Measuring Quantum Discord at the LHC
(for top quarks)

Navin McGinnis

Based on collaboration w/ Tao Han (Pitt), Matt Low (Pitt), and Shufang Su (AZ)

2412.21158 [hep-ph]

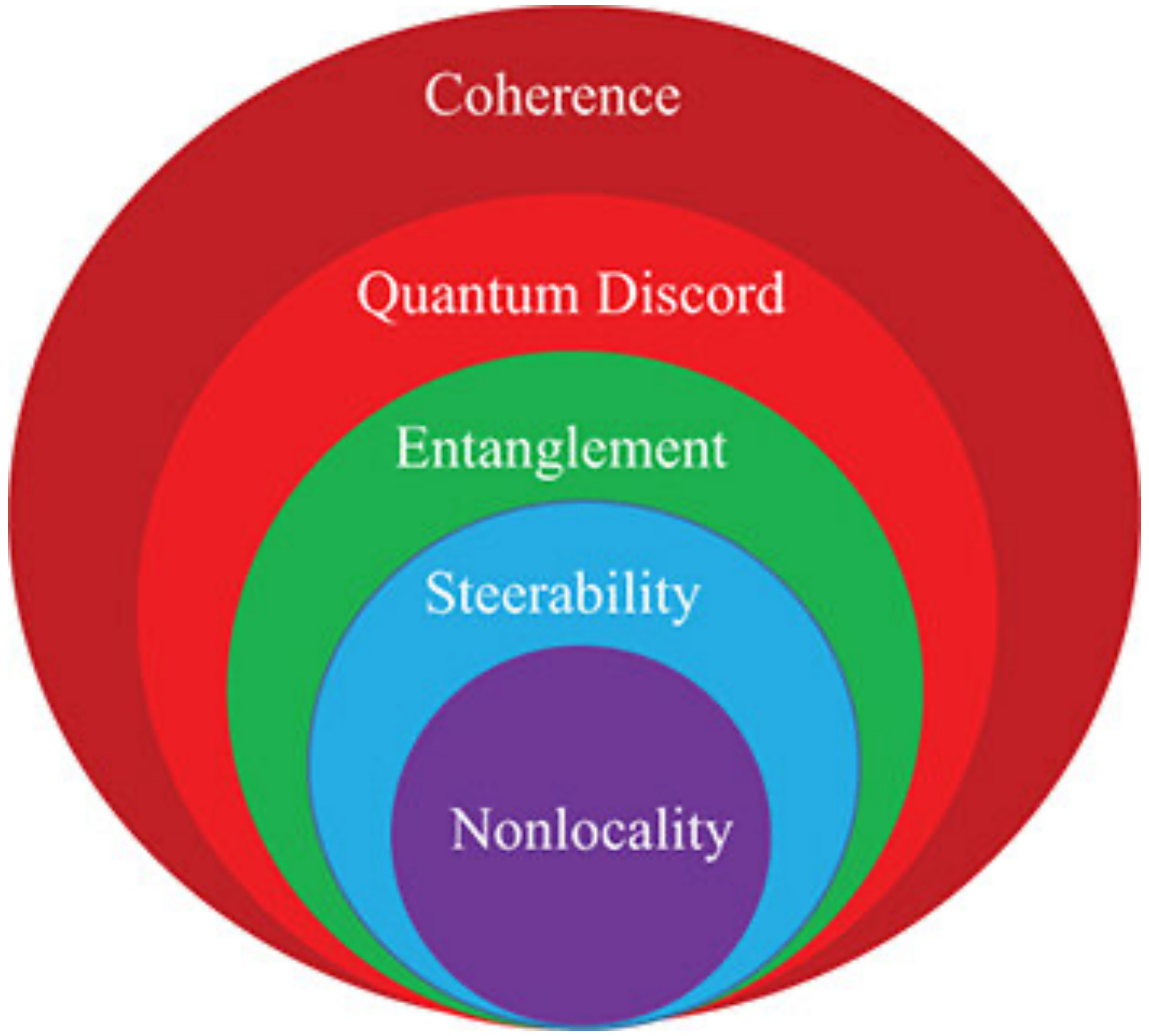
Quantum Observables for Collider Physics 2025

GGI

April 10, 2025

THE UNIVERSITY OF ARIZONA

Exploring Quantum Mechanics in High Energy Physics @ PITT PACC - March 2024


Coherence
Quantum Discord
Entanglement
Steerability
Nonlocality

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik[1,*] and Juan Ramón Muñoz de Nova[2,†]
[1] *Experimental Physics Department, CERN, 1211 Geneva, Switzerland*
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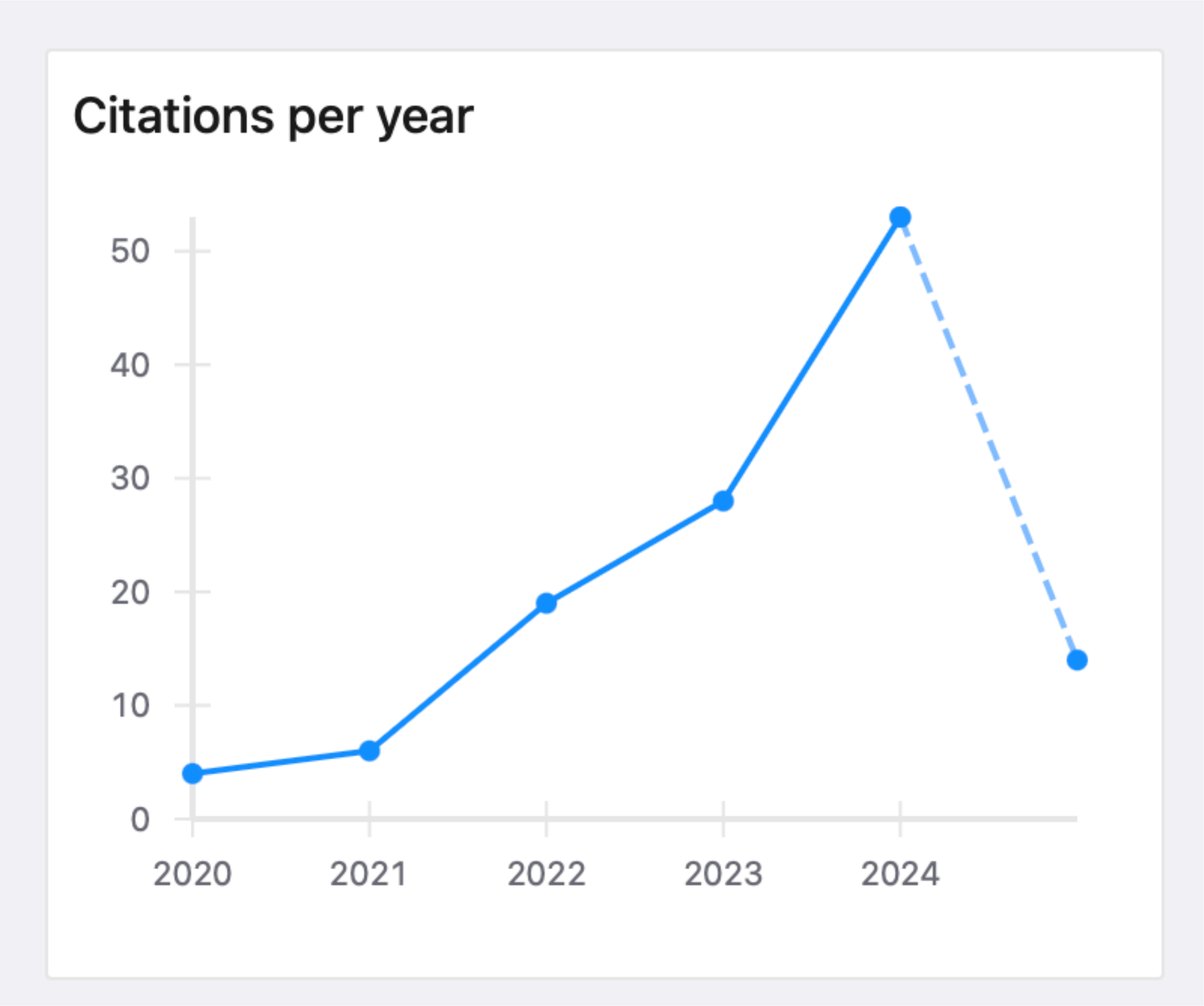
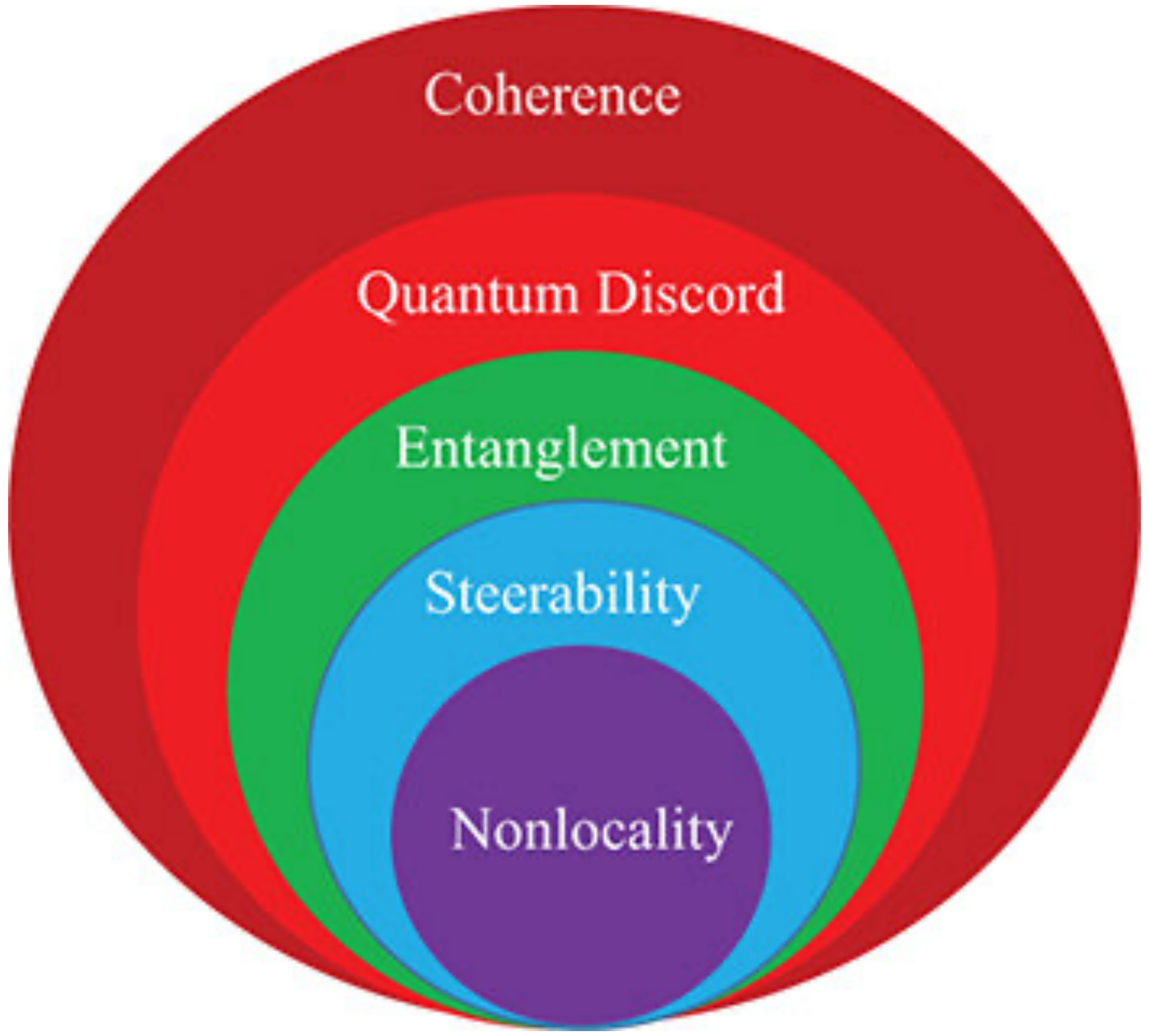
(Dated: September 8, 2021)





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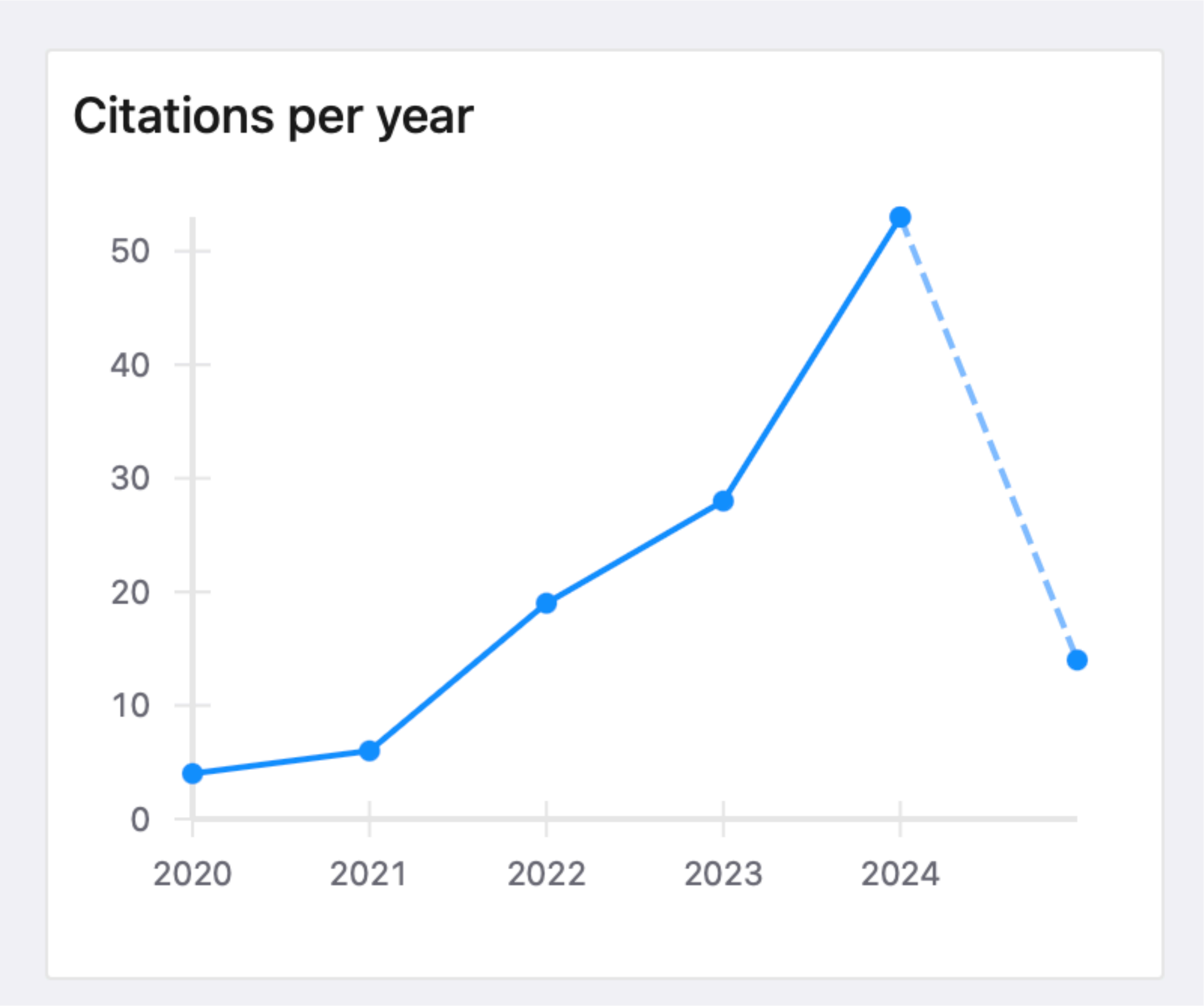

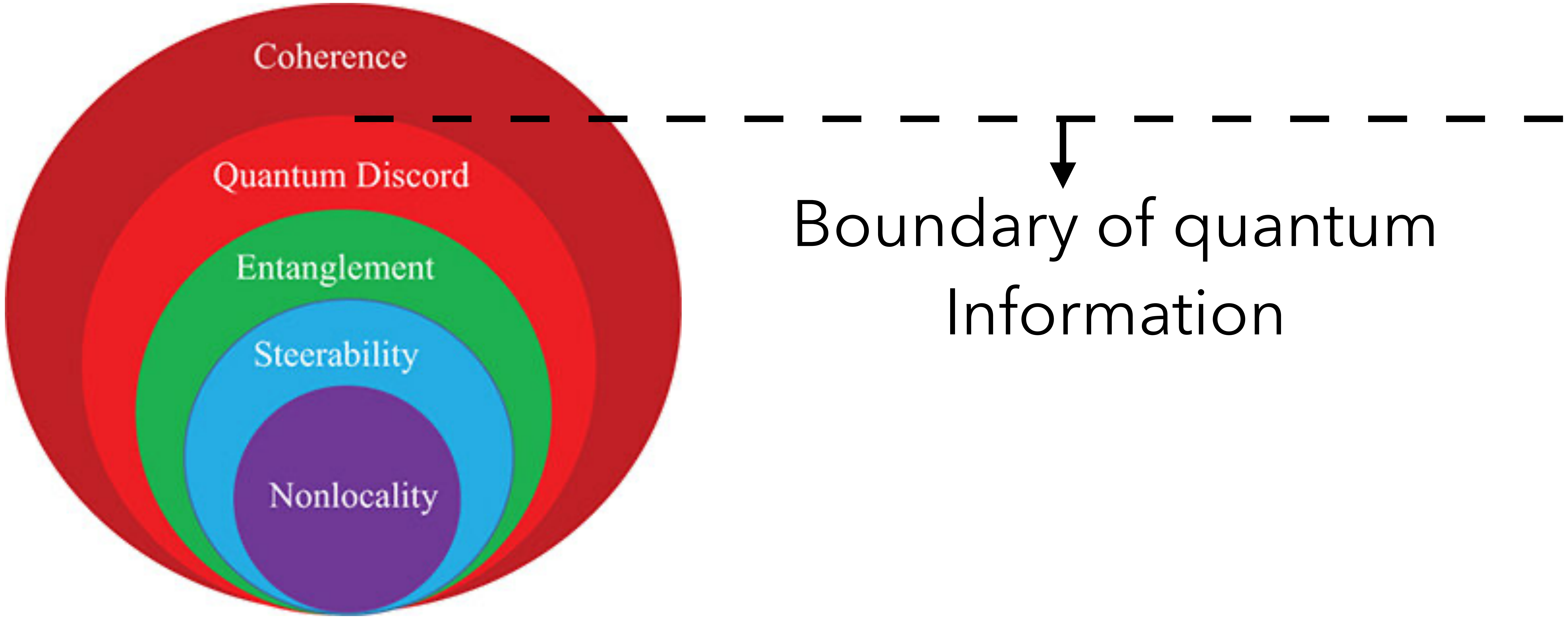

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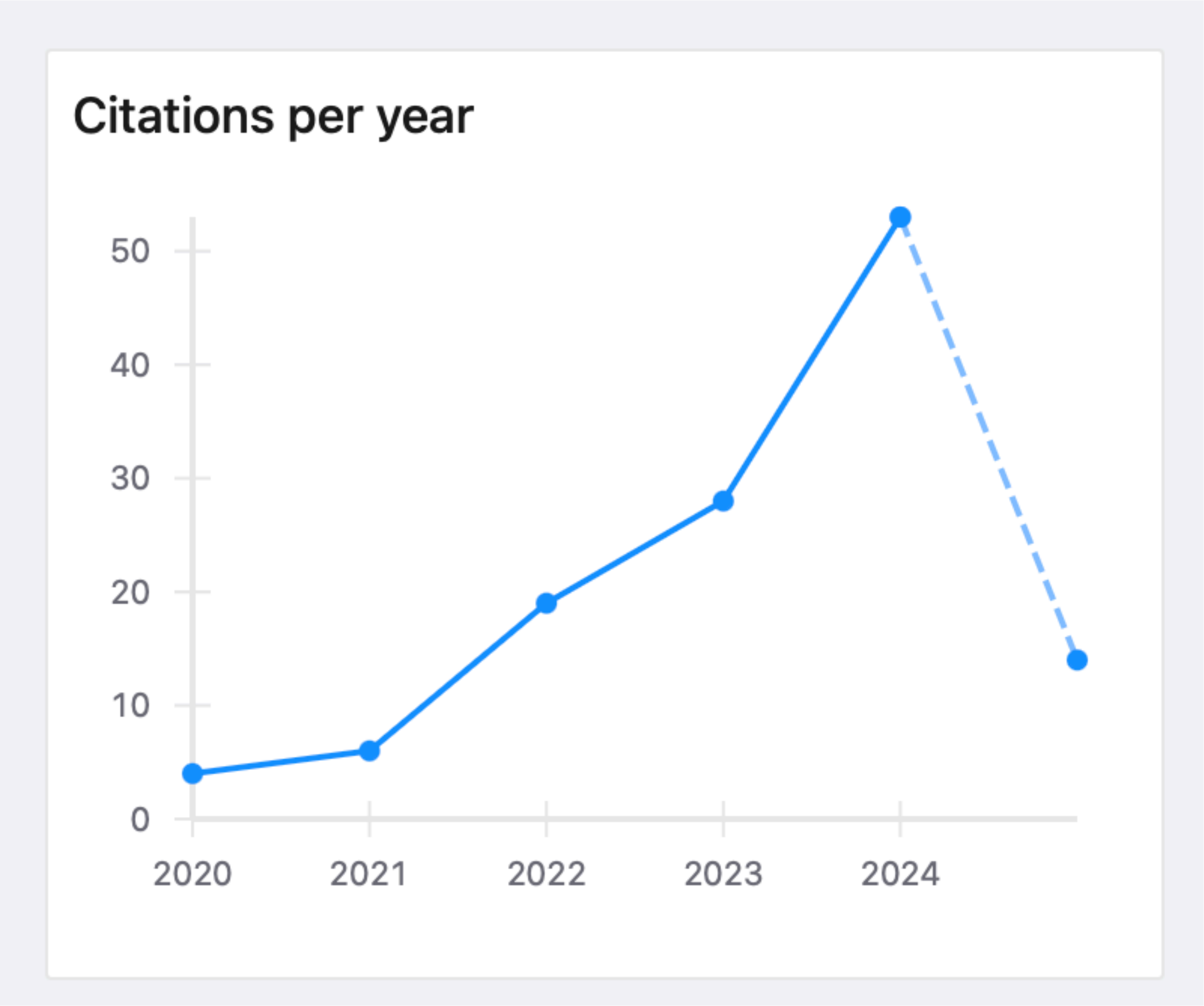

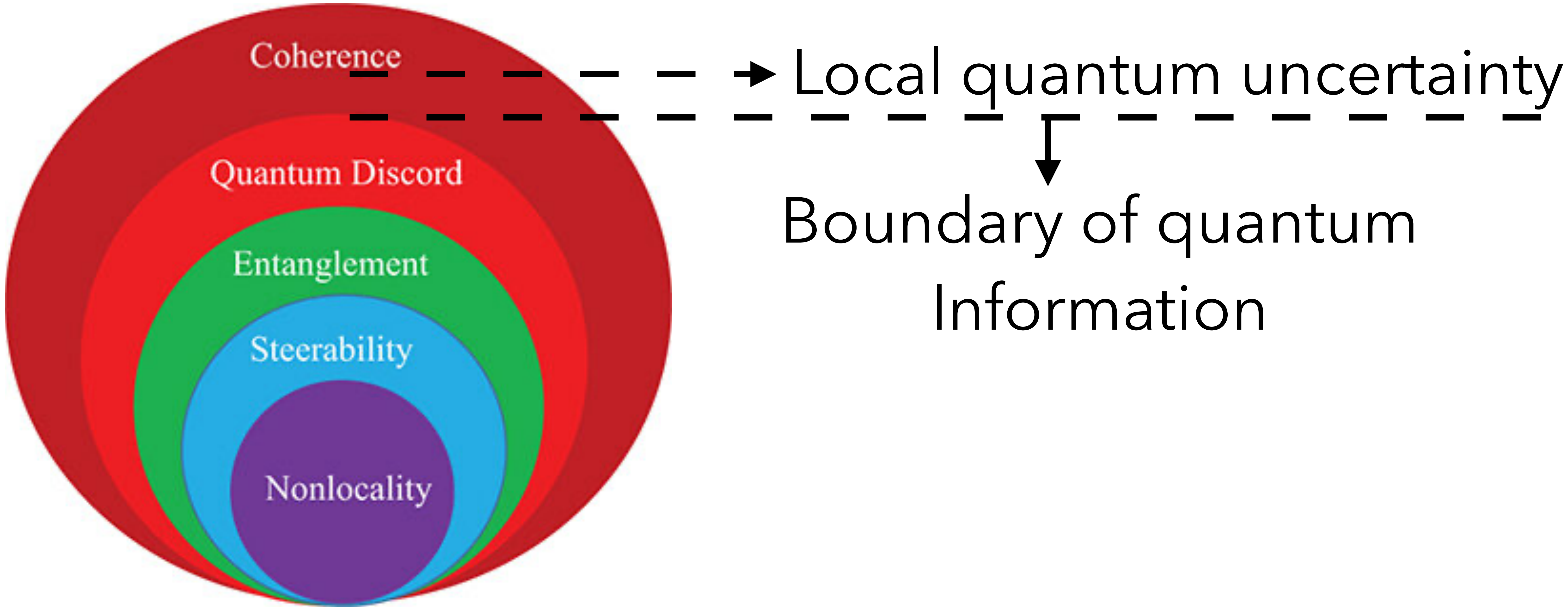

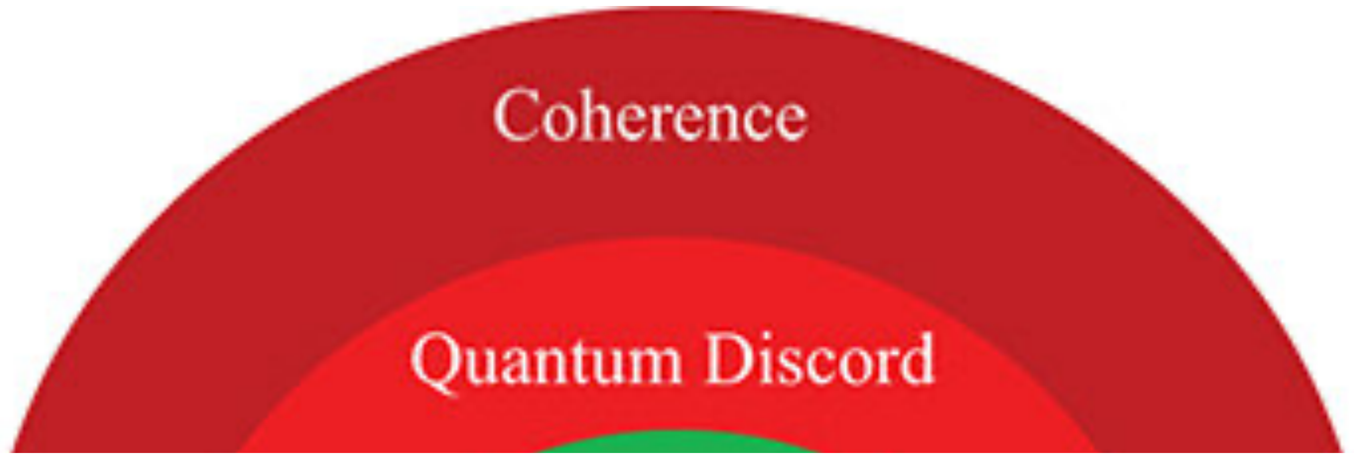

Quantum discord and steering in top quarks at the LHC

Yoav Afik[1,*] and Juan Ramón Muñoz de Nova[2,†]

[1] *Experimental Physics Department, CERN, 1211 Geneva, Switzerland*
[2] *Departamento de Física de Materiales, Universidad Complutense de Madrid, E-28040 Madrid, Spain*

(Dated: June 7, 2023)

Discord for top quarks

Quantum Discord

$$\rho = |A, B> < A, B|$$

$$\mathcal{D}_A(\rho) = I(\rho) - J_A(\rho)$$

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$

$$J_A(\rho_{AB}) = \max_{\hat{n}} J_A(\rho_{AB}; \hat{n})$$

Discord for top quarks

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$$J_A(\rho_{AB}; \hat{n}) = S(\rho_A) - S(\rho_A|\rho_B; \hat{n})$$

Discord for top quarks

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Mutual Information
(all correlations)

Conditional information
(only classical correlations)

Discord for top quarks

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Conditional information (only classical correlations)

$\mathcal{D}_A(\rho) \rightarrow = 0$ Classical

Discord for top quarks

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$I(\rho)$ → Mutual Information (all correlations)

$J_A(\rho)$ → Conditional information (only classical correlations)

$\mathcal{D}_A(\rho)$ → $= 0$ Classical

$\mathcal{D}_A(\rho)$ → $\neq 0$ Quantum (Can have separable states w $D_A \neq 0$)

Discord for top quarks

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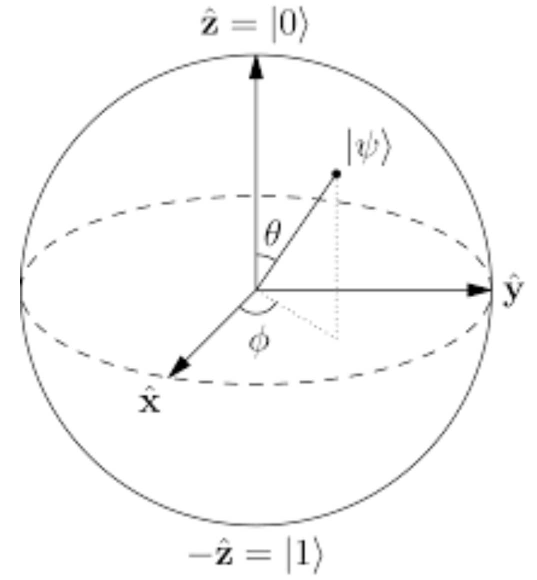
$$(\ \vec{\sigma}\cdot\hat{n}\,|\pm n\rangle = \pm\,|\pm n\rangle\ )$$



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$$S(\rho_A|\rho_B; \hat{n}) = p_{+\hat{n}} S(\rho_{+\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}})$$

$$\rho_{\pm\hat{n}} = \frac{1}{p_{\pm\hat{n}}} \mathrm{tr}_B(\Pi_{\pm\hat{n}} \rho_{AB} \Pi_{\pm\hat{n}})$$

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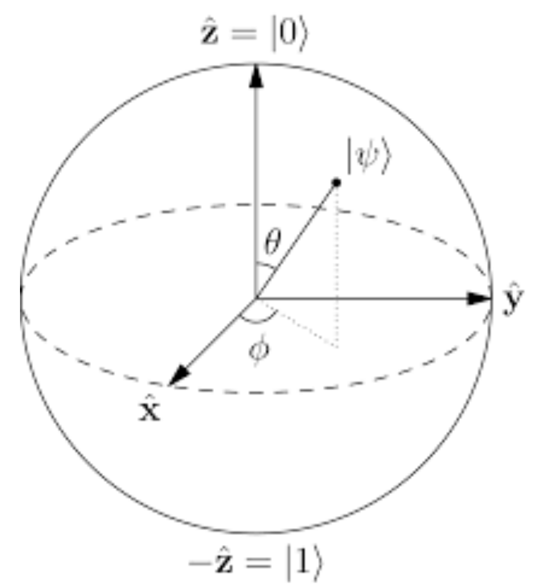

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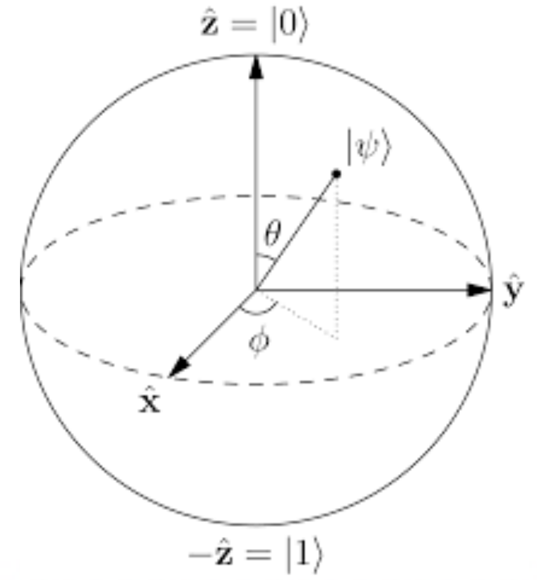
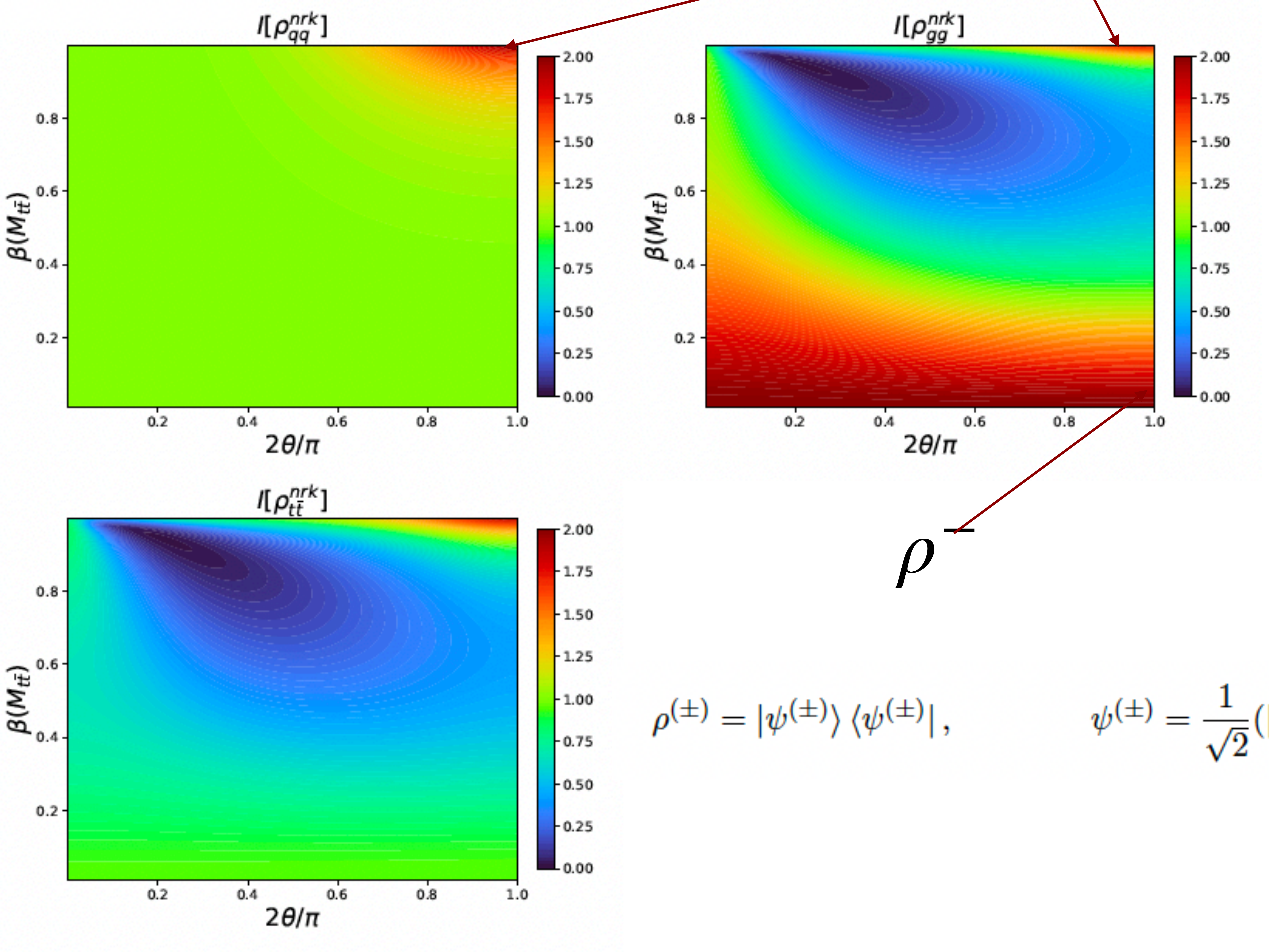


$$p_{\pm\hat{n}} = \mathrm{tr}(\Pi_{\pm\hat{n}} \rho_{AB} \Pi_{\pm\hat{n}})$$

$$J_A(\rho_{AB}) = S(\rho_A) - \min_{\hat{n}} \left(p_{+\hat{n}} S(\rho_{+\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}}) \right)$$

Discord for top quarks

$$I(\rho_{AB}) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$$



$$\rho^{(\pm)} = |\psi^{(\pm)}\rangle \langle \psi^{(\pm)}| \,, \qquad \psi^{(\pm)} = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle \pm |\uparrow\downarrow\rangle),$$

Discord for top quarks

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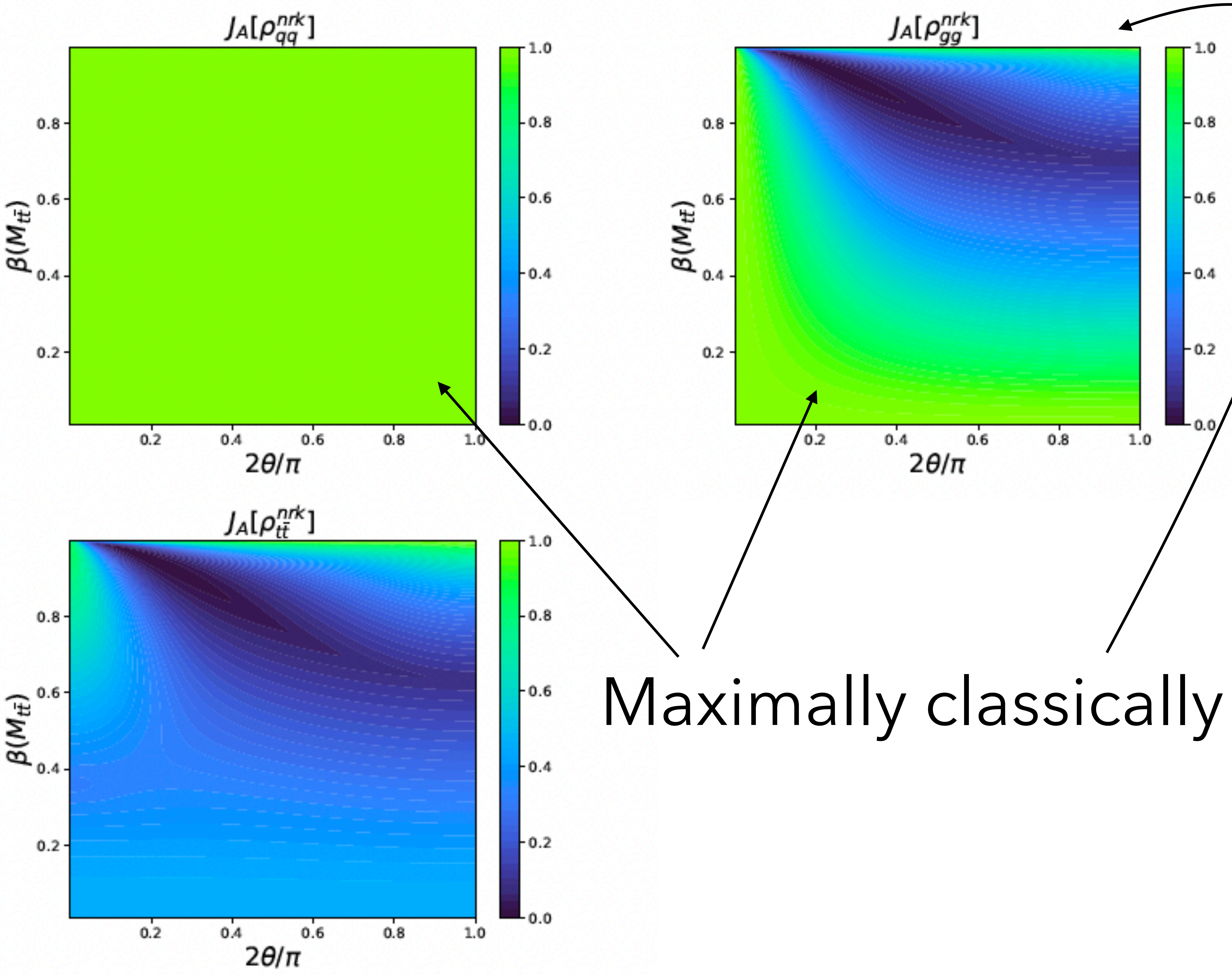

Maximally classically correlated

Discord for top quarks

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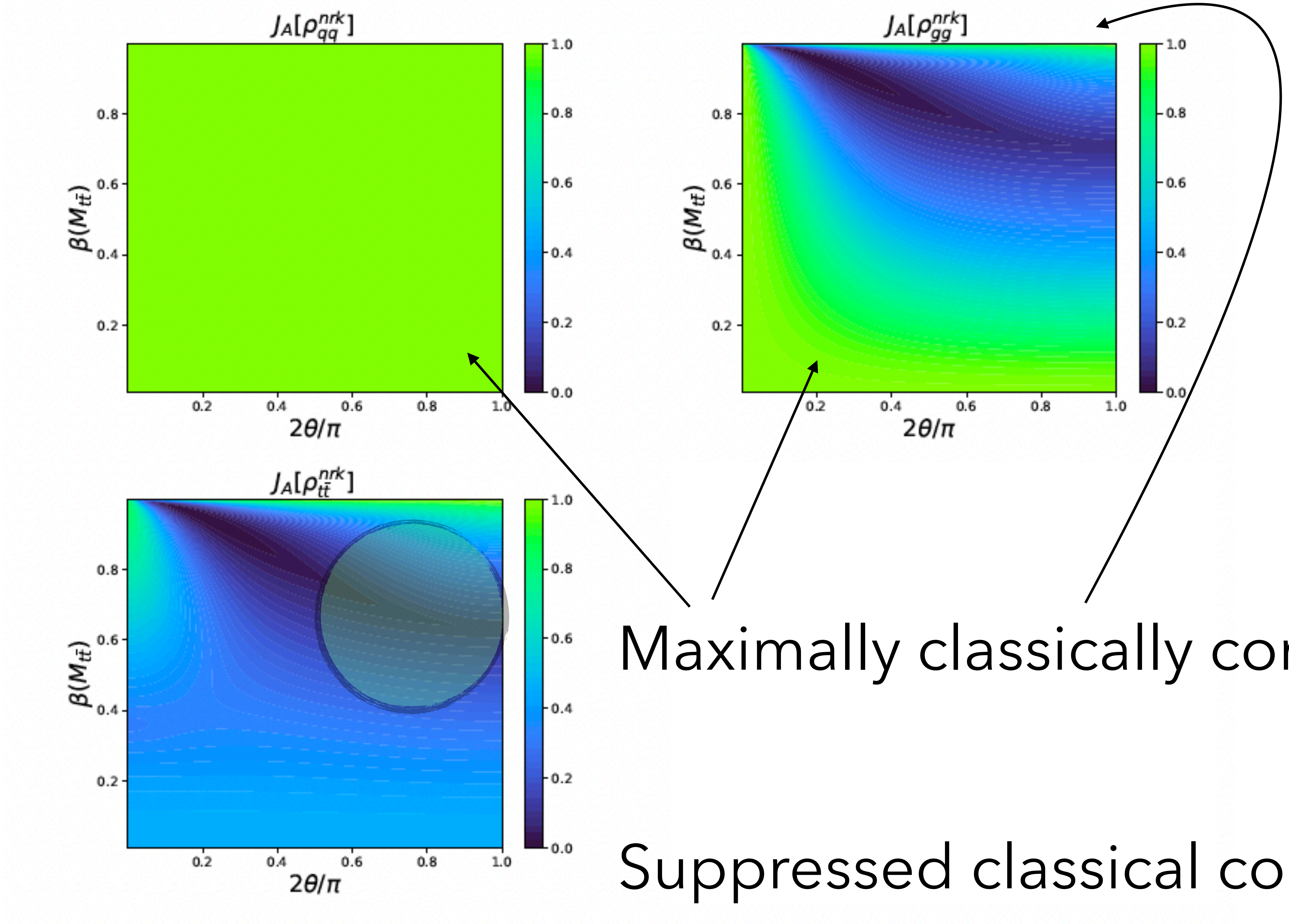

Maximally classically correlated

Suppressed classical correlations

Discord for top quarks

$$\mathcal{D}_A(\rho) = I(\rho) - J_A(\rho)$$

$$= S(\rho_B) - S(\rho_{AB}) + \min_{\hat{n}} \left(p_{+\hat{n}} S(\rho_{+\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}})\right)$$

$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+ (\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^- (\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij} (\sigma_i \otimes \sigma_j)\right]$$

$$p_{\pm\hat{n}} = \frac{1 \pm \hat{\mathbf{n}} \cdot \mathbf{B}^-}{2}, \qquad \rho_{\pm\hat{n}} = \frac{\mathbb{I}_2 + \mathbf{B}^+_{\pm\hat{\mathbf{n}}} \cdot \sigma}{2}, \qquad \mathbf{B}^+_{\pm\hat{\mathbf{n}}} = \frac{\mathbf{B}^+ \pm \mathbf{C} \cdot \hat{\mathbf{n}}}{1 \pm \hat{\mathbf{n}} \cdot \mathbf{B}^-}.$$

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$$U_A \otimes V_B \longrightarrow \quad \longleftarrow U_A^\dagger \otimes V_B^\dagger$$

$$\rho'_{AB} = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i \Lambda_i \sigma_i \otimes \sigma_i\right)$$

$\Lambda_i =$ Singular values of C_{ij} in any basis of choice

Discord for top quarks

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$$D_A(\rho'_{AB}) = 1 + \sum_i e_i \log_2(e_i) - \frac{1}{2}(1+\lambda)\log_2\left(\frac{1+\lambda}{2}\right) - \frac{1}{2}(1-\lambda)\log_2\left(\frac{1-\lambda}{2}\right)$$

e_i = Eigenvalues of ρ_{AB}

λ = Largest singular value of C_{ij}

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Calculation appeared before:

S. Luo, Quantum discord for two-qubit systems, Phys. Rev. A 77 (2008) 042303.

Discord for top quarks

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$e_i =$ Eigenvalues of ρ_{AB}

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$$\begin{aligned} D_A(\rho_{AB}) = 1 &+ \frac{1}{4}(1 - C_k - C_n - C_r)\log_2\left(\frac{(1 - C_k - C_n - C_r)}{4}\right) \\ &+ \frac{1}{4}(1 + C_k - C_n + C_r)\log_2\left(\frac{(1 + C_k - C_n + C_r)}{4}\right) \\ &+ \frac{1}{4}(1 + C_n - \Delta)\log_2\left(\frac{(1 + C_n - \Delta)}{4}\right) + \frac{1}{4}(1 + C_n + \Delta)\log_2\left(\frac{(1 + C_n + \Delta)}{4}\right) \\ &- \frac{1}{2}(1+\lambda)\log_2\left(\frac{1+\lambda}{2}\right) - \frac{1}{2}(1-\lambda)\log_2\left(\frac{1-\lambda}{2}\right) \end{aligned}$$

where $\Delta = \sqrt{C_k^2 + 4C_{kr}^2 + C_r^2 - 2C_kC_r}$, and $\lambda = \max\{|C_n|, \frac{1}{2}|C_k + C_r - \Delta|, \frac{1}{2}|C_k + C_r + \Delta|\}$.

Experiments ⟶ C_{ij} ⟶ $D_A(\rho)$

Discord at colliders

Experiments

$$\overline{C}_{ij} = \frac{1}{\sigma_\Pi} \int_\Pi d\Omega \frac{d\sigma}{d\Omega} C_{ij}(\Omega).$$

Fictitious states

Discord at colliders

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Fictitious states

For entanglement, not a big deal:

$$C[\bar{\rho}] \neq 0 \implies C[\rho] \neq 0$$

K. Cheng, T. Han, M. Low: Phys.Rev.D 109 (2024)

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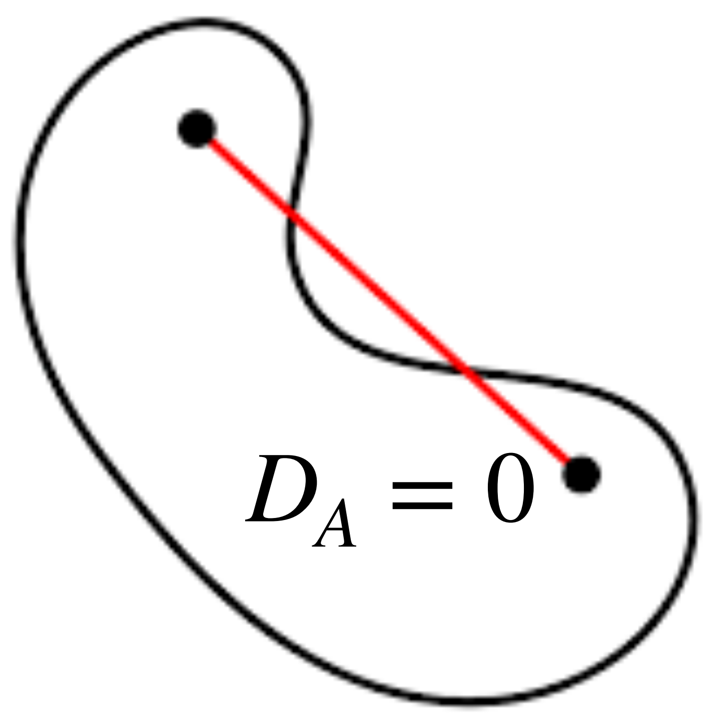
- Set of zero-discord states not convex: mixtures of zero-discord states can lead to a fictitious states with $D_A[\bar{\rho}] \neq 0$..

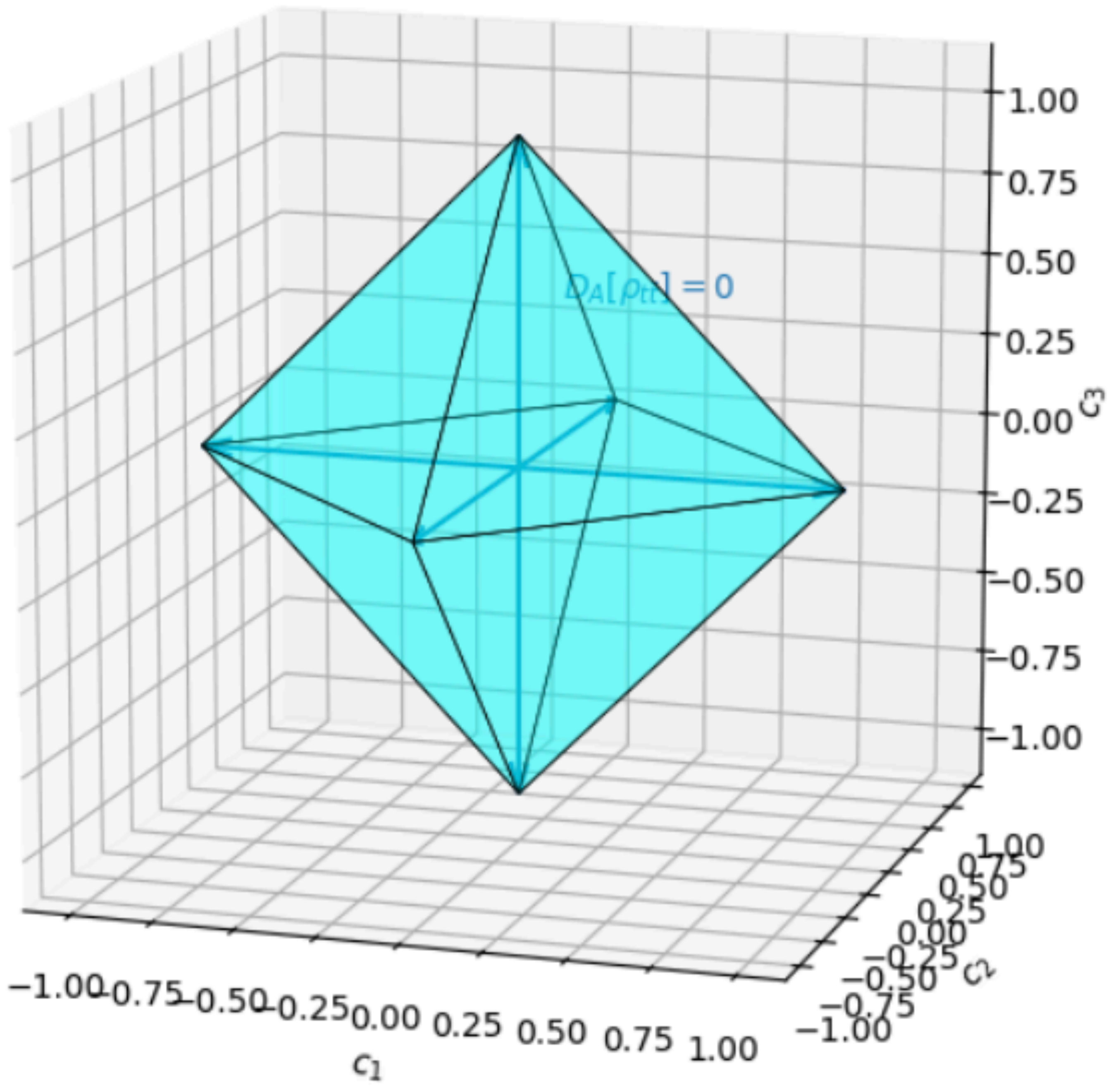
$$\bar{\rho} = \lambda \rho_0 + (1-\lambda)\rho_0'$$



Discord at colliders

Quantum Discord and the Geometry of Bell-Diagonal States

Matthias D. Lang* and Carlton M. Caves
Center for Quantum Information and Control, University of New Mexico, MSC07–4220, Albuquerque, New Mexico 87131-0001, USA
(Dated: July 25, 2018)



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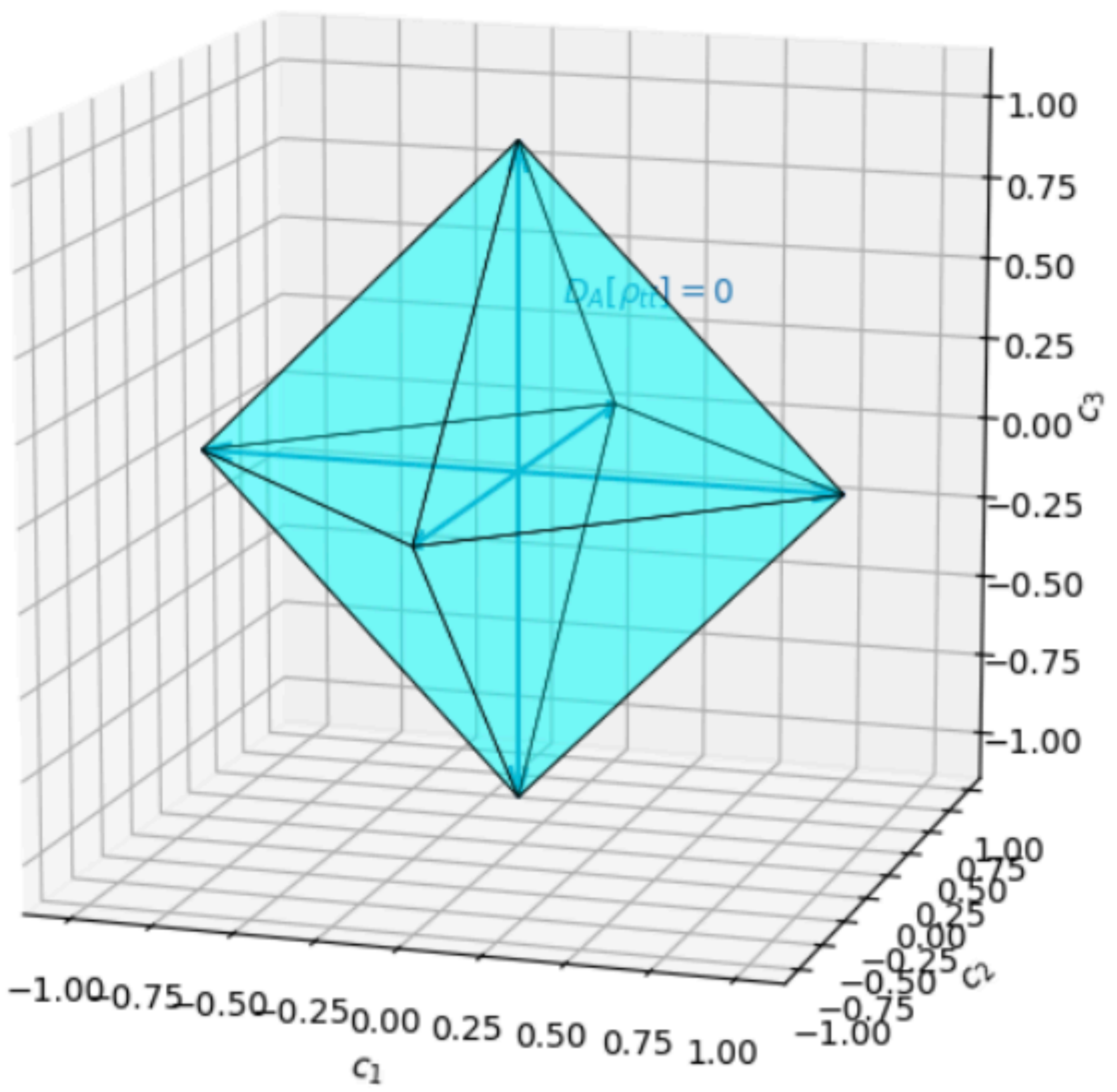

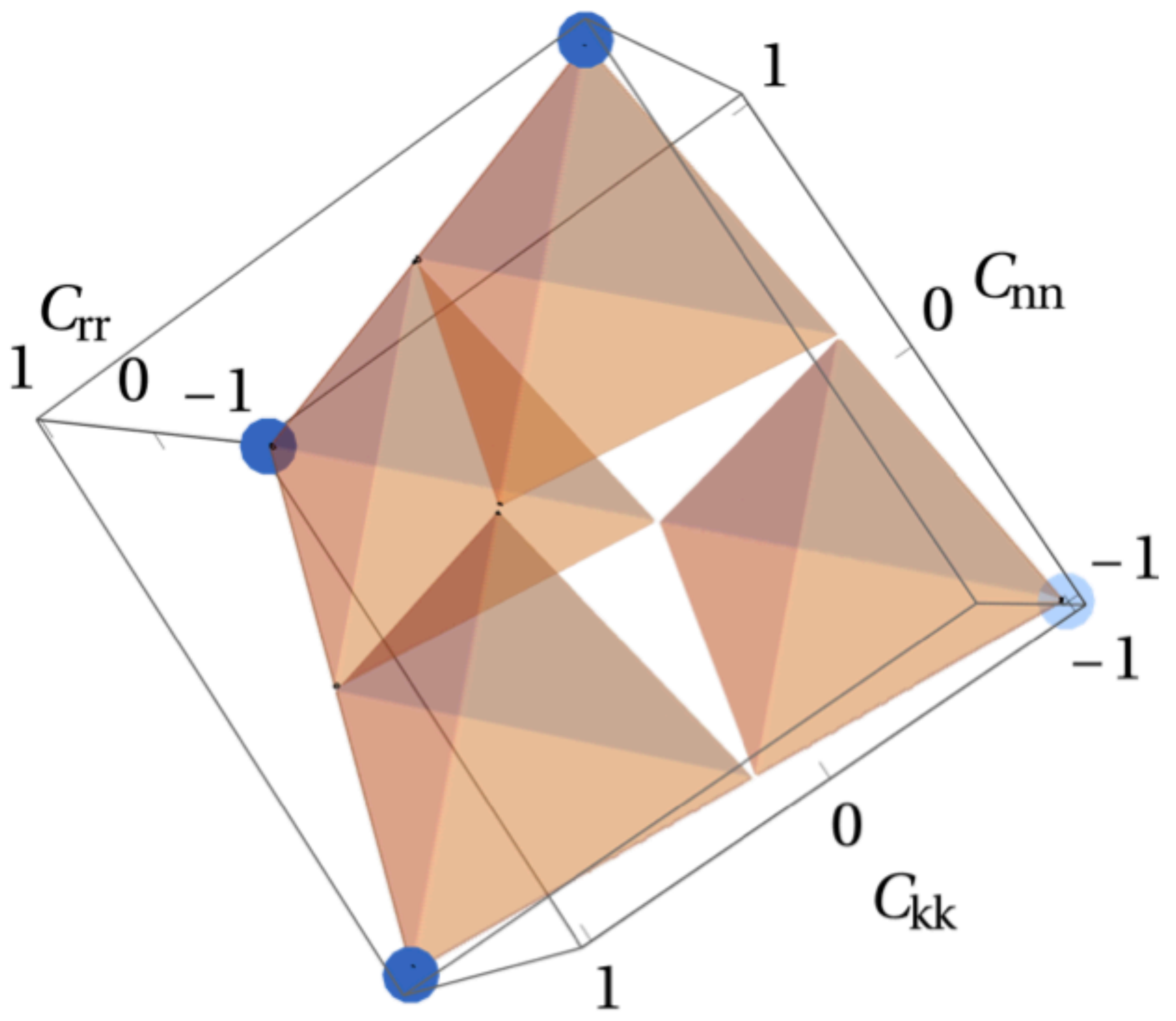

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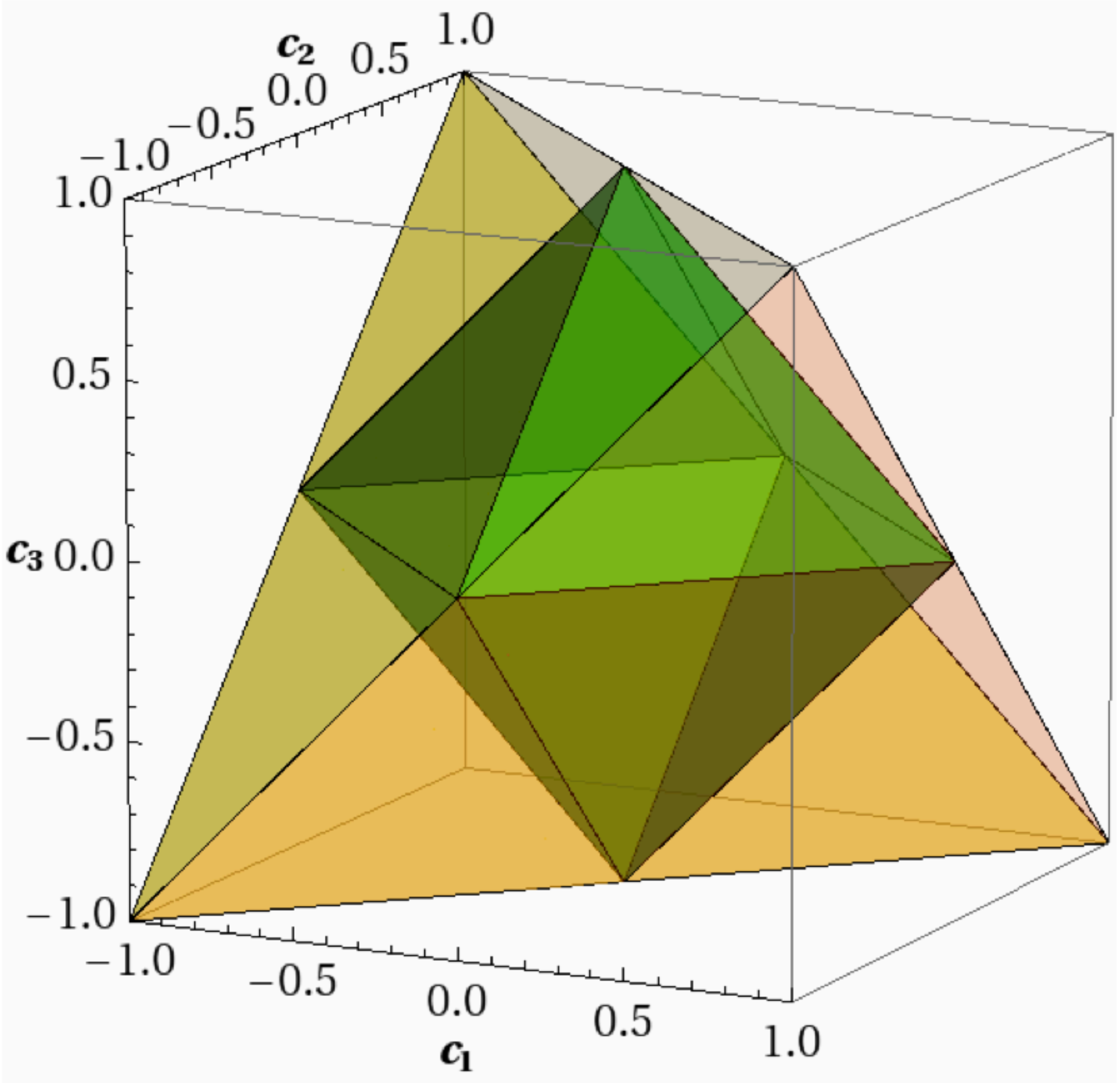

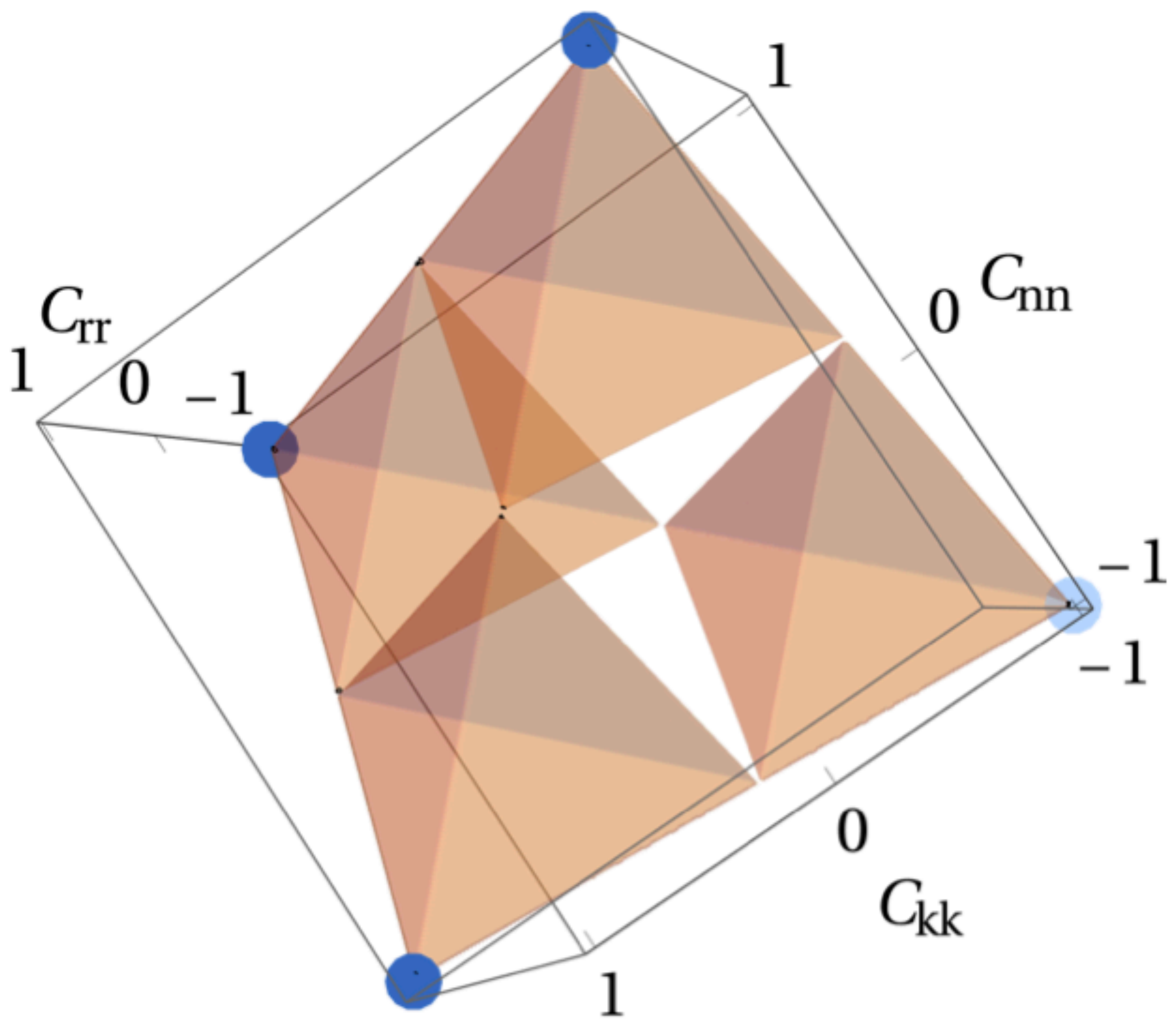

Discord at colliders

Experiments

$$\overline{C}_{ij} = \frac{1}{\sigma_\Pi}\int_\Pi d\Omega \frac{d\sigma}{d\Omega} C_{ij}(\Omega).$$

Fictitious states

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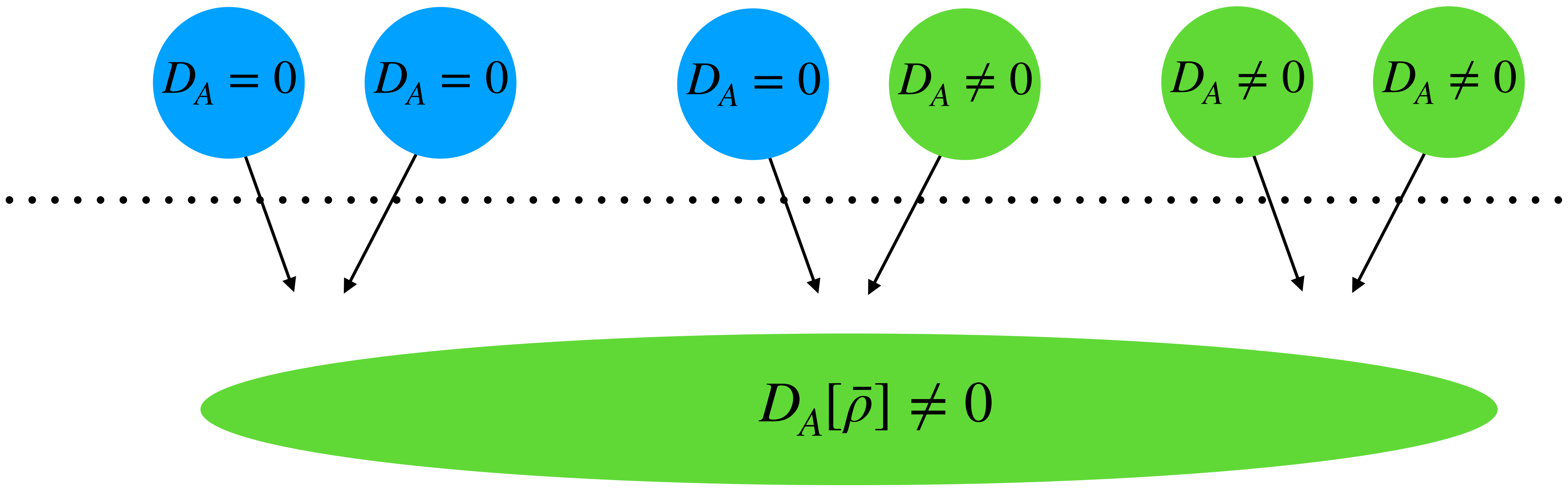

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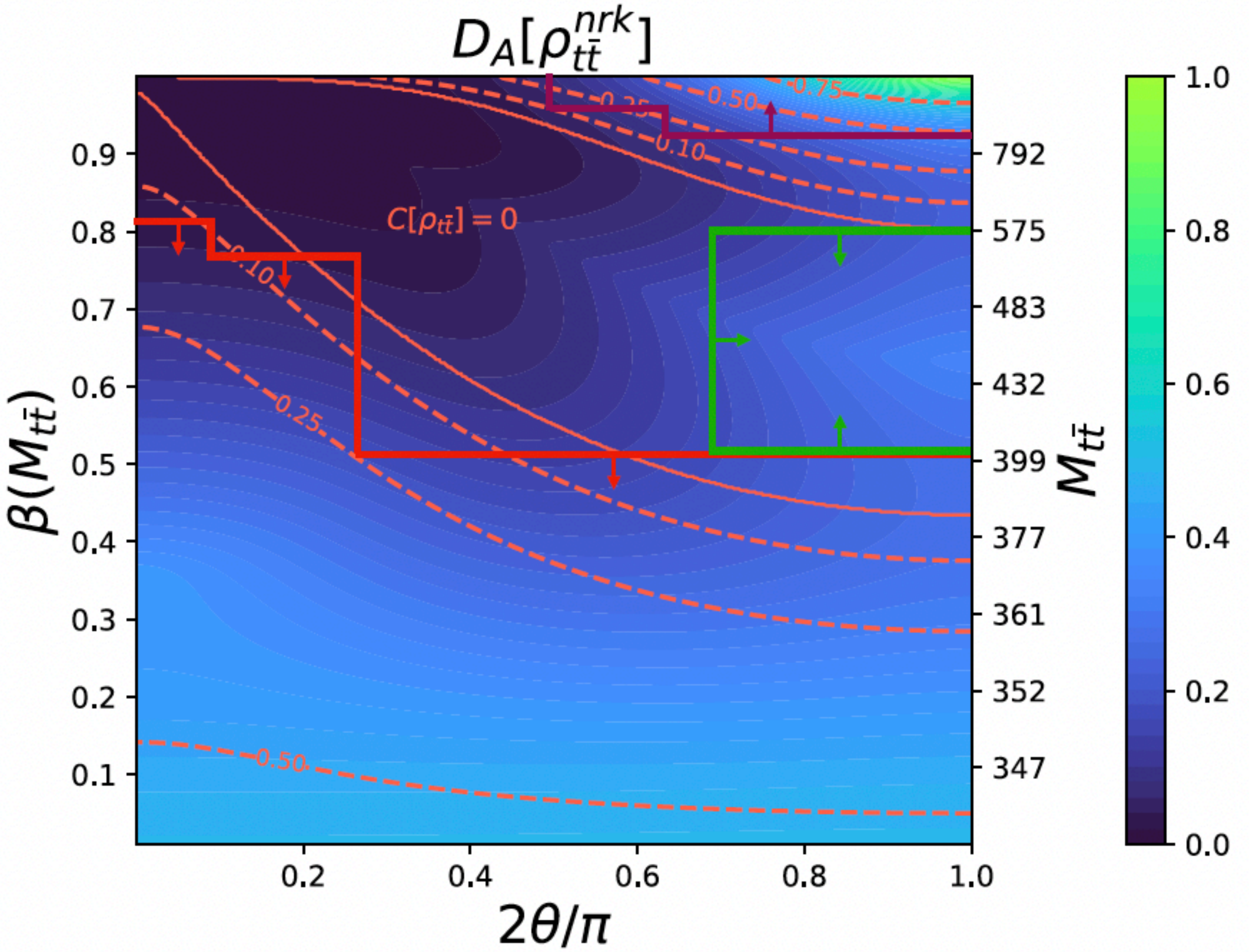
Two solutions:

- Measure discord in regions of phase space which give an entangled fictitious state
- Restrict phase space to regions where <u>all</u> sub-states have $D_A[\rho] \neq 0$

Discord at colliders

Three signal regions:

- Threshold
- Separable
- Boosted



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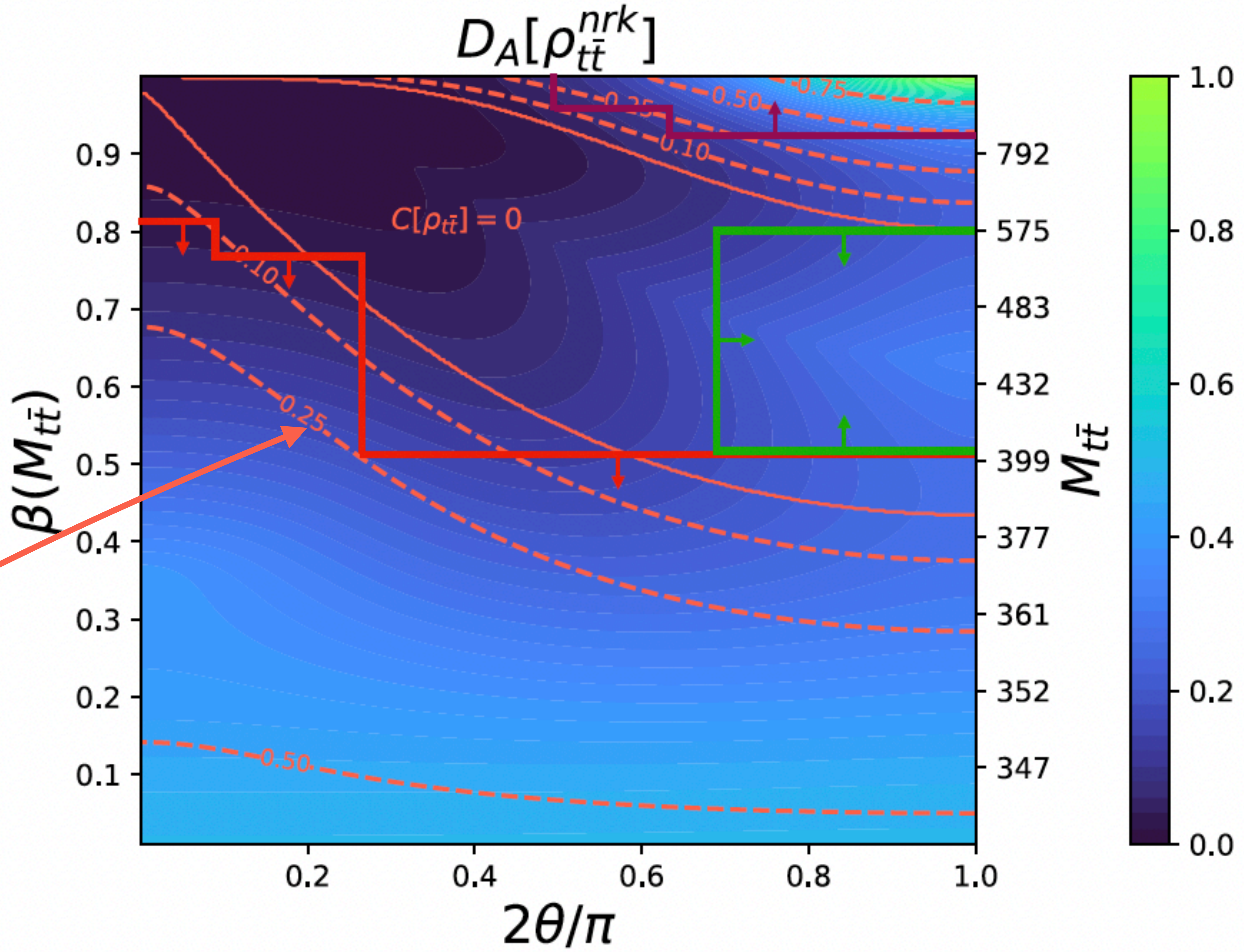

Contours of concurrence

Discord at colliders

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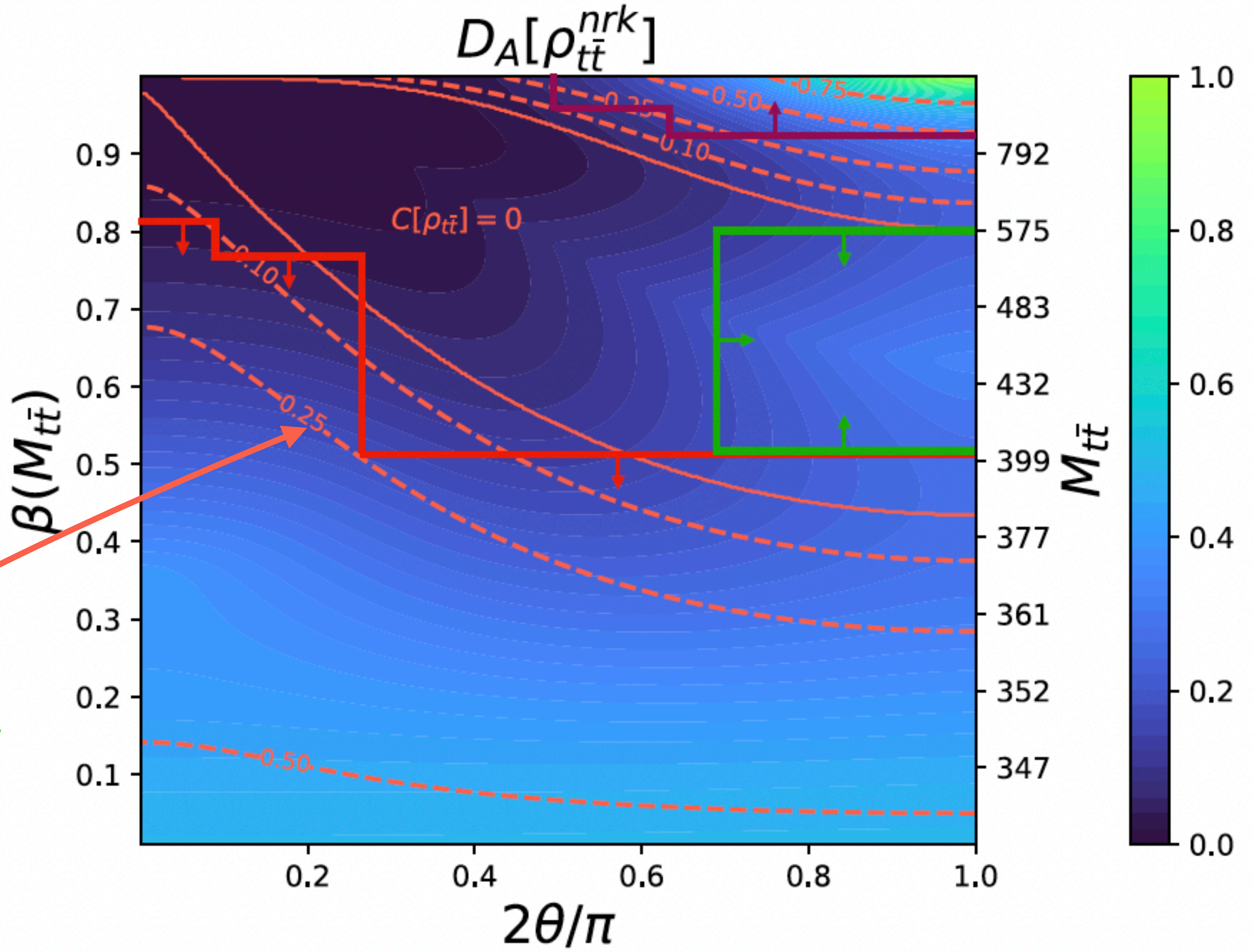
Separable states w genuine quantum correlations!



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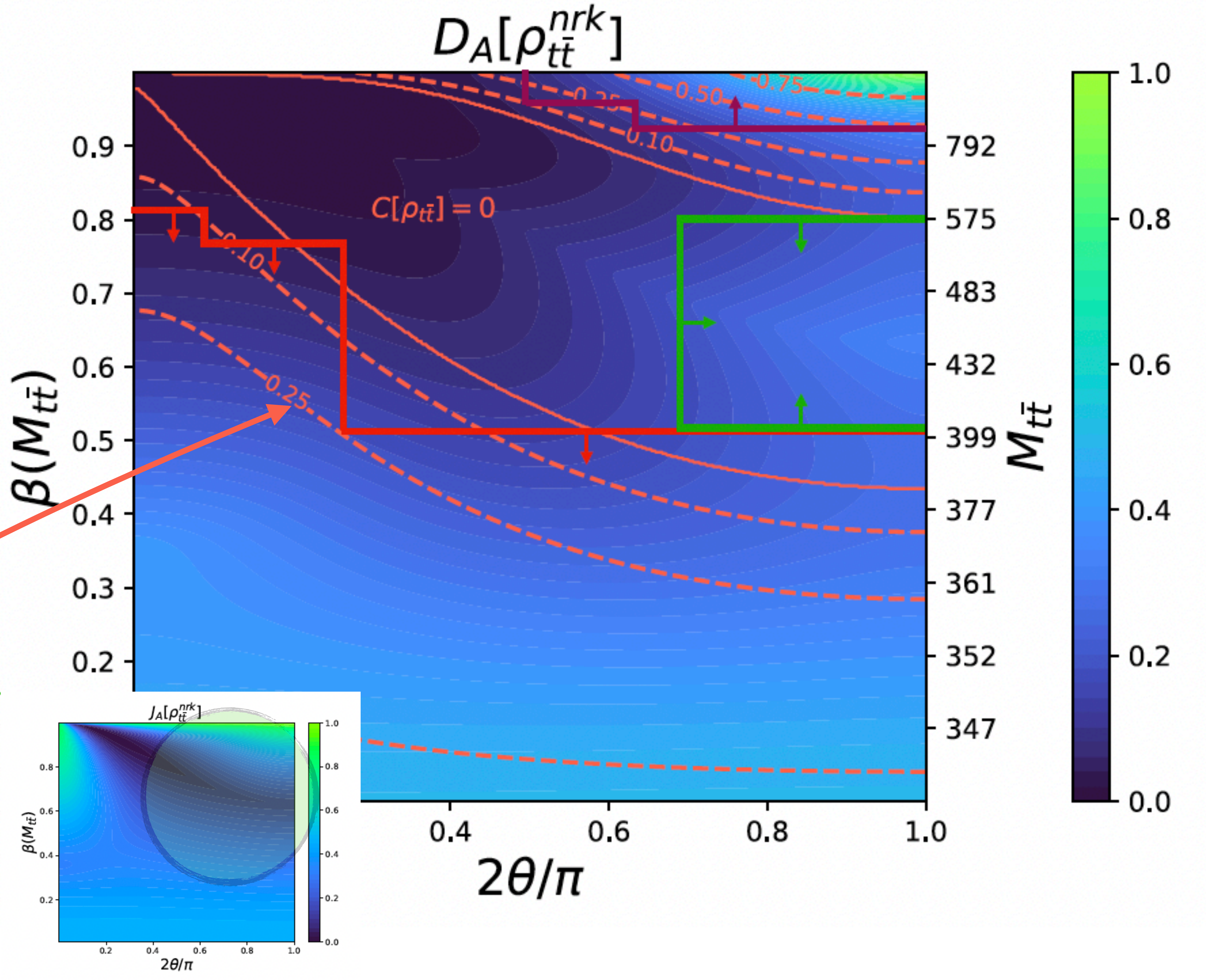
- Boosted

Separable states w genuine quantum correlations!

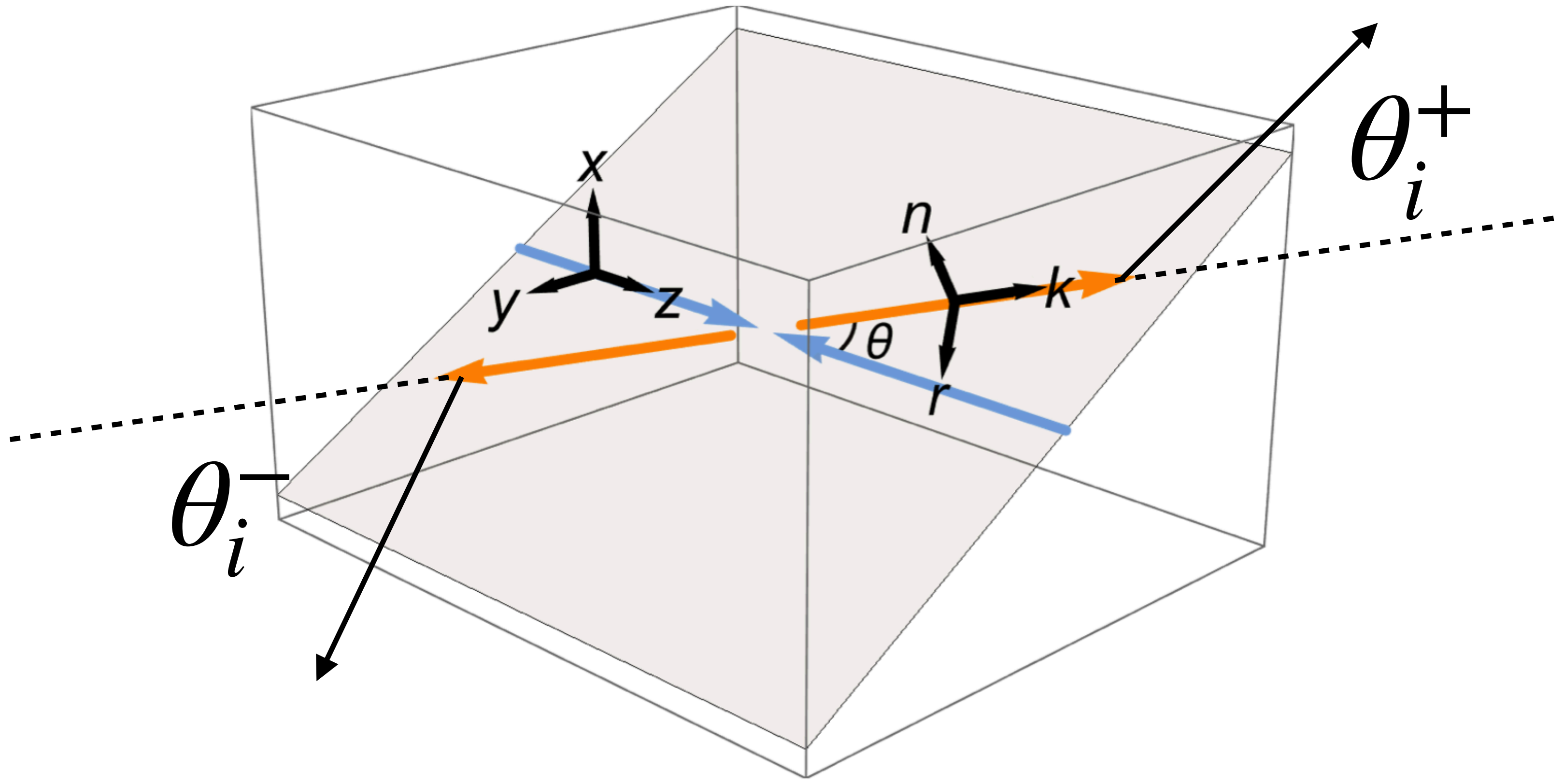


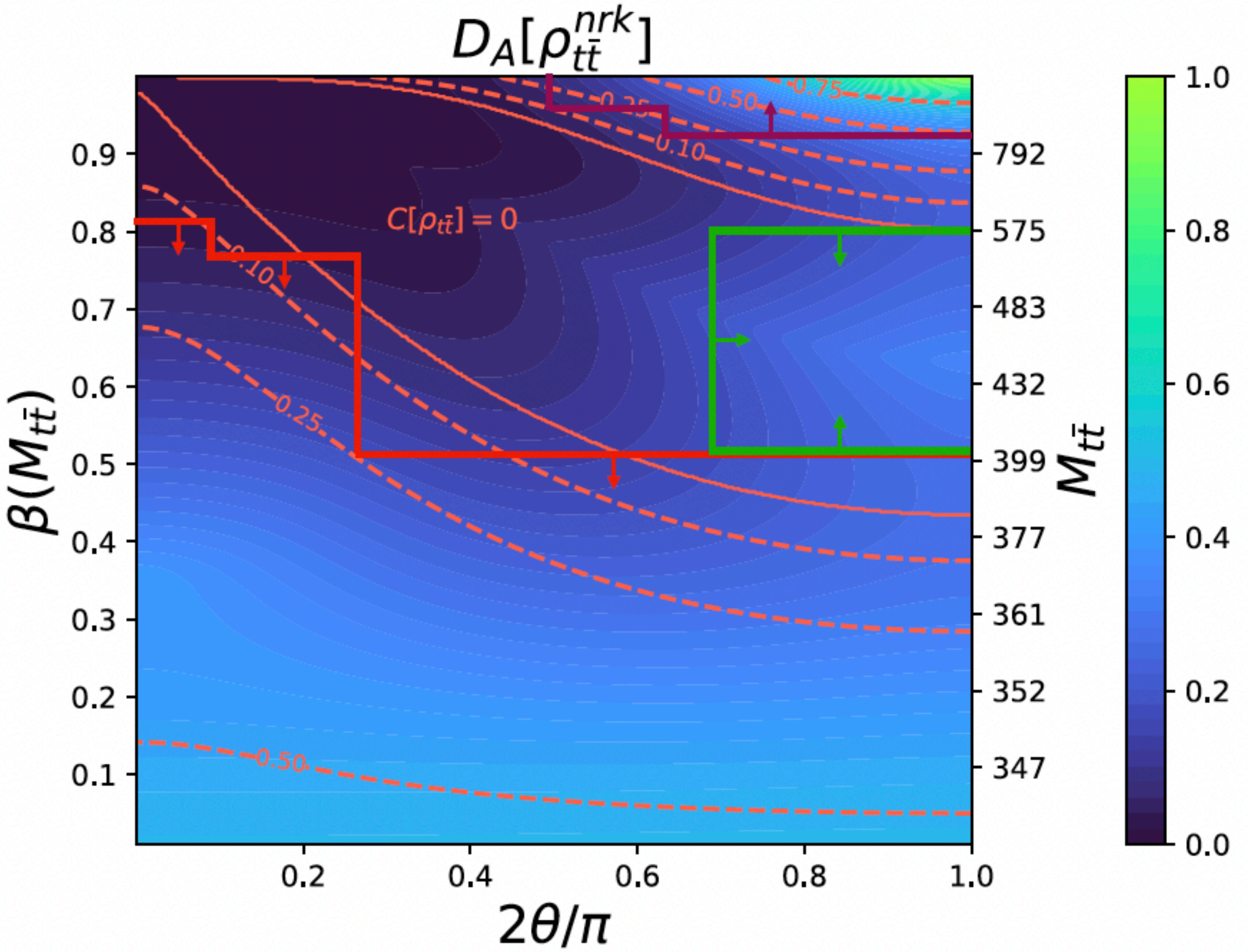
Contours of concurrence

Collider Analysis

$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Decay method

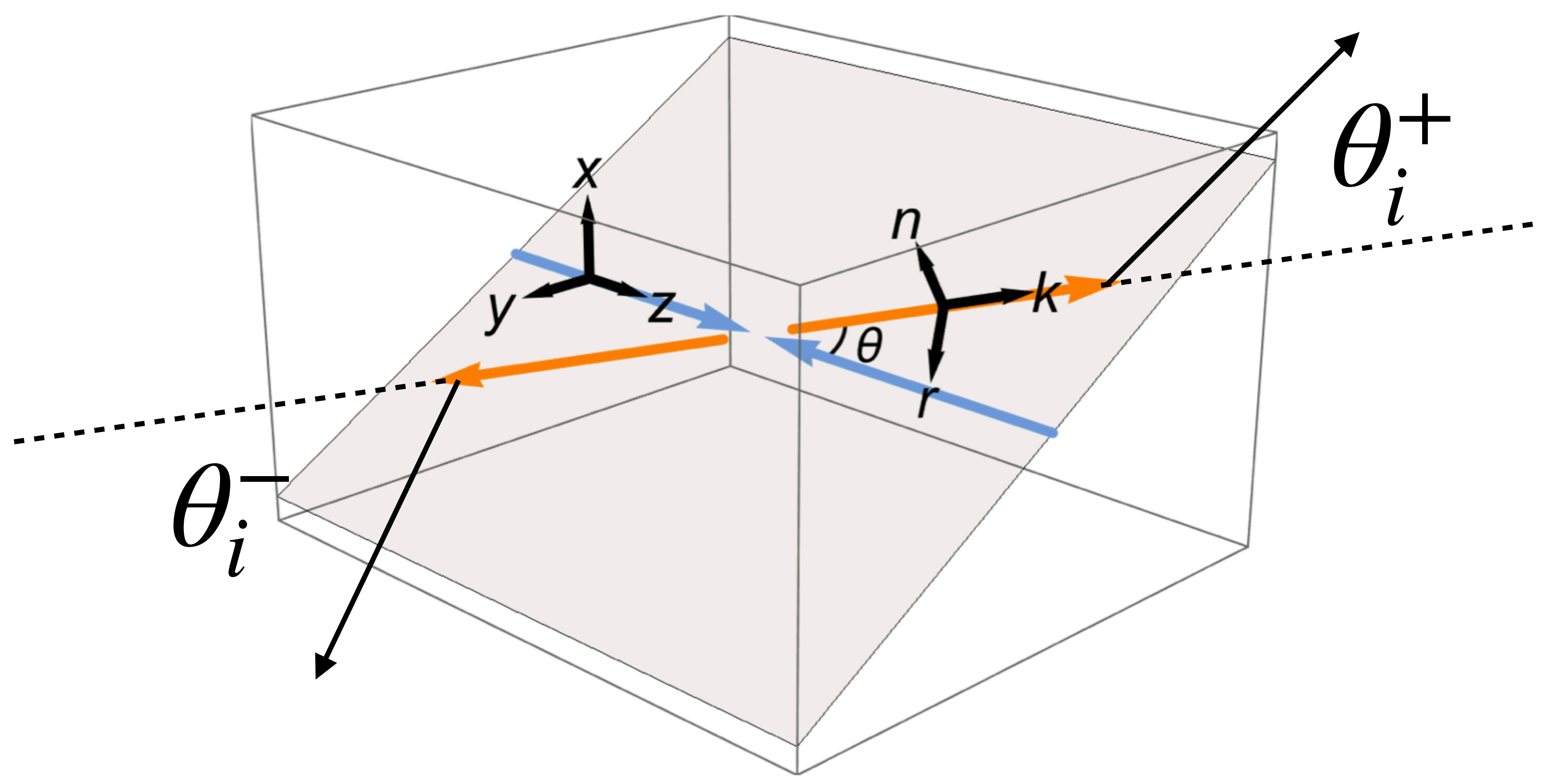




Collider Analysis

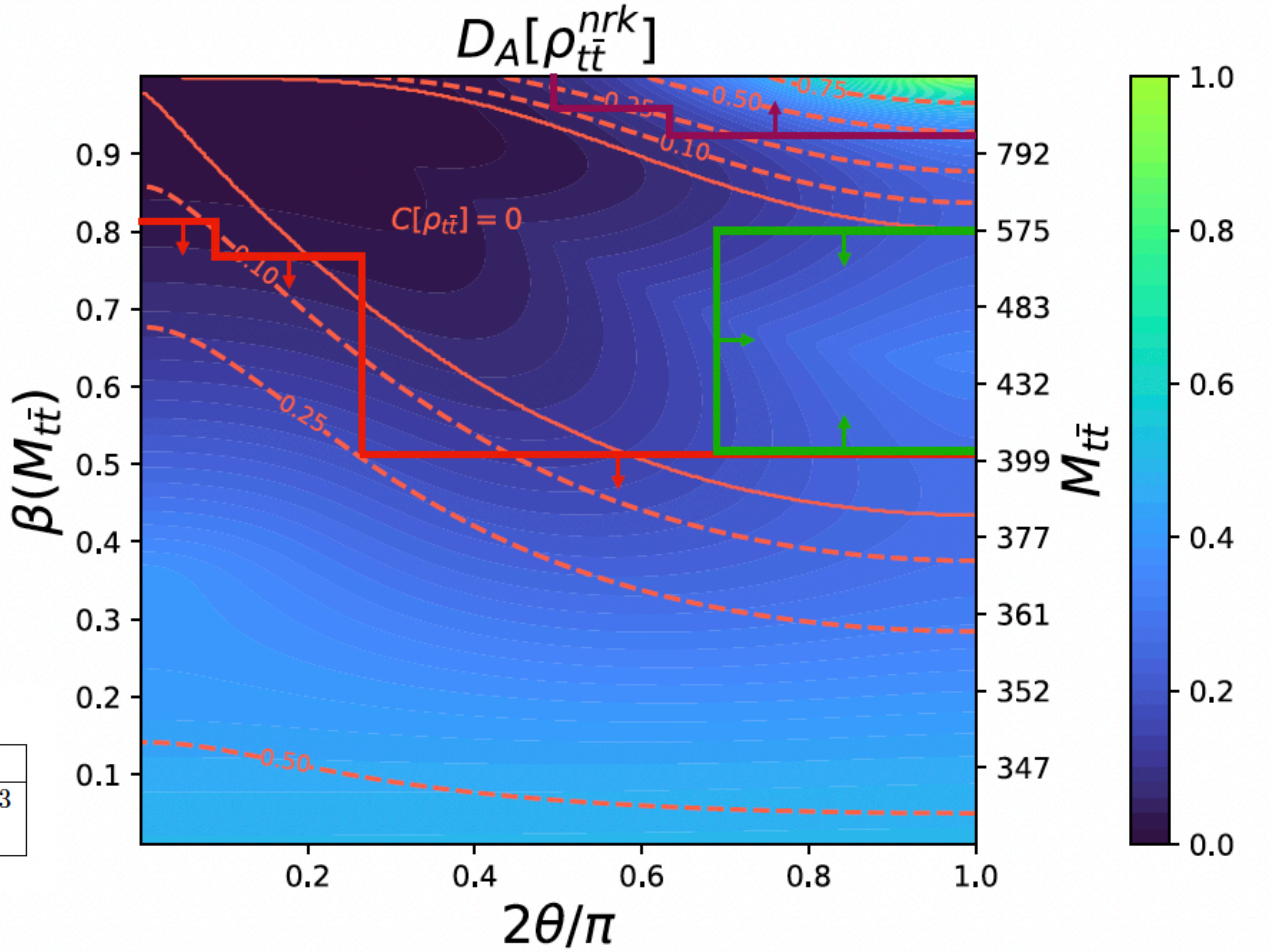
$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Decay method



	Threshold Region		Separable Region		Boosted Region	
	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$
Parton		0.200 ± 0.003		0.255 ± 0.008		0.197 ± 0.003
Reconstructed	0.10	0.23 ± 0.04	0.28	0.18 ± 0.05	0.08	0.20 ± 0.05

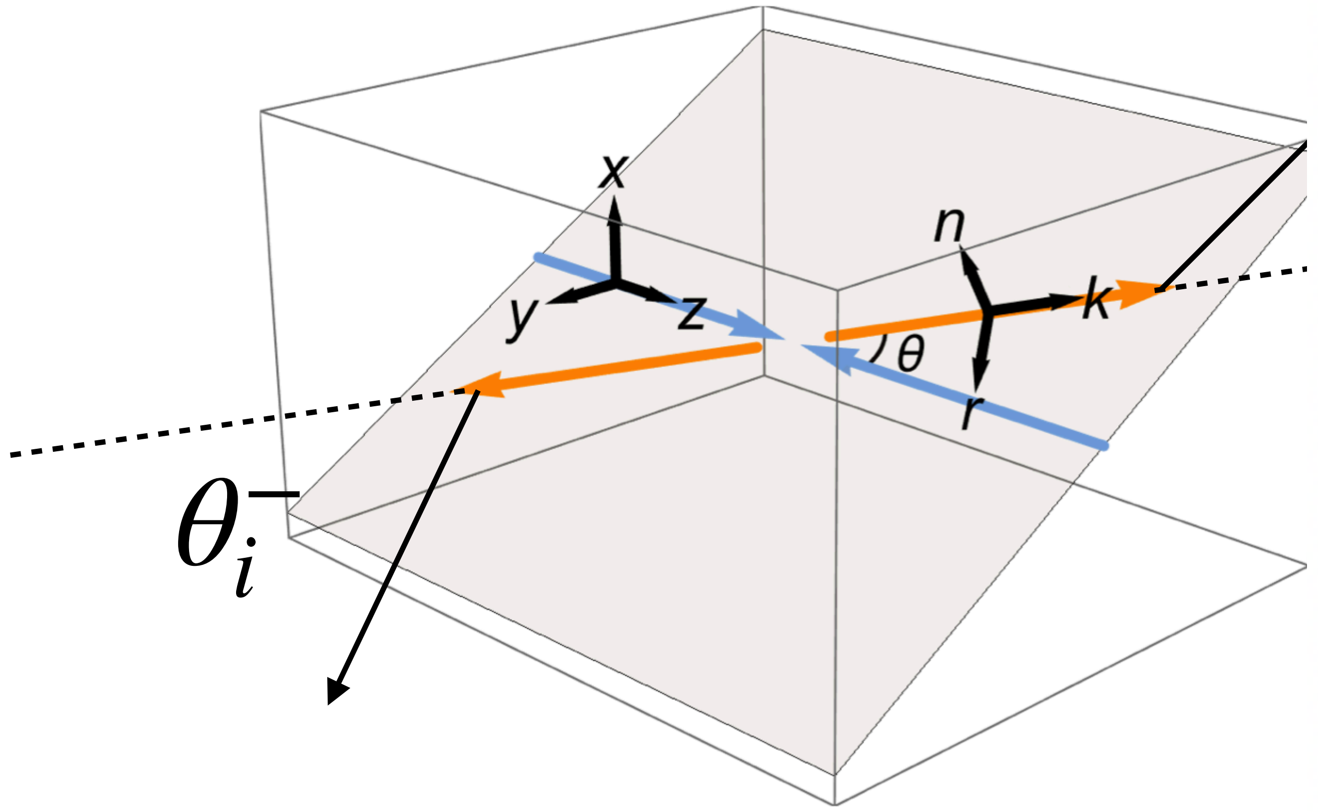
Uncertainties: statistical $\mathscr{L} = 139\ \text{fb}^{-1}$ + syst. (detector efficiencies + unfolding)

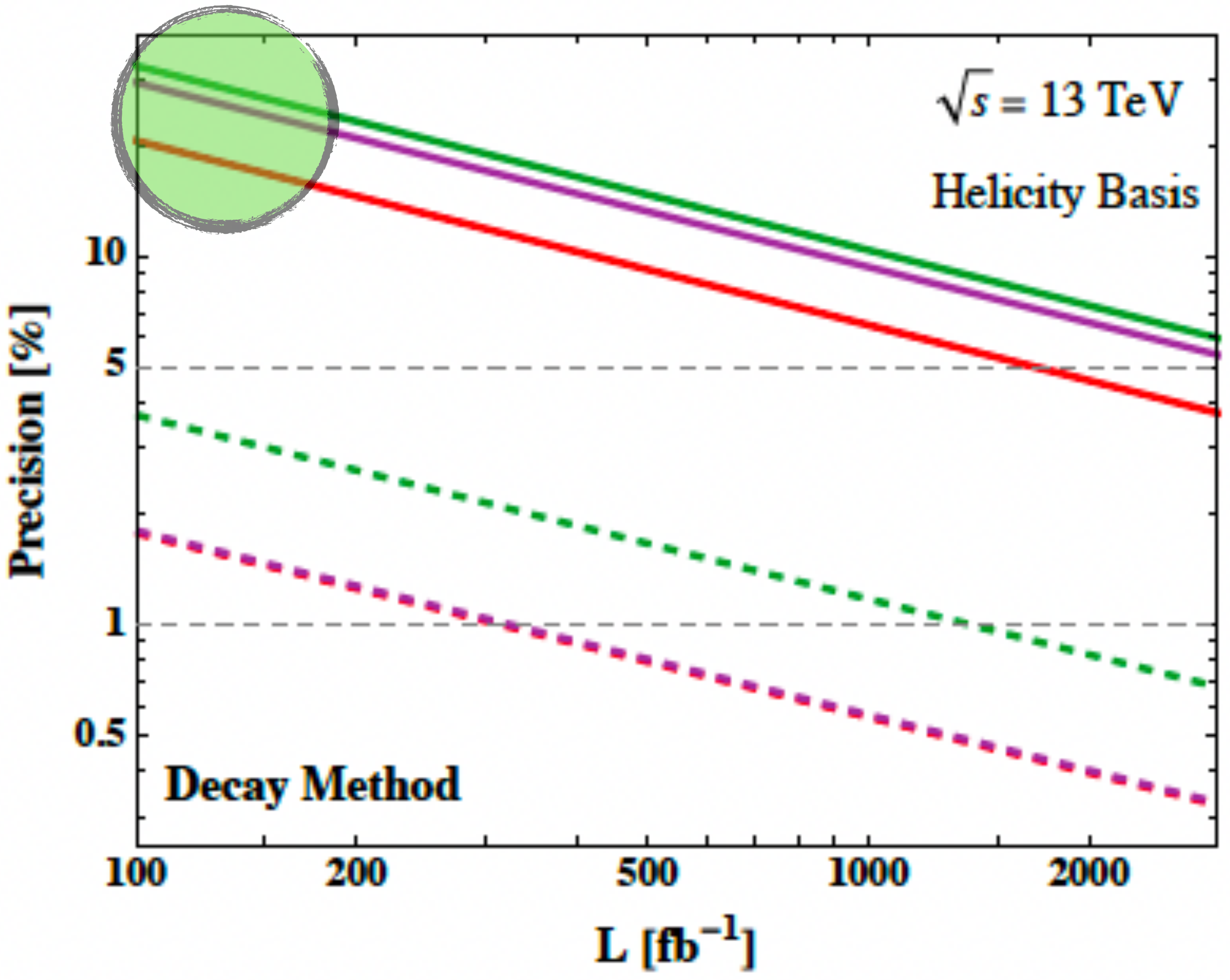


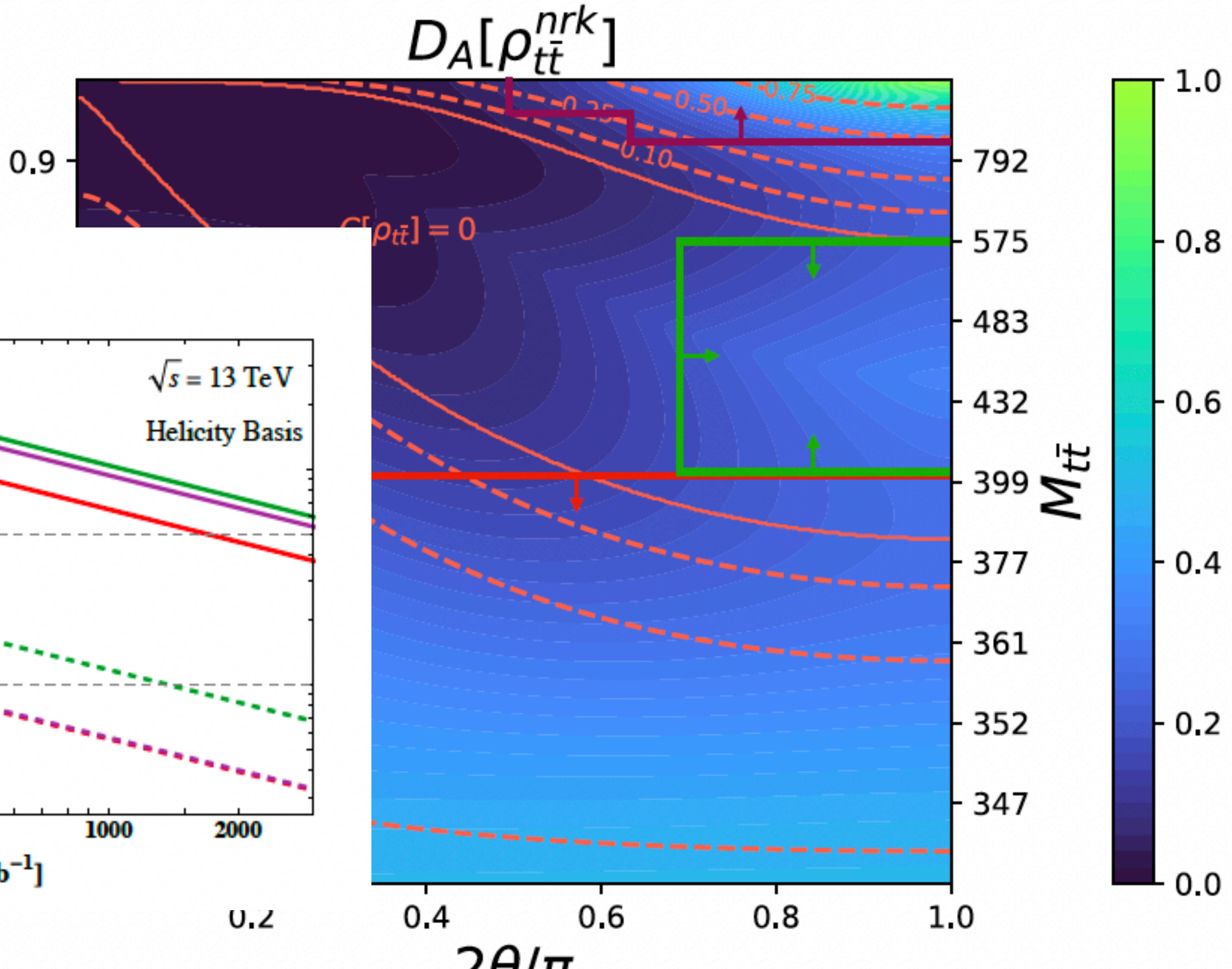
Collider Analysis

$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Decay method







	Threshold Region		Separable Re	
	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$	$\langle\epsilon_{rec}\rangle$	D
Parton		0.200 ± 0.003		0.255
Reconstructed	0.10	0.23 ± 0.04	0.28	0.18

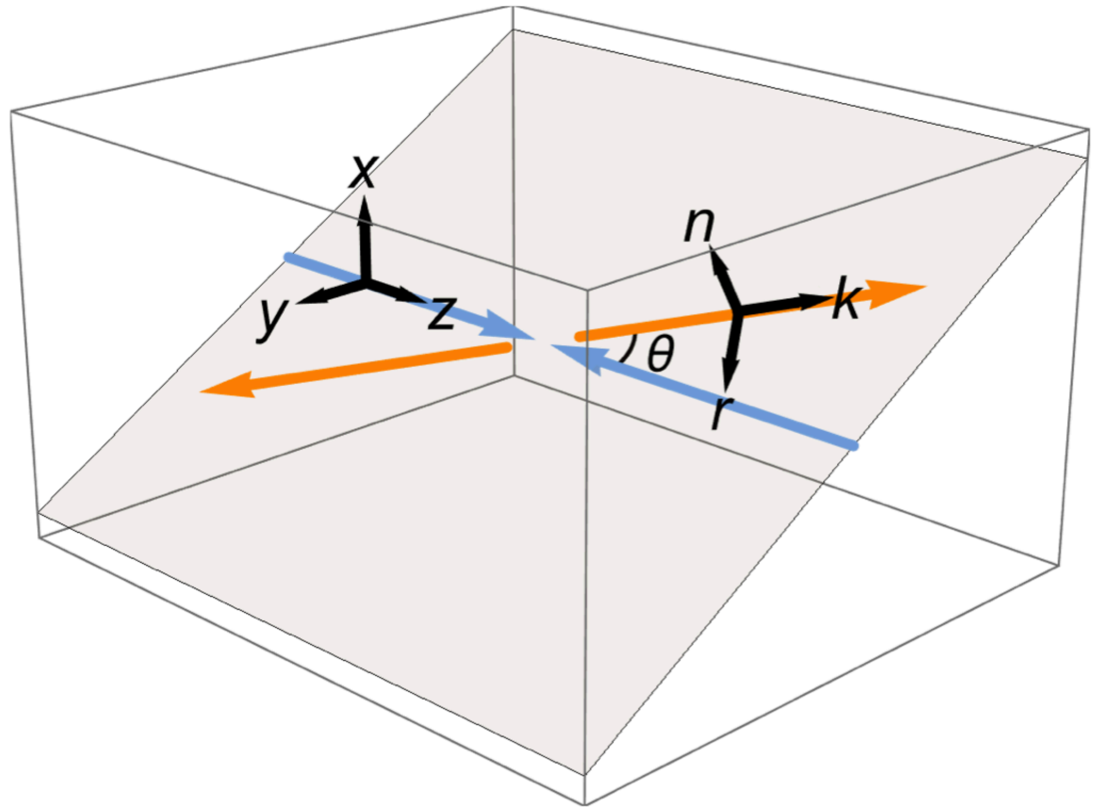
Uncertainties: statistical $\mathscr{L} = 139\ \text{fb}^{-1}$ + syst. (detector efficiencies + unfolding)

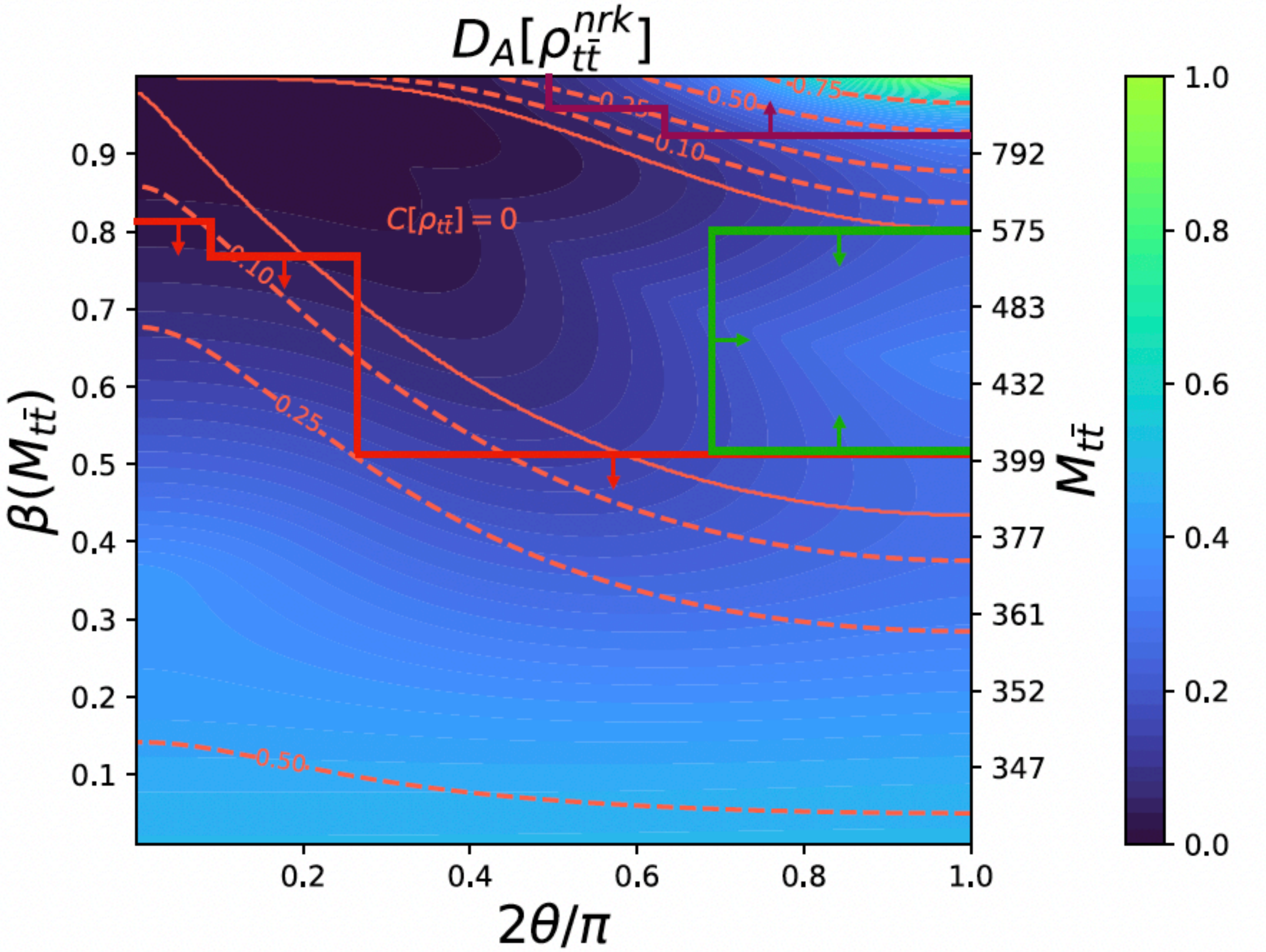
Est. precision w/ current data: ~20%

Collider Analysis

$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Kinematic method





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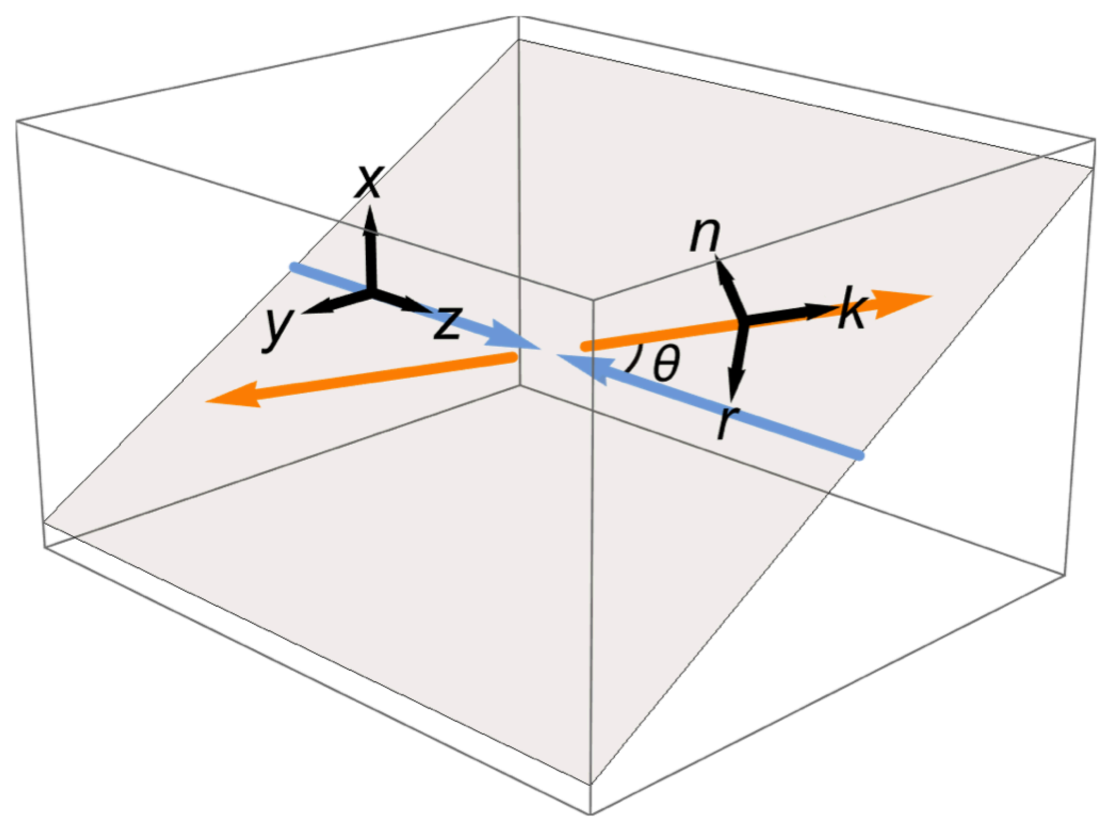
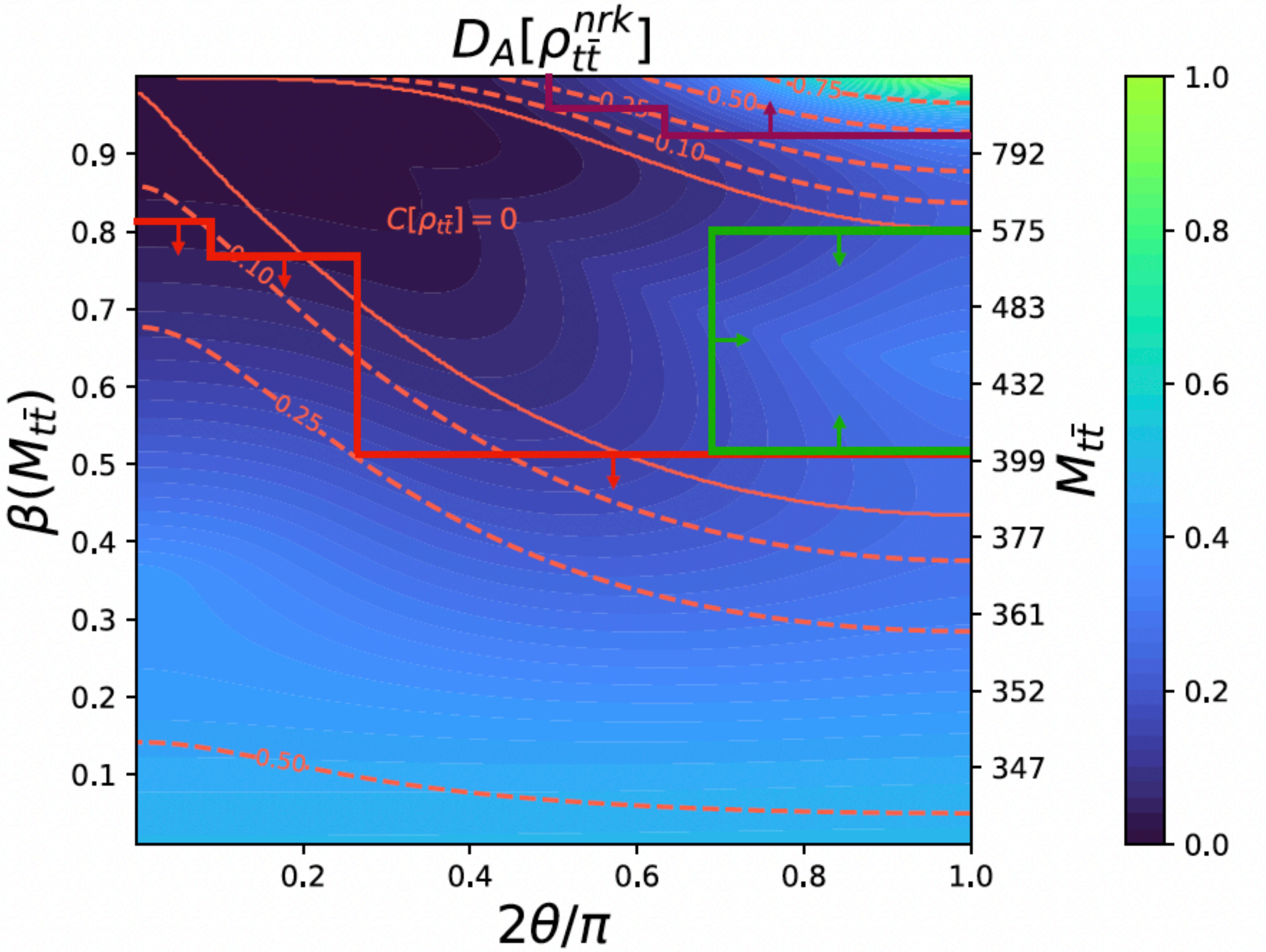
Collider Analysis

$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Kinematic method



$$C_{ij}^{\text{helicity}} = \begin{pmatrix} C_k(\theta, M_{t\bar{t}}) & C_{kr}(\theta, M_{t\bar{t}}) & 0 \\ C_{kr}(\theta, M_{t\bar{t}}) & C_r(\theta, M_{t\bar{t}}) & 0 \\ 0 & 0 & C_n(\theta, M_{t\bar{t}}) \end{pmatrix},$$



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Collider Analysis

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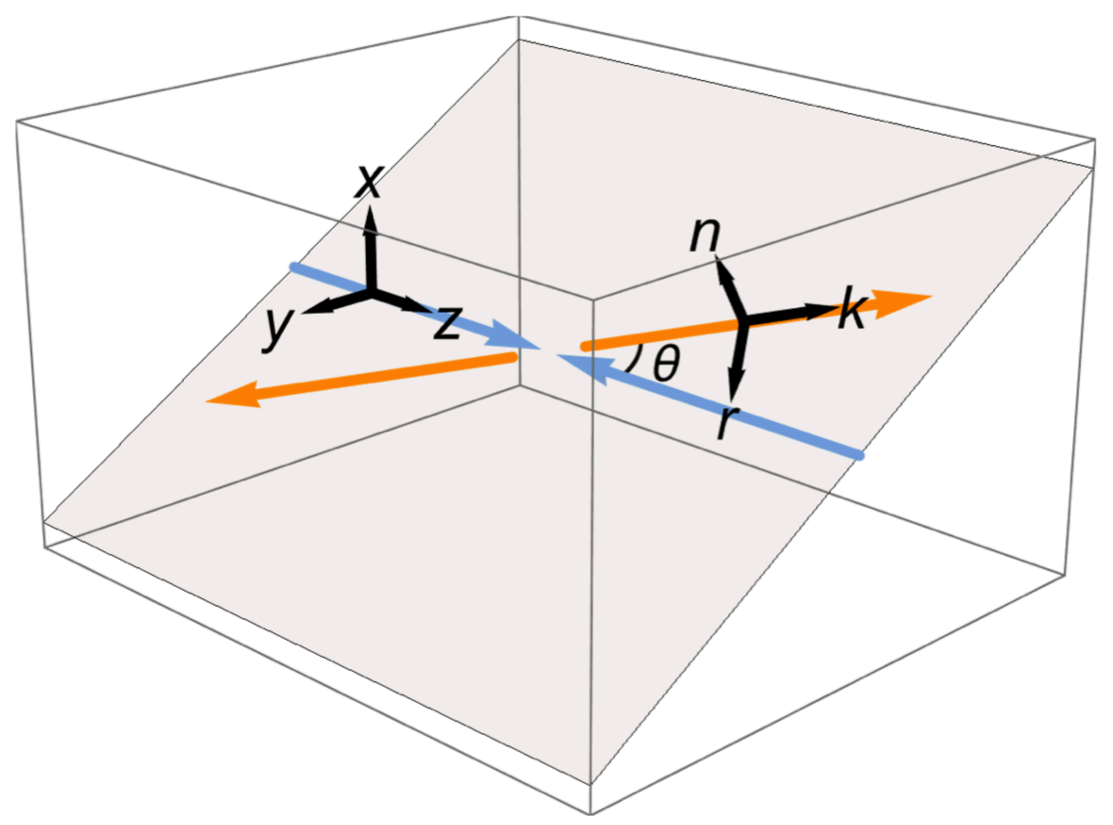

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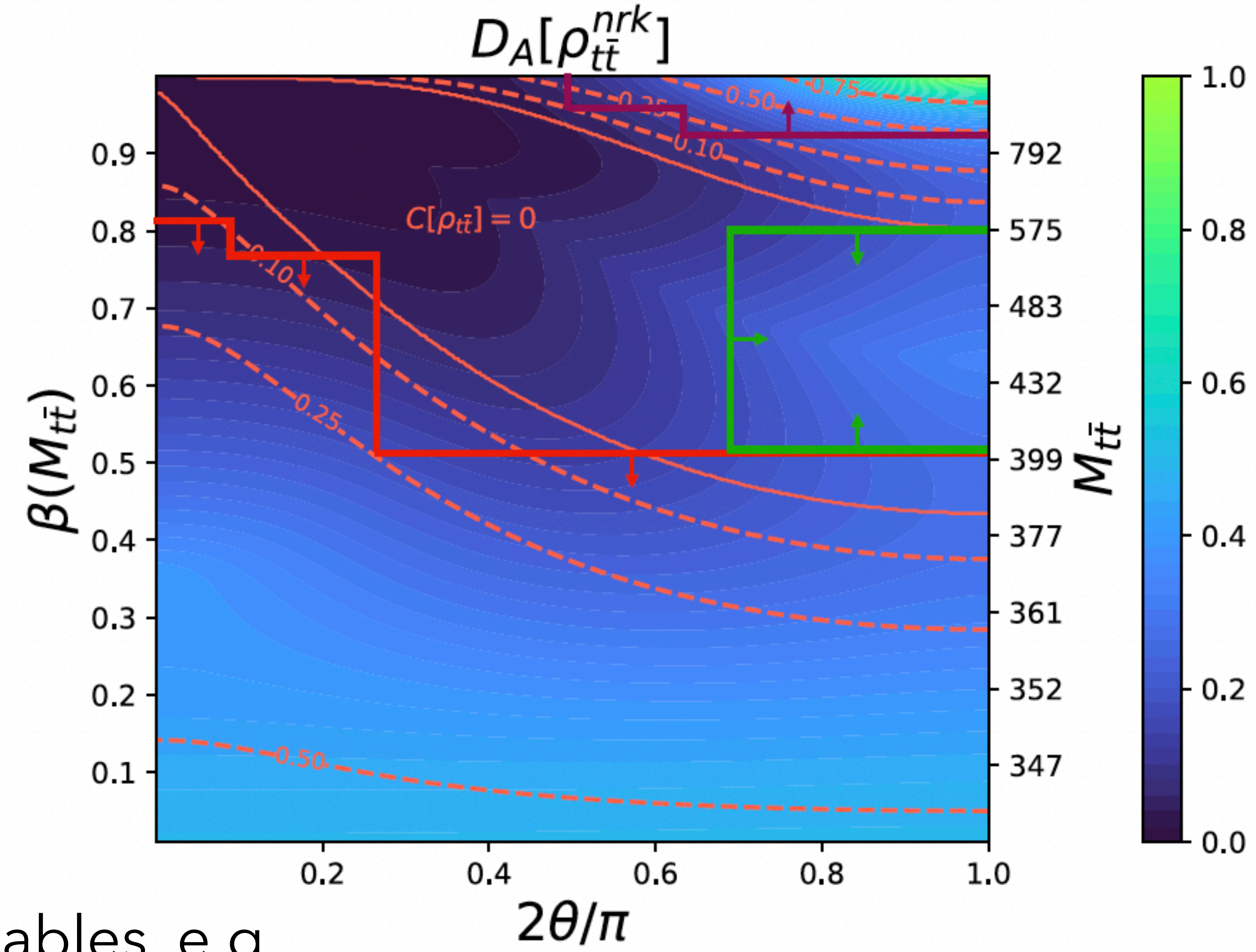


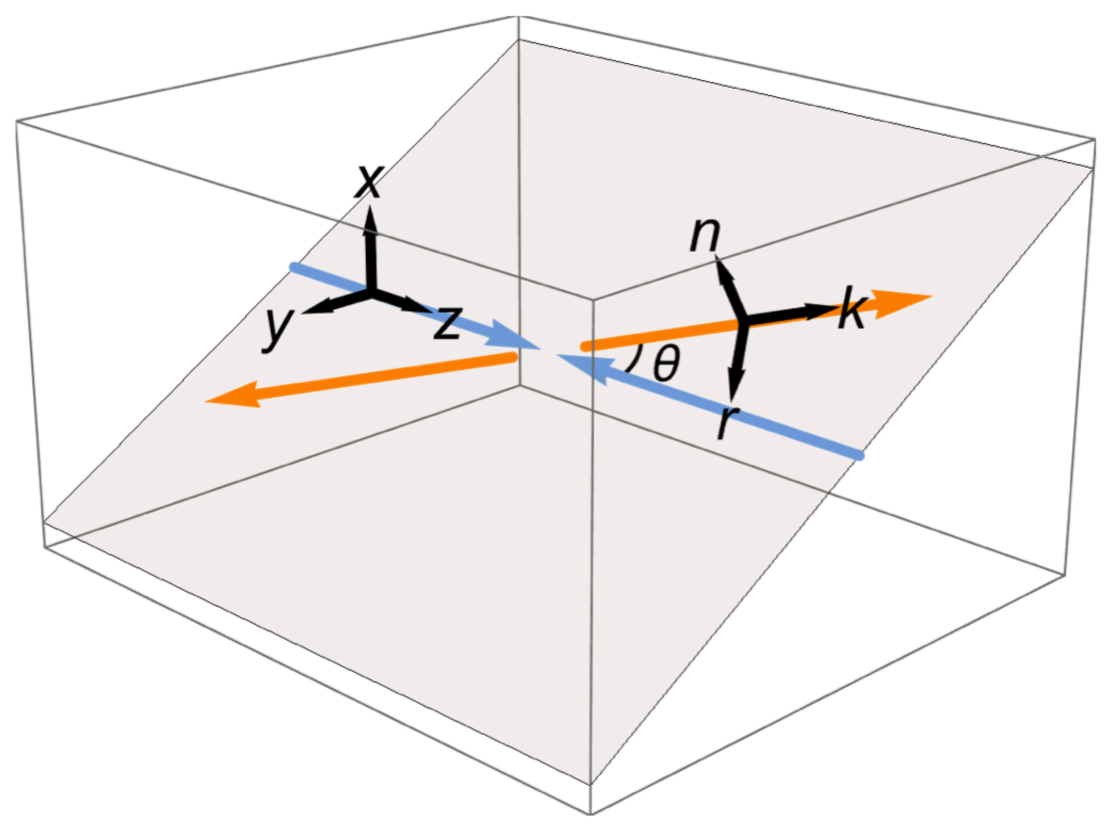
Subtlety: $\mathcal{O}(\bar{C}_{ij})$ for non-linear observables, e.g. Discord, VN entropy, etc. (for Bell can do $\bar{\mathcal{B}}(\theta, M_{t\bar{t}})$)

K. Cheng, T> Han, M. Low 2410.08303 [hep-ph]

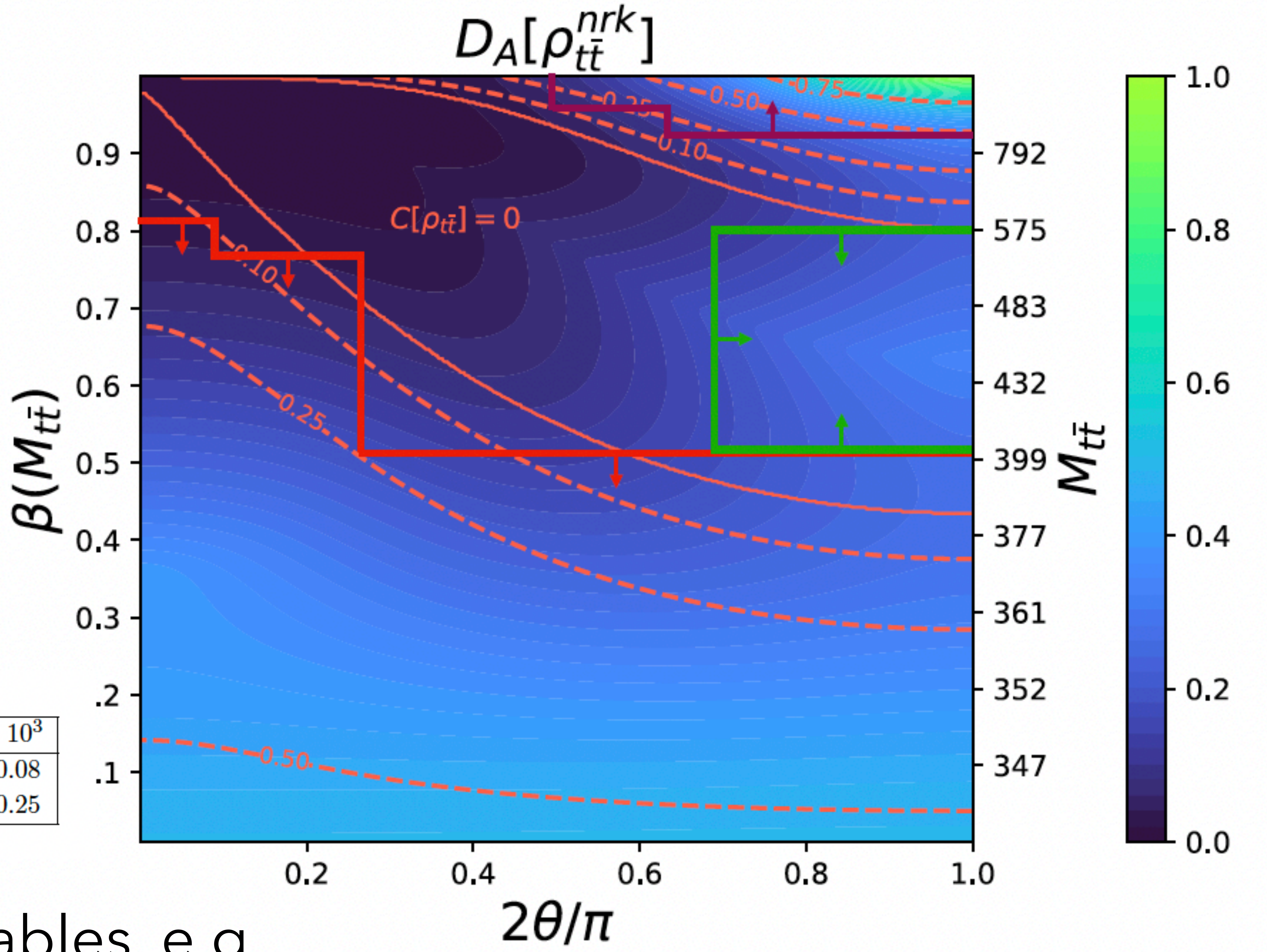
Collider Analysis

$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Kinematic method



	Threshold Region		Separable Region		Boosted Region	
	$\langle \epsilon_{rec} \rangle$	$D_A(\rho_{t\bar{t}}) \times 10^3$	$\langle \epsilon_{rec} \rangle$	$D_A(\rho_{t\bar{t}}) \times 10^3$	$\langle \epsilon_{rec} \rangle$	$D_A(\rho_{t\bar{t}}) \times 10^3$
Parton		173.42 ± 0.07		249.72 ± 0.24		200.81 ± 0.08
Reconstructed	0.10	147.10 ± 0.24	0.28	232.54 ± 0.47	0.08	188.49 ± 0.25



Subtlety: $\mathcal{O}(\bar{C}_{ij})$ for non-linear observables, e.g.
Discord, VN entropy, etc. (for Bell can do $\bar{\mathscr{B}}(\theta, M_{t\bar{t}})$)

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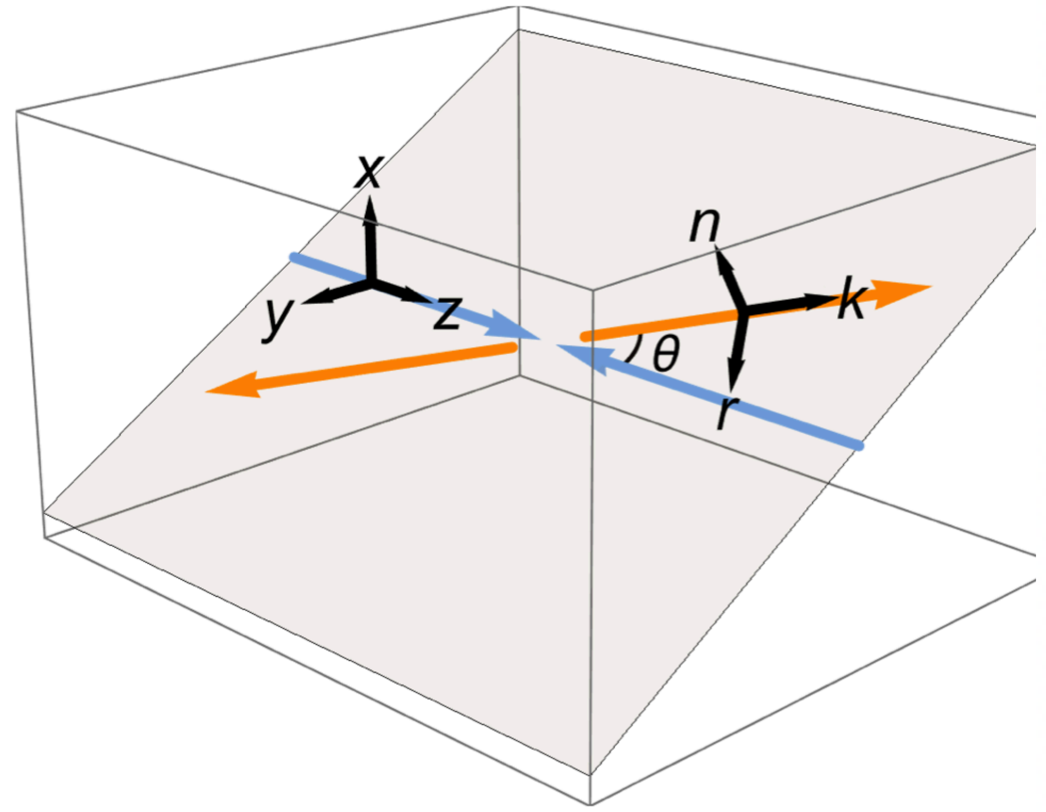
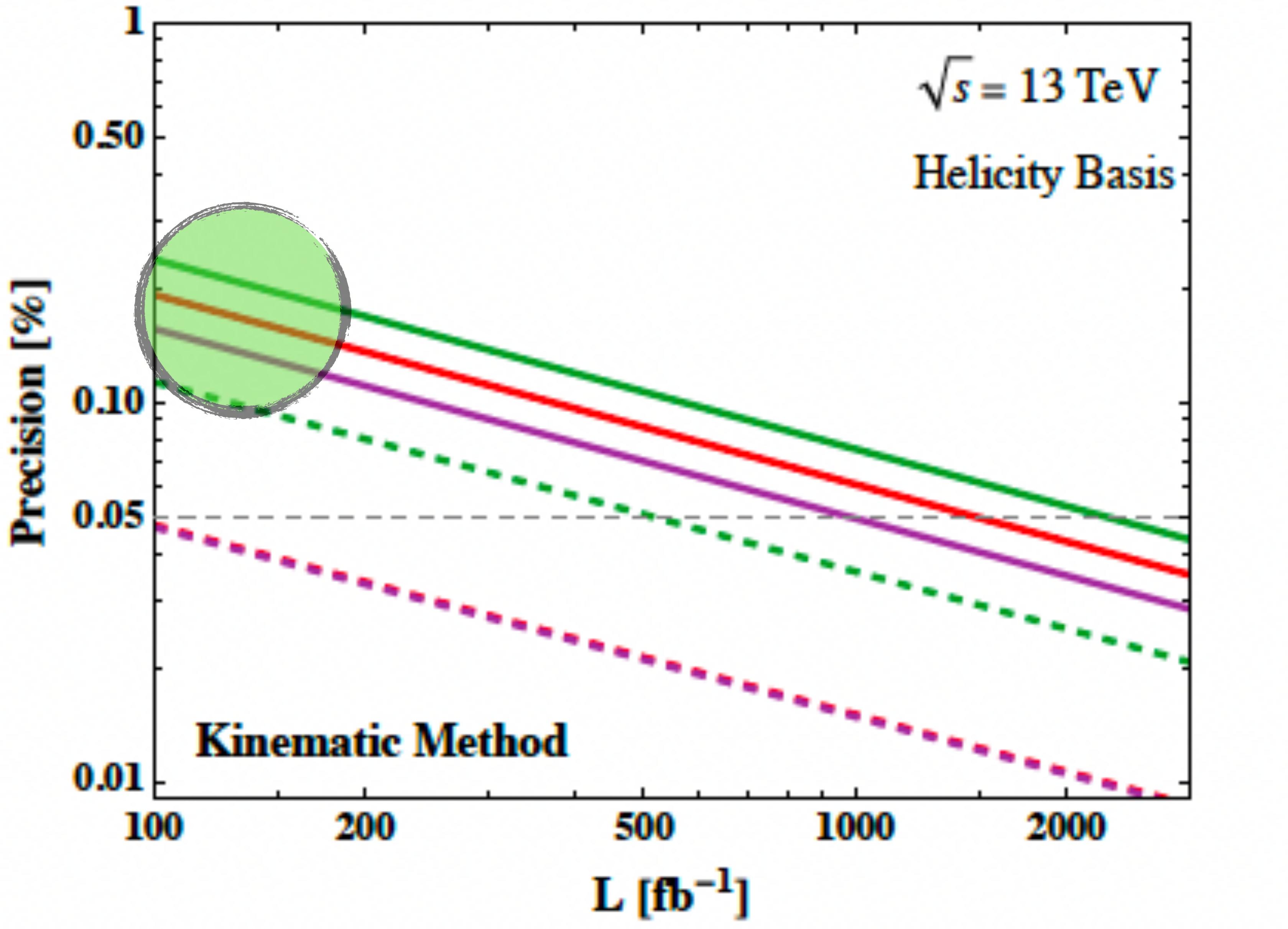
Collider Analysis

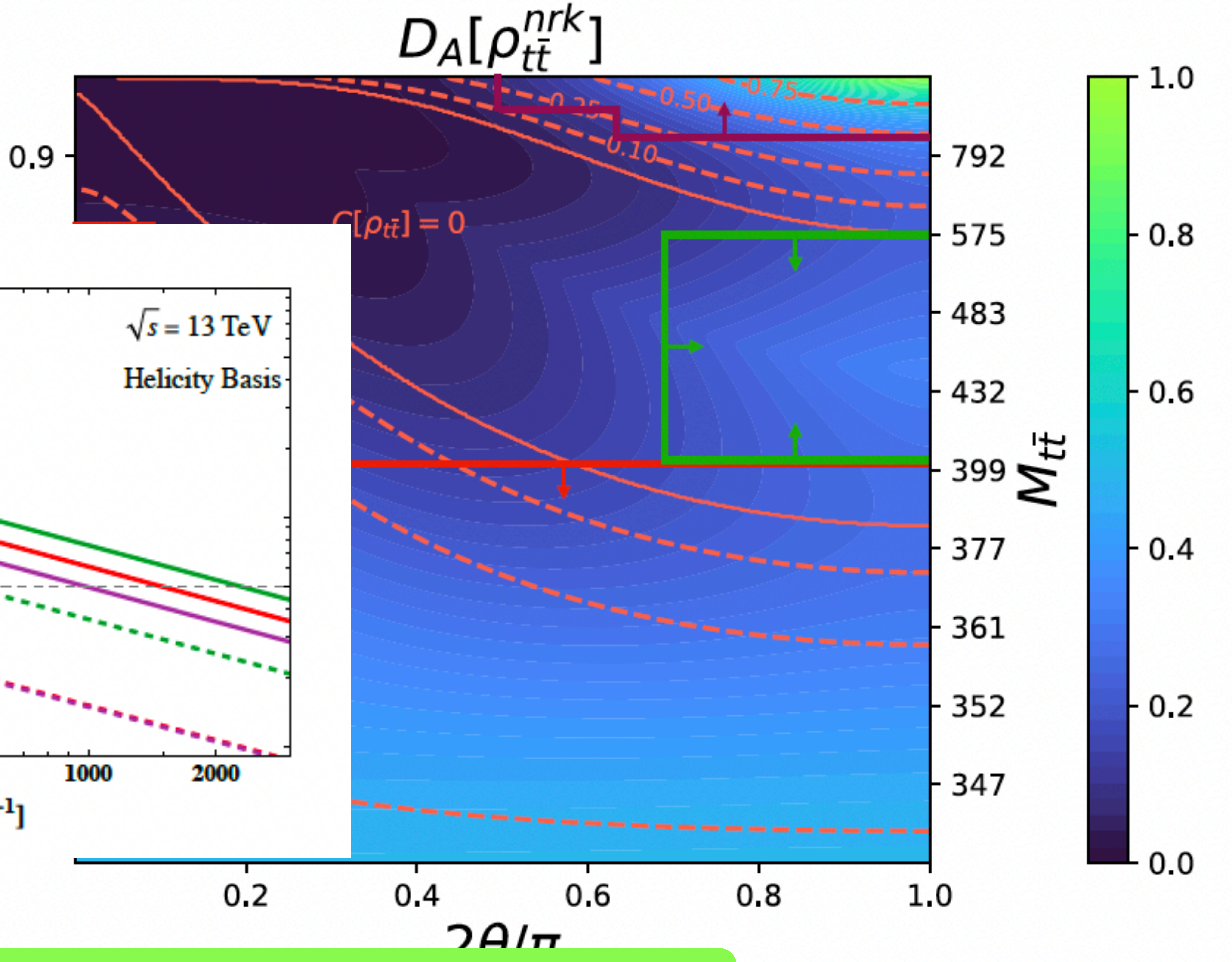
$$pp \to t\bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + \not{E}_T.$$

- Kinematic method



	Threshold Region		Separabl	
	$\langle \epsilon_{rec} \rangle$	$D_A(\rho_{t\bar{t}}) \times 10^3$	$\langle \epsilon_{rec} \rangle$	I
Parton		173.42 ± 0.07		2
Reconstructed	0.10	147.10 ± 0.24	0.28	2





Subtlety: $\mathcal{O}(\bar{C}_{ij})$ fo

Discord, VN entrop

Est. precision w/ current data: ~0.3%

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Collider Analysis

Metric	Measured
D=Tr[C]/3	-0.221 ± 0.010
Magic	0.238 ± 0.014
Discord	0.073 ± 0.010
LQU	0.051 ± 0.007

Obtained from the **inclusive**
(100k toys) → **clear observa**
But how do w

From yesterday's talk:

Est. precision w/ <u>actual</u> data: ~14%

(Using full spin-density matrix)

Summary

- Discord is a clear next step in the exploration of QI at colliders
  - Computable analytically for $t\bar{t}$ (at LO) in terms of "collider friendly" observables
  - Can be framed in robust way in terms of existing analysis strategies (dilepton, lepton + jets, etc.), clear advantages for kinematic method
- Important subtleties uncovered (convexity, linearity) which must be considered for other observables

- Future directions:
  - Higher order effects
  - CP-odd corrections (EW, NP)