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Probing heavy New Physics through entanglement at the LHC

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In collaboration with:
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UNIVERSITY OF CAMBRIDGE

PBSP

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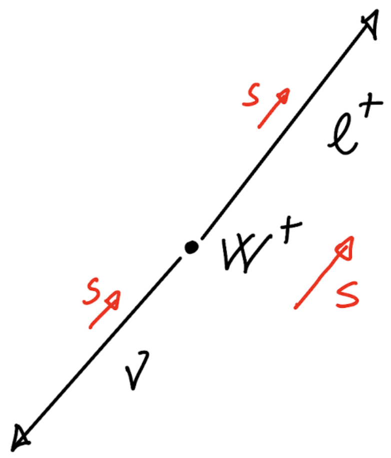

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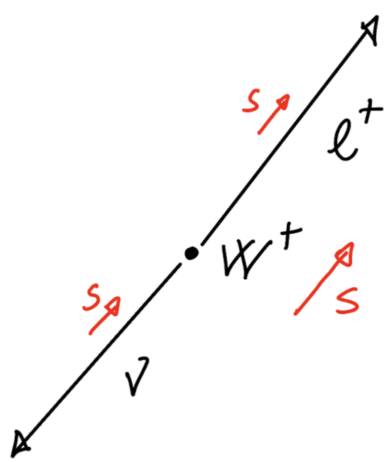

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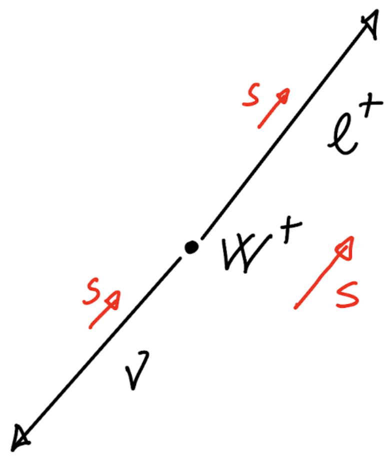

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Z boson more complicated but doable:
spin can be reco if right/left asymmetry

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

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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

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

Matrix-element

$$\mathcal{M}_{\alpha\beta} \equiv \langle t(k_1,\alpha)\bar{t}(k_2,\beta)|\mathcal{T}|a(p_1)b(p_2)\rangle$$

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

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Cross section

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If normalised, we define the density matrix of the system

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Concurrence

$$\mathcal{C}(\rho) = \inf \left[\sum_i p_i c(|\psi_i\rangle) \right]$$

Entangled if > 0

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

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

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Bell inequality

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

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

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- **Define target operators: e.g. top-philic EFT** [arXiv:1802.07237]
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$$e^+e^- \to W^+W^-$$

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Cross section

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

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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!

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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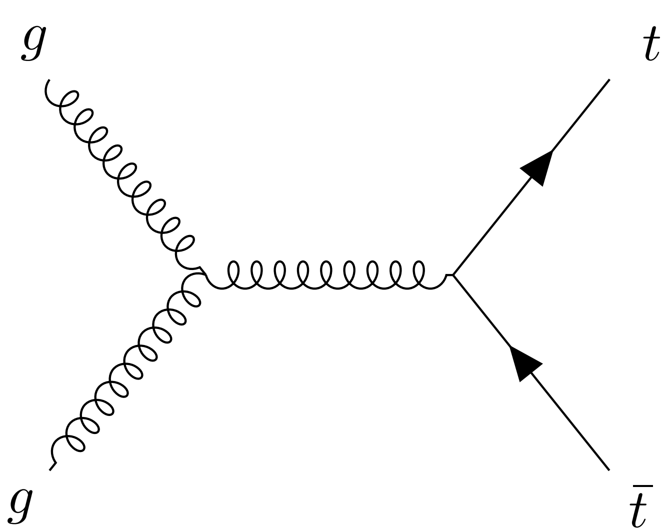
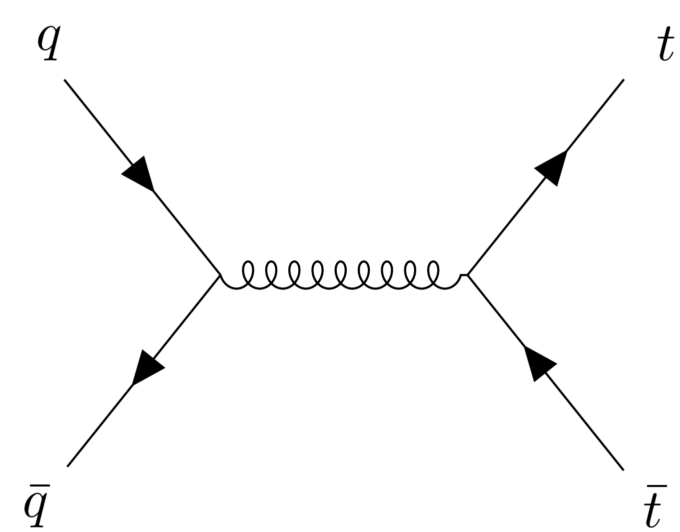


We collide protons



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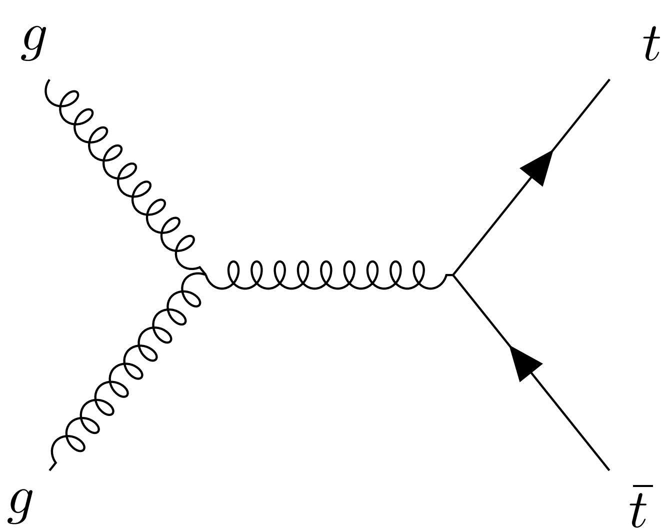

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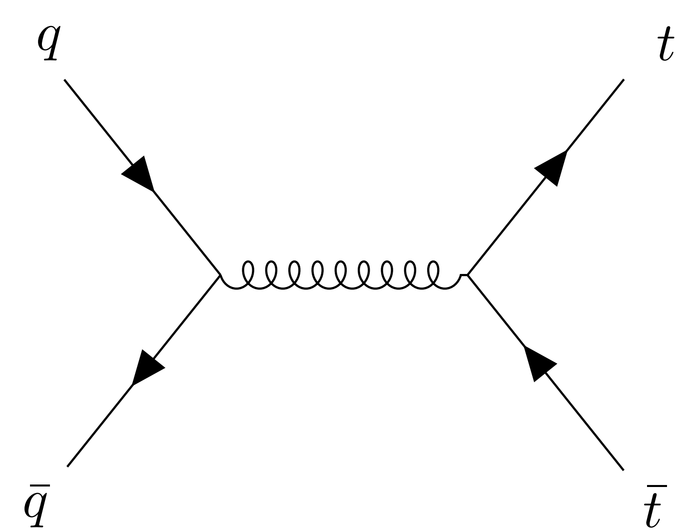
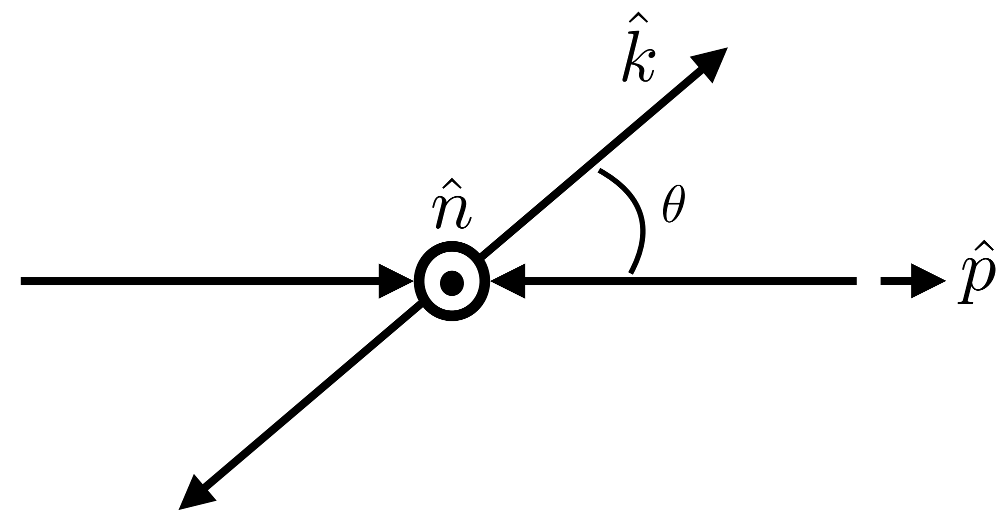


$$R(\hat{s},\boldsymbol{k}) = \sum_I L^I(\hat{s}) R^I(\hat{s},\boldsymbol{k})$$

Full correlation matrix is mixed state, weighted by parton luminosity

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



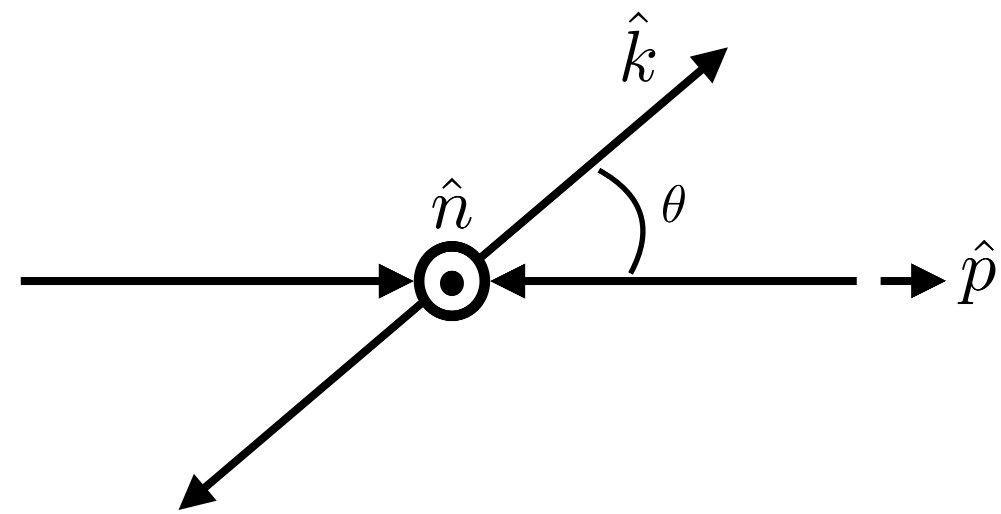
$$\beta^2 = (1 - 4m_t^2/\hat{s})$$

$$\cos\theta$$

To expand in this basis, e.g.

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

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



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

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

$$\cos\theta$$

Operative definition of entanglement:

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

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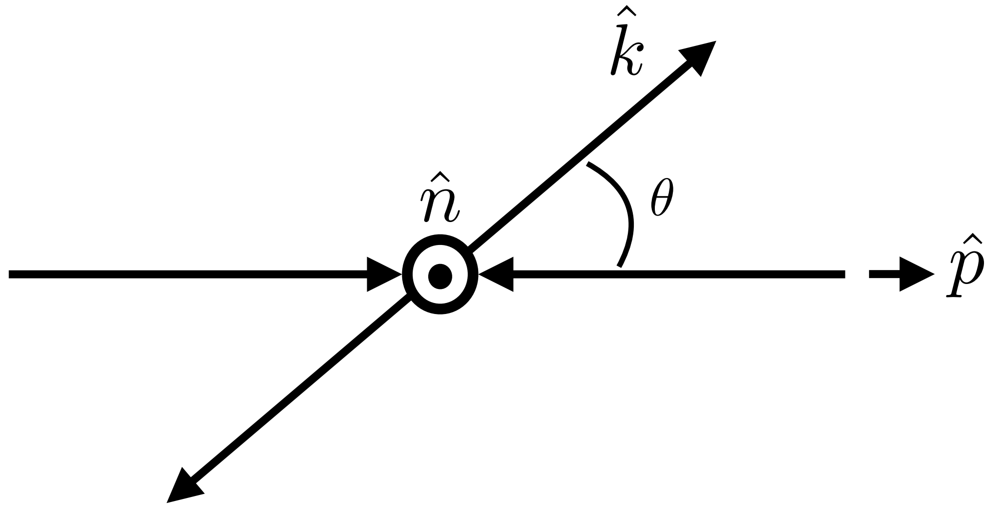

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Operative definition of entanglement:

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

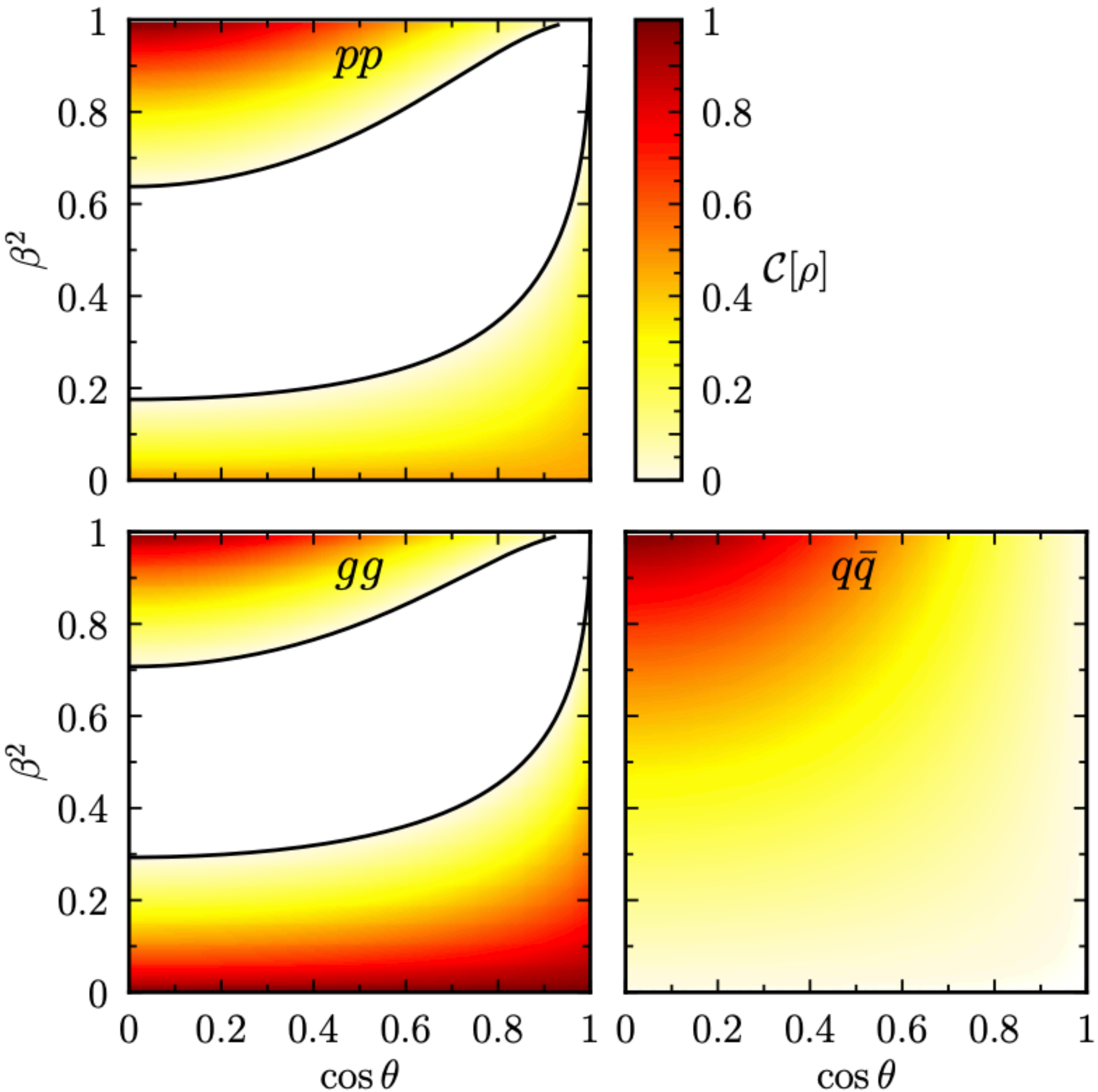
entangled

We can then define the concurrence

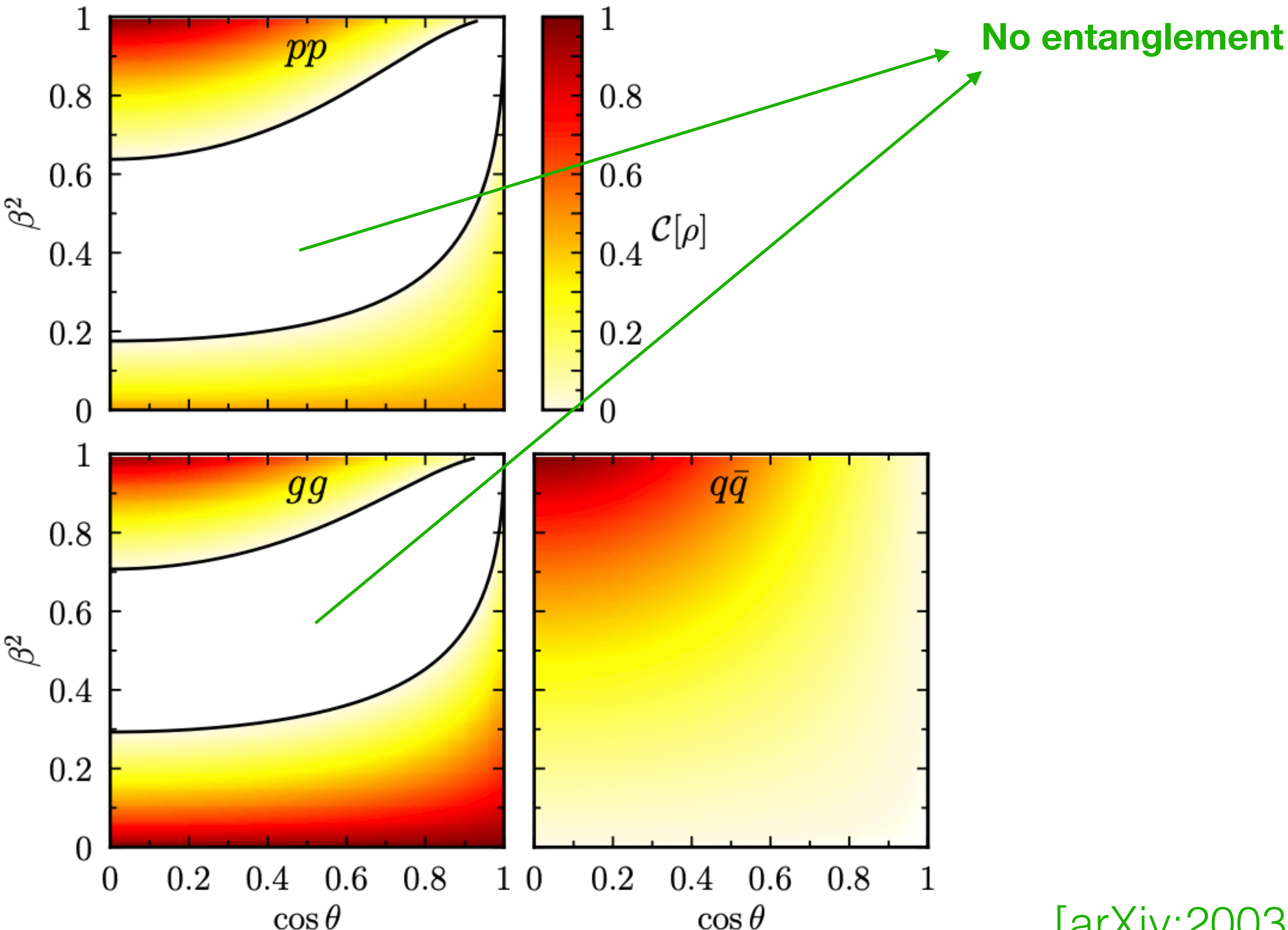
$$C[\rho] = \max(\Delta/2, 0)$$

$$C[\rho] = 1$$

Max entanglement



[arXiv:2003.02280]



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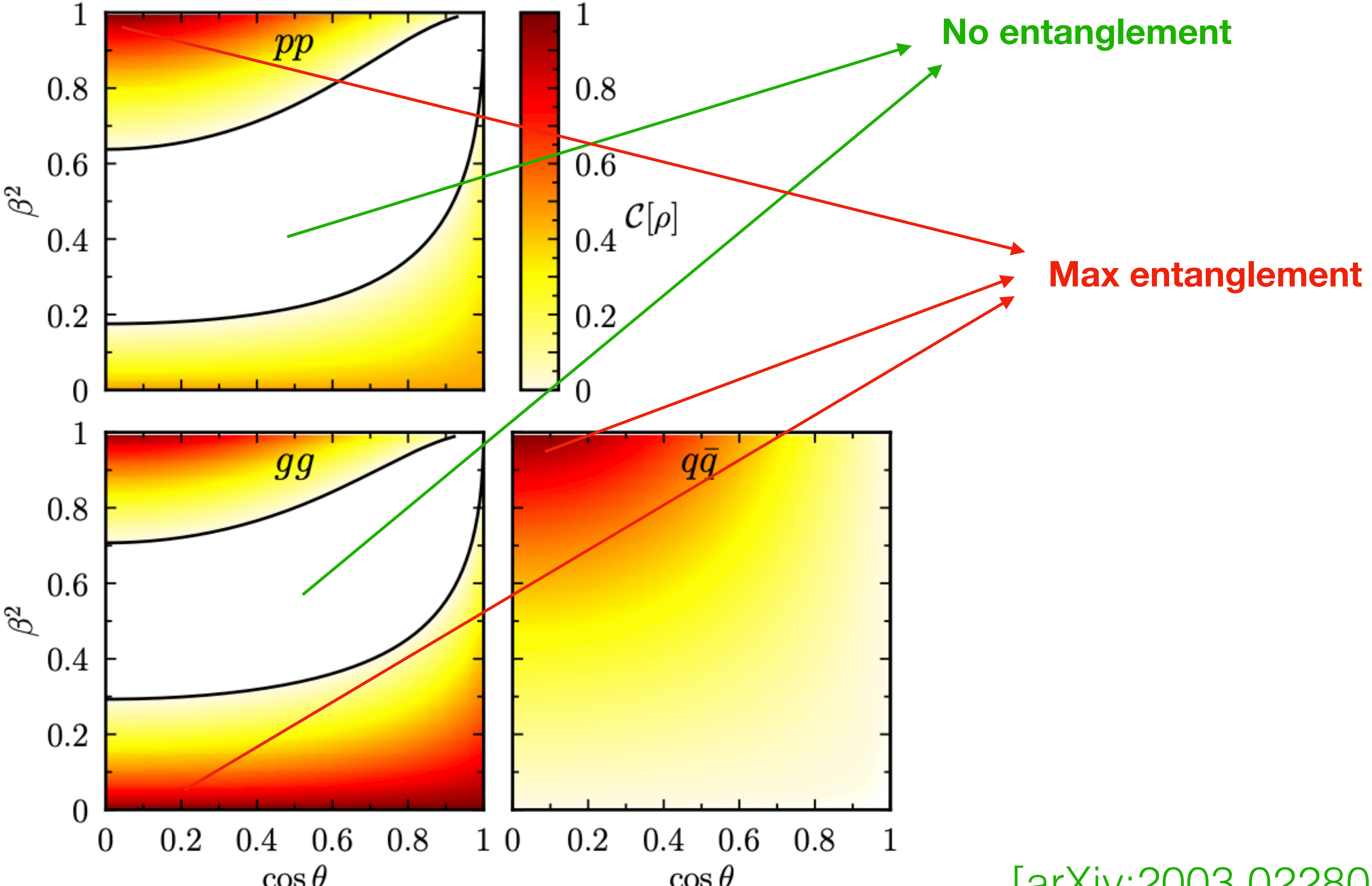

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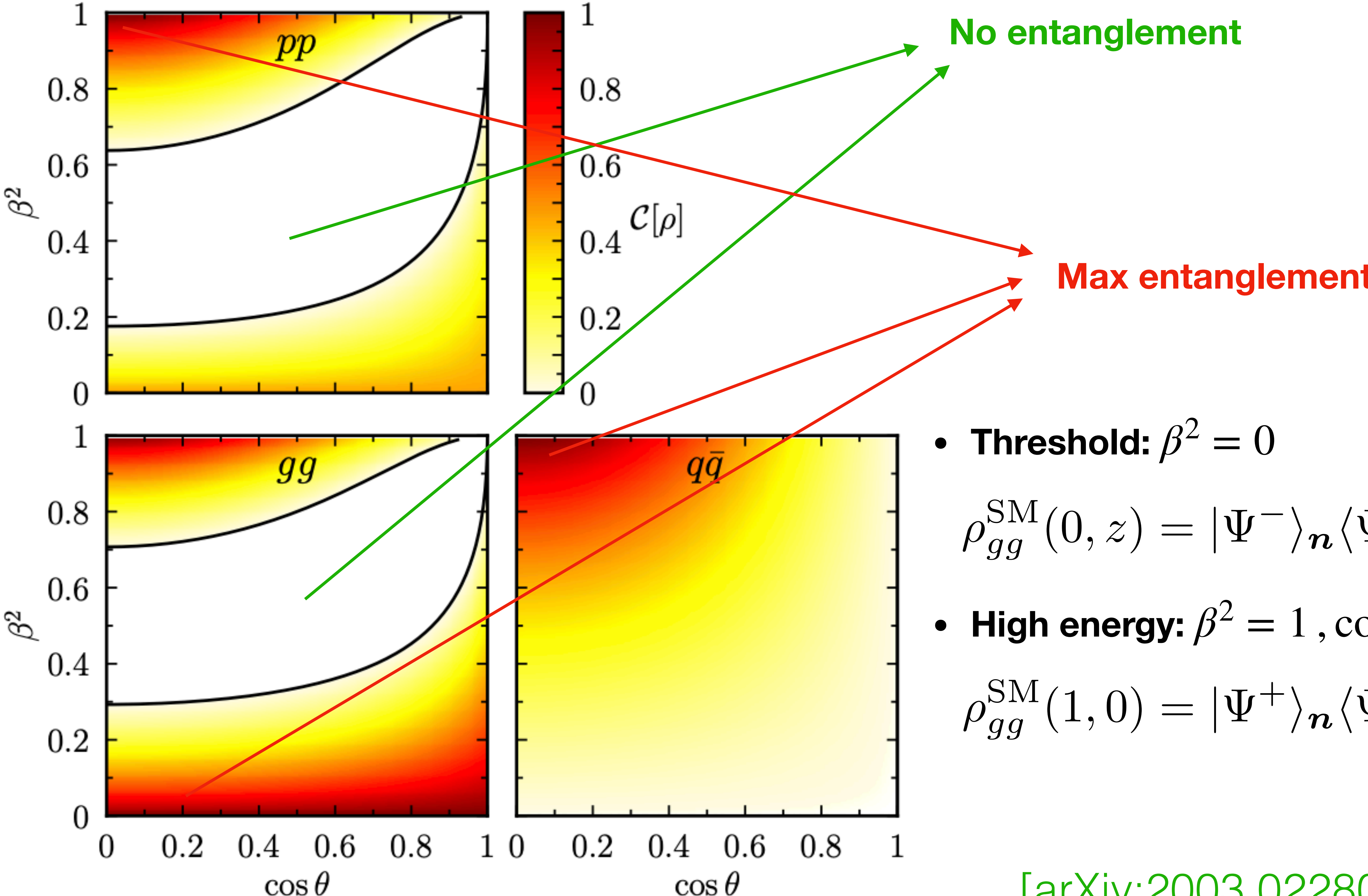

- **Threshold:** $\beta^2 = 0$

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

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

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

[arXiv:2003.02280]

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

$$\mathcal{M}_{\alpha\beta} = \mathcal{M}^{\text{SM}}_{\alpha\beta} + \frac{1}{\Lambda^2}\mathcal{M}^{(\text{d6})}_{\alpha\beta} \quad \Longrightarrow \quad \rho = \frac{R^{\text{SM}} + R^{\text{EFT}}}{\text{tr}(R^{\text{SM}}) + \text{tr}(R^{\text{EFT}})}$$

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

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

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

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

$\rightarrow$

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

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

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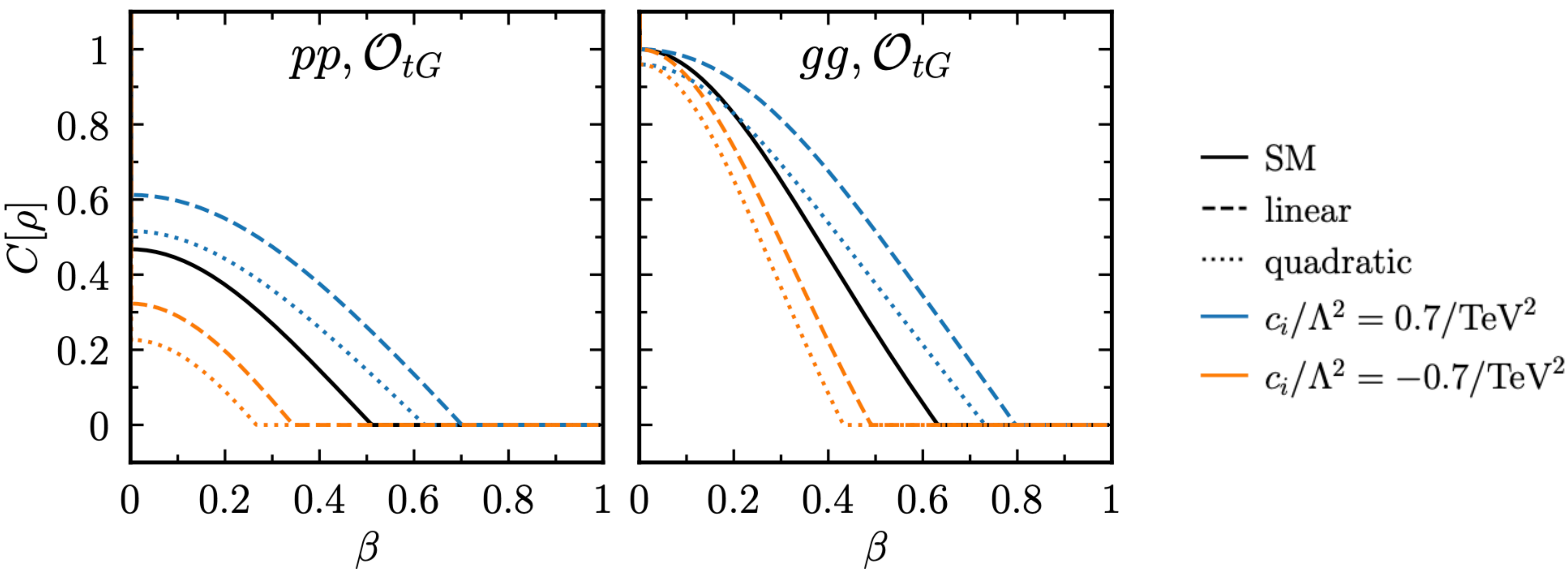

gg-induced

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

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

Only quadratic effects!

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qq-induced

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

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

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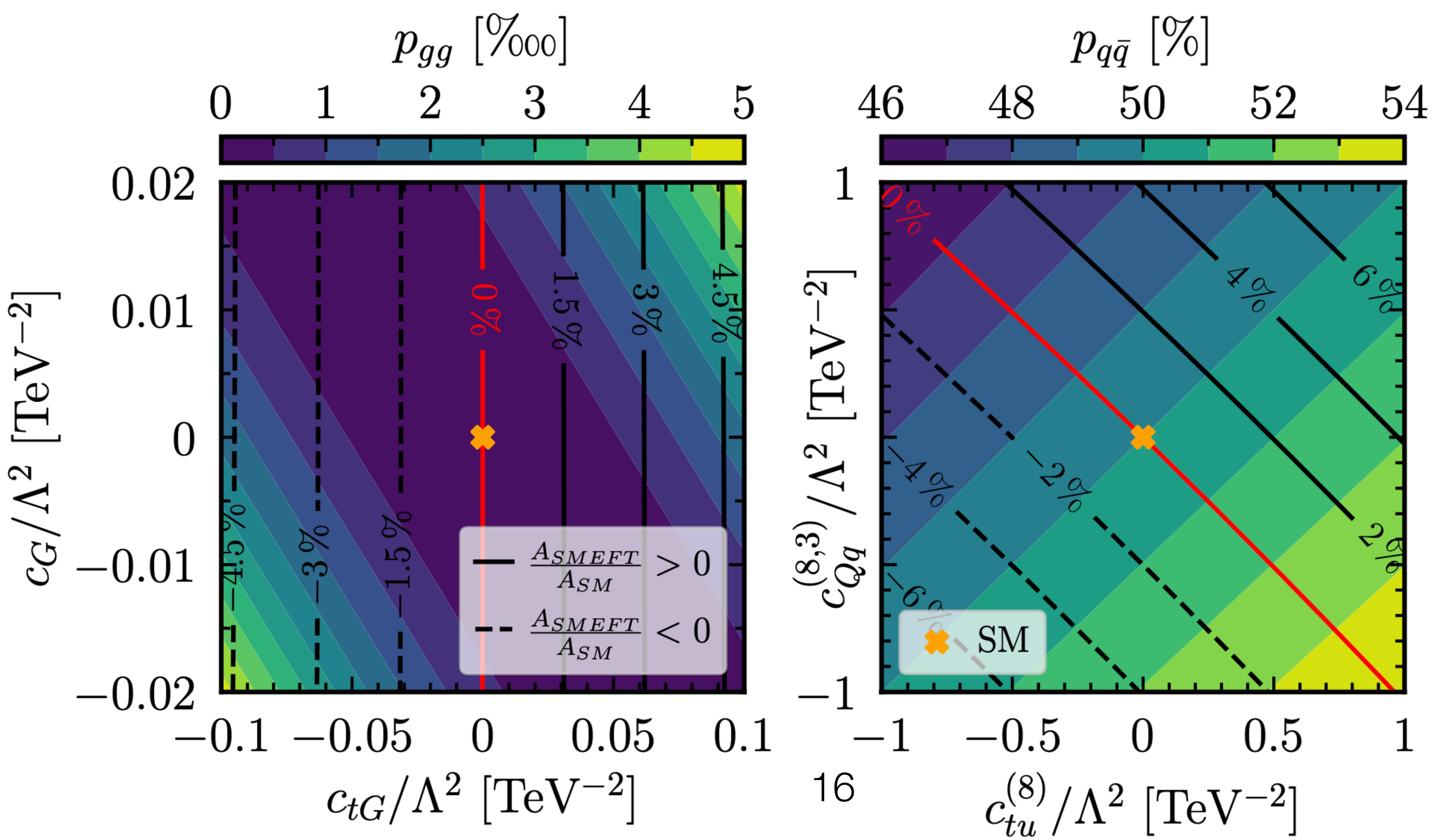
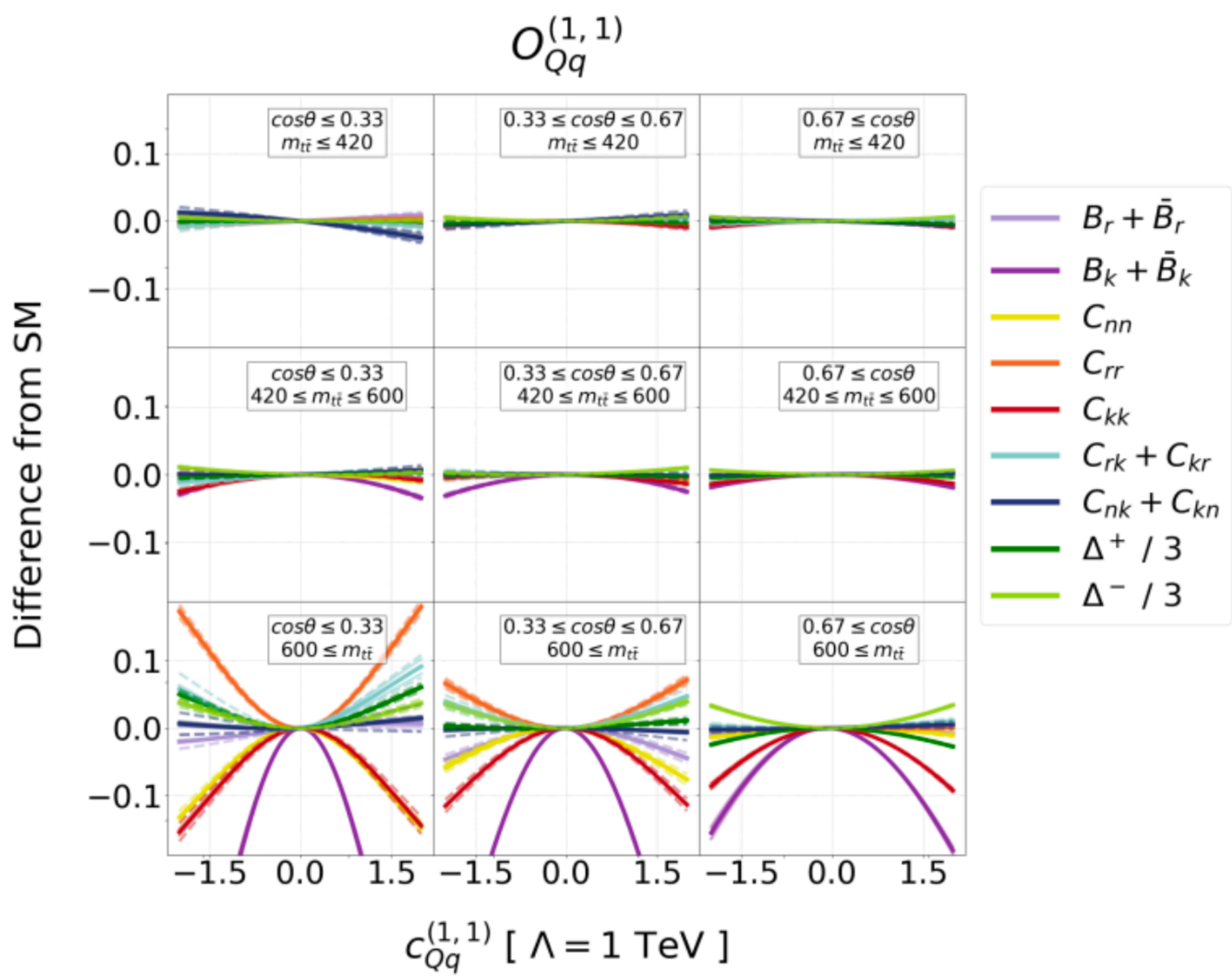


Stolen slide [arXiv:2210.09330]

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.

Claudio Severi LHCP 2023

[arXiv: 2307.10370] Diboson production is also a promising candidate:
broad sensitivity to SMEFT operators

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

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

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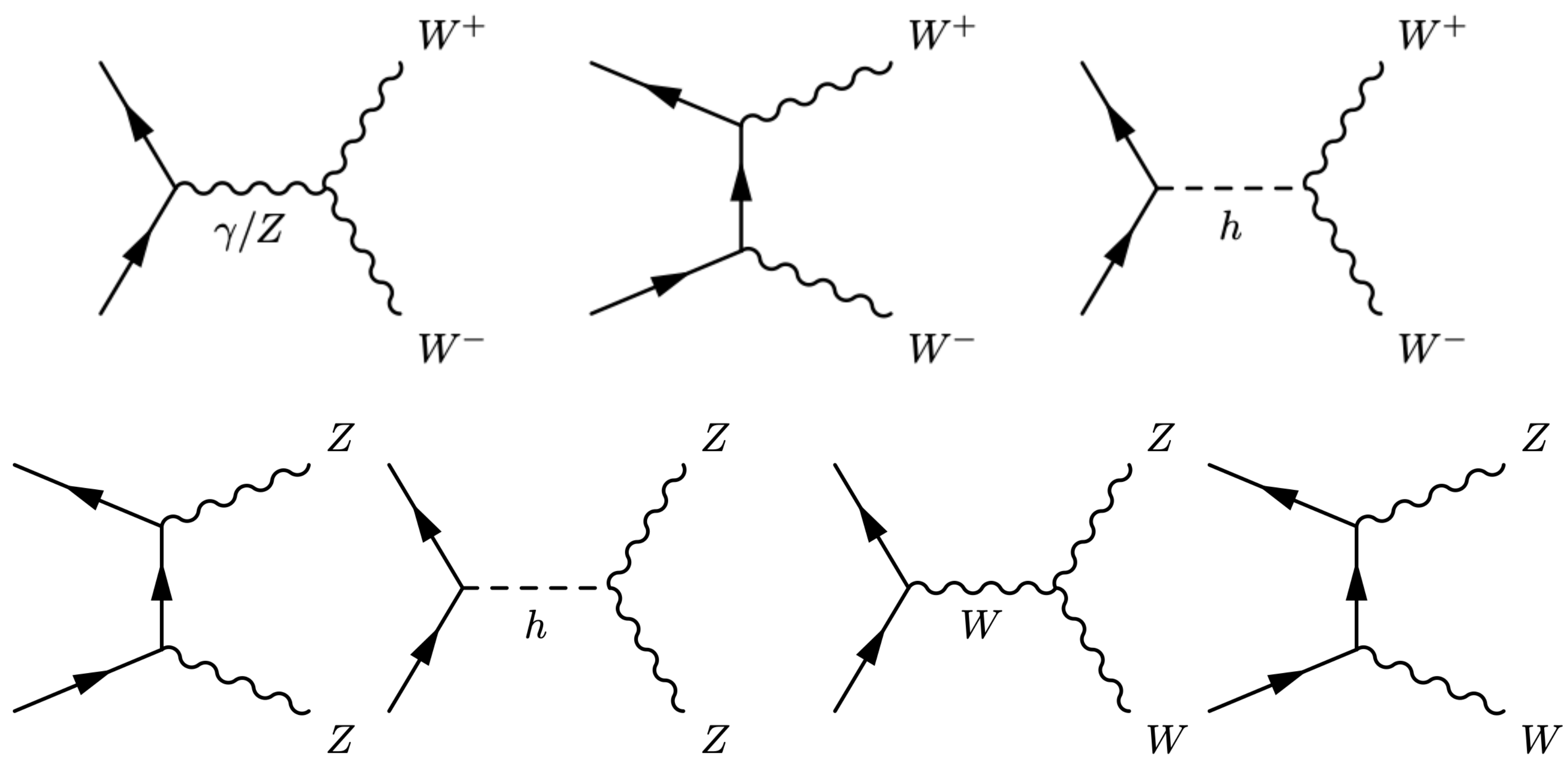
We studied both lepton and hadron collider



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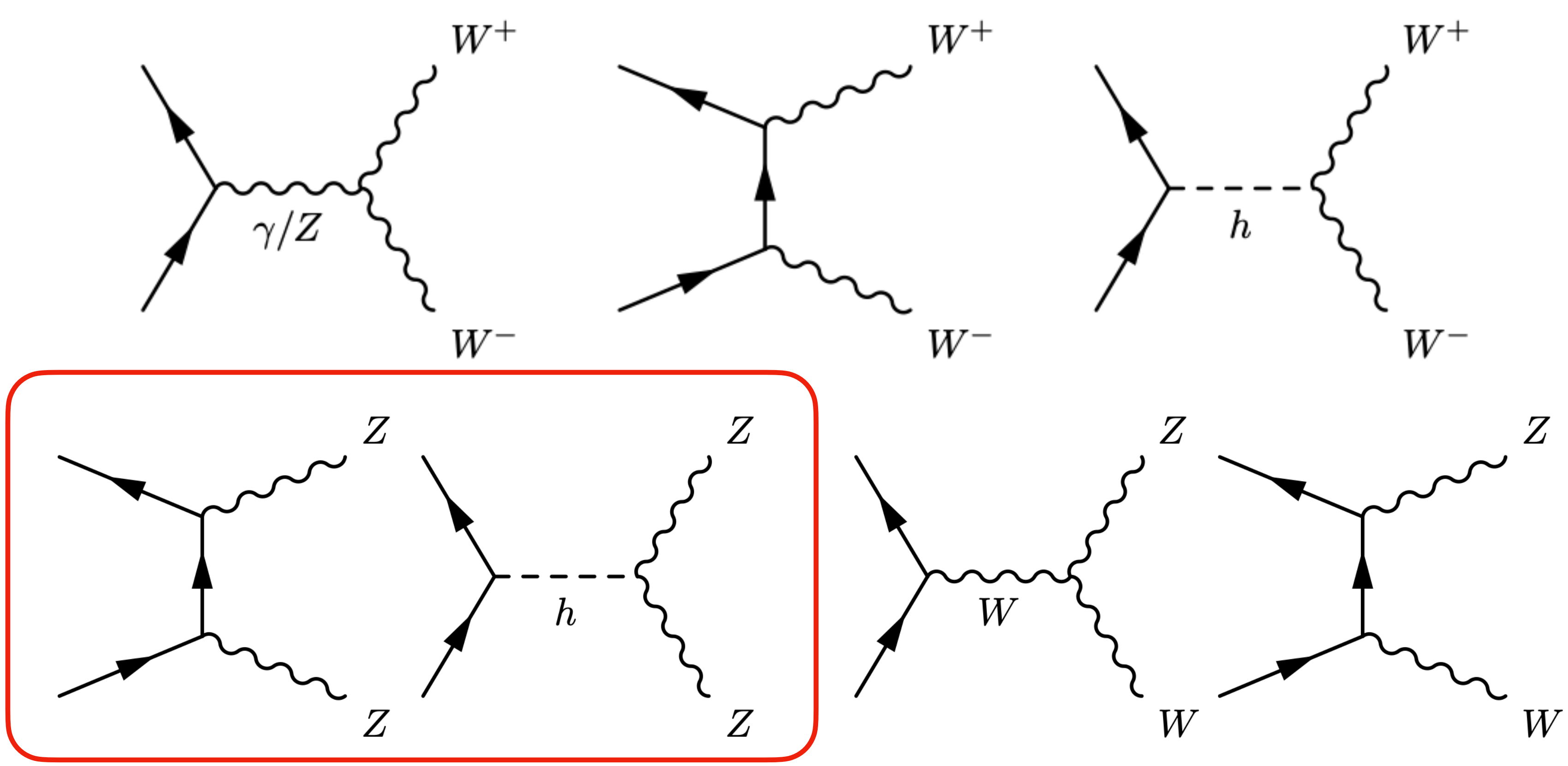
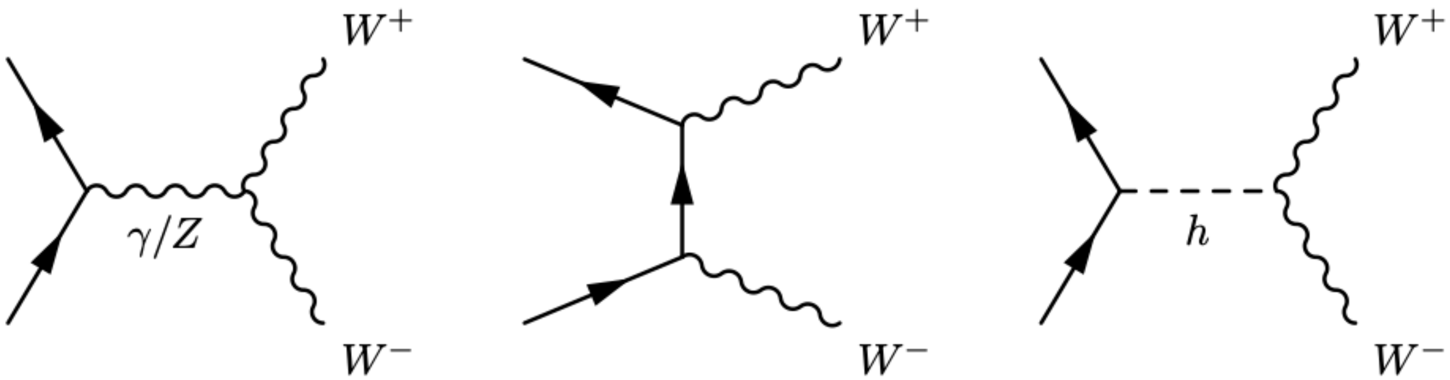
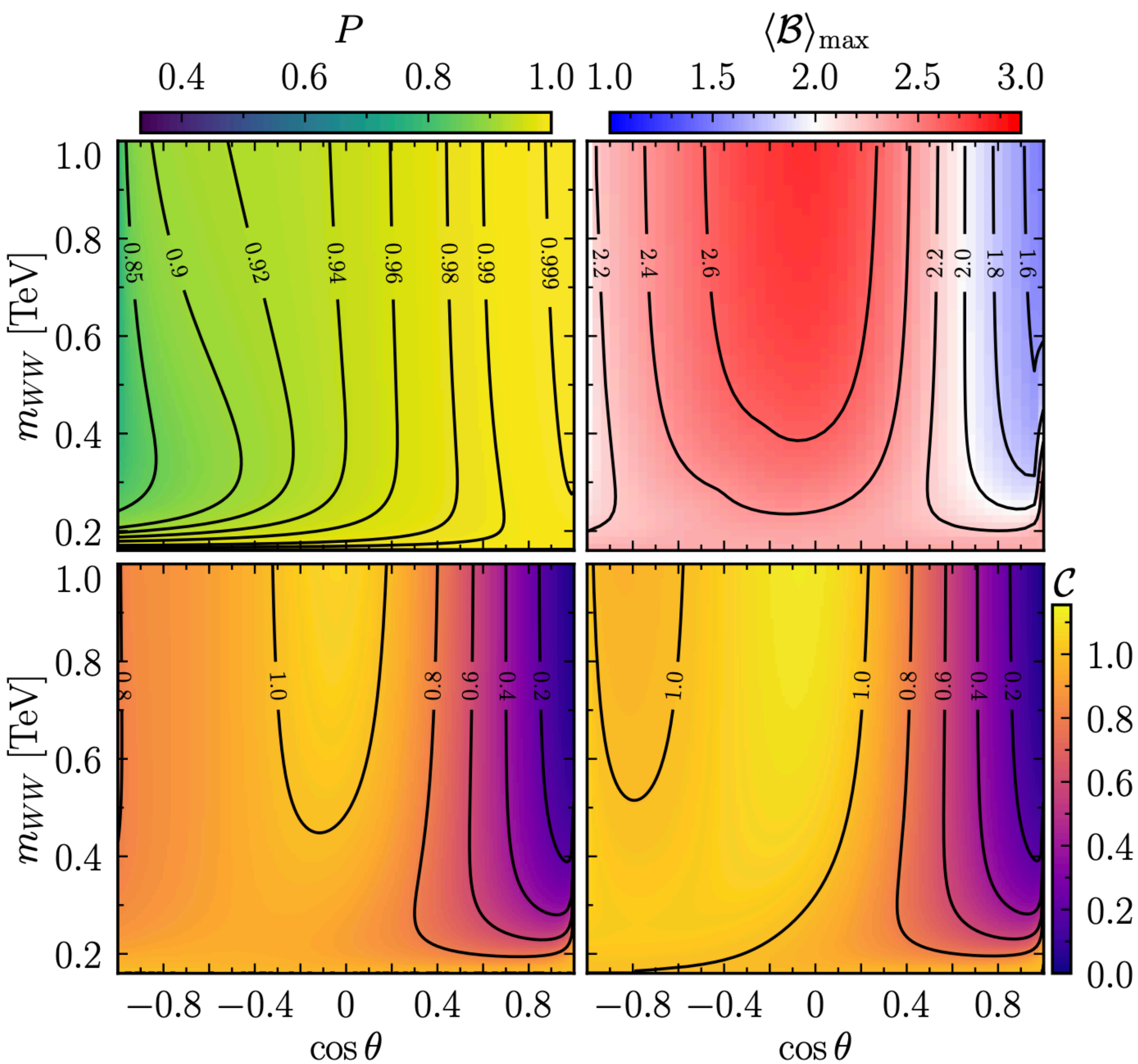
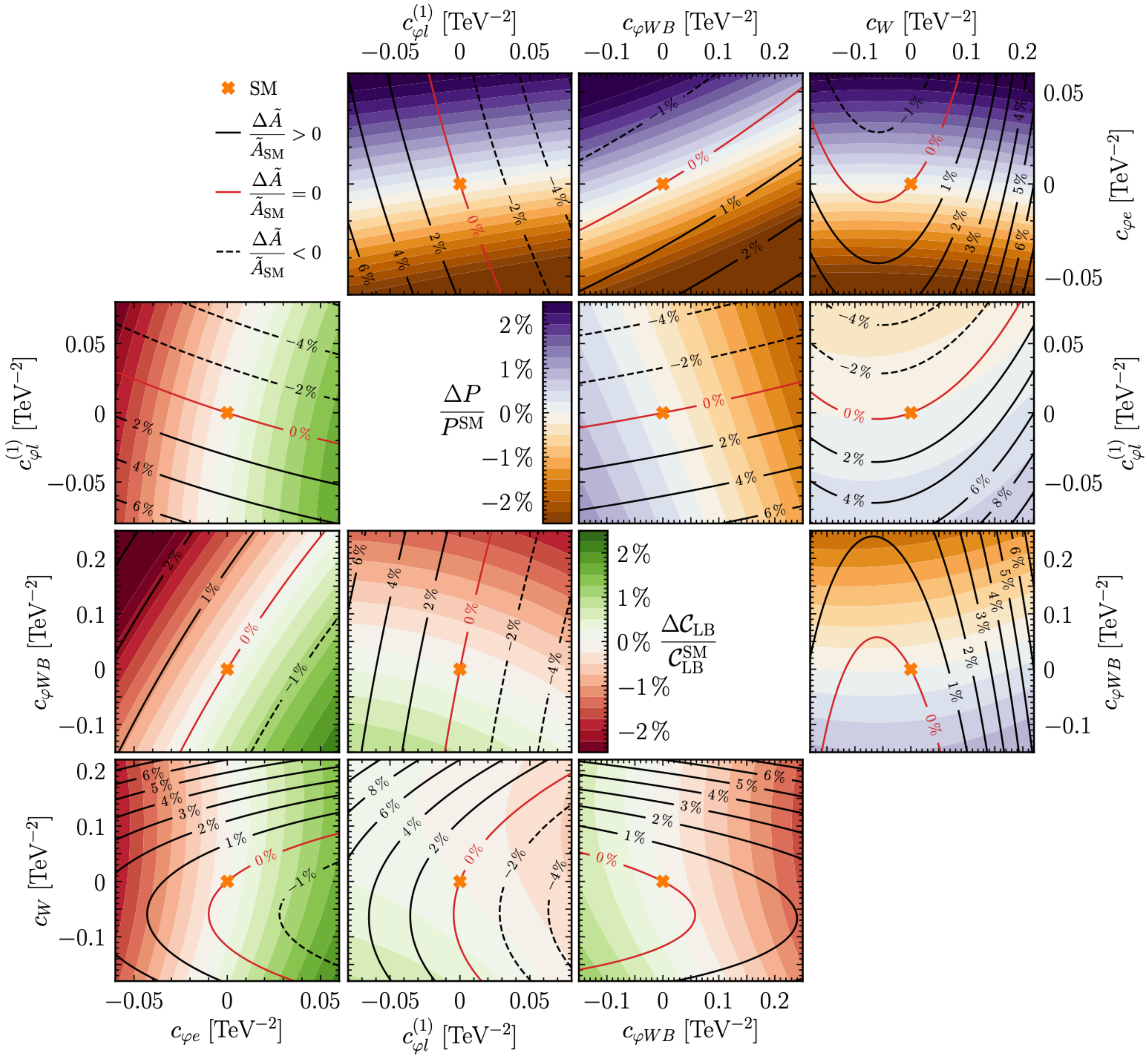
Not very sensitive





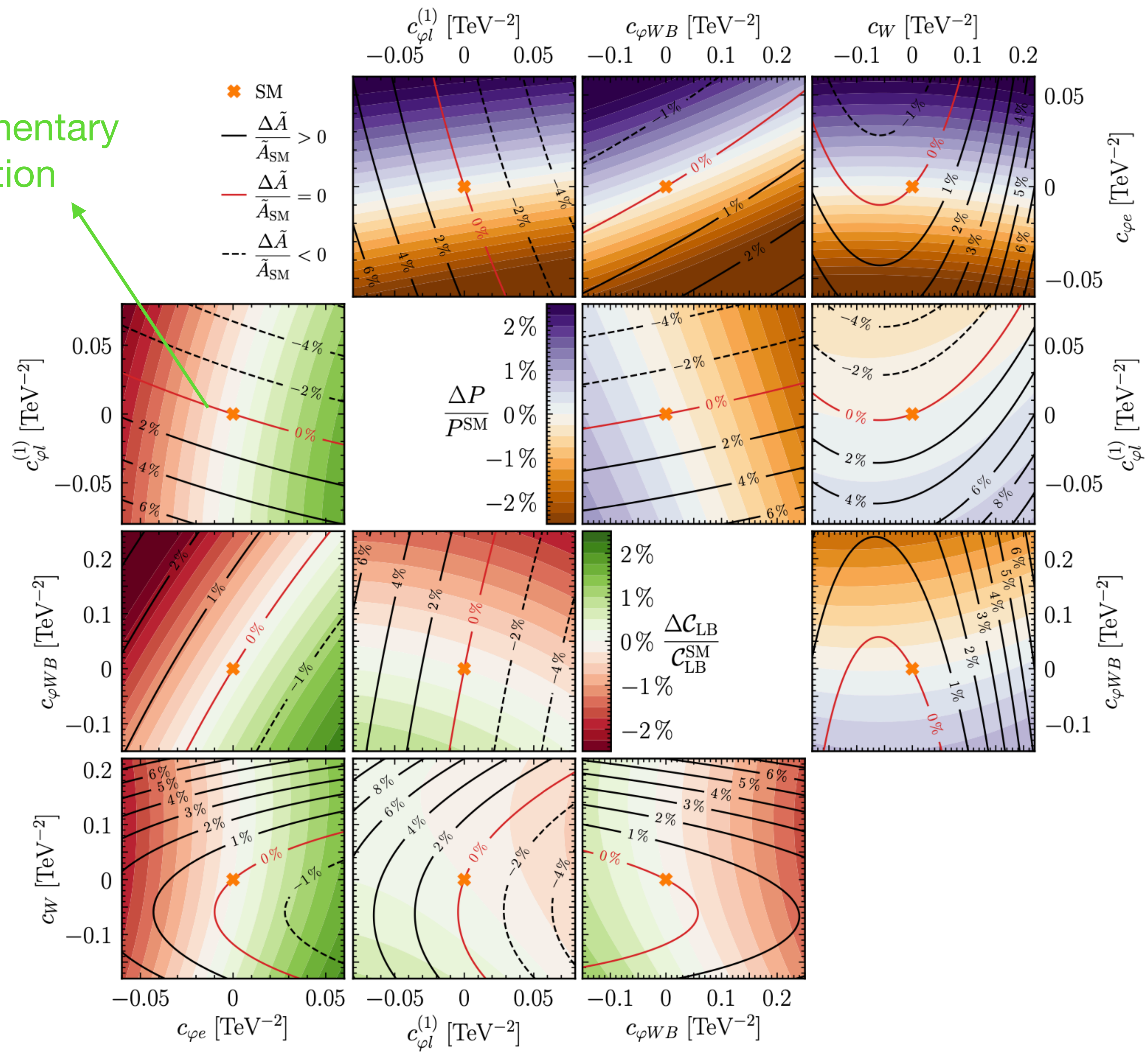


$$e^+e^- \to W^+W^-$$



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

Complementary direction



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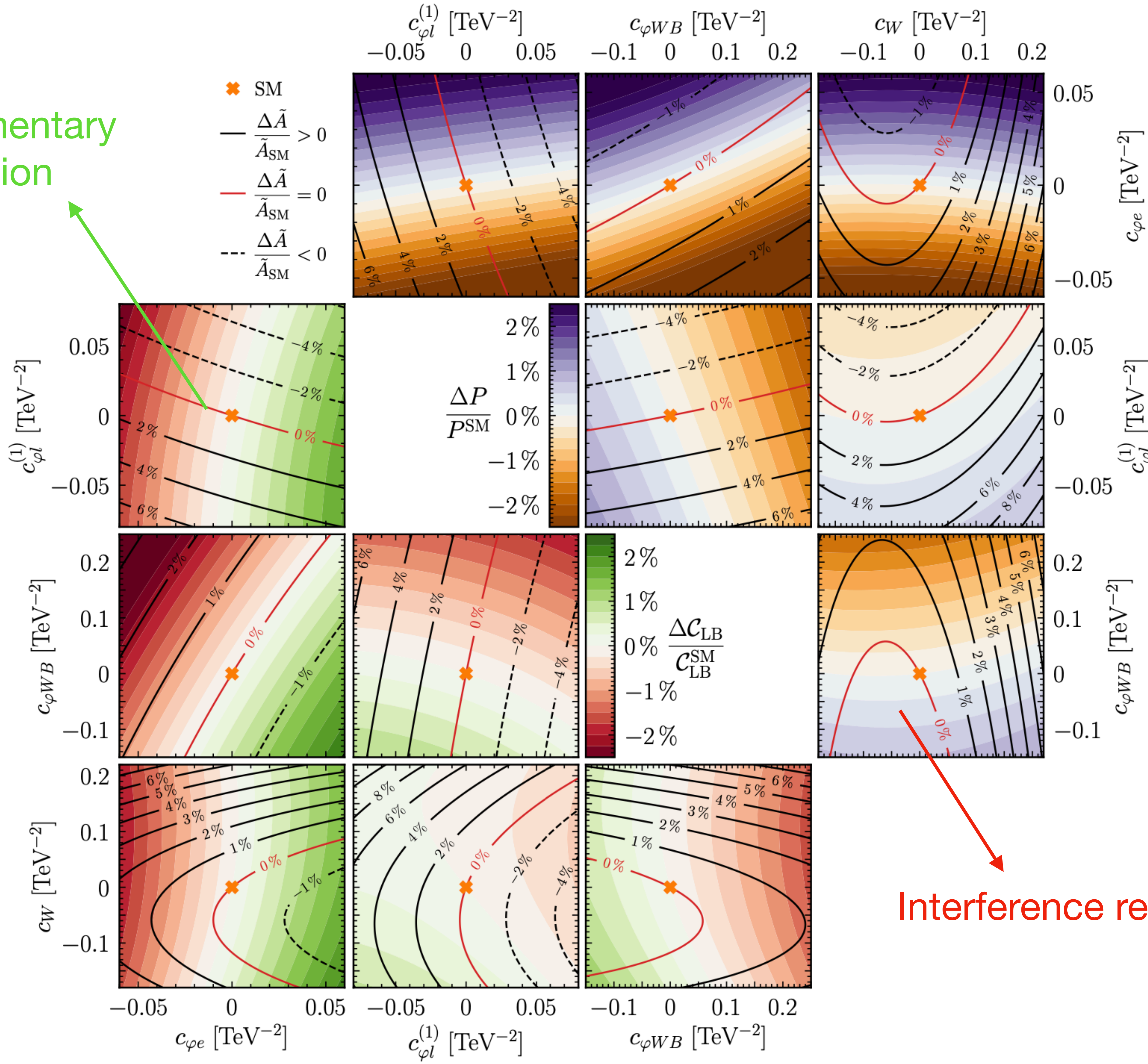
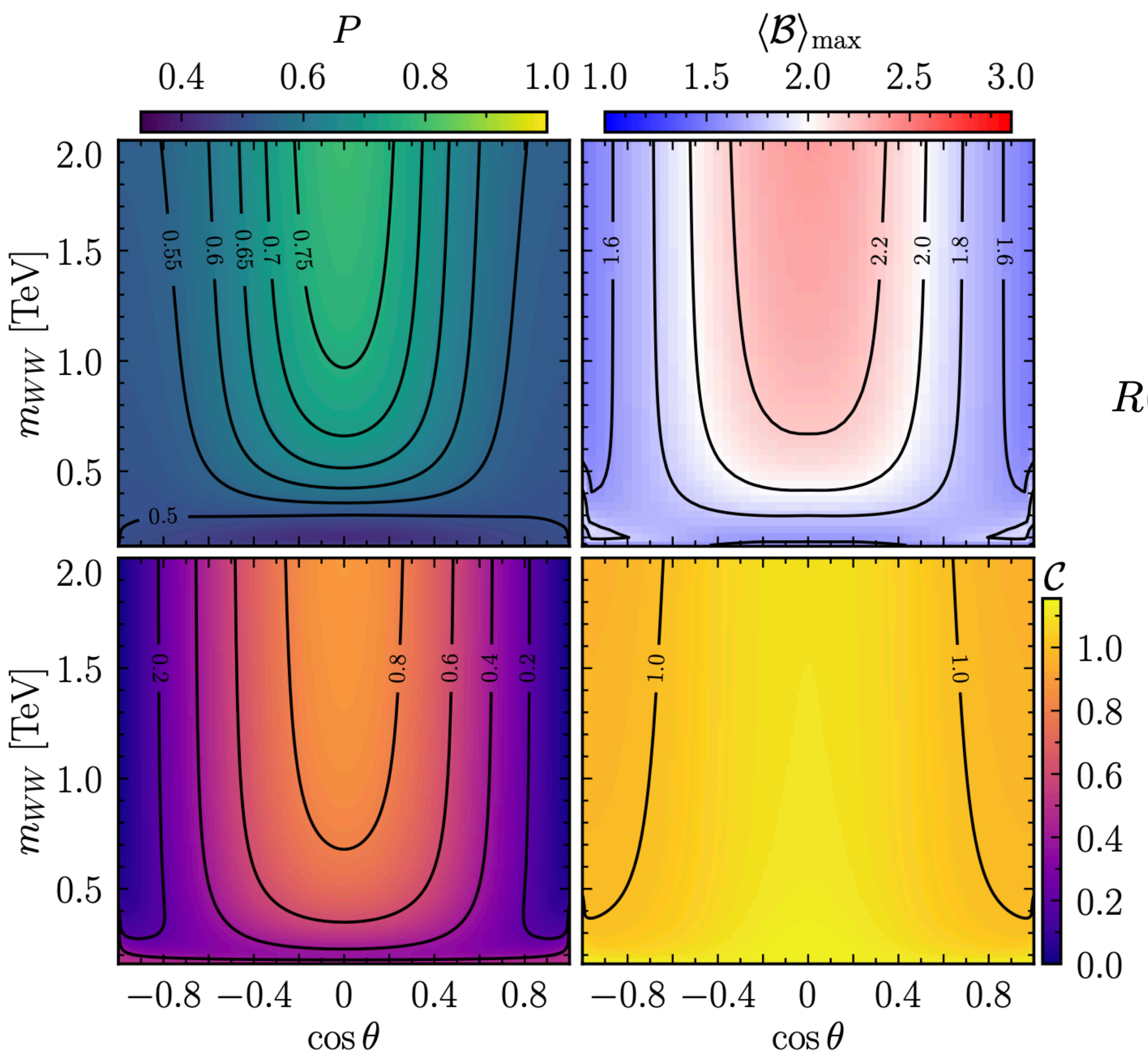


Interference resurrection

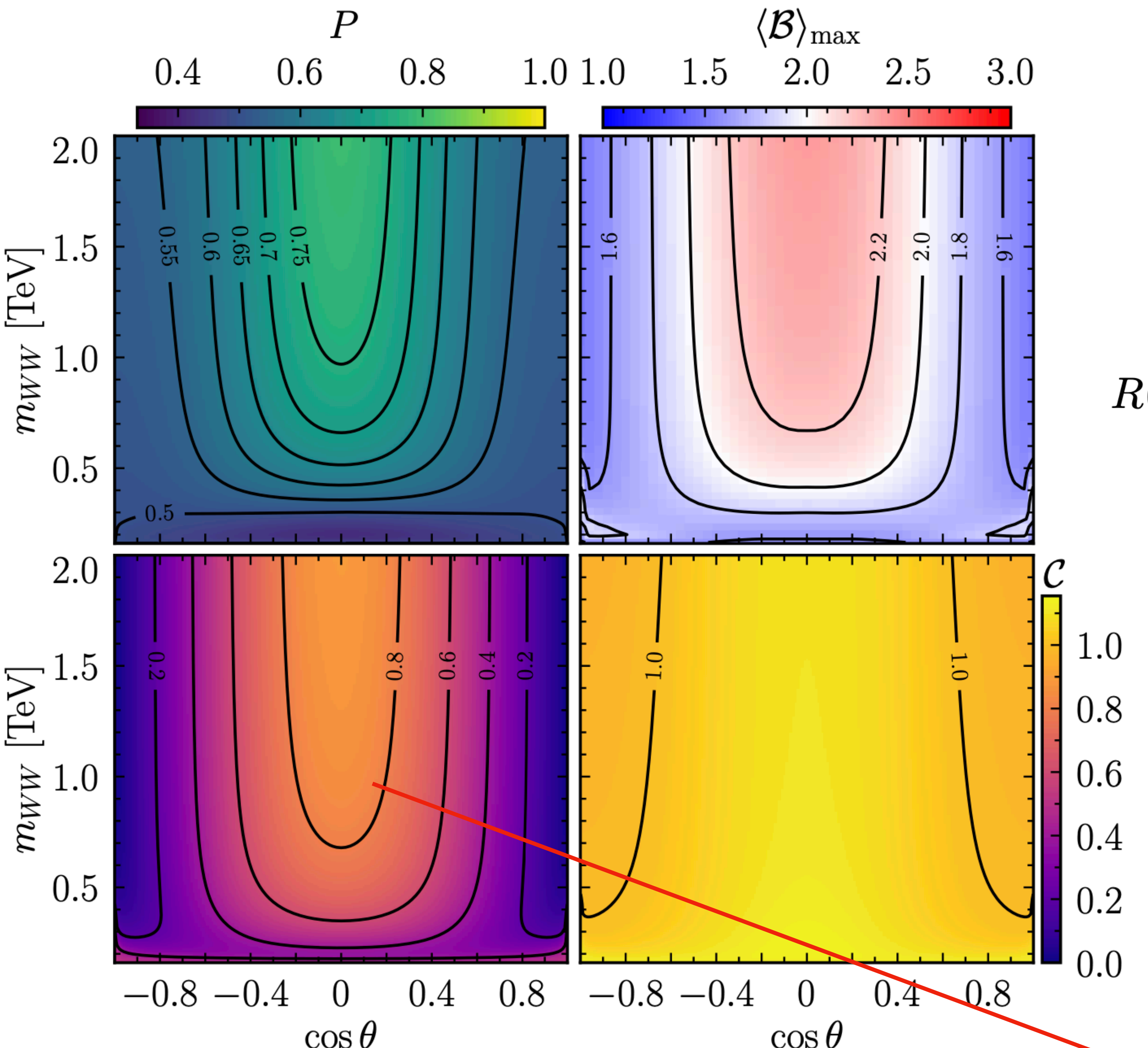
$$pp \to W^+W^-$$



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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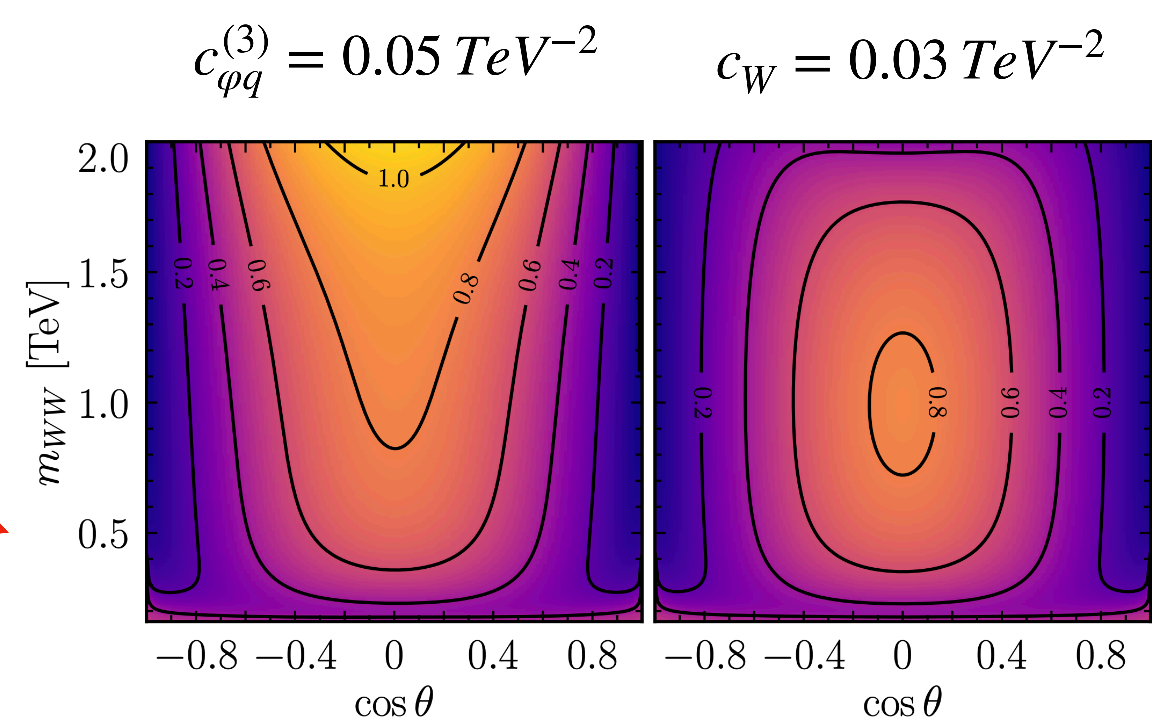

How do we reconstruct the spin density matrix at colliders?

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Quantum tomography

Measure angular distributions of the decay products

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Measure angular distributions of the decay products

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

$$\Phi_1^{P\pm} = \sqrt{2}(5\cos\theta \pm 1)\sin\theta\cos\phi$$
$$\Phi_2^{P\pm} = \sqrt{2}(5\cos\theta \pm 1)\sin\theta\sin\phi$$
$$\Phi_3^{P\pm} = \frac{1}{4}(\pm 4\cos\theta + 15\cos 2\theta + 5)$$
$$\Phi_4^{P\pm} = 5\sin^2\theta\cos 2\phi$$
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$$\Phi_7^{P\pm} = \sqrt{2}(\pm 1 - 5\cos\theta)\sin\theta\sin\phi$$
$$\Phi_8^{P\pm} = \frac{1}{4\sqrt{3}}(\pm 12\cos\theta - 15\cos 2\theta - 5)$$

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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.

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.) $\pm$ 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.

- Possibility to exploit quantum spin observables as entanglement proposed.
- Measurement of entanglement at LHC would be highest energy evidence ever.
- In the SM, specific spin configurations are expected, dictated by interactions.
- SMEFT effects induce presence of different quantum states, modifying the overall pattern.
- Quantum observables probe complementary directions to the cross-section in EFT param space and can resurrect the interference.

Conclusions

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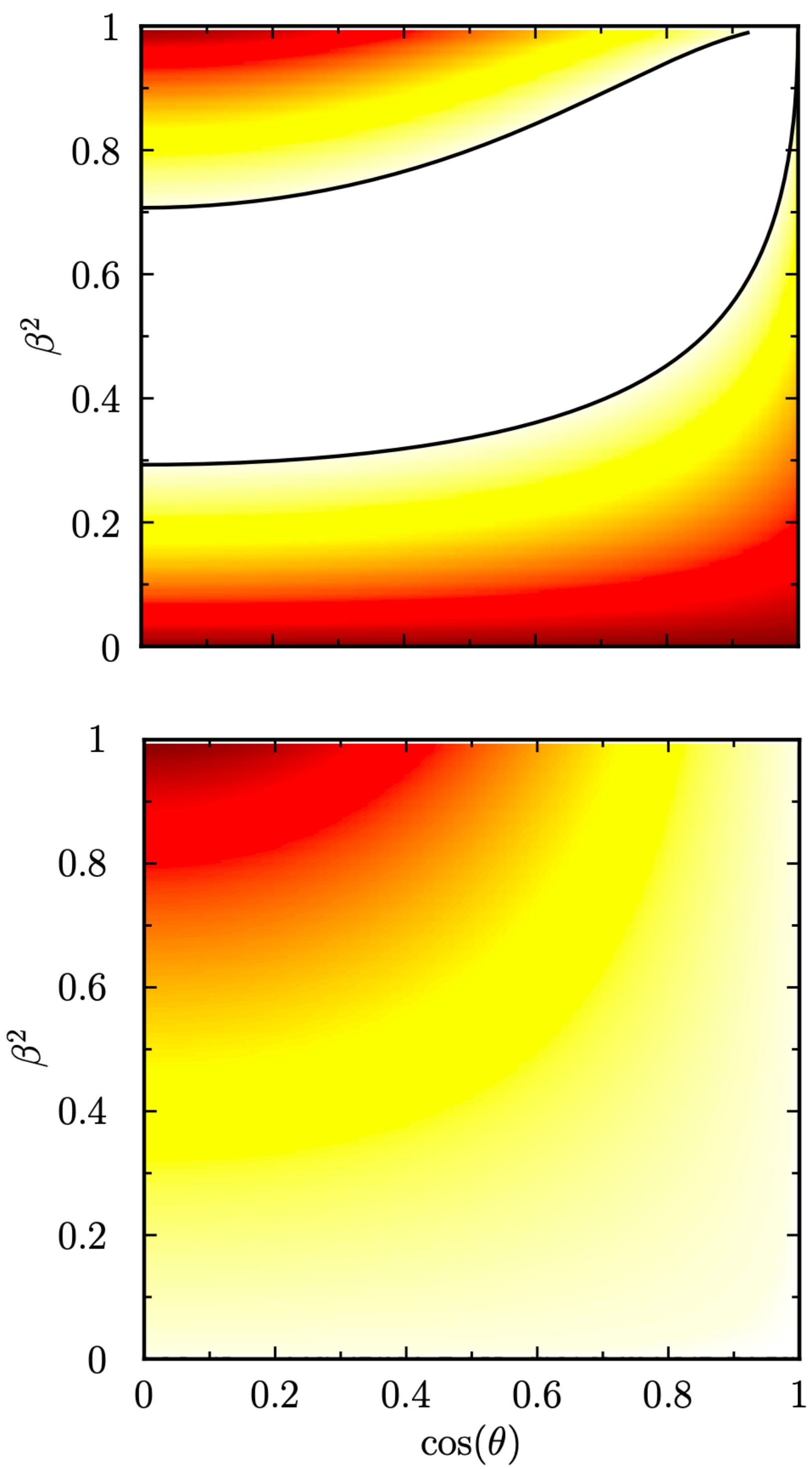
- Measurement of entanglement at LHC would be highest energy evidence ever.
- In the SM, specific spin configurations are expected, dictated by interactions.
- SMEFT effects induce presence of different quantum states, modifying the overall pattern.
- Quantum observables probe complementary directions to the cross-section in EFT param space and can resurrect the interference.

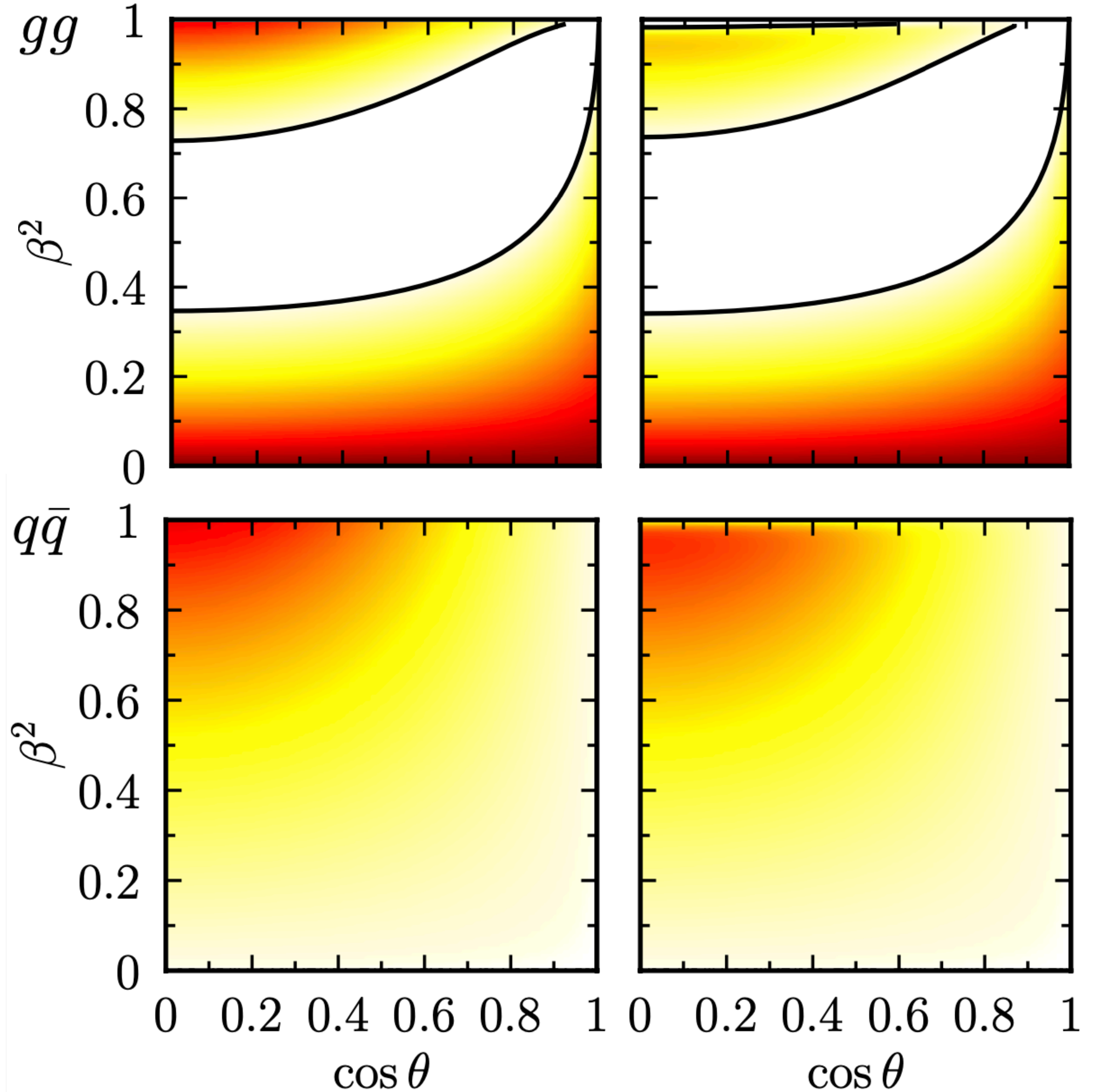
Backup

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

SM



Linear Quad



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

$\Delta_1 \equiv \Delta - \Delta_0$ — 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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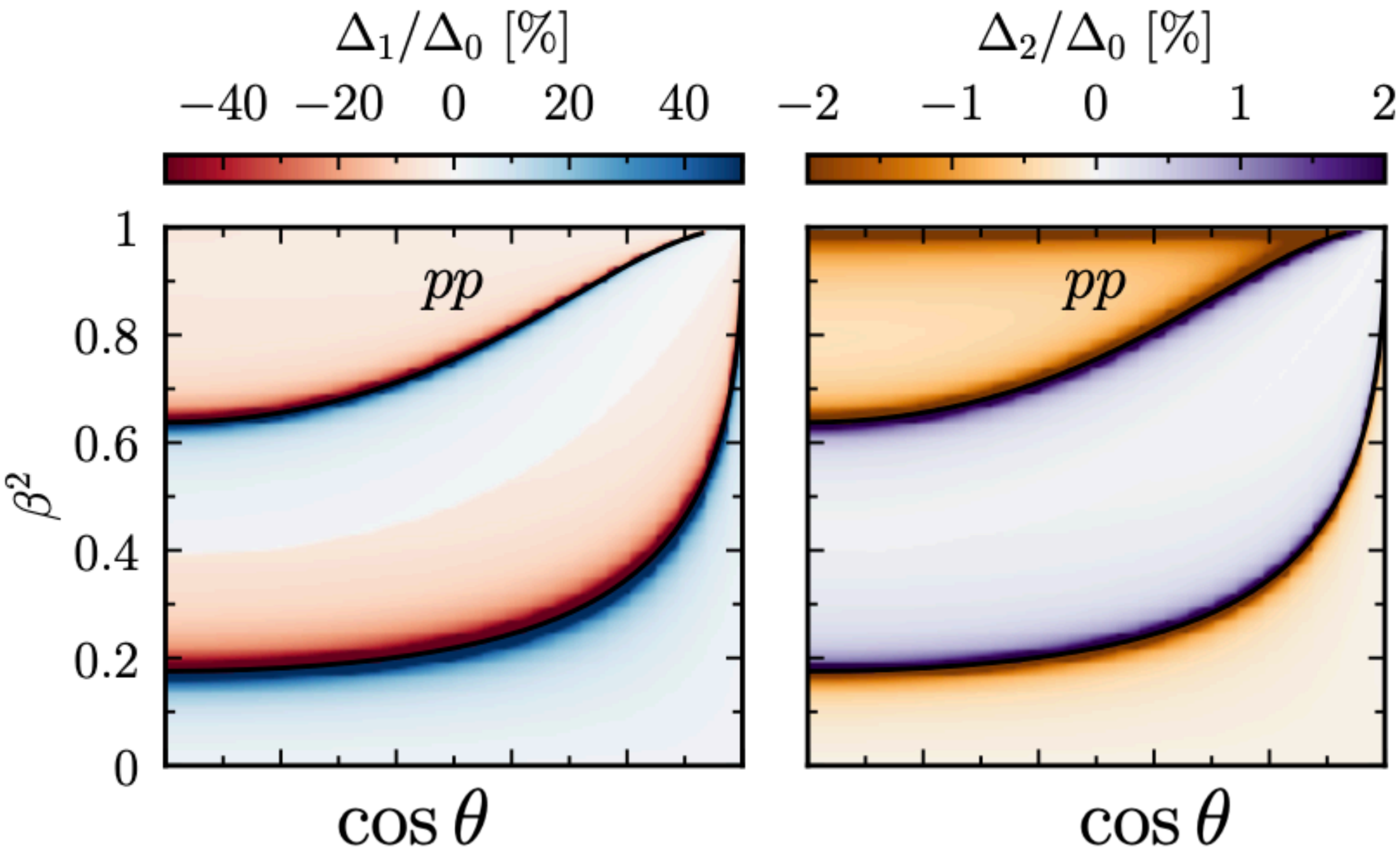

$$c_{tG}/\Lambda^2 = 0.1\,\mathrm{TeV}^{-2}$$

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

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

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

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

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

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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

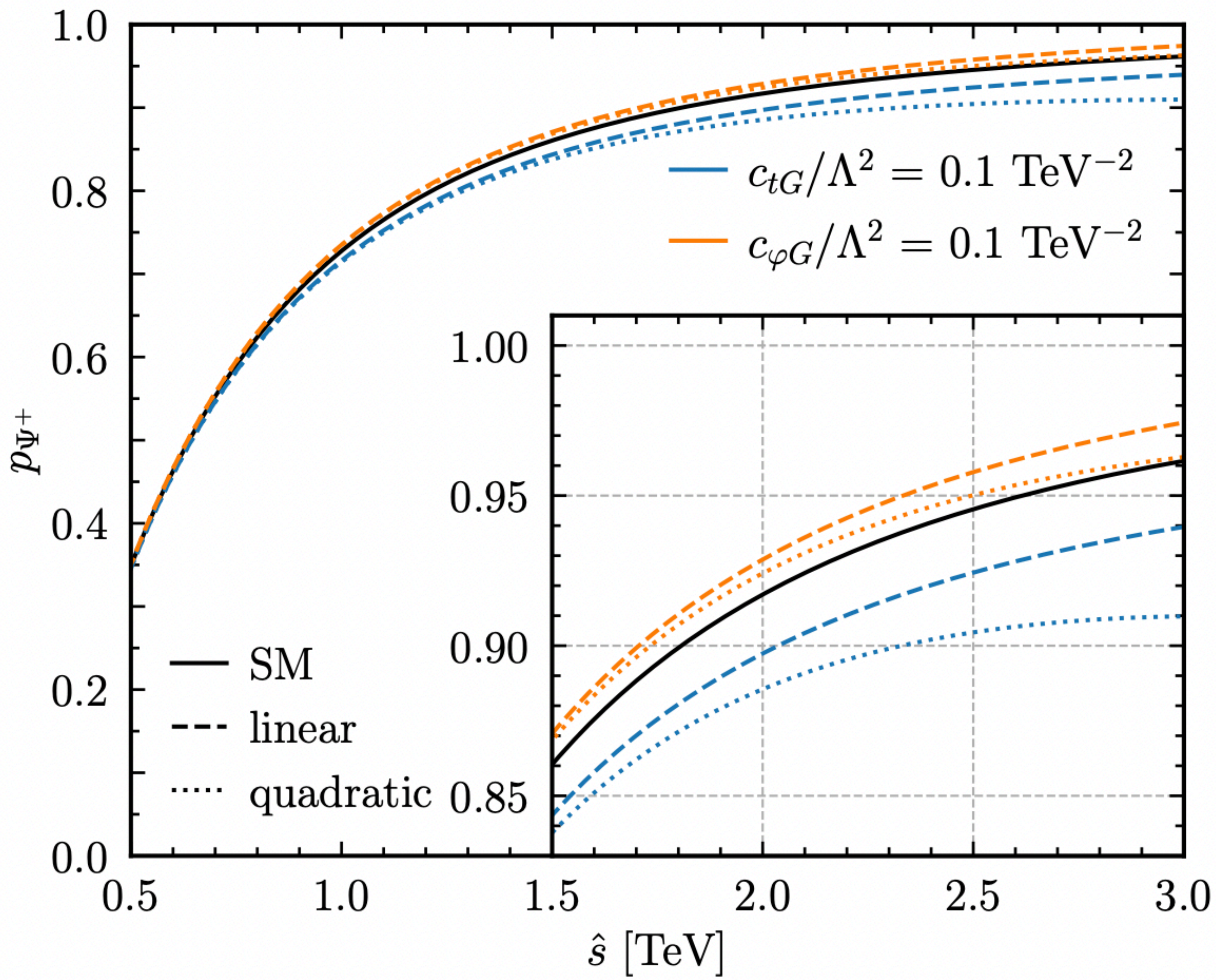
$$C[\rho] = \max(\Delta/2, 0)$$

$$C[\rho] = 1$$

Max entanglement

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

Probability triplet state



LO coefficients - gg channel

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

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

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

$$\tilde{C}_{rr}^{gg,(1)} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{g_s^2 v m_t\left(-9\beta^4\left(z-z^3\right)^2-7\beta^2\left(z^4-z^2+1\right)+7\right)}{12\sqrt{2}\left(\beta^2 z^2-1\right)}c_{tG}\right.$$
$$\left. - \frac{\beta^2 m_t^4}{4m_t^2-\left(1-\beta^2\right)m_h^2}c_{\varphi G} + \frac{9g_s^2\beta^2 m_t^2 z^2}{8}c_G\right],$$

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

LO coefficients - qq channel

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

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

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

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

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

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

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

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

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