

Quantum Information at Colliders

Ivo Young

10th April 2026

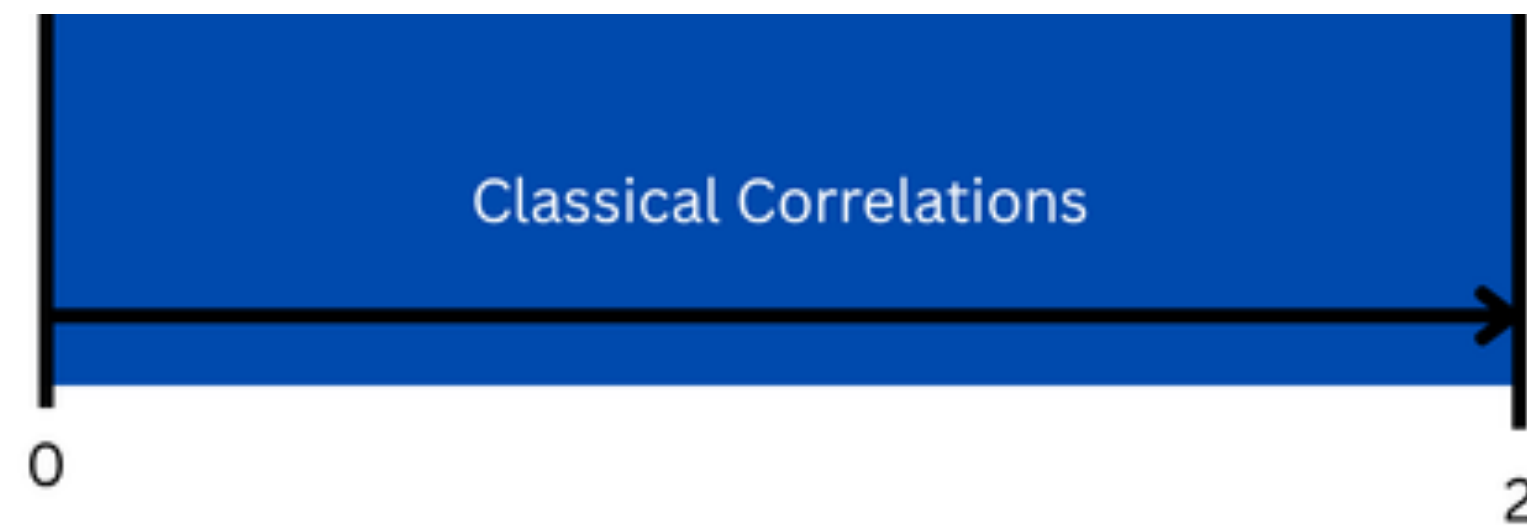
IOP APP + HEPP Annual Conference



The Motivation

- Quantum Mechanics (QM) can be tested at colliders
- Can use [Clauser-Horne-Shimony-Holt](#) (CHSH) to test QM:

$$\left| E(\vec{a}, \vec{b}) - E(\vec{a}, \vec{b}') \right| + \left| E(\vec{a}', \vec{b}') - E(\vec{a}', \vec{b}) \right| \leq 2$$



- Lots of quantum information variables are sensitive to BSM Physics and can be used as a source of new physics

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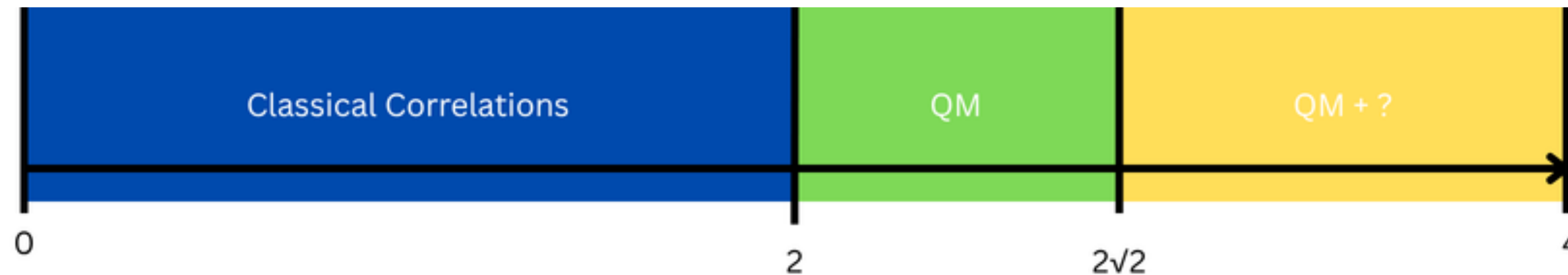


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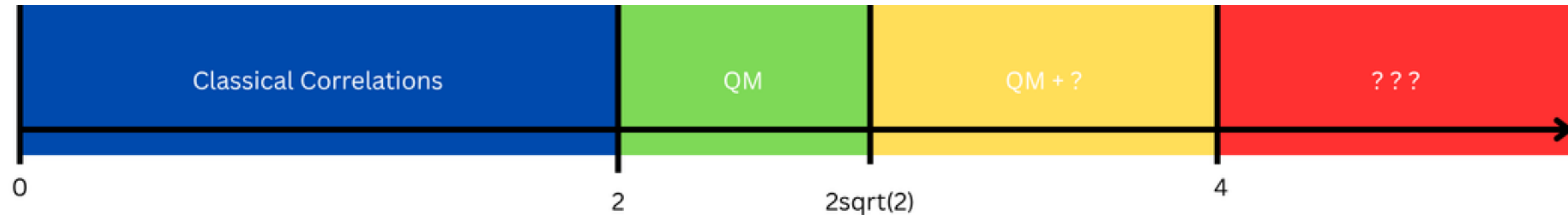


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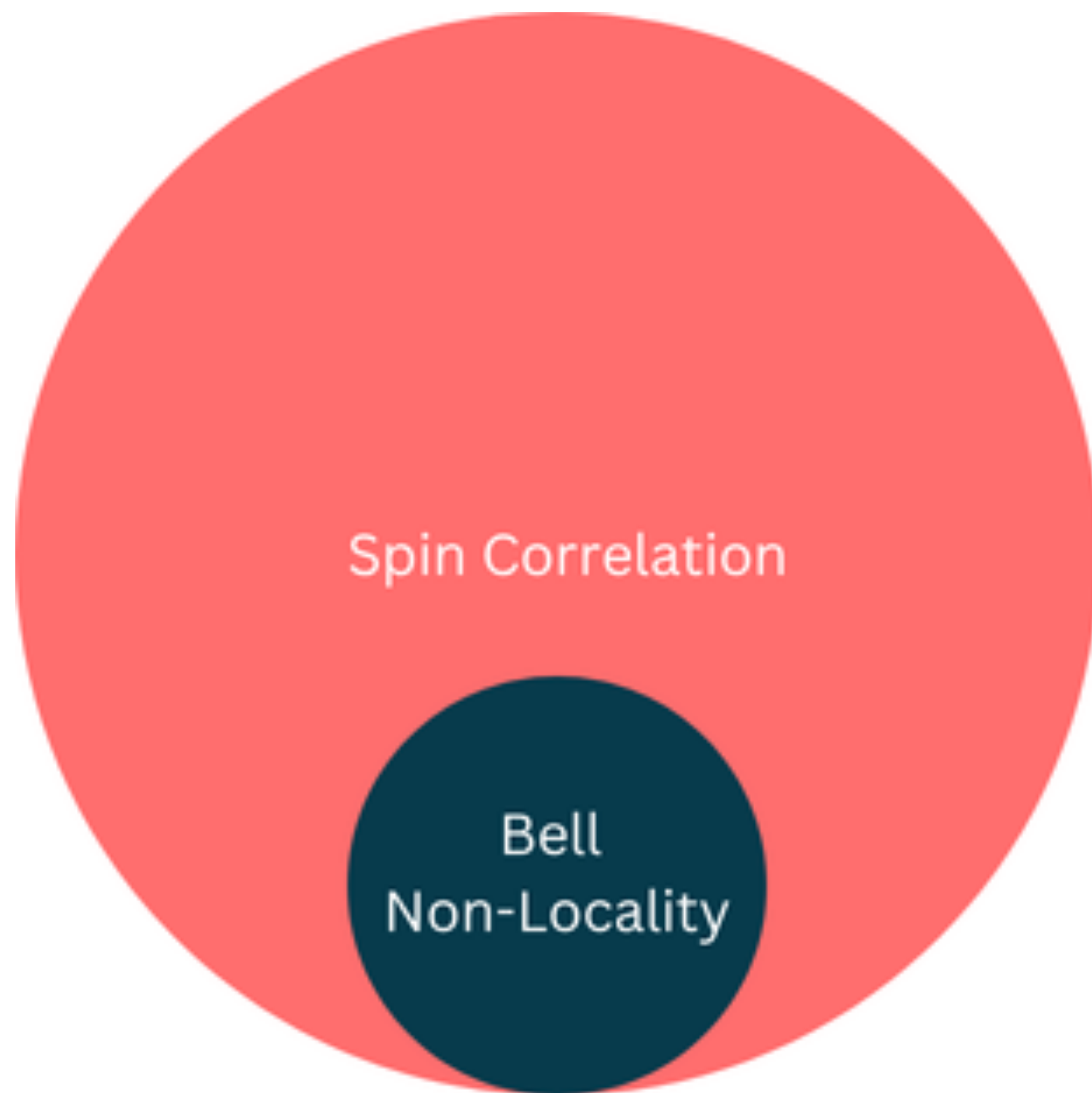


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Quantum at Colliders

Pure States

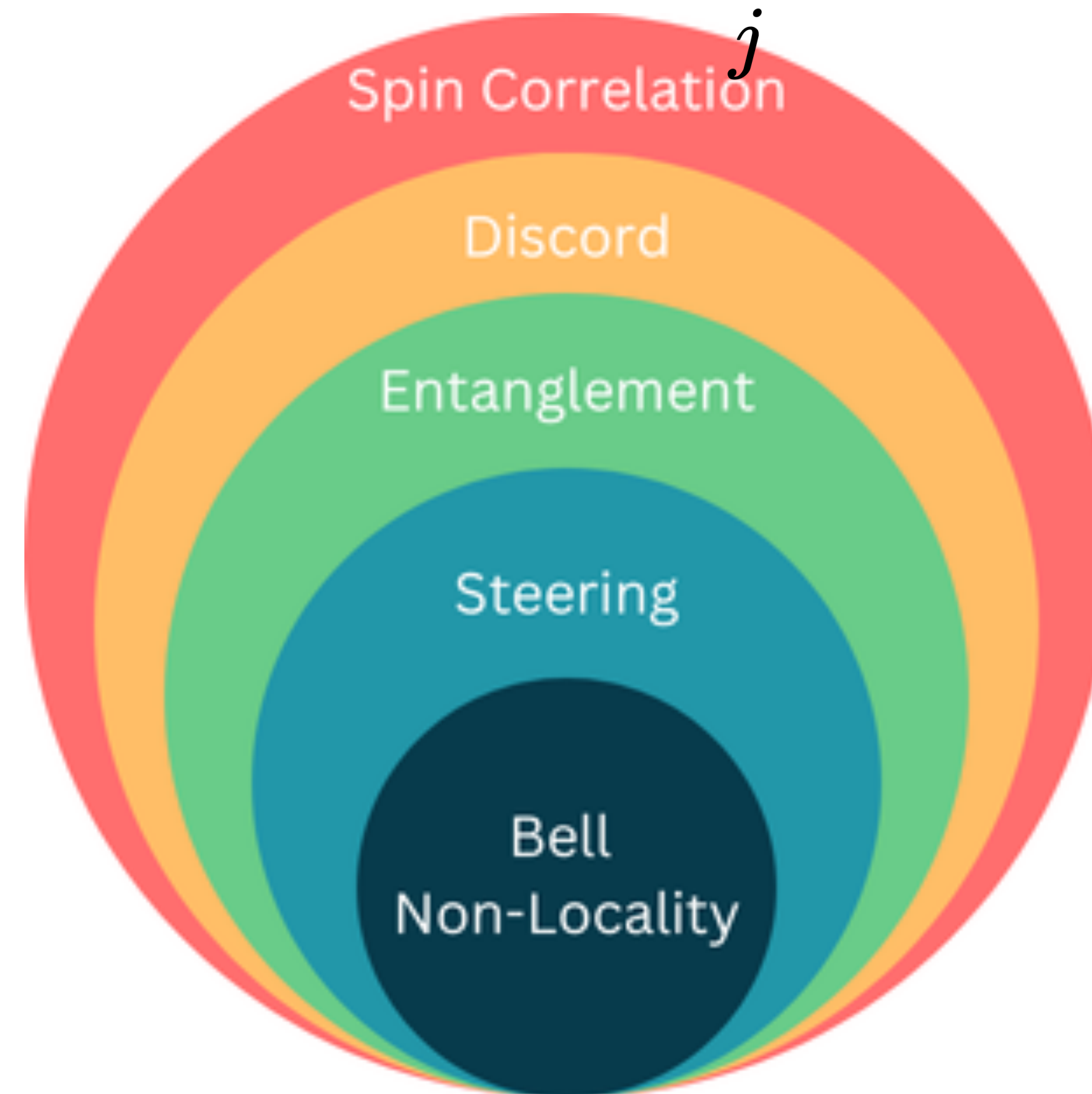
$$\rho = |\psi\rangle\langle\psi|$$



$$\text{Tr} [\rho^2] = 1$$

Mixed States

$$\rho = \sum_j p_j |\psi_j\rangle\langle\psi_j|$$



$$\text{Tr} [\rho^2] < 1$$

Why top?

LHC is a top factory!

Top quarks are ideal for measuring entanglement due to their short lifetime as their spin information is transferred to their decay products.

$$\underbrace{\frac{1}{m_t}}_{\text{production } 10^{-27} \text{ s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime } 10^{-25} \text{ s}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\text{hadronization } 10^{-24} \text{ s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip } 10^{-21} \text{ s}}$$

-Quantum Observables can be probed in other channels ie: $H \rightarrow \underline{ZZ}/\underline{WW}, \underline{\tau\tau}, \underline{b\bar{b}}$.

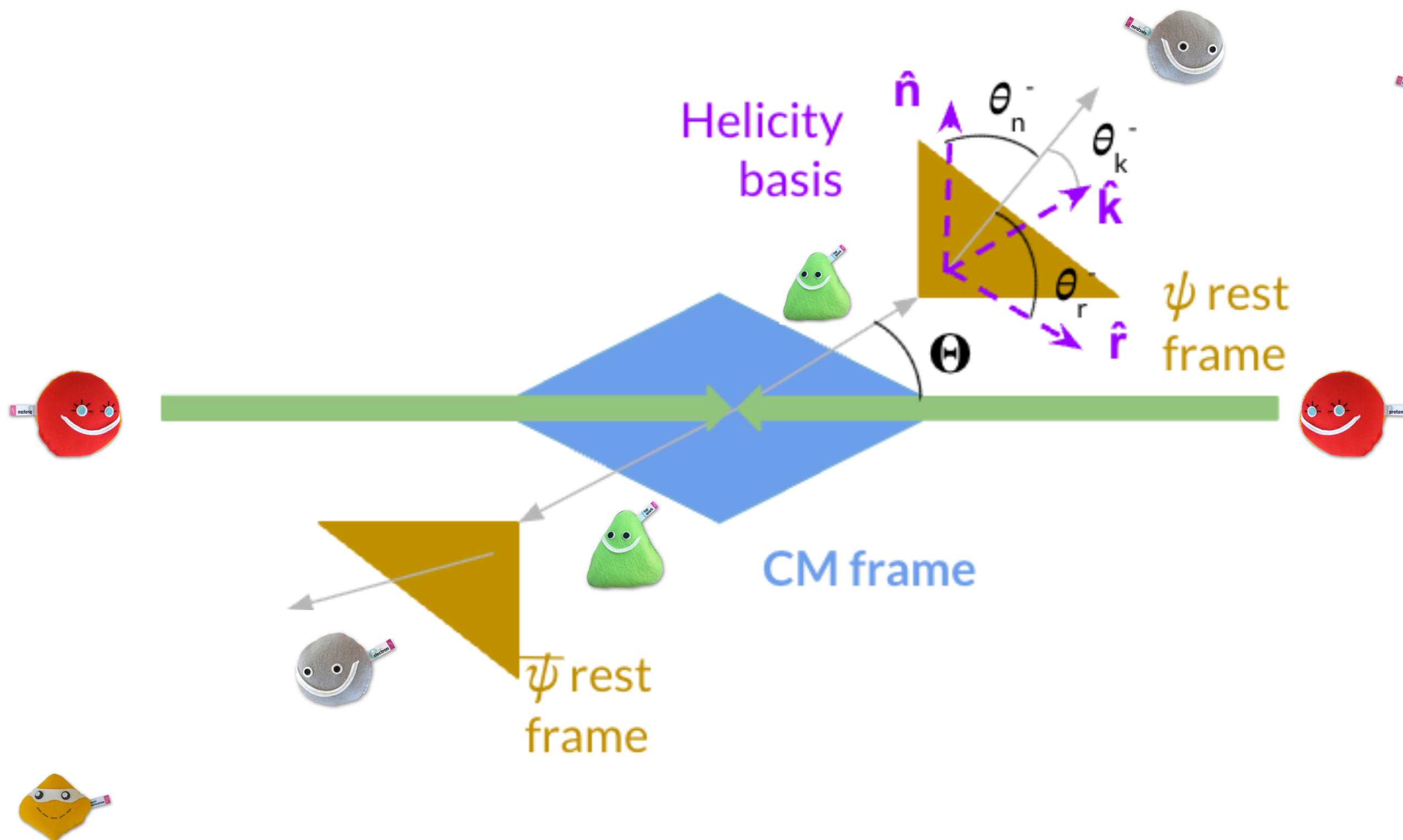
Why top?

LHC is a top factory!

Can use the spin density matrix to access and calculate quantum observables like entanglement and discord.

$$\rho_{t\bar{t}} = \frac{1}{4} \left(1 \otimes 1 + \sum_{i=1}^3 \cancel{B_i}^0 \sigma_i \otimes 1 + \sum_{j=1}^3 \cancel{\bar{B}_j}^0 1 \otimes \sigma_j + \sum_{i=1}^3 \sum_{j=1}^3 C_{ij} \sigma_i \otimes \sigma_j \right)$$

Quantum Measurements



- Can calculate Spin Correlations with:

$$C_{ij} = \frac{9}{\beta_a \beta_b} \langle \cos(\theta_a^i) \cos(\theta_b^j) \rangle$$

θ_a^i : The angle between the top decay product a and the i^{th} axis of the helicity basis in the t rest frame

θ_b^j : The angle between the \bar{t} decay product a and the j^{th} axis of the helicity basis in the \bar{t} rest frame

β_{alb} : the spin analysing power of the decay product of the t/\bar{t} decay products

| Particle | Spin analyzing power (β_i) |
|-------------------------|------------------------------------|
| lepton/ down-type quark | 1.0 |
| b-quark/ W-boson | 0.4 |
| up-type quark | 0.31 |

Quantum Measurements

- How do we access quantum observables...
- Using Spin Correlations:

$$C_{ij} = \frac{9}{\beta_a \beta_b} \langle \cos(\theta_a^i) \cos(\theta_b^j) \rangle$$

$$\begin{pmatrix} C_{kk} & C_{kr} & C_{kn} \\ C_{rk} & C_{rr} & C_{rn} \\ C_{nk} & C_{nr} & C_{nn} \end{pmatrix}$$

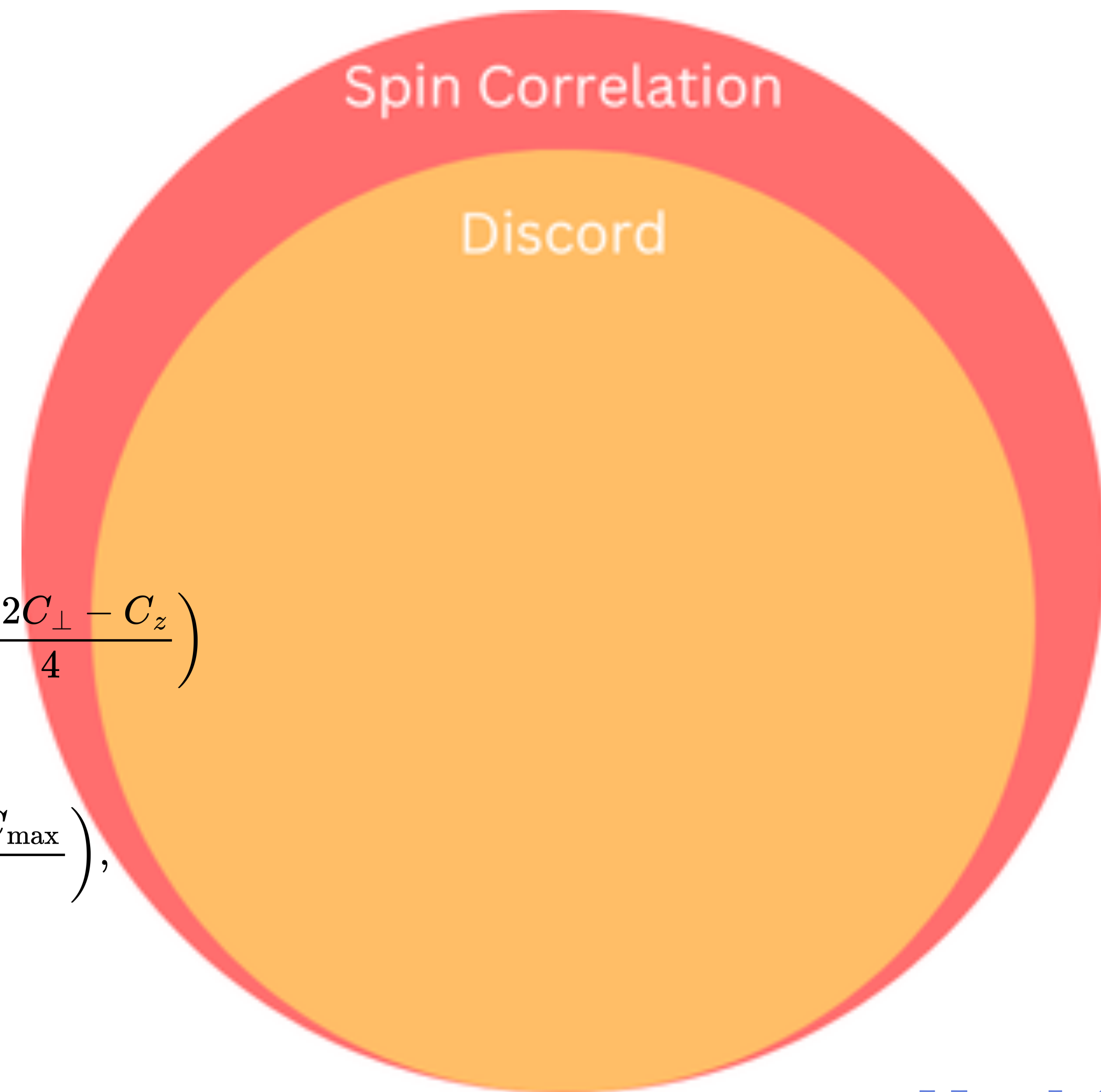
Spin Correlation



Quantum Measurements

- How do we access quantum observables...
- Calculated via Von Neumann entropy (a way to measure information in a quantum state):

$$D_A(\rho_{\bar{t}\bar{t}}) = 1 + \frac{1}{2}(1 + C_z) \log_2 \left(\frac{1 + C_z}{4} \right) + \frac{1}{4}(1 + 2C_{\perp} - C_z) \log_2 \left(\frac{1 + 2C_{\perp} - C_z}{4} \right) \\ + \frac{1}{4}(1 - 2C_{\perp} - C_z) \log_2 \left(\frac{1 - 2C_{\perp} - C_z}{4} \right) \\ - \frac{1}{2}(1 + C_{\max}) \log_2 \left(\frac{1 + C_{\max}}{2} \right) - \frac{1}{2}(1 - C_{\max}) \log_2 \left(\frac{1 - C_{\max}}{2} \right),$$

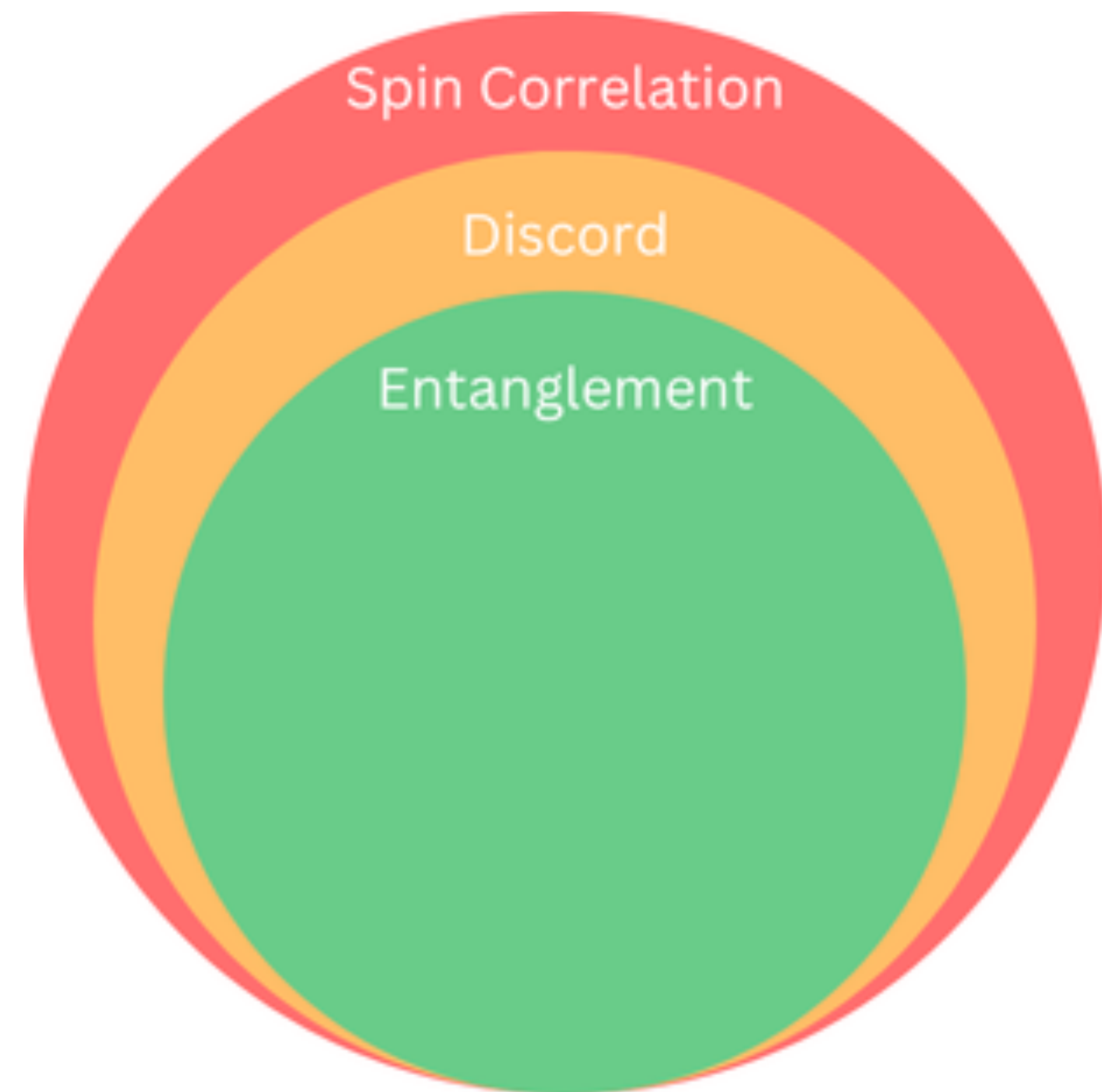


Quantum Measurements

- How do we access quantum observables...
- Using Spin Correlations:
- Calculated from diagonal elements of the spin density matrix

$$D = \frac{\text{Tr}(C)}{3} < -\frac{1}{3}$$

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



Quantum Measurements

- How do we access quantum observables...

- Using Spin Correlations:

$$C_{ij} = \frac{9}{\beta_a \beta_b} \langle \cos(\theta_a^i) \cos(\theta_b^j) \rangle$$

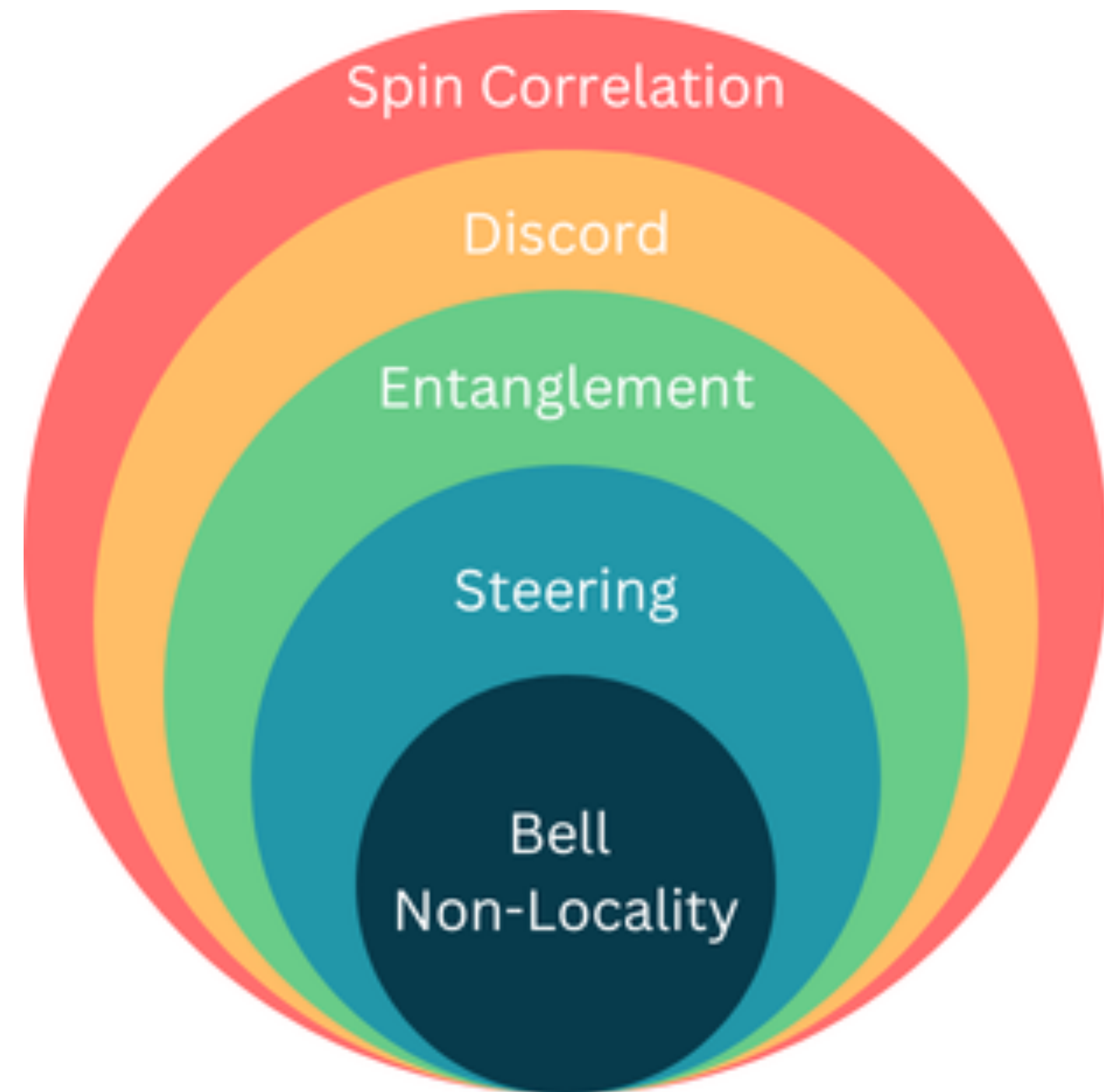
- Constructed from [CHSH](#) Inequalities

$$\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0,$$

$$\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0,$$

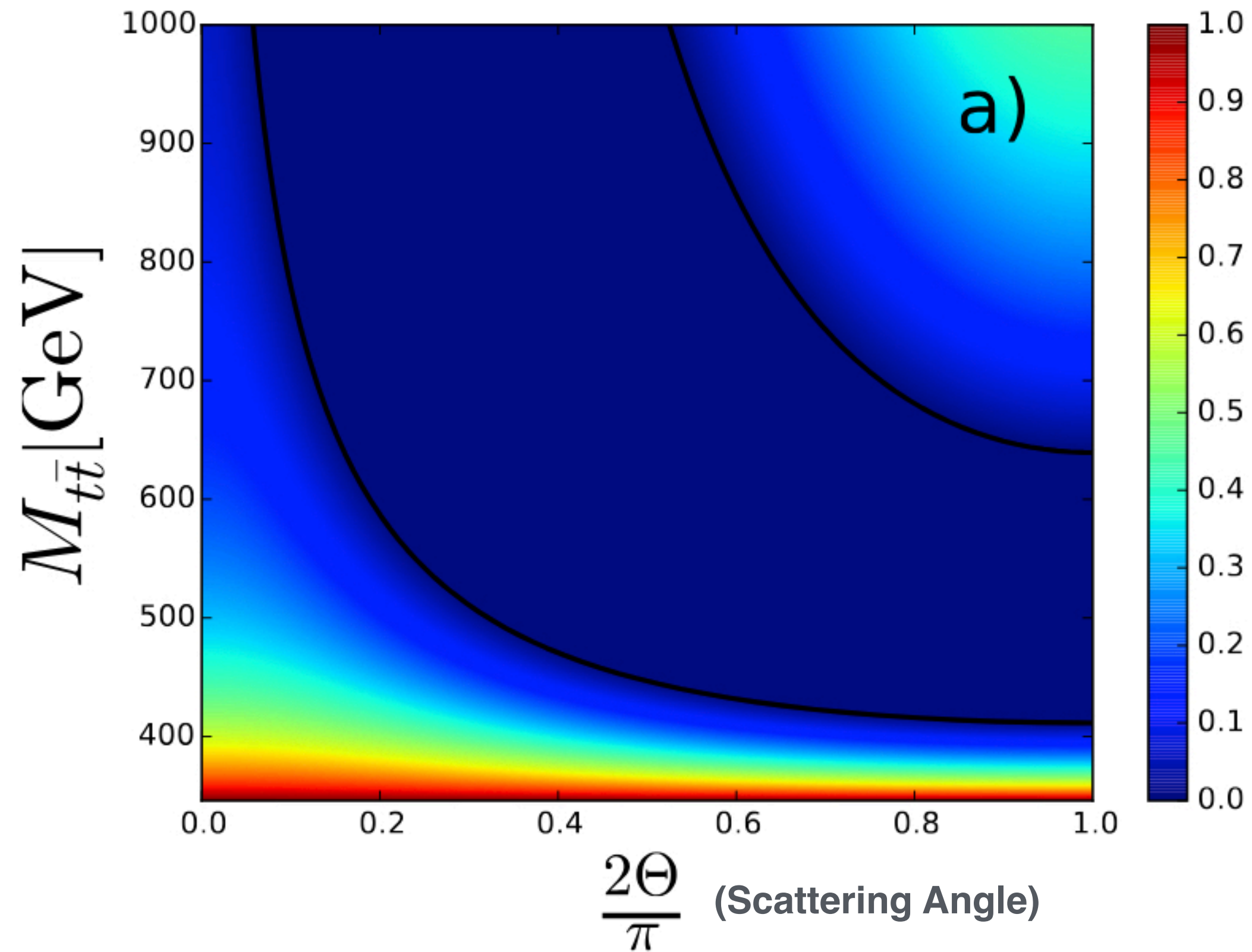
$$\mathcal{B}_3 \equiv |C_{kk} + C_{nn}| - \sqrt{2} > 0,$$

$$\mathcal{B}_4 \equiv |C_{rr} + C_{nn}| - \sqrt{2} > 0.$$

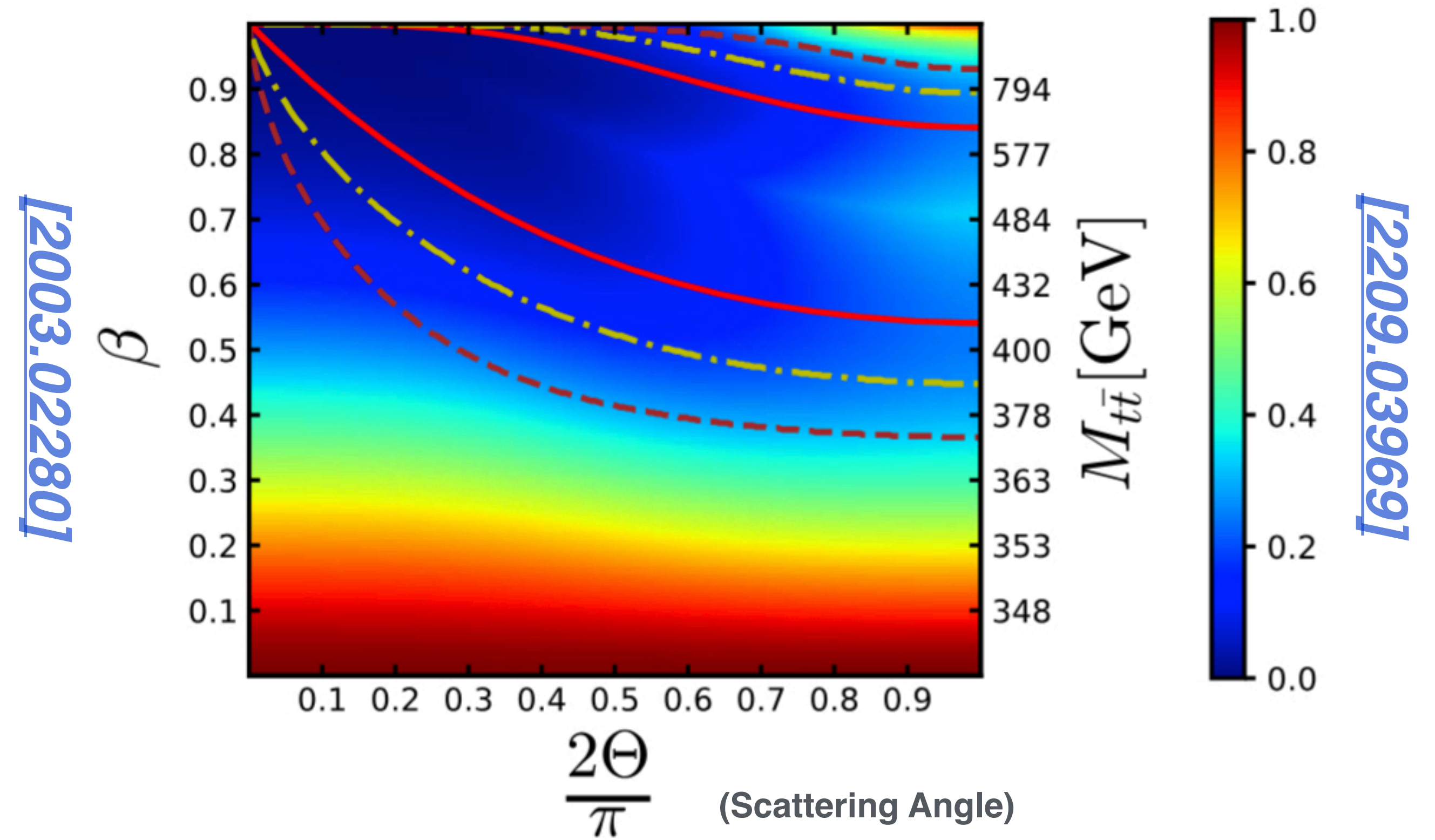


Where can we measure it

Entanglement

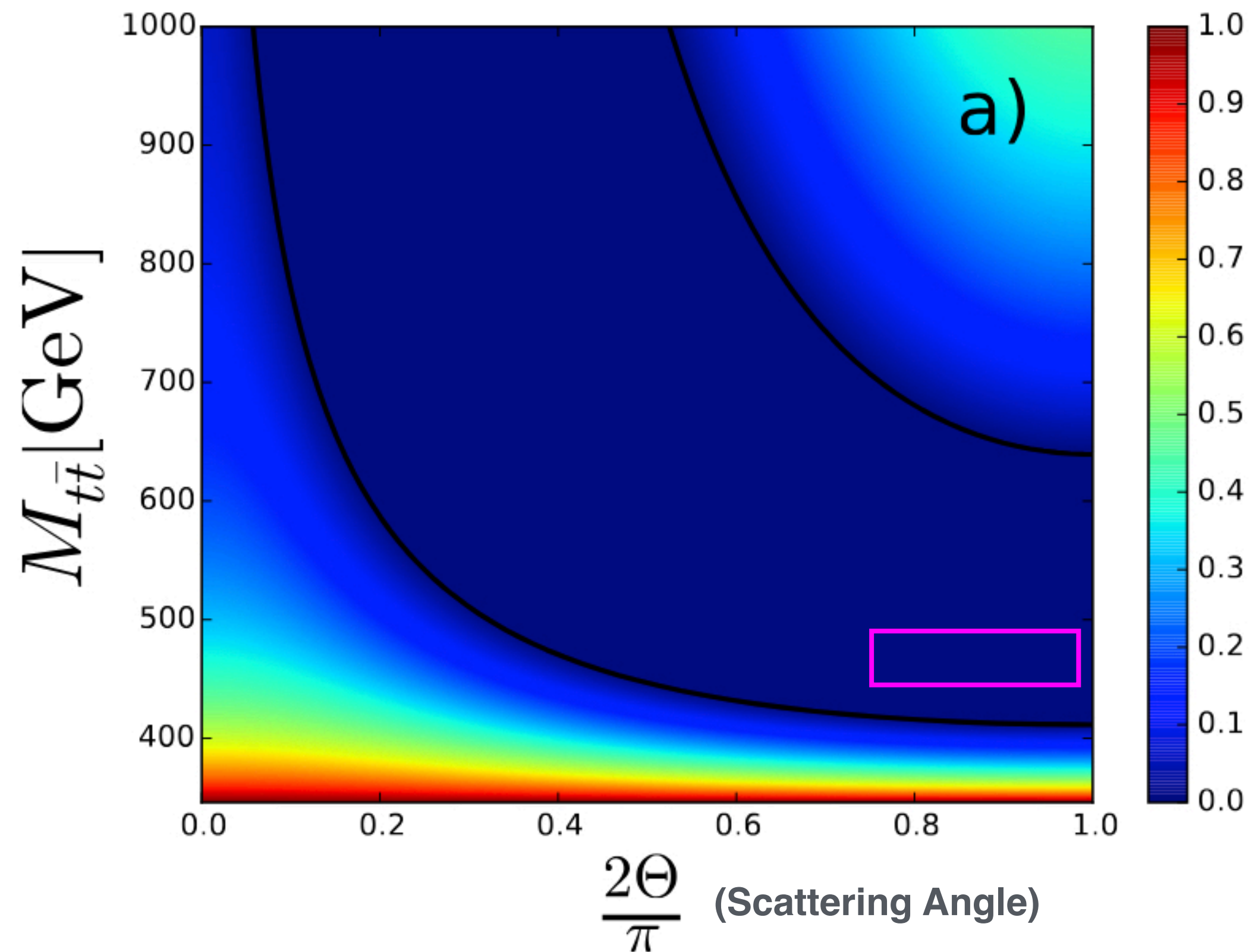


Discord

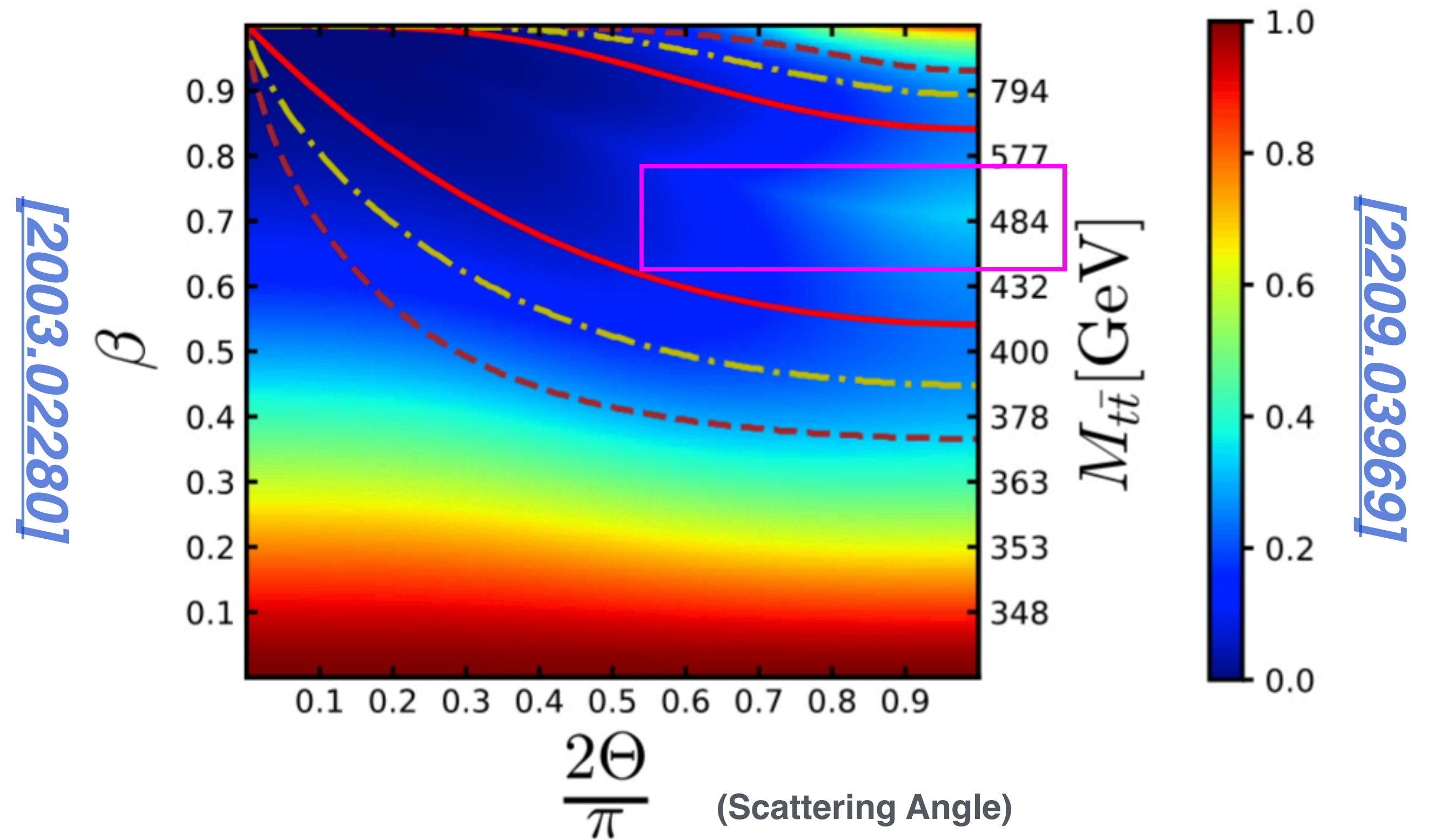


Where can we measure it

Entanglement

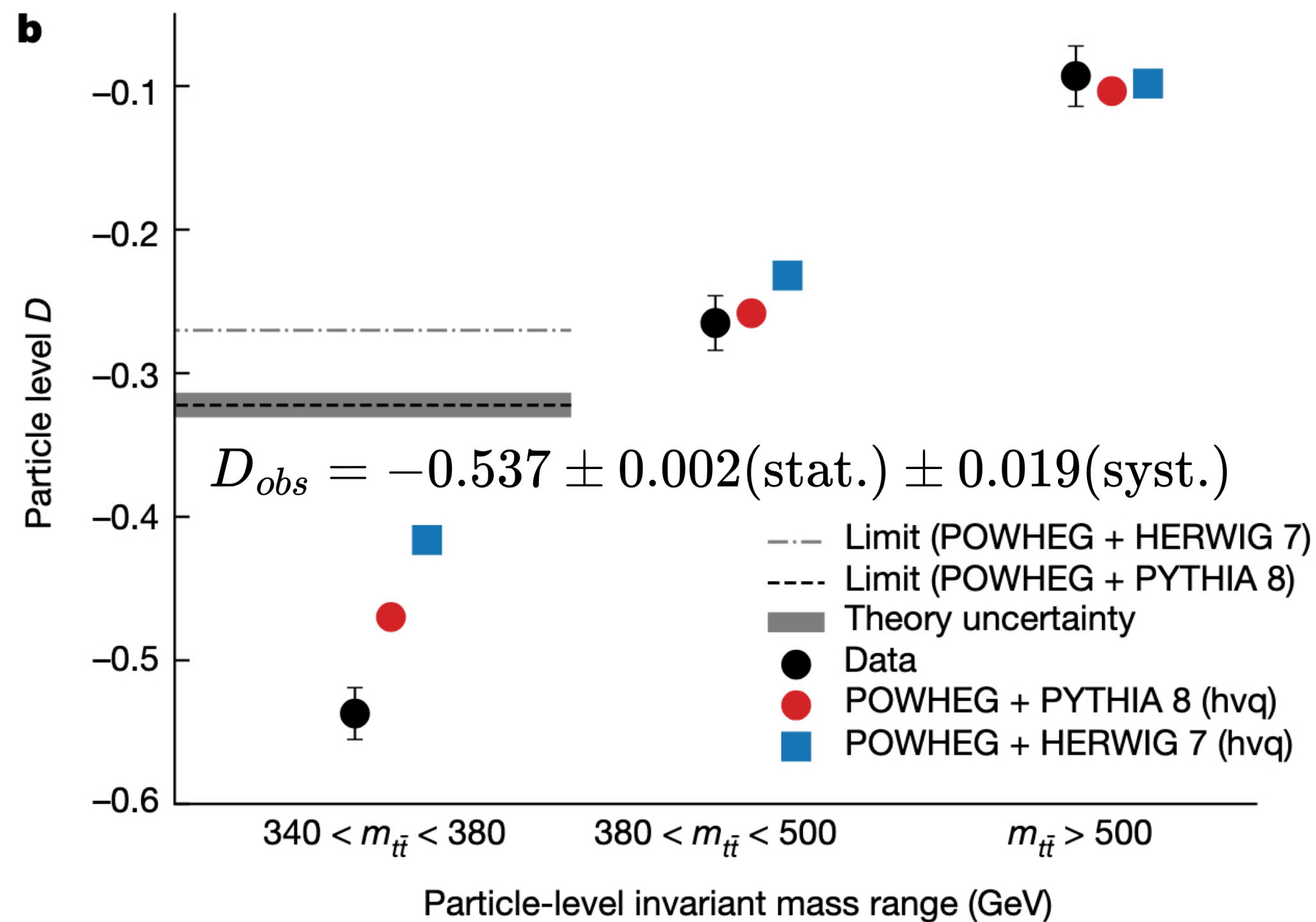


Discord



What have we found so far...

Entanglement observation by ATLAS



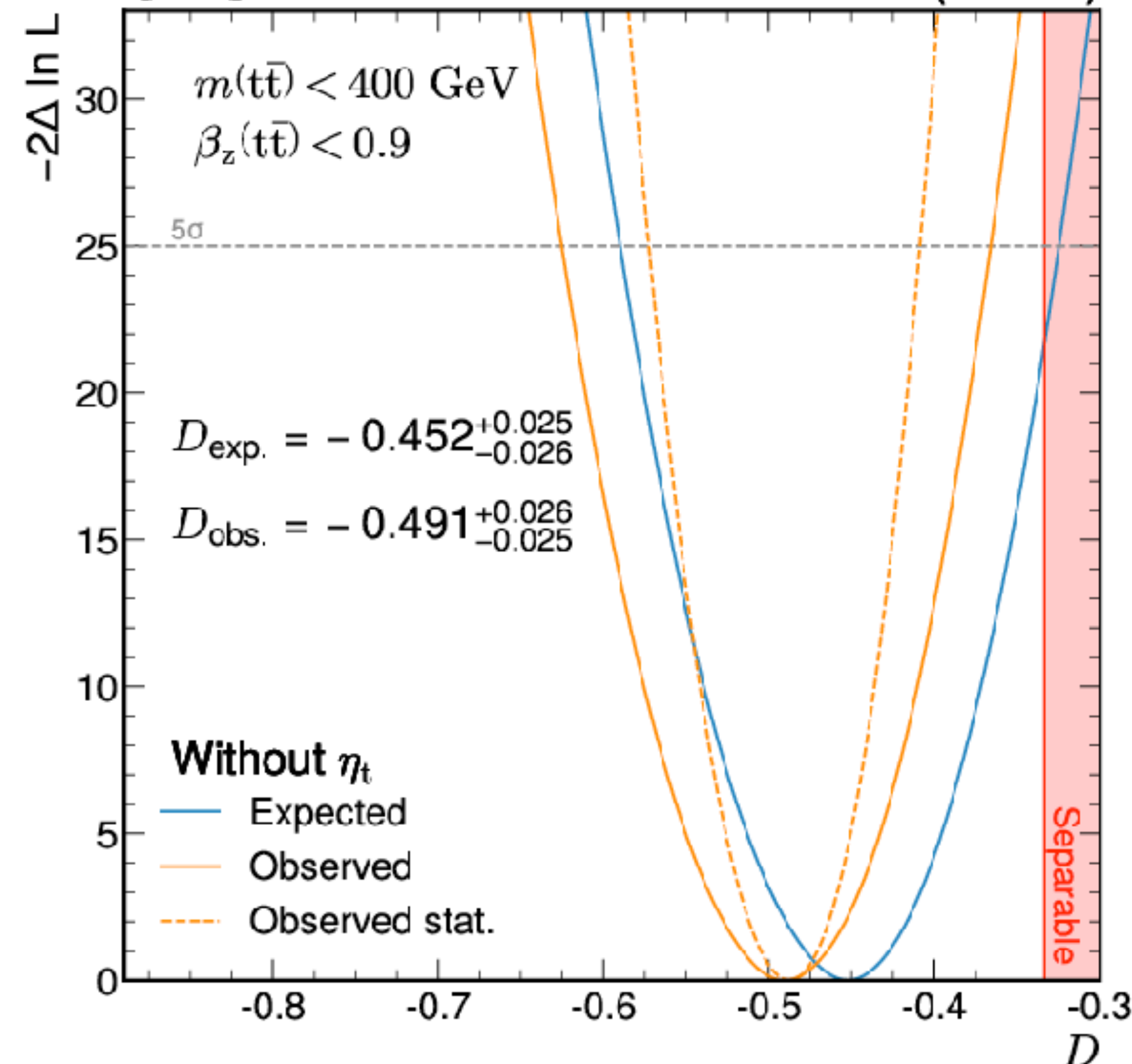
Nature 633, 542-547

$$D = \frac{\text{Tr}(C)}{3} < -\frac{1}{3}$$

Quantum Magic

CMS

36.3 fb⁻¹ (13 TeV)



TOP-23-001

Entanglement observation by CMS

Ongoing work

In Both Channels

- Measurement of top quark pair full spin density matrix (SDM), differential measurement in $m_{t\bar{t}}$

Dilepton Channel

- Measurement of new quantum information observables like discord

Examine:

EFT interpretations, BSM model tests, Tests of CP violation

Pros

- Higher spin analysing power

Cons

- Hard reconstruction
- Lower stats

Single Lepton Channel

- Measure the entanglement in the “boosted” region
- put bounds on bell’s inequality type operators

Pros

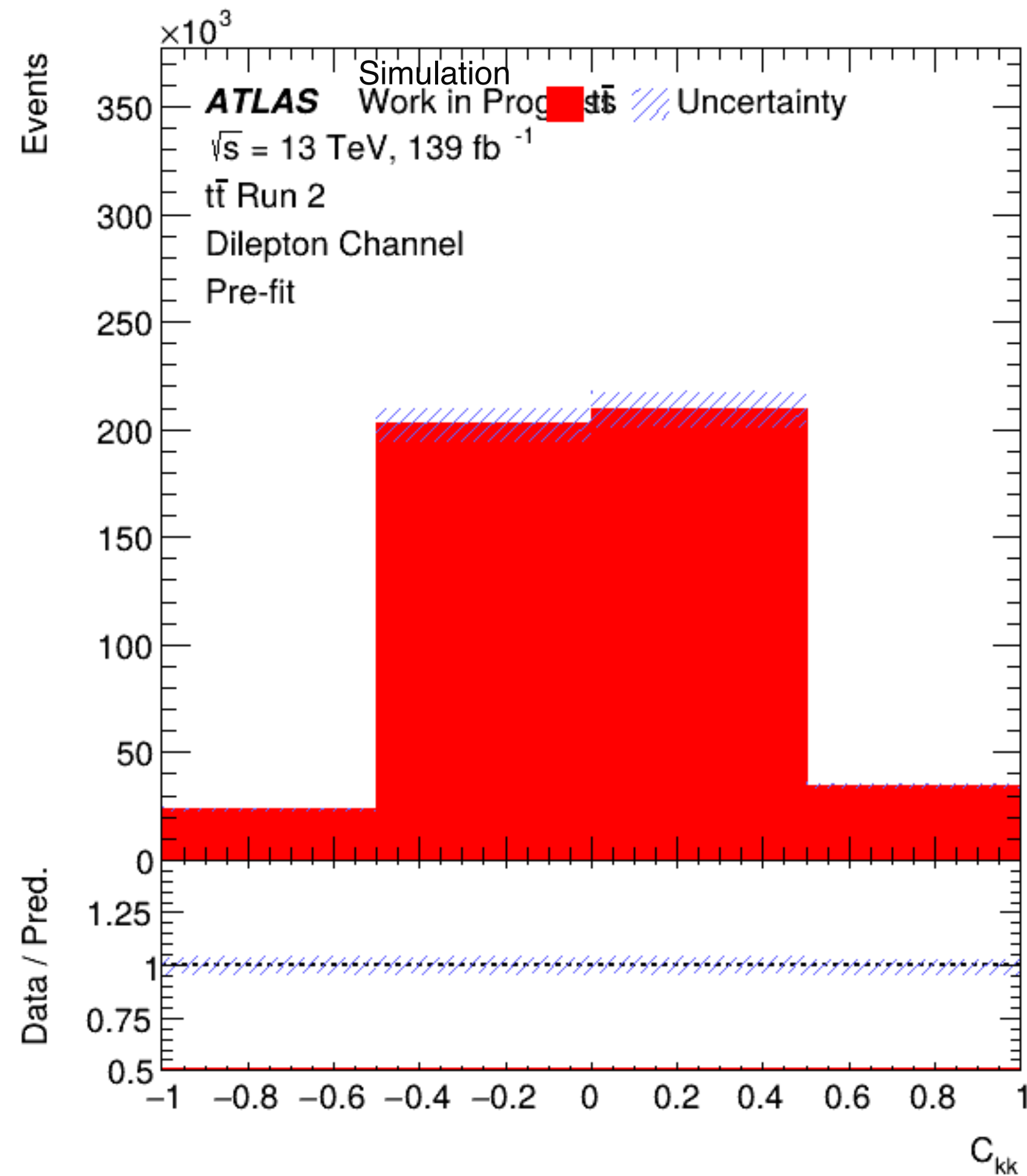
- Higher stats
- Easy reconstruction

Cons

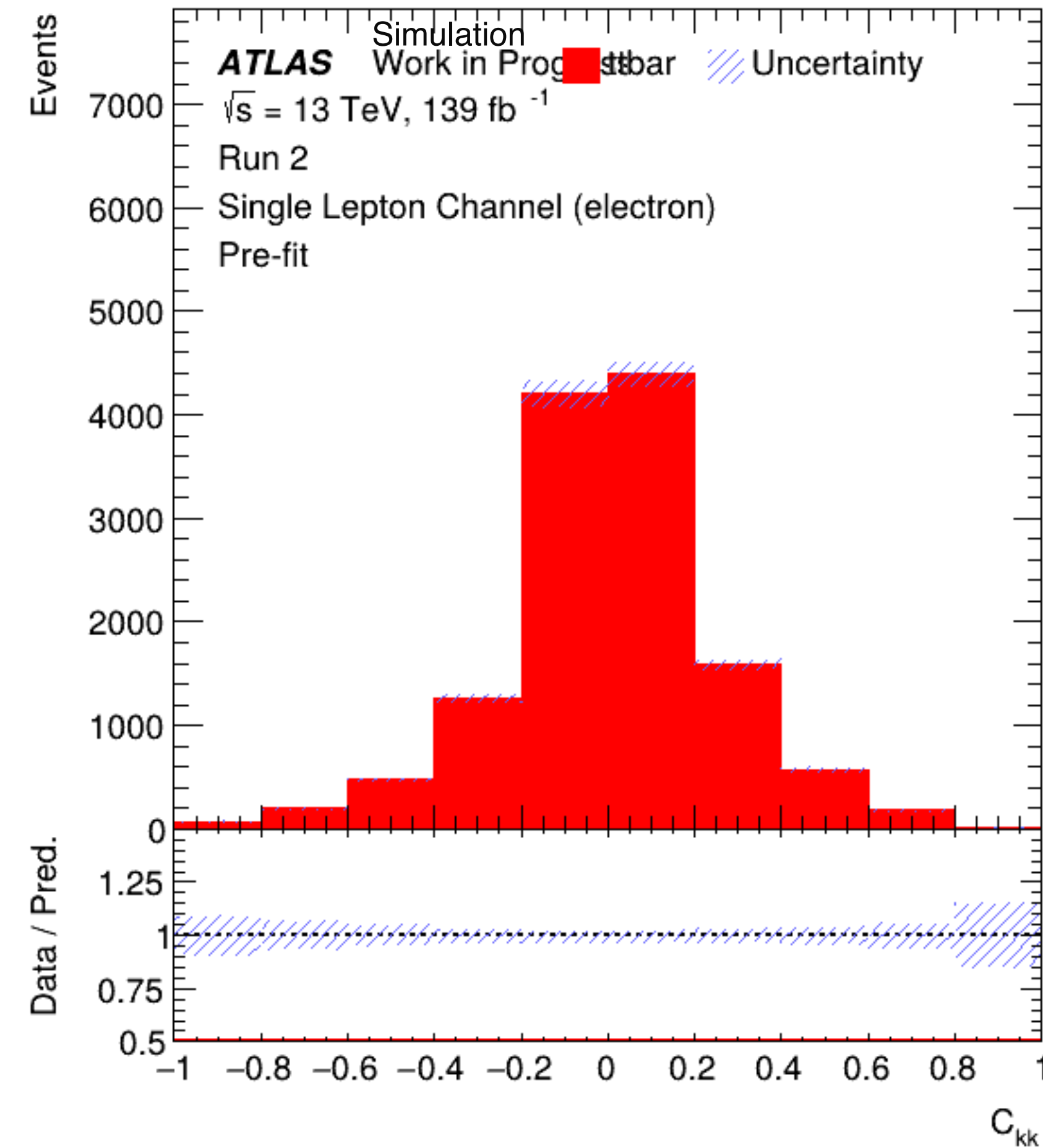
- Lower spin analysing power

Where are we measuring it?

Dilepton Channel



Single Lepton Channel



Conclusions

- Quantum observables provide a rich and largely unexplored window into new physics.

The HL-LHC opens up significant new opportunities to measure quantum observables:

- Bounds on Bell operators already reaching up to $\sim 4\sigma$ in $t\bar{t}$ production
- Emerging evidence in additional channels
- Growing theoretical and experimental interest in understanding the implications of these measurements

