Quantum information theory at colliders

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in collaboration with
Shiuli Chatterjee, Enrico Sessolo

based on:
KK, E.Sessolo, JHEP 07 (2024) 156, JHEP 04 (2026) 014
and work in progress

3rd International Workshop on Machine Learning and Quantum Computing Applications in Medicine and Physics

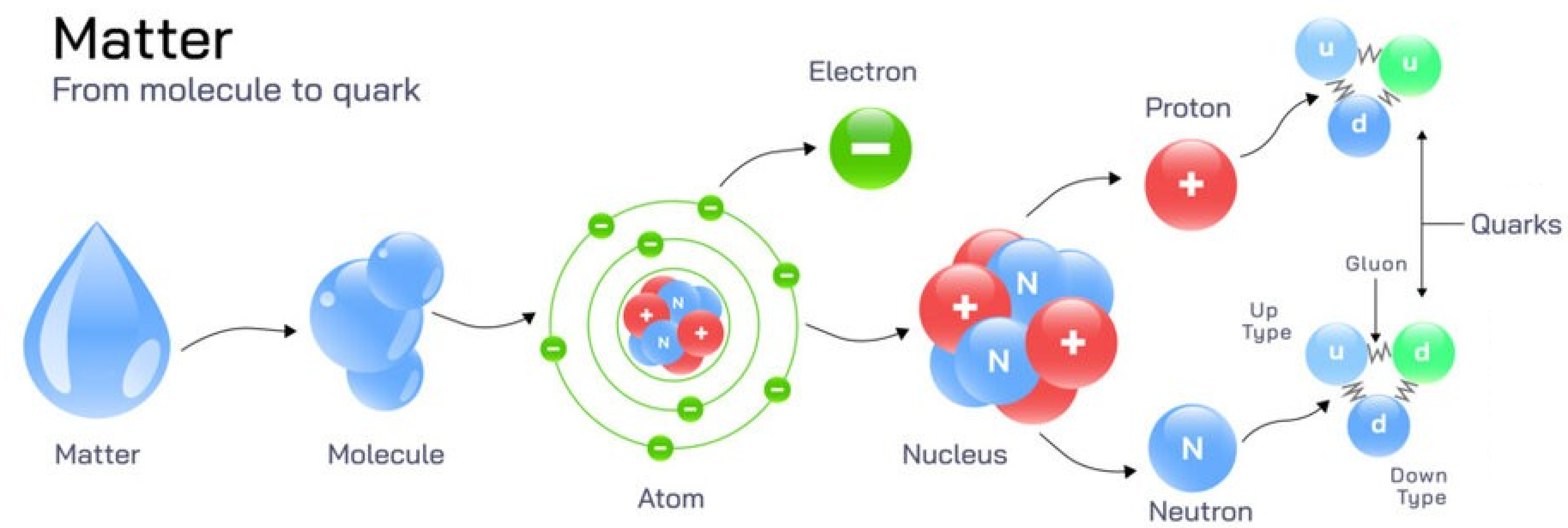
Warsaw, 08.09.2026

National Science Centre Poland

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

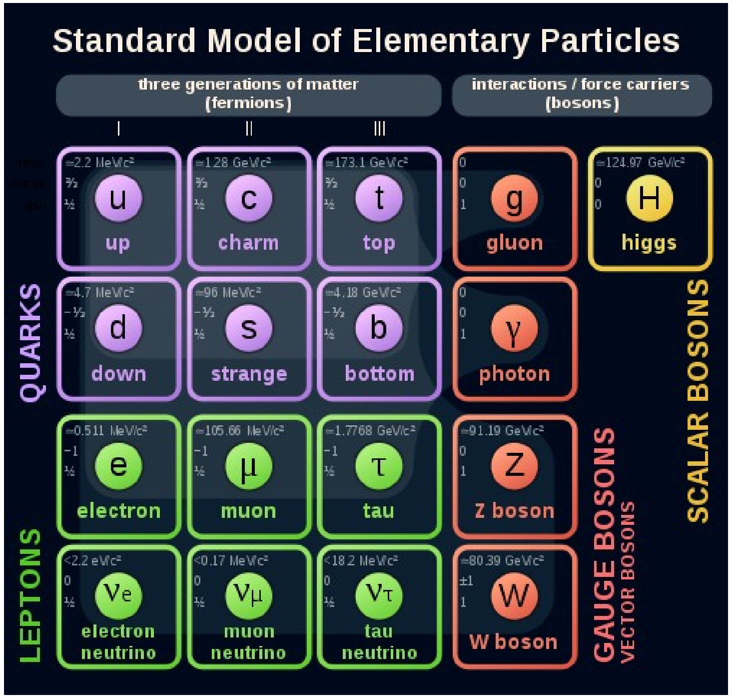
Particle physics in a nutshell

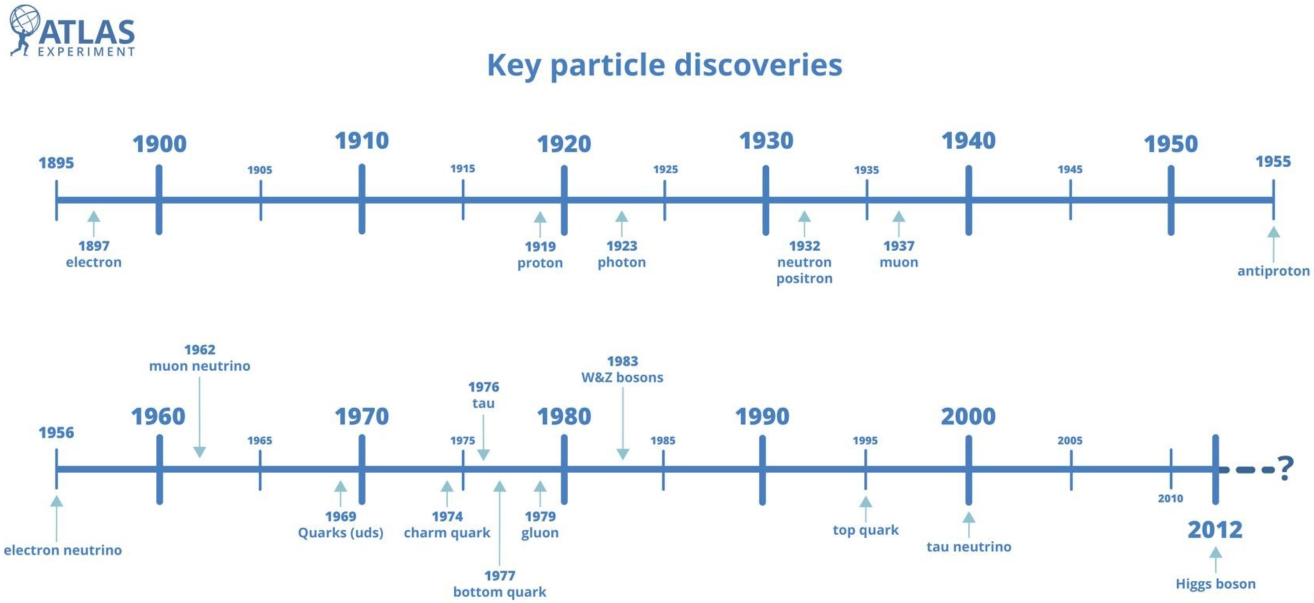
Particles - fundamental building blocks



macroscopic $\quad 10^{-9}\,\mathrm{m} \quad 10^{-10}\,\mathrm{m} \quad 10^{-14}\,\mathrm{m} \quad 10^{-15}\,\mathrm{m} \quad \leq 10^{-18}\,\mathrm{m}$

Standard Model - history of success

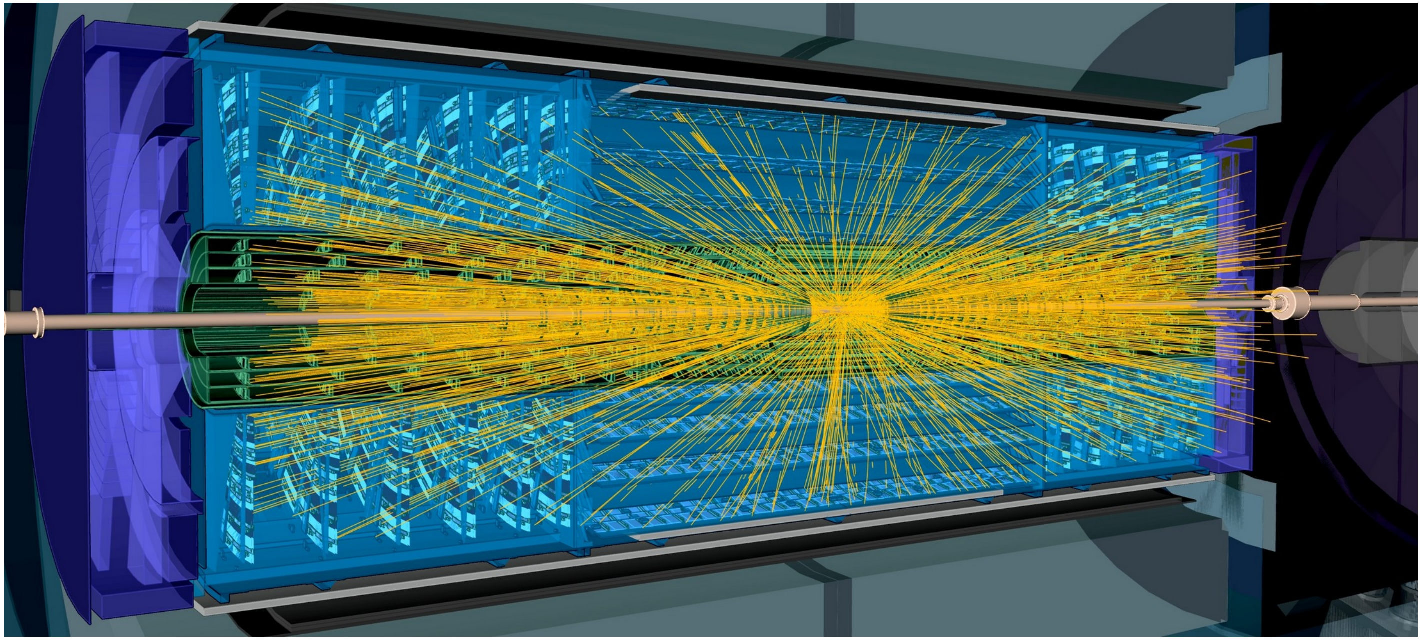




Theoretical predictions agree with the experiment with great accuracy

Colliding particles - a needle in a haystack

accelerator eg. Large Hadron Collider at CERN



ultrarelativistic collisions of particles

detector

we **measure** properties of the outgoing particles: energy, direction, angular distribution

→

data analysis + theory

we construct **observables** and **kinematical variables**

eg. cross section, decay widths, transverse mass

→

we test Standard Model, we look for New Physics

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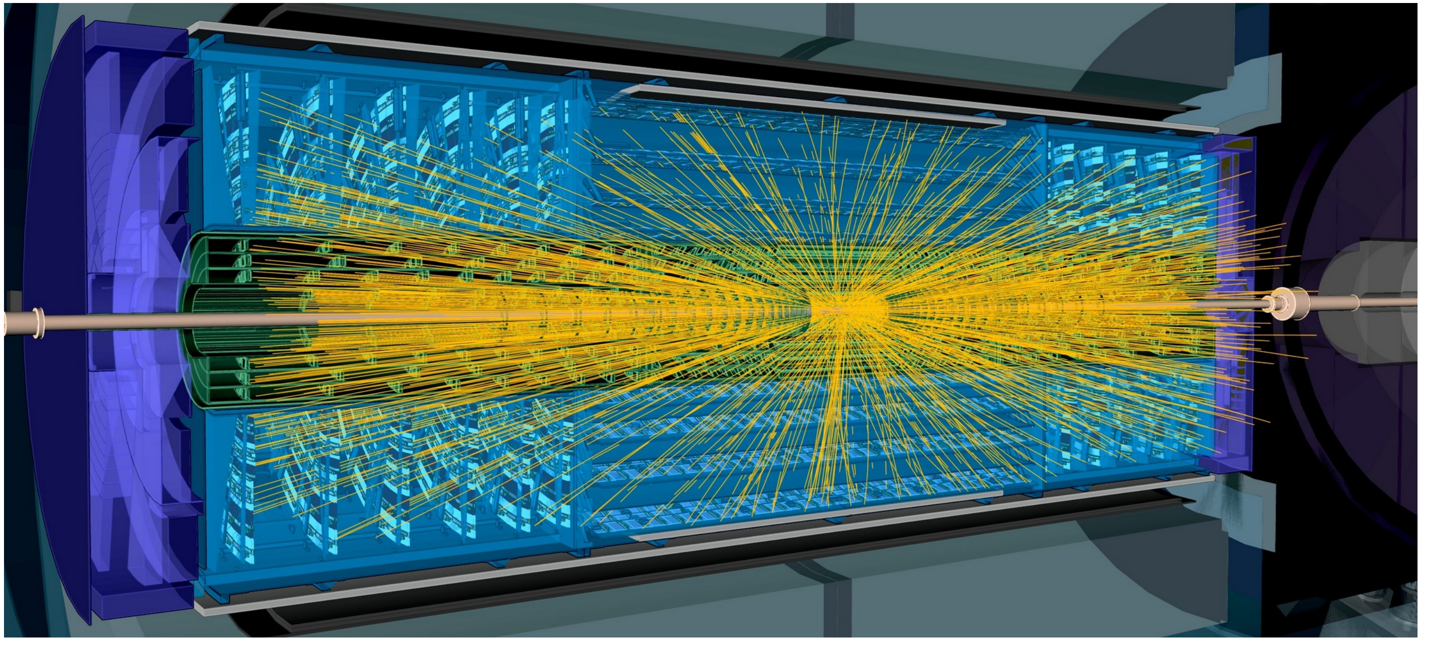

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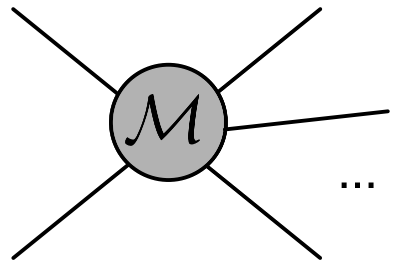
data analysis + theory

MACHINE LEARNING see talks by: Sascha, Alexander, Pietro, Piotr

Theoretical toolbox - perturbation theory

to compare with experiment:



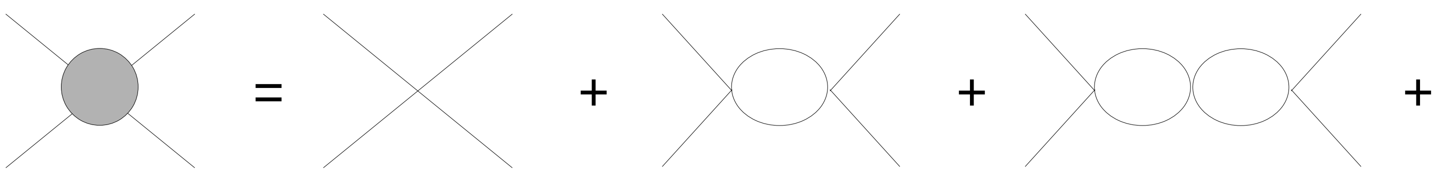
= ?

scattering amplitude

$$\mathcal{M} \quad = \quad \mathcal{M}^{(0)} \quad + \quad \mathcal{M}^{(1)} \quad + \quad \mathcal{M}^{(2)} \quad + \cdots$$

small parameter (coupling): g $\qquad g^2 \qquad g^3$

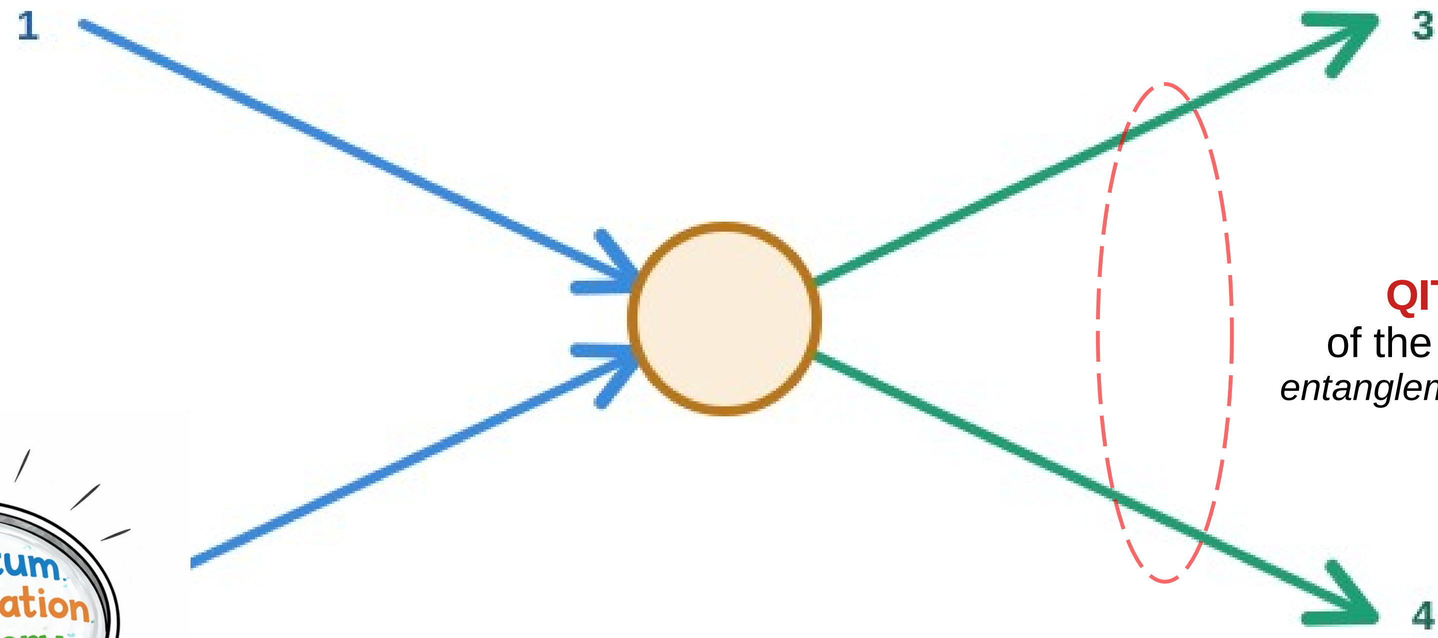
Feynman diagrams:



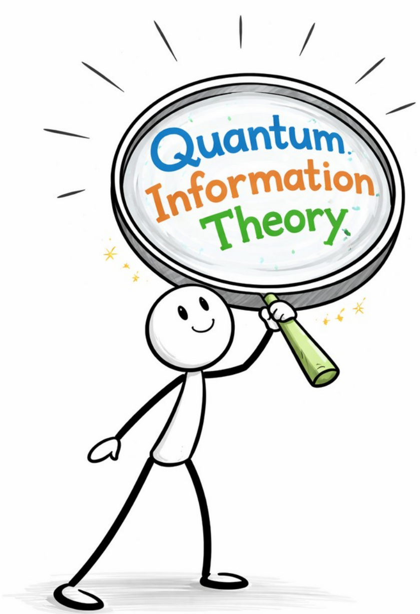
tree level 1 loop 2 loops

Quantum information in particle physics

Quantum information in scattering



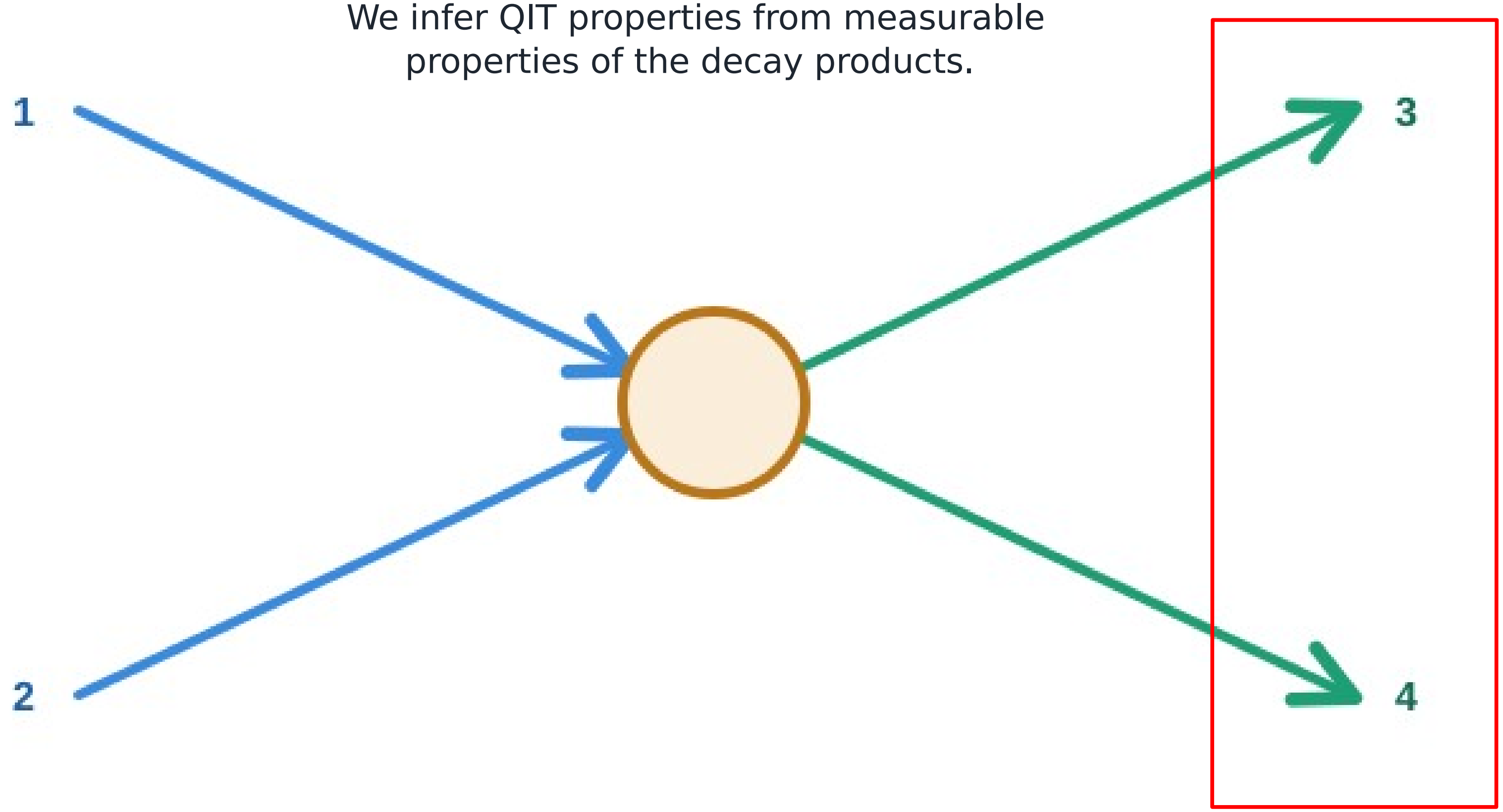
QIT properties
of the scattered state:
entanglement, magic, steering



Quantum information in scattering

QUANTUM TOMOGRAPHY

We infer QIT properties from measurable
properties of the decay products.

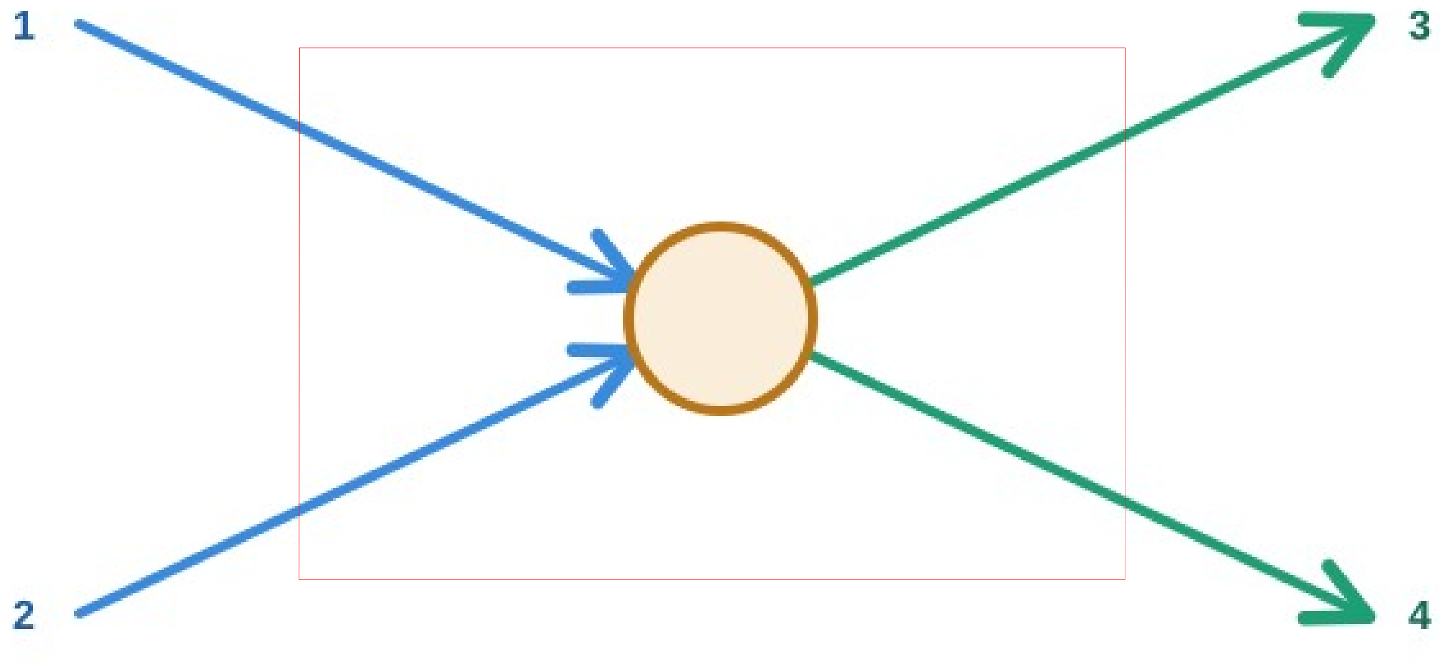


**Goal: to build QIT-based observables
for future colliders**

Quantum information in scattering

QI PROPERTIES OF THE SCATTERING OPERATOR

how QIT properties are generated
in a scattering event



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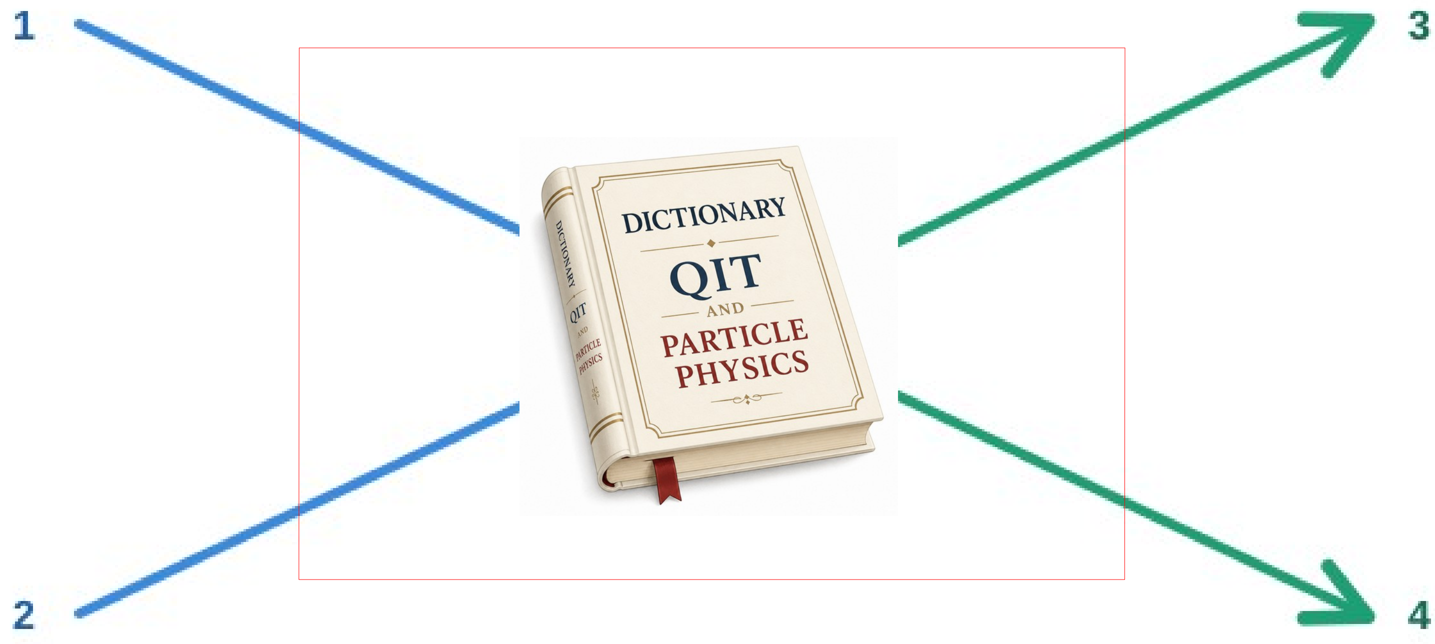
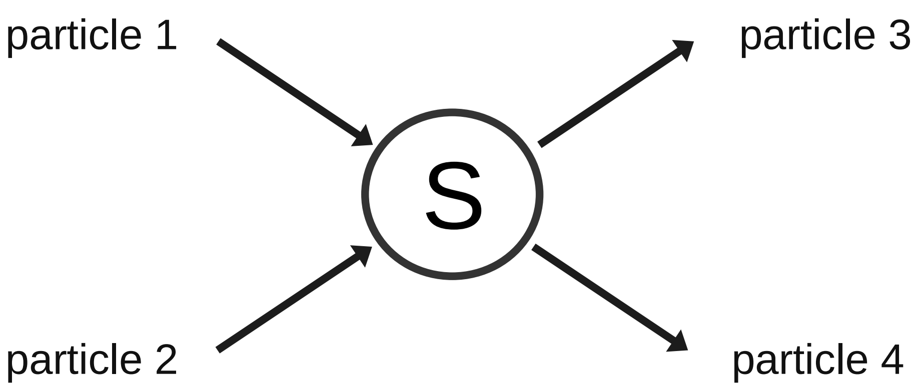


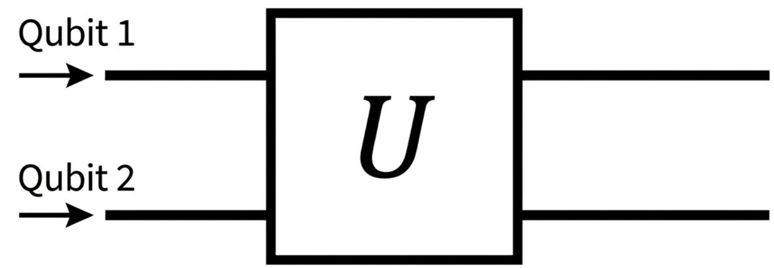
**Goal: to build a "dictionary" between
QIT and particle physics**

Scattering event as a quantum gate

particle physics



quantum information theory



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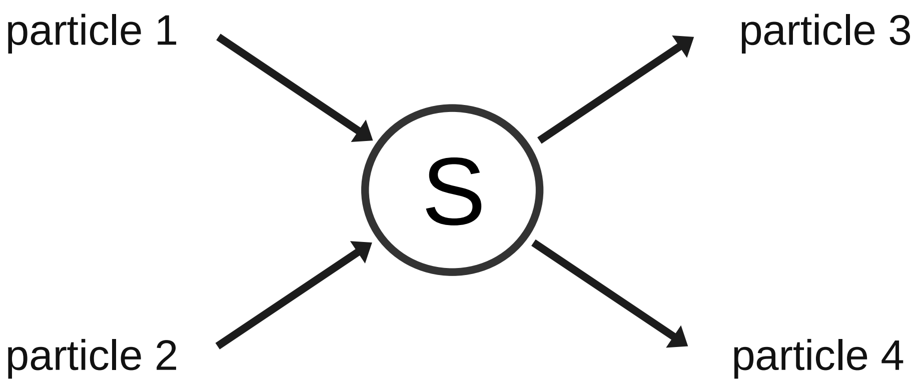
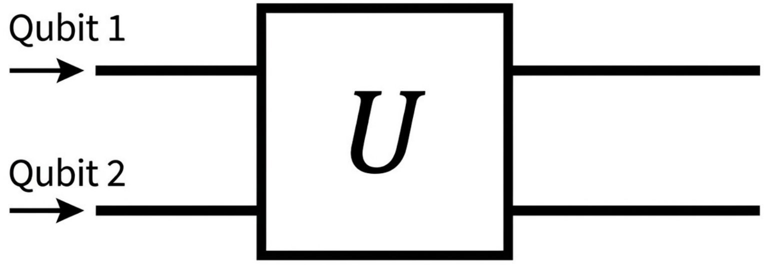


ex. SWAP in low-scale QCD
I. Low and T. Mehen, Phys. Rev. D 104, 074014

quantum information theory



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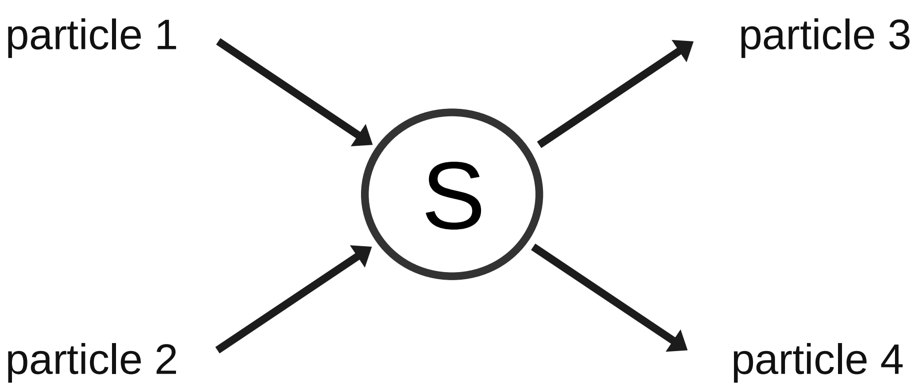

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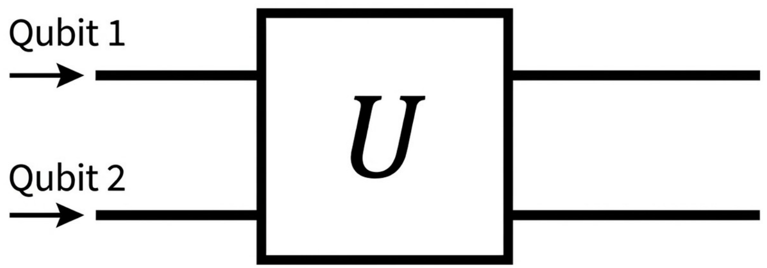
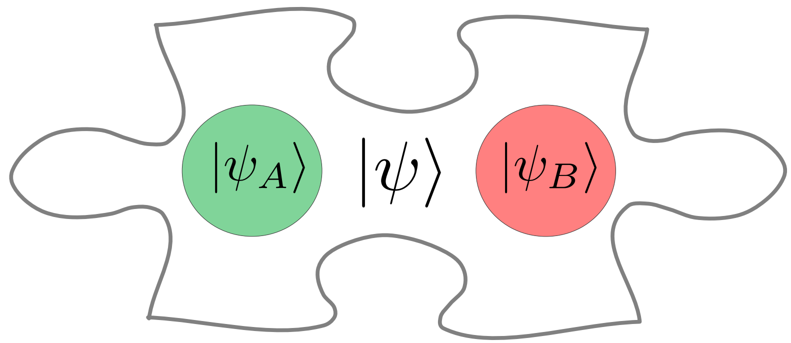


Let's look at entanglement in a scattering process!

Entanglement in scattering

Entanglement bit by bit

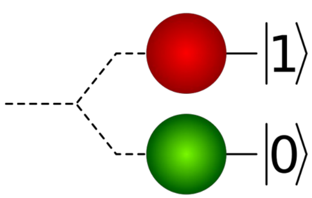


$$|\psi\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle$$

entanglement = non-separability

Example 1: **a qubit**

$$\boxed{|\psi\rangle = \alpha|0\rangle + \beta|1\rangle}$$



$$|\alpha|^2 + |\beta|^2 = 1$$

two-qubit state

$$\boxed{|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle}$$

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$$

separable $|\psi\rangle = (\alpha_1|0\rangle + \beta_1|1\rangle) \otimes (\alpha_2|0\rangle + \beta_2|1\rangle)$

entangled $|\psi\rangle = \frac{1}{\sqrt{2}}|00\rangle \pm \frac{1}{\sqrt{2}}|11\rangle \qquad |\psi\rangle = \frac{1}{\sqrt{2}}|01\rangle \pm \frac{1}{\sqrt{2}}|10\rangle$

Which entanglement?

A particle carries several kinds of quantum information:

MOMENTUM	SPIN	FLAVOR	
Where is the particle going? Direction, energy.	Where is the particle spin pointing to?	What particle it is?	and others ...

$$|\text{particle}\rangle = |\text{momentum, spin, flavor,} \ldots\rangle$$

$$\mathcal{H} = \mathcal{H}_{\text{momentum}} \otimes \mathcal{H}_{\text{spin}} \otimes \mathcal{H}_{\text{flavour}} \otimes \ldots$$

So before asking “how much entanglement?”, we must say:
entanglement between which degrees of freedom?

What if we don't observe everything?

FULL FINAL STATE

momentum + spin + ...

$\rho = |\text{out}\rangle\langle\text{out}|$

this is what comes out from the scattering

IGNORE MOMENTUM

Trace over momentum

$\mathrm{Tr}_{\text{momentum}}(\rho)$

this is what we do not observe

REDUCED STATE

spin state

ρ_{spin}

this is what we want to entangle

Reduced state depends on:

- scattering operator $S = \mathbf{1} + i\mathcal{M}$

  remember: perturbative expansion

- initial spin state $|\mathcal{A}\rangle$

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Unitarity preserved!

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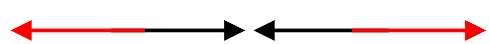
Unitarity preserved!

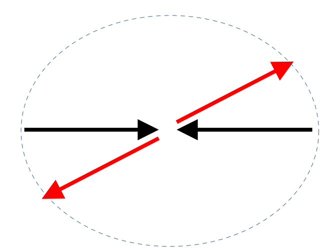
reduced state reflects perturbative nature of the interaction

$$\rho_{\mathrm{spin}} = |\mathcal{A}\rangle\langle\mathcal{A}| + i\Delta(\mathcal{M}_{FW}|\mathcal{A}\rangle\langle\mathcal{A}|) - i\Delta(|\mathcal{A}\rangle\langle\mathcal{A}|\mathcal{M}_{FW}^{\dagger}) + \Delta\int d\Pi_2\,(\mathcal{M}|\mathcal{A}\rangle\langle\mathcal{A}|\mathcal{M}^{\dagger})$$

no interaction



interaction with no momentum exchange



(Perturbative) qubit entanglement

concurrence: $C(\rho_{\text{spin}}) = \max\{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\}$

λ: eigenvalues of $R_F = \rho_F(\sigma_y \otimes \sigma_y)\rho_F^*(\sigma_y \otimes \sigma_y)$

Hill, Wooters Phys. Rev. Lett. 78 (1997)
Wooters Phys. Rev. Lett. 80 (1998)

entanglement measure:

$\mathcal{C} = 0$ **no entanglement** $\mathcal{C} = 1$ **max. entanglement**

in perturbative scattering:

KK, E.M. Sessolo, JHEP 04 (2026) 014

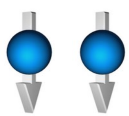
$$\boxed{\mathcal{C}(\rho_F) = 2\Delta|\langle\mathcal{B}|\mathcal{M}_{FW}|\mathcal{A}\rangle|}$$

$|\mathcal{B}\rangle = (\sigma_y \otimes \sigma_y)|\mathcal{A}^*\rangle$

"spin"-flipped initial state

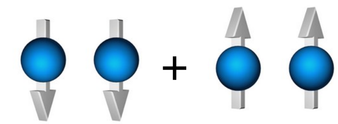
entanglement is generated by the **inelastic forward amplitude**

cartoon interpretation:

$|00\rangle$  $\longrightarrow$ $\boxed{S = \mathbf{1} + i\mathcal{M}_{\text{FW}}}$ $\longrightarrow$

no interaction

inelastic interaction



$\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$

(Perturbative) qubit entanglement

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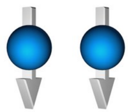
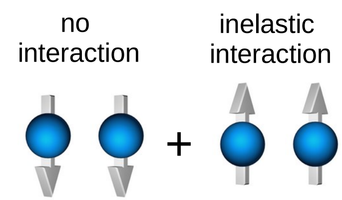
$|00\rangle$  $\longrightarrow$ $\boxed{S = \mathbf{1} + i\mathcal{M}_{\text{FW}}}$ $\longrightarrow$ 

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

No entanglement condition: $\boxed{\mathcal{M}_{\text{FW}}^{\text{inelastic}} = 0}$

may indicate a symmetry of the underlying theory

symmetries may prevent entanglement generation

Emergent symmetries

A very enticing idea ...

Symmetries arise from **entanglement extremization** in scattering processes

- non-relativistic baryon-baryon scattering → SU(4) and SU(16) global symmetries from **minimizing** entanglement among spins

  Beane, Kaplan, Klco, Savage,
  PRL 122 (2019) 102001

- quantum electrodynamics → U(1) gauge symmetry from **maximizing** entanglement among helicities

  Cervera-Lierta et al., SciPost Phys 3 (2017) 036
  Fedida, Serafini, PRD 107 (2023) 116007

- Two-Higgs-doublet model → indications of SO(8) global symmetry from **minimizing** entanglement among Higgs boson “flavors”

  Carena, Low, Wagner, Xiao
  PRD 109 (2024) L051901

Example: flavored scalar scattering

KK, E.M.Sessolo, JHEP 07 (2024) 156

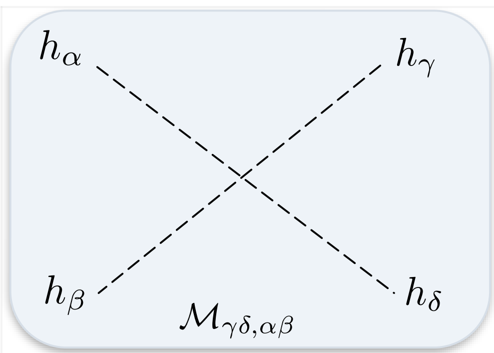
Qubit: type (flavor) of a scalar $H_\alpha = \begin{pmatrix} h_\alpha^+ \\ h_\alpha^0 \end{pmatrix} \quad \alpha = 1,2$

scalar potential:

$$V(H_1,H_2) = \lambda_1\,(H_1^\dagger H_1)^2 + \lambda_2\,(H_2^\dagger H_2)^2 + \lambda_3\,(H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4\,(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \Big(\lambda_5\,(H_1^\dagger H_2)^2 + \lambda_6\,(H_1^\dagger H_1)(H_1^\dagger H_2) + \lambda_7\,(H_2^\dagger H_2)(H_1^\dagger H_2) + \mathrm{H.c.}\Big)$$

different ways particles interact

Let's look at the process:



different channels possible

$$h^+h^0 \to h^+h^0$$
$$h^+h^- \to h^0h^0$$
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$$h^+h^- \to h^+h^-$$
$$h^0h^0 \to h^+h^-$$

different amplitudes

ex: $\mathcal{M}^{(0)}(h^+h^0 \to h^+h^0) = \begin{pmatrix} 2\lambda_1 & \lambda_6 & \lambda_6 & 2\lambda_5 \\ \lambda_6 & \lambda_3 & \lambda_4 & \lambda_7 \\ \lambda_6 & \lambda_4 & \lambda_3 & \lambda_7 \\ 2\lambda_5 & \lambda_7 & \lambda_7 & 2\lambda_2 \end{pmatrix}$

couplings λ indicate flavor exchange ex:

$$h_1^+h_1^0 \xrightarrow{\lambda_5} h_2^+h_2^0$$
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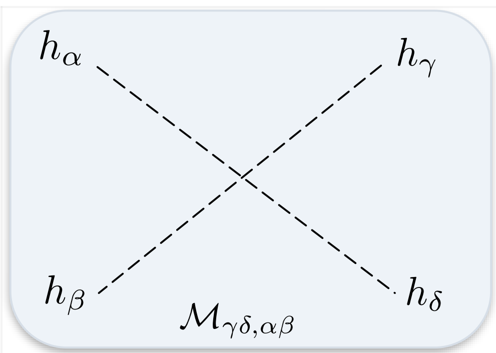

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Let's calculate entanglement:

$$\mathcal{C}(|11\rangle) = \mathcal{C}(|22\rangle) = 4\Delta|\lambda_5|$$

$$\mathcal{C}(|12\rangle) = \mathcal{C}(|21\rangle) = 2\Delta|\lambda_4|$$

Our postulate: **interaction does not entangle qubits**

$$\boxed{\mathcal{C} = 0}$$

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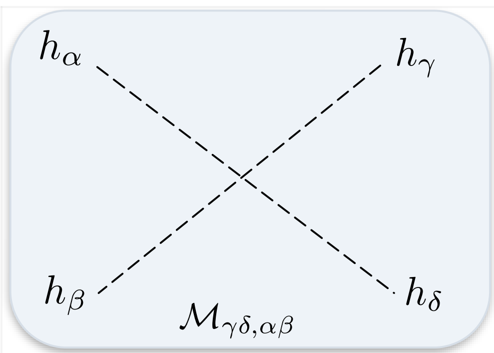

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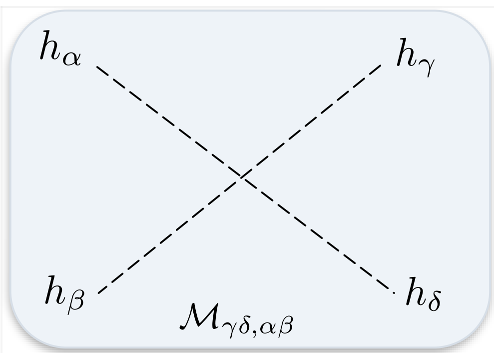

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$$h^+h^- \to h^0h^0$$
$$h^0h^0 \to h^0h^0$$
$$h^+h^- \to h^+h^-$$
$$h^0h^0 \to h^+h^-$$

different amplitudes

ex: $\mathcal{M}^{(0)}(h^+h^0 \to h^+h^0) = \begin{pmatrix} 2\lambda_1 & \lambda_6 & \lambda_6 & 2\lambda_5 \\ \lambda_6 & \lambda_3 & \lambda_4 & \lambda_7 \\ \lambda_6 & \lambda_4 & \lambda_3 & \lambda_7 \\ 2\lambda_5 & \lambda_7 & \lambda_7 & 2\lambda_2 \end{pmatrix}$

couplings λ indicate flavor exchange ex: $h_1^+h_1^0 \xrightarrow{\lambda_5} h_2^+h_2^0$

$h_1^+h_1^0 \xrightarrow{\lambda_1} h_1^+h_1^0$

Let's calculate entanglement

$$\mathcal{C}(|11\rangle) = \mathcal{C}(|22\rangle) = 4\Delta|\lambda_5|$$

$$\mathcal{C}(|12\rangle) = \mathcal{C}(|21\rangle) = 2\Delta|\lambda_4|$$

Our postulate: **interaction does not entangle qubits**

$$\boxed{\mathcal{C} = 0} \longrightarrow \lambda_5 = \lambda_4 = 0$$

We add all channels and a generic separable initial state

$$\lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0$$

Example: flavored scalar scattering

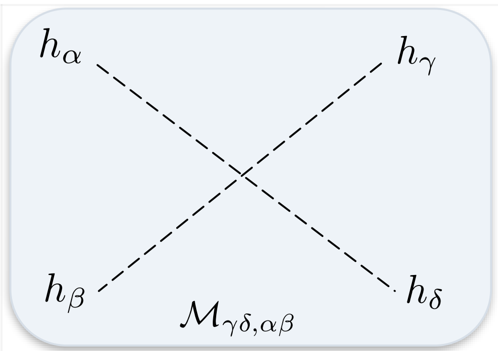
KK, E.M.Sessolo, JHEP 07 (2024) 156

Qubit: type (flavor) of a scalar $H_\alpha = \begin{pmatrix} h_\alpha^+ \\ h_\alpha^0 \end{pmatrix} \quad \alpha = 1, 2$

scalar potential: $V(H_1, H_2) = \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \cancel{\lambda_3} (H_1^\dagger H_1)(H_2^\dagger H_2) + \cancel{\lambda_4} (H_1^\dagger H_2)(H_2^\dagger H_1)$
$+ \left(\cancel{\lambda_5} (H_1^\dagger H_2)^2 + \cancel{\lambda_6} (H_1^\dagger H_1)(H_1^\dagger H_2) + \cancel{\lambda_7} (H_2^\dagger H_2)(H_1^\dagger H_2) + \mathrm{H.c.} \right)$

different ways particles interact

Let's look at the process:



different channels possible

$$\begin{aligned} h^+ h^0 &\to h^+ h^0 \\ h^+ h^- &\to h^0 h^0 \\ h^0 h^0 &\to h^0 h^0 \\ h^+ h^- &\to h^+ h^- \\ h^0 h^0 &\to h^+ h^- \end{aligned}$$

different amplitudes

ex: $\mathcal{M}^{(0)}(h^+ h^0 \to h^+ h^0) = \begin{pmatrix} 2\lambda_1 & \lambda_6 & \lambda_6 & 2\lambda_5 \\ \lambda_6 & \lambda_3 & \lambda_4 & \lambda_7 \\ \lambda_6 & \lambda_4 & \lambda_3 & \lambda_7 \\ 2\lambda_5 & \lambda_7 & \lambda_7 & 2\lambda_2 \end{pmatrix}$

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We add all channels and a generic separable initial state

$$\lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0 \Rightarrow SO(4) \times SO(4)$$

symmetry of the theory

Impact of the initial state

The quantum input: beam polarization

$$e^+ + e^- \rightarrow e^+ + e^-$$

qubit = spin

UNPOLARIZED

Spin directions are random.

The state is maximally mixed.

$$\rho_{\rm in}^{\rm Un} = \begin{pmatrix} \frac{1}{4} & 0 & 0 & 0 \\ 0 & \frac{1}{4} & 0 & 0 \\ 0 & 0 & \frac{1}{4} & 0 \\ 0 & 0 & 0 & \frac{1}{4} \end{pmatrix}$$

LONGITUDINAL

Spin aligned with beam direction.

The state is pure.

$$\rho_{\rm in}^{\rm L} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

TRANSVERSE

Spin perpendicular to the beam.

Tunable coherence parameter b_x.

$$\rho_{\rm in}^{\rm T} = \begin{pmatrix} \frac{1}{4} & \frac{b_x}{4} & \frac{b_x}{4} & \frac{b_x^2}{4} \\ \frac{b_x}{4} & \frac{1}{4} & \frac{b_x^2}{4} & \frac{b_x}{4} \\ \frac{b_x}{4} & \frac{b_x^2}{4} & \frac{1}{4} & \frac{b_x}{4} \\ \frac{b_x^2}{4} & \frac{b_x}{4} & \frac{b_x}{4} & \frac{1}{4} \end{pmatrix}$$

b_x controls purity:
$b_x = 0$ maximally mixed
$0 < b_x < 1$ mixed
$b_x = 1$ pure

The interaction is the same.

We change the quantum state that we feed into it.

Too much mixing kills entanglement

Transverse polzarization controls entanglement

very mixed | partially polarized | highly polarized

NO ENTANGLEMENT | **THRESHOLD** | **ENTANGLEMENT POSSIBLE**

$$b_x = 0.4$$

absolute separability

Verstraete, Audenaert, De Moor, PRA 64 (2001)

A sufficiently mixed state cannot be entangled by any unitary interaction.

$$\mathcal{C} = -\frac{1}{2}\left(1 - b_x^2\right) + 4 b_x e^2 \Delta$$

S. Chatterjee, KK, E.M.Sessolo, work in progress

Entanglement increases with the beam polarization.

This is a statement about the input state - not about the scattering operator.

Conclusions

- Quantum information theory can provide a **new insight** in our understaning of scattering processes.
- Qubit entanglement **generated by inelastic forward amplitude** at the leading perturbative order.
- **Absolute separability of mixed states** (driven by the amount of transverse polarization) introduces a threshold for entanglement generation.
- Entanglement extremization may lead to **emergence of symmetries** in particle physics.