河南师范大学 HENAN NORMAL UNIVERSITY

理论物理中心 Centre for Theoretical Physics

对撞机上的量子信息

郭禹辰

辽宁师范大学

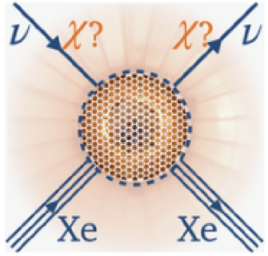
第四届新物理数值计算与模拟前沿讲习班

河南师范大学 · 新乡

2026 年 7 月 6 日—13 日

I. Introduction

Interesting physics ≠ ‘new’ physics ≠ beyond-SM physics



EDITORS' SUGGESTION

[First Search for Light Dark Matter in the Neutrino Fog with XENONnT]

E. Aprile *et al.* (XENON Collaboration)

Phys. Rev. Lett. **134**, 111802 (2025) - Published 20 March, 2025

Bounds on GeV-scale dark matter are placed for the first time in the range of parameter space effected by the neutrino fog.

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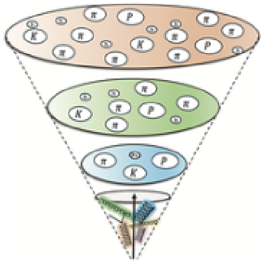

EDITORS' SUGGESTION

[Entanglement as a Probe of Hadronization]

Jaydeep Datta, Abhay Deshpande, Dmitri E. Kharzeev, Charles Joseph Naïm, and Zhoudunming Tu

Phys. Rev. Lett. **134**, 111902 (2025) - Published 19 March, 2025

The entropy of hadrons produced within highly energetic jets can be related to the fragmentation function if the initial quarks and gluons in the jets are maximally entangled.

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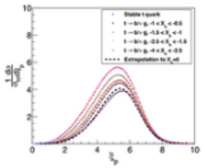

EDITORS' SUGGESTION

[How to identify the dead cone in the top-quark jet]

Stefan Kluth, Wolfgang Ochs, and Redamy Perez-Ramos

Phys. Rev. D **113**, 114048 (2026) - Published 26 June, 2026

The dead cone is the angular region about the momentum direction of a heavy quark in which QCD radiation is suppressed. While well-studied and even experimentally validated for bottom quarks, observing the dead cone for the most massive quark, the top, is exceedingly subtle because of its nearly immediate decay. The authors present a thorough study of the dead cone for top quarks, and establish techniques that can be used to isolate this intriguing effect from the physics of its decay.

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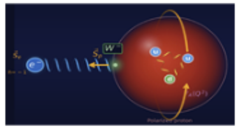


EDITORS' SUGGESTION

[Constraining neutrino-nucleon form factors with charged-current scattering at the Electron-Ion Collider]

Guang Yang and Praveen Kumar

Phys. Rev. D **113**, 116031 (2026) - Published 22 June, 2026

This study investigates the potential of electron–proton scattering at the Electron–Ion Collider to constrain the neutrino–nucleon axial form factor with unprecedented precision. By exploiting a free-proton target, the proposed measurements largely avoid nuclear-model uncertainties and offer a promising avenue for advancing the precision frontier of neutrino interaction physics.

Show Abstract ⌄ PDF

Some of the old problems are amongst the deepest. . .

1935: Einstein-Podolsky-Rosen

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality.

- Einstein-Podolsky-Rosen were famously uncomfortable with quantum entanglement and suggested Quantum Mechanics was not a complete description

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

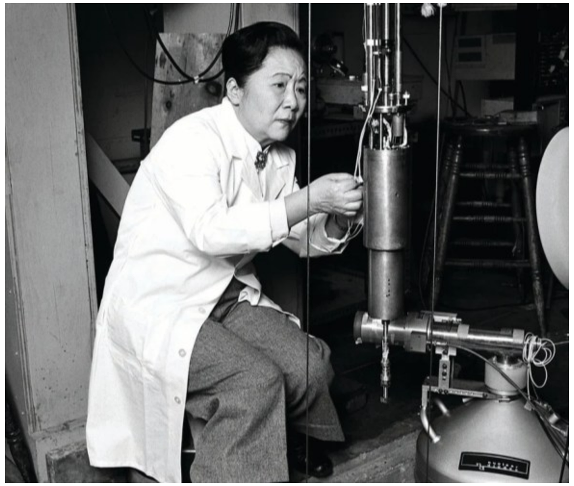
SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

A. Einstein B. Podolsky N. Rosen

Einstein–Podolsky–Rosen paradox

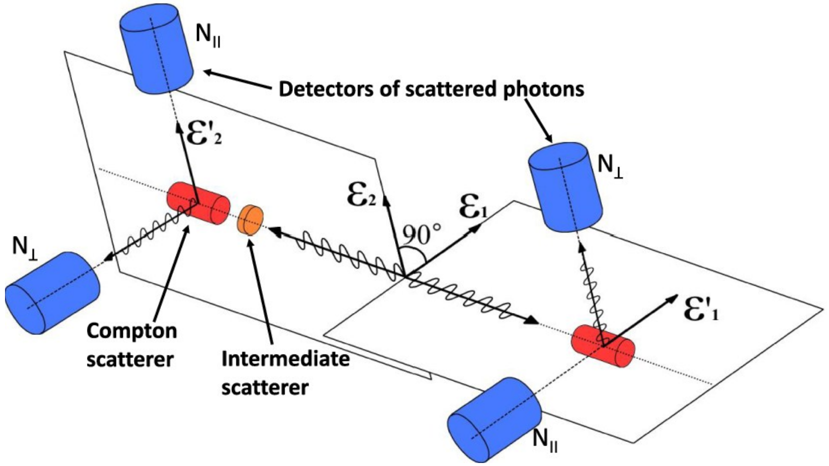
Quantum Entanglement Timeline

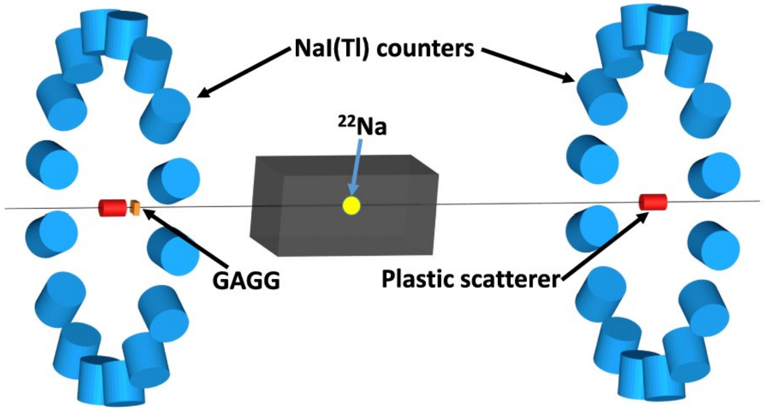


1935: Einstein-Podolsky-Rosen

1950: Wu-Shaknov Experiment

- The first experiment on quantum entanglement
- The angular correlation of two Compton-scattered photons





Wu-Shaknov Experiment

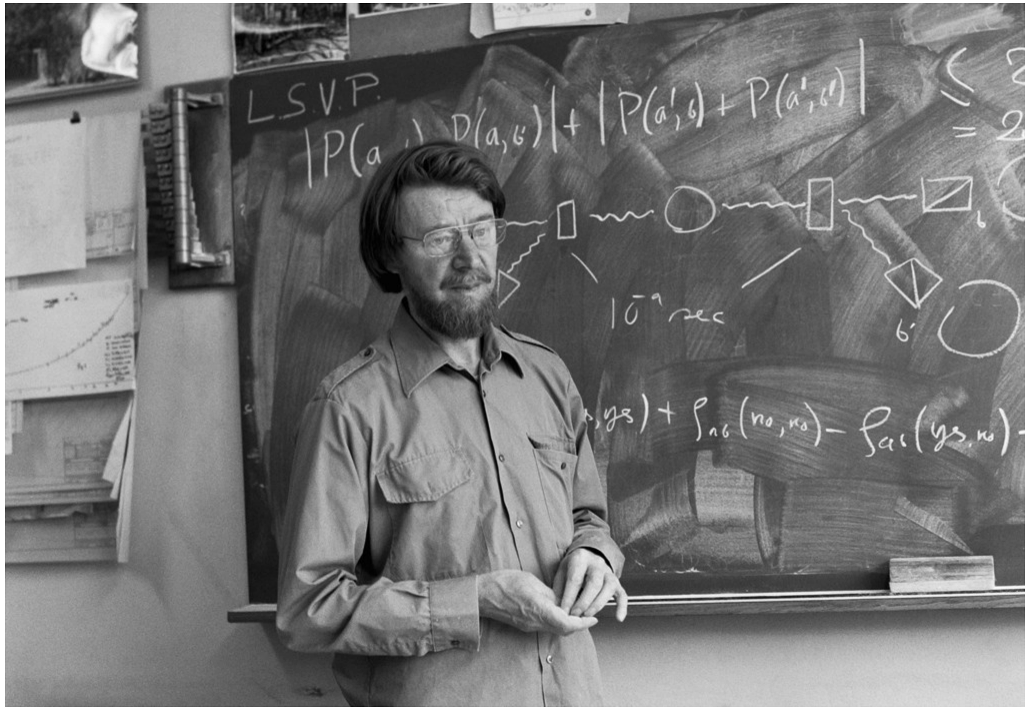
Quantum Entanglement Timeline

1935: Einstein-Podolsky-Rosen

1950: Wu-Shaknov

1964: Bell's Theorem

They are experimentally accessible !



- Predictions of QM incompatible with any "local" theory
- Gedanken experiment for demonstrating Q nonlocality

J.S. Bell 'On the Einstein Podolsky Rosen paradox' (1964)

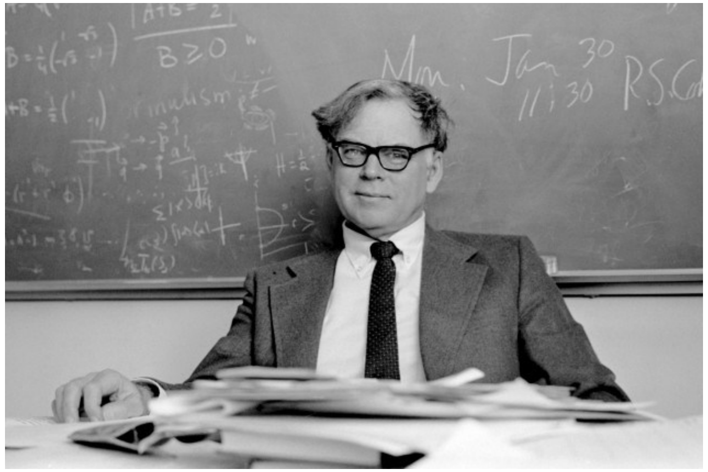
Quantum Entanglement Timeline

1935: Einstein-Podolsky-Rosen

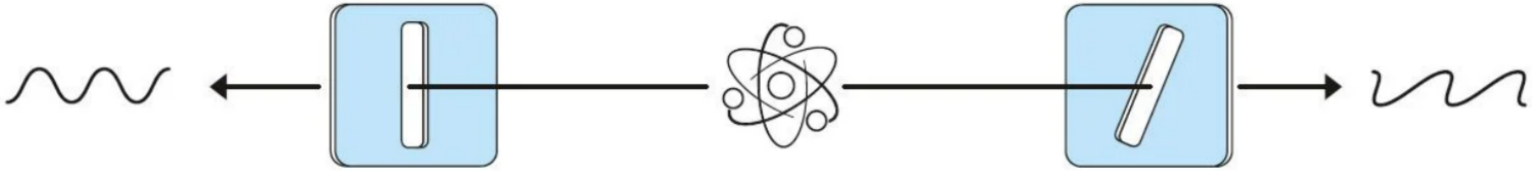
1950: Wu-Shaknov

1964: Bell's Theorem

1969: Clauser-Horne-Shimony-Holt



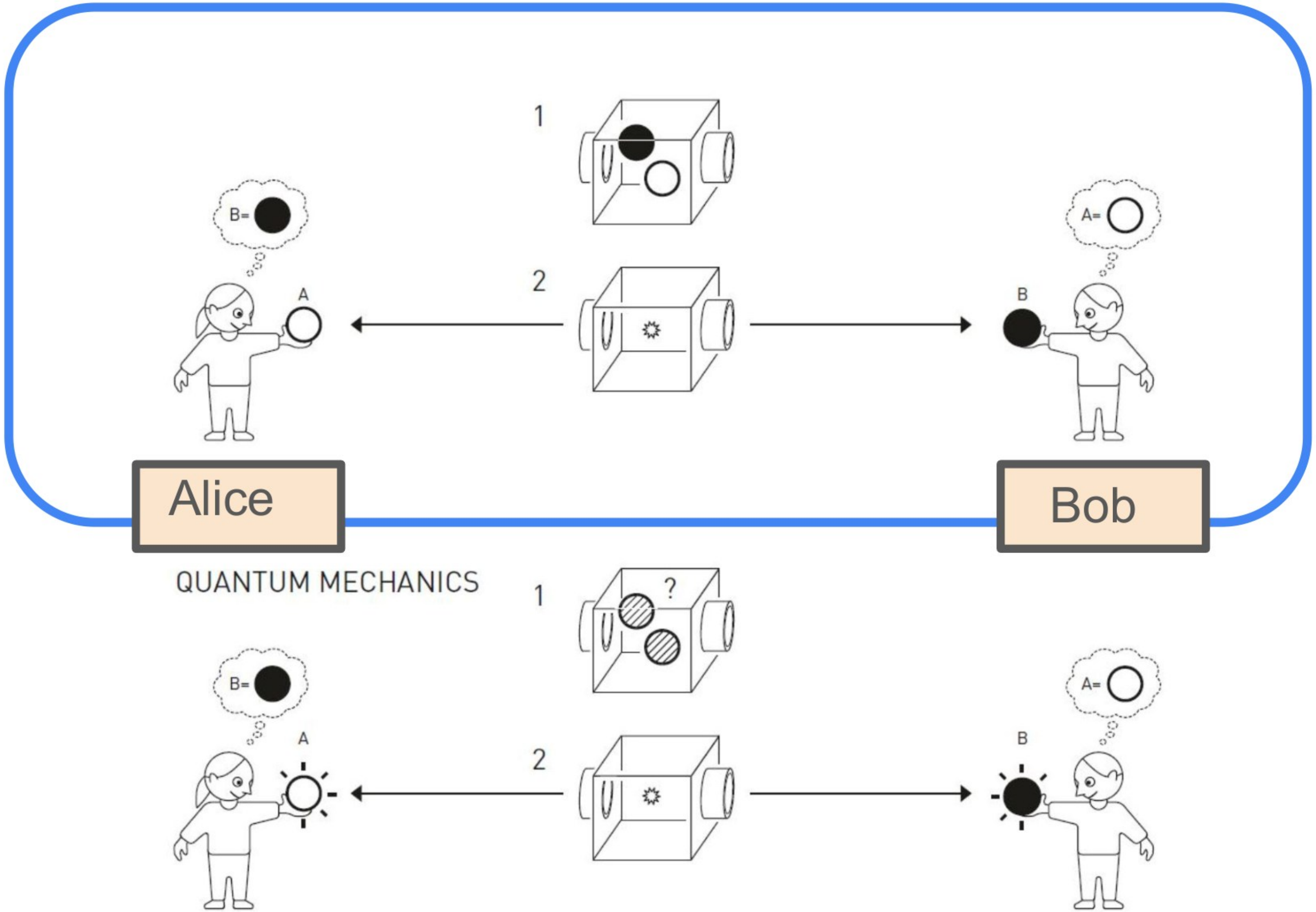
- Realistic proposal for a Bell experiment



John Clauser used calcium atoms that could emit entangled photons after he had illuminated them with a special light. He set up a filter on either side to measure the photons' polarisation. After a series of measurements, he was able to show they violated a Bell inequality.

Hidden Variables vs. Quantum Entanglement

Classical physics



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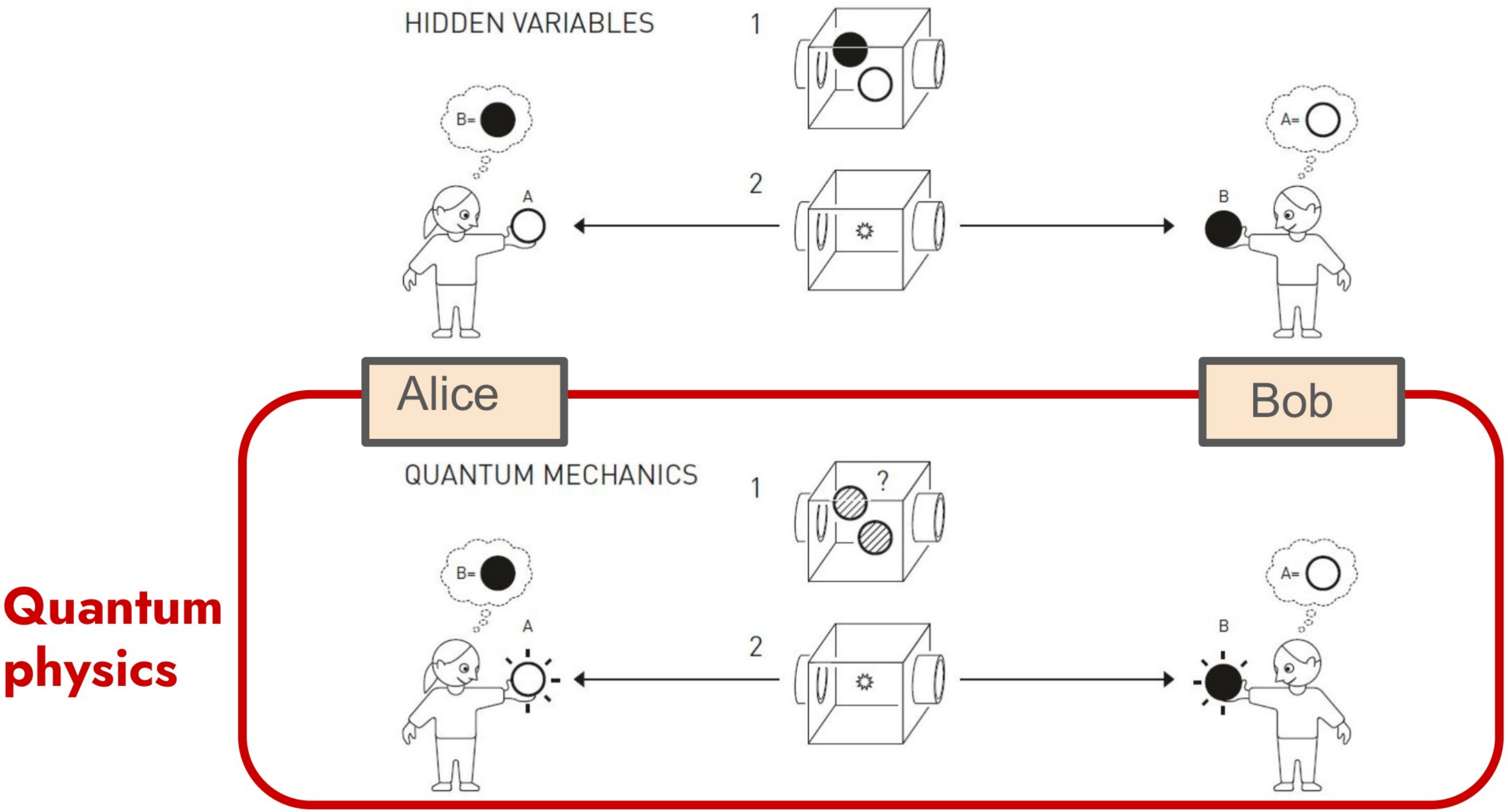
Hidden Variables vs. Quantum Entanglement



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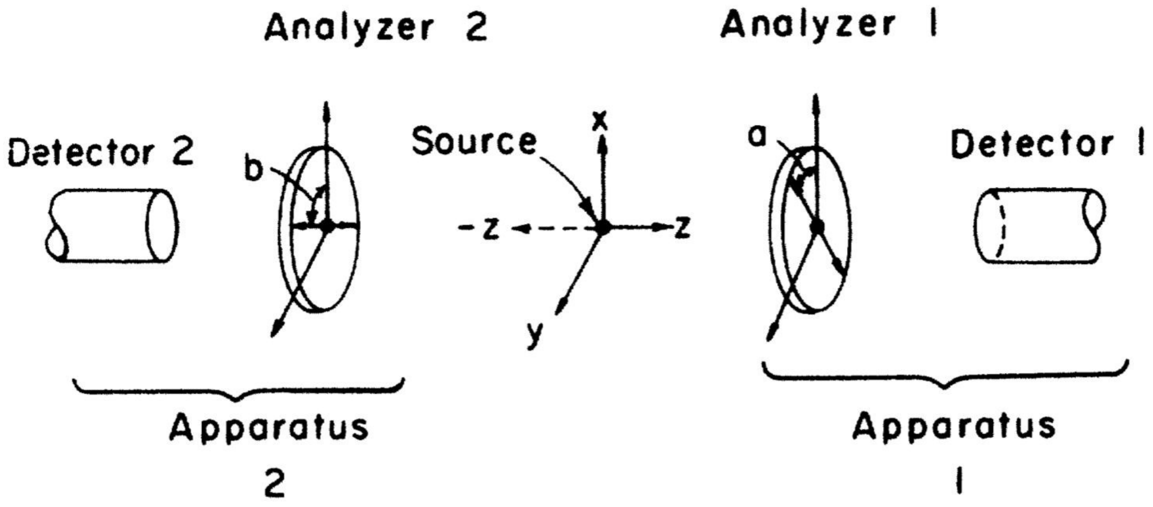
Experiment of Bell's Inequality

- Experiment of Bell's inequality

Detector settings:

b_1 and b_2



Detector settings:

a_1 and a_2

Measurements:

1	a_1	b_1	E_{11}
2	a_1	b_2	E_{12}
3	a_2	b_1	E_{21}
4	a_2	b_2	E_{22}

N^{++} number of times both Alice measures + and Bob measures +

N^{+-} number of times both Alice measures + and Bob measures -

N^{-+} number of times both Alice measures - and Bob measures +

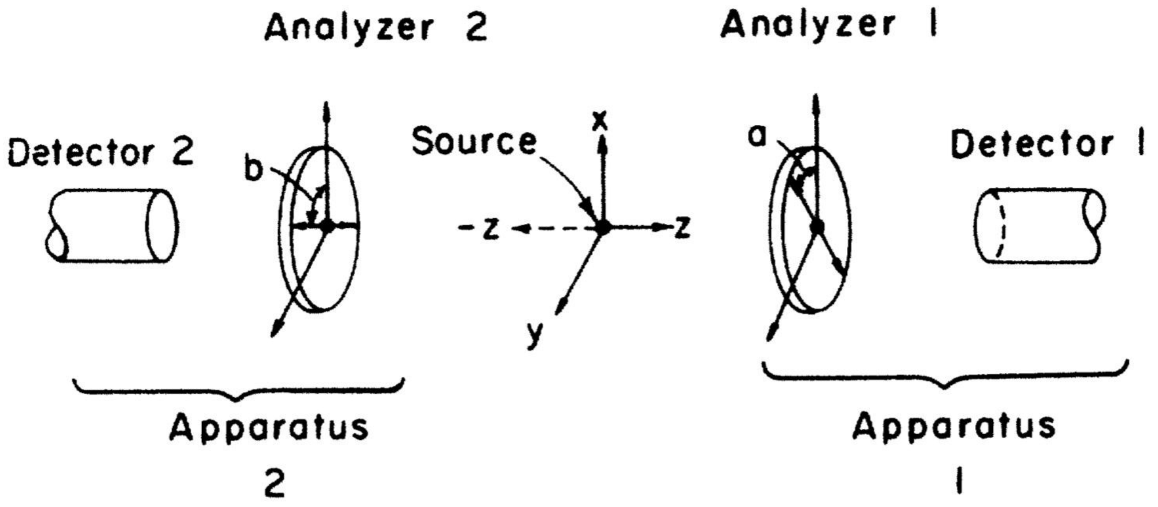
N^{--} number of times both Alice measures - and Bob measures -

Experiment of Bell's Inequality

- Experiment of Bell's inequality

Detector settings:

b_1 and b_2



Detector settings:

a_1 and a_2

Measurements:

1	a_1	b_1	E_{11}
2	a_1	b_2	E_{12}
3	a_2	b_1	E_{21}
4	a_2	b_2	E_{22}

$$E = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{N^{++} + N^{--} + N^{+-} + N^{-+}}$$

E=-1 Fully anti-correlated

E=0 Uncorrelated

E=+1 Fully correlated

Experiment of Bell's Inequality

- Experiment of Bell's inequality

Bell 1964

Clauser, Horne, Shimony, Holt 1969

Clauser, Horne 1974

$$|E_{11} - E_{12} + E_{21} + E_{22}| \leq 2$$

Measurements:

1	a_1	b_1	E_{11}
2	a_1	b_2	E_{12}
3	a_2	b_1	E_{21}
4	a_2	b_2	E_{22}

- All classical theories satisfy this inequality
- Quantum theories can satisfy this inequality

Bell local state

- Or quantum theories can violate this inequality

Bell nonlocal state

Quantum Entanglement Timeline

1935: Einstein-Podolsky-Rosen

1950: Wu-Shaknov

1964: Bell's Theorem

1969: Clauser-Horne-Shimony-Holt

1980s: Experiments by Aspect, Clauser

- The experiment using entangled photons
- Clear violation of Bell's inequality
- Excellent agreement with quantum mechanics predictio

Nobel Prize in Physics 2022

© Nobel Prize Outreach. Photo: Stefan Bladh
Alain Aspect
Prize share: 1/3

© Nobel Prize Outreach. Photo: Stefan Bladh
John F. Clauser
Prize share: 1/3

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Anton Zeilinger
Prize share: 1/3

$$S = E_{11} - E_{12} + E_{21} + E_{22}$$

$$\boxed{\begin{aligned} S_{\text{expt}} &= 2.697 \pm 0.015\,. \\ S_{\text{QM}} &= 2.70 \pm 0.05\,. \end{aligned}}$$

Quantum Entanglement Timeline

1935: Einstein-Podolsky-Rosen

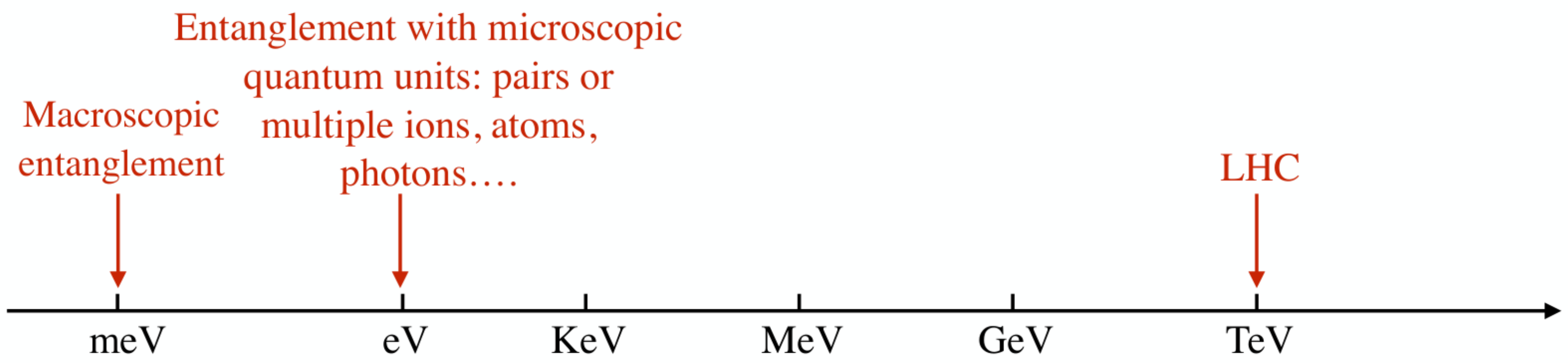
1950: Wu-Shaknov

1964: Bell's Theorem

1969: Clauser-Horne-Shimony-Holt

1980s: Experiments by Aspect, Clauser

2020-2026： Entanglement measurement at colliders



Entanglement measurement at Colliders

Letter | Published: 06 May 2019

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration

Nature Physics **15**, 631–634 (2019) | Cite this article

8157 Accesses | **190** Citations | **63** Altmetric | Metrics

Article | Open access | Published: 01 June 2022

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

Nature **606**, 64–69 (2022) | Cite this article

37k Accesses | **82** Citations | **86** Altmetric | Metrics

- **Entangled double baryons $\Lambda\bar{\Lambda}$ system**

CP violation

Entanglement measurement at Colliders

PAPER • OPEN ACCESS

Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Published 23 October 2024 • © CERN, for the benefit of the CMS Collaboration

Reports on Progress in Physics, Volume 87, Number 11

Citation The CMS Collaboration 2024 *Rep. Prog. Phys.* **87** 117801

DOI 10.1088/1361-6633/ad7e4d

Article | Open access | Published: 18 September 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Nature **633**, 542–547 (2024) | Cite this article

- **Entangled double baryons $\Lambda\bar{\Lambda}$ system**

- **Entangled $t\bar{t}$ system**

Top quarks decay before hadronization, spin information can be transferred to their decay products

Entanglement measurement at Colliders

PAPER • OPEN ACCESS

Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

PAPER • OPEN ACCESS

Observation of a cross-section enhancement near the $t\bar{t}$ production threshold in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

Published 7 May 2026 • © 2026 The Author(s). Published by IOP Publishing Ltd

Reports on Progress in Physics, Volume 89, Number 5

Citation The ATLAS Collaboration 2026 *Rep. Prog. Phys.* **89** 057801

DOI 10.1088/1361-6633/ae60a0

Article

Nature **633**, 542–547 (2024) | Cite this article

87k Accesses | **19** Citations | **476** Altmetric | Metrics

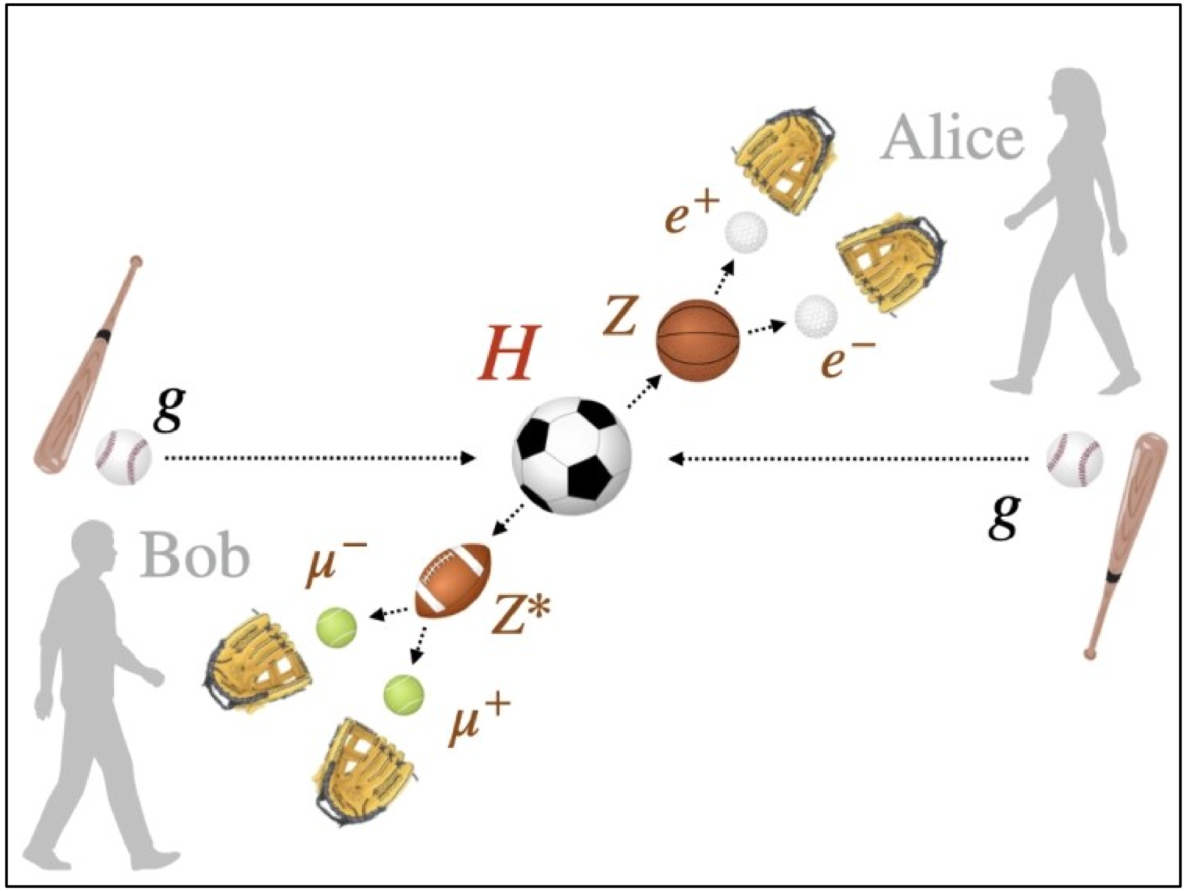
- **Entangled double baryons $\Lambda\bar{\Lambda}$ system**
- **Entangled $t\bar{t}$ system**
- **"quasi-bound state" toponium**

Entanglement measurement at Colliders

News: ATLAS and CMS measured entanglement in Higgs boson decay.

ATLAS EXPERIMENT

arXiv: 2603.26463



CMS Compact Muon Solenoid

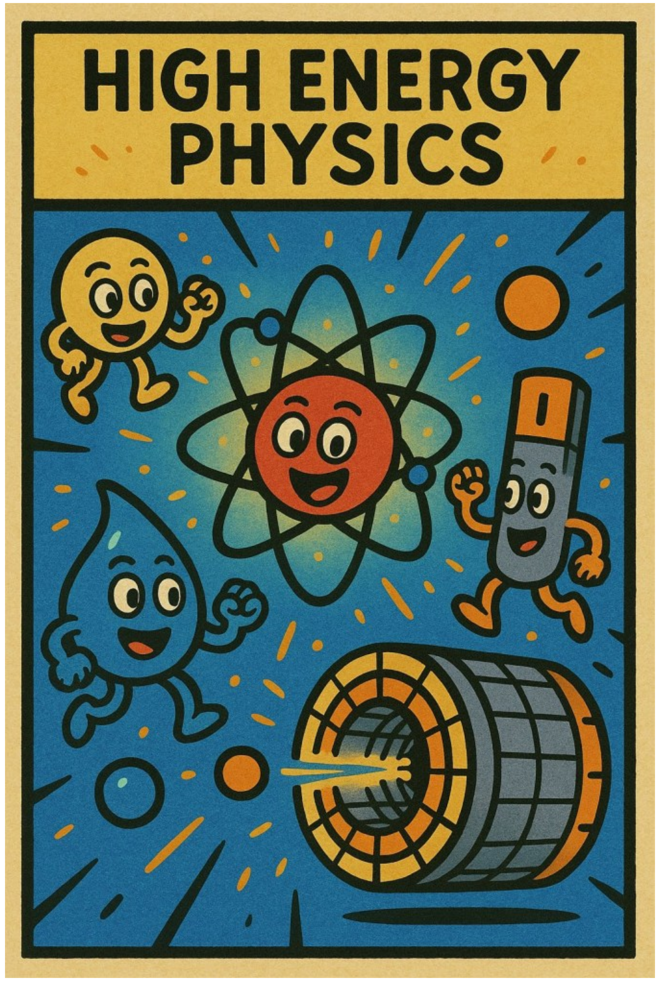
CMS PAS HIG-25-011

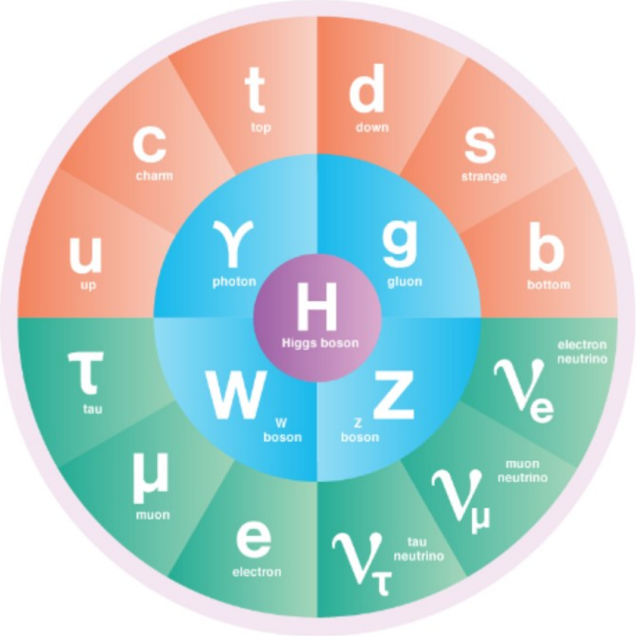
Strong evidence for quantum entanglement between spin-qutrit bosons at the electroweak scale

Unique role of the Higgs boson as a natural laboratory for precision studies of entanglement.

High-Energy Physics and Quantum Information Science

Each of these are individually **interesting** and **vibrant** fields

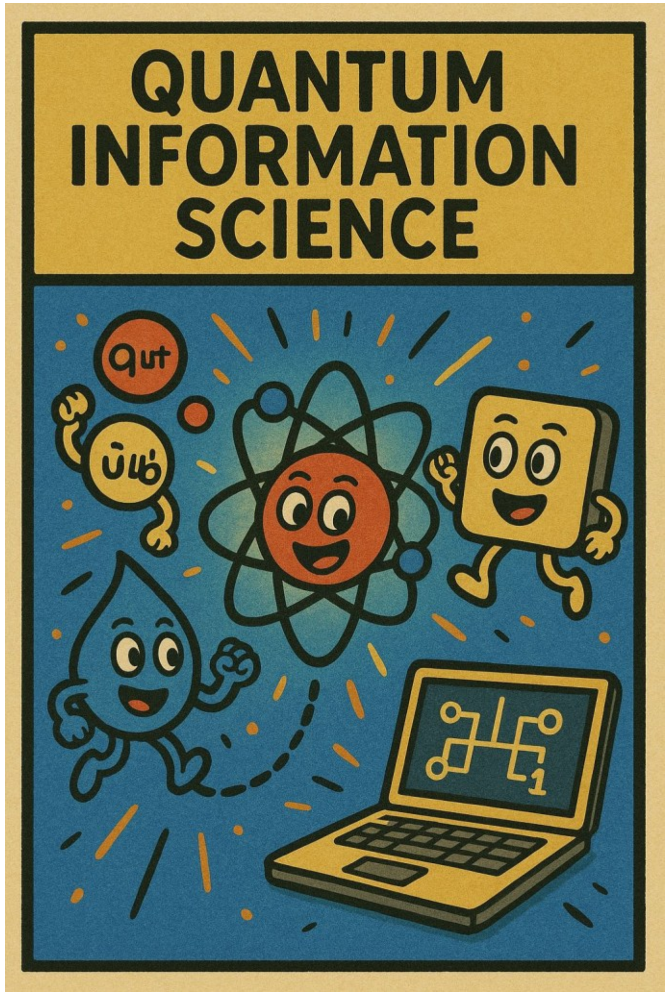


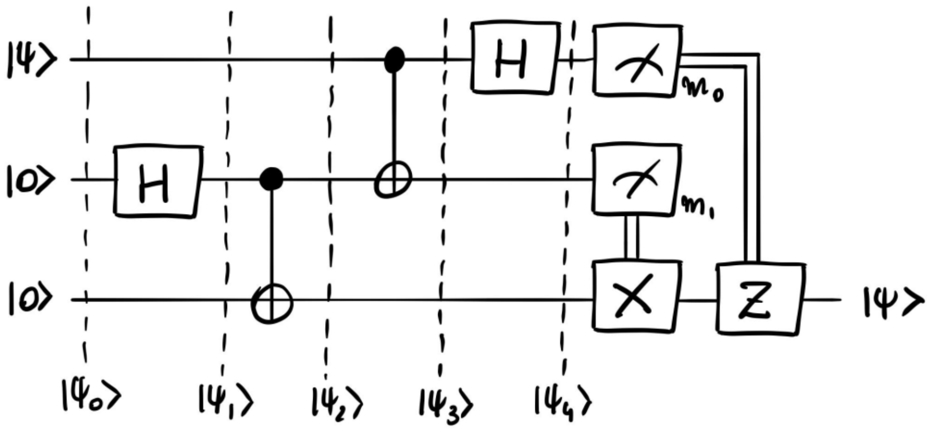


- ✓ Identify the **fundamental constituents** and laws of nature
- ✓ Explore **symmetries** and conservation laws
- ✓ Test and refine the **Standard Model**

High-Energy Physics and Quantum Information Science

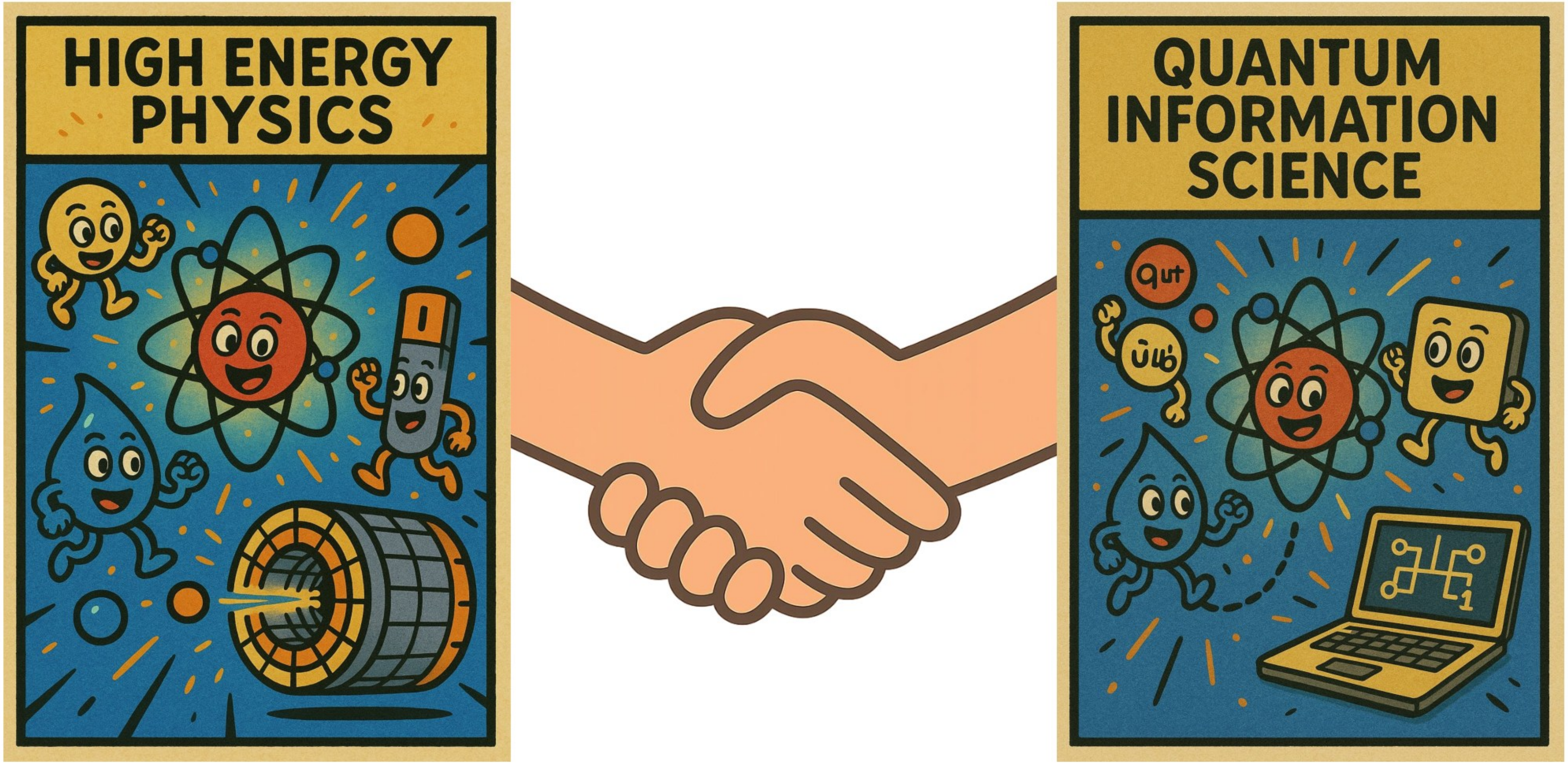
Each of these are individually **interesting** and **vibrant** fields





- ✓ Explore quantum systems as a resource for **information processing**
- ✓ Understand the **foundations** of quantum mechanics
- ✓ Build **quantum computers**

High-Energy Physics and Quantum Information Science



High-Energy Physics and Quantum Information Science

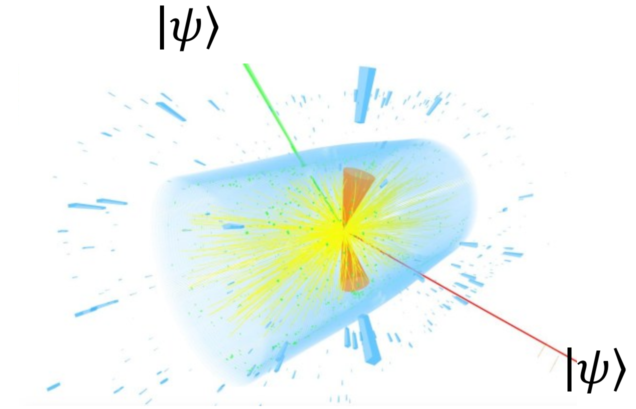
The quantum nature of the SM is so pervasive in the daily life of the particle physicist, that we often forget about it. Naively:

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

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

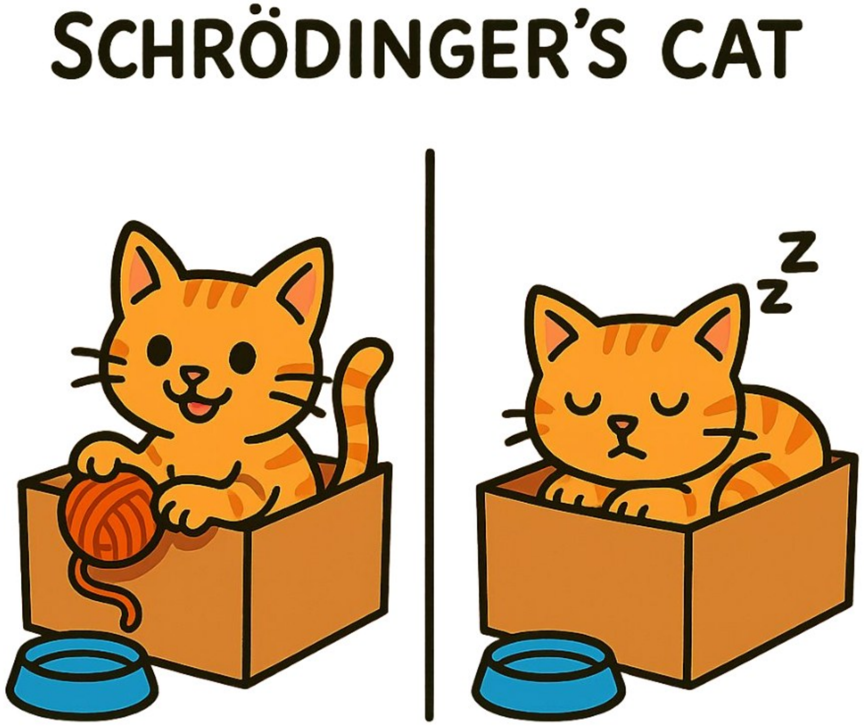
We have extensively validated QFT at different scales, and always found it a consistent way of making predictions in HEP.

- What is the information-theoretic structure of QFT?
- Can quantum-information observables reveal new aspects of fundamental interactions?
- Can quantum information provide new probes of physics beyond the SM?
- How does quantum information flow in time?



II. Theoretical Concept

Quantum Mechanics



- In classical physics, states have **definite** values

  0 or **1**

- In quantum mechanics, states are in **superpositions**

  (Probability(0), Probability(1))

- We write this as a **wavefunction**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$|\alpha|^2$ = Probability(0)

$|\beta|^2$ = Probability(1)

- or a **density matrix**

$$\rho^\dagger = \rho, \quad \mathrm{Tr}(\rho) = 1.$$

Features of Quantum Mechanics

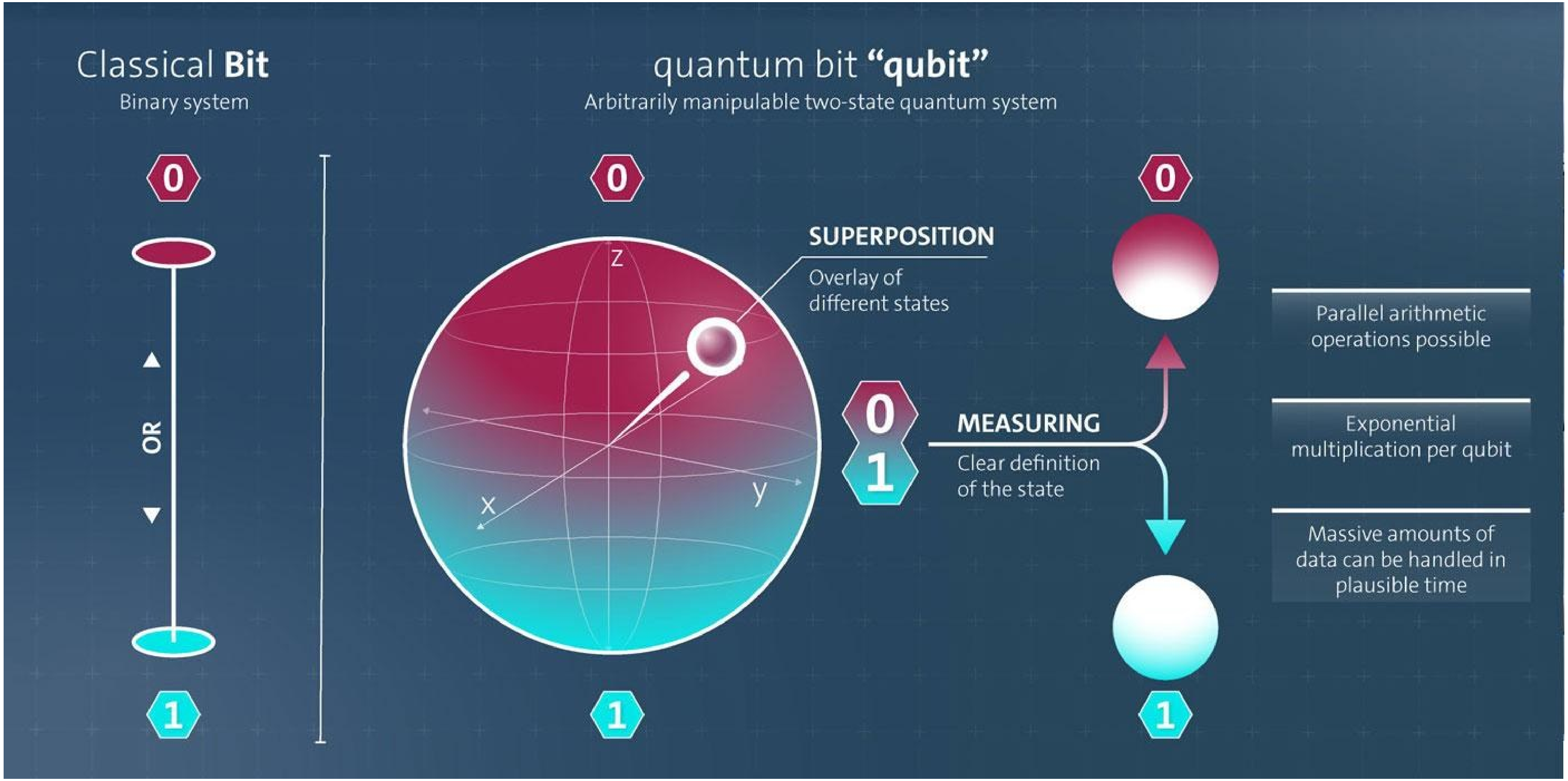


Image from Volkswagen

Quantum State

- For a quantum state: a set of conserved quantum numbers $(m, \vec{S}, \vec{p}, t, \text{charges})$
- Observables represented by operators A

	Pure State		Mixed State
	Wave function (Schrodinger)	**Density Matrix** (Heisengerg)	
Superposition	$\vert\Psi\rangle = \sum_n \alpha_n \vert\phi_n\rangle$	$\rho = \vert\Psi\rangle\langle\Psi\vert$	$\rho = \sum_i p_i \vert\Psi_i\rangle\langle\Psi_i\vert,\ \sum_i p_i = 1,\ p_i \geq 0$
Normalization	$\langle\Psi\vert\Psi\rangle = \sum_n \vert\alpha_n\vert^2 = 1$	$\mathrm{Tr}[\rho] = 1$	
Measurement	$\langle A\rangle = \langle\Psi\vert A\vert\Psi\rangle$	$\langle A\rangle = \mathrm{Tr}[\rho A]$	
Purity		$\mathrm{Tr}[\rho^2] = 1$	$\mathrm{Tr}[\rho^2] < 1$

- Density matrix: a state an observable

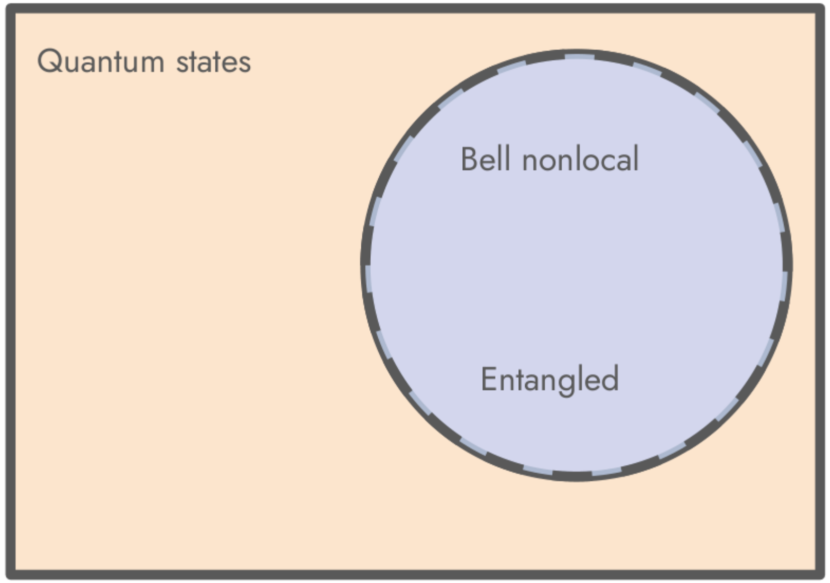
$$\rho = \sum_i n_i |\psi_i\rangle\langle\psi_i| \qquad \langle A\rangle = \mathrm{Tr}[\rho A]$$

Quantum State

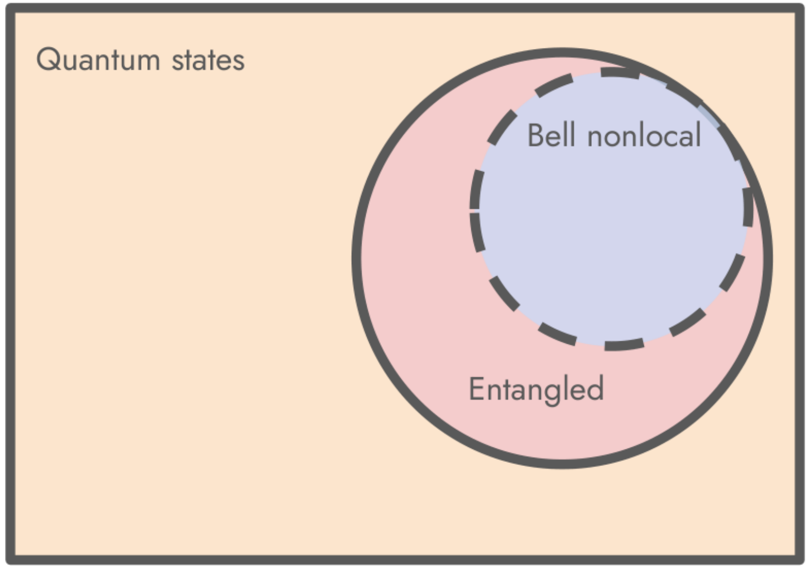
- For **pure** states, Bell's inequality and entanglement distinguish the same states
  wavefunction $|\psi\rangle$

- For **mixed** states, there are more entangled states than Bell nonlocal
  density matrix ρ

pure $|\psi\rangle$



mixed ρ



Quantum State

Quantum state

pure state $\xrightarrow{100\% \, |\psi\rangle}$ observable $\boxed{\mathcal{O}}$

$$\langle \mathcal{O} \rangle = \langle \psi | \mathcal{O} | \psi \rangle = \mathrm{Tr}(\mathcal{O} \cdot \rho)$$

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

mix state $\xrightarrow{70\% \, |\psi_1\rangle, \;\; 30\% \, |\psi_2\rangle}$ observable $\boxed{\mathcal{O}}$

$$\langle \mathcal{O} \rangle = \mathrm{Tr}(\mathcal{O} \cdot \rho)$$

$$\rho = 70\% |\psi_1\rangle\langle\psi_1| + 30\% |\psi_2\rangle\langle\psi_2|$$

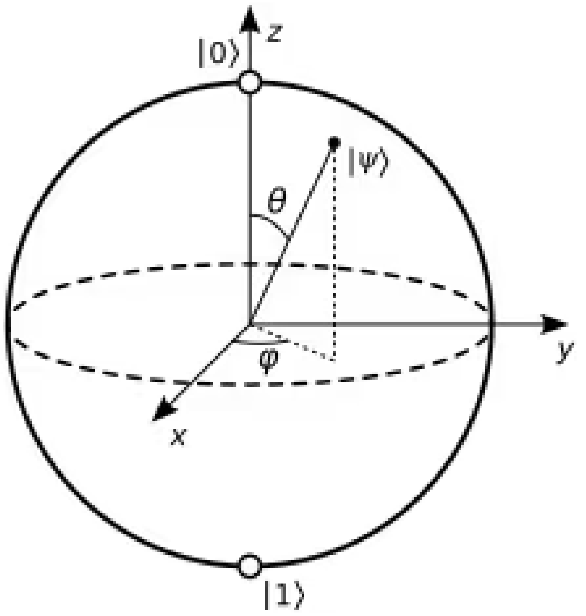
Single Qubit

- For a **single qubit** $|\psi\rangle$ (i.e., a doublet of spin, iso-spin etc.) describes two-level state $|\uparrow\rangle, |\downarrow\rangle$ or $|1\rangle, |0\rangle$ in terms of **Bloch vector B_i** :

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

Qubit described by 3 parameters use Pauli decomposition

$$\rho = \frac{1}{2}(\mathbb{I}_2 + \sum_i B_i\sigma_i)$$



- Observables represented by operators **A**

- **Measurement** of given by $a = \langle\psi|A|\psi\rangle$

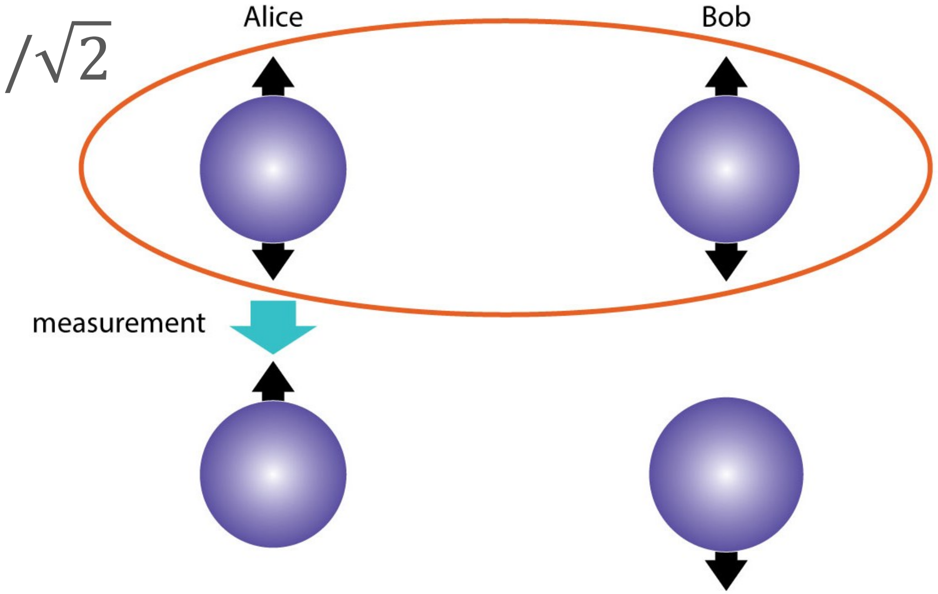
Bipartite Systems

Given a bipartite system, with Hilbert space $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$

- If state **separable** $|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$ $\Longrightarrow$ **No Entanglement**

- **Bell State**: **maximally entangled** states (spin 1/2)

$|\Phi^{\pm}\rangle = (|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle)/\sqrt{2}$ and $|\Psi^{-}\rangle = (|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle)/\sqrt{2}$



- In the case of a statistical ensemble (mixed state)

$$\rho = \sum_k p_k \rho_k$$ entangled if $\rho_k \neq \rho_1 \otimes \rho_2$

Measurement in one subsystem immediately affect the other, even if they are causally disconnected

Bipartite Systems

Entanglement

Can only describe sub-system A with knowledge of sub-system B

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Separable state

E.g., can be written as $|\psi\rangle = |\psi_A\rangle \otimes |\psi_B\rangle$

$$|\psi\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle + |11\rangle\right)$$

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \qquad |\psi_1\rangle = |\psi_2\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Separable

Non-Separable

Concurrence

- Given quantum density matrix ρ the **concurrence C** measures **entanglement**

  2-qubits system measured at a collider using $\mathcal{C}(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$

$$\mathcal{C} = \begin{cases} \dfrac{-\mathrm{Tr}(C) - 1}{2}, & \text{(spin singlet)} \\ \max_i \left[\dfrac{\mathrm{Tr}(C) - 2C_{ii} - 1}{2}\right], & \text{(spin triplet)} \end{cases}$$

λ_i are eigenvalues of $\sqrt{\sqrt{\rho}\,(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)\sqrt{\rho}}$

$\mathcal{C} = 0$	separable
$0 < \mathcal{C} \leq 1$	entangled

- Experimentally it is preferred to do this using **1 measurement** rather than 3

$$D = -\frac{1+\mathcal{C}}{3} \qquad \frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

$D = -\frac{1}{3}$	separable
$-\frac{2}{3} \leq D < -\frac{1}{3}$	entangled

Concurrence

- Given quantum density matrix ρ the **concurrence C** measures **entanglement**

2-qubits system measured at a collider using $\mathcal{C}(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$

$$\mathcal{C} = \begin{cases} \dfrac{-\operatorname{Tr}(C) - 1}{2}, & \text{(spin singlet)} \\ \max_i \left[\dfrac{\operatorname{Tr}(C) - 2C_{ii} - 1}{2}\right], & \text{(spin triplet)} \end{cases}$$

λ_i are eigenvalues of $\sqrt{\sqrt{\rho}\,(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)\sqrt{\rho}}$

$\mathcal{C} = 0$	separable
$0 < \mathcal{C} \leq 1$	entangled

How to tell a state is entangled or separable?

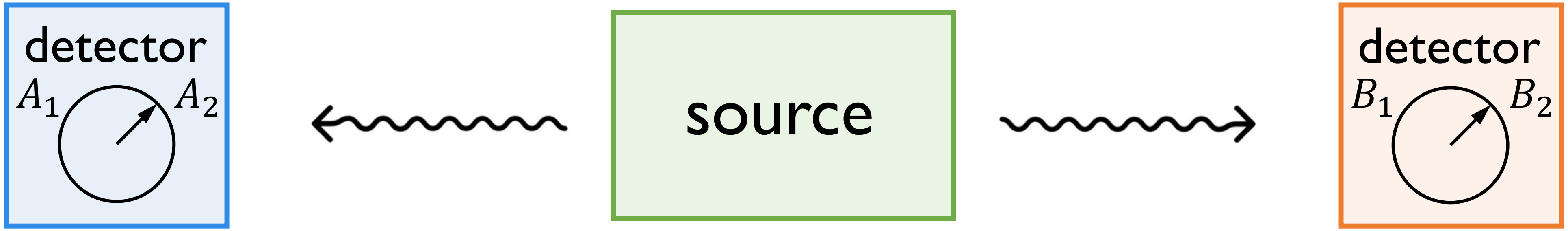
E.g. pure state $\mathcal{C}(\psi) = \sqrt{2(1 - \operatorname{Tr}(\psi_A^2))}$ $\psi_A = \operatorname{Tr}_B(\psi)$

E.g. mixed state $\mathcal{C}(\rho) = \min_{|\psi_i\rangle} \sum_i p_i \, \mathcal{C}(\psi_i)$ $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$

over all possible decompositions

Bell Nonlocality

- Another measure of quantumness is **Bell Nonlocality**



$$\langle A_1 B_1 \rangle - \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle \leq 2$$

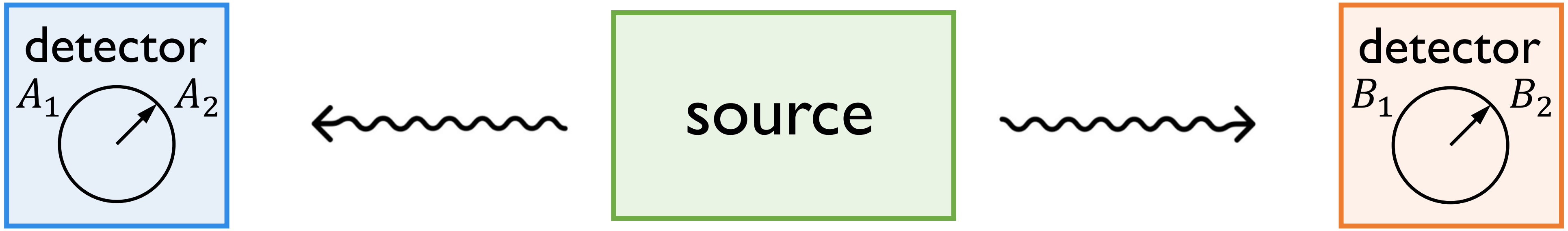
E.g., choosing

$$A_1 = \sigma_1, \quad A_2 = \sigma_3, \quad B_1 = \pm\frac{1}{\sqrt{2}}(\sigma_1 + \sigma_3), \quad B_2 = \pm\frac{1}{\sqrt{2}}(-\sigma_1 + \sigma_3)$$

$$\Rightarrow \quad \langle A_1 B_1 \rangle = \mathrm{Tr}\left(\left(\sigma_1 \otimes \frac{\pm 1}{\sqrt{2}}(\sigma_1 + \sigma_3)\right) \cdot \rho\right) = \pm\frac{1}{\sqrt{2}}(C_{11} + C_{13})$$

Bell Nonlocality

- Another measure of quantumness is **Bell Nonlocality**



$$\langle A_1 B_1 \rangle - \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle \leq 2$$

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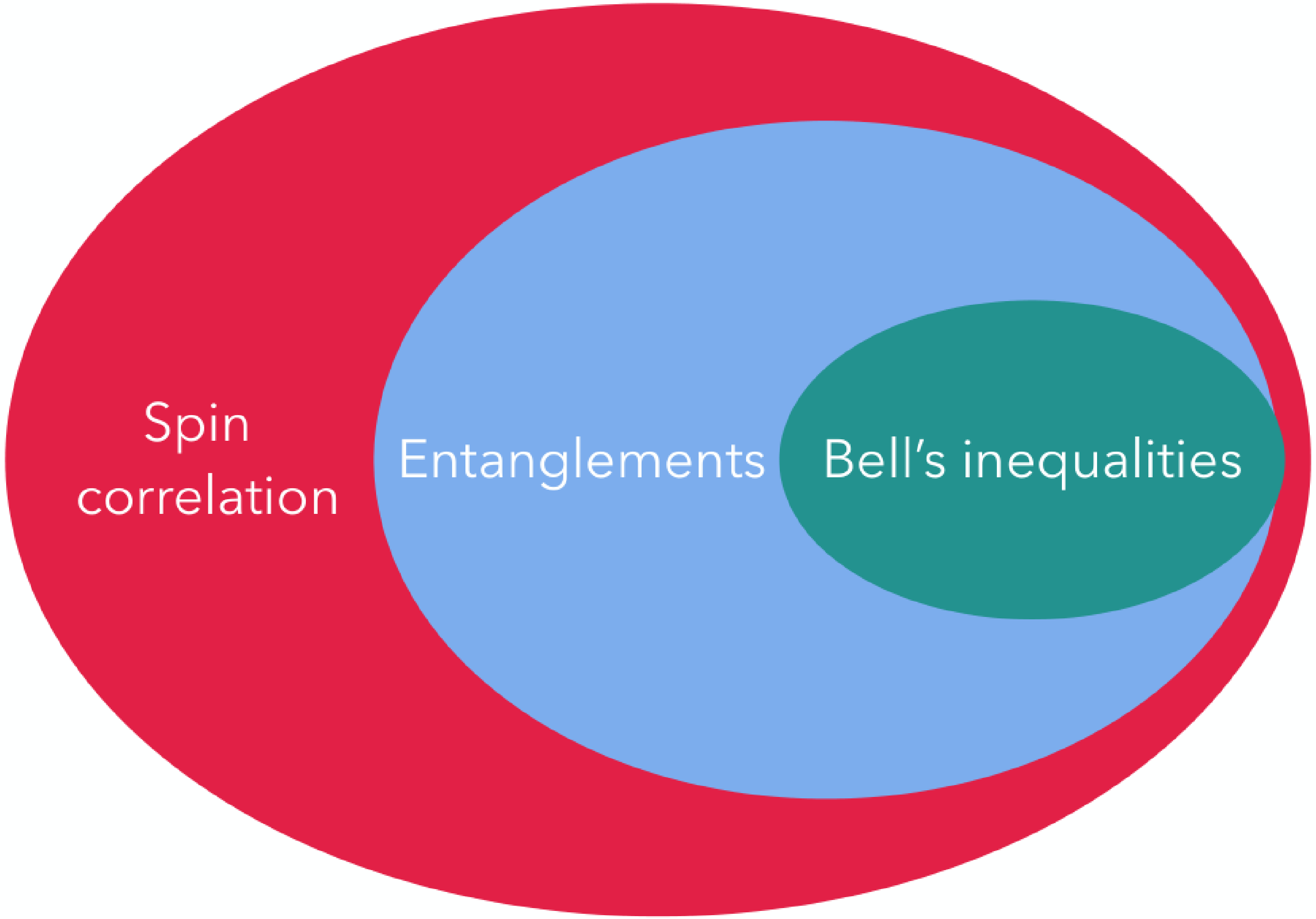
$\Rightarrow \quad |C_{11} \pm C_{33}| \leq \sqrt{2}$ The violation of Bell's inequality corresponds to $\mathcal{B} > 2$

Quantum Correlations



Quantum Magic

What separates "Quantum" from "Classical"?

- Much of the hype on Quantum advantage in quantum computing is based on identifying quantum resources, such as the entanglement.
- However, not all quantum resources provide computational advantages over classical algorithms.
- Some quantum circuits, even with entangled states, can still be efficiently simulated classically.
- A second layer of "**quantumness**" is needed to for quantum speedup – the **magic** (non-stablizerness).

Bravyi and Kitaev, quant-ph/0403025

Quantum Magic

- **Stabilizer states** that can be efficiently simulated by a classical computer.
  - Entanglement is not enough to guarantee the advantage of quantum computing
  - Bell states have C = 1 but $M_2 = 0$!
- **Magic states**: A second layer of "**quantumness**" where quantum computing has advantages

$$\mathcal{M}_2 = -\log_2 \frac{1+\sum_i (B_i^+)^4 + \sum_j (B_j^-)^4 + \sum_{ij} (C_{ij})^4}{1+\sum_i (B_i^+)^2 + \sum_j (B_j^-)^2 + \sum_{ij} (C_{ij})^2}.$$

Stabilizer state $\mathcal{M}_2 = 0$

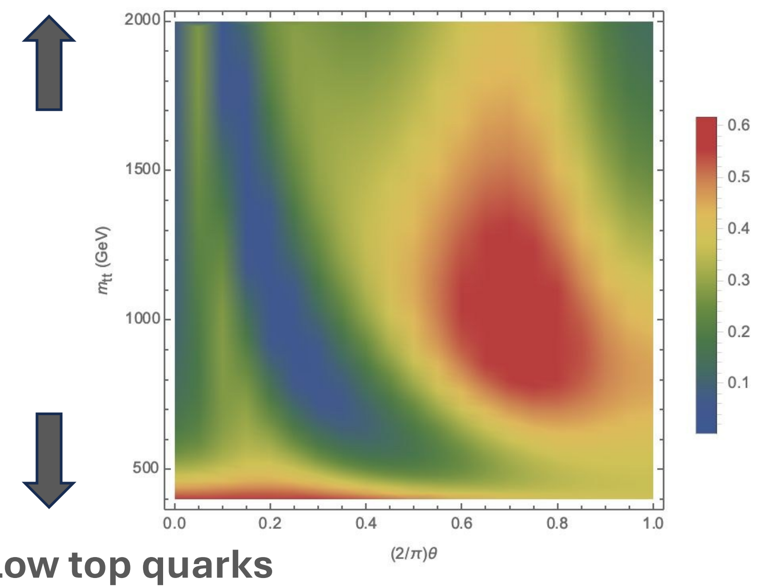
Magic state $0 < \mathcal{M}_2 \leq \log_2 \frac{16}{7} \approx 1.192$ Liu, Low, and Yin, 2502.17550

Quantum Magic

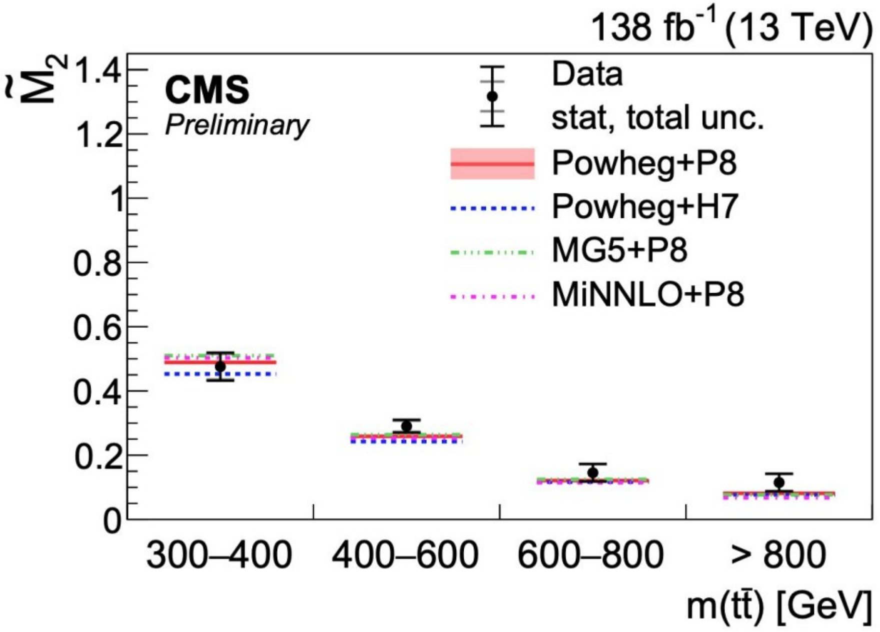
Quantum Magic

- The **top-antitop** state has measurable magic — White, White. 2406.07321
- Measurements of magic for $t\bar{t}$ have been made by **CMS** — CMS. CMS-PAS-TOP-25-001
- Discussion about how to understand magic: "The SM tends to **minimize magic**" — Liu, Low, Yin. 2509.18251

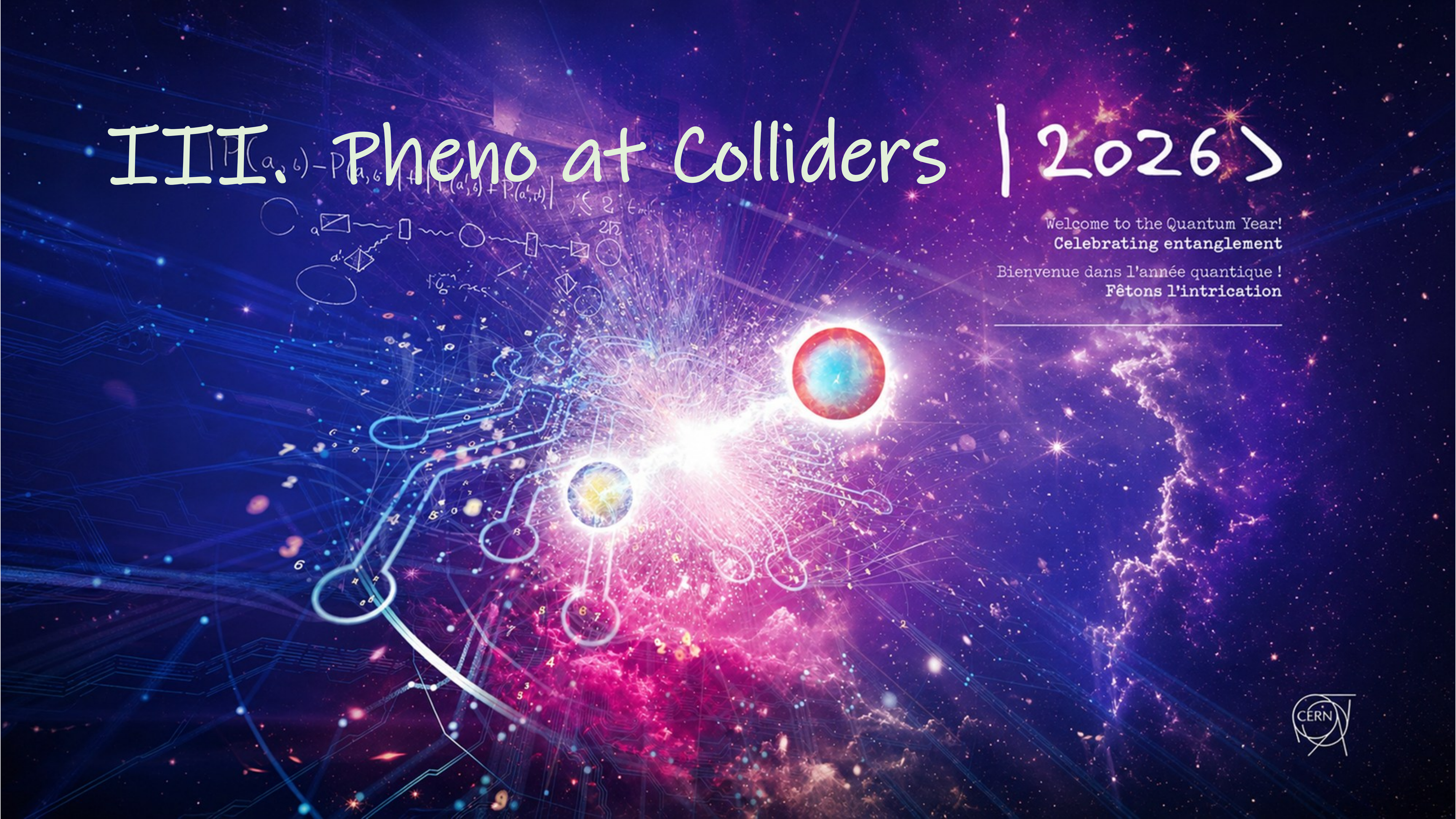
Fast top quarks



Slow top quarks



III. Pheno at Colliders



Colliders as a Quantum Mechanical System

- Low-energy experiments

Alice $\xleftarrow{\gamma}$ source $\xrightarrow{\gamma}$ Bob

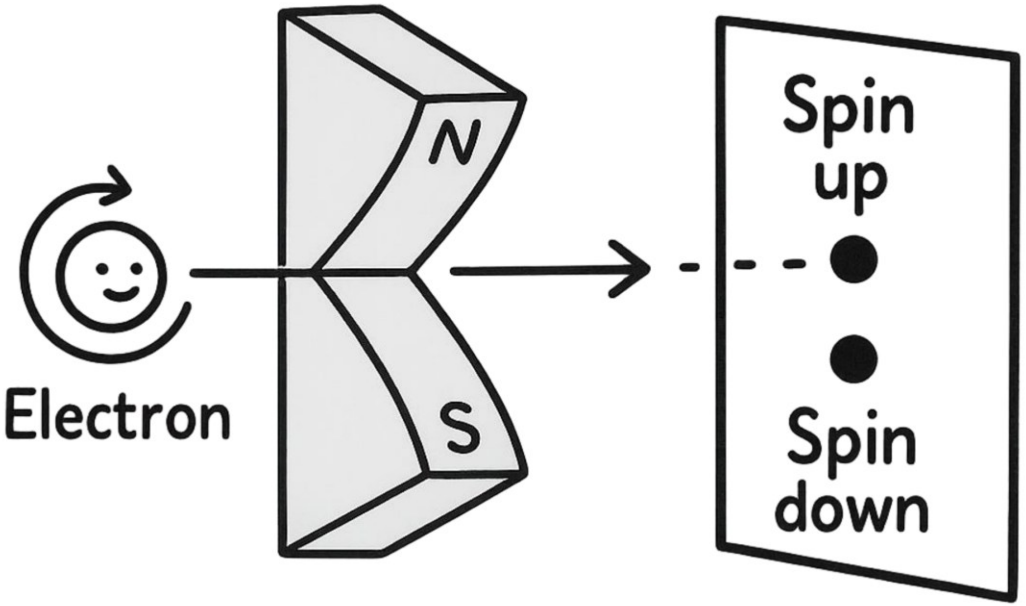
We use spin correlations as a diagnostic tool to reveal underlying quantum correlations, notably entanglement.

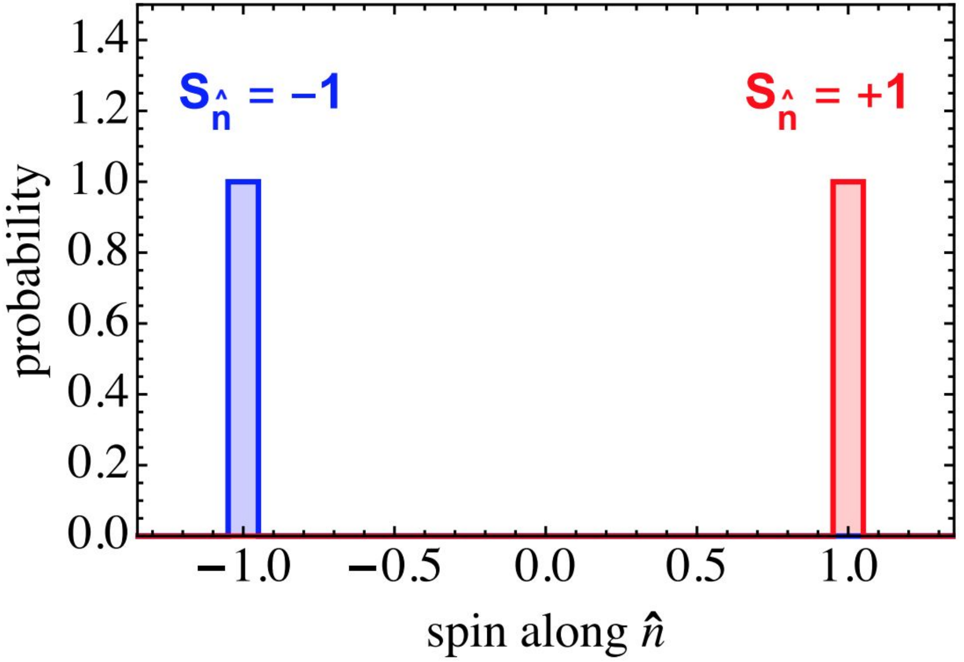
- Collider experiments

 $\xleftarrow{t}$ collision $\xrightarrow{\bar{t}}$ 

Colliders as a Quantum Mechanical System

- How to measure the **spin** of a particle?



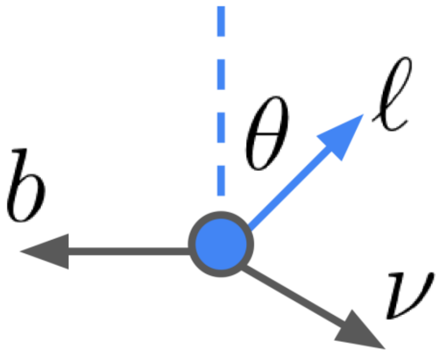


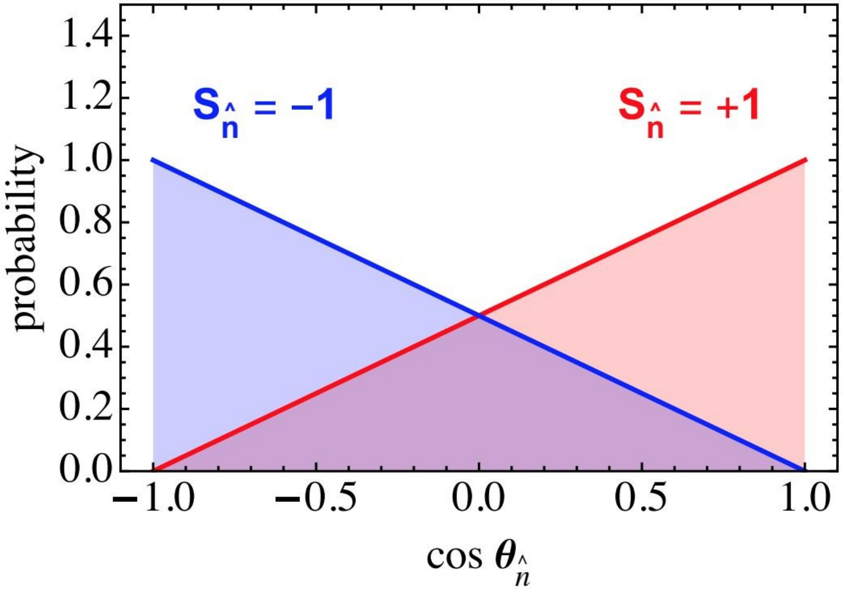
- Each spin bends differently in the **magnetic field**
- In each **event**, the spin is known

Colliders as a Quantum Mechanical System

- How to measure the **spin** of a particle?
  - At high-energy colliders, particles decay

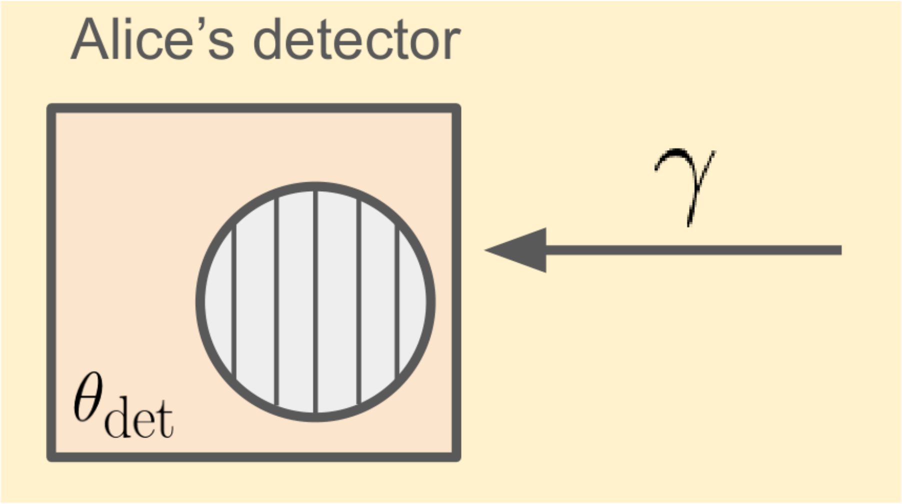
$$t \to \ell \nu b$$

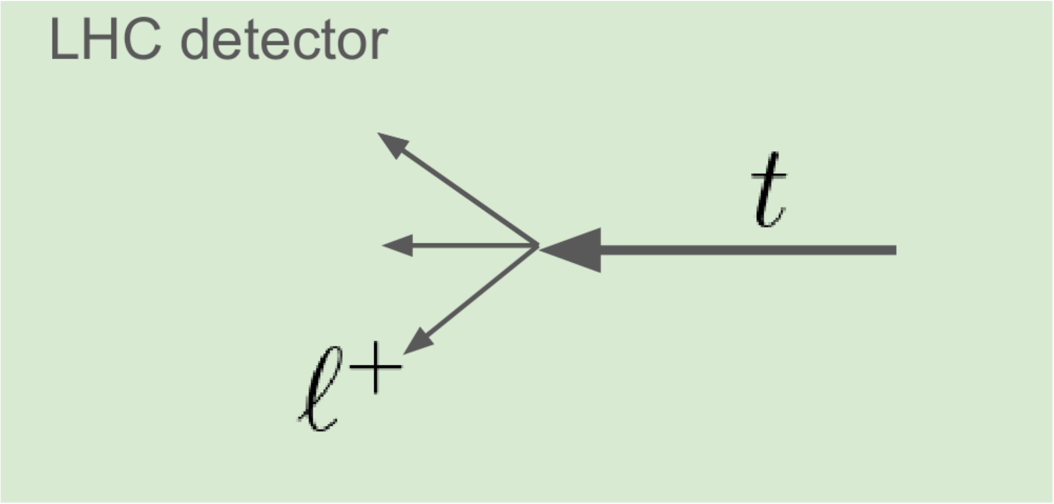


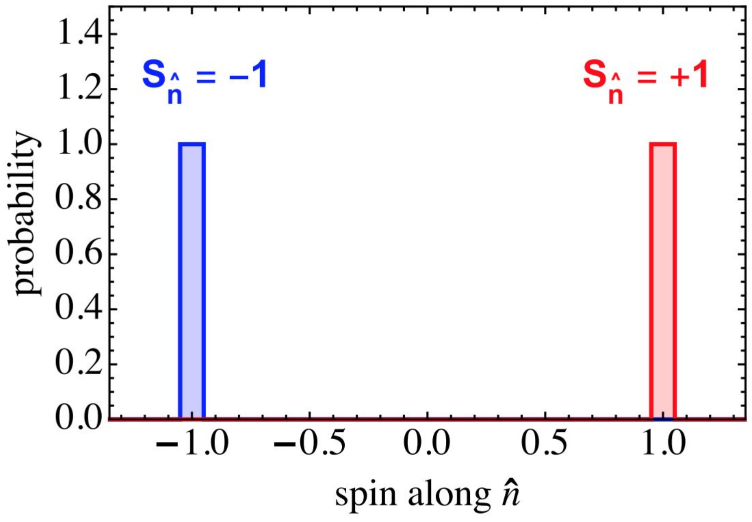


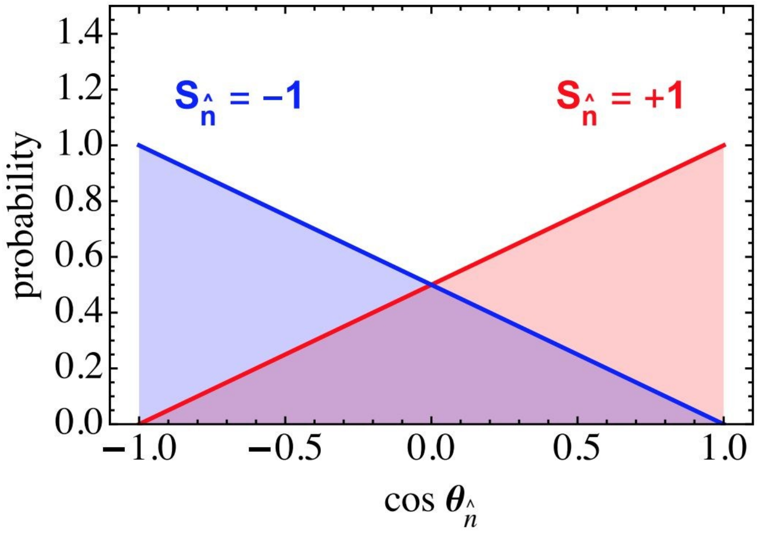
  - Decay products have **preferred direction**
  - Only the **distribution** is known

Colliders as a Quantum Mechanical System









Quantum Tomography for Qubits

- For **two qubits**, use **Fano-Bloch decomposition** a bipartite system described by

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i \underbrace{B_i^+ \sigma_i \otimes \mathbb{I}_2}_{} + \sum_j \underbrace{B_j^- \mathbb{I}_2 \otimes \sigma_j}_{} + \sum_{ij} \underbrace{C_{ij} \sigma_i \otimes \sigma_j}_{}\right)$$

Polarization vector

$$\mathrm{B}_i = \langle \mathrm{B}_i \rangle = \mathrm{Tr}(\sigma_i \cdot \rho)$$

Spin correlation matrix

$$C_{ij} = \langle \mathrm{B}_i \mathrm{B}_j \rangle = \mathrm{Tr}\Big((\sigma_i \otimes \sigma_j) \cdot \rho\Big)$$

- two spin $\frac{1}{2}$ particles: $|00\rangle, |01\rangle, |10\rangle, |11\rangle$

E.g.

$$\rho = \begin{pmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & \frac{1}{2} \end{pmatrix} \Longleftrightarrow B_i = B_j = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad C_{ij} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Quantum Tomography for Qubits

- For **two qubits**, use **Fano-Bloch decomposition** a bipartite system described by

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i \underline{B_i^+ \sigma_i \otimes \mathbb{I}_2} + \sum_j \underline{B_j^- \mathbb{I}_2 \otimes \sigma_j} + \sum_{ij} \underline{C_{ij} \sigma_i \otimes \sigma_j}\right)$$

B_i^+	**Qubit 1 polarization** (3 parameters)
B_j^-	**Qubit 2 polarization** (3 parameters)
C_{ij}	**Spin correlations** (9 parameters)

The **15** coefficients for the bipartite → **Quantum Tomography**

which encodes the full quantum information.

Straightforward to generalize to qutrits, qudits …

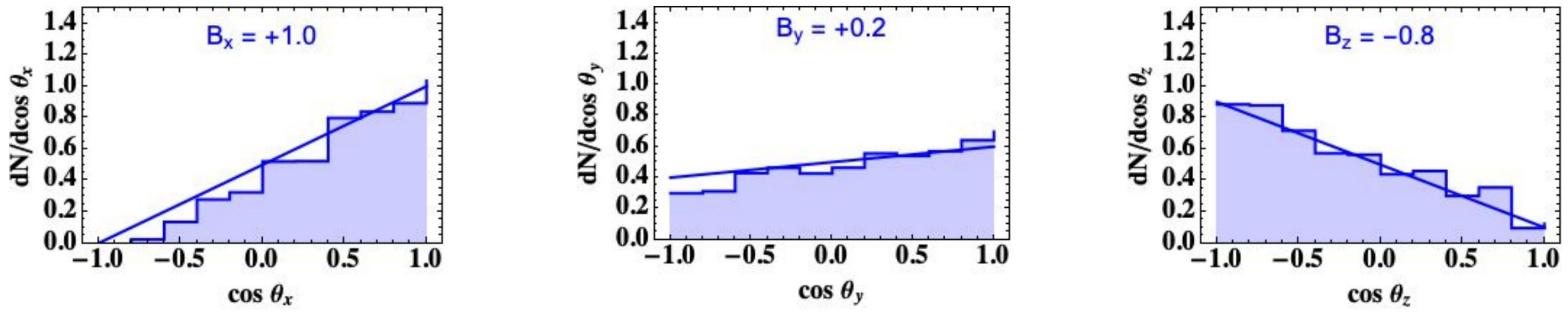
Quantum Tomography for Qubits

- Can perform **quantum tomography** through **angular distribution** measurements

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i \underline{B_i^+ \sigma_i \otimes \mathbb{I}_2} + \sum_j \underline{B_j^- \mathbb{I}_2 \otimes \sigma_j} + \sum_{ij} \underline{C_{ij}\sigma_i \otimes \sigma_j}\right)$$

B_i^+ **Qubit 1 polarization** (3 parameters)

- **Extract** density matrix parameters from data



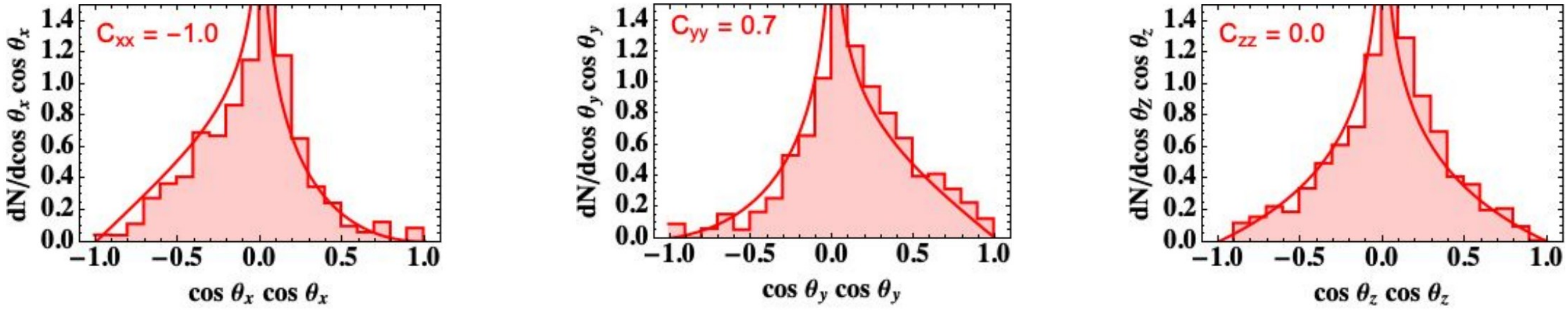
Quantum Tomography for Qubits

- Can perform **quantum tomography** through **angular distribution** measurements

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

C_{ij} **Spin correlations** (9 parameters)

- **Extract** density matrix parameters from data



Fictitious state

- Paradox?
  - ✓ Quantum states are spin basis-independent
  - ✓ Spin correlations are spin basis-dependent
- We are not using genuine quantum states, we are using ``fictitious states”
  - ✓ Basis-dependent state
  - ✓ State reconstructed from averaged quantities
  - ✓ Convex sum of quantum sub-states, but with coefficients due to rotations

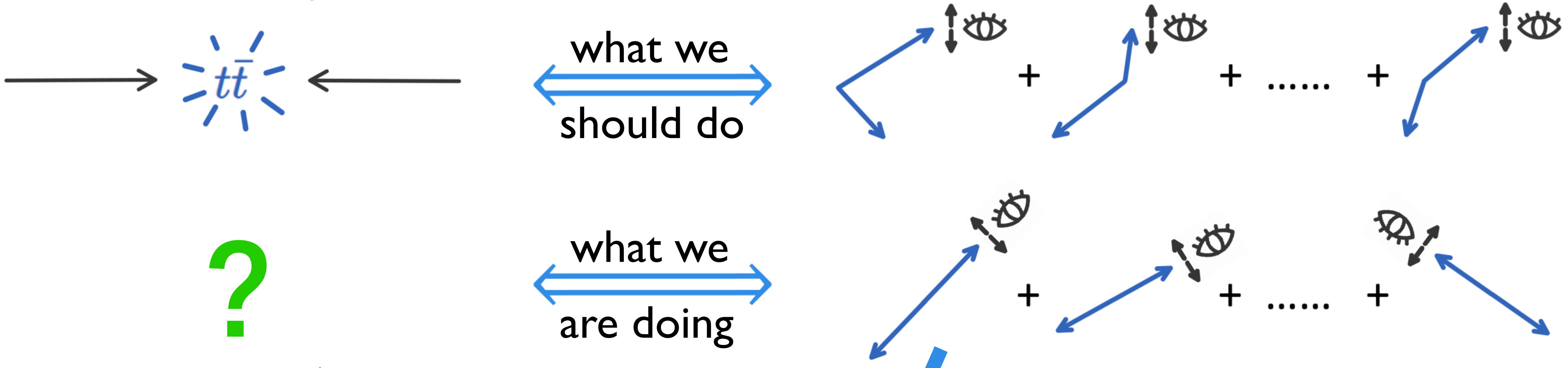
Quantum state $$\rho_Q = \sum_a \rho_a$$

Fictitious state $$\rho_{\text{fic}} = \sum_a c_a \rho_a \qquad c_a = \mathrm{tr}(\sigma_{i,a} \otimes \sigma_{j,a} \cdot \sigma_i \otimes \sigma_j)$$

Fictitious state

$$\rho = \ldots\ldots + \sum_{i,j} C_{ij}(\sigma_i \otimes \sigma_j)$$

$$C_{ij} = \langle S_i^t S_j^{\bar{t}} \rangle$$



$$C_{\bar{i}\bar{j}} = \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix} + \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix} + \ldots\ldots + \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix}$$

$$\bar{\rho} = \ldots\ldots + \sum_{\bar{i},\bar{j}} C_{\bar{i}\bar{j}}(\sigma_{\bar{i}} \otimes \sigma_{\bar{j}})$$

Fictitious state

physical

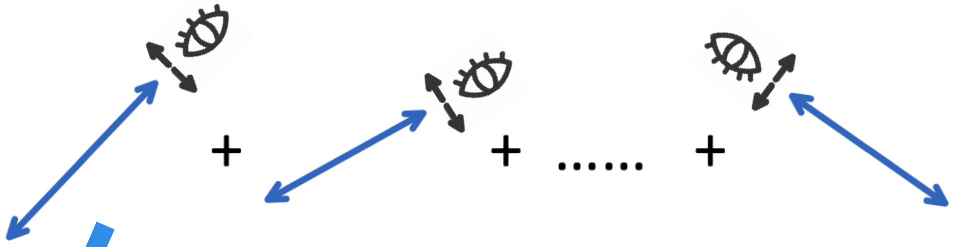
$$\rho = \ldots\ldots + \sum_{i,j} C_{ij}(\sigma_i \otimes \sigma_j)$$

$$C_{ij} = \langle S_i^t S_j^{\bar{t}} \rangle$$

what we
should do

?

what we
are doing



$$C_{\bar{i}\bar{j}} = \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix} + \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix} + \ldots\ldots + \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix}$$

fictitious

$$\bar{\rho} = \ldots\ldots + \sum_{\bar{i},\bar{j}} C_{\bar{i}\bar{j}}(\sigma_{\bar{i}} \otimes \sigma_{\bar{j}})$$

Fictitious state

$$\mathcal{C}(\rho_{\text{fictitious}}) > 0 \quad \Rightarrow \quad \mathcal{C}(\rho_{\text{sub}} \in \rho) > 0$$

$$\text{Bell}(\rho_{\text{fictitious}}) > \sqrt{2} \quad \Rightarrow \quad \text{Bell}(\rho_{\text{sub}} \in \rho) > \sqrt{2}$$

mathematically useful

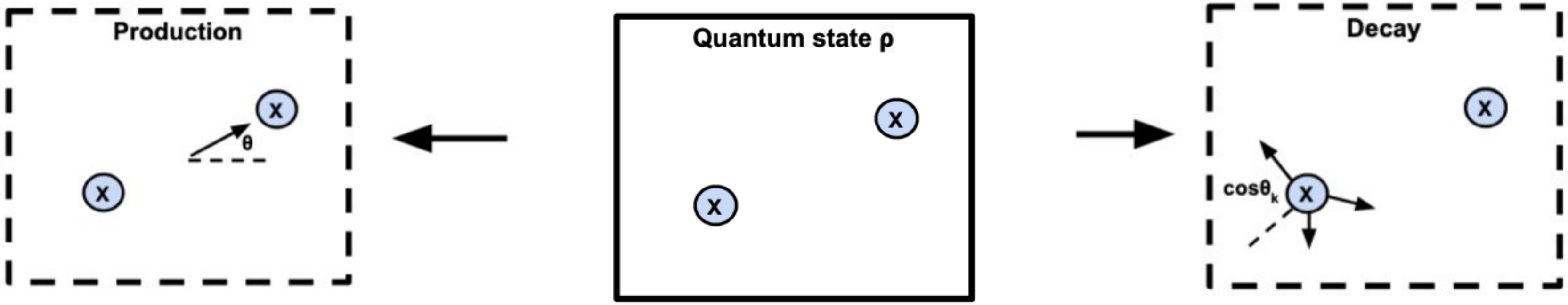
conceptually different

Note: Physics is **described** by an underlying quantum state, we **reconstruct** the fictitious state

Quantum Tomography @ Colliders

Two paths to proceed to quantum tomography

$$\rho = \frac{1}{4}\left(\mathbb{I}_2 \otimes \mathbb{I}_2 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_i + \sum_{ij} C_{ij}\sigma_i \otimes \sigma_j\right)$$



Kinematic Approach

Cheng, Han, Low 2410.08383

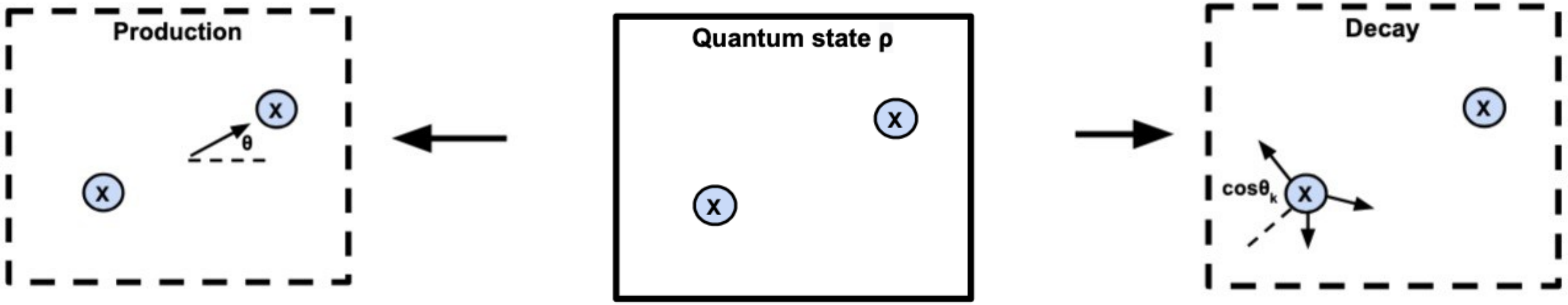
- Theory input on the production
- Spin is related with scattering kinematic
- Initial states and scattering angle **θ**, speed of particle **β**
- Useful for stable particles

Historically, the determination of the quark spin in $e^-e^+ \to q\bar{q}$ and the gluon spin in 3-jet events $e^-e^+ \to q\bar{q}g$ are inferred from **kinematic** distributions.

Quantum Tomography @ Colliders

Two paths to proceed to quantum tomography

$$\rho = \frac{1}{4}\left(\mathbb{I}_2 \otimes \mathbb{I}_2 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_i + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$



Kinematic Approach

Cheng, Han, Low 2410.08383

- Theory input on the production
- Spin is related with scattering kinematic
- Initial states and scattering angle **θ**, speed of particle **β**
- Useful for stable particles

Decay Approach

Afik, de Nova. 2003.02280

- Theory input on the decay
- Spin is related with decay distribution
- Angles in rest frames of decay products
- Useful for particles with tracked decay products

Both inherit the corresponding quantum information:

Interaction @ production ⟵ Theory ⟶ Interaction @ decays

Kinematic Approach

Cross section

$$\sigma(pp \to t\bar{t}) = \int \mathrm{d}\Pi \overline{\sum_{\text{initial}}} \sum_{ab,\bar{a}\bar{b}} \mathcal{M}(XY \to t_a \bar{t}_{\bar{a}})\, \mathcal{M}^*(XY \to t_b \bar{t}_{\bar{b}})$$

- Average over initial spin, color, ...
- Sum over final spin, color, ...

Production density matrix

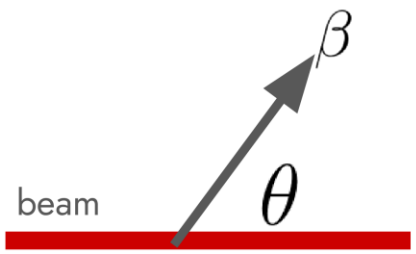
$$\rho_{ab,\bar{a}\bar{b}} \propto R_{ab,\bar{a}\bar{b}} = \int \mathrm{d}\Pi \overline{\sum_{\text{initial}}} \mathcal{M}(XY \to t_a \bar{t}_{\bar{a}})\, \mathcal{M}^*(XY \to t_b \bar{t}_{\bar{b}})$$

- Leave final spins unsummed

Kinematic Approach

Cheng, Han, Matthew. 2410.08303

- Parametrize density matrix as $\rho(\theta, \beta)$



- Process-specific components of the density matrix

For example: $q\bar{q} \to t\bar{t}$

$$C_{ij} = \frac{1}{2-\beta^2\sin^2\theta}\begin{pmatrix} (2-\beta^2)\sin^2\theta & 0 & \sqrt{1-\beta^2}\sin(2\theta) \\ 0 & -\beta^2\sin^2\theta & 0 \\ \sqrt{1-\beta^2}\sin(2\theta) & 0 & \beta^2+(2-\beta^2)\cos^2\theta \end{pmatrix}_{ij} .$$

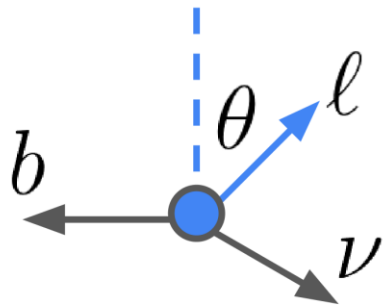
- From θ and β distributions

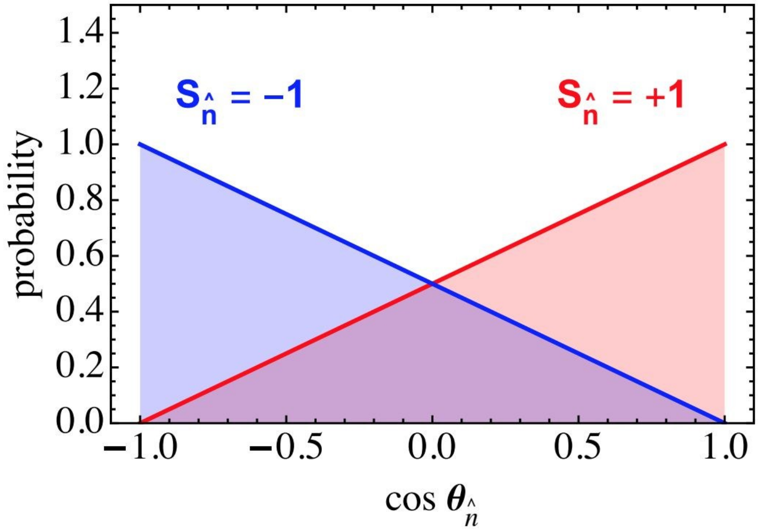
$$C_{11} = \langle \frac{(2-\beta^2)\sin^2\theta}{2-\beta^2\sin^2\theta} \rangle \qquad C_{12} = 0$$

Tips: Entries that are predicted to be zero are often used in practice

Decay Approach

- How to **measure** the **spin** of the top?





$$\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + B\kappa\cos\theta)$$

Θ = **angle** to one of the decay products

B = **polarization** of sample

κ = **spin analyzing power**

κ=-1	κ=0	κ=+1
Fully anti-correlated	Uncorrelated	Fully correlated

- Full set of spin correlations **reconstructs** the quantum density matrix

Decay Approach

$\rho_{ab,\bar{a}\bar{b}}$ can be extracted from the angular distribution of decay product

$$d\sigma(XY \to AB \to decay) \sim \Gamma^A R^{AB} \Gamma^B$$

In the decay of a top, consider one particle – **the spin analyzer** – and take the **angle** between its momentum and a reference axis (in the mother A,B rest frame)

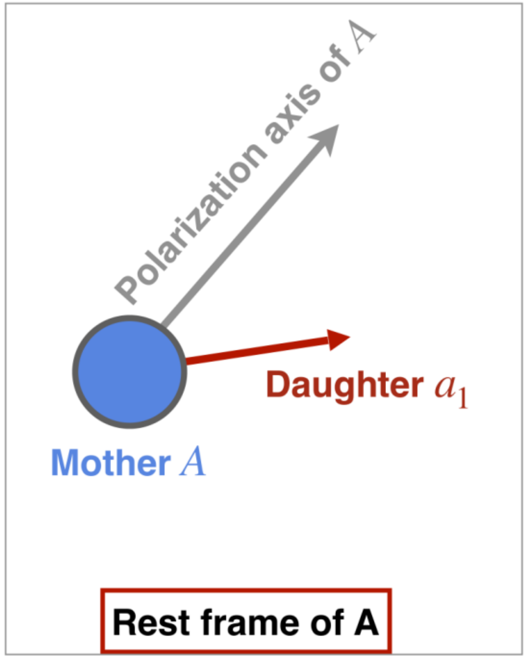
κ is **spin analyzing power**

$$\tilde{\Gamma}(\Omega) \propto I + \kappa\, \Omega_i \sigma_i.$$

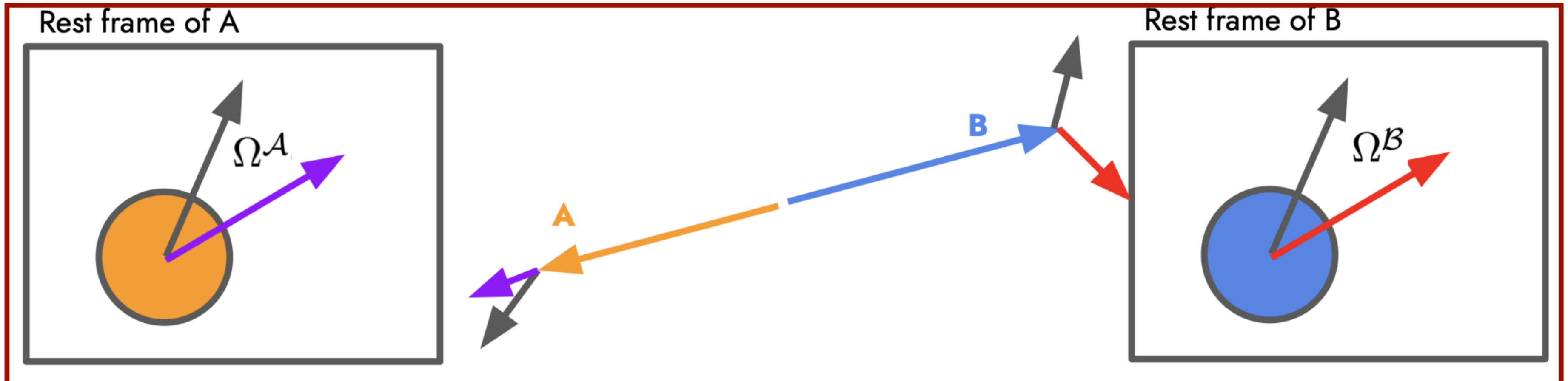
Spin Analyzer	Power
lepton/down-quark	1.00
neutrino/up-quark	-0.34
b-quark or W	$\mp$0.40
soft-quark	0.50
optimal hadronic	0.64

Brock Tweedie 1401.3021

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{A,i}} = \frac{1}{2}\left(1 + \kappa_A B_i^+ \cos\theta_{A,i}\right),$$
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{B,j}} = \frac{1}{2}\left(1 + \kappa_B B_j^- \cos\theta_{B,j}\right),$$



Decay Approach



$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}^2\Omega^{\mathcal{A}}\mathrm{d}^2\Omega^{\mathcal{B}}}=\frac{1}{(4\pi)^2}\left(1+\sum_i\left(\kappa^{\mathcal{A}}B_i^{\mathcal{A}}\Omega_i^{\mathcal{A}}+\kappa^{\mathcal{B}}B_i^{\mathcal{B}}\Omega_i^{\mathcal{B}}\right)+\sum_{i,j}\kappa^{\mathcal{A}}\kappa^{\mathcal{B}}\,\Omega_i^{\mathcal{A}}C_{ij}\Omega_j^{\mathcal{B}}\right),$$

Direction of A, B

$$\Rightarrow\quad \frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_{A,i}\,d\cos\theta_{B,j}}=\frac{1}{4}\left[1+\kappa_A B_i^-\cos\theta_{A,i}+\kappa_B B_j^+\cos\theta_{B,j}+\kappa_A\kappa_B C_{ij}\cos\theta_{A,i}\cos\theta_{B,j}\right].$$

$$\Rightarrow\quad \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}(\cos\theta_i^A\cos\theta_j^B)}=-\frac{1+\kappa^A\kappa^B C_{ij}\cos\theta_i^A\cos\theta_j^B}{2}\log\left|\cos\theta_i^A\cos\theta_j^B\right|$$

Polar angle of A with respect to the i-th axis

Decay Approach

- Parametrize density matrix as $\rho(B_i^+, B_j^-, C_{ij})$

A. Extract **components** of the density matrix

$$\langle \cos\theta \rangle = \int_{-1}^{1} d\,x\; x\; \frac{1}{2}(1+\kappa B x), \qquad x = \cos\theta\,.$$

$$\langle x \rangle = \frac{1}{2}\int_{-1}^{1} x\,(1+\kappa B x)\,dx = \frac{\kappa B}{3}, \qquad \langle xy \rangle = \frac{\kappa_A \kappa_B C_{ij}}{9}.$$

$$\boxed{B_i^- = \frac{3\langle \cos\theta_{A,i}\rangle}{\kappa_A}, \quad B_j^+ = \frac{3\langle \cos\theta_{B,j}\rangle}{\kappa_B}, \quad C_{ij} = \frac{9\langle \cos\theta_{A,i}\cos\theta_{B,j}\rangle}{\kappa_A \kappa_B}.}$$

Decay Approach

- Parametrize density matrix as $\rho(B_i^+, B_j^-, C_{ij})$

B. Positive-negative **asymmetry**

$$A(x) = \frac{N(x>0) - N(x<0)}{N(x>0) + N(x<0)}.$$

$$A(\cos\theta) = \int_0^1 \frac{1}{2}(1+\kappa Bx)dx - \int_{-1}^0 \frac{1}{2}(1+\kappa Bx)dx = \frac{\kappa B}{2},$$

$$\Downarrow$$

$$B_i^- = \frac{2}{\kappa_A} A(\cos\theta_{A,i}), \qquad B_j^+ = \frac{2}{\kappa_B} A(\cos\theta_{B,j}),$$

$$A(xy) = \frac{\kappa_A \kappa_B C_{ij}}{4},$$

$$\Downarrow$$

$$C_{ij} = \frac{4}{\kappa_A \kappa_B} A(\cos\theta_{A,i} \cos\theta_{B,j}).$$

Decay Approach

- Parametrize density matrix as $\rho(B_i^+, B_j^-, C_{ij})$

C. Fit the **angular distribution** from event-level observables

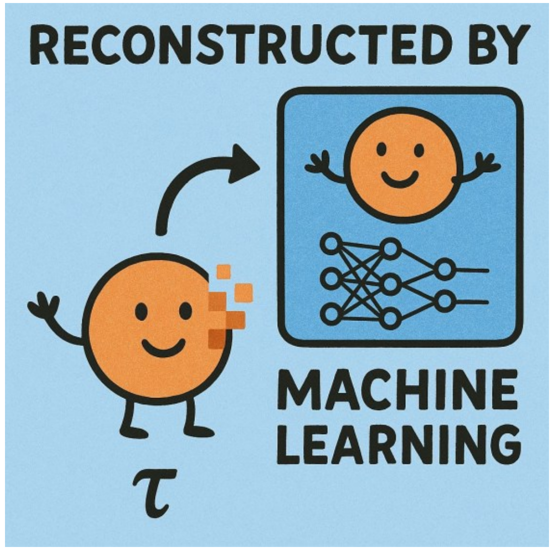
- True distribution $\xrightarrow[\text{Smearing, missing } \nu\ldots]{\textbf{Fold}}$ Detected distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1 \mathrm{d}\Omega_2} \propto \sum_{ss'\bar{s}\bar{s}'} \bar{\rho}_{ss',\bar{s}\bar{s}'} \Gamma_{ss'} \Gamma_{\bar{s}\bar{s}'}$$

$$\Gamma_{ss'} = \mathcal{M}_{t_s \to X} \mathcal{M}^*_{t_{s'} \to X}$$

Unfolding,
Templete fitting
Machine Learning
…

Experimental reconstructions

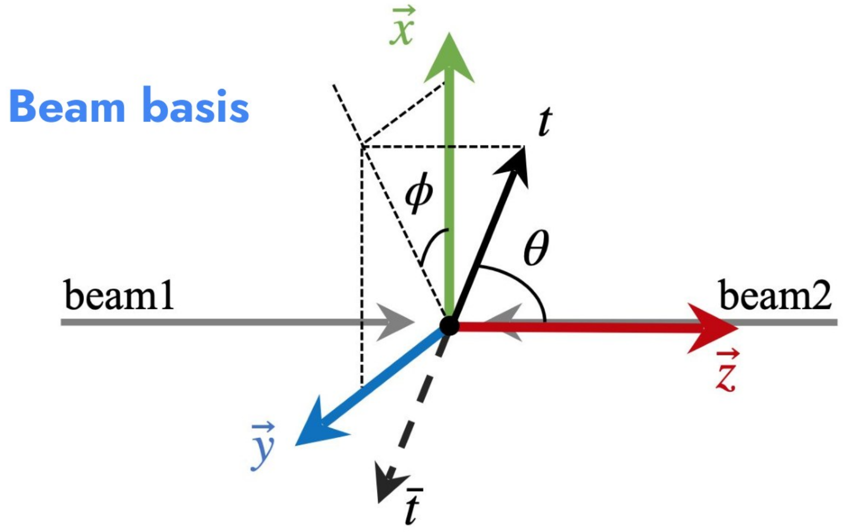


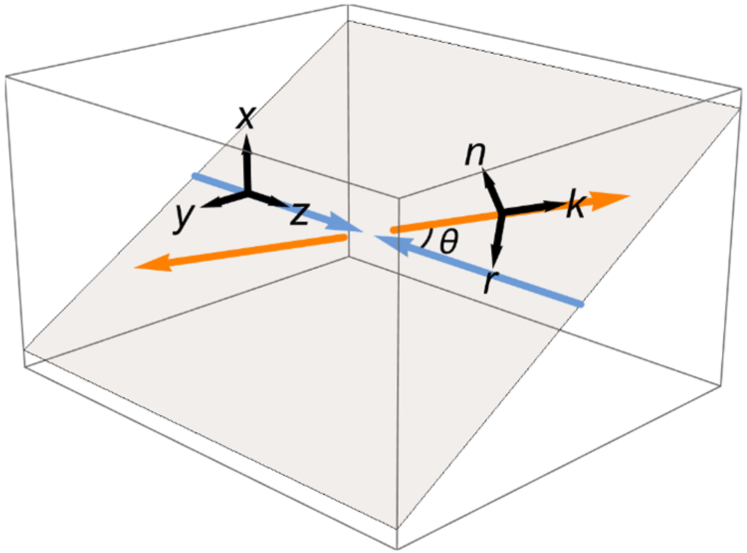
Choice of Basis

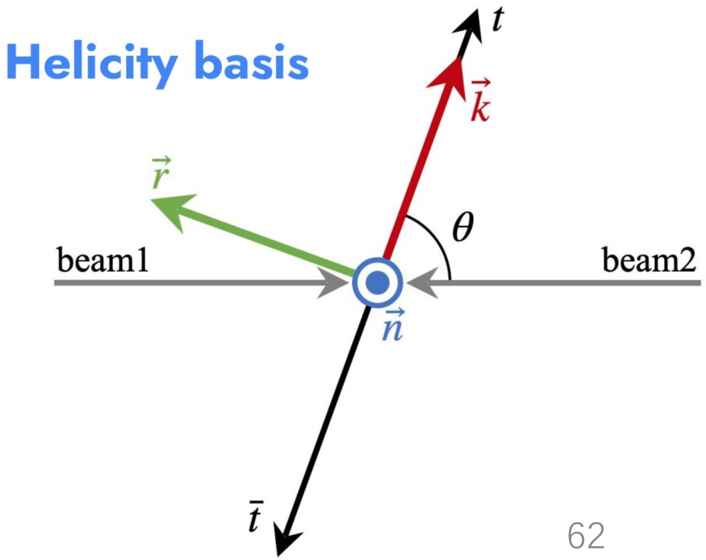
Cheng, Han, Low 2311.09166
Cheng, Fang, Han, Low 2502.14065

- Equivalent to **axes** for spin measurement
- Beam basis {x,y,z}: cancellation leads to null result
- Helicity basis {r,k,n} : entanglement with no cancellations after averaging over phase space

Chirality ≈ helicity at high energy, simplifies physical interpretation







Choice of Basis

- Example: $q\bar{q} \to t\bar{t}$
  - **Helicity Basis**

$$C_{\text{hel}} = \begin{pmatrix} 0.66 & 0 & -0.33 \\ 0 & -0.003 & 0 \\ -0.33 & 0 & 0.34 \end{pmatrix}$$

$$\lambda = \{0.87, 0.13, -0.003\}$$

  - **Beam Basis**

$$C_{\text{beam}} = \begin{pmatrix} 0.003 & 0 & 0.002 \\ 0 & -0.003 & 0 \\ 0.002 & 0 & 0.99 \end{pmatrix}$$

$$\lambda = \{0.99, 0.003, -0.003\}$$

Choice of Basis

- Quantum states do **not** depend on the spin basis

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

- Change of basis is a unitary rotation U

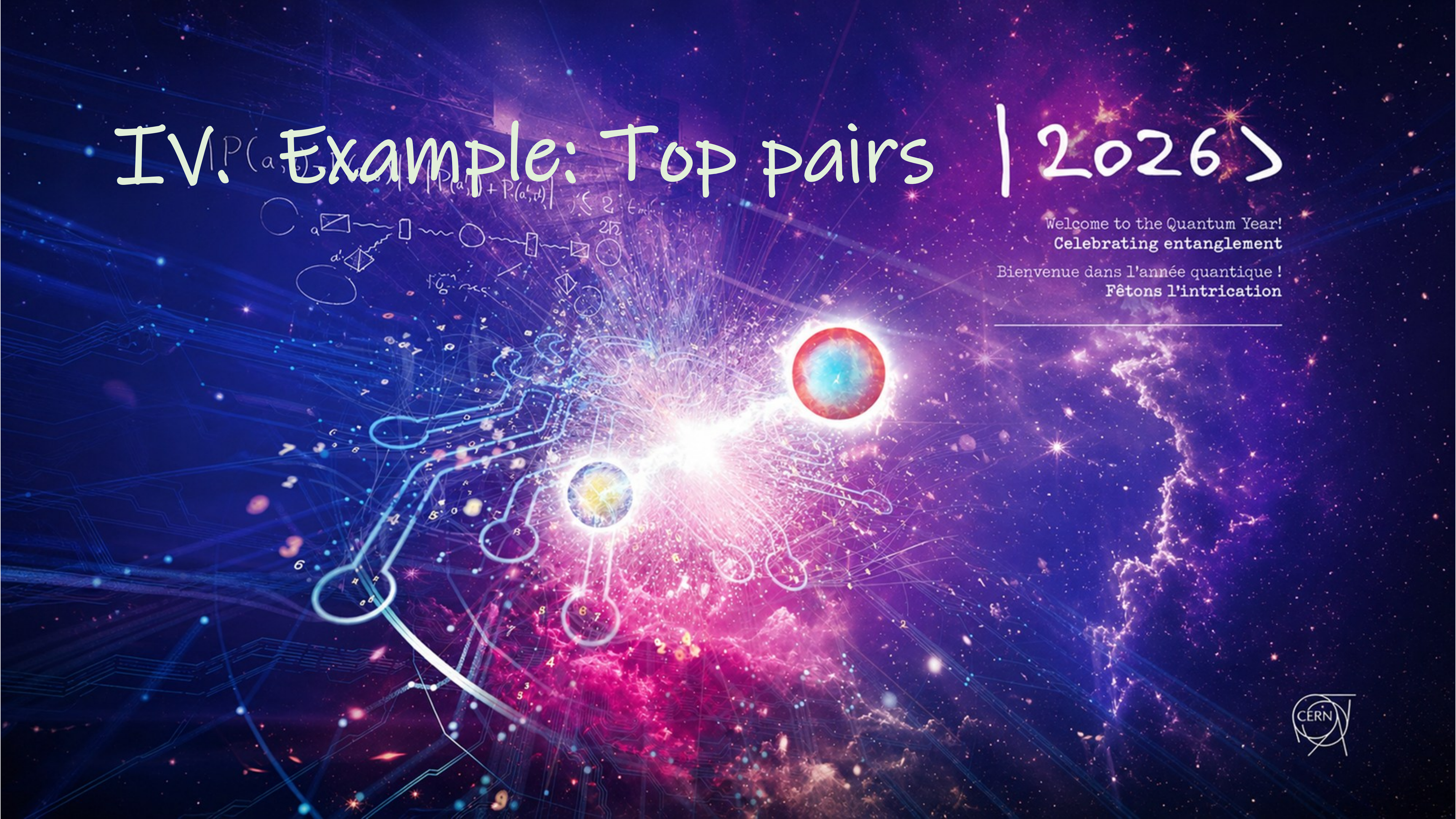
$$\rho \rightarrow U^\dagger \rho U$$

- We can directly see quantities of interest are **basis-independent**

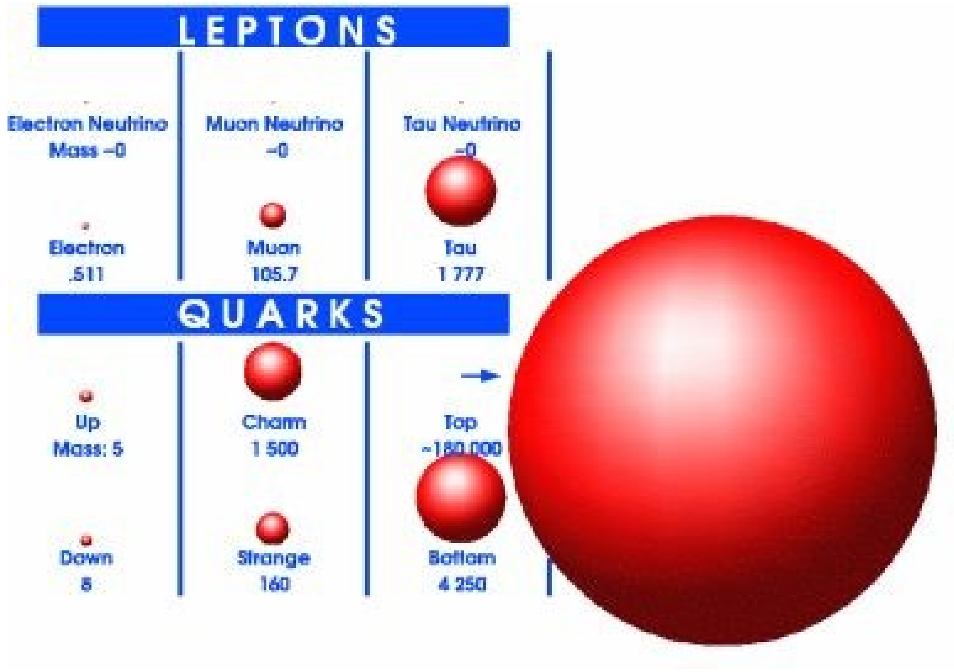
✓ **Concurrence** $\mathcal{C}(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$

✓ **Bell variable** $\mathcal{B}(\rho) = 2\sqrt{\lambda_1 + \lambda_2}$

IV. Example: Top pairs



Top quark pair production as a two-qubit system



Top Quark is Unique:

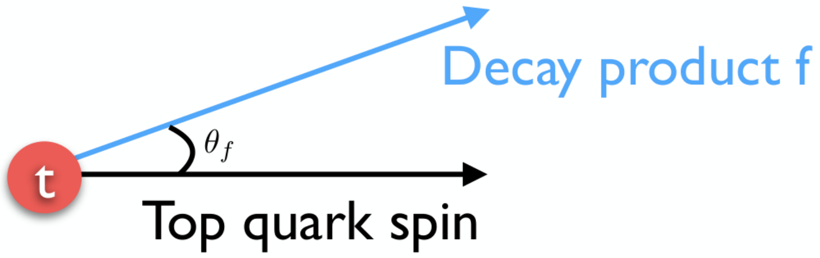
- Top quark is the heaviest fermion in the SM (**172 GeV**)
- Lifetime of **10^{-25} seconds** $\tau_{top} \approx 5 \times 10^{-25} s$

  Decays before it hadronizes $\tau_{had} \sim 1/\Lambda_{QCD} \sim 10^{-24} s$
- Fully reconstructable $t \to Wb \to (qq')b$ $t \to Wb \to (\ell\nu)b$
- Top polarization directly observable via angular distributions of its decay products

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + \beta_f \cos\theta_f)$$

	$l^+, \bar{d}$	b	$\bar{\nu}, u$
β_f	1	-0.4	-0.3

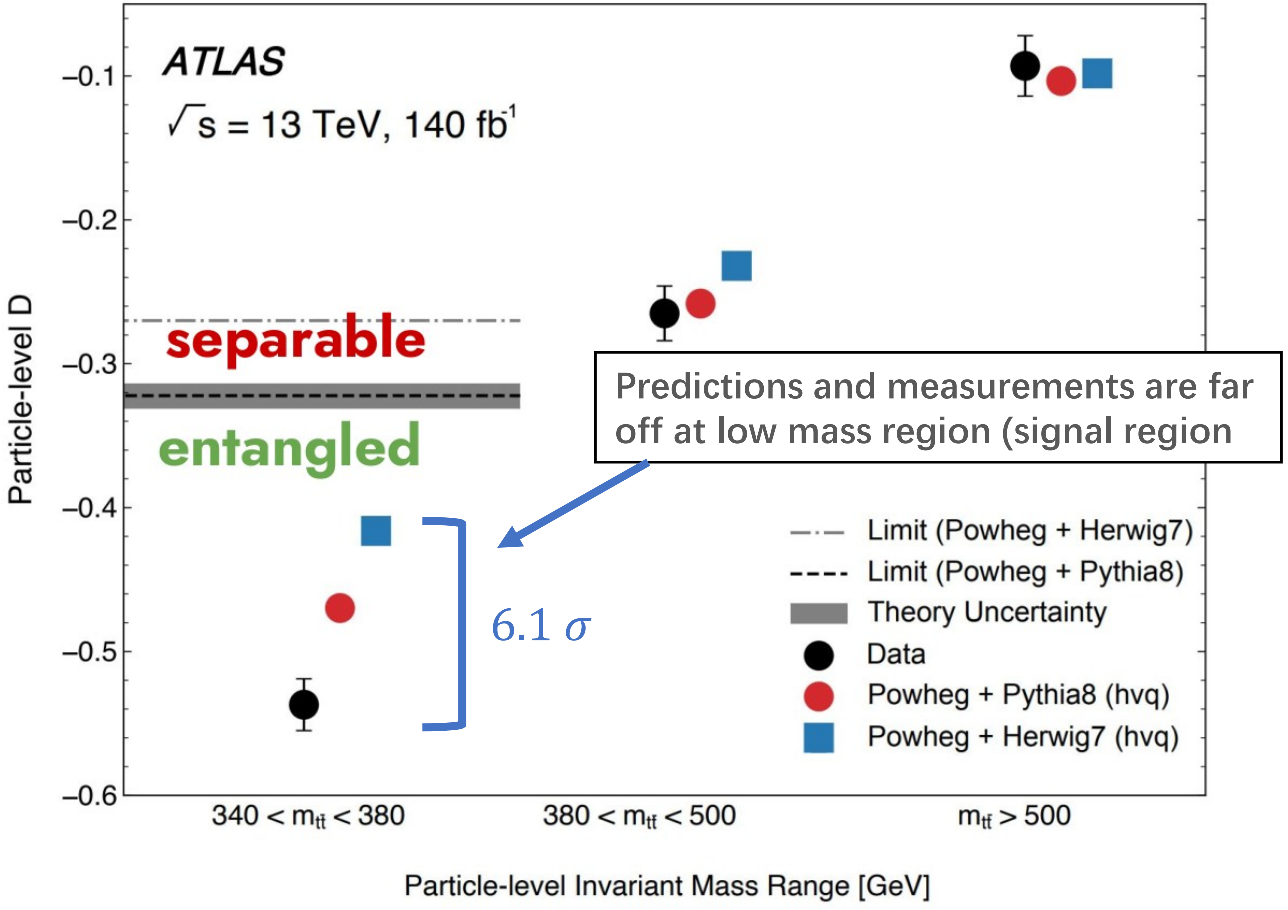
Spin analyzing power: maximum for charged leptons

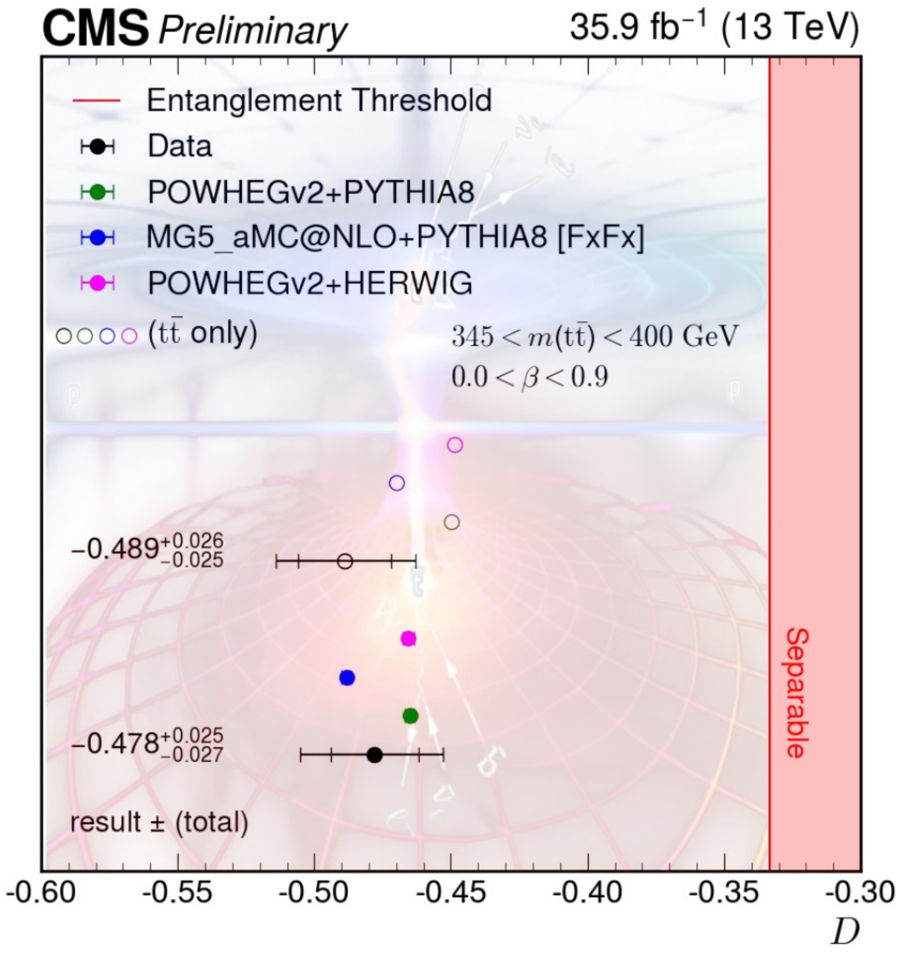


Top quark pair production as a two-qubit system

- **ATLAS** and **CMS** have measured entanglement (in tt)

[ATLAS, 2311.07288, CMS: 2406.03976]





Slower top quarks Faster top quarks

(Only slower top quarks)

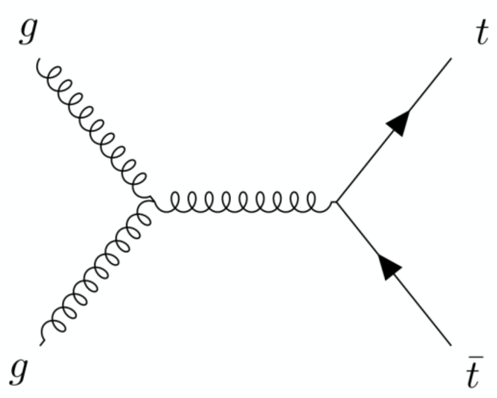
Top quark pair production as a two-qubit system

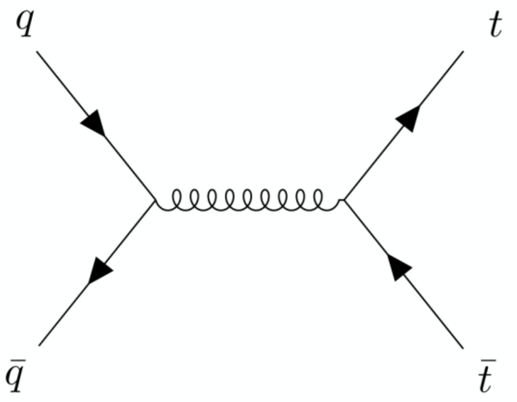
- Top pairs ideal probe: spin correlations preserved after decay

$$R^I_{\alpha_1\alpha_2,\beta_1\beta_2} \equiv \frac{1}{N_a N_b} \sum_{\substack{\text{colors} \\ \text{a,b spins}}} \mathcal{M}^*_{\alpha_2\beta_2} \mathcal{M}_{\alpha_1\beta_1}$$

At LO in QCD $I = gg, q\bar{q}$

$$\mathcal{M}_{\alpha\beta} \equiv \langle t(k_1,\alpha)\bar{t}(k_2,\beta)|\mathcal{T}|a(p_1)b(p_2)\rangle$$





$$R(\hat{s},\boldsymbol{k}) = \sum_I L^I(\hat{s}) R^I(\hat{s},\boldsymbol{k}) \, .$$

Full correlation matrix is mixed state, weighted by parton luminosity

Top quark pair production as a two-qubit system

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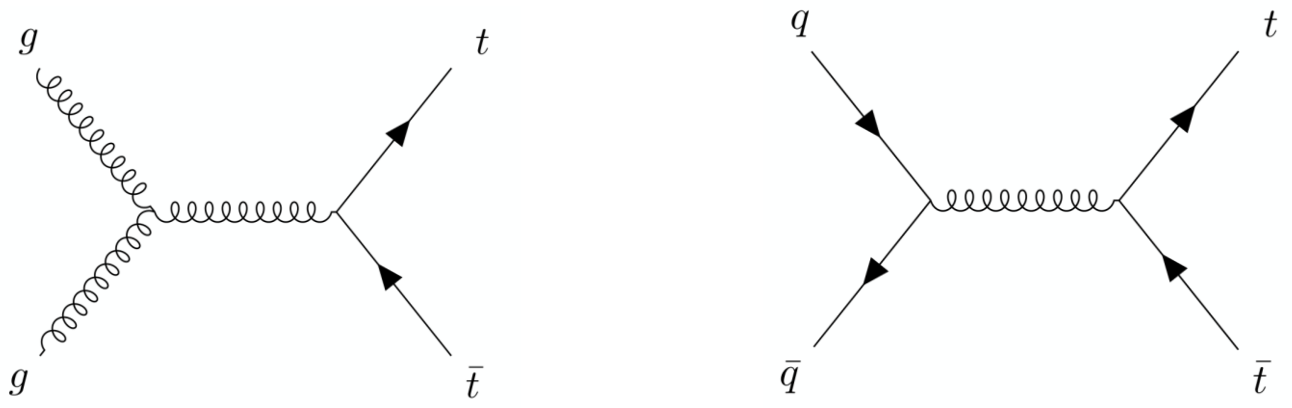

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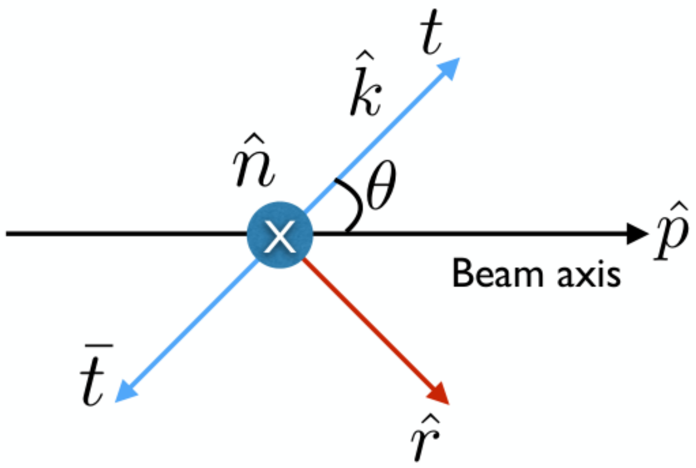
Full correlation matrix is mixed state, weighted by parton luminosity

Top quark pair production as a two-qubit system

- Definitions

$$\{\boldsymbol{k},\boldsymbol{n},\boldsymbol{r}\}: \ \boldsymbol{r}=\frac{(\boldsymbol{p}-z\boldsymbol{k})}{\sqrt{1-z^2}}, \quad \boldsymbol{n}=\boldsymbol{k}\times\boldsymbol{r},$$

$$\beta=\sqrt{1-4\mathrm{m}_\mathrm{t}^2/\mathrm{s}}\ ,\ \cos\theta$$



- P and CP invariance under tt production ! $\mathrm{B_i}=\overline{\mathrm{B}}_\mathrm{i}=\ 0$ and Cij = Cji
- Things further simplify in the helicity basis: only non-vanishing parameters are the diagonal terms Cii and one off-diagonal term $\mathrm{C}_{12}\simeq\mathrm{C}_{21}$

Top quark pair production as a two-qubit system

initial state	$\overline{\sum}\lvert\mathcal{M}\rvert^2$	Correlation matrix
$q\bar{q}$	$\kappa_q\,(2-\beta^2 s_\theta^2)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2+\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$
$g_L g_R$	$\kappa_g \beta^2 s_\theta^2 (2-\beta^2 s_\theta^2)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2+\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$
$g_L g_L / g_R g_R$	$\kappa_g(1-\beta^4)$	$\begin{pmatrix} \frac{\beta^2-1}{\beta^2+1} & 0 & 0 \\ 0 & \frac{\beta^2-1}{\beta^2+1} & 0 \\ 0 & 0 & -1 \end{pmatrix}$

$$\kappa_q = g_s^2 \frac{(N^2-1)}{N^2}, \quad \kappa_g = \frac{2g_s^2}{(\beta^2 c_\theta^2 - 1)^2} \frac{N^2(\beta^2 c_\theta^2 + 1) - 2}{N(N^2-1)}$$

Top quark pair production as a two-qubit system

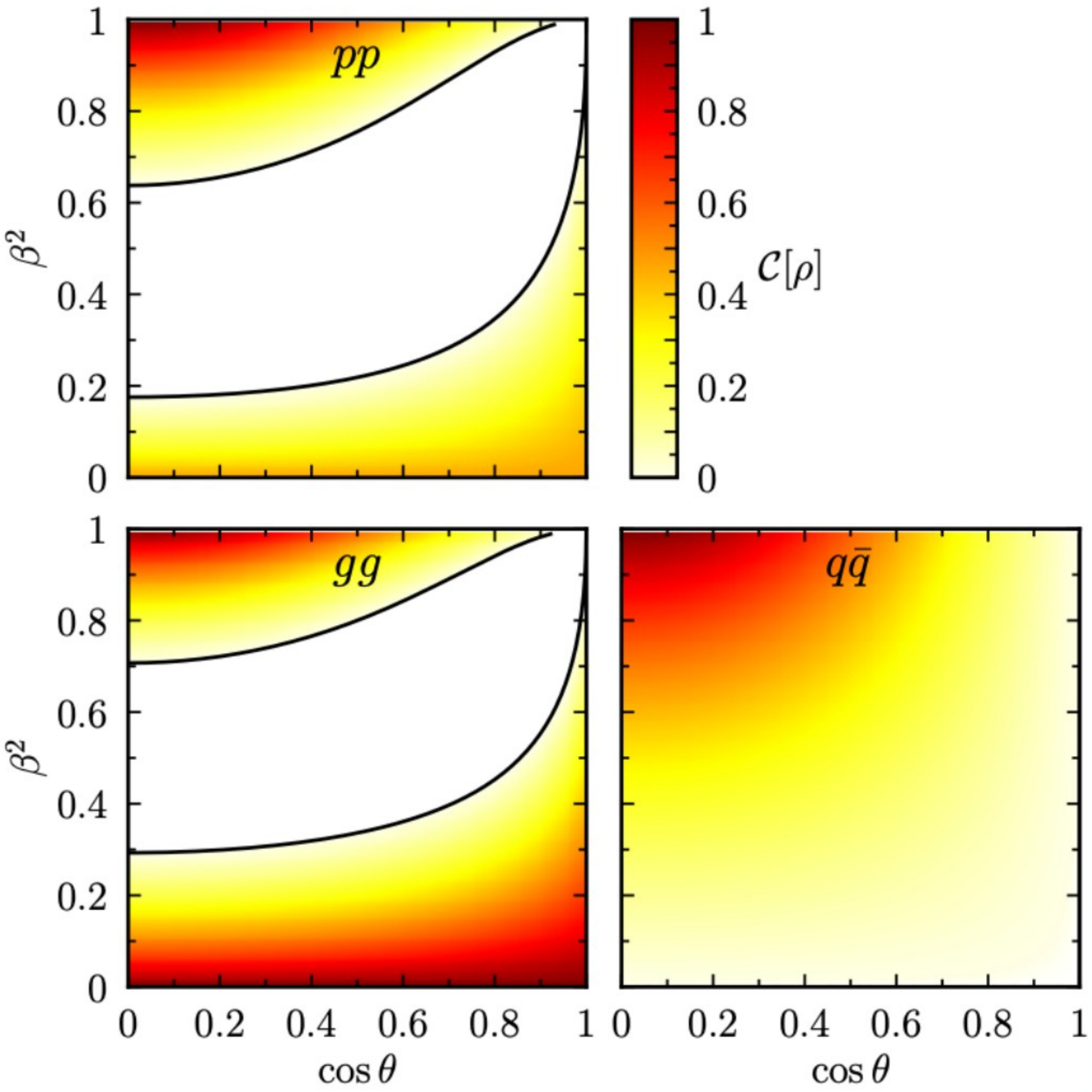
initial state	$\overline{\sum}\lvert\mathcal{M}\rvert^2$	Correlation matrix
$q\bar{q}$	$\kappa_q\,(2-\beta^2 s_\theta^2)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2+\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$
$g_L g_R$	$\kappa_g \beta^2 s_\theta^2 (2-\beta^2 s_\theta^2)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2+\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$
$g_L g_L / g_R g_R$	$\kappa_g(1-\beta^4)$	$\begin{pmatrix} \frac{\beta^2-1}{\beta^2+1} & 0 & 0 \\ 0 & \frac{\beta^2-1}{\beta^2+1} & 0 \\ 0 & 0 & -1 \end{pmatrix}$

$|\Phi^+\rangle = (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)/\sqrt{2}$

$|\Phi^-\rangle = (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)/\sqrt{2}$

$$\kappa_q = g_s^2 \frac{(N^2-1)}{N^2}, \quad \kappa_g = \frac{2g_s^2}{(\beta^2 c_\theta^2 - 1)^2} \frac{N^2(\beta^2 c_\theta^2+1)-2}{N(N^2-1)}$$

Theoretic & parton level result



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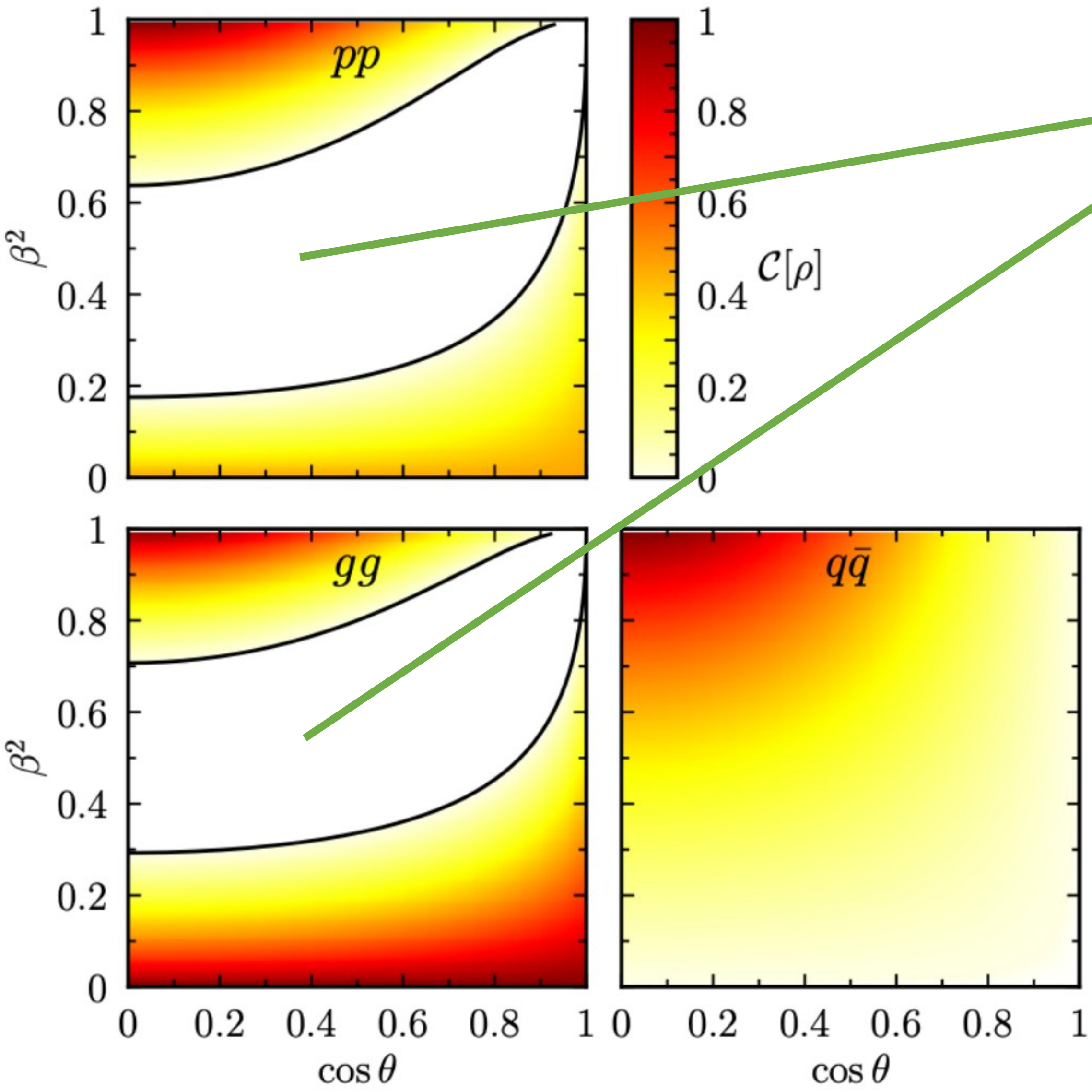
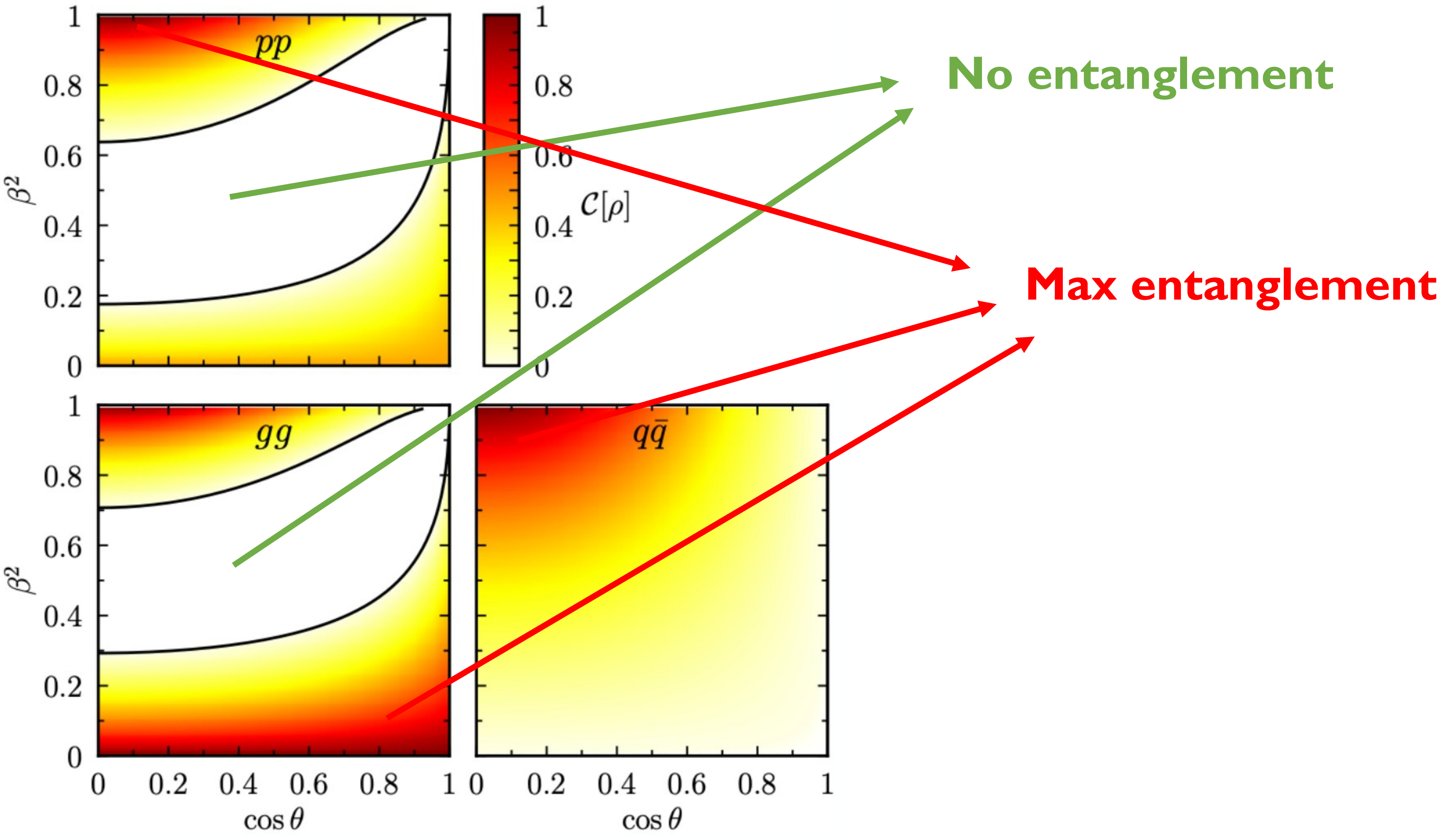
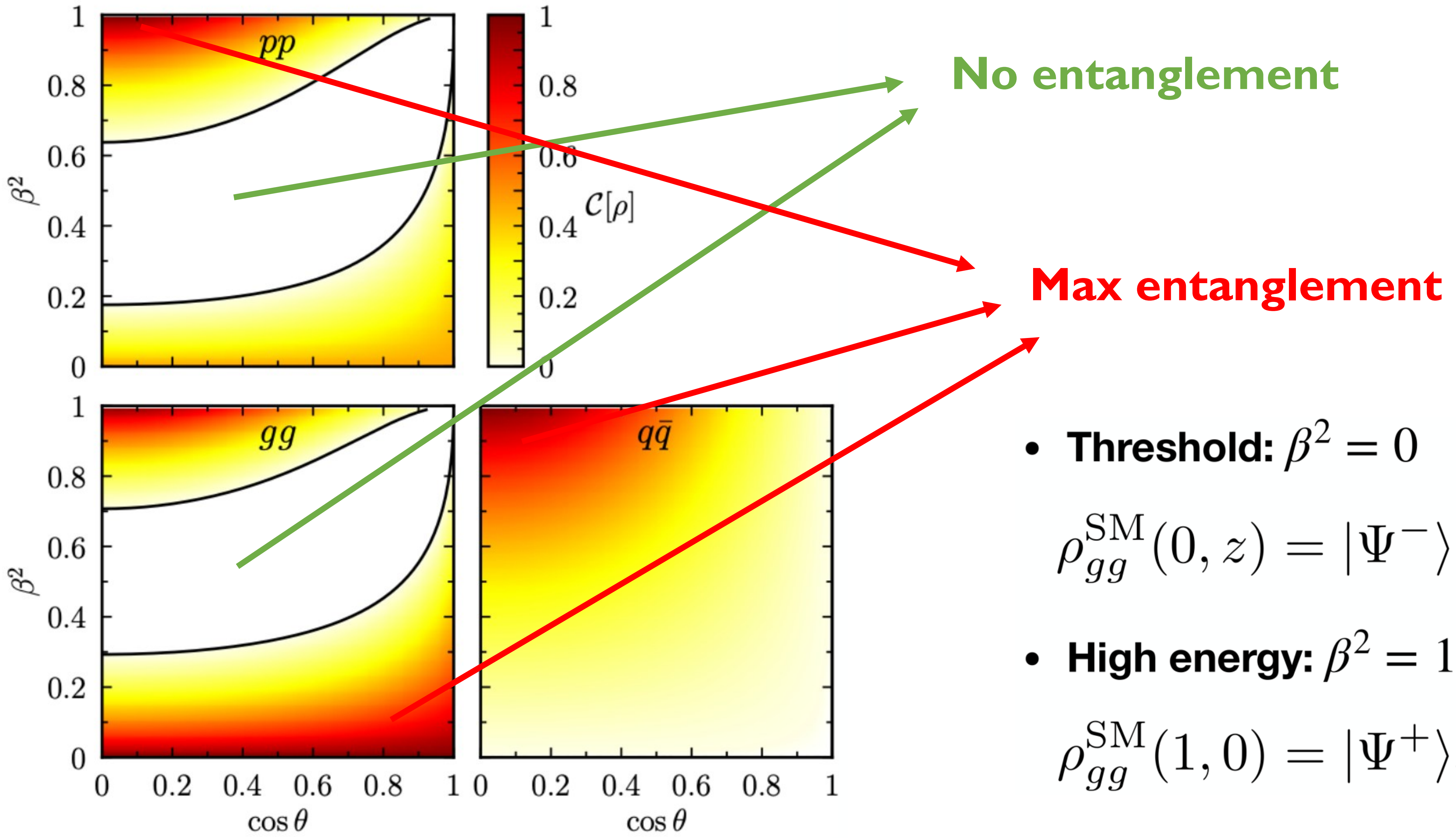


No entanglement

Theoretic & parton level result



Theoretic & parton level result



- **Threshold:** $\beta^2 = 0$

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

- **High energy:** $\beta^2 = 1\,, \cos\theta = 0$

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

As a probe of BSM interactions

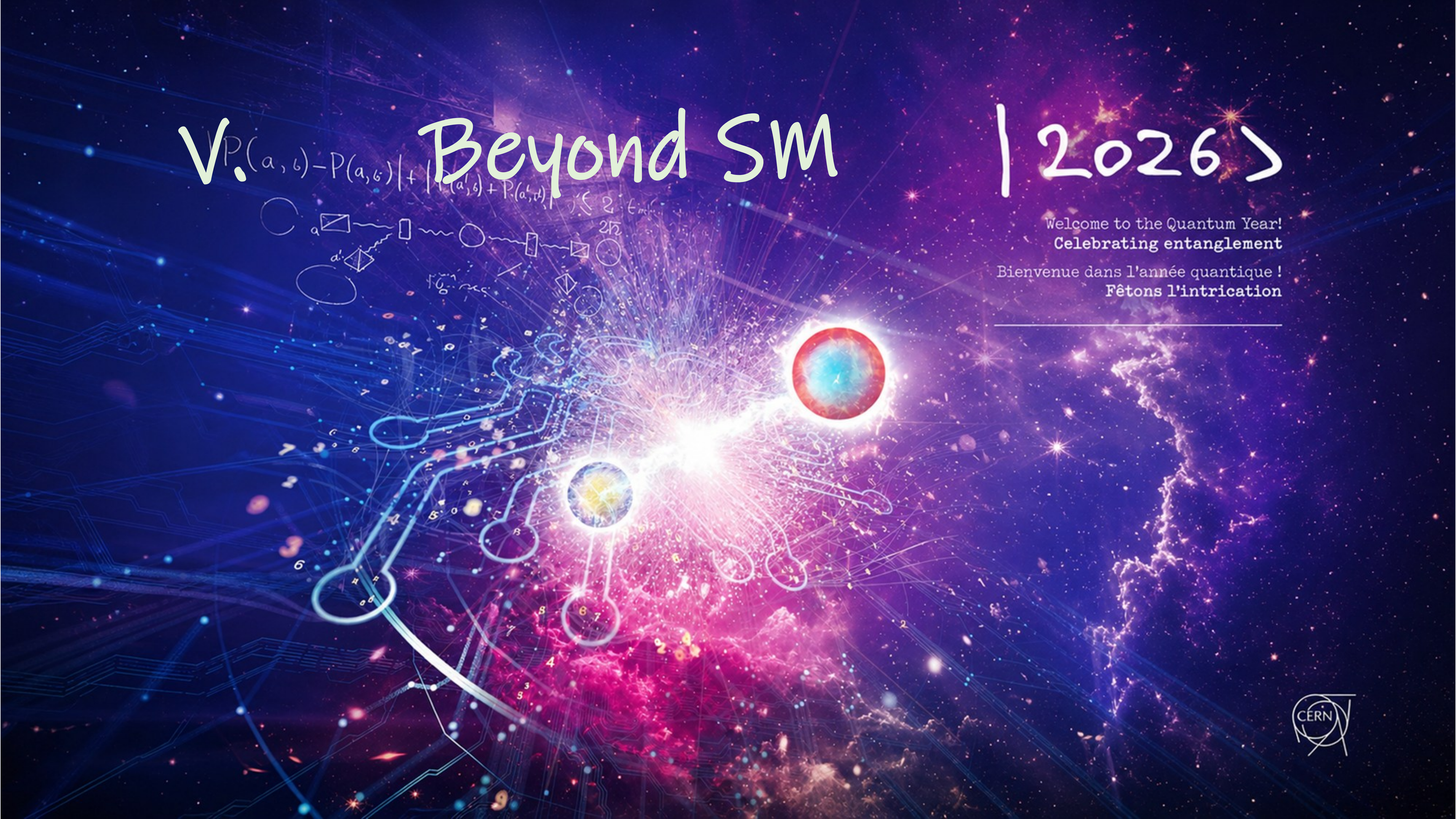
For $e^+e^- \to f\bar{f}$ in the high-energy limit $m_f^2 \ll s$, the final-state spins form a two-qubit state:

$$|\psi\rangle = a|\uparrow\uparrow\rangle + b|\downarrow\downarrow\rangle + c|\uparrow\downarrow\rangle + d|\downarrow\uparrow\rangle$$

Interaction structure $\Longrightarrow$ Bell-state sector

Lorentz structure	Dominant spin sector	Entanglement pattern	Physics message
Vector / axial-vector ($\gamma/Z/Z'$)	$c, d \simeq 0$	$\lvert\Phi^\pm\rangle = (\lvert\uparrow\uparrow\rangle \pm \lvert\downarrow\downarrow\rangle)/\sqrt{2}$	Gauge-like helicity structure
CP-even scalar (H)	$a, b \simeq 0$	$\lvert\Psi^-\rangle = (\lvert\uparrow\downarrow\rangle - \lvert\downarrow\uparrow\rangle)/\sqrt{2}$	Chirality-flipping scalar coupling
CP-odd pseudoscalar (A^0)	$a, b \simeq 0$	$\lvert\Psi^+\rangle = (\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle)/\sqrt{2}$	Relative phase/sign carries CP information

V. Beyond SM


|2026⟩
Welcome to the Quantum Year!
Celebrating entanglement
Bienvenue dans l'année quantique !
Fêtons l'intrication
CERN

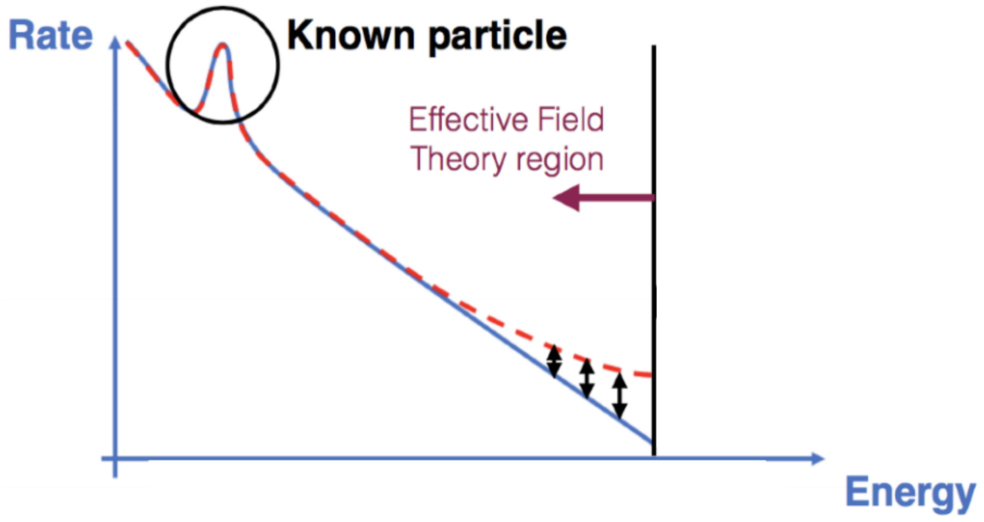
How to look for new physics?

How do we interpret the measurement results?

Model-dependent

SUSY, 2HDM…

New particles



Deviations in tails

Direct and Indirect Searches for BSM

How do we interpret the measurement results?

Model-dependent

SUSY, 2HDM…

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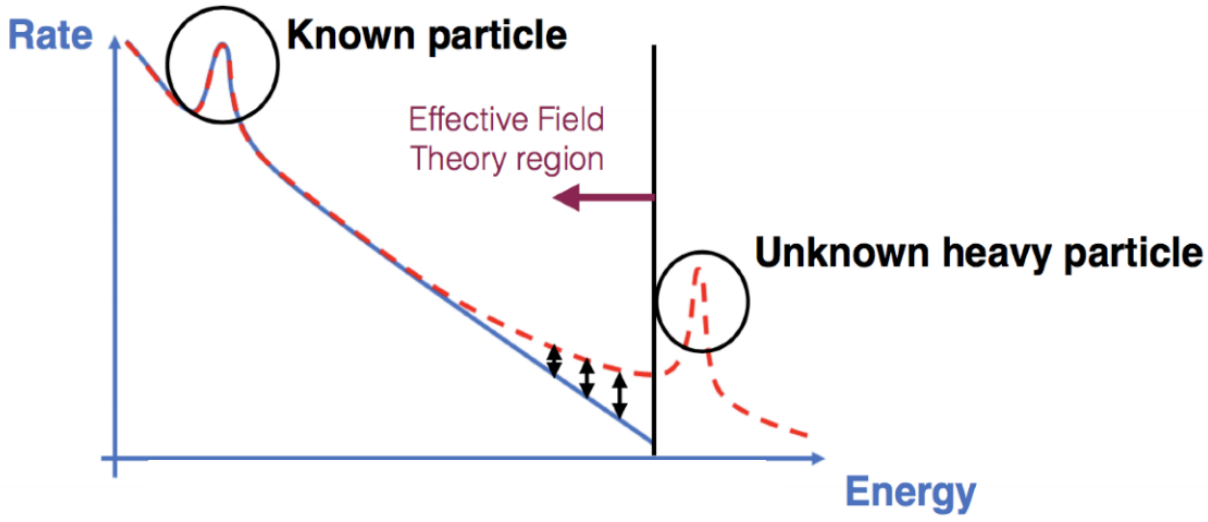


Deviations in tails

Model-Independent

Simplified models, EFT

New Interactions
of SM particles

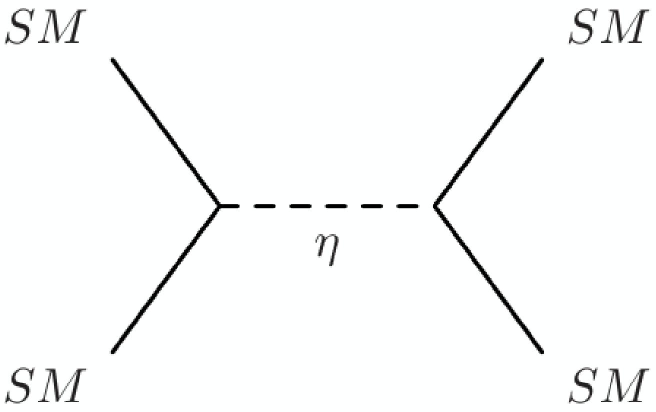
anomalous couplings

Framework to describe both precision physics and Heavy New Physics.

How can we describe the presence of new interactions?

New particles being exchanged in collisions

$$\frac{g^2}{p^2 - M^2}$$



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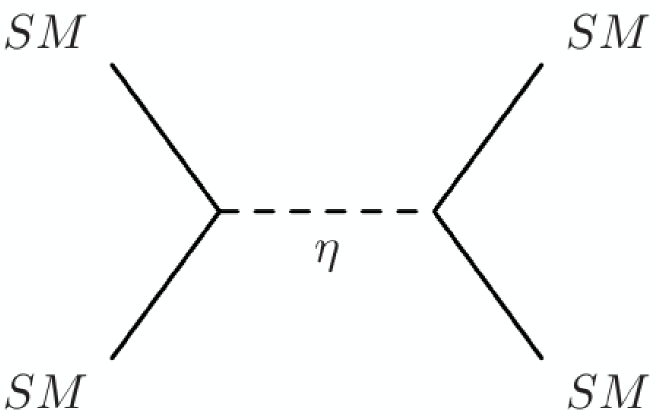

$$M \equiv \Lambda$$
$$p^2 \ll \Lambda^2$$

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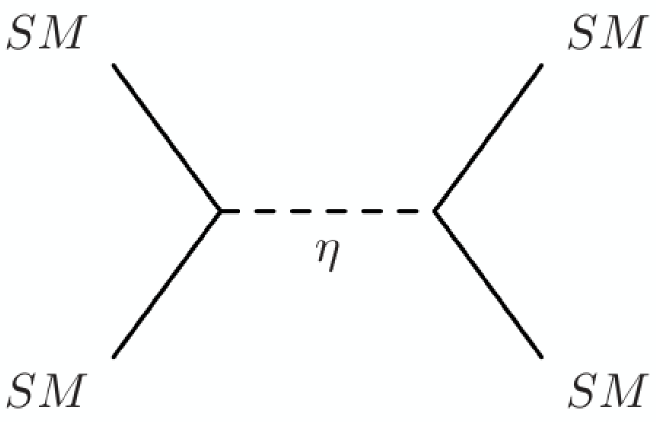

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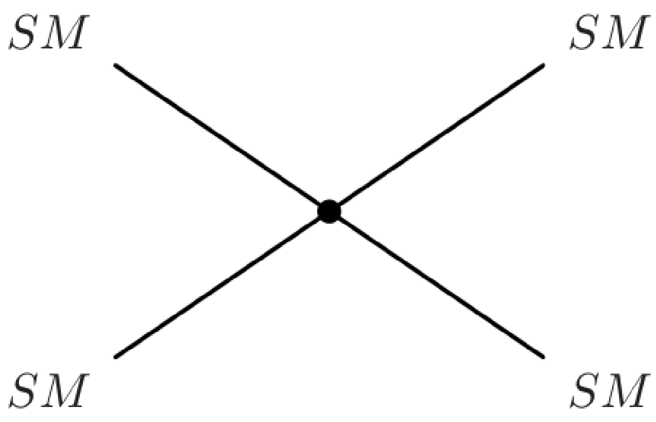

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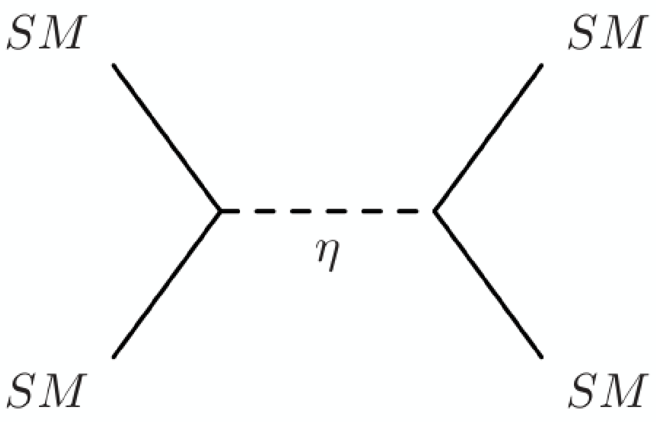
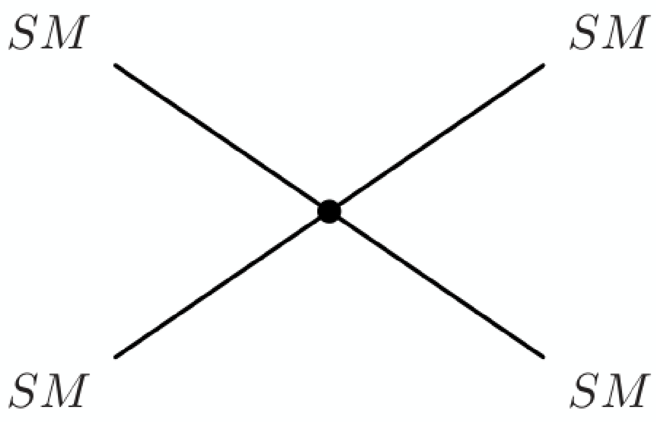


$$M \equiv \Lambda$$
$$p^2 \ll \Lambda^2$$

$\longrightarrow$



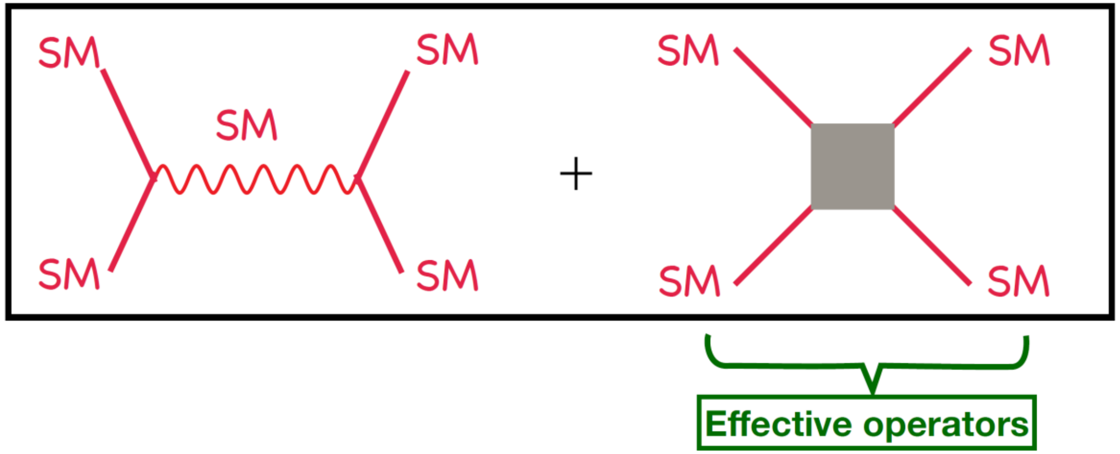
Interaction can be described without explicit presence of new states!

New framework $\longrightarrow$ Effective Field Theory

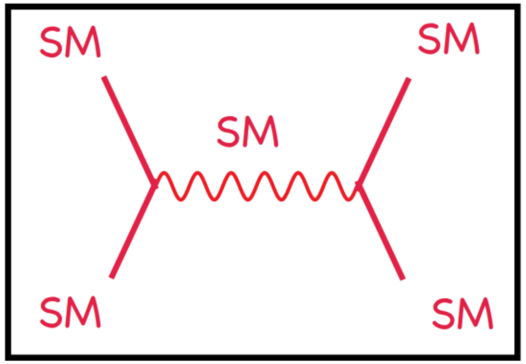
The Standard Model Effective Field Theory (SMEFT)

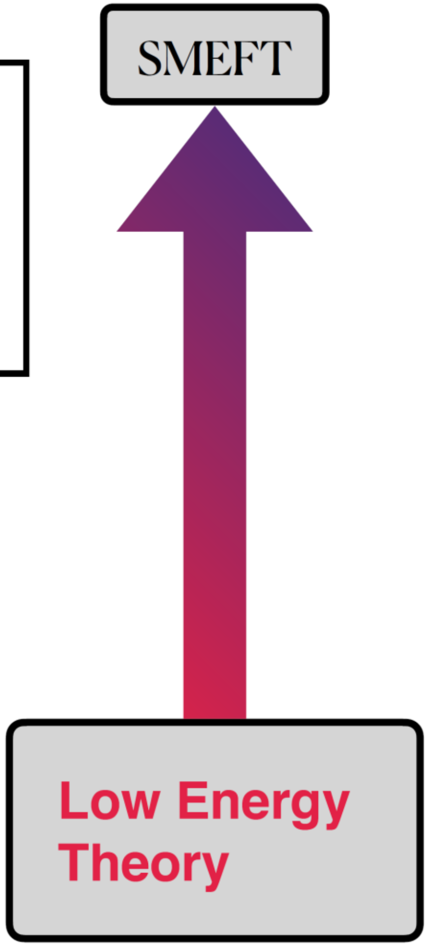
EFT: Bottom-Up approach with general parameterization

$$\mathcal{L}_{\mathrm{SM}} + \underbrace{\sum_{j=5,\ldots}\sum_i \frac{C_i^{(j)}}{\Lambda^{j-4}} Q_i^{(j)}}_{\text{Effective operators}}$$



$$\mathcal{L}_{\mathrm{SM}}$$





Dim-6 operators

59 operators flavour universal

2499 operators flavour general

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$

$(\bar L L)(\bar L L)$		$(\bar R R)(\bar R R)$		$(\bar L L)(\bar R R)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi \widetilde W B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

R-matrix in SMEFT

$$R^{I}_{\alpha_1\alpha_2,\beta_1\beta_2} \equiv \frac{1}{N_a N_b} \sum_{\substack{\text{colors} \\ \text{a,b spins}}} \mathcal{M}^*_{\alpha_2\beta_2} \mathcal{M}_{\alpha_1\beta_1}$$

$$\mathcal{M}_{\alpha\beta} = \mathcal{M}^{\rm SM}_{\alpha\beta} + \frac{1}{\Lambda^2}\mathcal{M}^{(\rm d6)}_{\alpha\beta} \quad \longrightarrow \quad \rho = \frac{R^{\rm SM} + R^{\rm EFT}}{{\rm tr}(R^{\rm SM}) + {\rm tr}(R^{\rm EFT})}$$

At $\mathcal{O}(1/\Lambda^2)$

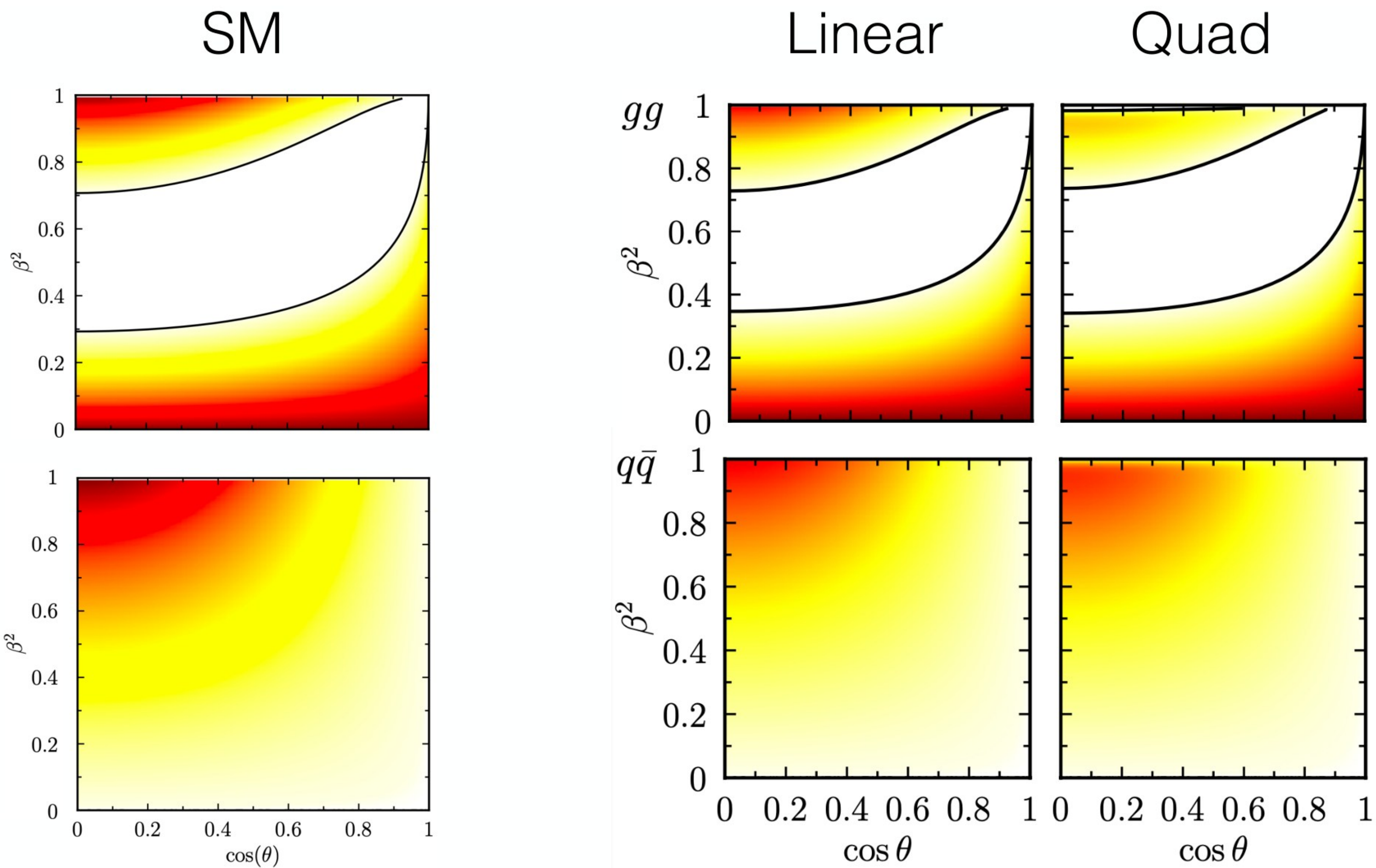
$$\tilde{A}^{gg,(1)} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{g_s^2 v m_t(9\beta^2 z^2+7)}{12\sqrt{2}}c_{tG} - \frac{\beta^2 m_t^4}{4m_t^2-(1-\beta^2)m_h^2}c_{\varphi G} + \frac{9g_s^2\beta^2 m_t^2 z^2}{8}c_G\right],$$

$$\tilde{C}^{gg,(1)}_{nn} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{-7g_s^2 v m_t}{12\sqrt{2}}c_{tG} - \frac{\beta^2 m_t^4}{4m_t^2-(1-\beta^2)m_h^2}c_{\varphi G} + \frac{9g_s^2\beta^2 m_t^2 z^2}{8}c_G\right],$$

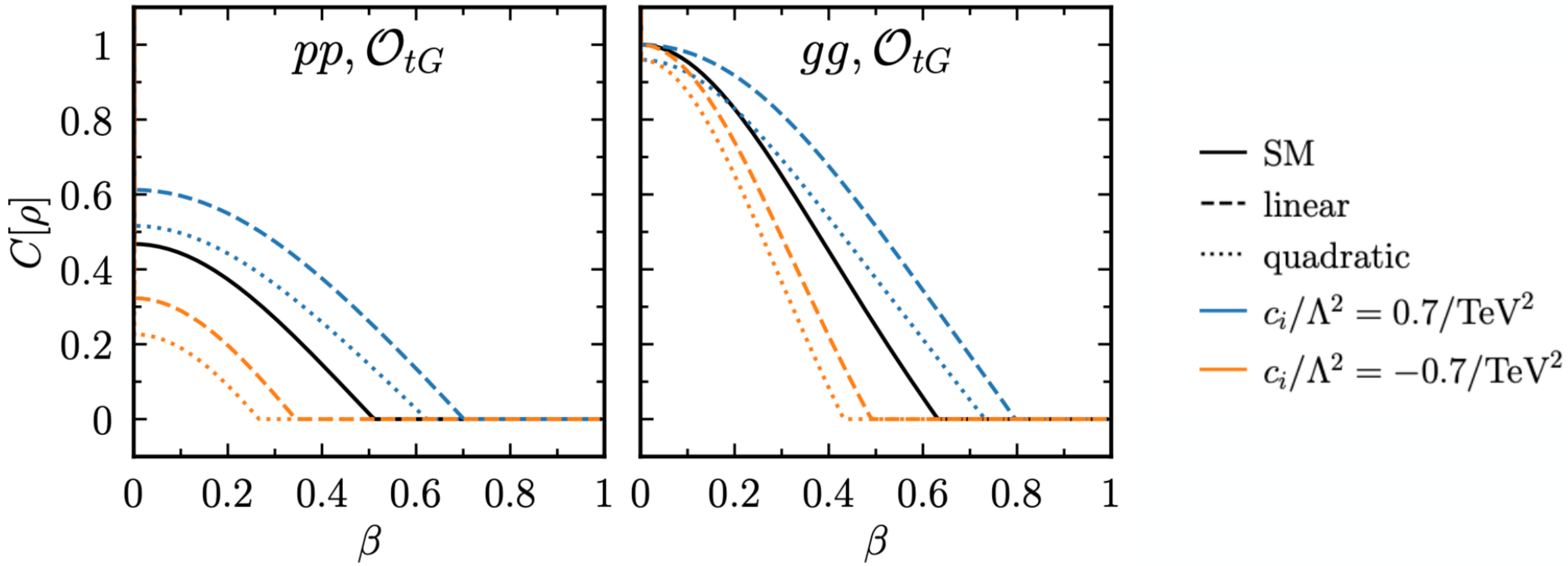
$$\tilde{C}^{gg,(1)}_{kk} = \frac{g_s^2}{\Lambda^2}\frac{1}{1-\beta^2 z^2}\left[\frac{g_s^2 v m_t\left(9\beta^2 z^2+7\right)\left(\beta^2\left(z^4-z^2-1\right)+1\right)}{12\sqrt{2}\left(\beta^2 z^2-1\right)}c_{tG}\right.$$
$$\left. + \frac{\beta^2 m_t^4}{4m_t^2-\left(1-\beta^2\right)m_h^2}c_{\varphi G} - \frac{9g_s^2\beta^2 m_t^2 z^2}{8}c_G\right],$$

SMEFT entanglement

$$\mathcal{O}_{tG} = g_s(\bar{Q}\sigma^{\mu\nu}T^A\,t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}$$



SMEFT entanglement



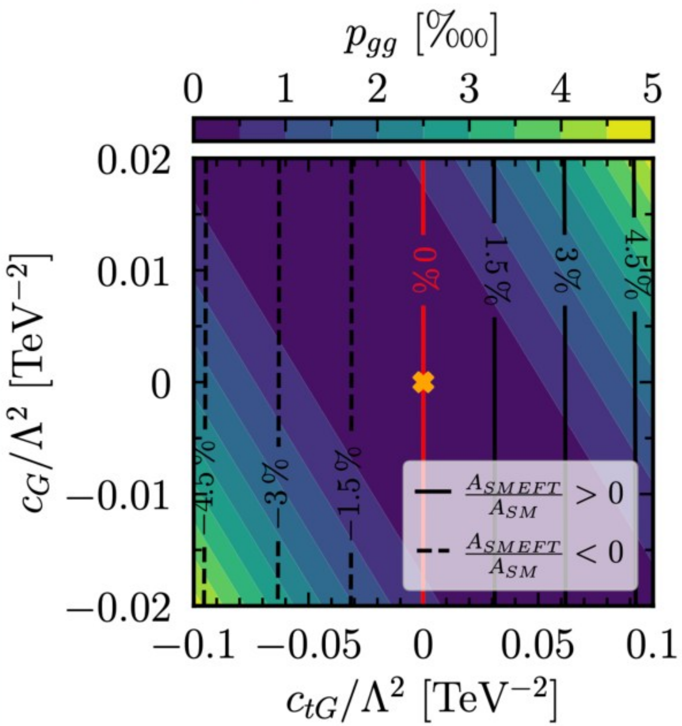
SMEFT entanglement

gg-induced

$$\rho_{gg}^{\mathrm{EFT}}(0,z) = p_{gg}|\Psi^+\rangle_{\boldsymbol{p}}\langle\Psi^+|_{\boldsymbol{p}} + (1-p_{gg})|\Psi^-\rangle_{\boldsymbol{p}}\langle\Psi^-|_{\boldsymbol{p}}$$

$$p_{gg} = \frac{72}{7\Lambda^4} m_t^2 (3\sqrt{2} m_t\, c_G + v\, c_{tG})^2$$

Only quadratic effects!



SMEFT entanglement

gg-induced

$$\rho^{\mathrm{EFT}}_{gg}(0,z) = p_{gg}|\Psi^+\rangle_{\boldsymbol{p}}\langle\Psi^+|_{\boldsymbol{p}} + (1-p_{gg})|\Psi^-\rangle_{\boldsymbol{p}}\langle\Psi^-|_{\boldsymbol{p}}$$

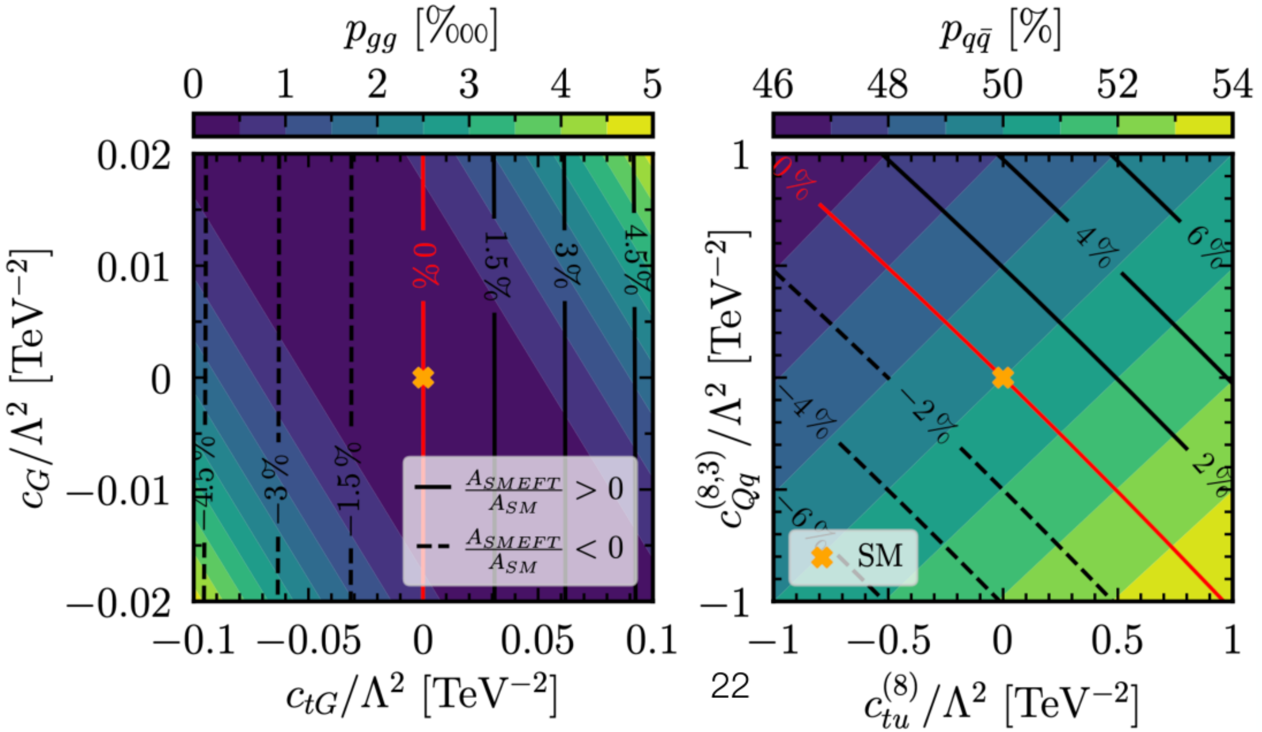
$$p_{gg} = \frac{72}{7\Lambda^4} m_t^2 (3\sqrt{2} m_t\, c_G + v\, c_{tG})^2$$

Only quadratic effects!

qq-induced

$$\rho^{\mathrm{EFT}}_{q\bar{q}}(0,z) = p_{q\bar{q}}\,|\uparrow\uparrow\rangle_{\boldsymbol{p}}\,\langle\uparrow\uparrow|_{\boldsymbol{p}} + (1-p_{q\bar{q}})\,|\downarrow\downarrow\rangle_{\boldsymbol{p}}\,\langle\downarrow\downarrow|_{\boldsymbol{p}}$$

$$p_{q\bar{q}} = \frac{1}{2} - 4\frac{c^{(8),u}_{VA}}{\Lambda^2} + \frac{8m_t^4}{\Lambda^4}\left(\frac{v\sqrt{2}}{m_t} c^{(8),u}_{VA} c_{tG} - 9 c^{(1),u}_{VA} c^{(1),u}_{VV} + 2 c^{(8),u}_{VA} c^{(8),u}_{VV}\right)$$



22

As a probe of BSM interactions

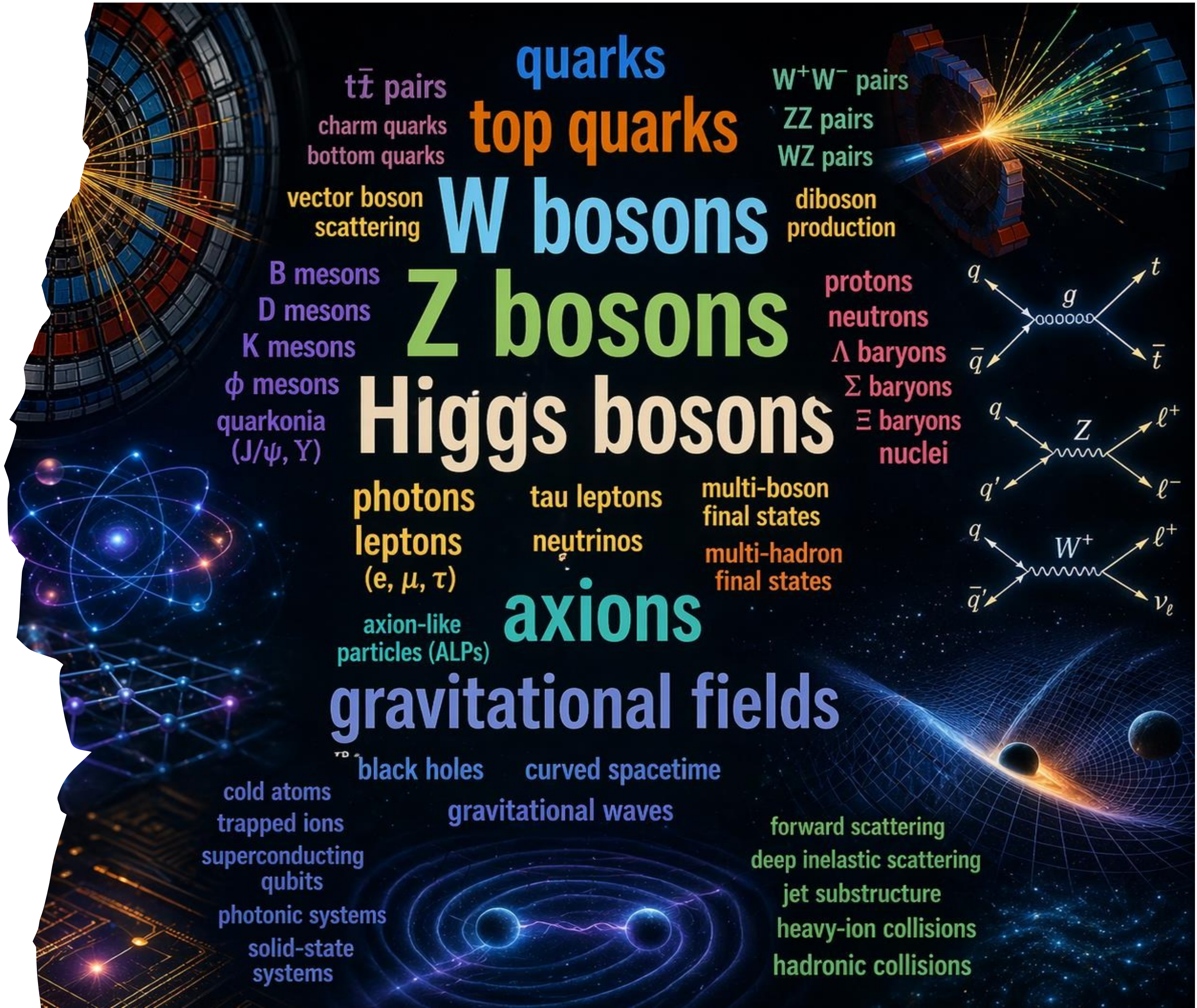
BSM Lorentz

$\Downarrow$

Contributes to B_i, C_{ij}

$\Downarrow$

Distinct pattern in the spin density matrix



VI. Outlook


|2026⟩
Welcome to the Quantum Year!
Celebrating entanglement
Bienvenue dans l'année quantique !
Fêtons l'intrication
CERN

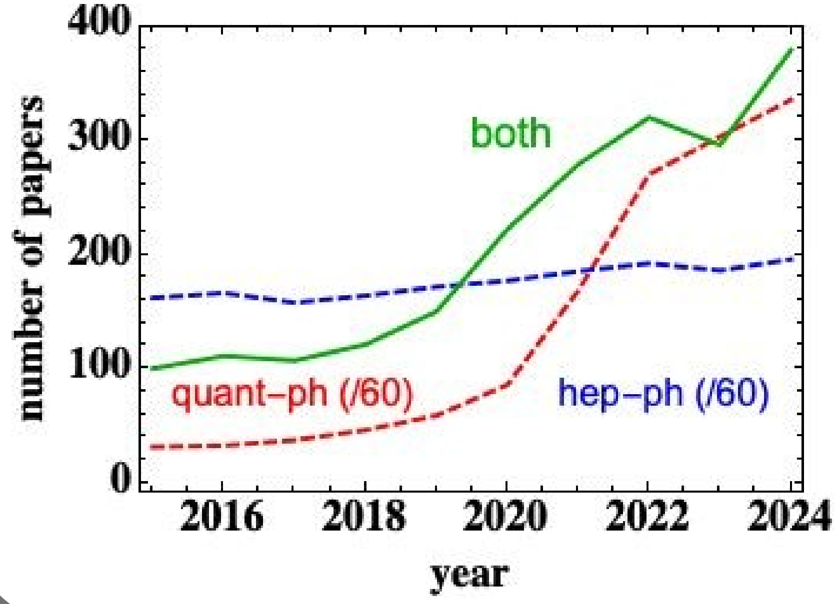
Quantum Information meets High-Energy Physics

What QIS offers

New methods,

Rich information,

Highlight unique signal regions…



High-Energy Physics

Quantum Information Science

What HEP offers

New quantum systems,

Relativistic environment,

Enormous amounts of data…

Quantum Information meets High-Energy Physics

• Entanglement and Bell nonlocality	2504.01496; 2506.16077; 2410.17025; 2307.14895; 2309.08103; 2411.12518; 2401.01162…
• QI in Particle Physics	2605.06907; 2510.0803; 2506.10673; 2411.11294; 2410.08303; 2002.04283 …
• QI at the QCD Frontier	2509.18276; 2501.03321; 2512.22837; 2504.15798; 2309.09487; 2406.16298; 1909.10626…
• Decohering	2510.13951; 2504.07030 …
• Flavor	2605.09682; 2507.12513; 2407.19242 …
• CP violation	2601.22248; 2512.07939; 2409.15418…
• Symmetry and Computation	2511.17321; 2506.08960; 2505.00873; 2307.08112 …
• Magic	2509.18251; 2508.14967; 2502.17550; 2406.07321…
• New Physics & SMEFT	2605.12033; 2604.21332; 2503.19072; 2405.09201; …
• Phase transitions …	2505.06001…

Apologies to many papers

Quantum is everywhere

- **Flavor**

  Meson pair system — Cheng, Han, Low, Wu. 2507.12513

  $$\rho = \frac{a}{4}\left(\mathbb{1}_4 + b_i^{\mathcal{A}}\,\sigma_i \otimes \mathbb{1}_2 + b_i^{\mathcal{B}}\,\mathbb{1}_2 \otimes \sigma_i + C_{ij}\,\sigma_i \otimes \sigma_j\right)$$

  Spin-Flavor structure — Du, Geng, He, Liu, Liu. 2605.09682

  $$\rho_{\vec{k}} = \frac{1}{4}\left[\mathbb{1}_F \otimes \mathbb{1}_s + \mathbb{1}_F \otimes \left(\vec{B}_s \cdot \vec{\sigma}_s\right) + (\boldsymbol{B}_D \cdot \boldsymbol{\sigma}) \otimes \mathbb{1}_s + \sum_{i,j} C_{ij}\,\boldsymbol{\sigma}_i \otimes \sigma_s^j\right]$$

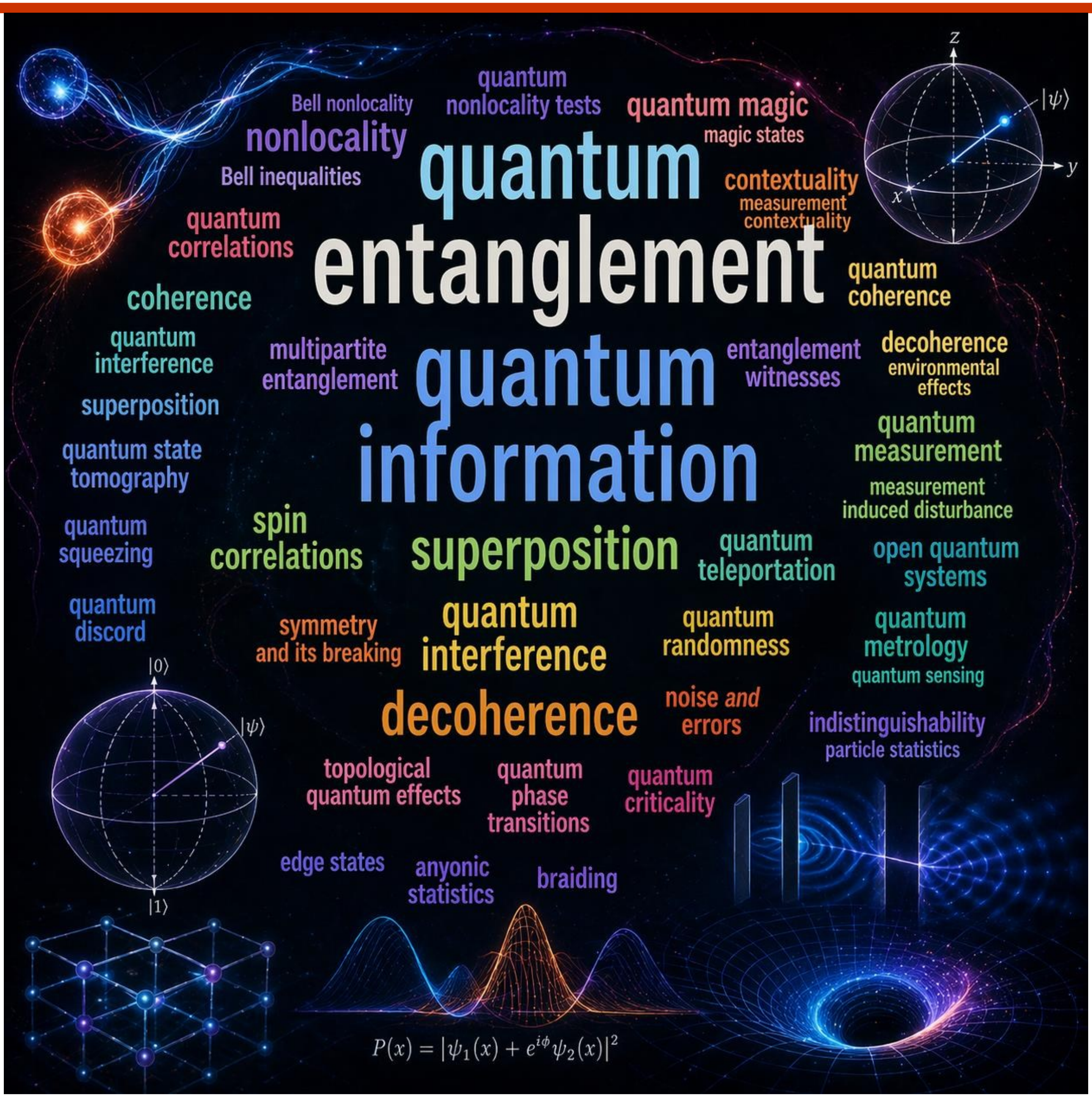
- **Understanding sources**

  Does Entanglement Suppression Lead to Enhanced Symmetries?

- **Decoherence**

  Radiation, leaking information from the “system”, decoherence in spin correction

Spin in hadrons, CP violation, Magic, Quantum swapping, Quantum teleportation…



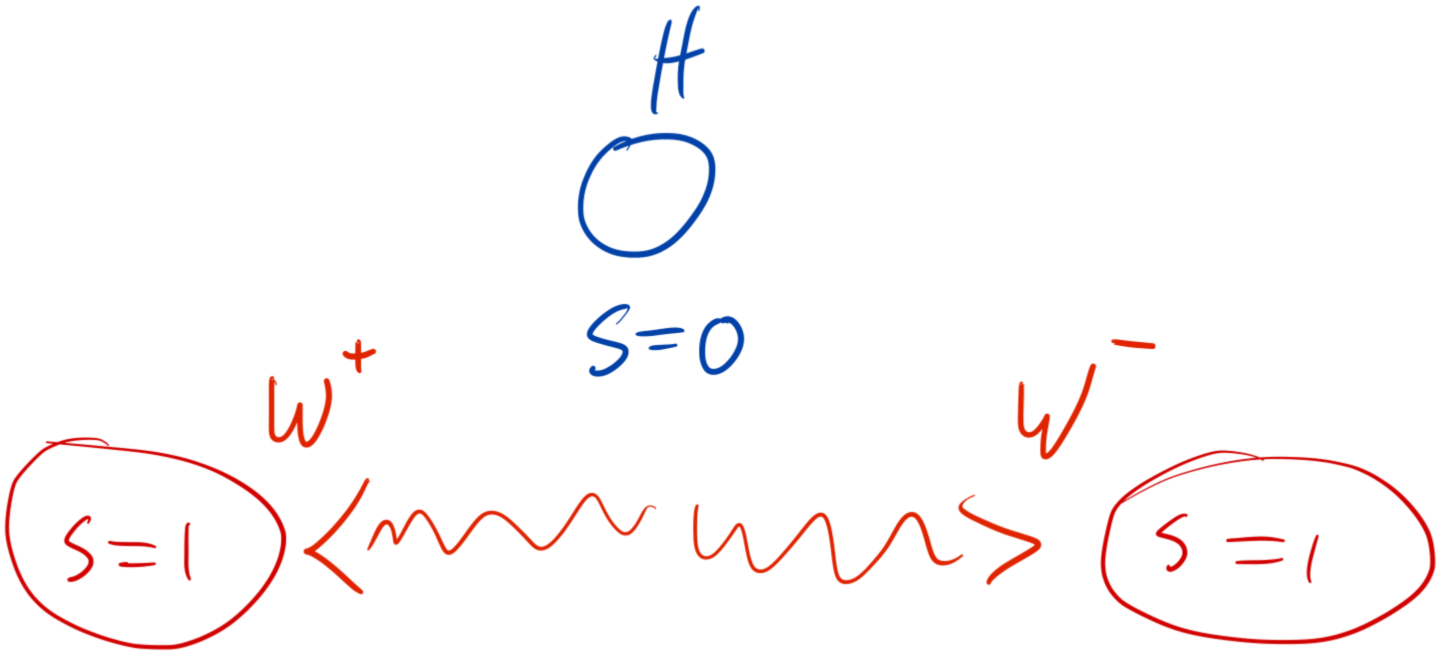
Summary

- Quantum nature of particle physics is a foundational part of the theoretical framework underpinning calculations in QFT
- Quantum tomography serve as powerful tool for precision measurements and searches for new physics
- We are just at the beginning:
  - ✓ Brand new experimental results
  - ✓ Many new channels can be analogously studied in the SM and beyond
  - ✓ Many new ideas appearing on the arXiv everyday

Back up

Quantum Tomography for Qutrits

Spin in the Higgs boson decay



The Higgs boson is a scalar, while $W^{\pm}$ bosons are vector bosons

$H \rightarrow W^{+}W^{-}$ decays produce pairs of W bosons in a singlet spin state

Quantum Tomography for Qutrits

In the narrow-width and non-relativistic approximations:

Qutrits $$|\psi_s\rangle = \frac{1}{\sqrt{3}}\big(\,|+\rangle\,|-\rangle - |0\rangle\,|0\rangle + |-\rangle\,|+\rangle\,\big)$$

- This is a maximally entangled state of two **qutrits**
- $|\psi\rangle_{AB} \in (\mathbb{C}^{\mathbf{3}})^2$
- Basis for each qutrit $\{0, 1, 2\}$

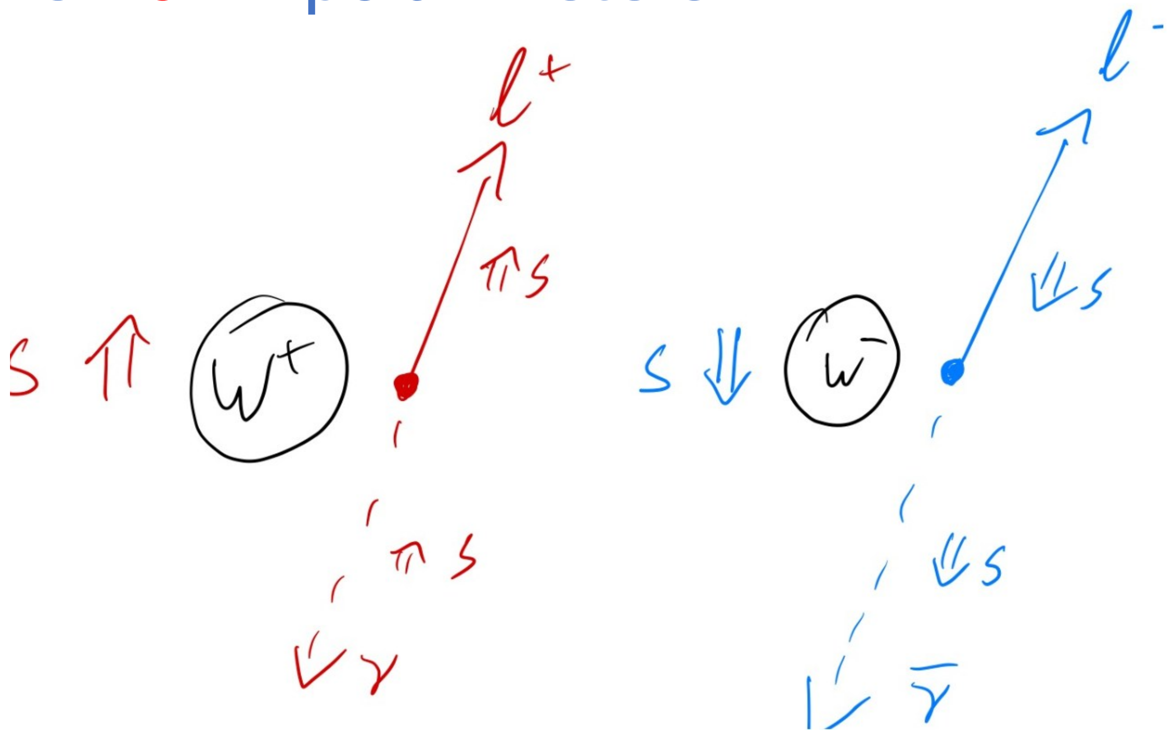
This is a Bell state

$\Rightarrow$ Entanglement and Bell inequality tests deep in the realm of QFT

[On the board: qutrits vs 3-state systems]

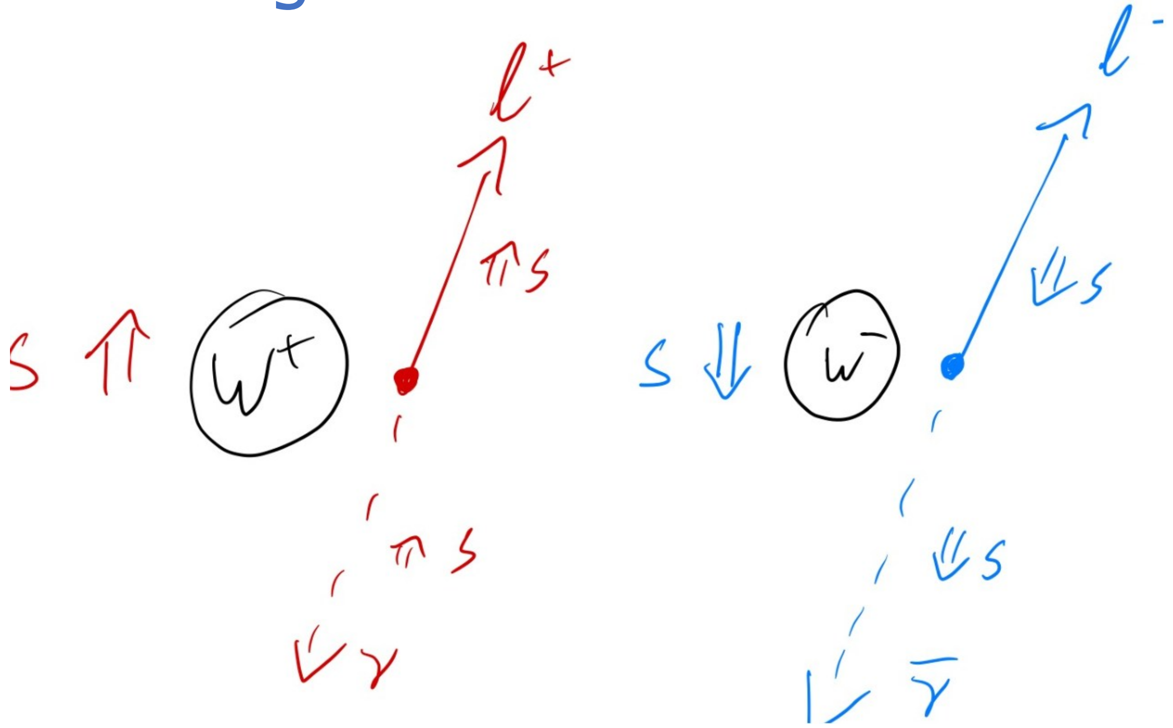
Quantum Tomography for Qutrits

W bosons are their own polarimeters



Decay of a $W^\pm$ boson is equivalent to a measurement of its spin along the axis of the emitted lepton

Getting the directions right



- ℓ^+ (ℓ^-) is emitted preferentially along (against) spin direction of W^+(W^-)
- For $H \rightarrow W^+W^-$ the $W^\pm$ spins are in different directions
- So the two leptons prefer to go in the same direction as each other

More precisely

The probability density function for a $W^{\pm}$ boson to emit its charged lepton in the $\hat{\mathbf{n}}$ direction is:

$$p(\ell^{\pm}_{\hat{\mathbf{n}}};\rho) = \frac{3}{4\pi}\,\mathrm{tr}(\rho\,\Pi_{\pm,\hat{\mathbf{n}}})\,,$$

where ρ is the W boson spin density matrix and the projection operator is

$$\Pi_{\pm,\hat{\mathbf{n}}} \equiv |\pm_{\hat{\mathbf{n}}}\rangle\langle\pm_{\hat{\mathbf{n}}}|$$

observe decay $\Longleftrightarrow$ measure spin

Weak gauge bosons measure their own spin

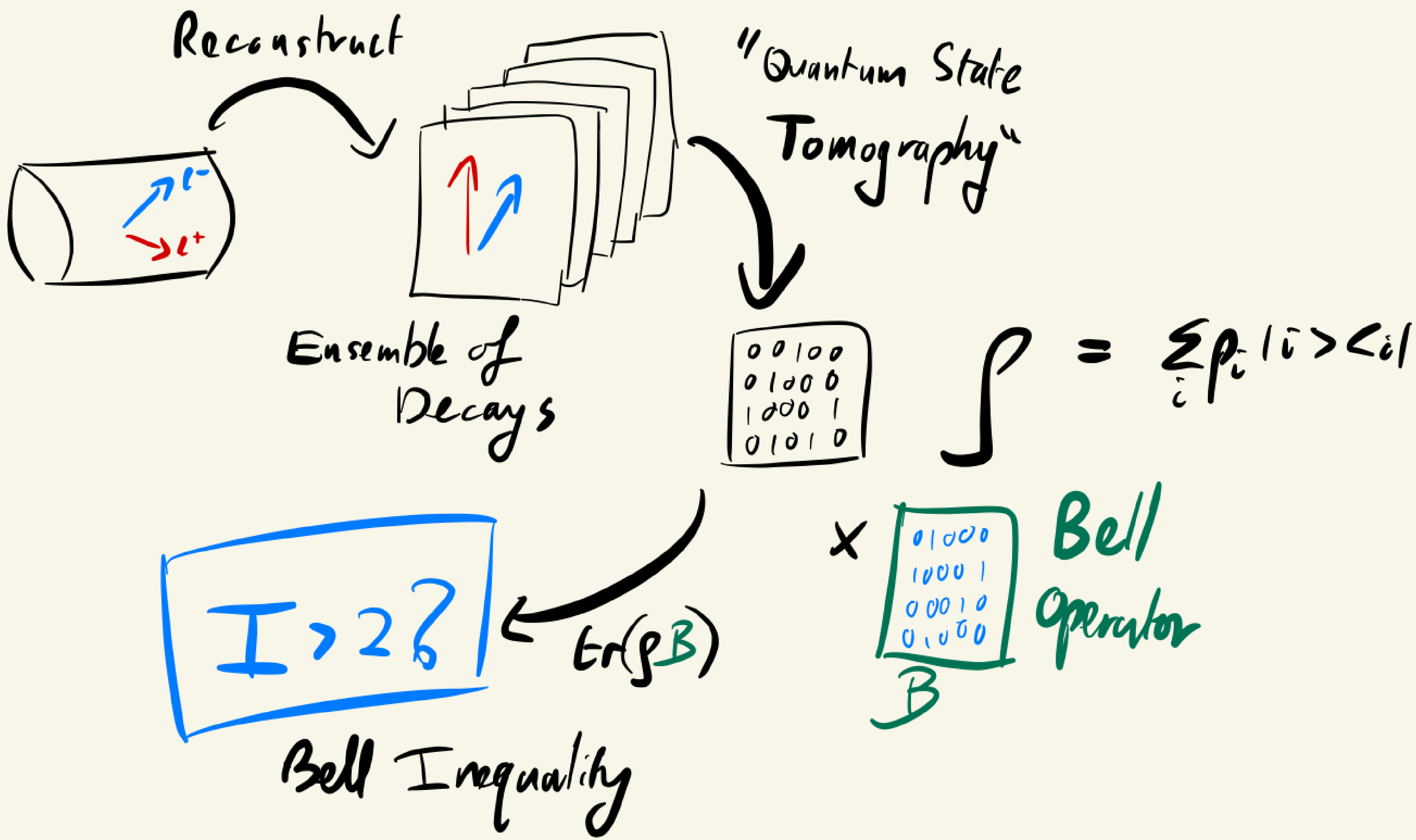
SU(2) weak force is chiral: $\gamma^\mu(1-\gamma^5)$

W boson

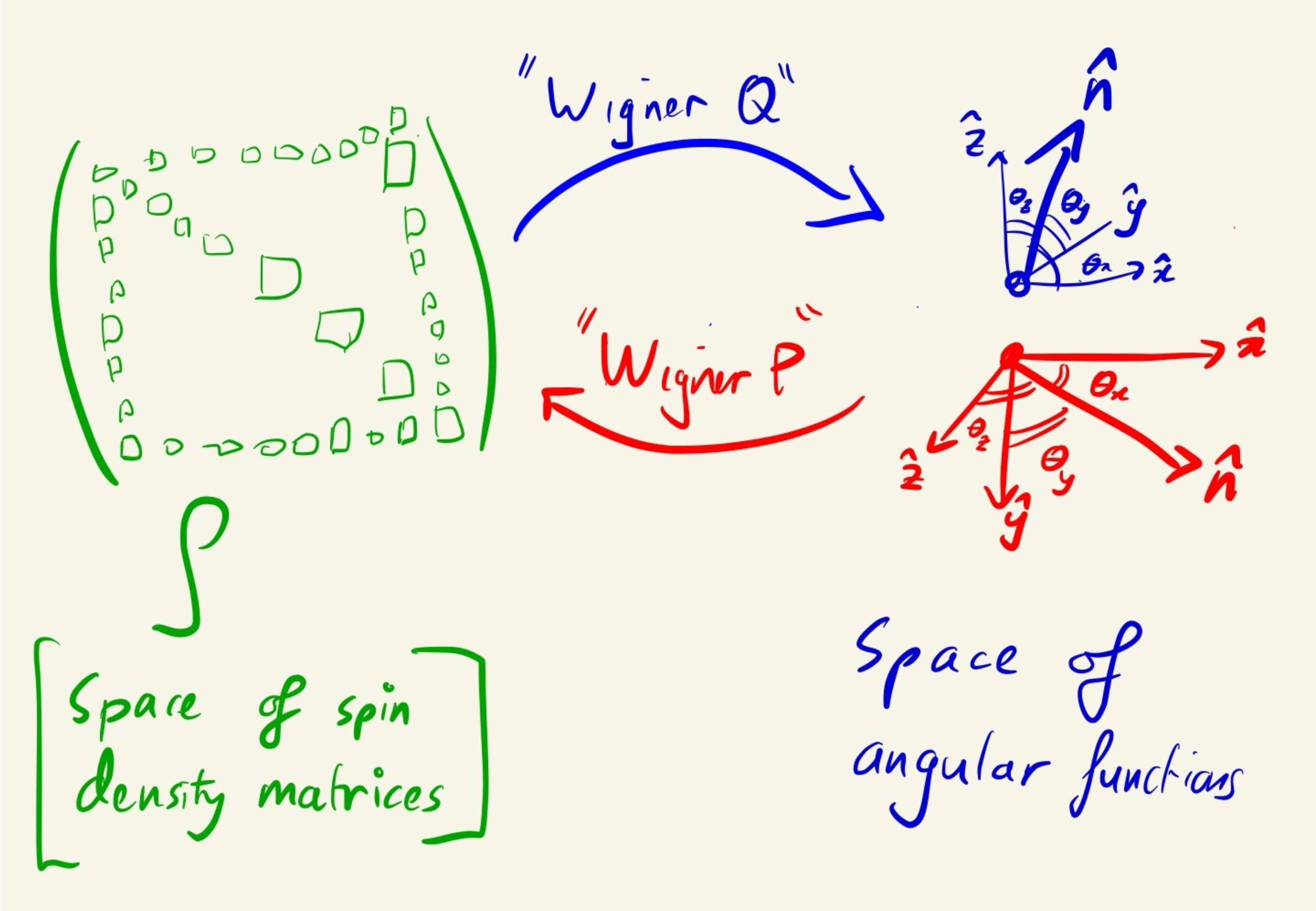
$$W^+ \rightarrow \ell_R^+ + \nu_L$$
$$W^- \rightarrow \ell_L^- + \bar{\nu}_R$$

Decay of a $W^\pm$ boson is equivalent to a projective (von Neumann) quantum measurement of its spin along the axis of the emitted lepton

Observables and density matries



Observables and density matries



Observables and density matries

Transforming between the spaces

Operator $\to$ function

$$\Phi_A^Q(\hat{\mathbf{n}}) = \langle \hat{\mathbf{n}} | A | \hat{\mathbf{n}} \rangle$$

Wigner Q symbols

The Wigner-Weyl formalism for spin

Function $\to$ operator

$$A = \frac{2j+1}{4\pi} \int \mathrm{d}\Omega_{\hat{\mathbf{n}}} \, |\hat{\mathbf{n}}\rangle \, \Phi_A^P(\hat{\mathbf{n}}) \, \langle \hat{\mathbf{n}}| \, ,$$

Wigner P symbols

Observables and density matries

Parameterise ρ

Symmetrically for qutrits in terms of the Gell-Mann matrices λ_i

Single vector boson

$$\rho = \frac{1}{3} I_3 + \sum_{i=1}^{8} a_i \lambda_i,$$

a_i : 8 real parameters $(3^2 - 1)$

- Generalised Gell-Mann matrices $\lambda_i^{(d)}$ exist for any spin
- For spin-half ($d = 2$) they are the Pauli matrices and we get the Bloch sphere
- For $d = 3$ they are the eight generators of SU(3)

Parameterise ρ – bipartite system

Symmetrically for qutrits in terms of the Gell-Mann matrices λ_i

Single vector boson

$$\rho = \tfrac{1}{3} I_3 + \sum_{i=1}^{8} a_i \lambda_i,$$

a_i : 8 real parameters $(3^2 - 1)$

Two vector bosons

$$\rho = \tfrac{1}{9} I_3 \otimes I_3 + \sum_{i=1}^{8} a_i \, \lambda_i \otimes \tfrac{1}{3} I_3 + \sum_{j=1}^{8} b_j \, \tfrac{1}{3} I_3 \otimes \lambda_j + \sum_{i,j=1}^{8} c_{ij} \, \lambda_i \otimes \lambda_j,$$

$8+8+64 = 80$ real parameters $(9^2 - 1)$

Observables and density matries

Extracting the parameters experimentally

Parameters of ρ are the experimentally-measurable classical averages of the Wigner P functions

$$\hat{a}_i = \frac{1}{2}\left\langle \Phi_i^P(\hat{\mathbf{n}}_1) \right\rangle_{\mathrm{av}}$$

$$\hat{b}_i = \frac{1}{2}\left\langle \Phi_i^P(\hat{\mathbf{n}}_2) \right\rangle_{\mathrm{av}}$$

$$\hat{c}_{ij} = \frac{1}{4}\left\langle \Phi_i^P(\hat{\mathbf{n}}_1)\, \Phi_j^P(\hat{\mathbf{n}}_2) \right\rangle_{\mathrm{av}}$$