=1}^{8} a_i \lambda_i$ a_i : 8 real parameters

Two Qutrits (9x9)

$$\rho = \frac{1}{9}\mathbb{I}\otimes\mathbb{I} + \frac{1}{3}\sum_{i=1}^{8} a_i\,\lambda_i\otimes\mathbb{I} + \frac{1}{3}\sum_{j=1}^{8} b_j\,\mathbb{I}\otimes\lambda_j + \sum_{i=1}^{8}\sum_{j=1}^{8} c_{ij}\,\lambda_i\otimes\lambda_j$$

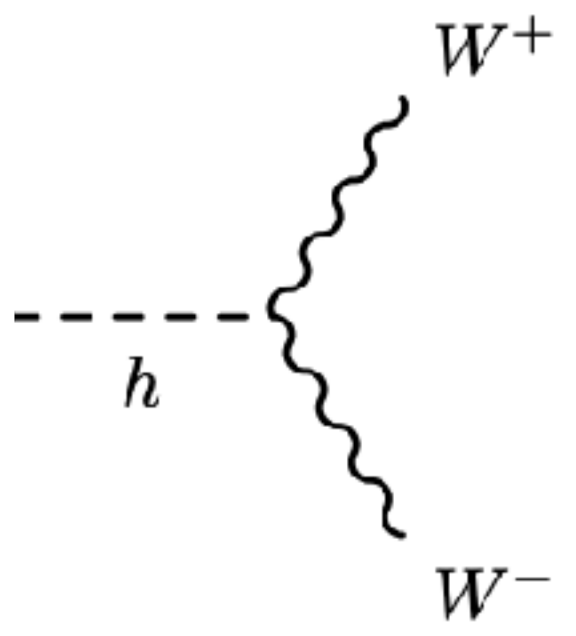
a_i, b_j, c_{ij} 8+8+64 real parameters

λ_i are Gell-Mann matrices

Entanglement in Higgs decays

[Fabbrichesi, Floreanini, Gabrielli, Mazola ’23]

At tree level:

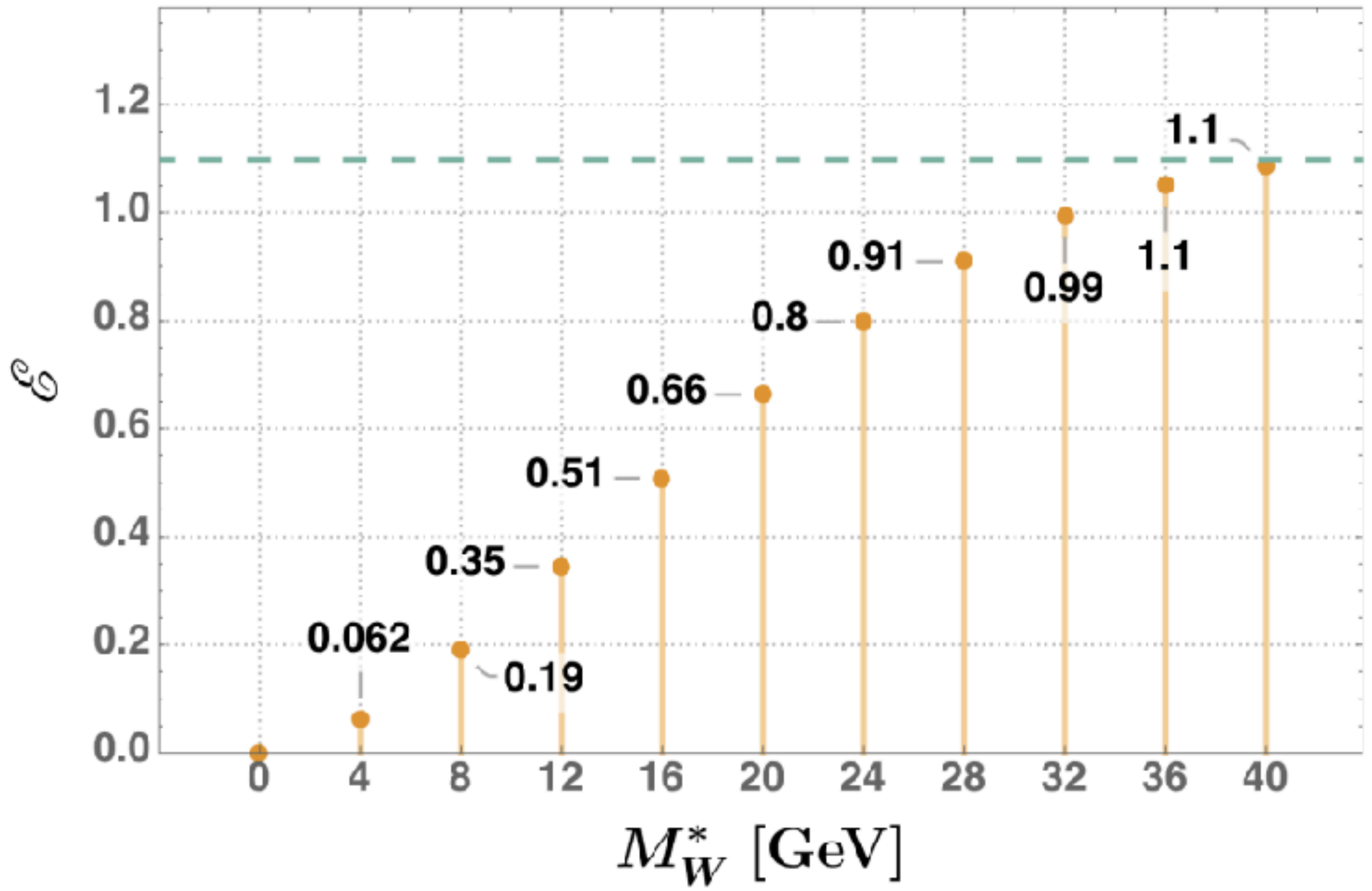


$$\rho_{h\to WW} = 2\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_{44} & 0 & \rho_{16} & 0 & \rho_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_{16} & 0 & 2\rho_{33} & 0 & \rho_{16} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_{44} & 0 & \rho_{16} & 0 & \rho_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Pure state!

$$\rho^2 = \rho = |\Psi\rangle\langle\Psi|$$

$$|\Psi\rangle = \frac{1}{\sqrt{2+\kappa^2}}\{|\uparrow\uparrow\rangle - \kappa|00\rangle + |\downarrow\downarrow\rangle\}$$



See also Bell inequalities

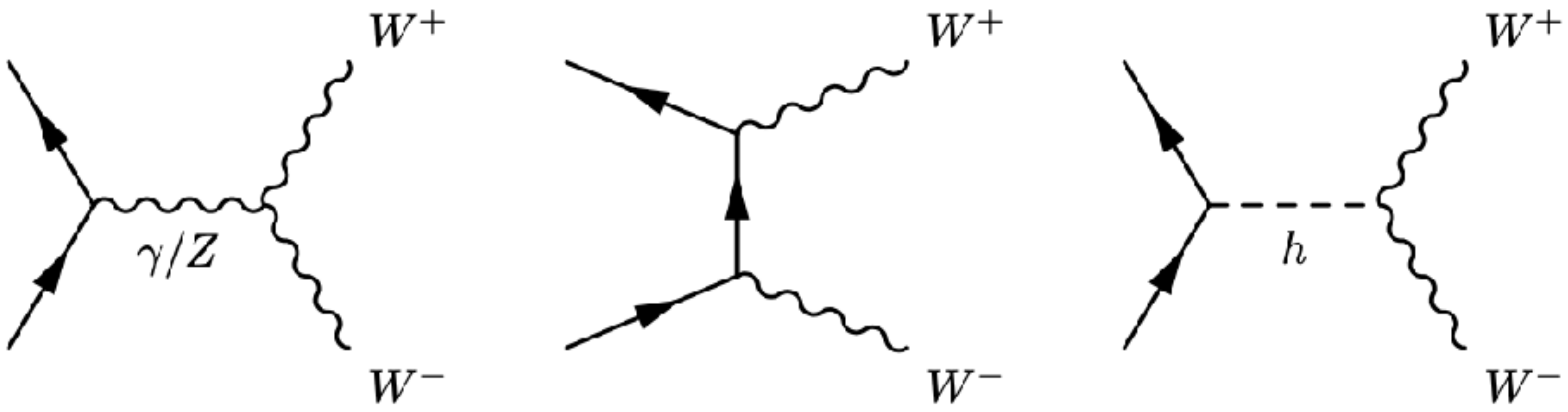
[Fabbri, Howarth, Maurin, 24’]

EW boson production at colliders

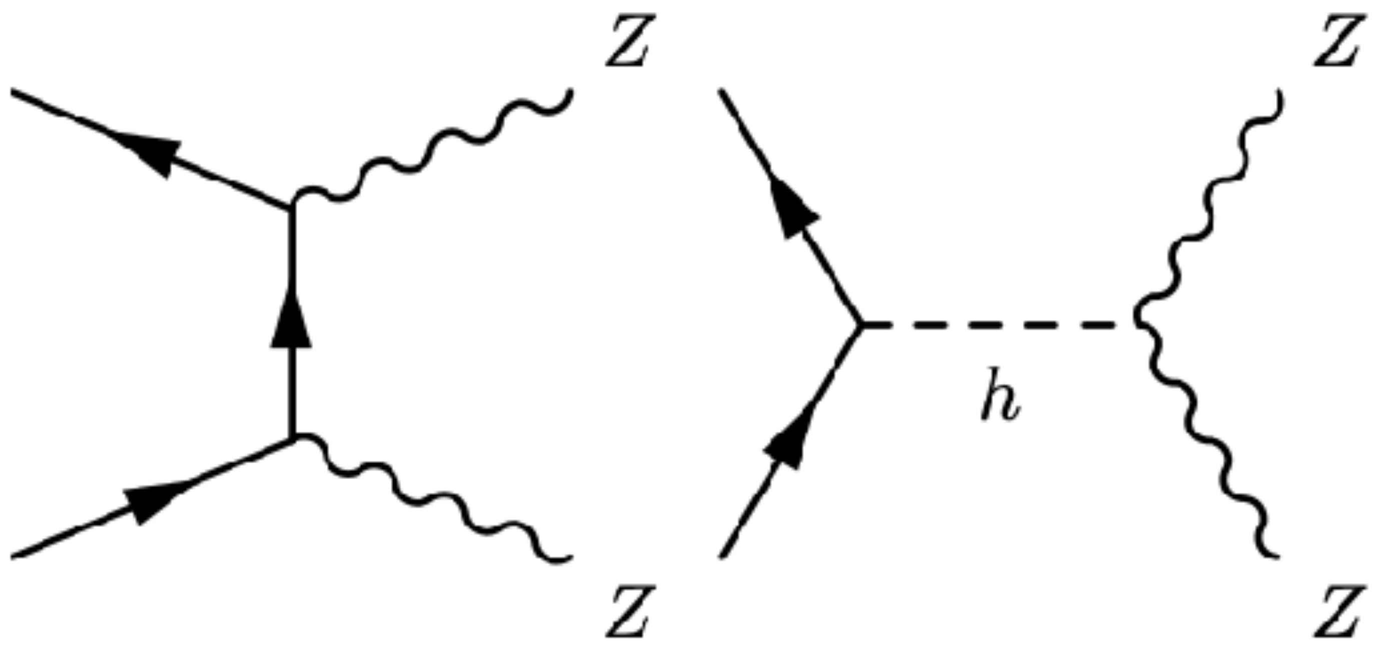
[Horodecki, Horodecki, Horodecki, Horodecki, 09’]

[Ashby-Pickering, Barr, Wierzchuca, ‘22]

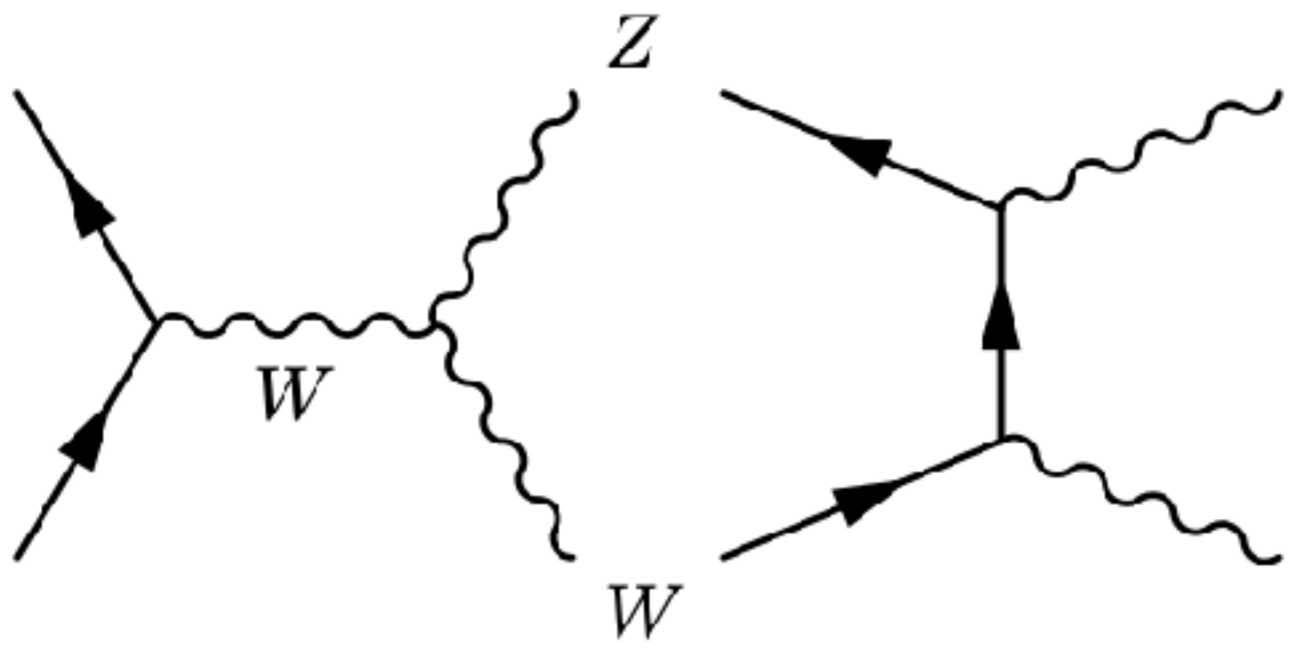
WW:



ZZ:



WZ:



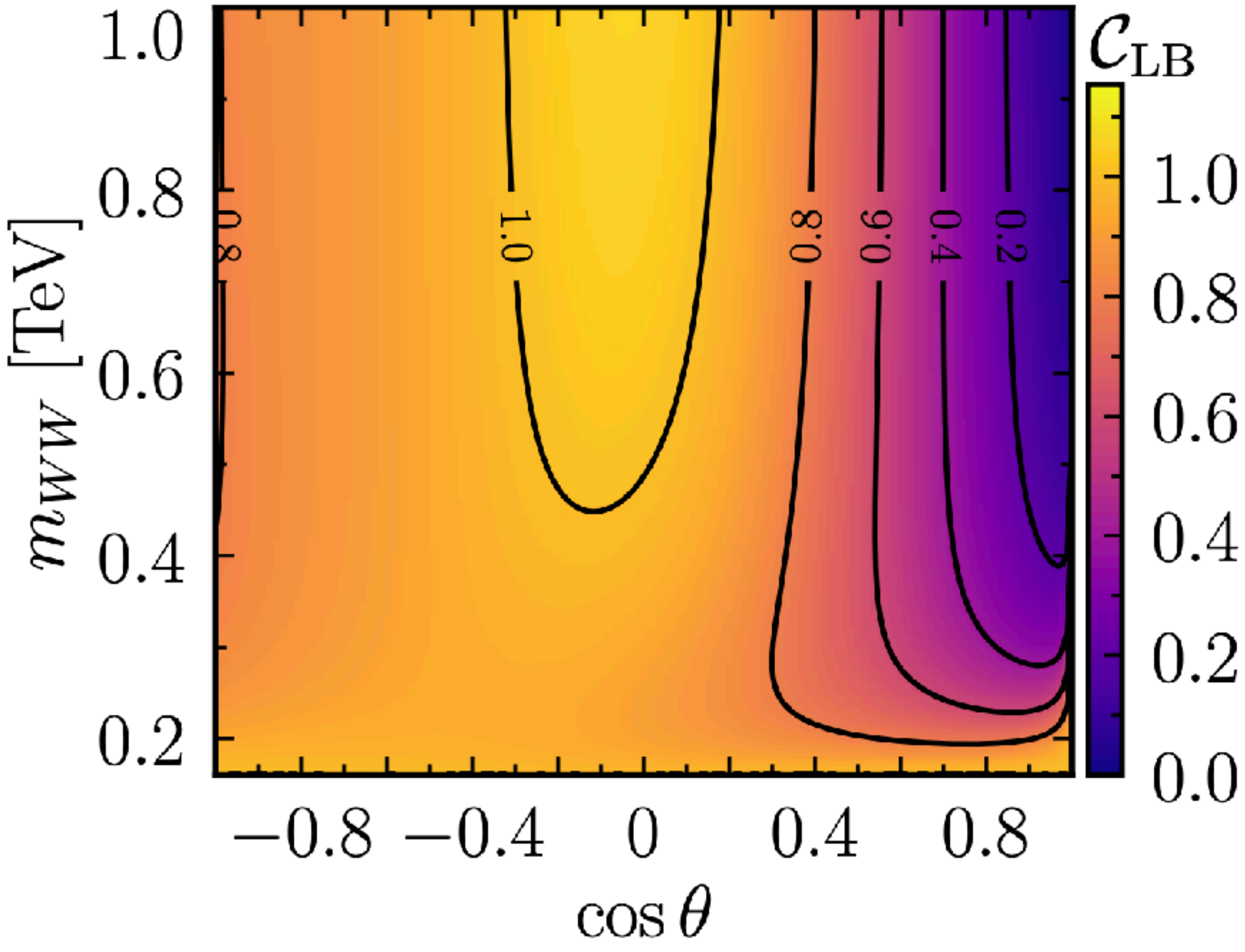
What’s the story for the Standard Model?

[Ashby-Pickering, Barr, Wierzchuca, ‘22]

[Aoude, Madge, Maltoni, Mantani, 23’]

$$e^+e^- \to W^+W^-$$

Lower bound:



No symmetry around $\theta = \pi/2$ as in ttbar

Entanglement is mostly present across the phase space

Zero entanglement at $\theta = 0$

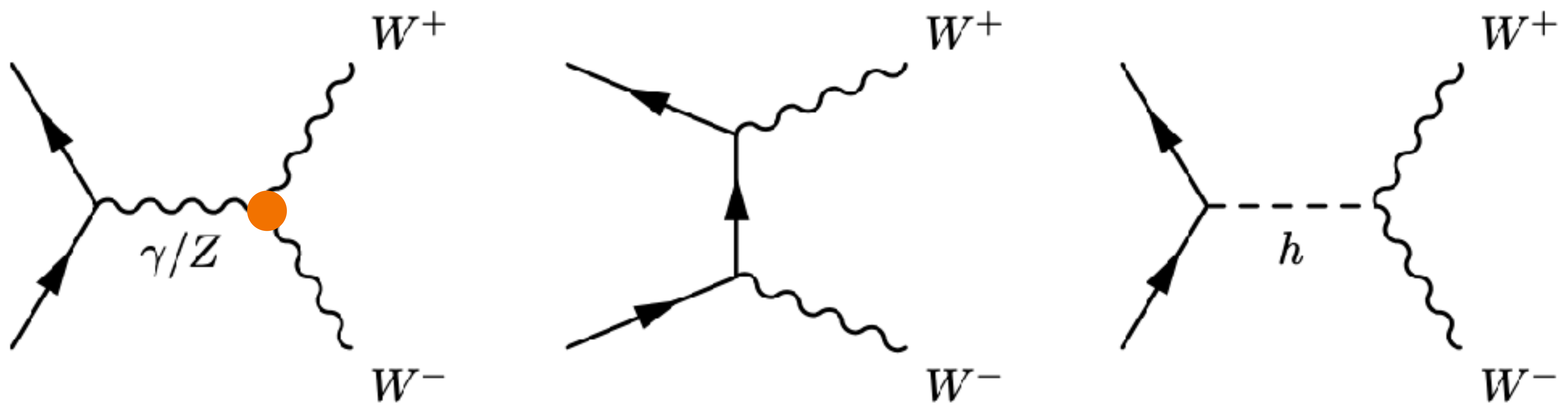
High entanglement at central HE region

SMEFT entanglement deviations

$e^+e^- \to W^+W^-$

$\mathcal{O}_{\varphi WB}$ changes TGC coupling

$\mathcal{O}_W$ new Lorentz structure



[Aoude, Madge, Maltoni, Mantani, 23']

SMEFT entanglement deviations

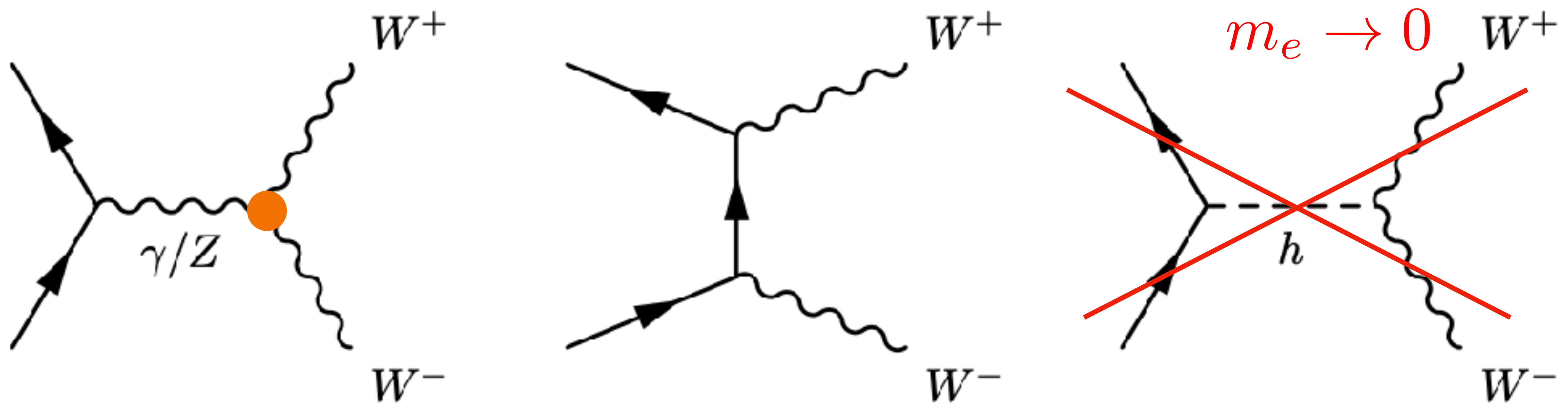
$e^+e^- \to W^+W^-$

$\mathcal{O}_{\varphi WB}$ changes TGC coupling

- more ent. in central and backward HE

$\mathcal{O}_W$ new Lorentz structure

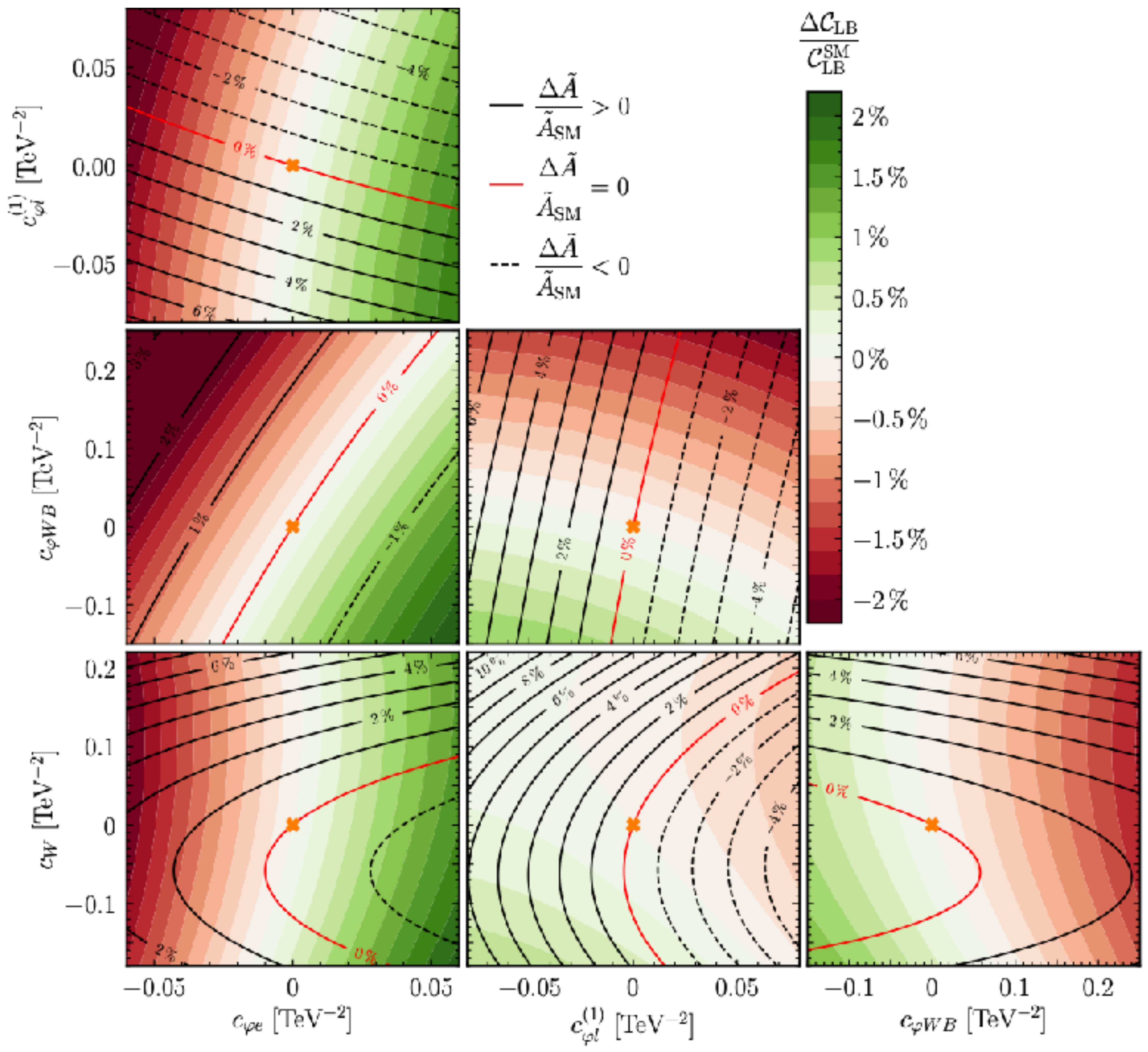
- small effect



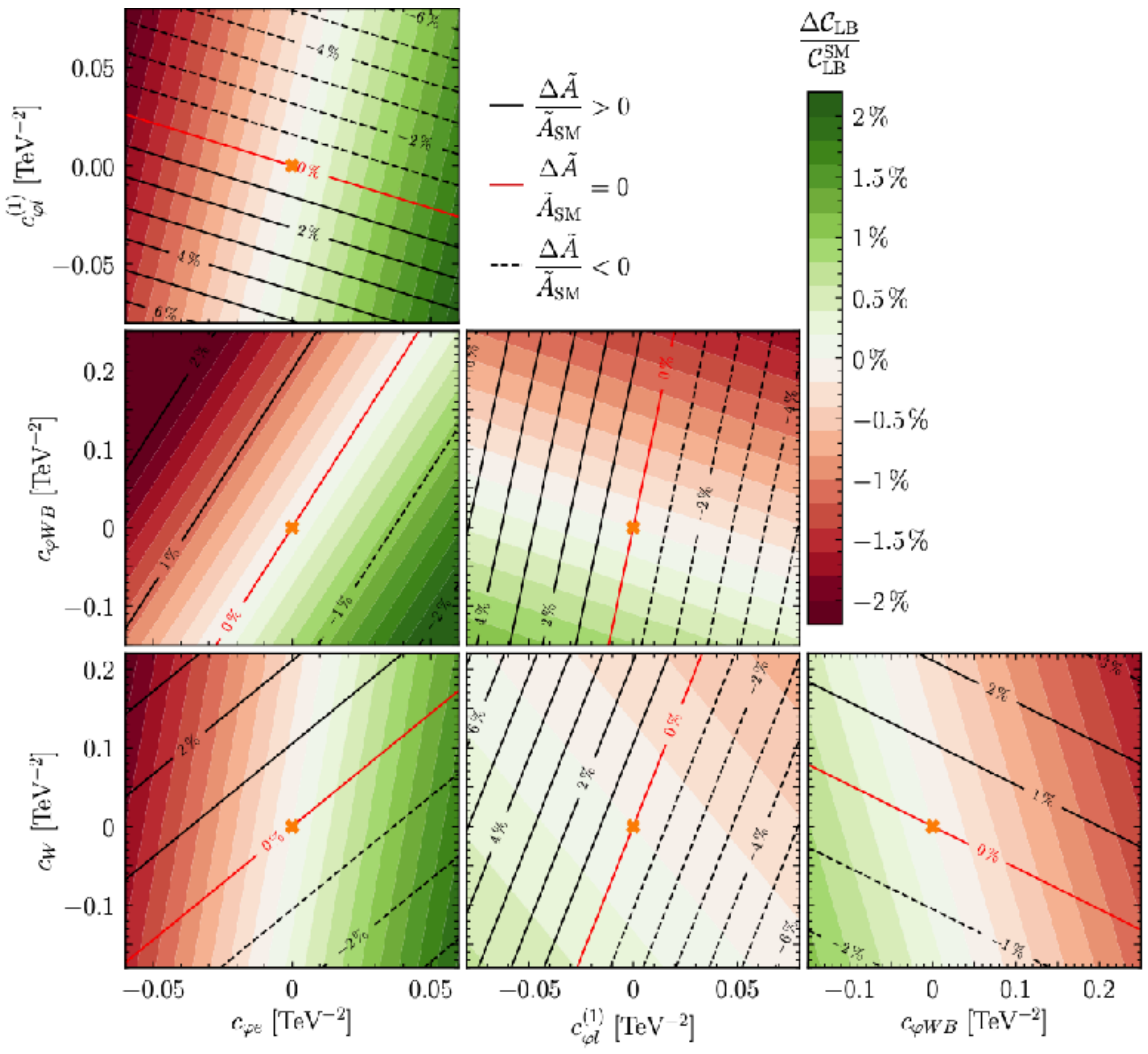
[Aoude, Madge, Maltoni, Mantani, 23']

SMEFT entanglement deviations: Central region

$$m_{WW} = 500\,\mathrm{GeV} \quad \cos\theta = 0$$



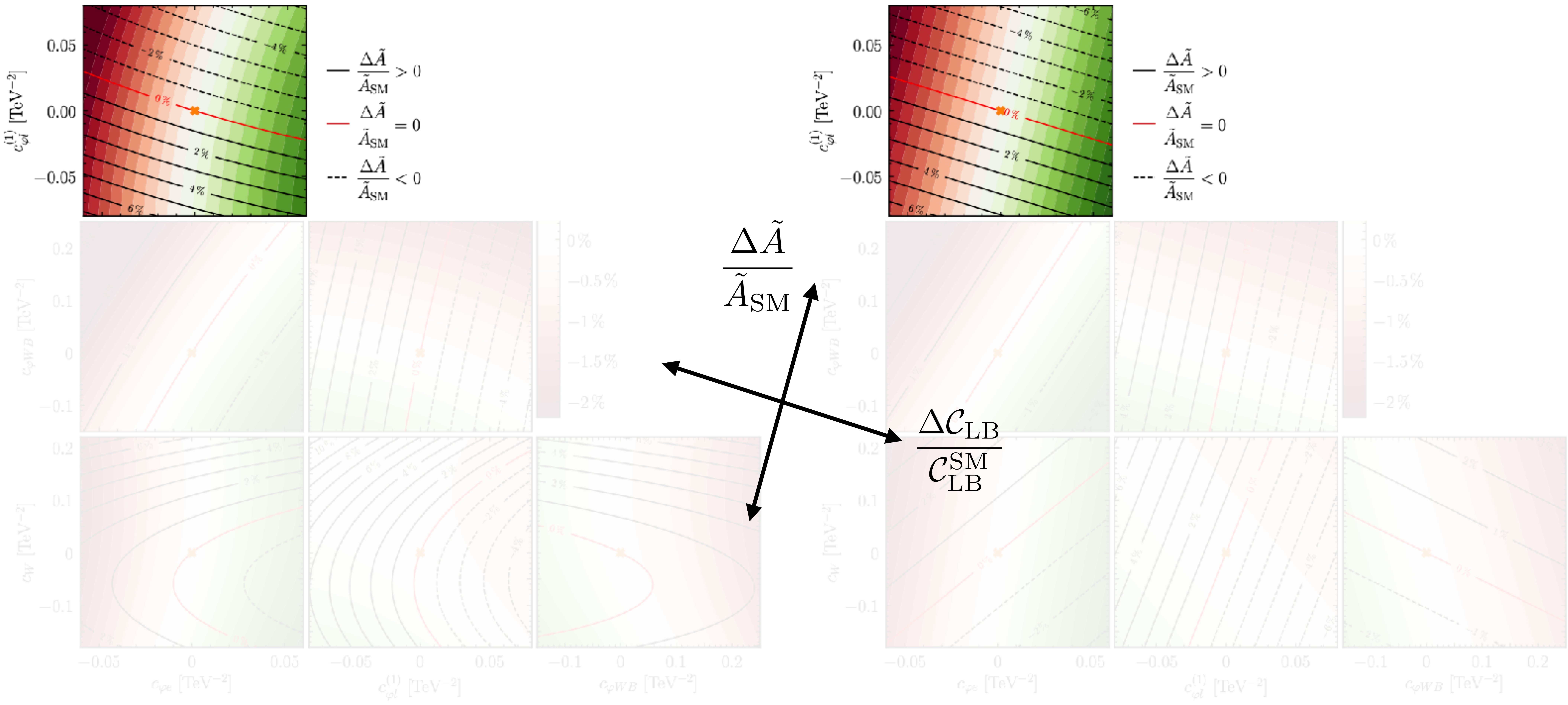
linear+squared dim-6



Linear dim-6

SMEFT entanglement deviations: Central region

$$m_{WW} = 500\,\mathrm{GeV} \qquad \cos\theta = 0$$



linear+squared dim-6

Linear dim-6

Growing subfield: many new directions

*not a complete list!

Symmetries from Entanglement

[Beane, Kaplan, Klco, Savage '18]

[Beane, Farrell '21]

[Low, Mehen 21'] [Liu, Low, Mehen, '21]

[Carena, Low, Wagner, Xiao, '24]

[Thaler, Trifinopoulos, '24]

Post decay

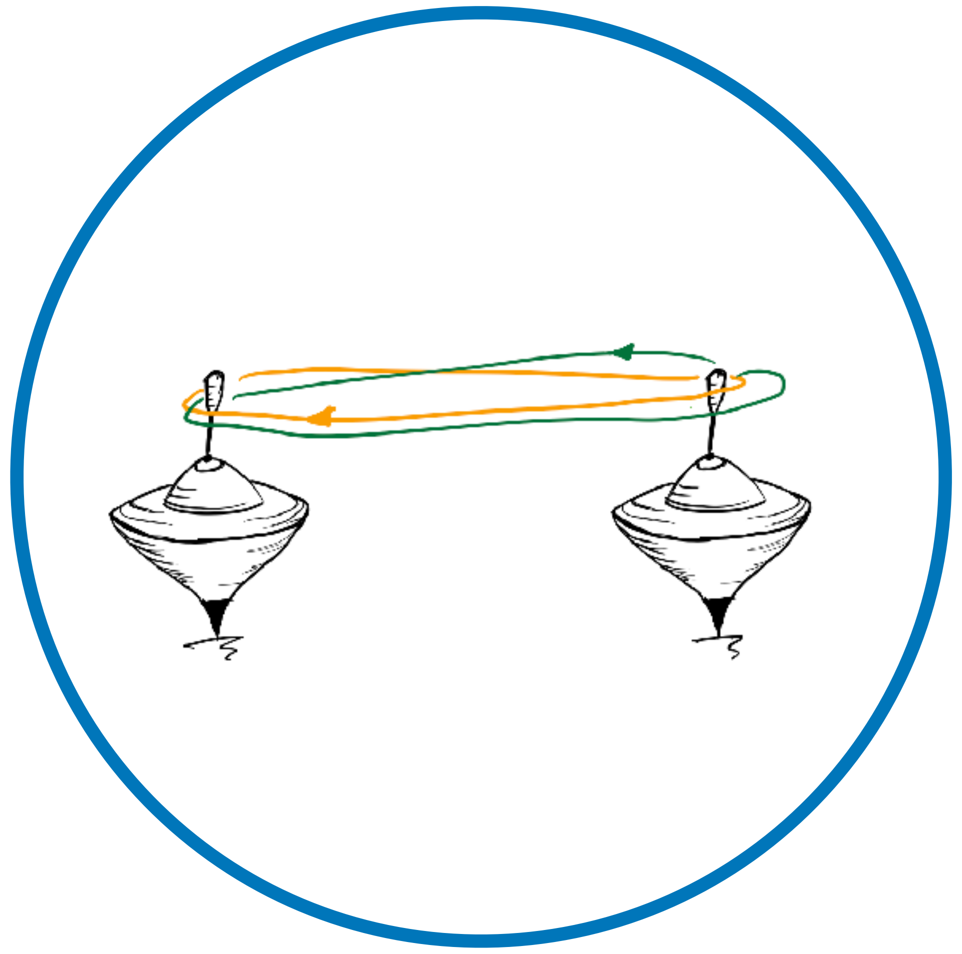
[J. A. Aguilar-Saavedra 24']

Multipartite entanglement

[Sakurai, Spannowsky 23']

[Bernal, Casas, Moreno 23']

[Bernal 24']



Entanglement in flavour space/ Momenta space

[Cheung, He, Sivaramakrishnan 24']

[Aoude, Elor, Remen, Sumensari, 24']

[Low, Yin 24']

[Duaso Pueyo, Goodhew, McCulloch, Pajer 24']

Beyond Quantum Mechanics

[Eckestein]

Bell Inequalities

[many refs!]

Quantum Simulations in HEP

[Gustafson, Prestel, Spannowky, Williams, '22]

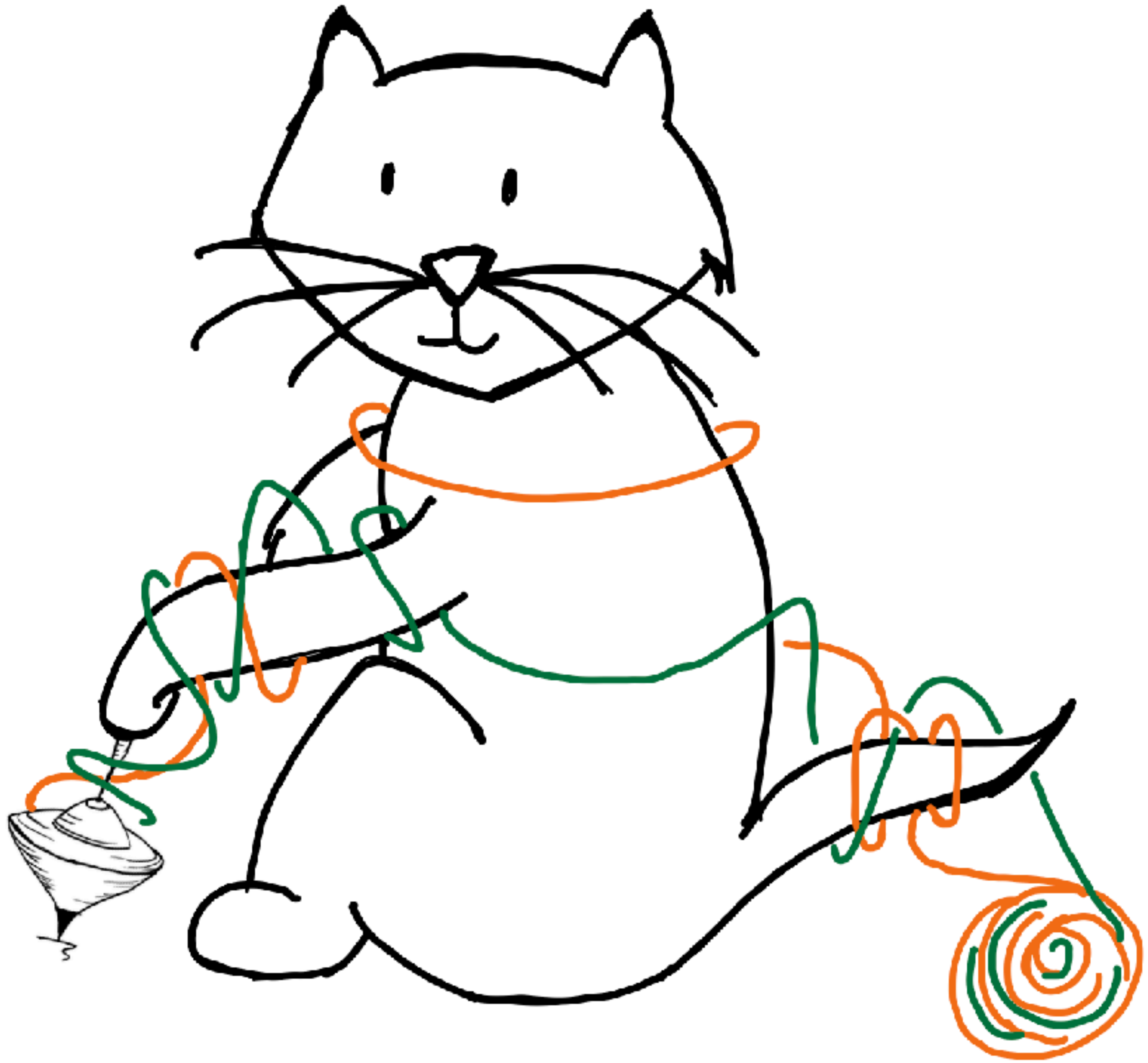
[many refs!]

Recent Review [Barr, Fabbrichesi, Floreanini, Gabrielli and Marzola 24']

Conclusions

- Entanglement (Quantum Information) in High Energy Physics is cool!
- SM in ttbar has high entanglement at threshold and high-pT
- SMEFT typically decreases the amount of entanglement
- Recent experimental results appeared this year!
- Synergies between HEP and QIS
- Useful to probe/constrain new physics
- New interpretation for a spin correlations subset

Tack!



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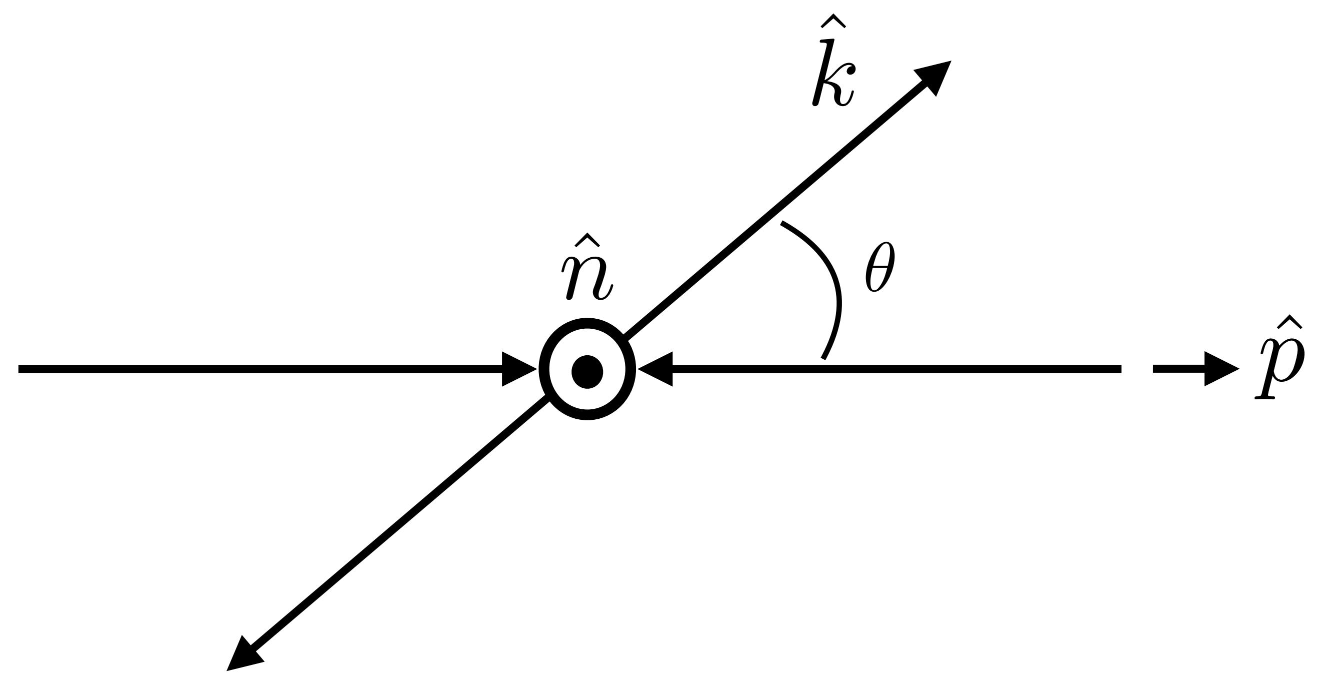
MARIE CURIE ACTIONS

UKRI

Density matrix and helicity-basis

Helicity basis:

$$\{\boldsymbol{k}, \boldsymbol{n}, \boldsymbol{r}\}: \ \boldsymbol{r} = \frac{(\boldsymbol{p} - z\boldsymbol{k})}{\sqrt{1-z^2}}, \quad \boldsymbol{n} = \boldsymbol{k} \times \boldsymbol{r},$$



To expand in this basis, e.g.

$$C_{nn} = \mathrm{tr}[C_{ij}\, \boldsymbol{n} \otimes \boldsymbol{n}\,]$$

Phase-space parametrized by: $\beta^2 = (1 - 4m_t^2/\hat{s})$ and $z = \cos\theta$

SMEFT R-matrix

$$R^{\text{SM}} \sim \mathcal{M}^{\text{SM}}\mathcal{M}^{\dagger\text{SM}}$$

$$R^{\text{EFT},(1)} \sim \mathcal{M}^{\text{SM}}\mathcal{M}^{\dagger(\text{d6})}$$

$$R^{\text{EFT},(2)} \sim \mathcal{M}^{(\text{d6})}\mathcal{M}^{\dagger(\text{d6})}$$

The R-matrix coefficients $X = X^{(0)} + \frac{1}{\Lambda^2}X^{(1)} + \frac{1}{\Lambda^4}X^{(2)}$ where

$X = \tilde{A},\ \tilde{C}_{ij}$ and $\tilde{B}_i^{\pm}$

At $\mathcal{O}(\Lambda^{-2})$

$$\tilde{C}_{nn}^{gg,(1)} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{-7g_s^2 v m_t}{12\sqrt{2}}c_{tG} - \frac{\beta^2 m_t^4}{4m_t^2-(1-\beta^2)m_h^2}c_{\varphi G} + \frac{9g_s^2\beta^2 m_t^2 z^2}{8}c_G\right]$$

SMEFT entanglement: gg-initiated

[Aoude, Madge, Maltoni, Mantani, 22']

only $\mathcal{O}_{tG}, \mathcal{O}_{G}, \mathcal{O}_{\varphi G}$ contributes

$$\rho = \frac{R^{\mathrm{SM}} + R^{\mathrm{EFT}}}{\mathrm{tr}(R^{\mathrm{SM}}) + \mathrm{tr}(R^{\mathrm{EFT}})}$$

gg-initiated at threshold $\beta^2 = 0$

- linear interference exactly cancel, maximally entangled state unchanged
- quadratics vanish for $\mathcal{O}_{\varphi G}$ and decreases for $\mathcal{O}_{tG}, \mathcal{O}_{G}$

gg-initiated at high-E: $\beta^2 \to 1$: EFT not valid but $m_t^2 \ll \hat{s} \ll \Lambda^2$

- linear interference: sign dependent
- quadratics always decreases

SMEFT entanglement: qq-initiated

[Aoude, Madge, Maltoni, Mantani, 22']

only $\mathcal{O}_{tG}$ and 4F contributes

$$\rho = \frac{R^{\mathrm{SM}} + R^{\mathrm{EFT}}}{\mathrm{tr}(R^{\mathrm{SM}}) + \mathrm{tr}(R^{\mathrm{EFT}})}$$

qq-initiated at threshold $\beta^2 = 0$

- no contributions for linear and quad

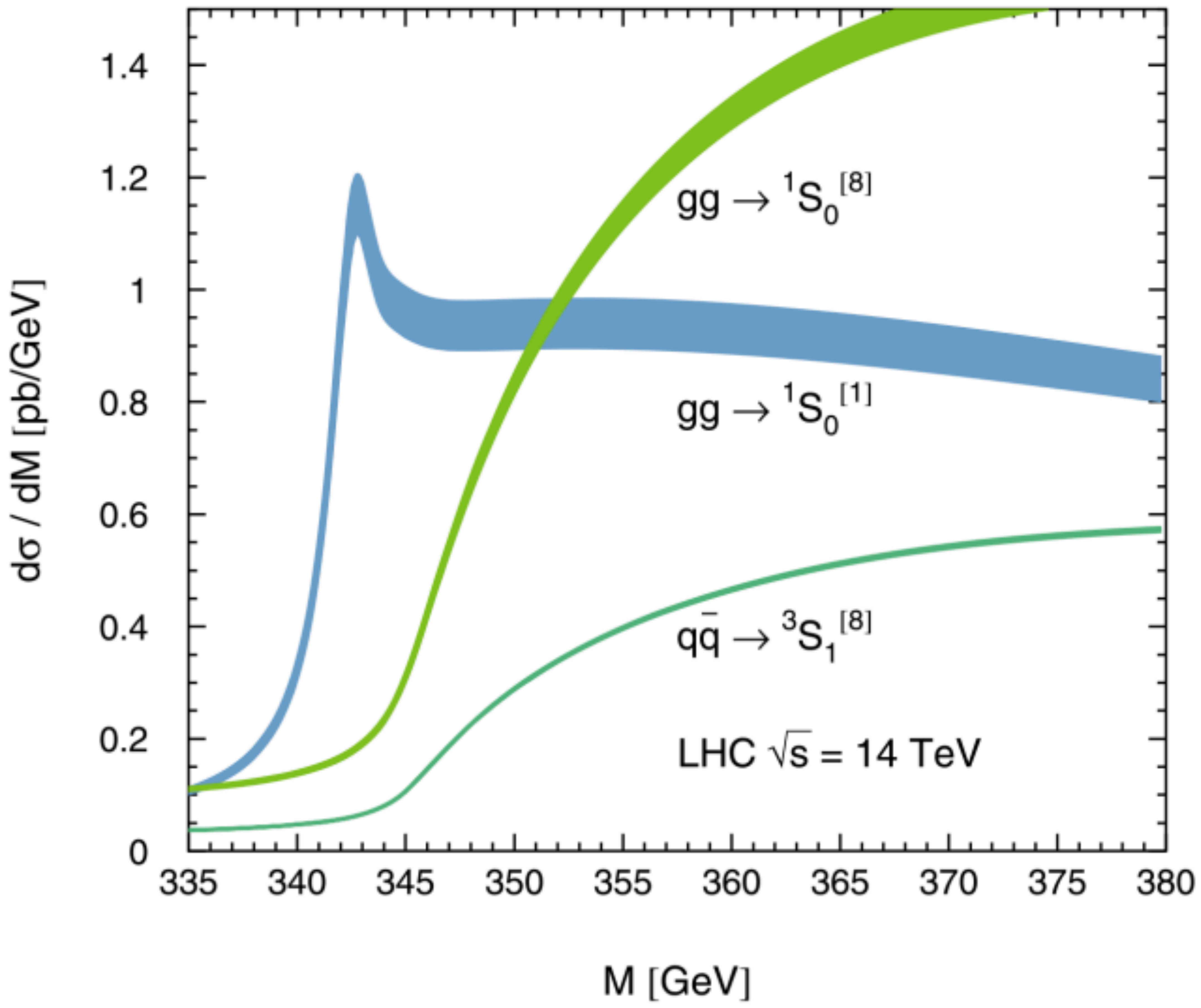
qq-initiated at high-E: $m_t^2 \ll \hat{s} \ll \Lambda^2$

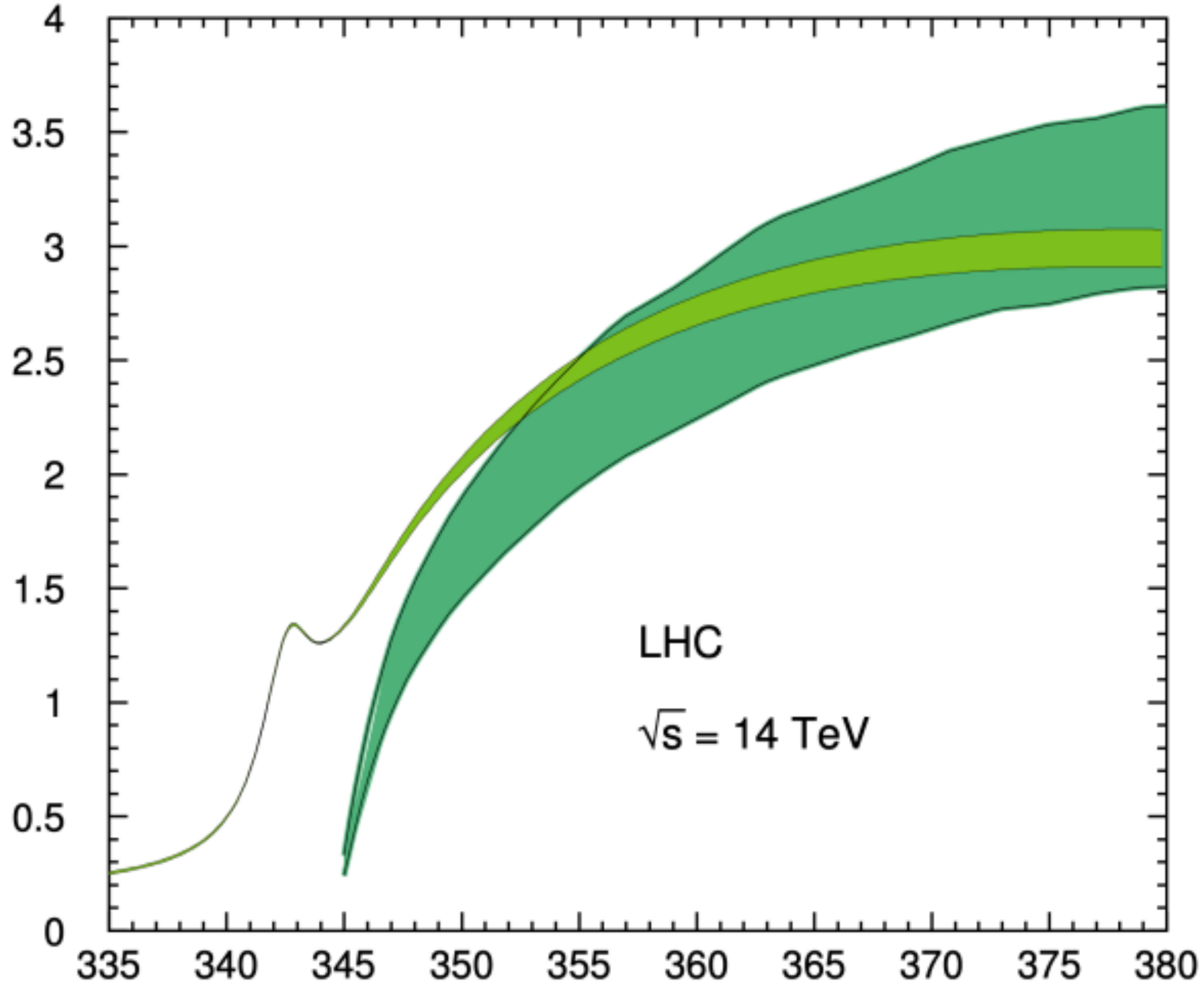
- sign dependent for linear and quadratics always decreases

everything gets more involved for pp

Threshold effects ("topponium")

[Kiyo, Kuhn, Moch, Steinhause, Uwer, 09']





Concurrence Bounds for qutrits

However, we can define lower and upper bounds $\mathcal{C}_{\rm LB} \leq \mathcal{C}(\rho) \leq \mathcal{C}_{\rm UB},$

Lower: $$(\mathcal{C}(\rho))^2 \geq 2\max\left(0, \mathrm{Tr}\left[\rho^2\right] - \mathrm{Tr}\left[\rho_A^2\right], \mathrm{Tr}\left[\rho^2\right] - \mathrm{Tr}\left[\rho_B^2\right]\right) \equiv \mathcal{C}_{\rm LB}^2\,,$$

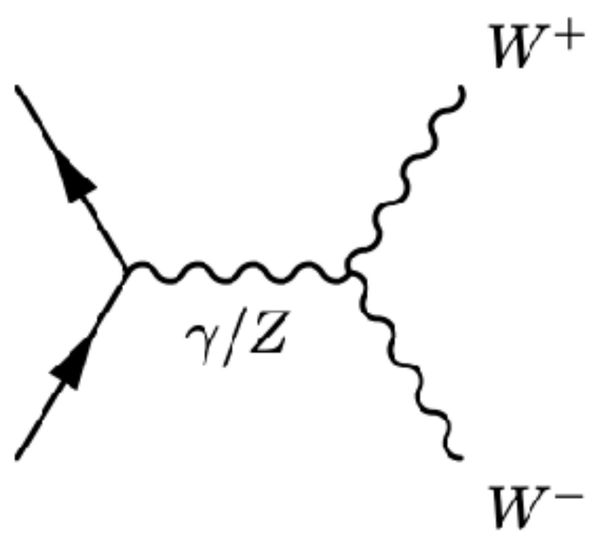
Upper: $$(\mathcal{C}(\rho))^2 \leq 2\min\left(1 - \mathrm{Tr}[\rho_A^2], 1 - \mathrm{Tr}[\rho_B^2]\right) \equiv \mathcal{C}_{\rm UB}^2\,,$$

For a pure state: $P(\rho) = \mathrm{tr}\rho^2 = 1$ $\longrightarrow$ $\mathcal{C}_{\rm LB}(\rho) = \mathcal{C}(\rho) = \mathcal{C}_{\rm UB}(\rho)$

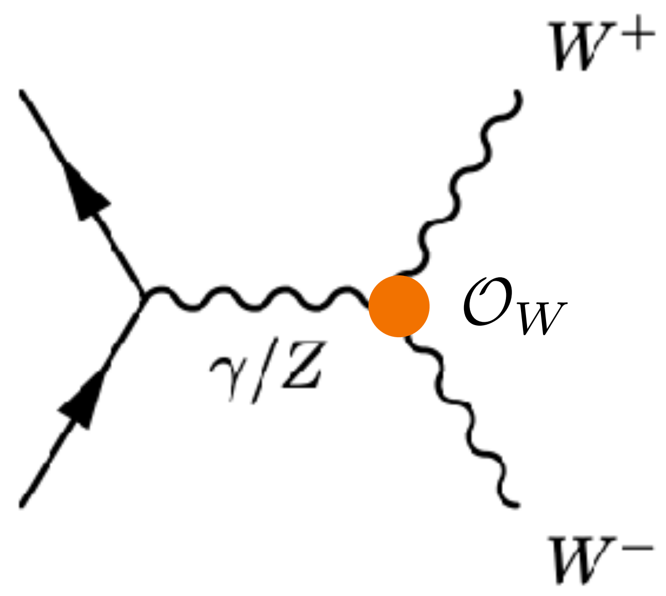
Perturbative Unitarity and Entanglement

The density matrix (and angular observables) are sensitive to new directions

$$e^+e^- \to W^+W^-$$



$(\lambda_1\lambda_2\|\alpha\,\beta)$	SM	EFT Λ^{-2} : c_{WWW}
$+-00$	$-2\sqrt{2}G_F m_Z^2 \sin\theta$	-
$+--+$	$2\sqrt{2}G_F m_W^2 \sin\theta$	-
$+-+-$	$-\frac{1}{\sqrt{2}}G_F m_W^2 \sin^3\theta \csc^4(\theta/2)$	-
$+-\pm\pm$	-	$3\cdot 2^{1/4}\sqrt{G_F}m_W \sin\theta\,(4m_W^2 x^2 - m_Z^2)$
$+-0\pm$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\pm 1+\cos\theta)\,x$
$+-\pm 0$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\mp 1+\cos\theta)\,x$
$-+00$	$2\sqrt{2}G_F(m_Z^2 - m_W^2)\sin\theta$	-
$-+\pm\pm$	-	$6\cdot 2^{1/4}\sqrt{G_F}m_W(m_Z^2 - m_W^2)\sin\theta$



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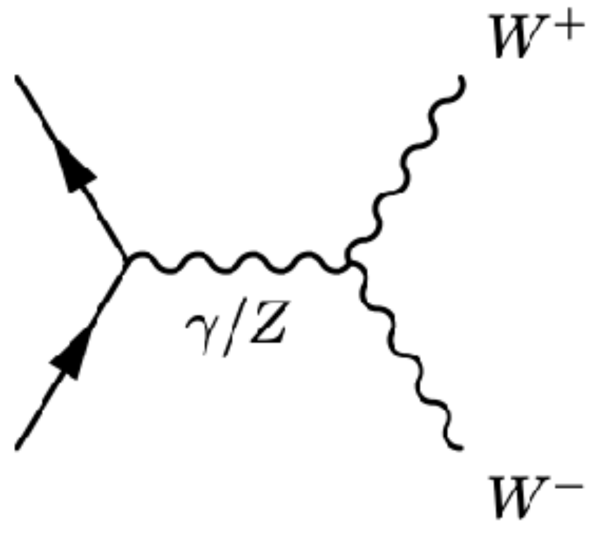
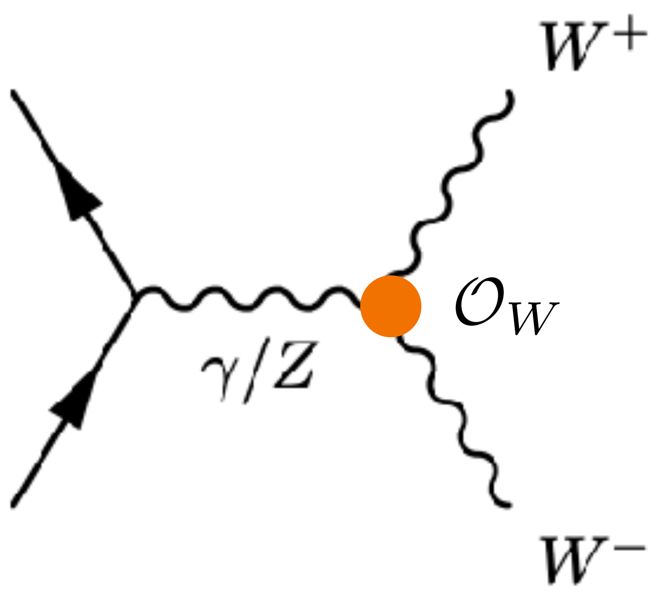


$(\lambda_1\lambda_2\|\alpha\,\beta)$	SM	EFT Λ^{-2} : c_{WWW}
$+-00$	$-2\sqrt{2}G_F m_Z^2 \sin\theta$	-
$+--+$	$2\sqrt{2}G_F m_W^2 \sin\theta$	-
$+-+-$	$-\frac{1}{\sqrt{2}}G_F m_W^2 \sin^3\theta \csc^4(\theta/2)$	-
$+-\pm\pm$	-	$3\cdot 2^{1/4}\sqrt{G_F}m_W \sin\theta\,(4m_W^2x^2 - m_Z^2)$
$+-0\pm$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\pm 1 + \cos\theta)\,x$
$+-\pm 0$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\mp 1 + \cos\theta)\,x$
$-+00$	$2\sqrt{2}G_F(m_Z^2 - m_W^2)\sin\theta$	-
$-+\pm\pm$	-	$6\cdot 2^{1/4}\sqrt{G_F}m_W(m_Z^2 - m_W^2)\sin\theta$



No interference! → Cross-section $\tilde{A}(\mathcal{O}_W) \sim 0$

Perturbative Unitarity and Entanglement

$(\lambda_1\lambda_2\|\alpha\,\beta)$	SM	EFT Λ^{-2} : c_{WWW}
$+-00$	$-2\sqrt{2}G_F m_Z^2 \sin\theta$	-
$+--+$	$2\sqrt{2}G_F m_W^2 \sin\theta$	-
$+-+-$	$-\frac{1}{\sqrt{2}}G_F m_W^2 \sin^3\theta \csc^4(\theta/2)$	-
$+-\pm\pm$	-	$3\cdot 2^{1/4}\sqrt{G_F}m_W \sin\theta\,(4m_W^2 x^2 - m_Z^2)$
$+-0\pm$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\pm 1+\cos\theta)\,x$
$+-\pm 0$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\mp 1+\cos\theta)\,x$
$-+00$	$2\sqrt{2}G_F(m_Z^2 - m_W^2)\sin\theta$	-
$-+\pm\pm$	-	$6\cdot 2^{1/4}\sqrt{G_F}m_W(m_Z^2 - m_W^2)\sin\theta$

$$\rho = \begin{bmatrix} \mathcal{M}_{++}\mathcal{M}^*_{++} & \mathcal{M}_{++}\mathcal{M}^*_{+-} & \cdots \\ \mathcal{M}_{+-}\mathcal{M}^*_{++} & \mathcal{M}_{+-}\mathcal{M}^*_{+-} & \cdots \\ \vdots & & \ddots \end{bmatrix}$$

The spin-density matrix has different helicity products

$$\tilde{a}_1(\mathcal{O}_W) \simeq \tilde{b}_1(\mathcal{O}_W) \simeq \bar{c}_W\, 2^{5/4}\, x\, \cos^4(\theta/2)(\cos\theta + 3)\csc\theta\,,$$

Entanglement is sensitive to off-diagonal contractions

$$\tilde{c}_{13} \simeq 3\,\bar{c}_W \cdot 2^{3/4}\cos^2(\theta/2)(3\cos\theta + 1)\cot(\theta/2)\,x$$

Recovers the energy growth!