Quantum Entanglement at Higgs Factory

Based on arXiv:25xx.xxxxx in collaboration with Yi-Jing Fang, Amit Bhoonah, Kun Cheng, Tao Han and Yandong Liu

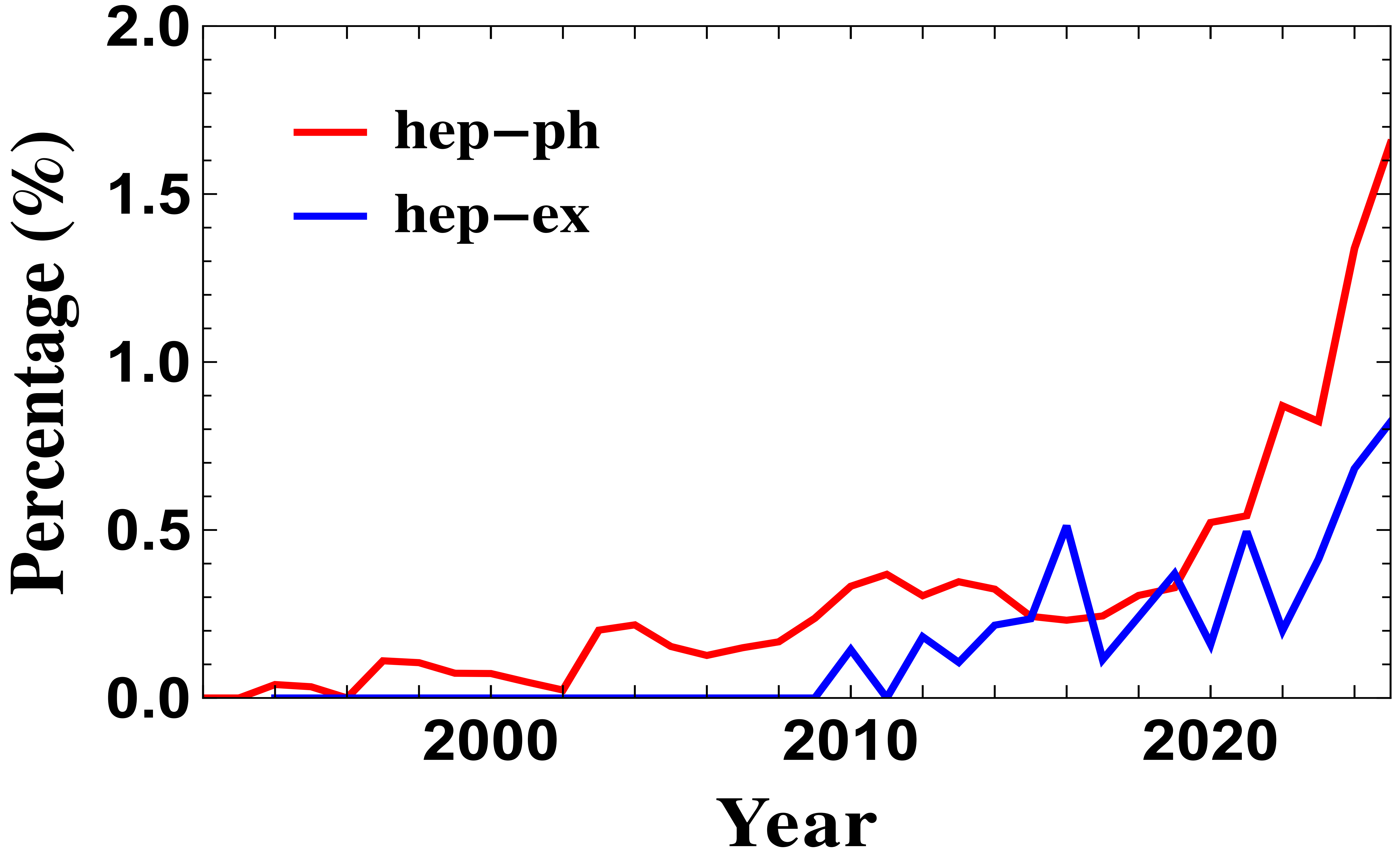
Hao Zhang

Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences

For The 2025 International Workshop on the High Energy Circular Electron Positron Collider, Guangzhou, Nov 8th, 2025

Quantum Entanglement at Colliders

- A "new" hot topic in particle physics.



Paper with "***entanglement***" in its title or abstract.

Quantum Entanglement at Colliders

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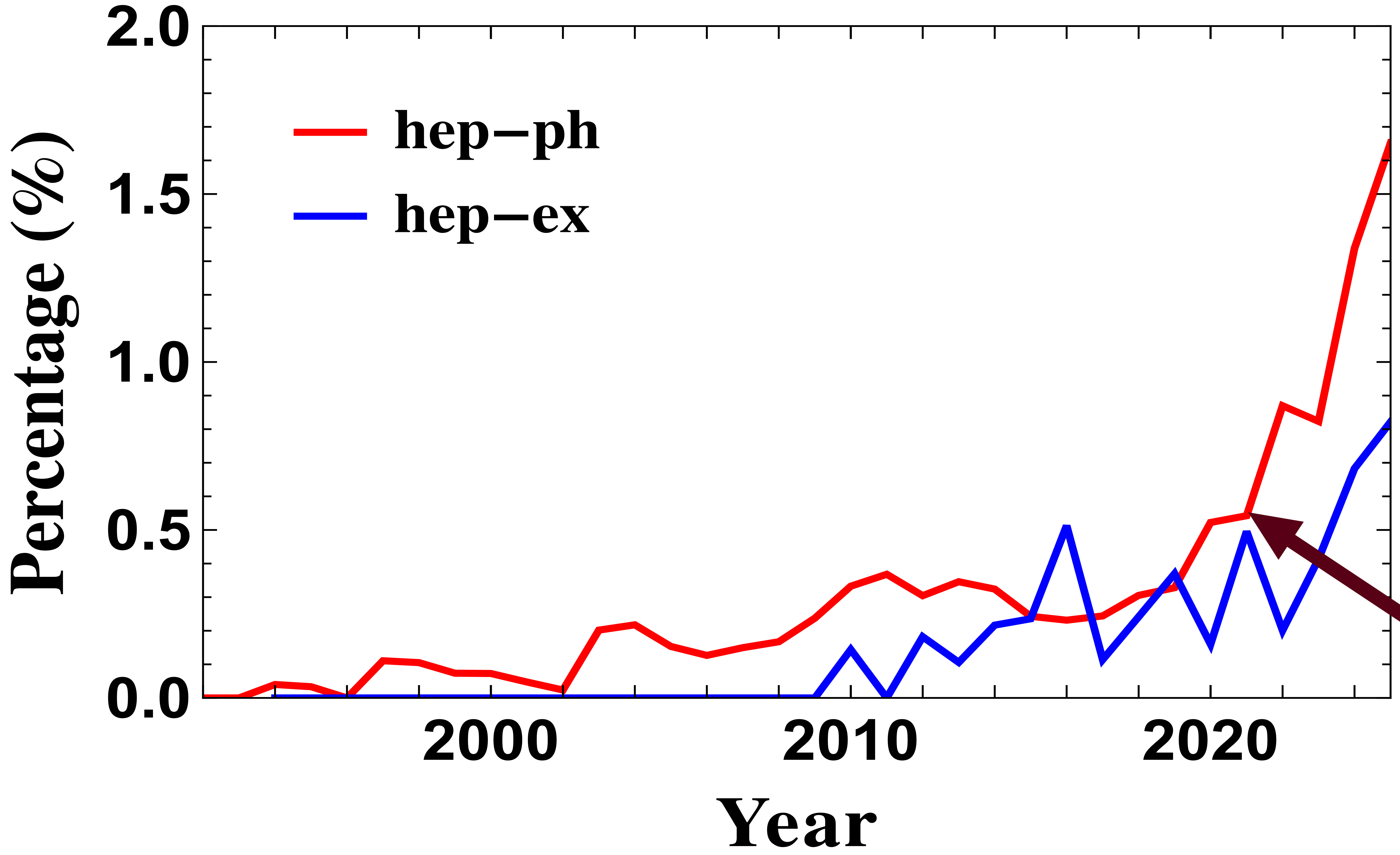

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Entanglement and quantum tomography with top quarks at the LHC

Regular Article | Open access | Published: 03 September 2021

Volume 136, article number 907, (2021) Cite this article

Quantum Entanglement at Colliders

- Lepton collider is efficient machine for preparing energetic entangled particles.

Quantum Entanglement at Colliders

- An example: top-pair production.
- The description of the degree of entanglement.
  - For 2×2 and 2×3 system, it could be measured by concurrence:

$$\mathscr{C}[\hat{\rho}] = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}, \quad 0 \leqslant \mathscr{C}[\hat{\rho}] \leqslant 1$$

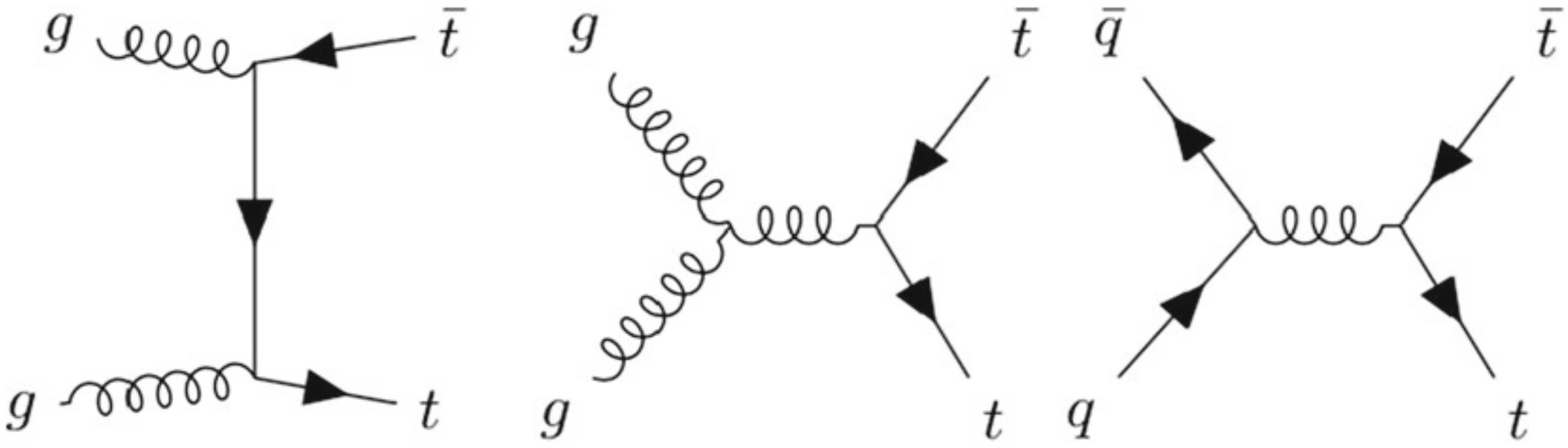
$$\lambda_i \in \sigma\left(\sqrt{\sqrt{\hat{\rho}}(\sigma_2 \otimes \sigma_2)\hat{\rho}^*(\sigma_2 \otimes \sigma_2)\sqrt{\hat{\rho}}}\right)$$

  - A state is entangled **iff** $\mathscr{C}[\hat{\rho}] > 0$.

A. Peres, “Separability Criterion for Density Matrices”, Phys. Rev. Lett. 77 (1996) 1413;
Michał Horodecki, Paweł Horodecki, Ryszard Horodecki, “Separability of mixed states: necessary and sufficient conditions”, Phys. Lett. A 223 (1996) 1.

Quantum Entanglement at Colliders

- An example: top-pair production.
- At the Large Hadron Collider:



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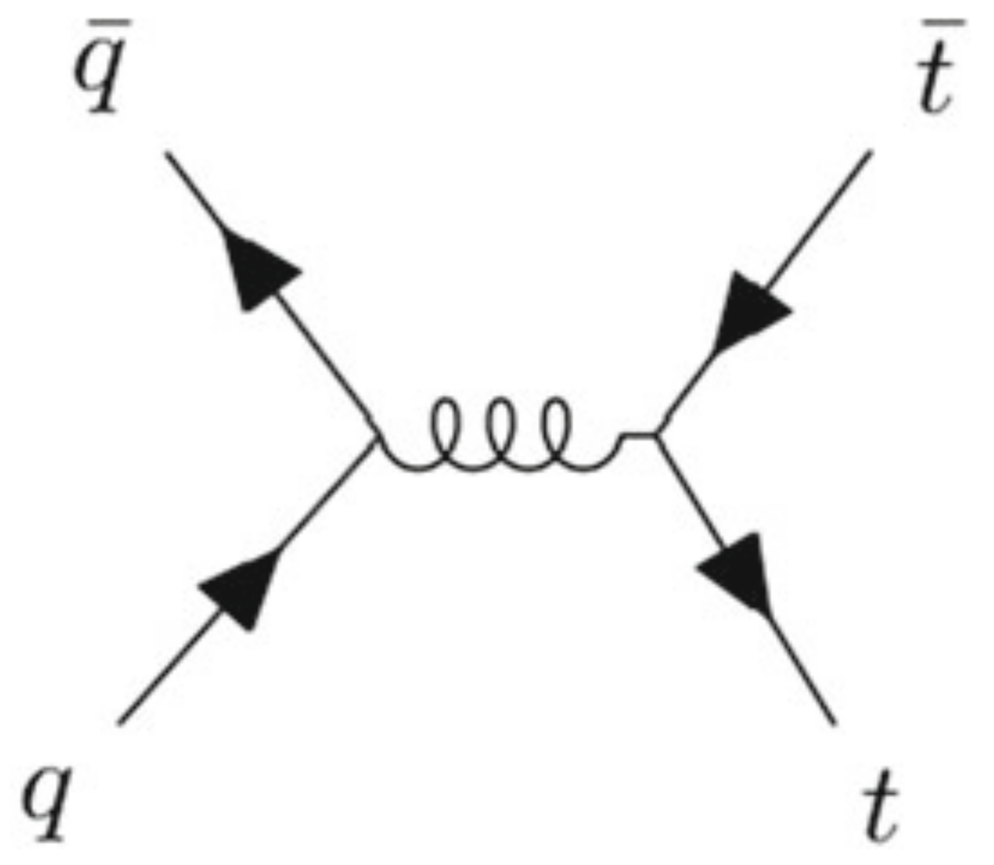


- s-channel:

  highly suppressed at high energy region

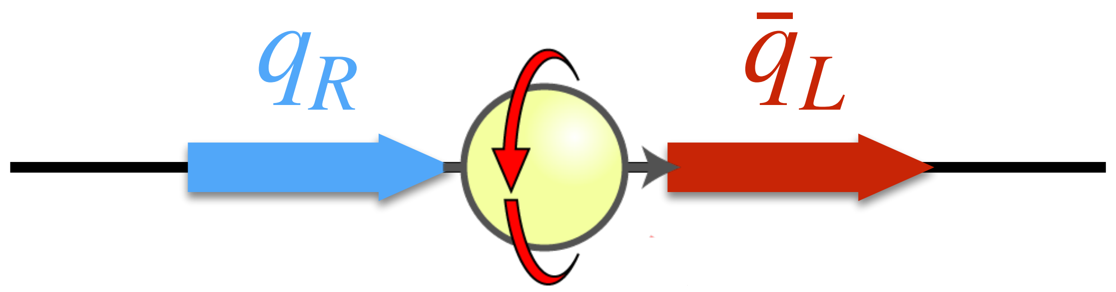
- quark-antiquark initial state:

  less in small-x region;

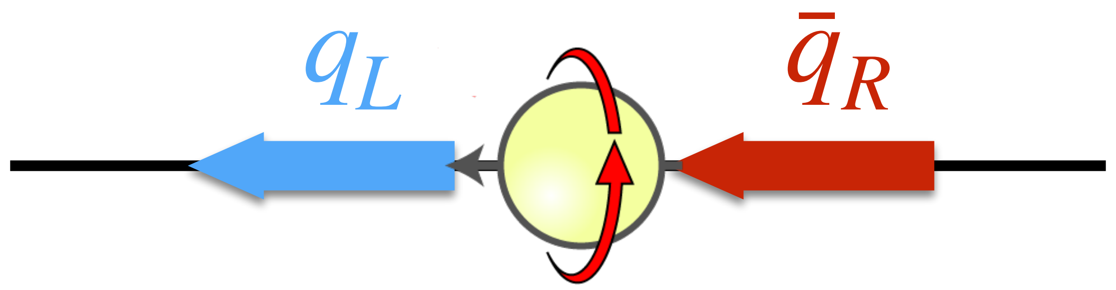
  boosted c.m. frame at high energy region.

Quantum Entanglement at Colliders

- An example: top-pair production.
- At the Large Hadron Collider:
  - Entanglement from quark-antiquark initial state



$(+-)$



$(-+)$

$$|\, t\bar{t}\rangle \sim (1 \pm \cos\theta)\,|\uparrow_{\hat{n}}\uparrow_{\hat{n}}\rangle + (1 \mp \cos\theta)\,|\downarrow_{\hat{n}}\downarrow_{\hat{n}}\rangle + \mathcal{O}(\gamma^{-1})$$

un(longitudinal)polarized initial state fermions, both left- and right-handed interactions

Quantum Entanglement at Colliders

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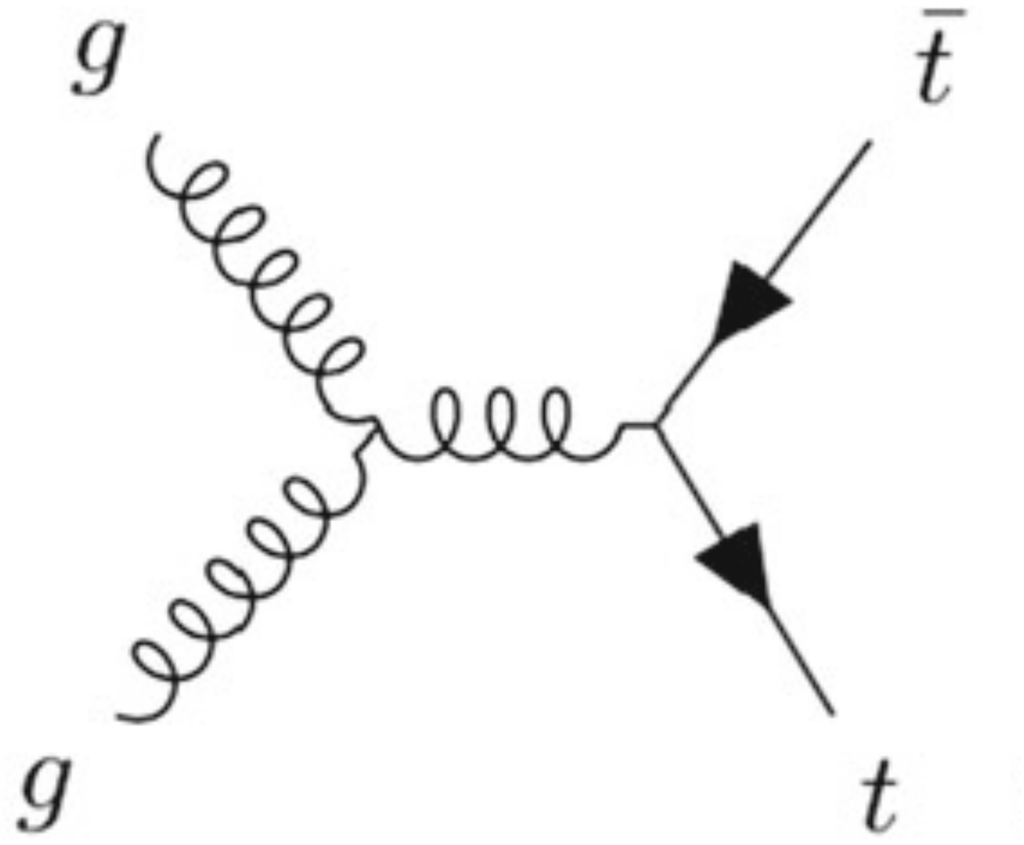

- s-channel:

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- gluon-gluon initial state:

  more in small-x region.

Quantum Entanglement at Colliders

- An example: top-pair production.
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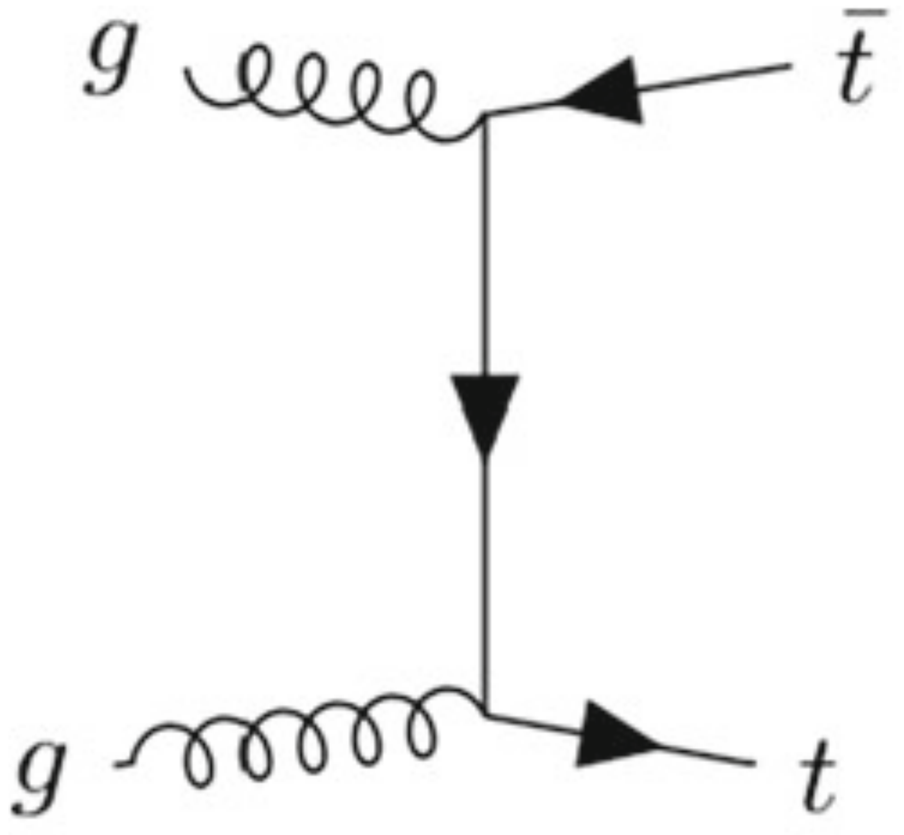


- t-channel:

  dominant at high energy region

- gluon-gluon initial state:

  more in small-x region.

Quantum Entanglement at Colliders

- An example: top-pair production.
- At the Large Hadron Collider:
  - Entanglement from gluon-gluon initial state

$$|t\bar{t}\rangle \sim (1 \pm \cos\theta)|\uparrow_{\hat{n}}\uparrow_{\hat{n}}\rangle + (1 \mp \cos\theta)|\downarrow_{\hat{n}}\downarrow_{\hat{n}}\rangle + \mathcal{O}(\gamma^{-1})$$

with another p-wave suppression factor.

Quantum Entanglement at Colliders

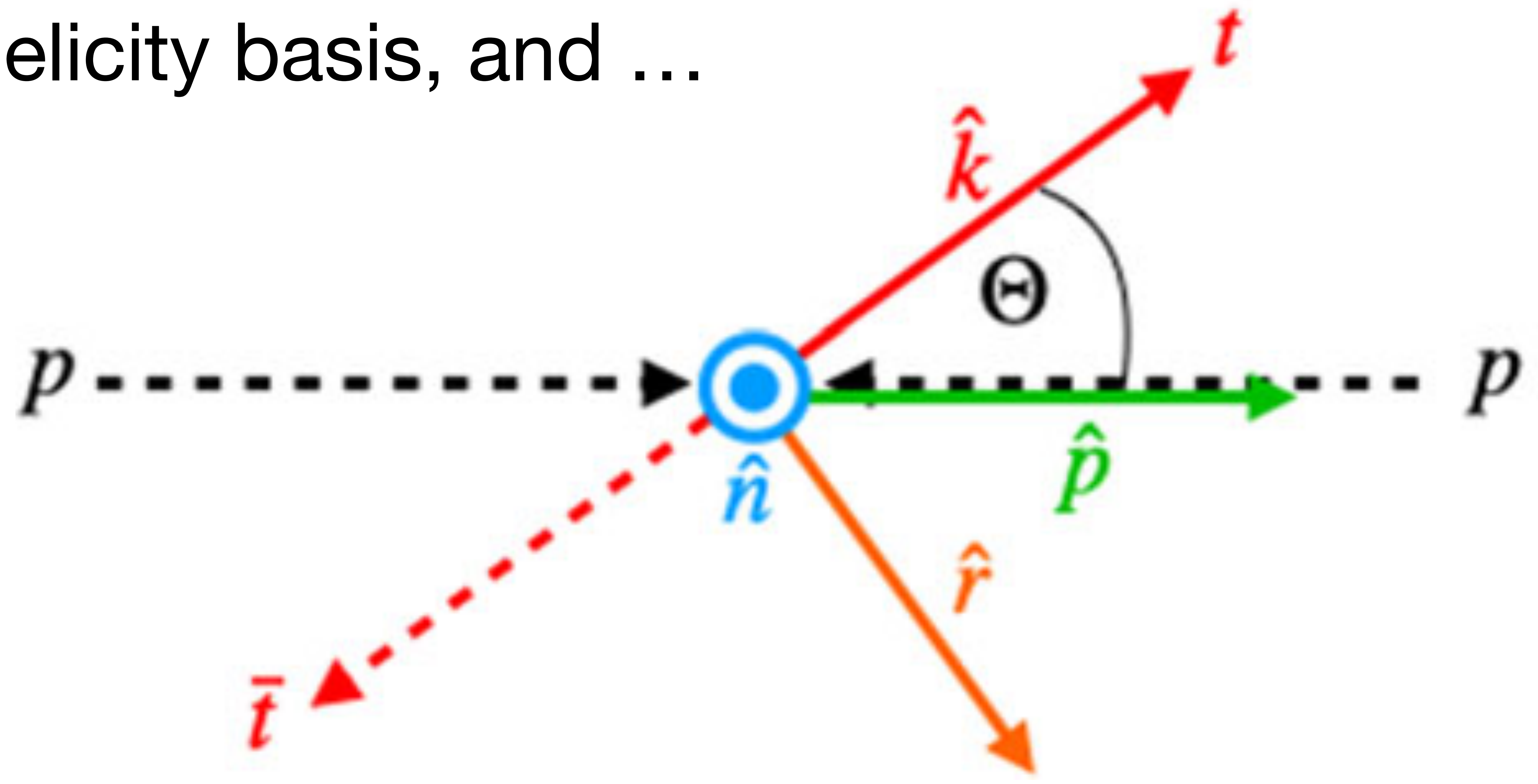
- An example: top-pair production.
- At the Large Hadron Collider:
  - Entanglement from gluon-gluon initial state

$$|t\bar{t}\rangle \sim (1 \pm \beta)|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle - (1 \mp \beta)|\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle$$

Unfortunately, the direction $\hat{n}$ is different event by event.

Quantum Entanglement at Colliders

- An example: top-pair production.
- At the Large Hadron Collider: helicity basis, and …



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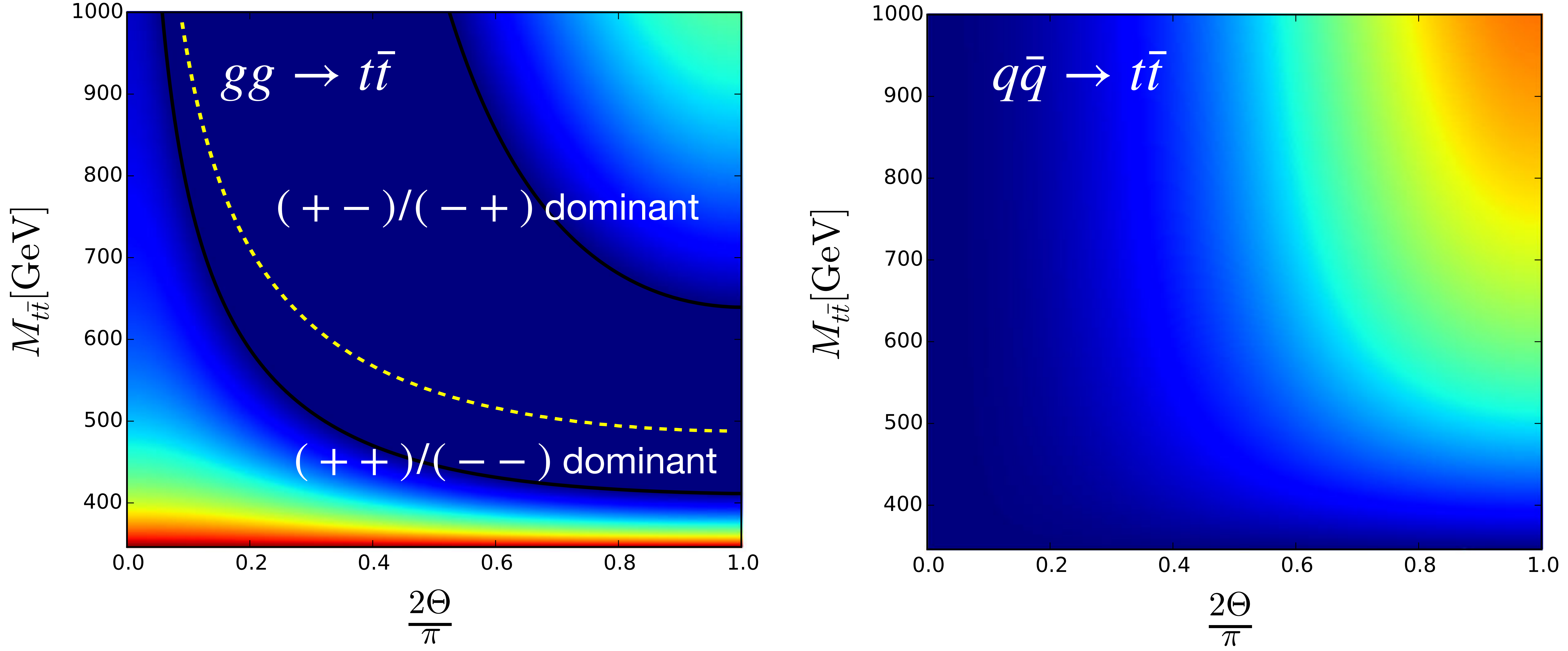
- An example: top-pair production.
- At the Large Hadron Collider: helicity basis



Y. Afik, J. R. M. de Nova, Eur. Phys. J. Plus, (2021) 136:907.

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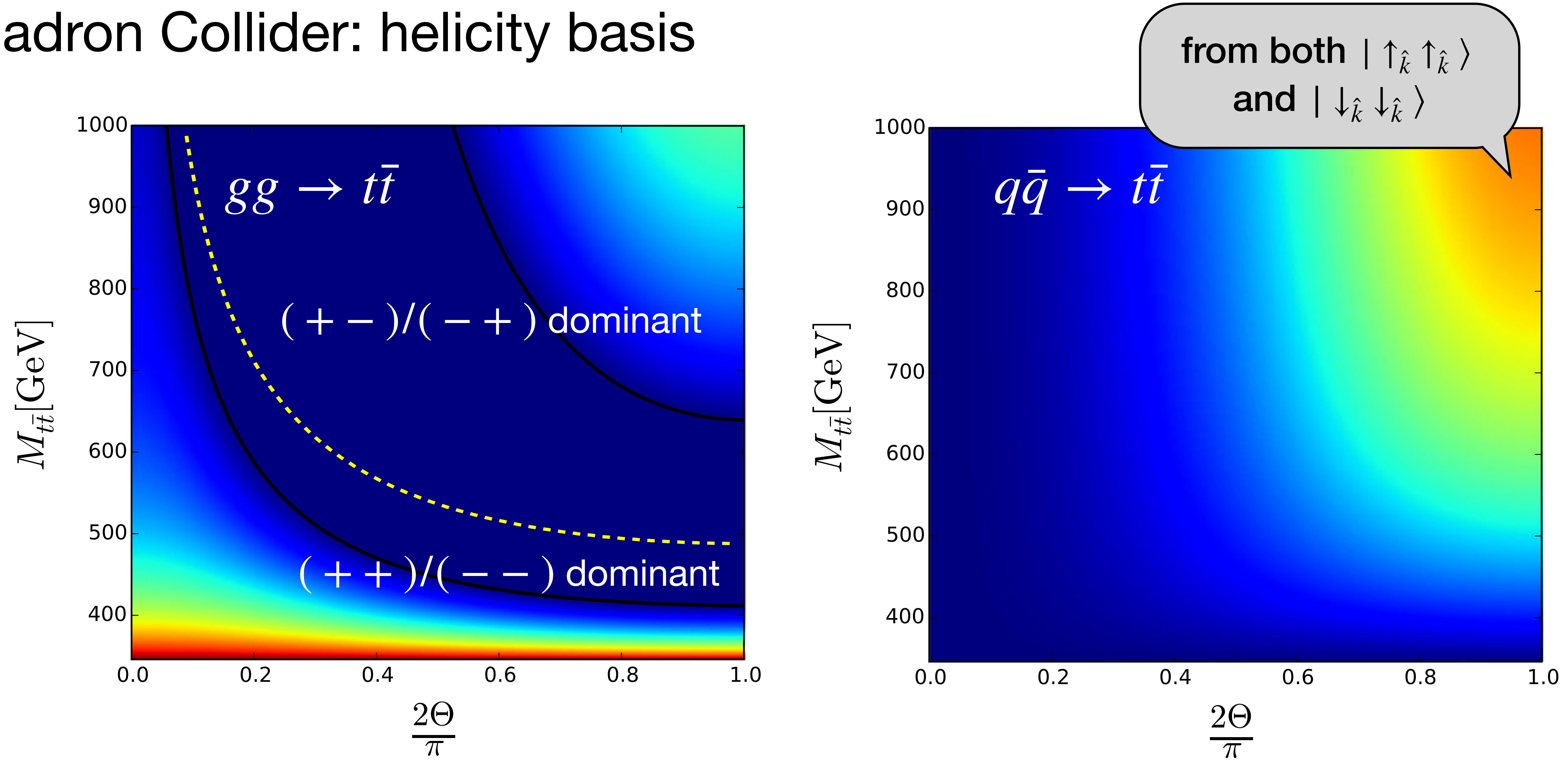

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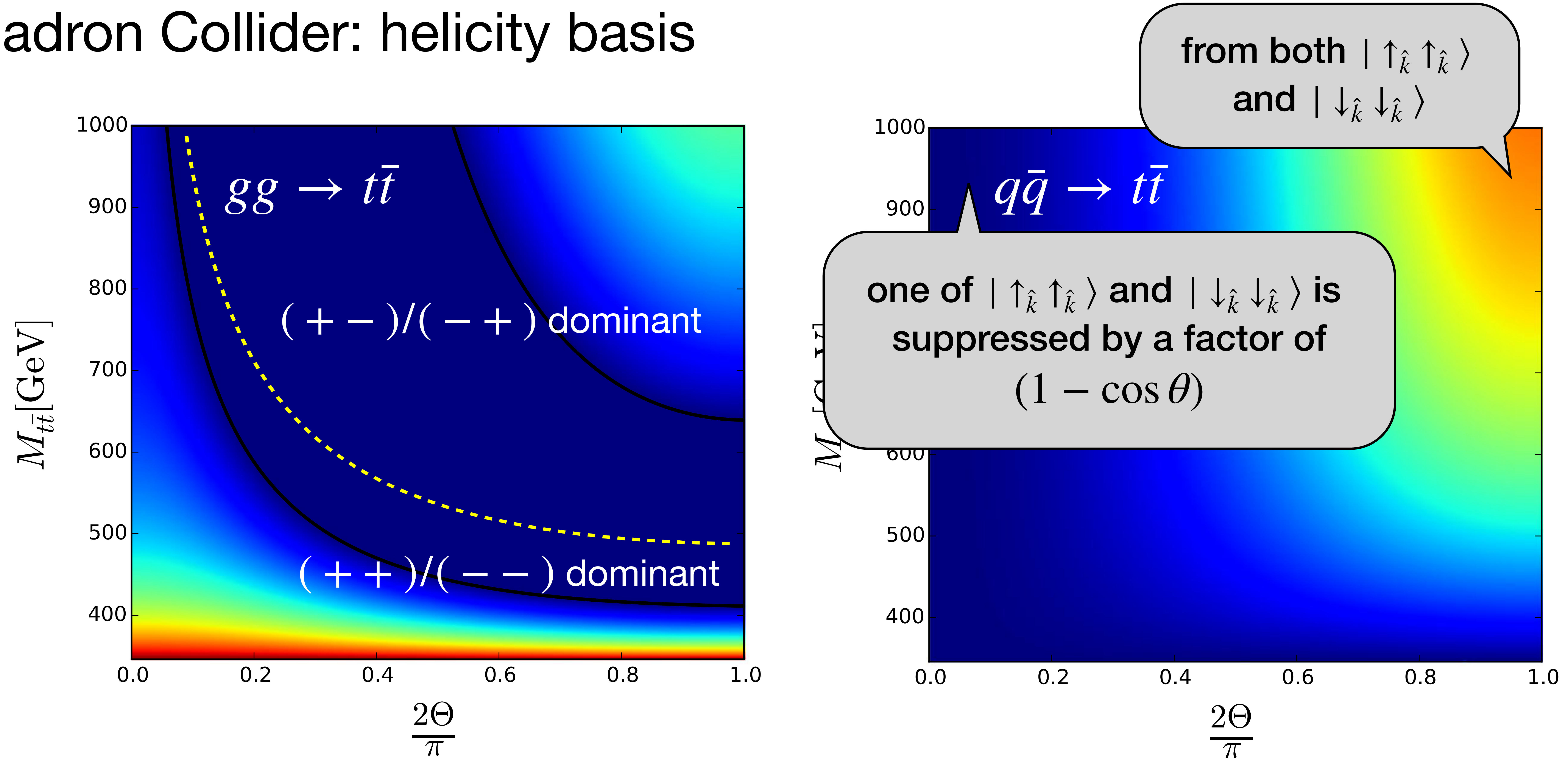

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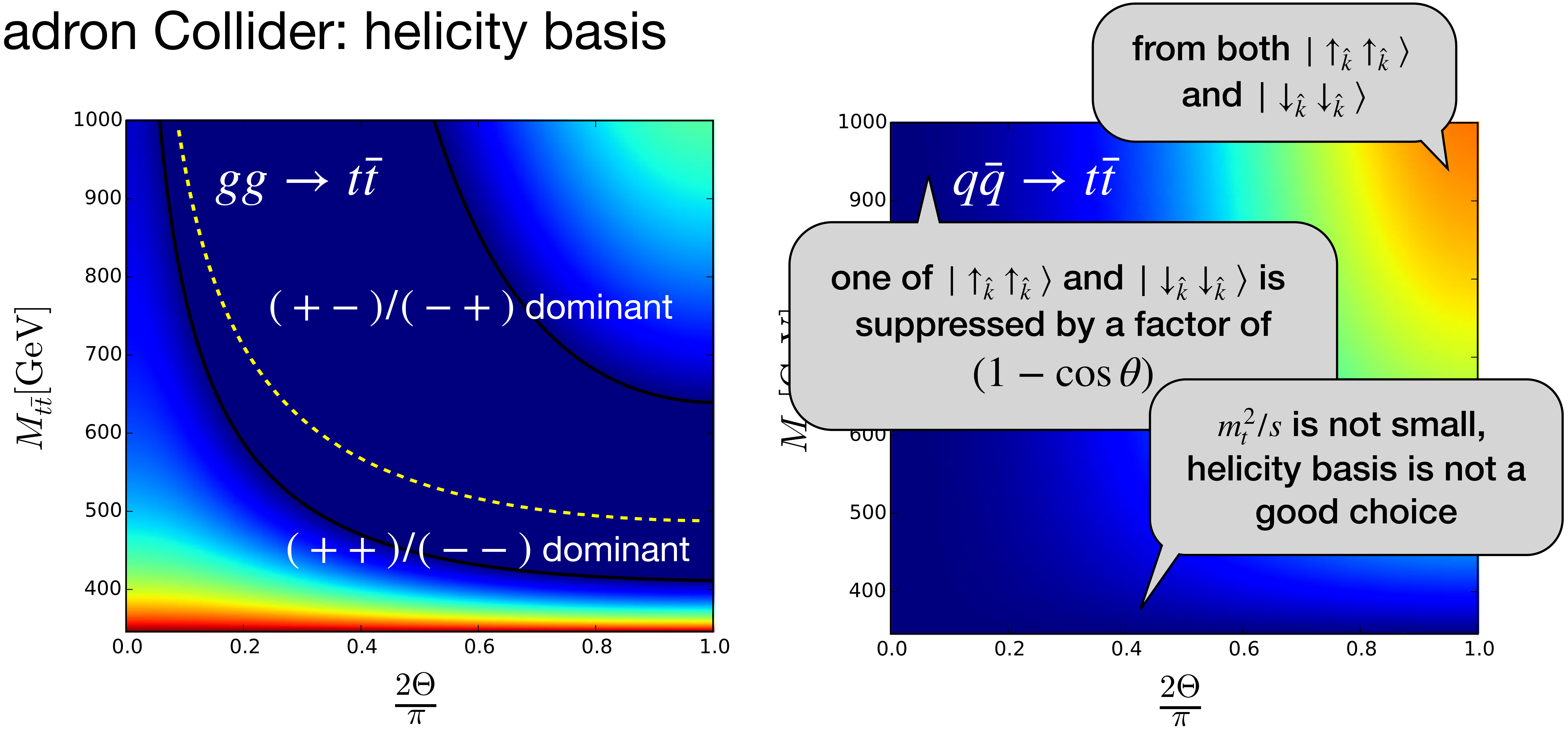

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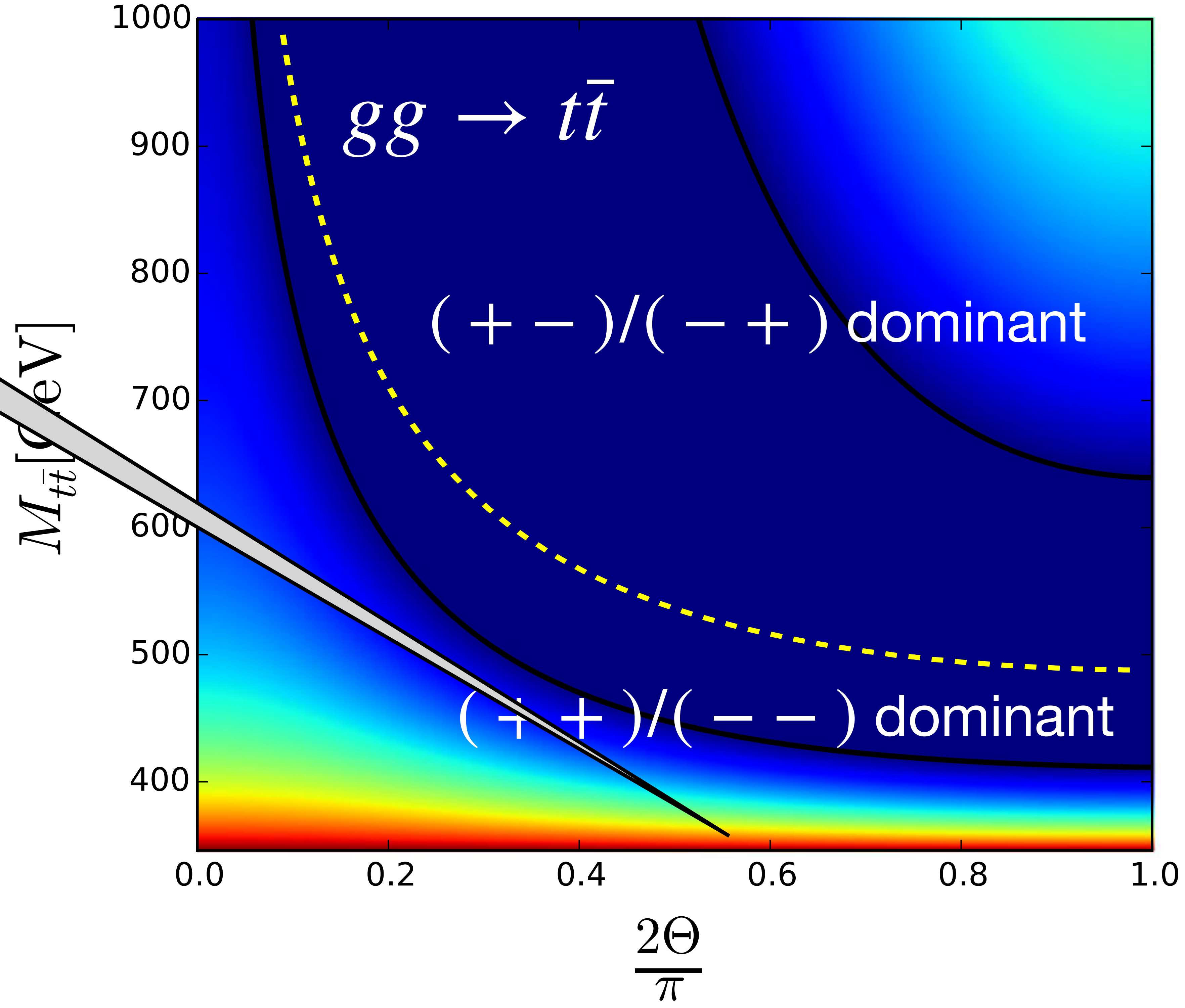
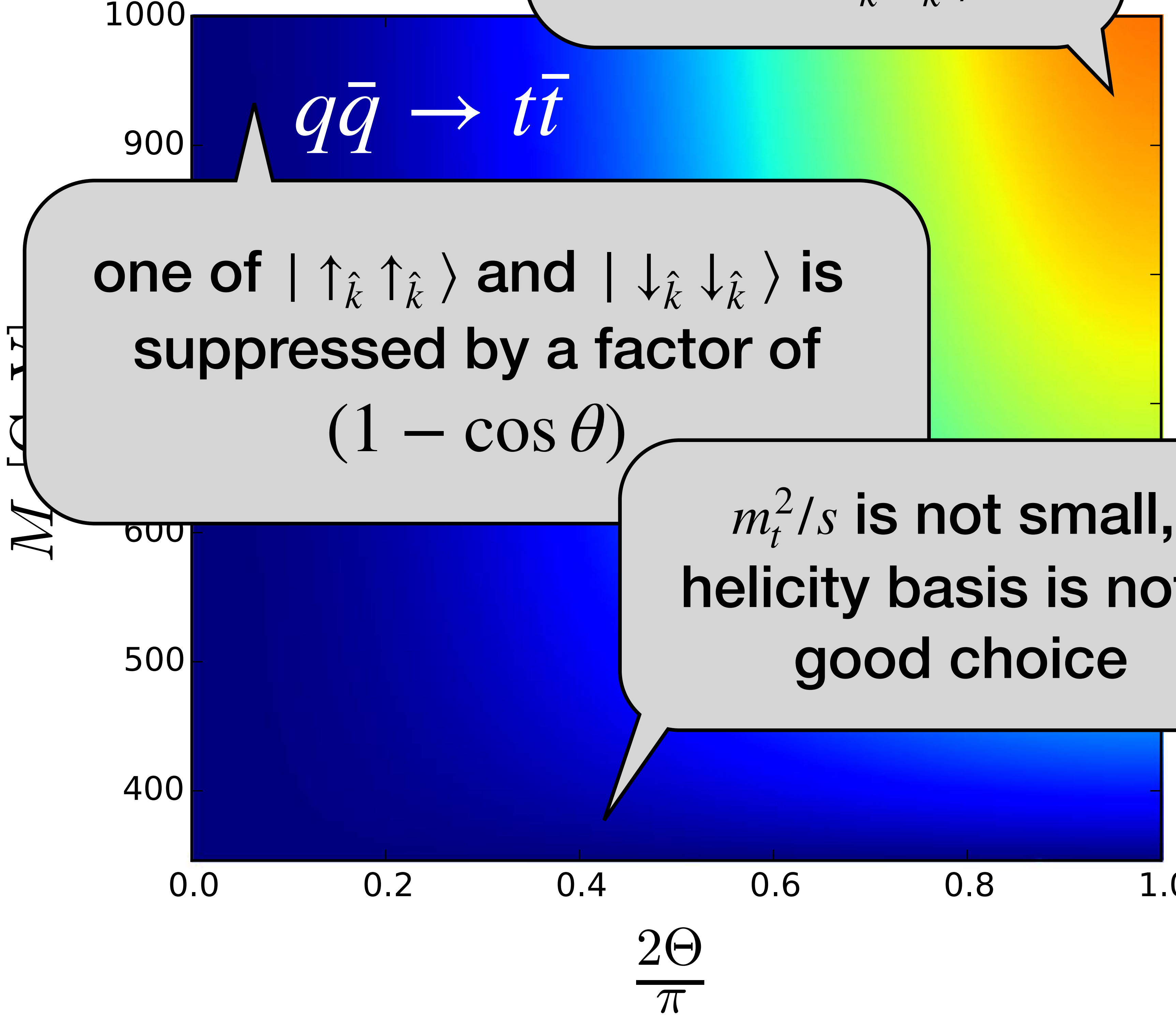
Quantum Entanglement at Colliders

- An example: top-pair production.
- At the Large Hadron Collider: helicity basis

The most important contribution to the entanglement at the LHC



from both $|\uparrow_{\hat{k}}\uparrow_{\hat{k}}\rangle$ and $|\downarrow_{\hat{k}}\downarrow_{\hat{k}}\rangle$



one of $|\uparrow_{\hat{k}}\uparrow_{\hat{k}}\rangle$ and $|\downarrow_{\hat{k}}\downarrow_{\hat{k}}\rangle$ is suppressed by a factor of $(1-\cos\theta)$

m_t^2/s is not small, helicity basis is not a good choice

Y. Afik, J. R. M. de Nova, Eur. Phys. J. Plus, (2021) 136:907.

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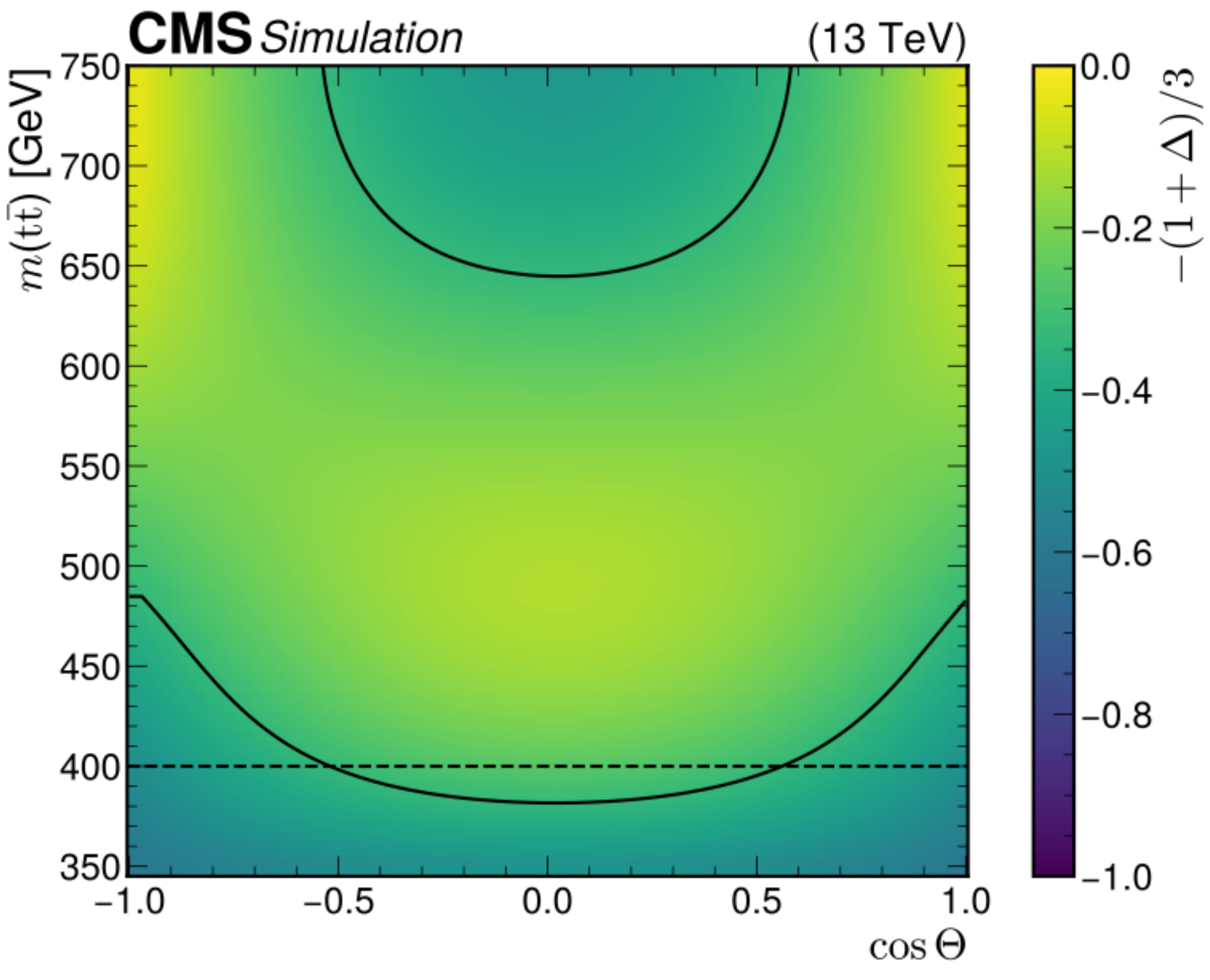
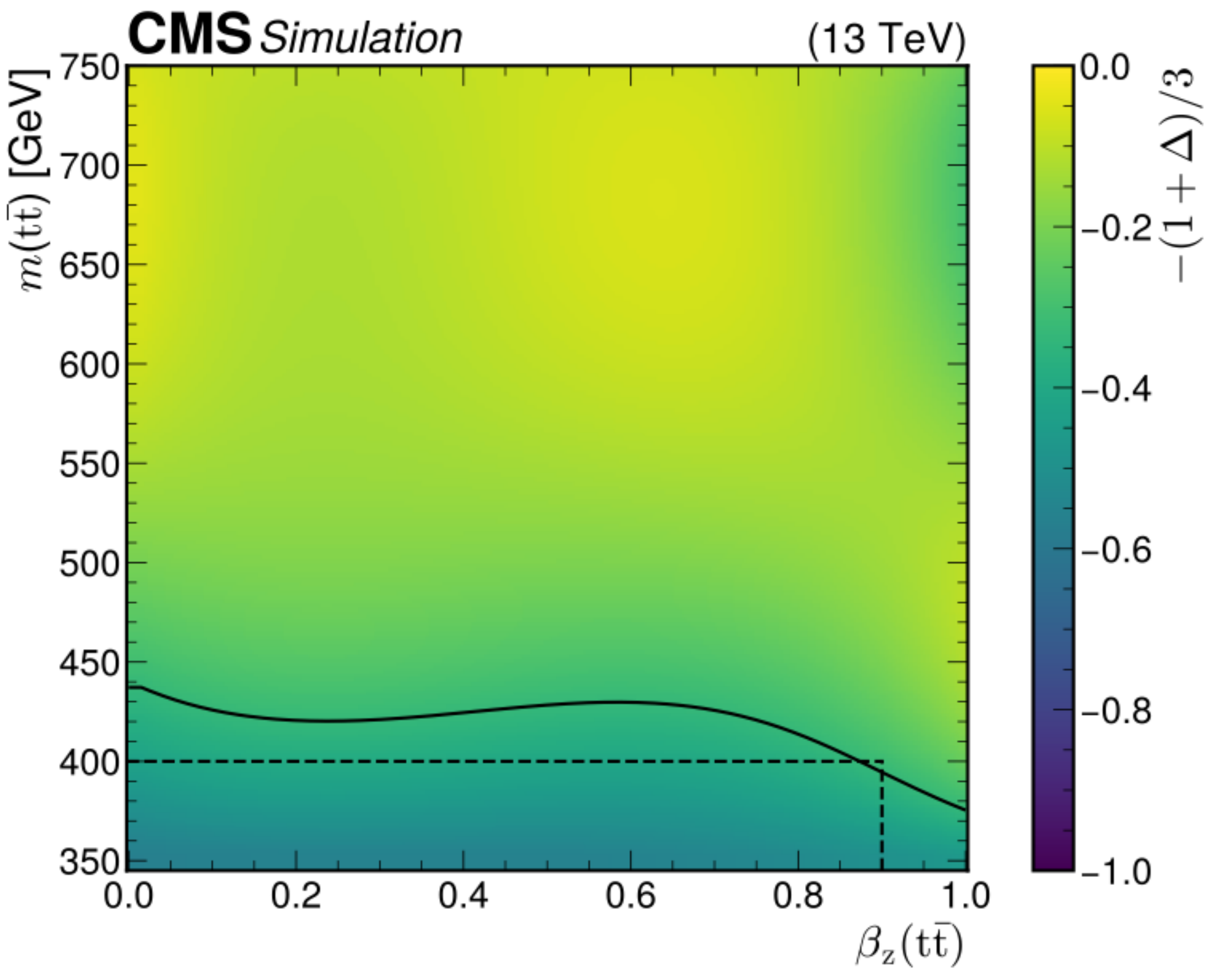
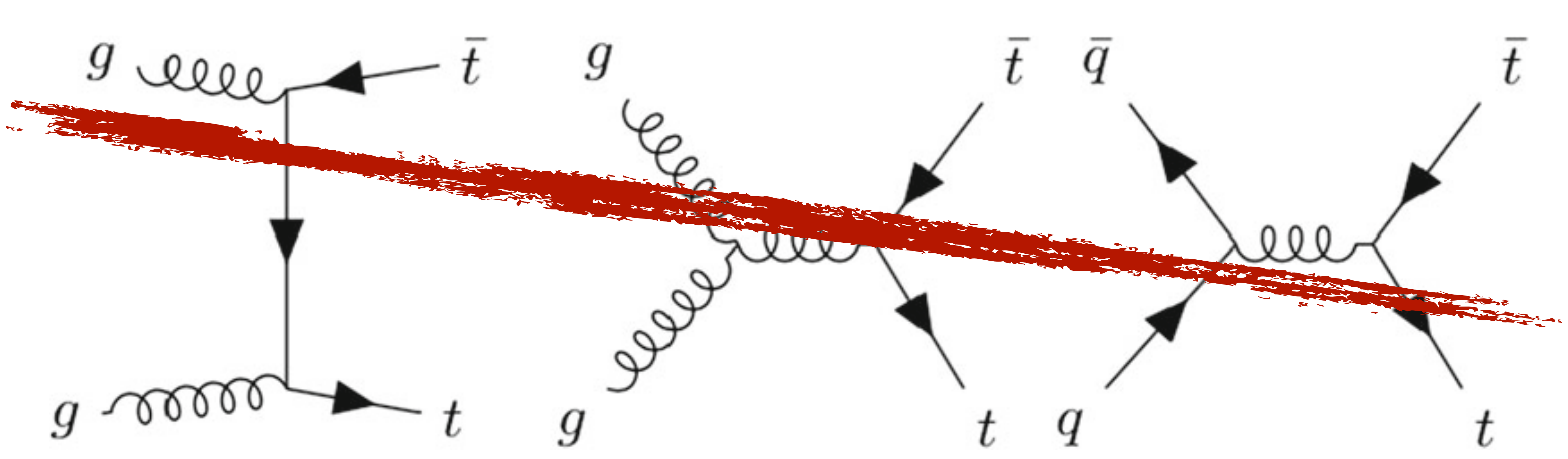


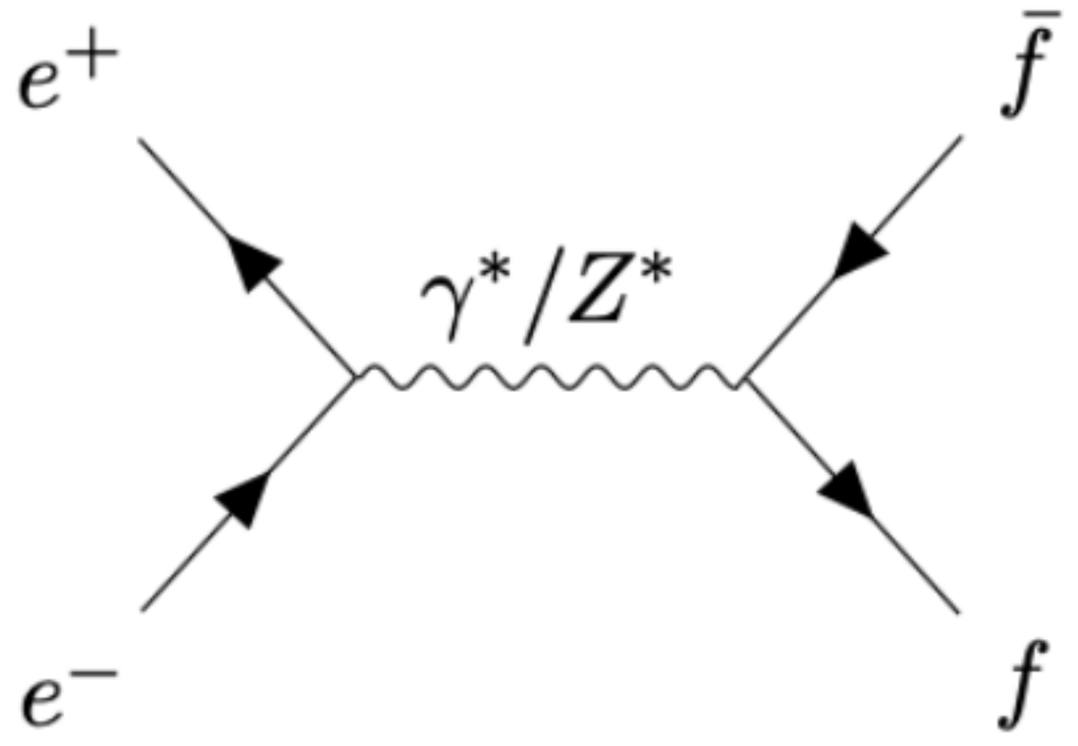


CMS collaboration, Rep. Prog. Phys. 87 (2024) 117801.

Quantum Entanglement at Colliders

- The advantage at lepton colliders.
  - Simpler and clear contribution:





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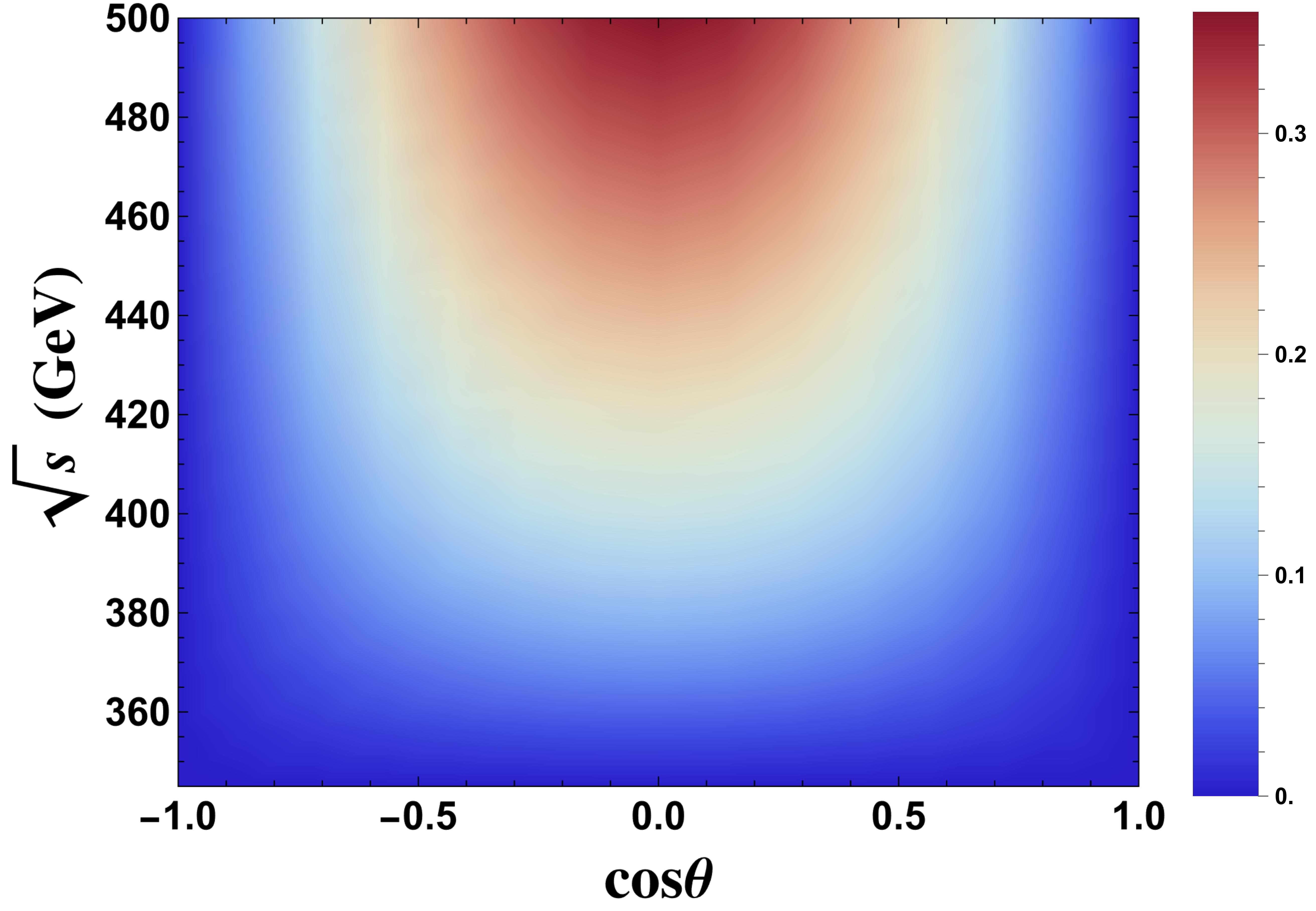


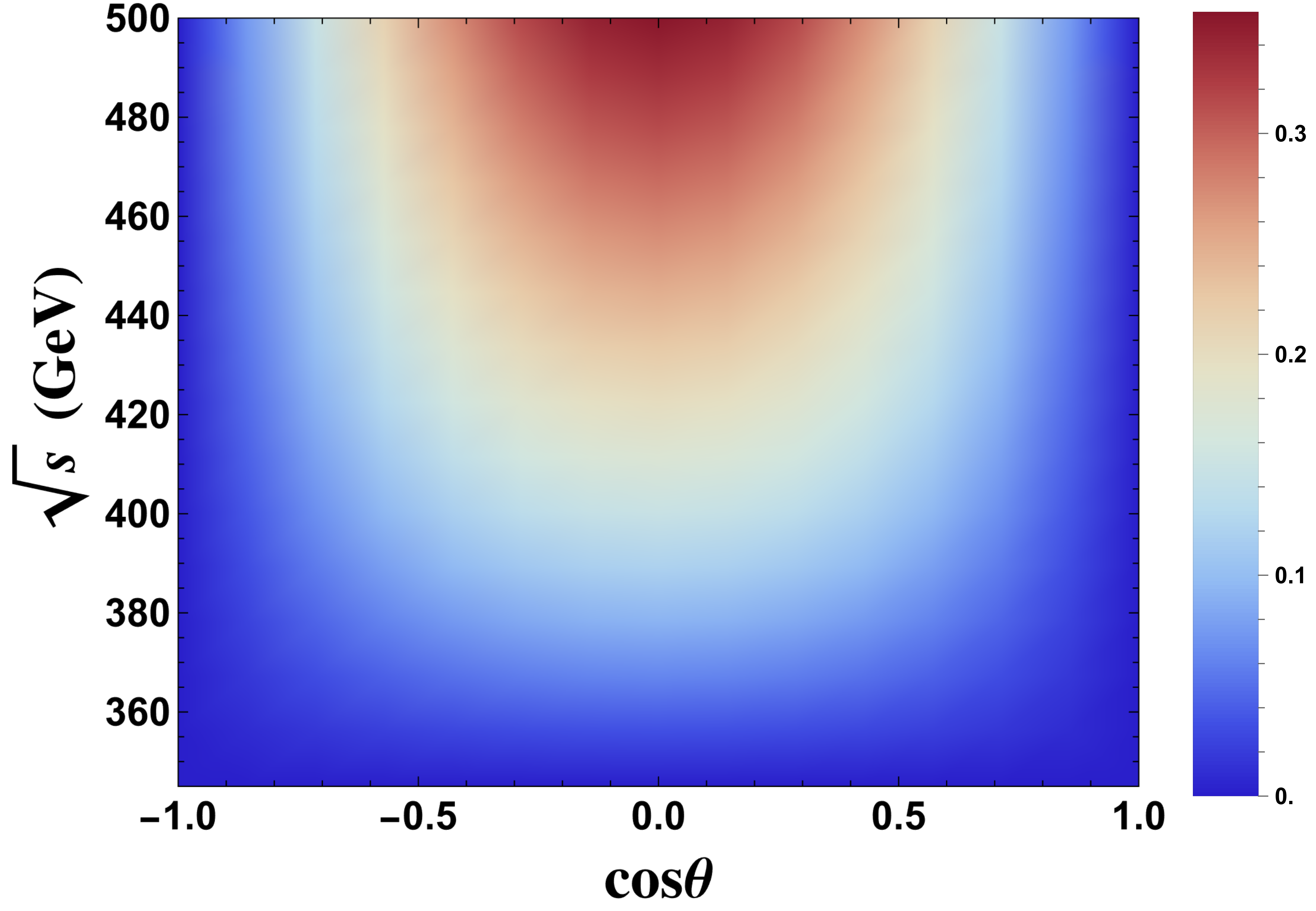
For simplicity and clearly, we do not show the contribution from the Z-boson in this figure, which will shift the distribution to left a little.

Quantum Entanglement at Colliders

- The advantage at lepton colliders.
  - Simpler and clear contribution:

The top-quarks are not energetic enough

The helicity basis is not good enough



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Quantum Entanglement at Colliders

- A (disordered) mixing of highly entangled states could miss the property of entanglement:
  - Bell states $\rho_\pm = |\Psi_\pm\rangle\langle\Psi_\pm| = 2^{-1}(|01\rangle\langle 01| \pm |10\rangle\langle 01| \pm |01\rangle\langle 10| + |10\rangle\langle 10|)$ are entangled (pure) states.
  - But their mixing $(\rho_+ + \rho_-)/2 = (|0\rangle\langle 0| \otimes |1\rangle\langle 1| + |1\rangle\langle 1| \otimes |0\rangle\langle 0|)/2$ is **not**!

Quantum Entanglement at Colliders

- It is helpful to use the transverse polarized initial state to increase the degree of the entanglement.

- In this case, the initial state is a Bell state selected by the interaction:

$$\frac{1}{2}(|\uparrow\rangle + |\downarrow\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle) = \frac{1}{2}(|\uparrow\uparrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$

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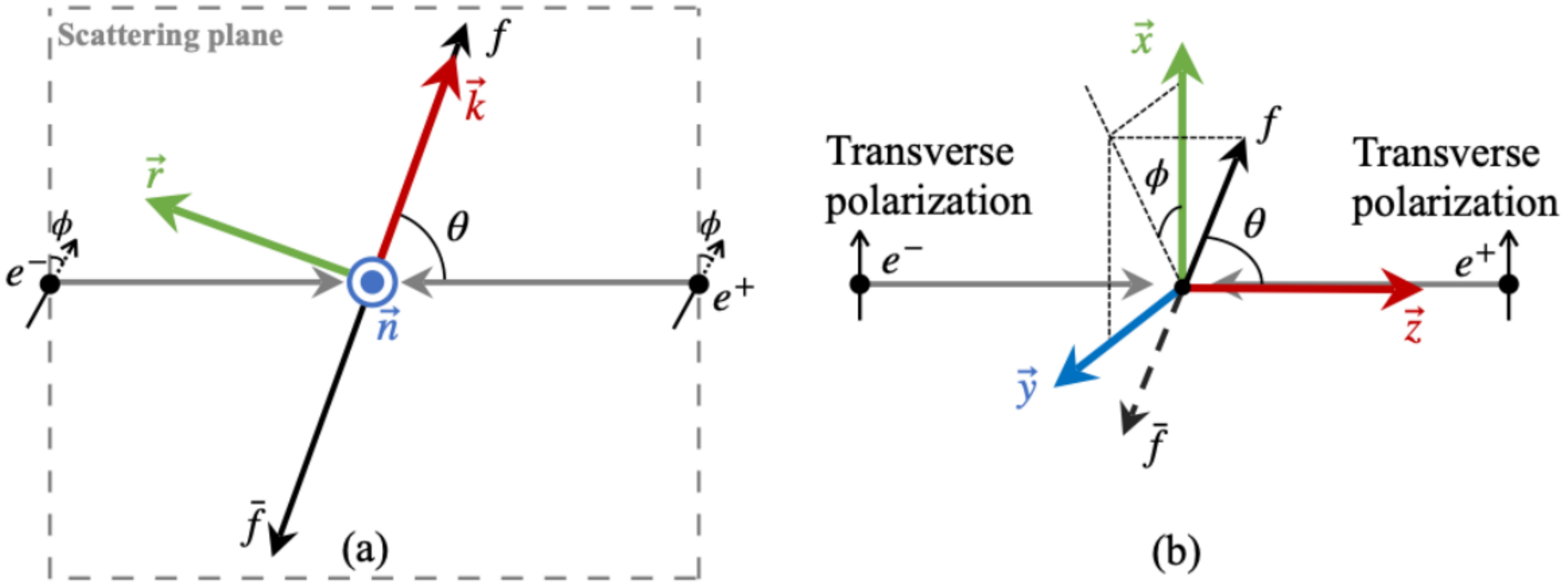
- The final state is always the Bell state along the direction $\hat{e}_2 = (\cos\theta \sin\phi, \cos\phi, \sin\theta \sin\phi\sqrt{1-\beta^2})$ in the helicity basis, which is just $\hat{y} - \left(1 - \sqrt{1-\beta^2}\right)\hat{k}$.



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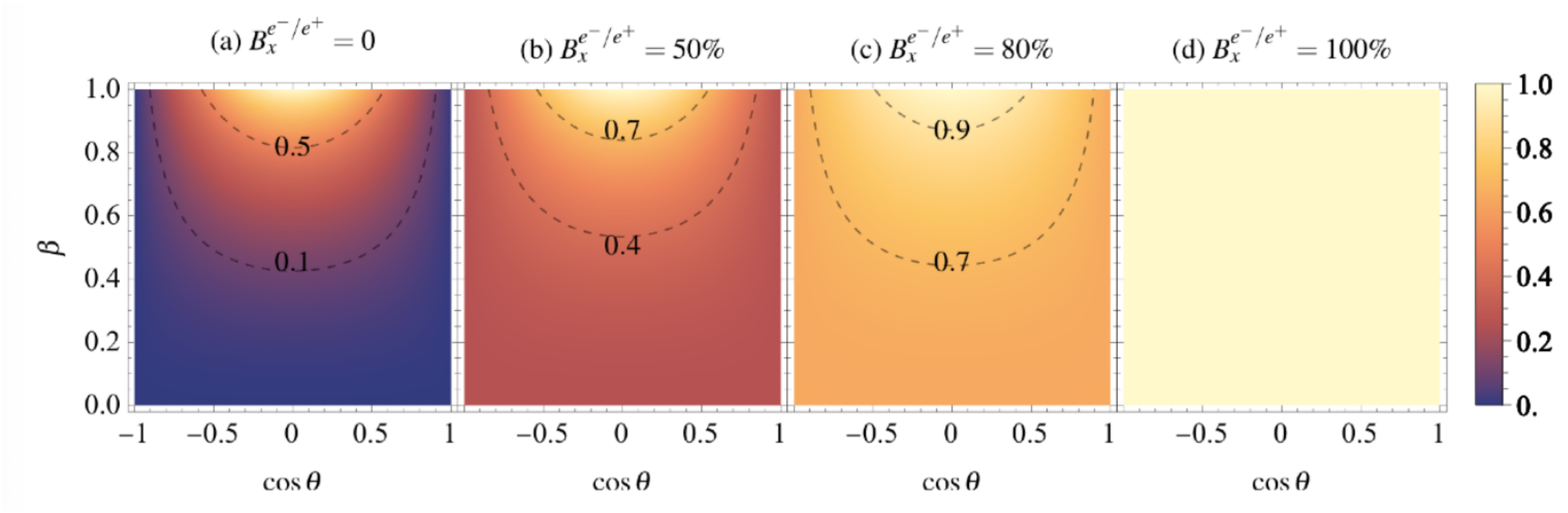

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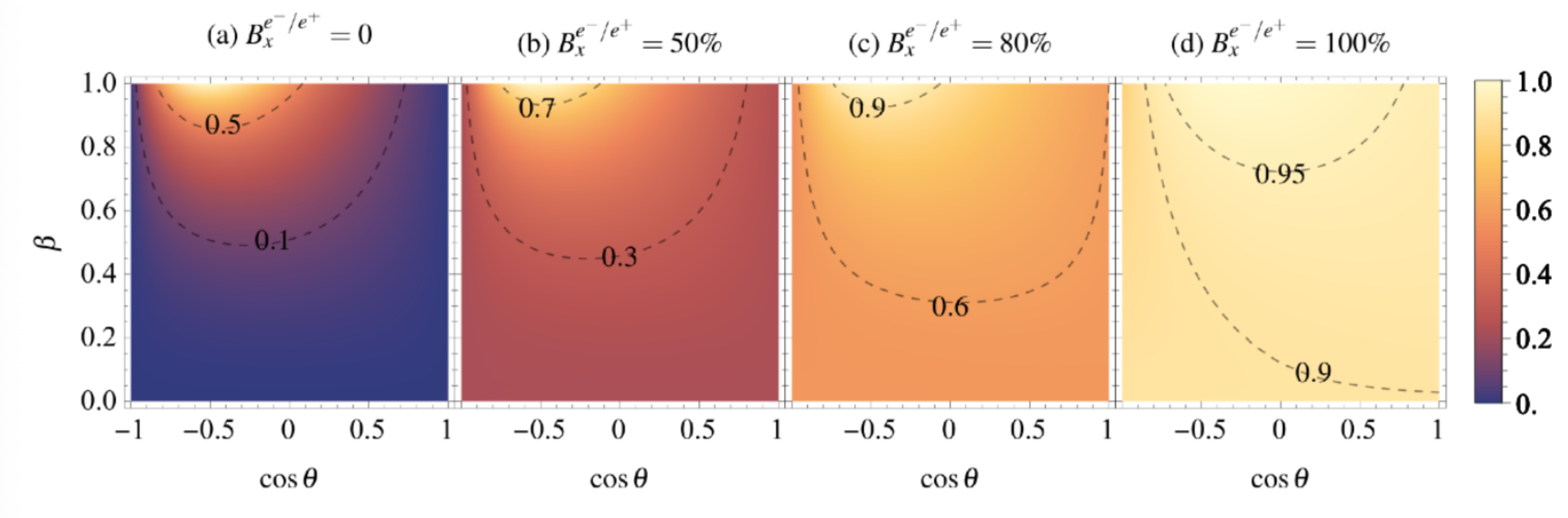

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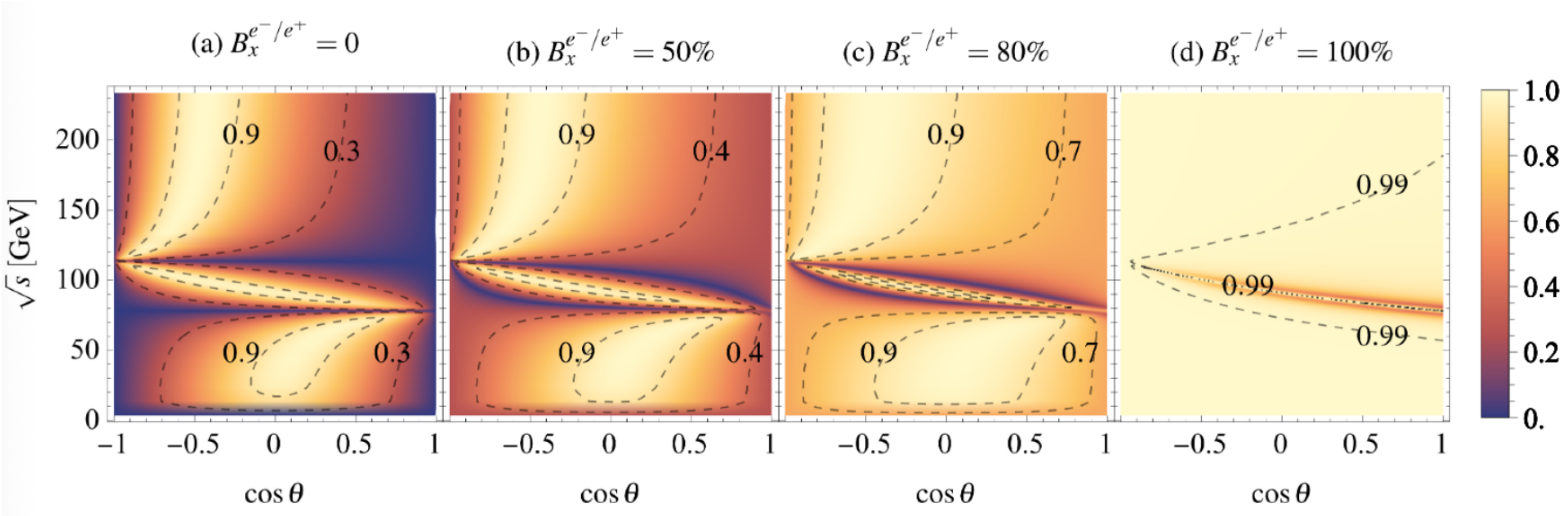

Conclusion

- Quantum entanglement and quantum nonlocality are essential properties for distinguishing quantum physics from classical physics **and new physics beyond quantum physics**, which should be tested at higher and higher energy scale.

- The first step of using quantum entanglement search for new physics is to understand the SM prediction, and to enhance the entanglement effect.

- The lepton colliders, especially with the transverse polarized initial state, offer a good chance to investigate the entanglement effect.

- Other topics: the influences from ISR and FSR, off-shell effects, …


Thank you!
IFC