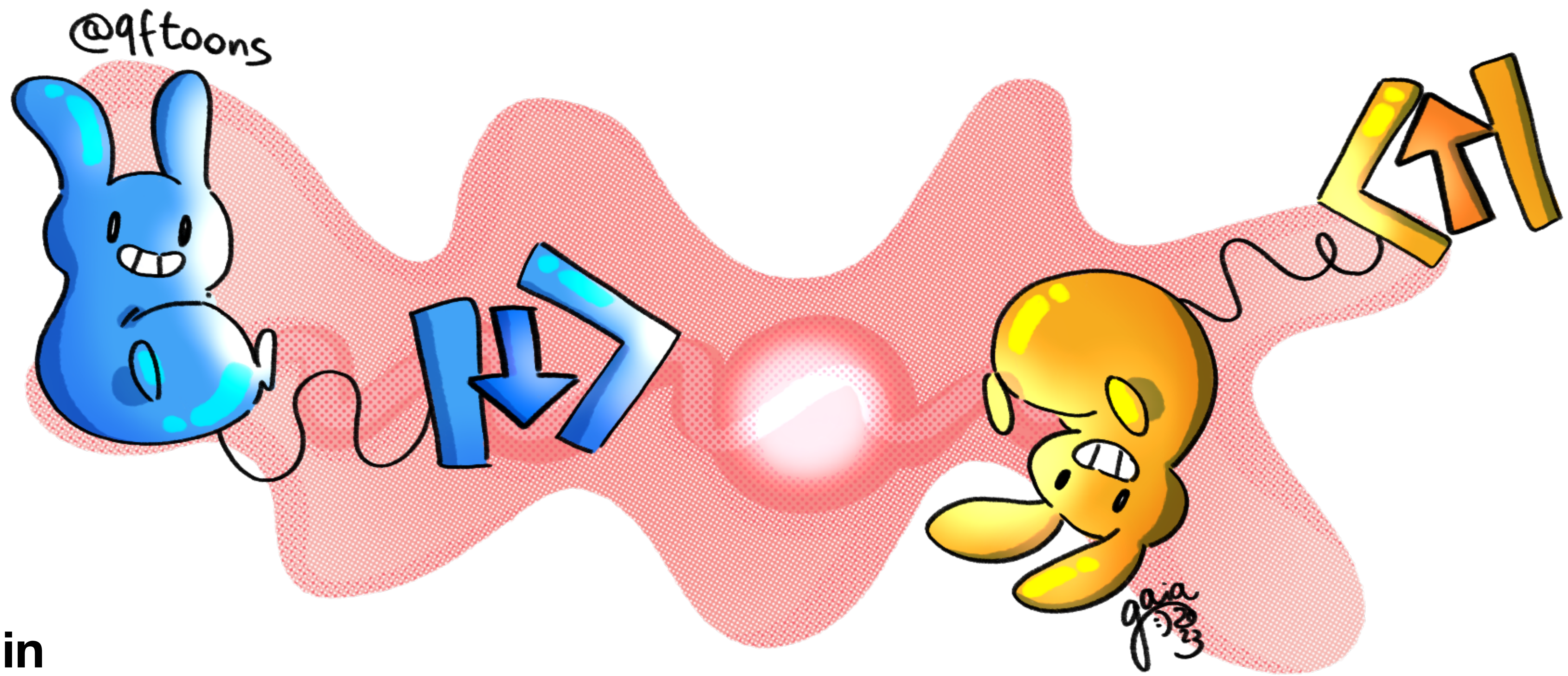
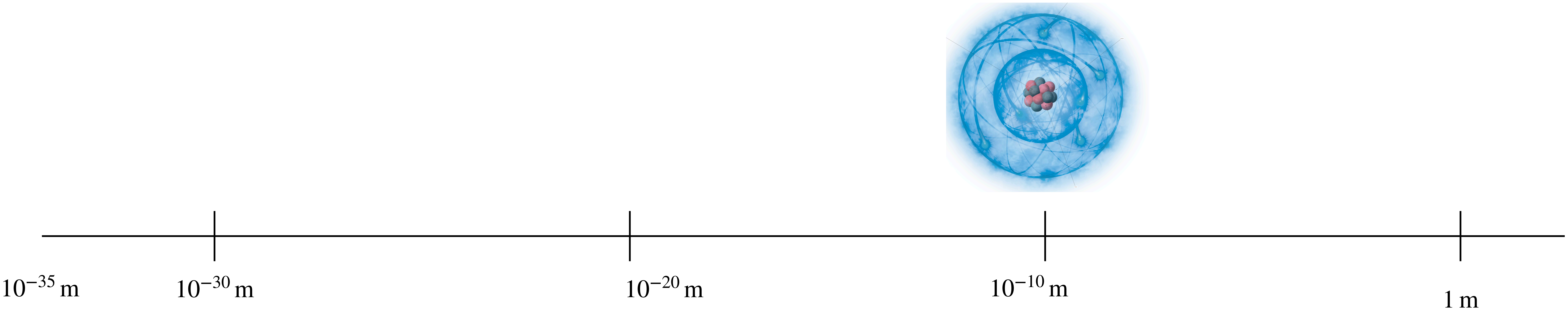
Quantum Information meets Collider Physics



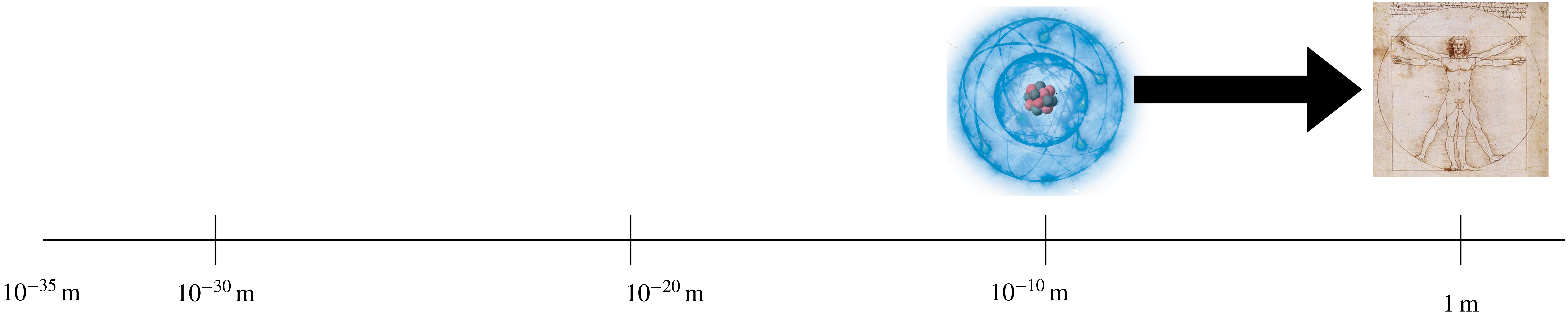
Fabio Maltoni
Università di Bologna
Université catholique de Louvain

Introduction



Quantum computers, quantum communications, quantum devices,…

Introduction



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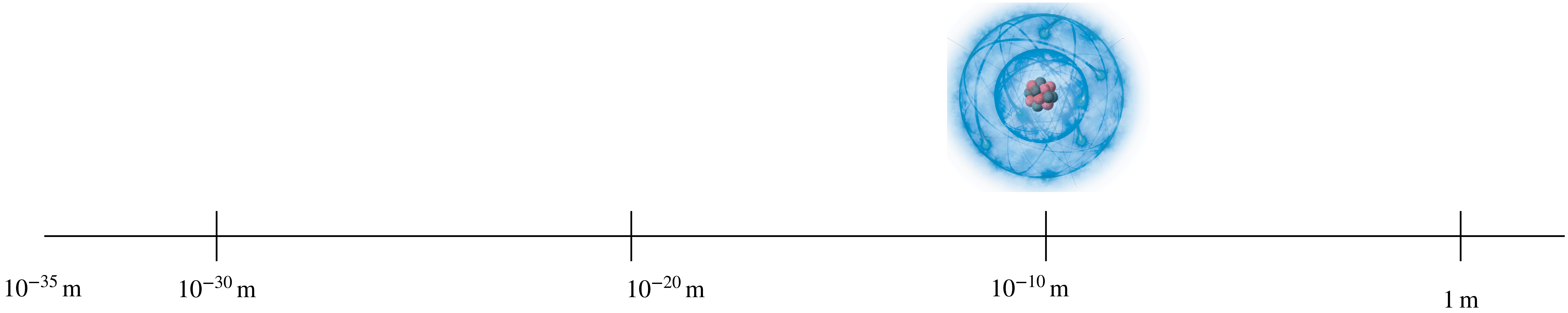
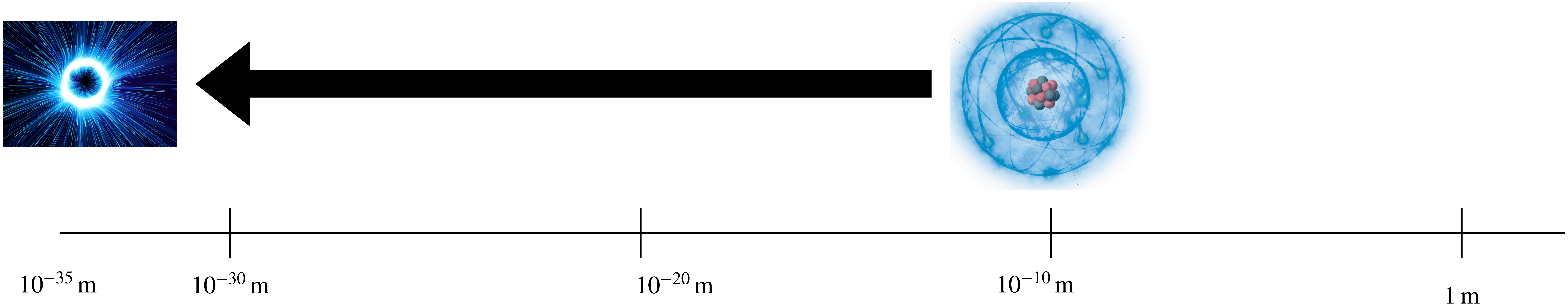


Quantum computers, quantum communications, quantum devices,…

Introduction

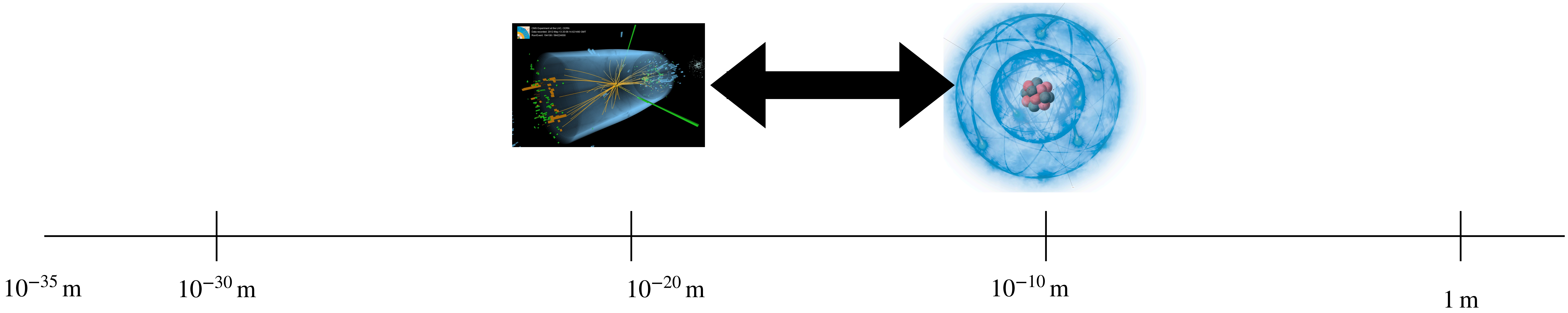


It from Qubit:

- 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?



Introduction

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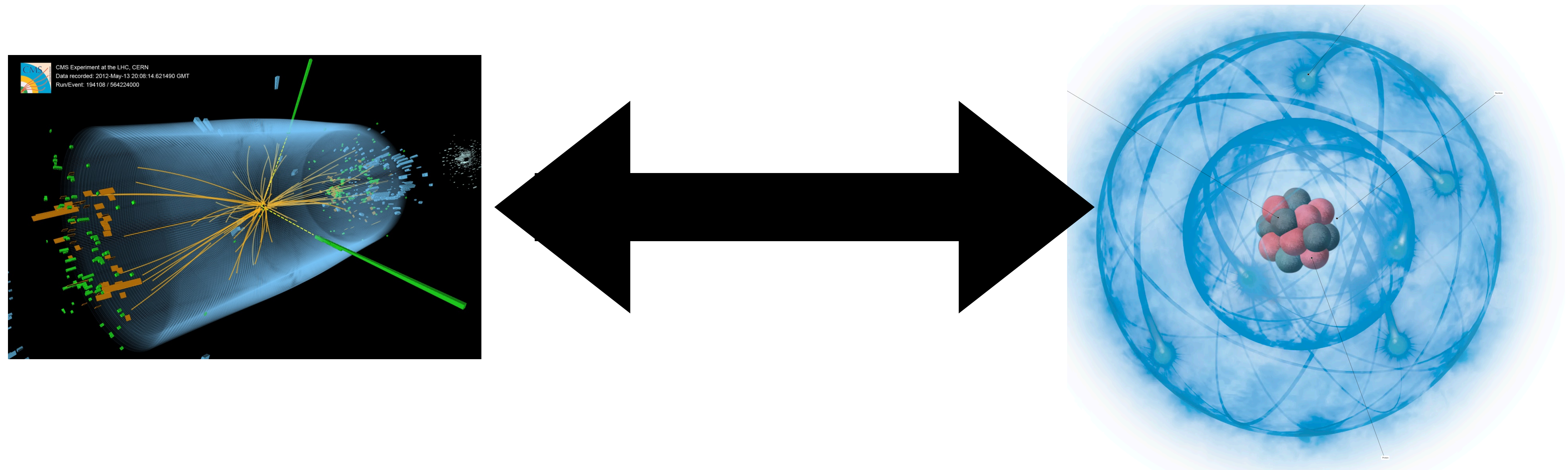
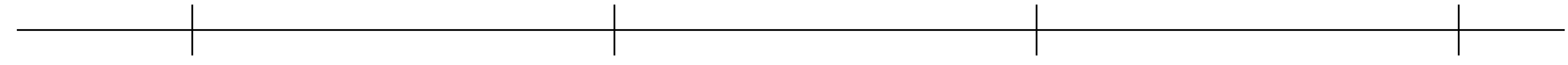
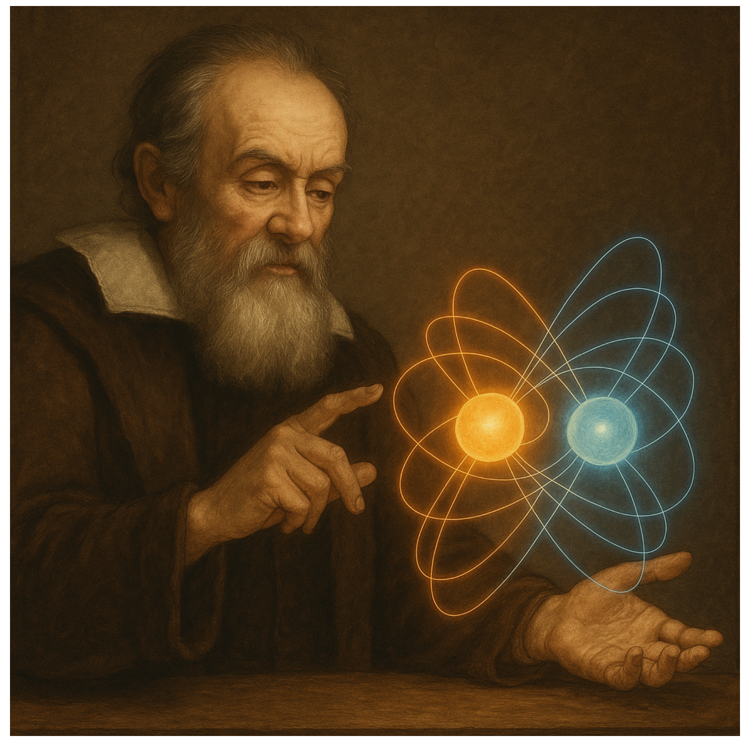




*Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.



Introduction

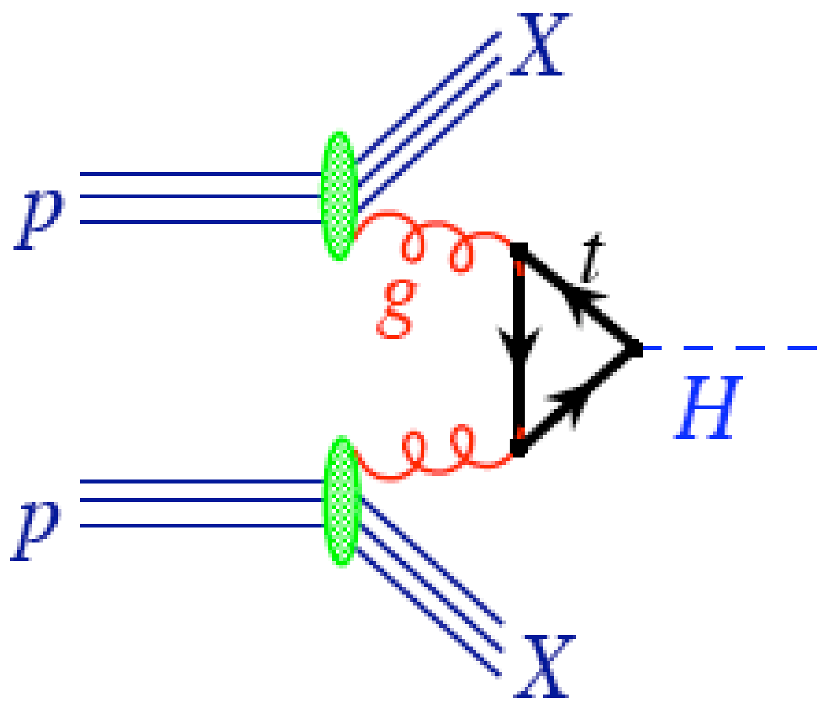
The quantum nature of the SM is so pervasive in the daily life of the particle physicist, that we often forget about it. Naively:

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

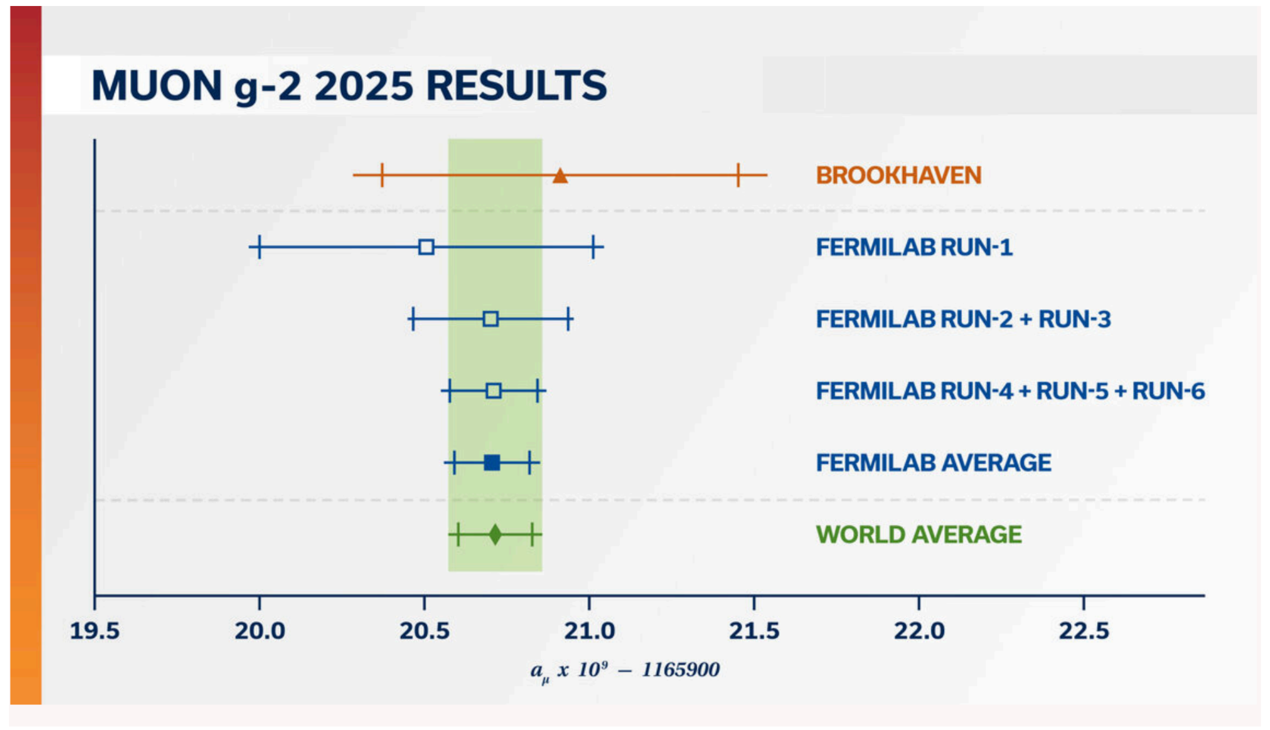
- **tree level** → order $\hbar^0$
- **1-loop** → order $\hbar^1$
- **2-loop** → order $\hbar^2$
- etc.

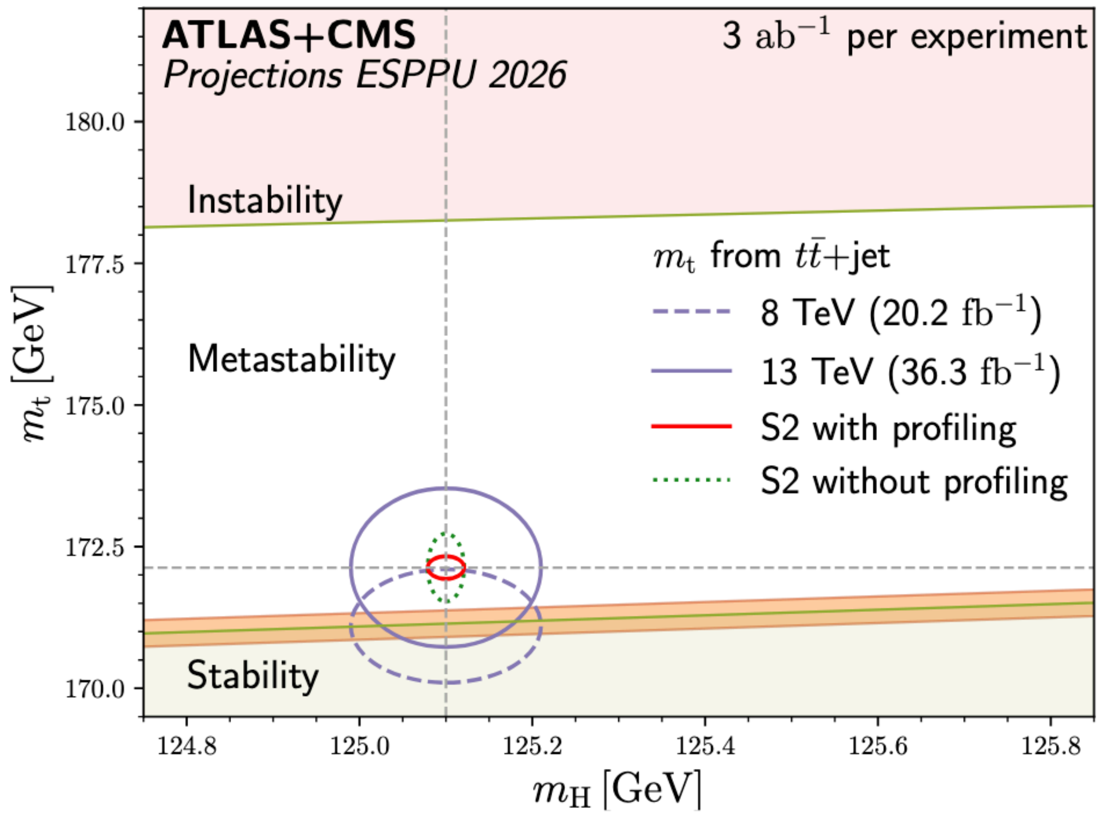
We have extensively validated QFT at different scales, and always found it a consistent way of making predictions in HEP.

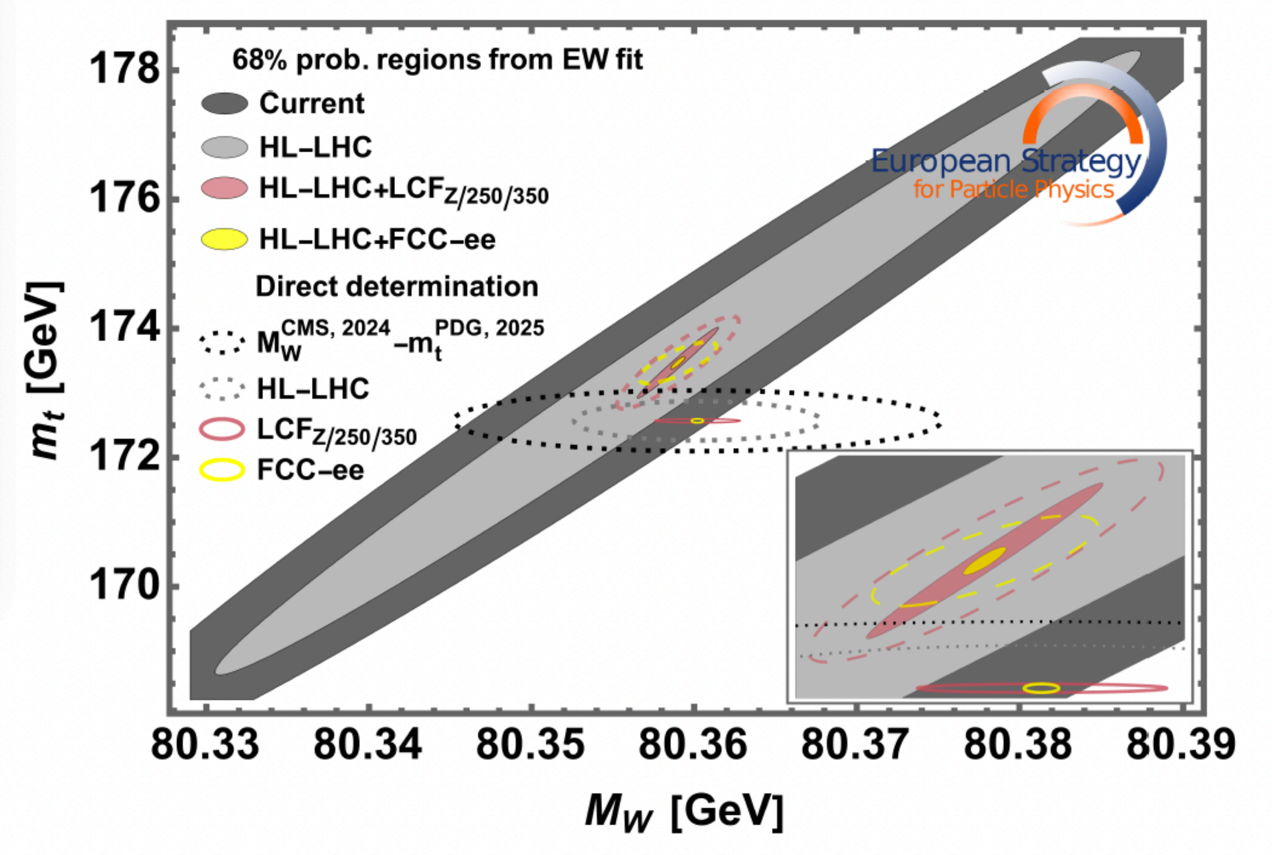
Are there other features predicted by QFT that we can study/exploit?



Gluon fusion

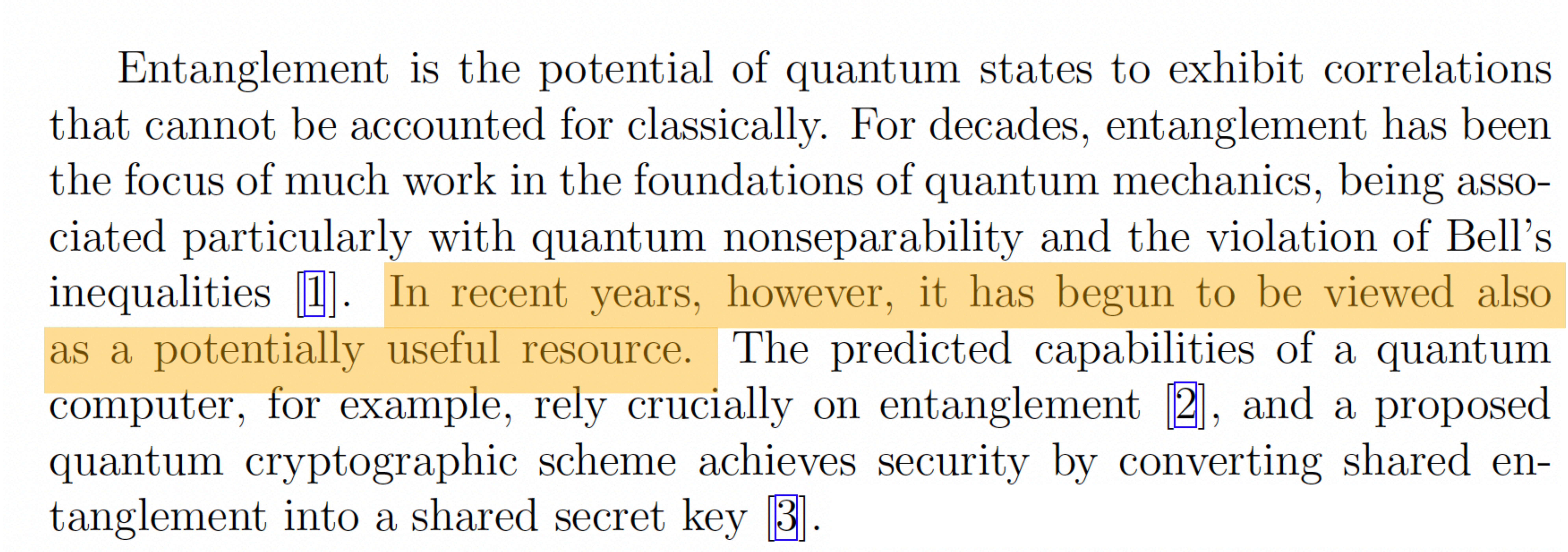






“Entanglement of a pair of quantum bits”, by Hill and Wootters, arXiv:quant-ph/9703041

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 ⇒

Entanglement => communication resource
Magic => computational resource

“Entanglement of a pair of quantum bits”, by Hill and Wootters, arXiv:quant-ph/9703041

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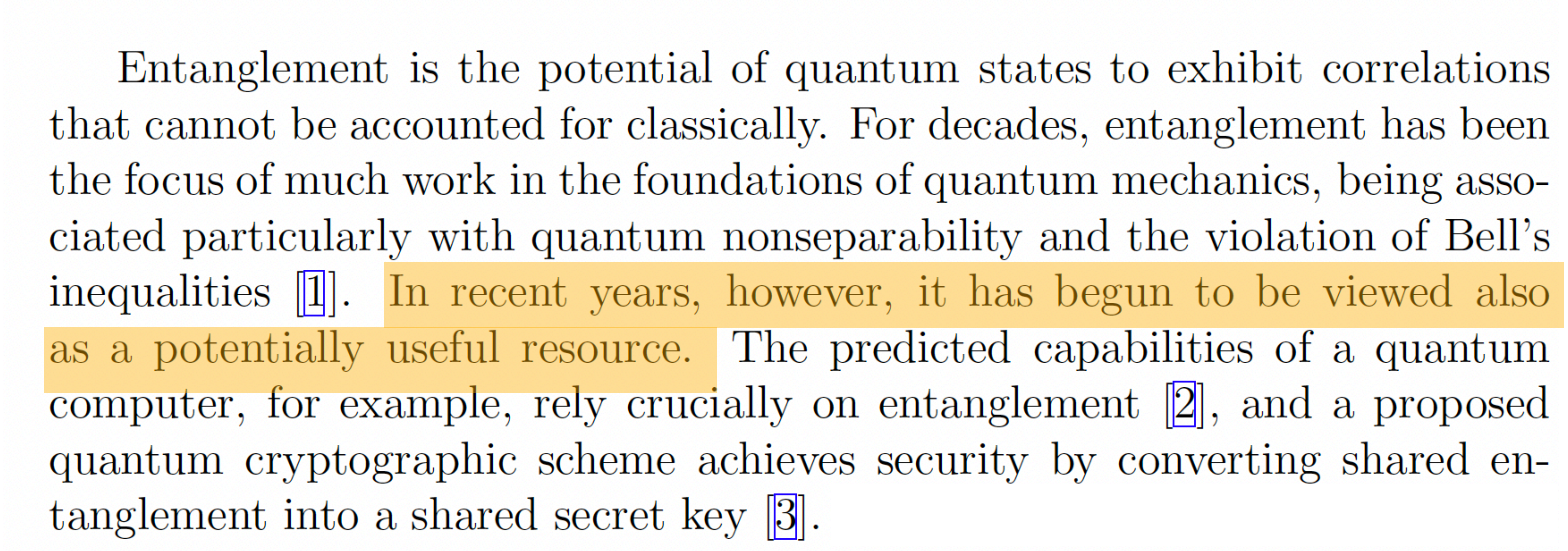

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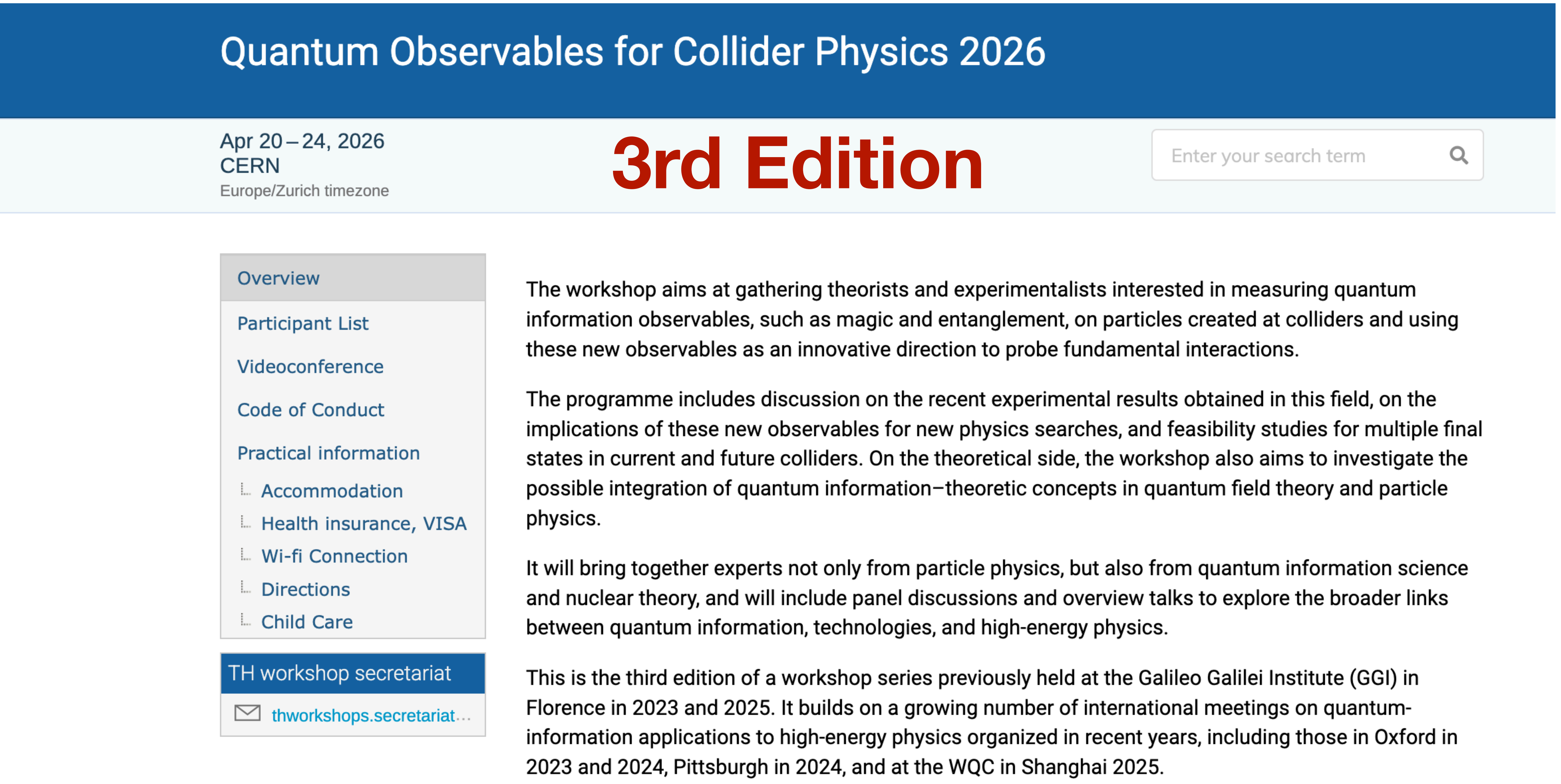
Theory of Resources ⇒

Entanglement => communication resource

Magic => computational resource

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



Quantum Observables for Collider Physics 2026

Apr 20 – 24, 2026
CERN
Europe/Zurich timezone

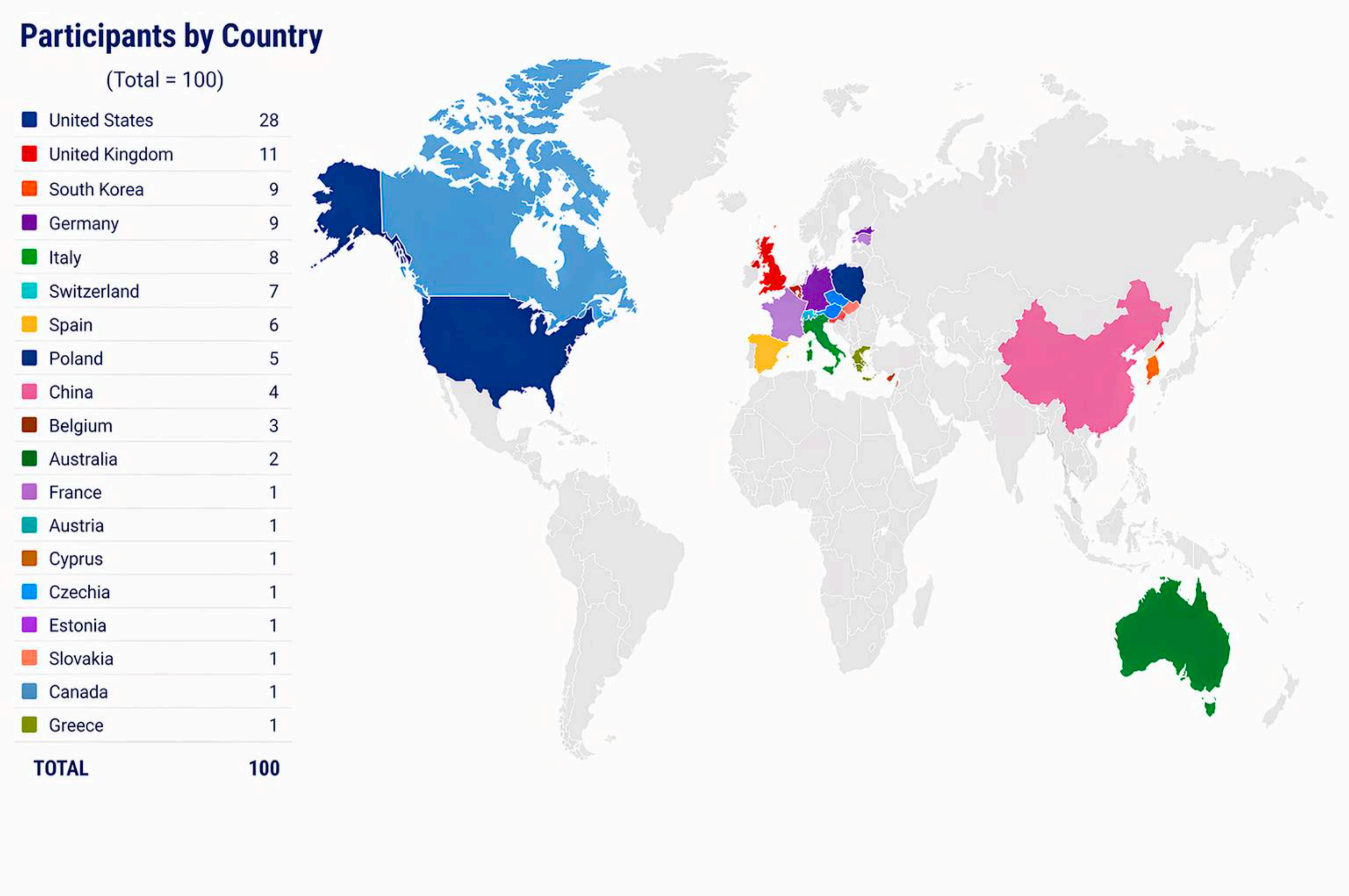
3rd Edition

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
qihep2027.northwestern.edu

4th Edition

Much more this afternoon…

PHENO 2026
QUANTUM
FESTIVAL

TWO HOURS OF FUN

★ LAWRENCE HALL 106 – THIS AFTERNOON ★

TIME	SPEAKER	TITLE
★ 14:00 - 14:15	Dorival Gonçalves	Quantum Observables and Higher-Order effects in Leptonic h -> VV* Decays
★ 14:15 - 14:30	Alberto Navarro	Higher-order corrections to quantum observables in semileptonic Higgs decays
★ 14:30 - 14:45	Nicholas Pinto	Study of spin correlations in Higgs boson decays to four leptons at CMS
★ 14:45 - 15:00	Marcel I. Yanez	Spin-Density Matrices as probes of CP violation in Top–Higgs Interactions
★ 15:00 - 15:15	Harman Singh	Decoherence or Recoherence in the Radiative Decay of Z boson
★ 15:15 - 15:30	Peng-Cheng Lu	NLO EW Corrections and Spin Observables for aa-> tau+ tau- in Pb-Pb UPCs
★ 15:30 - 15:45	Youle Su	Quantum Tomography of Fermion Pairs in e+e- Collisions: Longitudinal Beam Polarization Effects
★ 15:45 - 16:00	Morgan Cassidy	Leggett-Garg Inequality Violation with Muon g-2 Experiments

★★ SCIENCE IS OUR STORY. DISCOVER THE PLOT. ★★

OpenAI

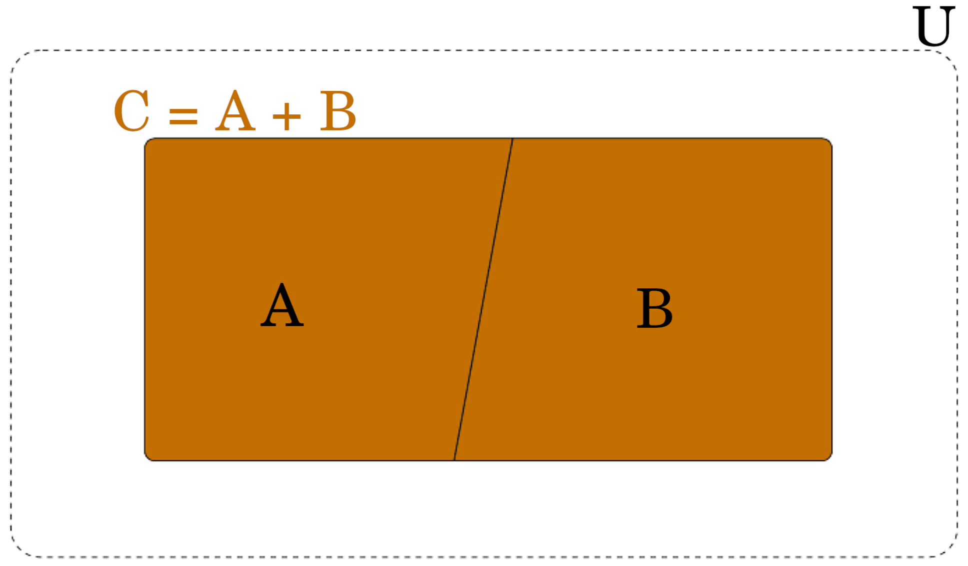
Basics

Density matrix : pure versus mixed

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

Basics

Composite systems



Pure	$\vert\psi\rangle = \vert a\rangle \otimes \vert b\rangle$	$\vert\psi\rangle = \sum_{ij} p_{ij} \vert a_i\rangle \otimes \vert b_j\rangle \quad p_{ij} \in \mathbb{C}\,, \sum_{ij} p_{ij} p^*_{ij} = 1$ $\vert a_i\rangle, \vert b_j\rangle$ orthonormal bases
	Separable	Non-separable=ENTANGLED
Mixed	$\rho = \sum_i p_i\, \rho_A^i \otimes \rho_B^i$	$\rho \neq \sum_i p_i\, \rho_A^i \otimes \rho_B^i$

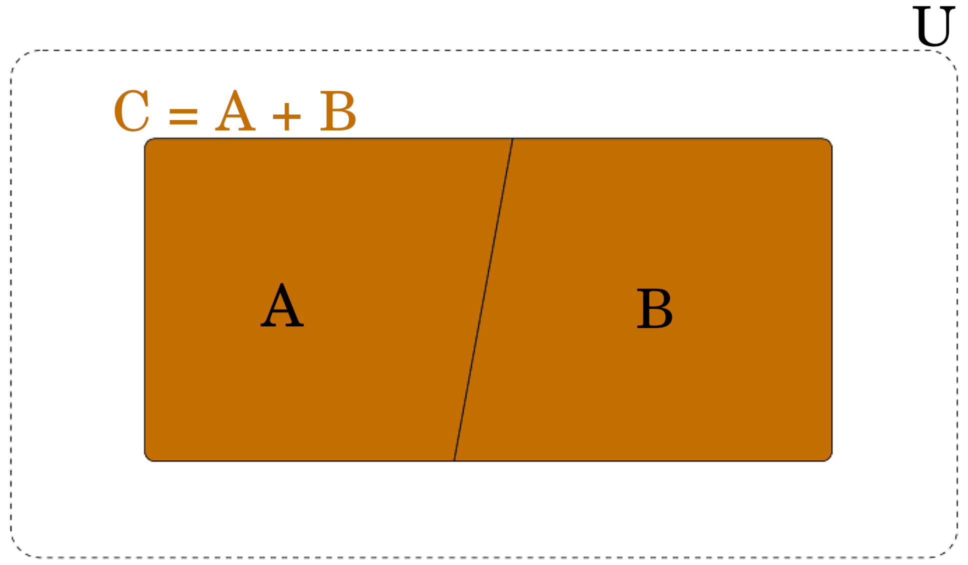
$p_i \geq 0\,, \sum_i p_i = 1$

Here one can use pure states instead of ρ_A, ρ_B

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

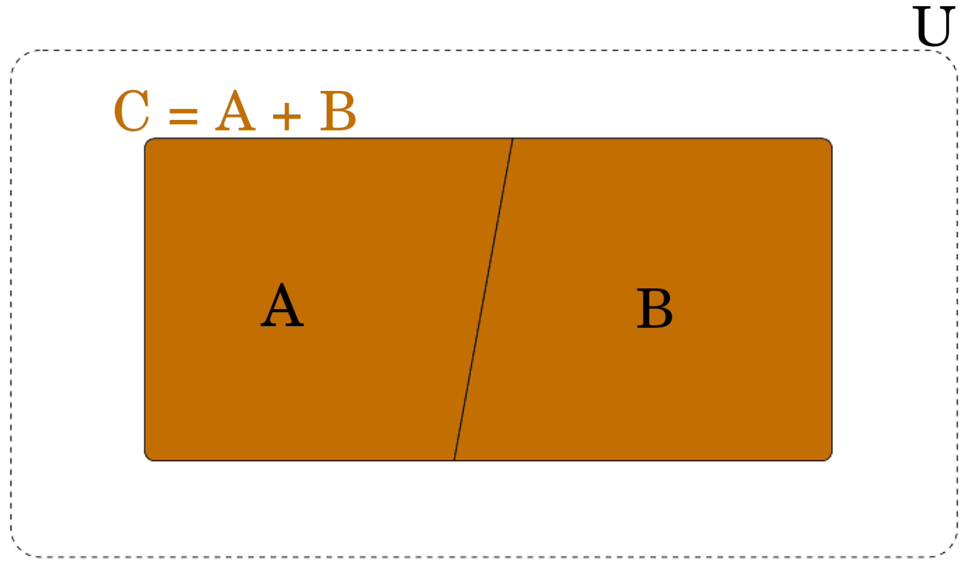
$$|\psi\rangle = \sum_i \sqrt{\lambda_i}\, |w_i\rangle_A \otimes |z_i\rangle_B \qquad \text{with} \qquad \sum_i \lambda_i = 1, \quad \lambda_i \geq 0$$

$$\rho_A = \sum_i \lambda_i |w_i\rangle_A\, {}_A\langle w_i|$$

$$\rho_B = \sum_i \lambda_i |z_i\rangle_B\, {}_B\langle z_i|$$

$\Rightarrow$

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



Entanglement

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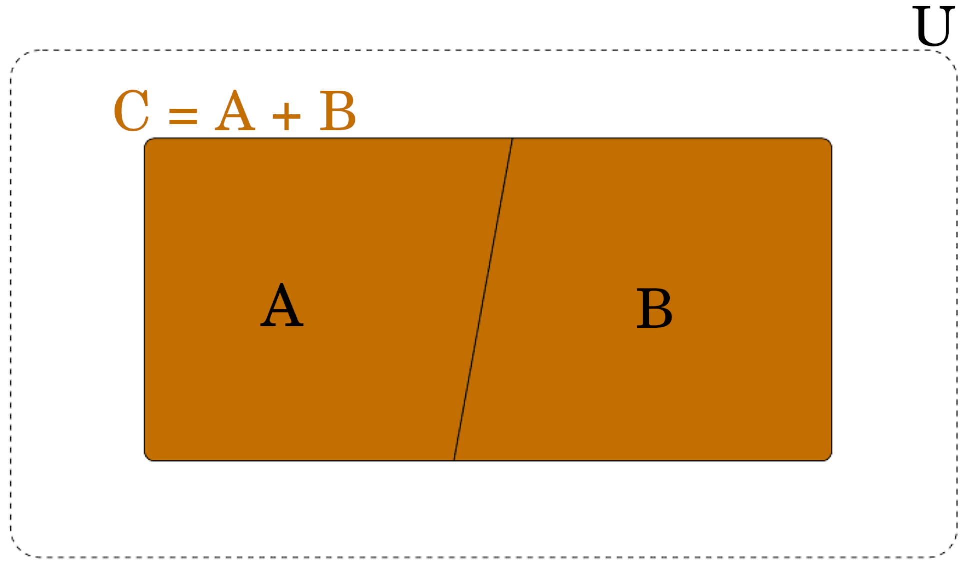
- The states of the subsystems are mixed-states!
- They have the same eigenvalues => they are equally impure

Consequences:

1. One can always think of a mixed state as the trace out a subsystem 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. $\mathscr{H} = \mathscr{H}_A \otimes \mathscr{H}_B$

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

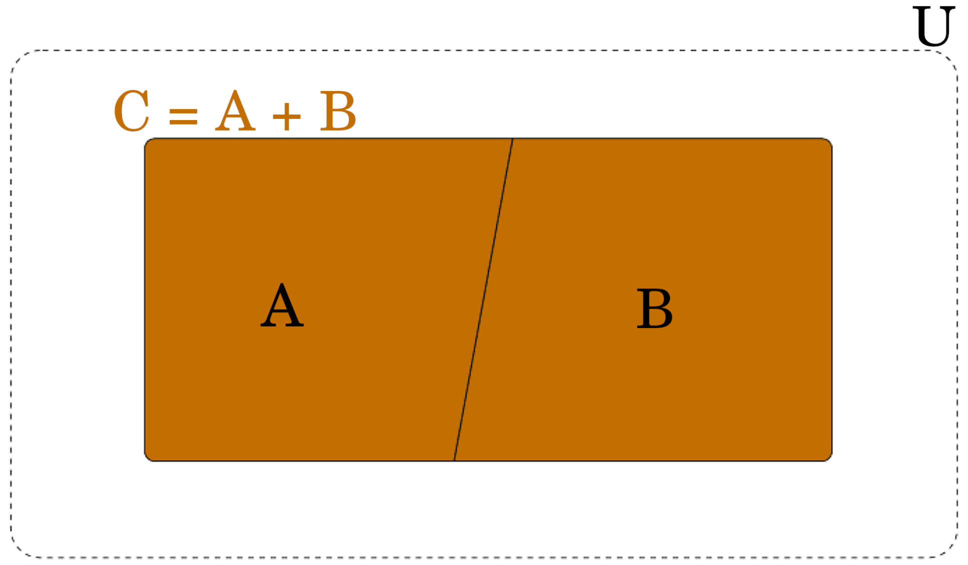
$\mathrm{Tr}\left[\rho_A^2\right] \leq 1$ and $\mathrm{Tr}\left[\rho_B^2\right] \leq 1$

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

$$0 \leq C^2_{A|B} = 2(1 - \mathrm{Tr}[\rho_A^2]) = C^2_{B|A} \leq 1$$

$$C^2_{A|B} = 2S_2(\rho_A)$$ 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

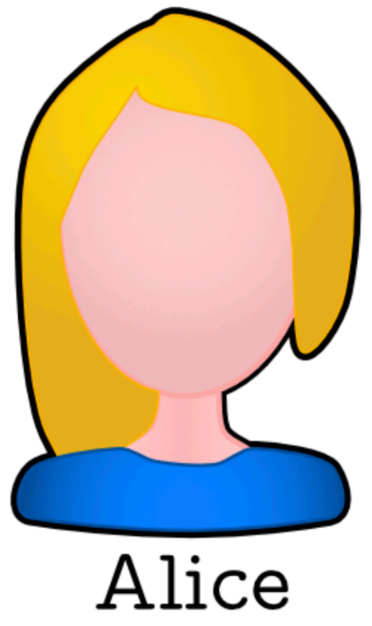
$$\rho^{T_B} = (I \otimes T)[\rho] = \sum_{ijkl} p_{ij} p^*_{kl} \,|a_i\rangle\langle a_k| \otimes (|b_j\rangle\langle b_l|)^T = \sum_{ijkl} p_{ij} p^*_{kl} \,|a_i\rangle\langle a_k| \otimes |b_l\rangle\langle b_j| = \sum_{ijkl} p_{il} p^*_{kj} \,|a_i\rangle\langle a_k| \otimes |b_j\rangle\langle b_l|$$

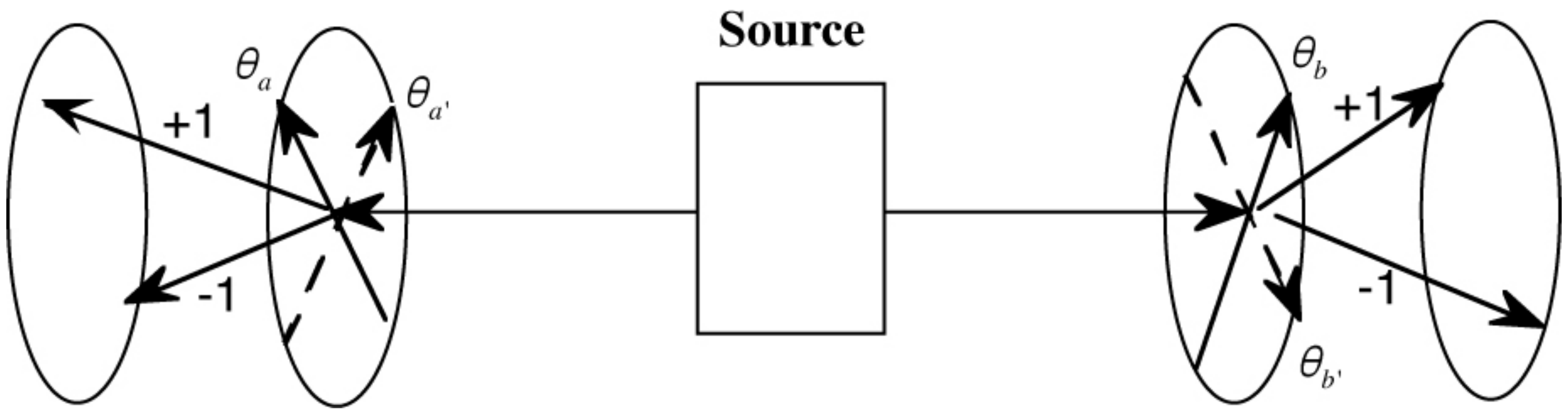
The criterion states that if ρ is separable then all the eigenvalues of ρ^{T_B} are non-negative.
In other words, if ρ^{T_B} has a negative eigenvalue, then the system is guaranteed to be entangled.

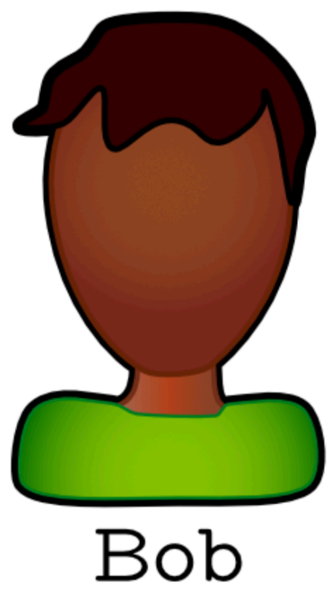
For 2 qubits or 1 qubit x 1 quitrit is a IFF

Basics

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







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

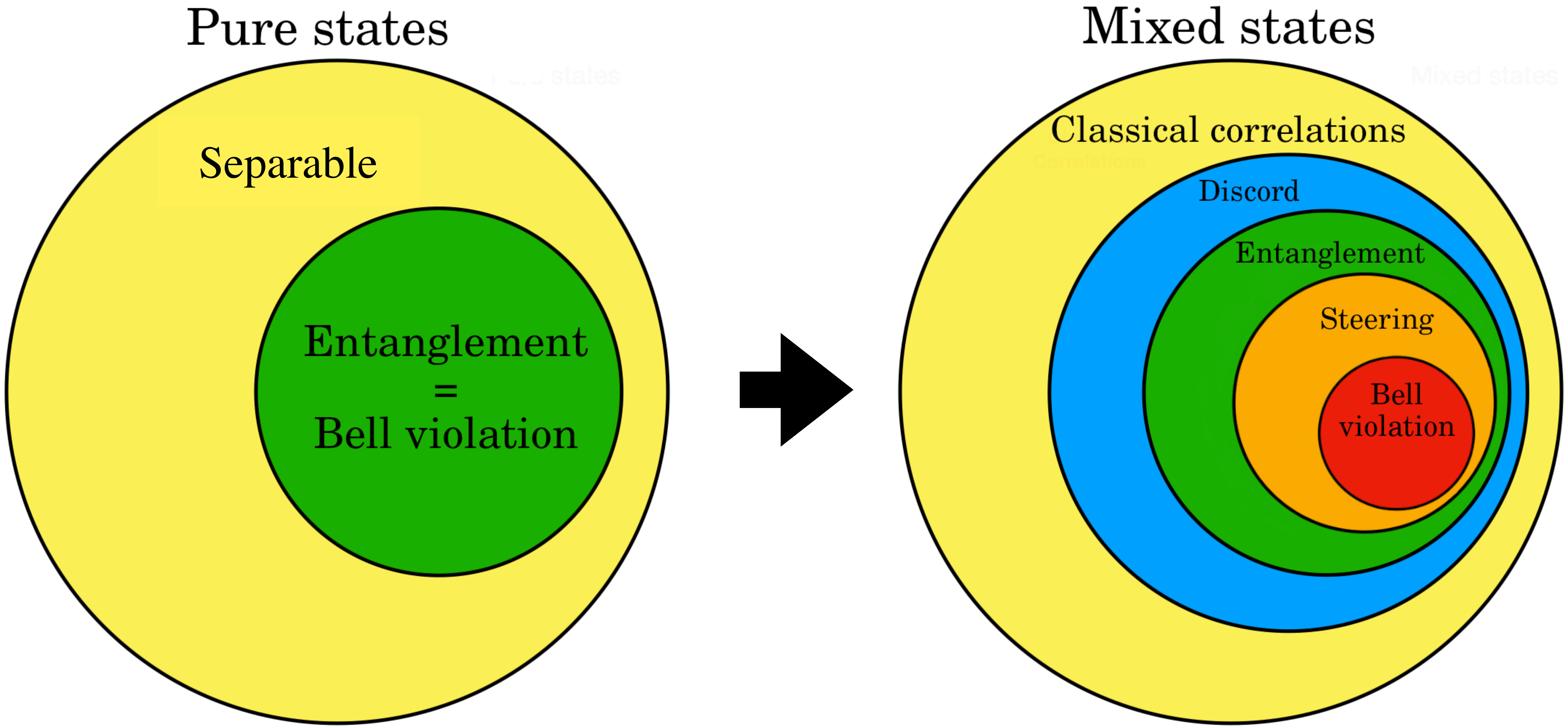
QM: $E(AB) + E(AB') + E(A'B) - E(A'B') \leq 2\sqrt{2}$

$$B = \pm 1$$
$$B' = \pm 1$$

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

Basics

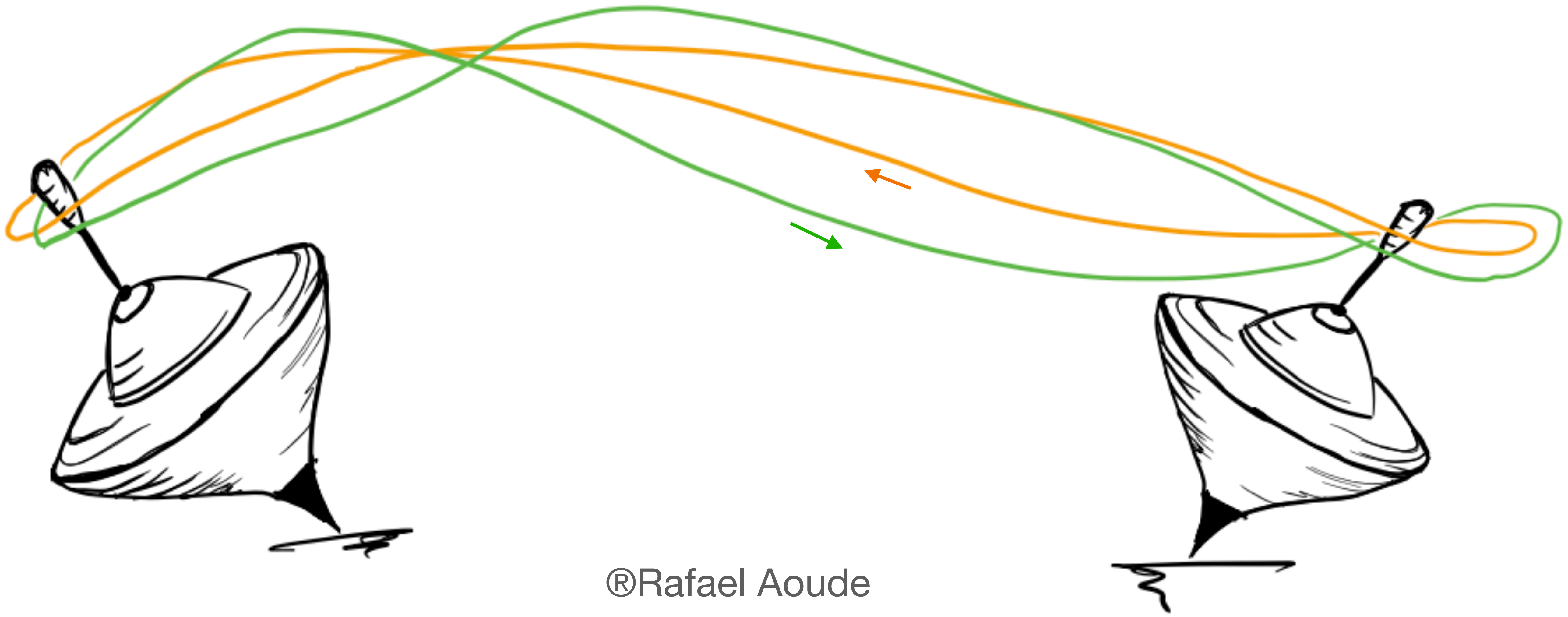
Grading QM correlations



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

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

Quantum tops



®Rafael Aoude

Qubit

Qubit

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

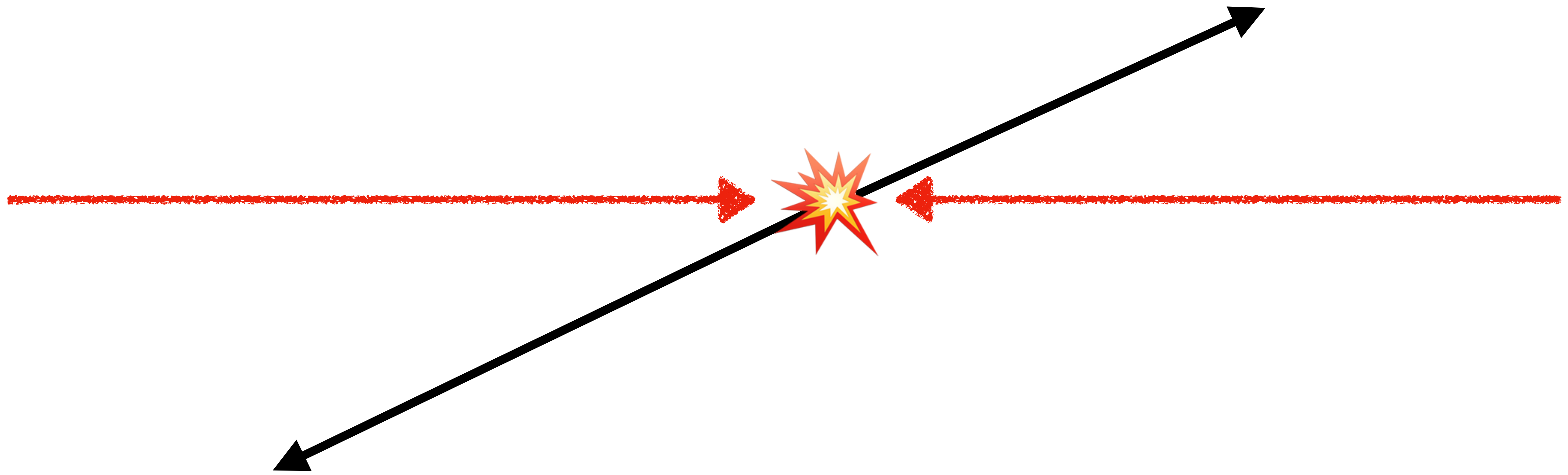
Caution: possibly incomplete list!

Quantum tops

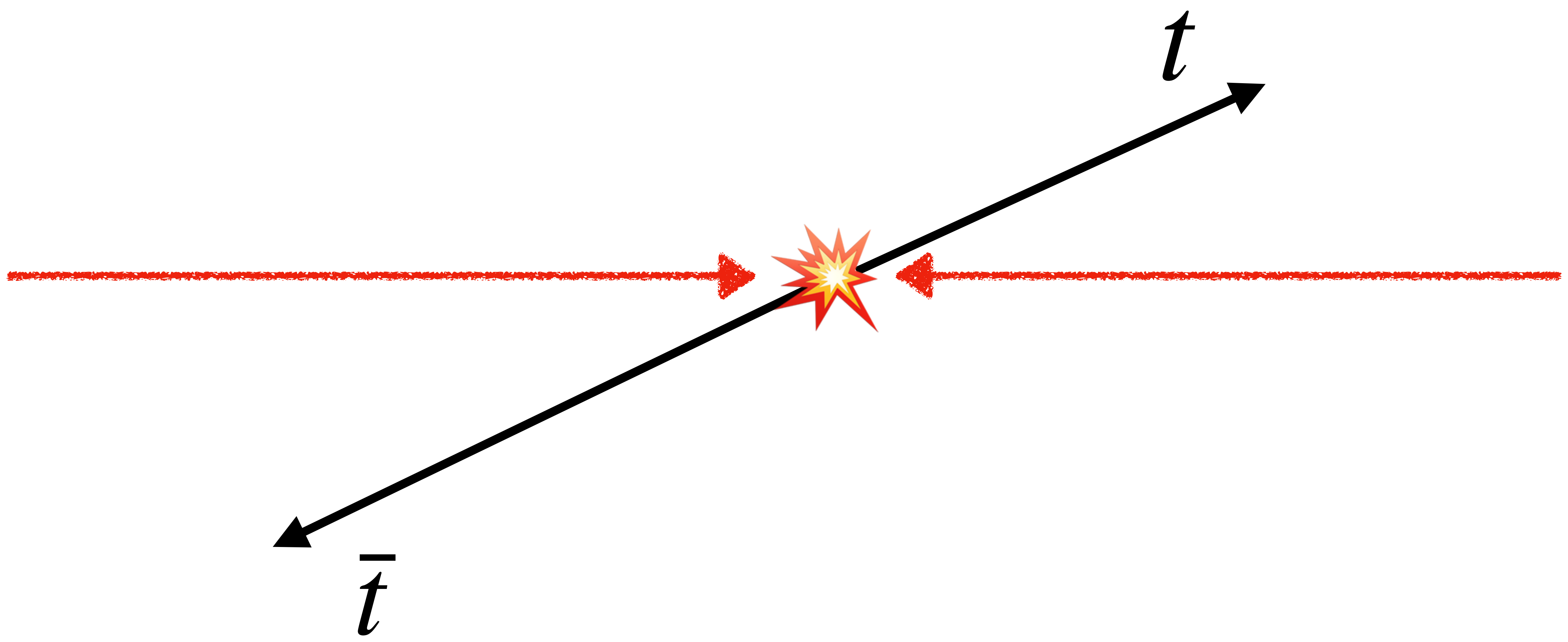
Quantum tops

Quantum tops

Quantum tops



Quantum tops



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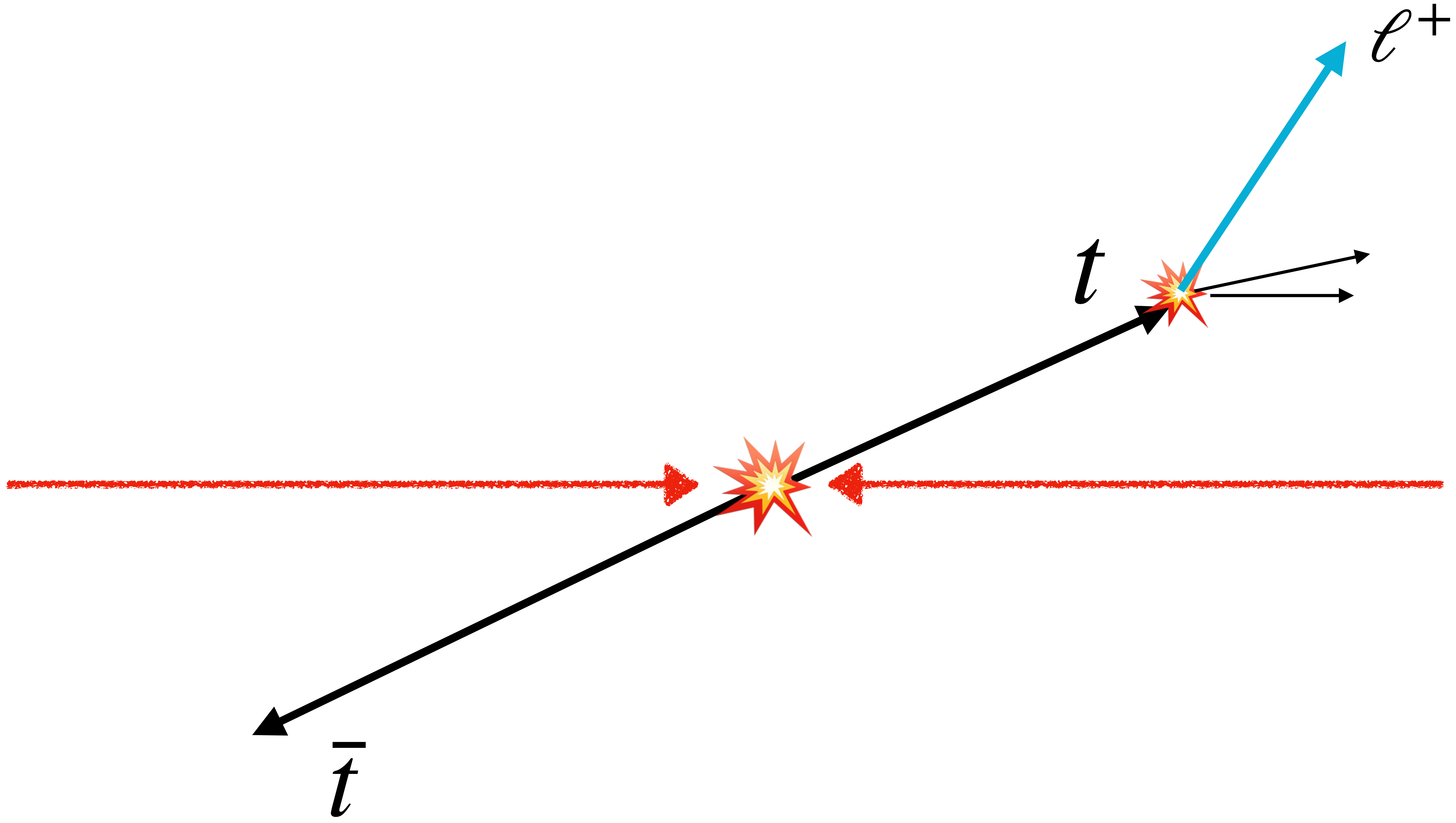

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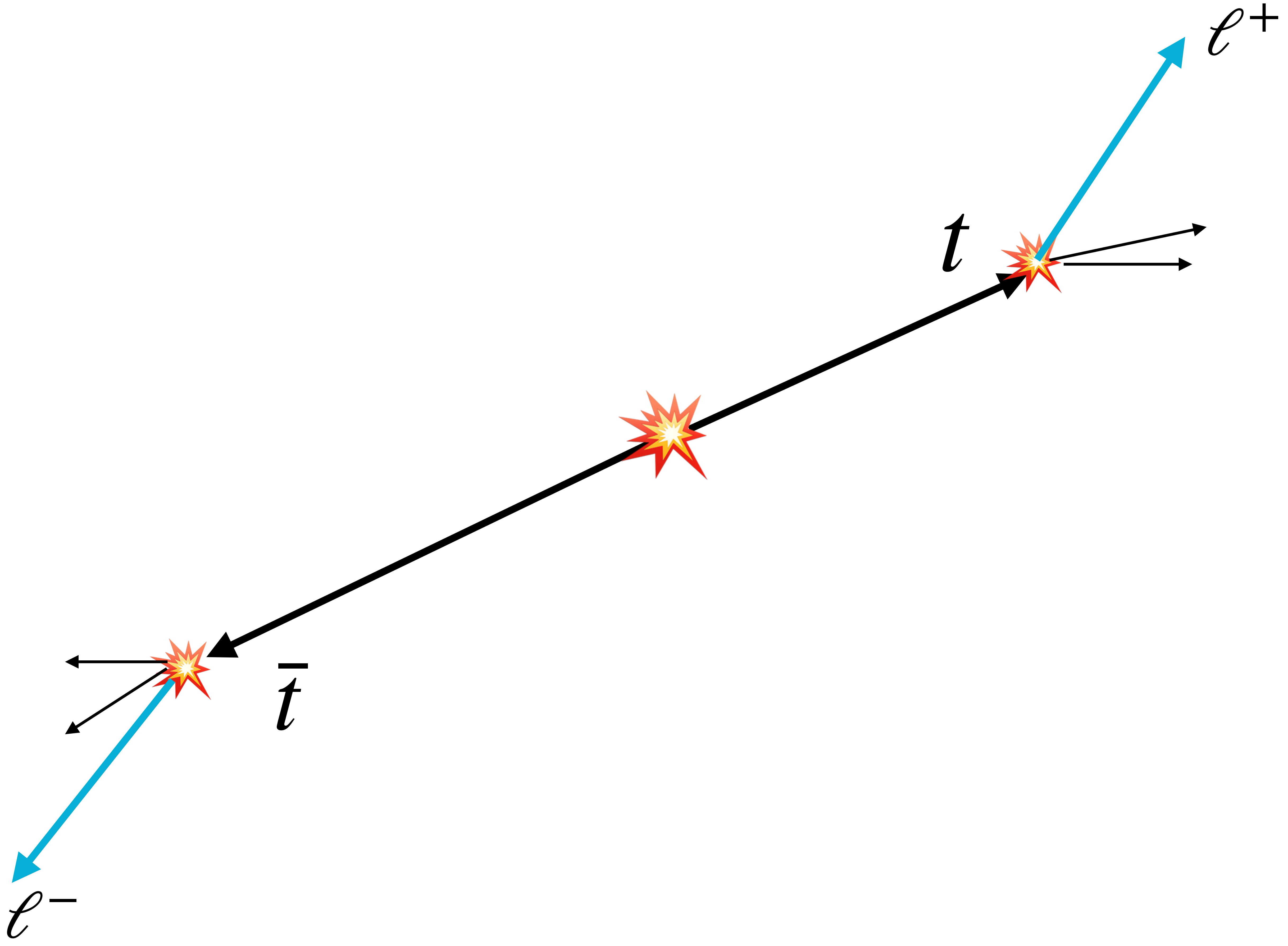

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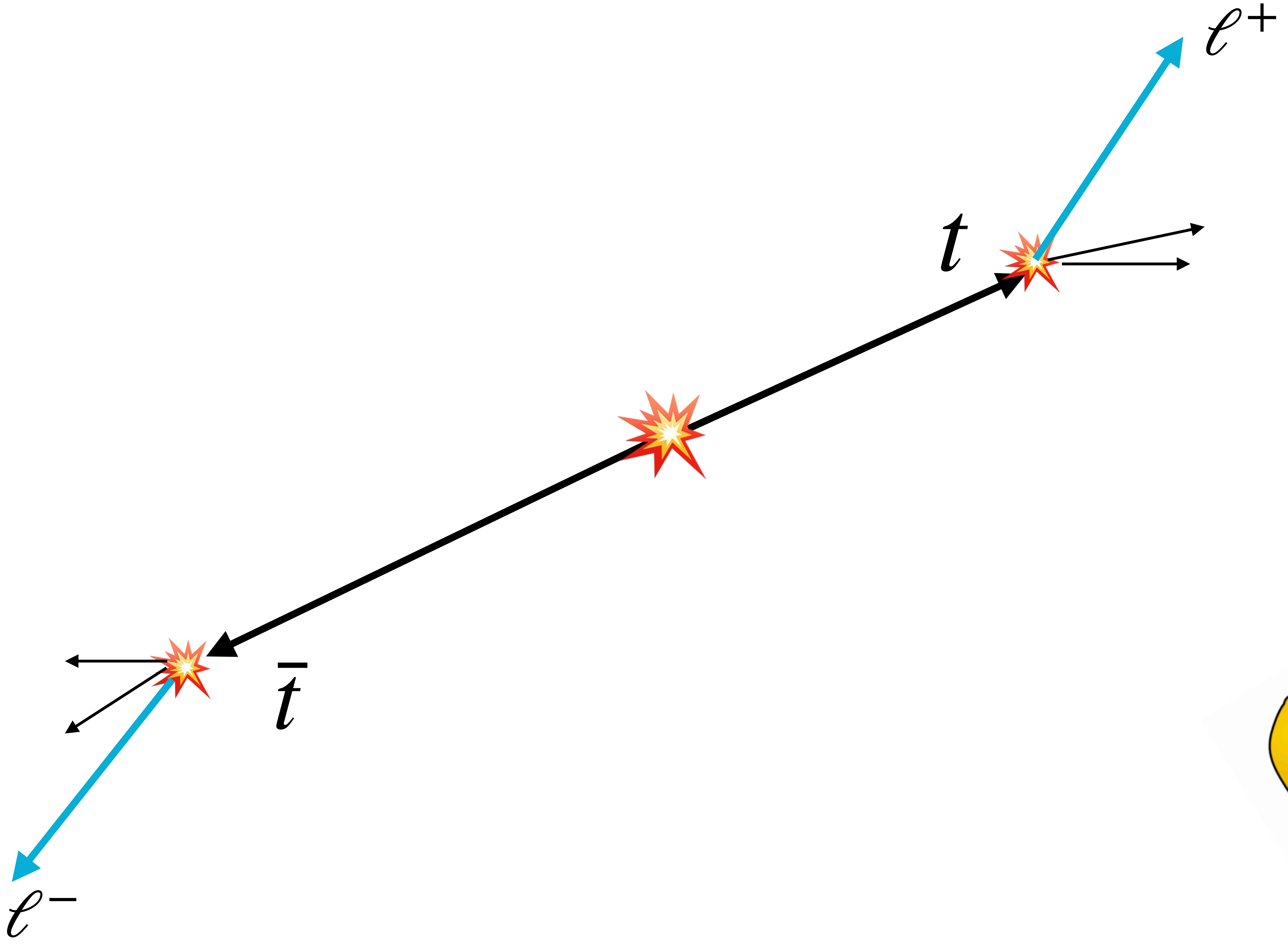

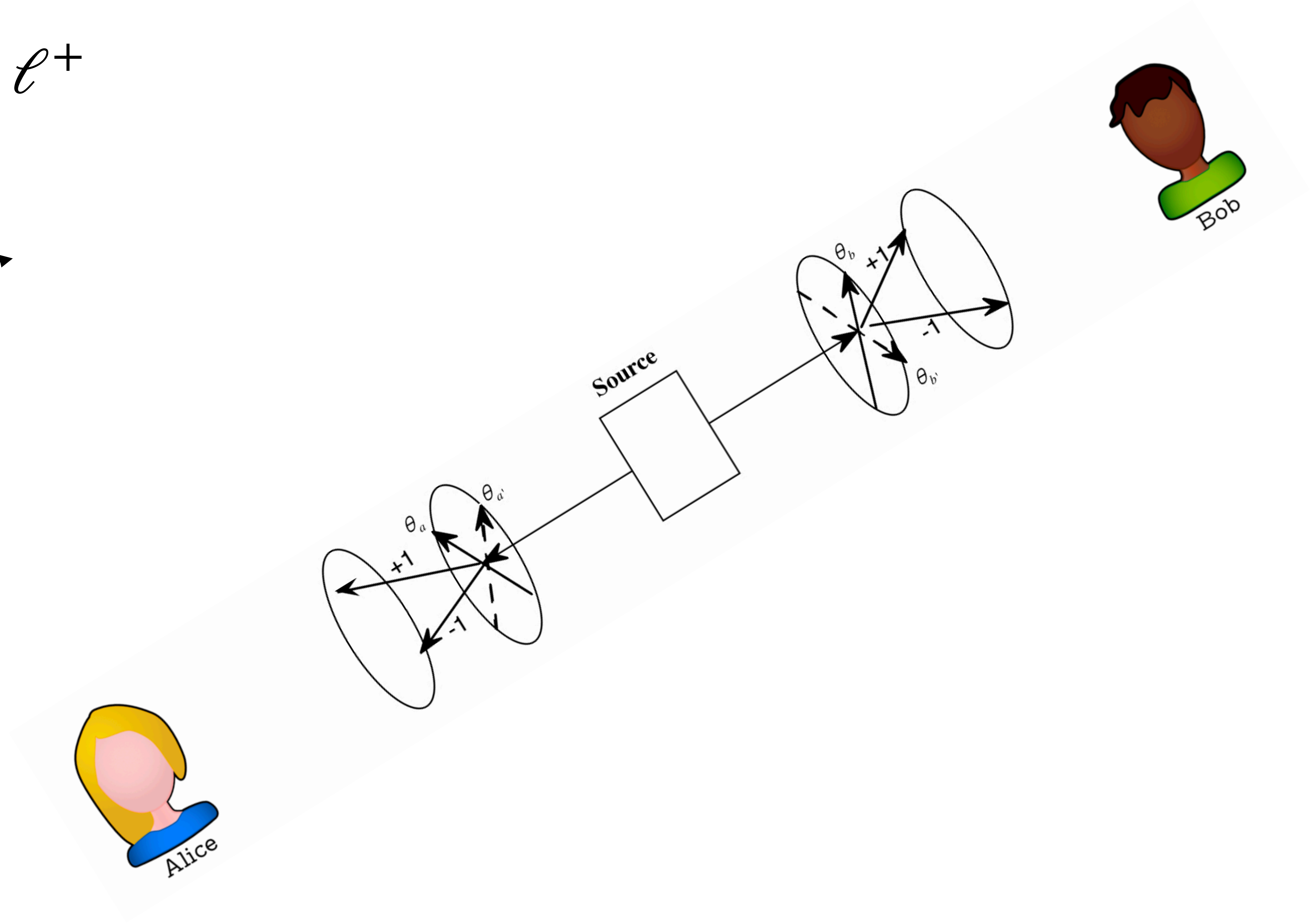

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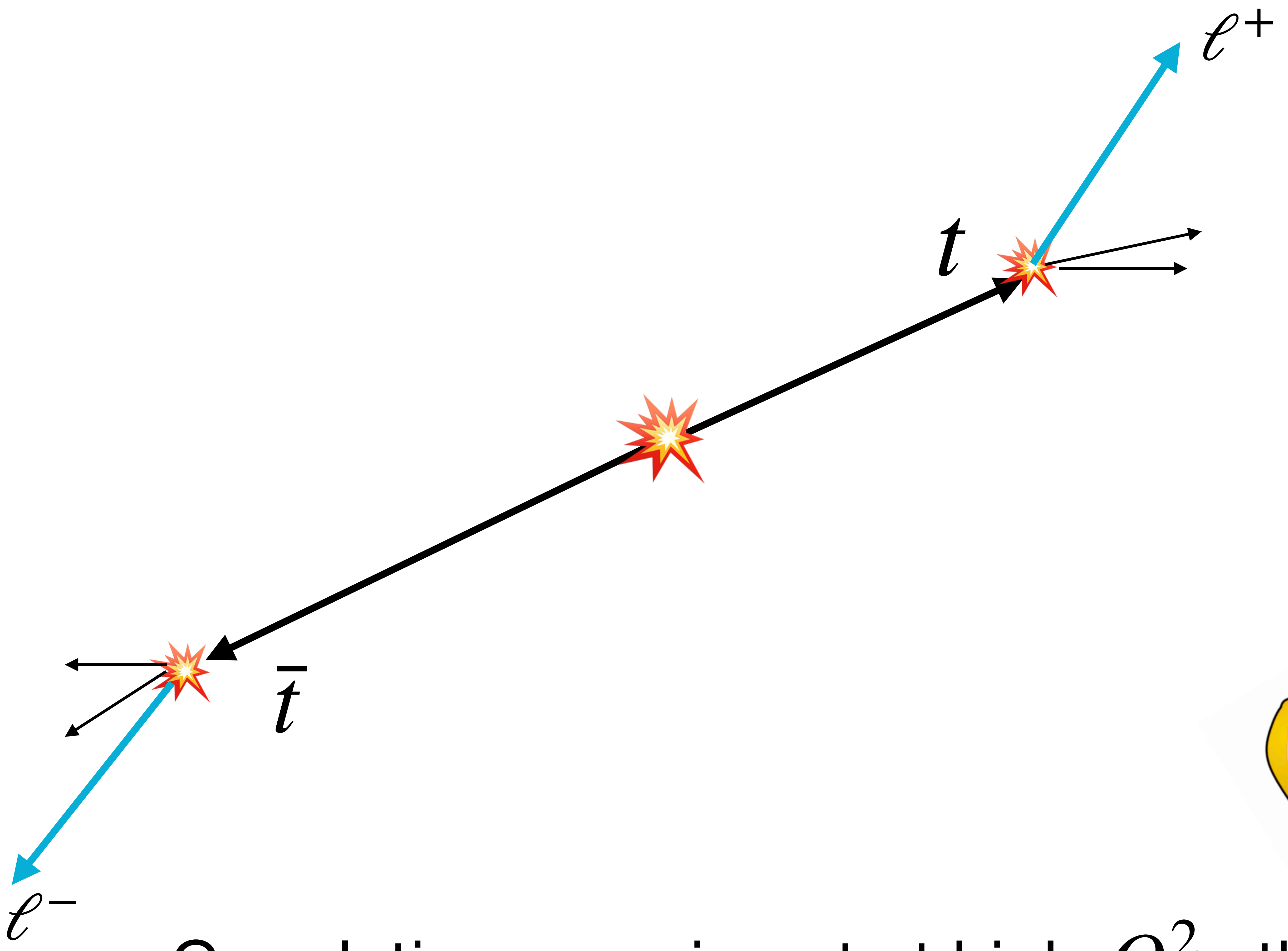
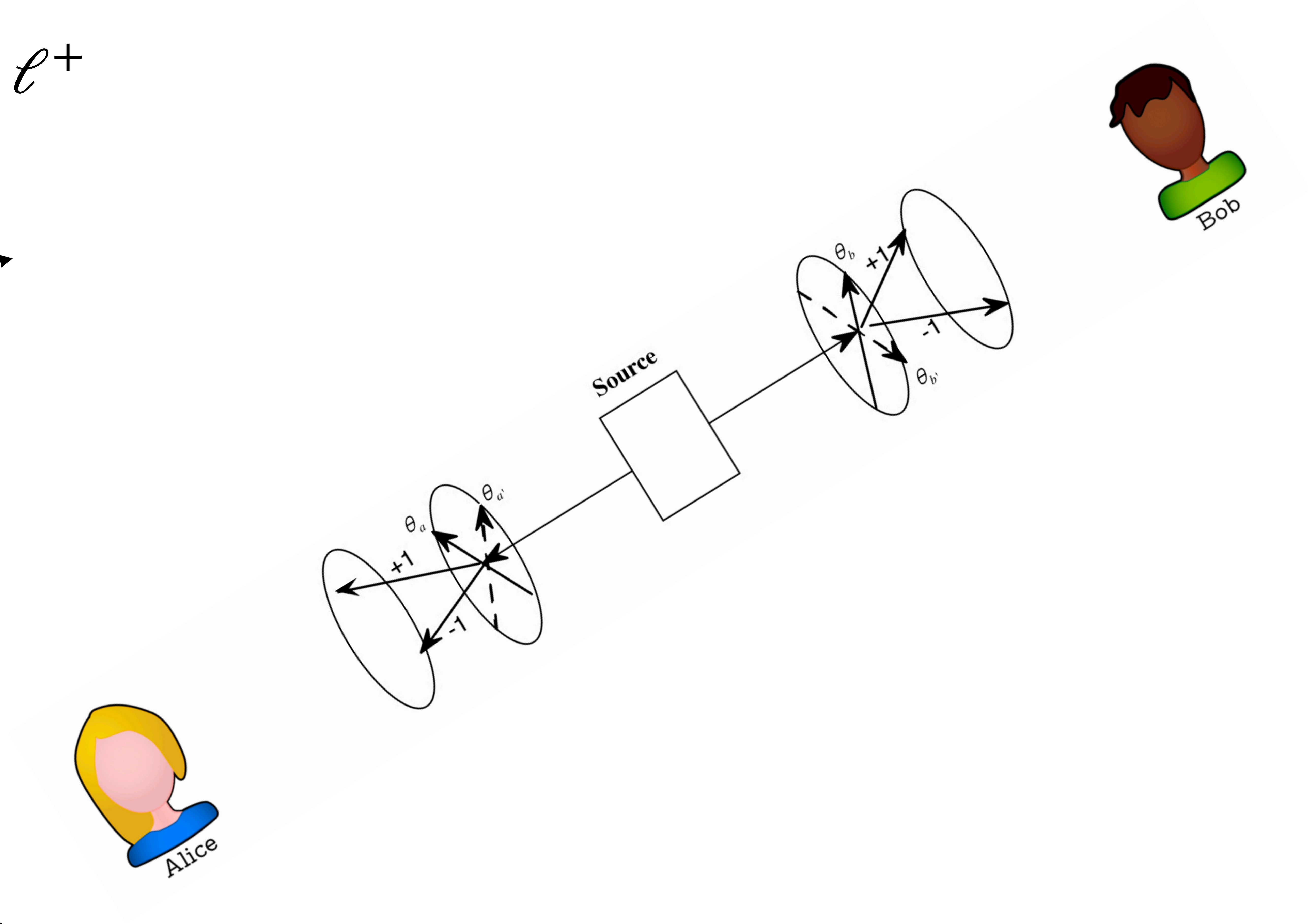
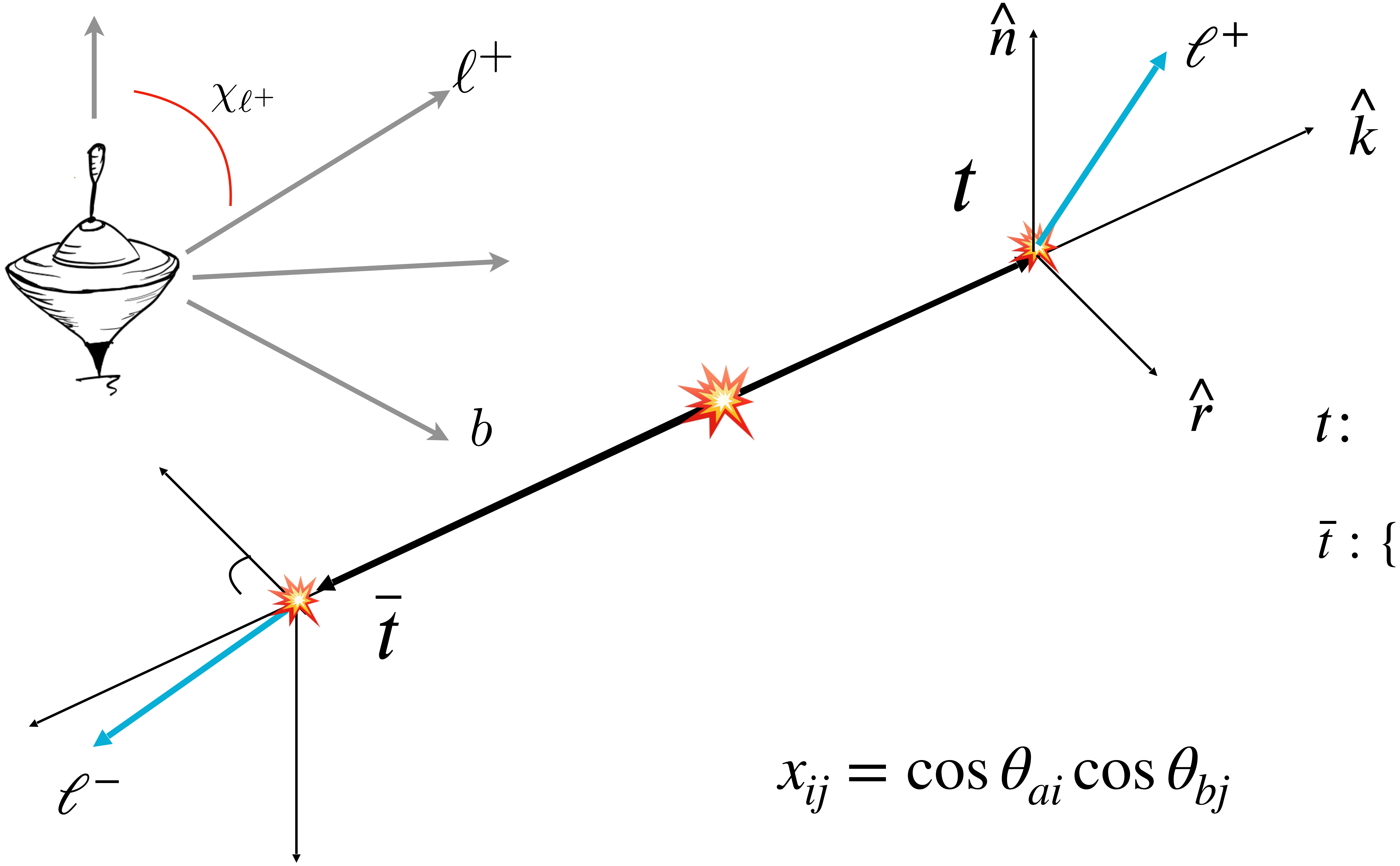




Correlation experiment at high-Q^2 : the lepton is correlated with the spin.

$t\bar{t}$ 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

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

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.

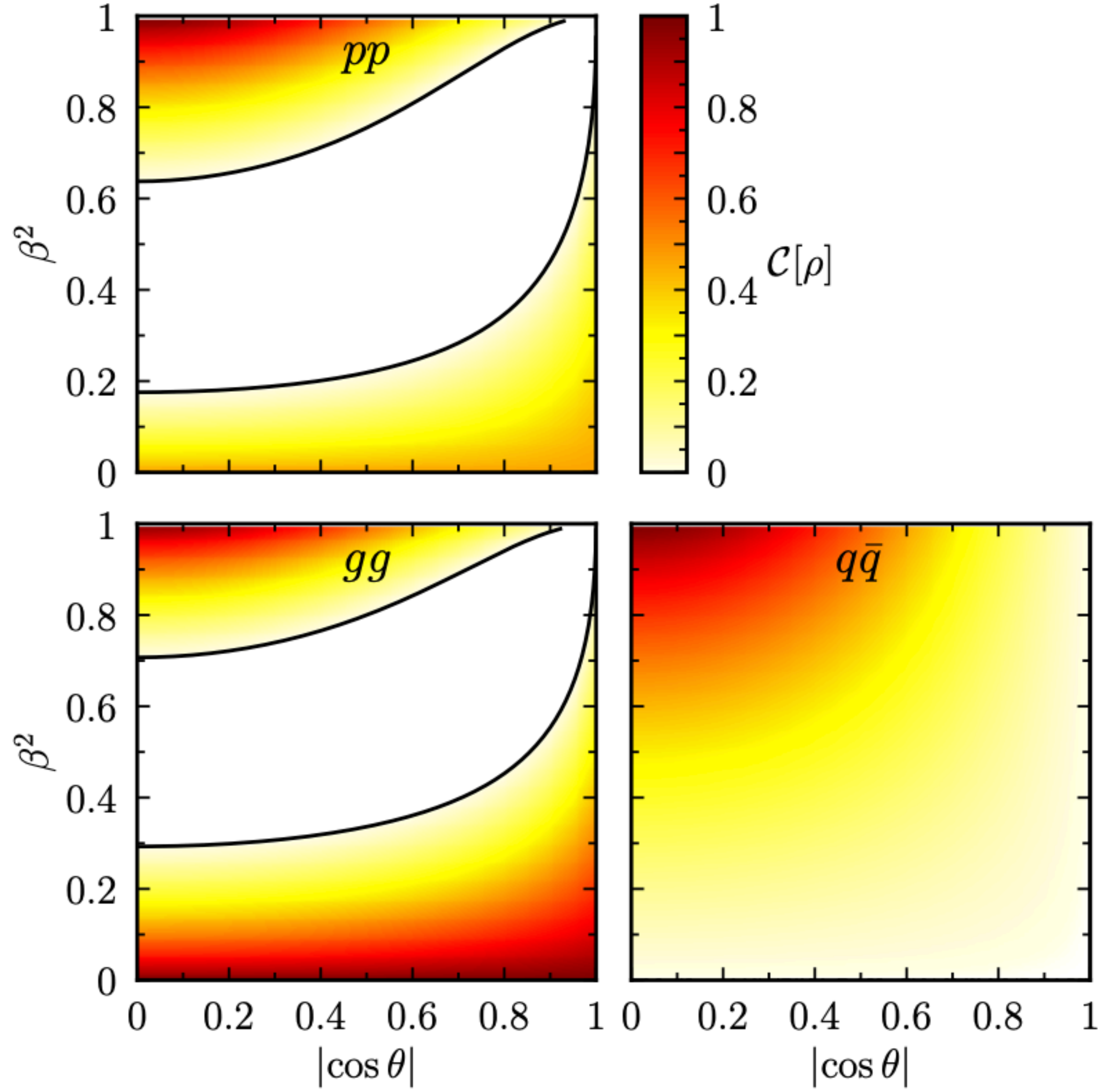
$$\langle S_i \rangle = B_i, \quad \langle \bar{S}_i \rangle = \bar{B}_j, \quad \langle S_i \bar{S}_j \rangle = C_{ij}$$

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

SM Entanglement



White regions: zero-entanglement

Maximal entanglement points/regions:

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

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

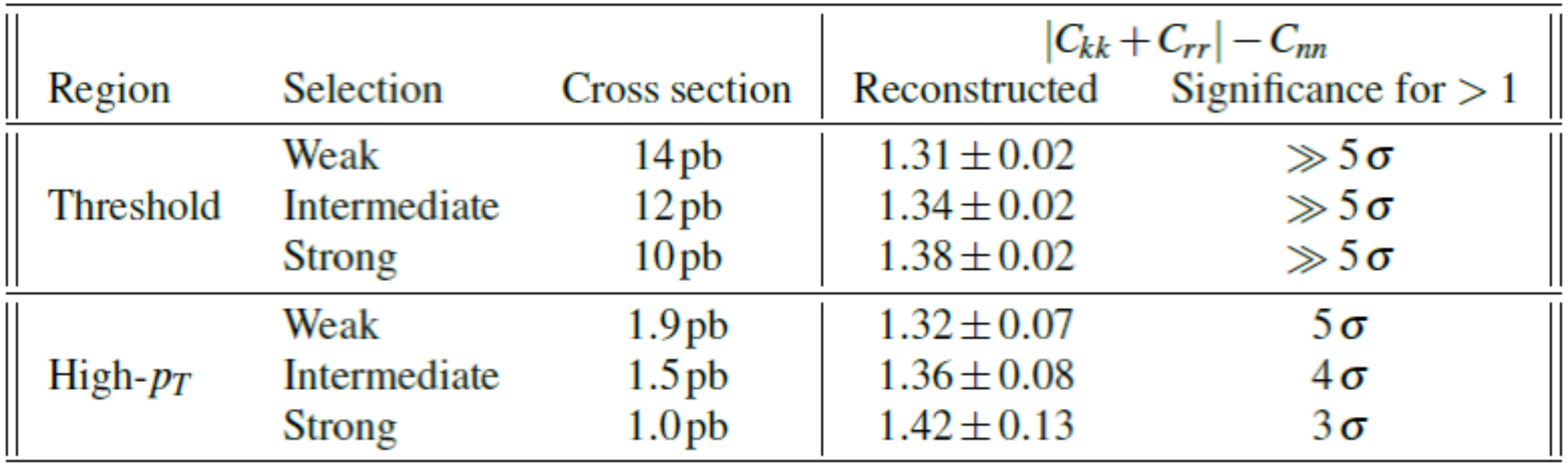
- high-E: $\beta^2 \to 1, \cos\theta = 0$

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

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

(triplet)

SM Entanglement

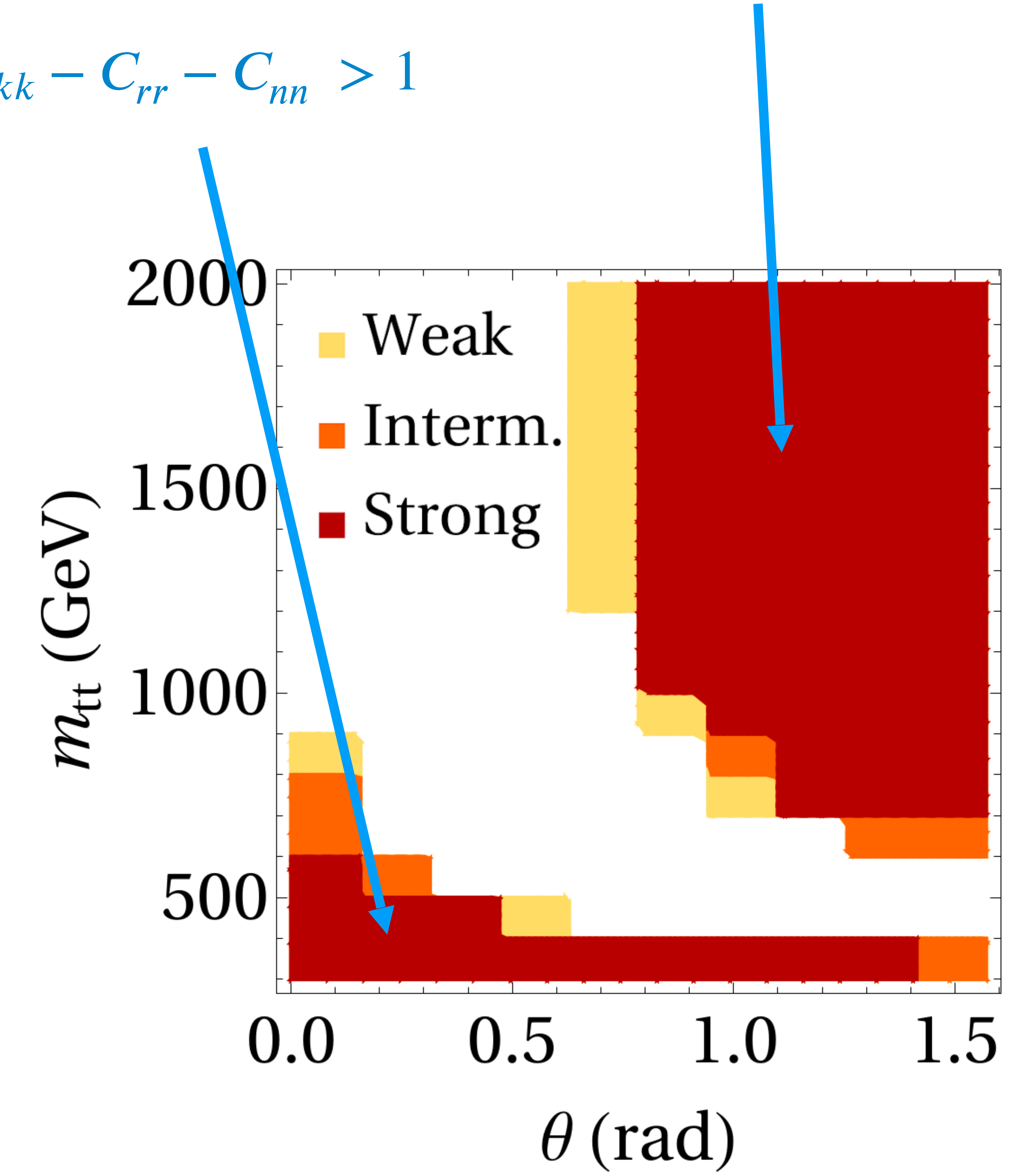


Region	Selection	Cross section	$\lvert C_{kk}+C_{rr}\rvert - C_{nn}$ Reconstructed	Significance for >1
Threshold	Weak	14 pb	1.31 ± 0.02	$\gg 5\sigma$
	Intermediate	12 pb	1.34 ± 0.02	$\gg 5\sigma$
	Strong	10 pb	1.38 ± 0.02	$\gg 5\sigma$
High-p_T	Weak	1.9 pb	1.32 ± 0.07	5σ
	Intermediate	1.5 pb	1.36 ± 0.08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

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

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

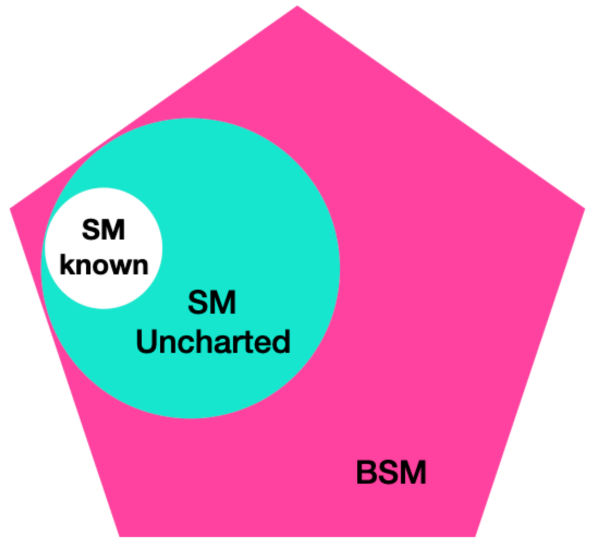
$-C_{kk} - C_{rr} - C_{nn} > 1$



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

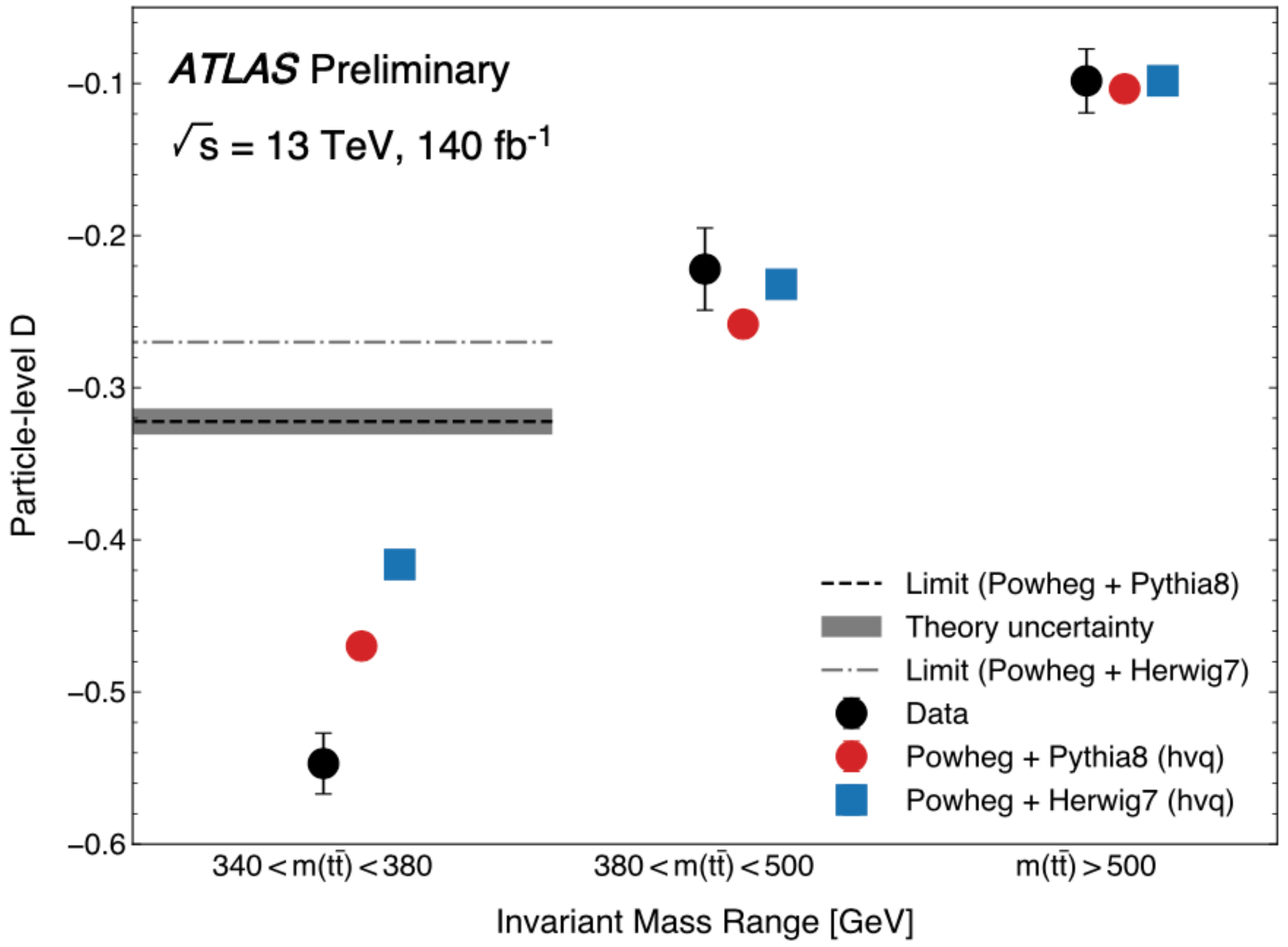
Measurements

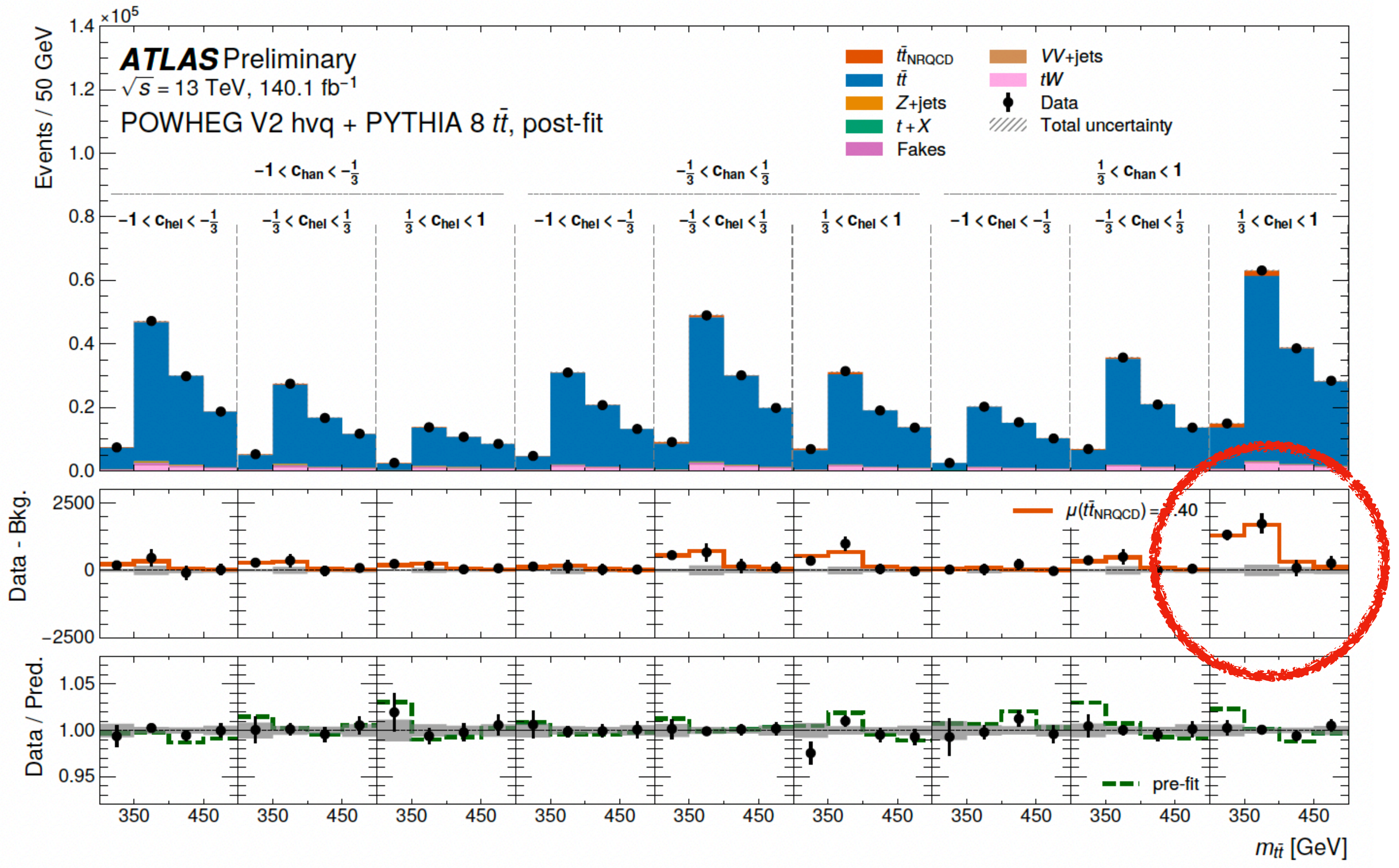
Dilepton channel at threshold

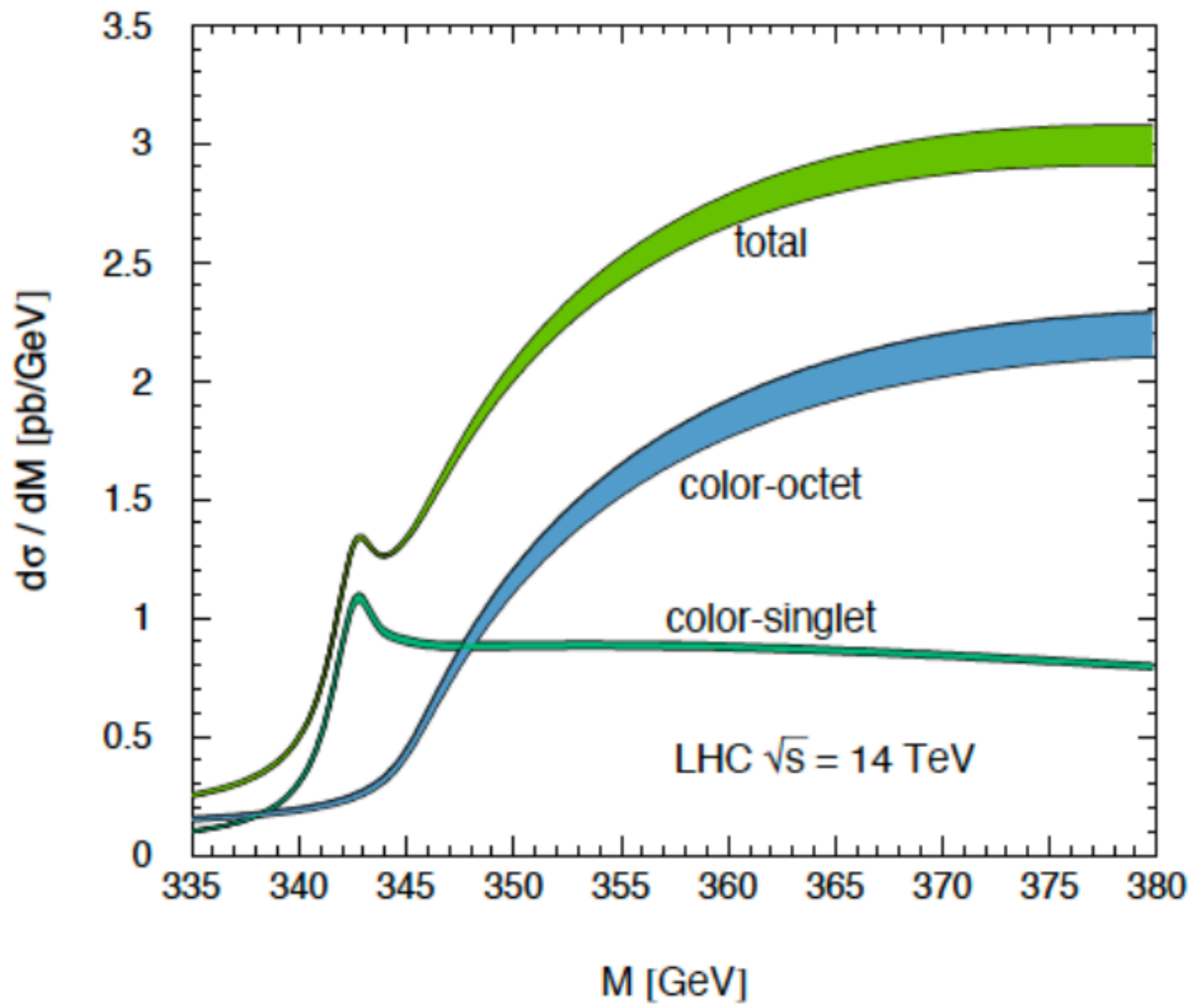


Hagiwara, Sumino, Yokoya, arXiv: 0804.1014

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





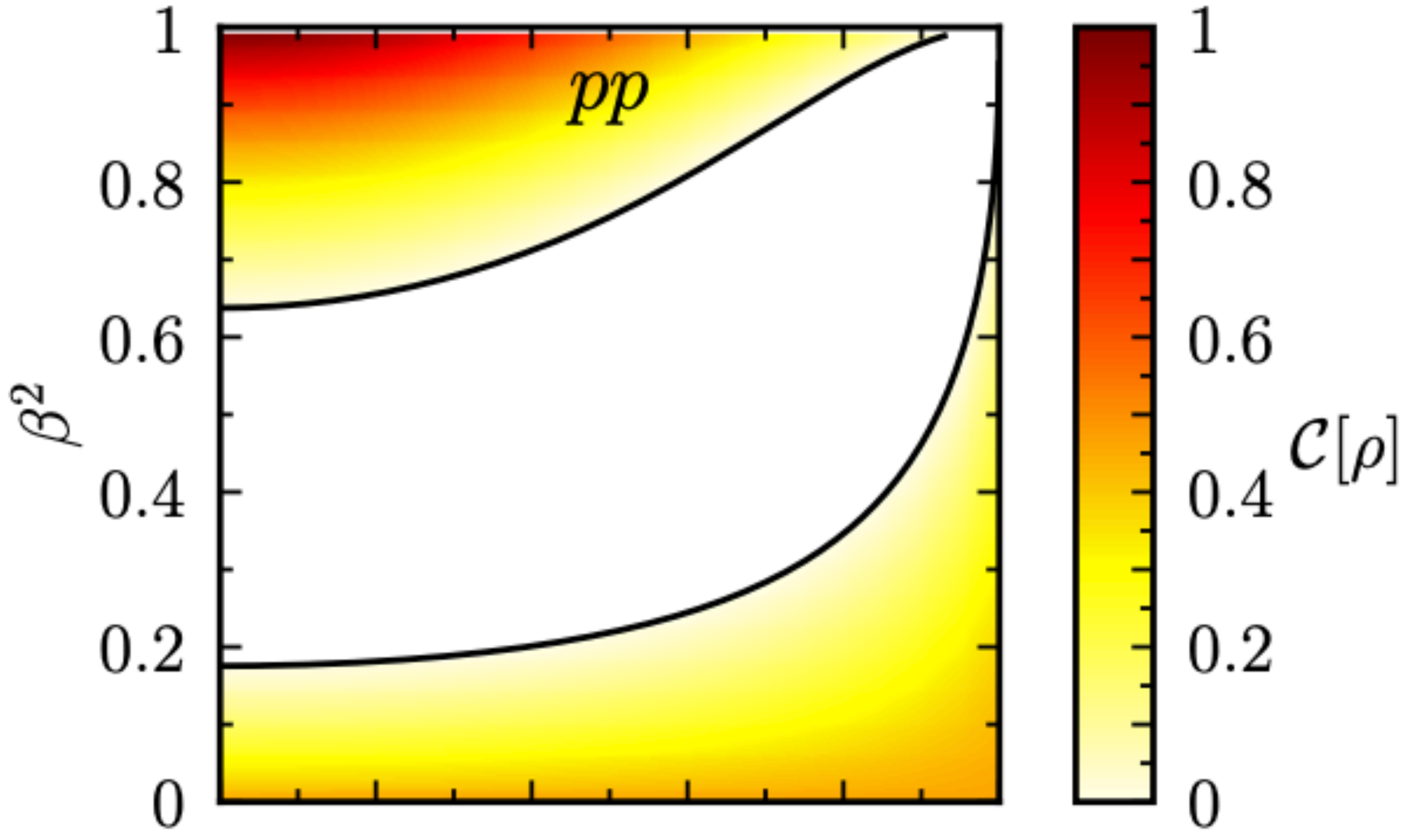


Early CMS and ATLAS entanglement measurements near the $t\bar{t}$ threshold revealed more entanglement than expected.

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

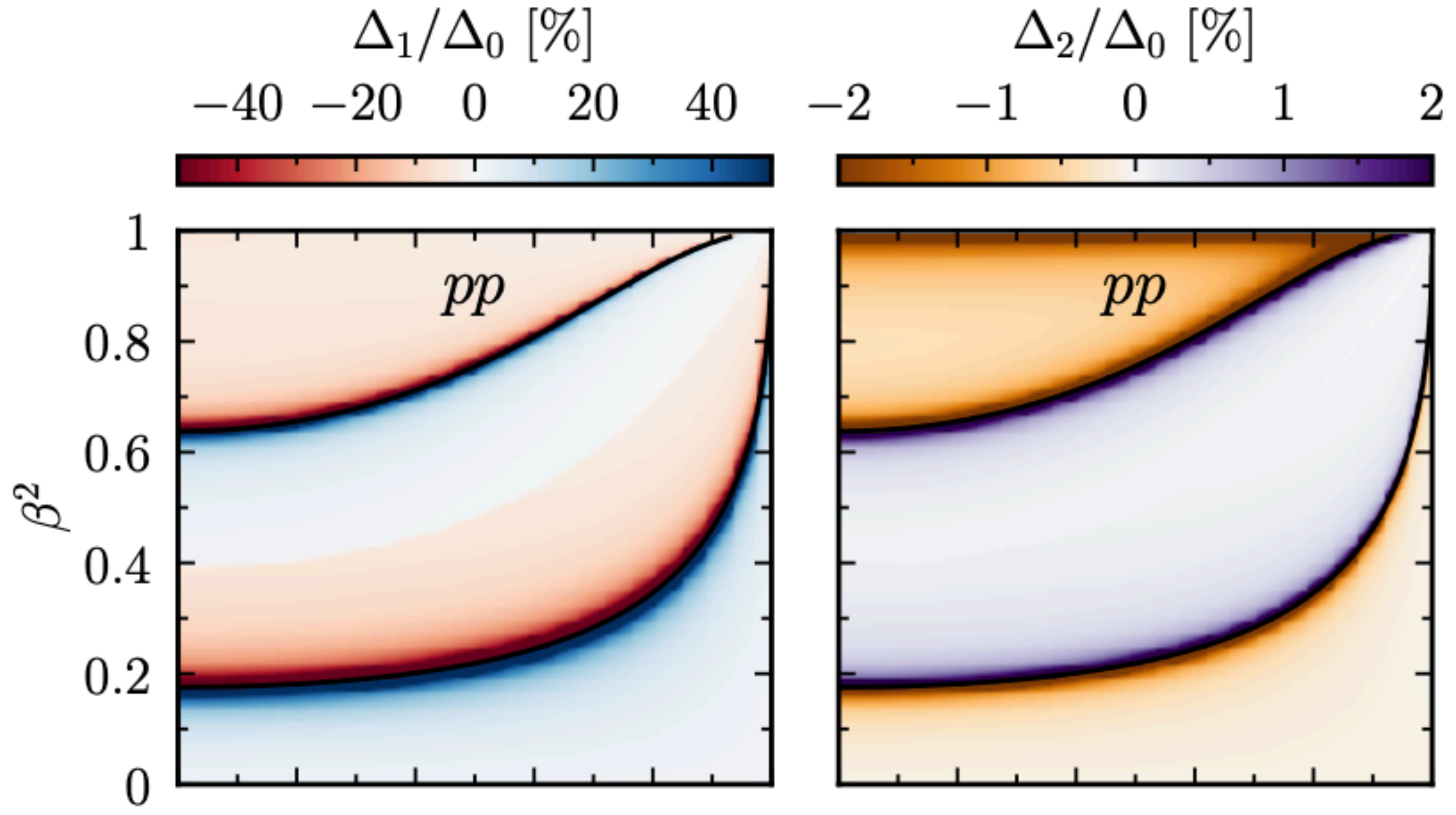
Consistent with near-threshold toponium contribution for hadro colliders in 2008 by two independent groups.

Quantum Advantage for SMEFT : Entanglement



SM

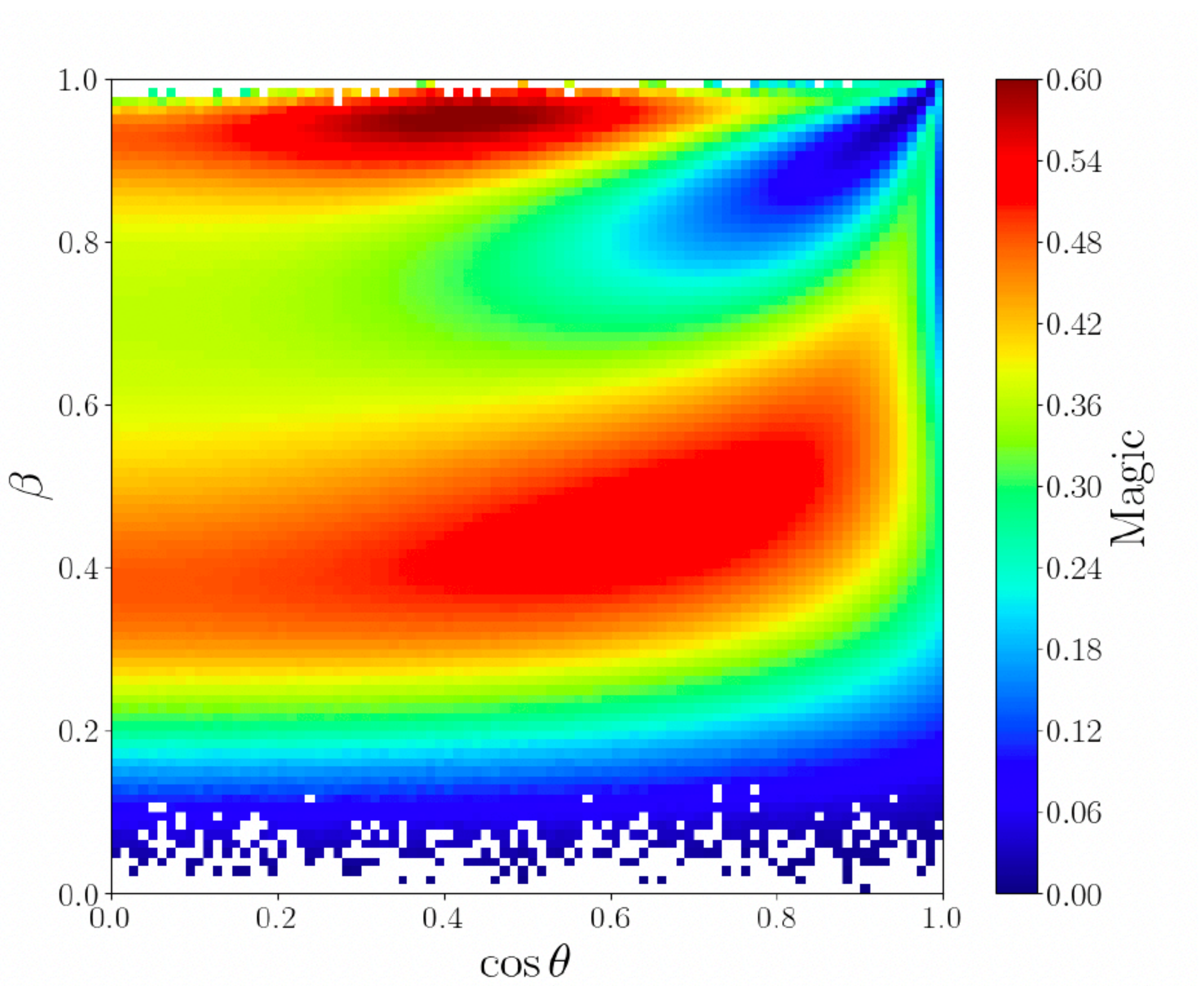
EFT



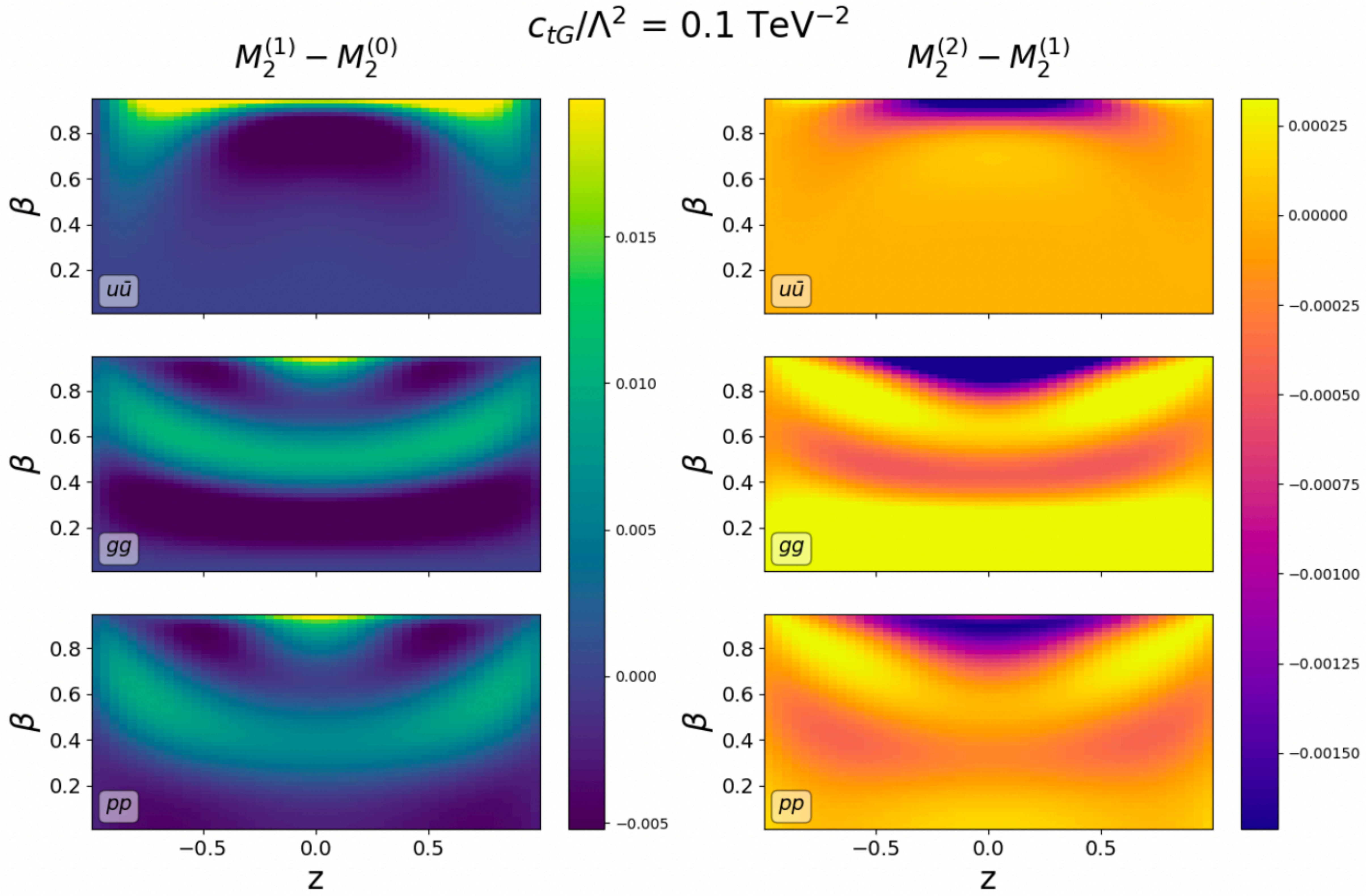
- New interactions modify both conventional and quantum observables
- Dimension-6 operators can modify the degree of entanglement between top quarks
- SMEFT introduce new structures, thus probing new linear combinations between coefficients and breaking degeneracies.

White^2 2406.07321
Aoude, Banks, White^2 2505.12522

Quantum Advantage for SMEFT : Magic



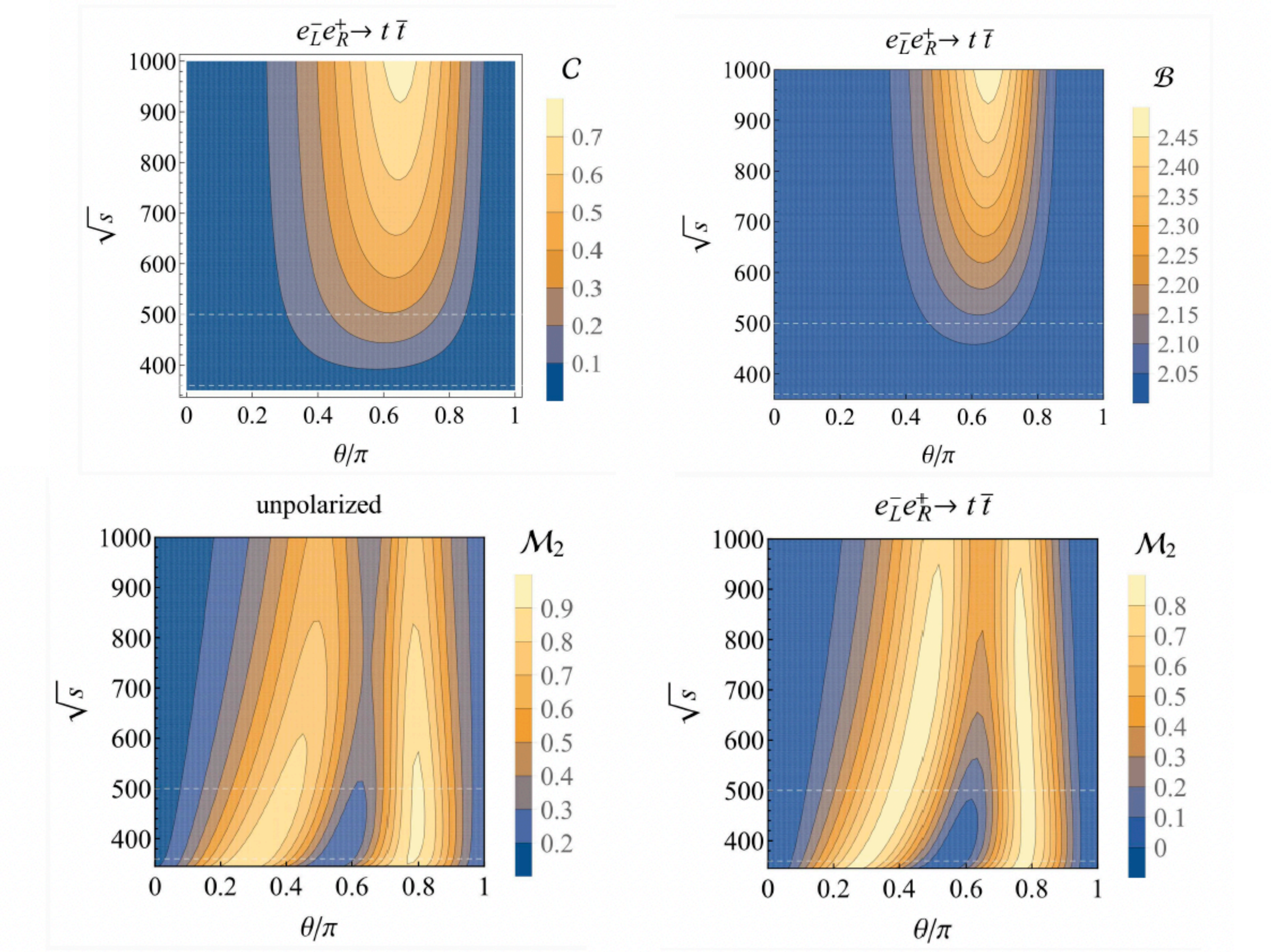
SM | **EFT**



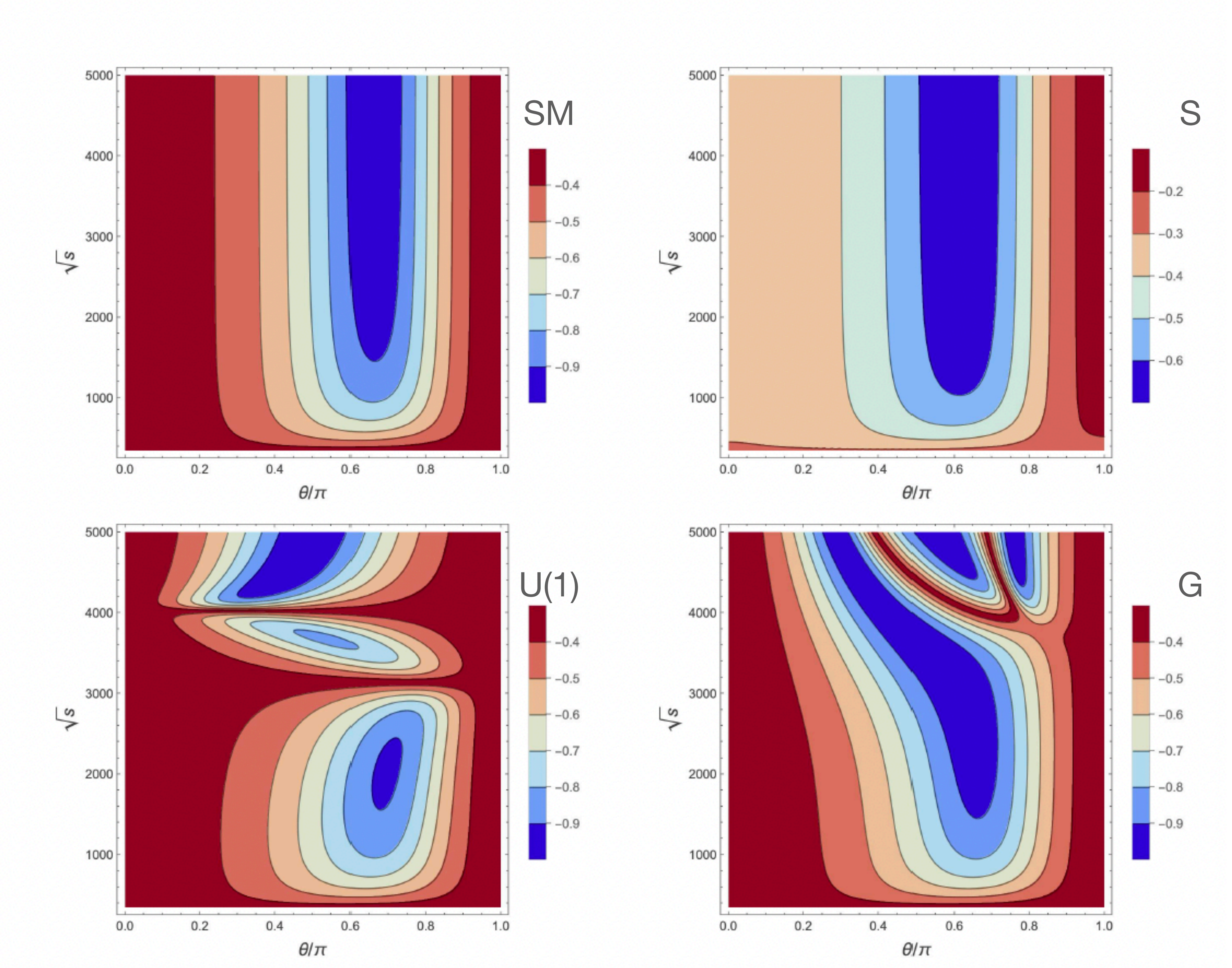
In quantum information, **magic** refers to the amount of *non-Clifford, non-stabilizer* structure present in a quantum state or operation. It quantifies **how far** a state is from the set of states that can be efficiently simulated classically via stabilizer methods (Gottesman–Knill).

C. Severi, FM, S. Tentori, E. Vryonidou: 2401.08751
M. Altakach, P. Lambda, FM, K. Sakurai : 2601.09558
H.-W. Zhang, X. Cao, T.-F. Feng, 2602.10389
Y.-C. Guo, T. Han, M. Low, Y. Su 2602.02719
Yi-Jing Fang, Bhoonah, Cheng, Han, Liu 2604.11887
M. Arai, K. Mawatari, N. Okada, 2604.21332

Quantum tops at e+e- colliders



Polarized beams increase entanglement, Bell nonlocality, and quantum magic.



Top-pair entanglement can provide precision information for characterising new resonance.

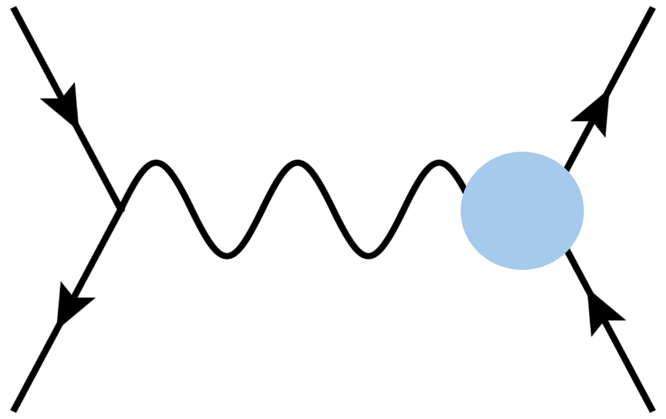
Lamba, FM, Miniati, Vryonidou, to appear

Quantum tops at e+e- colliders : CP violation

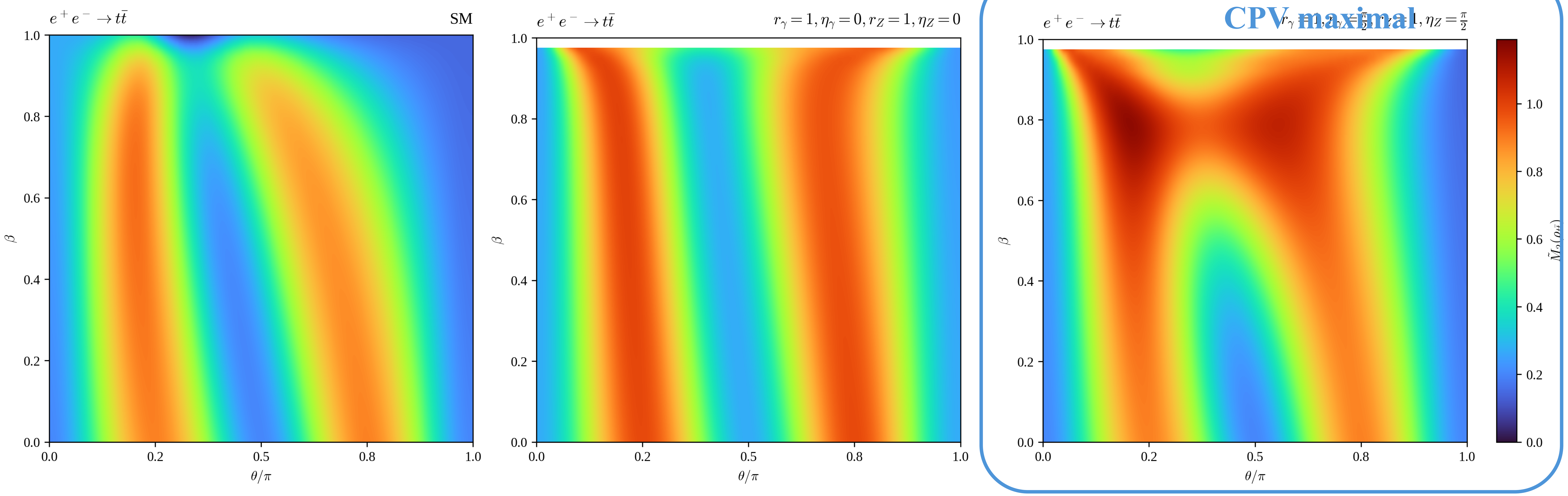
- 4-fermion CP-odd operators → no CPV effects.
- O_{uW}, O_{uB} → magnetic and electric dipole moment form factors:

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

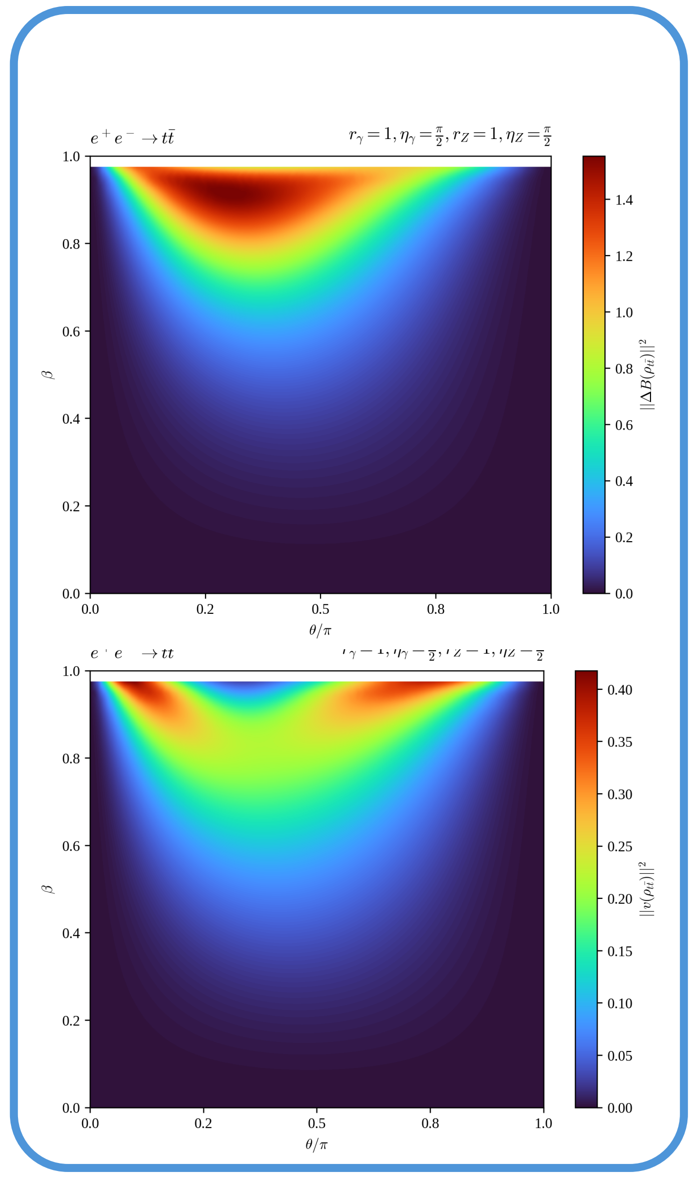
- $t\bar{t}$ individually polarized and correlated.



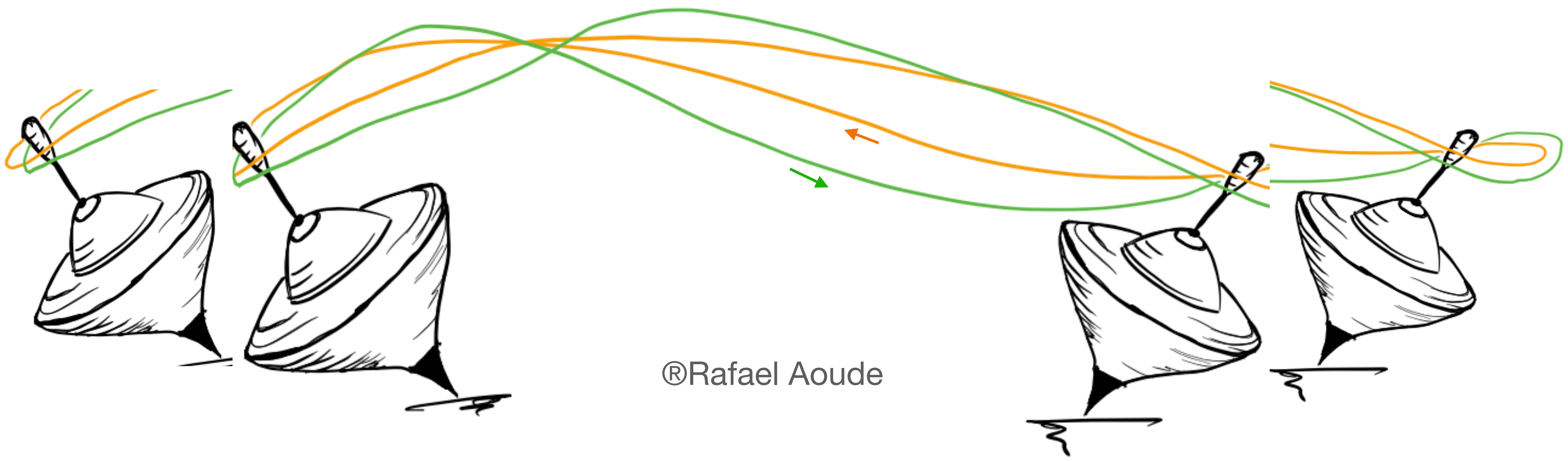
$$d_Z = r_Z(\cos\eta_Z + i\sin\eta_Z)$$
$$d_\gamma = r_\gamma(\cos\eta_\gamma + i\sin\eta_\gamma)$$



CPV maximal



Quantum W’s and Z’s


®Rafael Aoude

Qutrit

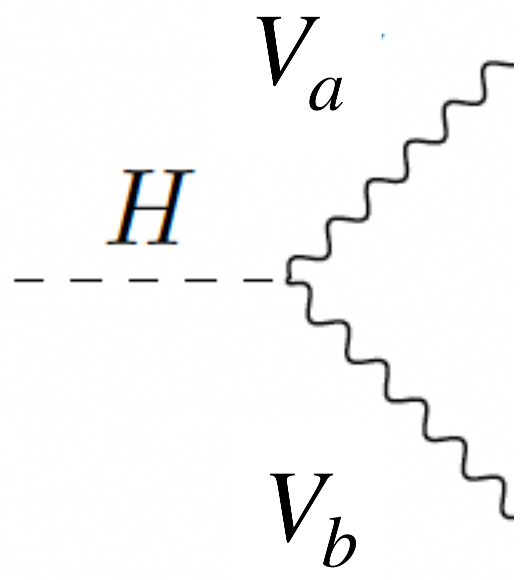
Qutrit

A. J. Barr, 2106.01377
A. J. Barr, P. Caban, J. Rembieliński, 2204.11063
R. Ashby-Pickering, A. J. Barr, A. Wierzchucka, 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

Caution: possibly incomplete list!

$H \to V_a V_b$

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



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

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

$H \to V_a V_b$

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

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

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

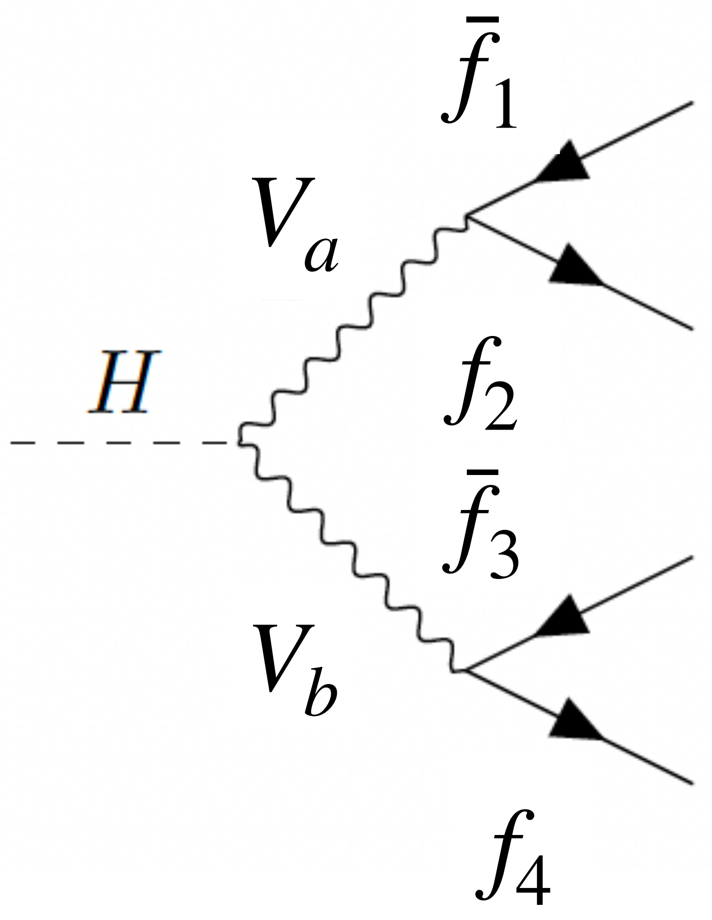
$$\rho_{\mathrm{LO}} = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & x & \cdot & y & \cdot & x & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot &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

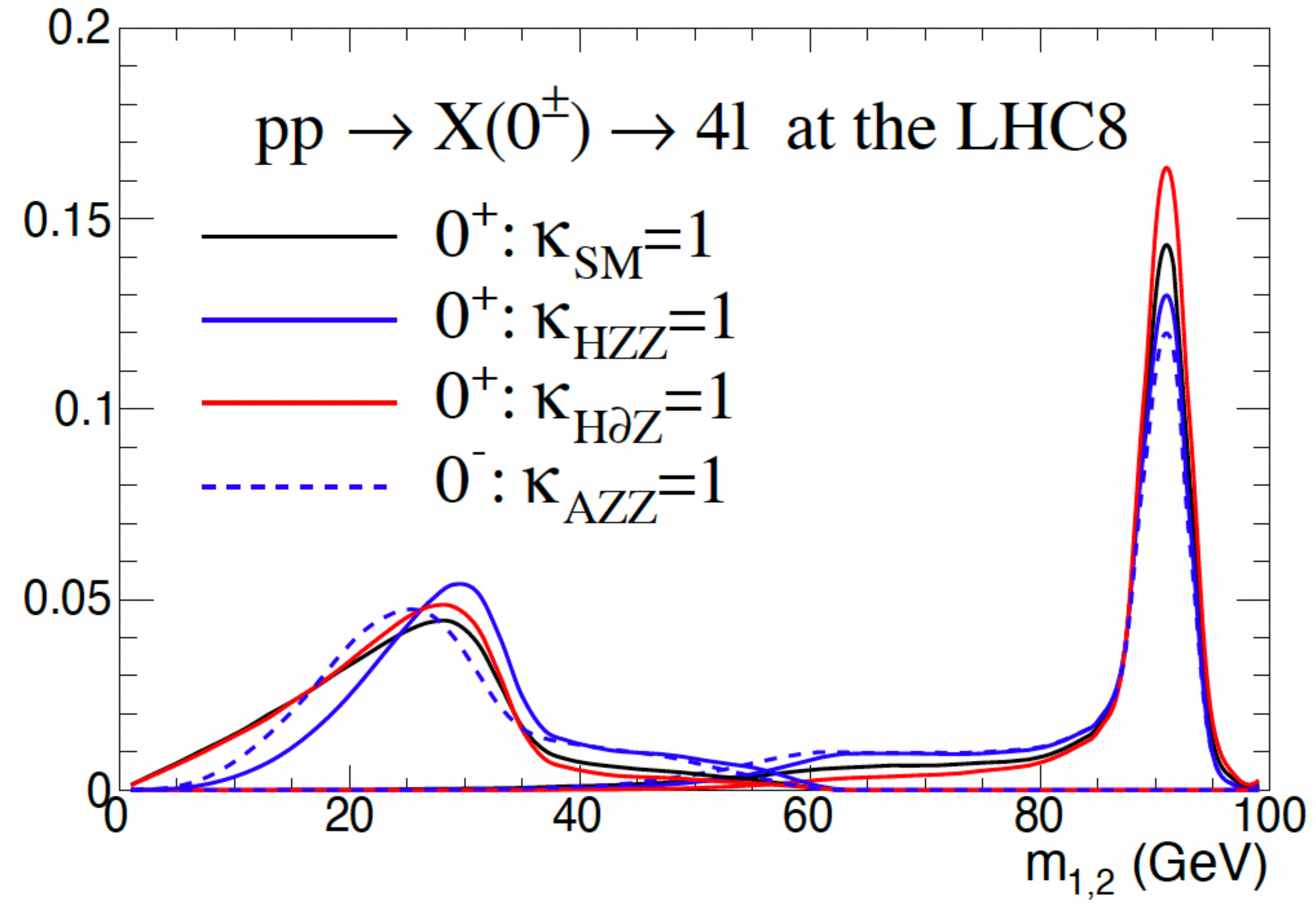
$$\rho_{\mathrm{LO}} = \int \rho_{\mathrm{LO}}(\beta) w(\beta) d\beta$$

See also J. A. Aguilar-Saavedra, 2411.13464

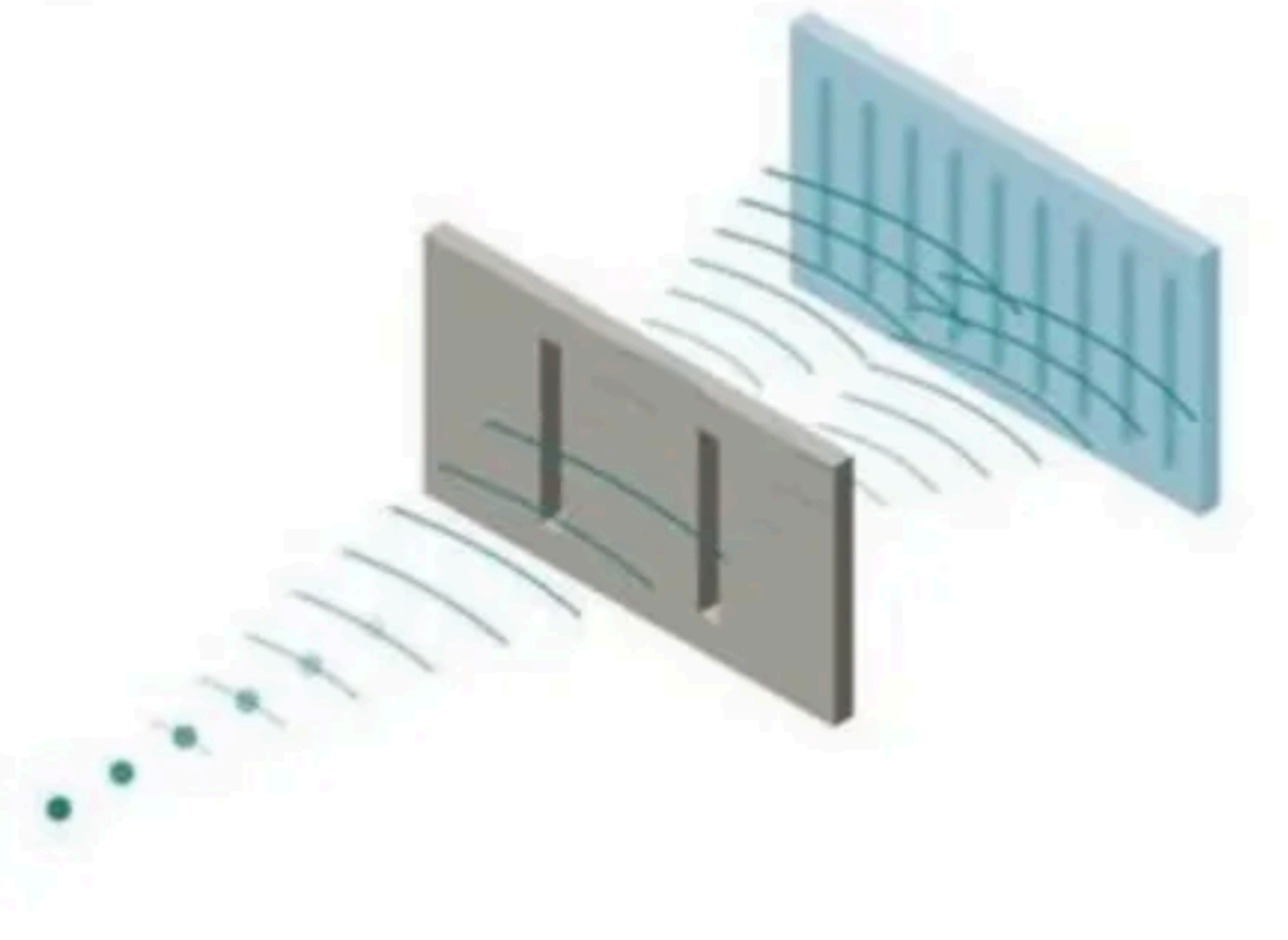
$H \to V_a^{(*)} V_b^{*} \to 4f$

In the Higgs decay one pair is always off-shell. The other is typically on shel 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.

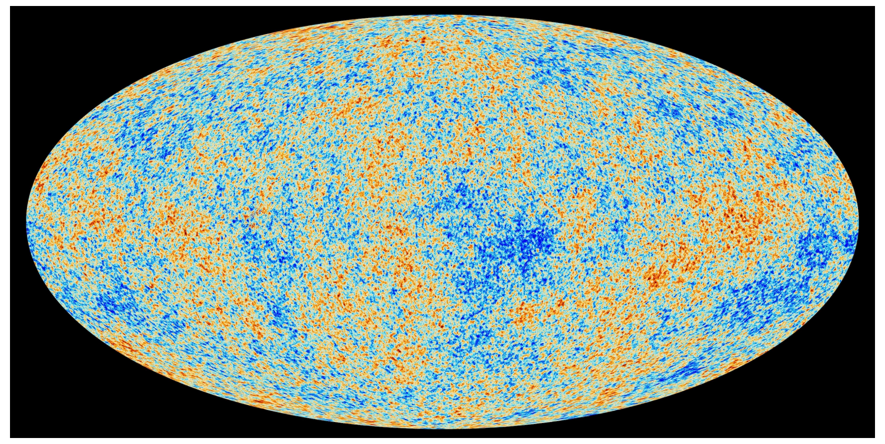


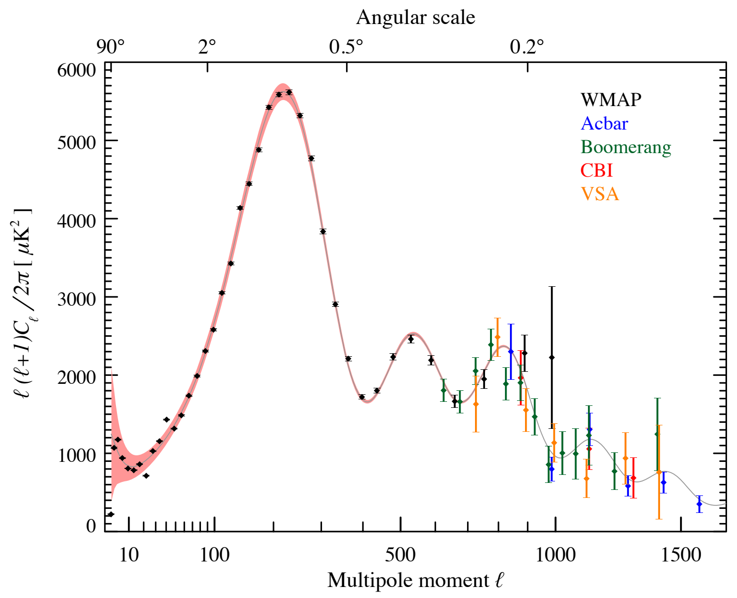


$1/m_a \simeq 1/m_b \simeq 2/m_H$



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





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

$$\frac{16\pi^2}{9\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} \hat{=} \frac{1}{(4\pi)^2} \longrightarrow \rho = \frac{1}{9}\Big[\mathbf{1}_3 \otimes \mathbf{1}_3$$

$$+\frac{1}{4\pi}\sum_{l=1}^{2}\sum_{m=-l}^{l}\alpha_{lm}^{(1)} Y_{lm}(\theta_1,\phi_1) + \frac{1}{4\pi}\sum_{l=1}^{2}\sum_{m=-l}^{l}\alpha_{lm}^{(2)} Y_{lm}(\theta_2,\phi_2) \longrightarrow + A_{lm}^{(1)}(T_{lm}\otimes \mathbf{1}_3) + A_{lm}^{(2)}(\mathbf{1}_3 \otimes T_{lm})$$

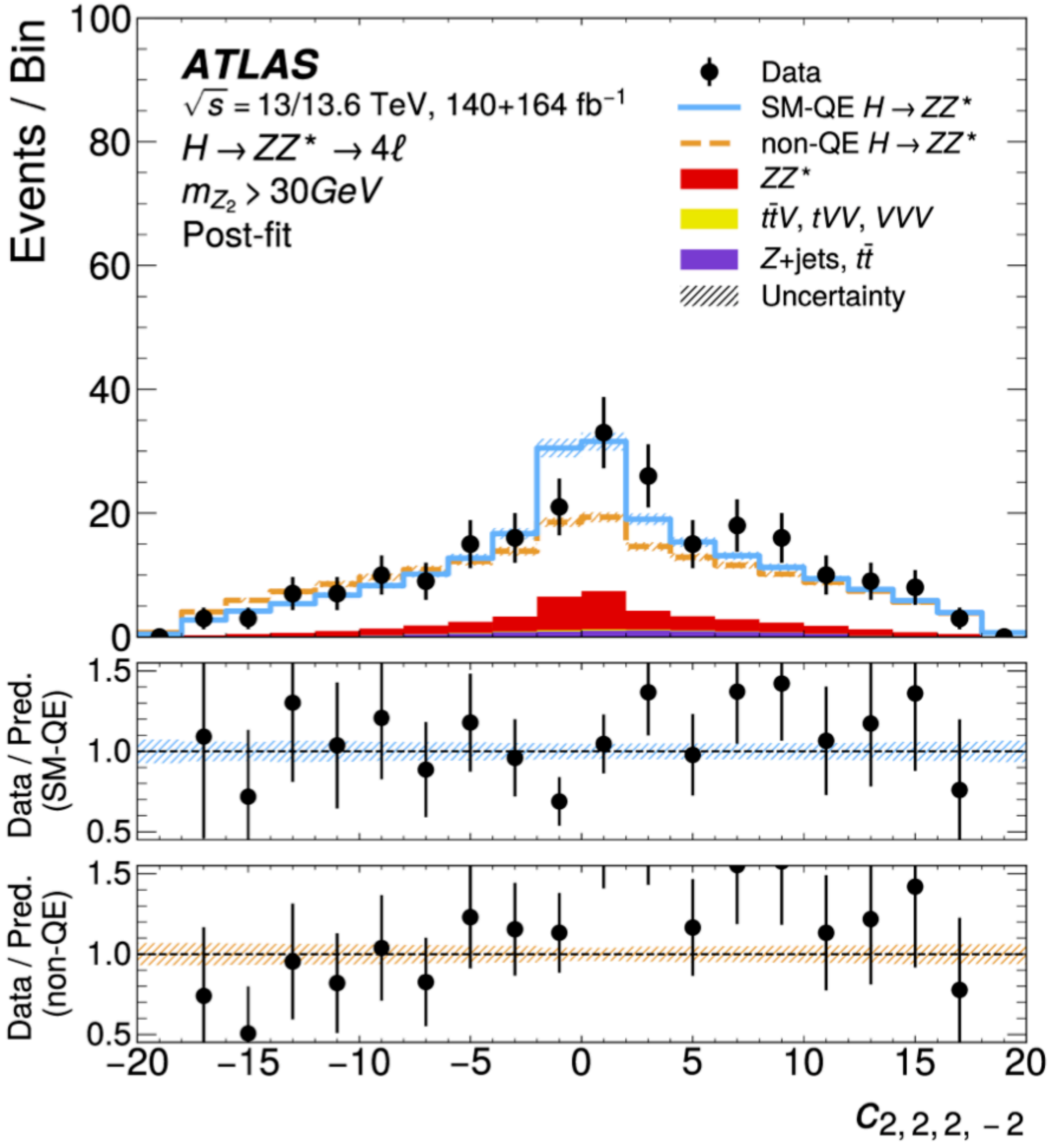
$$+\sum_{l=1}^{2}\sum_{l'=1}^{2}\sum_{m=-l}^{l}\sum_{m'=-l'}^{l'}\gamma_{lml'm'} Y_{lm}(\theta_1,\phi_1) Y_{l'm'}(\theta_2,\phi_2) \longrightarrow + C_{lml'm'}(T_{lm}\otimes T_{l'm'})\Big].$$

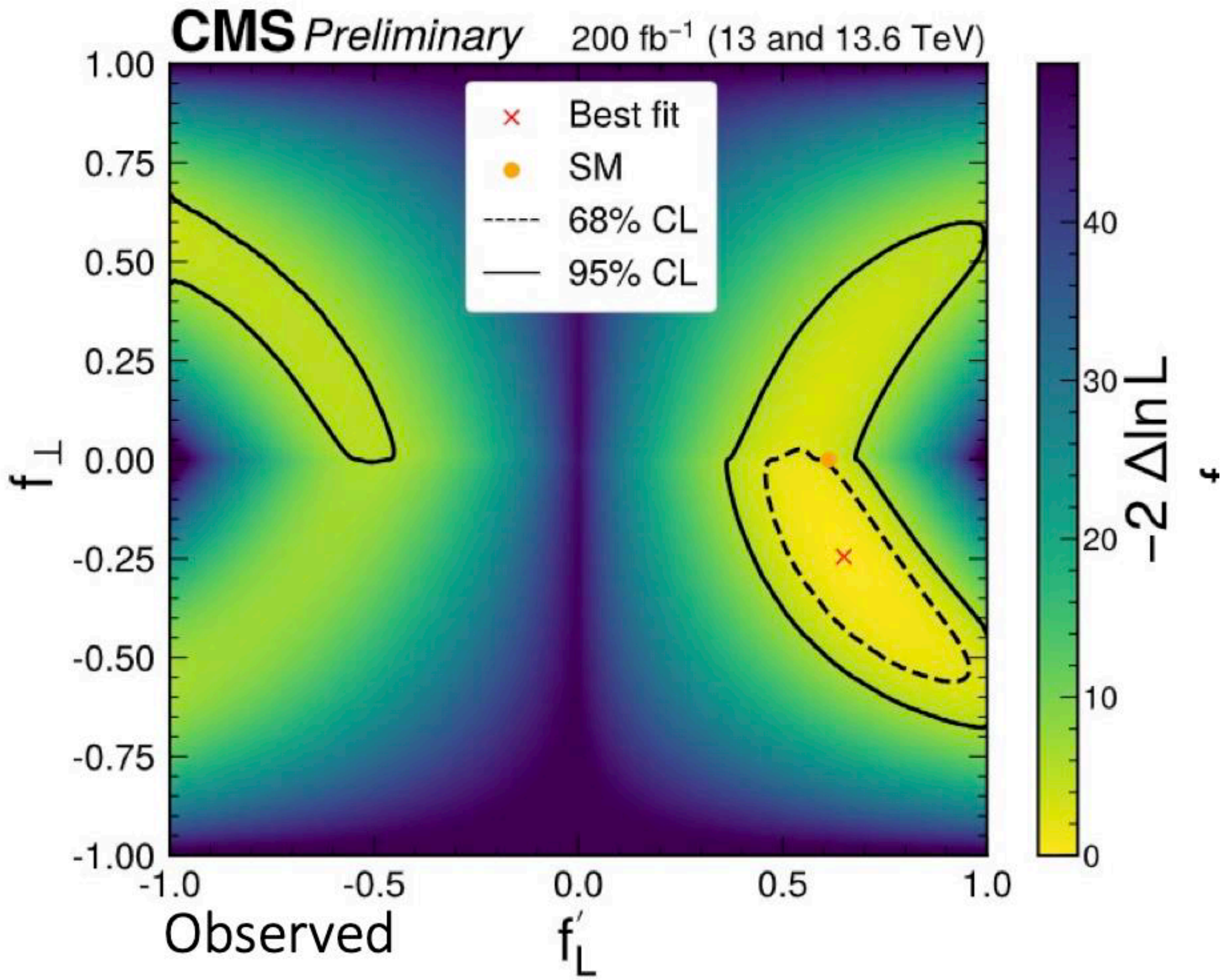
$$\sqrt{8\pi}\alpha_{1m} = \eta_\ell A_{1m}, \qquad \sqrt{40\pi}\alpha_{2m} = A_{2m}, \qquad 8\pi\gamma_{1m1m'} = \eta_\ell^2 C_{1m1m'},$$

$$40\pi\gamma_{2m2m'} = C_{2m2m'}, \qquad 8\pi\sqrt{5}\gamma_{2m1m'} = \eta_\ell C_{2m1m'}, \qquad 8\pi\sqrt{5}\gamma_{1m2m'} = \eta_\ell C_{1m2m'}.$$

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

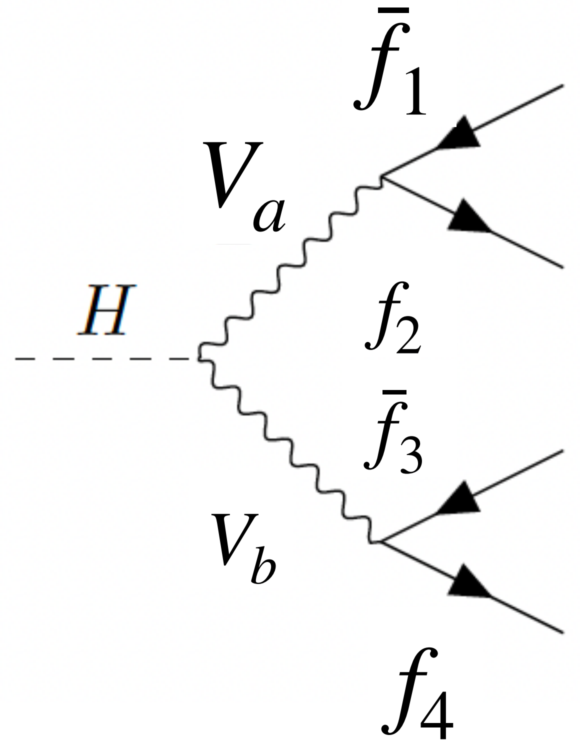
$H \to V_a^{(*)} V_b^* \to 4f$



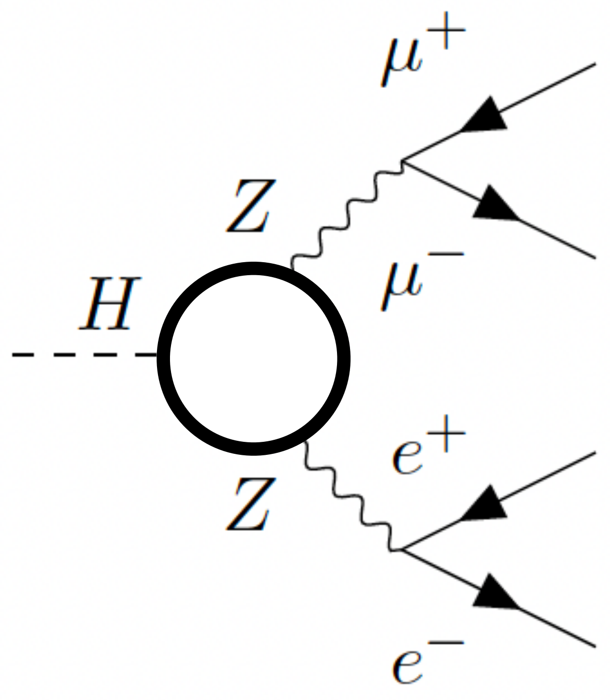


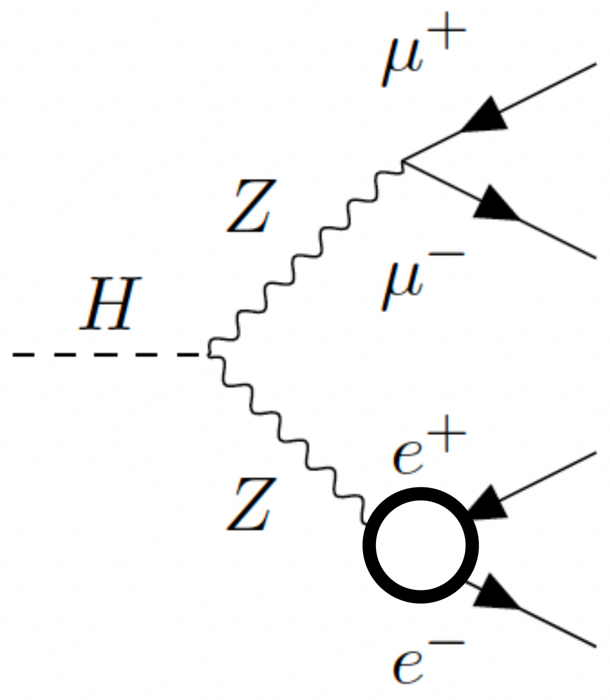
ATLAS reports strong evidence for spin entanglement between the two (Z) bosons in (H $H \to ZZ^* \to 4\ell$ at 4.7σ, and CMS confirms the spin correlation pattern.

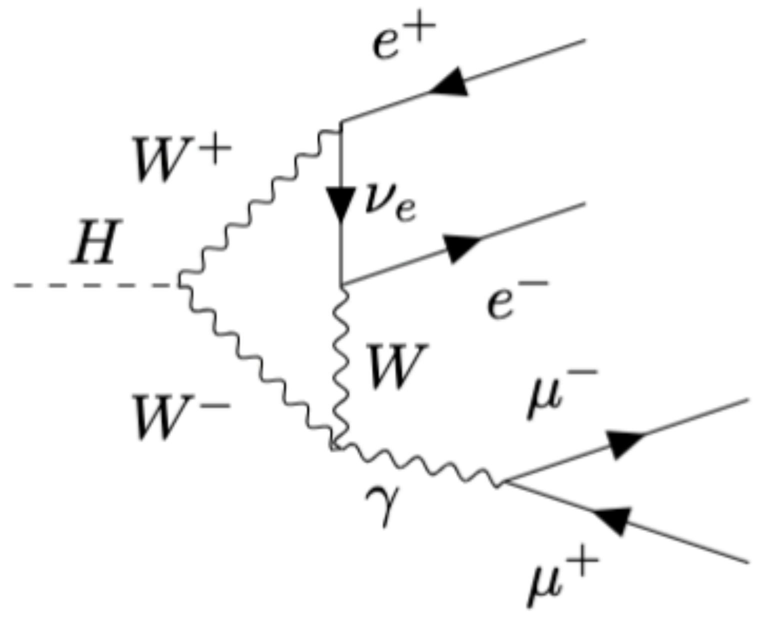
Quantum observables beyond LO

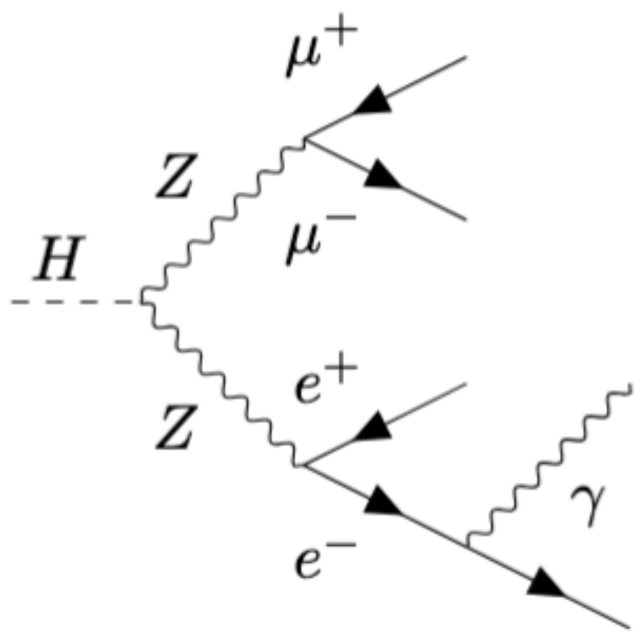


LO







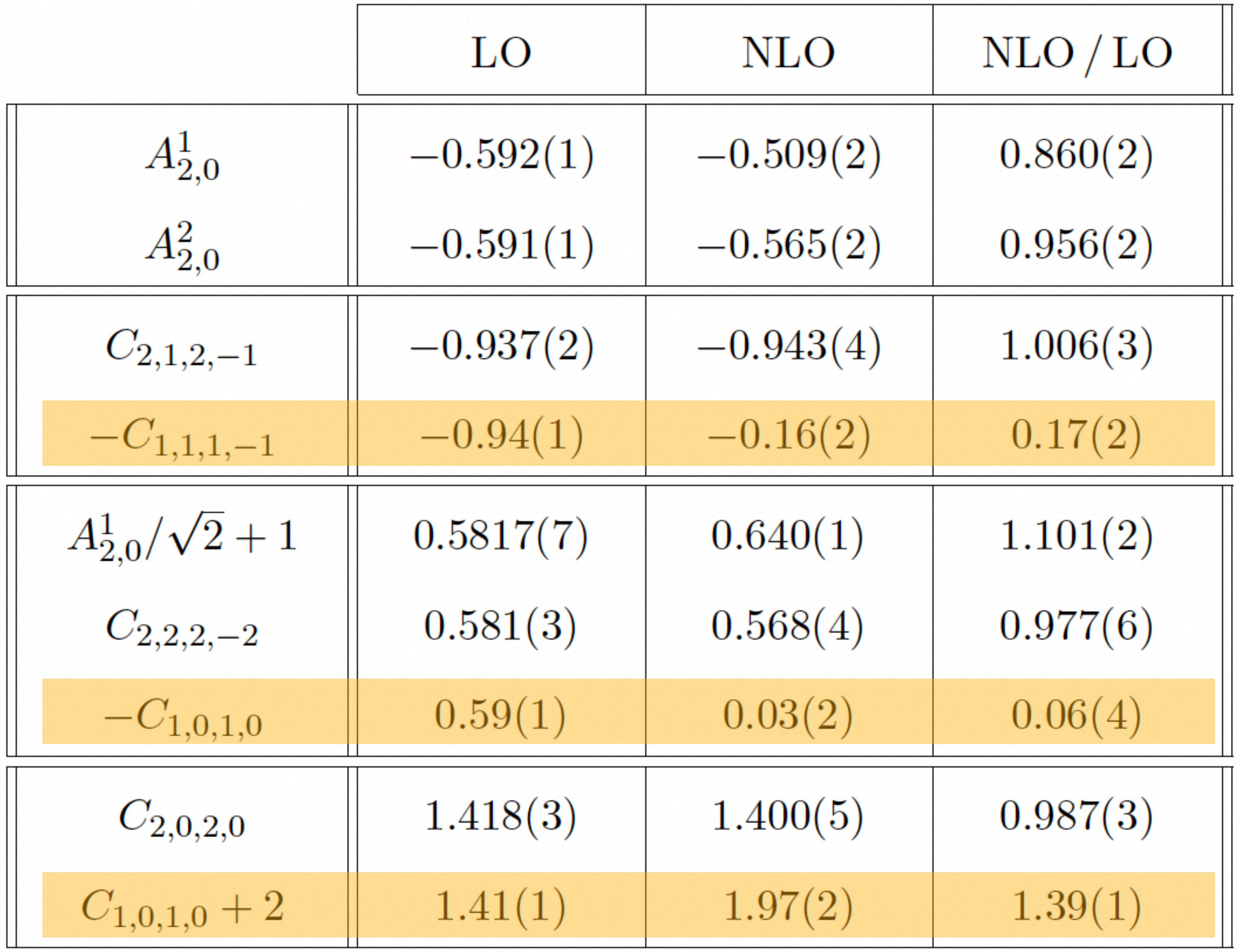


- Do quantum corrections affect the quantum correlations?
- Do two quirts exist at NLO?
- Is the quantum tomography procedure stable?

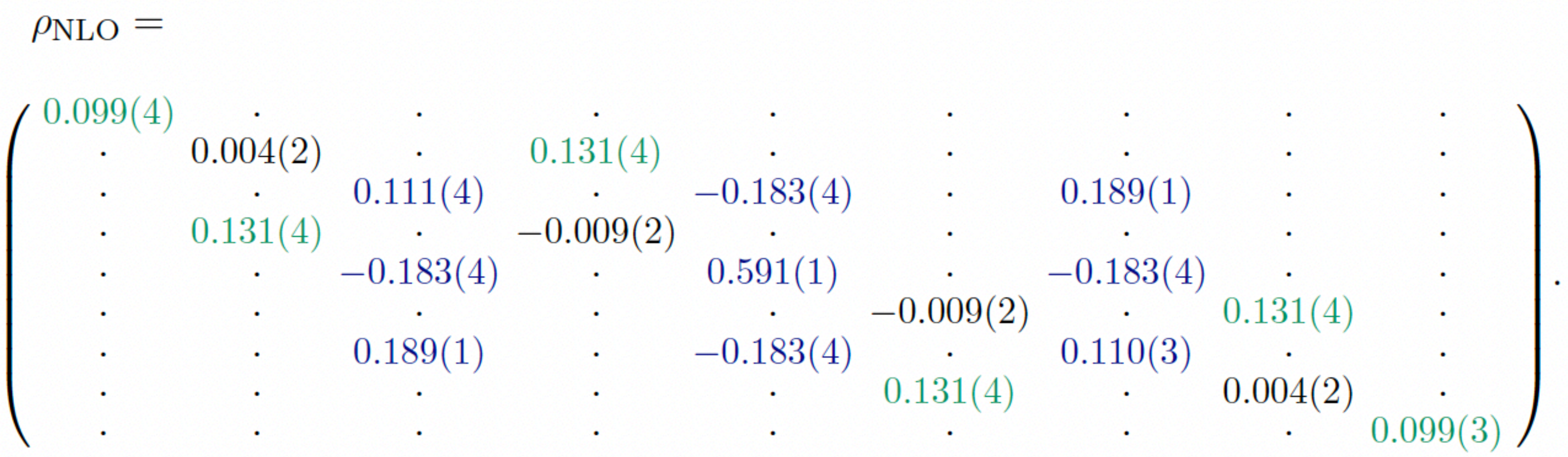
$H \to V_a^{(*)} V_b^* \to 4f$ at NLO

M. Grossi, G. Pelliccioli, A. Vicini, 2409.16731
Del Gratta, Fabbri, Lamba, FM, Pagani, 2504.03841
Goncalves, Kaladharan, Krauss, Navarro, 2505.12125
Goncalves, Kaladharan, Navarro 2506.19951
Del Gratta, Fabbri, Grossi, FM, Pellicciolì, Pagani, Vicini, 2509.20456
Aguilar-Saavedra, Giardino, 2603.19389

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



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



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

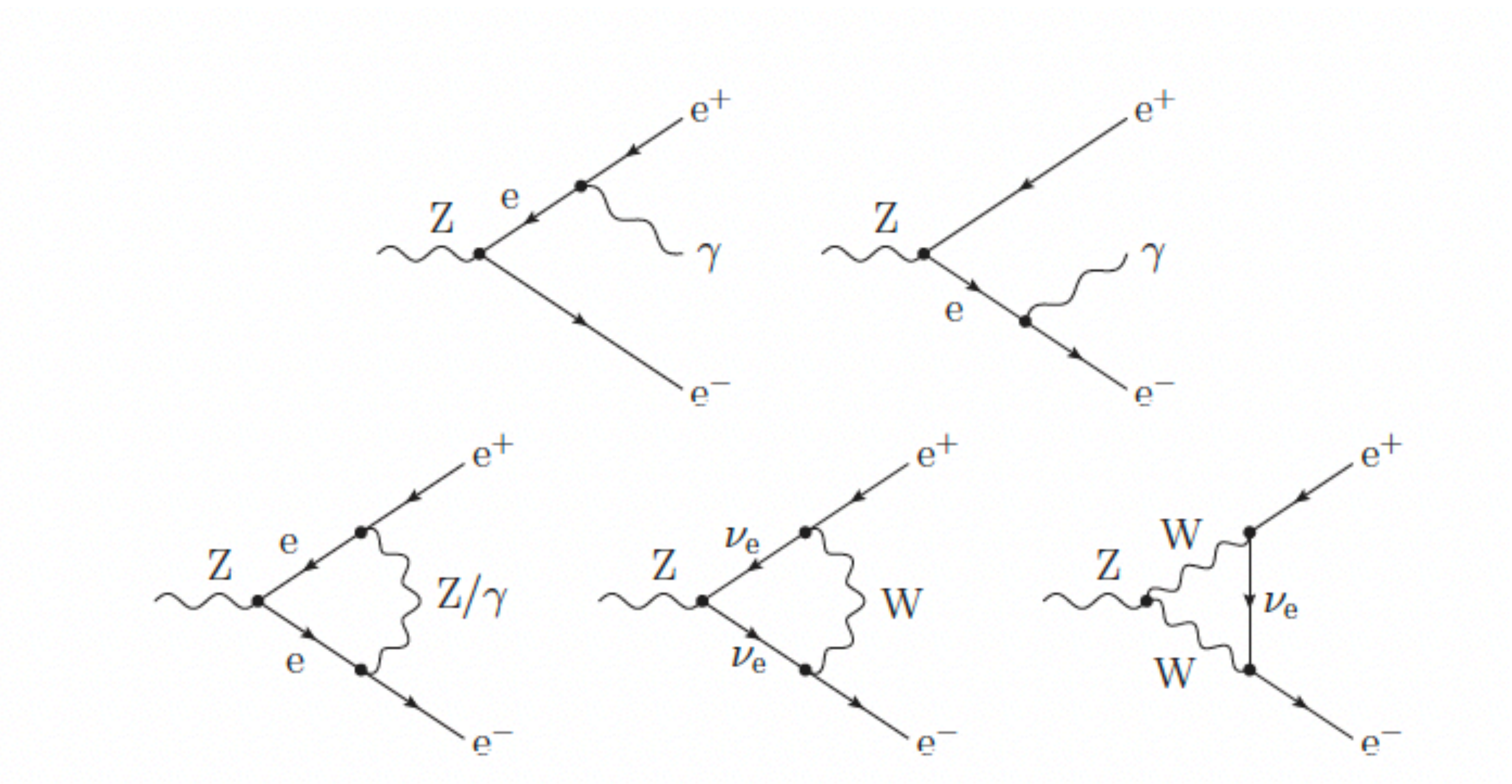
$$|\rho_{ij}|^2 \leq \rho_{ii}\rho_{jj}, \quad i \neq j$$

The reconstructed ρ is not positive definite !

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

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

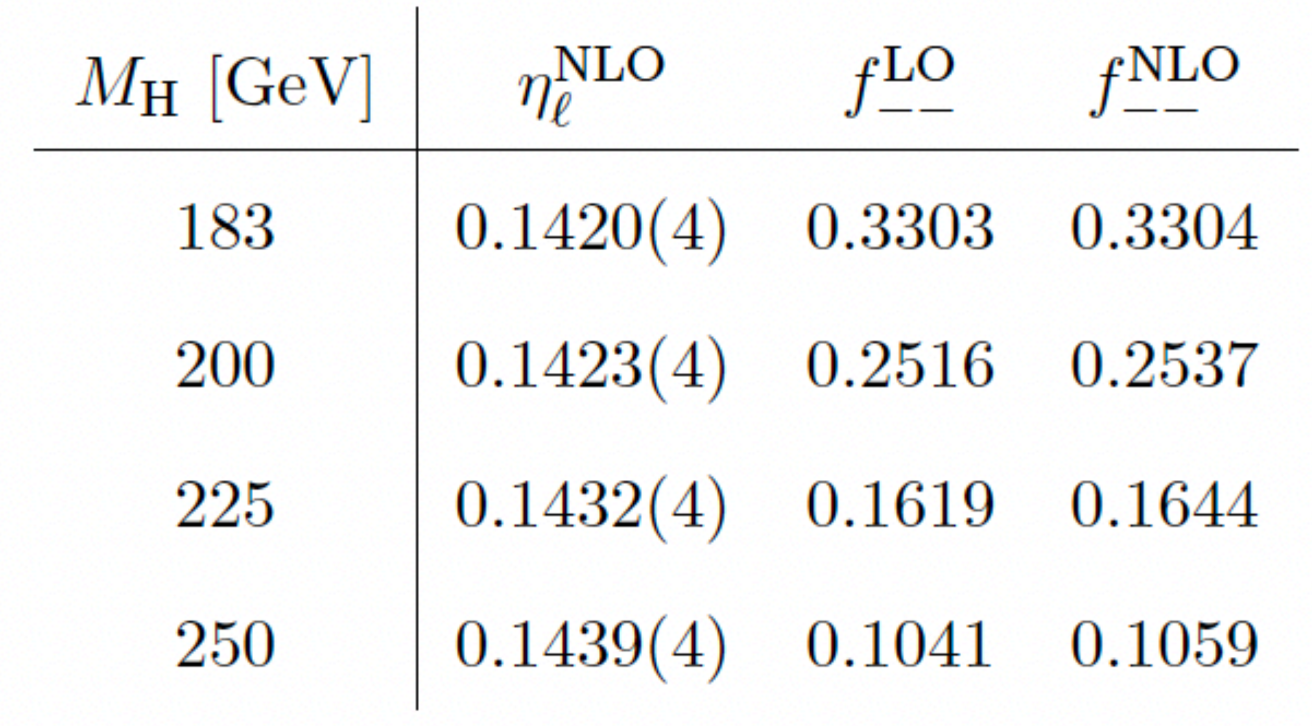
A careful look at the table shows the large K-factors are associated to l=1 components which depend on the spin analysing power which receives huge corrections



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

That can be effectively taken into account by using:

$$\eta_\ell^{\mathrm{eff}} \equiv \eta_\ell^{\mathrm{LO}}\Big|_{\sin^2\theta_{\mathrm{w}} \to \sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}} = \frac{1 - 4\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}}{1 - 4\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}} + 8\sin^4\theta_{\mathrm{w}}^{\mathrm{eff}}}\,.$$



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

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…**

Aoude, Barr, FM, Satrioni, 2504.07030

Gu, Lin, Shao, Wang, Yang, 2510.13951

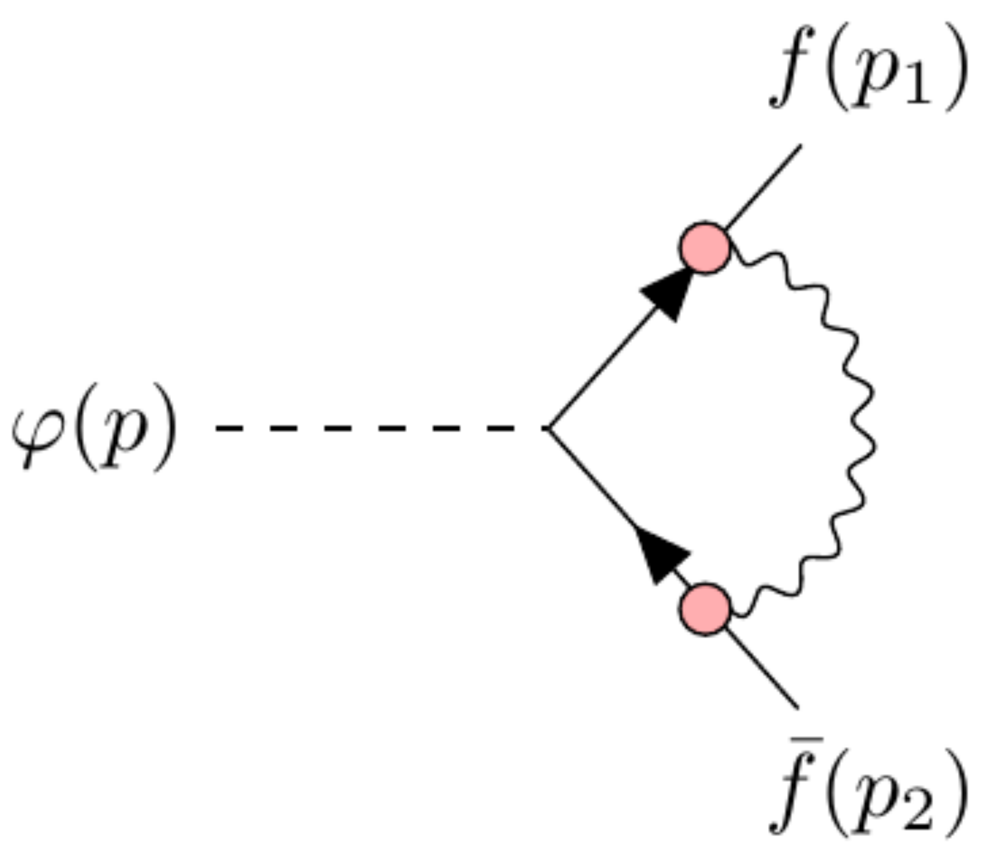
Aoude, Camacho, Durupt, García Mir, FM, Moreno Llácer, Satrioni, Vos 2604.16268

Decoherence

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

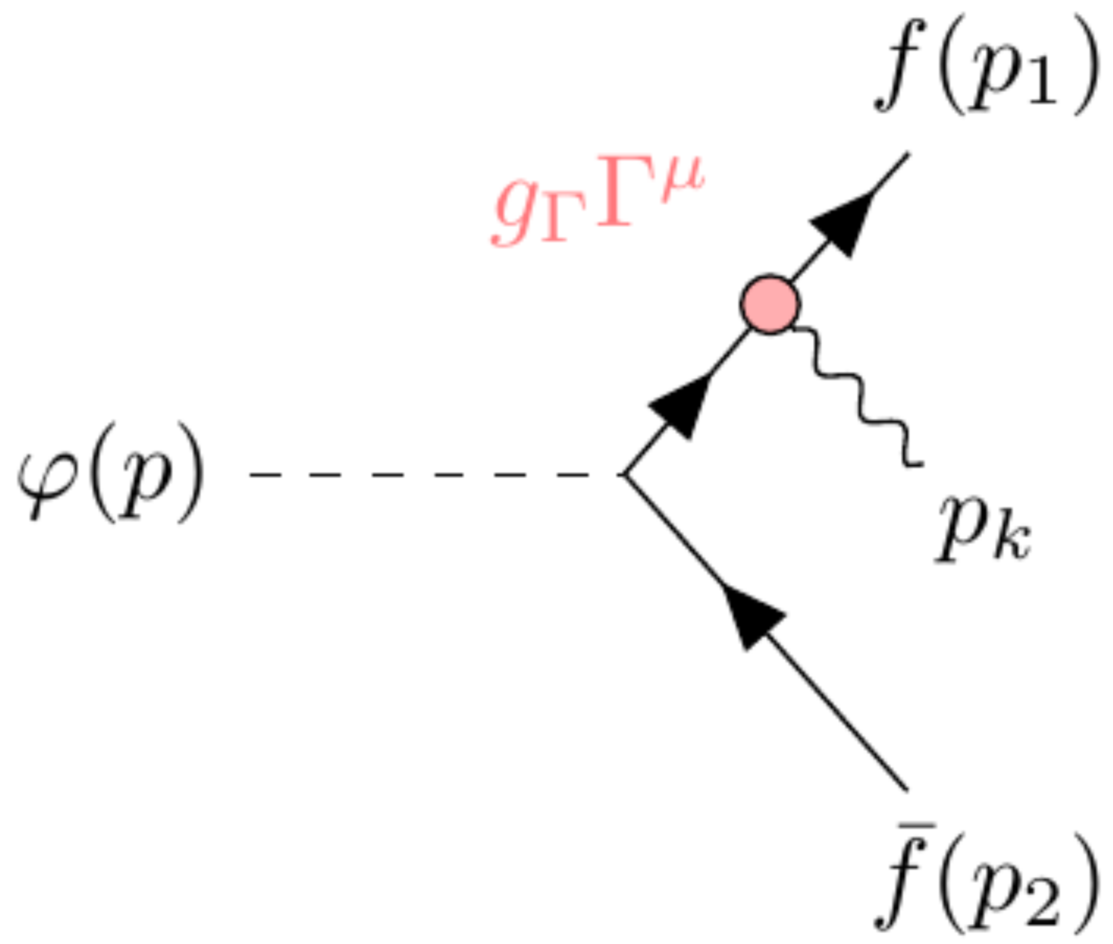
Scalar, pseudo scalar, vector and axial $g_\Gamma \Gamma^\mu = \{g_S 1, g_P \gamma^5, g_V \gamma^\mu, g_A \gamma^\mu \gamma^5\}$

Virtual correction: one-loop



+

Real emission



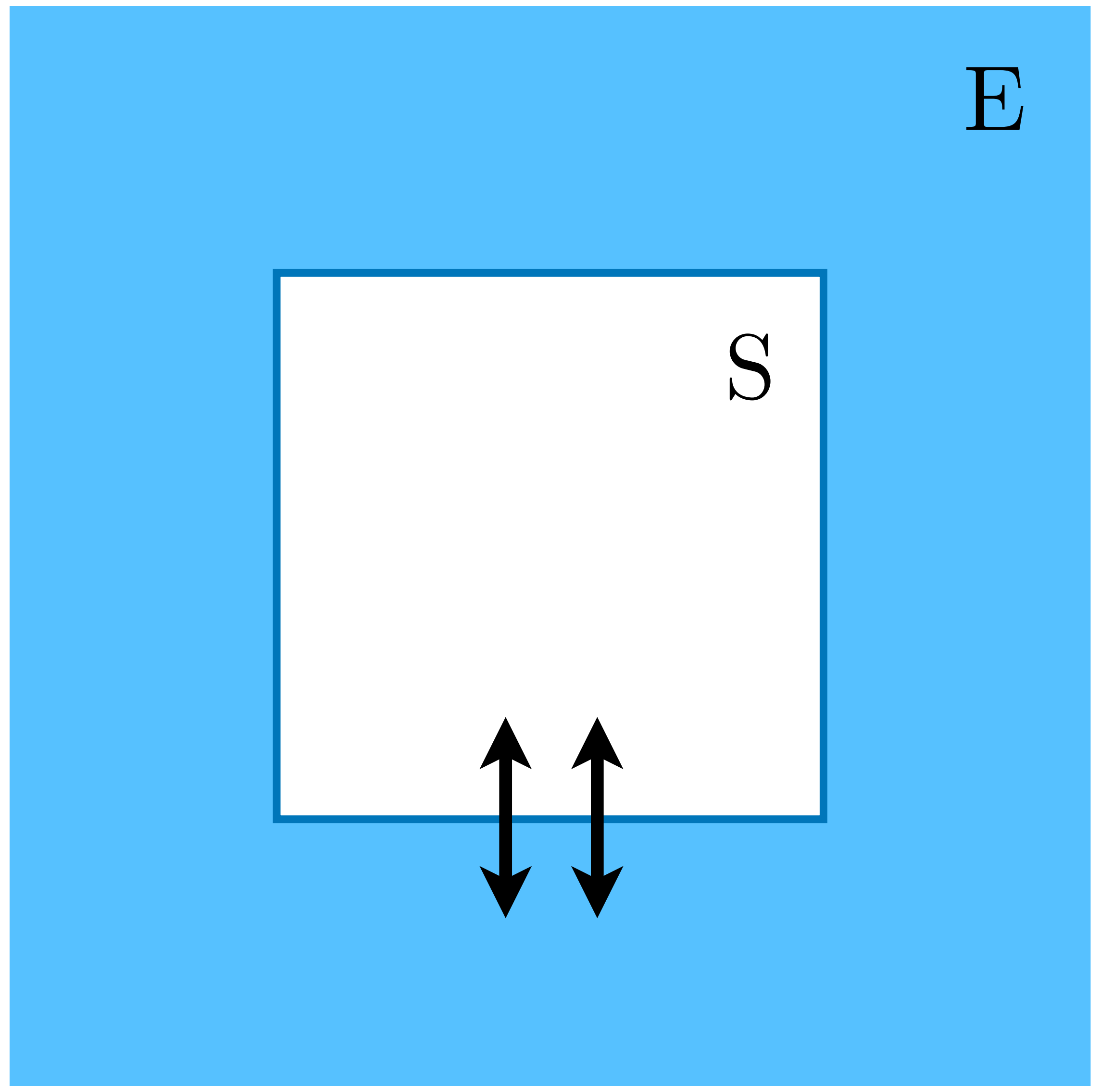
Trace over the extra
d.o.f (environment)

↓

Quantum Map.
Open Quantum system

Same Hilbert space and no change.

Quantum Maps



The evolution of a system+environment is unitary

$$\rho'(t) = U(t)\rho_{\mathrm{S}}(0) \otimes \rho_E(0)U^\dagger(t)$$

Tracing over the environment subsystem

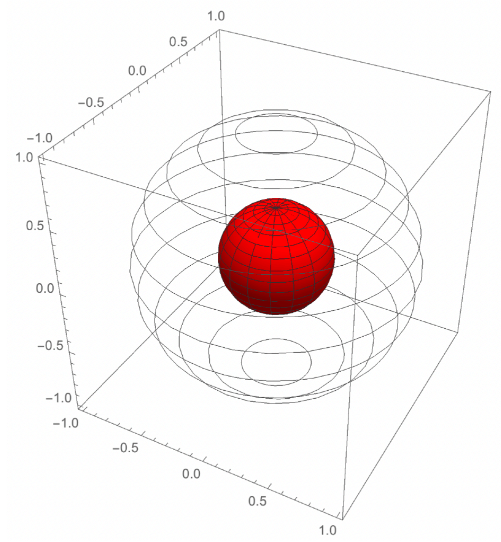
$$\rho_{\mathrm{S}}(t) = \mathrm{tr}_E\left[U(t)\rho_{\mathrm{S}}(0) \otimes \rho_E(0)U^\dagger(t)\right]$$

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

$$\rho_{\mathrm{S}}(t) = \sum_j K_j \rho_{\mathrm{S}}(0) K_j^\dagger =: \mathcal{E}[\rho_{\mathrm{S}}(0)] \qquad \text{s.t} \qquad \sum_j K_j^\dagger K_j = 1$$

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

Decoherence channels



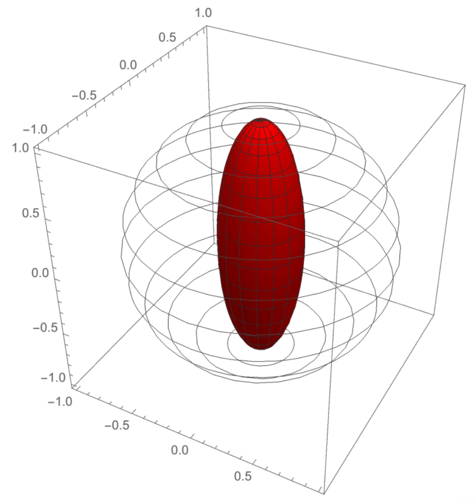
$$K_1 = \sqrt{1 - \frac{3p}{4}}\mathbb{1} \quad , \quad K_2 = \sqrt{\frac{p}{4}}\sigma_1,$$

$$K_3 = \sqrt{\frac{p}{4}}\sigma_2 \quad , \quad K_4 = \sqrt{\frac{p}{4}}\sigma_3.$$

Depolarizing

Typical random noise

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

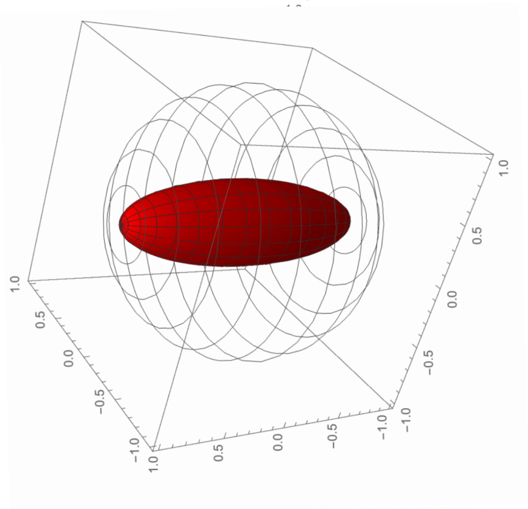


$$K_1 = \sqrt{1 - \frac{p}{2}}\mathbb{1} \qquad K_2 = \frac{p}{2}\sigma_3$$

Phase damping

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

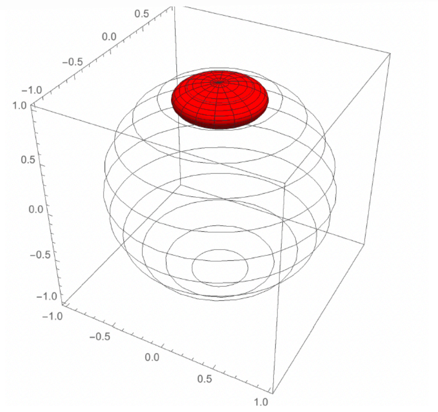
$$\mathcal{E}(\rho) = \left(1 - \frac{p}{2}\right)\rho + \frac{p}{2}Z\rho Z$$



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

Spin flip

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

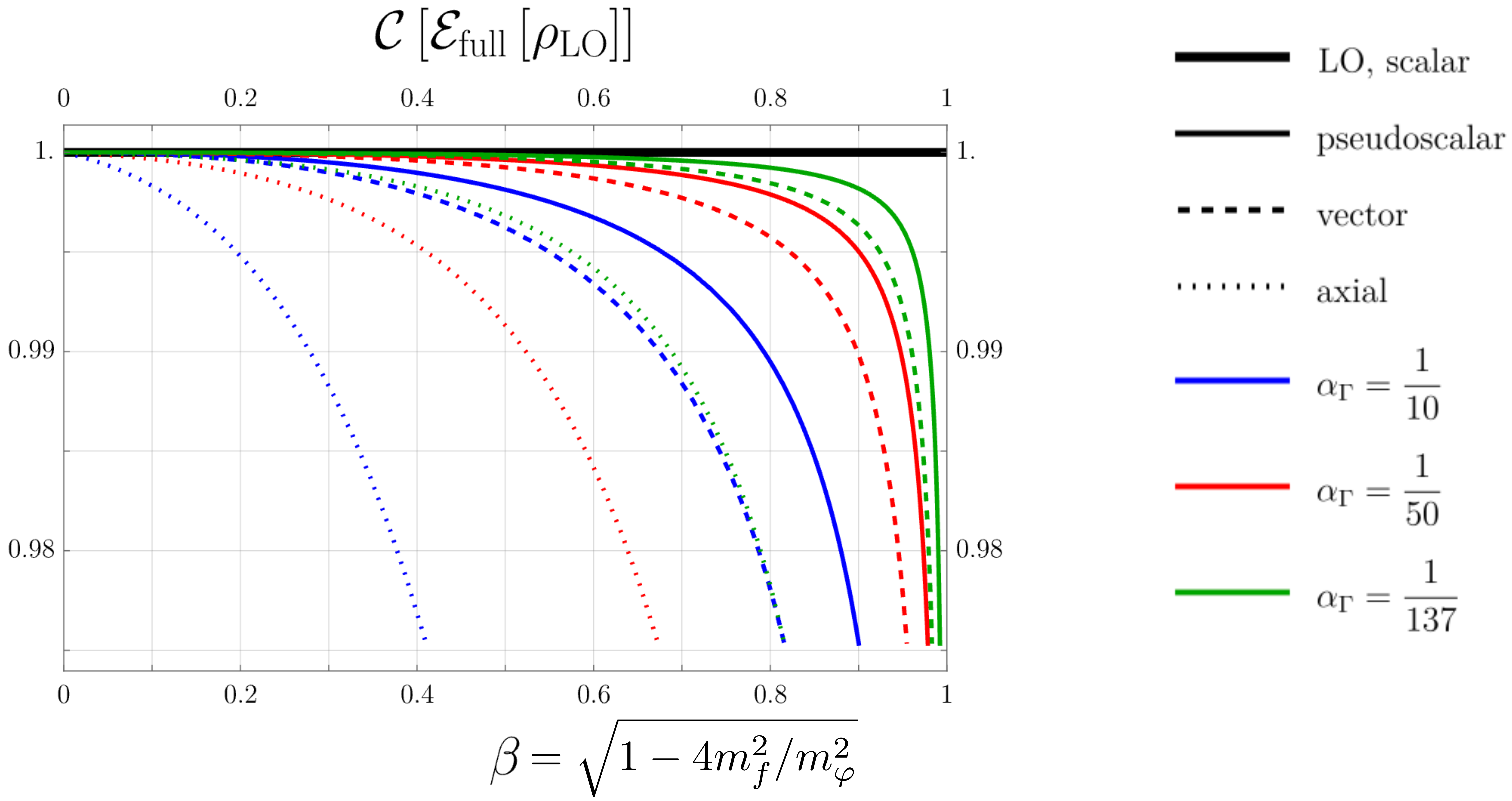


$$K_1 = \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{pmatrix}, \quad K_2 = \begin{pmatrix} 0 & \sqrt{p} \\ 0 & 0 \end{pmatrix}$$

Amp damping

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

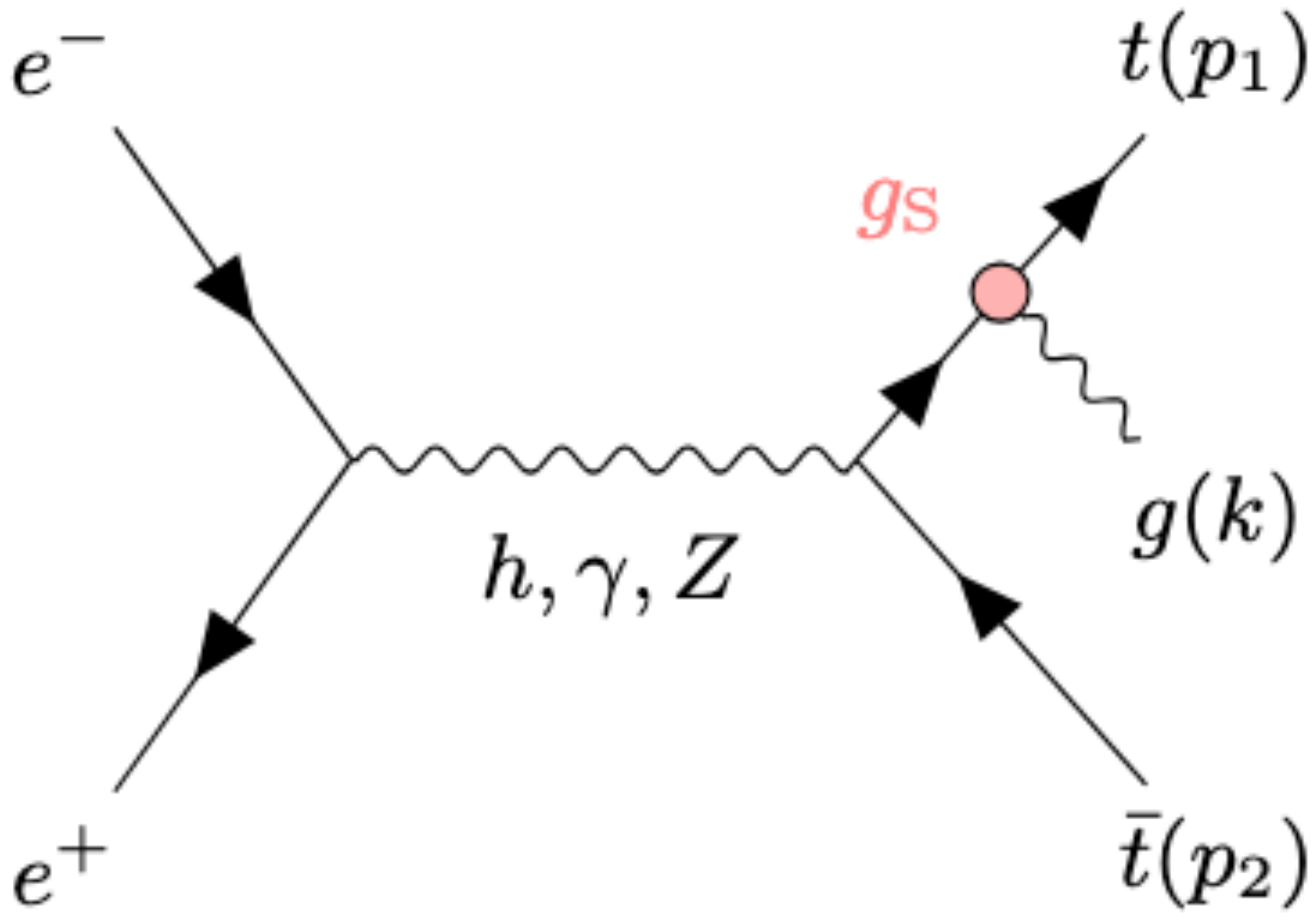
Decoherence

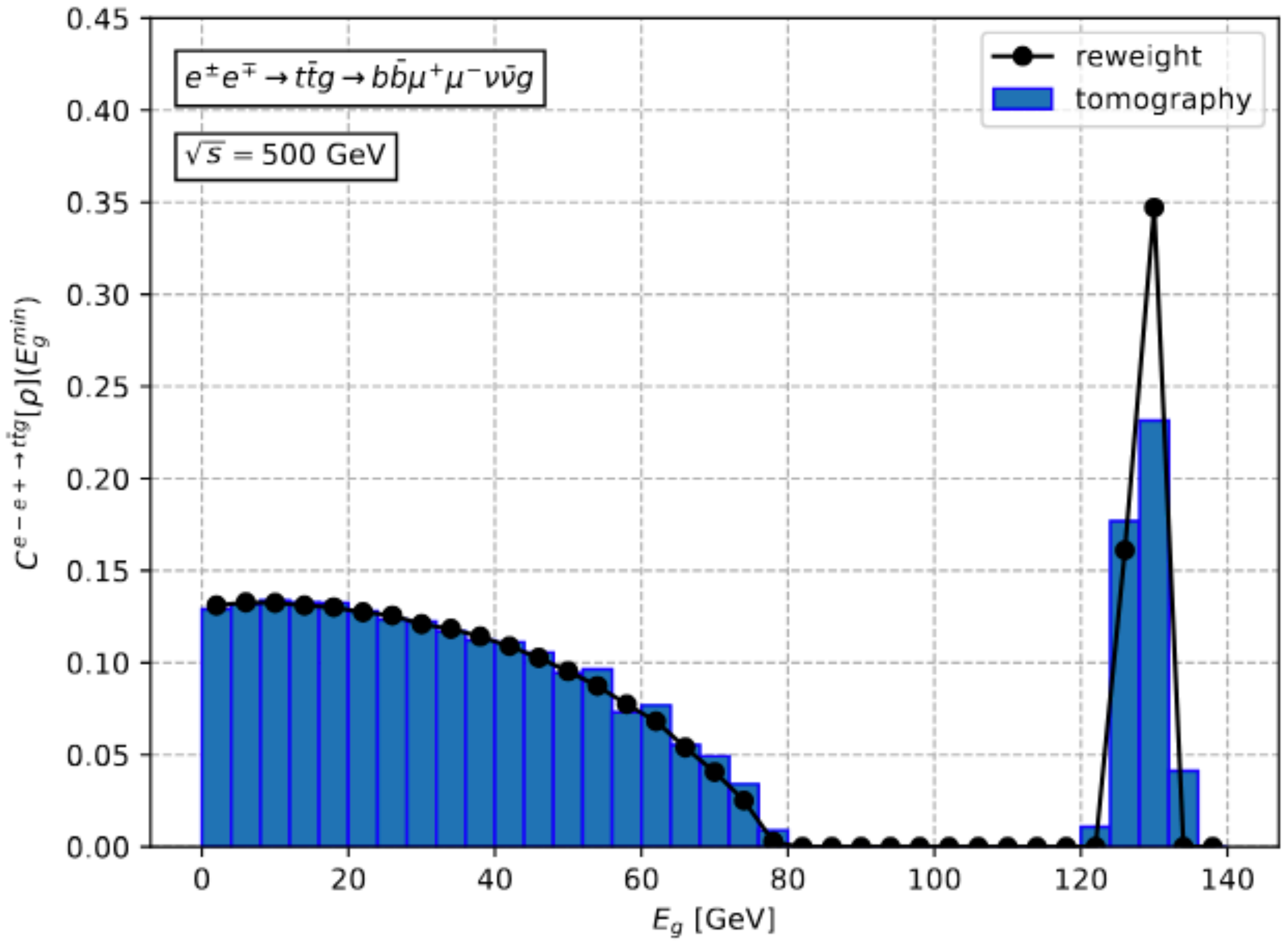


Entanglement is lost mainly due to collinear emission $\Rightarrow$ Small effects ~ 1%

Aoude, Camacho, Durupt, García Mir, FM, Moreno Llácer, Satrioni, Vos 2604.16268

Application: $e^+e^- \to t\bar{t}g$





In addition, the virtual also gives 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 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 and 2410.23343
- Magic : 2406.07321, 2508.14967

Caution: incomplete list!

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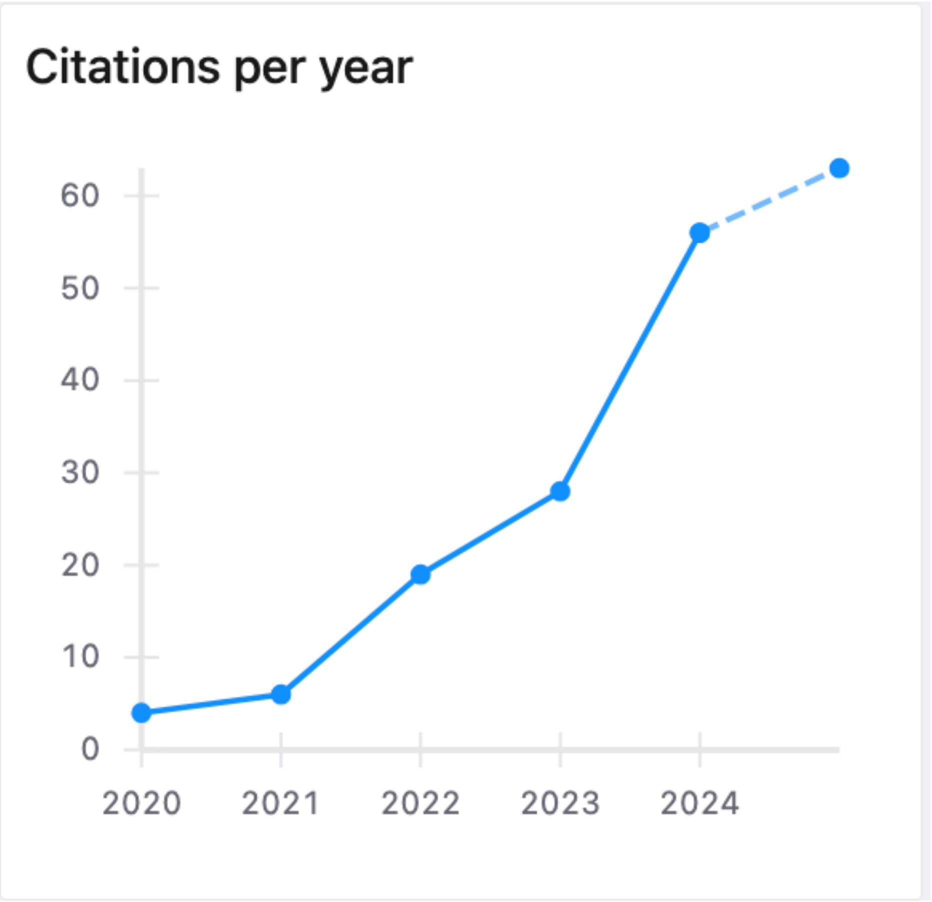
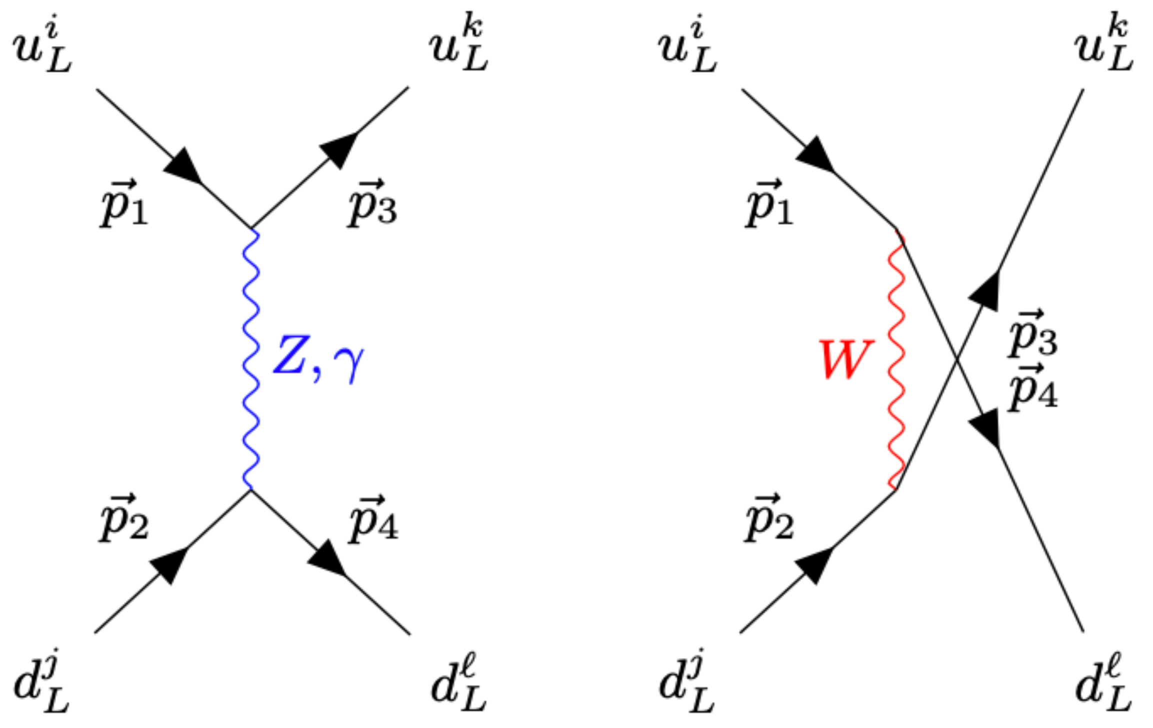


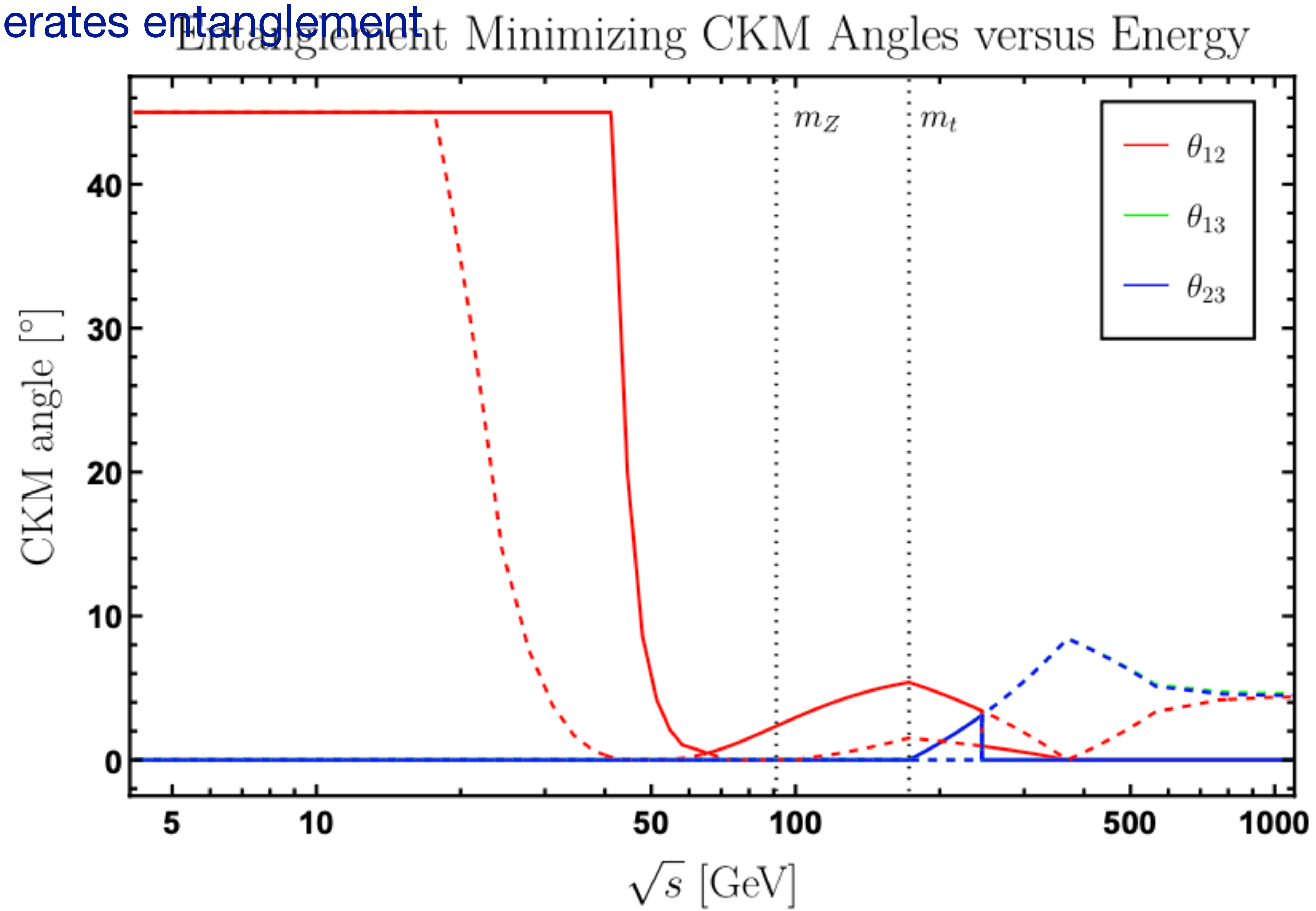
Citations to the
Afik & de Nova paper

Caution: incomplete list!

Entanglement as a principle?

Cervera-Lierta, Latorre, Rojo, Rottoli,1703.02989	⇒QED as minimal theory
Carena, Low, Wagner, Xiao 2307.08112	⇒ symmetry enhancement
Thaler, Trifinopoulos. 2410.23343	⇒CKM/PMNS matrix structure
Liu, Low, Yin, 2509.18251	⇒Value of sin(thetaW)
Nunez, Pardina, Asorey, Latorre, Cervera-Lierta, 2511.04358	⇒Gauge invariance
McGinnis 2511.10559	⇒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,

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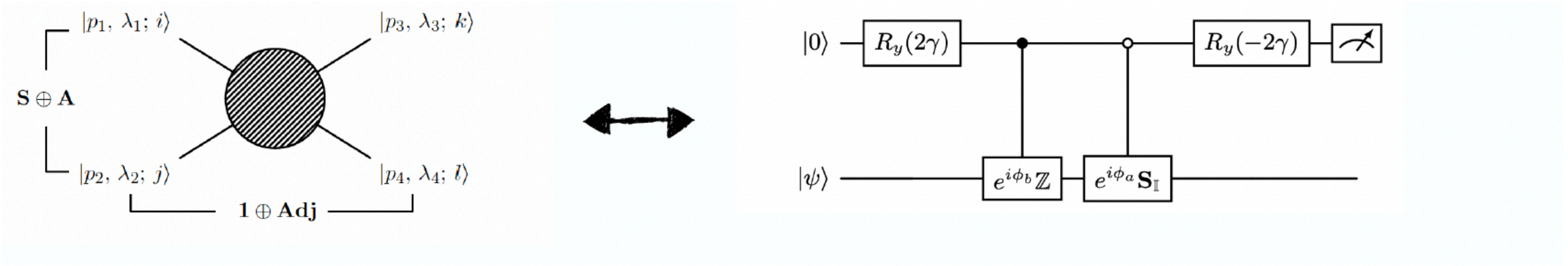


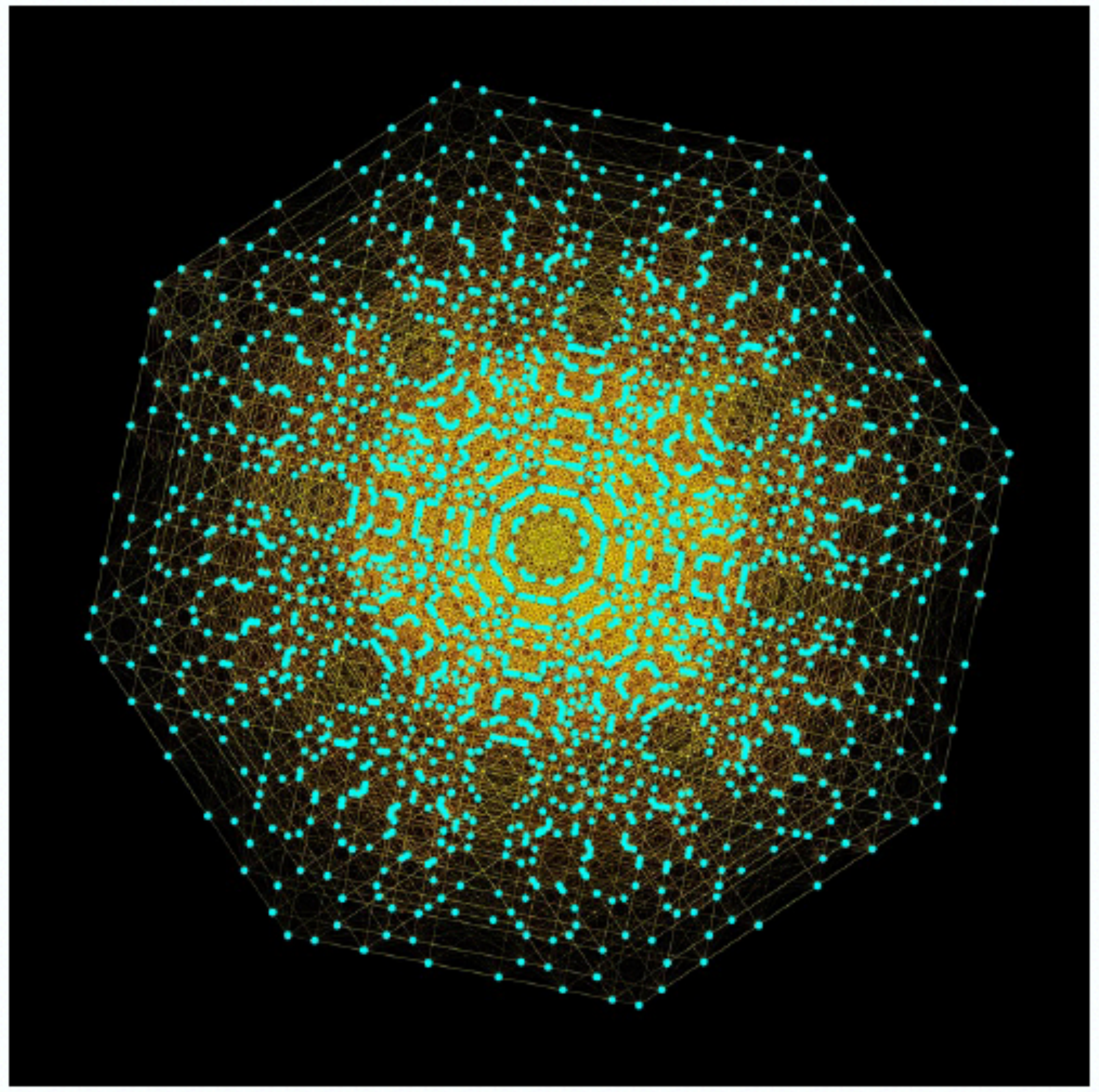
By viewing fixed-helicity SU(N) scattering as quantum gates acting on internal qudits, it is shown that crossing symmetry ties the channels together so tightly that any interacting SU(N)-symmetric field theory must create entanglement in at least one of them.

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

Q. Liu, I. Low, Z. Yin 2502.17550
M. Ohta , K. Sakurai 2506.11725

Classification of magic states

E_8, BW_{16}, E_6, …



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Minimal and Maximal

Magic states

		1st shortest	2nd 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	$\boxed{\mathbf{15360}}$

A new geometric route to understanding quantum magic.By mapping vectors from highly symmetric lattices (E8, BW16, and E6) 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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