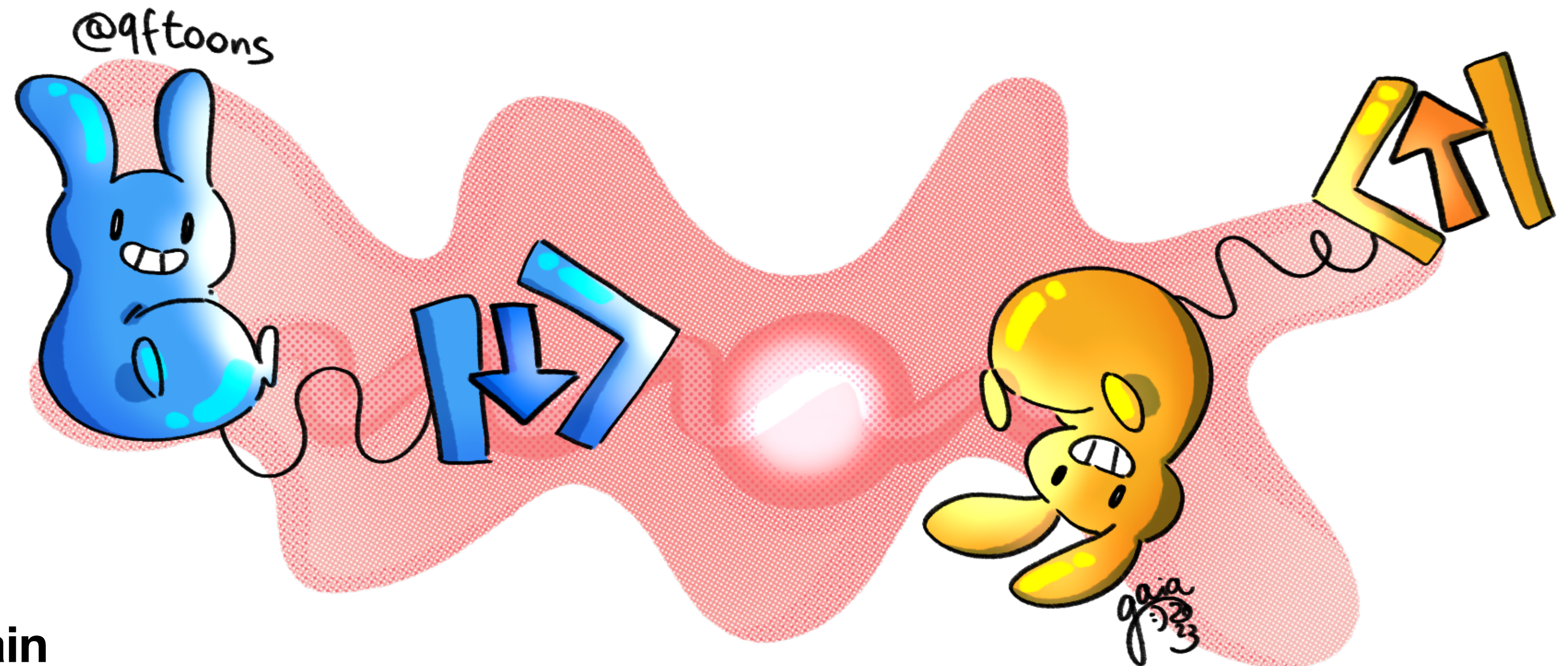
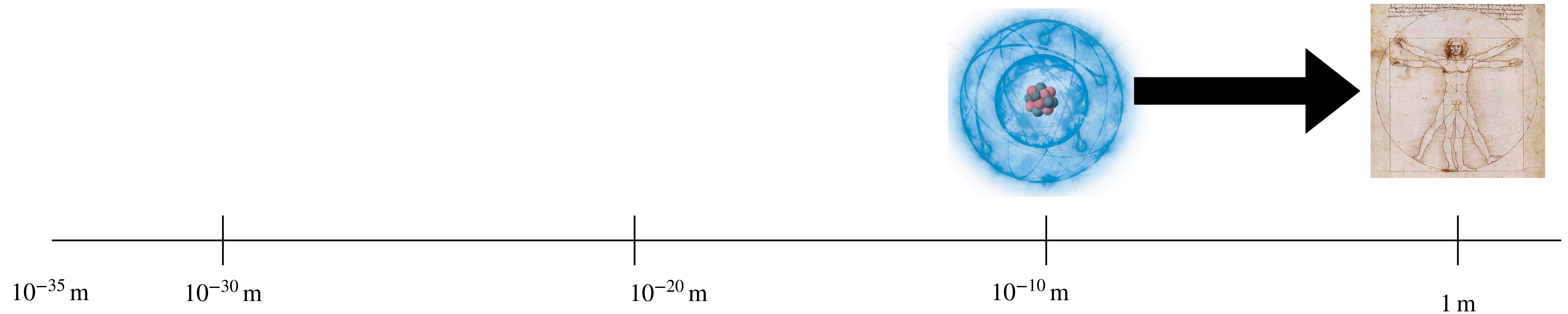


The quantum fabric of the SM



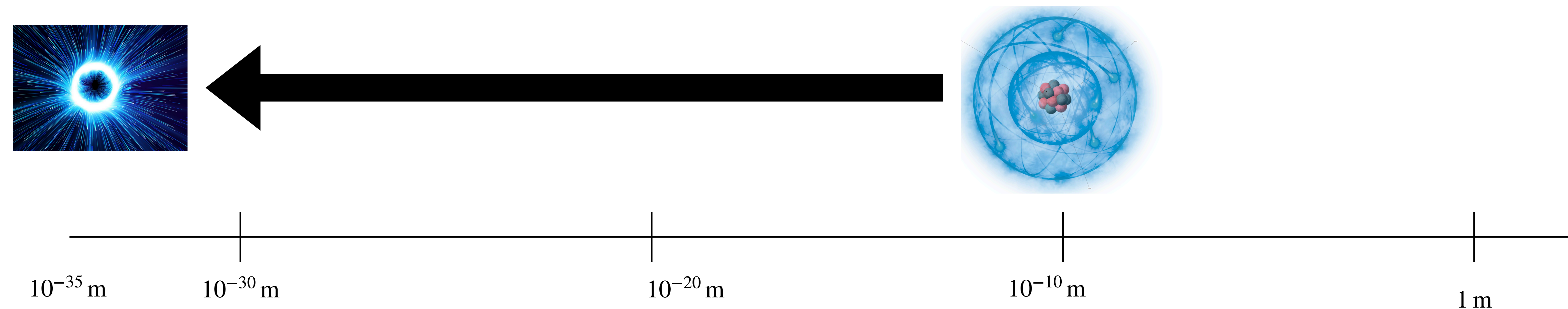
Fabio Maltoni
Università di Bologna
Université catholique de Louvain

Introduction



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

Introduction

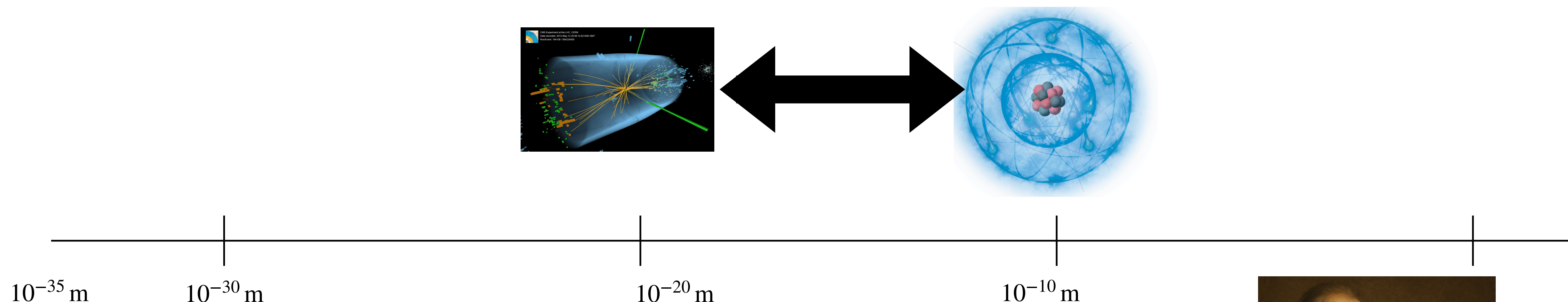


It from Qubit:

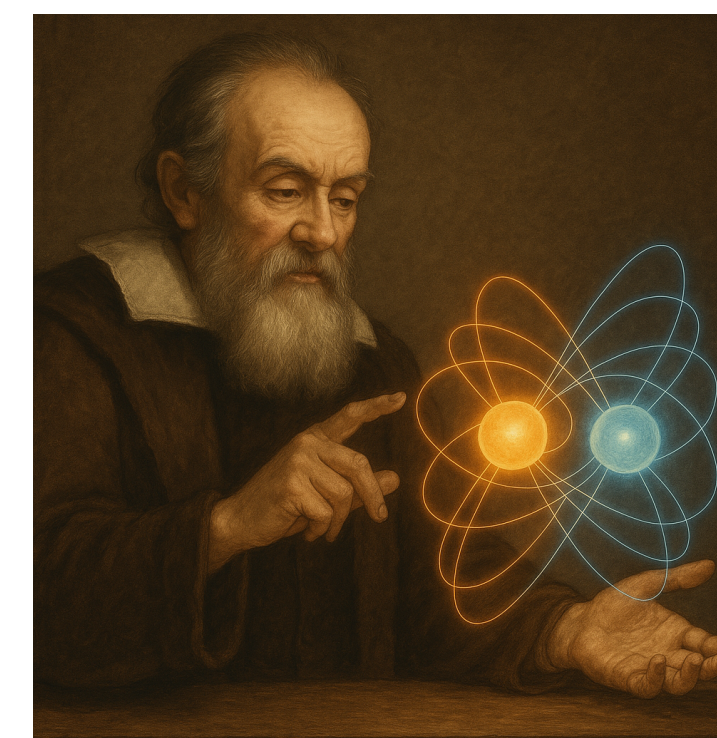
- Does spacetime emerge from entanglement?
- Do black holes have interiors?
- Does the universe exist outside our horizon?
- **What is the information-theoretic structure of quantum field theories?**
- Can quantum computers simulate all physical phenomena?
- How does quantum information flow in time?

Introduction

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



*Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.



Introduction

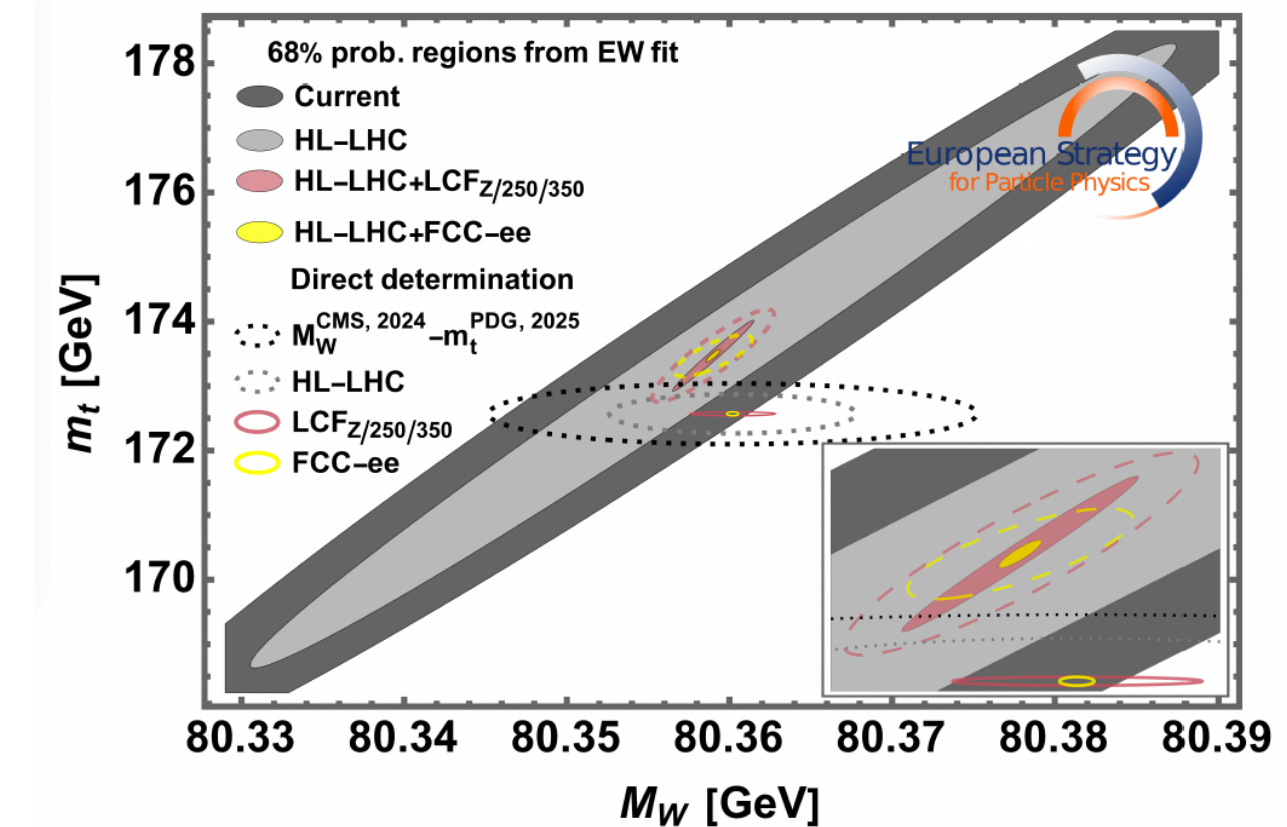
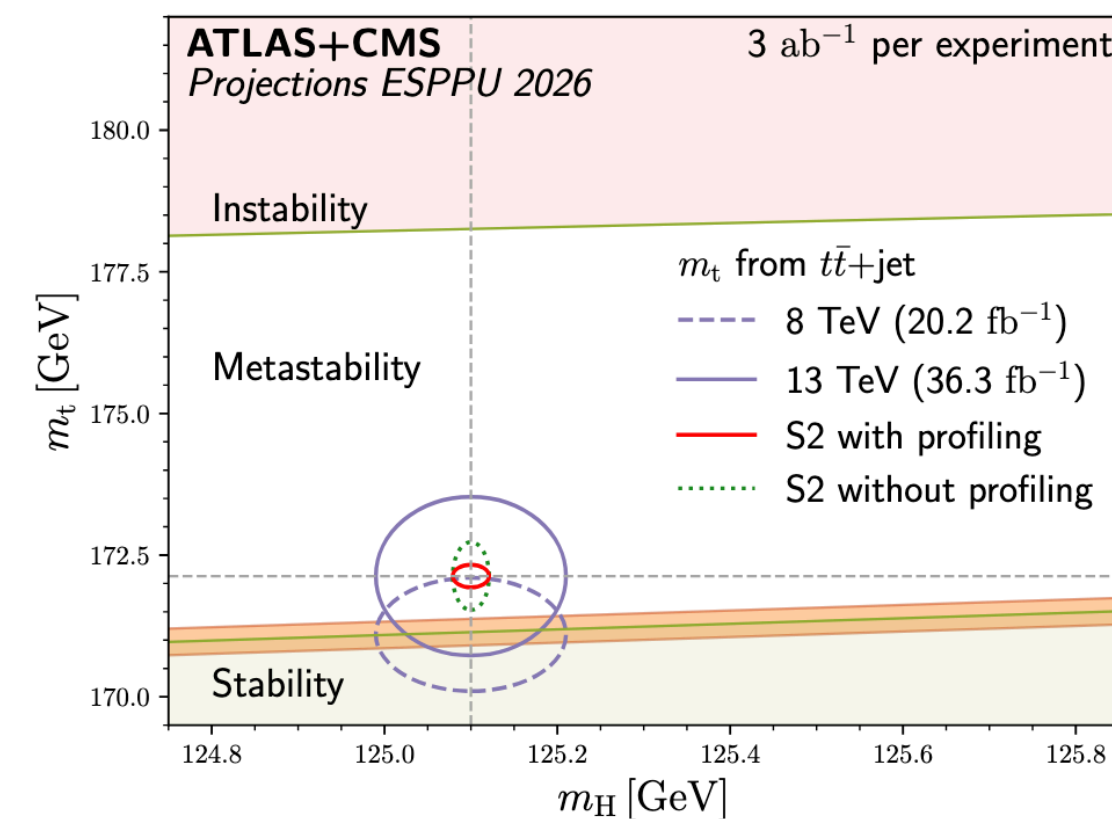
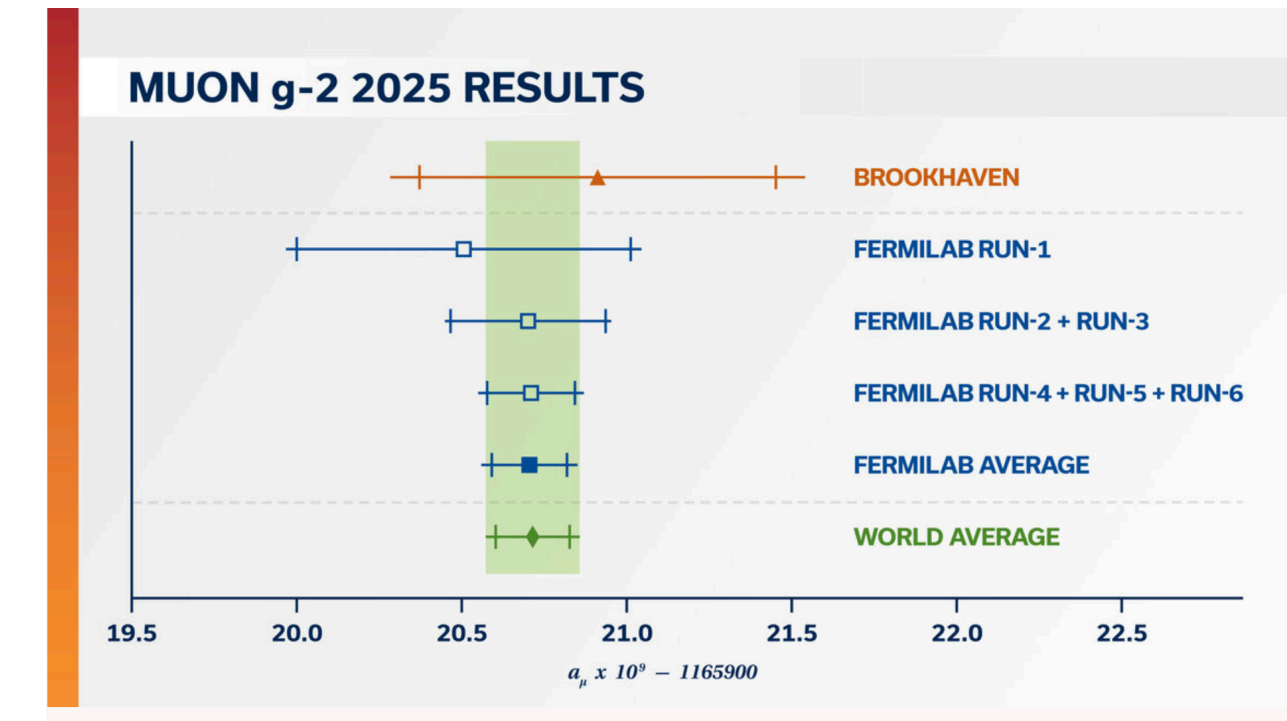
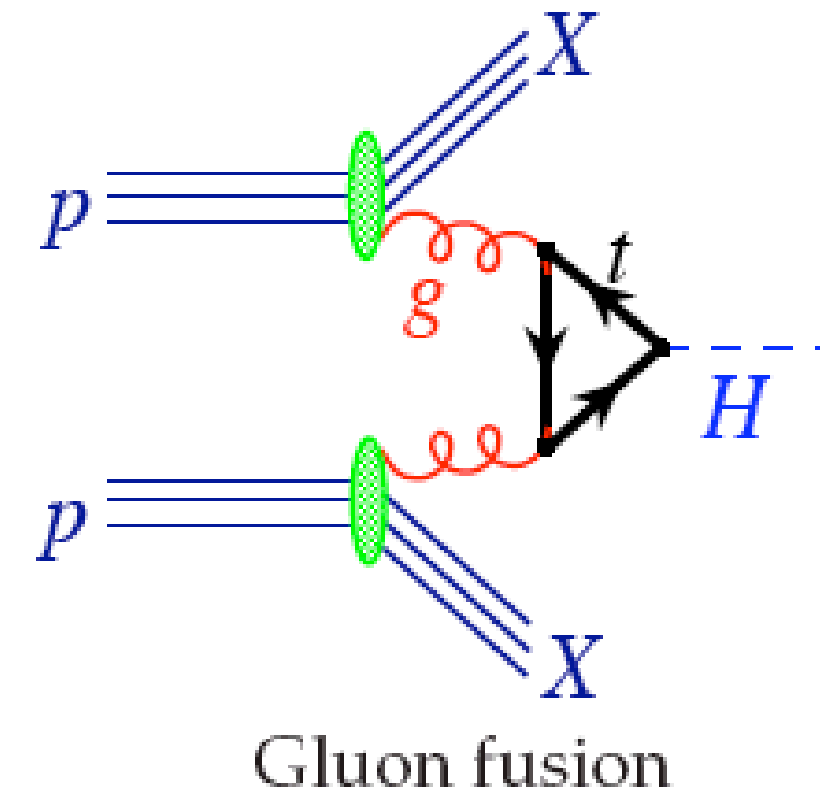
The quantum nature of the SM is so pervasive in the daily life of the particle physicist, that we often forget about it. Naively:

- tree level $\rightarrow$ order $\hbar^0$
- 1-loop $\rightarrow$ order $\hbar^1$
- 2-loop $\rightarrow$ order $\hbar^2$
- etc.

$$Z = \int D\phi e^{\frac{i}{\hbar} S[\phi]}$$

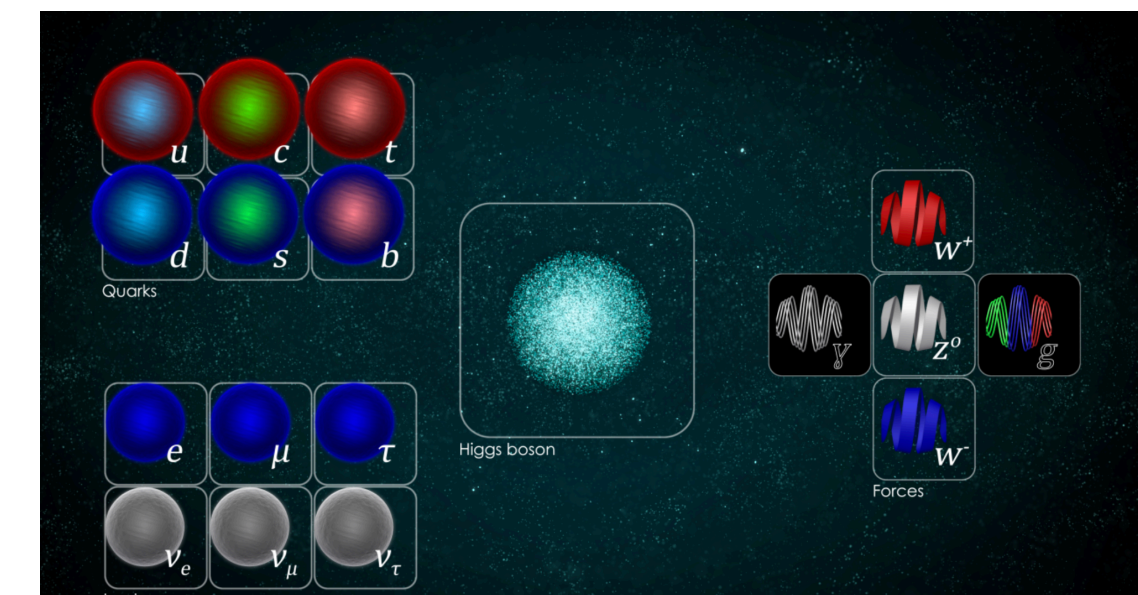
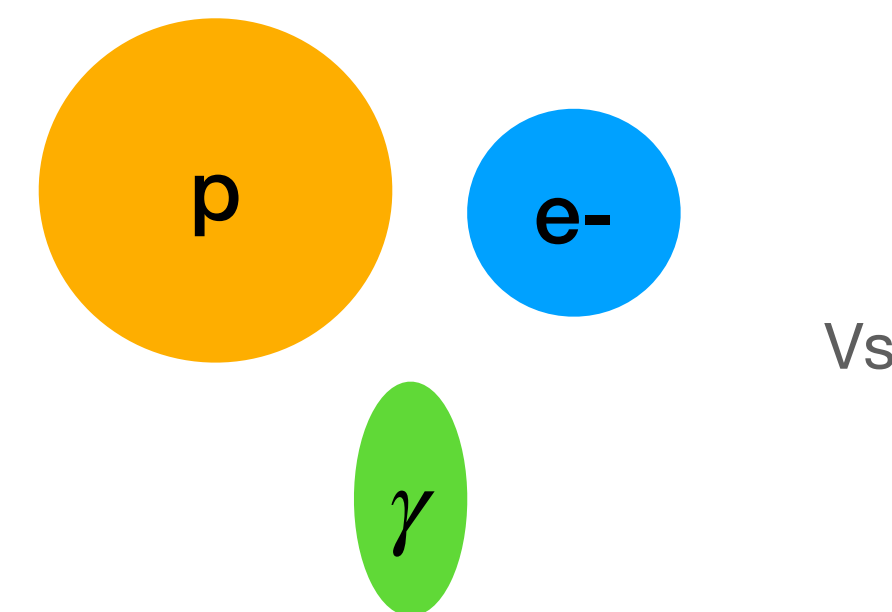
We have extensively validated QFT at different scales, and always found it a consistent way of making predictions in HEP.

Are there other features predicted by QFT that we can study/exploit?

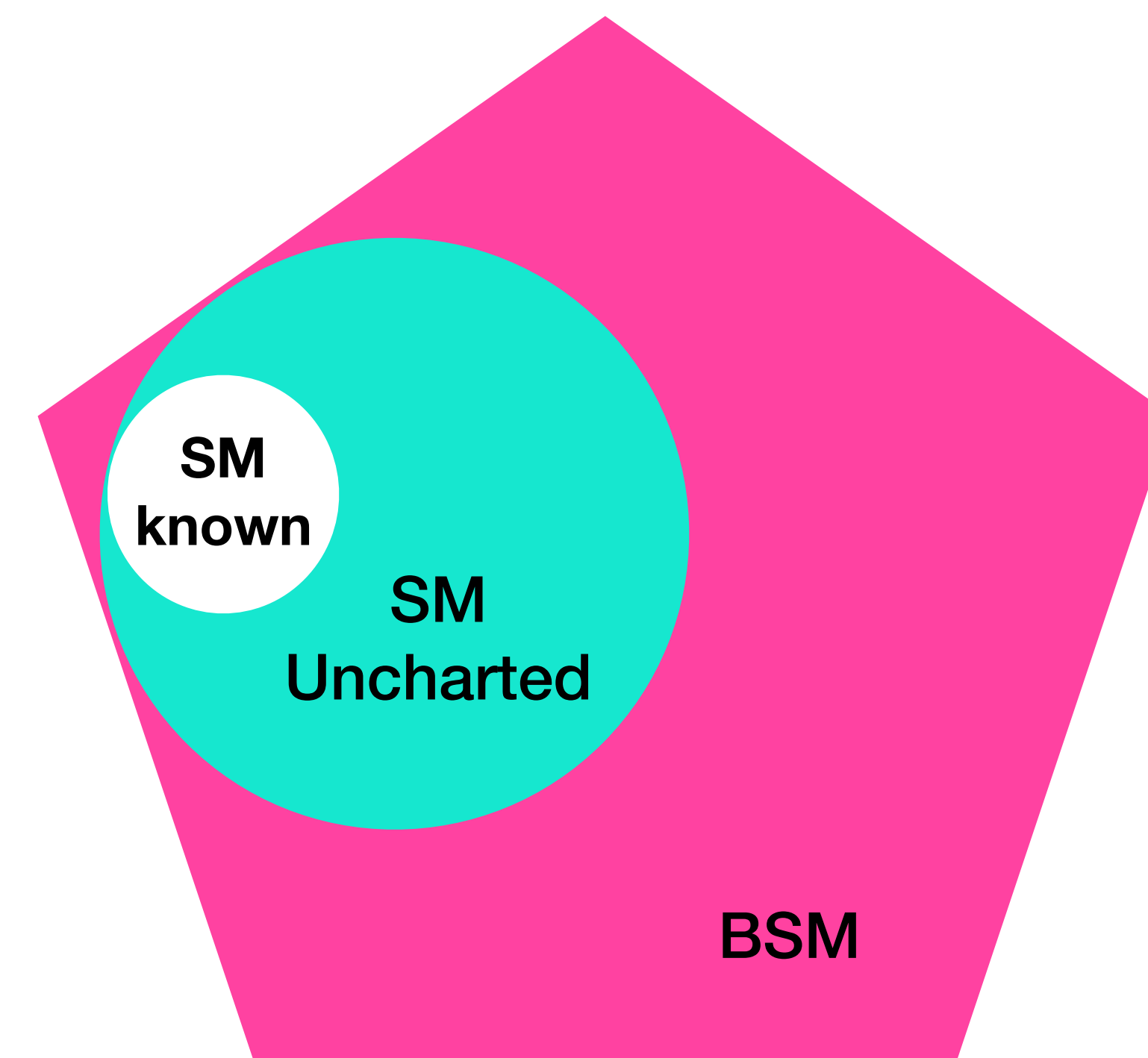


Introduction

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



- **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

Introduction

Entanglement is the potential of quantum states to exhibit correlations that cannot be accounted for classically. For decades, entanglement has been the focus of much work in the foundations of quantum mechanics, being associated particularly with quantum nonseparability and the violation of Bell's inequalities [1]. In recent years, however, it has begun to be viewed also as a potentially useful resource. The predicted capabilities of a quantum computer, for example, rely crucially on entanglement [2], and a proposed quantum cryptographic scheme achieves security by converting shared entanglement into a shared secret key [3].

Theory of Resources $\Rightarrow$ Entanglement $\Rightarrow$ communication resource
 Magic $\Rightarrow$ computational resource

Don't ask what you can do for QM, but what QM can do for you!

Overview
Participant List
Videoconference
Code of Conduct
Practical information
Accommodation
Health insurance, VISA
Wi-fi Connection
Directions
Child Care
TH workshop secretariat
thworkshops.secretariat...

The workshop aims at gathering theorists and experimentalists interested in measuring quantum information observables, such as magic and entanglement, on particles created at colliders and using these new observables as an innovative direction to probe fundamental interactions.

The programme includes discussion on the recent experimental results obtained in this field, on the implications of these new observables for new physics searches, and feasibility studies for multiple final states in current and future colliders. On the theoretical side, the workshop also aims to investigate the possible integration of quantum information–theoretic concepts in quantum field theory and particle physics.

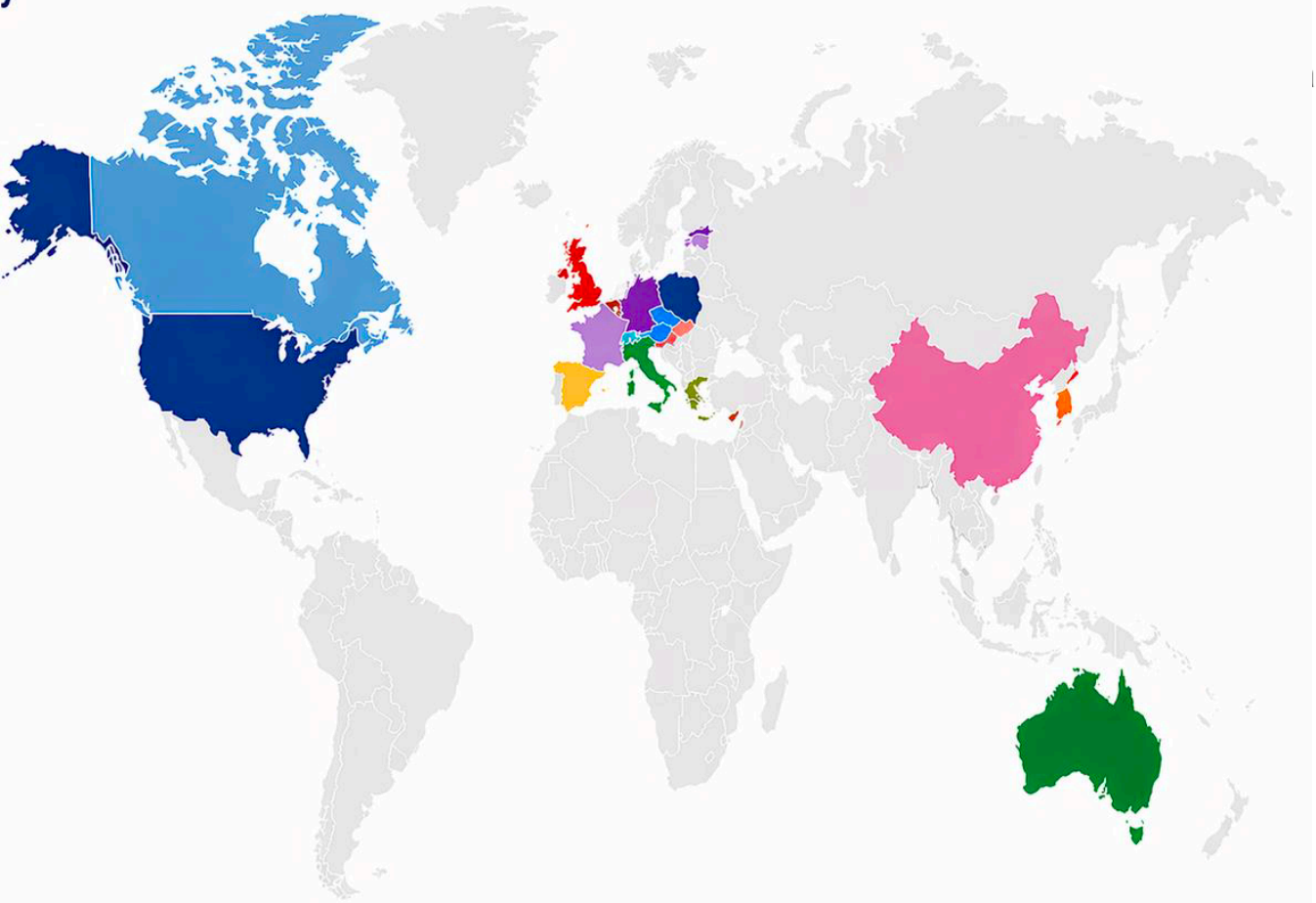
It will bring together experts not only from particle physics, but also from quantum information science and nuclear theory, and will include panel discussions and overview talks to explore the broader links between quantum information, technologies, and high-energy physics.

This is the third edition of a workshop series previously held at the Galileo Galilei Institute (GGI) in Florence in 2023 and 2025. It builds on a growing number of international meetings on quantum-information applications to high-energy physics organized in recent years, including those in Oxford in 2023 and 2024, Pittsburgh in 2024, and at the WQC in Shanghai 2025.

Participants by Country

(Total = 100)

United States	28
United Kingdom	11
South Korea	9
Germany	9
Italy	8
Switzerland	7
Spain	6
Poland	5
China	4
Belgium	3
Australia	2
France	1
Austria	1
Cyprus	1
Czechia	1
Estonia	1
Slovakia	1
Canada	1
Greece	1
TOTAL	100



Alan Barr
Fabio Maltoni
Federica Fabbri
Hyun Min Lee
Michele Grossi
Myeonghun Park
Regina Demina
Sokratis Trifinopoulos
Yoav Afik

QIHEP

Quantum Information and High Energy Physics

DATE

May 3 – 7, 2027

VENUE

Northwestern University
Evanston, Illinois — on the shores of Lake Michigan

INTERNATIONAL ADVISORY COMMITTEE

Yoav Afik · Alan Barr · Regina Demina · Federica Fabbri · Tao Han · Paweł Horodecki · Ian Low ·
Fabio Maltoni · Juan Ramón Muñoz de Nova · Marcel Vos · Carlos Wagner

NORTHWESTERN UNIVERSITY

qihp2027.northwestern.edu

4th Edition

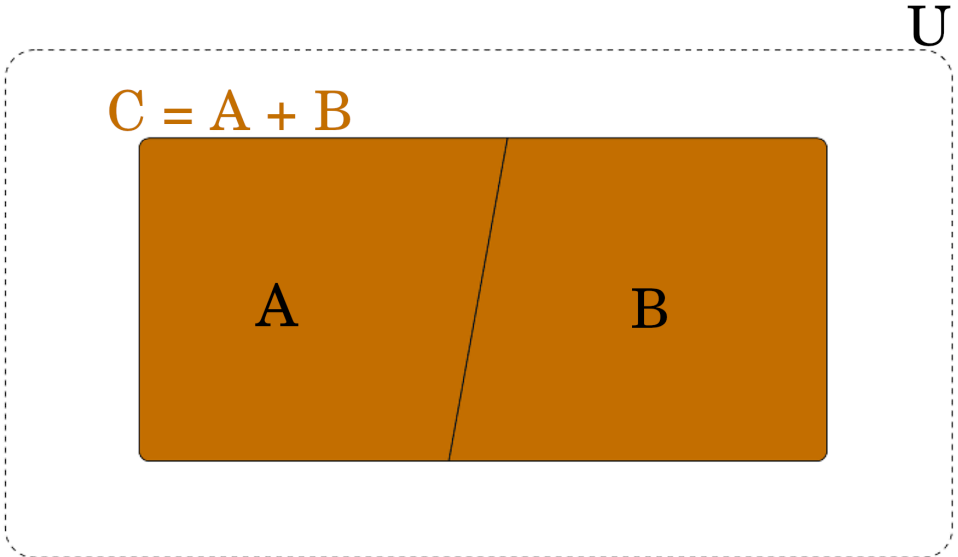
Basics

Density matrix : pure versus mixed

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

Basics

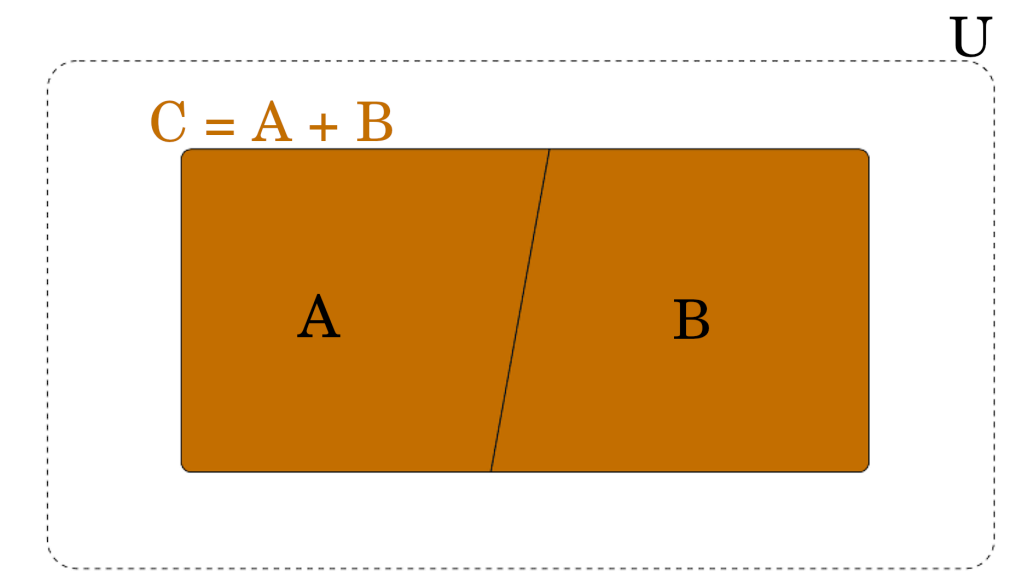
Composite systems



Pure	$ \psi\rangle = a\rangle \otimes b\rangle$	$ \psi\rangle = \sum_{ij} p_{ij} a_i\rangle \otimes b_j\rangle \quad p_{ij} \in \mathbb{C}, \sum_{ij} p_{ij} p_{ij}^* = 1$ $a_i\rangle, b_j\rangle$ orthonormal bases
	Separable	Non-separable=ENTANGLED
Mixed	$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$ $p_i \geq 0, \sum_i p_i = 1$ Here one can use pure states instead of ρ_A, ρ_B	$\rho \neq \sum_i p_i \rho_A^i \otimes \rho_B^i$

The properties are different for pure and mixed states

Entanglement Theorem

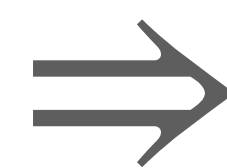


If $|\psi\rangle$ is a **pure state** of the AB system, then two (orthonormal) bases (in A and B) exist such that

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

$$\rho_A = \sum_i \lambda_i |w_i\rangle_A \langle w_i|$$

$$\rho_B = \sum_i \lambda_i |z_i\rangle_B \langle z_i|$$



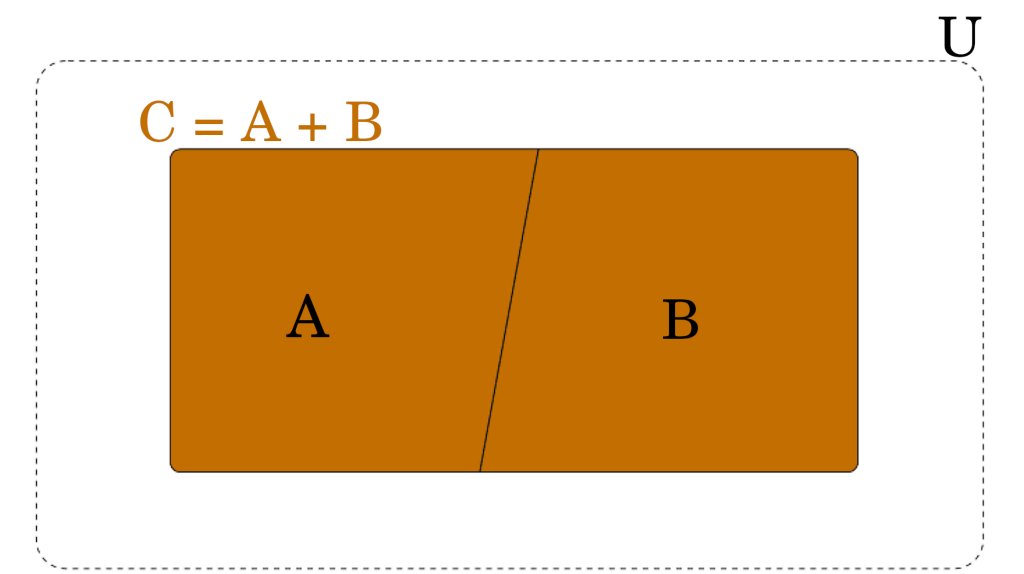
- The states of the subsystems are mixed-states!
- They have the same eigenvalues $\Rightarrow$ they are equally impure

Consequences:

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

Basics

Concurrence



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

$$\text{Tr} [\rho_A^2] \leq 1 \text{ and } \text{Tr} [\rho_B^2] \leq 1$$

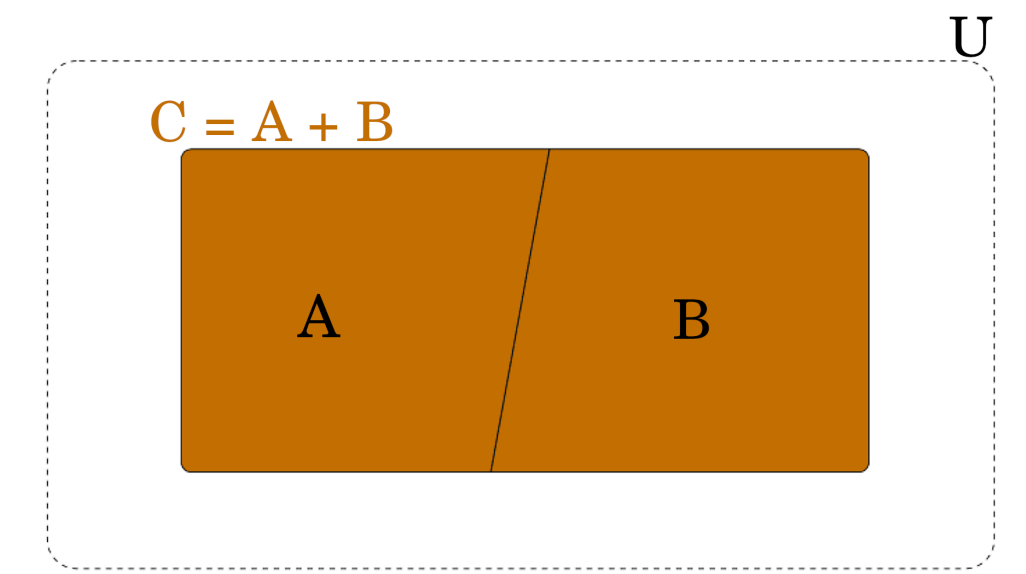
The concurrence $C_{A|B}$ is defined as

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

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:

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

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

And the partial transpose on B

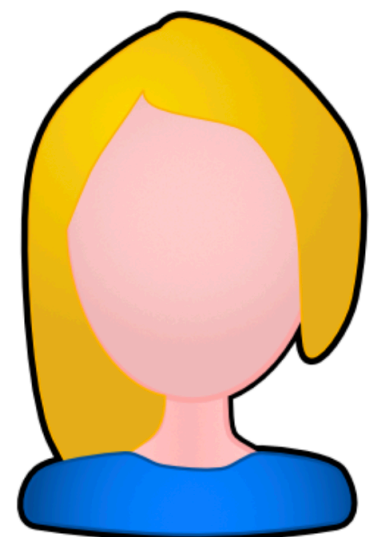
$$\rho^{T_B} = (I \otimes T)[\rho] = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle \langle a_k| \otimes (|b_j\rangle \langle b_l|)^T = \sum_{ijkl} p_{ij} p_{kl}^* |a_i\rangle \langle a_k| \otimes |b_l\rangle \langle b_j| = \sum_{ijkl} p_{il} p_{kj}^* |a_i\rangle \langle a_k| \otimes |b_j\rangle \langle b_l|$$

The criterion states that if ρ is separable then all the eigenvalues of ρ^{T_B} are non-negative. In other words, if ρ^{T_B} has a negative eigenvalue, then the system is guaranteed to be entangled.

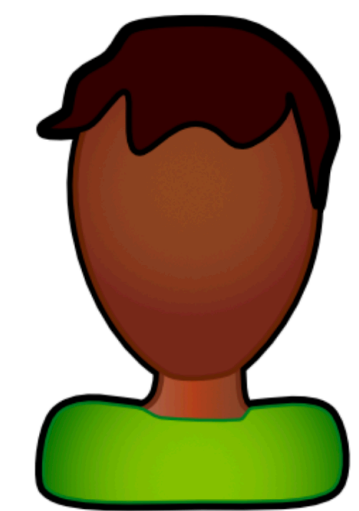
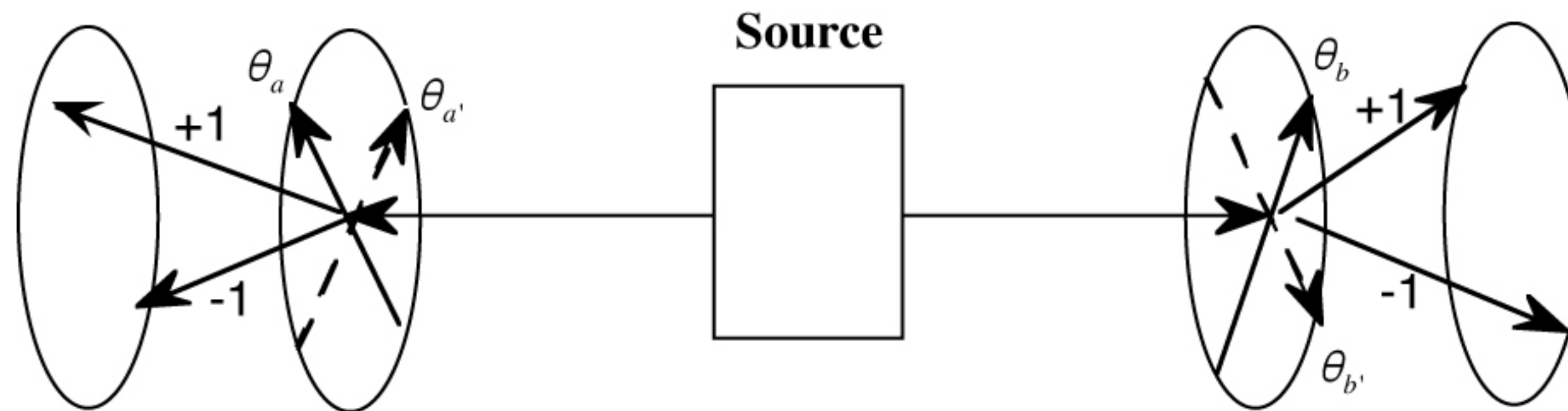
For 2 qubits or 1 qubit x 1 qutrit is a IFF

Basics

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



Alice



Bob

Assuming:

- 1] Measurements reveal element of reality, physical properties present beforehand.
- 2] Alice and Bob are separated by a space-like distance

$$A = \pm 1$$

$$A' = \pm 1$$

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

QM: $E(AB) + E(AB') + E(A'B) - E(A'B') \leq 2\sqrt{2}$

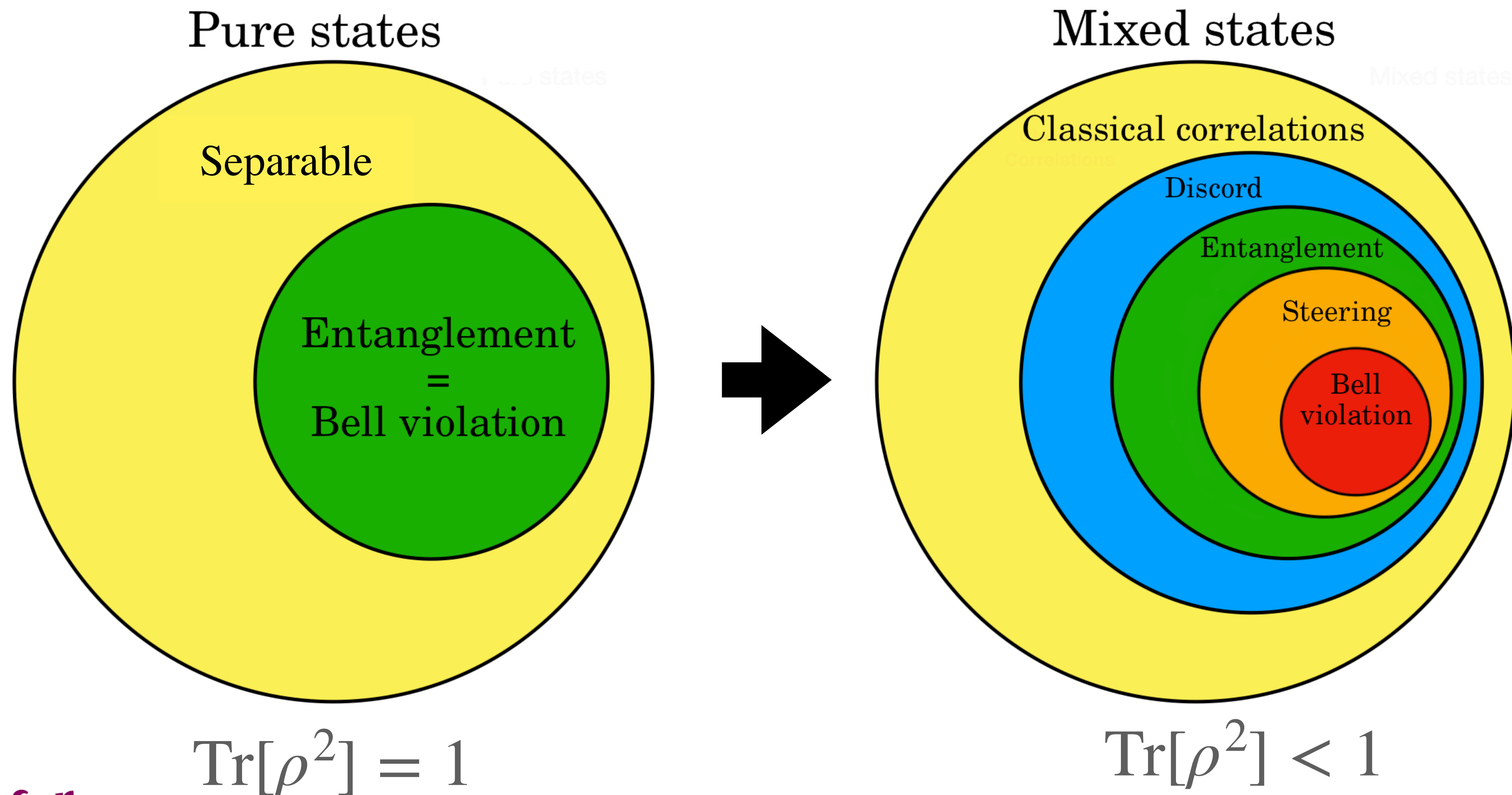
$$B = \pm 1$$

$$B' = \pm 1$$

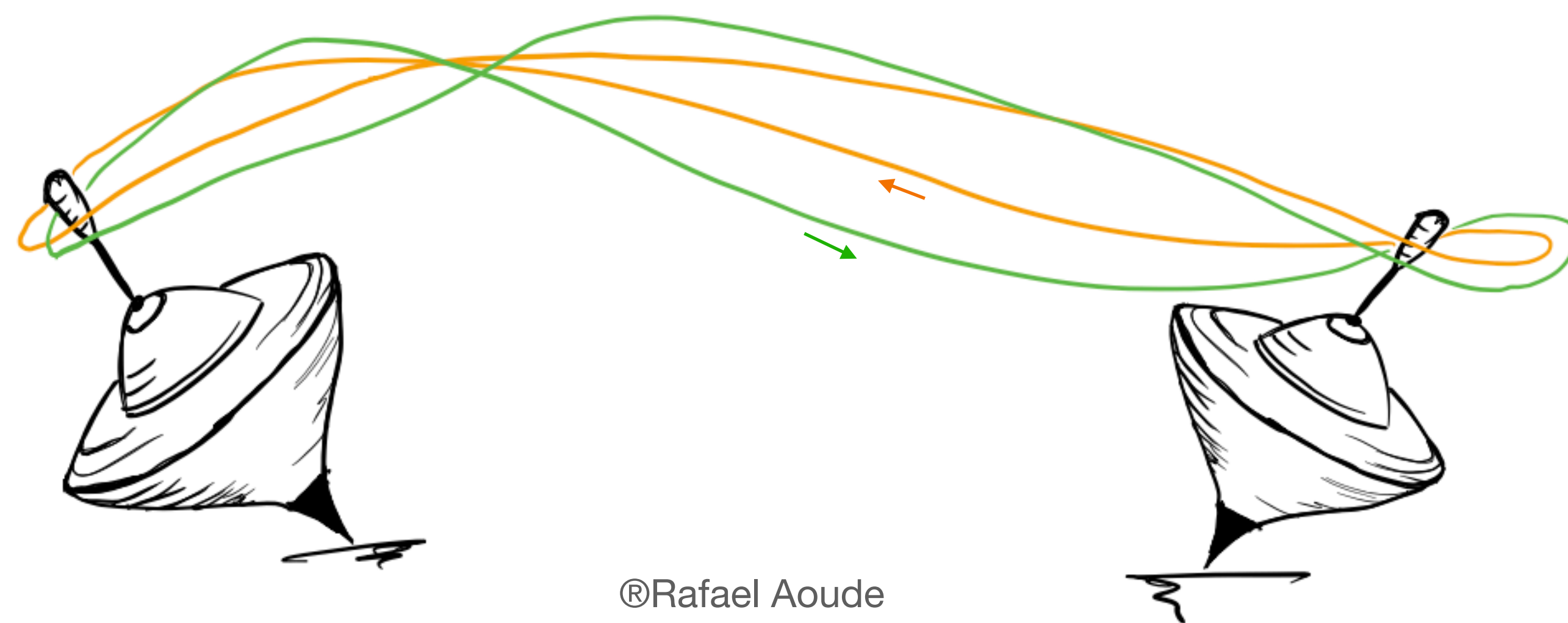
In principle, CHSH can be tested independently of QM.
However, we will use it as a measure of a strong entanglement.

Basics

Grading QM correlations



Quantum tops



Qubit

Qubit

©Rafael Aoude

Y. Afik and JRM de Nova: 2003.02280

M. Fabbrichesi, R. Floreanini, G. Panizzo: 2102.11883

C. Severi, C. Boschi, FM, M. Sioli : 2110.10112

Y. Afik and JRM de Nova: 2203.05582

R. Aoude, E. Madge, FM, L. Mantani: 2203.05619

J.A. Aguilar-Saavedra, J.A. Casas: 2205.00542

Y. Afik and JRM de Nova: 2209.03969

C. Severi, E. Vryonidou: 2210.09330

Z. Dong, D. Gonçalves, K. Kong, A. Navarro: 2305.07075

J.A. Aguilar-Saavedra : 2307.06991

T. Han, M. Low, TA Wu: 2310.17696

J.A. Aguilar-Saavedra, J.A. Casas: 2401.06854

J.A. Aguilar-Saavedra : 2402.14725

C. Severi, FM, S. Tentori, E. Vryonidou: 2401.08751

C. Severi, FM, S. Tentori, E. Vryonidou: 2404.08049

White, White : 2406.07321

K. Cheng, T. Han, M. Low: 2407.01672

Z. Dong, D. Gonçalves, K. Kong, Larkowski, A. Navarro: 2407.07147

R. Aoude, Banks Whjite and White: 2505.12522

M. Altakach, P. Lambda, FM, K. Sakurai : 2601.09558

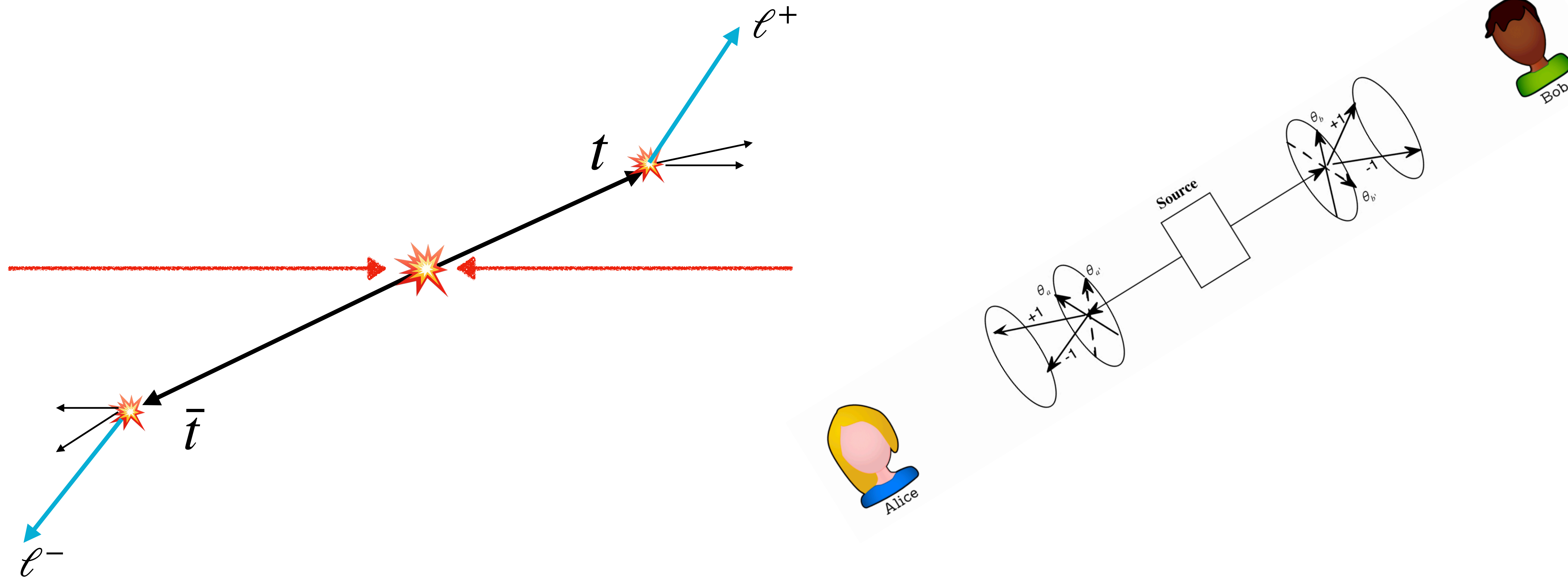
L. Antozzi et al. : 2602.23426

Y. Afik et al. : 2602.15115

Y.C. Guo, T. Han, M. Low, Y. Su : 2602.02719

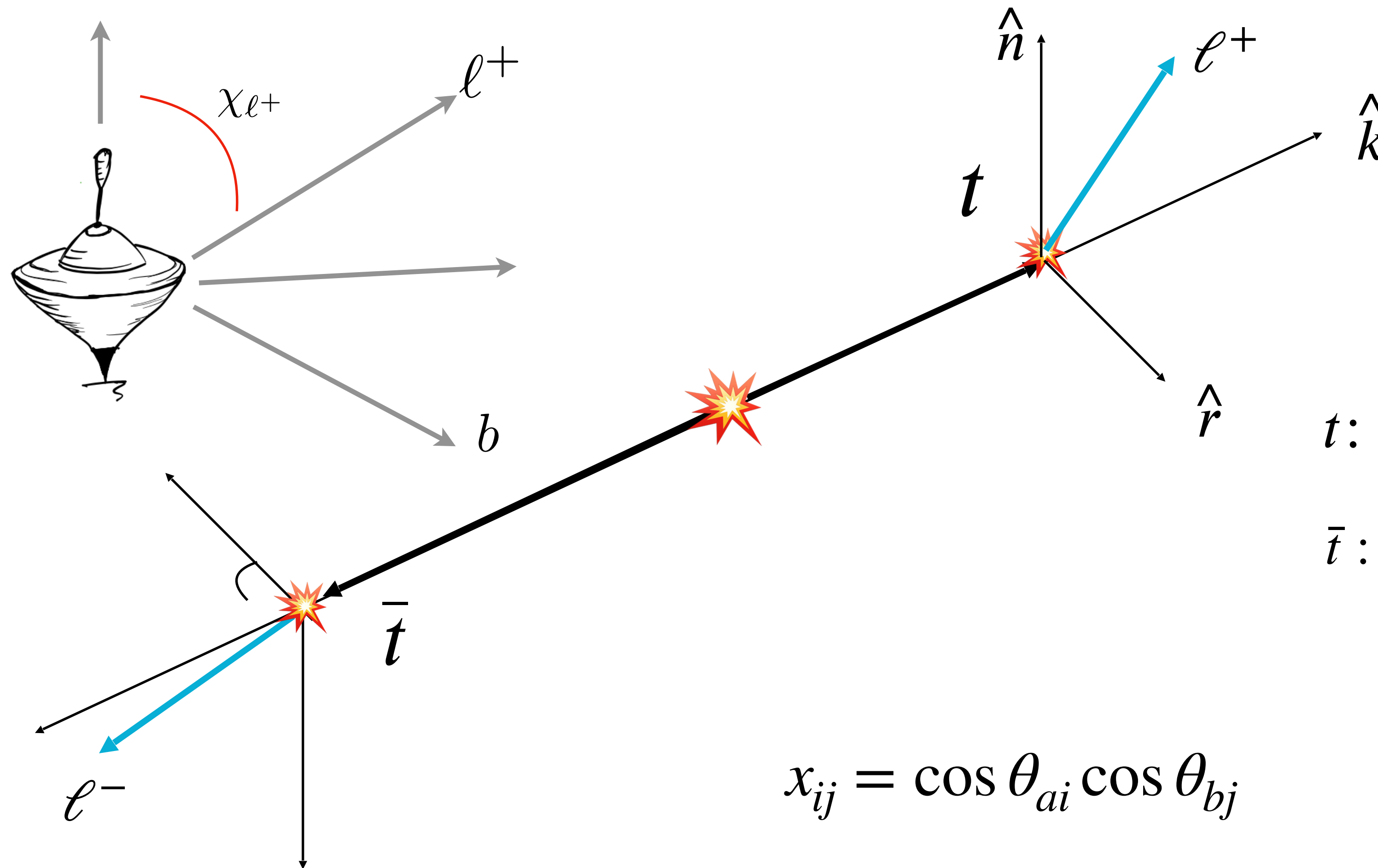
R. Aoude, JM. Camacho, V. Durupt, G. García Mir, FM, M. Moreno Llácer, L. Satrioni, M. Vos, 2604.13479

Quantum tops



SAME mathematics, but actually subtly different (QM vs non-QM)

$t\bar{t}$ tomography



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

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

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

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

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

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

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.

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

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:

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

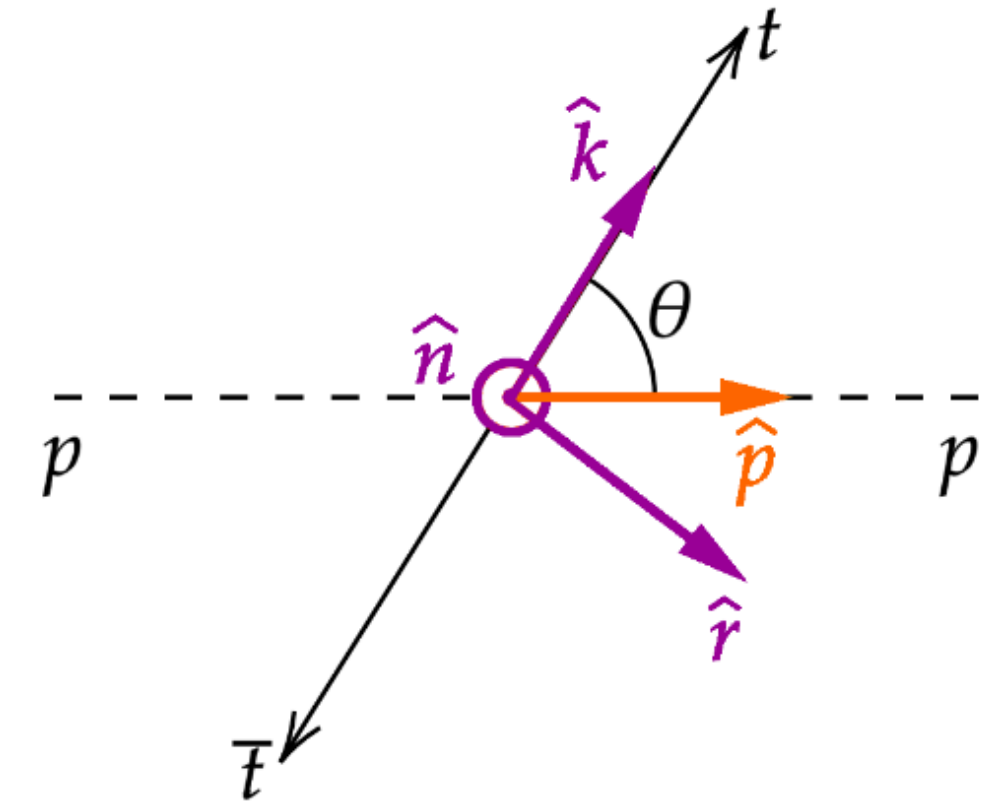
$$-C_{kk} + C_{rr} + C_{nn} \equiv -3D^{(k)} > 1$$

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

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

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

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \varphi} = \frac{1}{2} (1 - D \cos \varphi)$$



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

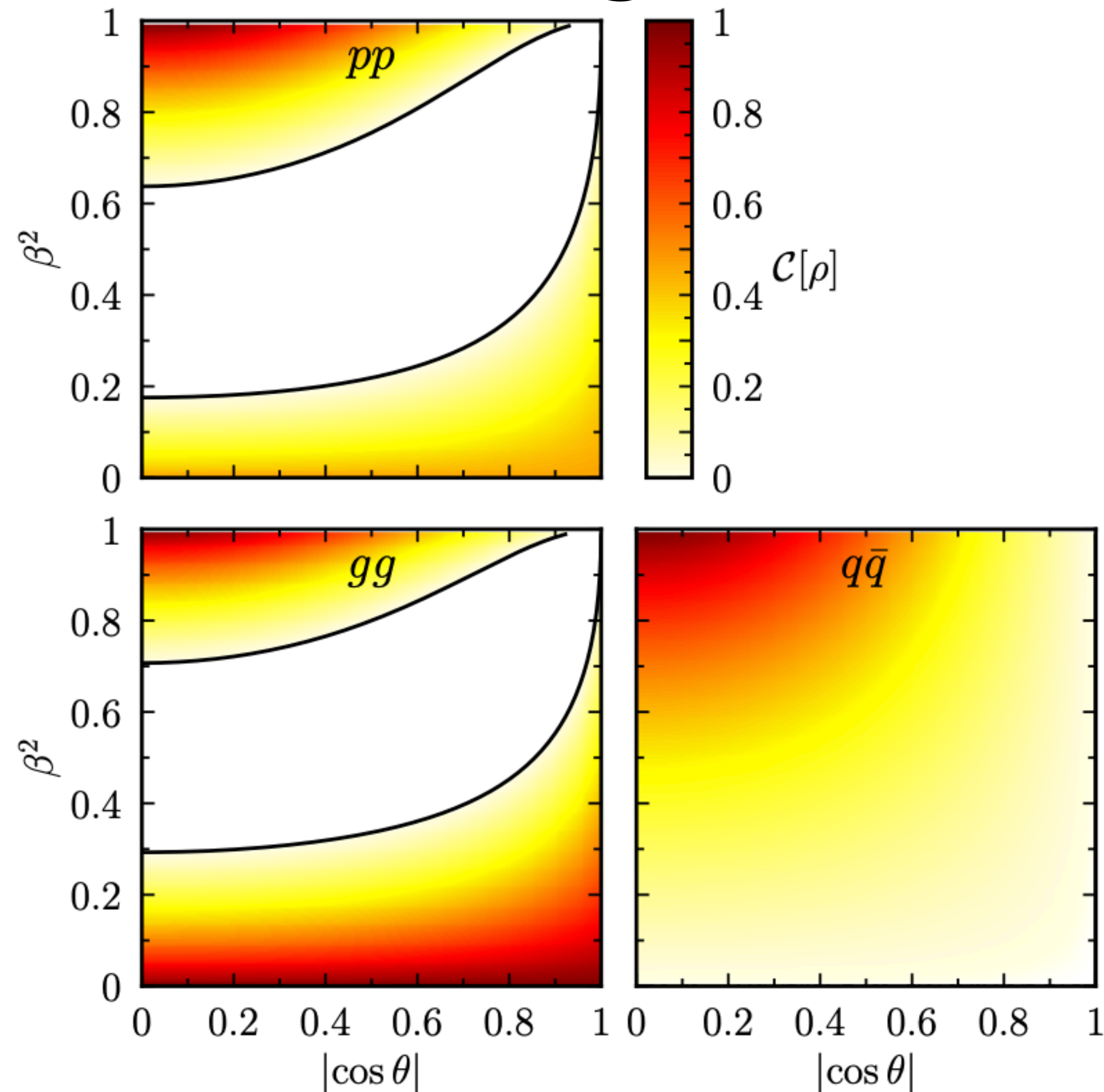
$$\mathcal{C}^{(\text{triplet})} = \begin{pmatrix} \eta & 0 & 0 \\ 0 & \eta & 0 \\ 0 & 0 & -\eta \end{pmatrix}, \quad 0 < \eta \leq 1$$

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

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

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

SM Entanglement



White regions: zero-entanglement

Maximal entanglement points/regions:

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

$$\rho_{gg}^{\text{SM}}(0, z) = |\Psi^-\rangle_n \langle \Psi^-|_n \quad (\text{singlet})$$

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

$$\rho_{gg}^{\text{SM}}(1, 0) = |\Psi^+\rangle_n \langle \Psi^+|_n \quad (\text{triplet})$$

$$\rho_{q\bar{q}}^{\text{SM}}(1, 0) = |\Psi^+\rangle_n \langle \Psi^+|_n.$$

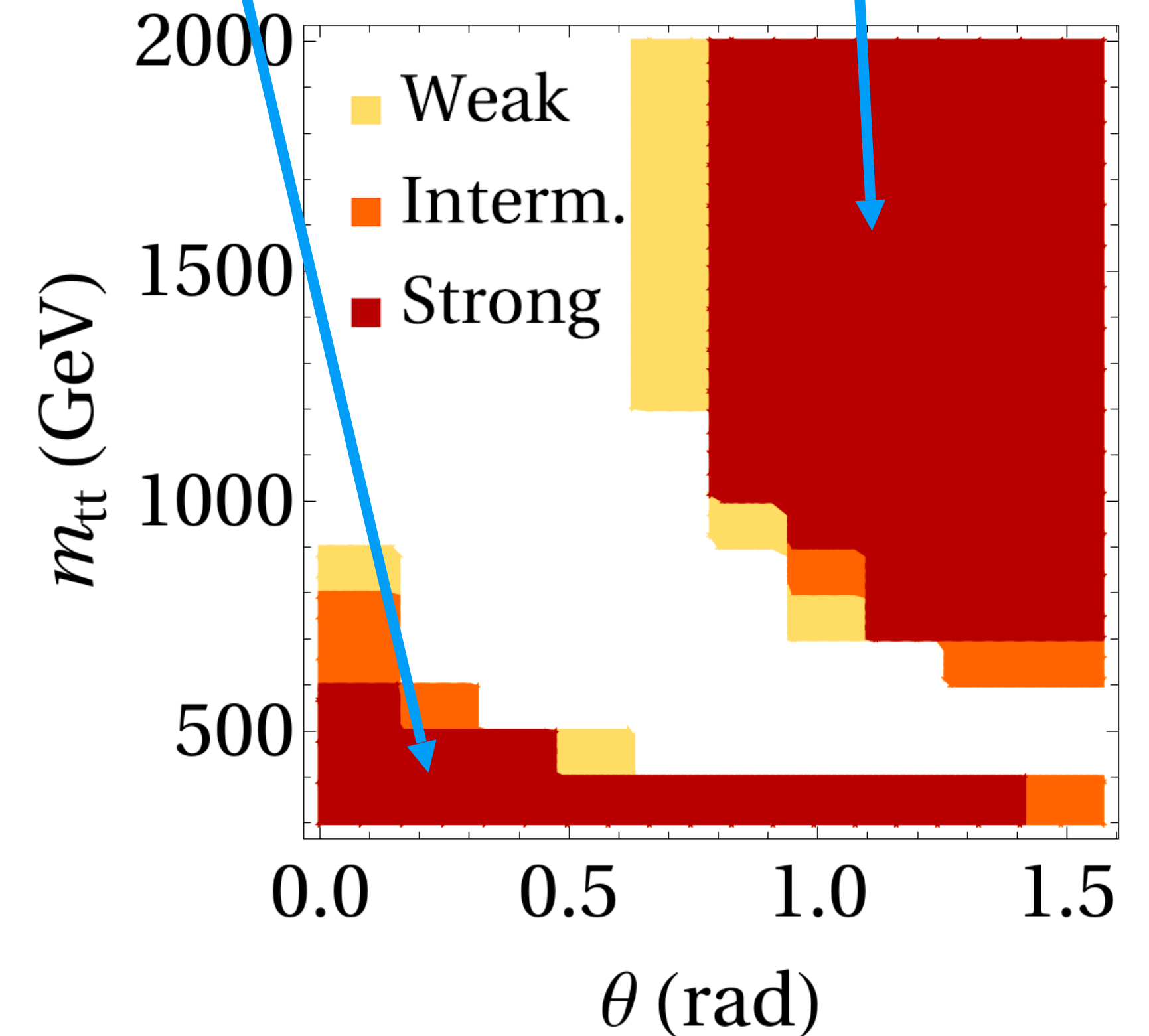
$$C_{kk} + C_{rr} - C_{nn} > 1$$

SM Entanglement

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

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

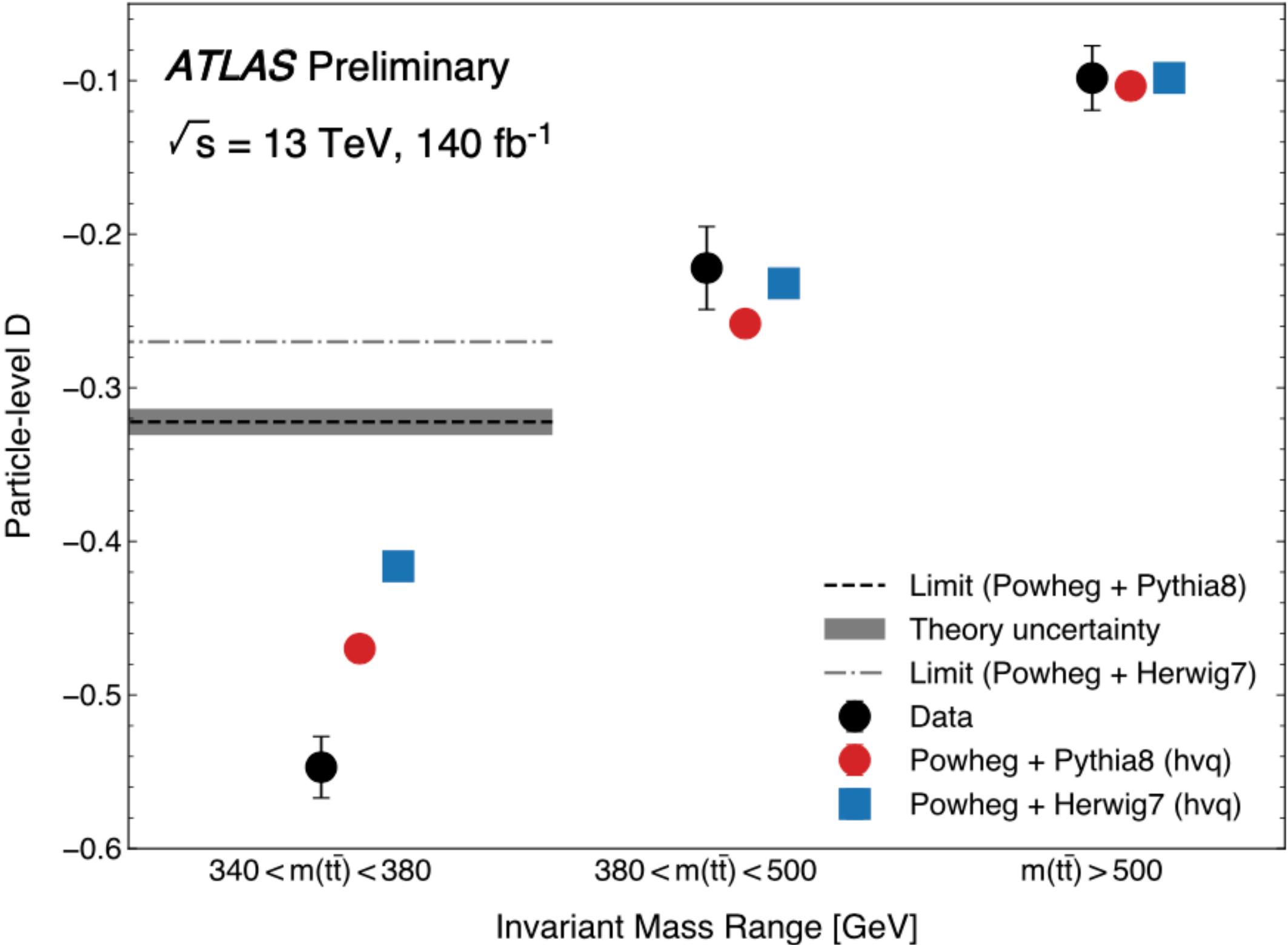
C. Severi, C. Boschi, FM, M. Sioli : 2110.10112



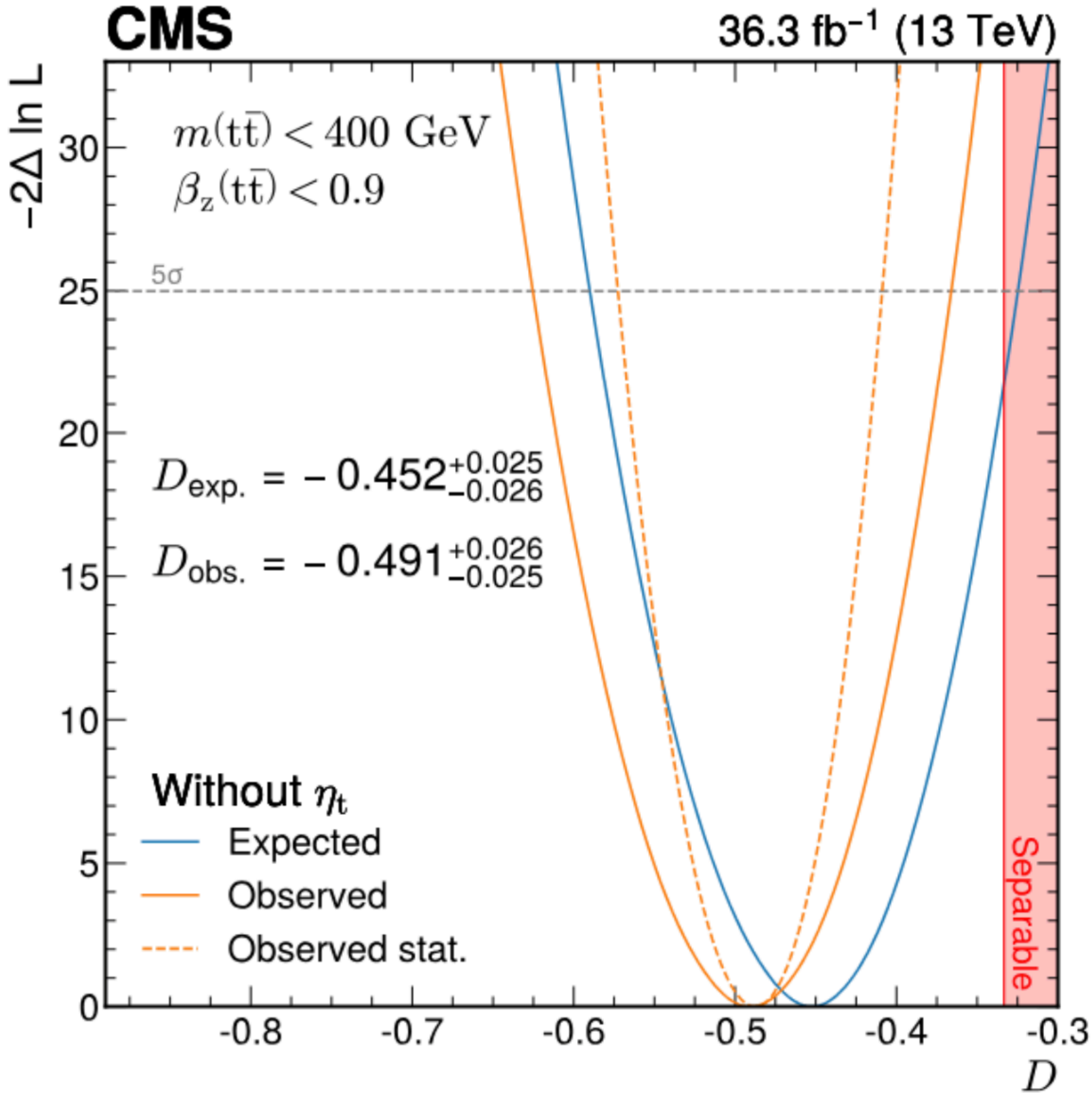
Foreseen to be seen easily with the data available from Run II/Run III.

First measurements

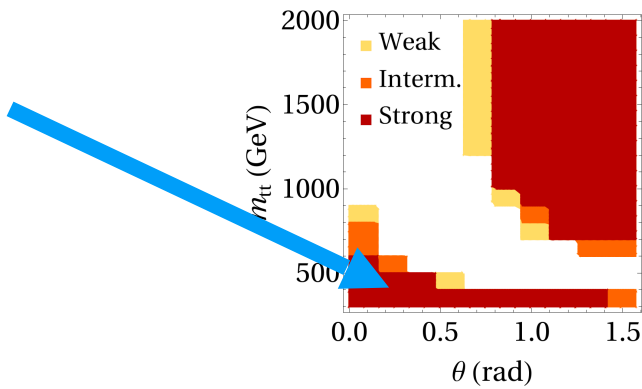
Dilepton channel at threshold



ATLAS-CONF-2023-069



TOP-23-001-pas



Entanglement observation by ATLAS

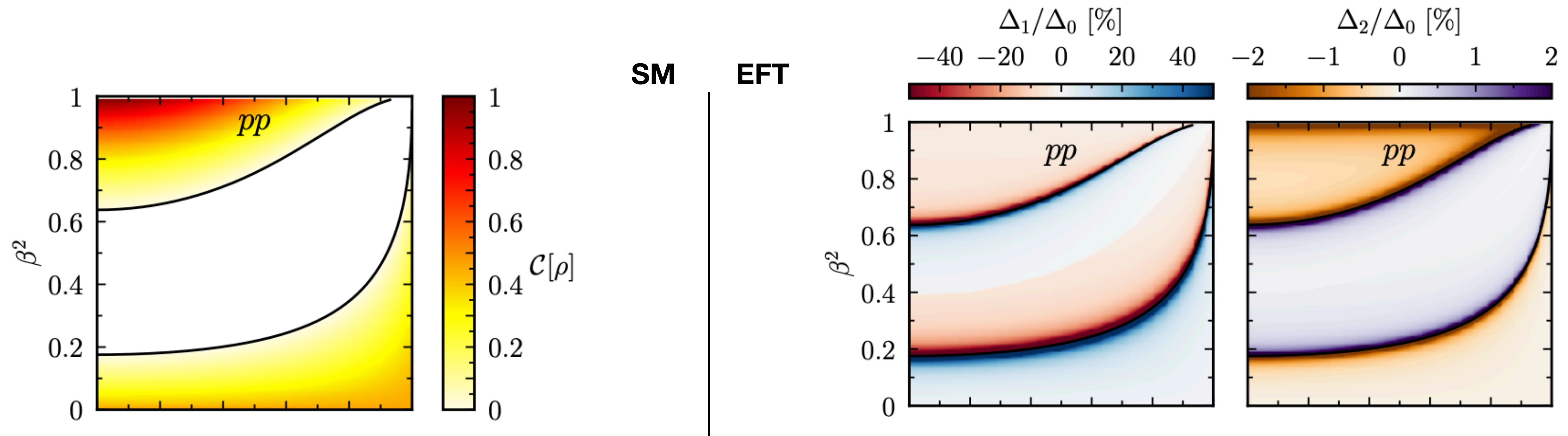
Entanglement observation by CMS

Is there a *Quantum Advantage* in the search for New Physics?

Two model-independent approaches:

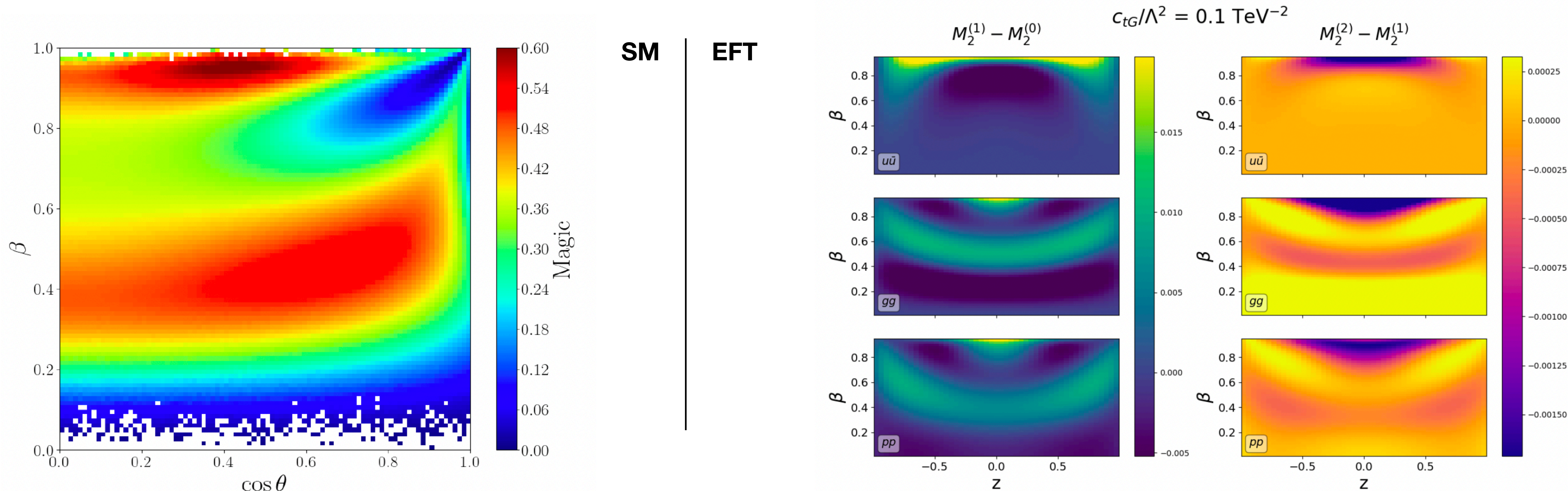
- 1] BSM resides beyond the scales directly explored by the experiment
⇒ Effective Field Theory
- 2] BSM resonances can be directly produced
⇒ Simplified models

Quantum Advantage for SMEFT : Entanglement



- 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 and breaking degeneracies.

Quantum Advantage for SMEFT : Magic



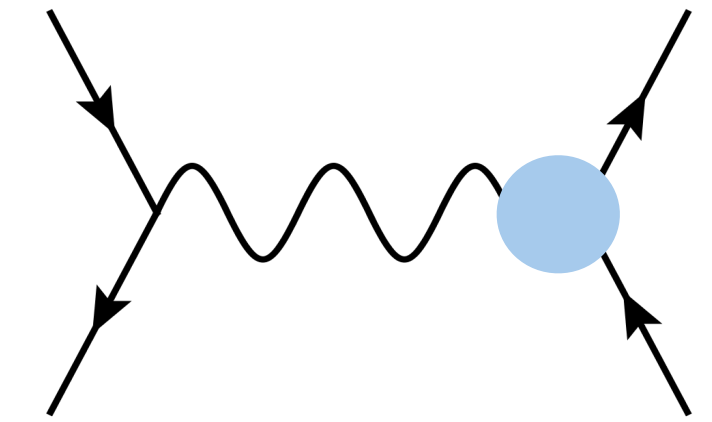
In quantum information, **magic** refers to the amount of *non-Clifford, non-stabilizer* structure present in a quantum state or operation. It quantifies **how far** a state is from the set of states that can be efficiently simulated classically via stabilizer methods (Gottesman–Knill).

Quantum tops: CP violation

- 4-fermion CP-odd operators $\rightarrow$ no CPV effects.
- $O_{uW}, O_{uB} \rightarrow$ magnetic and electric dipole moment form factors:

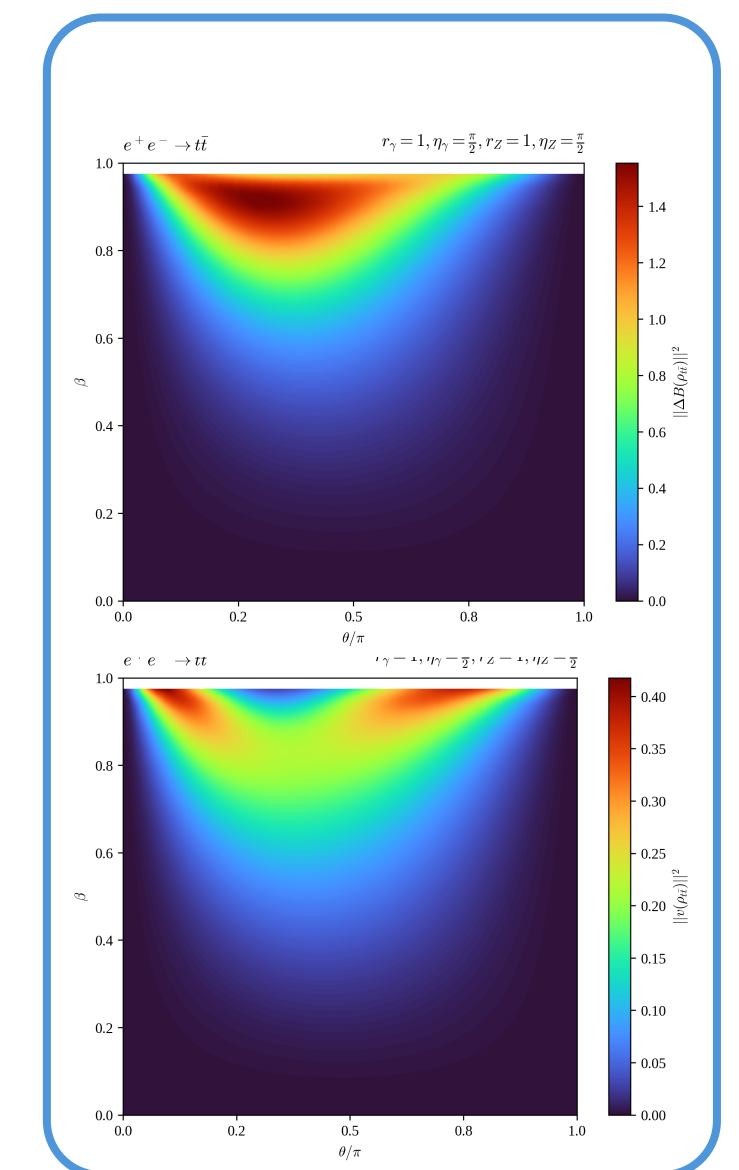
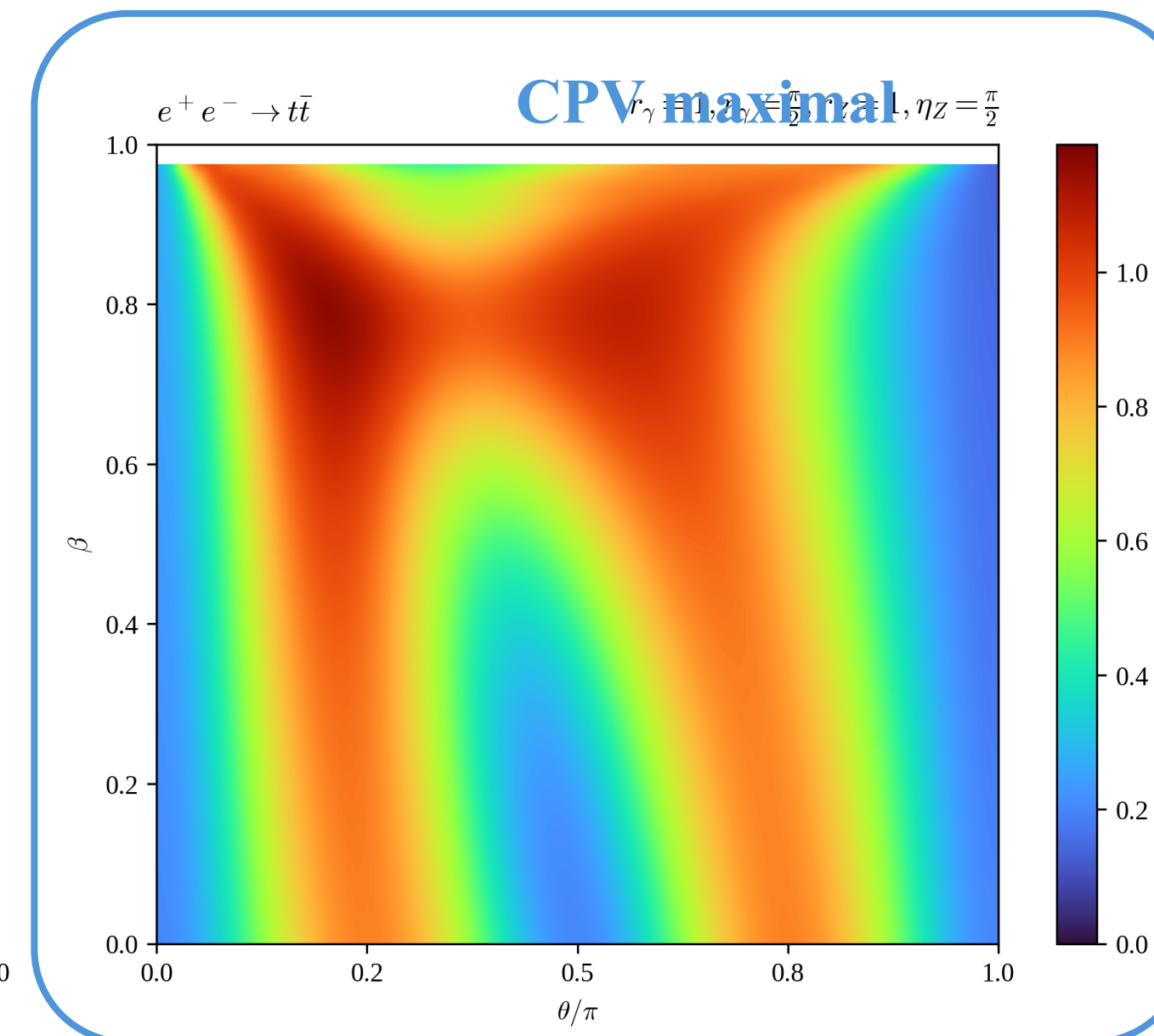
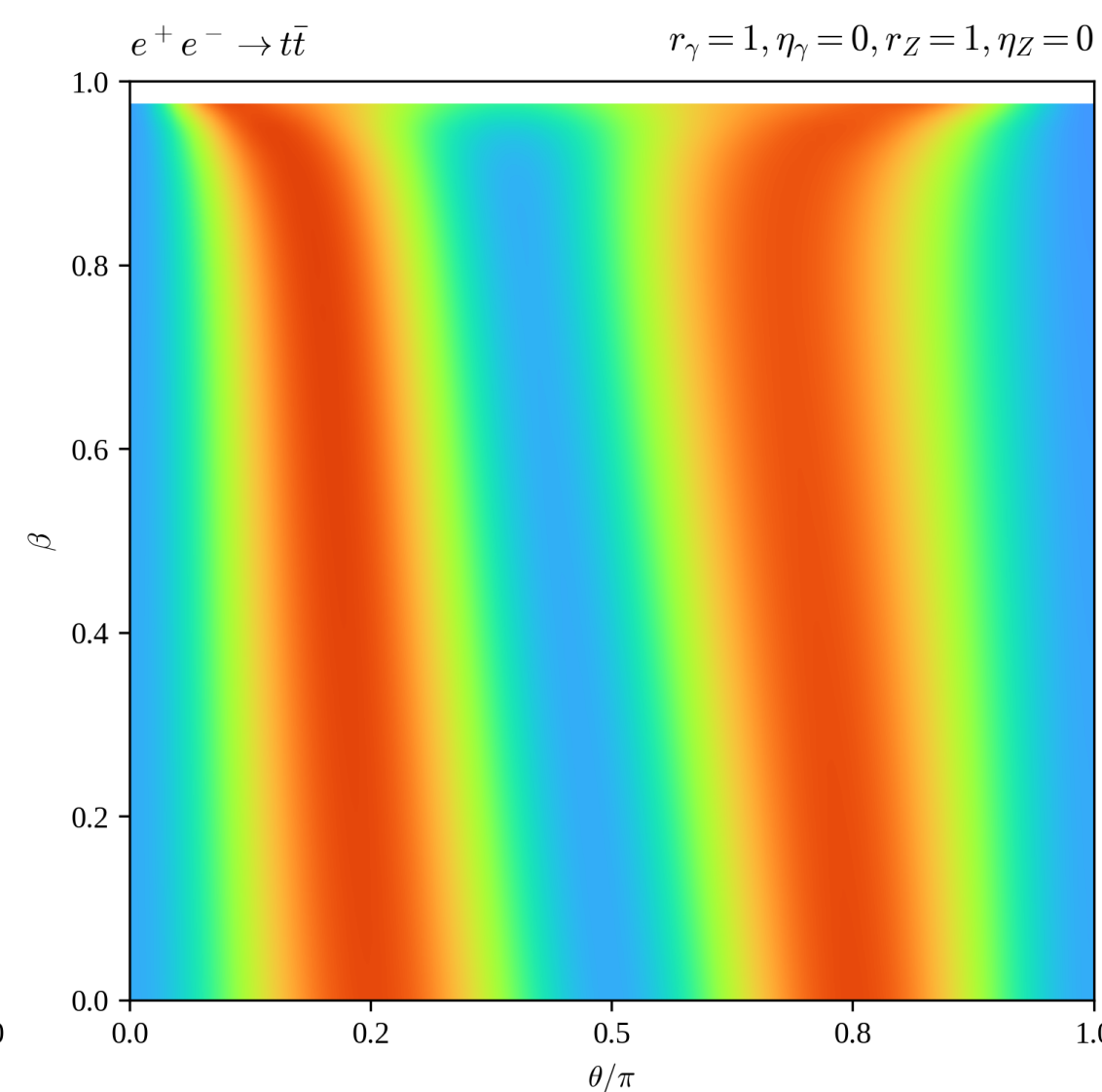
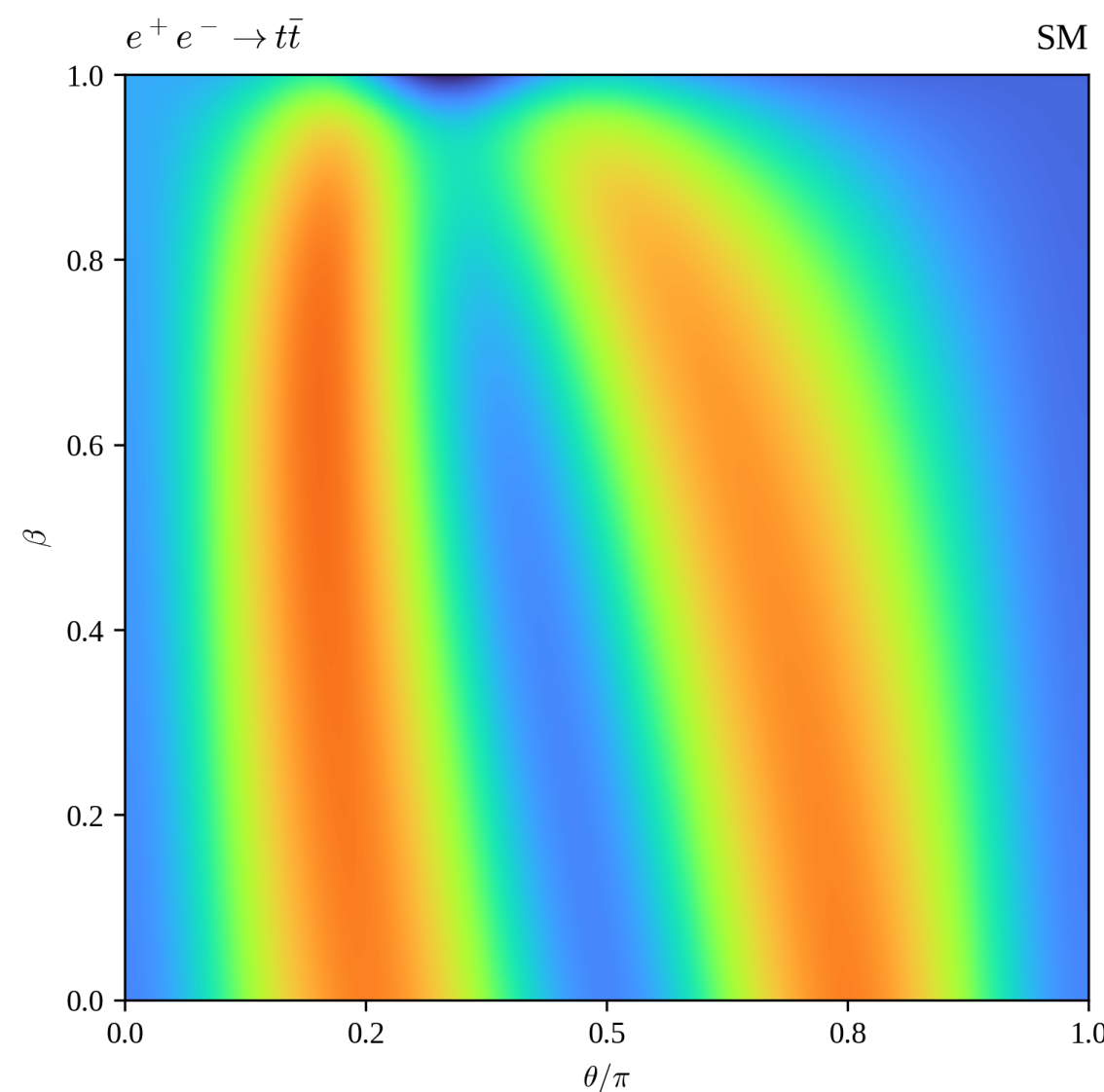
$$t\bar{t}V^\mu = ie\gamma^\mu(\bar{g}_V^V - \bar{g}_V^A\gamma^5) - \frac{v}{\Lambda^2}\sigma^{\mu\nu}q_\nu(d_V P_R + d_V^* P_L)$$

- $t\bar{t}$ individually polarized and correlated.

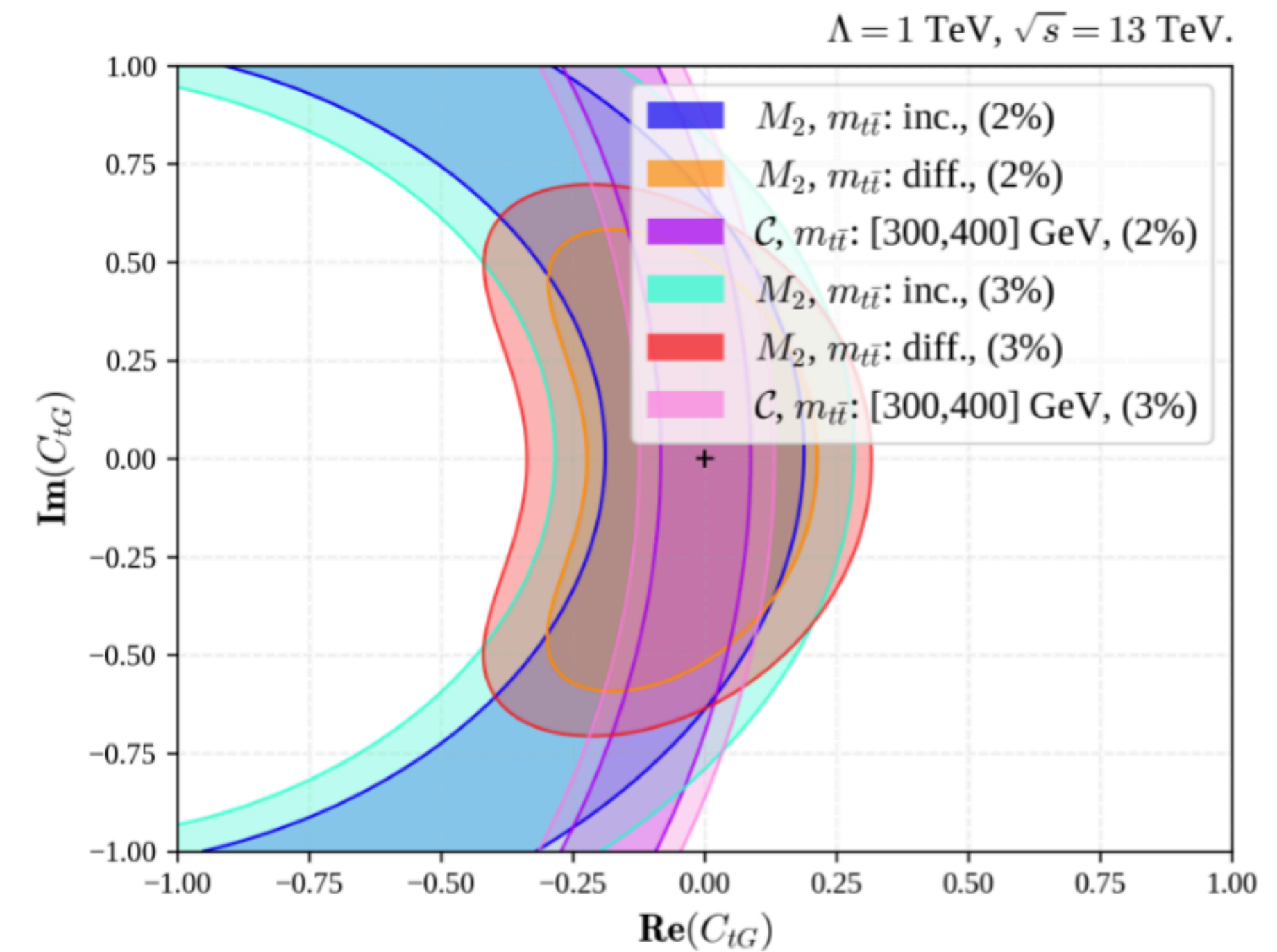
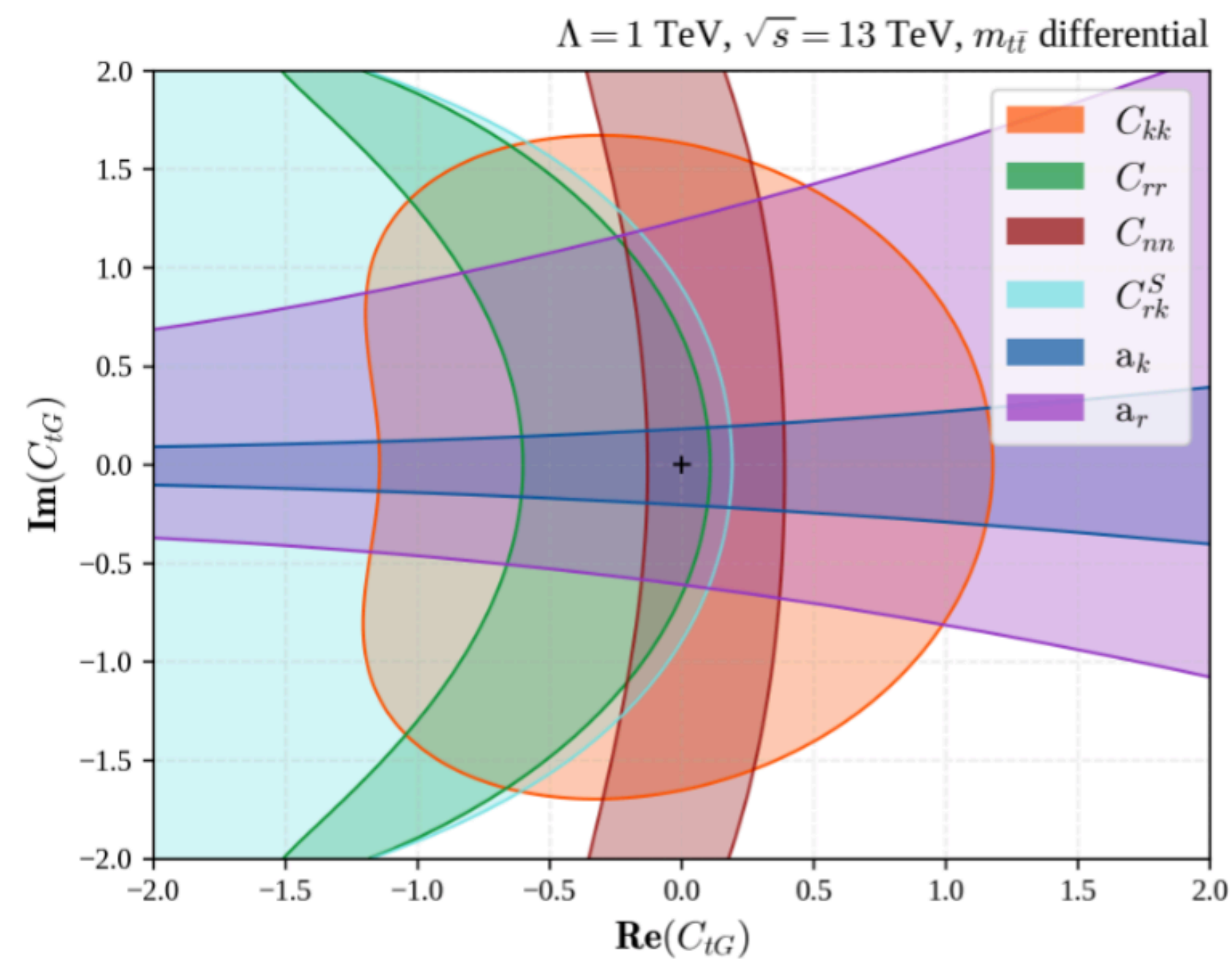


$$d_Z = r_Z(\cos \eta_Z + i \sin \eta_Z)$$

$$d_\gamma = r_\gamma(\cos \eta_\gamma + i \sin \eta_\gamma)$$



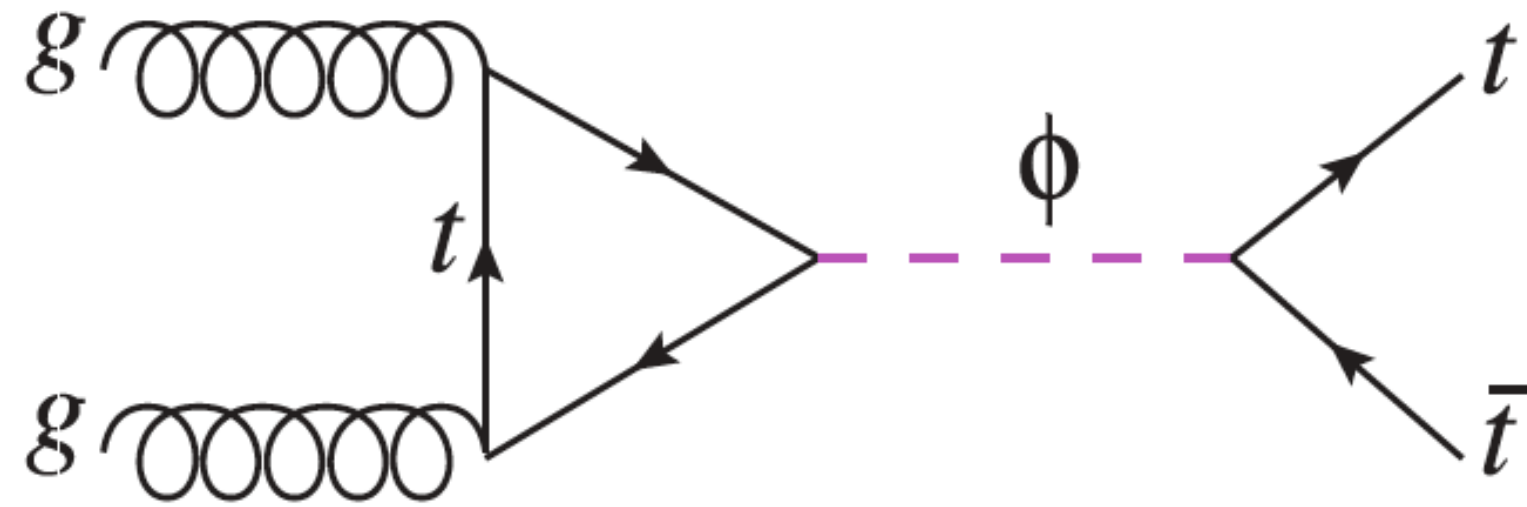
Quantum tops: CP violation



CP violation from chromo-electric contribution at the LHC. Constraints imposed from current data using different quantum observables and distributions.

BSM resonances

Scalar

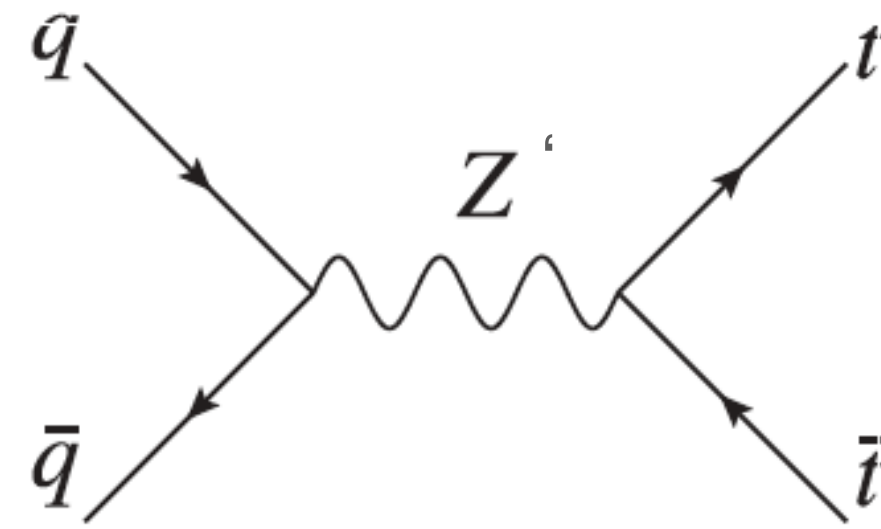


$$c_y \frac{y_t}{\sqrt{2}} \phi \bar{t} (\cos \alpha + i \gamma^5 \sin \alpha) t$$

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

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

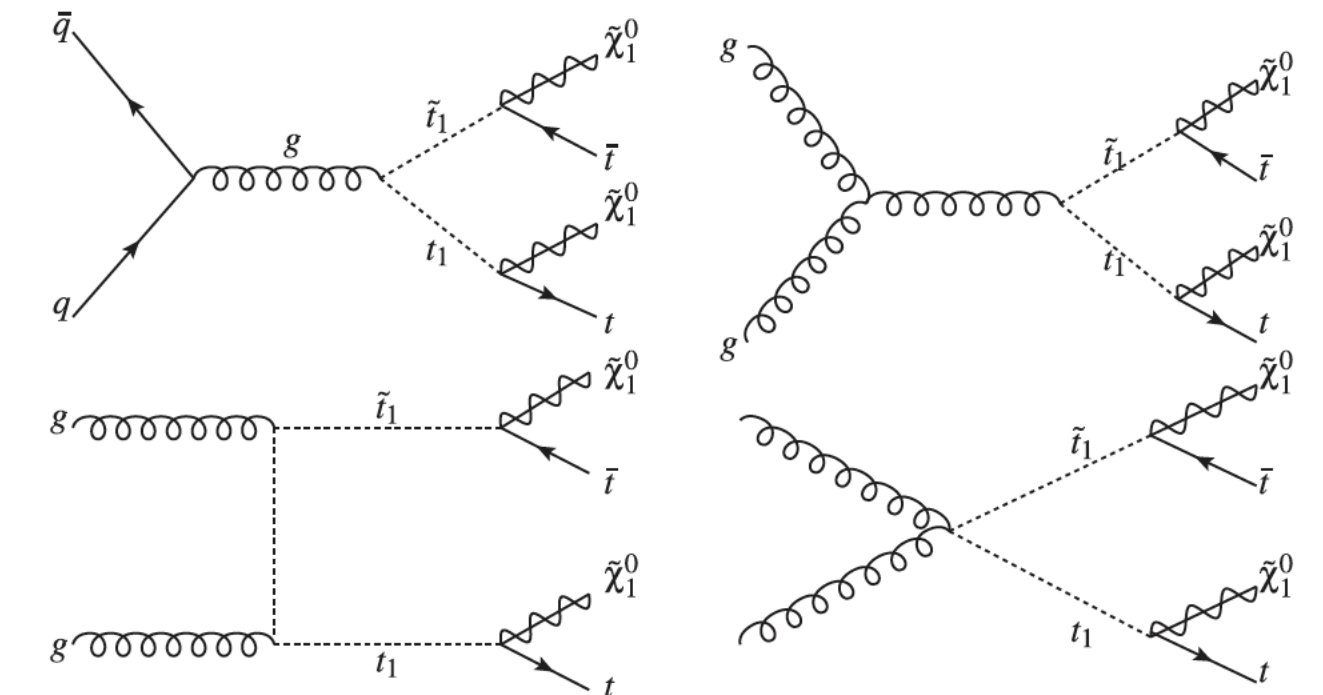
Z'



Sequential Z'

It interferes with SM EW top production.

Stops



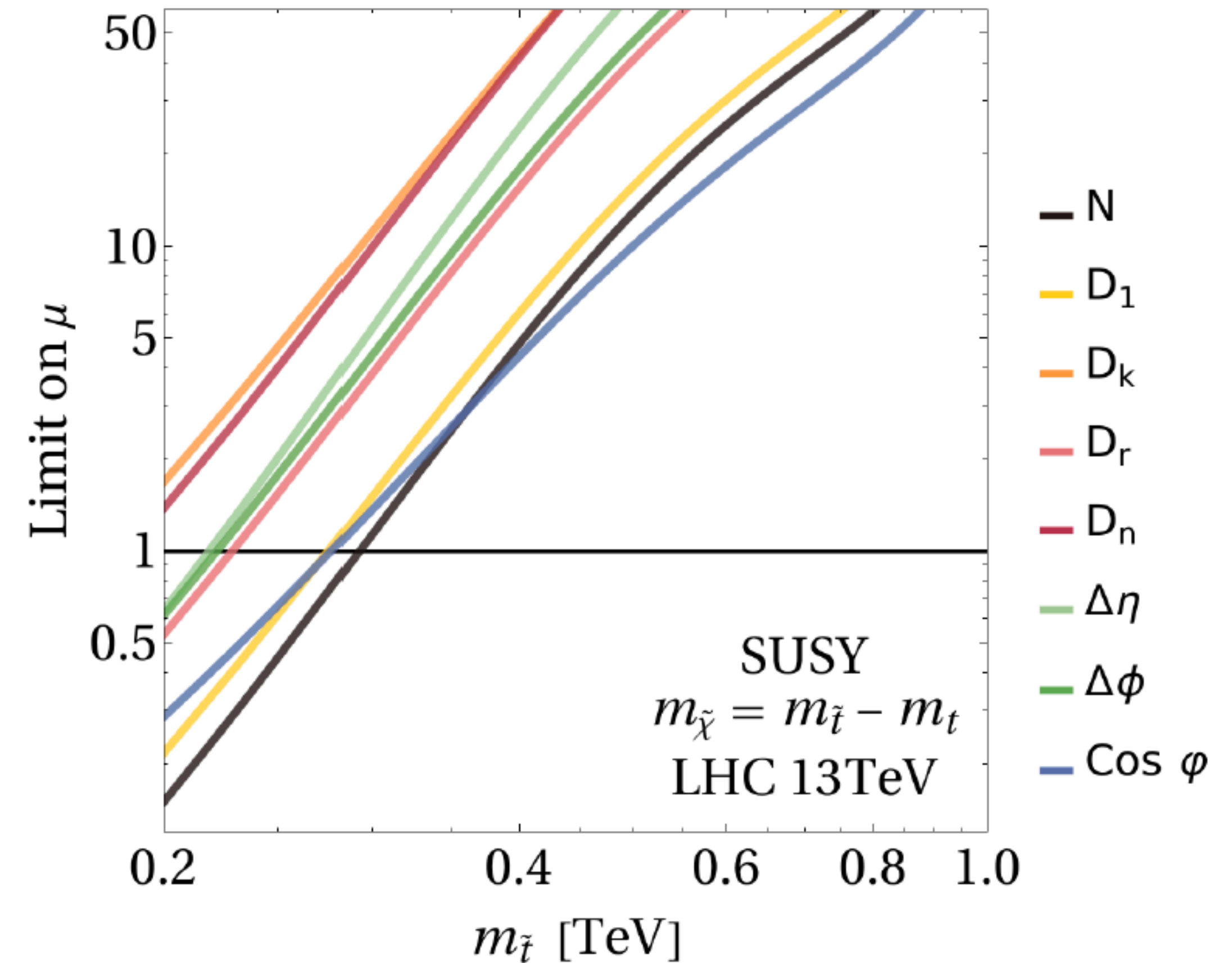
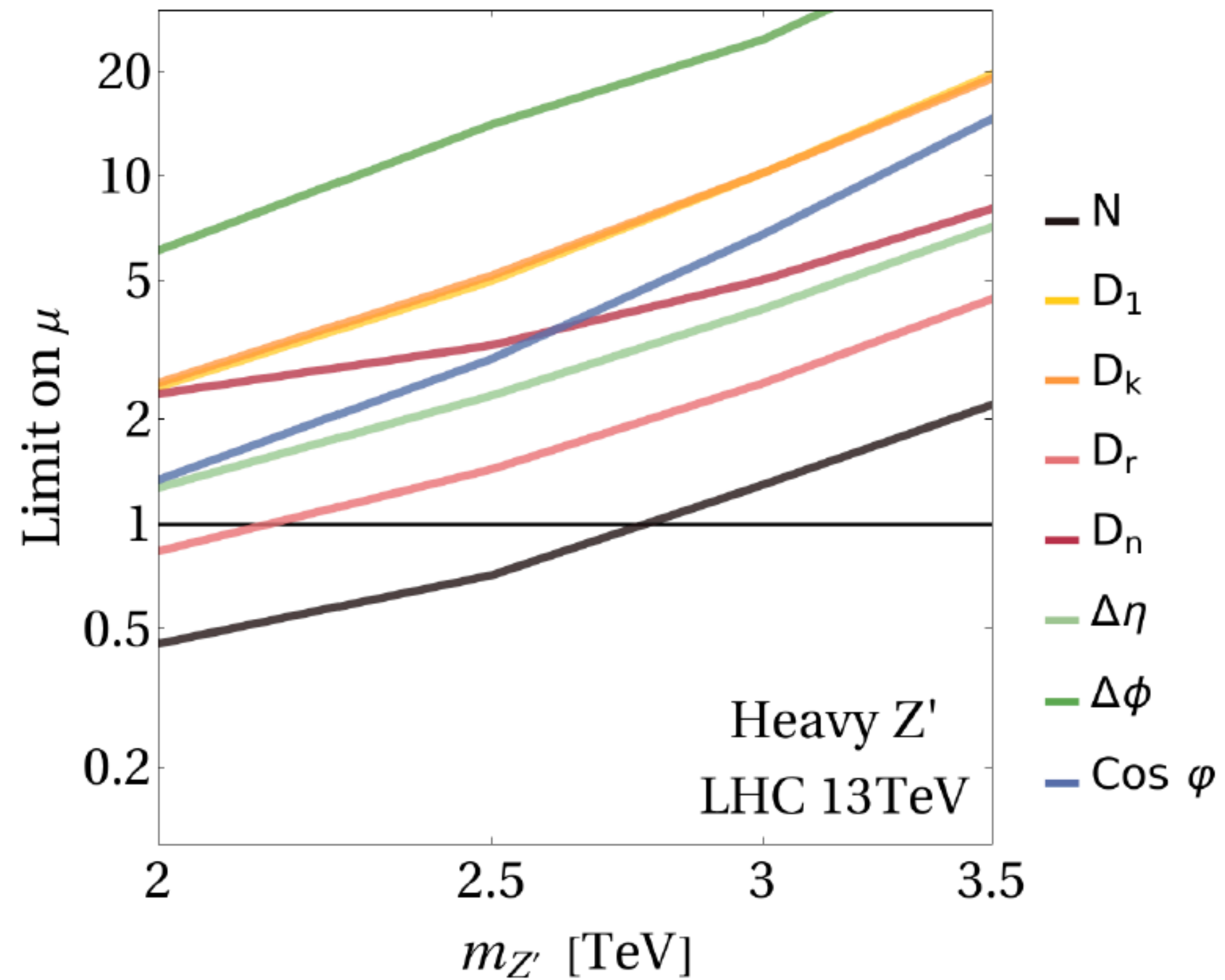
$$|m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} - m_t| \approx \Gamma_t,$$

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

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

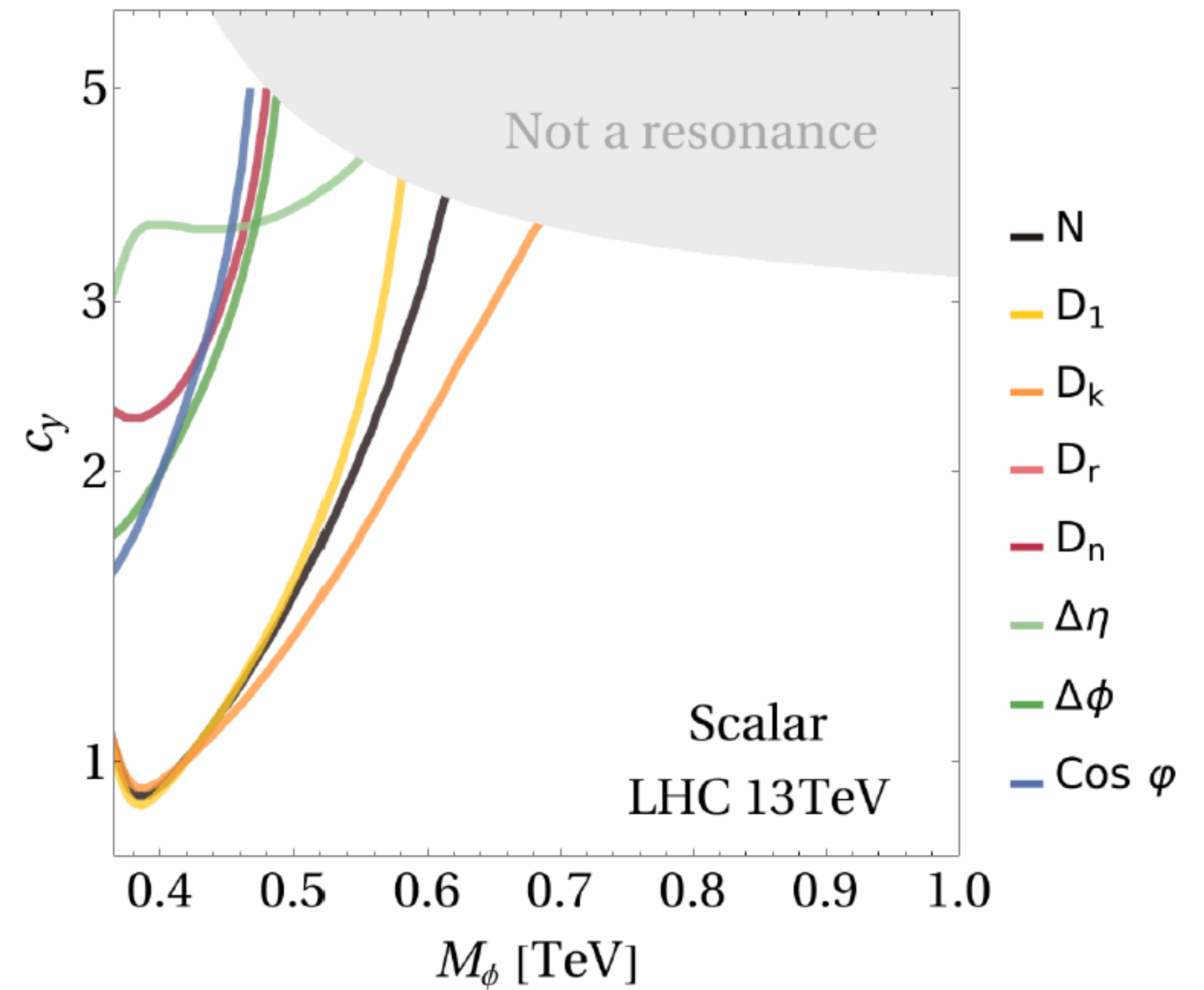
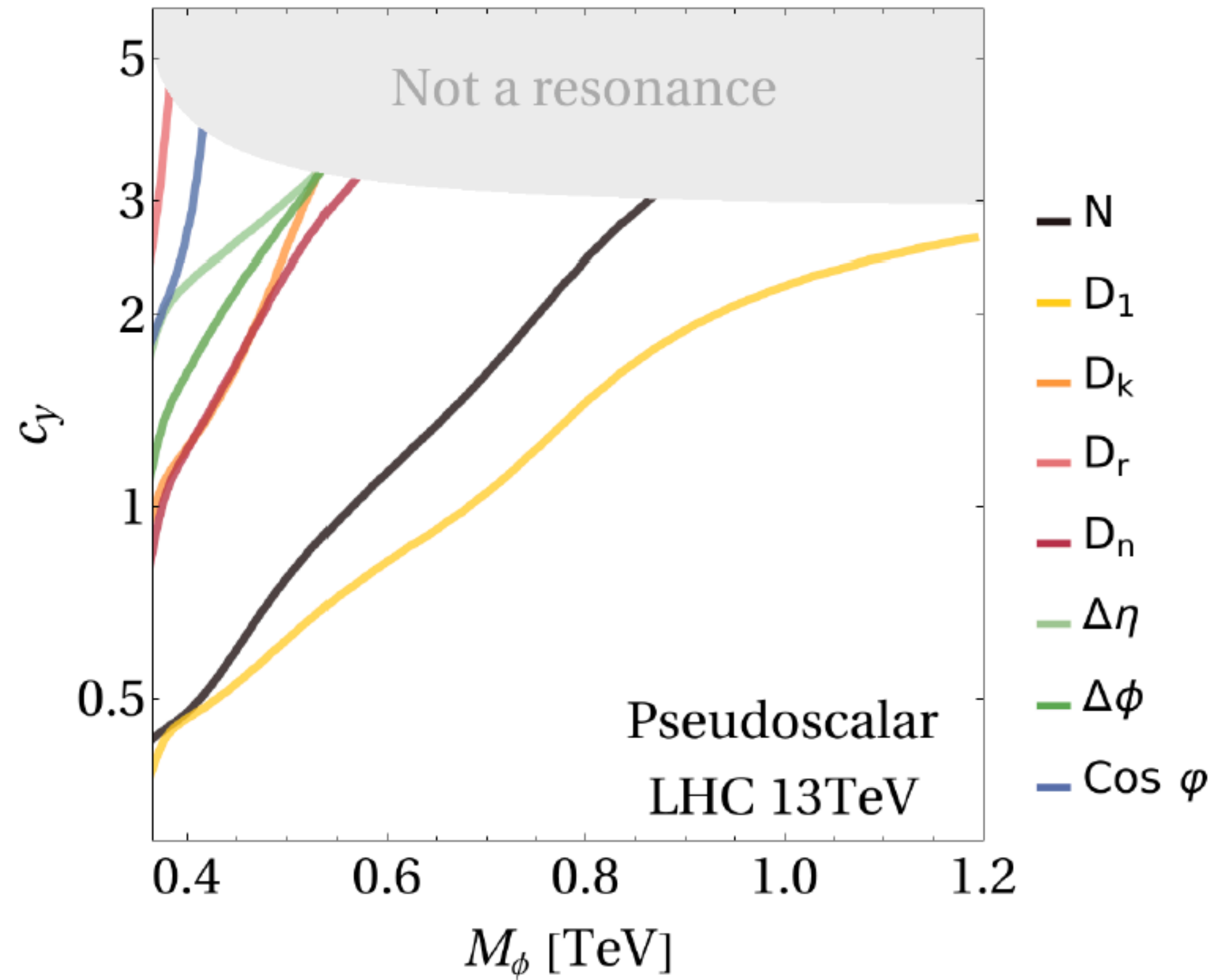
$$\mathcal{C} = \frac{A^{[\text{SM}]}{A^{[\text{TOT}]}}} \mathcal{C}^{[\text{SM}]} + \frac{A^{[\text{SUSY}]}{A^{[\text{TOT}]}}} \mathcal{C}^{[\text{SUSY}]} = \frac{A^{[\text{SM}]}{A^{[\text{TOT}]}}} \mathcal{C}^{[\text{SM}]},$$

Quantum Advantage for BSM resonances



Not adding much...

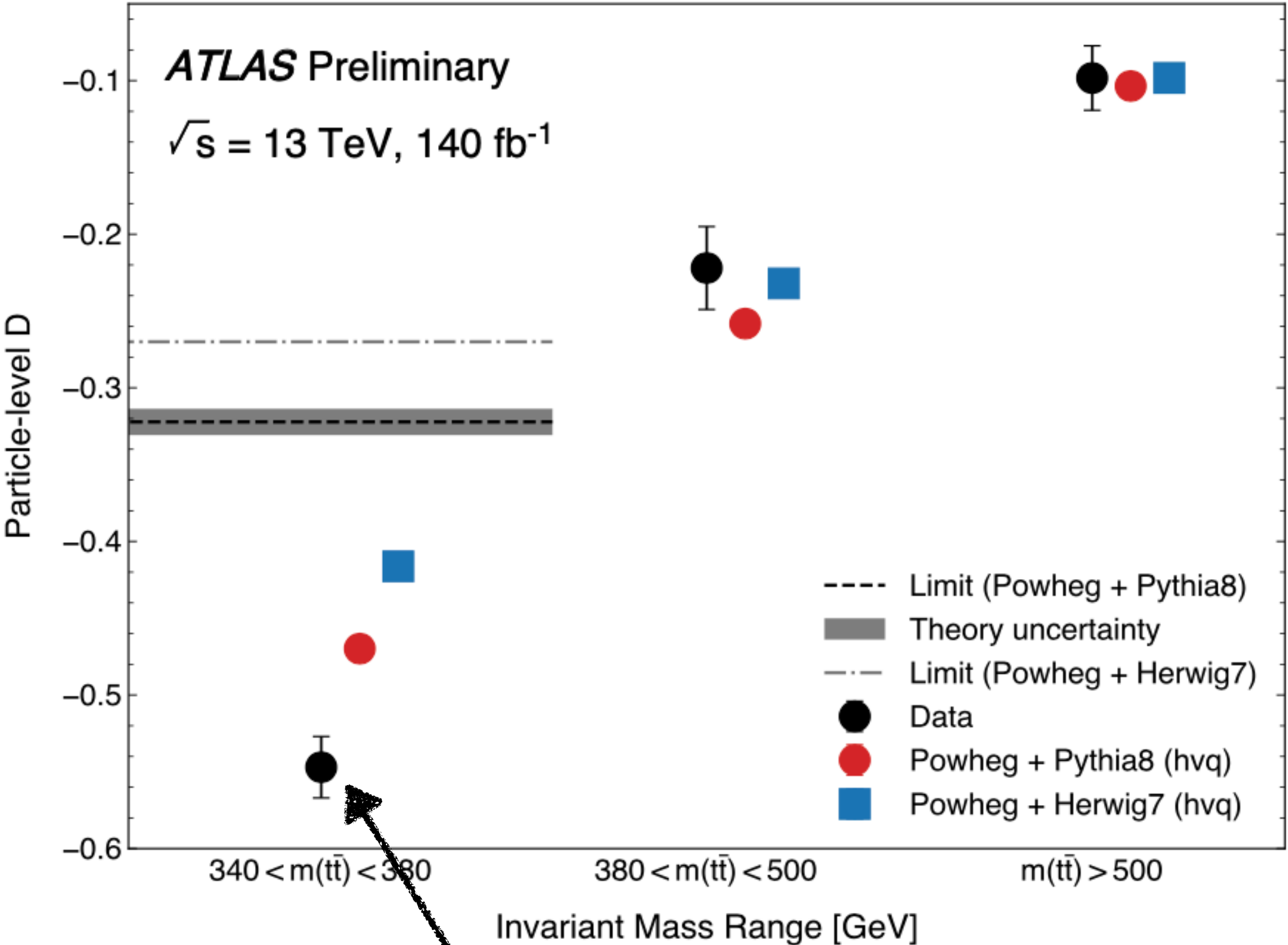
Quantum Advantage for BSM resonances



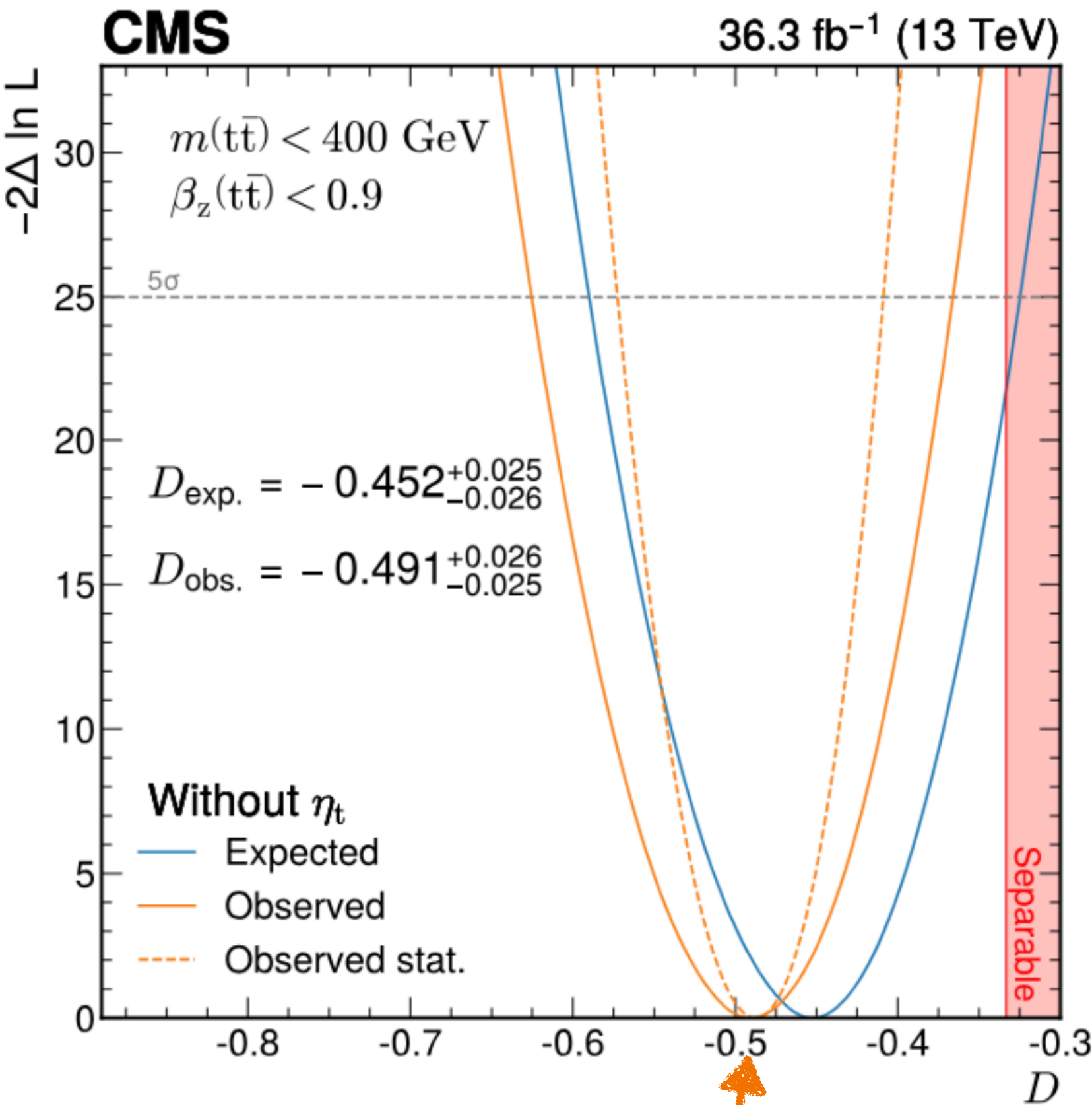
Promising!

First measurements

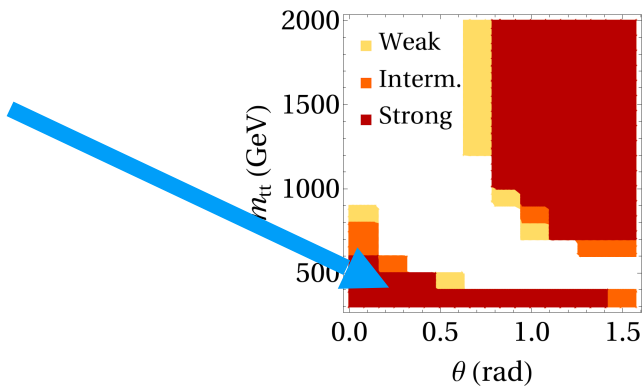
Dilepton channel at threshold



ATLAS-CONF-2023-069



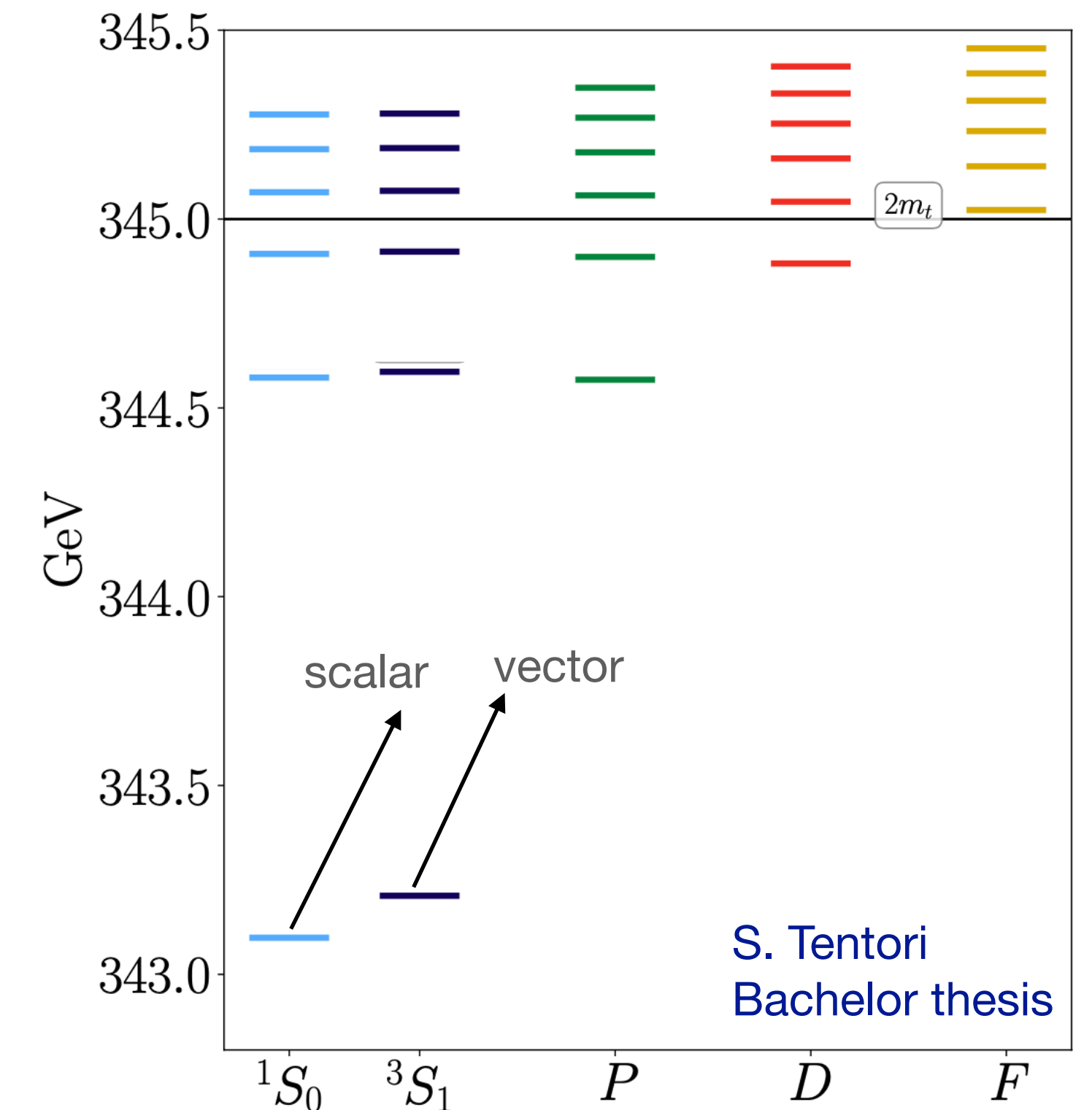
TOP-23-001-pas



More entanglement than predicted by NLO+PS QCD!

New SM Physics: Toponium

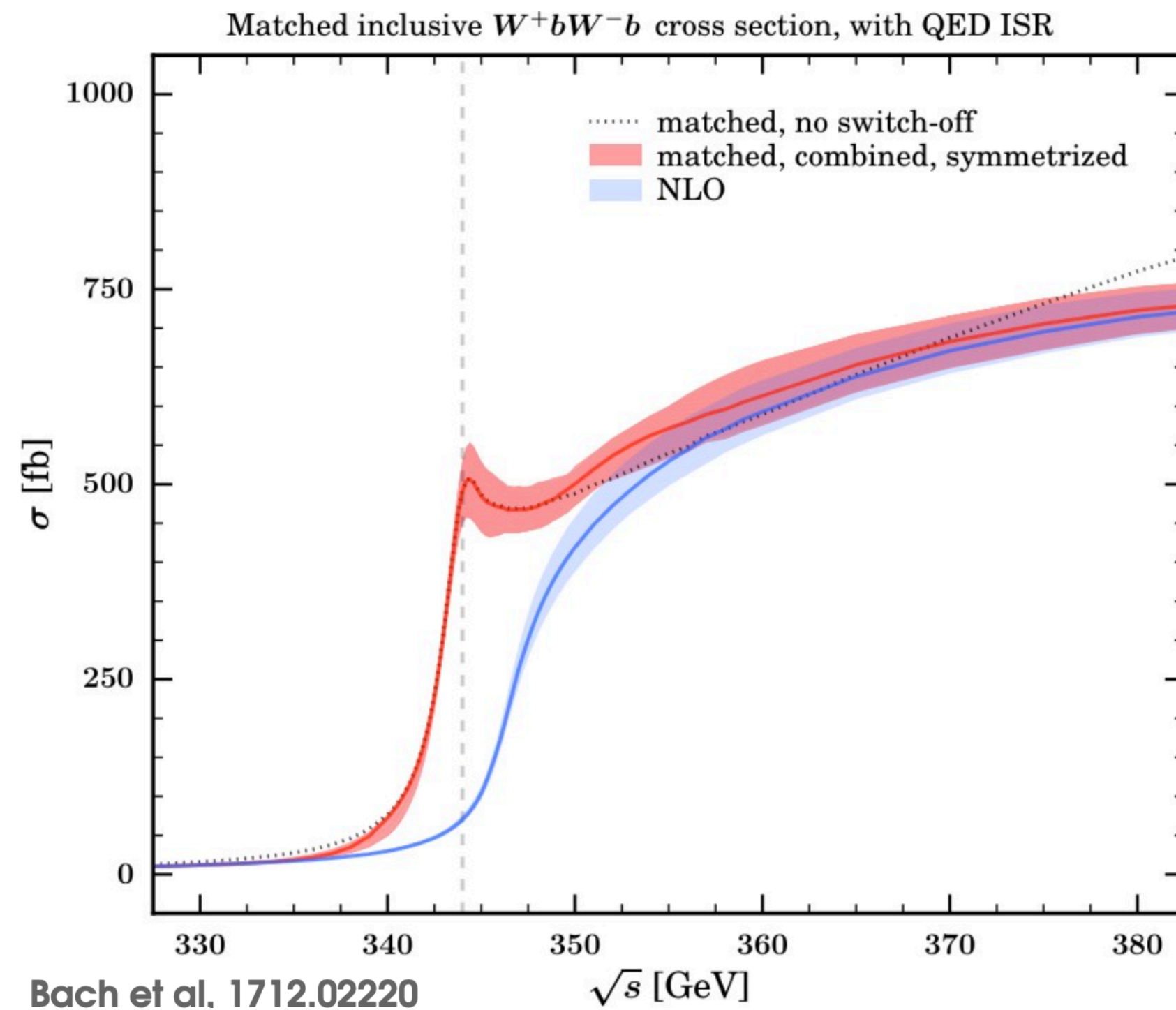
- Quasi-Bound State of top and antitop
- Energy states obtained by solving Schrödinger equation with QCD potential
- Described by NRQCD
- Ground state $n=1$ S-wave
- Spin-singlet vs spin-triplet depending on production mode
 - spin singlet for pp and spin triplet for e^+e^-



$$\left[(E + i\Gamma_t) - \left(\frac{\nabla^2}{m_t} + V(\mathbf{r}) \right) \right] G(\mathbf{r}, E + i\Gamma_t) = \delta^{(3)}(\mathbf{r}) \quad V_{\text{QCD}}(r, \mu_B) = C^{[\text{col}]} \frac{\alpha_s(\mu_B)}{r} \left[1 + \frac{\alpha_s}{4\pi} \left(2\beta_0 \log(e\gamma\mu_B r) + \frac{31}{9}C_A - \frac{10}{9}n_f \right) + \mathcal{O}(\alpha_s^2) \right]$$

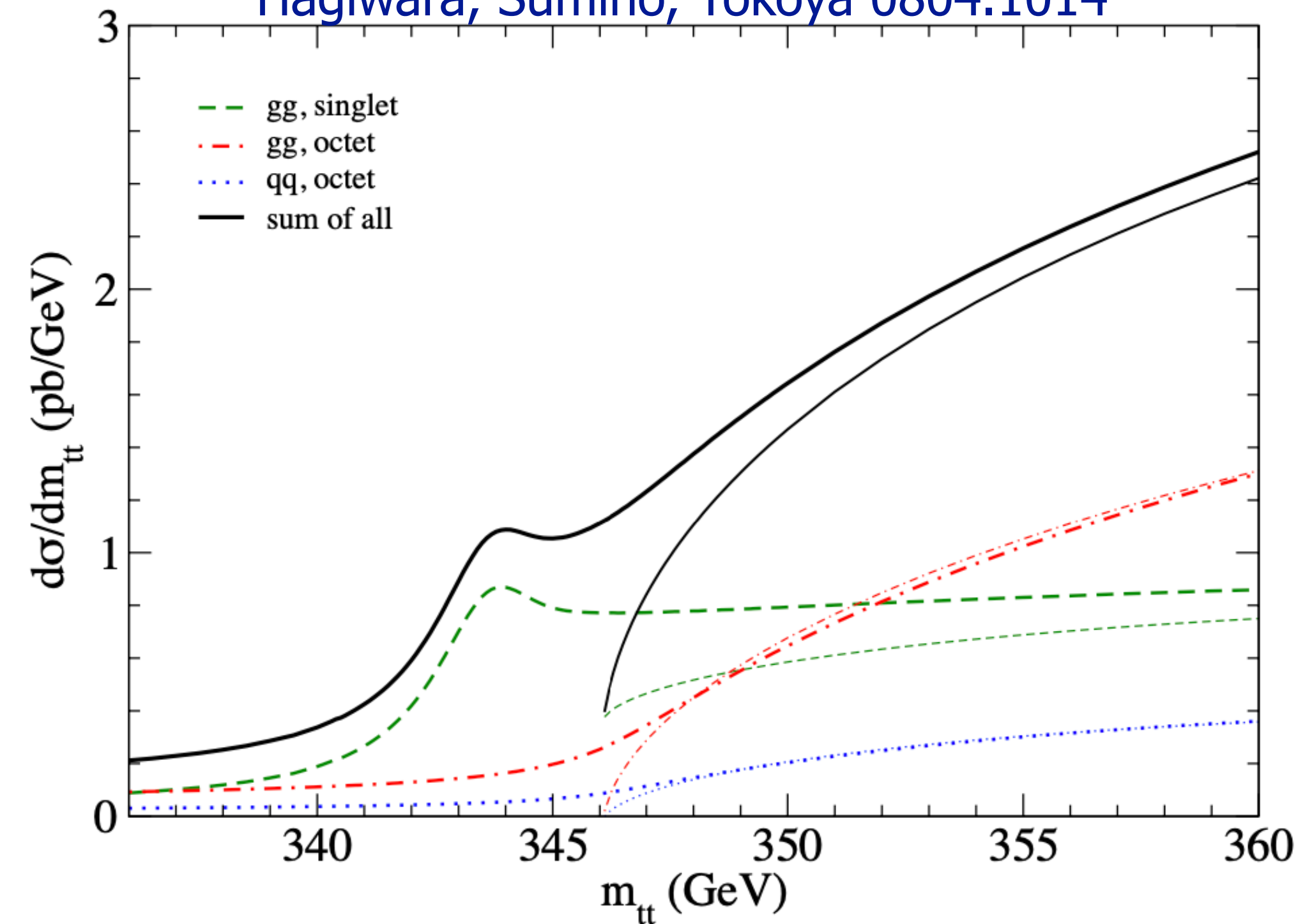
New SM Physics: Toponium

e^+e^- predictions



LHC predictions

Hagiwara, Sumino, Yokoya 0804.1014



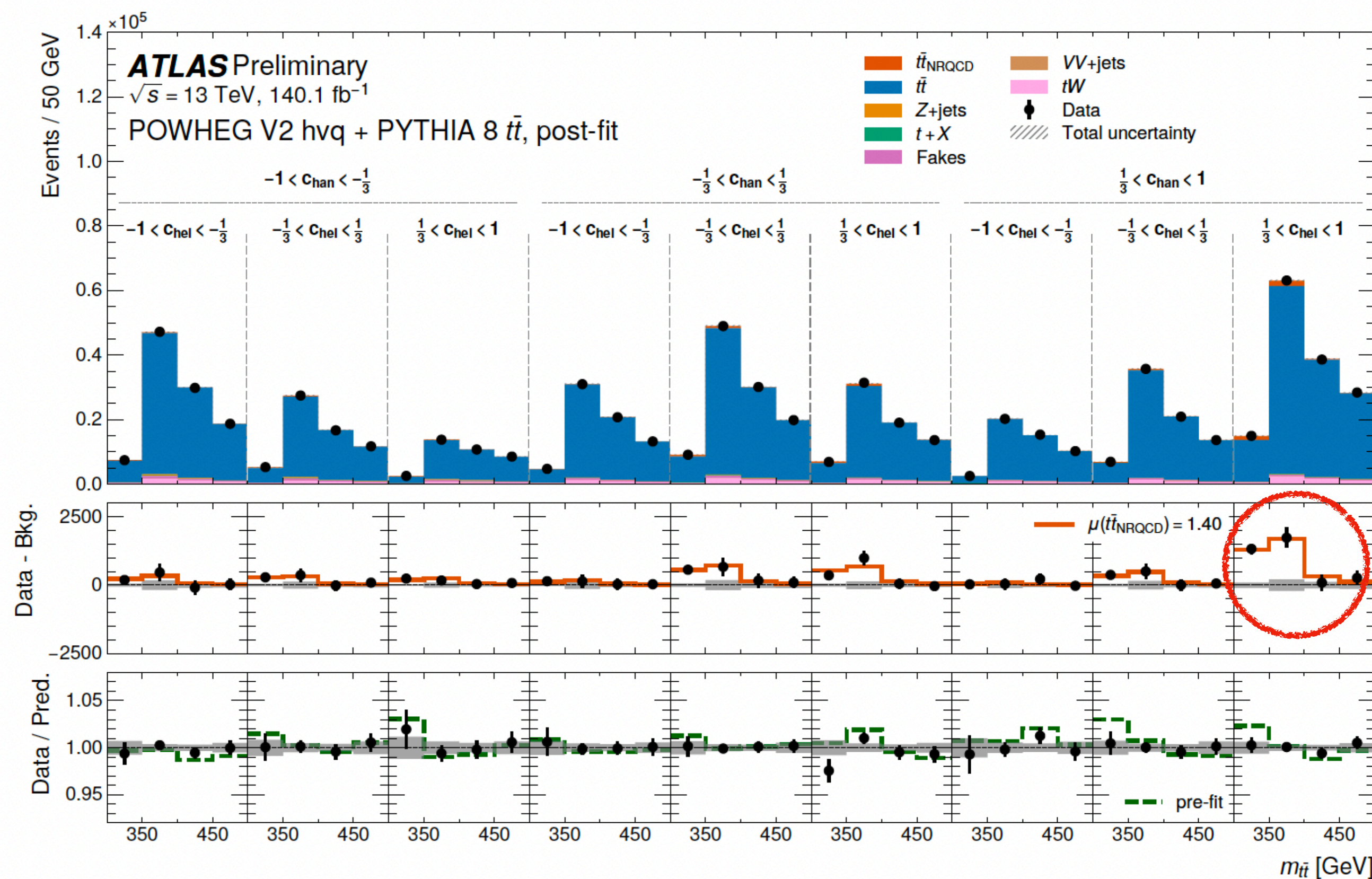
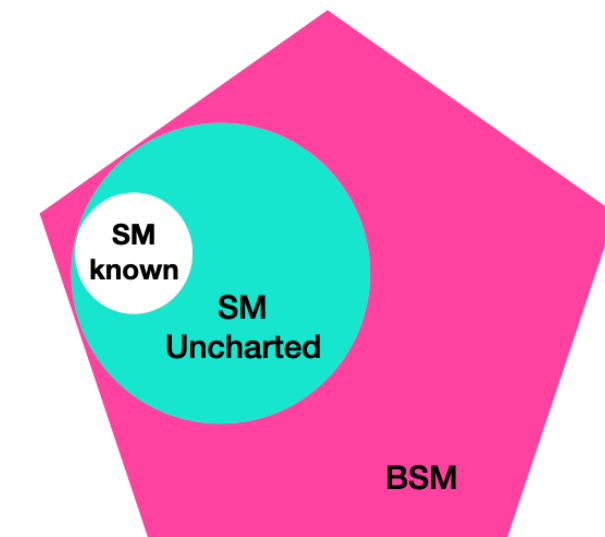
Fully differential NLO+LL, Coulomb Resummation

Coulomb Resummation

Needs matching between below threshold, toponium region, continuum

Measurements

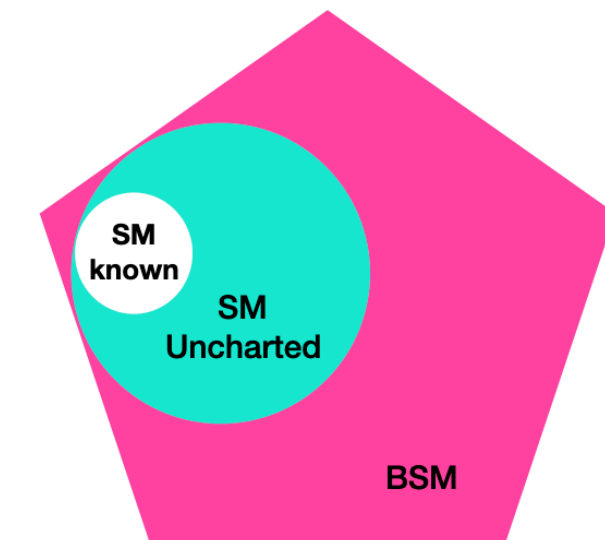
Dilepton channel at threshold



Follow-up studies localized the effect through $m_{t\bar{t}}$ binning and spin-correlation observables.

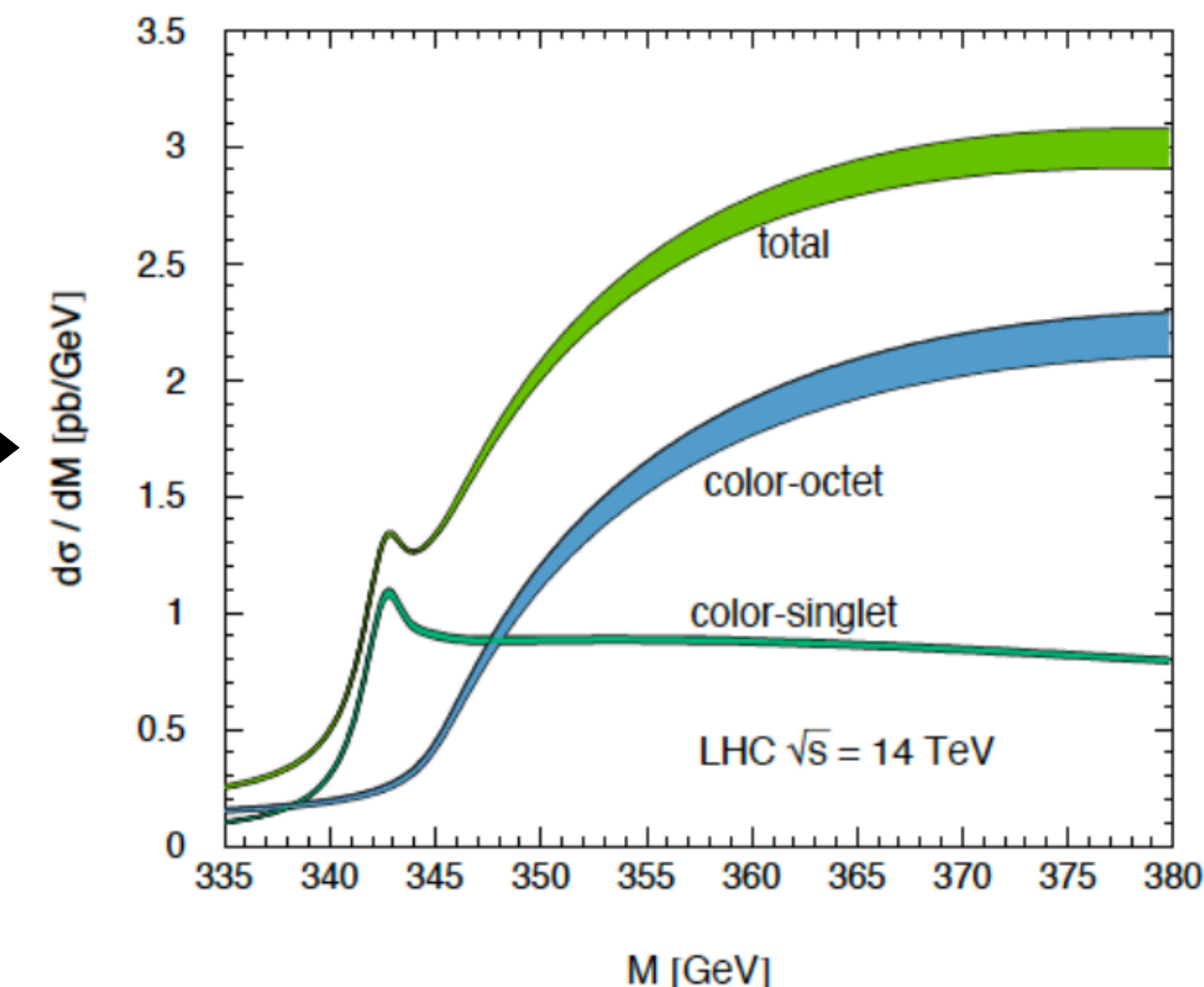
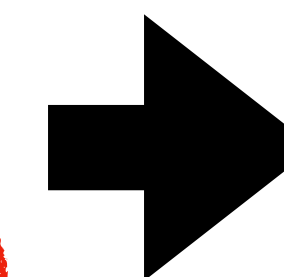
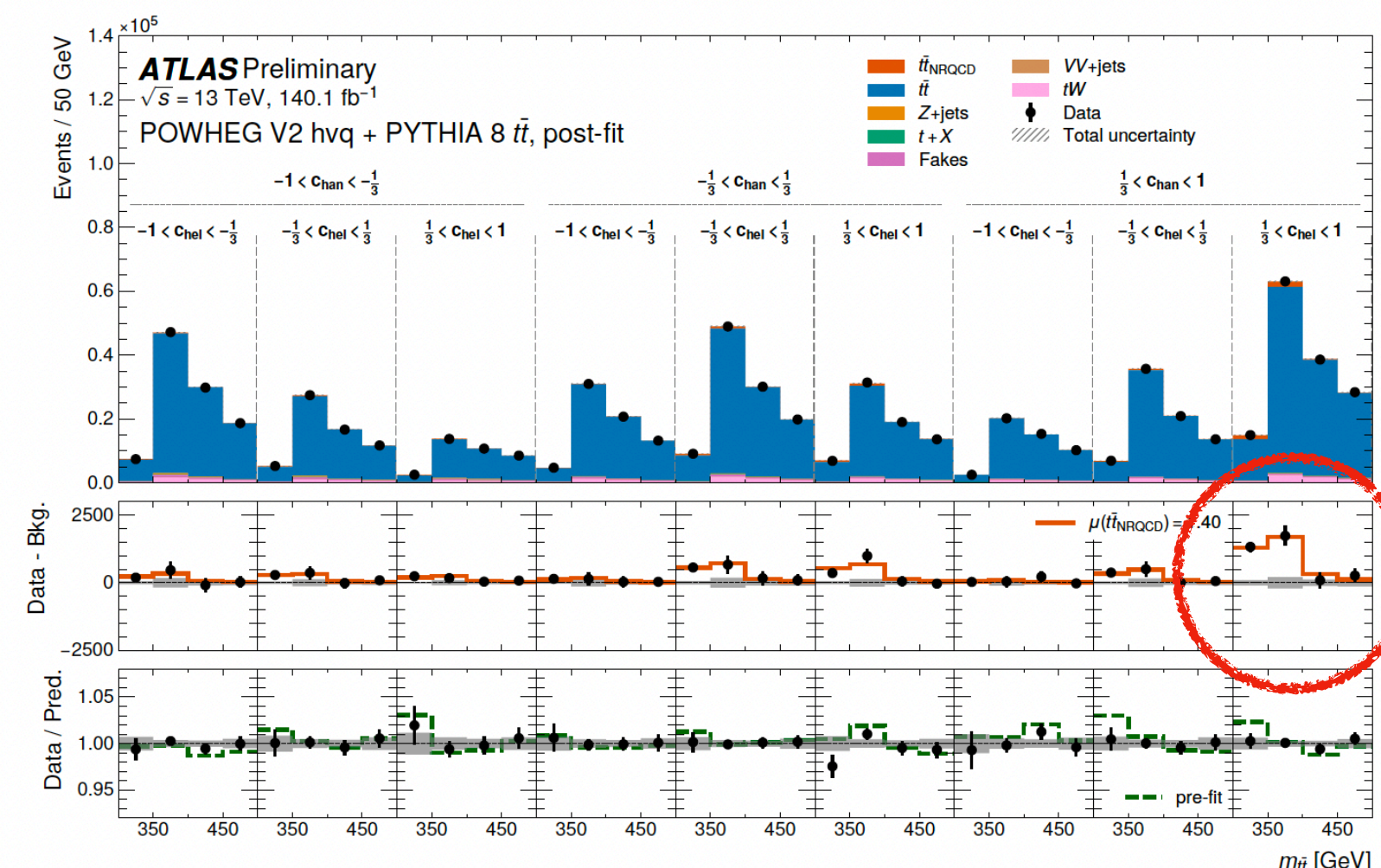
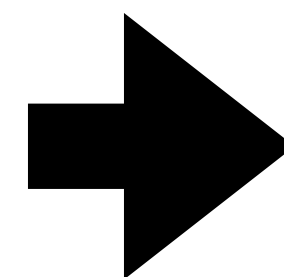
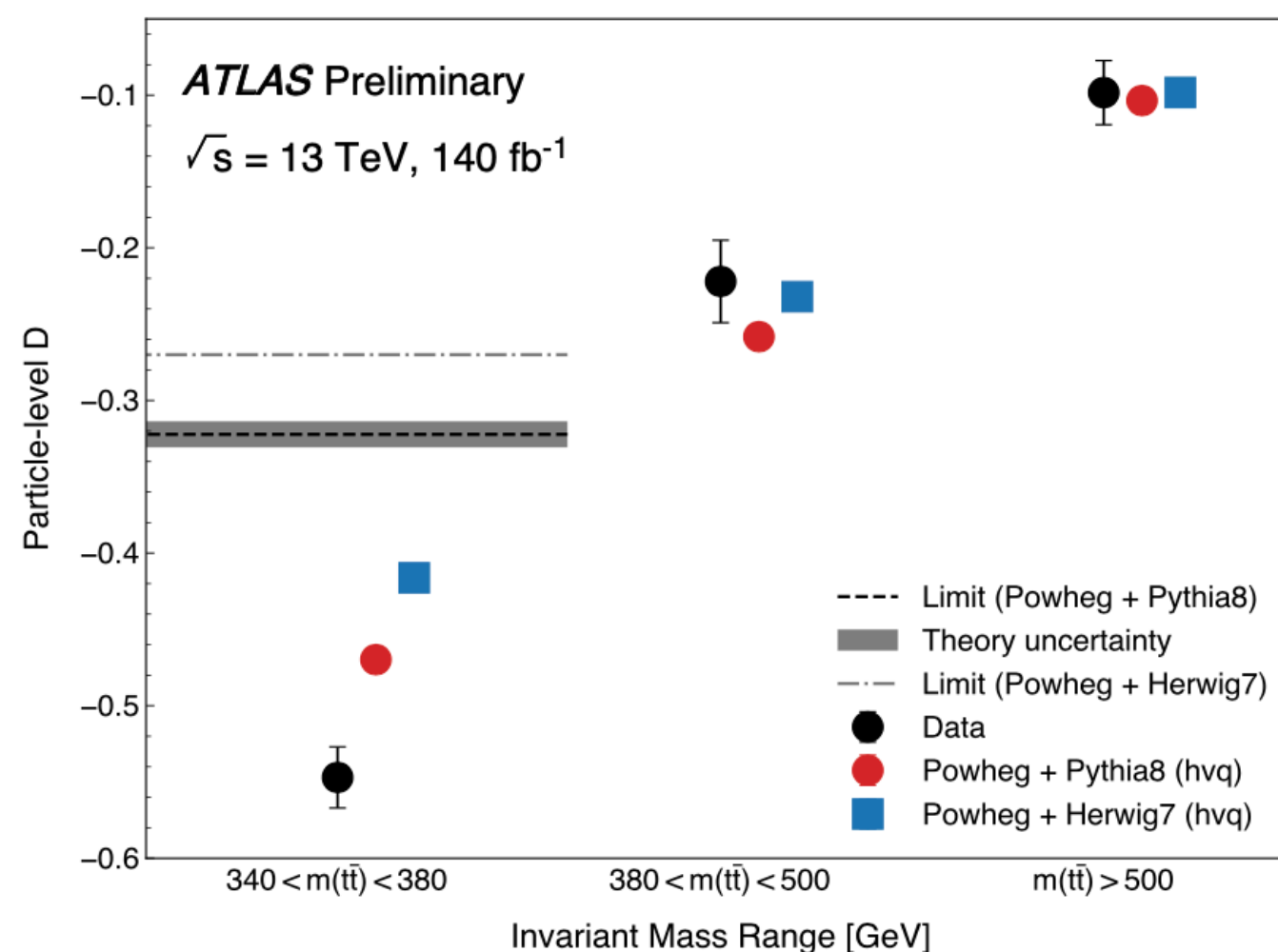
Measurements

Dilepton channel at threshold



Hagiwara, Sumino, Yokoya, arXiv: 0804.1014

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



Early CMS and ATLAS entanglement measurements near the $t\bar{t}$ threshold revealed more entanglement than expected.

Follow-up studies localized the effect through $m_{t\bar{t}}$ binning and spin-correlation observables.

Consistent with near-threshold toponium contribution for hadron colliders in 2008 by two independent groups.

A natural question

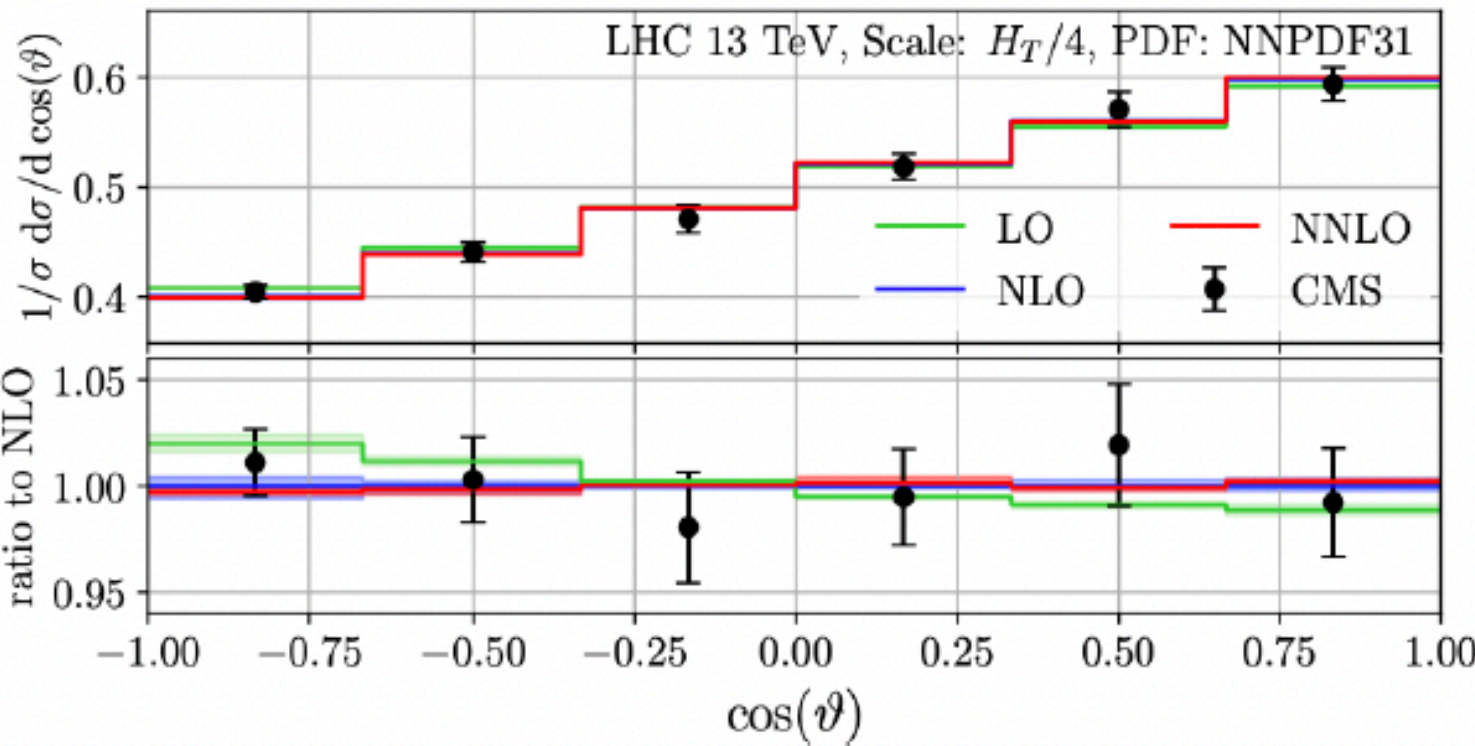
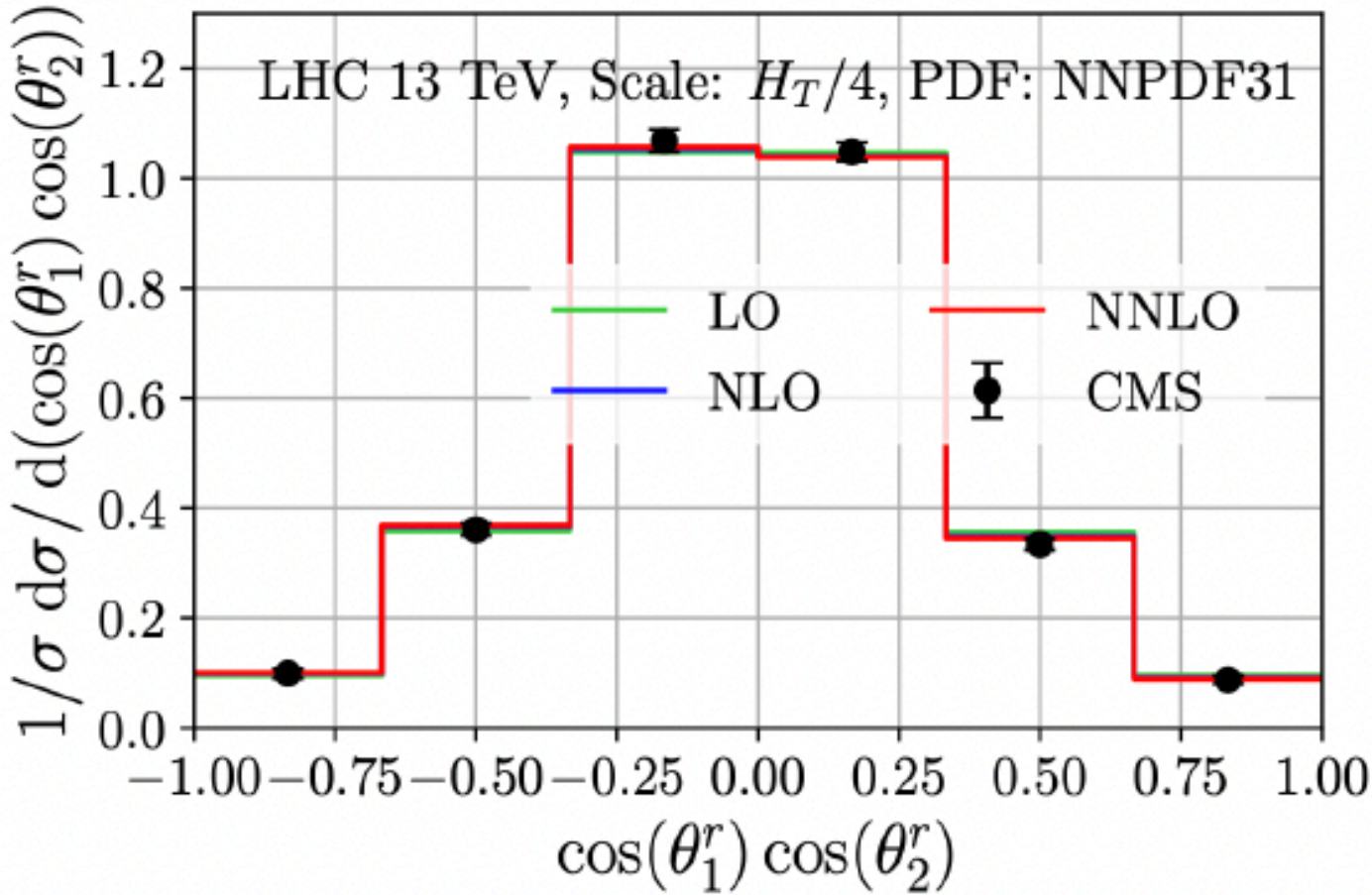
How do higher-order corrections change
the naive leading-order picture?

The “simplest” case

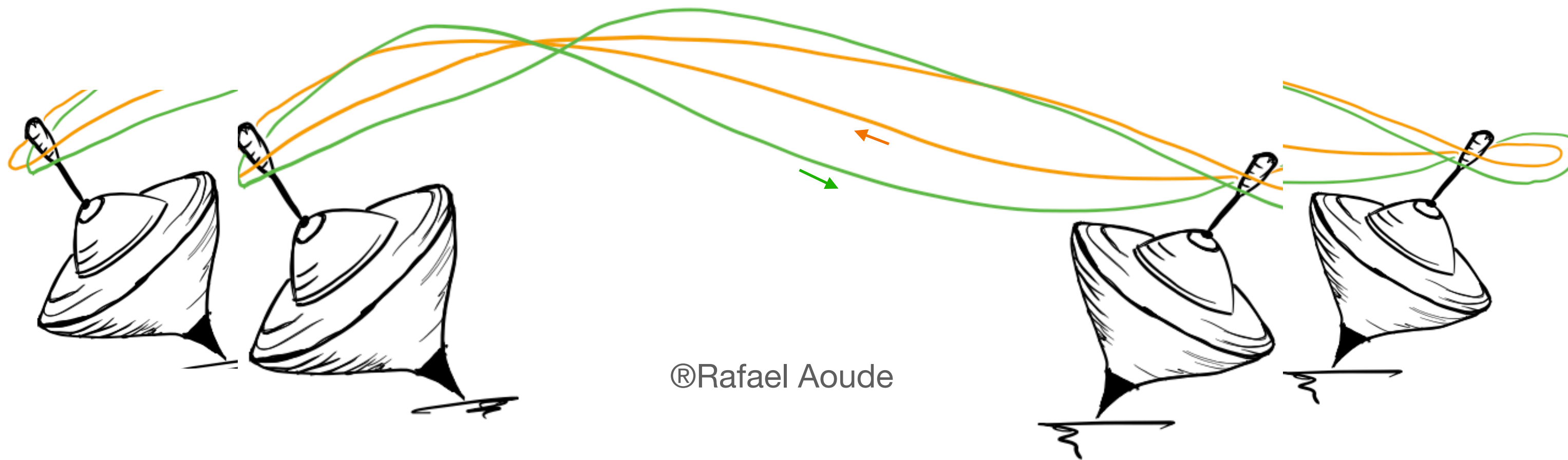
$t\bar{t}$ production at NNLO in QCD

Coefficient	LO ($\times 10^3$)	NLO ($\times 10^3$)	NNLO ($\times 10^3$)	CMS ($\times 10^3$)
B_1^k	$1_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$1_{-1}^{+0} [\text{sc}] \pm 2 [\text{mc}]$	$-1_{-1}^{+0} [\text{sc}] \pm 4 [\text{mc}]$	5 ± 23
B_1^r	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$0_{-0}^{+1} [\text{sc}] \pm 2 [\text{mc}]$	$0_{-2}^{+1} [\text{sc}] \pm 2 [\text{mc}]$	-23 ± 17
B_1^n	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$3_{-1}^{+1} [\text{sc}] \pm 1 [\text{mc}]$	$4_{-0}^{+1} [\text{sc}] \pm 3 [\text{mc}]$	6 ± 13
B_2^k	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$0_{-1}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$-5_{-3}^{+2} [\text{sc}] \pm 3 [\text{mc}]$	7 ± 23
B_2^r	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$0_{-0}^{+2} [\text{sc}] \pm 1 [\text{mc}]$	$-2_{-1}^{+0} [\text{sc}] \pm 2 [\text{mc}]$	-10 ± 20
B_2^n	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$-2_{-1}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$-3_{-0}^{+1} [\text{sc}] \pm 3 [\text{mc}]$	17 ± 13
C_{kk}	$324_{-7}^{+7} [\text{sc}] \pm 1 [\text{mc}]$	$330_{-2}^{+2} [\text{sc}] \pm 3 [\text{mc}]$	$323_{-5}^{+2} [\text{sc}] \pm 6 [\text{mc}]$	300 ± 38
C_{rr}	$6_{-5}^{+5} [\text{sc}] \pm 1 [\text{mc}]$	$58_{-12}^{+18} [\text{sc}] \pm 2 [\text{mc}]$	$69_{-7}^{+8} [\text{sc}] \pm 3 [\text{mc}]$	81 ± 32
C_{nn}	$332_{-0}^{+1} [\text{sc}] \pm 1 [\text{mc}]$	$330_{-1}^{+1} [\text{sc}] \pm 2 [\text{mc}]$	$326_{-1}^{+1} [\text{sc}] \pm 4 [\text{mc}]$	329 ± 20
$C_{nr} + C_{rn}$	$1_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$-1_{-0}^{+1} [\text{sc}] \pm 3 [\text{mc}]$	$-4_{-0}^{+4} [\text{sc}] \pm 6 [\text{mc}]$	-4 ± 37
$C_{nr} - C_{rn}$	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$-1_{-0}^{+1} [\text{sc}] \pm 2 [\text{mc}]$	$2_{-2}^{+4} [\text{sc}] \pm 8 [\text{mc}]$	-1 ± 38
$C_{nk} + C_{kn}$	$0_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$2_{-0}^{+1} [\text{sc}] \pm 1 [\text{mc}]$	$3_{-1}^{+4} [\text{sc}] \pm 3 [\text{mc}]$	-43 ± 41
$C_{nk} - C_{kn}$	$1_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$1_{-1}^{+1} [\text{sc}] \pm 2 [\text{mc}]$	$6_{-2}^{+0} [\text{sc}] \pm 7 [\text{mc}]$	40 ± 29
$C_{rk} + C_{kr}$	$-229_{-4}^{+4} [\text{sc}] \pm 1 [\text{mc}]$	$-203_{-7}^{+9} [\text{sc}] \pm 2 [\text{mc}]$	$-194_{-6}^{+8} [\text{sc}] \pm 7 [\text{mc}]$	-193 ± 64
$C_{rk} - C_{kr}$	$1_{-0}^{+0} [\text{sc}] \pm 1 [\text{mc}]$	$1_{-1}^{+0} [\text{sc}] \pm 4 [\text{mc}]$	$-1_{-3}^{+1} [\text{sc}] \pm 5 [\text{mc}]$	57 ± 46

- Perturbative series (QCD) under control
- Very small corrections at the inclusive level
- NNLO results within scale uncertainties of NLO results
- Agreement with CMS measurement



Quantum W's and Z's



Qutrit

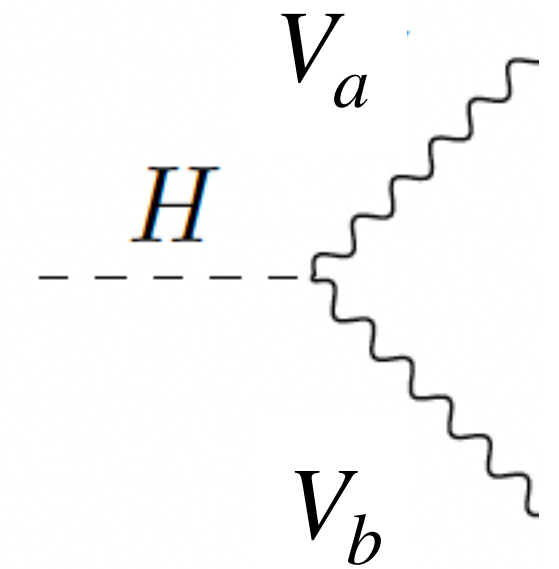
Qutrit

A. J. Barr, 2106.01377
A. J. Barr, P. Caban, J. Rembieliński, 2204.11063
R. Ashby-Pickering, A. J. Barr, A. Wierchucka, 2209.13990
J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno, 2209.13441
R. A. Morales, 2306.17247
J. A. Aguilar-Saavedra, 2307.06991
R. Aoude, E. Madge, FM, L. Mantani, 2307.09675
M. Fabbrichesi, R. Floreanini, E. Gabrielli, L. Marzola, 2302.00683
M. Fabbrichesi, R. Floreanini, E. Gabrielli, L. Marzola, 2304.02403
A. Subba, R. K. Singh, R. M. Godbole, 2411.19171
A. Bernal, P. Caban, J. Rembieliński, 2405.16525
M. Sullivan, 2410.10980
Q. Bi, Q.-H. Cao, K. Cheng, H. Zhang, 2307.14895
A. Bernal, P. Caban, J. Rembieliński, 2307.13496
F. Fabbri, J. Howarth, T. Maurin, 2307.13783
M. Grossi, G. Pelliccioli, A. Vicini, 2409.16731
J. A. Aguilar-Saavedra, 2411.13464
Y. Wu, R. Jiang, A. Ruzi, Y. Ban, X. Yan, Q. Li, 2410.17025
A. Ruzi, Y. Wu, R. Ding, S. Qian, A. M. Levin, Q. Li, 2408.05429
R. Ding, A. Ruzi, S. Qian, A. Levin, Y. Wu, Q. Li, 2504.09832
M. Fabbrichesi, R. Floreanini, E. Gabrielli, L. Marzola, 2503.14587
Del Gratta, Fabbri, Lamba, FM, Pagani, 2504.03841
Goncalves, Kaladharan, Krauss, Navarro, 2505.12125
Goncalves, Kaladharan, Navarro 2506.19951
Del Gratta, Fabbri, Grossi, FM, Pelliccioli, Pagani, Vicini, 2509.20456
Pelliccioli, Re. 2601.09540
Aguilar-Saavedra, Giardino, 2603.19389

$$H \rightarrow V_a V_b$$

Qutrit-qutrit $H \rightarrow V_a V_b$ production at present and future colliders studies in the SM and BSM, many papers in the last years. In-depth study of the process $H \rightarrow V_a V_b$ performed by several groups.

$$|\psi\rangle = a_L |0\ 0\rangle + a_T \frac{|+\ -\rangle + |-\ +\rangle}{\sqrt{2}}$$



$$a_L = \frac{-\beta}{\sqrt{2 + \beta^2}}, \quad a_T = \frac{\sqrt{2}}{\sqrt{2 + \beta^2}}, \quad \beta = 1 + \frac{m_H^2 - (m_a + m_b)^2}{2m_a m_b}$$

$$H \rightarrow V_a V_b$$

Qutrit-qutrit $H \rightarrow V_a V_b$ production at present and future colliders studies in the SM and BSM, many papers in the last years. In-depth study of the process $H \rightarrow V_a V_b$ performed by several groups.

$$\rho = \frac{1}{9} \left[\mathbf{1}_3 \otimes \mathbf{1}_3 + A_{lm}^{(1)} (T_{lm} \otimes \mathbf{1}_3) + A_{lm}^{(2)} (\mathbf{1}_3 \otimes T_{lm}) + C_{lm l' m'} (T_{lm} \otimes T_{l' m'}) \right].$$

$$\rho_{\text{LO}}(\beta) = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \frac{a_T^2}{2} & \cdot & \frac{a_L a_T}{\sqrt{2}} & \cdot & \frac{a_T^2}{2} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \frac{a_L a_T}{\sqrt{2}} & \cdot & a_L^2 & \cdot & \frac{a_L a_T}{\sqrt{2}} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \frac{a_T^2}{2} & \cdot & \frac{a_L a_T}{\sqrt{2}} & \cdot & \frac{a_T^2}{2} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix}$$

$$\rho_{\text{LO}} = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & x & \cdot & y & \cdot & x & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & y & \cdot & 1 - 2x & \cdot & y & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & x & \cdot & y & \cdot & x & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix}$$

$$\rho_{\text{LO}} = \int \rho_{\text{LO}}(\beta) w(\beta) d\beta$$

$$V \rightarrow 2f$$

In practice, the qutrits are reconstructed via the tomography. Let's assume fermions can be detected and identified and first consider one vector boson:

$$\frac{4\pi}{3} \frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta d\phi} = \sum_{\lambda,\lambda'} \rho_{\lambda,\lambda'} \Gamma_{\lambda,\lambda'}(\theta, \phi) \quad \hat{=} \quad \frac{1}{4\pi} + \sum_{l=1}^2 \sum_{m=-l}^l \alpha_{lm} Y_{lm}(\theta, \phi)$$

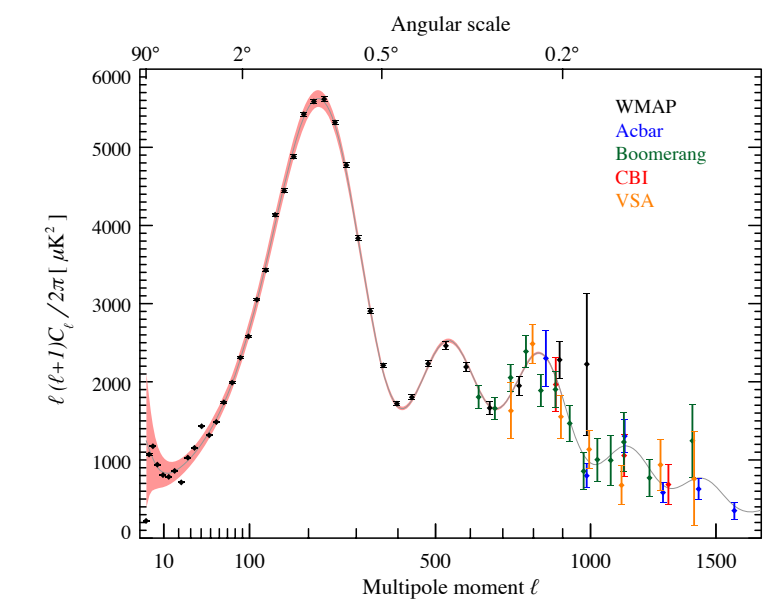
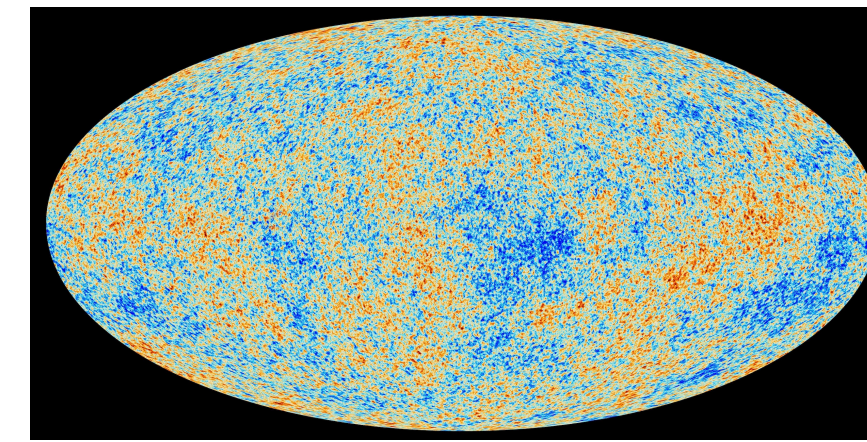
$$\rho = \frac{1}{3} [\mathbf{1}_3 + A_{lm} T_{lm}] \quad \Gamma = \frac{1}{3} \left[\mathbf{1}_3 + \sqrt{2\pi} \eta_\ell T_{1m} Y_{1m} + \sqrt{\frac{2\pi}{5}} T_{2m} Y_{2m} \right]$$

$$\sqrt{8\pi} \alpha_{1m} = \eta_\ell A_{1m}$$

$$\sqrt{40\pi} \alpha_{2m} = A_{2m}$$

$$\eta_\ell = \frac{2 g_{V,\ell} g_{A,\ell}}{g_{V,\ell}^2 + g_{A,\ell}^2} = \frac{1 - 4 \sin^2 \theta_w}{1 - 4 \sin^2 \theta_w + 8 \sin^4 \theta_w} = 0.2131 \dots$$

$$H \rightarrow V_a^{(*)} V_b^* \rightarrow 4f$$



For two vector bosons, we can do the quantum **tomography** using the leptons in the decay

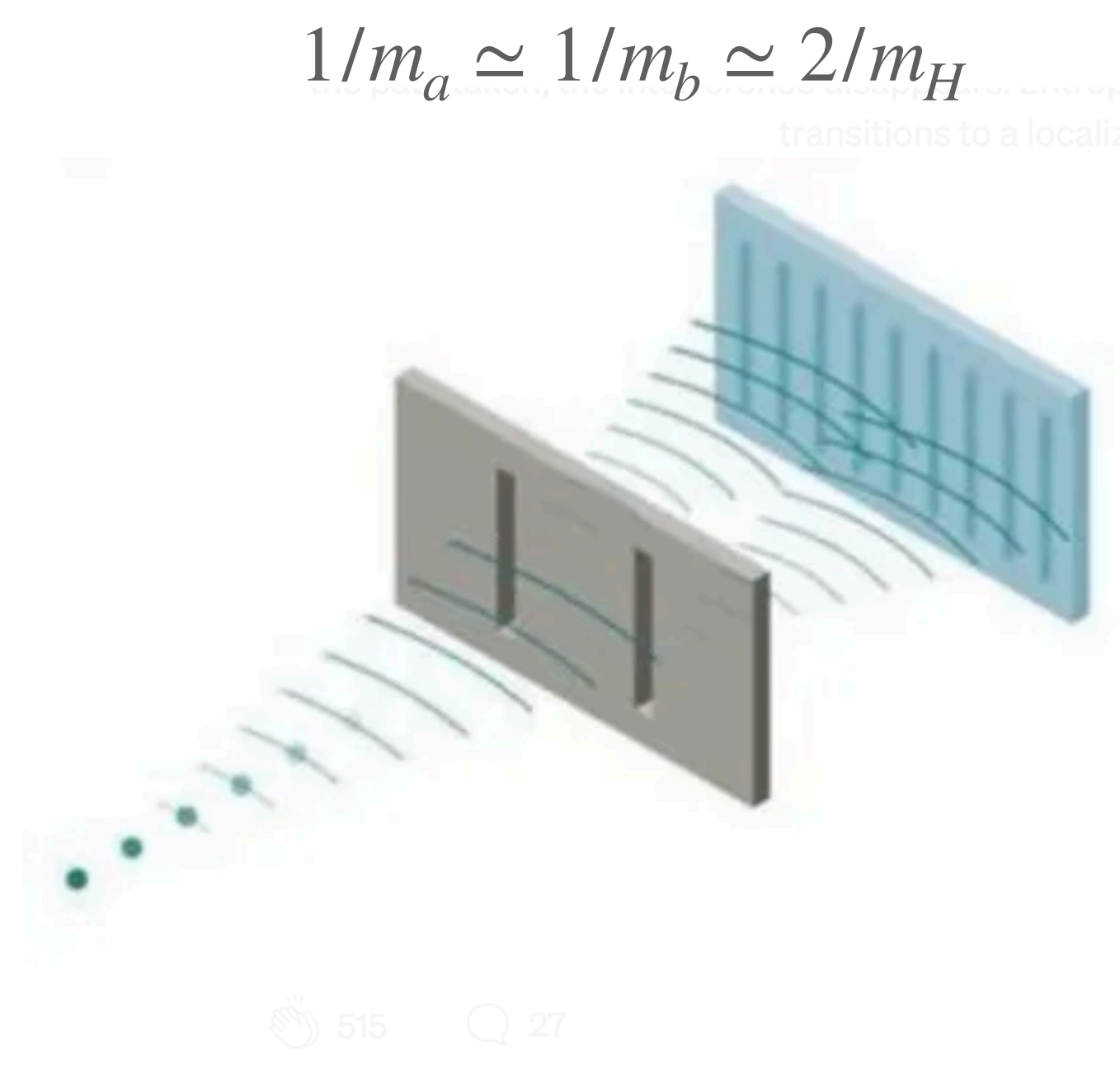
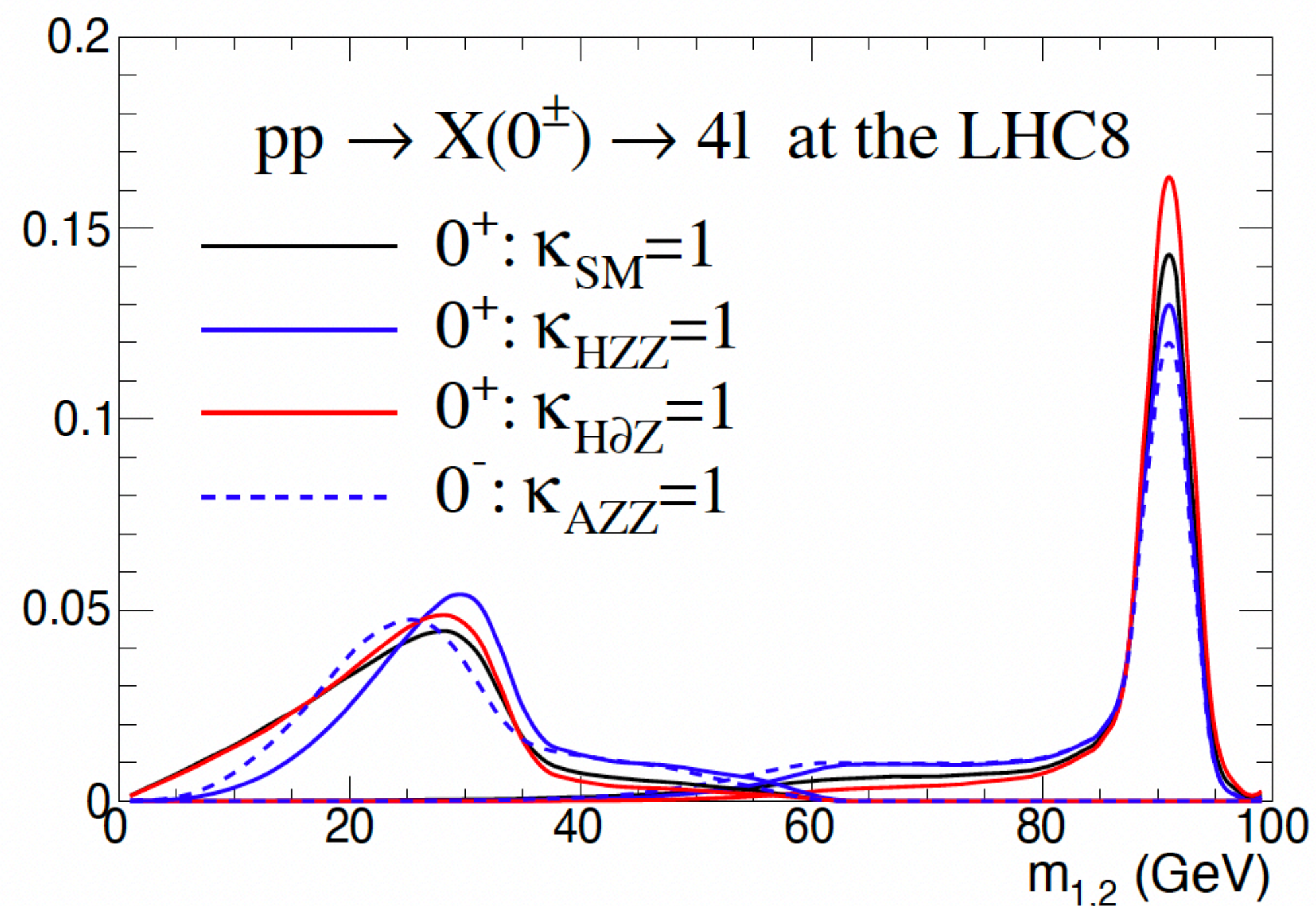
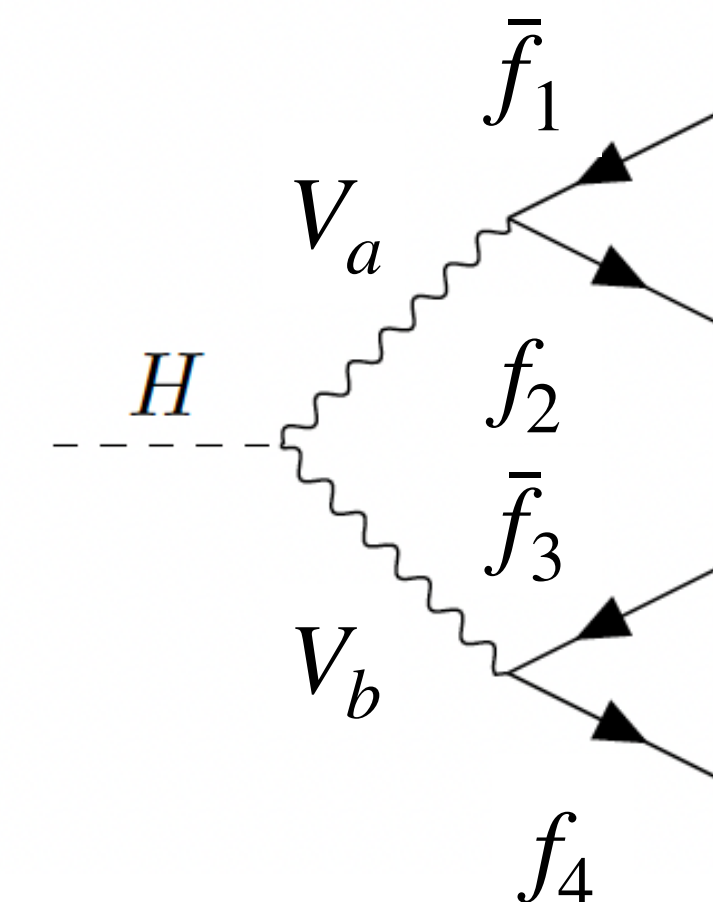
$$\begin{aligned} \frac{16\pi^2}{9\sigma} \frac{d^4\sigma}{d\Omega_1 d\Omega_2} &\hat{=} \frac{1}{(4\pi)^2} \\ &+ \frac{1}{4\pi} \sum_{l=1}^2 \sum_{m=-l}^l \alpha_{lm}^{(1)} Y_{lm}(\theta_1, \phi_1) + \frac{1}{4\pi} \sum_{l=1}^2 \sum_{m=-l}^l \alpha_{lm}^{(2)} Y_{lm}(\theta_2, \phi_2) \\ &+ \sum_{l=1}^2 \sum_{l'=1}^2 \sum_{m=-l}^l \sum_{m'=-l'}^{l'} \gamma_{lml'm'} Y_{lm}(\theta_1, \phi_1) Y_{l'm'}(\theta_2, \phi_2) \end{aligned} \quad \begin{aligned} &\longrightarrow \rho = \frac{1}{9} \left[\mathbf{1}_3 \otimes \mathbf{1}_3 \right. \\ &\longrightarrow + A_{lm}^{(1)} (T_{lm} \otimes \mathbf{1}_3) + A_{lm}^{(2)} (\mathbf{1}_3 \otimes T_{lm}) \\ &\longrightarrow \left. + C_{lml'm'} (T_{lm} \otimes T_{l'm'}) \right] . \end{aligned}$$

$$\begin{aligned} \sqrt{8\pi} \alpha_{1m} &= \eta_\ell A_{1m}, & \sqrt{40\pi} \alpha_{2m} &= A_{2m}, & 8\pi \gamma_{1m1m'} &= \eta_\ell^2 C_{1m1m'}, \\ 40\pi \gamma_{2m2m'} &= C_{2m2m'}, & 8\pi \sqrt{5} \gamma_{2m1m'} &= \eta_\ell C_{2m1m'}, & 8\pi \sqrt{5} \gamma_{1m2m'} &= \eta_\ell C_{1m2m'} . \end{aligned}$$

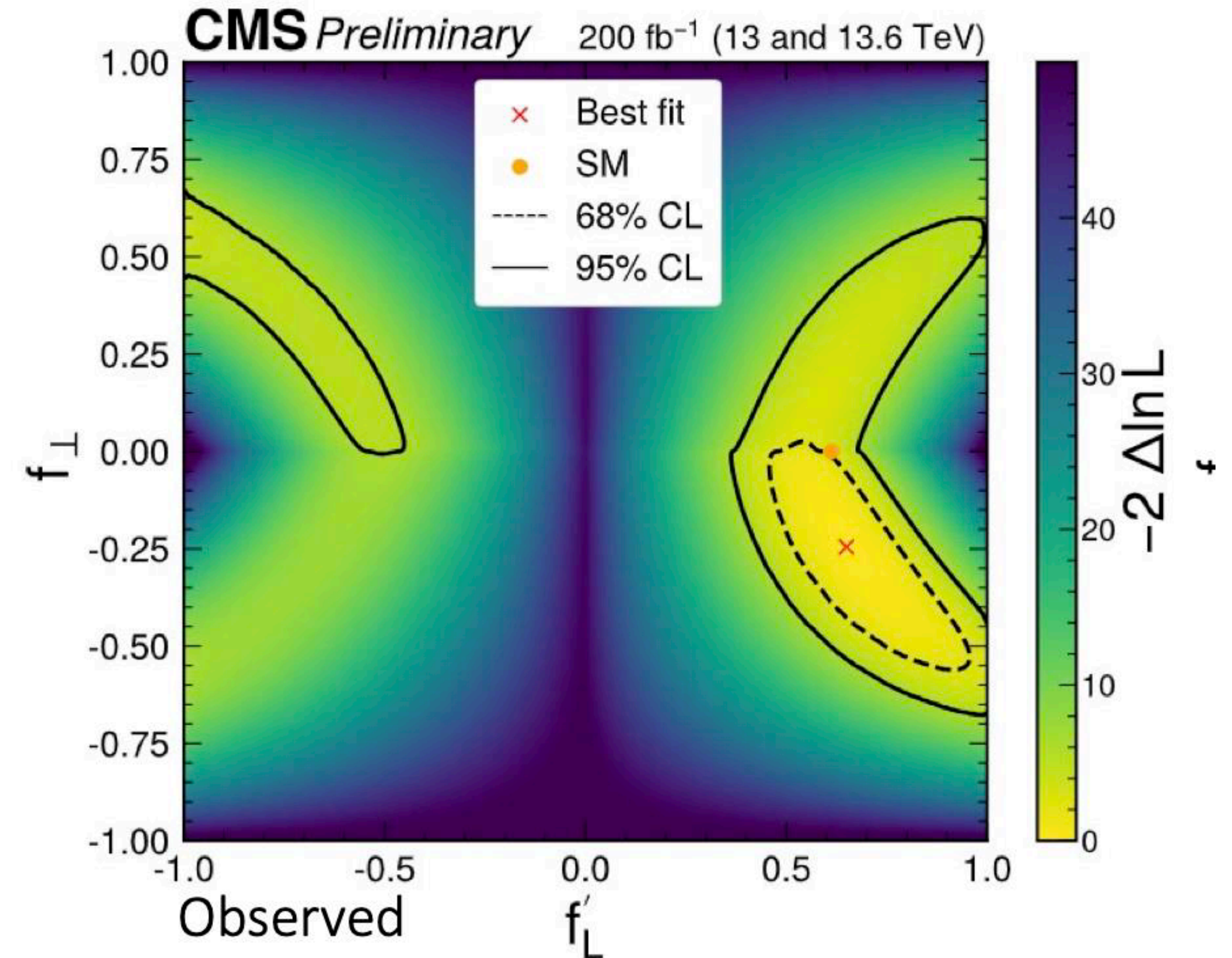
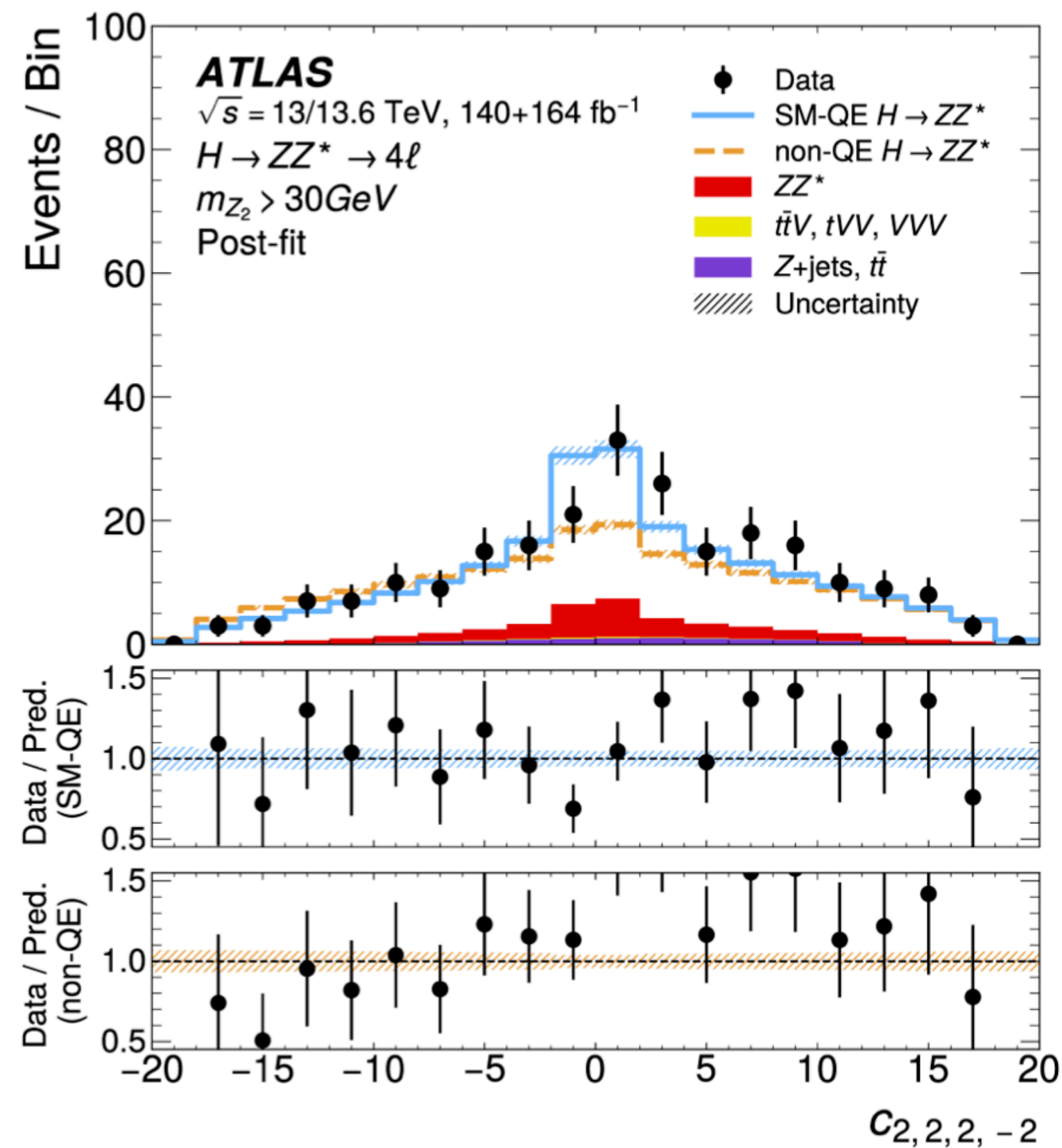
$$\boxed{C_{2,1,2,-1} \neq 0 \quad \text{or} \quad C_{2,2,2,-2} \neq 0.} \Rightarrow \text{Entanglement}$$

$$H \rightarrow V_a^{(*)} V_b^* \rightarrow 4f$$

In the Higgs decay one pair is always off-shell. The other is typically on shell and this is enough to say who's who. When both are off-shell and close to the maximum value, for identical fermions the system behaves as in a double-slit experiment.

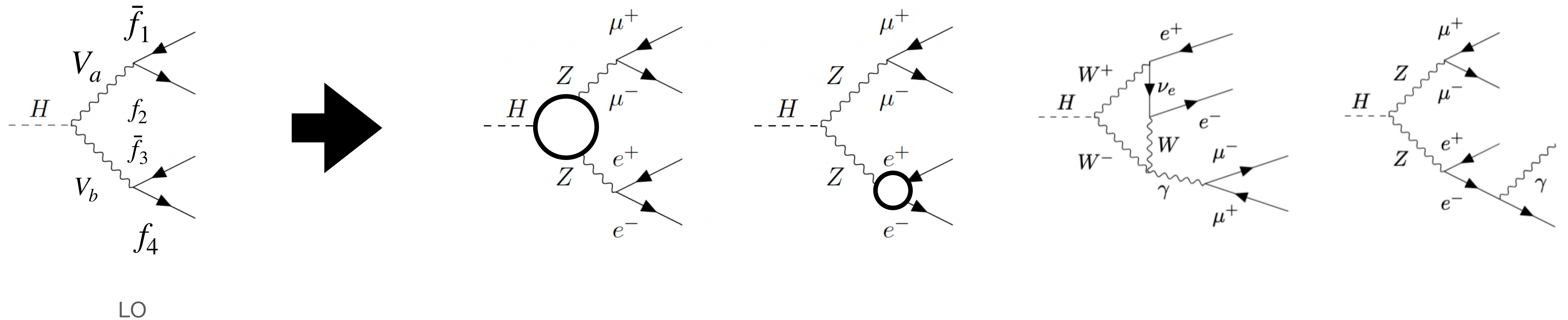


$$H \rightarrow V_a^{(*)} V_b^* \rightarrow 4f$$



ATLAS reports strong evidence for spin entanglement between the two (Z) bosons in ($H \rightarrow ZZ^* \rightarrow 4\ell$) at 4.7σ , and CMS confirms the spin correlation pattern.

Quantum observables beyond LO



- Do quantum corrections affect the quantum correlations?
- Do two quirks exist at NLO?
- Is the quantum tomography procedure stable?

$H \rightarrow V_a^{(*)} V_b^* \rightarrow 4f$ at NLO

Automatic tools are available to compute NLO EW. One can just use them and obtain:

	LO	NLO	NLO / LO
$A_{2,0}^1$	-0.592(1)	-0.509(2)	0.860(2)
$A_{2,0}^2$	-0.591(1)	-0.565(2)	0.956(2)
$C_{2,1,2,-1}$	-0.937(2)	-0.943(4)	1.006(3)
$-C_{1,1,1,-1}$	-0.94(1)	-0.16(2)	0.17(2)
$A_{2,0}^1/\sqrt{2} + 1$	0.5817(7)	0.640(1)	1.101(2)
$C_{2,2,2,-2}$	0.581(3)	0.568(4)	0.977(6)
$-C_{1,0,1,0}$	0.59(1)	0.03(2)	0.06(4)
$C_{2,0,2,0}$	1.418(3)	1.400(5)	0.987(3)
$C_{1,0,1,0} + 2$	1.41(1)	1.97(2)	1.39(1)

$\rho_{\text{NLO}} =$

$$\begin{pmatrix} 0.099(4) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & 0.004(2) & \cdot & 0.131(4) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & 0.111(4) & \cdot & -0.183(4) & \cdot & 0.189(1) & \cdot & \cdot & \cdot \\ \cdot & 0.131(4) & \cdot & -0.009(2) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -0.183(4) & \cdot & 0.591(1) & \cdot & -0.183(4) & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & -0.009(2) & \cdot & 0.131(4) & \cdot & \cdot \\ \cdot & \cdot & 0.189(1) & \cdot & -0.183(4) & \cdot & 0.110(3) & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & 0.131(4) & \cdot & 0.004(2) & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 0.099(3) & \cdot \end{pmatrix}.$$

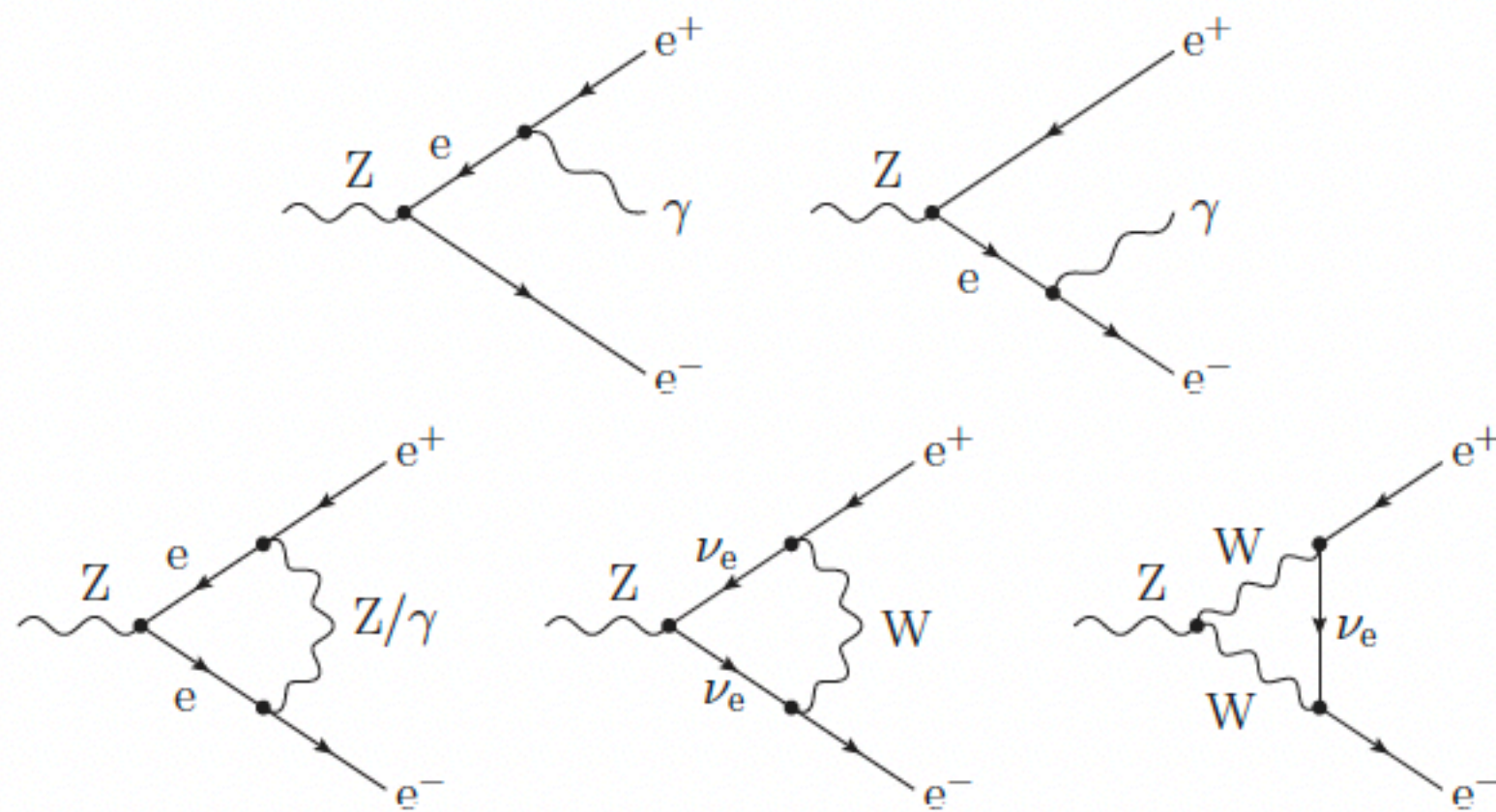
$$|\rho_{ij}|^2 \leq \rho_{ii}\rho_{jj}, \quad i \neq j$$

The reconstructed ρ is not positive definite !

How can than be??? Better think it over....

$H \rightarrow V_a^{(*)} V_b^* \rightarrow 4f$ at NLO

A careful look at the table shows the large K-factors are associated to $l=1$ components which depend on the spin analysing power which receives huge corrections



$$\eta_\ell^{\text{LO}} = 0.2131(1), \quad \eta_\ell^{\text{EW,virt}} = 0.1409(1), \quad \eta_\ell^{\text{NLO}} = 0.1405(8),$$

That can be effectively taken into account by using:

$$\eta_\ell^{\text{eff}} \equiv \eta_\ell^{\text{LO}} \Big|_{\sin^2 \theta_w \rightarrow \sin^2 \theta_w^{\text{eff}}} = \frac{1 - 4 \sin^2 \theta_w^{\text{eff}}}{1 - 4 \sin^2 \theta_w^{\text{eff}} + 8 \sin^4 \theta_w^{\text{eff}}}.$$

Real radiation can be accounted for using rather generous recombination ΔR (but it is a systematics). Optimal procedure proposed for on-shell Z's. Works for heavy Higgs. For the SM Higgs...for the moment use even correlations. **Still work to do...**

M_H [GeV]	η_ℓ^{NLO}	f_{--}^{LO}	f_{--}^{NLO}
183	0.1420(4)	0.3303	0.3304
200	0.1423(4)	0.2516	0.2537
225	0.1432(4)	0.1619	0.1644
250	0.1439(4)	0.1041	0.1059

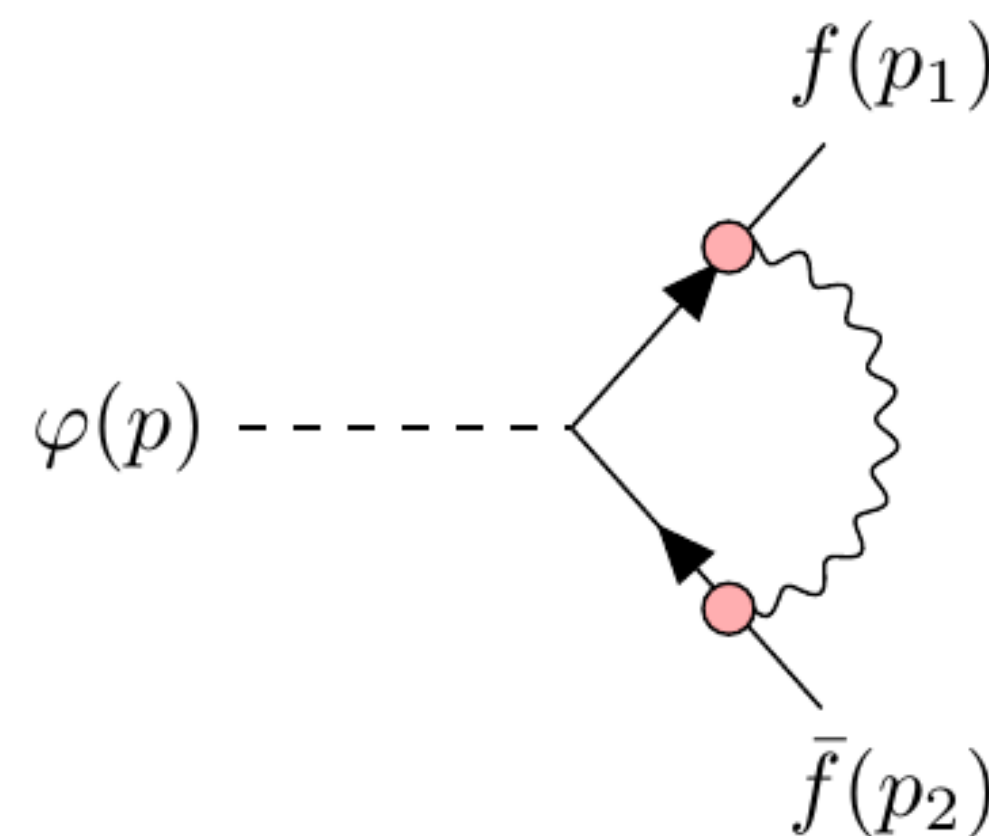
Decoherence

In general, what happens to entanglement in presence of QCD and QED radiation?

Scalar, pseudo scalar, vector and axial

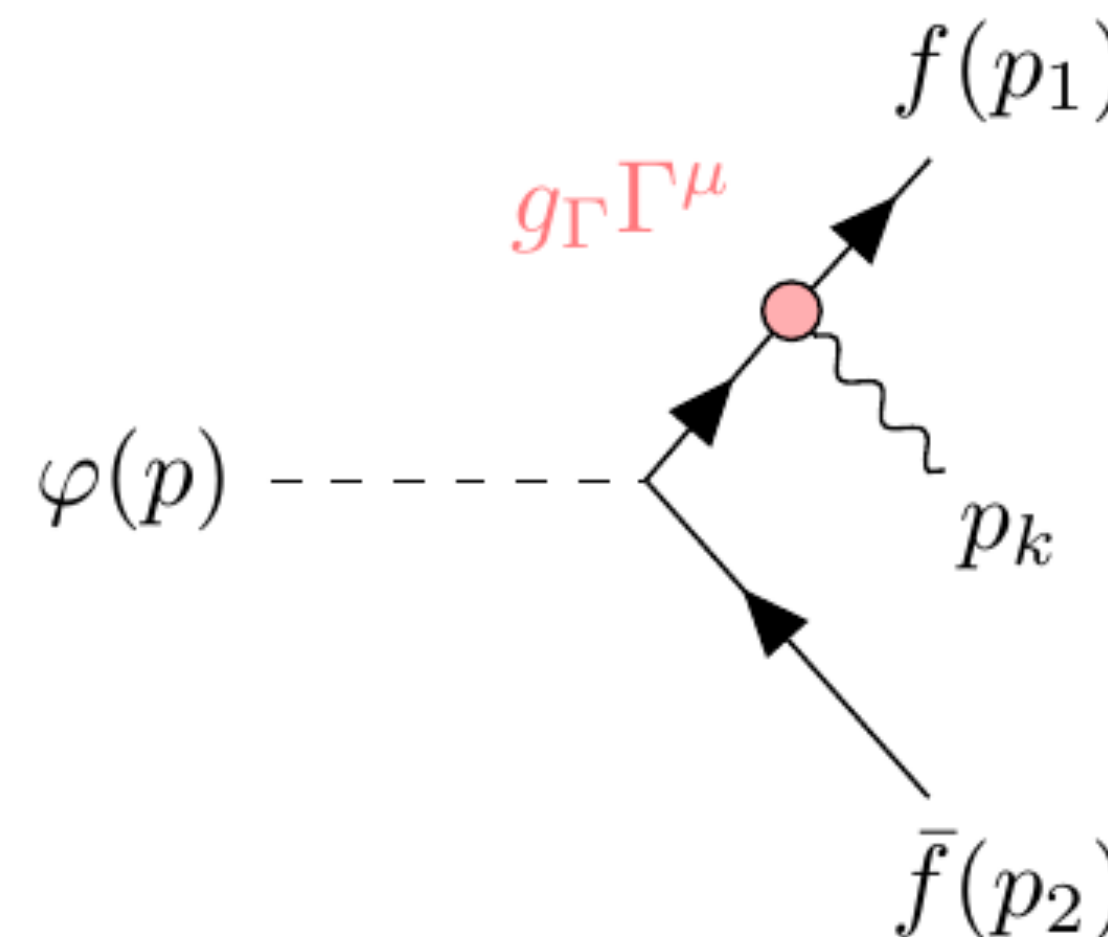
$$g_{\Gamma}\Gamma^{\mu} = \{g_S 1, g_P \gamma^5, g_V \gamma^{\mu}, g_A \gamma^{\mu} \gamma^5\}$$

Virtual correction: one-loop



+

Real emission



Trace over the extra
d.o.f (environment)



Same Hilbert space and no change.

Quantum Map.
Open Quantum system

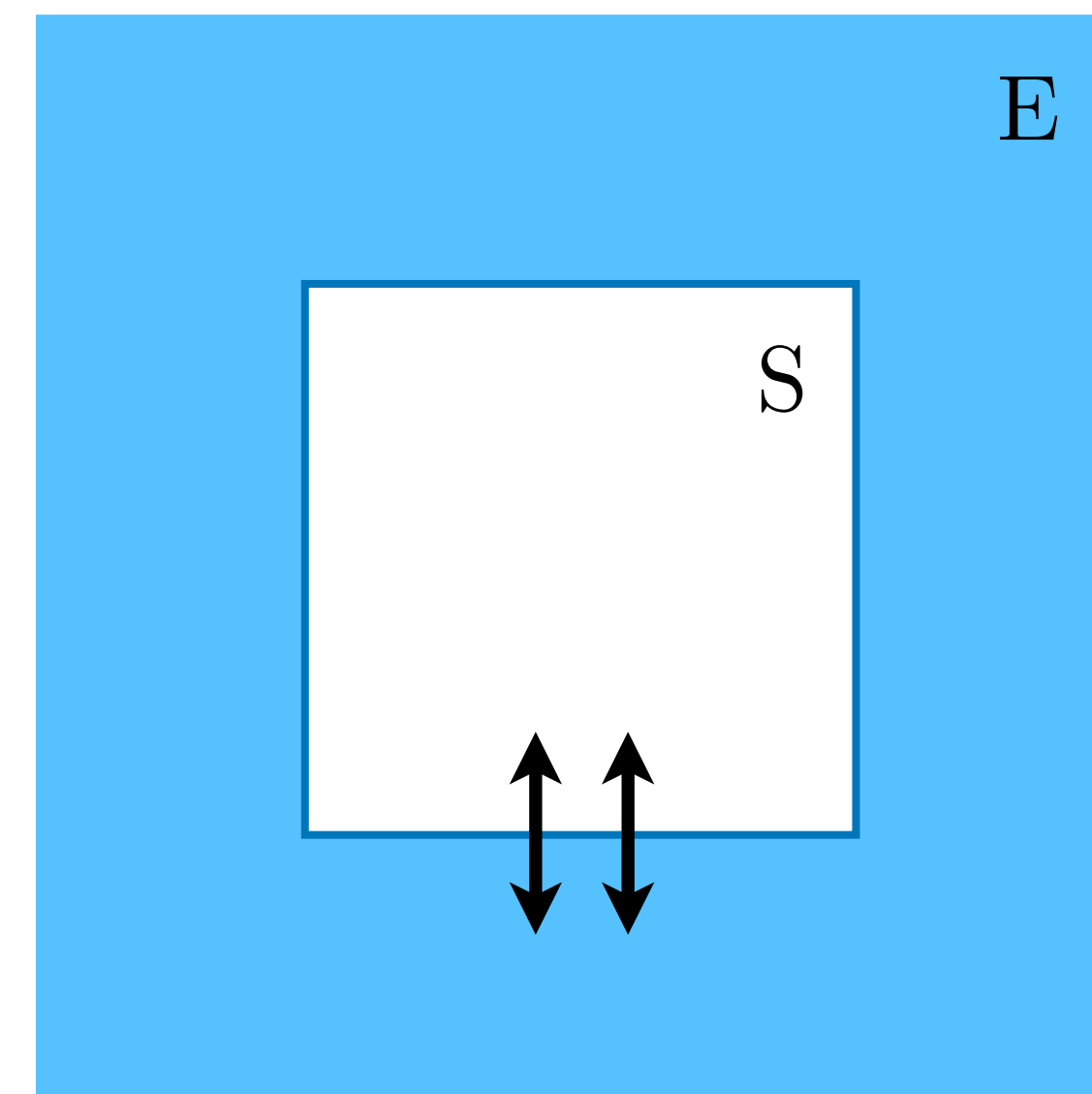
Quantum Maps

The evolution of a system+environment is unitary

$$\rho'(t) = U(t)\rho_S(0) \otimes \rho_E(0)U^\dagger(t)$$

Tracing over the environment subsystem

$$\rho_S(t) = \text{tr}_E [U(t)\rho_S(0) \otimes \rho_E(0)U^\dagger(t)]$$

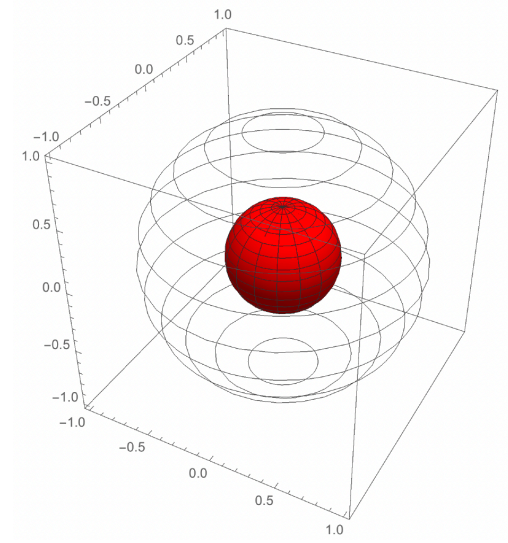


which we can write as a operator-sum representation (Kraus operators)

$$\rho_S(t) = \sum_j K_j \rho_S(0) K_j^\dagger =: \mathcal{E}[\rho_S(0)] \quad \text{s.t} \quad \sum_j K_j^\dagger K_j = 1$$

For bipartite qubits: K_j Tensor product of Pauli's and Id.

Decoherence channels

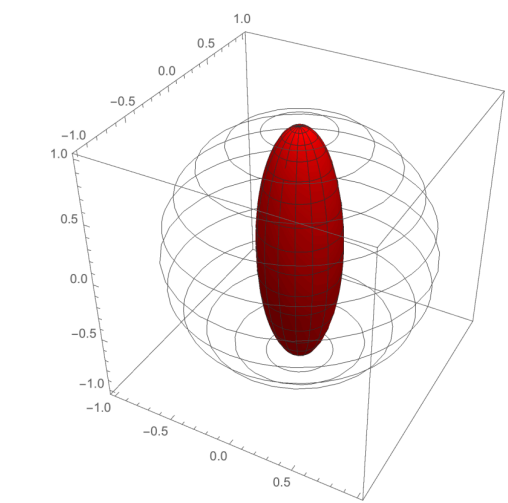


$$K_1 = \sqrt{1 - \frac{3p}{4}} \mathbb{1}, \quad K_2 = \sqrt{\frac{p}{4}} \sigma_1, \\ K_3 = \sqrt{\frac{p}{4}} \sigma_2, \quad K_4 = \sqrt{\frac{p}{4}} \sigma_3.$$

Depolarizing

Typical random noise

$$\mathcal{E}(\rho) = (1 - p)\rho + p \frac{I}{2}$$

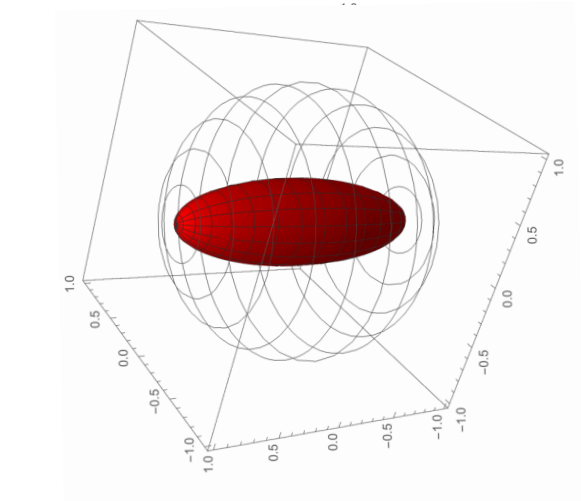


$$K_1 = \sqrt{1 - \frac{p}{2}} \mathbb{1}, \quad K_2 = \frac{p}{2} \sigma_3$$

Phase damping

This is the **pure decoherence channel**: it destroys **off-diagonal elements** but leaves populations unchanged.

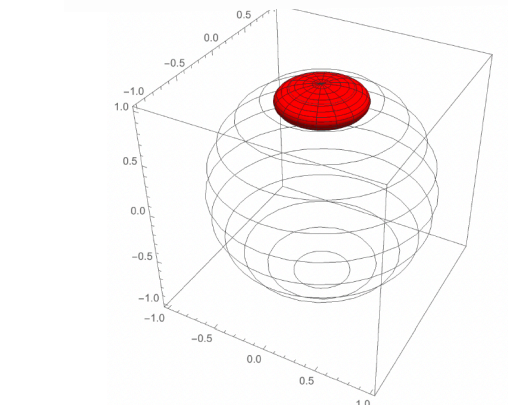
$$\mathcal{E}(\rho) = \left(1 - \frac{p}{2}\right) \rho + \frac{p}{2} Z \rho Z$$



$$K_0 = \sqrt{1 - p} I, \quad K_1 = \sqrt{p} X$$

Spin flip

$$\mathcal{E}(\rho) = (1 - p)\rho + p X \rho X$$

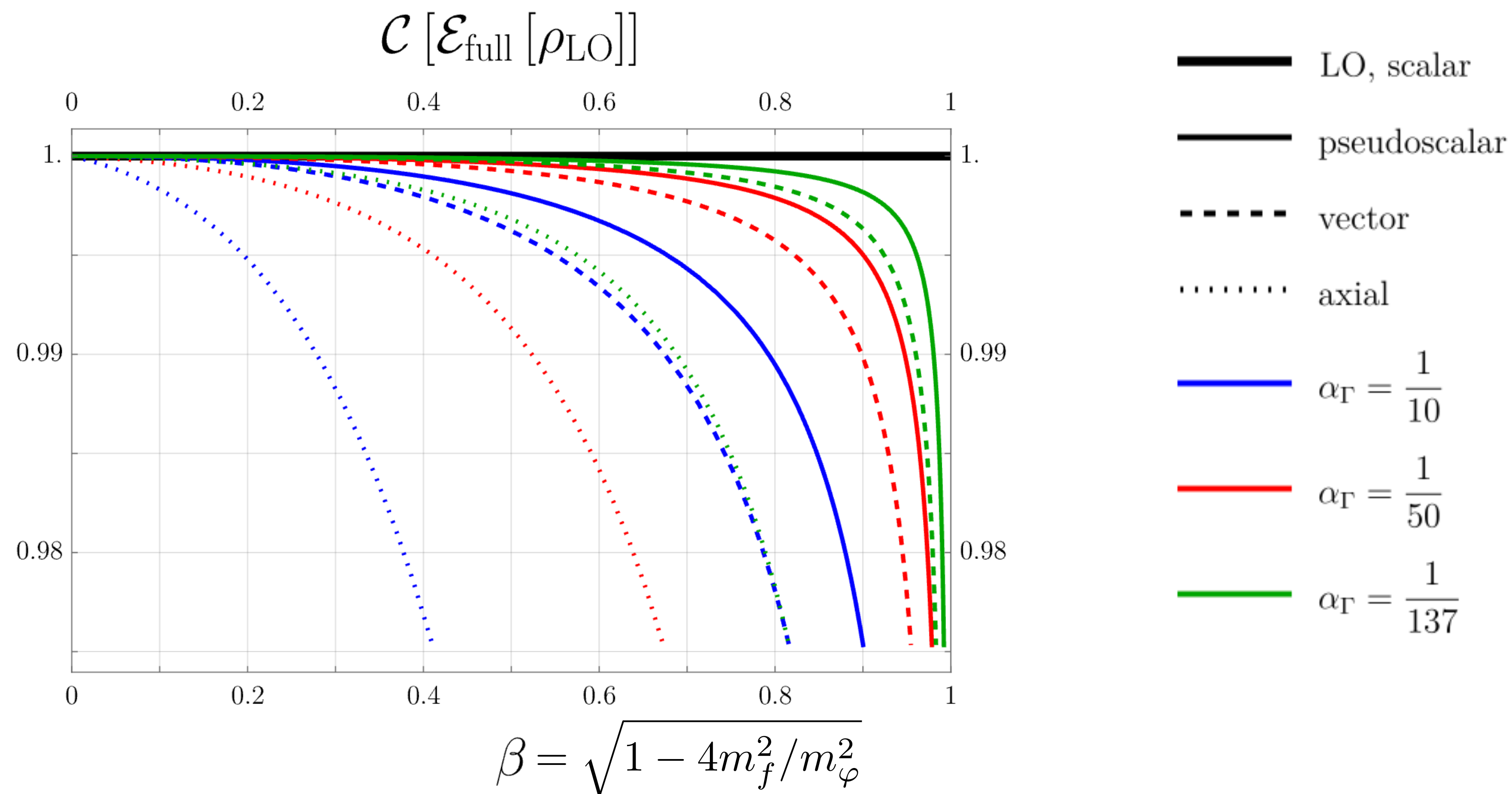


$$K_1 = \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{pmatrix}, \quad K_2 = \begin{pmatrix} 0 & \sqrt{p} \\ 0 & 0 \end{pmatrix}$$

Amp damping

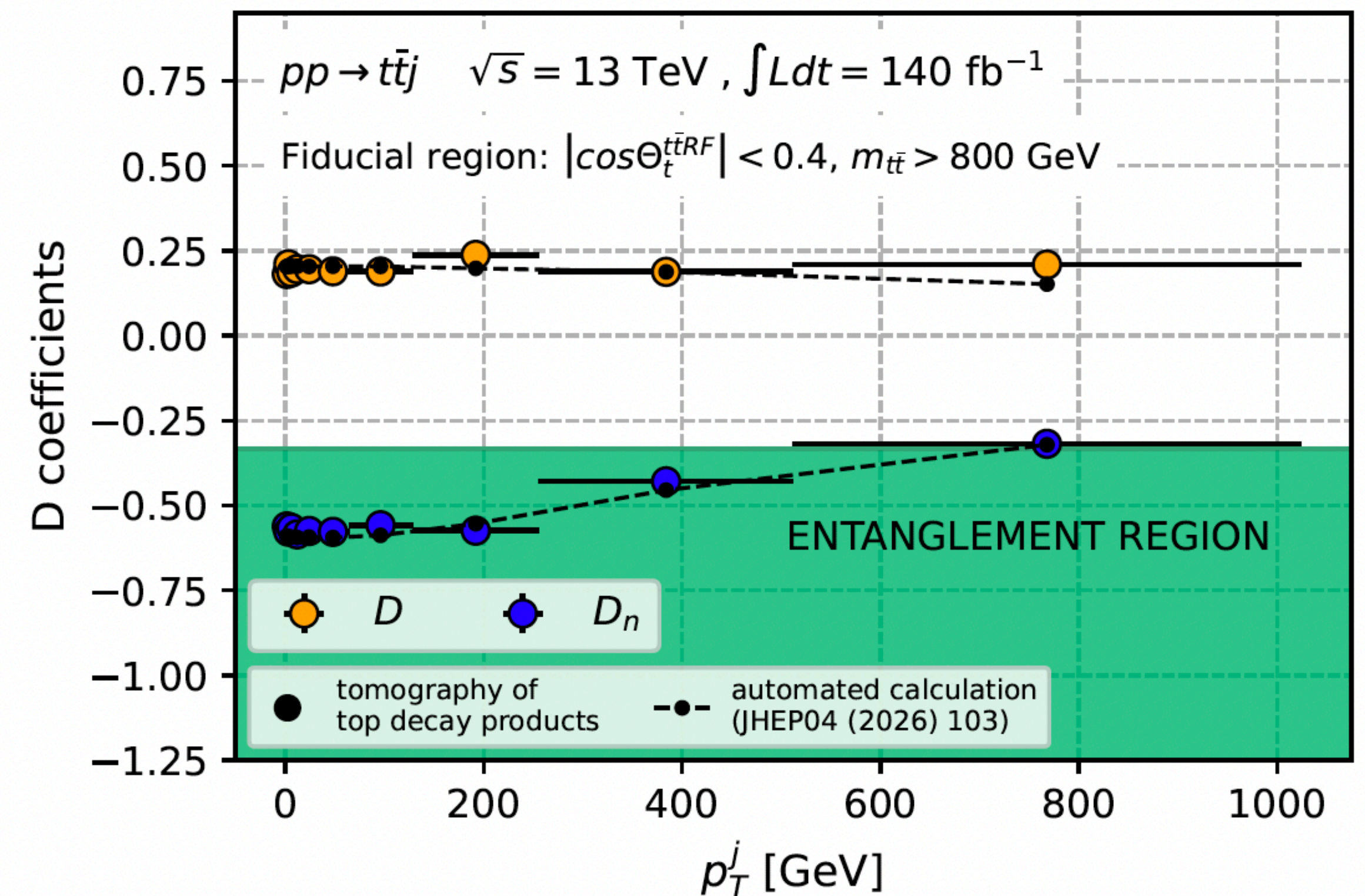
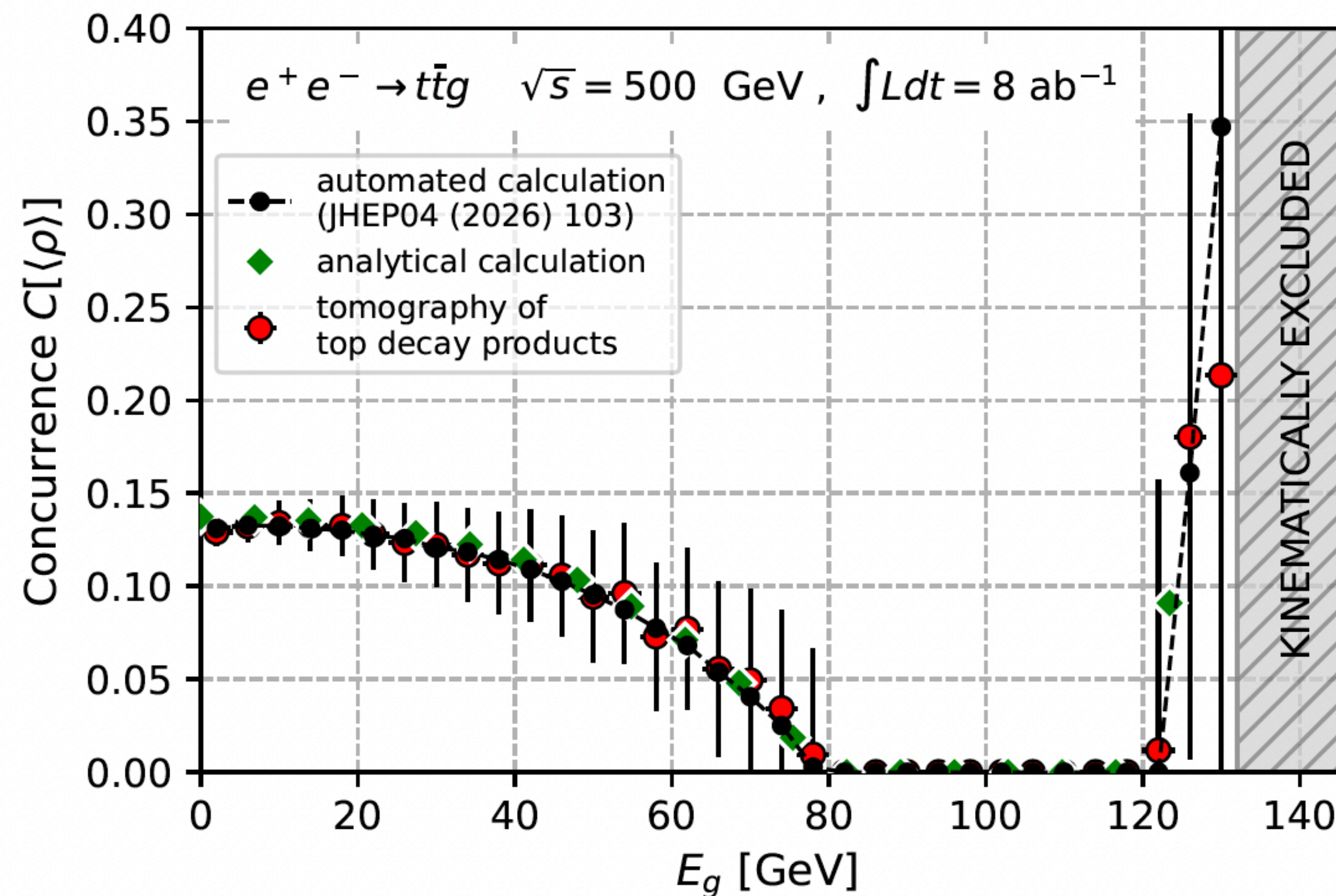
$$\mathcal{E}(\rho) = \rho + \gamma \left(\sigma_- \rho \sigma_+ - \frac{1}{2} \{ \sigma_+ \sigma_-, \rho \} \right)$$

Decoherence



Entanglement is lost mainly due to collinear emission $\Rightarrow$ Small effects $\sim 1\%$

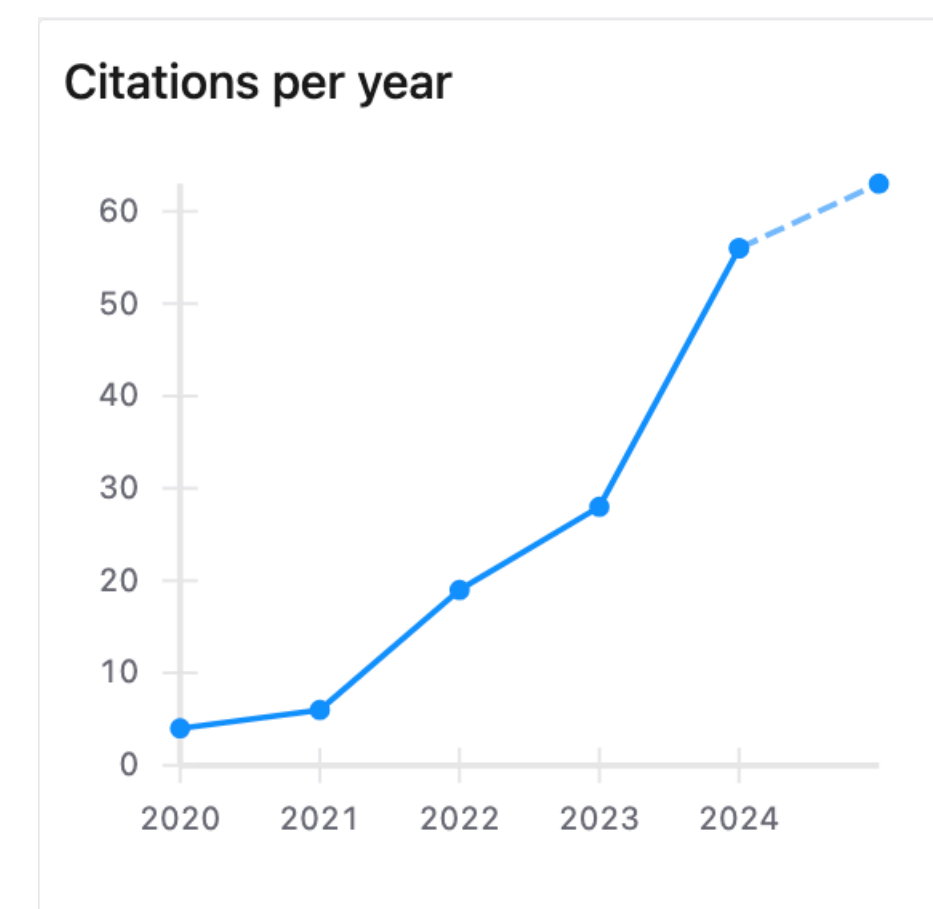
From $e^+e^- \rightarrow t\bar{t}g$ to $pp \rightarrow t\bar{t}j$



In addition, the virtual would also give a finite non-trivial spin-spin modification...

A wealth of new questions arising...

- ❖ **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? What about NLO? [2504.07030](#), [2510.13951](#)
- ❖ 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 Bell-inequalities be tested at colliders ? [2507.15949](#), [2507.15947](#)
- ❖ 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 B_0/B_0 -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](#) and [2410.23343](#)
- ❖ Magic : [2406.07321](#), [2508.14967](#)



Citations to the
Afik & de Nova paper

Entanglement as a principle?

Cervera-Lierta, Latorre, Rojo, Rottoli, 1703.02989

Carena, Low, Wagner, Xiao 2307.08112

Thaler, Trifinopoulos. 2410.23343

Liu, Low, Yin, 2509.18251

Nunez, Pardina, Asorey, Latorre, Cervera-Lierta, 2511.04358

McGinnis 2511.10559

⇒ QED as minimal theory

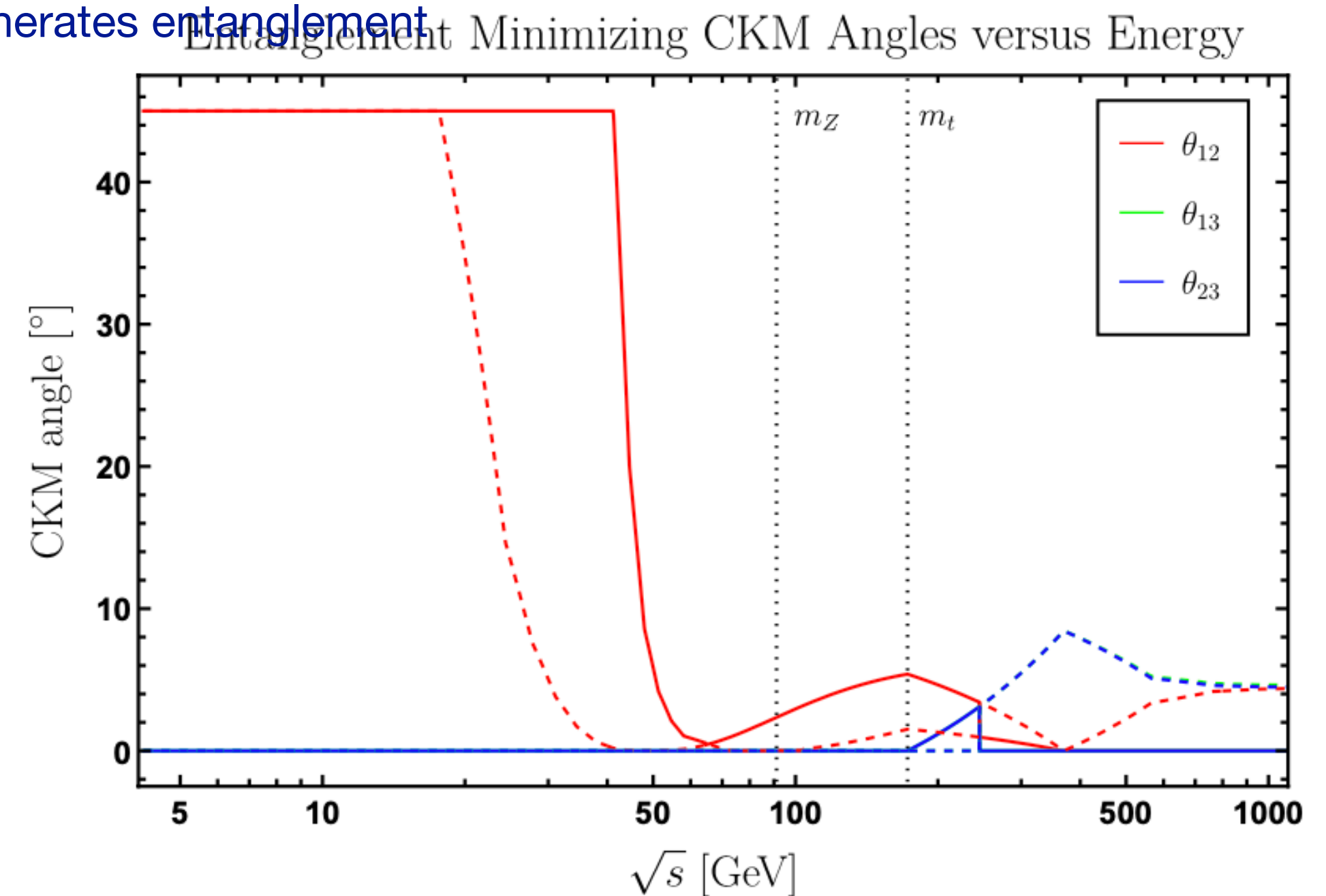
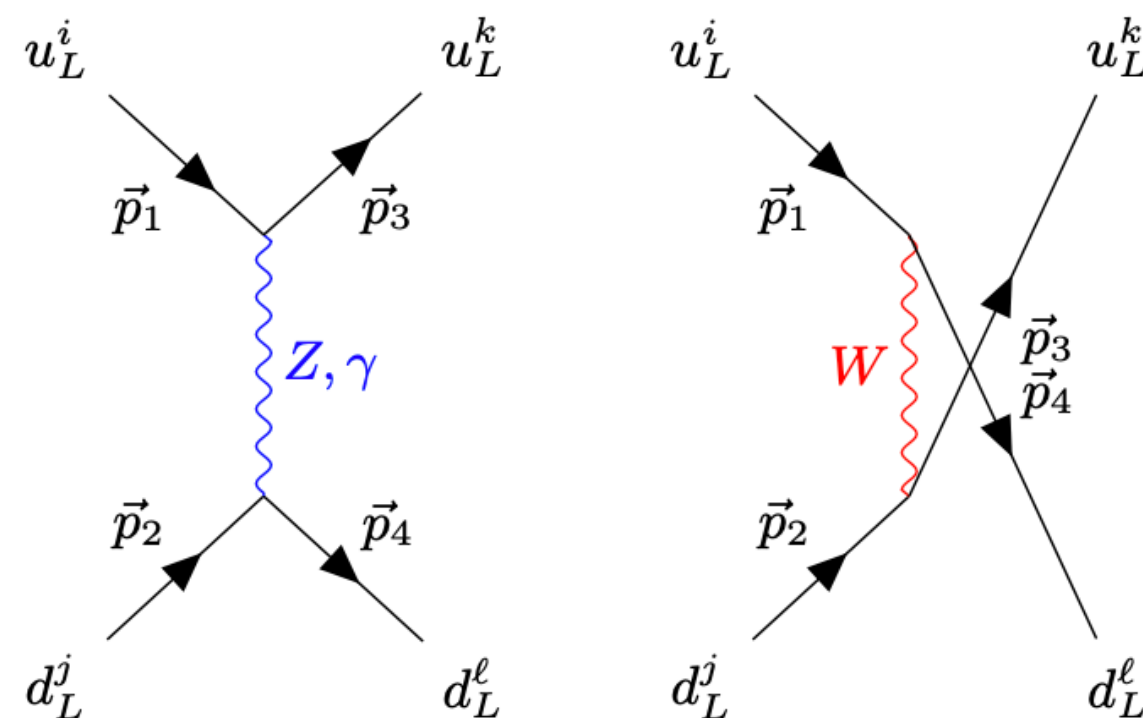
⇒ symmetry enhancement

⇒ CKM/PMNS matrix structure

⇒ Value of $\sin(\theta_W)$

⇒ Gauge invariance

⇒ SU(N) always generates entanglement



Ent. generated by scattering is minimized when the CKM matrix is almost (but not exactly) diagonal and when the PMNS matrix features two large angles and a smaller one,

Entanglement as a principle?

Cervera-Lierta, Latorre, Rojo, Rottoli, 1703.02989

Carena, Low, Wagner, Xiao 2307.08112

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McGinnis 2511.10559

⇒ QED as minimal theory

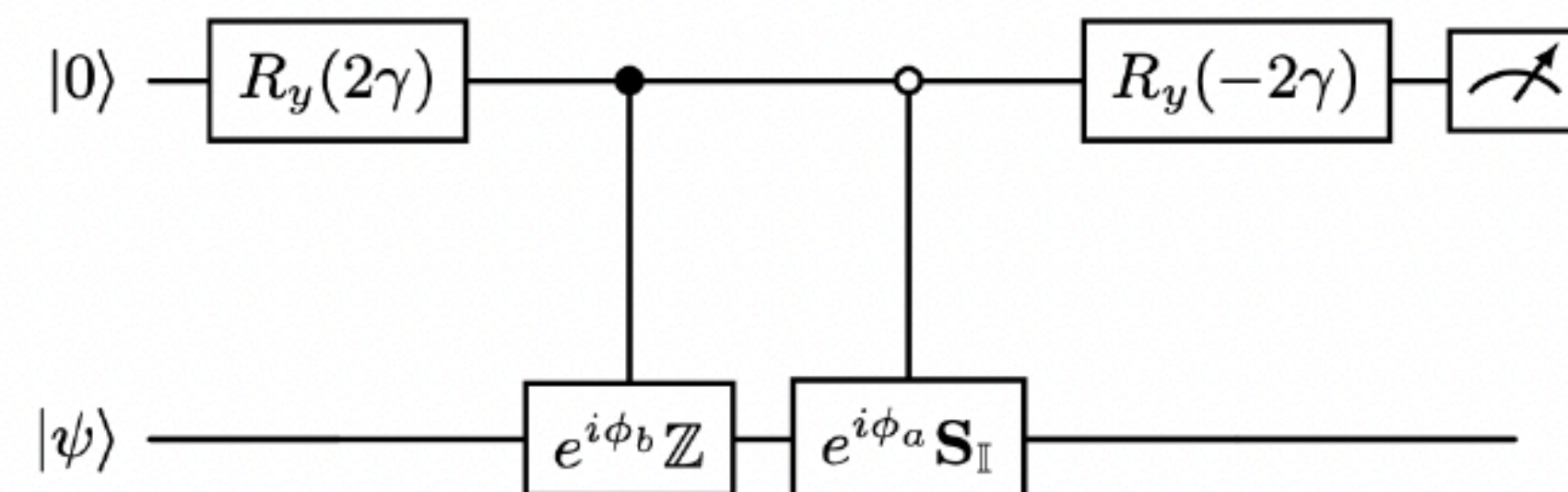
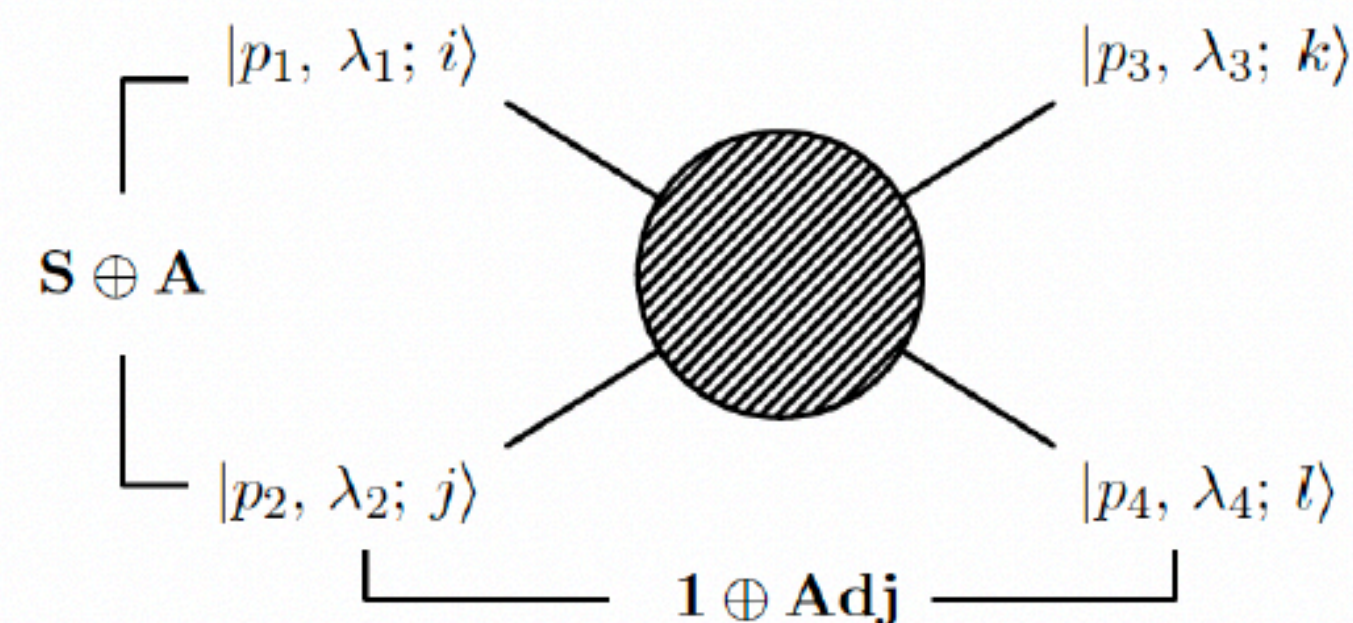
⇒ symmetry enhancement

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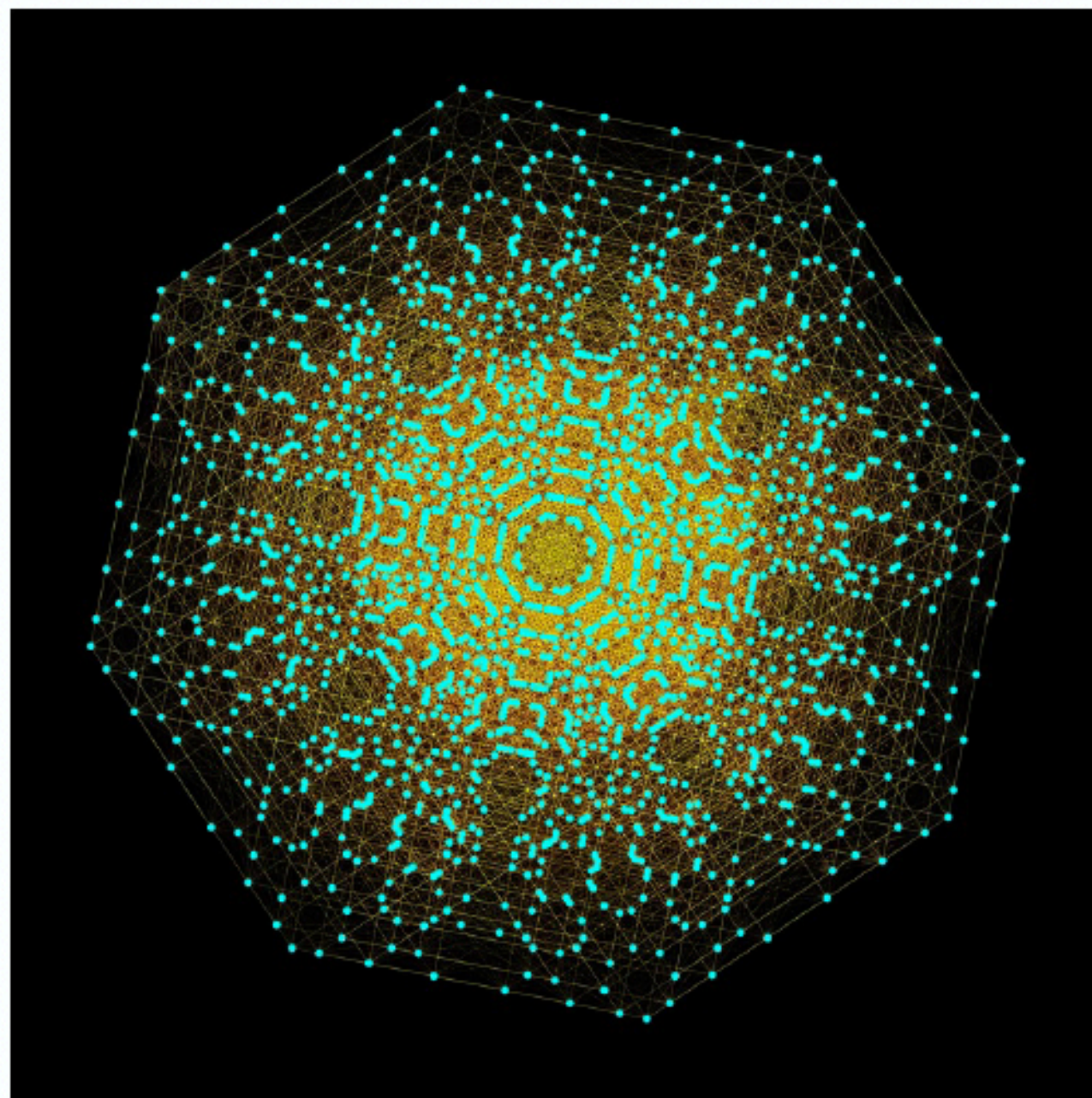


By viewing fixed-helicity SU(N) scattering as quantum gates acting on internal qudits, it is shown that crossing symmetry ties the channels together so tightly that any interacting SU(N)-symmetric field theory must create entanglement in at least one of them.

See also recent work by Haddad, Xu, Croft, Halimeh, Grossi 2602.21311 on amplitudes quantum computations..

Classification of magic states

E_8 , BW_{16} , E_6 , ...



Minimal and **Maximal**
Magic states

		1 st shortest ↓	2 nd shortest ↓
	System	# stabiliser	# max-magic
E_8 ←	2-qubit $(\mathbb{C}^2)^{\otimes 2}$	60	480
BW_{16} ←	3-qubit $(\mathbb{C}^2)^{\otimes 3}$	1080	15360

A new geometric route to understanding quantum magic. By mapping vectors from highly symmetric lattices (E_8 , BW_{16} , and E_6) into quantum Hilbert spaces, construct and classify both stabiliser states and maximal magic states for two-qubit, three-qubit, and one-qutrit systems.

Outlook

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 (quantum) correlations, but just counting experiments.

Looking at fundamental interactions at TeV scale with QI glasses is leading to a renewed interest in a variety of phenomena with novel ideas, questions and studies...

Elementary particles and forces provide a unique “experimental setup” to study QI on fundamental objects. Contributions with new results on QI from HEP just starting...



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