Quantum SMEFT tomography: top pair production at the LHC

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In collaboration with:
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UNIVERSITY OF CAMBRIDGE

PBSP

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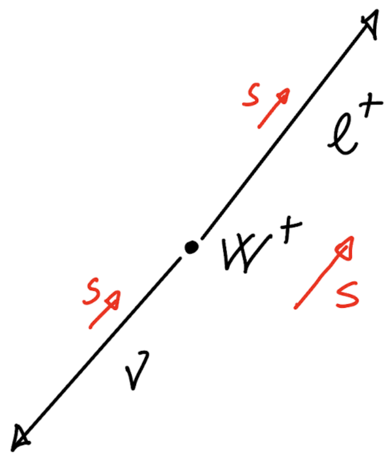

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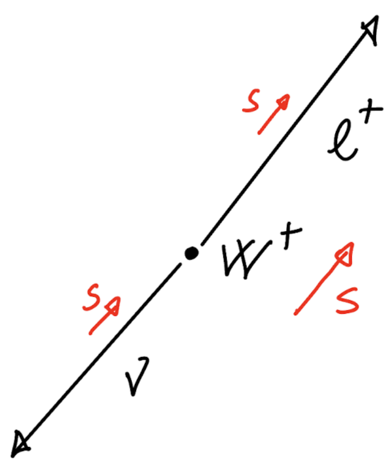

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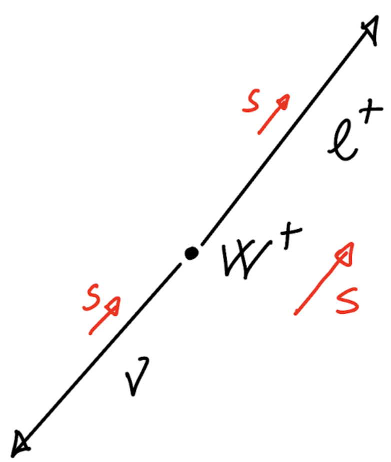

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Z boson more complicated but doable:
spin can be reco if right/left asymmetry

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In the case of a statistical ensemble (mixed state)

$$\rho = \sum_k p_k \rho_k$$

entangled if $\rho_k \neq \rho_1 \otimes \rho_2$

The fundamental object to study quantum observables is the spin density matrix

One particle of spin s:

d=2s+1

$$\rho = \frac{1}{d}\mathbb{I} + \sum_{i=1}^{d^2-1} a_i \lambda_i$$

Generalised Gell-Mann matrix

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The parameters completely characterise the quantum spin state of the system

We define the R-matrix

Sum over initial state only

$$R^I_{\alpha_1\alpha_2,\beta_1\beta_2} \equiv \frac{1}{N_a N_b} \sum_{\substack{\text{colors}\\ \text{a,b spins}}} \mathcal{M}^*_{\alpha_2\beta_2}\, \mathcal{M}_{\alpha_1\beta_1}$$

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$$\rho = \frac{R}{tr(R)}$$

The R matrix can be decomposed in the spin space

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

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Cross section

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

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If normalised, we define the density matrix of the system

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Bell inequality

$$\langle \mathcal{B} \rangle_{\max} = \max_{U,V} \left(\mathrm{Tr} \left(\rho \left(U^\dagger \otimes V^\dagger \right) \mathcal{B} \left(U \otimes V \right) \right) \right) \geq 2$$

Top pairs ideal probe: spin correlations preserved after decay

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At LO in QCD

$$I = gg, q\bar{q}$$

[arXiv: 2203.05619]

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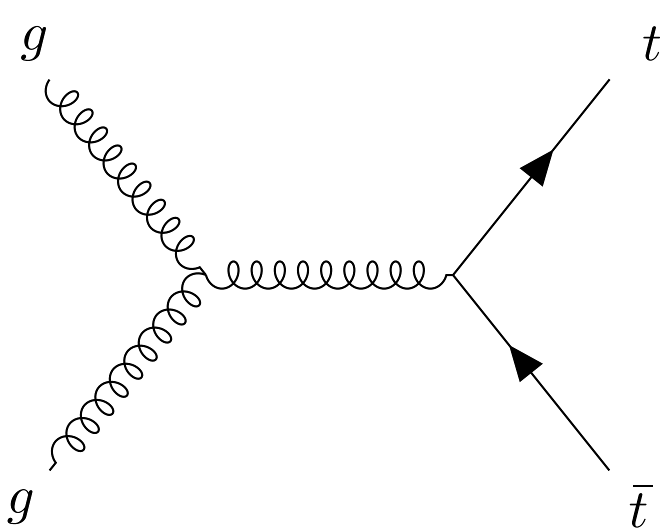
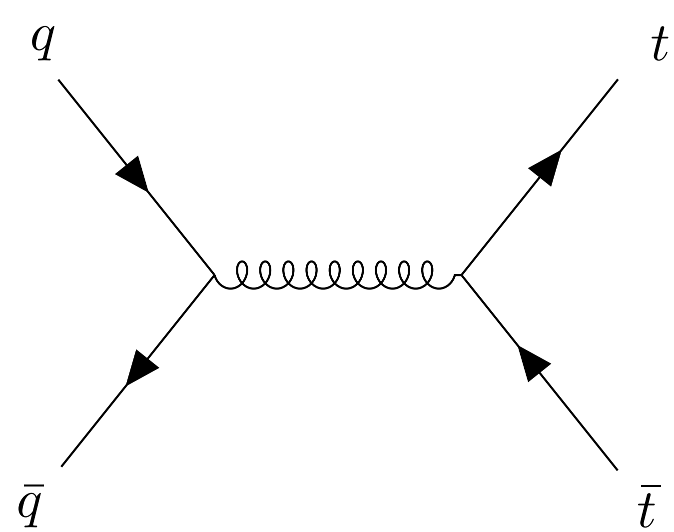
We collide protons





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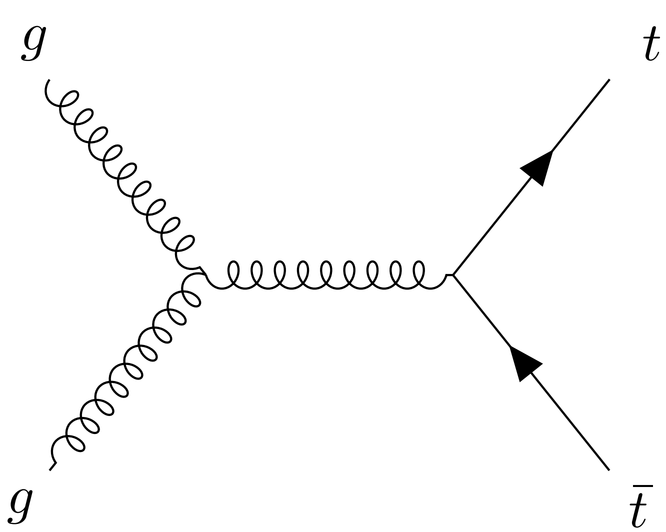

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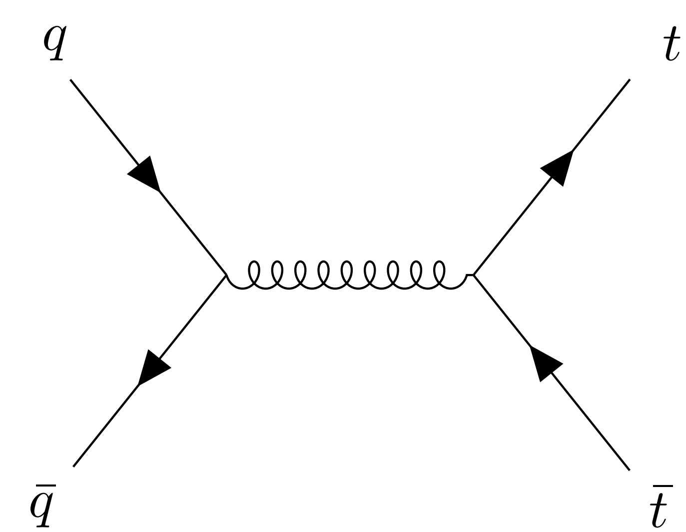
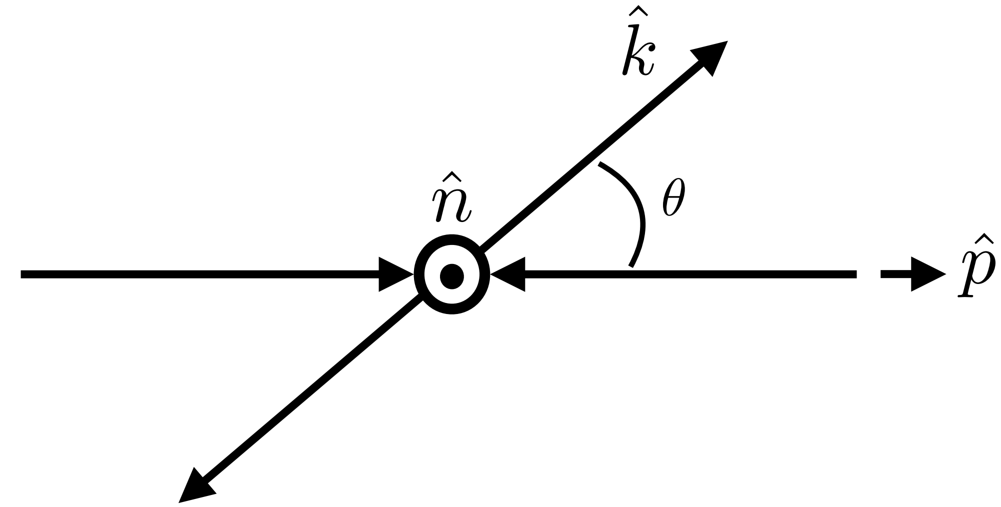
$$R(\hat{s},\boldsymbol{k}) = \sum_{I} L^{I}(\hat{s}) R^{I}(\hat{s},\boldsymbol{k})$$



Full correlation matrix is mixed state, weighted by parton luminosity

Definitions

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



To expand in this basis, e.g.

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

$$\beta^2 = (1 - 4m_t^2/\hat{s})$$

$$\cos\theta$$

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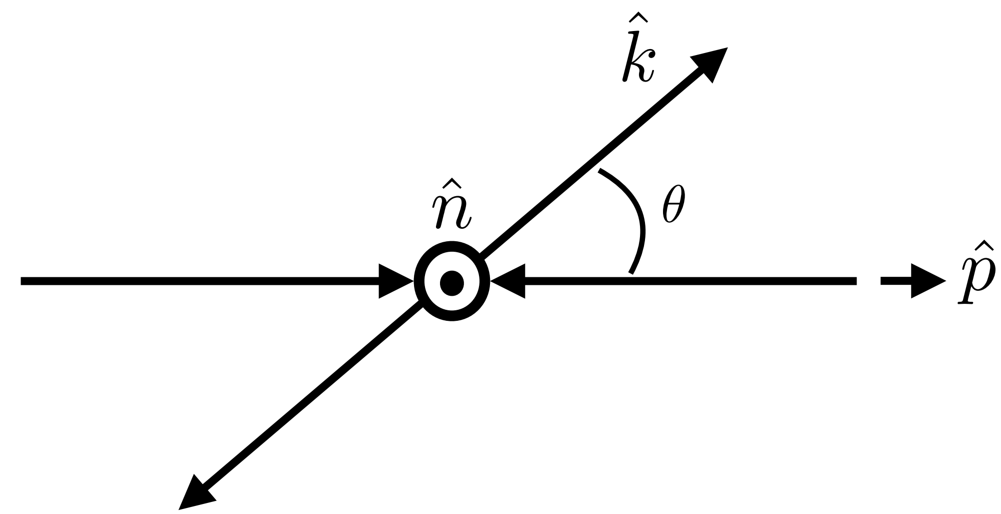

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$$\Delta = -C_{nn} + |C_{kk} + C_{rr}| - 1 > 0$$ **entangled**

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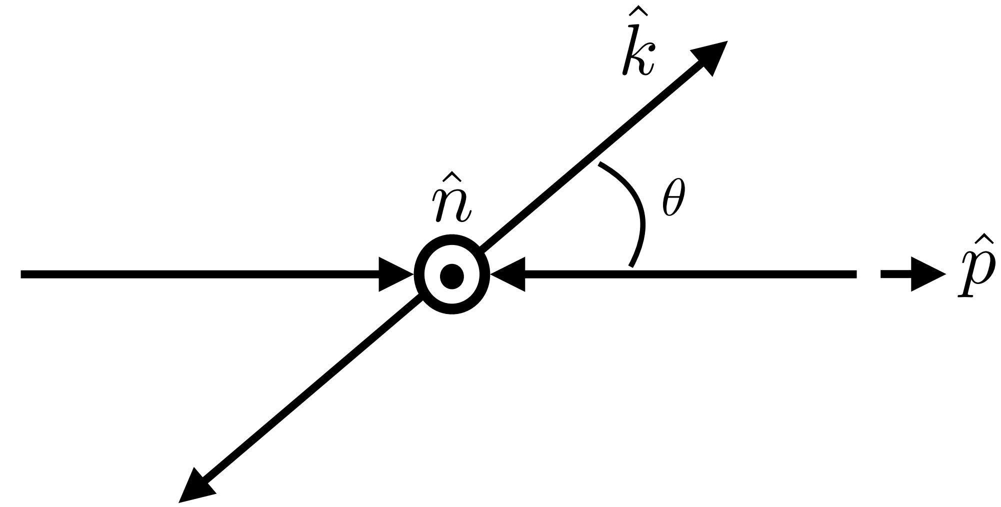

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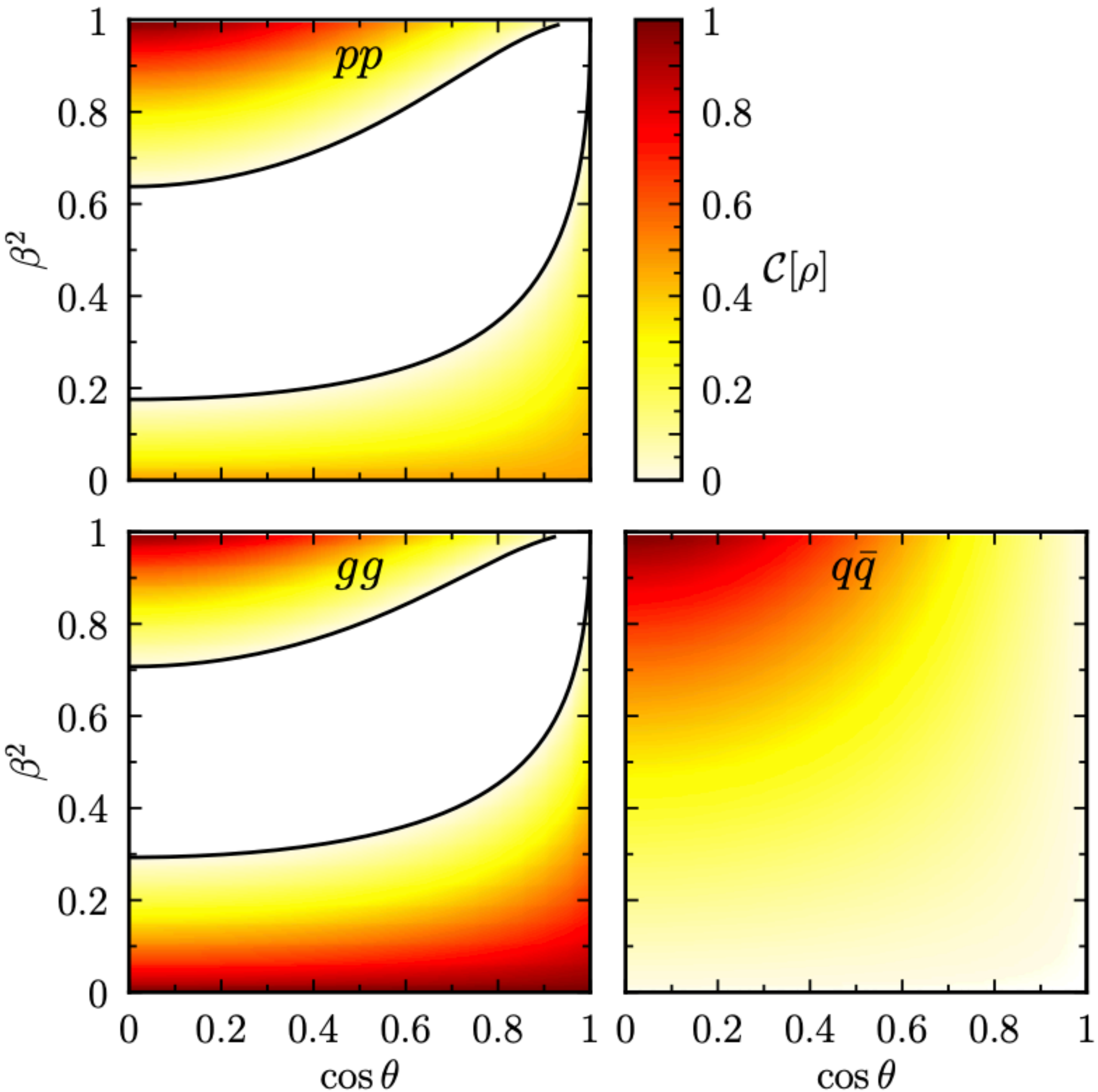
We can then define the concurrence

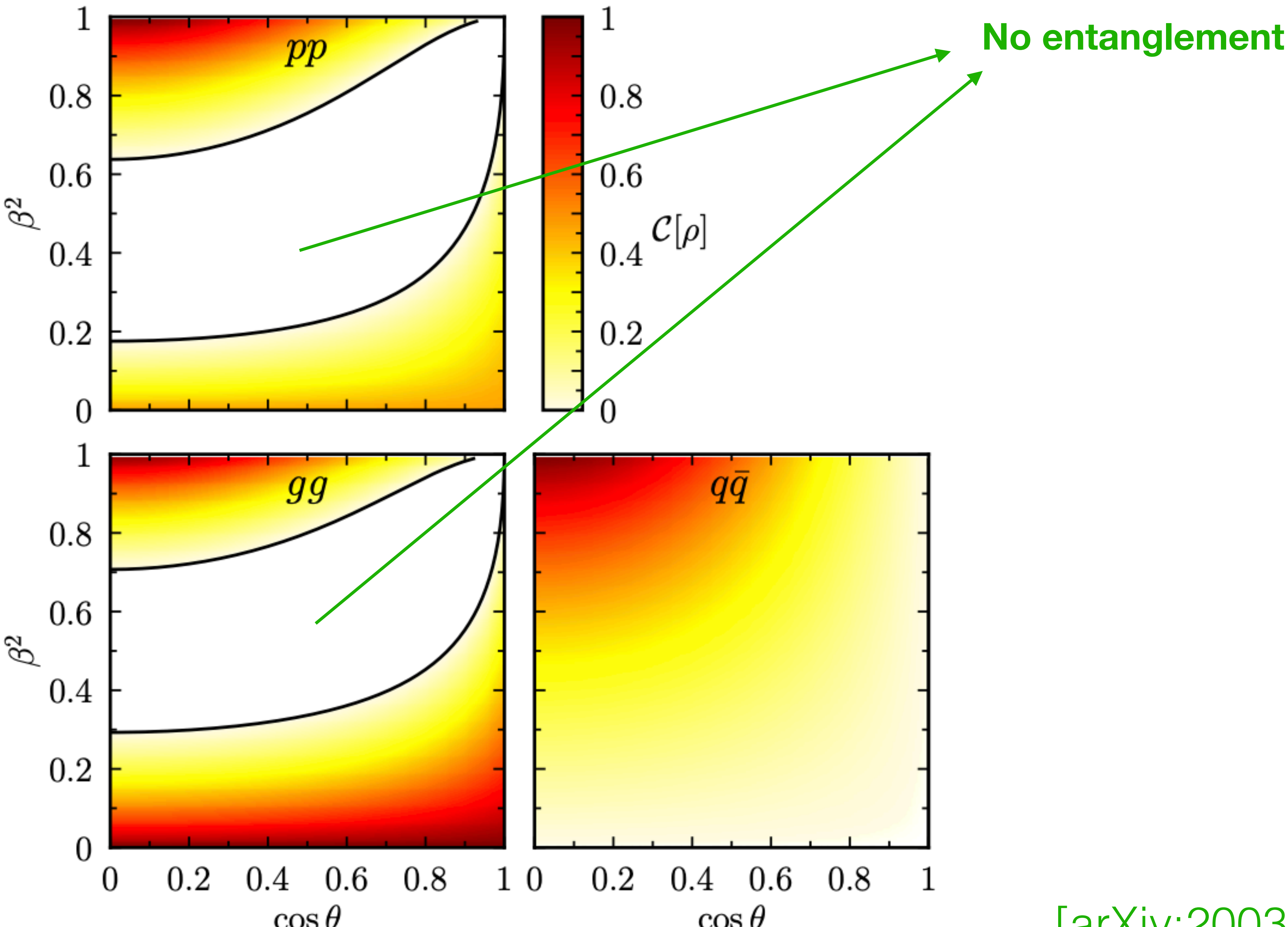
$$C[\rho] = \max(\Delta/2, 0)$$

$$C[\rho] = 1$$

Max entanglement



[arXiv:2003.02280]



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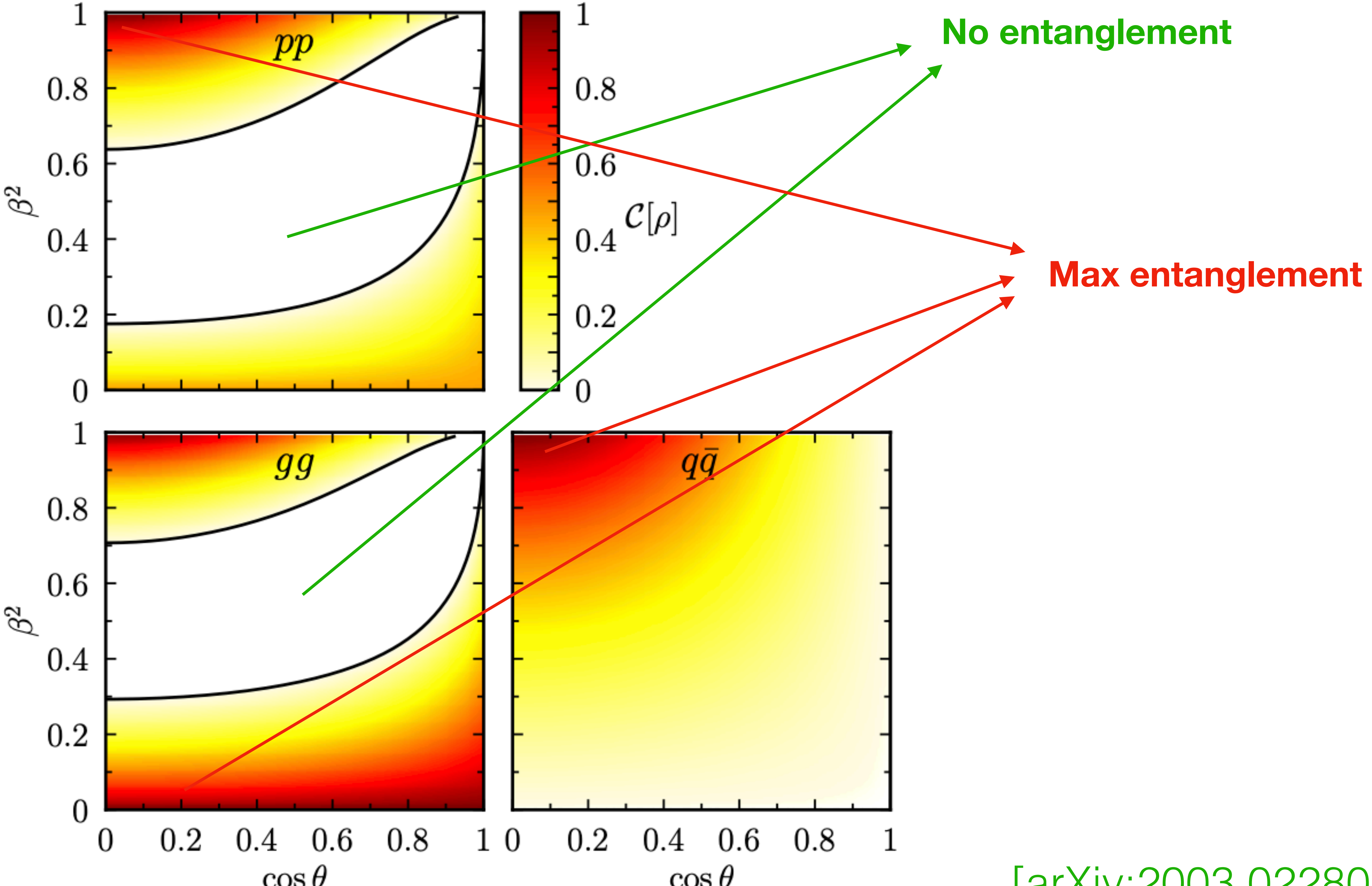

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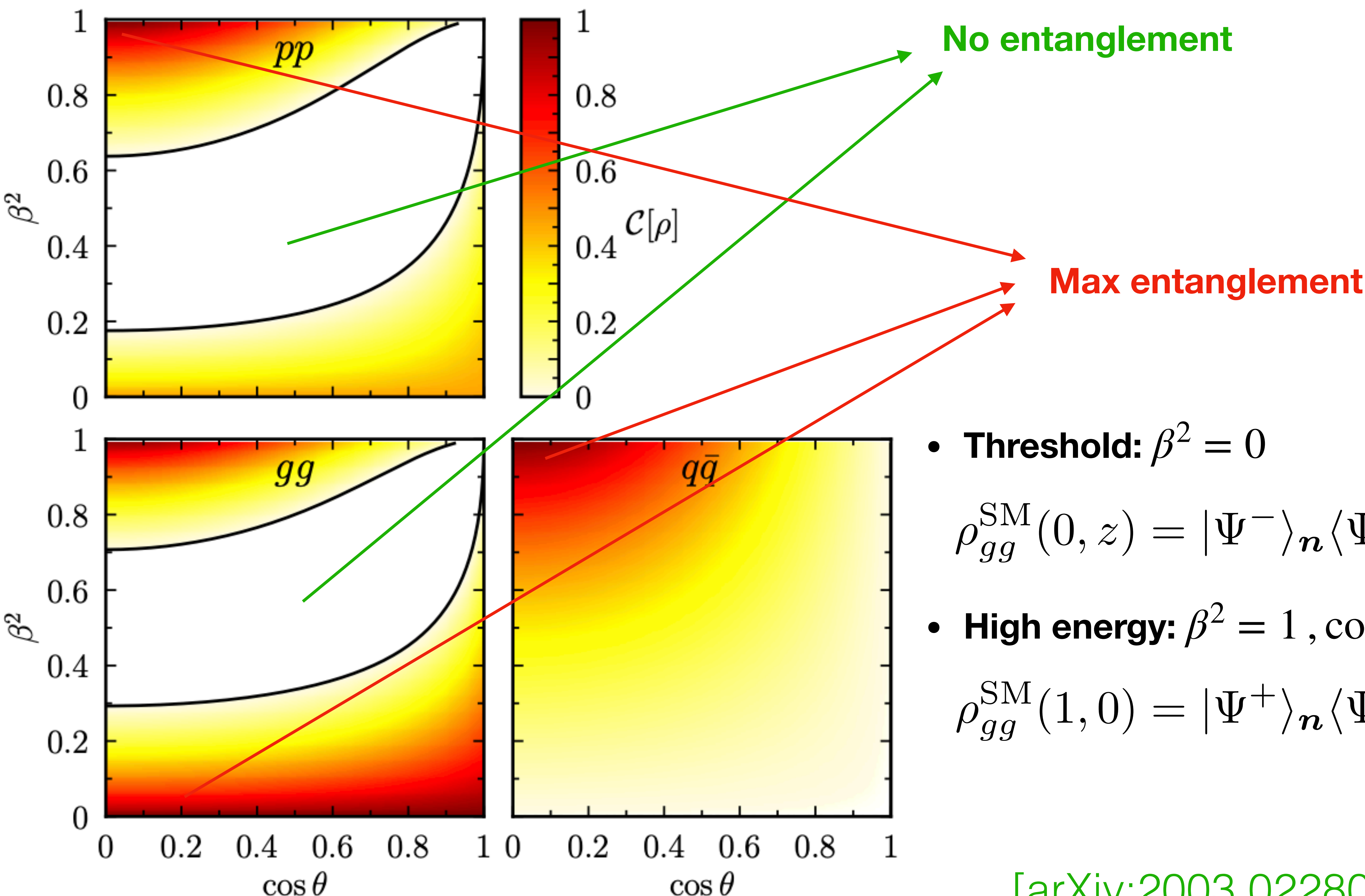

- **Threshold:** $\beta^2 = 0$

$$\rho_{gg}^{\mathrm{SM}}(0, z) = |\Psi^-\rangle_{\boldsymbol{n}}\langle\Psi^-|_{\boldsymbol{n}}$$

- **High energy:** $\beta^2 = 1\,, \cos\theta = 0$

$$\rho_{gg}^{\mathrm{SM}}(1, 0) = |\Psi^+\rangle_{\boldsymbol{n}}\langle\Psi^+|_{\boldsymbol{n}}$$

[arXiv:2003.02280]

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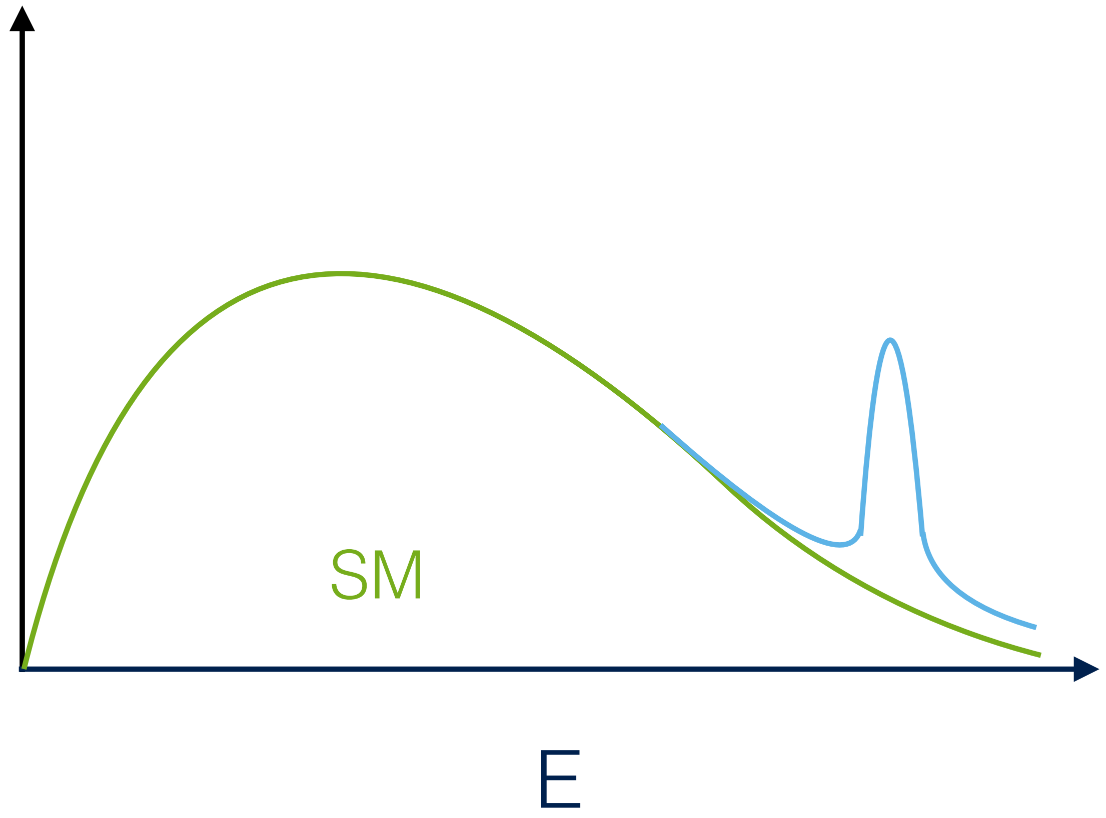

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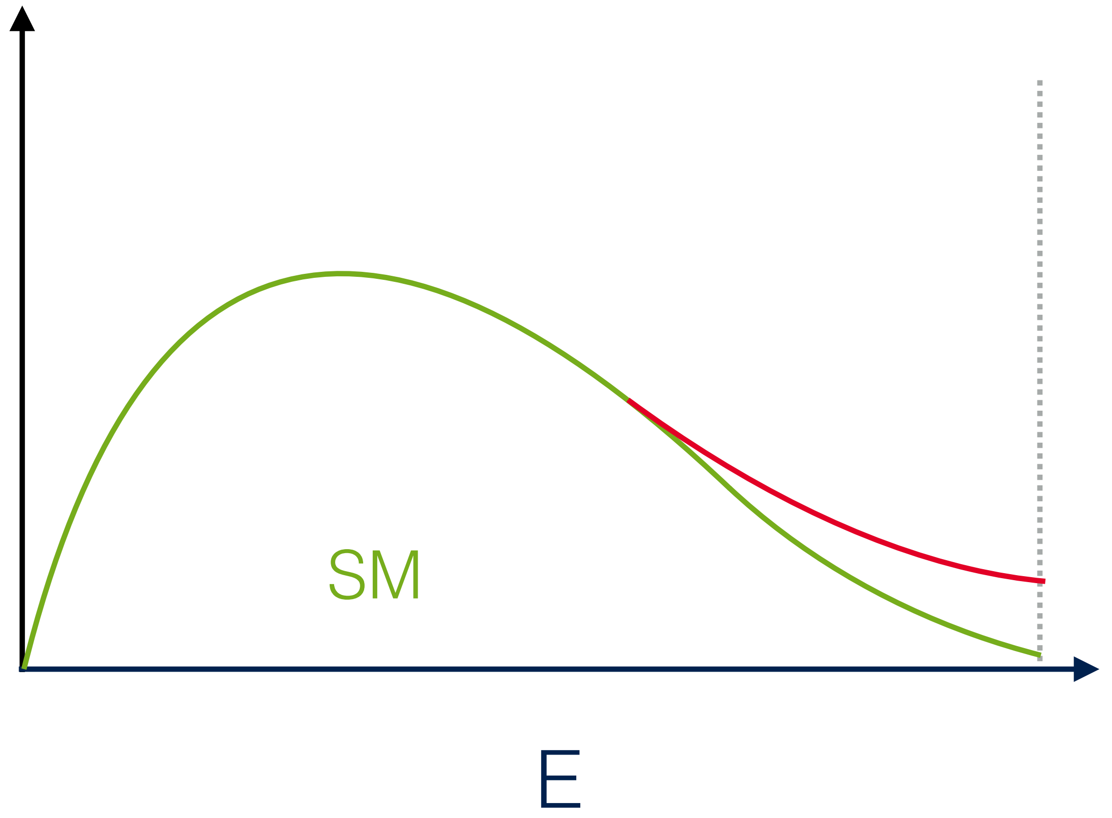
Indirect (scouting tails)



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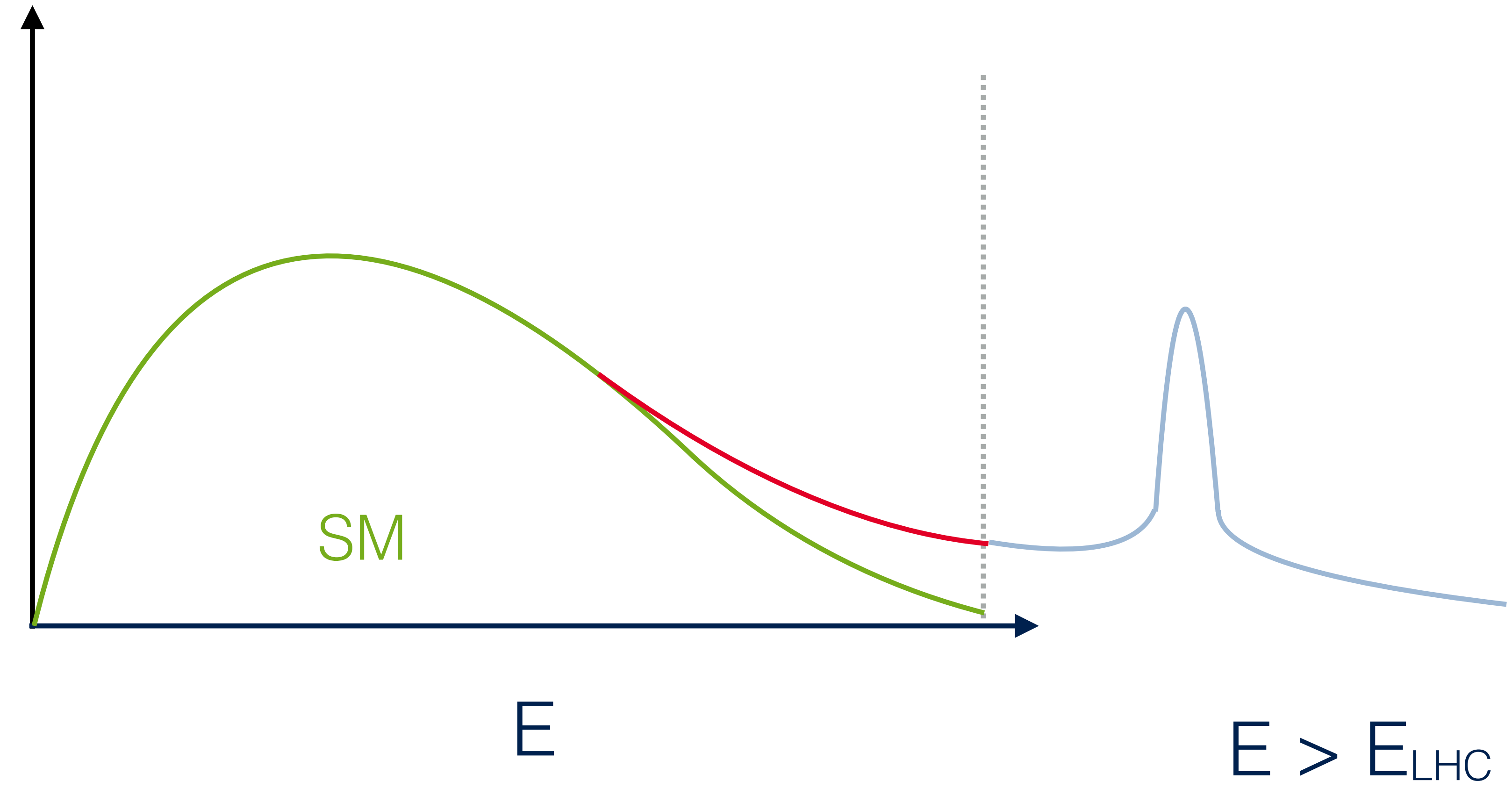
⇒ New physics is heavy



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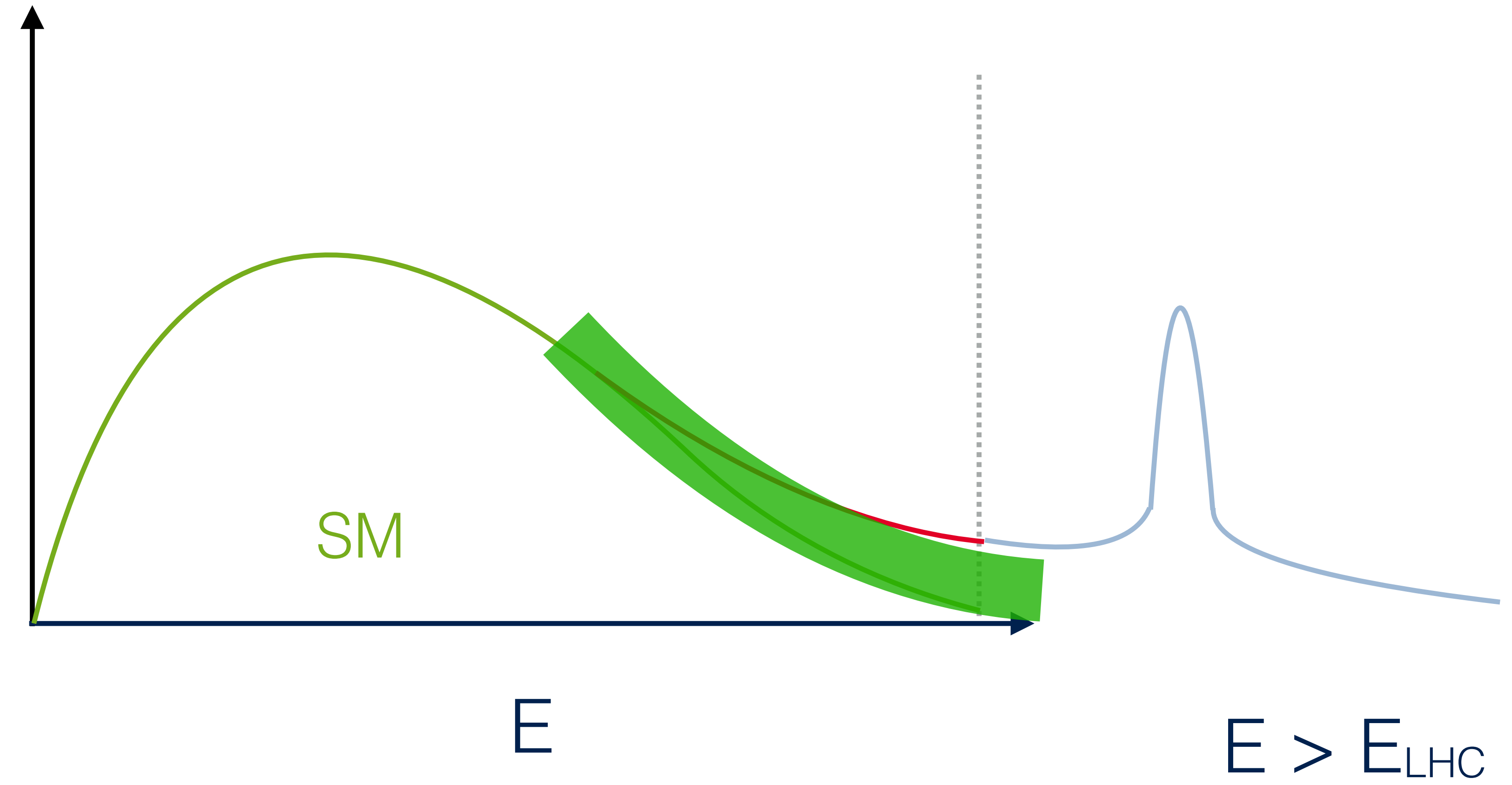

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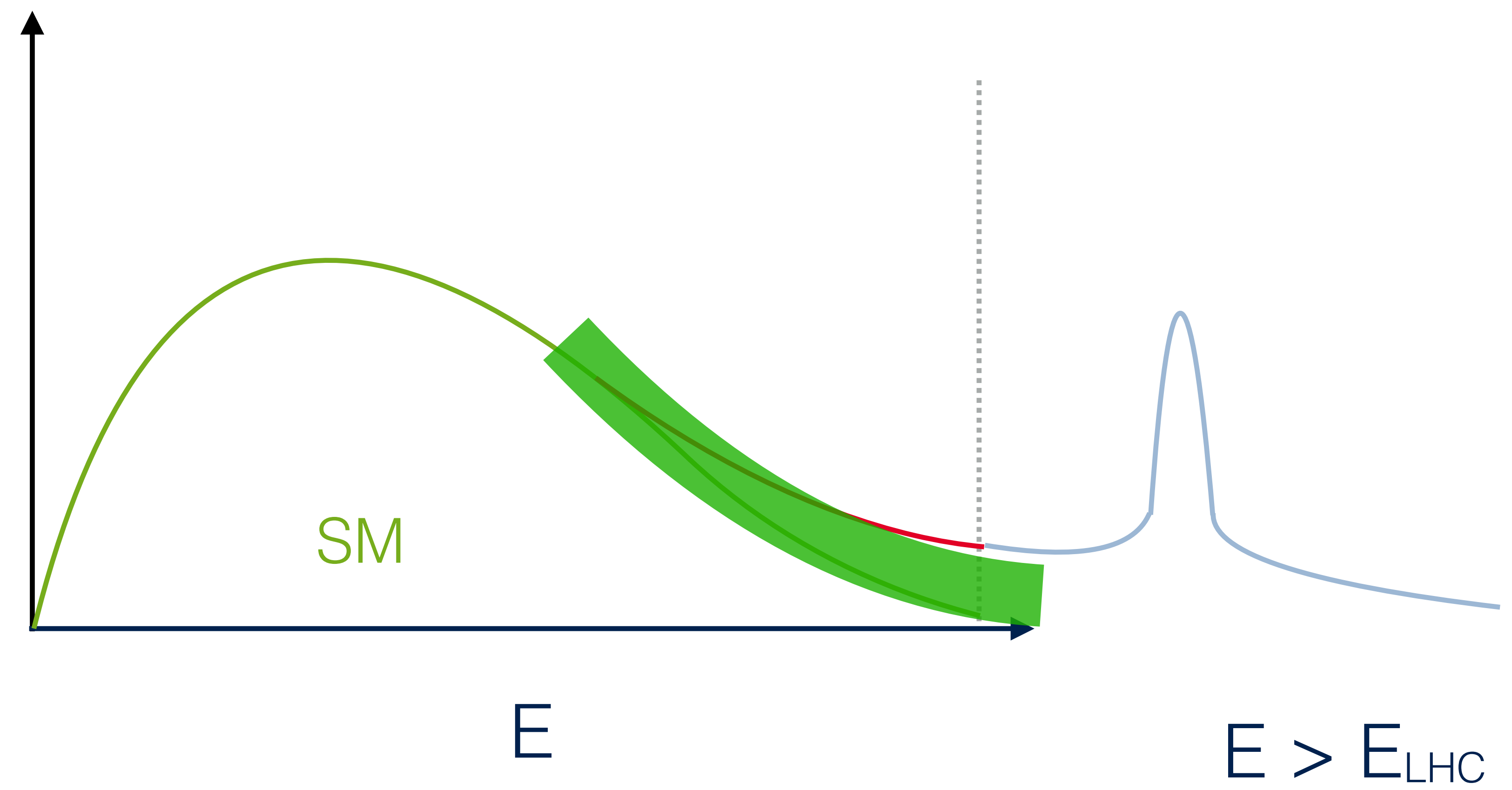

Framework to describe both precision physics and Heavy New Physics.

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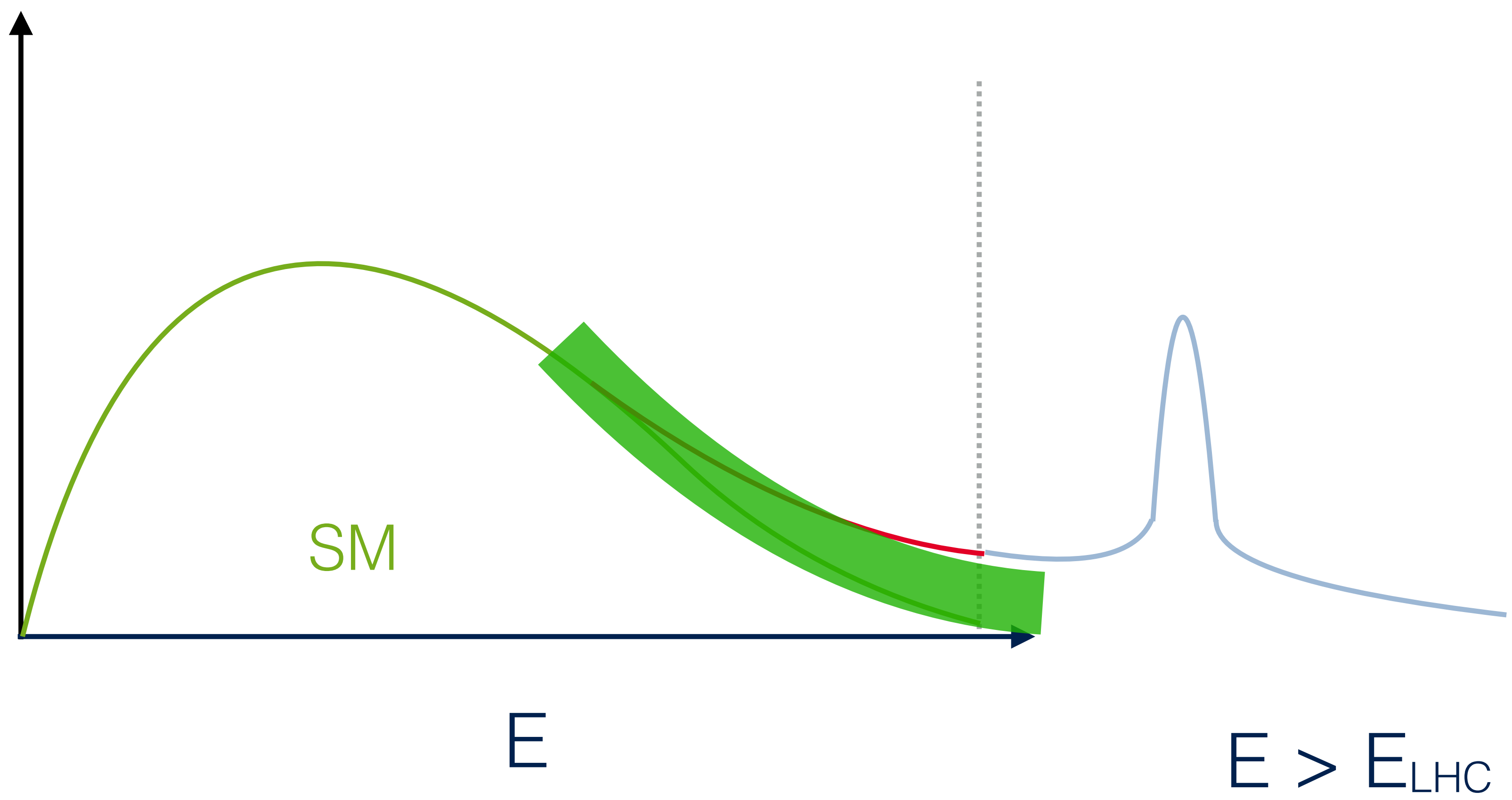

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Standard Model Effective Field Theory (SMEFT)

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New particles being exchanged in collisions

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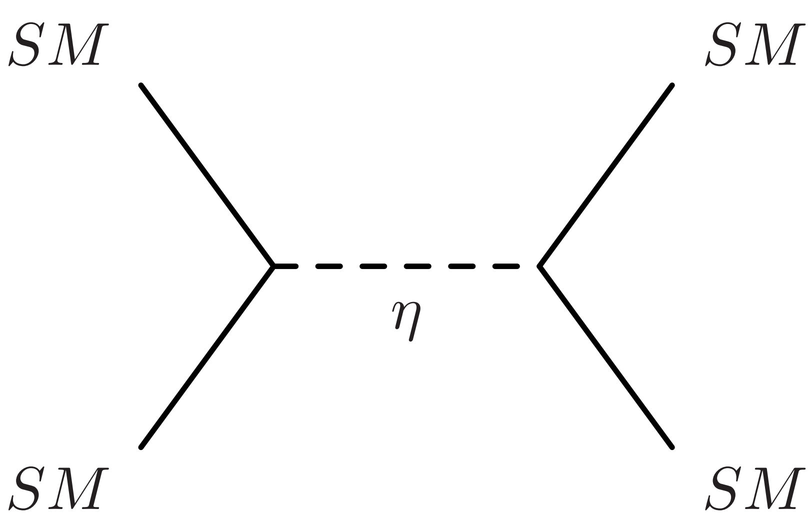
$$\frac{g^2}{p^2 - M^2}$$



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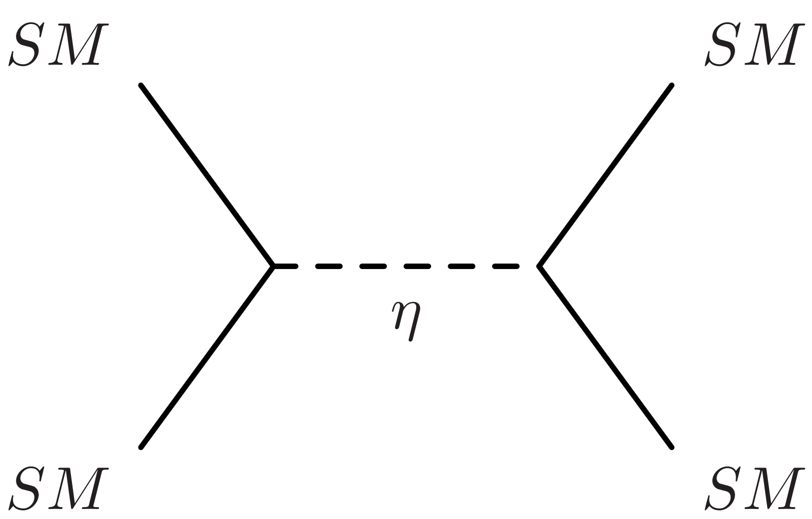

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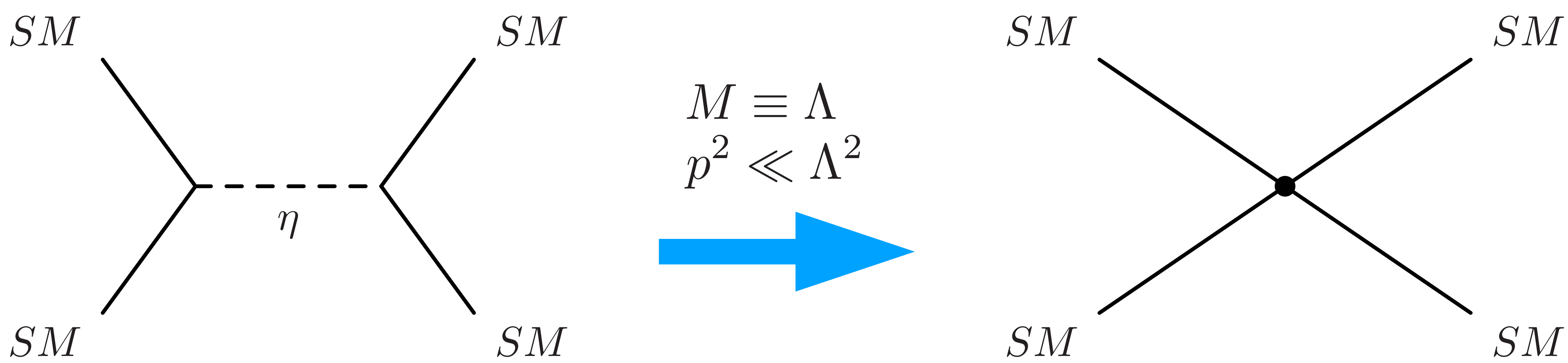

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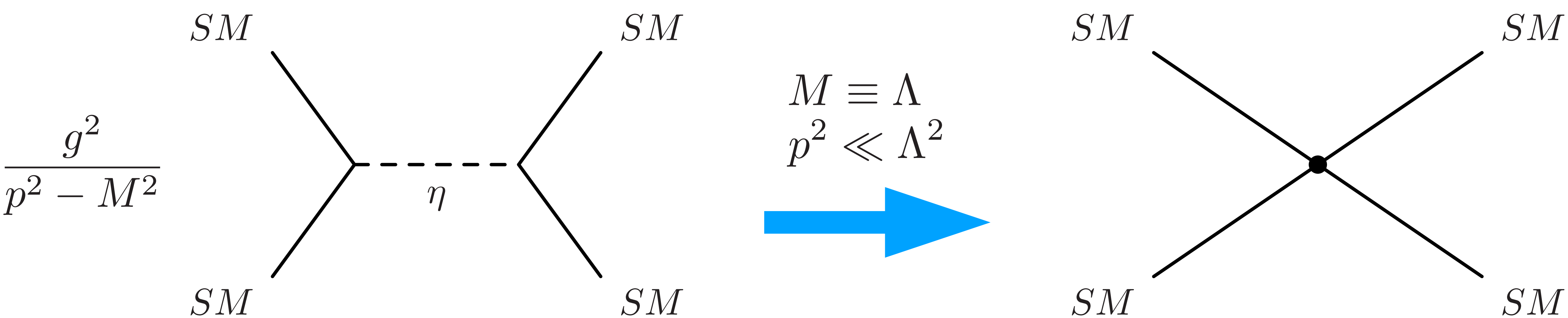

Interaction can be described without explicit presence of new states!

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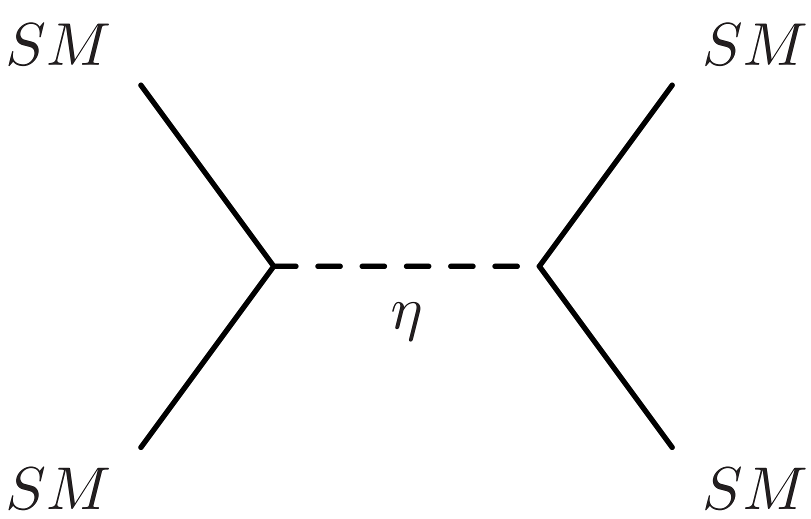

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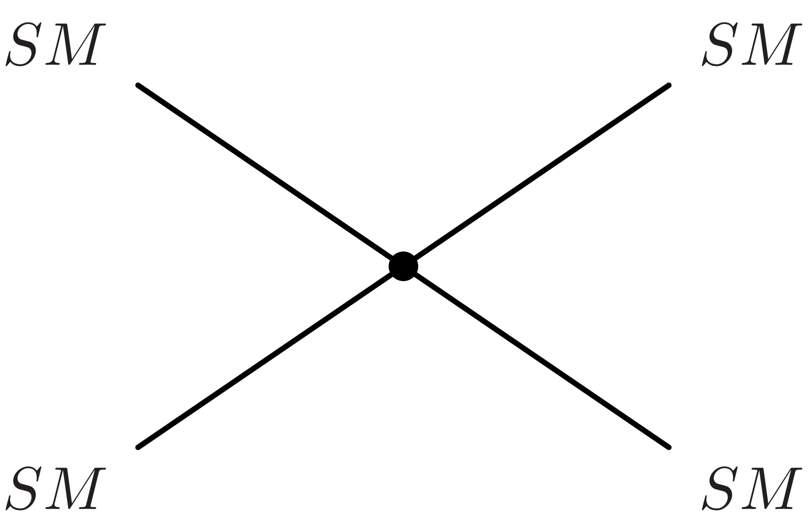

Interaction can be described without explicit presence of new states!

New framework → **Effective Field Theory**

59 operators flavour universal

2499 operators flavour general

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}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
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$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
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$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \ldots$$

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- **Higher dimensional operators preserve SM symmetries.**
- **Mappable to a large class of BSM models.**
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EFT to-do list

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- **Make accurate measurements**

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Quantum fluctuation

Typically fits of physics parameters and PDFs do not talk

$$\sigma(C,\theta) = f_1(C,\theta) \otimes f_2(C,\theta) \otimes \hat{\sigma}(C)$$

arXiv: 2307.10370
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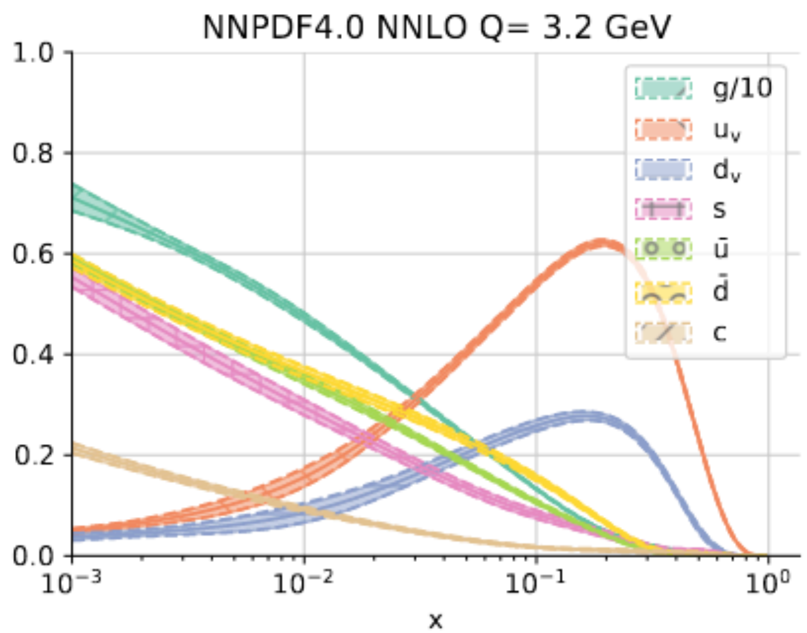
We extract the PDFs from data,
we have implicit dependence $\theta^* = \theta^*(\bar{C})$



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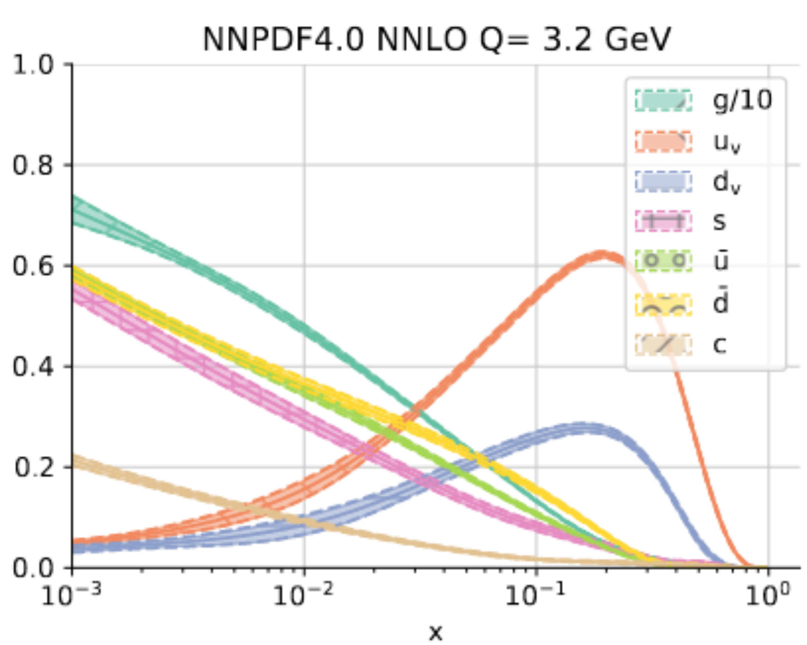

Physics parameters

- Fix PDFs parameters $\bar{C}, \bar{\theta}$

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We extract the physics parameters from data,
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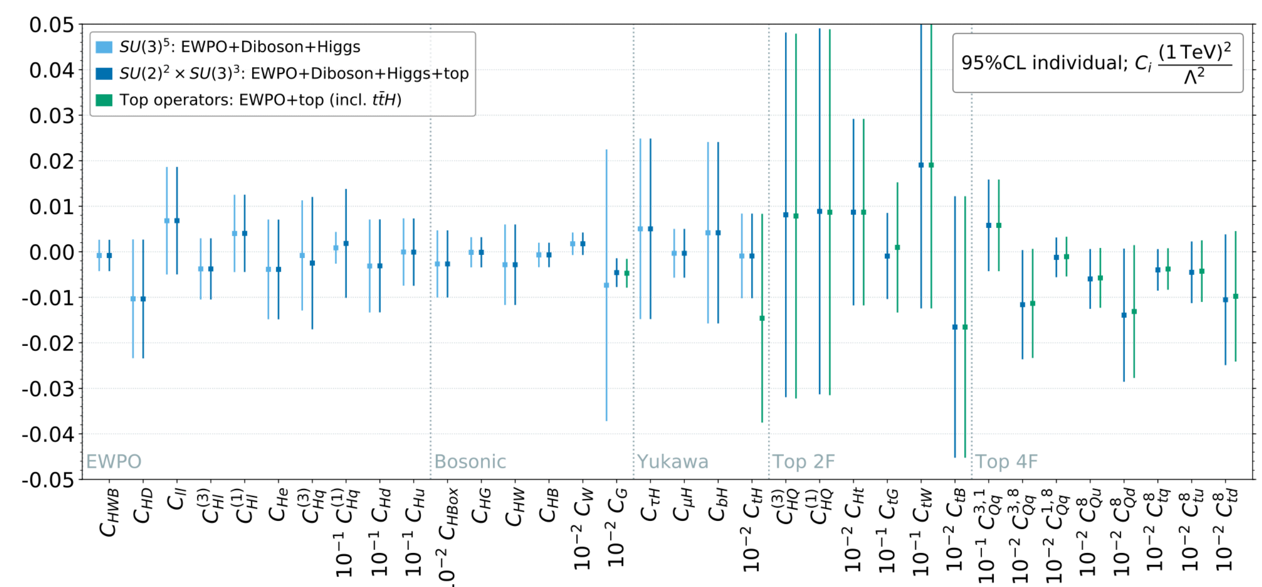

FitMaker [2012:02779]

$$R^I_{\alpha_1\alpha_2,\beta_1\beta_2} \equiv \frac{1}{N_a N_b} \sum_{\substack{\text{colors} \\ \text{a,b spins}}} \mathcal{M}^*_{\alpha_2\beta_2} \mathcal{M}_{\alpha_1\beta_1}$$

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At $\mathcal{O}(1/\Lambda^2)$

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

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The density matrix opens the window to new sensitivities

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

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$+-00$	$-2\sqrt{2}G_F m_Z^2 \sin\theta$	-
$+--+$	$2\sqrt{2}G_F m_W^2 \sin\theta$	-
$+-+-$	$-\frac{1}{\sqrt{2}}G_F m_W^2 \sin^3\theta \csc^4(\theta/2)$	-
$+-\pm\pm$	-	$3\cdot 2^{1/4}\sqrt{G_F}m_W \sin\theta\,(4m_W^2x^2 - m_Z^2)$
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Cross section

$$\tilde{A}(\mathcal{O}_W) \sim 0$$

 Luca Mantani

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

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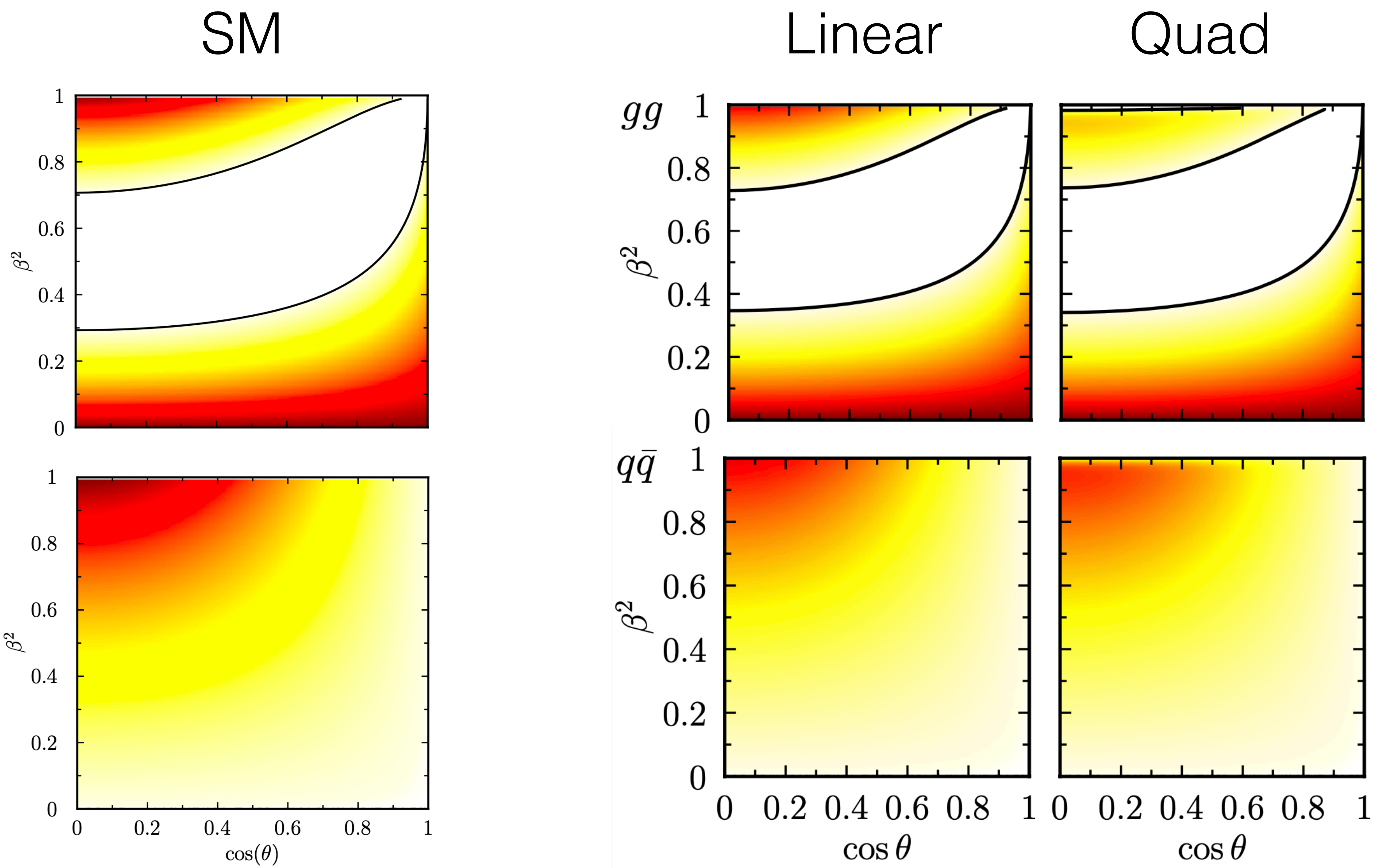
$$\tilde{a}_1(\mathcal{O}_W) \simeq \tilde{b}_1(\mathcal{O}_W) \simeq \bar{c}_W\, 2^{5/4}\, x\, \cos^4(\theta/2)(\cos\theta + 3)\csc\theta\,,$$

Resurrected sensitivity: energy growth!

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



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

$\Delta_1 \equiv \Delta - \Delta_0$ Δ computed up to $\mathcal{O}(1/\Lambda^2)$

$\Delta_2 \equiv \Delta - \Delta_1 - \Delta_0$ Δ computed up to $\mathcal{O}(1/\Lambda^4)$

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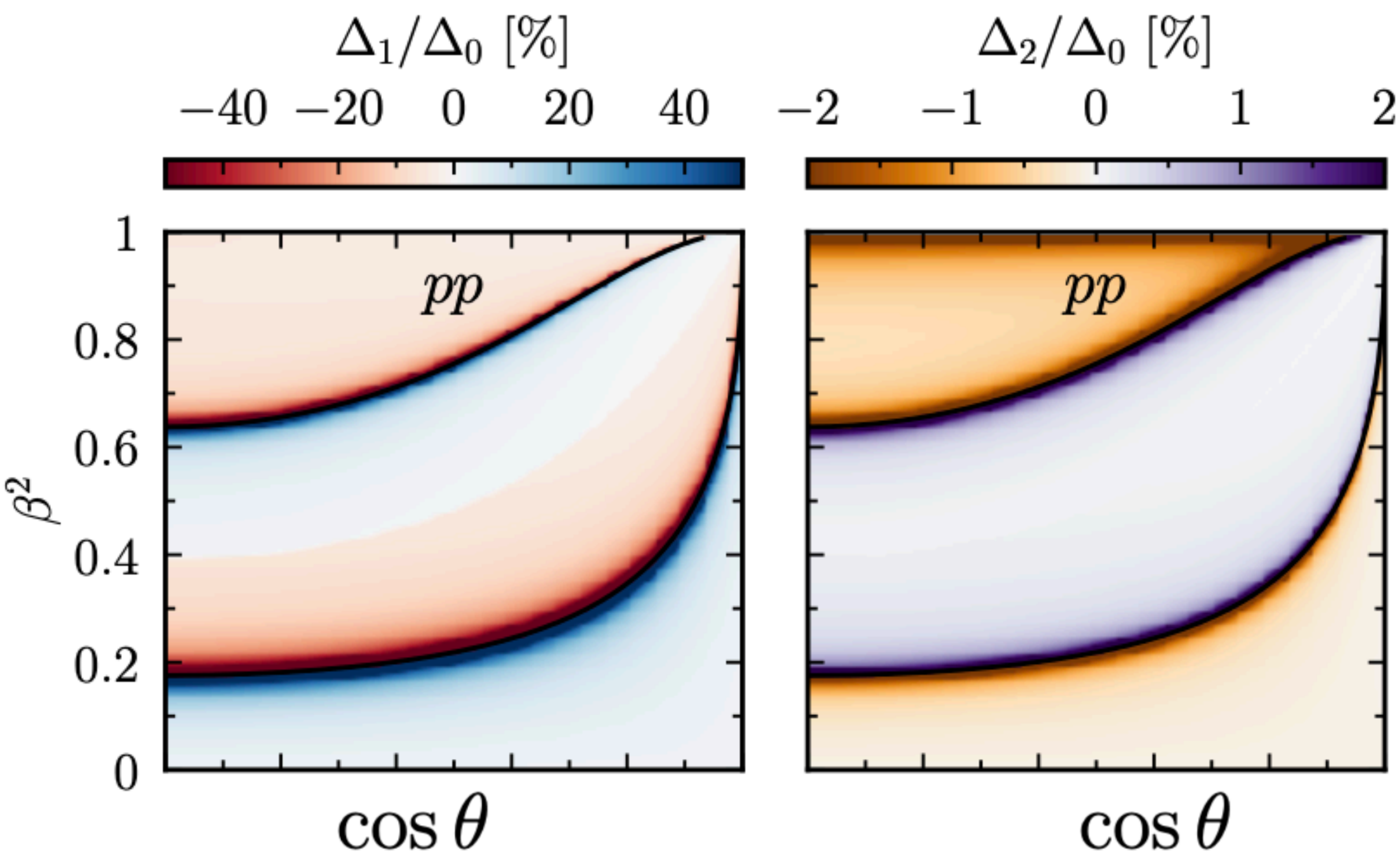

$c_{tG}/\Lambda^2 = 0.1\,\mathrm{TeV}^{-2}$

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

→

$$\delta \equiv -C_z + |2C_\perp| - 1 > 0$$

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

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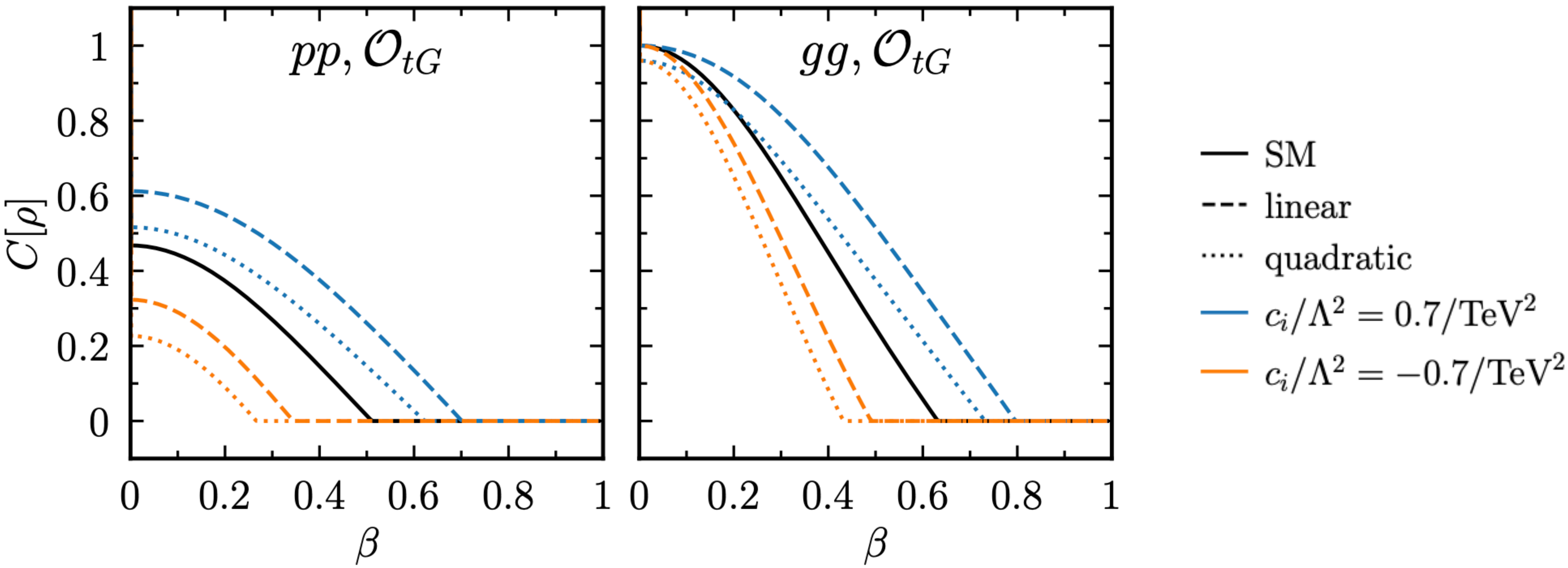

gg-induced

$$\rho_{gg}^{\mathrm{EFT}}(0,z) = p_{gg}|\Psi^+\rangle_{\boldsymbol{p}}\langle\Psi^+|_{\boldsymbol{p}} + (1-p_{gg})|\Psi^-\rangle_{\boldsymbol{p}}\langle\Psi^-|_{\boldsymbol{p}}$$

$$p_{gg} = \frac{72}{7\Lambda^4} m_t^2 (3\sqrt{2} m_t\, c_G + v\, c_{tG})^2$$

Only quadratic effects!

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qq-induced

$$\rho_{q\bar{q}}^{\mathrm{EFT}}(0,z) = p_{q\bar{q}}\,|\uparrow\uparrow\rangle_{\boldsymbol{p}}\,\langle\uparrow\uparrow|_{\boldsymbol{p}} + (1-p_{q\bar{q}})\,|\downarrow\downarrow\rangle_{\boldsymbol{p}}\,\langle\downarrow\downarrow|_{\boldsymbol{p}}$$

$$p_{q\bar{q}} = \frac{1}{2} - 4\frac{c_{VA}^{(8),u}}{\Lambda^2} + \frac{8m_t^4}{\Lambda^4}\left(\frac{v\sqrt{2}}{m_t} c_{VA}^{(8),u} c_{tG} - 9c_{VA}^{(1),u} c_{VV}^{(1),u} + 2c_{VA}^{(8),u} c_{VV}^{(8),u}\right)$$

gg-induced

$$\rho_{gg}^{\mathrm{EFT}}(0,z) = p_{gg}|\Psi^+\rangle_{\boldsymbol{p}}\langle\Psi^+|_{\boldsymbol{p}} + (1-p_{gg})|\Psi^-\rangle_{\boldsymbol{p}}\langle\Psi^-|_{\boldsymbol{p}}$$

$$p_{gg} = \frac{72}{7\Lambda^4} m_t^2 (3\sqrt{2} m_t\, c_G + v\, c_{tG})^2$$

Only quadratic effects!

qq-induced

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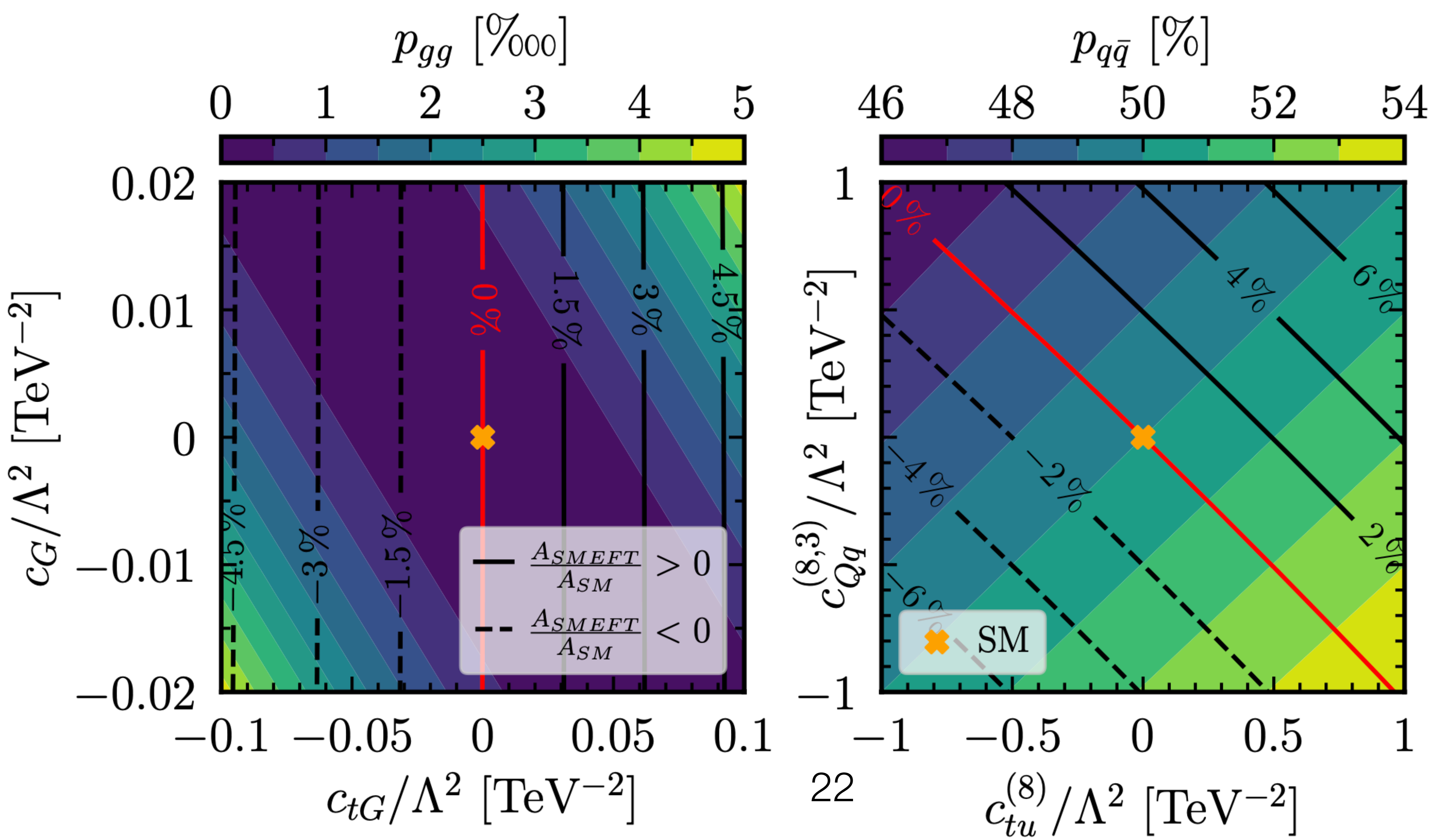

- ❖ Possibility to exploit quantum observables as entanglement proposed.
- ❖ Measurement of top pair entanglement is the highest energy evidence ever.
- ❖ In the SM, top pairs are maximally entangled at threshold and very high energy.
- ❖ SMEFT effects induce presence of different quantum states, decreasing entanglement at threshold and modifying the overall pattern.
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Backup

How do we reconstruct the spin density matrix at colliders?

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Quantum tomography — Measure angular distributions of the decay products

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Quantum tomography Measure angular distributions of the decay products

For example, for the density matrix of a W boson **[arXiv: 2209.13990]**

$$\Phi_1^{P\pm} = \sqrt{2}(5\cos\theta \pm 1)\sin\theta\cos\phi$$
$$\Phi_2^{P\pm} = \sqrt{2}(5\cos\theta \pm 1)\sin\theta\sin\phi$$
$$\Phi_3^{P\pm} = \frac{1}{4}(\pm 4\cos\theta + 15\cos 2\theta + 5)$$
$$\Phi_4^{P\pm} = 5\sin^2\theta\cos 2\phi$$
$$\Phi_5^{P\pm} = 5\sin^2\theta\sin 2\phi$$
$$\Phi_6^{P\pm} = \sqrt{2}(\pm 1 - 5\cos\theta)\sin\theta\cos\phi$$
$$\Phi_7^{P\pm} = \sqrt{2}(\pm 1 - 5\cos\theta)\sin\theta\sin\phi$$
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$$a_j = \frac{1}{2}\int d\Omega_{\hat{\mathbf{n}}}\, p(\ell^{\pm}_{\hat{\mathbf{n}}};\rho)\,\Phi_j^{P\pm}$$

$$c_{ij} = \left(\frac{1}{2}\right)^2 \iint d\Omega_{\hat{\mathbf{n}}_1}\, d\Omega_{\hat{\mathbf{n}}_2}\, p\left(\ell^+_{\hat{\mathbf{n}}_1}, \ell^-_{\hat{\mathbf{n}}_2};\rho\right)\Phi_i^P(\hat{\mathbf{n}}_1)\,\Phi_j^P(\hat{\mathbf{n}}_2)$$

Expectation value of the Wigner P functions

In the case of top pair things are simpler **[arXiv: 2003.02280]**

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_+\mathrm{d}\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

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Spin density matrix coefficients

Interestingly, at threshold, a specific angular distributions is **directly proportional to the entanglement**

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi) \qquad D = \frac{\mathrm{tr}[\mathbf{C}]}{3} \qquad C[\rho] = \max(-1 - 3D, 0)/2$$

Angle between leptons

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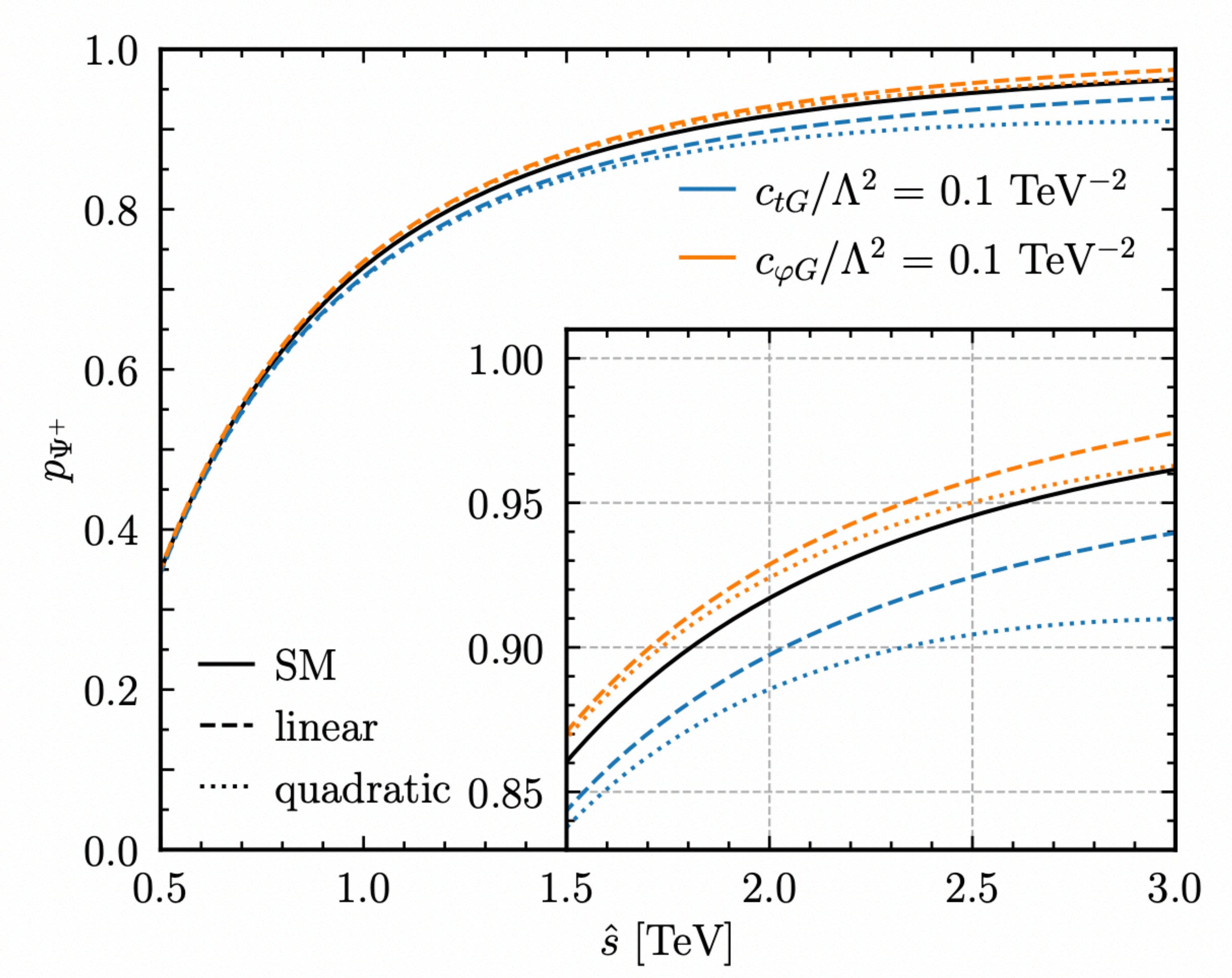
Angle between leptons

However not trivial!

Despite high degree of entanglement in certain phase space, when integrating we wash out the effects: design of optimal signal region needed.

$$p_{\Psi^+} = \langle \Psi^+|_{\boldsymbol{n}}\, \rho \,|\Psi^+\rangle_{\boldsymbol{n}}$$

Probability triplet state



$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda}\mathcal{O}_i^5 + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i^6 + \ldots$$

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4-Fermion operators

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

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What are the effects of NP on the entanglement regions?

Is NP affecting the quantum state?

Given a bipartite system, with Hilbert space $\mathscr{H} = \mathscr{H}_1 \otimes \mathscr{H}_2$

If state separable $|\Psi\rangle = |\Psi\rangle_1 \otimes |\Psi\rangle_2$ → **No entanglement**

Operative definition of entanglement: **Peres-Horodecki criterion**

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

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Operative definition of entanglement: **Peres-Horodecki criterion**

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

We can then define the concurrence

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

$$C[\rho] = 1$$

Max entanglement

LO coefficients - gg channel

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

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

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$$\tilde{C}_{rk}^{gg,(1)} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{g_s^2 v m_t \beta^2 z\left(1-z^2\right)\left(9\beta^2+\left(\beta^2-2\right)z^2\left(9\beta^2\left(z^2-1\right)+7\right)-2\right)}{24\sqrt{2}\sqrt{\left(\beta^2-1\right)\left(z^2-1\right)}\left(\beta^2 z^2-1\right)}c_{tG} + \frac{9g_s^2\beta^2 m_t^2 z}{8}\sqrt{\frac{1-z^2}{1-\beta^2}}c_G\right].$$

LO coefficients - qq channel

$$\tilde{A}^{q\bar{q},(1)} = \frac{4g_s^2 m_t^2}{9\Lambda^2(1-\beta^2)}\left[\sqrt{2}g_s^2\frac{v}{m_t}(1-\beta^2)c_{tG} + \left(2-(1-z^2)\beta^2\right)c_{VV}^{(8),u} + 2z\beta c_{AA}^{(8),u}\right],$$

$$\tilde{C}_{nn}^{q\bar{q},(1)} = -\frac{g_s^2 m_t^2}{\Lambda^2}\frac{4\beta^2(1-z^2)}{9(1-\beta^2)}c_{VV}^{(8),u},$$

$$\tilde{C}_{kk}^{q\bar{q},(1)} = \frac{2g_s^2 m_t^2}{9\Lambda^2(1-\beta^2)}\left[2\sqrt{2}g_s^2\frac{v}{m_t}(1-\beta^2)z^2 c_{tG} + \left(2+\beta^2-(2-\beta^2)(1-2z^2)\right)c_{VV}^{(8),u} + 4\beta z c_{AA}^{(8),u}\right]$$

$$\tilde{C}_{rr}^{q\bar{q},(1)} = \frac{4g_s^2 m_t^2(1-z^2)}{9\Lambda^2(1-\beta^2)}\left[\sqrt{2}g_s^2\frac{v}{m_t}(1-\beta^2)c_{tG} + (2-\beta^2)c_{VV}^{(8),u}\right],$$

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$$B_k^{\pm,q\bar{q},(1)} = 4g_s^2\frac{m_t^2}{9\Lambda^2}\frac{1}{1-\beta^2}\left(\beta(z^2+1)c_{AV}^{(8),u} + 2z c_{VA}^{(8),u}\right),$$

$$B_r^{\pm,q\bar{q},(1)} = -4g_s^2\frac{m_t^2}{9\Lambda^2}\sqrt{\frac{1-z^2}{1-\beta^2}}\left(\beta z c_{AV}^{(8),u} + 2c_{VA}^{(8),u}\right).$$

$$c_{VV}^{(8),u} = (c_{Qq}^{(8,1)} + c_{Qq}^{(8,3)} + c_{tu}^{(8)} + c_{tq}^{(8)} + c_{Qu}^{(8)})/4, \qquad c_{AA}^{(8),u} = (c_{Qq}^{(8,1)} + c_{Qq}^{(8,3)} + c_{tu}^{(8)} - c_{tq}^{(8)} - c_{Qu}^{(8)})/4,$$

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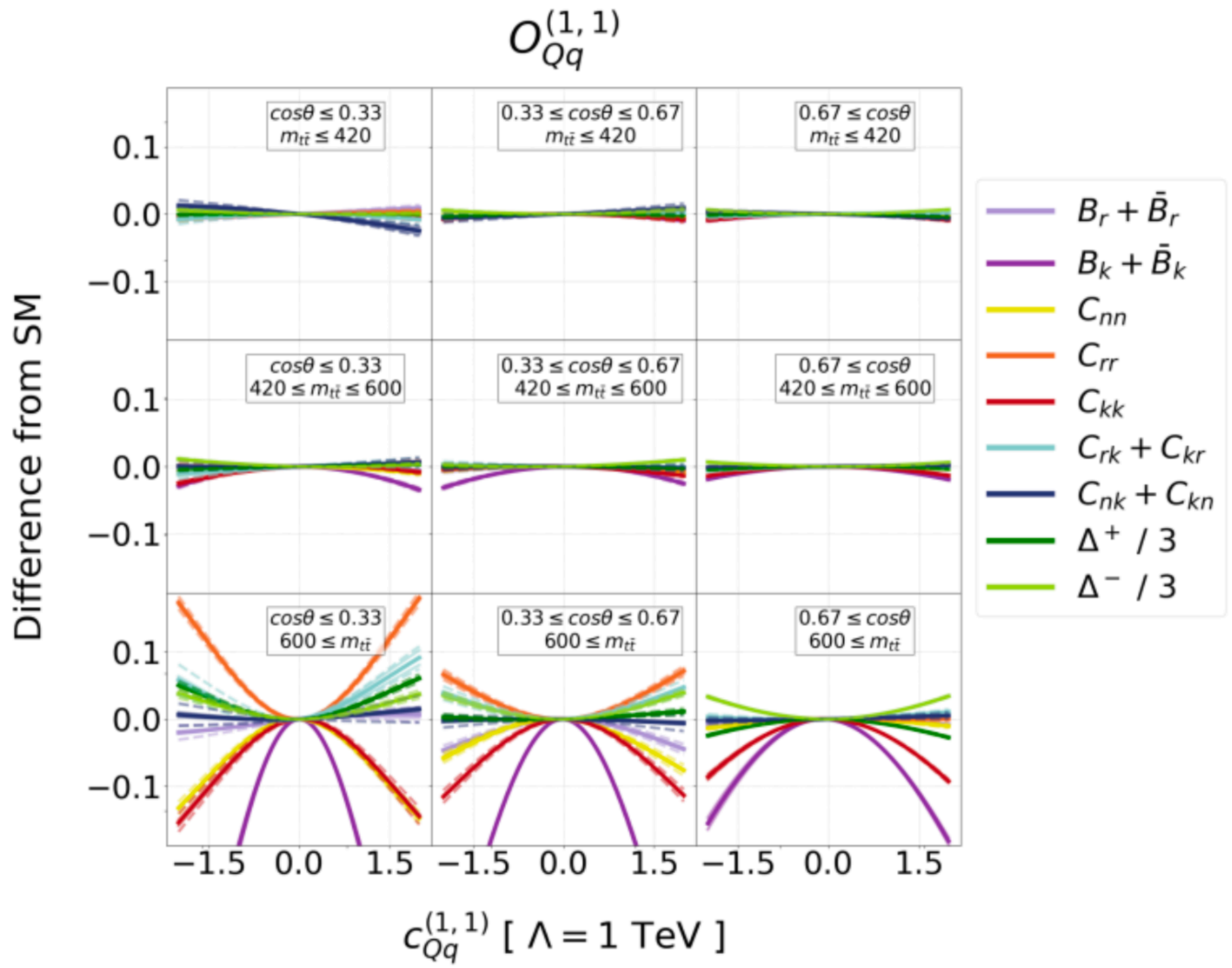
Stolen slide [arXiv:2210.09330]

The structure of spin correlations in phase space makes a differential measurement ~ 10x more effective than an inclusive one.



Quantum observables and spin correlations in general will yield remarkable improvements to BSM searches and SMEFT global fits.

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broad sensitivity to SMEFT operators

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Density matrix more complex:
spin components not sufficient for complete characterisation

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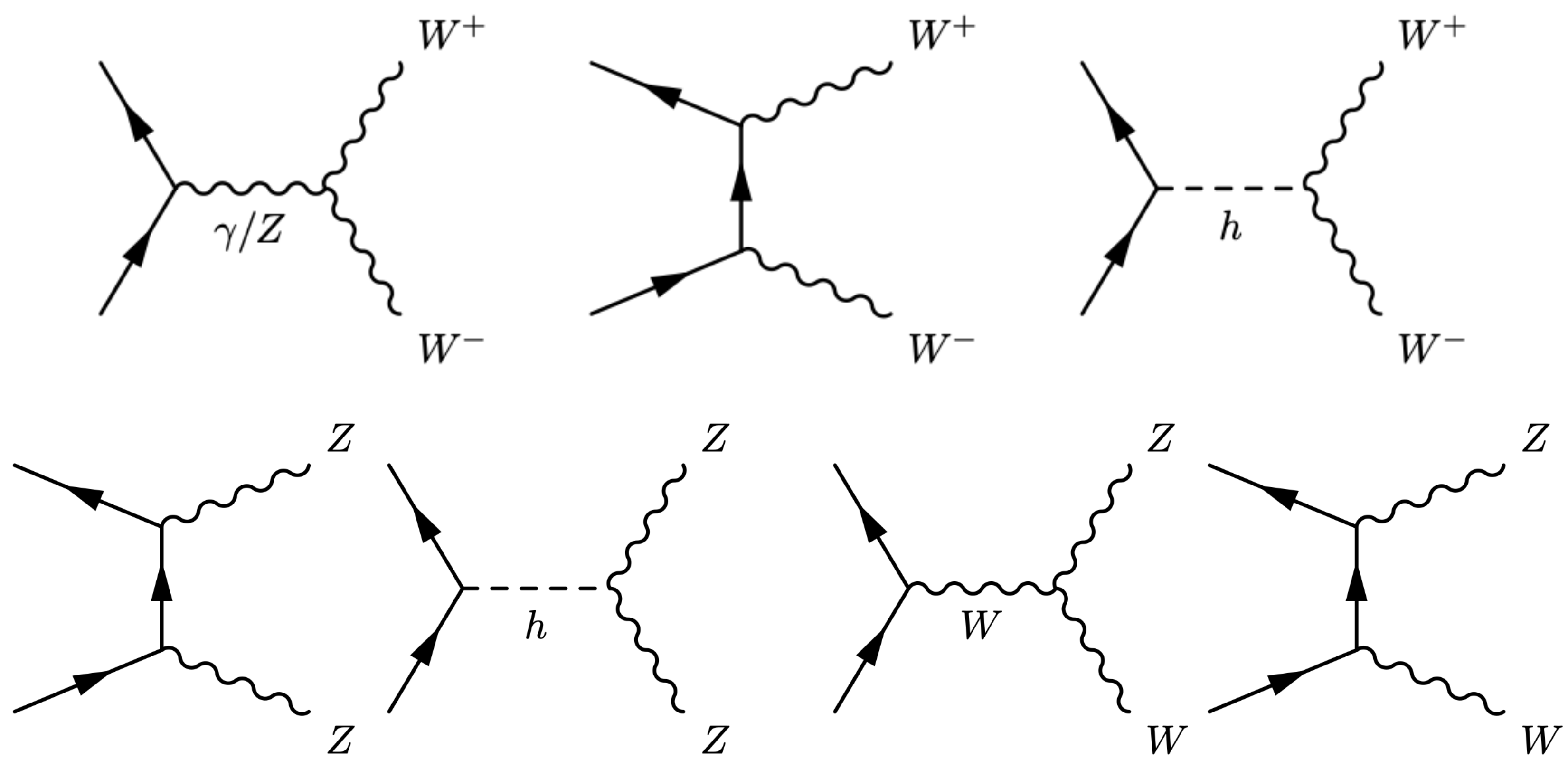
We studied both lepton and hadron collider



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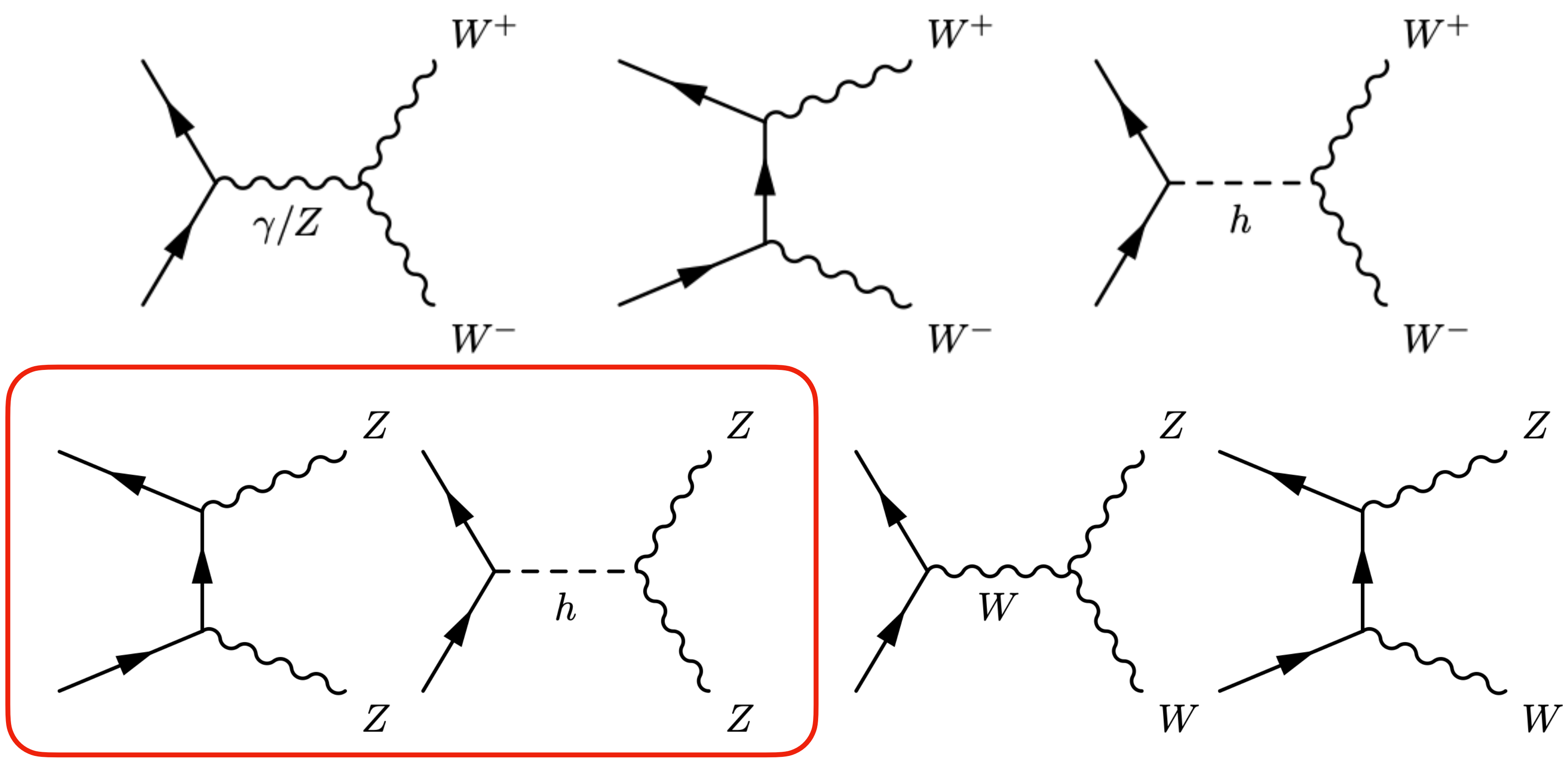
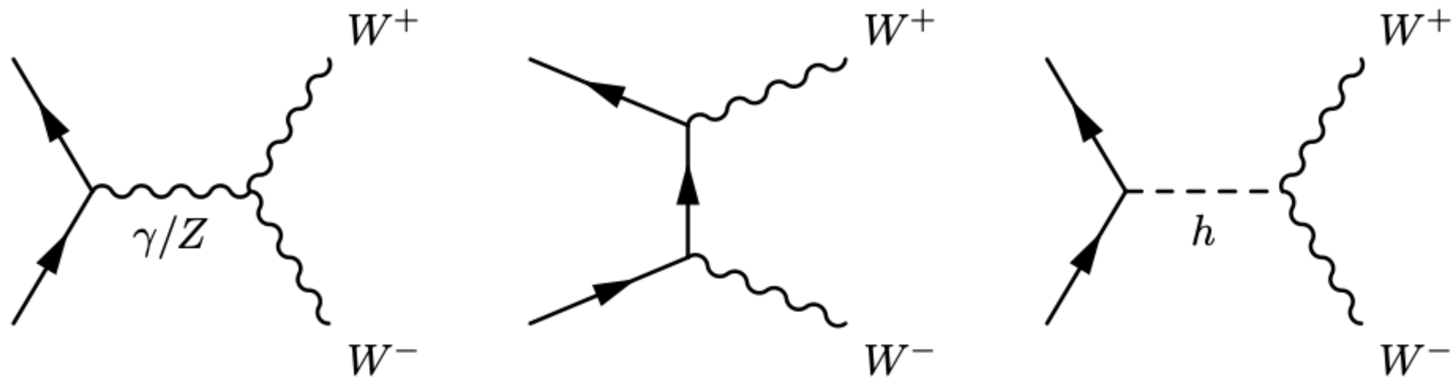
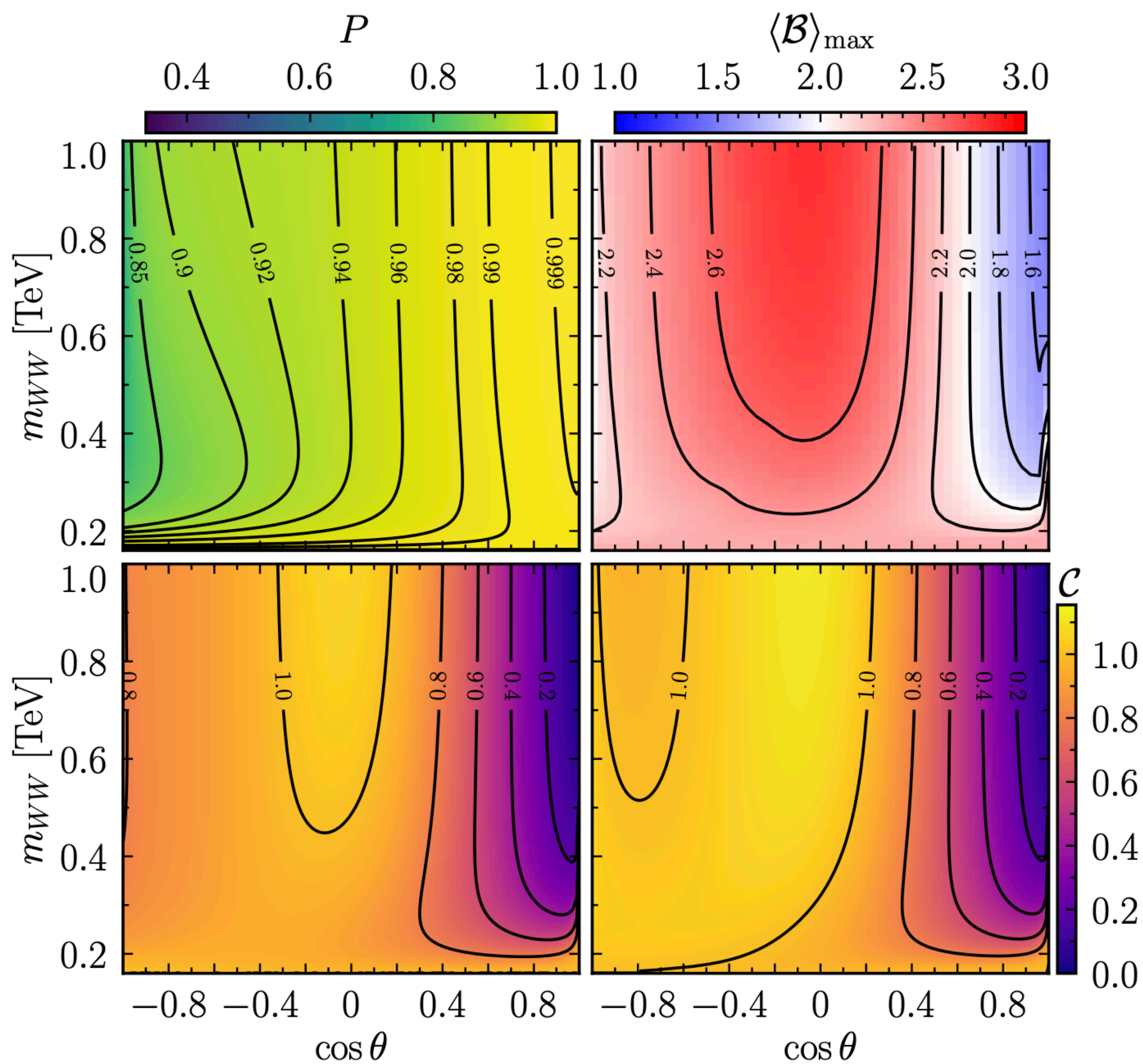
Not very sensitive

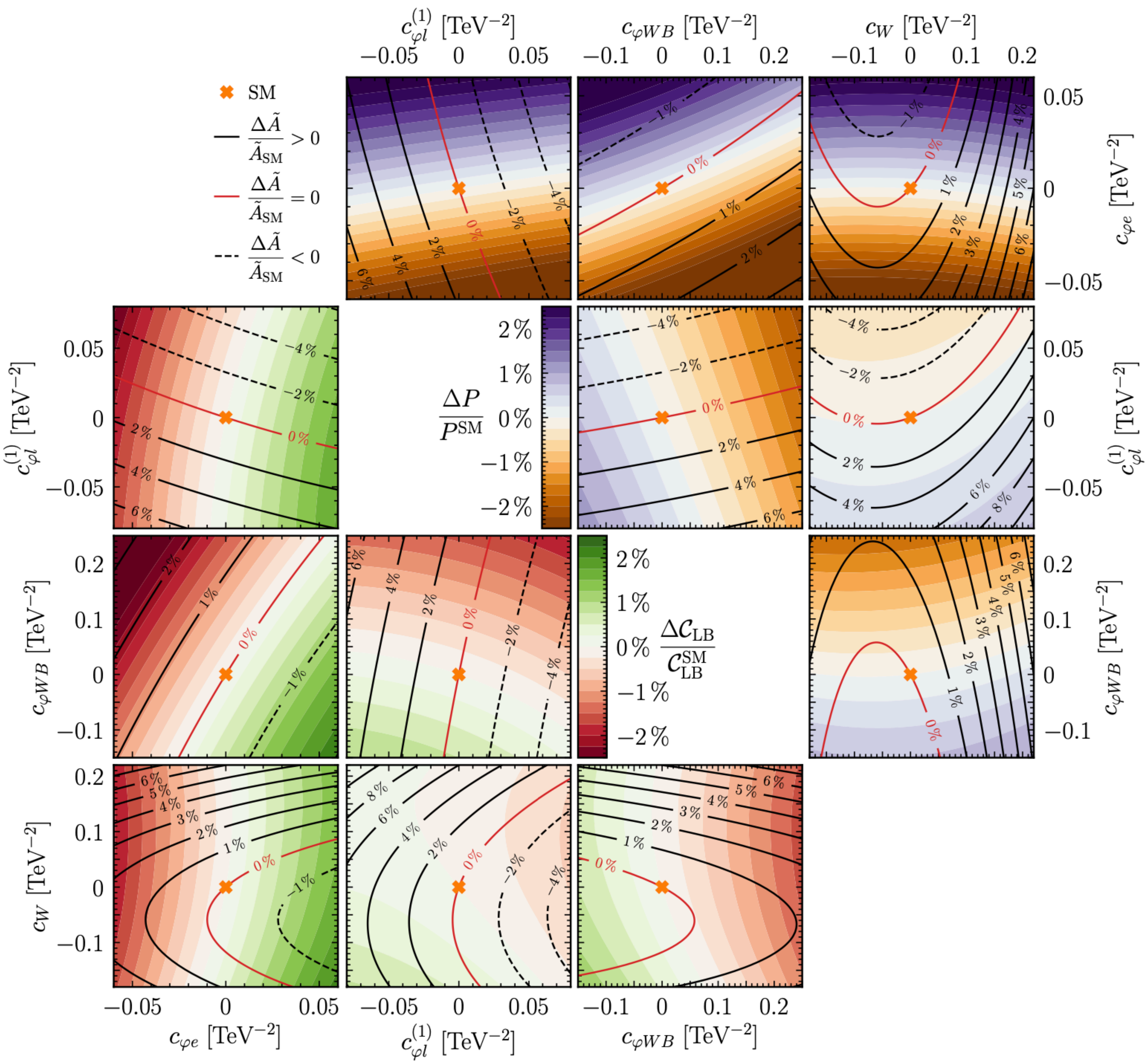


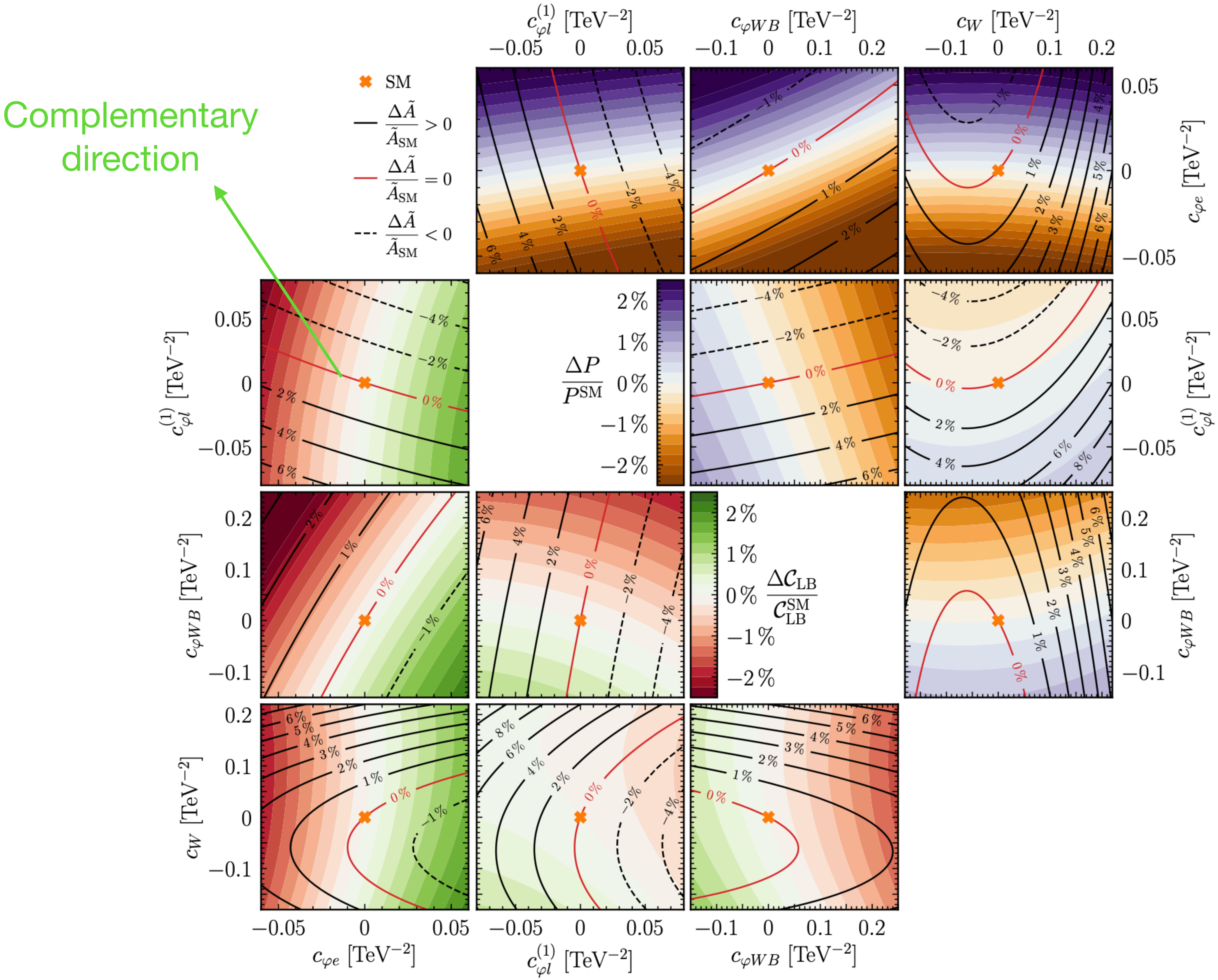
WW production





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


SM
$\frac{\Delta\tilde{A}}{\tilde{A}_{SM}} > 0$
$\frac{\Delta\tilde{A}}{\tilde{A}_{SM}} = 0$
$\frac{\Delta\tilde{A}}{\tilde{A}_{SM}} < 0$
$\frac{\Delta P}{P^{SM}}$
$\frac{\Delta \mathcal{C}_{LB}}{\mathcal{C}_{LB}^{SM}}$
$c_{\varphi l}^{(1)}$ [TeV^{-2}]
$c_{\varphi WB}$ [TeV^{-2}]
c_W [TeV^{-2}]
$c_{\varphi e}$ [TeV^{-2}]


Complementary direction
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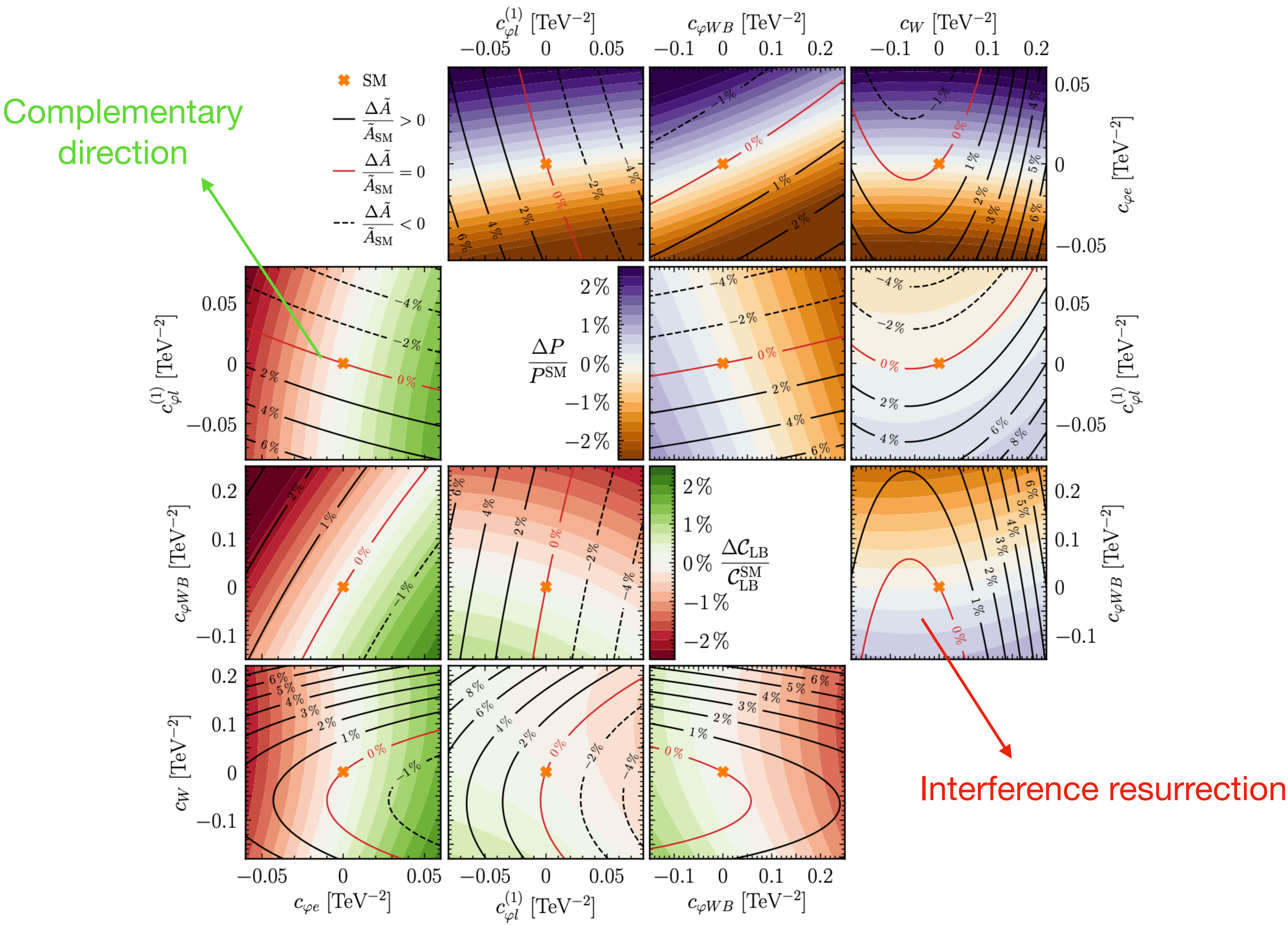
Complementary direction
Interference resurrection
SM
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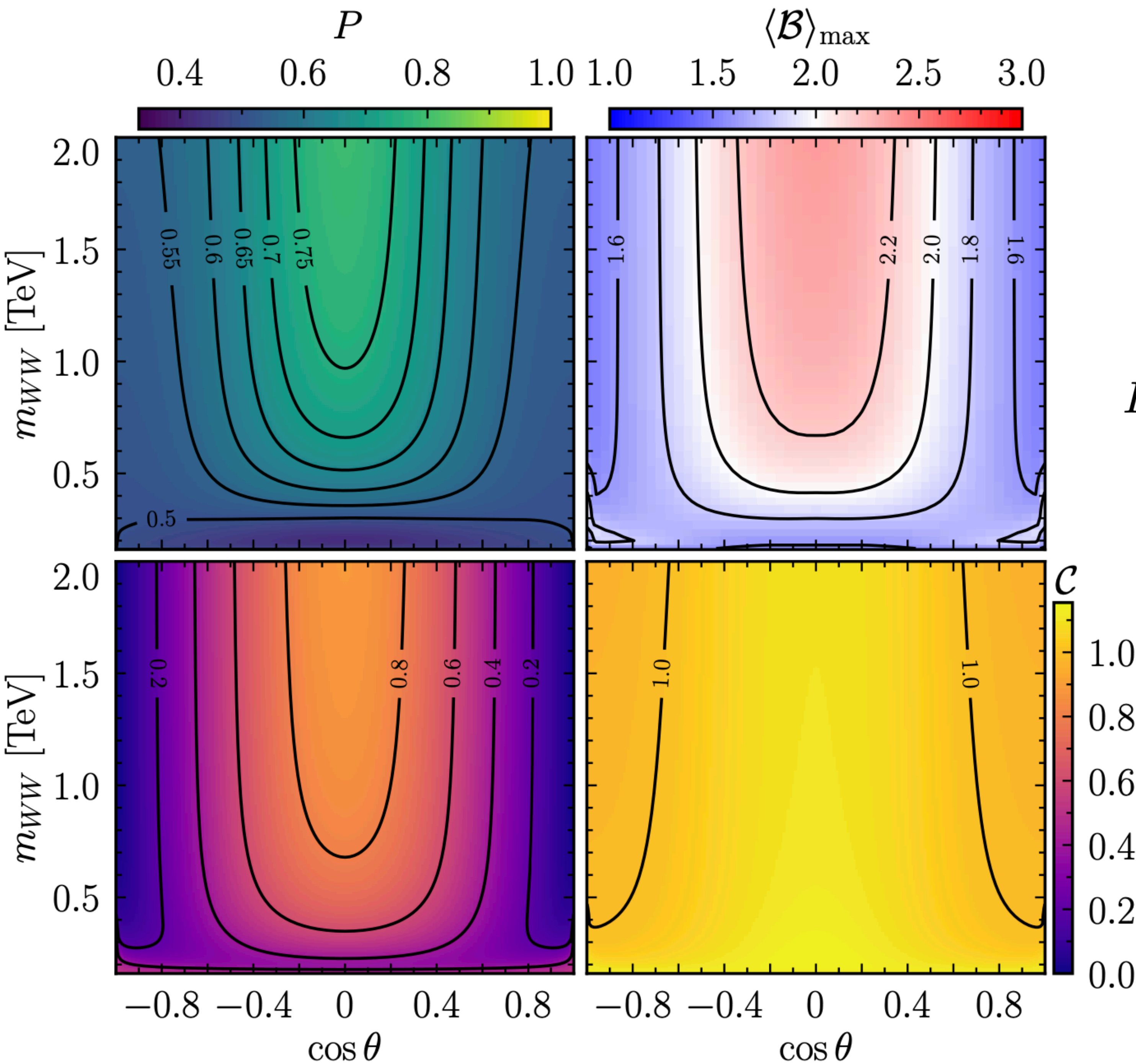
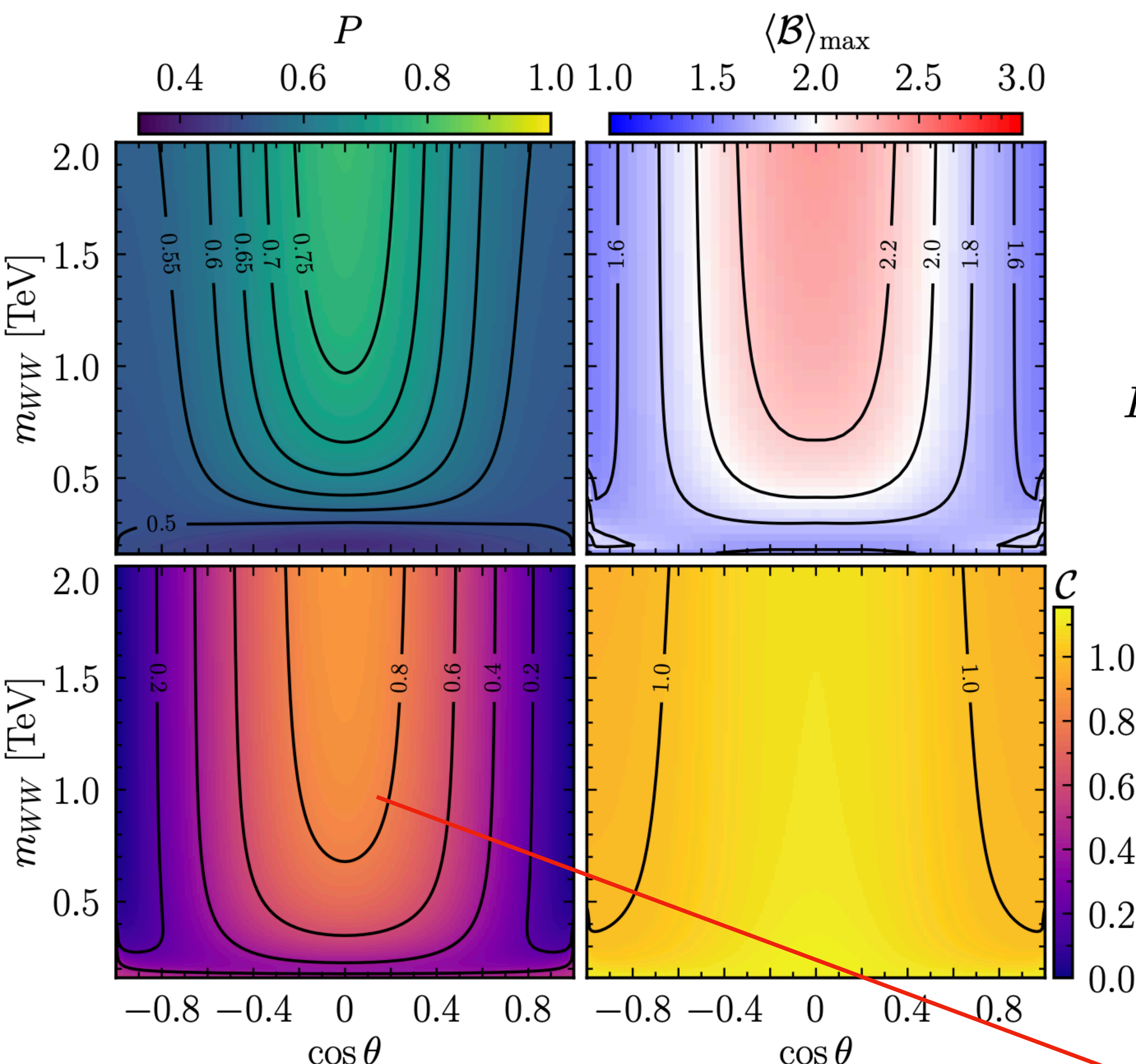
$$pp \to W^+W^-$$



Milder signs due to the initial state mixing

$$R(\hat{s},\theta) = \sum_q L^{q\bar{q}}(\hat{s})(R^{q\bar{q}}(\hat{s},\theta) + R^{q\bar{q}}(\hat{s},\theta+\pi))$$

$$pp \to W^+W^-$$



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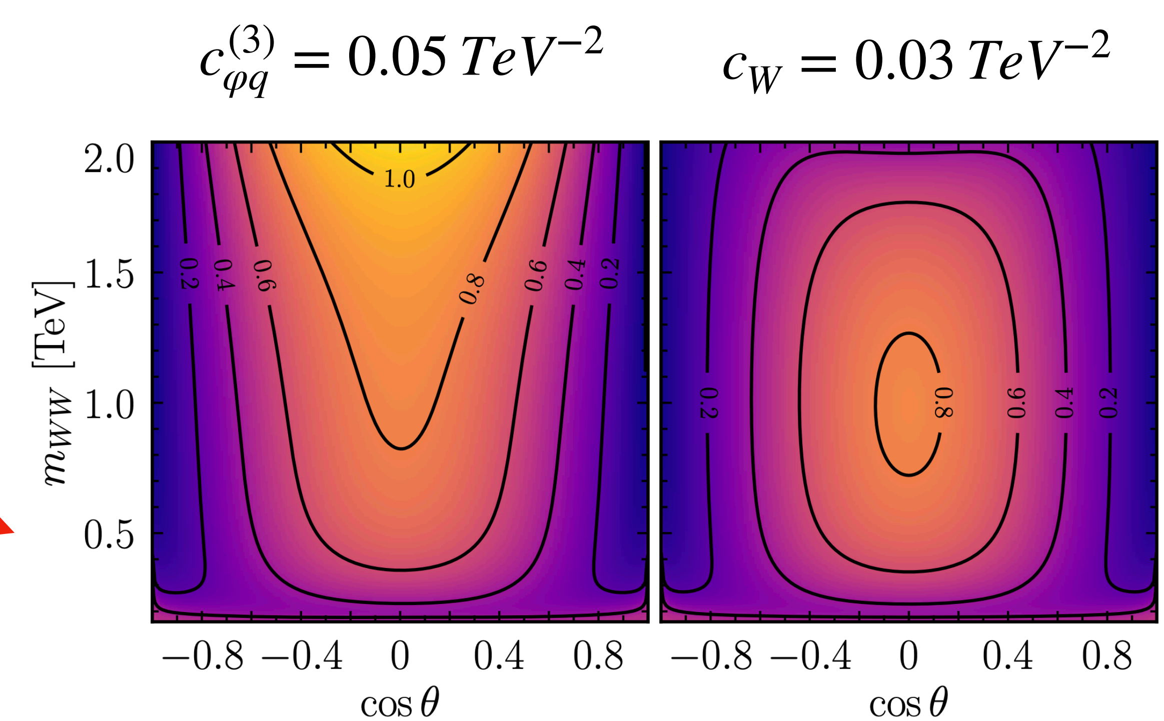
$c_{\varphi q}^{(3)} = 0.05\ TeV^{-2}$ $c_W = 0.03\ TeV^{-2}$



ATLAS CONF Note

ATLAS-CONF-2023-069

28th September 2023

Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s} = 13$ TeV with the ATLAS detector

entanglement detection is expected to be significant. The entanglement observable is measured in a fiducial phase-space with stable particles. The entanglement witness is measured to be $D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The large spread in predictions from several mainstream event generators indicates that modelling this property is challenging. The predictions depend in particular on the parton-shower algorithm used. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks, and the observation of entanglement at the highest energy to date.