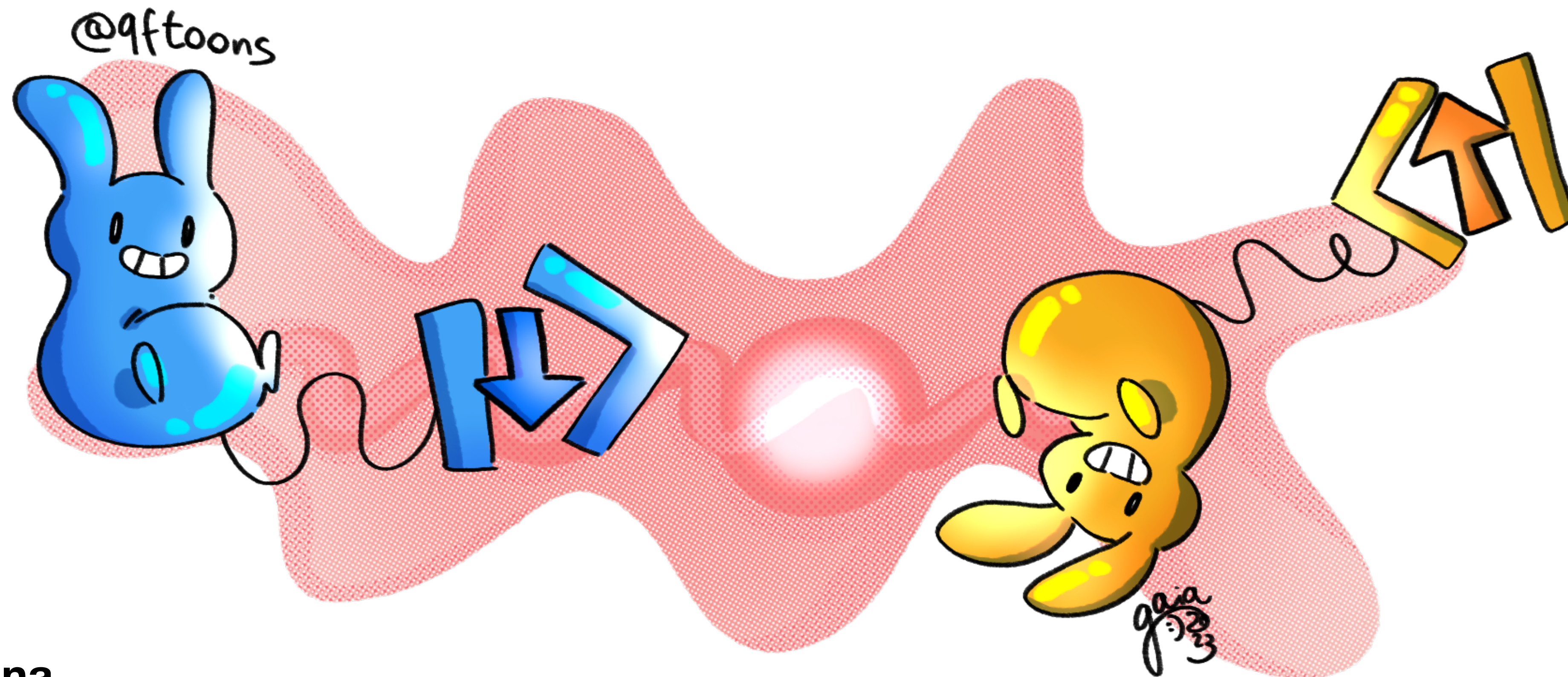# Particle physics and the quantum

Fabio Maltoni
Università di Bologna
Université catholique de Louvain
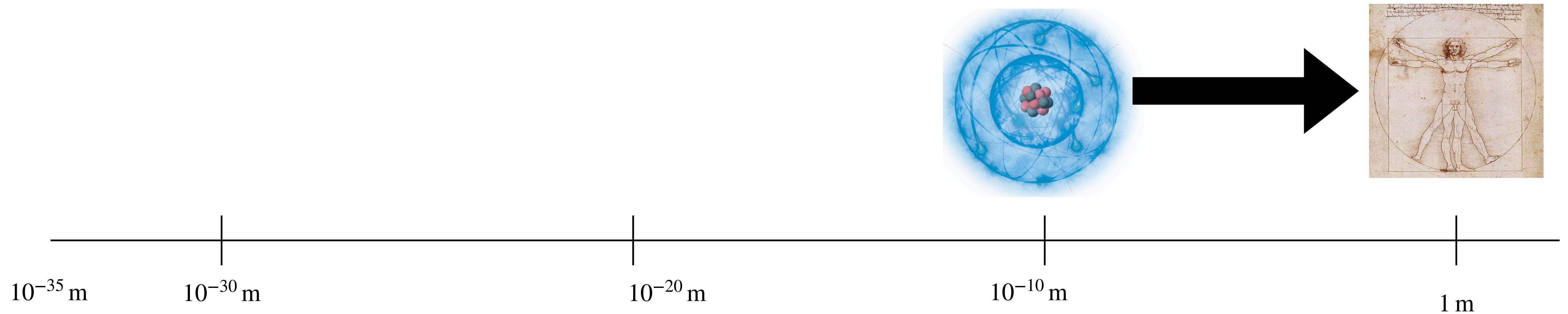
Introduction

Quantum information/computing/technology: push quantum into the macroscopic world

$10^{-35}\,\mathrm{m}$ $10^{-30}\,\mathrm{m}$ $10^{-20}\,\mathrm{m}$ $10^{-10}\,\mathrm{m}$ $1\,\mathrm{m}$

Quantum computers, quantum communications, quantum devices,...

Introduction

Quantum information/computing/technology: push quantum into the macroscopic world

$10^{-35}\,\text{m}$ $10^{-30}\,\text{m}$ $10^{-20}\,\text{m}$ $10^{-10}\,\text{m}$ $1\,\text{m}$
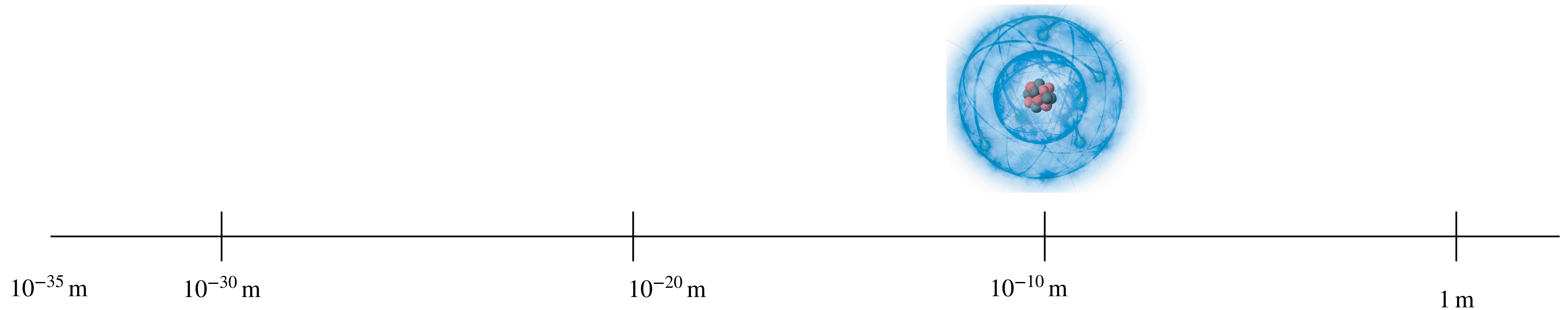
Quantum computers, quantum communications, quantum devices,...

Introduction

Quantum information paradox (gravity+quantum mechanics):

$10^{-35}\,\text{m}$ $10^{-30}\,\text{m}$ $10^{-20}\,\text{m}$ $10^{-10}\,\text{m}$ $1\,\text{m}$
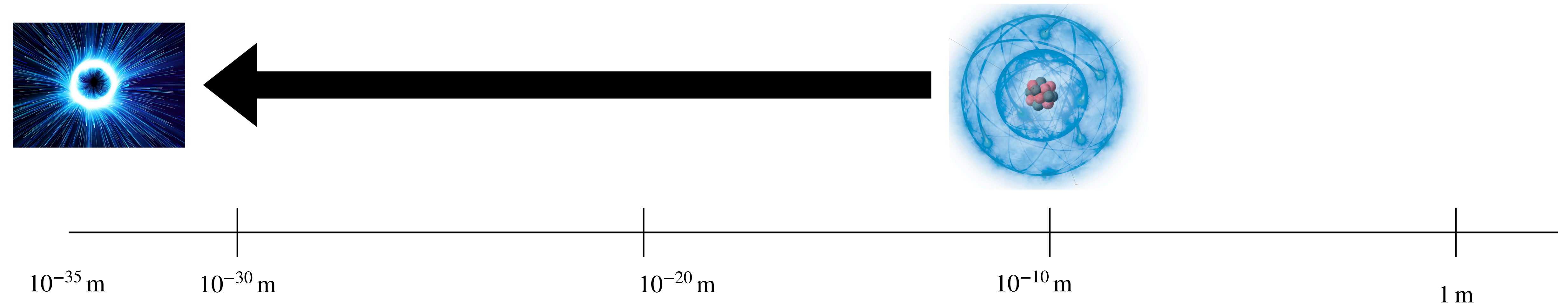
It from Qubit:
- Does spacetime emerge from entanglement?
- Do black holes have interiors?
- Does the universe exist outside our horizon?
- **What is the information-theoretic structure of quantum field theories?**
- Can quantum computers simulate all physical phenomena?
- How does quantum information flow in time?

Introduction

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?

$10^{-35}\,\mathrm{m}$ $10^{-30}\,\mathrm{m}$ $10^{-20}\,\mathrm{m}$ $10^{-10}\,\mathrm{m}$ $1\,\mathrm{m}$
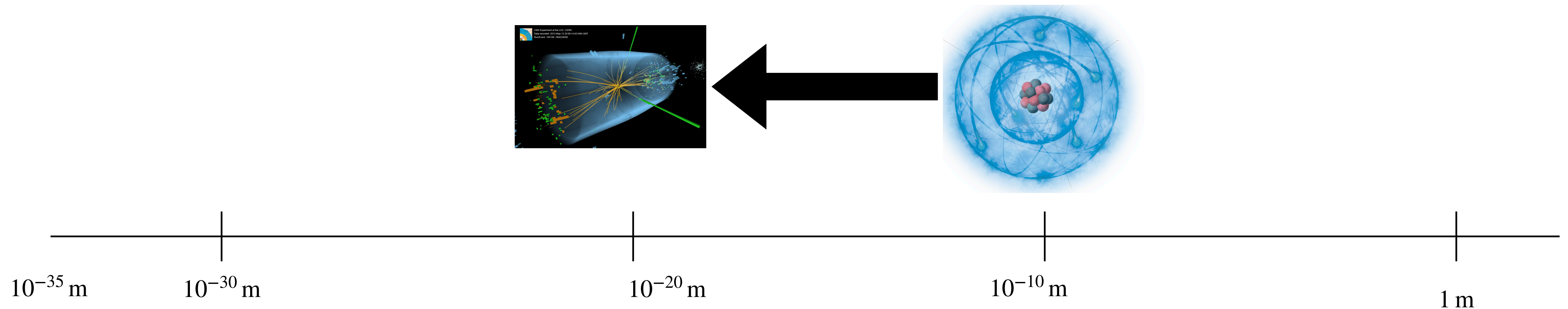
*Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.
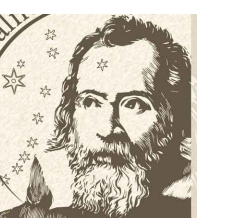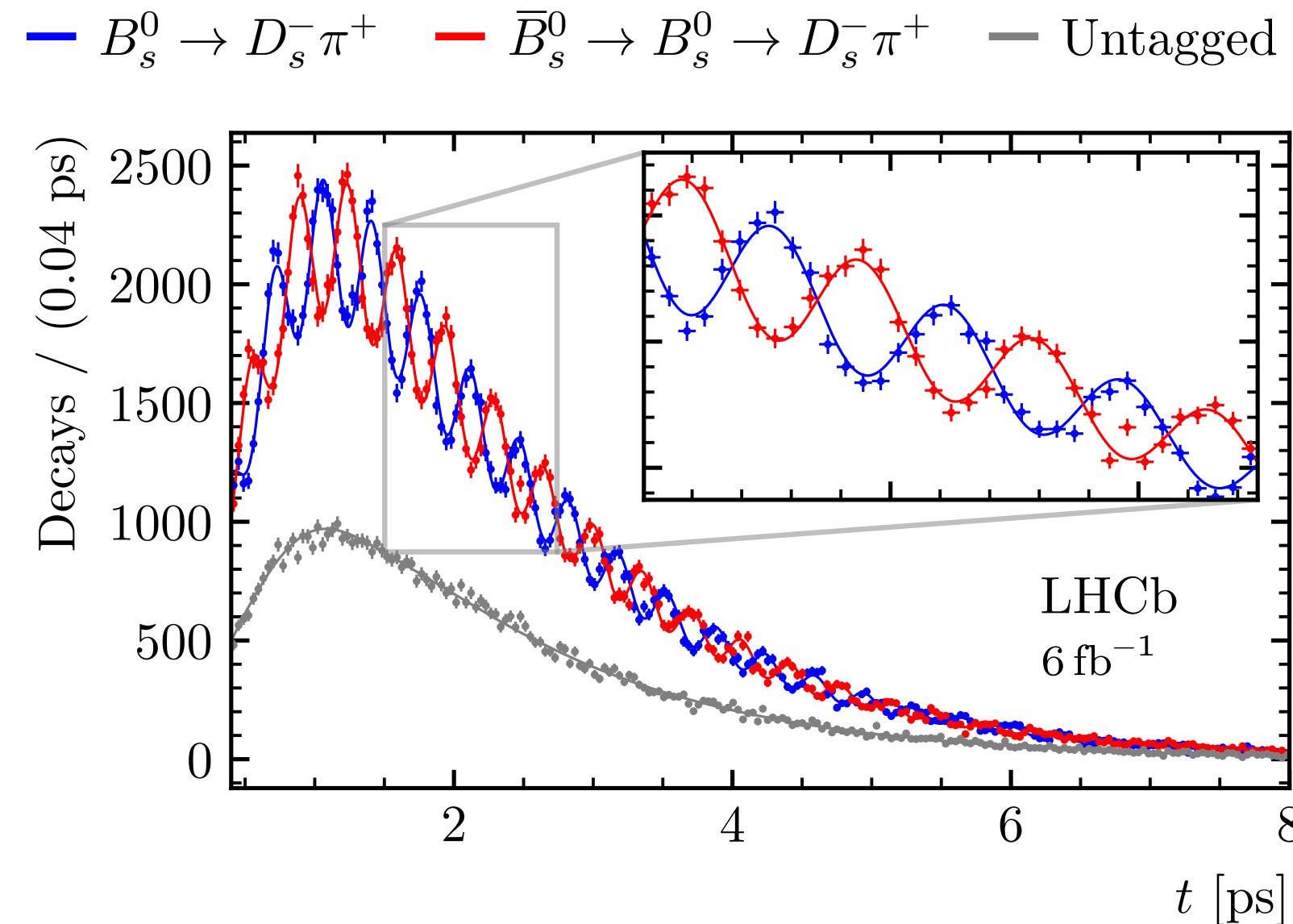
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Introduction

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?

This is not a new question in HEP: B-flavour oscillations

1-leg: Leggett-Garg K3
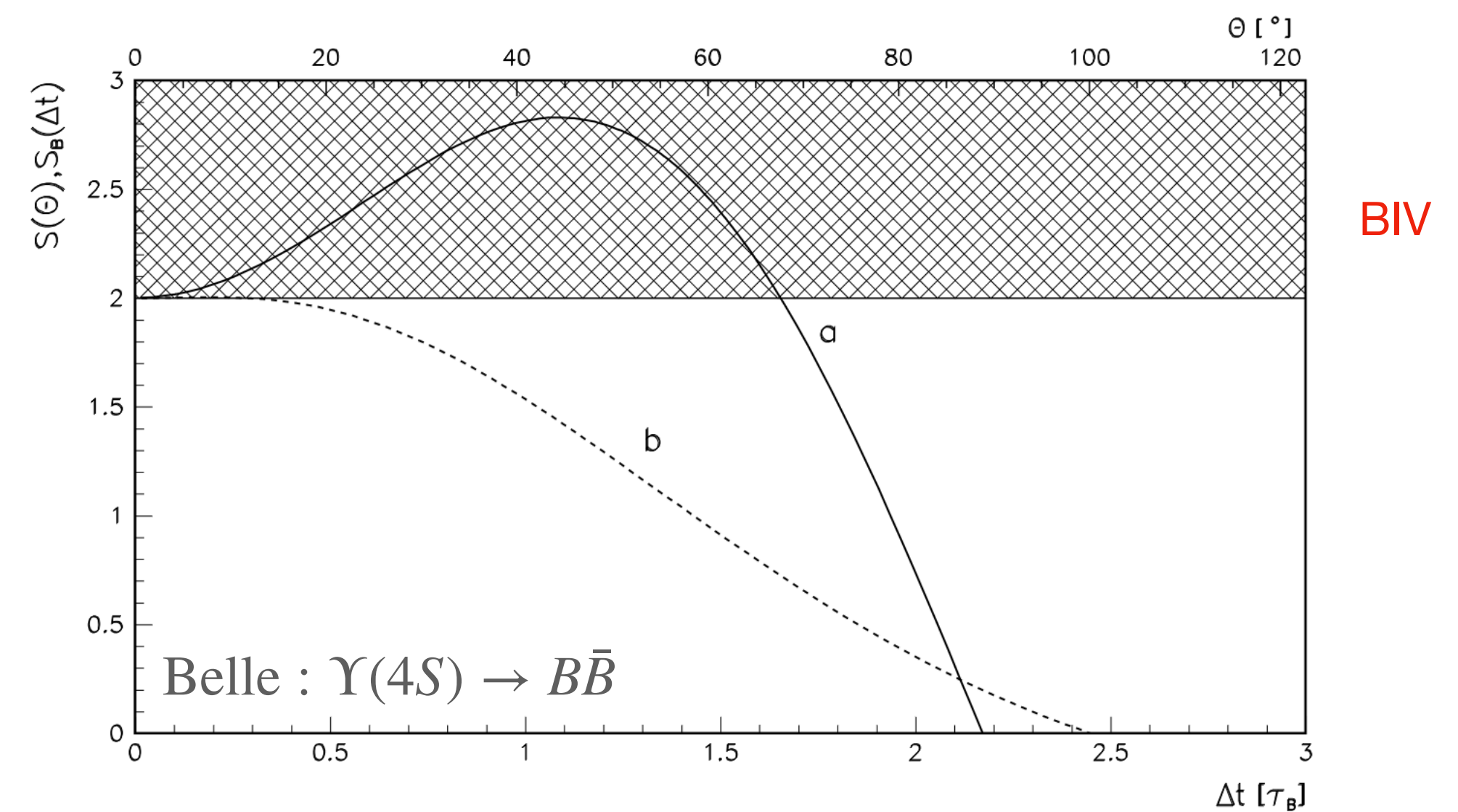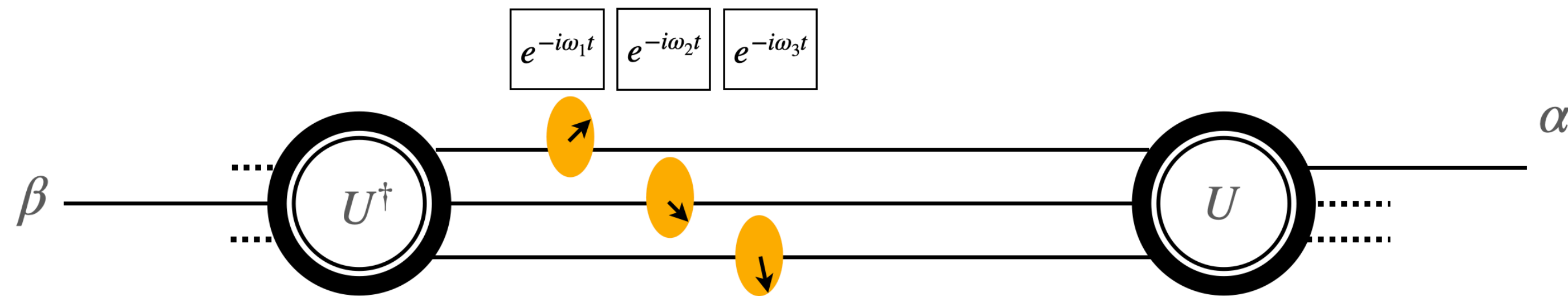
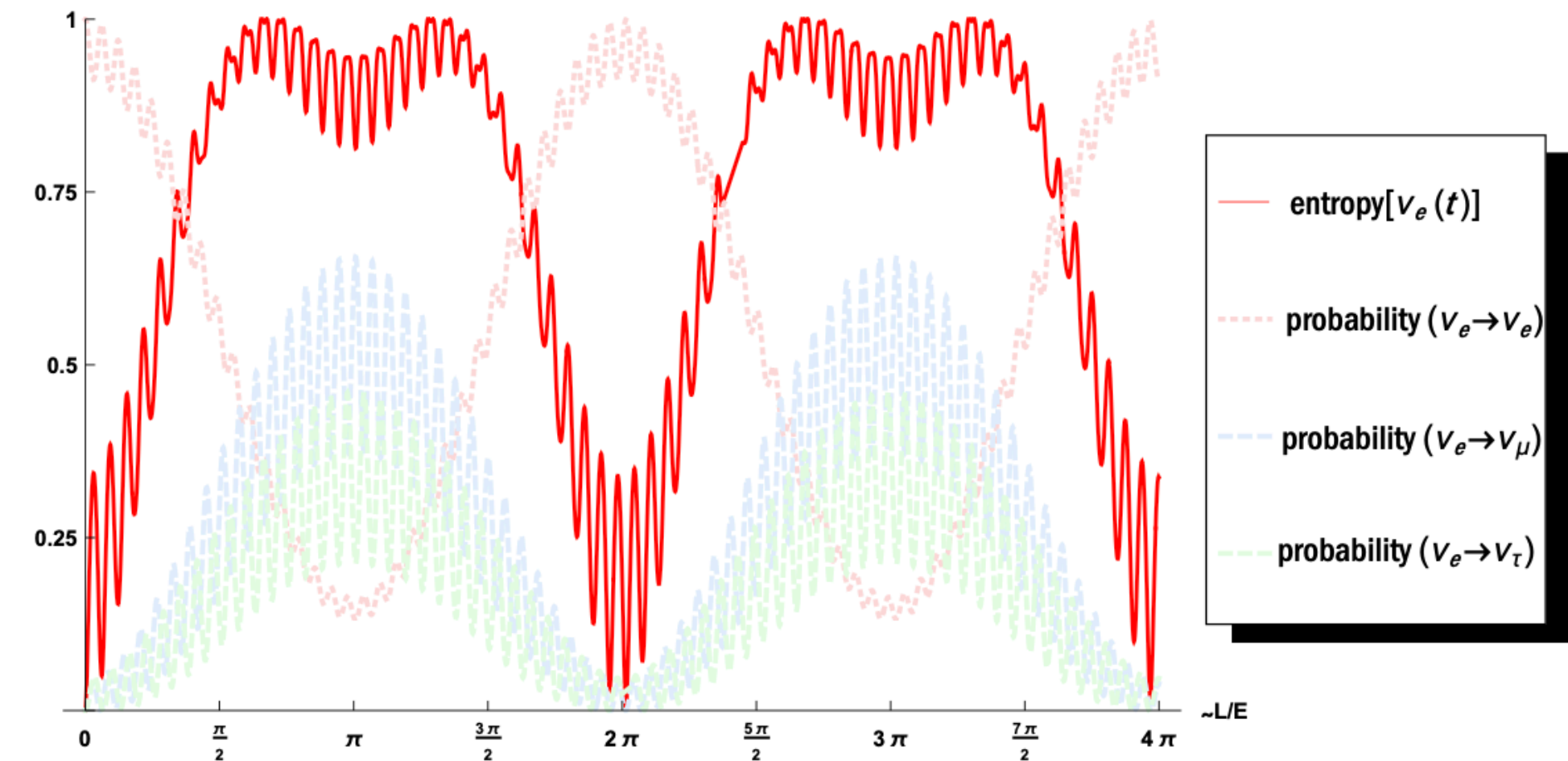

2-leg : Leggett-Garg K4 (like Bell)

Introduction

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?

This is not a new question in HEP: neutrino-flavour oscillations

$$|\Psi(t)\rangle_\alpha = a_{\alpha e}(t) \ |100\rangle + a_{\alpha\mu}(t) \ |010\rangle + a_{\alpha\tau}(t) \ |001\rangle$$
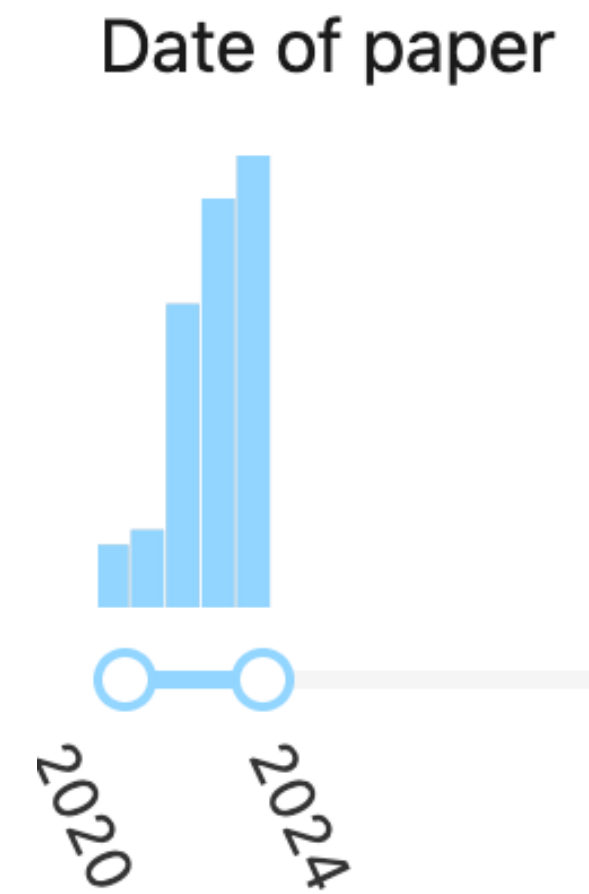
Neutrino oscillations as bi- and tri-partite systems [Blasone et al.] to more recent analyses of neutrino oscillations [Banerjee et al.]. See also [Kumar et al.].   Possibility of using quantum observables to access the mass hierarchy [Dixit et al.], distinguishing between Majorana vs Dirac [Richter et al.]. For a very interesting proposal to use Leggett-Garg violations at different energies was made [Formaggio et al.].

Introduction

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?

Date of paper

2020   2024

- Recent and growing interest in the high-Q^2 **collider community** with ~100 papers in the last few years.

Citations to the
Afik & de Nova paper

- Broadening of interests in more formal and pheno aspects.

- First experimental results appeared starting Nov 2023!

Introduction

My personal motivations:

- **Community pride:** $\mathbb{QM} \subset \mathbb{QFT}$

- **Meaning:** A plethora of fundamental results (theorems!) for QI : what do they mean for HEP?

- **Impact:** And viceversa, what can be learnt on QI from particle physics?

- **Value:** Opportunity to elaborate (and communicate) what is important/interesting in our field:

New Physics $\equiv$ Uncharted SM physics + BSM

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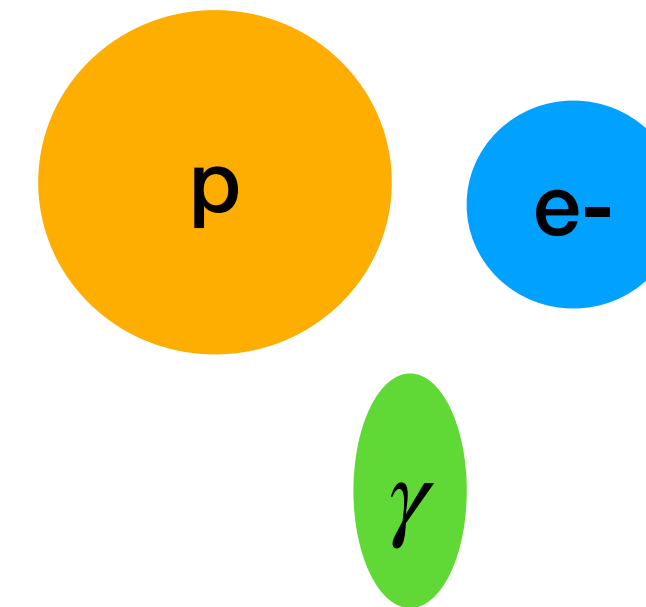- **Value:** Opportunity to elaborate (and communicate) what is important/interesting in our field:
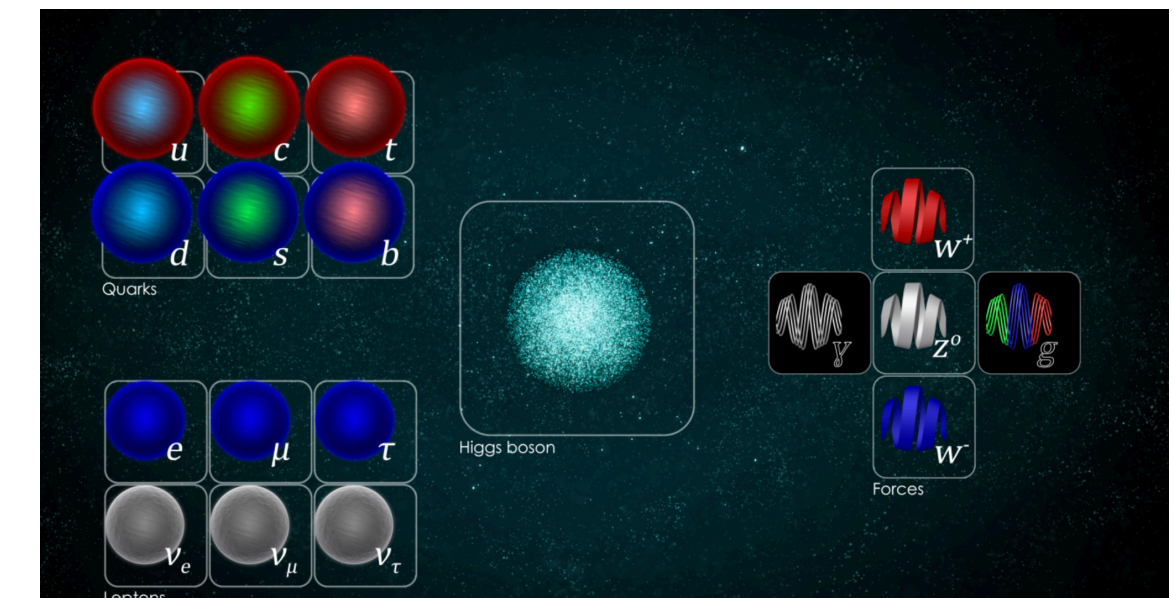
New Physics ≡ Uncharted SM physics + BSM

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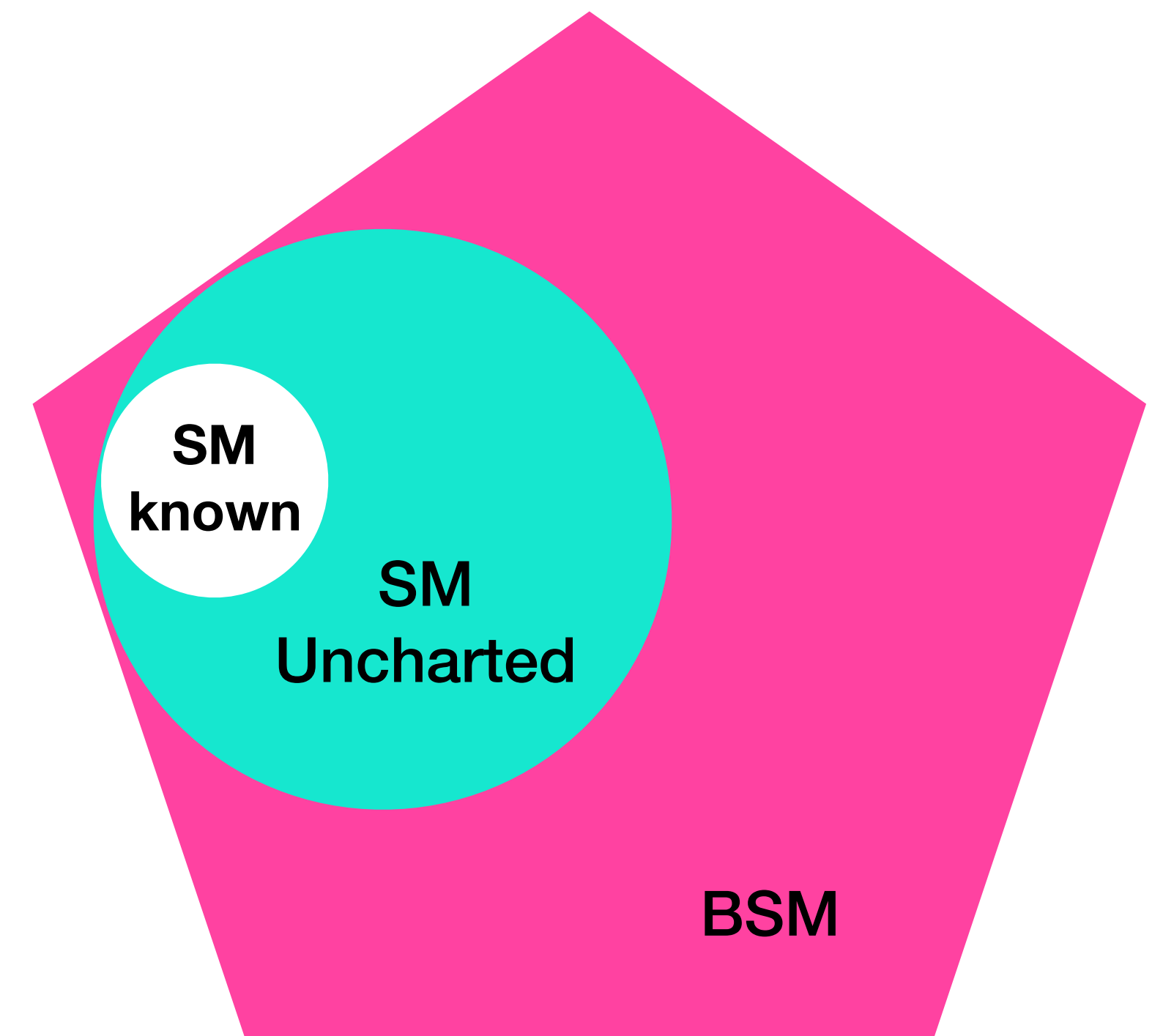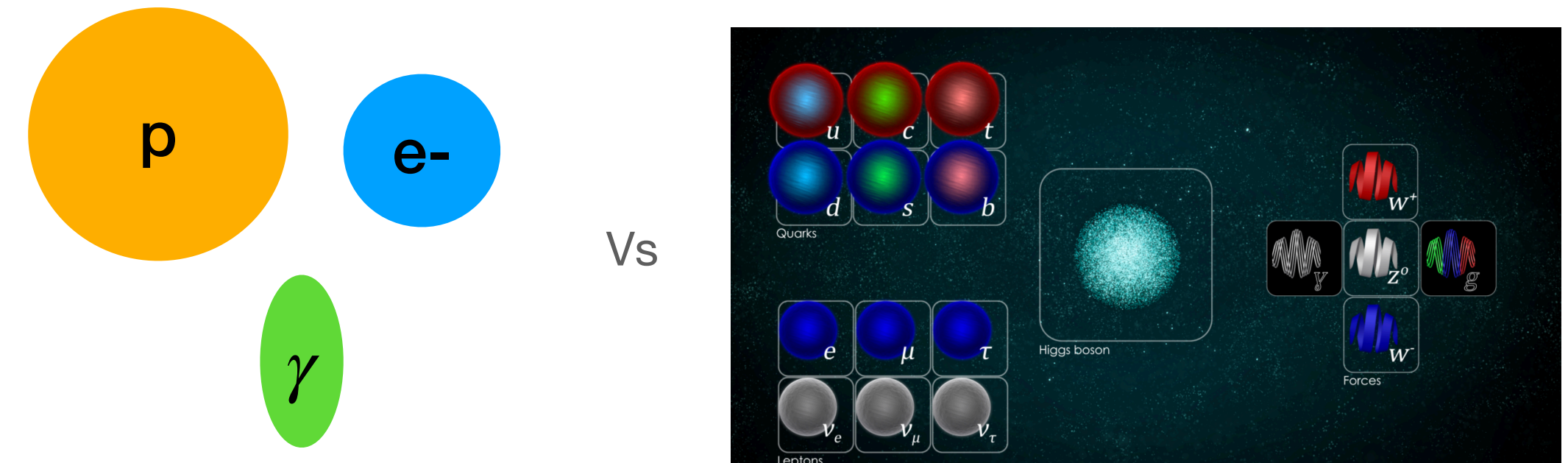New Physics $\equiv$ Uncharted SM physics + BSM

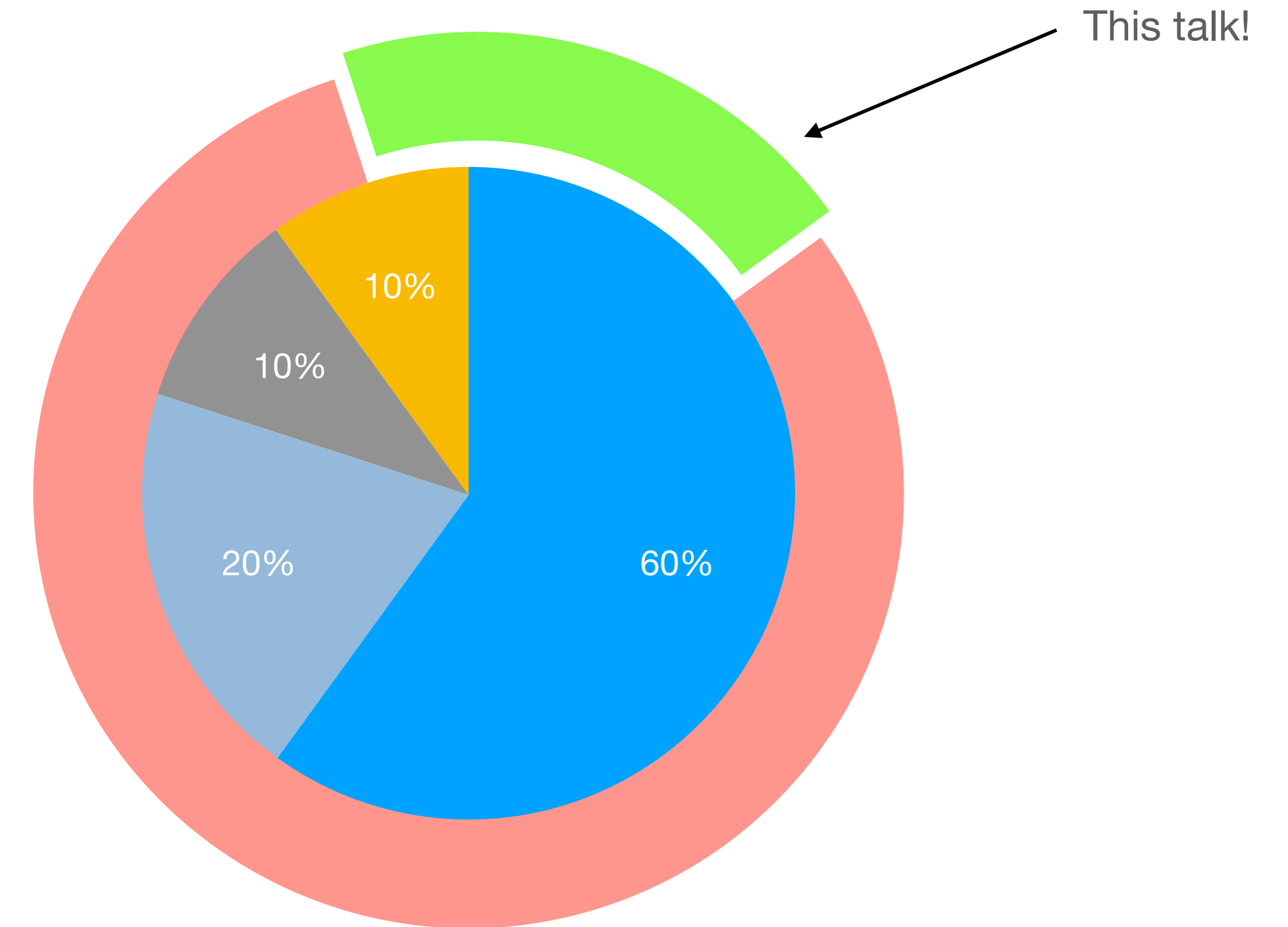p   e-

γ

Vs

SM known

SM Uncharted

BSM

Plan

- Crash course on QI tools

- $t\bar{t}$ production at the LHC

- Searching for New Physics

- Conclusions

Plan

- Crash course on QI tools

- $t\bar{t}$ production at the LHC

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- Conclusions

2 qubits   **2 qutrits**
Flavour   **Theory**

60%

20%

10%

10%

For a nice review:

Quantum entanglement and Bell inequality violation at colliders

Alan J. Barr [a,b], Marco Fabbrichesi [c,*], Roberto Floreanini [c], Emidio Gabrielli [d,c,e], Luca Marzola [e]

https://arxiv.org/pdf/2402.07972.pdf

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Basics
Density matrix : pure versus mixed

Schrödinger wave function (pure)

$$|\psi\rangle = \sum_n \alpha_n |\phi_n\rangle$$

$$i\hbar \frac{d}{dt} |\psi(t)\rangle = H |\psi(t)\rangle$$

$$\langle A \rangle = \langle \psi | A | \psi \rangle$$

$$\langle \psi | \psi \rangle = 1$$

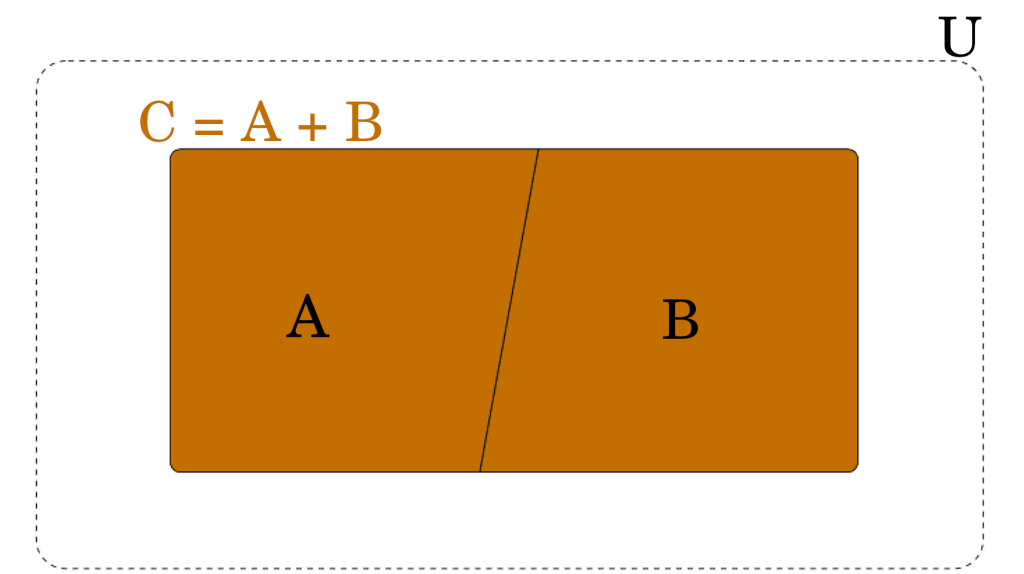$$|\langle \phi | \psi \rangle|^2 \geq 0$$

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Basics
Density matrix : pure versus mixed

Schrödinger wave function (pure)	Pure	Generic (mixed)
$\lvert\psi\rangle = \sum_n \alpha_n \lvert\phi_n\rangle$	$\rho = \lvert\psi\rangle\langle\psi\rvert$	$\rho = \sum_j p_j \lvert\psi_j\rangle\langle\psi_j\rvert$　$(\sum_j p_j = 1, p_j \geq 0)$
$i\hbar \dfrac{d}{dt}\lvert\psi(t)\rangle = H\lvert\psi(t)\rangle$	$i\hbar\dfrac{d\rho}{dt} = [H, \rho]$	
$\langle A \rangle = \langle\psi\lvert A \rvert\psi\rangle$	$\langle A \rangle = \mathrm{Tr}[A\rho]$	
$\langle\psi\lvert\psi\rangle = 1$	$\mathrm{Tr}[\rho] = 1$	
$\lvert\langle\phi\lvert\psi\rangle\rvert^2 \geq 0$	$\mathrm{Tr}[\rho^2] = 1$　$\rho = \rho^2$	$\mathrm{Tr}[\rho^2] < 1$　$\rho \neq \rho^2$

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C = A + B

A   B

Basics
Composite systems

Product pure state	Generic state (entangled)
$\|\psi\rangle = \|a\rangle \otimes \|b\rangle$	$\|\psi\rangle = \sum_{ij} p_{ij} \|a_i\rangle \otimes \|b_j\rangle \qquad p_{ij} \in \mathbb{C} \,,\ \sum_{ij} p_{ij} p_{ij}^* = 1$
	$\|a_i\rangle, \|b_j\rangle$ orthonormal bases

Separable	Non-separable (generic)
$\rho = \sum_i p_i\, \rho_A^i \otimes \rho_B^i$ $p_i \geq 0 \,,\ \sum_i p_i = 1$	$\rho = \sum_{ijkl} p_{ij} p_{kl}^* \|a_i\rangle \otimes \|b_j\rangle\langle a_k\| \otimes \langle b_l\| = \sum_{ijkl} p_{ij} p_{kl}^* \|a_i\rangle\langle a_k\| \otimes \|b_j\rangle\langle b_l\|$ $\rho_A = \mathrm{Tr}_B[\rho] = \sum_{ijl} p_{ij} p_{kj}^* \|a_i\rangle\langle a_k\|$ $\rho_B = \mathrm{Tr}_A[\rho] = \sum_{ijl} p_{ij} p_{il}^* \|b_j\rangle\langle b_l\|$

The properties are different for pure and mixed states
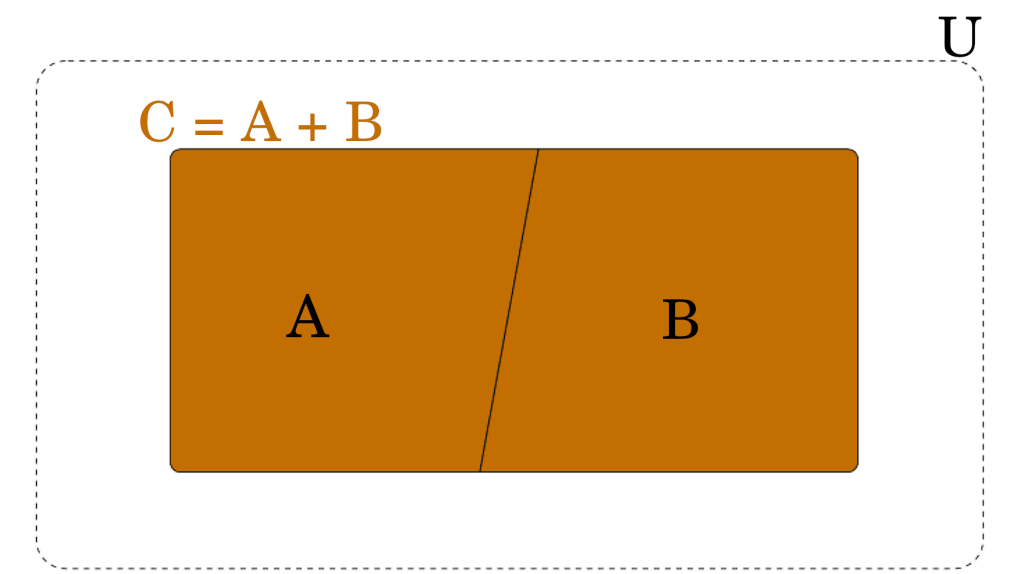
UCLouvain **fnrs** LA LIBERTÉ DE CHERCHER INFN Istituto Nazionale di Fisica Nucleare

C = A + B
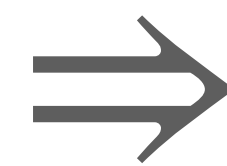
A   B

Basics
Entanglement

Theorem:

If $|\psi\rangle$ is a **pure state** of the AB system, then two bases exist such that (in A and B)

$$|\psi\rangle = \sum_i \sqrt{\lambda_i} \, |w_i\rangle_A \otimes |z_i\rangle_B \qquad \text{with} \qquad \sum_i \lambda_i = 1, \quad \lambda_i \geq 0$$

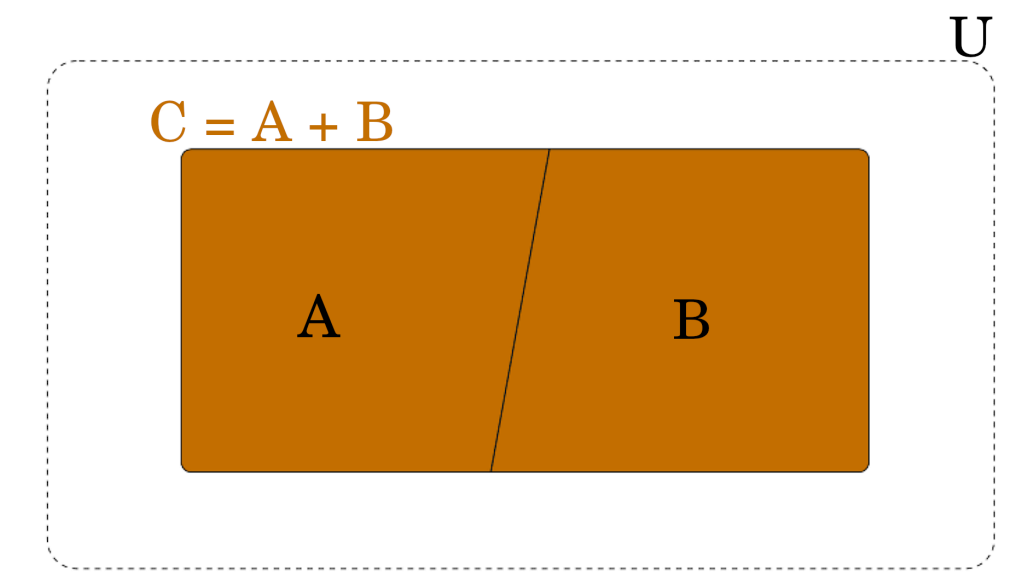$$\rho_A = \sum_i \lambda_i |w_i\rangle_{A\ A}\langle w_i|$$

$$\rho_B = \sum_i \lambda_i |z_i\rangle_{B\ B}\langle z_i|$$

$\Rightarrow$
- The states of the subsystems are mixed-states!
- They have the same eigenvalues => they are equally impure
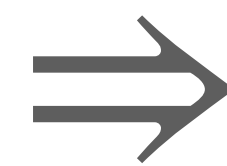
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$$\rho_A = \sum_i \lambda_i |w_i\rangle_{A\ A}\langle w_i|$$

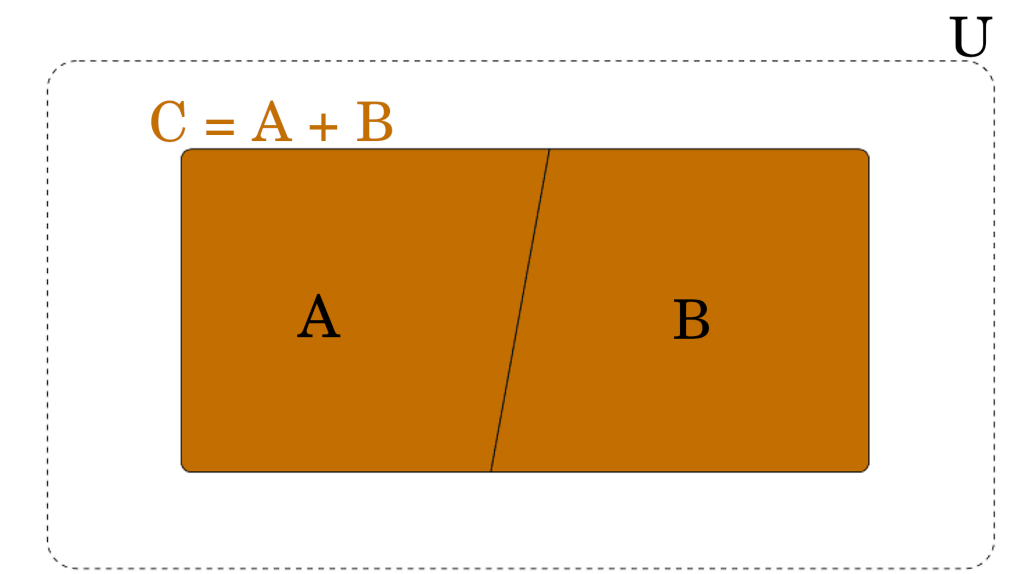$$\rho_B = \sum_i \lambda_i |z_i\rangle_{B\ B}\langle z_i|$$

$\Rightarrow$

- The states of the subsystems are mixed-states!
- They have the same eigenvalues => they are equally impure

Consequences:

1. One can always think of a mixed state as the trace out a subsystem in a large system (purification).
2. Two subsystems that partition a pure state are entangled IFF their reduced states are mixed.

C = A + B

A   B

Basics
Concurrency

Take an entangled **pure** state between the two subsystems A and B. $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$

As a result, the states in A and B must be mixed and

$$\mathrm{Tr}\left[\rho_A^2\right] \leq 1 \qquad \text{and} \qquad \mathrm{Tr}\left[\rho_B^2\right] \leq 1$$
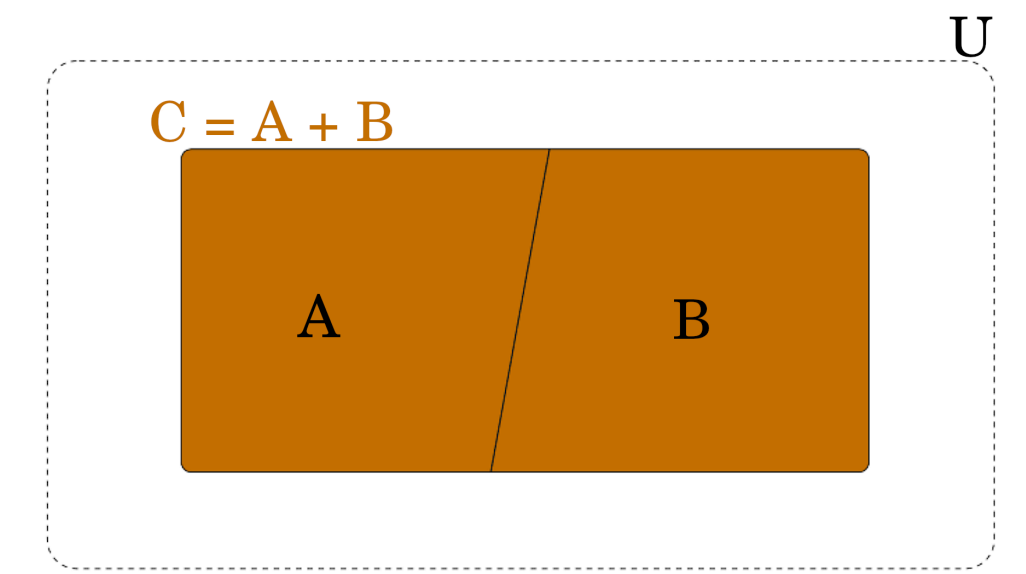
The concurrency $C_{A|B}$ is defined as

$$0 \leq C_{A|B}^2 = 2(1 - \mathrm{Tr}[\rho_A^2]) = C_{B|A}^2 \leq 1 \qquad\qquad C_{A|B}^2 = 2S_2(\rho_A) \quad \text{Tsallis-2 linear entropy}$$

For mixed states, things are in general more complicated.

Basics
Peres-Horodecki criterium

This is a necessary (and for two qubits sufficient) criterium for separability of a mixed state of two subsystems A and B. Consider a generic state:

$$\rho = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle \otimes |b_j\rangle\langle a_k| \otimes \langle b_l|$$

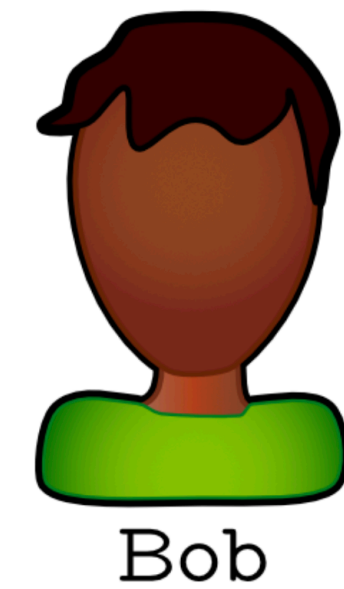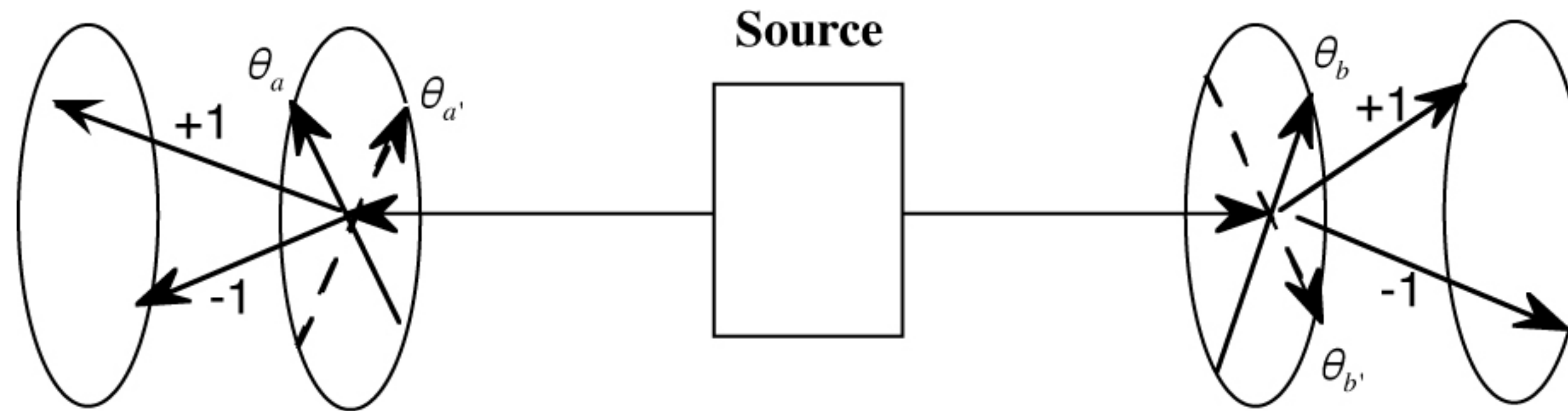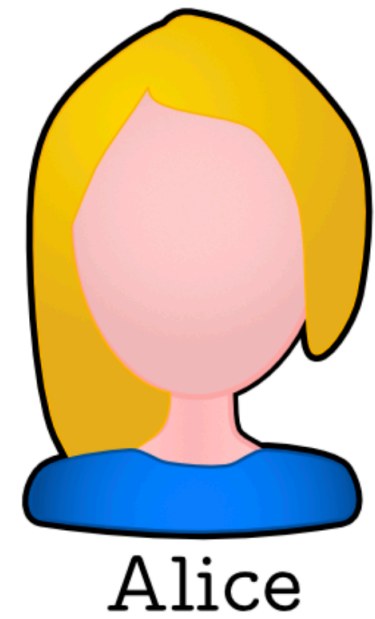$$\mathscr{H} = \mathscr{H}_A \otimes \mathscr{H}_B$$

And the partial transpose on B

$$\rho^{T_B} = (I \otimes T)[\rho] = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle\langle a_k| \otimes (|b_j\rangle\langle b_l|)^T = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle\langle a_k| \otimes |b_l\rangle\langle b_j| = \sum_{ijkl} p_{il} p_{kj}^* |a_i\rangle\langle a_k| \otimes |b_j\rangle\langle b_l|$$

The criterion states that if ρ is separable then all the eigenvalues of are non-negative.

In other words, if ρ has a negative eigenvalue, is guaranteed to be entangled.

Basics
Bell (Clauser, Horne, Shimony, and Holt) inequalities

$$A = \pm 1$$

$$A' = \pm 1$$

Assuming:

1] Measurements reveal element of reality, physical properties present beforehand.

2] Alice and Bob are separated by a space-like distance

Then:

$$B = \pm 1$$

$$B' = \pm 1$$

$$E(AB) + E(AB') + E(A'B) - E(A'B') \leq 2$$

Basics
Bell (Clauser, Horne, Shimony, and Holt) inequalities

Proof:

$$E(AB) + E(AB') + E(A'B) - E(A'B')$$

$$= E(AB + A'B + A'B - A'B')$$

$$= E(A(B + B') + A'(B - B'))$$

Now $B + B' = 0 \Rightarrow B - B' = \pm 2$ and viceversa. So

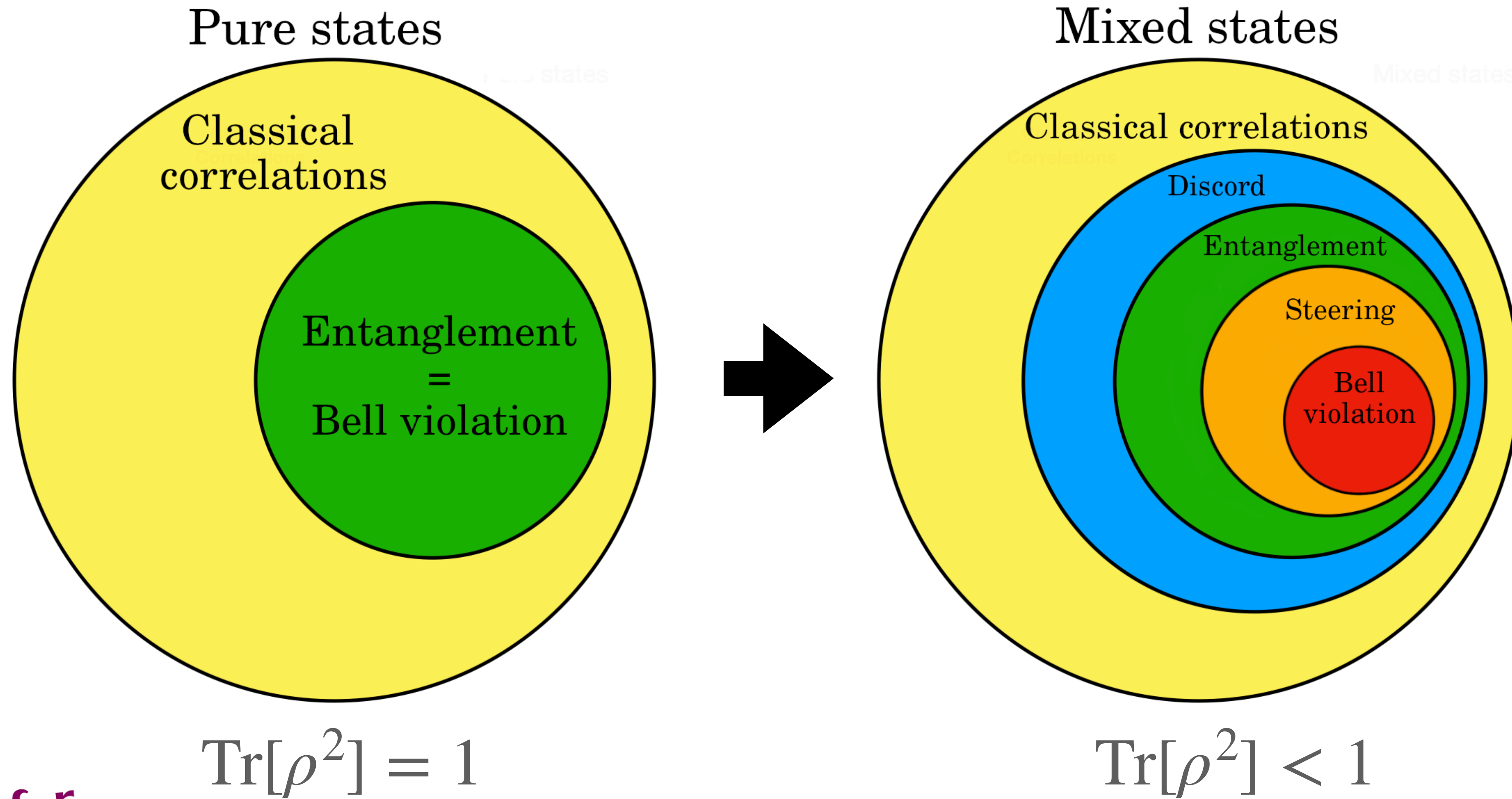$$AB + A'B + A'B - A'B' = \pm 2$$

So for the expectation value

$$E(AB) + E(AB') + E(A'B) - E(A'B') = \sum_{a,a',b,b'} p(a, a', b, b')(ab + ab' + a'b - a'b') \leq 2$$
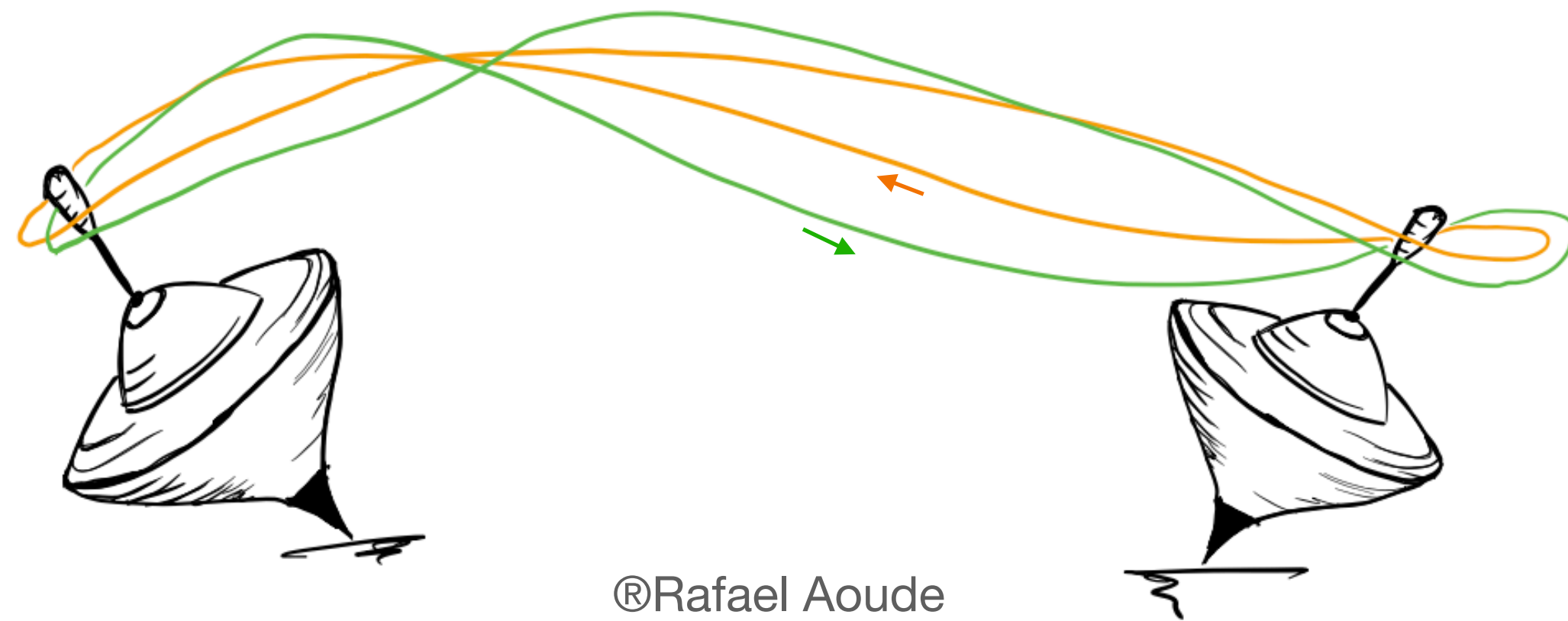
Comments:

i) Bell inequalities have nothing to do with quantum mechanics.

ii) In the last 40 years experiments have proven them over larger and larger distances.

iii) Discussions on possible loopholes have heated and continue to keep the community of experts busy.

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Basics
Grading quantum correlations

Pure states

Classical correlations

Entanglement
=
Bell violation

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

Mixed states

Classical correlations

Discord

Entanglement

Steering

Bell violation

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

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Quantum tops @ LHC

Y. Afik and JRM de Nova: 2003.02280 [quant-ph]

M. Fabbrichesi, R. Floreanini. G. Panizzo: 2102.11883 [hep-ph]

C. Severi, C. Boschi, **FM**, M. Sioli : 2110.10112 [hep-ph]

Y. Afik and JRM de Nova: 2203.05582 [quant-ph]

R. Aoude, E. Madge, **FM**, L. Mantani: 2203.05619 [hep-ph]

J.A. Aguilar-Saavedra, J.A. Casas: 2205.00542 [hep-ph]

Y. Afik and JRM de Nova: 2209.03969 [quant-ph]

C. Severi, E. Vryonidou: 2210.09330 [hep-ph]

Z. Dong, D. Gonçalves, K. Kong, A. Navarro: 2305.07075 [hep-ph]

J.A. Aguilar-Saavedra : 2307.06991 [hep-ph]

T. Han, M. Low, TA Wu: 2310.17696 [hep-ph]

J.A. Aguilar-Saavedra, J.A. Casas: 2401.06854 [hep-ph]

C. Severi, **FM**, S. Tentori, E. Vryonidou: 2401.08751[hep-ph]

C. Severi, **FM**, S. Tentori, E. Vryonidou: 2404.08049[hep-ph]

K. Cheng,T. Han, M. Low: 2407.01672[hep-ph]

®Rafael Aoude

On the shoulders of
Stephen J. Parke, Yael Shadmi hep-ph/9606419
G. Mahlon, S. J. Parke, hep-ph/9412250
G. Mahlon, S. J. Parke,hep-ph/9512264
G. Mahlon, S. J. Parke, ,hep-ph/9611367
G. Mahlon, S. J. Parke, hep-ph/9706304

Many other papers on (H→)WW,ZZ,ZW, $\tau^+\tau^-$, tW,…

Why looking at tops?

- **LHC:** a top factory.

- **Top decay:** The decay occurs in two steps, t→Wb is the first one:

  $\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s

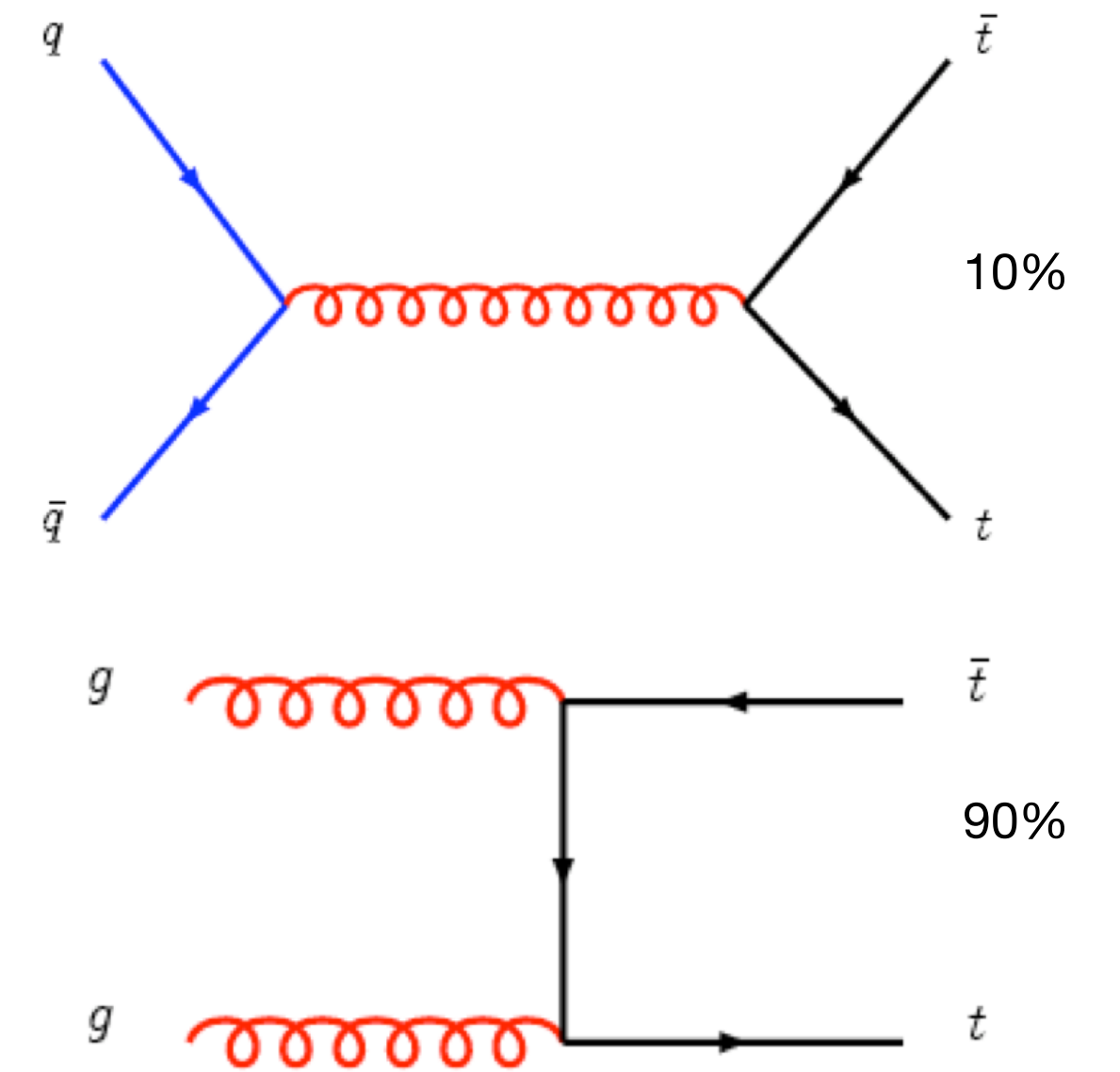 $\tau_{top} \approx h/\Gamma_{top} = 1/(G_F m_t^3 |Vtb|2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s (with h=6.6 10^{-25} GeV s)

  $\tau_{spin\text{-}flip} \approx \left(\dfrac{\Lambda^2_{QCD}}{m_t}\right)^{-1} \gg \tau_{had}$

- Due to the structure of weak interactions, it "magically" turns out that the direction of the lepton is 100% correlated with that of the spin of the top.
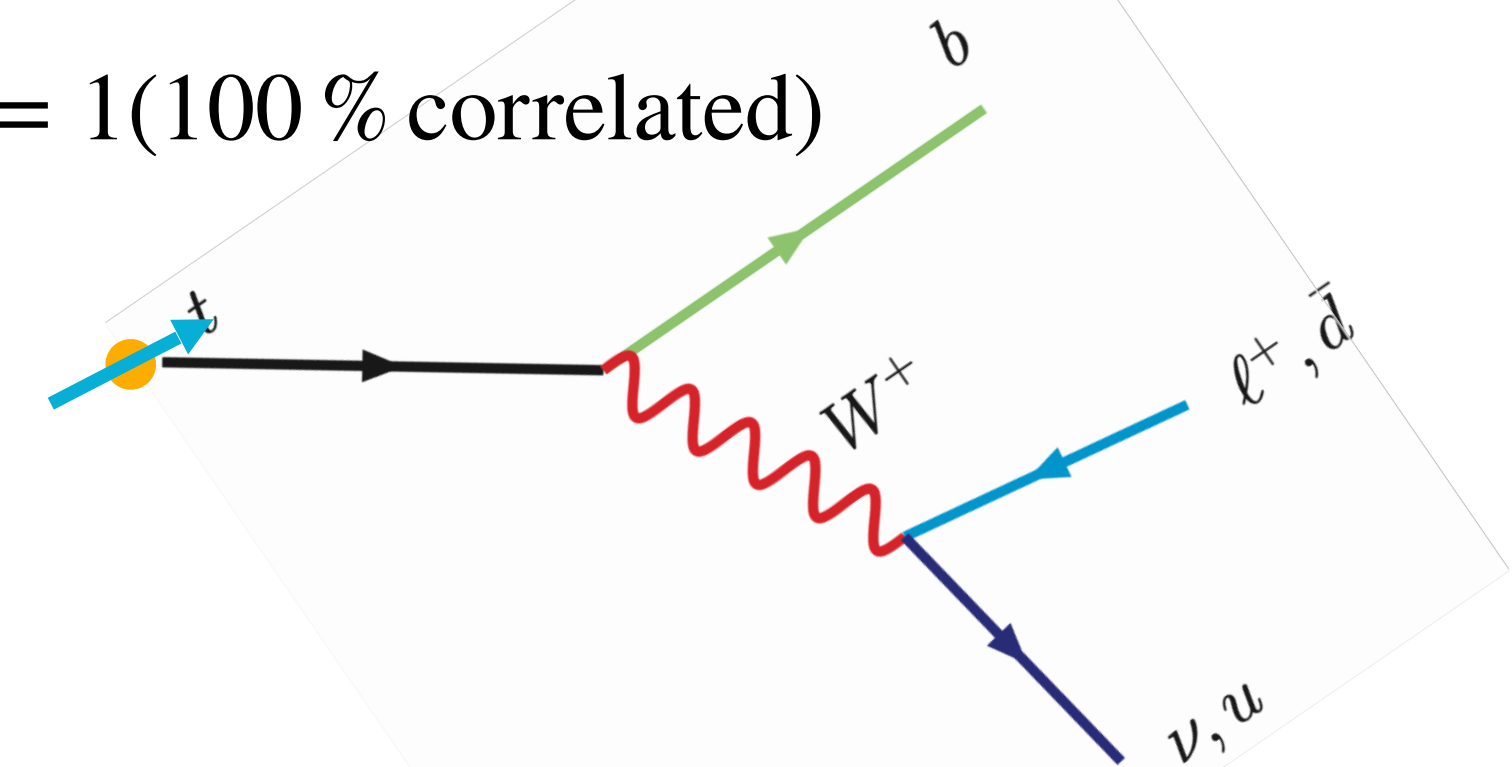
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\varphi} = \frac{1+\alpha\cos\varphi}{2}$$

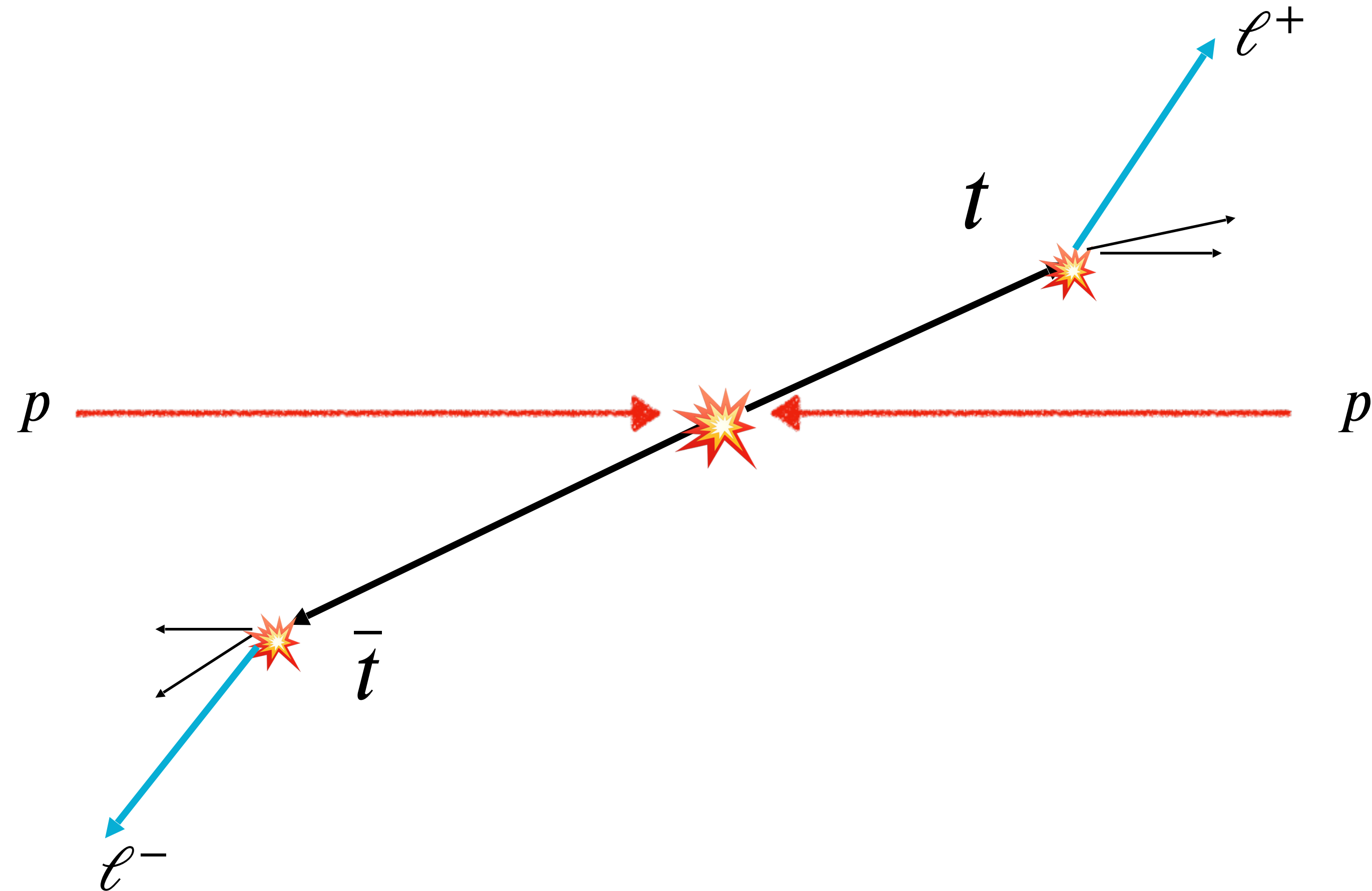$$\alpha_d = 1, \alpha_u = -0.3, \alpha_b = -0.4, \alpha_W = 0.4$$
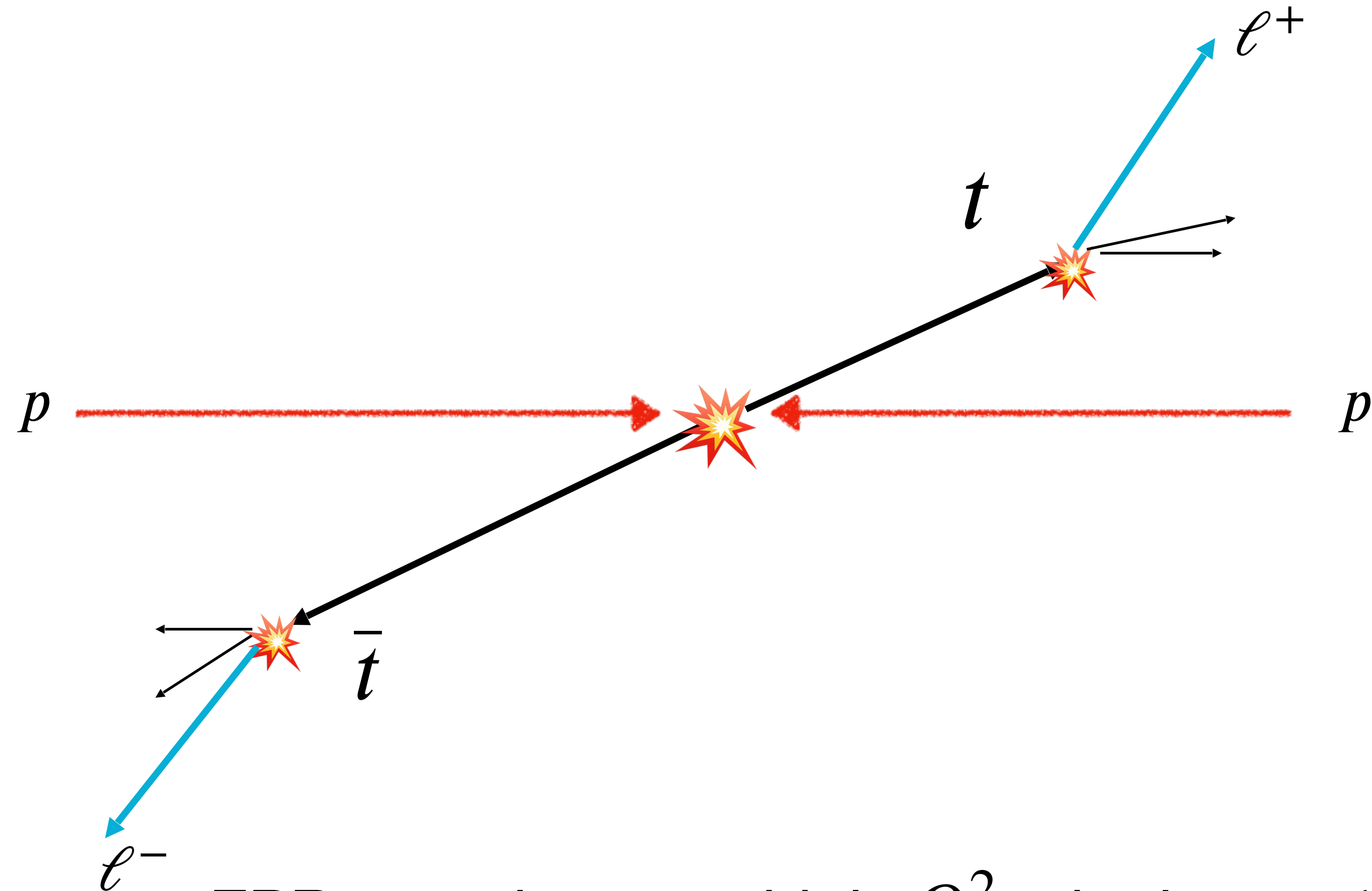
⇒ **The charged lepton is the best proxy for the spin**

10%

90%

$\alpha_\ell = 1 (100\,\%\text{ correlated})$

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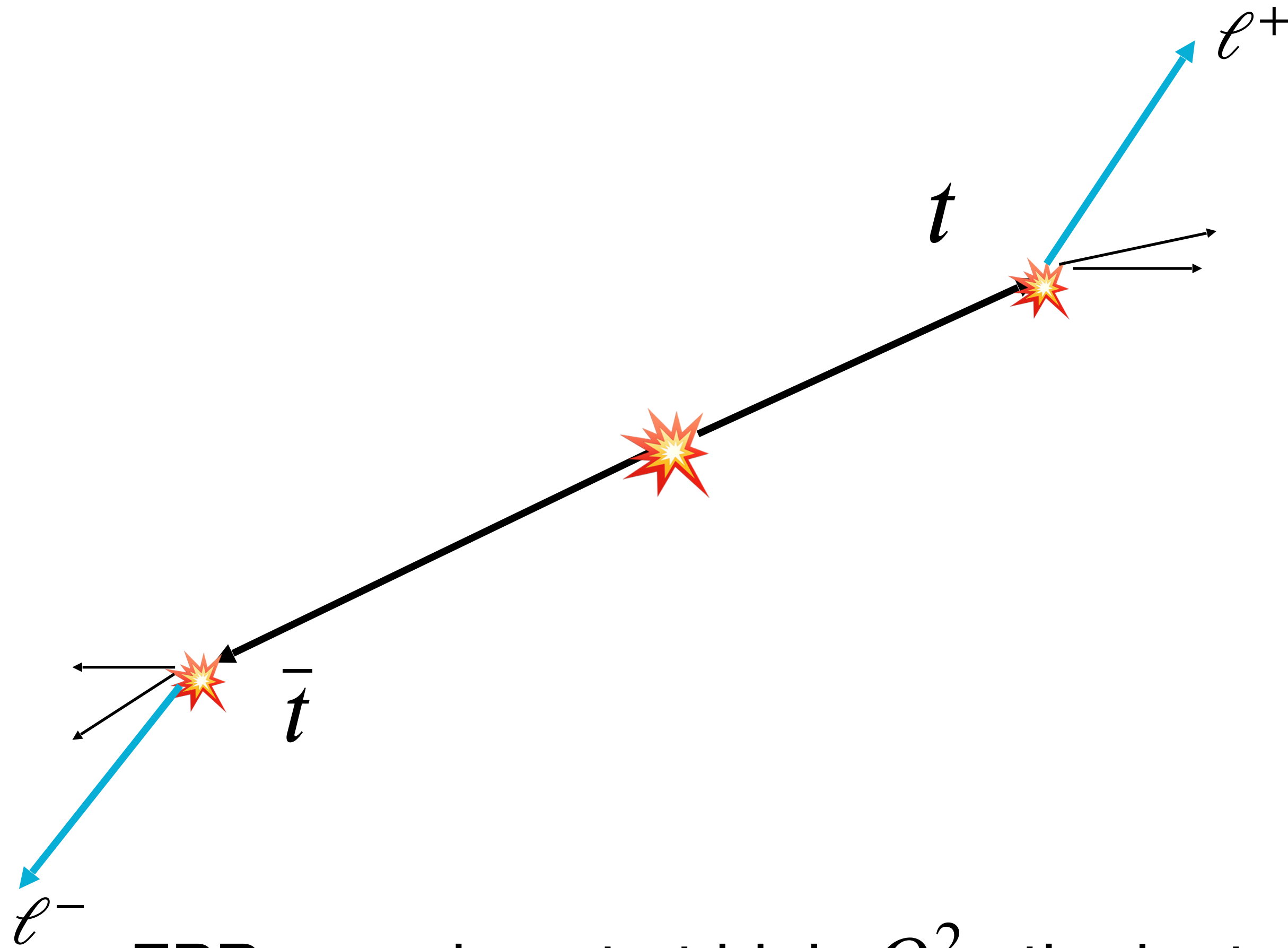
Quantum tops

Quantum tops
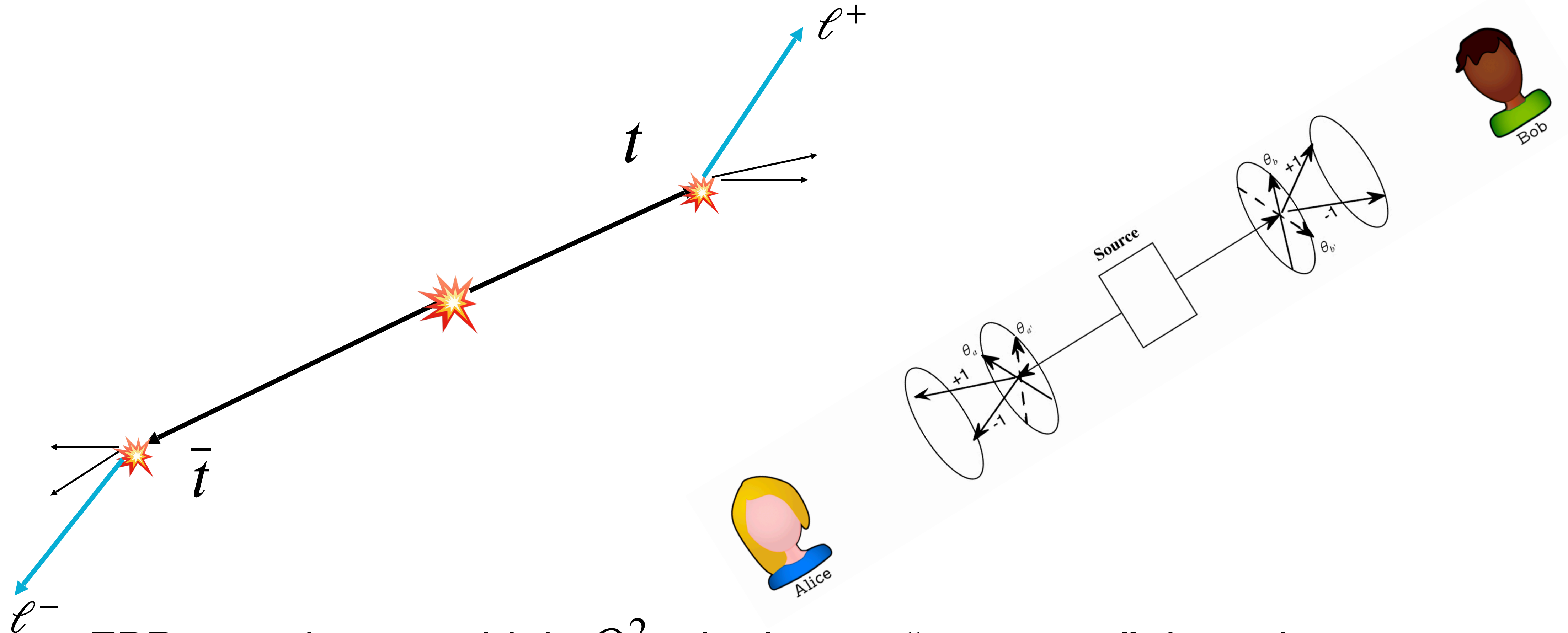

EPR experiment at high-Q^2 : the lepton "measures" the spin.

Quantum tops

EPR experiment at high-Q^2 : the lepton "measures" the spin.

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Quantum tops

EPR experiment at high-Q^2 : the lepton "measures" the spin.

Quantum tops

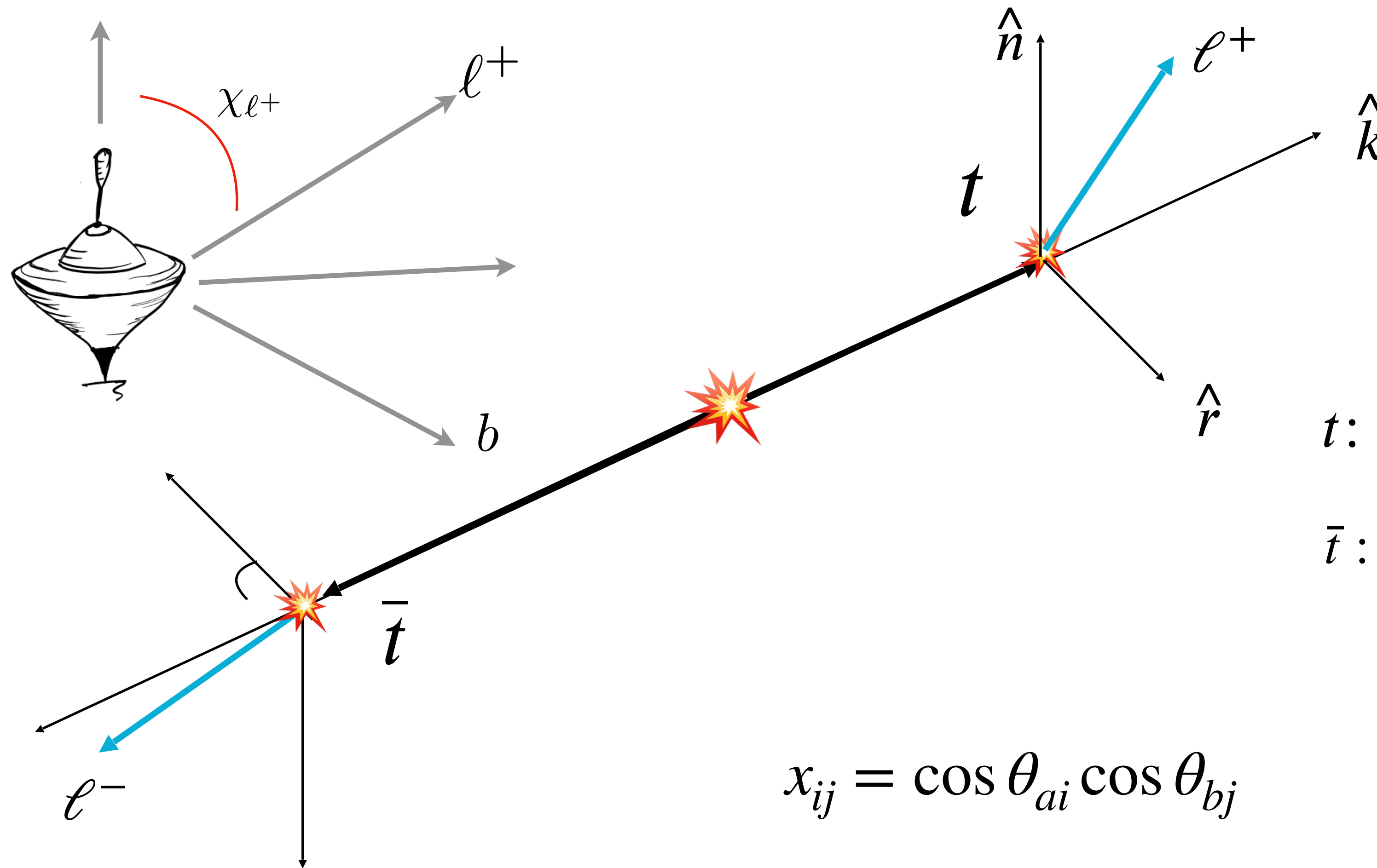"The devil is in the details" : $t\bar{t}$ pair is not in a pure state.

◉ The qubit-qubit system is described by the following density matrix

$$\rho = \frac{1}{4}\left(\mathbf{1} \otimes \mathbf{1} + \mathcal{B} \cdot \boldsymbol{\sigma} \otimes \mathbf{1} + \bar{\mathcal{B}} \cdot \mathbf{1} \otimes \boldsymbol{\sigma} + \mathcal{C} \cdot \boldsymbol{\sigma} \otimes \boldsymbol{\sigma}\right)$$

which, for $t\bar{t}$ can be approximated by $B_1 = B_2 = 0$, and C is symmetric (CP conservation) and almost diagonal in the helicity basis.

$$\langle S_i \rangle = B_i, \quad \langle \bar{S}_i \rangle = \bar{B}_j, \quad \langle S_i \bar{S}_j \rangle = C_{ij}$$
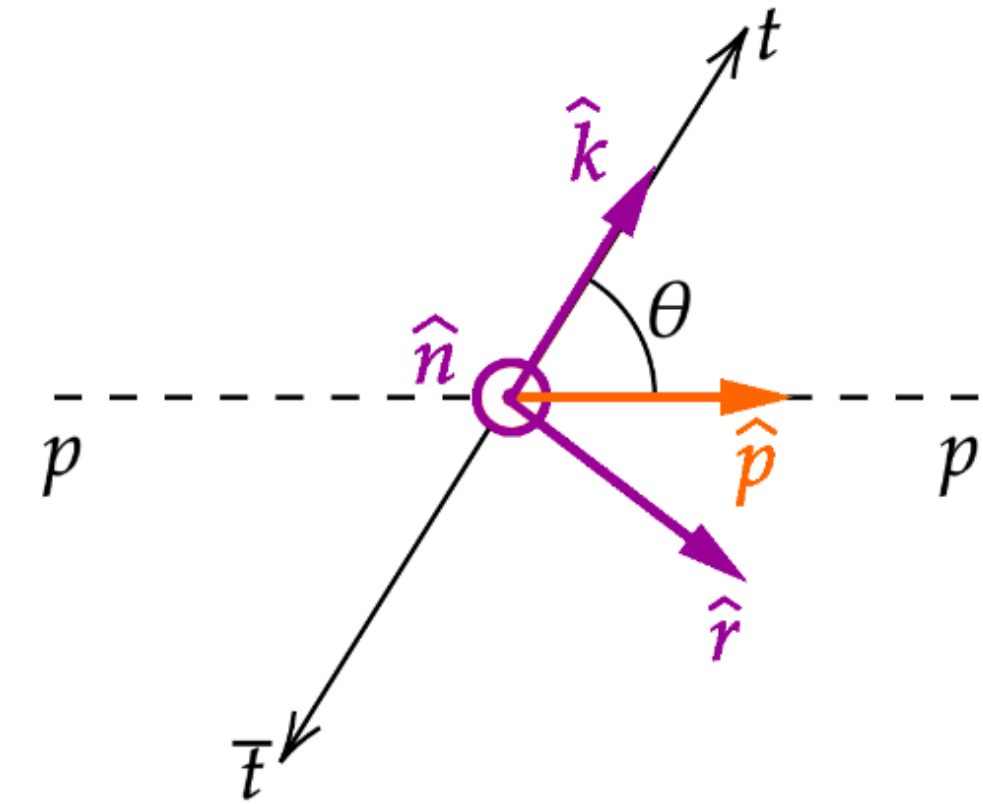
Kinematics

$$t: \quad \hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

$$\bar{t} : \{-\hat{k}, -\hat{r}, -\hat{n}\}$$

$$x_{ij} = \cos\theta_{ai}\cos\theta_{bj}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dx_{ij}} = \frac{C_{ij}x_{ij} - 1}{2}\log\left|x_{ij}\right|$$

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Quantum tops

$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

We can write four sufficient conditions for entanglement:

$$-C_{kk} - C_{rr} - C_{nn} \equiv -3D^{(1)} > 1$$

$$-C_{kk} + C_{rr} + C_{nn} \equiv -3\,D^{(k)} > 1$$

$$+C_{kk} + C_{rr} - C_{nn} \equiv -3\,D^{(n)} > 1$$

$$+C_{kk} - C_{rr} + C_{nn} \equiv -3\,D^{(r)} > 1$$

$$D < -\!\!\text{\small 1}/\text{\small 3} \qquad \Rightarrow \text{Entanglement}$$

$$\mathcal{C}^{(\text{singlet})} = \begin{pmatrix} -\eta & 0 & 0 \\ 0 & -\eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}, \; 0 < \eta \le 1$$

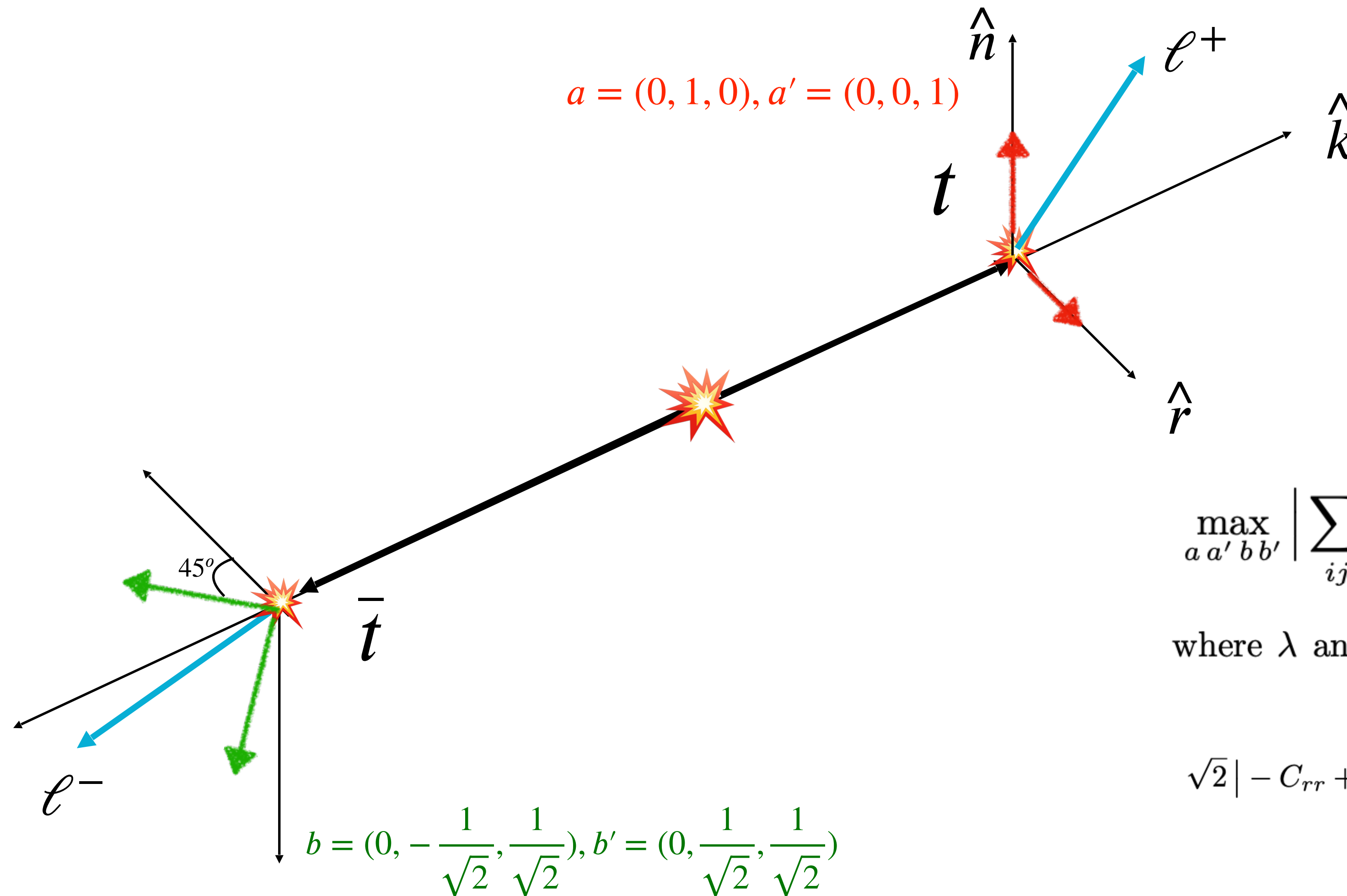$$\mathcal{C}^{(\text{triplet})} = \begin{pmatrix} \eta & 0 & 0 \\ 0 & \eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}, \qquad 0 < \eta \le 1$$

Where D=$-\eta$ and in the limiting case of $\eta = 1$ we have the four Bell states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\big),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

Kinematics

$a = (0, 1, 0), a' = (0, 0, 1)$

$b = (0, -\dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}}), b' = (0, \dfrac{1}{\sqrt{2}}, \dfrac{1}{\sqrt{2}})$

$$\max_{a\,a'\,b\,b'} \left| \sum_{ij} C_{ij} \left(a_i b_j - a_i b_j' + a_i' b_j + a_i' b_j' \right) \right| = 2\sqrt{\lambda + \lambda'}$$

where λ and λ' are the two largest eigenvalues of $C^T C$.

$$\sqrt{2}\left| -C_{rr} + C_{nn} \right| \leq 2 \qquad \Rightarrow \text{Bell condition (with axis choice)}$$

Summary

$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k} \, \cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

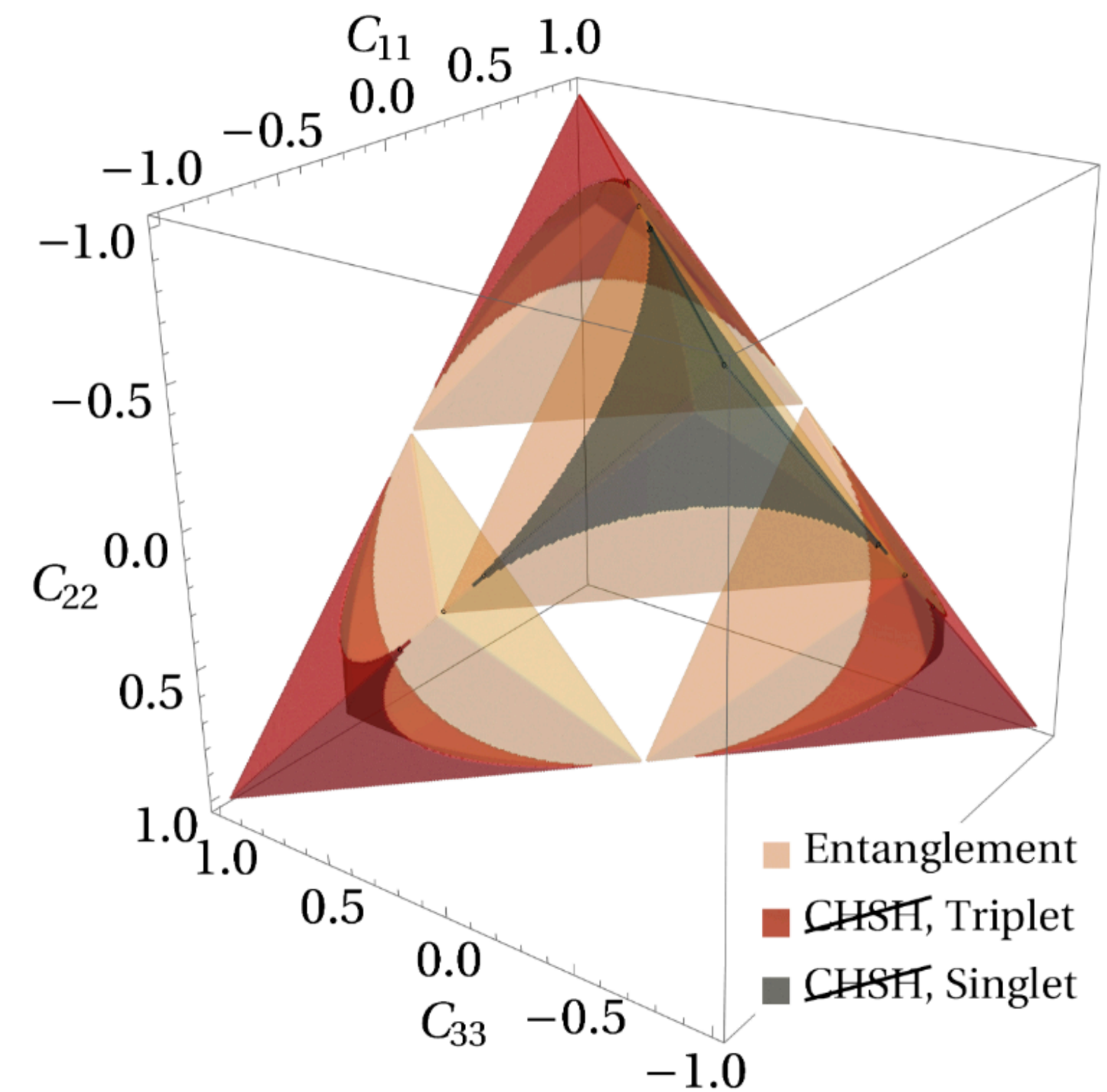We can write four sufficient conditions for entanglement:

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$$D < -1/3 \qquad \Rightarrow \text{Entanglement}$$

Summary

$$\hat{k} = \text{top direction}, \quad \hat{r} = \frac{\hat{p} - \hat{k} \cos\theta}{\sin\theta}, \quad \hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$$

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$$+C_{kk} - C_{rr} + C_{nn} \equiv -3 D^{(r)} > 1$$

$$D < -\sfrac{1}{3} \qquad \Rightarrow \text{Entanglement}$$

The specific case where $C_{xx} = C_{yy} = C_{zz} = -\eta$ with $0 < \eta < 1$ corresponds to the singlet Werner state, while $C_{xx} = C_{yy} = -C_{zz} = \eta$ and cyclic permutations correspond to a triplet of Werner states (with fidelity $F = \frac{3\eta+1}{4}$). It is known that for Werner states, $\eta > 1/3$ implies entanglement, while the CHSH inequality is violated when $\eta > \sqrt{2}/2$.[1]

Summary

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$$D < -1/3 \qquad \Rightarrow \text{Entanglement}$$

$$\sqrt{2}\left|-C_{rr} + C_{nn}\right| \leq 2; \qquad \Rightarrow \text{Bell violation (with axis choice)}$$
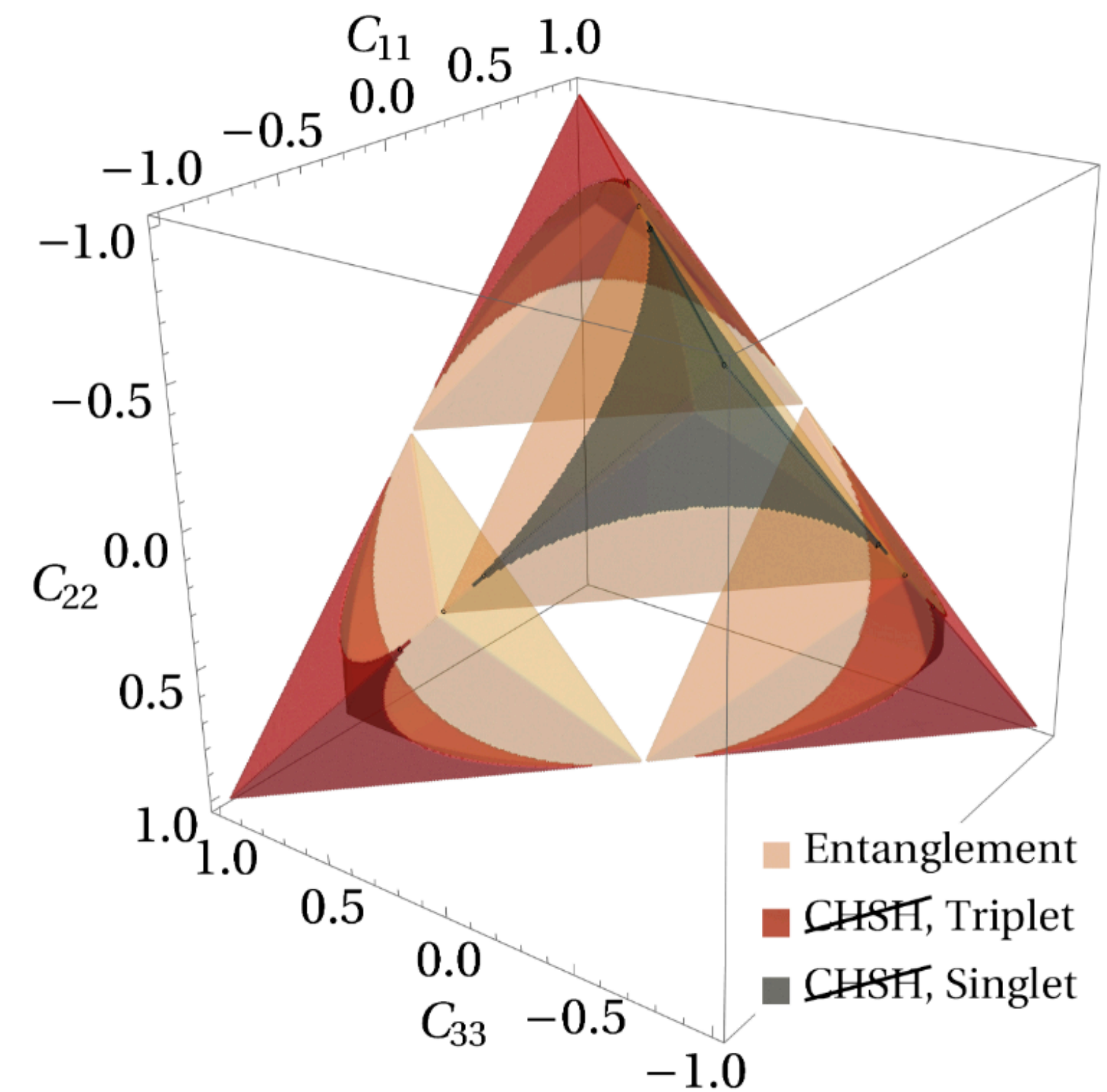
The specific case where $C_{xx} = C_{yy} = C_{zz} = -\eta$ with $0 < \eta < 1$ corresponds to the singlet Werner state, while $C_{xx} = C_{yy} = -C_{zz} = \eta$ and cyclic permutations correspond to a triplet of Werner states (with fidelity $F = \frac{3\eta+1}{4}$). It is known that for Werner states, $\eta > 1/3$ implies entanglement, while the CHSH inequality is violated when $\eta > \sqrt{2}/2$.[1]
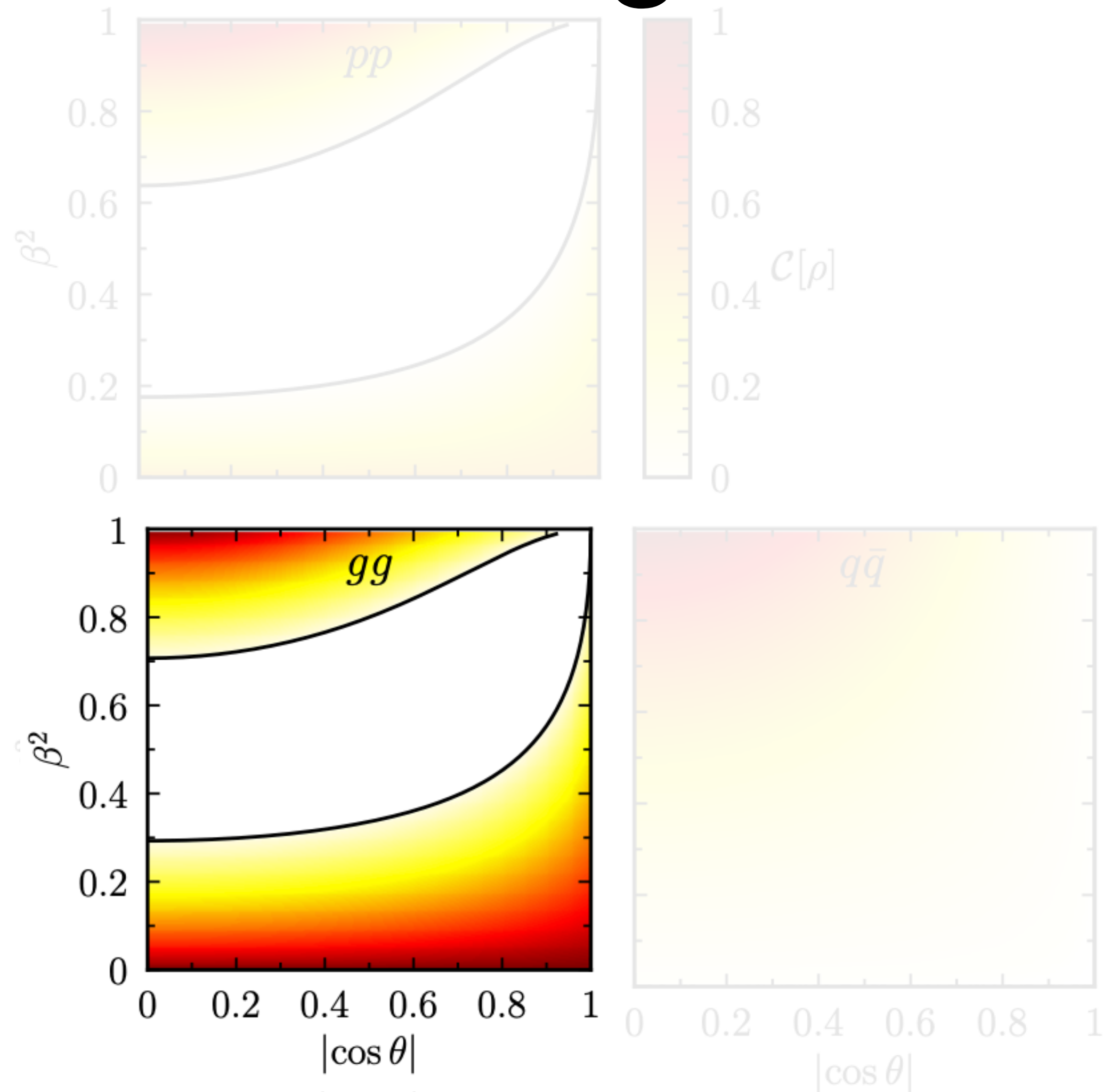
SM Entanglement
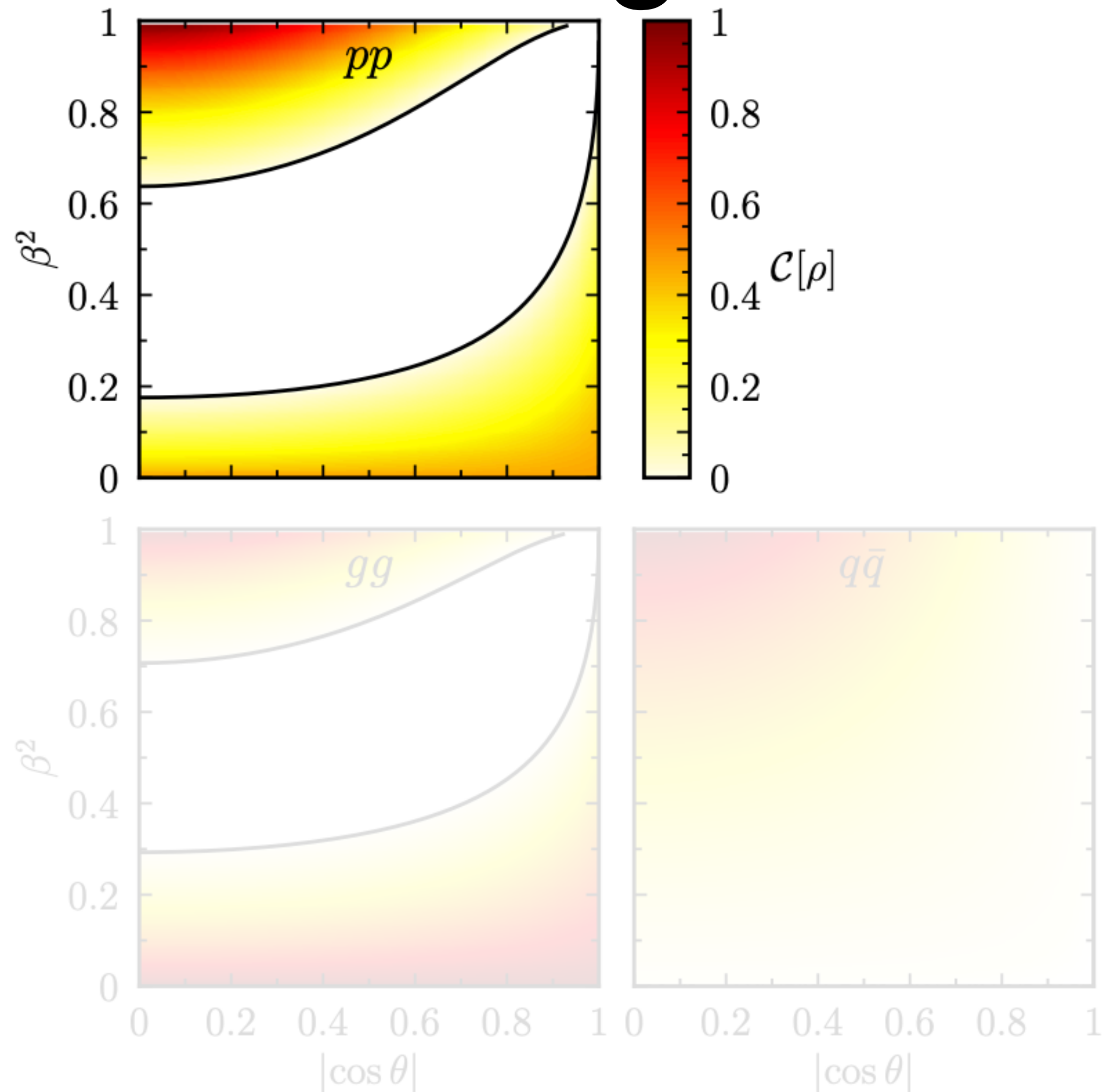
$$pp$$

White regions: zero-entanglement

Maximal entanglement points/regions:

- At threshold: $\beta^2 = 0, \forall \theta$

- high-E: $\beta^2 \to 1, \cos\theta = 0$

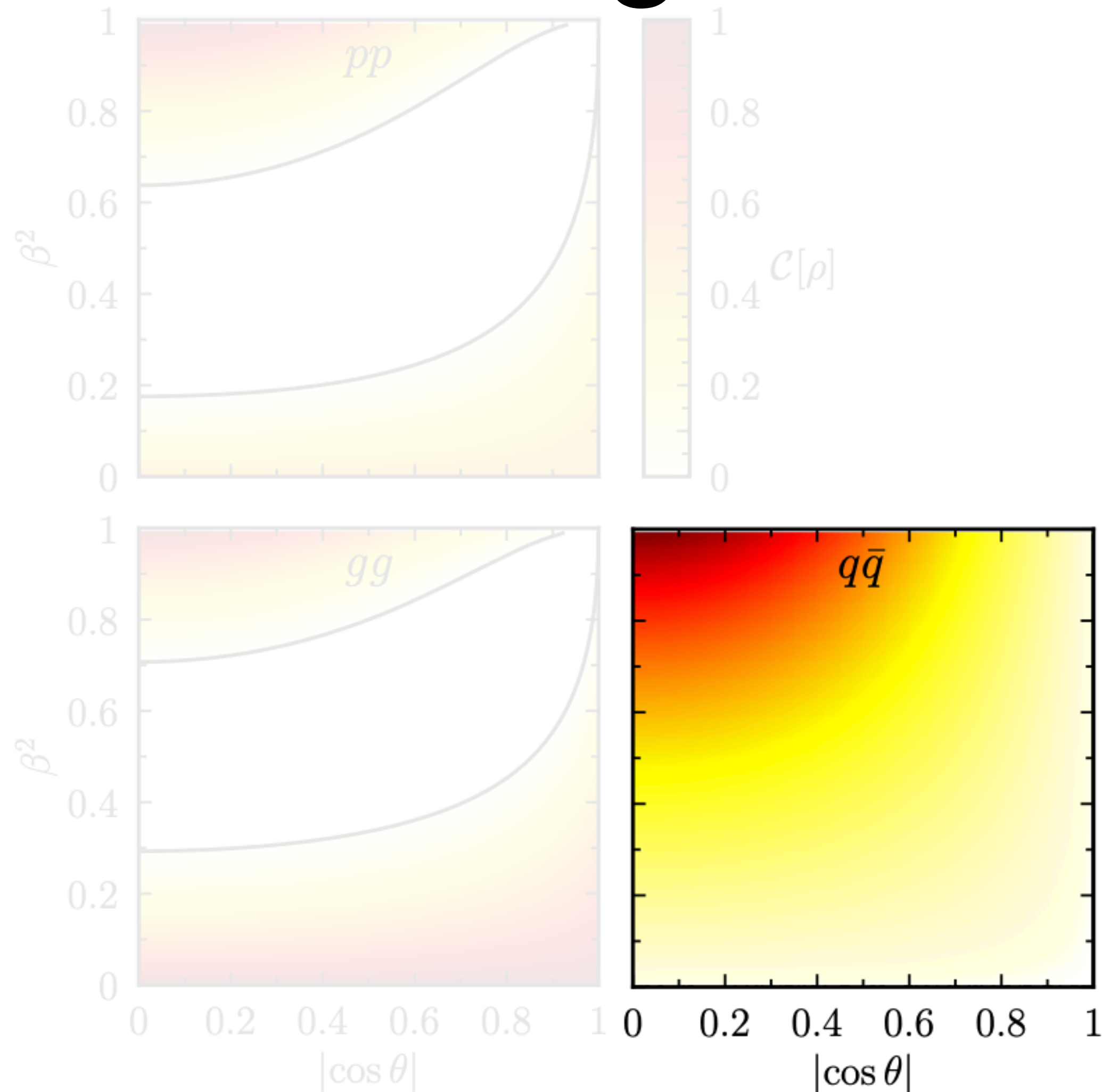# SM Entanglement

$$gg$$

Maximal entanglement points/regions:

- At threshold: $\beta^2 = 0, \forall \theta$

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

- High-E: $\beta^2 \to 1, \cos\theta = 0$

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

SM Entanglement

$$q\bar{q}$$

Maximal entanglement points/regions:

- At threshold: $\beta^2 = 0, \forall \theta$

  mixed but separable

- High-E: $\beta^2 \to 1, \cos\theta = 0$

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

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SM Entanglement

$$-C_{kk} - C_{rr} - C_{nn} > 1$$

$$C_{kk} + C_{rr} - C_{nn} > 1$$

Region	Selection	Cross section	$|C_{kk} + C_{rr}| - C_{nn}$ Reconstructed	Significance for > 1
Threshold	Weak	14 pb	1.31 ± 0.02	$\gg 5\sigma$
	Intermediate	12 pb	1.34 ± 0.02	$\gg 5\sigma$
	Strong	10 pb	1.38 ± 0.02	$\gg 5\sigma$
High-p_T	Weak	1.9 pb	1.32 ± 0.07	5σ
	Intermediate	1.5 pb	1.36 ± 0.08	4σ
	Strong	1.0 pb	1.42 ± 0.13	3σ

Severi et al. 2110.10112
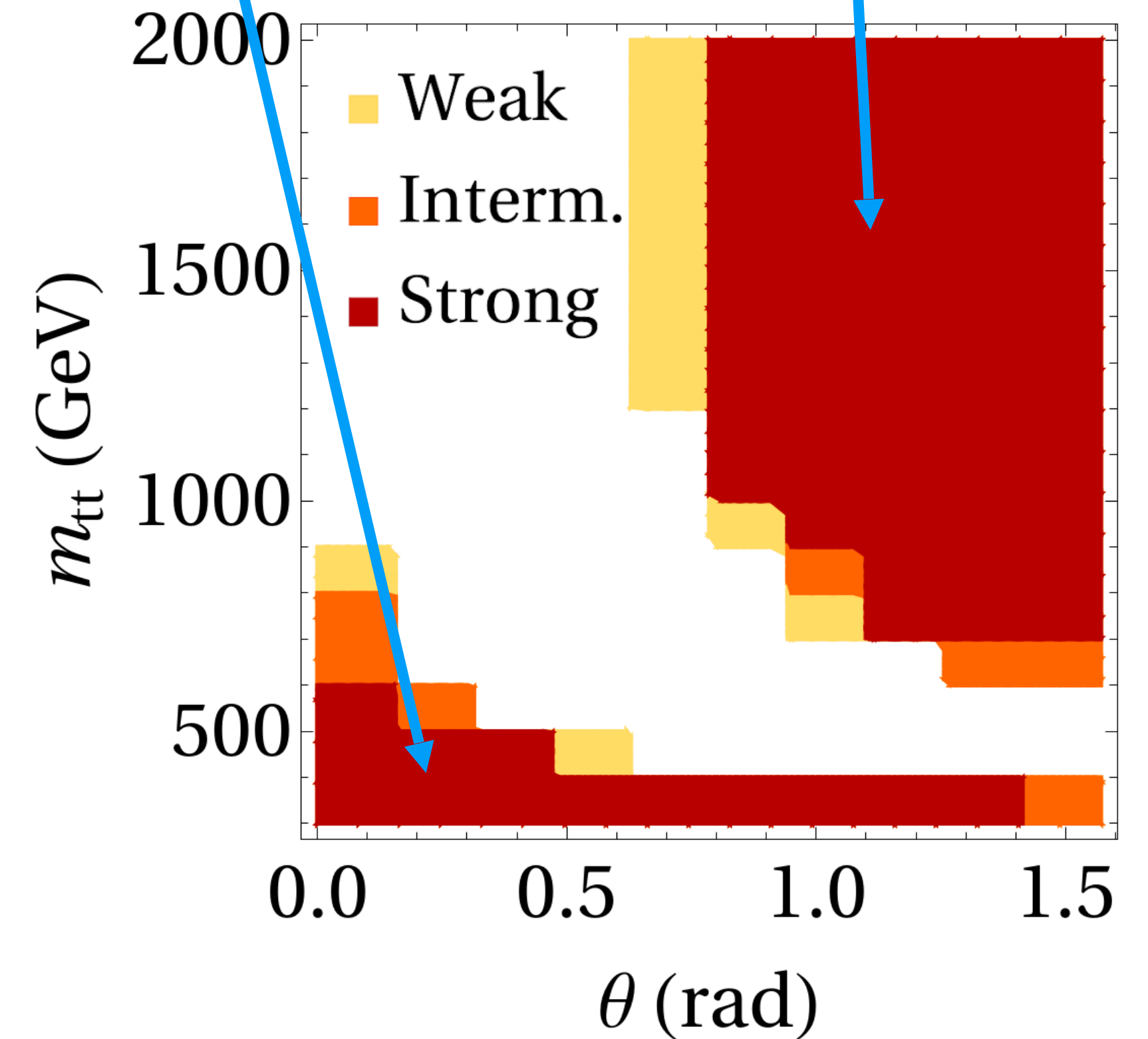
Entanglement "easily" observable at the LHC!

First measurements
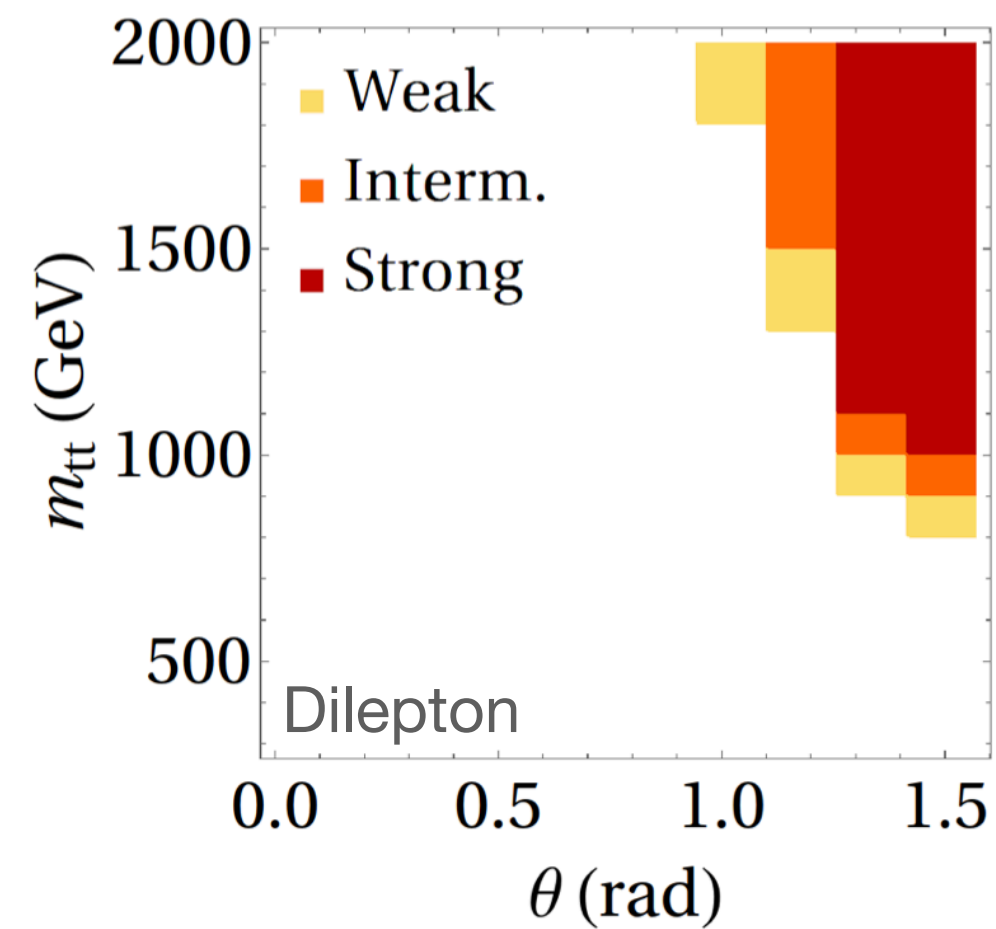## Dilepton channel at threshold
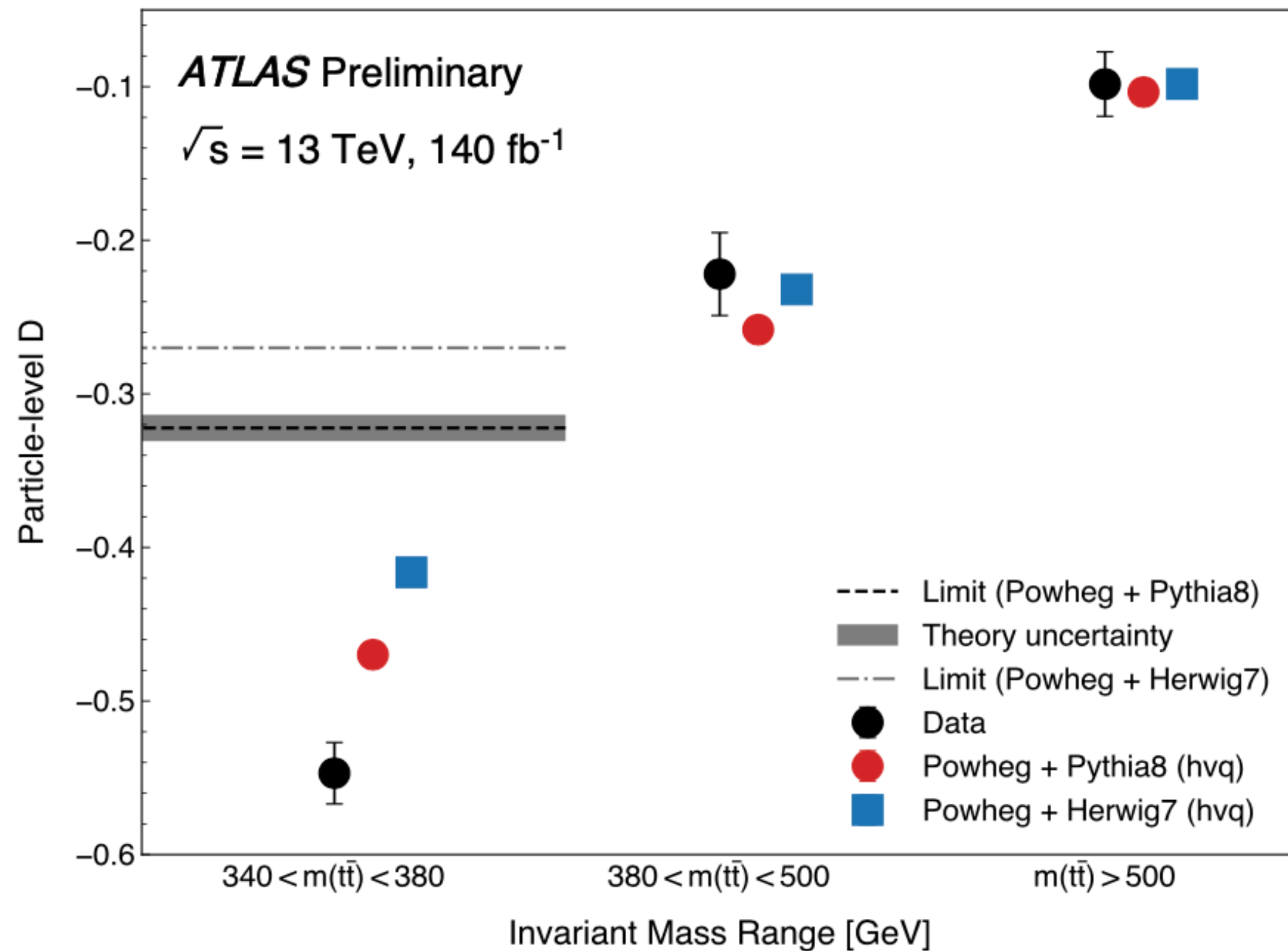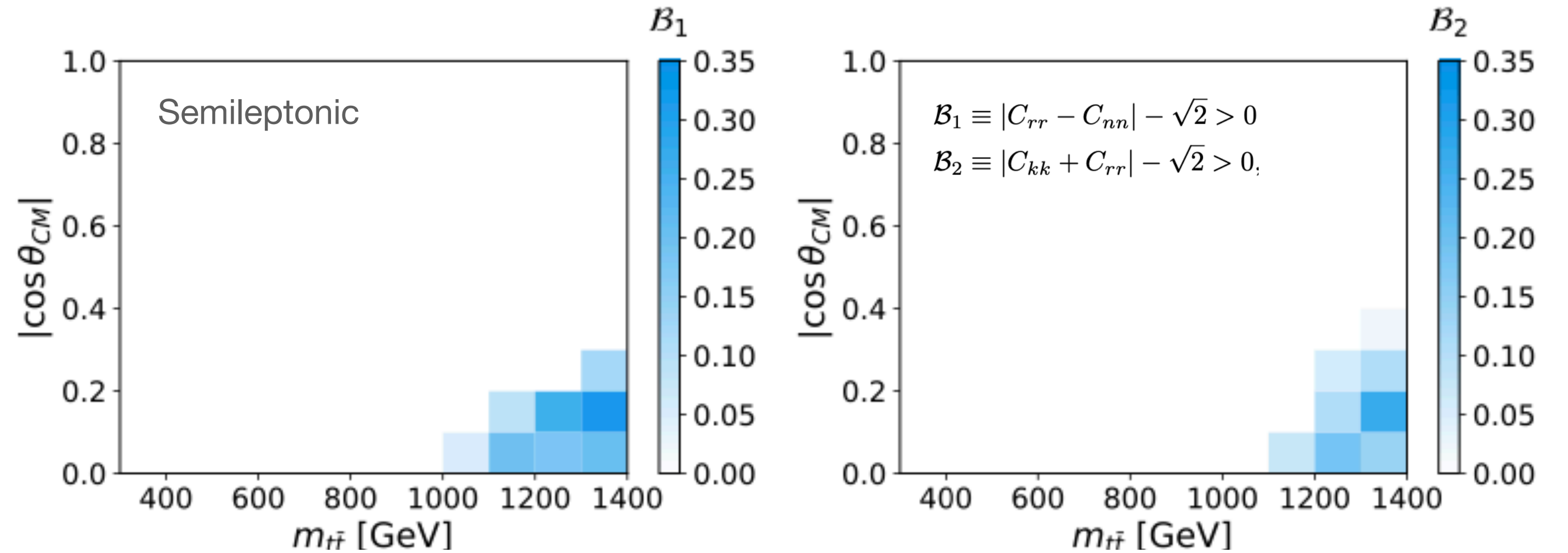

Entanglement observation by ATLAS
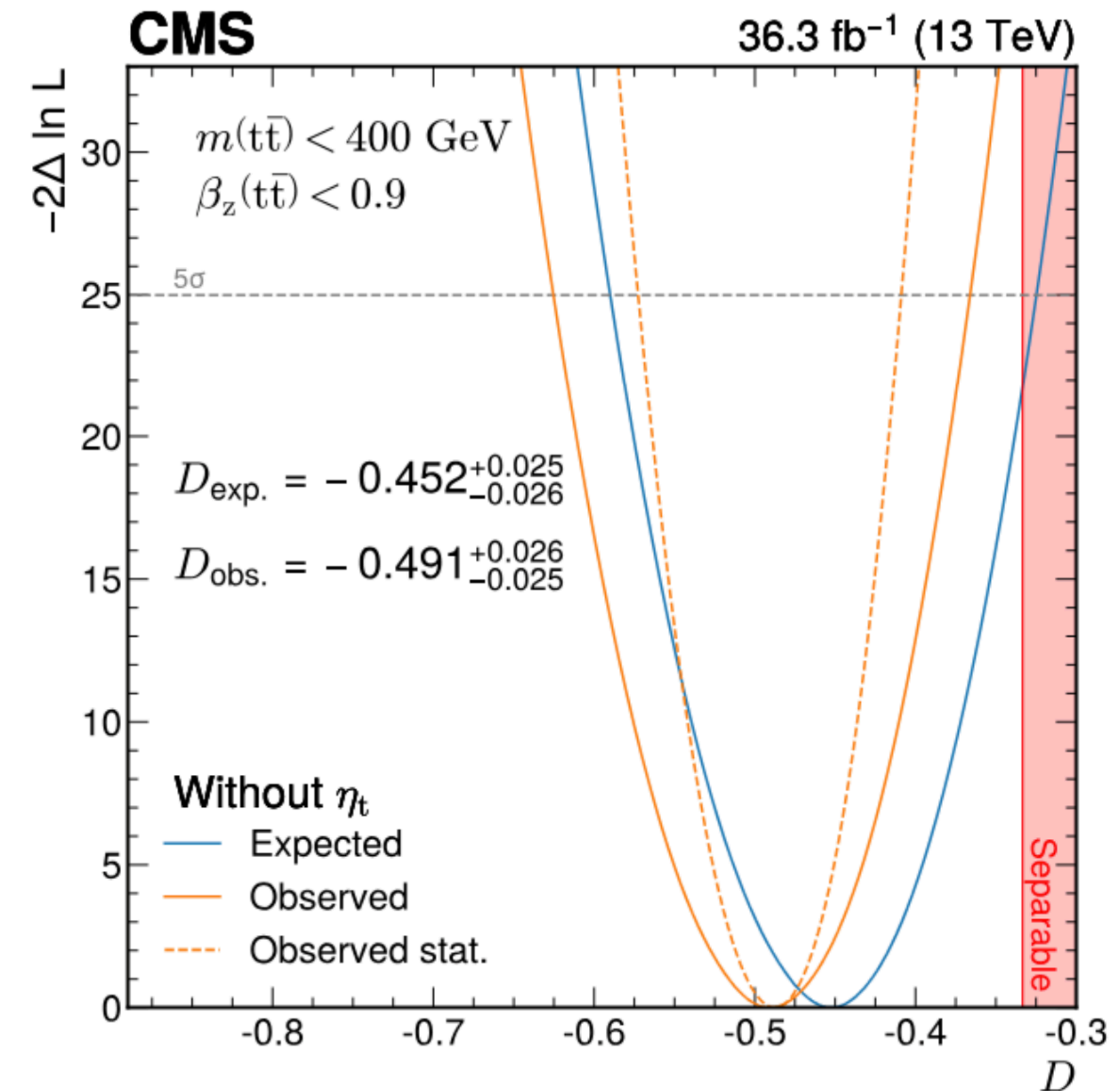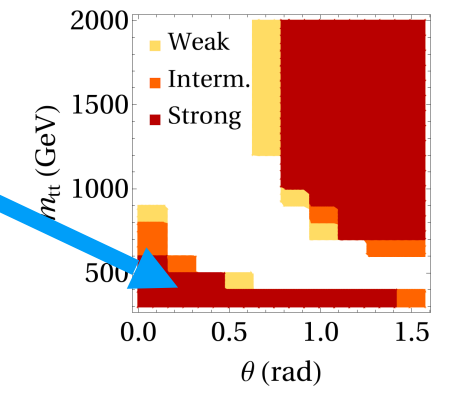
Entanglement observation by CMS

Bell inequalities violation

Severi et al. 2110.10112

Z. Dong et al. 2305.07075

High-p_T Selection	Cross section	Significance for > 2 w/ 3 ab^{-1}
Weak	0.58 pb	83% CL
Intermediate	0.31 pb	81% CL
Strong	0.17 pb	66% CL

Low statistics…

$\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$
$\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0;$

Indicator	Parton-level	Unfolded	Significance ($\mathcal{L} = 3$ ab^{-1})
$\mathcal{B}_1$	0.267 ± 0.023	0.274 ± 0.057	4.8
$\mathcal{B}_2$	0.204 ± 0.023	0.272 ± 0.058	4.7

Better statistics, use of boosted top tagging

Challenging!!

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First measurements
Semileptonic channel

Measurements going towards testing BIV (with many loopholes...)
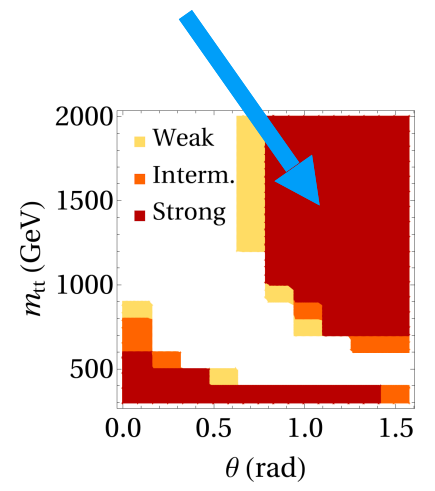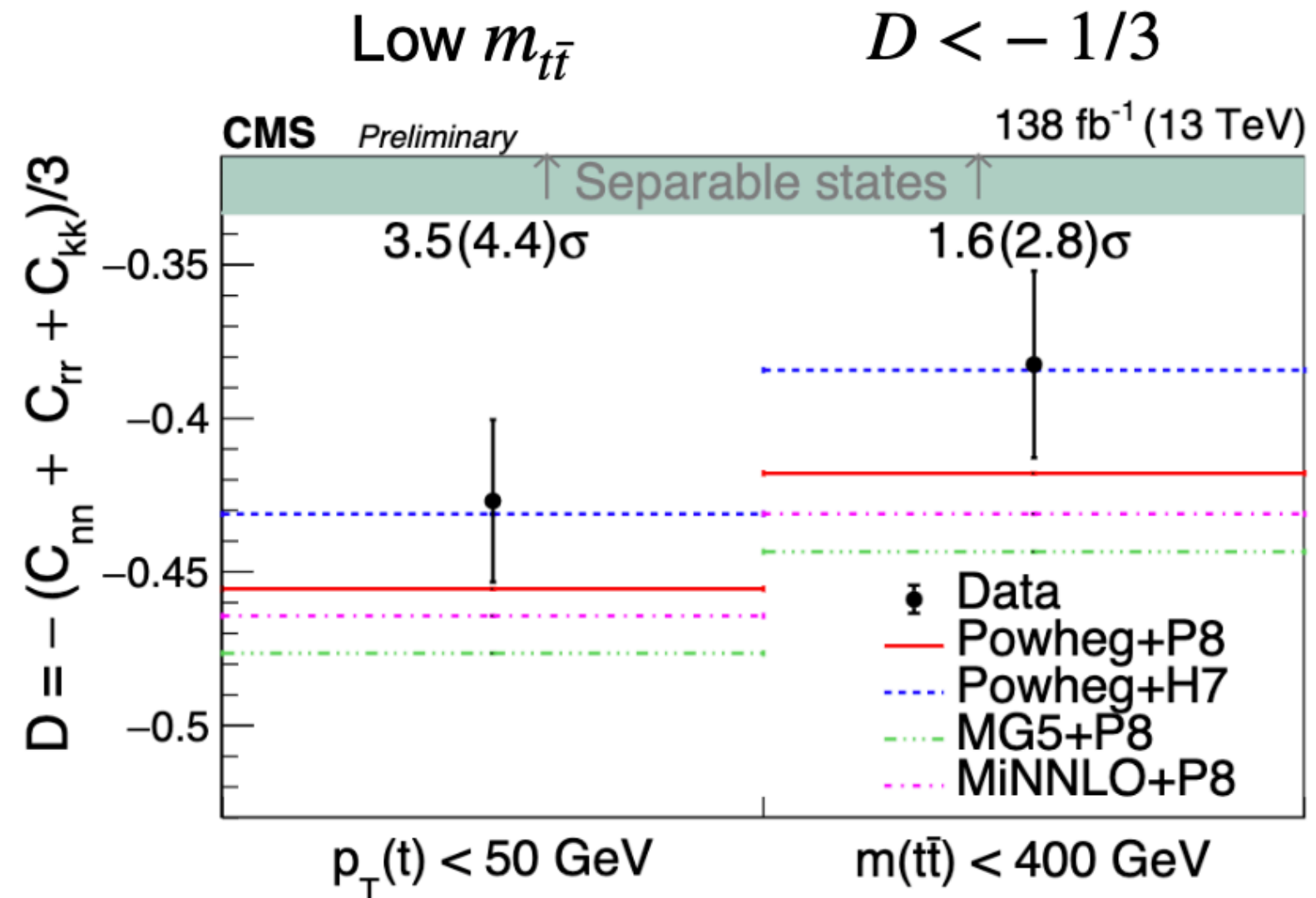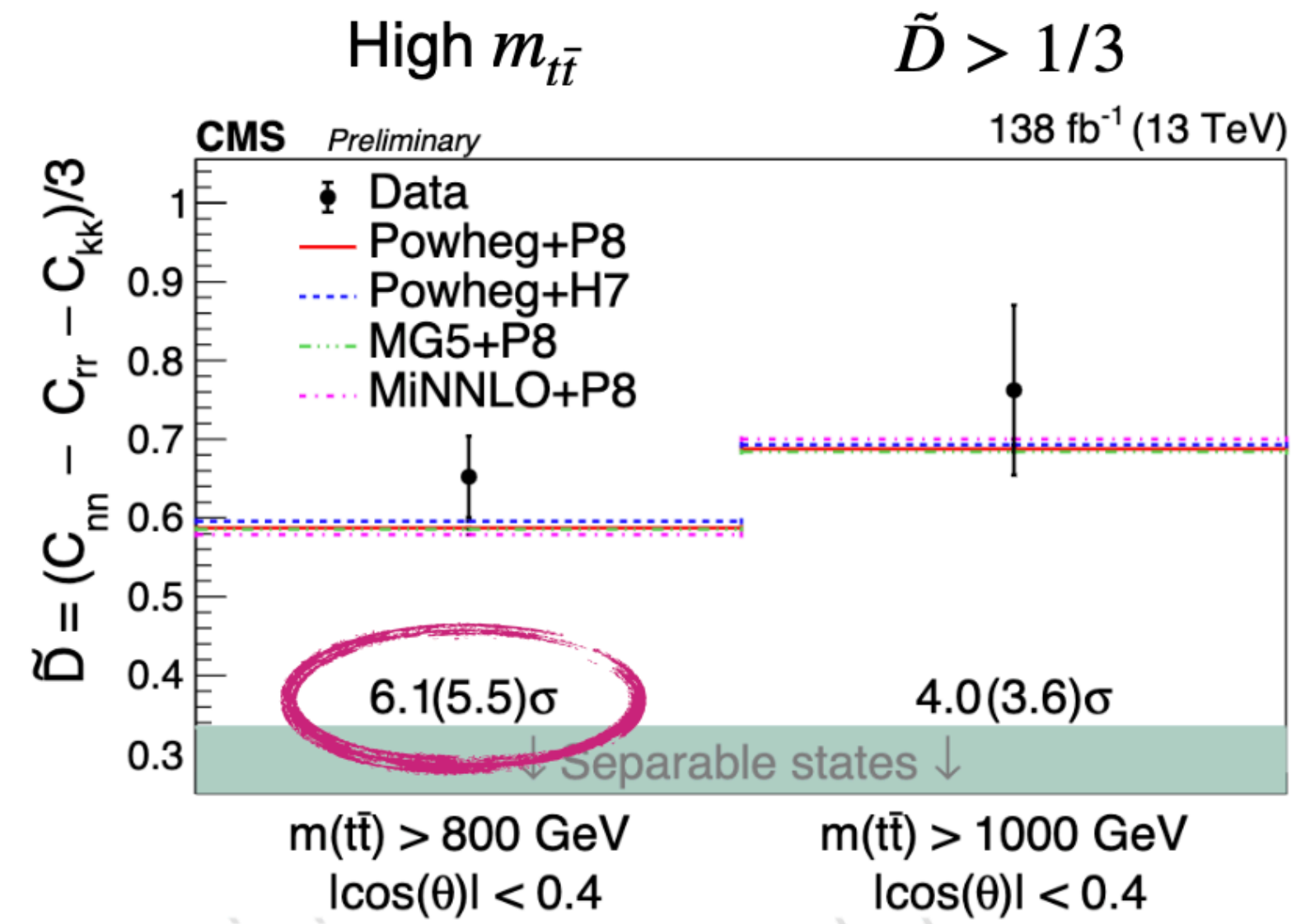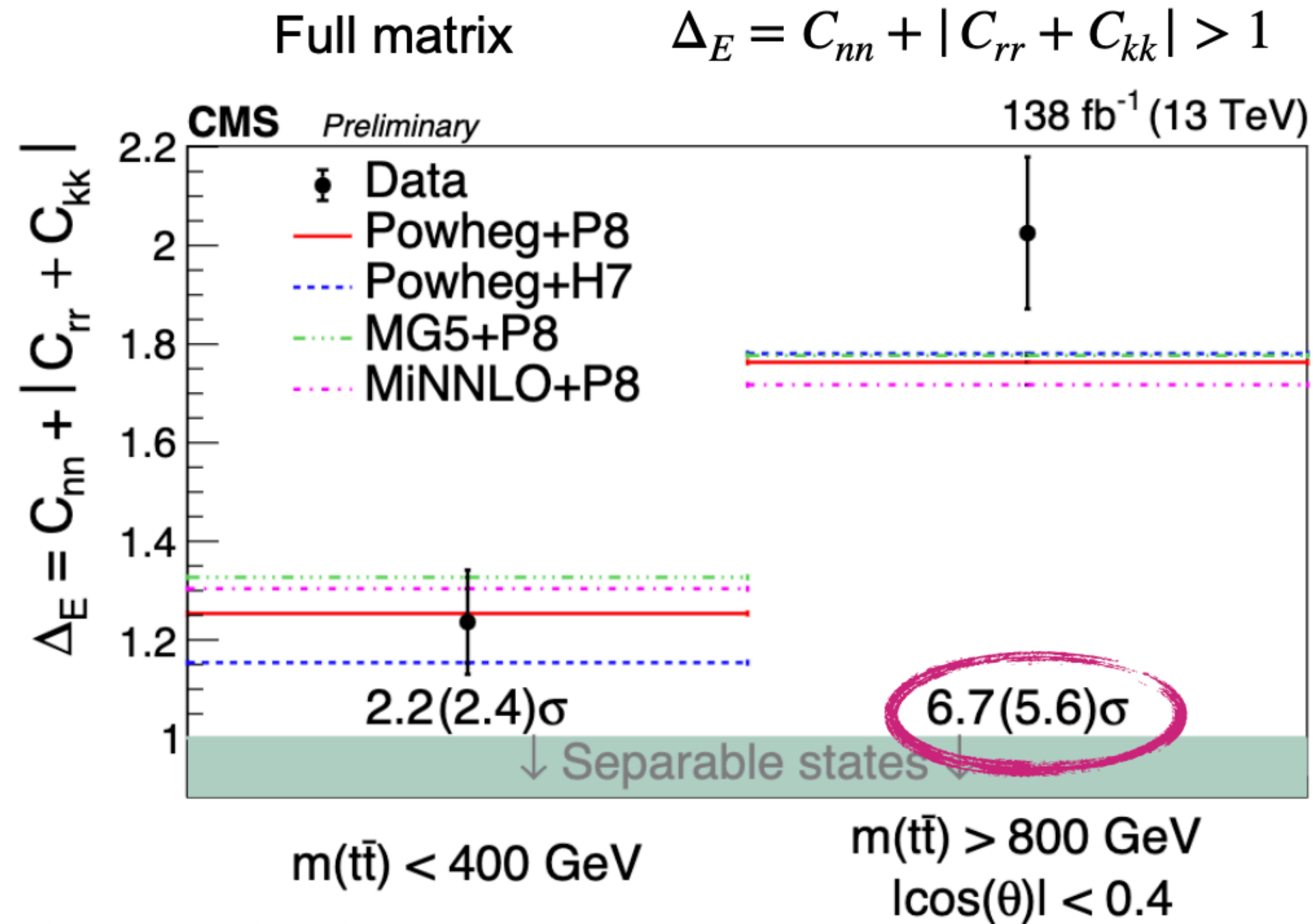
See Giulia Negro's seminar at CERN

Is there a *Quantum Advantage* in the search for New Physics?
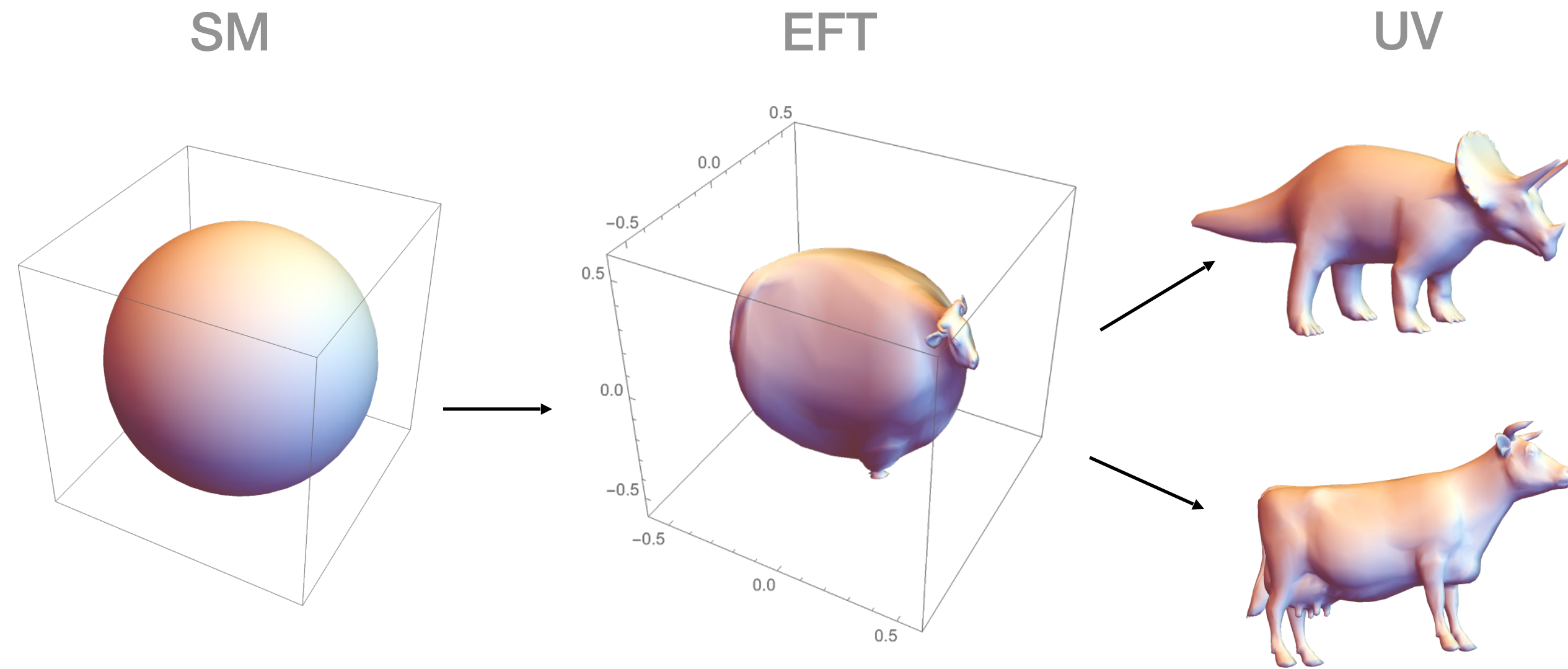
Two model-independent approaches:

1] BSM resides beyond the scales directly explored by the experiment
$\Rightarrow$ Effective Field Theory

2] BSM resonances can be directly produced
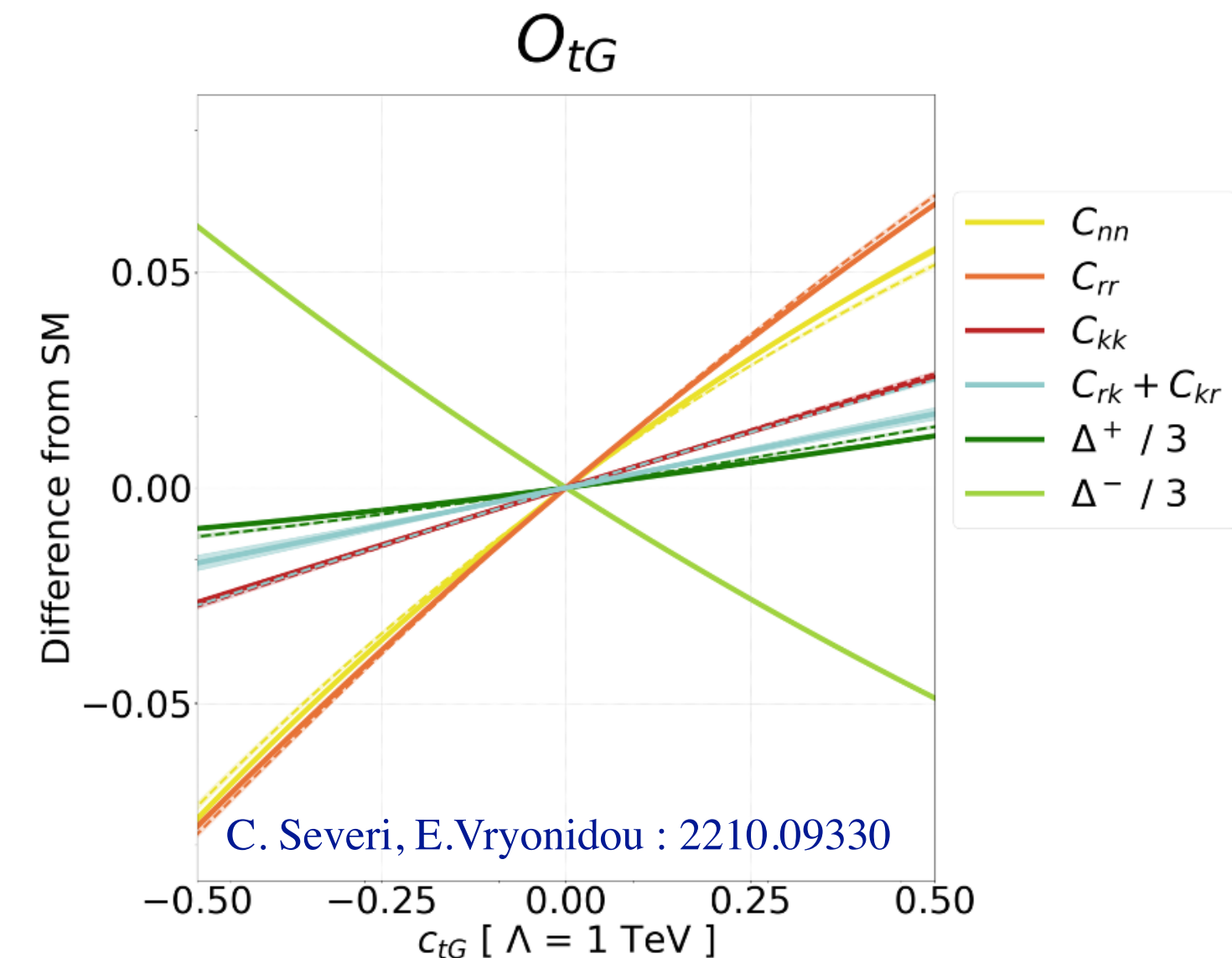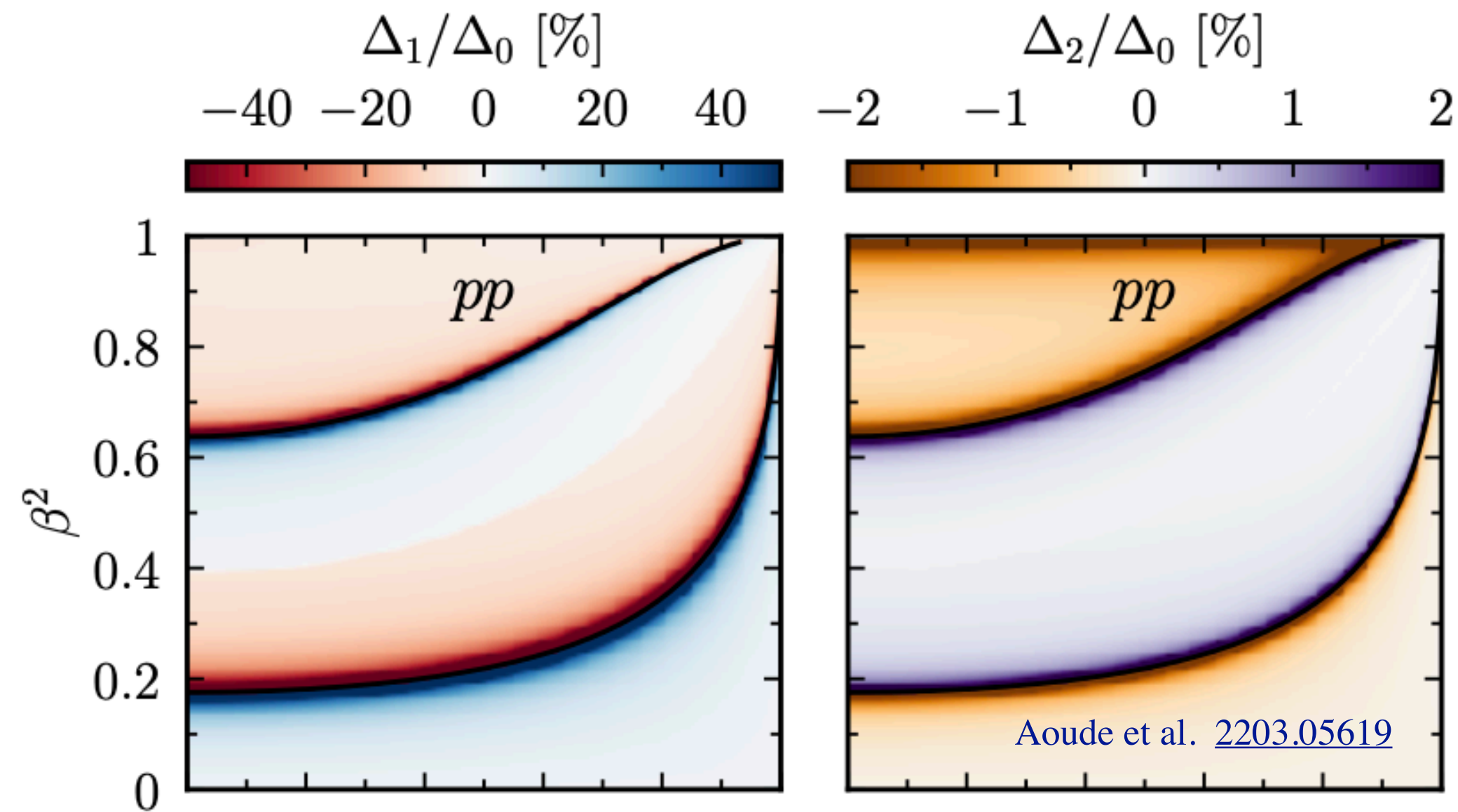$\Rightarrow$ Simplified models

SMEFT

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\slashed{D}\psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

SM   EFT   UV

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda^2}\sum_i^{N_6} c_i \mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_j^{N_8} c_j \mathcal{O}_i^{(8)} + \dots$$

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Quantum Advantage for SMEFT

Aoude et al. 2203.05619

C. Severi, E.Vryonidou : 2210.09330

- New interactions modify both conventional and quantum observables

- Dimension-6 operators can modify the degree of entanglement between top quarks

- SMEFT introduce new structures, thus probing new linear combinations between coefficients

- QI observables can break degeneracies between operators when combined with standard observables

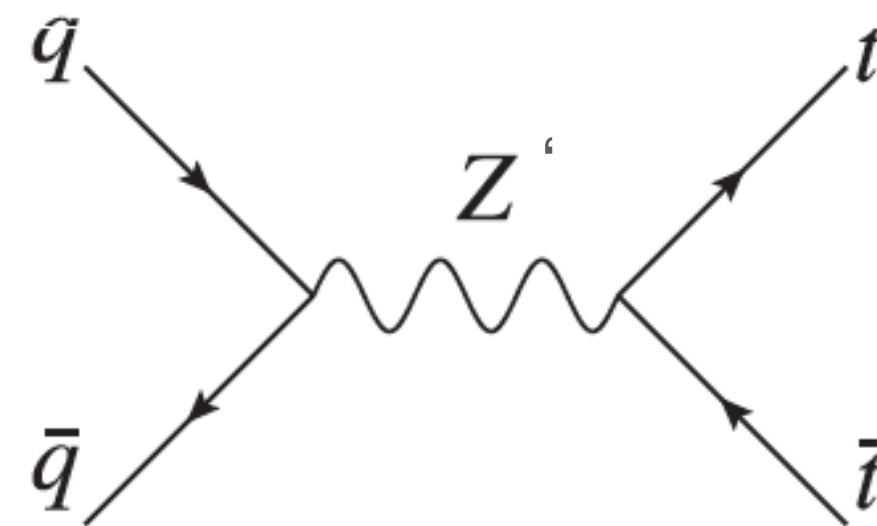## New sensitivity!

BSM resonances

Scalar
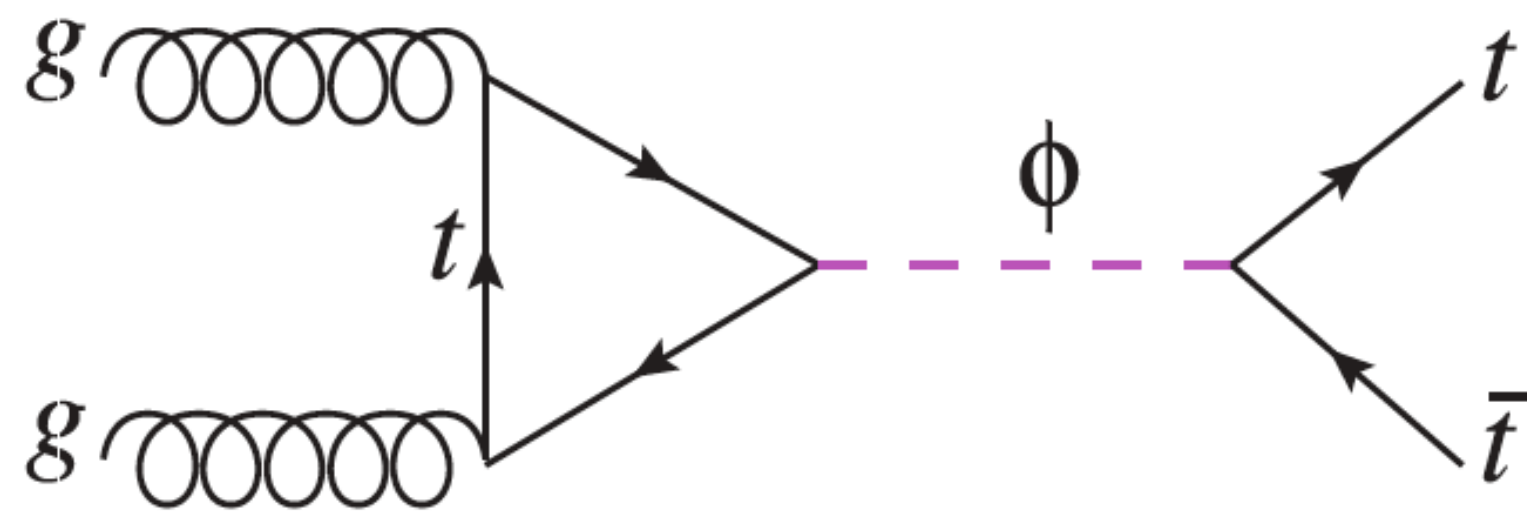
$$c_y \frac{y_t}{\sqrt{2}} \phi \, \bar{t} \left(\cos\alpha + i\gamma^5 \sin\alpha \right) t$$

$$\mathcal{C}^{[gg,\phi]}\big|_{\alpha=\pi/2} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\mathcal{C}^{[gg,\phi]}\big|_{\alpha=0} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$
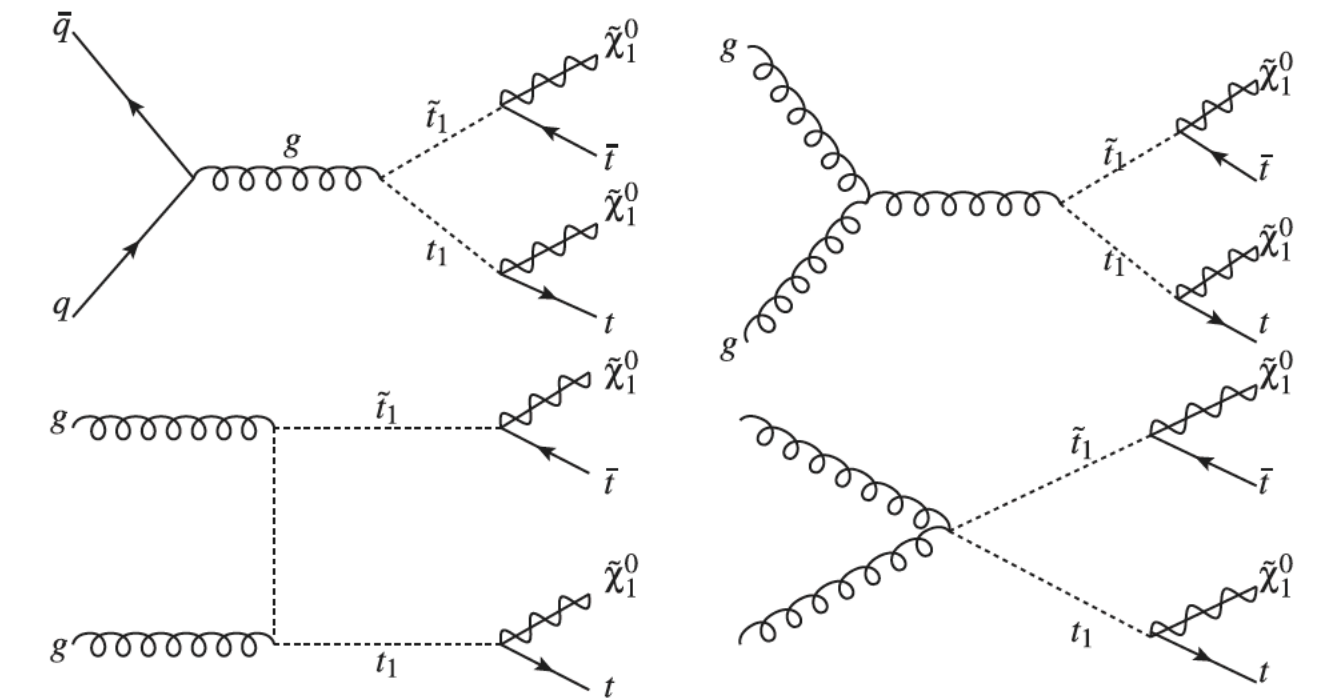
Z'

Sequential Z'
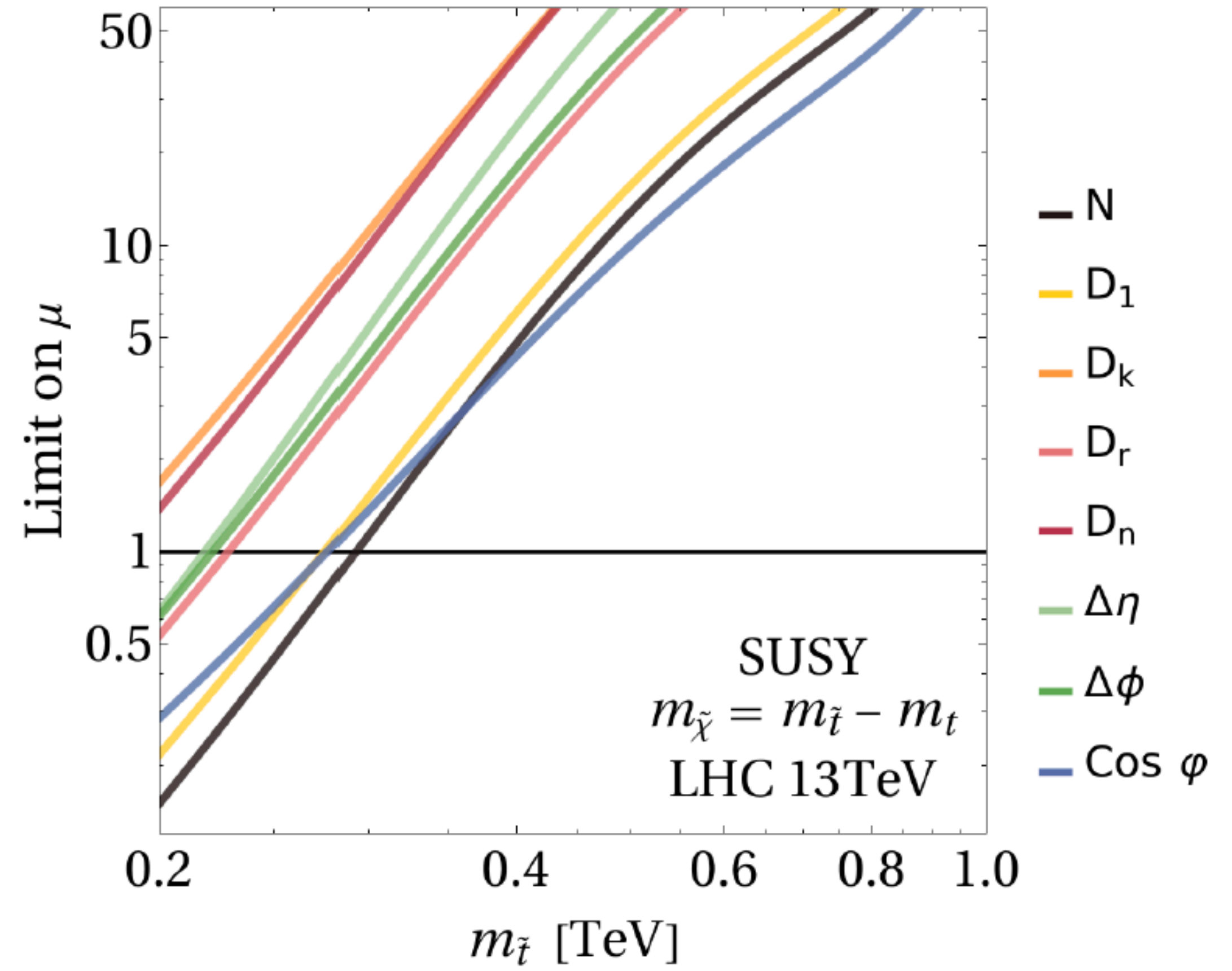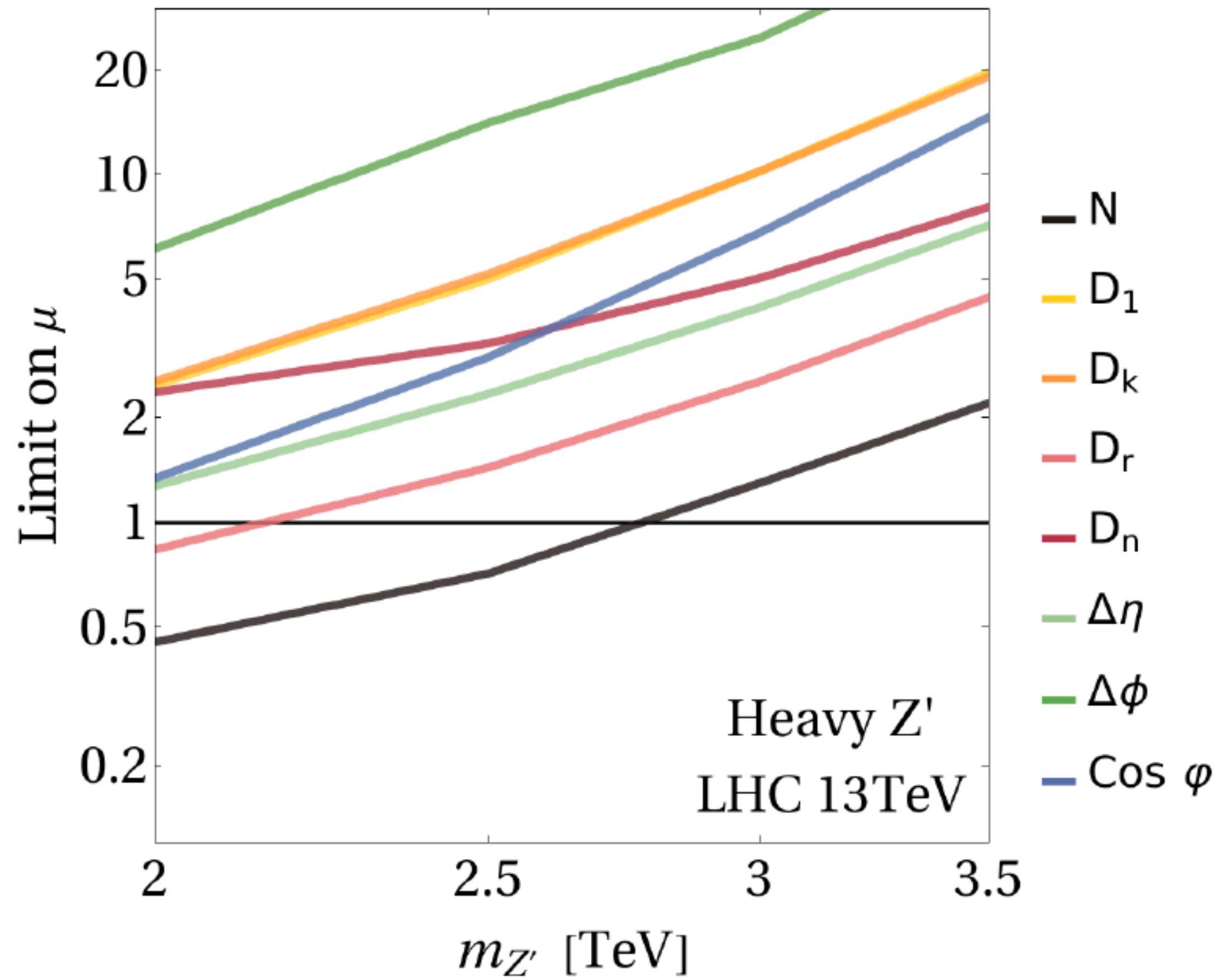
It interferes with SM EW top production.

Stops

$$|m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t| \approx \Gamma_t,$$

$$\mathcal{C}^{[\mathrm{SUSY}]} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

$$B_i = \frac{A^{[\mathrm{SM}]}}{A^{[\mathrm{TOT}]}} B_i^{[\mathrm{SM}]} + \frac{A^{[\mathrm{SUSY}]}}{A^{[\mathrm{TOT}]}} B_i^{[\mathrm{SUSY}]} \simeq \frac{A^{[\mathrm{SUSY}]}}{A^{[\mathrm{TOT}]}} B_i^{[\mathrm{SUSY}]},$$

$$\mathcal{C} = \frac{A^{[\mathrm{SM}]}}{A^{[\mathrm{TOT}]}} \mathcal{C}^{[\mathrm{SM}]} + \frac{A^{[\mathrm{SUSY}]}}{A^{[\mathrm{TOT}]}} \mathcal{C}^{[\mathrm{SUSY}]} = \frac{A^{[\mathrm{SM}]}}{A^{[\mathrm{TOT}]}} \mathcal{C}^{[\mathrm{SM}]},$$

Quantum Advantage for BSM resonances

Not adding much…

Quantum Advantage for BSM resonances

Pseudoscalar
LHC 13TeV

Scalar
LHC 13TeV
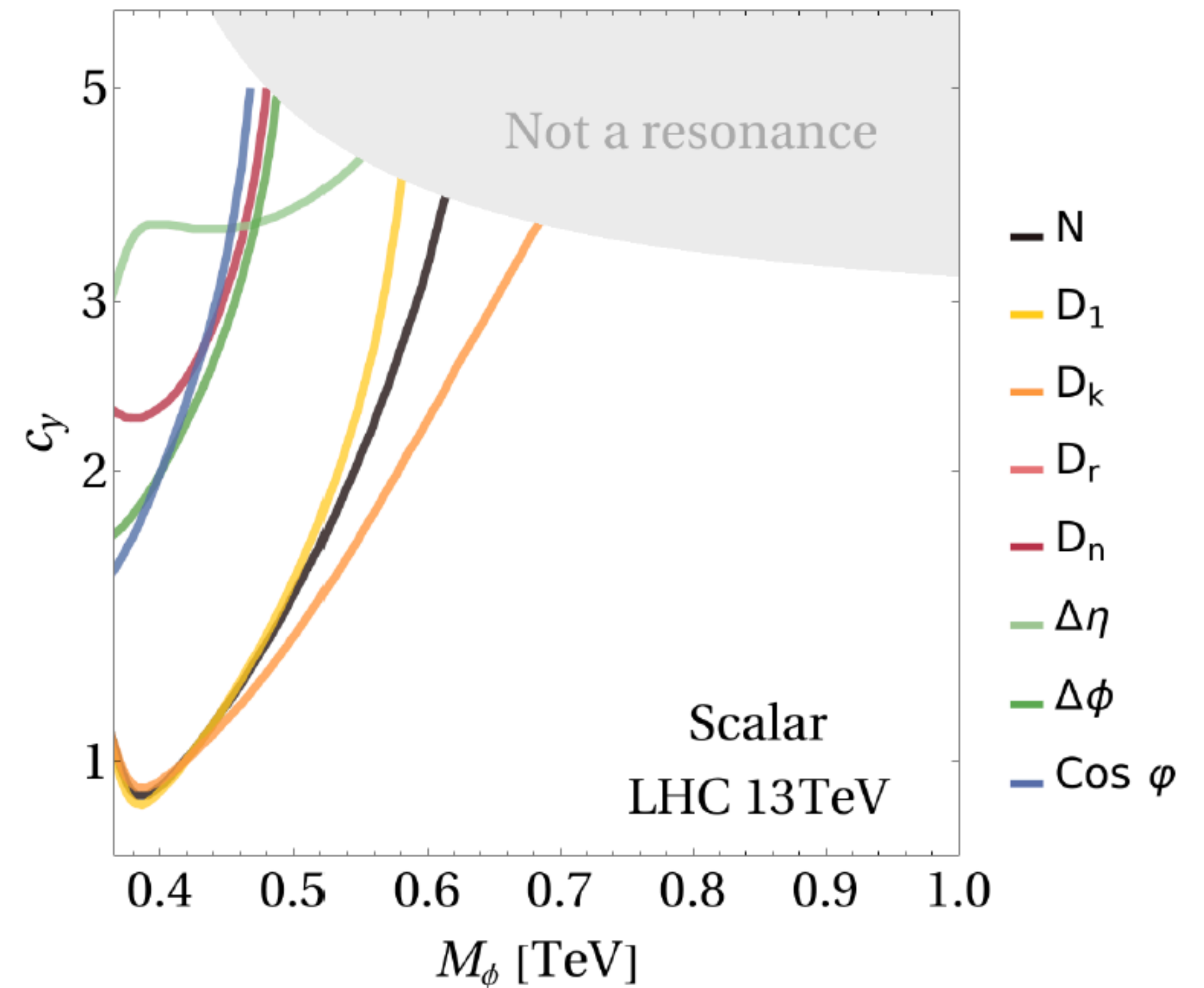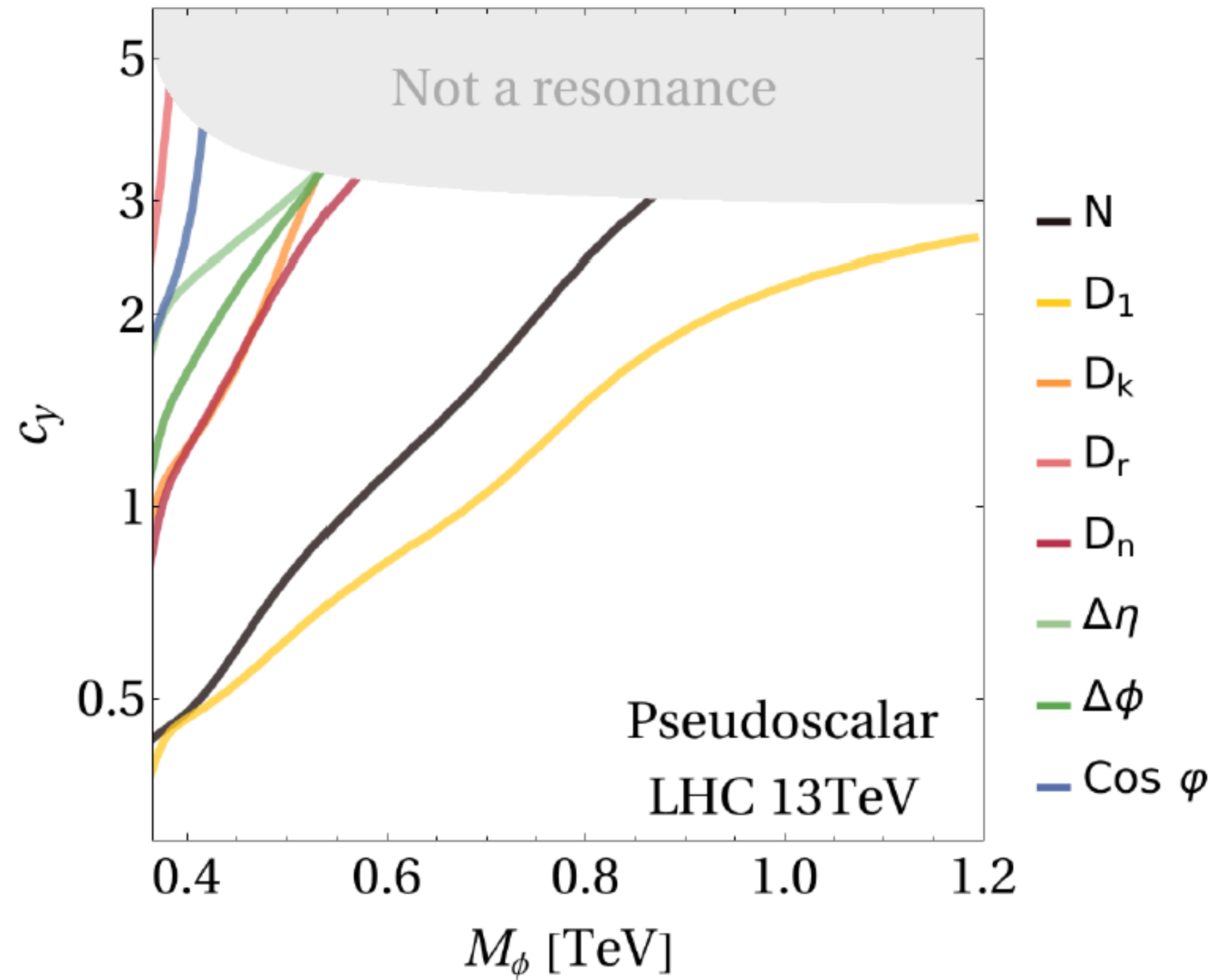
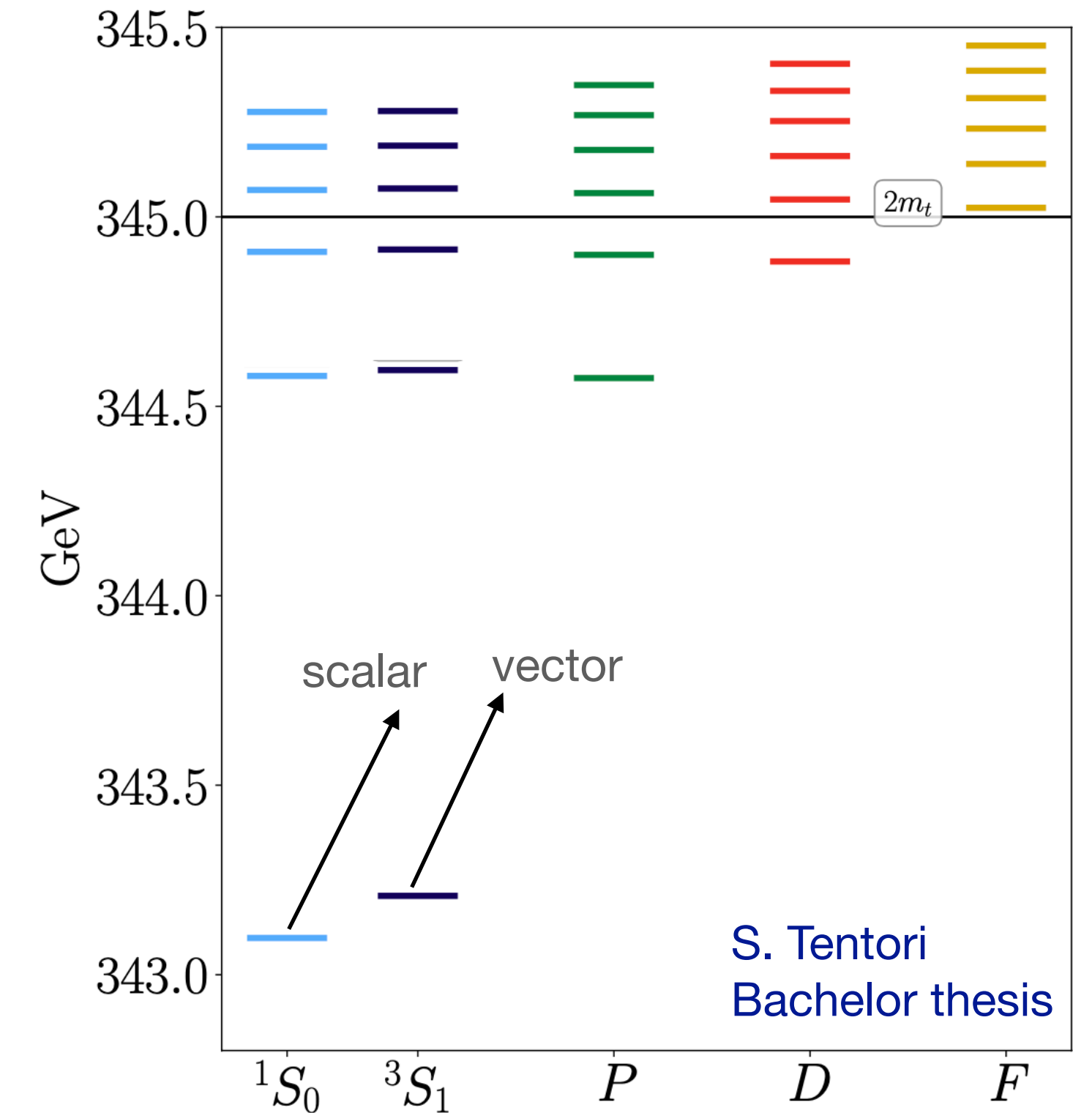Promising!

First measurements
Dilepton channel at threshold
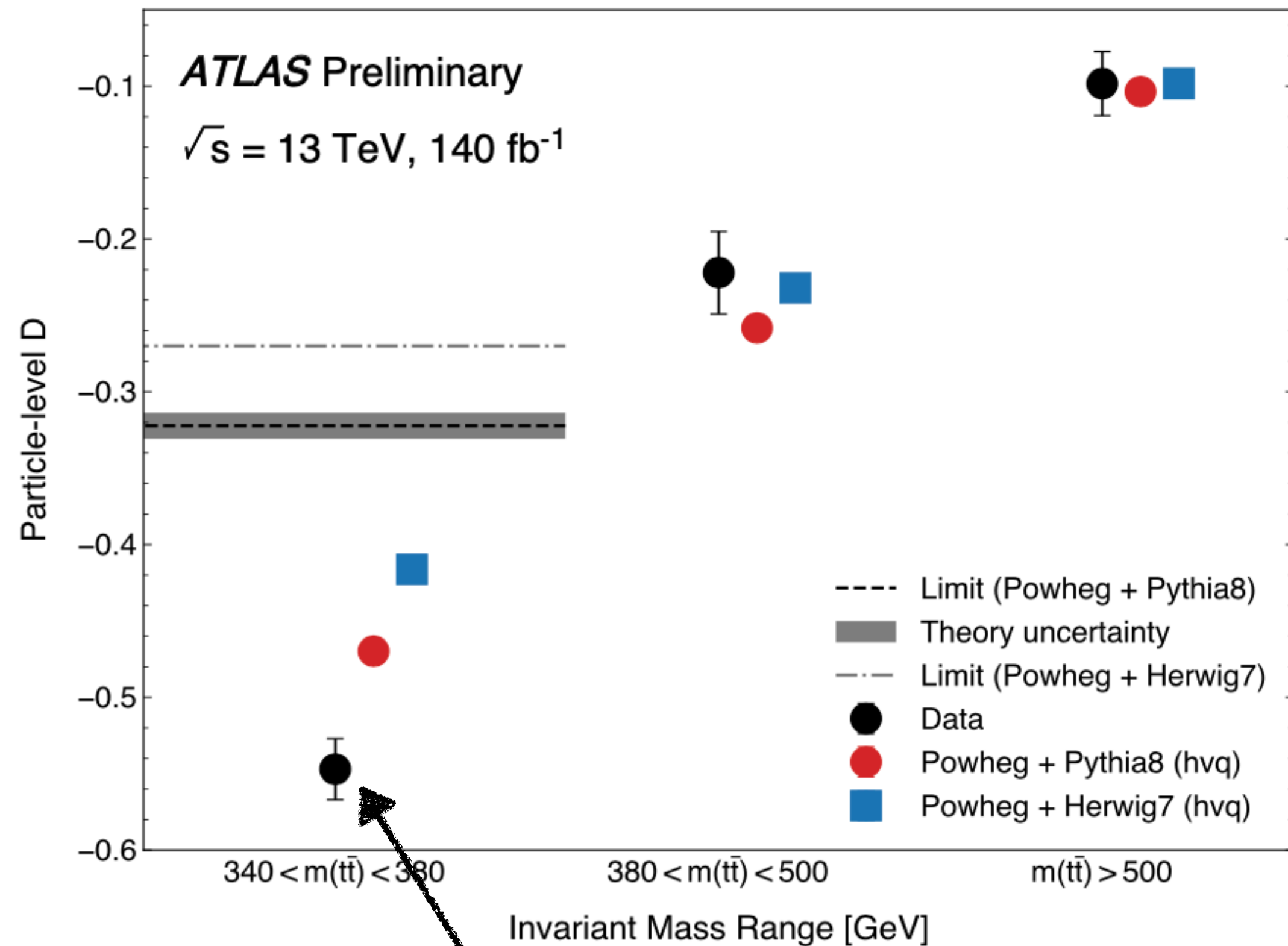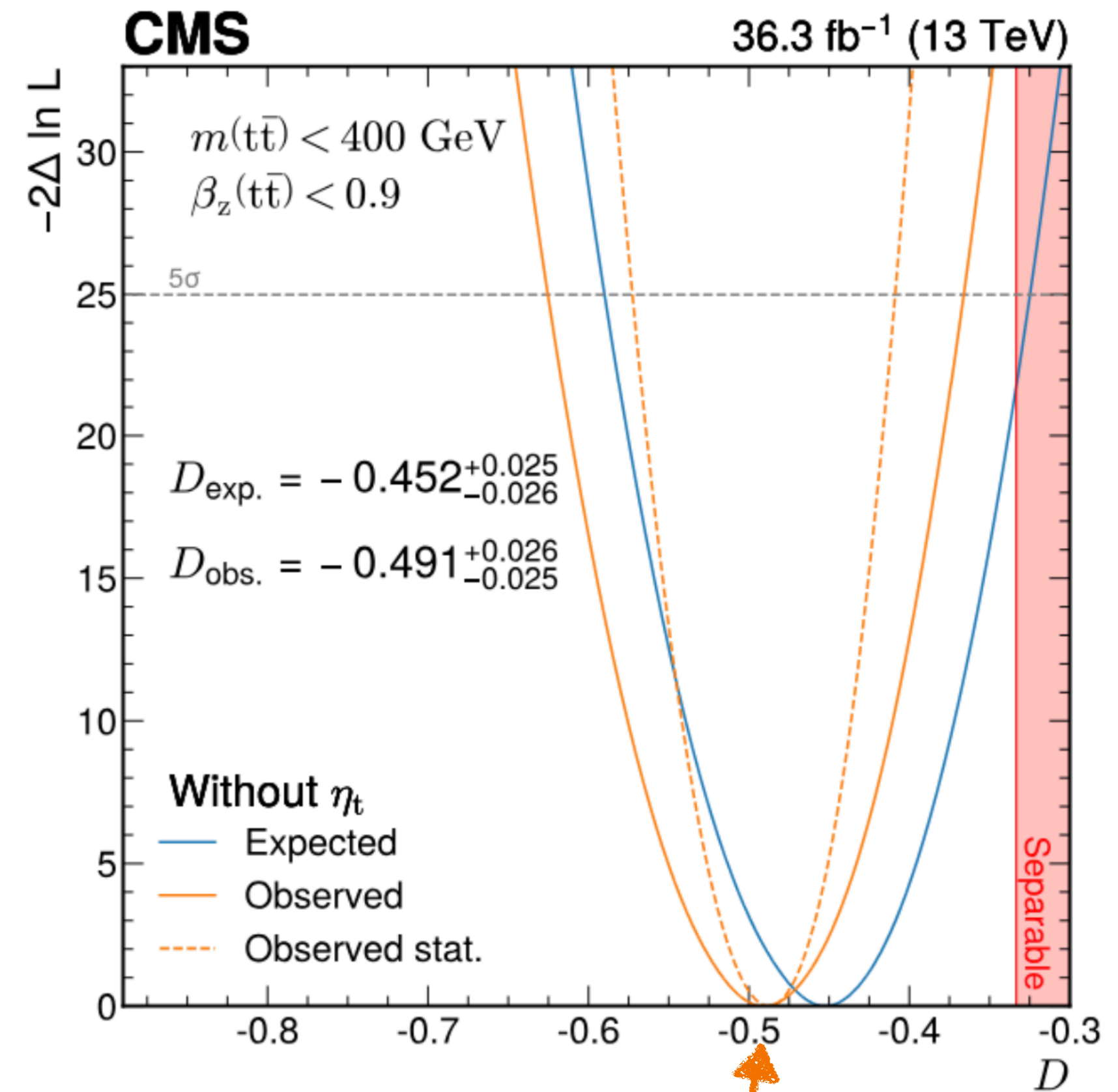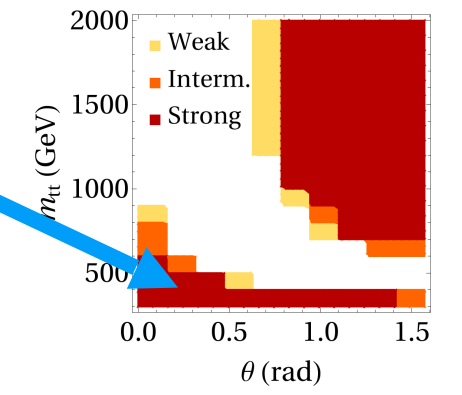
More entanglement than predicted by NLO+PS QCD!
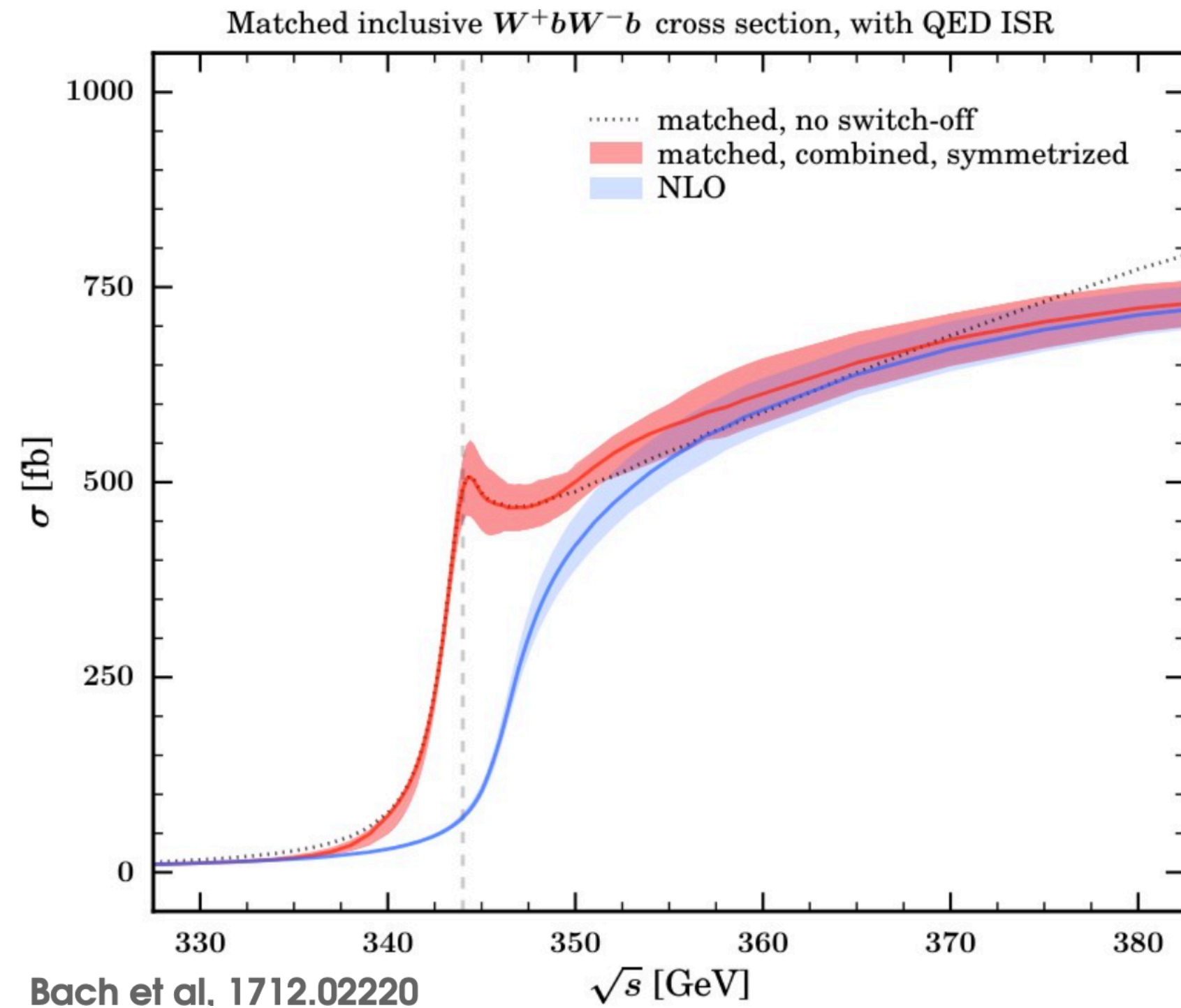
New SM Physics: Toponium

- Quasi-Bound State of top and antitop

- Energy states obtained by solving Schrödinger equation with QCD potential

- Described by NRQCD

- Ground state n=1 S-wave

- Spin-singlet vs spin-triplet depending on production mode

  - spin singlet for pp and spin triplet for e^+e^-

scalar   vector

S. Tentori
Bachelor thesis

$$\left[(E + i\Gamma_t) - \left(\frac{\boldsymbol{\nabla}^2}{m_t} + V(\boldsymbol{r}) \right) \right] G(\boldsymbol{r}, E + i\Gamma_t) = \delta^{(3)}(\boldsymbol{r})$$

$$V_{\text{QCD}}(r, \mu_B) = C^{[\text{col}]} \frac{\alpha_s(\mu_B)}{r} \left[1 + \frac{\alpha_s}{4\pi} \left(2\beta_0 \log(e^\gamma \mu_B r) + \frac{31}{9}C_A - \frac{10}{9}n_f \right) + \mathcal{O}(\alpha_s^2) \right]$$

New SM Physics: Toponium

e^+e^- predictions

Bach et al. 1712.02220

LHC predictions

Kiyo, Kühn, Steinhauser, Moch, Uwer arXiv: 0812.0919

Ju, Wang, Wang, Xu, Xu and Li Lin Yang arXiv:2004.03088

Fully differential NLO+LL, Coulomb Resummation
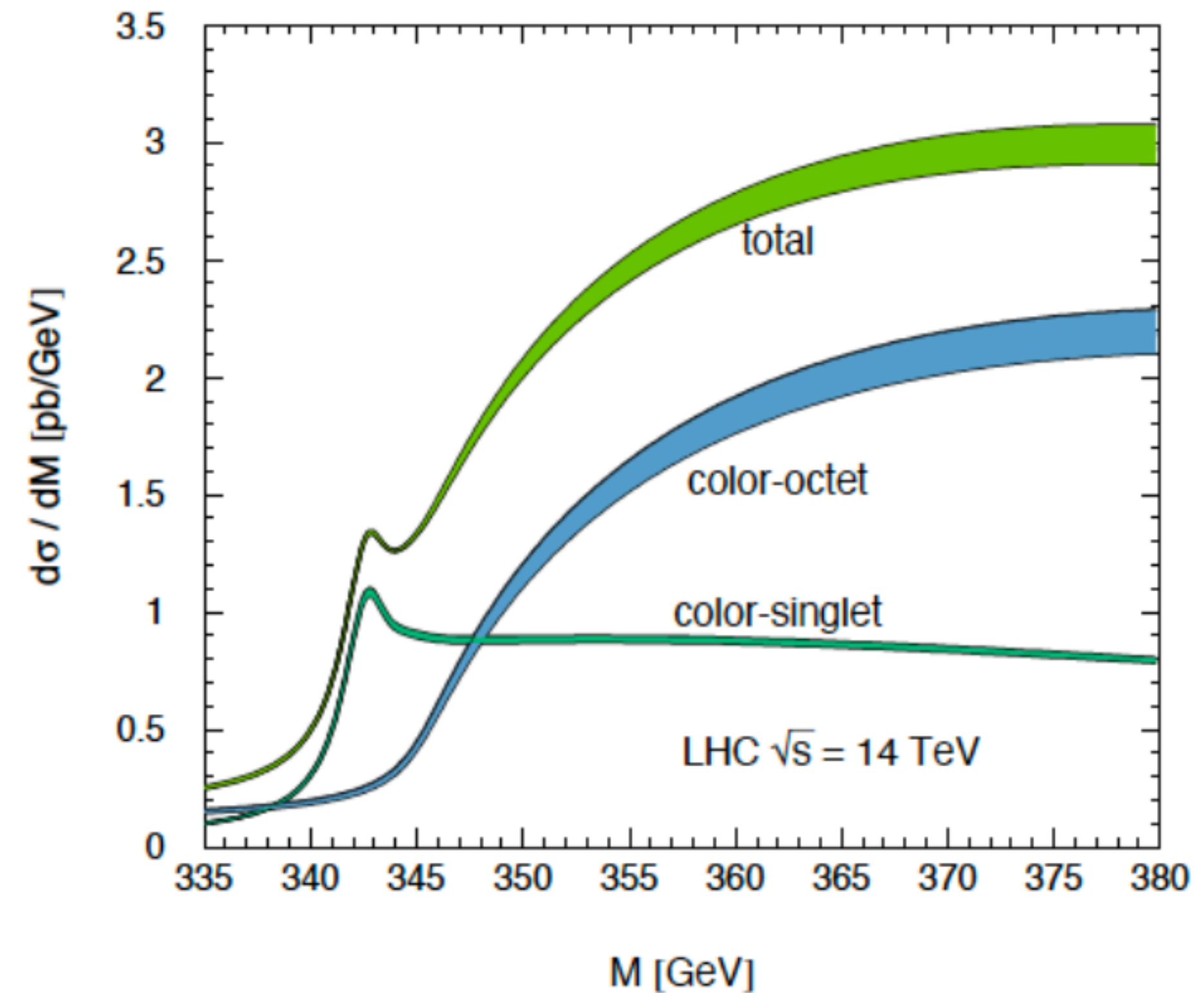
Coulomb Resummation

Needs matching between below threshold, toponium region, continuum

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Toponium modelling

We can approximate the impact in the Monte Carlo by introducing a toy model with a resonance

- vector resonance for lepton collisions
- psedoscalar resonance for proton collisions

$$m_\psi = m_\eta \simeq 2m_t - 2\,\mathrm{GeV}, \quad \text{and} \quad \Gamma_\psi = \Gamma_\eta \simeq 2\,\Gamma_t$$

Peak of resonance fitted to match the results obtained by the resummed computation

UCLouvain **fnrs** LA LIBERTÉ DE CHERCHER   Particle Physics and the quantum — Fabio Maltoni — Invisibles - Bologna 5 July 2024   INFN Istituto Nazionale di Fisica Nucleare
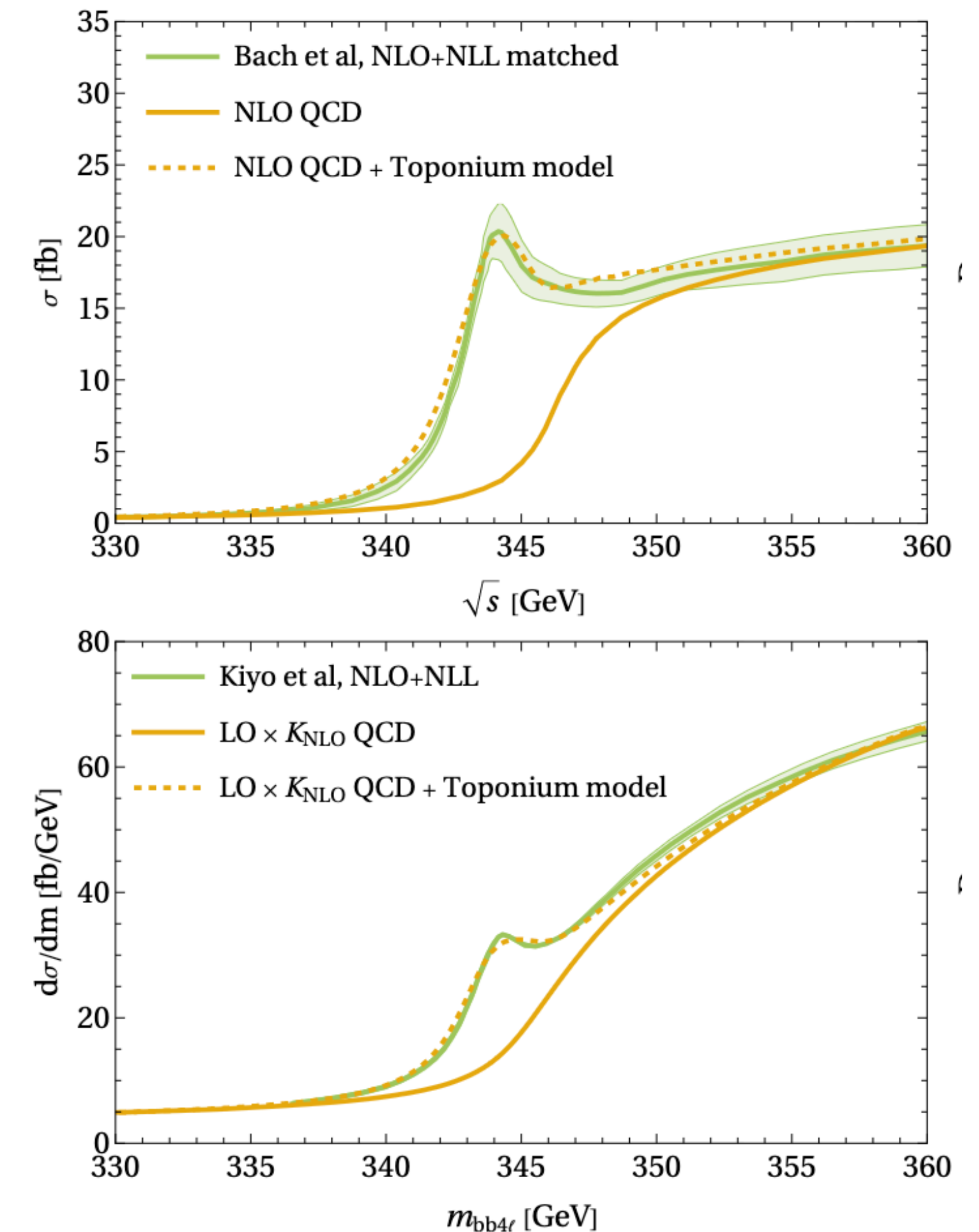
45

Toponium modelling

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$$m_\psi = m_\eta \simeq 2m_t - 2\,\text{GeV}, \quad \text{and} \quad \Gamma_\psi = \Gamma_\eta \simeq 2\,\Gamma_t$$
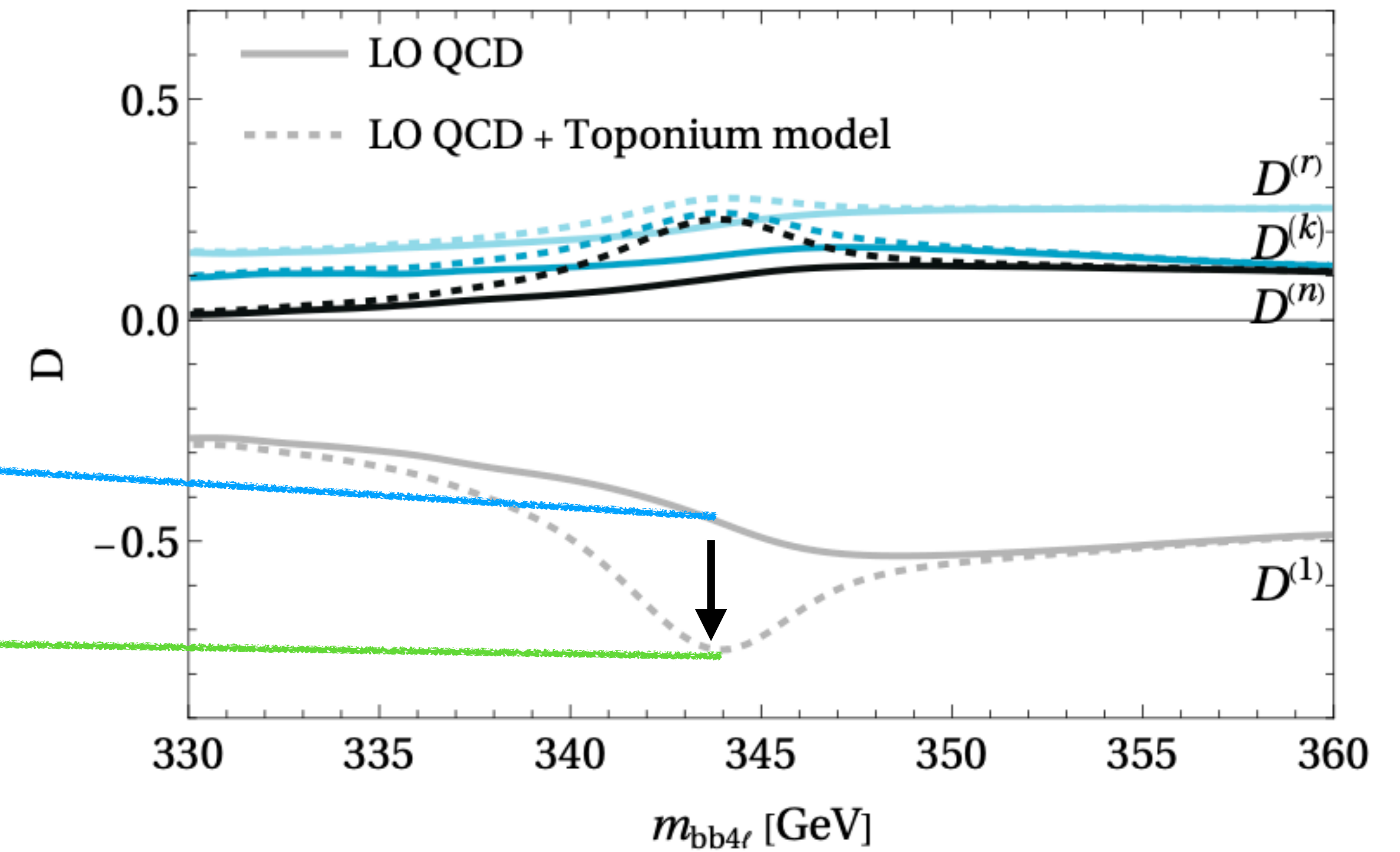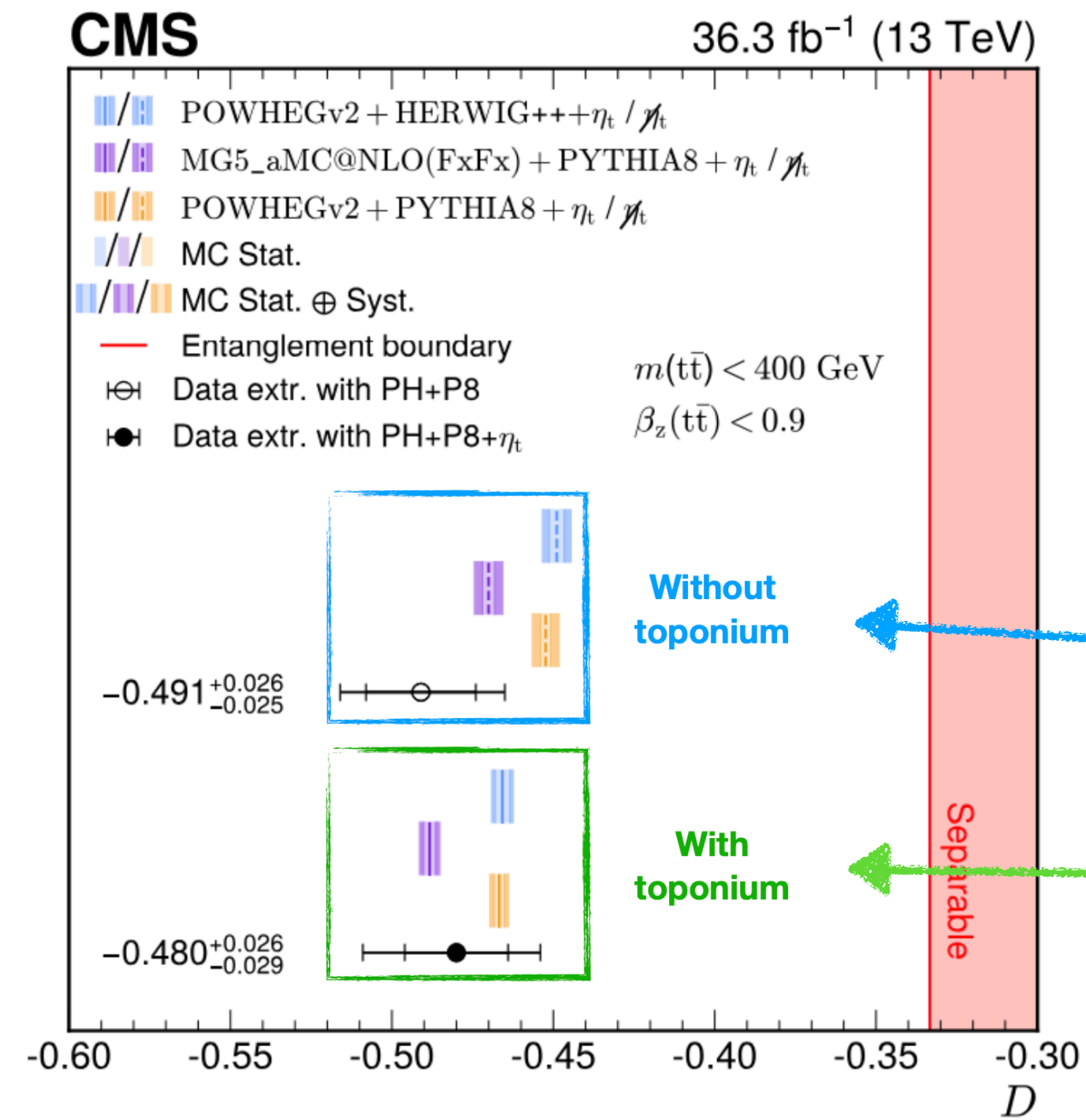
Peak of resonance fitted to match the results
obtained by the resummed computation

Significant impact on entanglement markers, hence
improvement of measurement agreement with theory
Pseudoscalar resonance leads to different spin
correlations compared to QCD
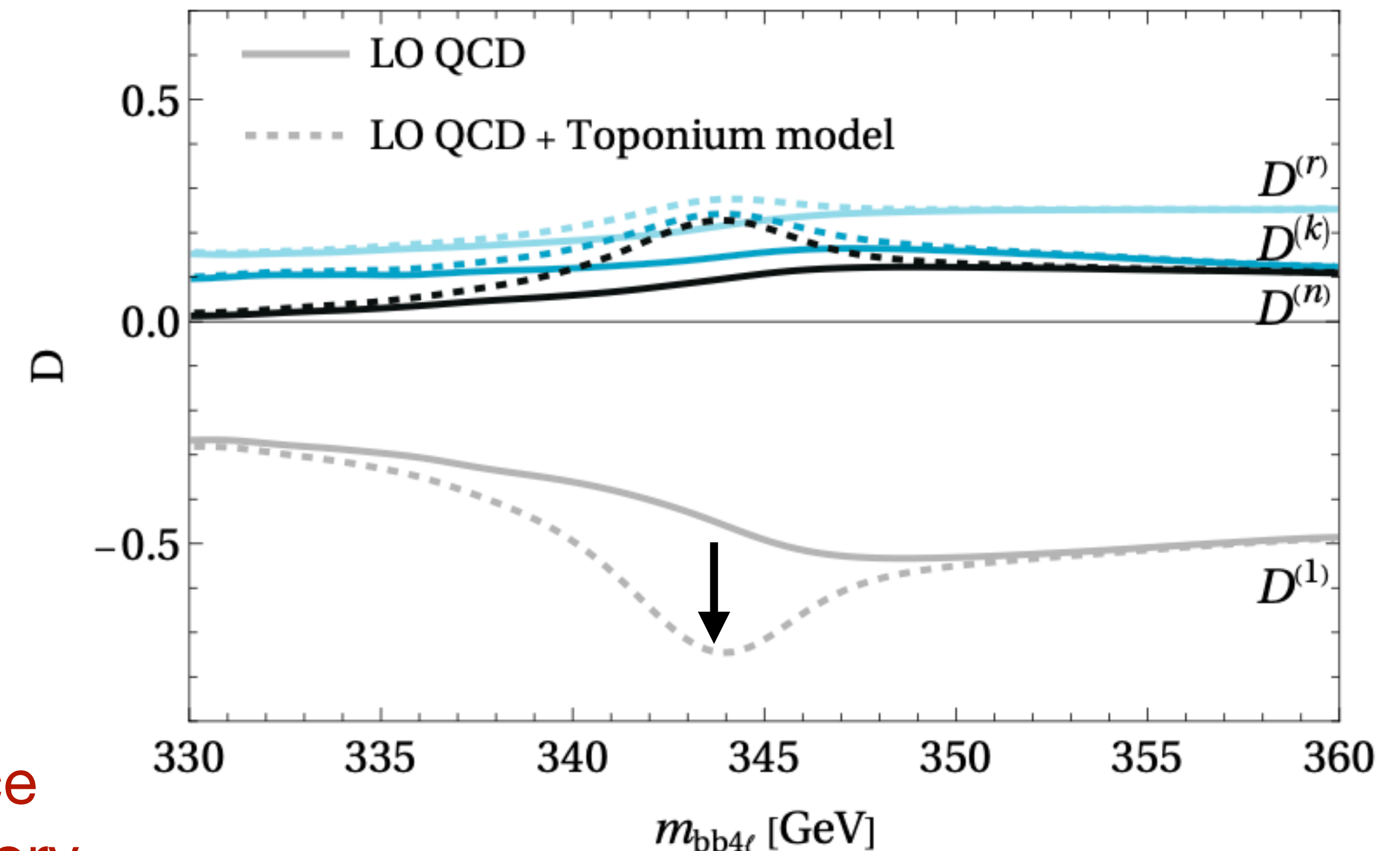
First measurements

Tantalising indication of New (SM) Physics!

Conclusions

❖ Quantum information and computing is hyped up. It promises a quantum advantage that, while not yet proven, could bring to transformative applications.

❖ The current status builds upon a number of theoretical and experimental advances in the last 30 years that have changed the way we think about quantum mechanics.

❖ Our current description of fundamental interactions, based on QFT, has QM at its core. Theoretically, it is embedded in our formalism so deeply that (sometimes) we do not even notice. Experimentally, however, most of our measurements are not correlations, but just counting experiments.

❖ A novel interest in looking at fundamental interactions at TeV scale with QI glasses has started since two/three years ago and has quickly lead to a variety of studies and interesting results, …
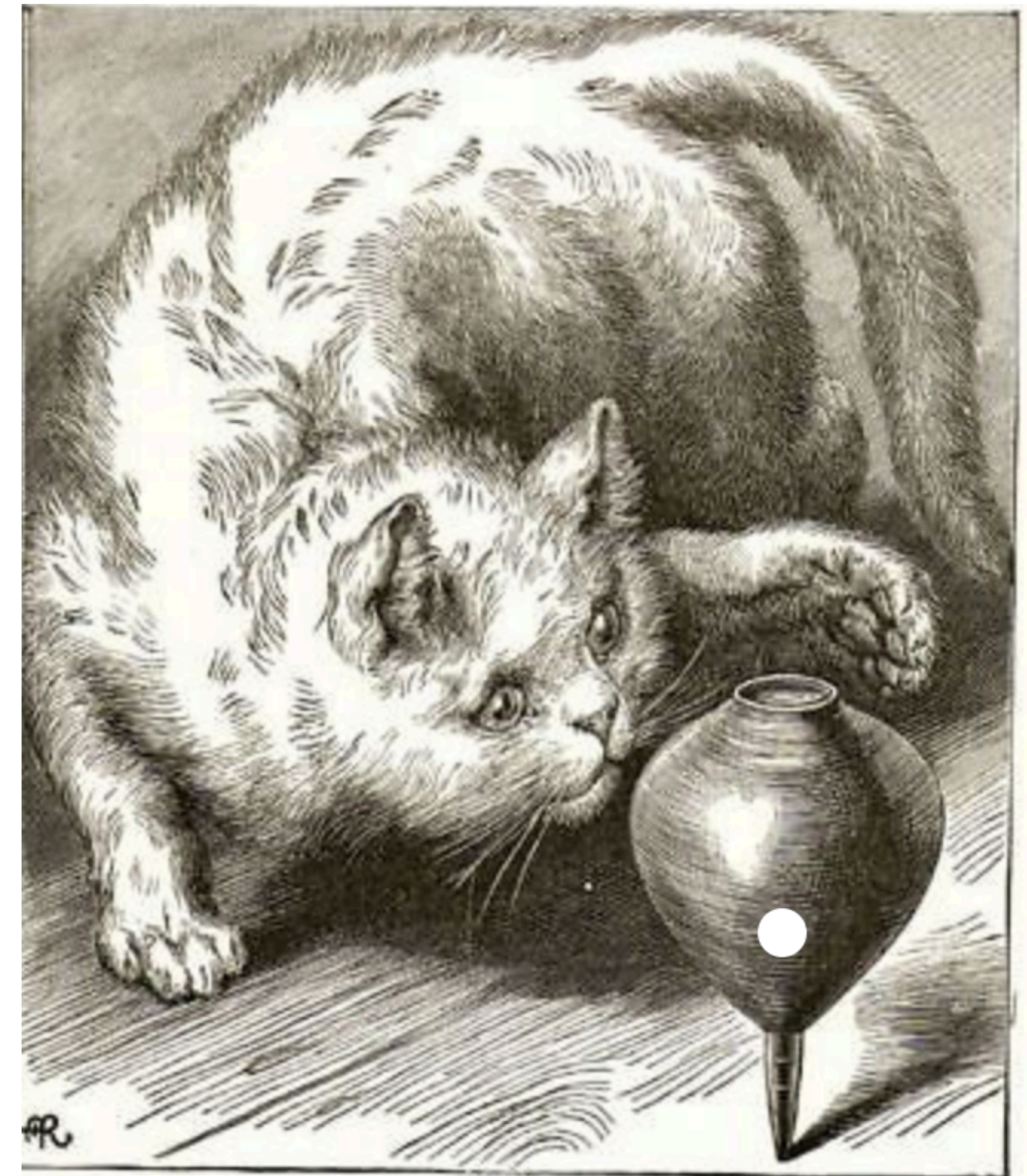
And all collaborators on QI:

Claudio Severi, Christian Degli Esposti Boschi, Max Sioli, Federica Fabbri, Rafael Aoude, Eric Madge, Luca Mantani, Eleni Vryodinou, Simone Tentori, Kentarou Mawatari, Kazuki Sakurai, Priyanka Lamba, Mohammad Altakach.

®Rafael Aoude

…raising new ideas and questions every day !

❖ Is there a relation between symmetries and entanglement? 1812.03138, 2210.12085
❖ What is the best frame for making quantum measurements? 2311.09166
❖ How is decoherence happening for collider final states?
❖ When is the actual measurement of spin really happening? 2401.06854
❖ Is there an optimal way to do quantum tomography? 2311.09166
❖ Is there a general approach to quantum measurements at colliders? 2201.03159
❖ Are there quantities in colliders that can be entangled beyond spin and flavour? Color?
❖ Is the information entropy a useful quantity in collider physics?
❖ Are SM interactions minimal in with respect to alternative theories? 2307.08112
❖ Can multi-partite systems be studied at colliders? 2310.01477
❖ Is entanglement conserved/augmented/lost in SM interactions? 1703.02989, 2209.01405
❖ Is there a relation between scattering in QFT and computing in IS? 2312.02242, 2310.10838
❖ Can entanglement be used to do model building? 2307.08112
❖ What is the analogue of purification at collider processes?
❖ Can we test Bell-inequalities on an event by event basis?
❖ What is the analogue of distillation? 2401.06854
❖ What is the most general constraint on non-locality from scattering processes? 2401.01162
❖ Entanglement in neutrino oscillations? Many papers, see 2305.06095
❖ Entanglement and Bell in B0/B0-mixing? Several papers, see 2106.07399
❖ How should we think about virtual particles? 2211.05782
❖ Maximal or minimal entanglement as a guiding principle? 1703.02989 vs 2307.08112
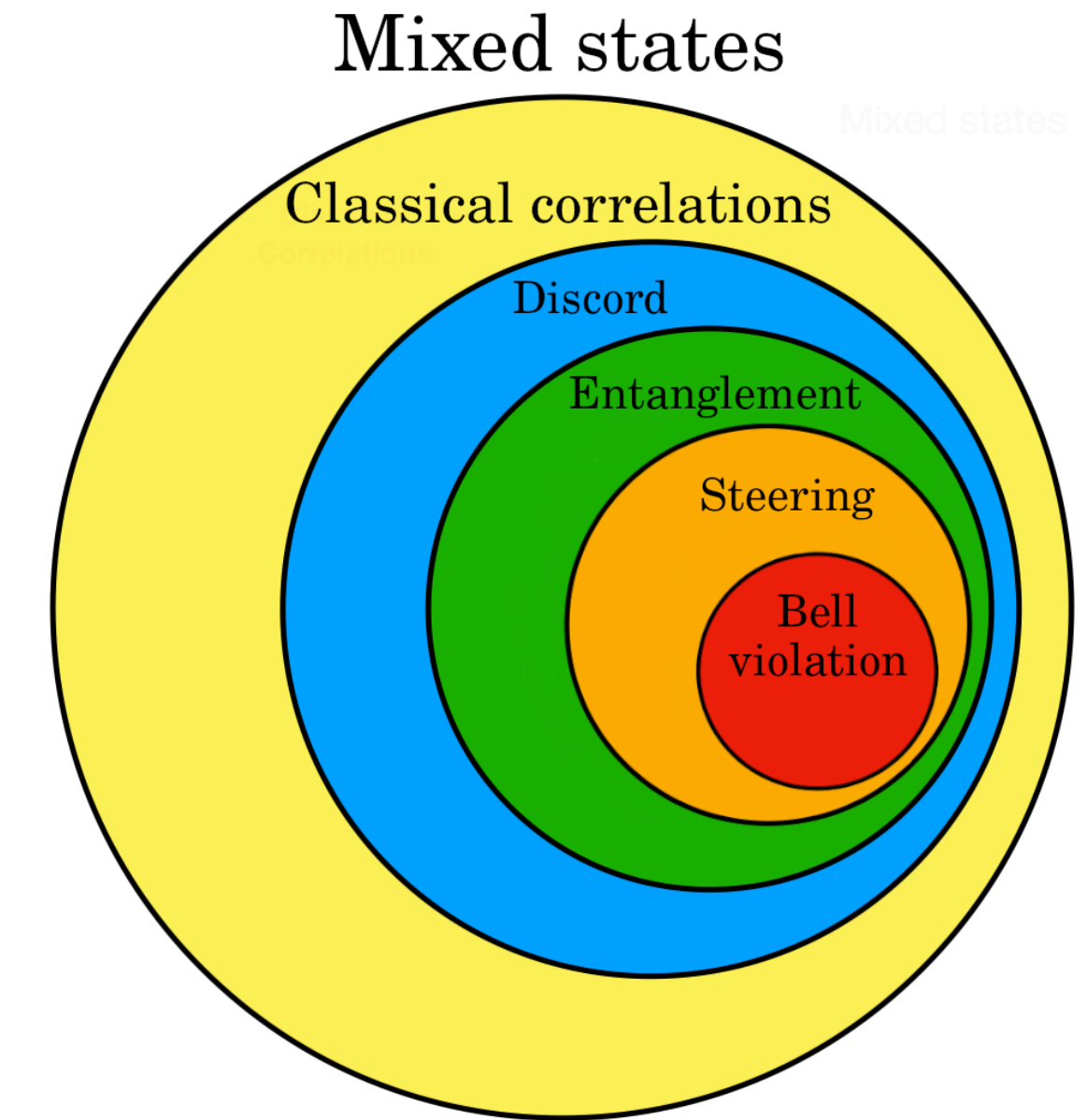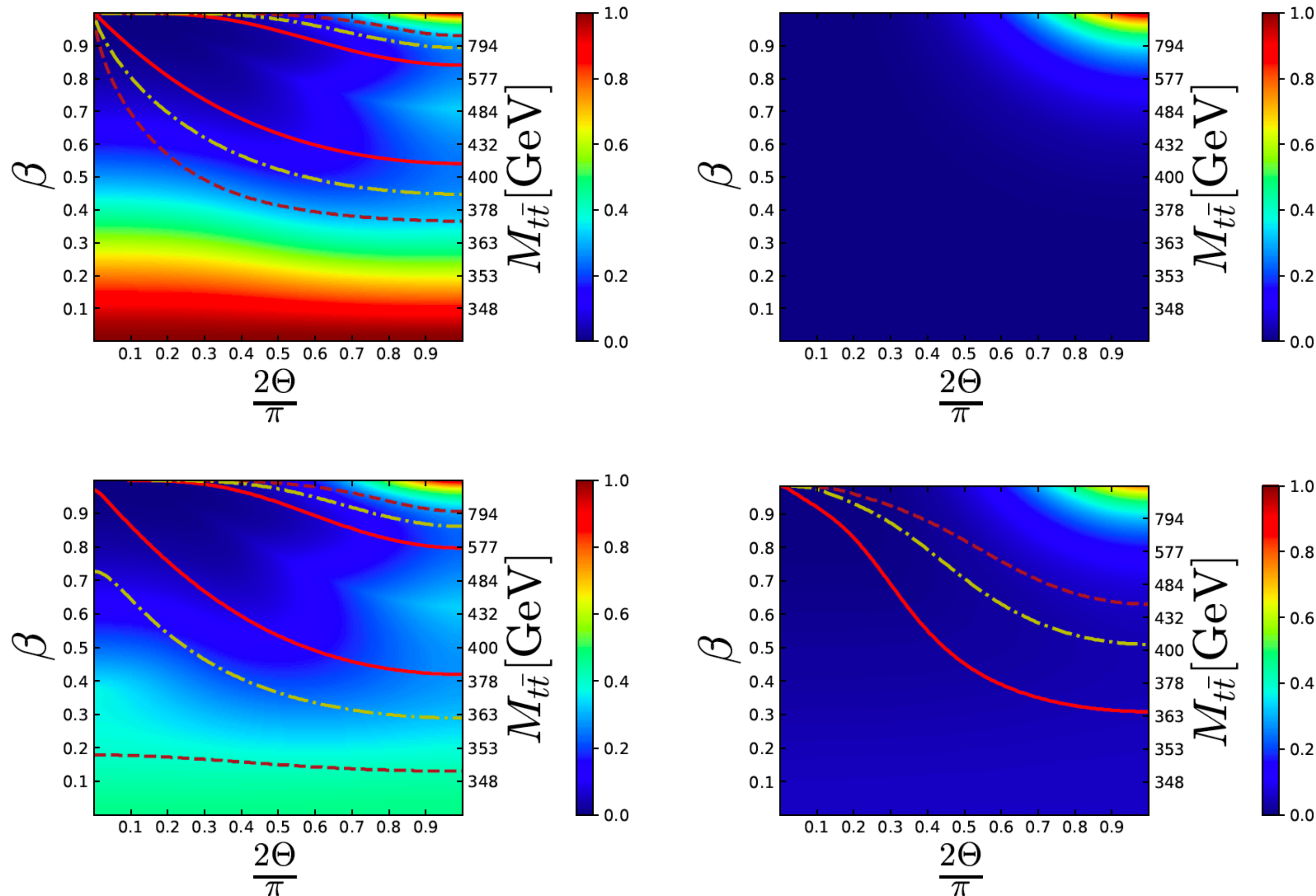
Quantum correlations

Mixed states

FIG. 2. Quantum discord of the spin density matrix $\rho(M_{t\bar{t}}, \hat{k})$ as a function of the top velocity β and the production angle Θ in the $t\bar{t}$ c.m. frame. All plots are symmetric under $\Theta \to \pi - \Theta$. Upper left: $gg \to t\bar{t}$. Upper right: $q\bar{q} \to t\bar{t}$. Lower left: $t\bar{t}$ production at the LHC for Run 2 c.m. energy, $\sqrt{s} = 13$ TeV [19]. Lower right: $t\bar{t}$ production at the Tevatron for $\sqrt{s} = 2$ TeV, close to its last-run c.m. energy $\sqrt{s} = 1.96$ TeV [15]. Solid red, dashed-dotted yellow, and dashed brown lines are the critical boundaries of separability, steerability, and Bell locality, respectively.

Basics
Bell (CHSH) inequalities : QM

$$|\Phi^{\pm}\rangle = \frac{|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle}{\sqrt{2}}$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle)$$

$$A(a) = \hat{S}_x \otimes I$$

$$A(a') = \hat{S}_z \otimes I$$

$$B(b) = -\frac{1}{\sqrt{2}}I \otimes (\hat{S}_z + \hat{S}_x)$$
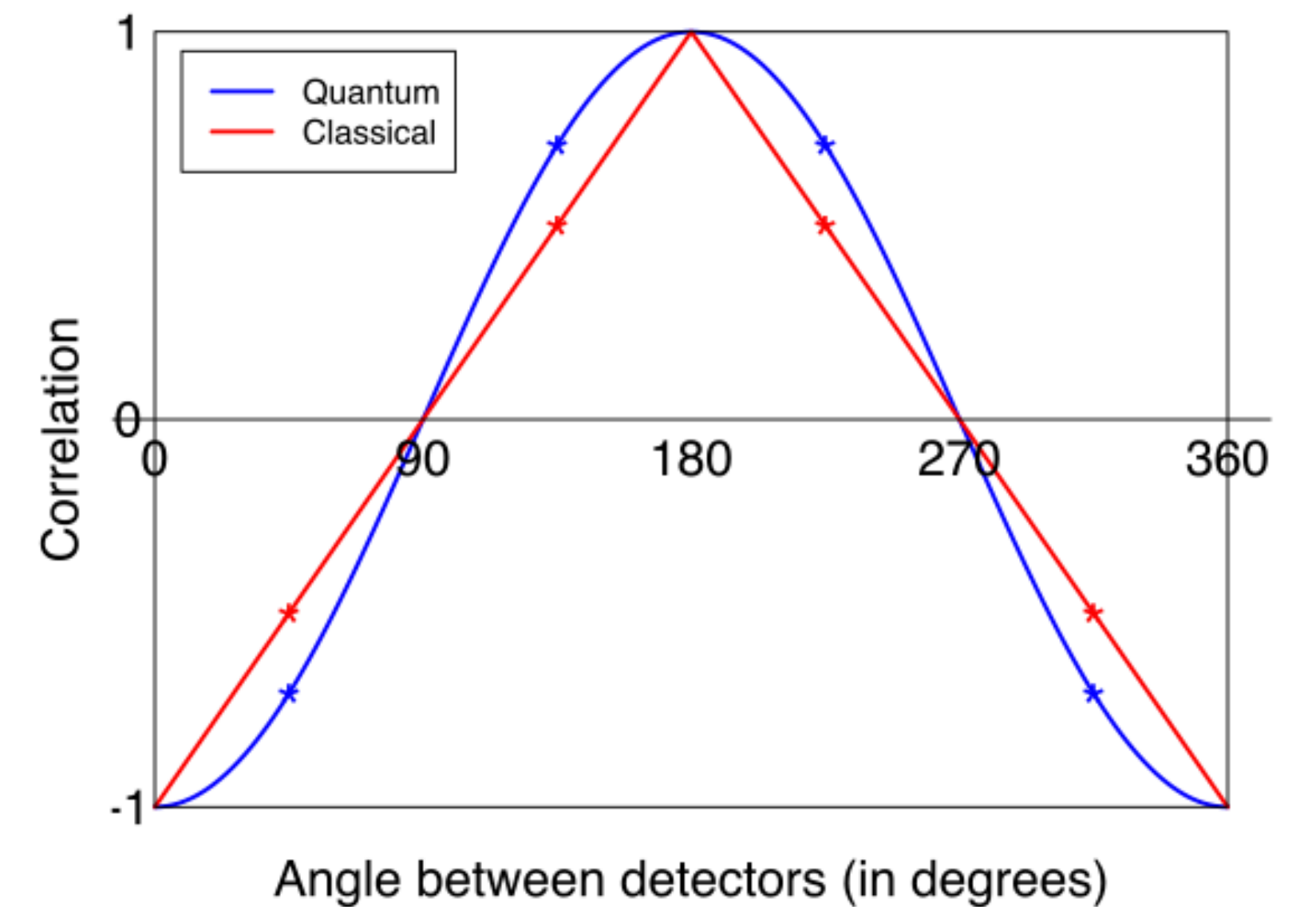
$$B(b') = \frac{1}{\sqrt{2}}I \otimes (\hat{S}_z - \hat{S}_x)$$

$$E(AB) = \langle A(a)B(b) \rangle = \frac{1}{\sqrt{2}}$$

$$E(AB') = \langle A(a)B(b') \rangle = \frac{1}{\sqrt{2}}$$

$$E(A'B) = \langle A(a')B(b) \rangle = \frac{1}{\sqrt{2}}$$

$$E(A'B') = \langle A(a')B(b') \rangle = -\frac{1}{\sqrt{2}}$$

$$E(AB) + E(AB') + E(A'B) - E(A'B') = 2\sqrt{2}$$

Basics
Grading quantum correlations

Entanglement rests on the difference between separable and non-separable sates. Is this the boundary of quantum and non-quantum effects?

Quantum discord is an asymmetric measure of nonclassical correlations between two subsystems of a system, based on the difference between two different quantum definitions of mutual information.

Quantum steering (proposed by Schrödinger) differs from entanglement for mixed states and it is also asymmetric (and base dependent).

Bell non-locality needs a strong quantum correlation. For pure states it just amounts to entanglement again.

Mixed states

® Yoav Afik

Classical effects

Discord

Entanglement

Steering

Bell Non-locality

Separability

Non-separability

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