Probing quantum entanglement with the ATLAS detector

XL Biennal RSEF

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2026 07 20

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CSIC Consejo Superior de Investigaciones Científicas

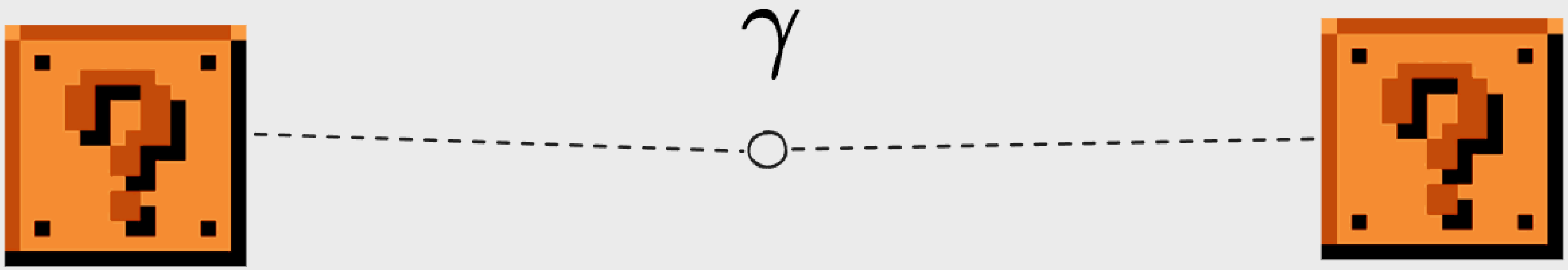
Vniversitat de València

IFIC Institut de Física Corpuscular

Excelencia Severo Ochoa

Introduction

Quantum Entanglement: Why is it interesting?



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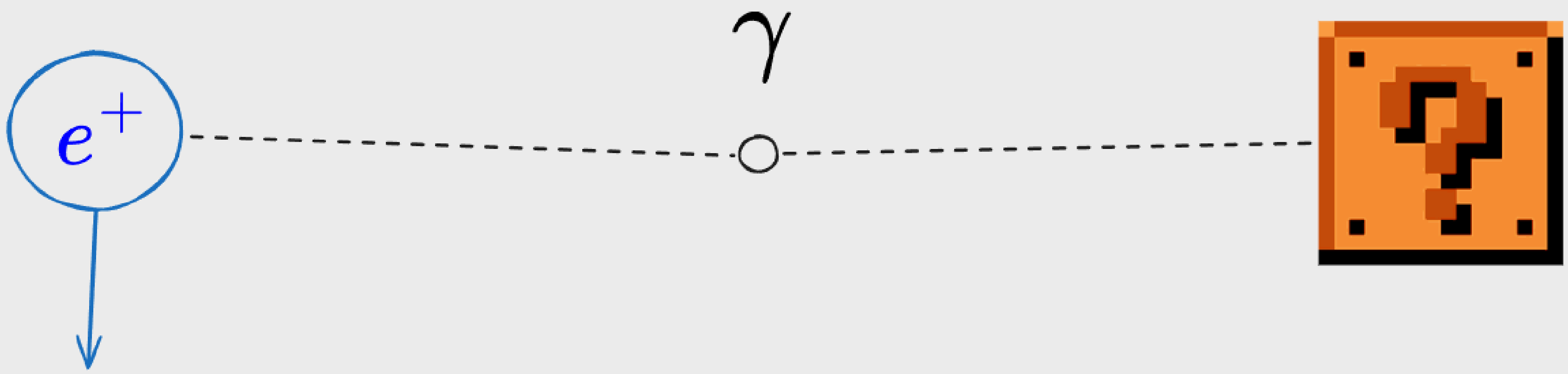

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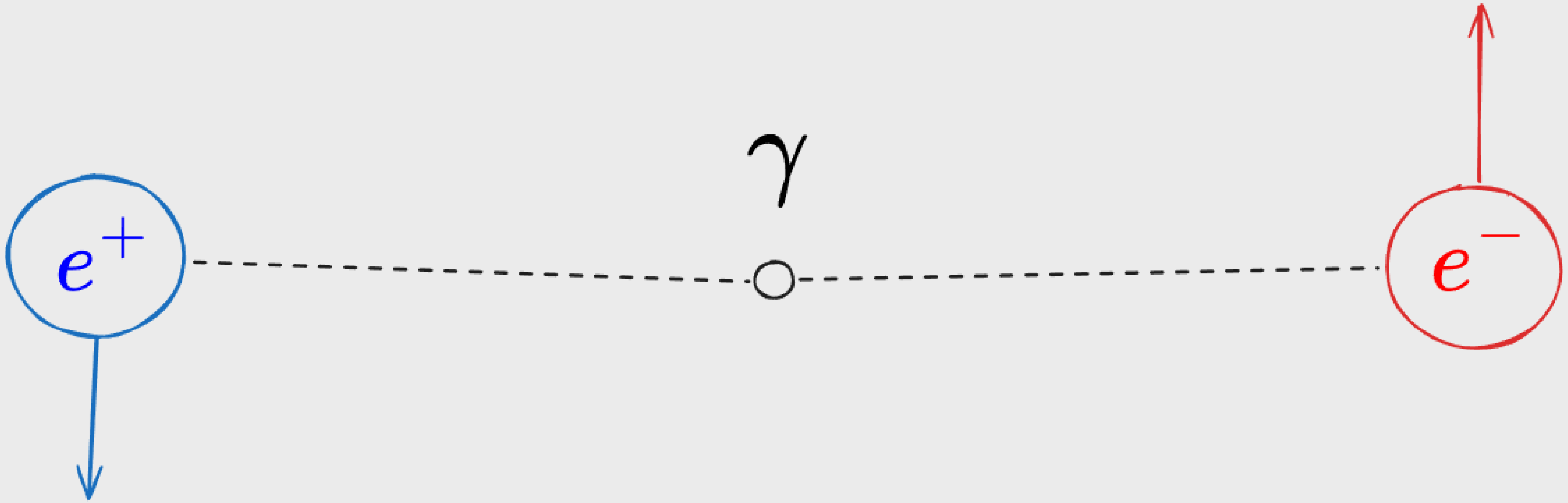

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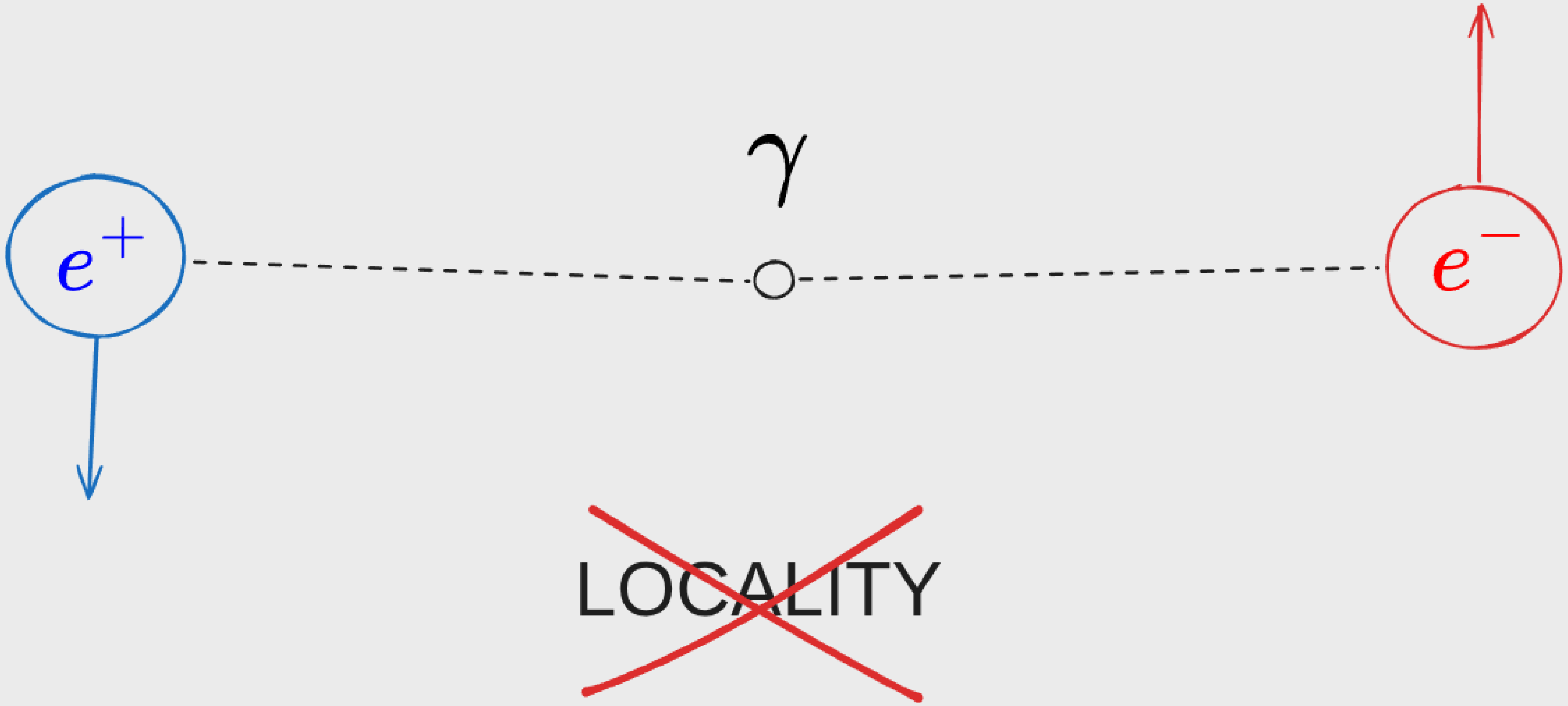

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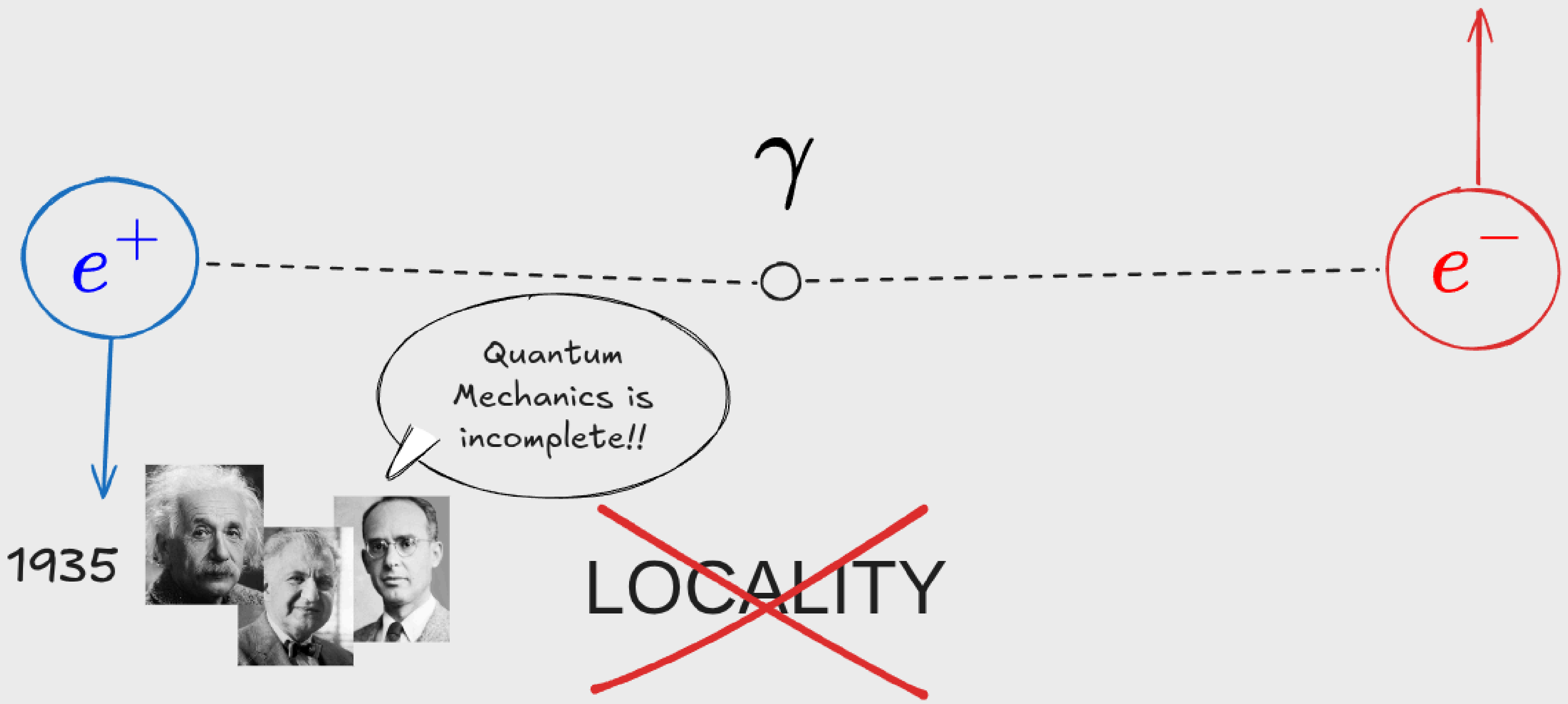
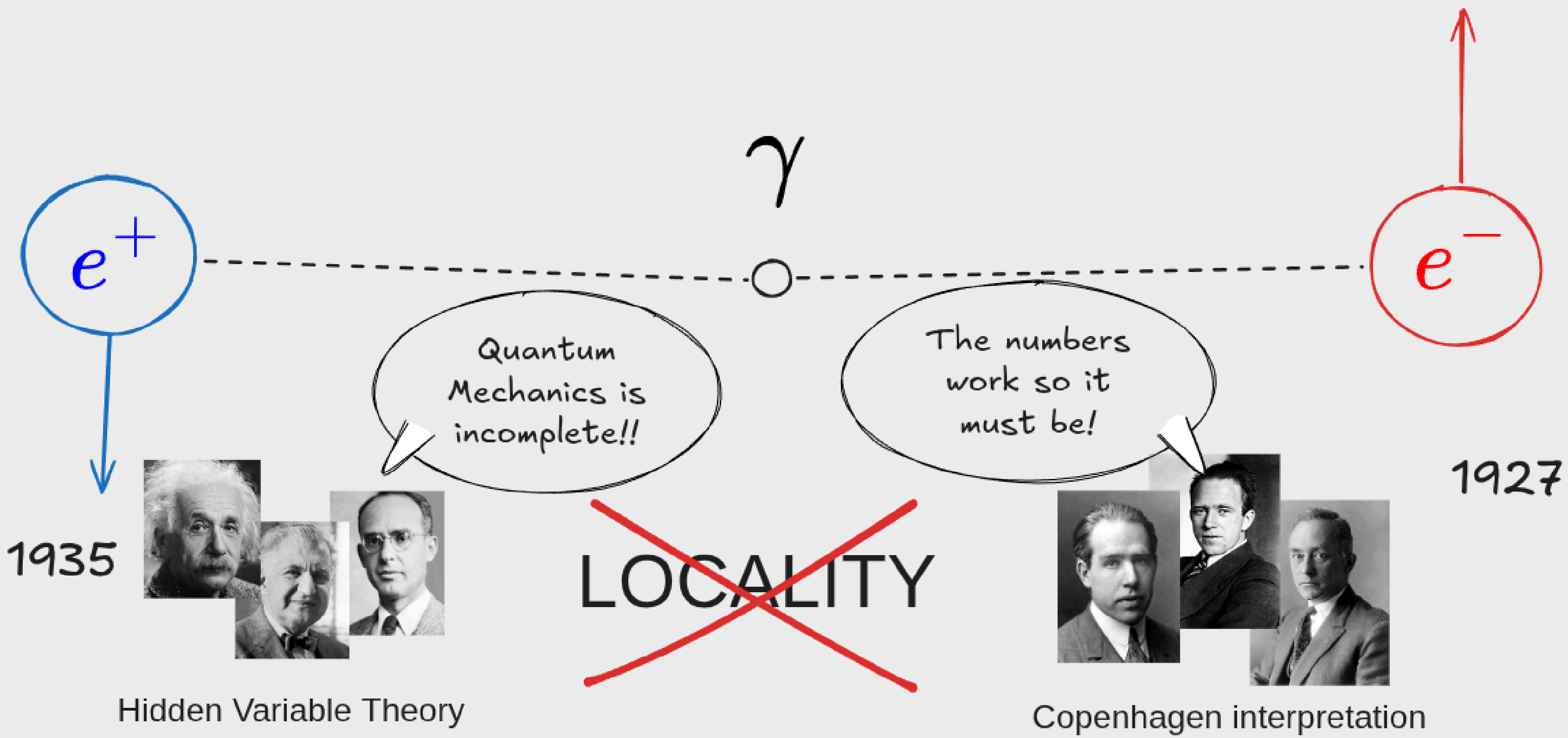


Hidden Variable Theory

Quantum Entanglement: Why is it interesting?



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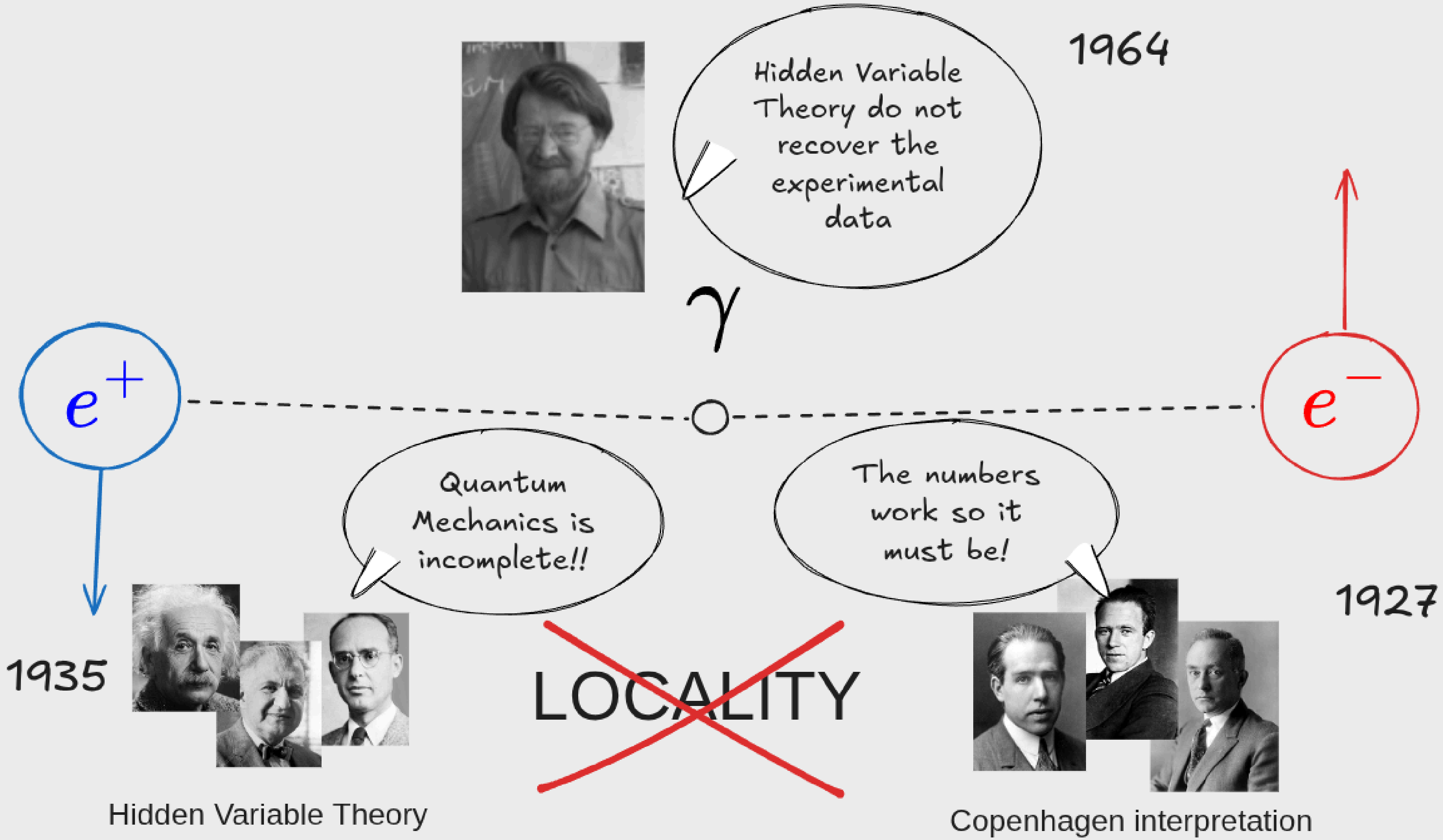

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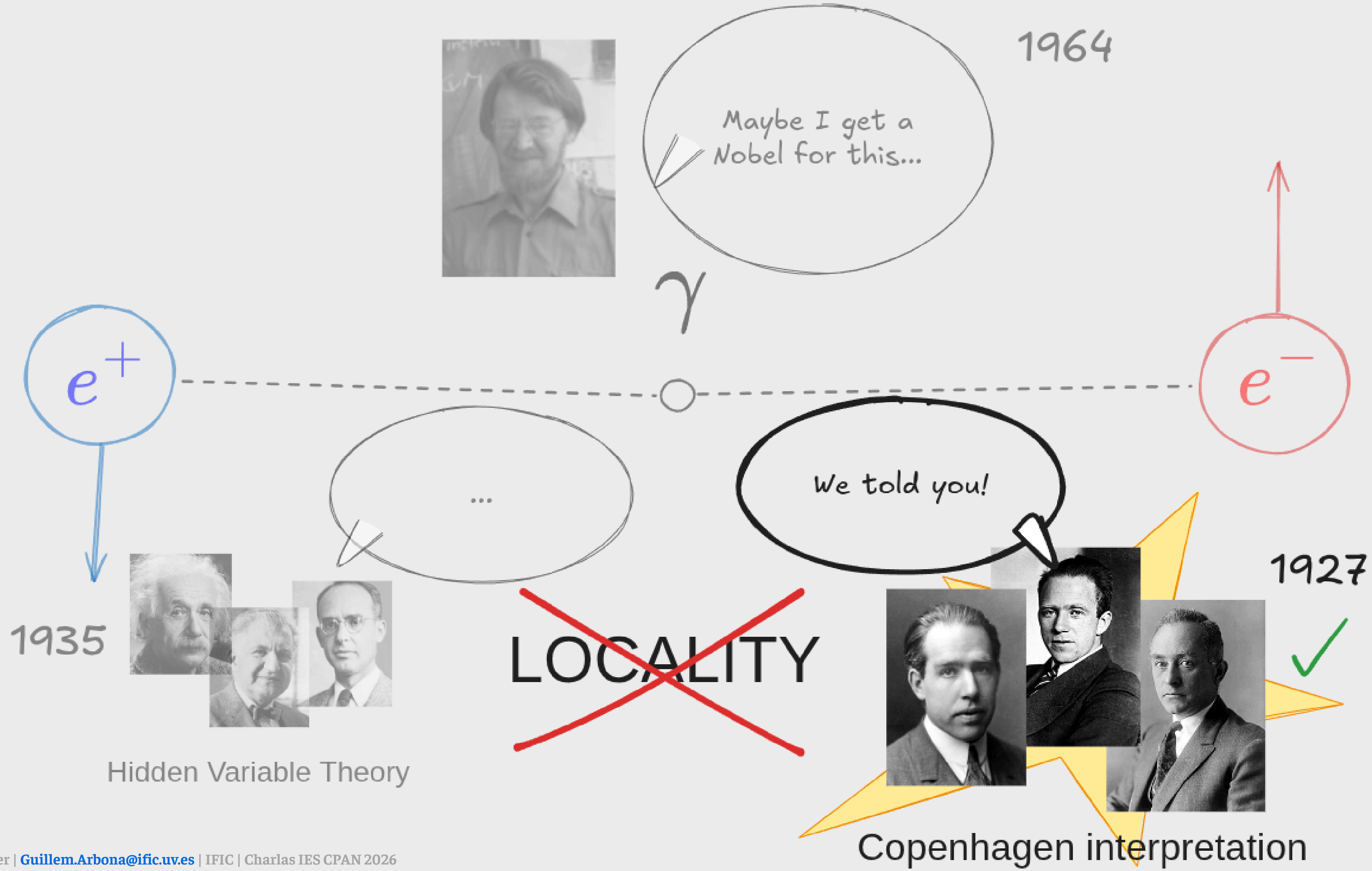


Entanglement through history

Observations

Photons (first measurement of Bell inequalities, 1987), Atoms (1997), Superconductors (2006), Mesons (2007), Neutrinos (2016), Analog Hawking radiation (2016), Nitrogen-vacancy centers in diamond (2013), Loophole free violations of Bell's inequality (2015).

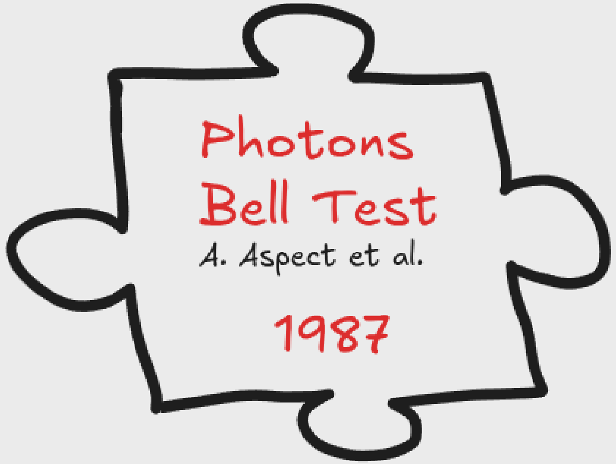
Studies in High Energy Physics (HEP)

Entanglement in relativistic QFT (2004), $K^0\bar{K}^0$ pairs Bell's inequalities (2002), Neutrino oscillations with entanglement (2010), $t\bar{t}$ pairs in LHC (2021)

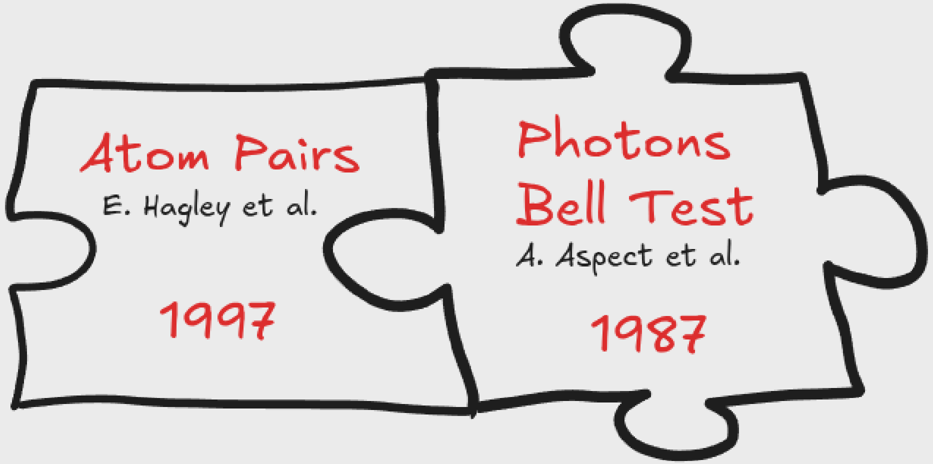
A part from its fundamental interest

Metrology (2004), Teleportation (1997), Q. Information 2000

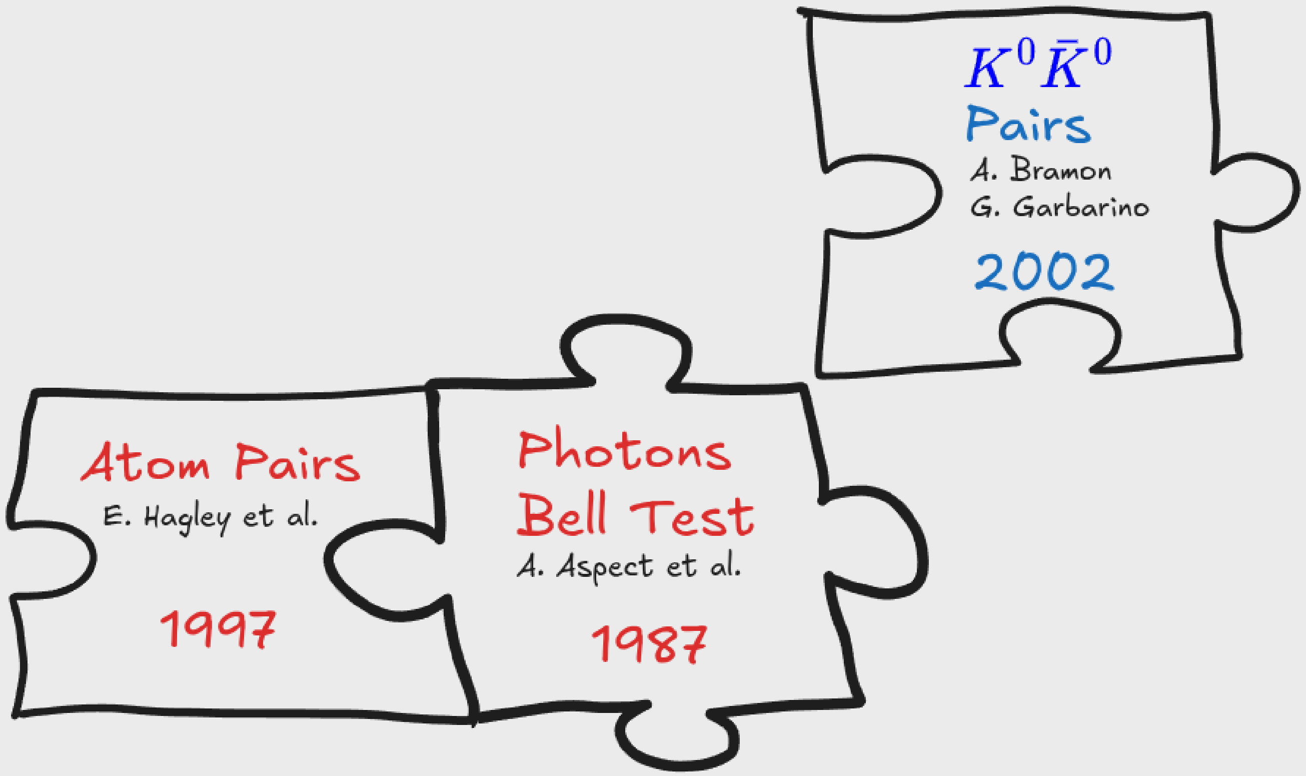
Entanglement through history



Entanglement through history



Entanglement through history



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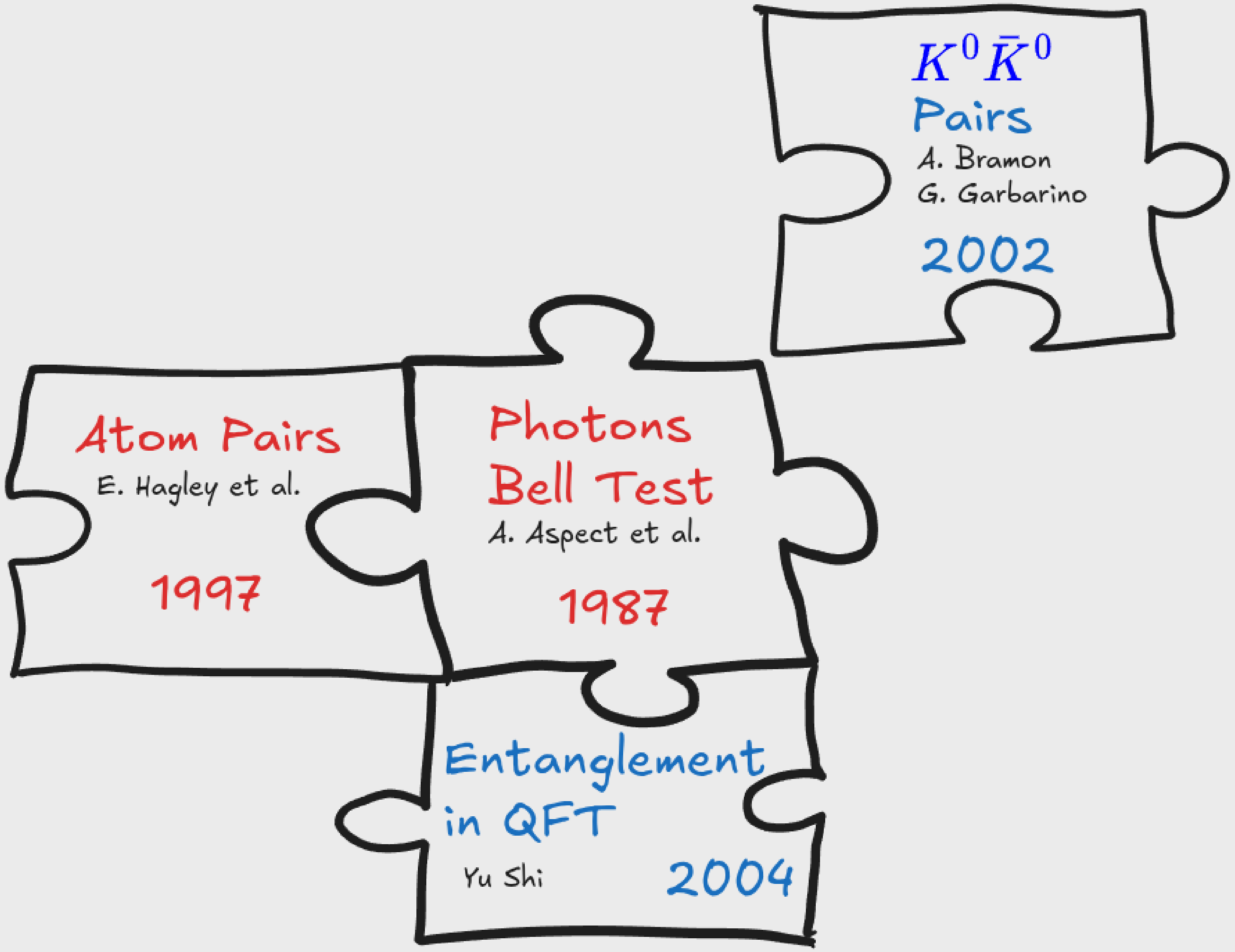

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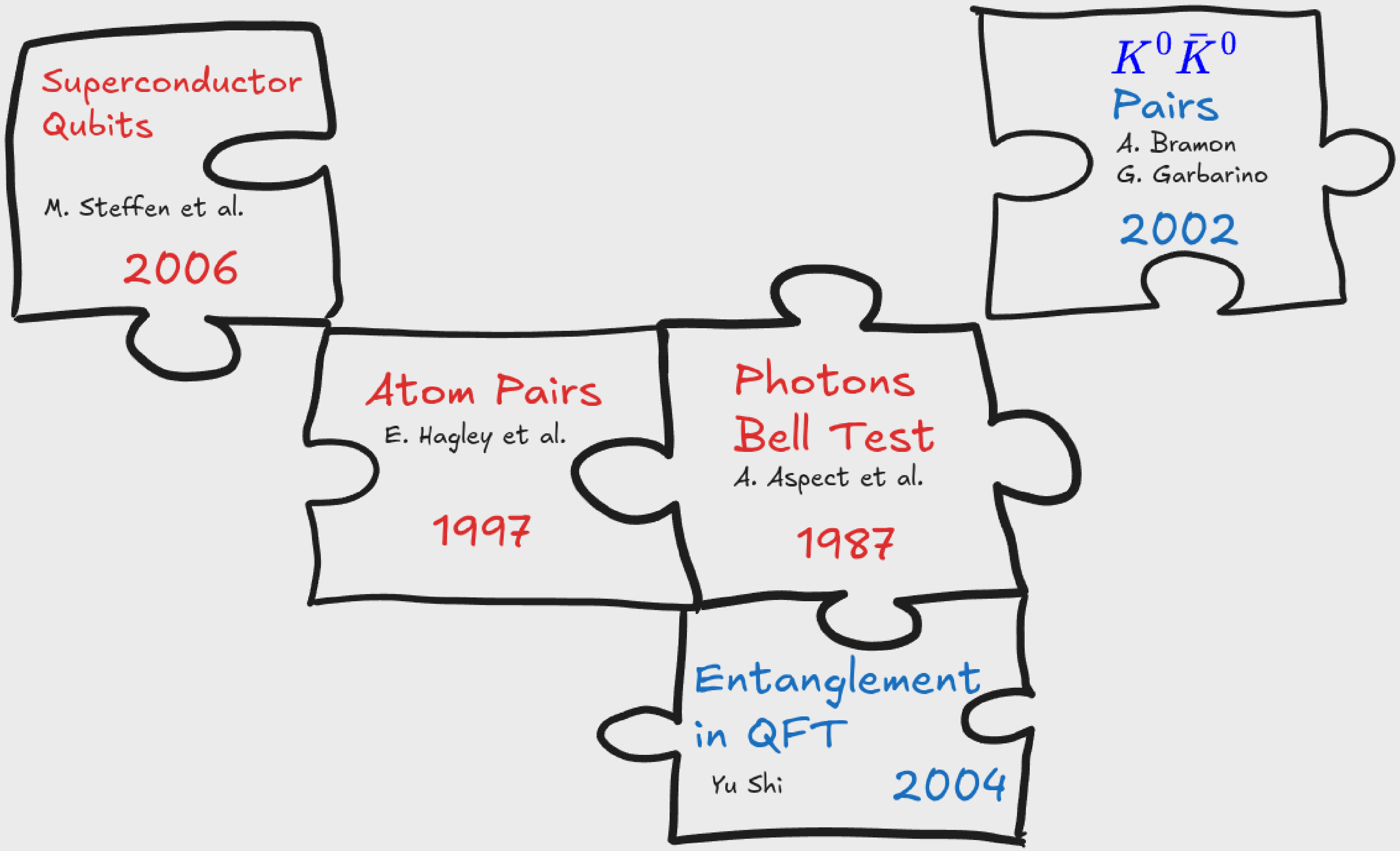

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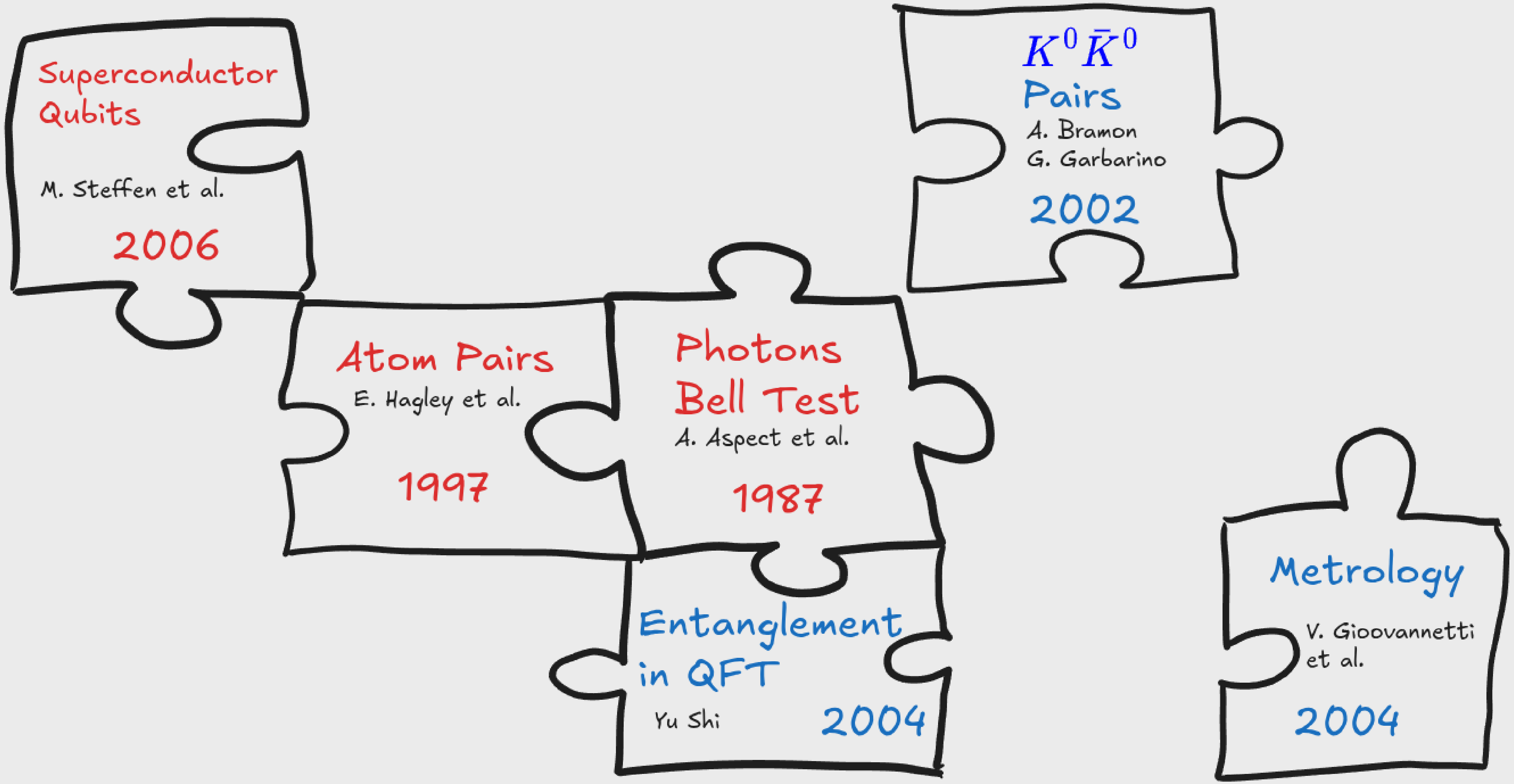

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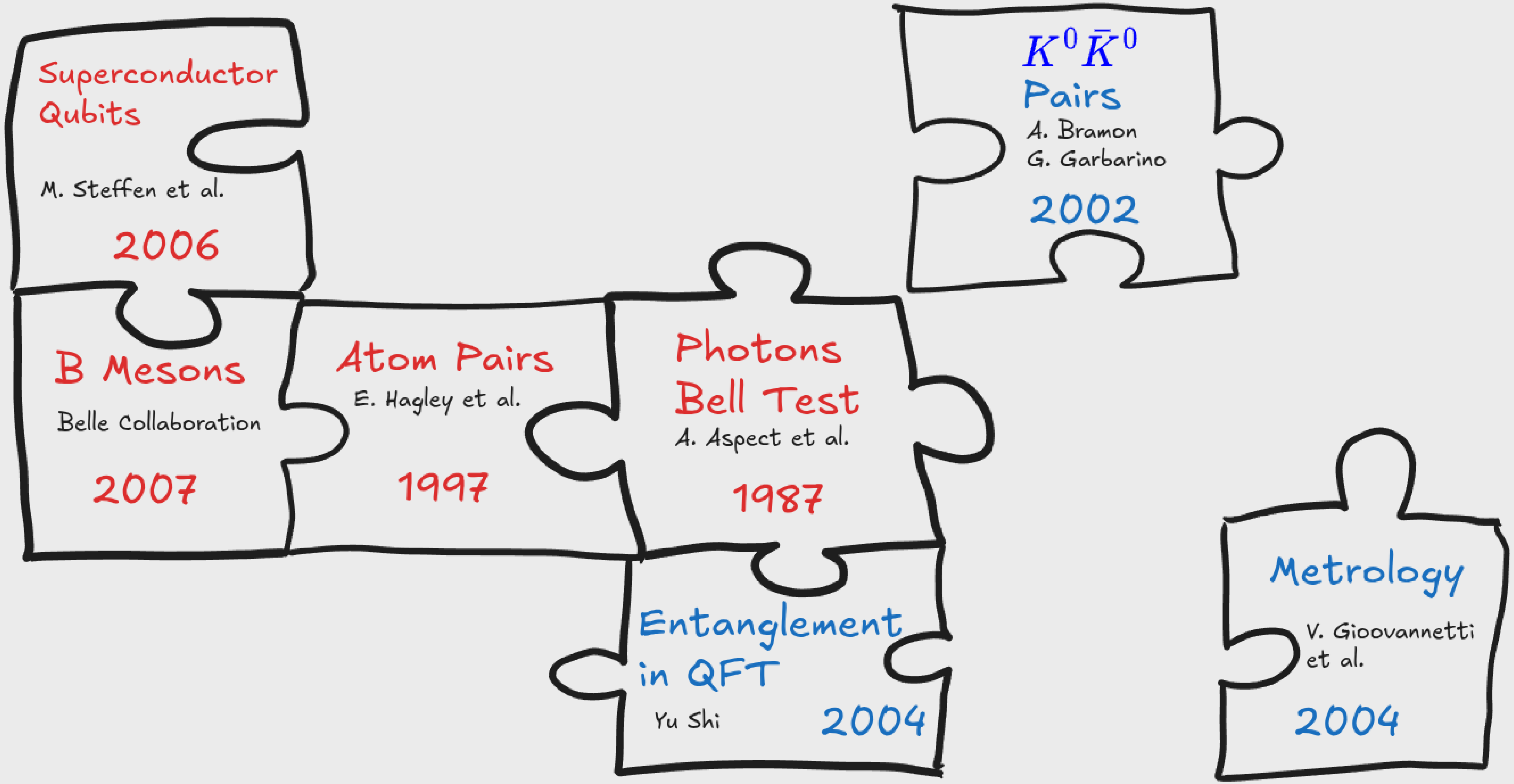

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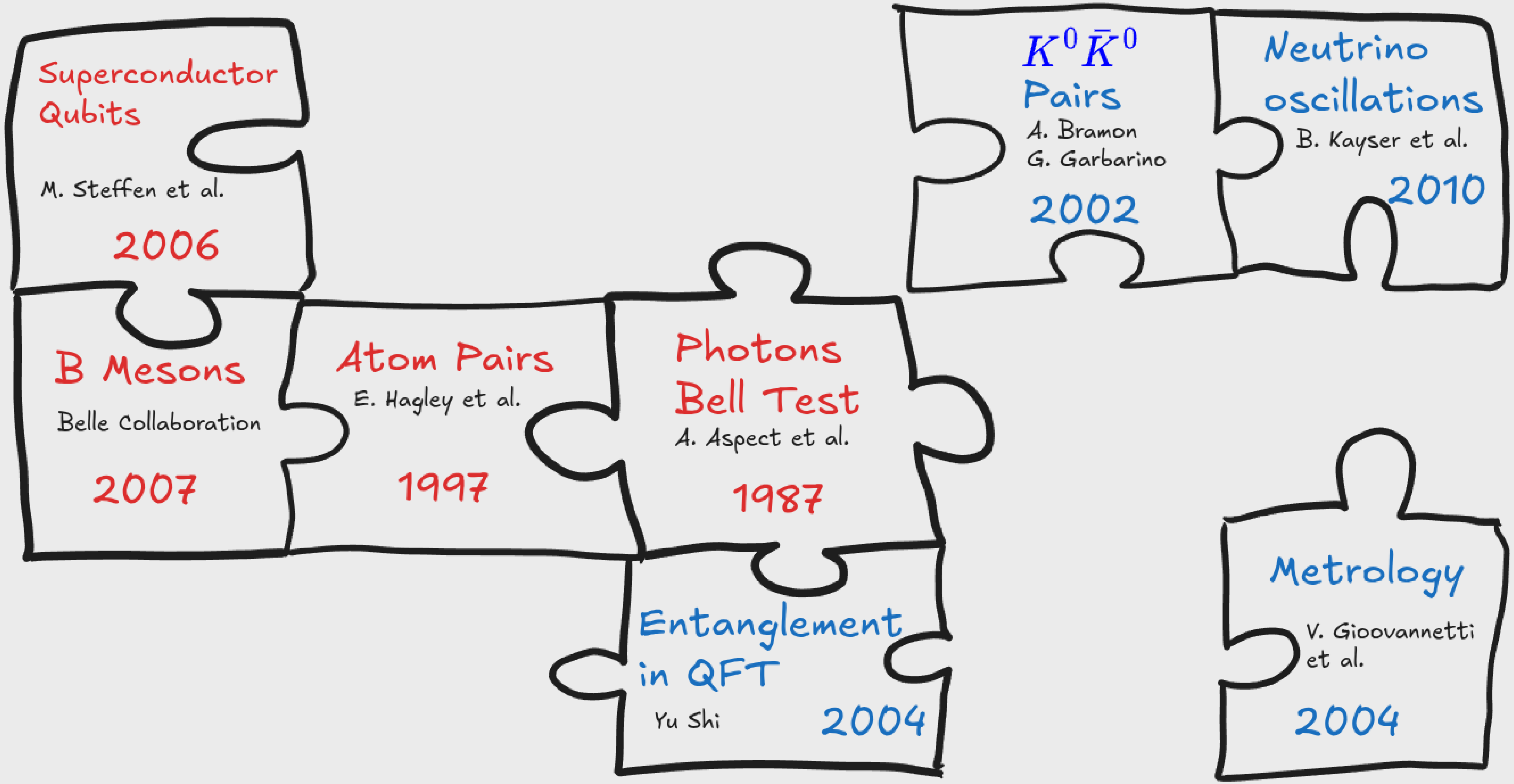

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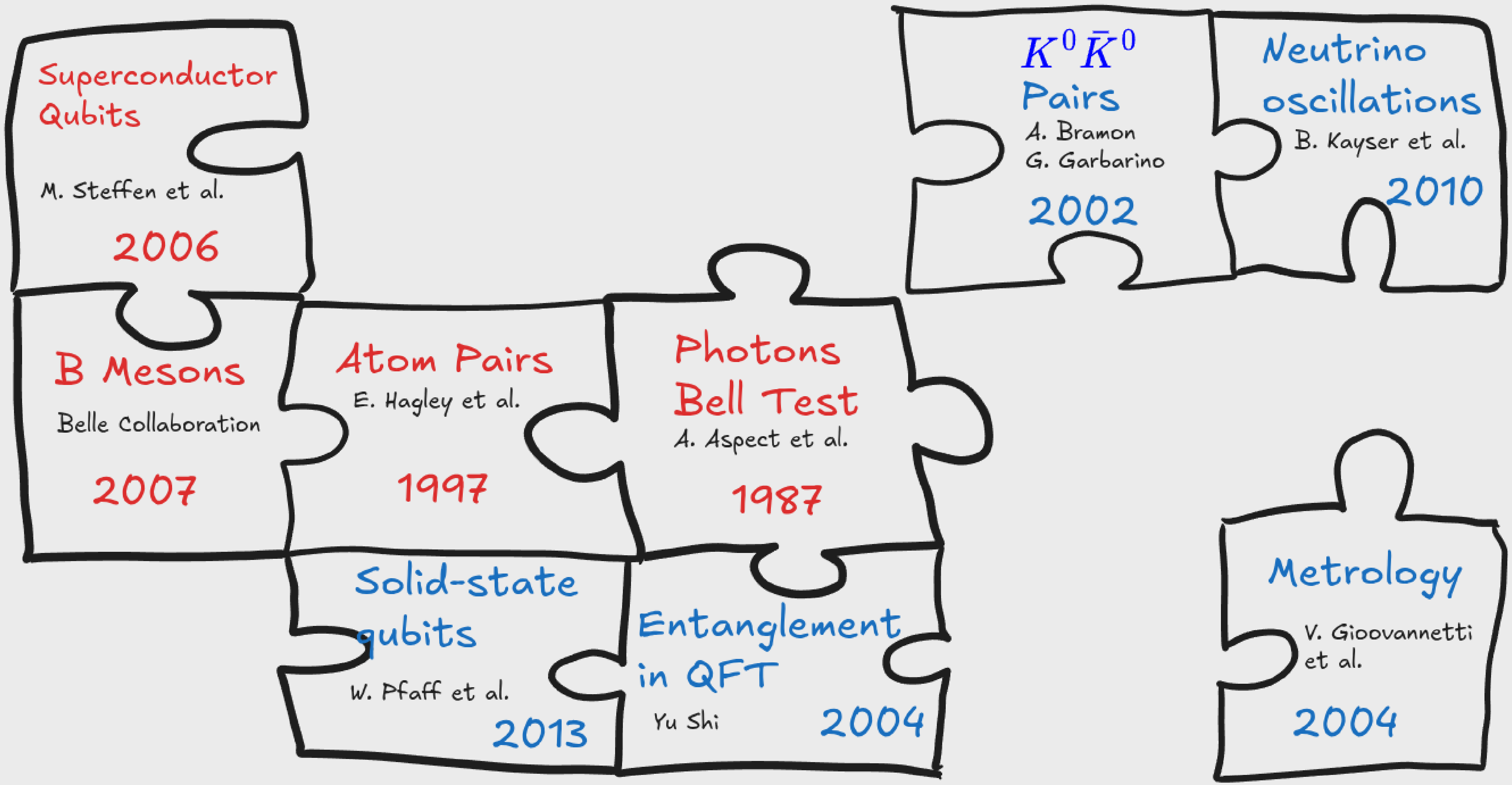

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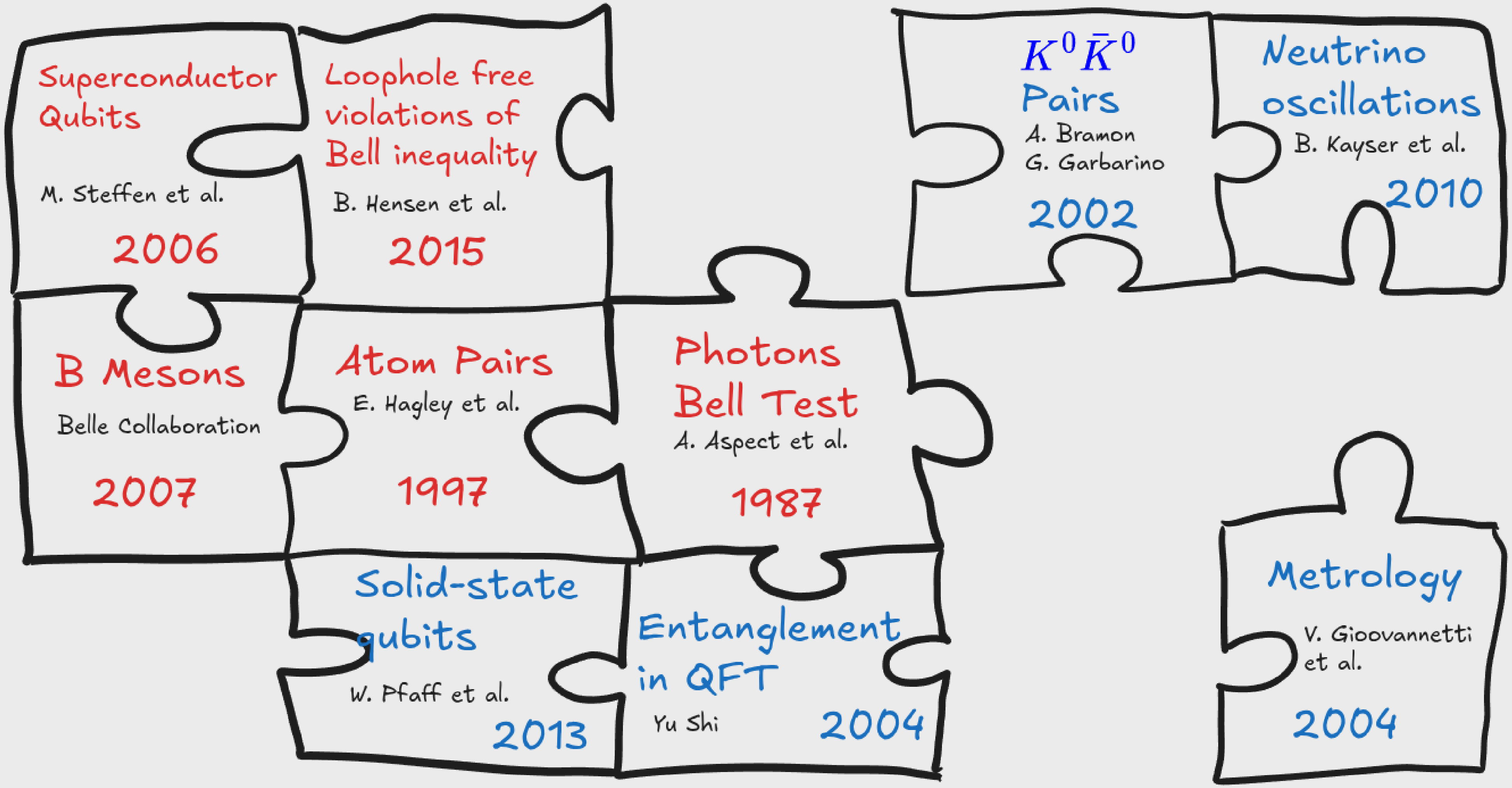

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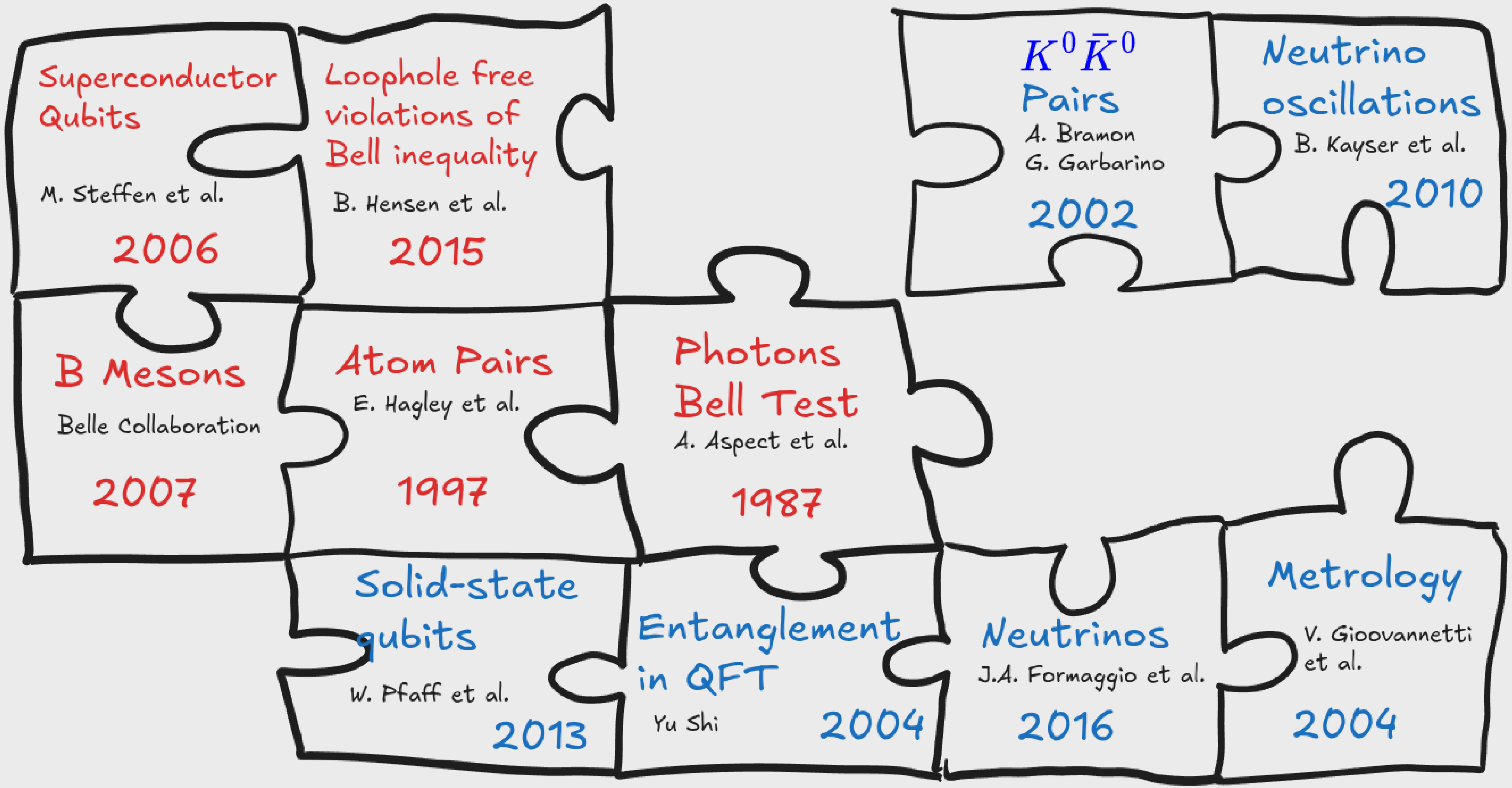

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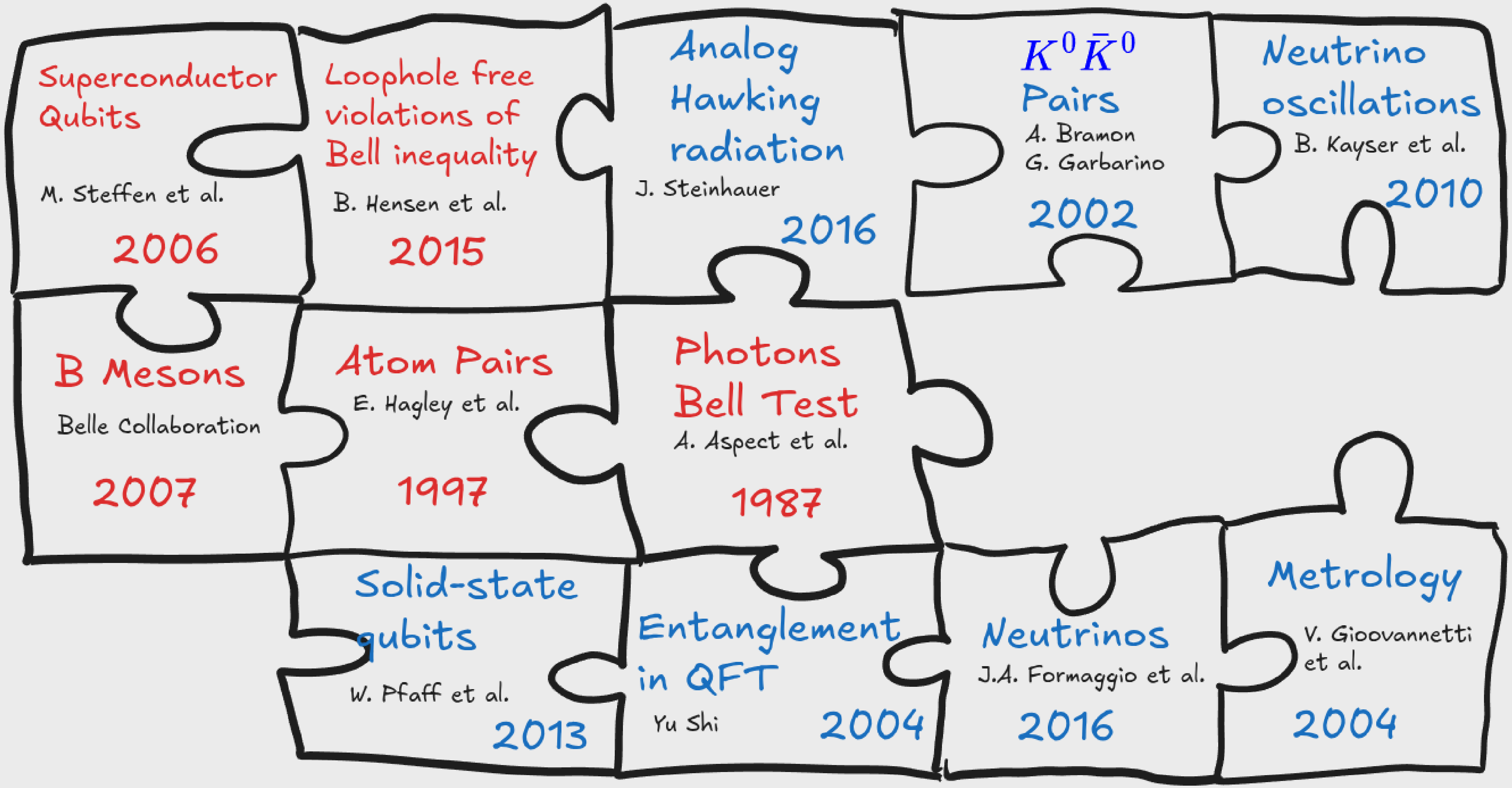
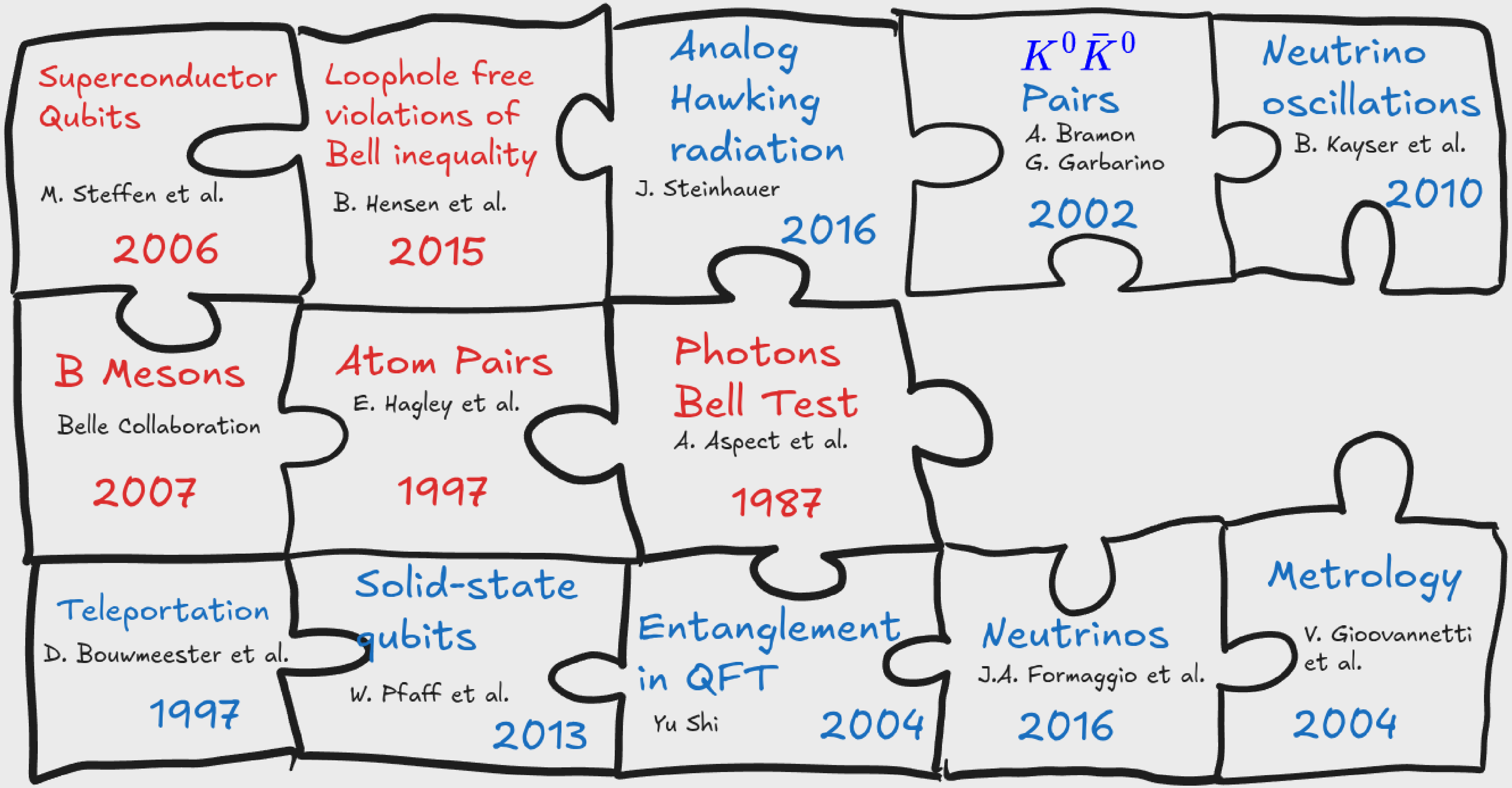


Entanglement through history



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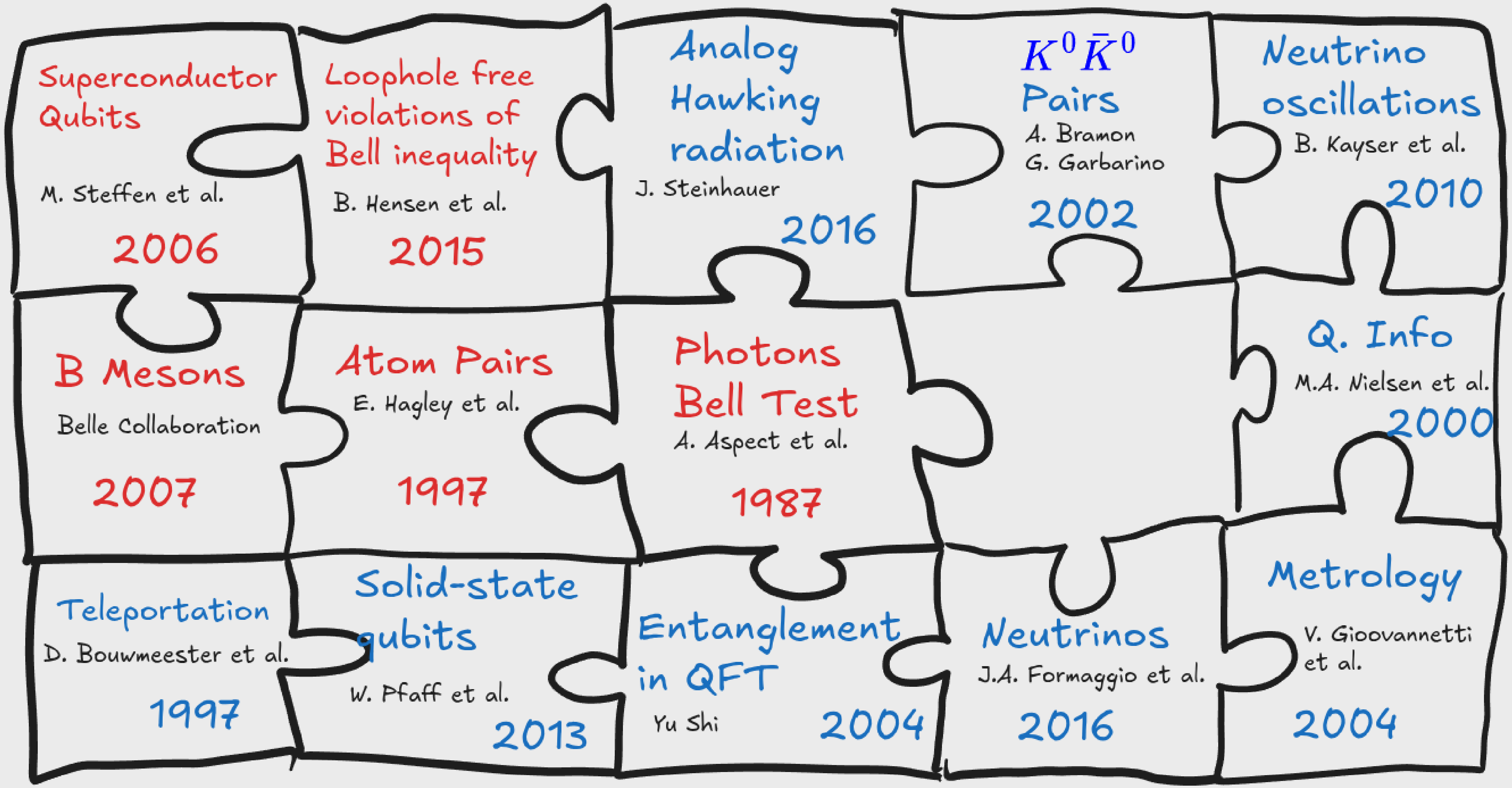

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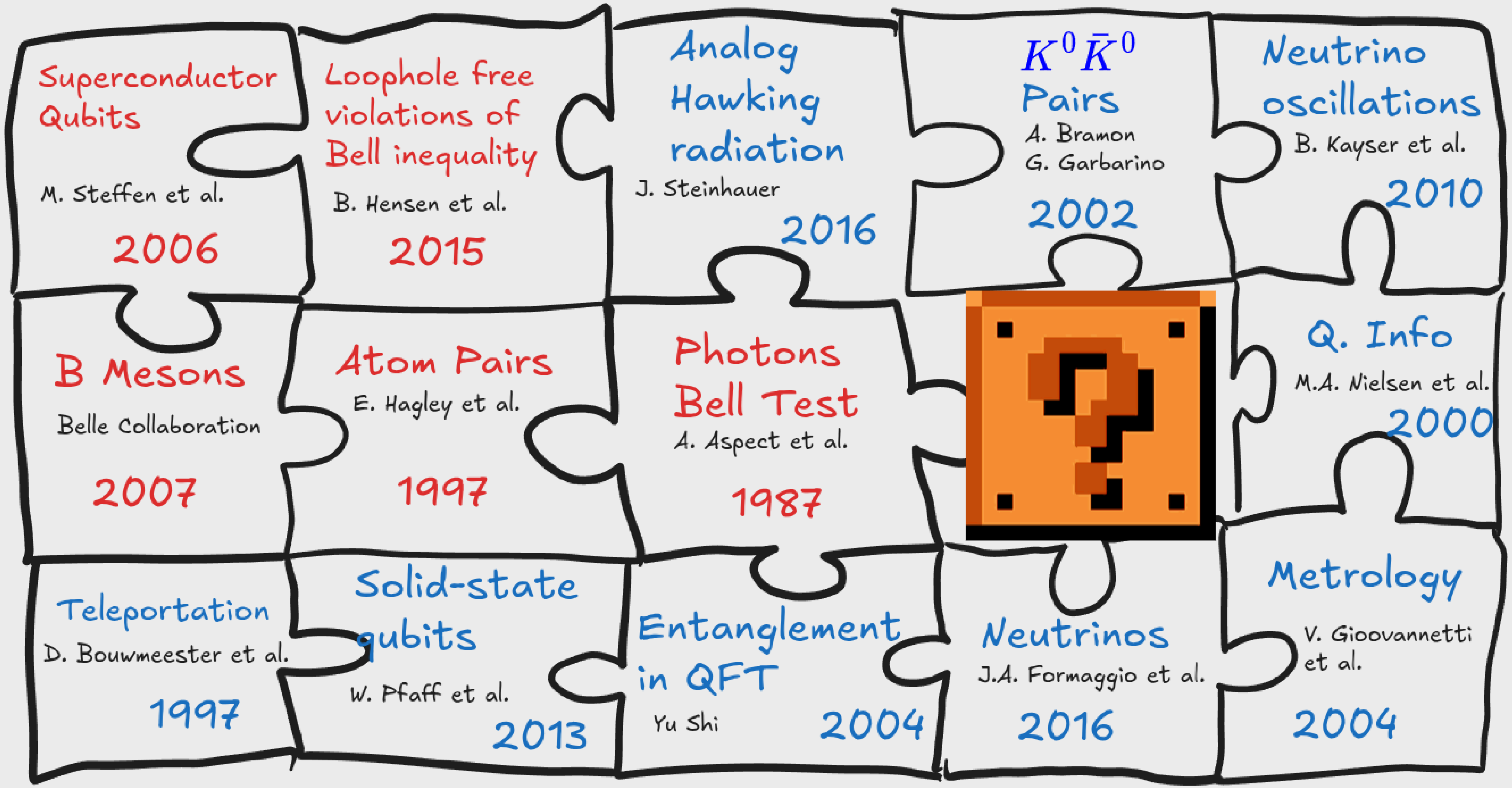
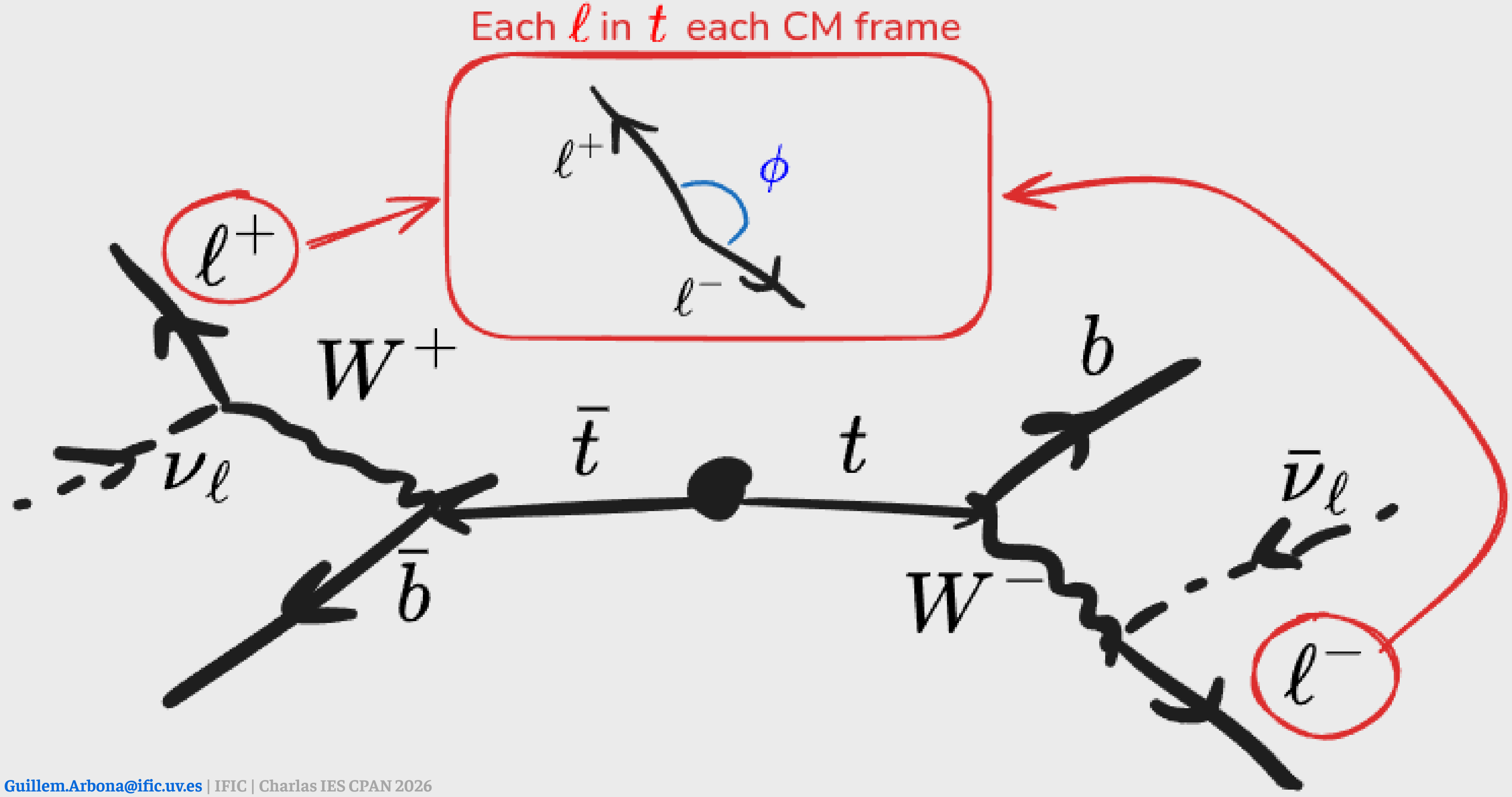


Entanglement in High Energy Physics (HEP)

The Peres-Horodecki criteria for entanglement

Full theory description: *Eur. Phys. J. Plus* 136, 907 (2021)

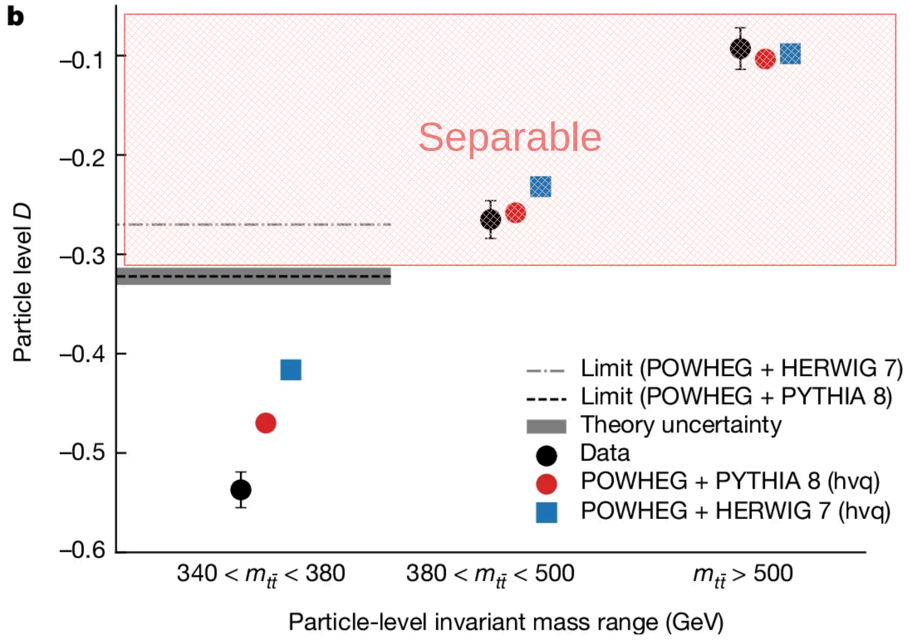
$$\boxed{D = -3\langle\cos\phi\rangle < -1/3} \implies t\bar{t}\text{ spin entanglement}$$



First observation of quantum entanglement in HEP

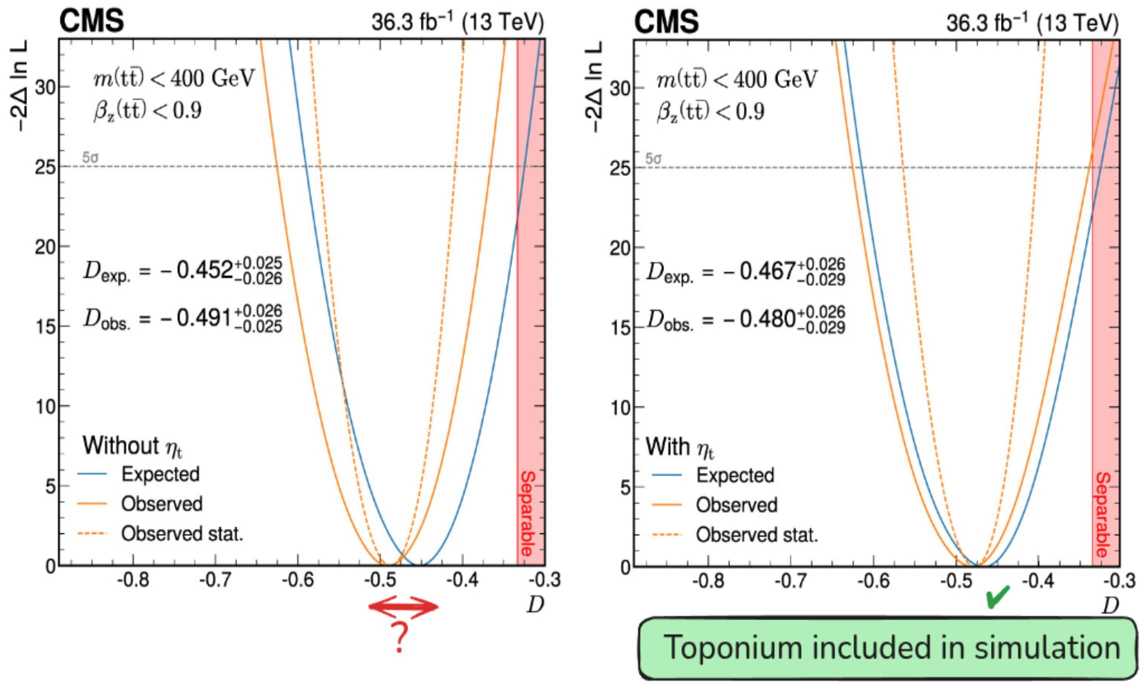
The ATLAS Collaboration

Nature 633, 542–547 (2024)



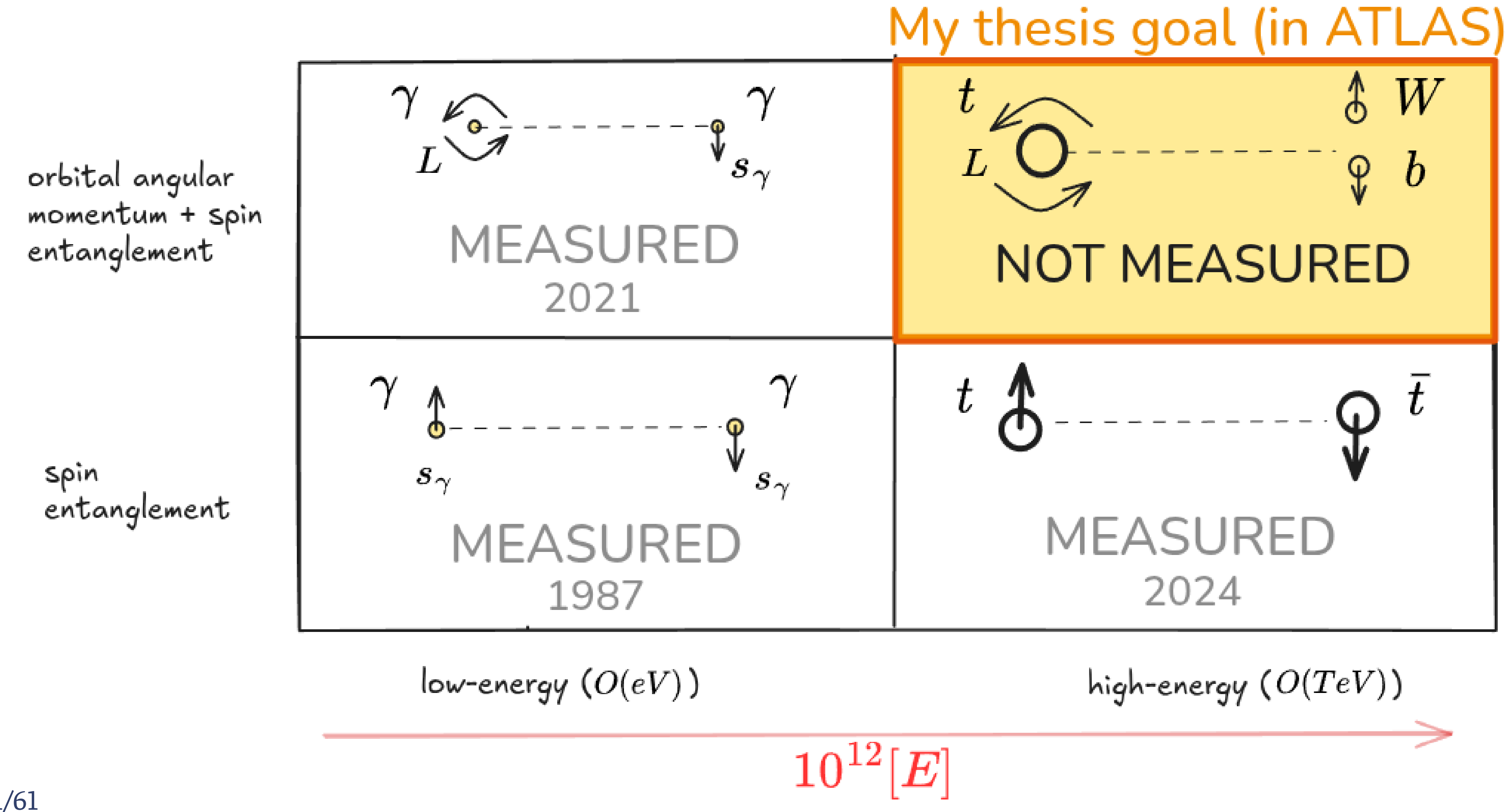
The CMS Collaboration

Rep. Prog. Phys. 87 (2024) 117801



Entanglement between orbital angular momentum and spin

Where spin + orbital entanglement has been measured



The ATLAS detector

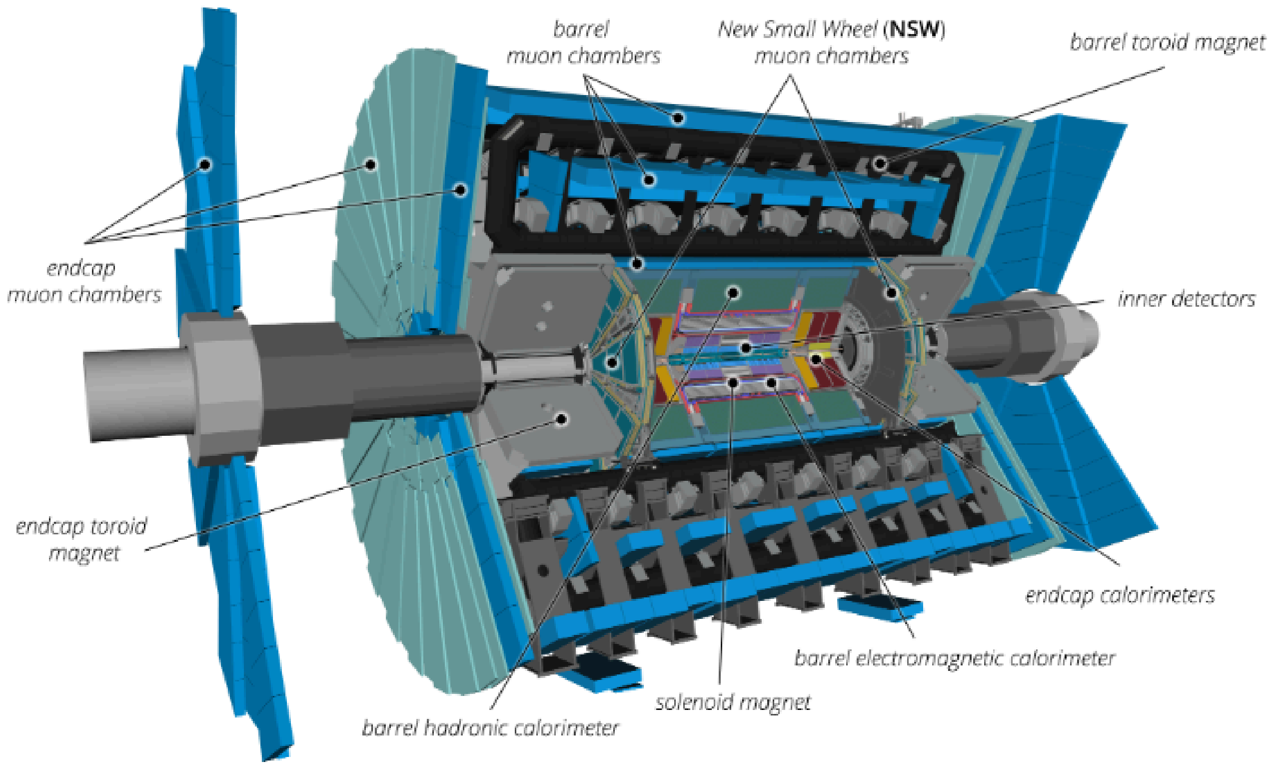
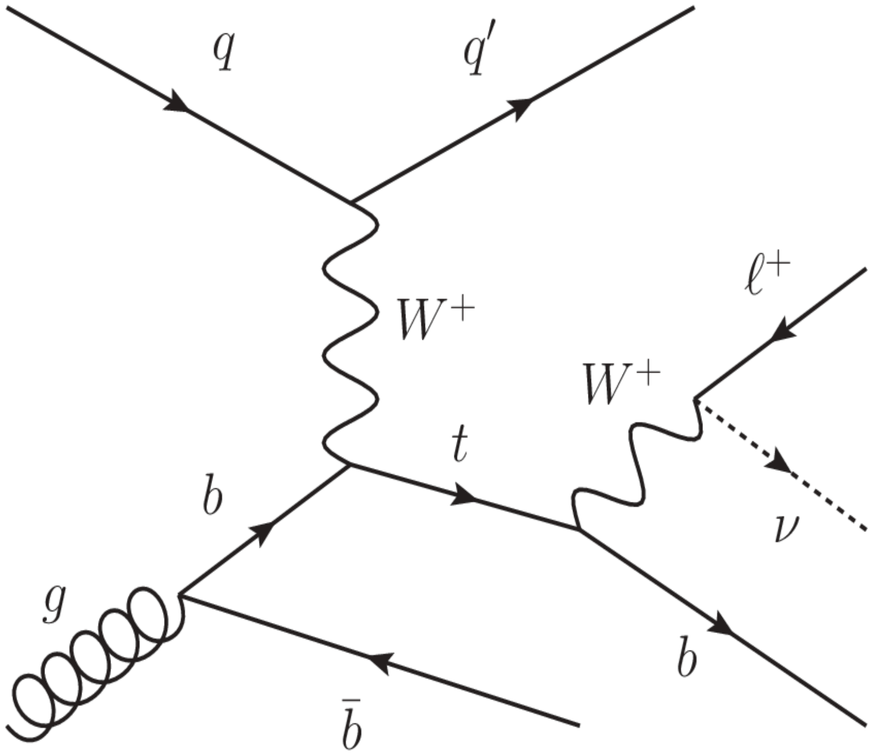


Fig. 32.1: ATLAS detector scheme for Run 3 [JINST 19 (2024) P05063]

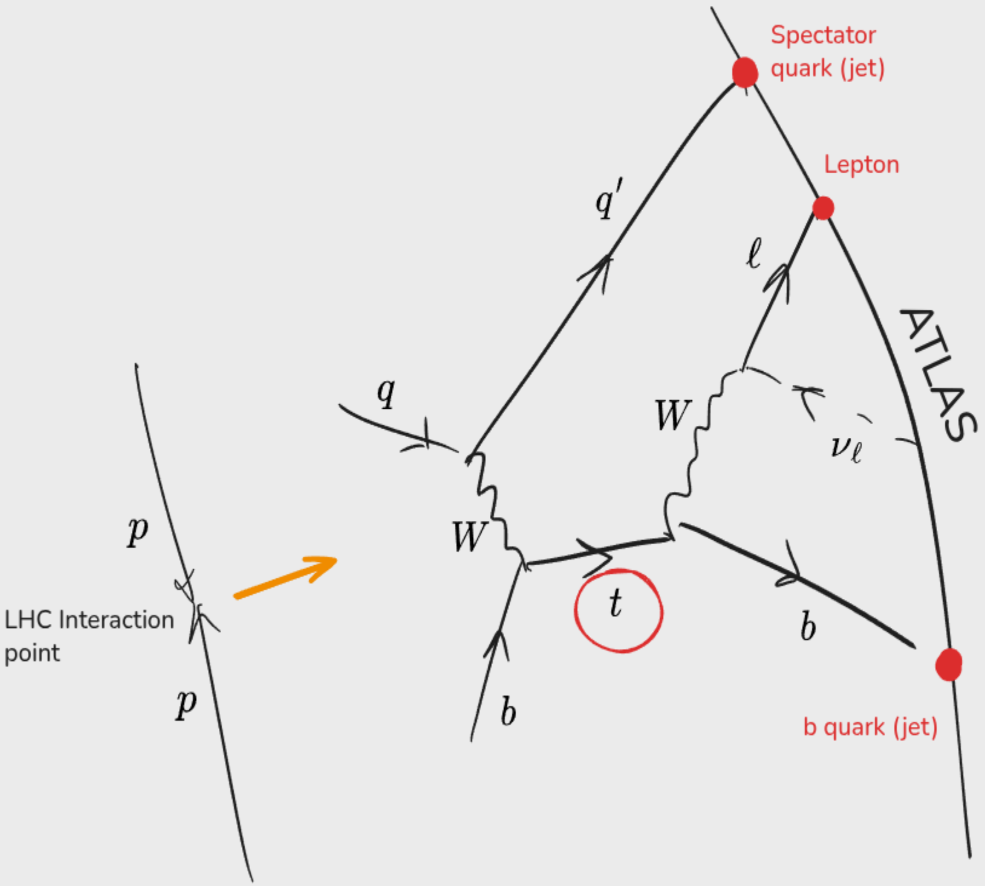
- One of the **general purpose LHC** detector.
- **Characterization** of **leptons** and **baryons**:
  - Inner Detector or Tracker
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter
  - Muon chambers

The particle: top quark



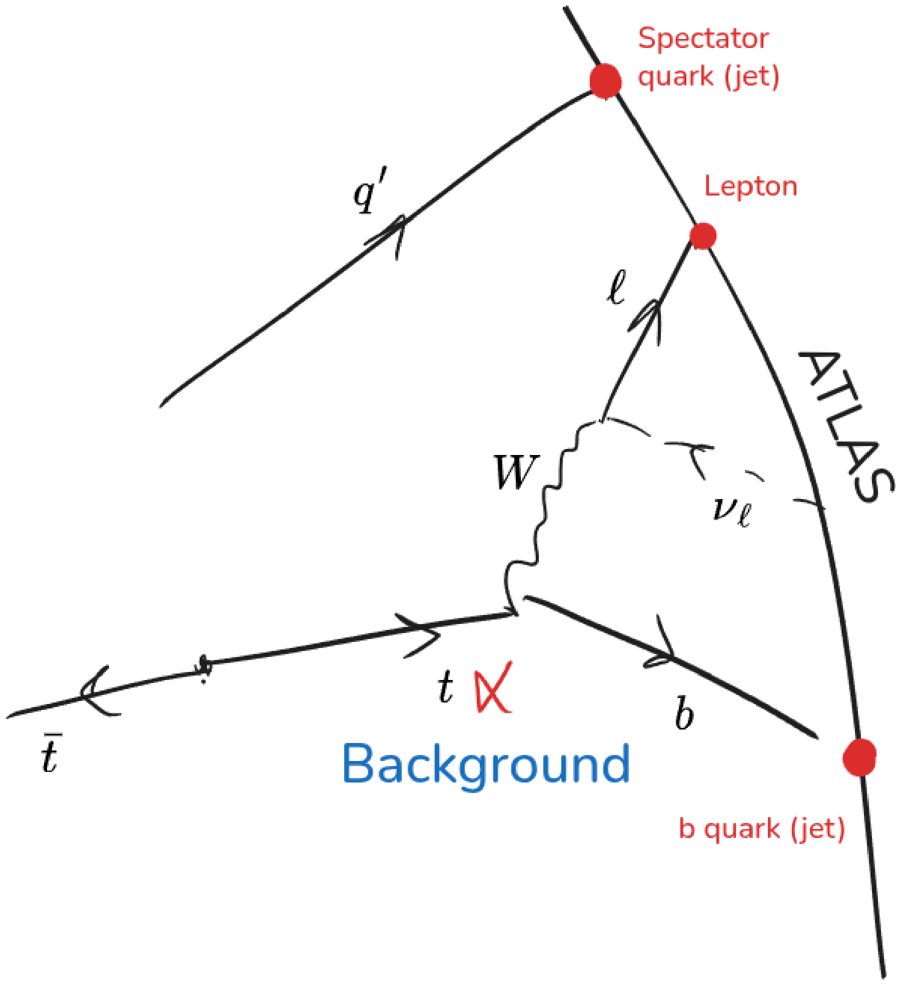
- $\boxed{\text{Top lifetime}} < \boxed{\text{Hadronization time}}$
- Decay products preserve the quantum information of the top quark.
- t-channel has the largest rate among all single-top production channels.
- Great laboratory for testing SM
  More in Mariam's talk.
  arXiv:2510.23372

Event reconstruction in ATLAS

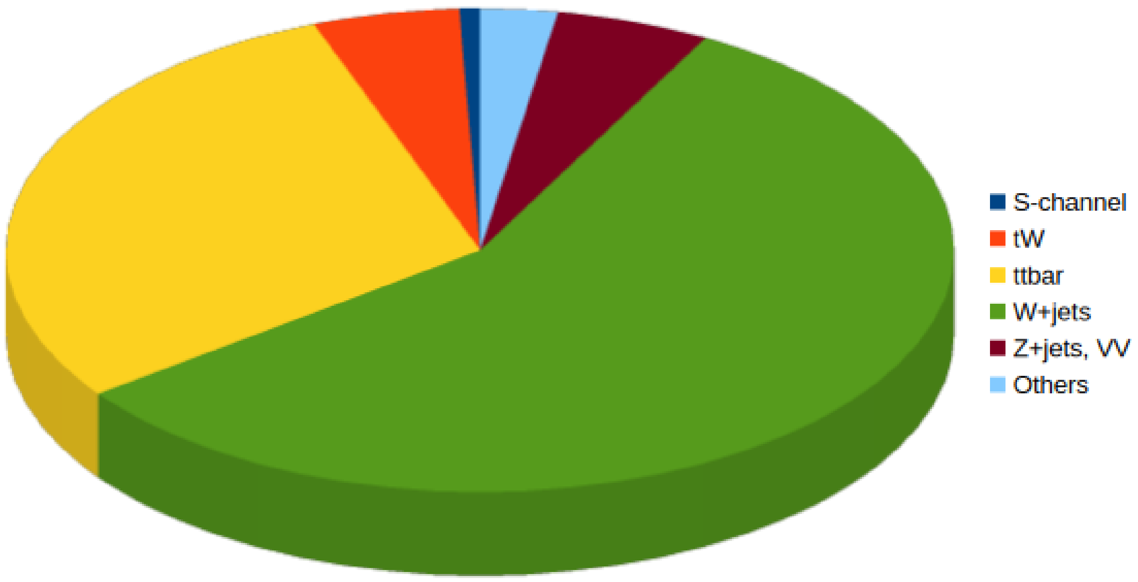


- We only "see":
  - the spectator quark q' jet
  - the lepton, ℓ, decaying from the W,
  - the b quark jet.
- So to identify these coming from a t in its t-channel, **events are selected considering ATLAS detector acceptance.**

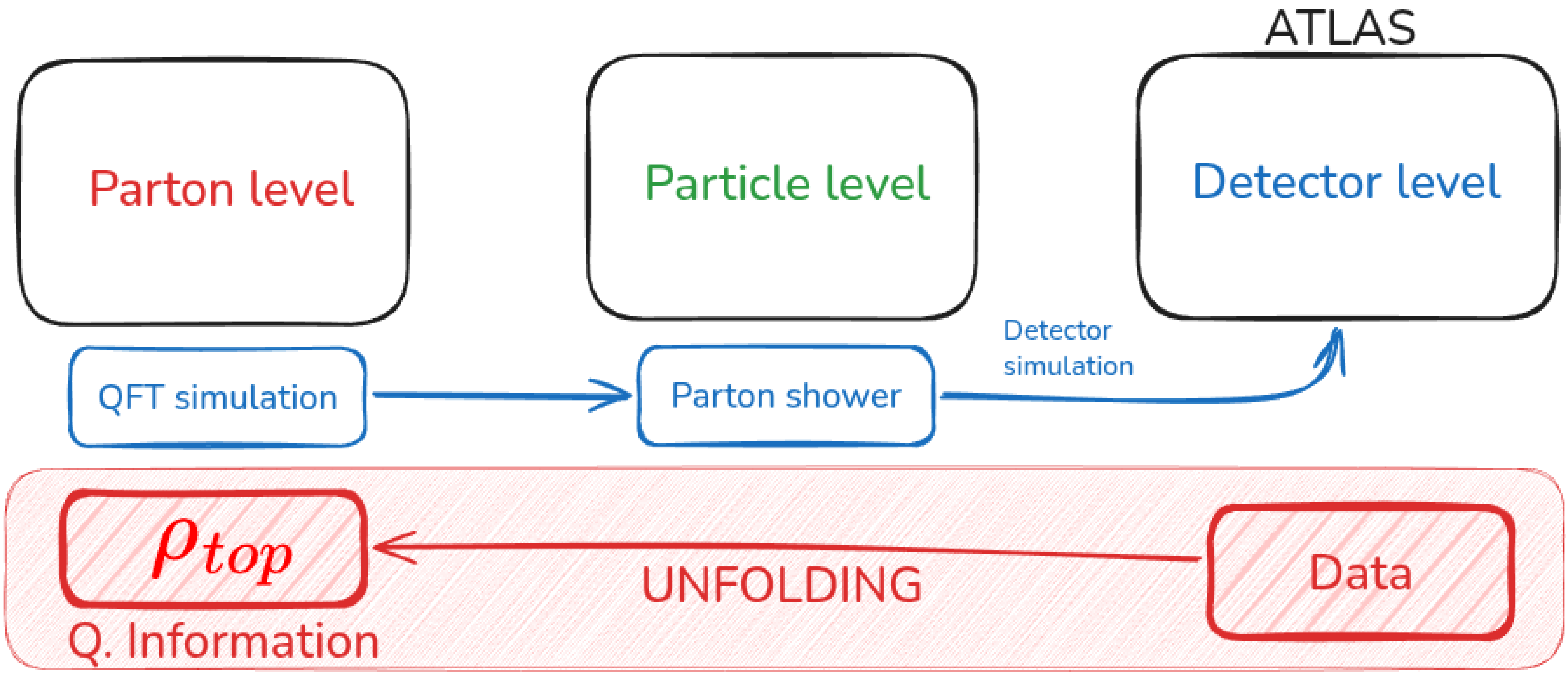
Be careful! Background



- Other non-desired events may decay in the same products. These conform the background
- It is important to know the background well and separate it afterwards.



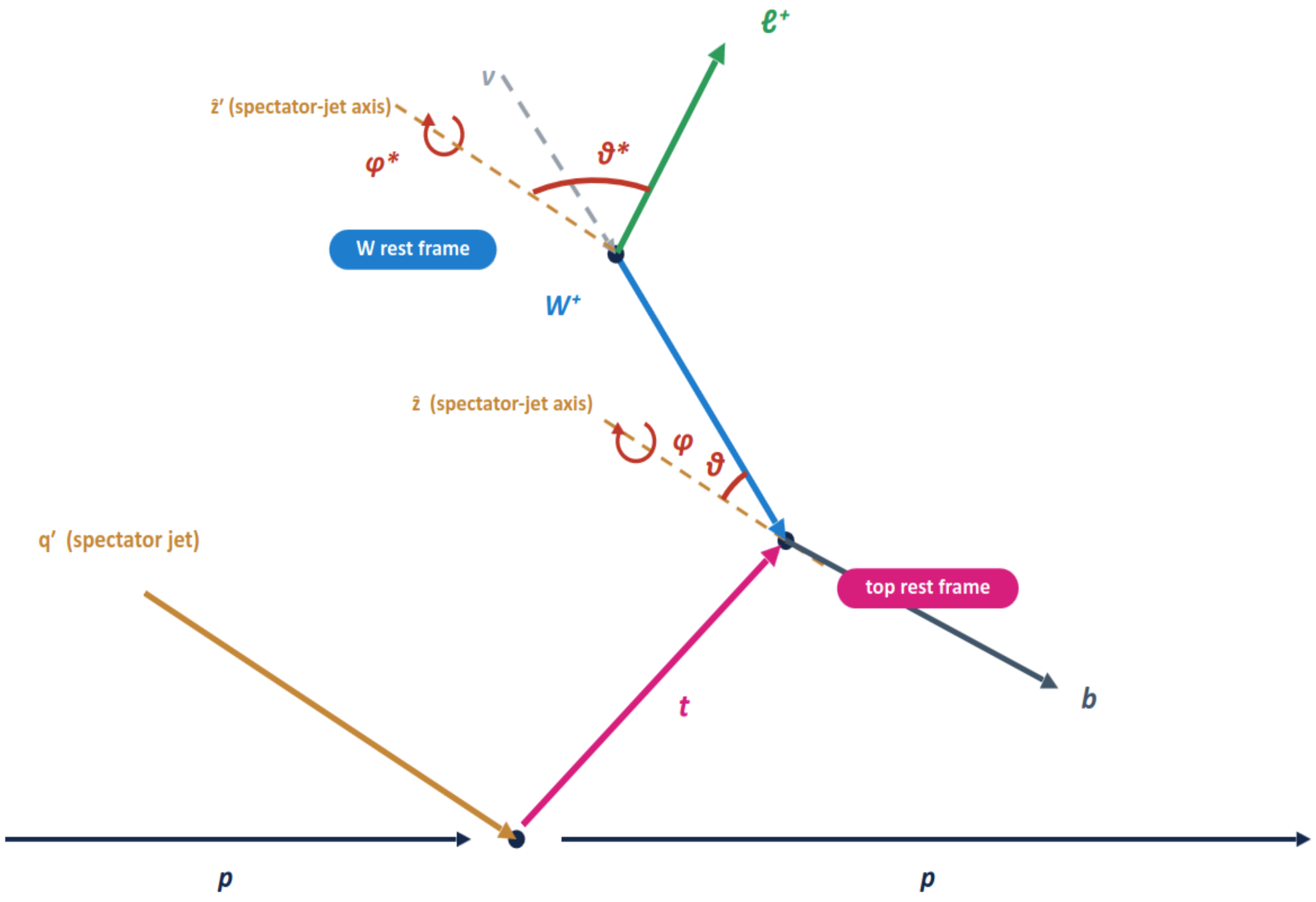
How to connect data to observables?



The observables: 4 angles of $t \to Wb$

Phys. Rev. D 89, 114009 (2014)

- (θ, ϕ) : W direction in t rest frame.
- (θ^*, ϕ^*) : ℓ direction in W rest frame.



Why these 4 angles are relevant?

Wigner D-functions

$$M^{j_1 j_2}_{m_1 m_2}(\theta, \phi, \theta^*, \phi^*) \propto D^{j_1}_{m'm}(\theta, \phi, 0) D^{j_2}_{m,0}(\theta^* \phi^*, 0)$$

Differential decay width

24 M-functions are needed to describe 4-fold differential decay rate (LO, parton level)

$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \sum_{j_1 j_2 m' m} c^{j_1 j_2}_{m'm} M^{j_1 j_2}_{m'm}(\theta, \phi, \theta^*, \phi^*)}$$

Orthonormal basis

$$c^{j_1 j_2}_{mm'} = \int_{4\pi}\int_{4\pi} d\Omega d\Omega^* \rho(\theta, \phi, \theta^*, \phi^*) M^{j_1 j_2}_{mm'}(\theta, \phi, \theta^*, \phi^*) = \overline{M^{j_1 j_2}_{mm'}}$$

Full quantum tomography from a_{λ_1,λ_2}

Full t-channel density matrix

Top polarized spin density matrix

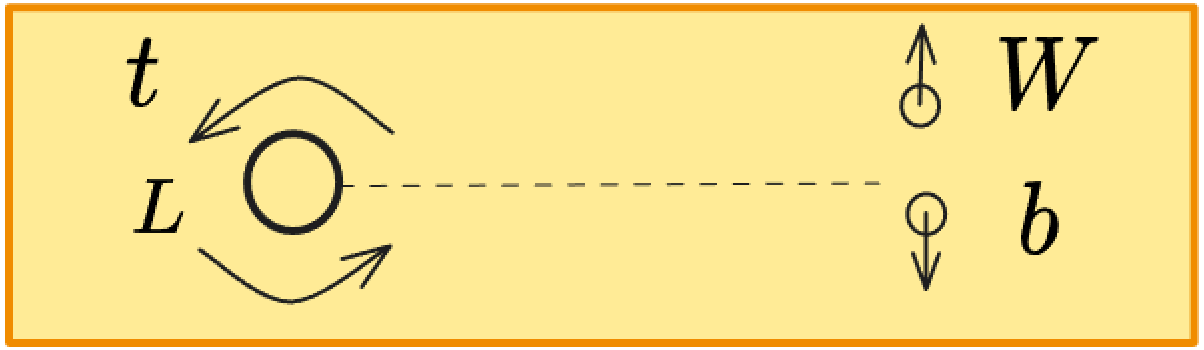
"Canonical" decay amplitudes

$$\boxed{(\rho_{LWb})_{s_1 s_2 \ell m; s_1' s_2' \ell' m'} = \sum_{M,M'} (\rho_t)_{MM'} \cdot A_{M,s_1 s_2;\ell m} \cdot A^*_{M',s_1' s_2';\ell' m'}}$$

$$\rho_t = \frac{1}{2}(1 + \vec{P}\vec{\sigma})$$

$$A_{M,s_1,s_2;\ell,m} \propto a_{\lambda_1,\lambda_2}$$

Orbital angular momentum (OAM) and spin entanglement from ρ_{LWb}



Peres-Horodecki criteria

$$\mathcal{N}(\rho) = \frac{||\rho^{T_B}|| - 1}{2}$$

$$\boxed{\mathcal{N}(\rho) > 0} \Longrightarrow \rho \text{ non-separable}$$

Expectation

$$N(\rho_{LW}) > 5\sigma$$

$$N(\rho_{Lb}) \sim 3.2\sigma$$

$$N(\rho_{L[Wb]}) > 5\sigma$$

Analysis workflow

1. **Simulate** the process parton level, particle level and detector level
2. **Background** estimation
3. Define the **4 angles**, and construct the **M functions and c coefficients**
4. Extract the **helicity amplitudes and polarization** $t \to Wb$ from c coeff
5. Compute the **complete density matrix** transforming the amplitudes to the canonical basis.
6. Compute the **negativity**, and test **entanglement**
7. **Unfolding**, extract **coefficients from data** and **compare** with the simulation
8. **Systematics** study

Outomes of measuring OAM + spin entanglement

It matches the SM

For the **first time at high energy physics** spin + orbital angular momentum entanglement will be **measured**.

It deviates!

Beyond the Standard Model signal. It could be a signal of **anomalous tWb couplings**, and will be correlated with **EFT fit**. (Mariam's talk)

Conclusion

- With 4-angle framework to reconstruct $t \to Wb$ amplitudes from the angular differential decay width we could reconstruct the full 54-dim density matrix of the state with L, ρ_{LWb}
- Then, after the unfolding, we could actually observe from data the complete quantum state of the tWb vertex.
- One of the measures available from this, is the angular momentum L and spin of W and b entanglement, first measure in HEP.

Backup

The EPR paradox

Phys. Rev. 47, 777 (1935)

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)

- According to Quantum Mechanics two previously interacting systems are described **by the wave function $\Psi(x_1, x_2)$**
- **Measuring** observable A **on system I** could **take an effect on system II**

$$\Psi(x_1, x_2) = \sum_n \psi_n(x_2) u_n(x_1)$$

$$A\Psi = a_k \Psi = a_k \psi_k(x_2) u_k(x_1)$$

The EPR paradox

Phys. Rev. 47, 777 (1935)

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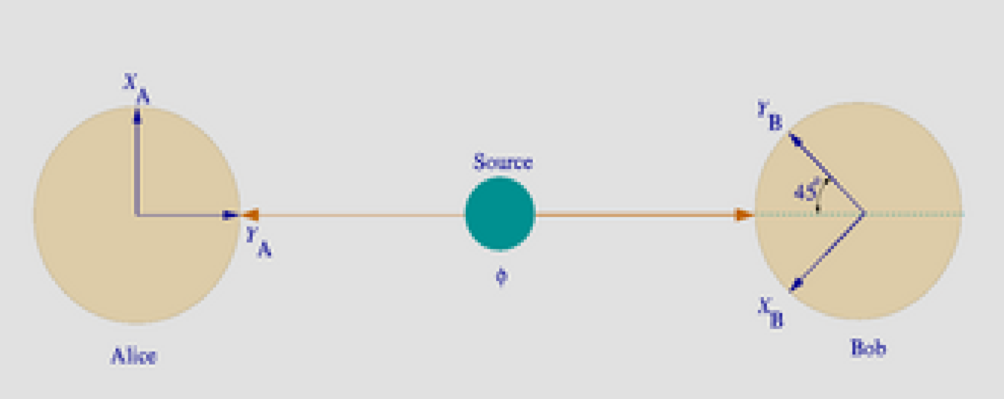
- Then, there's two possibilities:

1. The **description** **of** the physical **reality** **of the wave function** $\Psi(x_1, x_2)$ is **not complete.**

2. For **non-commuting observables** A **and** B, they **do not have simultaneous reality**, as measuring one, destroys information about the other.

John Bell inequalities

Physics Physique Fizika 1, 195 (1964)



"THE paradox of Einstein, Podolsky and Rosen was advanced as an argument that **quantum mechanics could not be a complete theory** but should be supplemented by additional variables. These **additional variables** were to **restore** to the theory **causality and locality**. In this note **that idea will be** formulated mathematically and **shown to be incompatible with the statistical predictions of quantum mechanics**."

Quantum Mechanics review

- The generalization of the *wave-function* $|\alpha\rangle$ which represents a pure quantum state is the density operator, $\rho = \sum_\alpha |\alpha\rangle p_\alpha \langle\alpha|$, as it also contemplates mixtures between states.
- The restrictions of ρ are that:
    1. $\rho = \rho^\dagger$,
    2. it is non-negative
    3. $tr(\rho) = 1$.

Quantum Mechanics review

- A quantum state is said to be **separable** i.e. **not entangled** if it can be expressed as:

$$\rho = \sum_n w_n \rho'_n \otimes \rho''_n$$

where $\rho \in \mathcal{H}$ and $\mathcal{H}$ is the Hilbert space that is formed by two subspaces, $\mathcal{H} = \mathcal{H}' \otimes \mathcal{H}''$.

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The Peres-Horodecki criteria for entanglement

Phys. Rev. Lett. 77, 1413 (1996) A. Peres

$$\boxed{\rho = \sum_n w_n \rho'_n \otimes \rho''_n} \Longrightarrow \boxed{\lambda^i_\sigma \geq 0 \; \forall i}$$

where λ^i_σ are the eigenvalues of another matrix $\sigma = \sum_n w_n (\rho'_n)^T \otimes \rho''_n$.

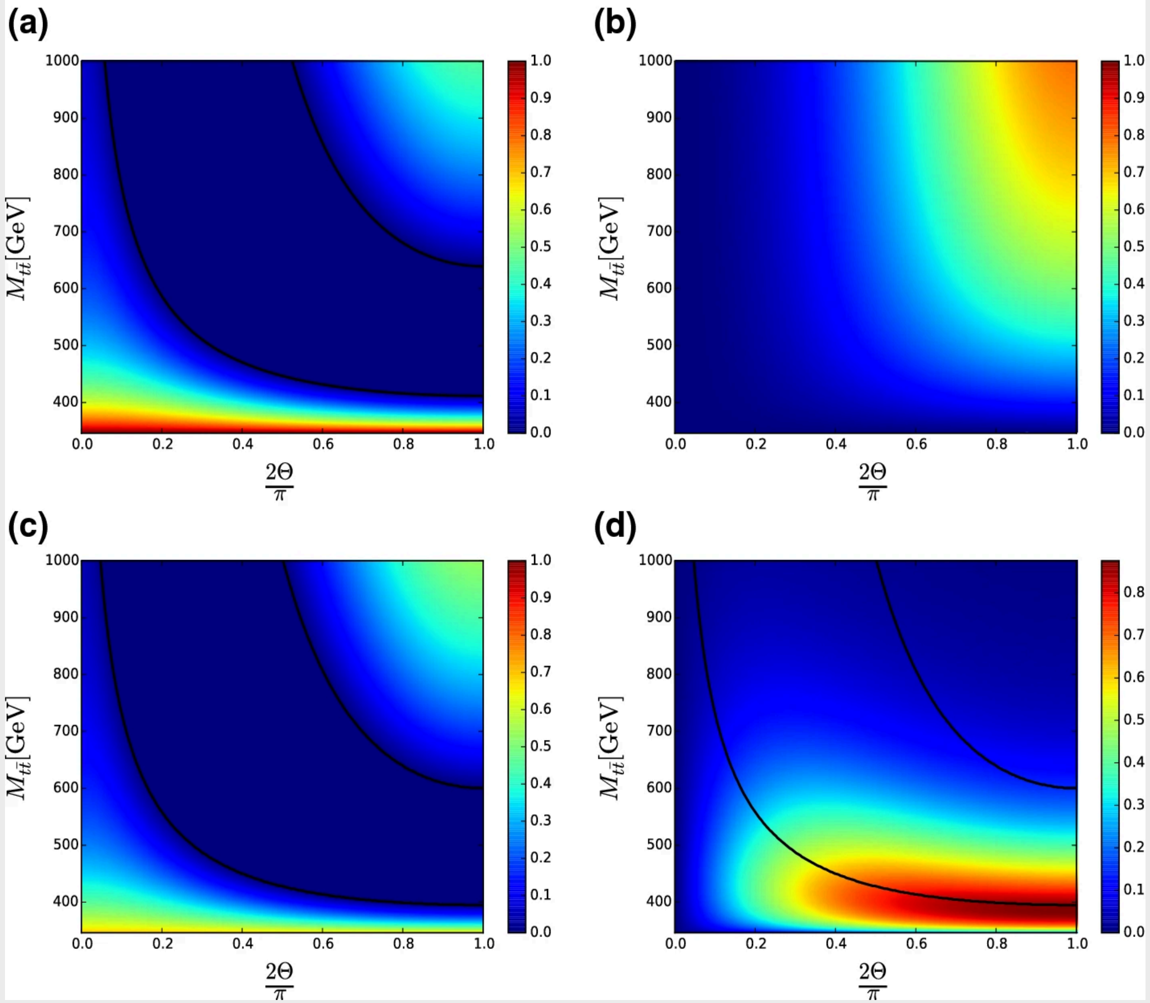
Phys.Lett. A232 (1997) 333 P. Horodecki

For 2×2 and 2×3 systems, the sufficient condition also complies.

$$\boxed{\rho \in \mathcal{A}' \otimes \mathcal{A}'' \text{ is separable}} \Longleftrightarrow \boxed{Tr(A\rho) \geq 0}$$

where $\mathcal{A}'$ and $\mathcal{A}''$ are the set of operators of $\mathcal{H}'$ and $\mathcal{H}''$, that form Hilbert-Schmidt spaces, and A is Hermitian and $Tr(AP \otimes Q) \geq 0$, being P and Q projections acting on $\mathcal{H}'$ and $\mathcal{H}''$

Entanglement treshold for $t\bar{t}$ pairs



Eur. Phys. J. Plus 136, 907 (2021)

- The figures represent entanglement as a function of the invariant mass $M_{t\bar{t}}$ in GeV and the production angle Θ in the $t\bar{t}$ CM frame, with separability limits in black.
- **(a)** and **(b)** represent $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$ processes
- **(c)** and **(d)** are the concurrence of the spin density matrix $\rho(M_{t\bar{t}}, \hat{k})$ and the differential cross section

Entanglement in HEP

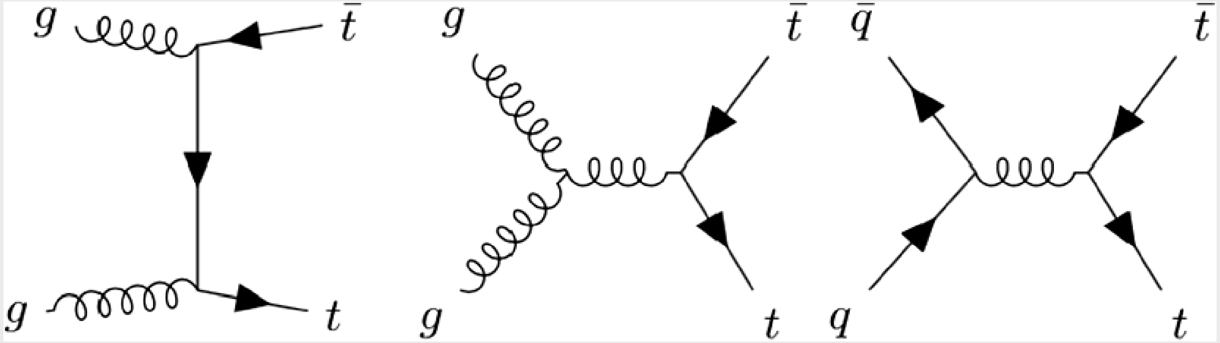
Eur. Phys. J. Plus 136, 907 (2021)

For a bipartite Hilbert space $\mathcal{H}$ of dimension 2×2 formed by two qubits, the general form of ρ is:

$$\rho \sim \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j$$

where $i, j = 1, 2, 3$, $\sigma^i \equiv \text{Pauli matrices}$, and $C_{ij} = \langle \sigma^i \otimes \sigma^j \rangle$ is the spin correlation between the two particles.

Relation with experiments in colliders: $t\bar{t}$ events



- $\tau_t \sim 10^{-25}s < t_{had} \sim 10^{-23}s < t_{spindecorr} \sim 10^{-21}s$ Phys. Rev. D 98, 030001 (2018)

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} \sim -\hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}$$

the so-called angular differential cross section, that is measurable, is related with $\mathbf{C}$, the spin correlation matrix. ($\hat{\mathbf{q}}_\pm$ are the directions of the lepton (antilepton) in the top (antitop) rest frame, and $\Omega_\pm$ their solid angles).

Entanglement marker observable

Eur. Phys. J. Plus 136, 907 (2021)

$$\boxed{tr(\mathbf{C}) + 1 < 0} \Longrightarrow t\bar{t} \text{ spin entanglement}$$

But a more convenient marker to measure the entanglemnt experimentally is:

$$D = tr(\mathbf{C})/3$$

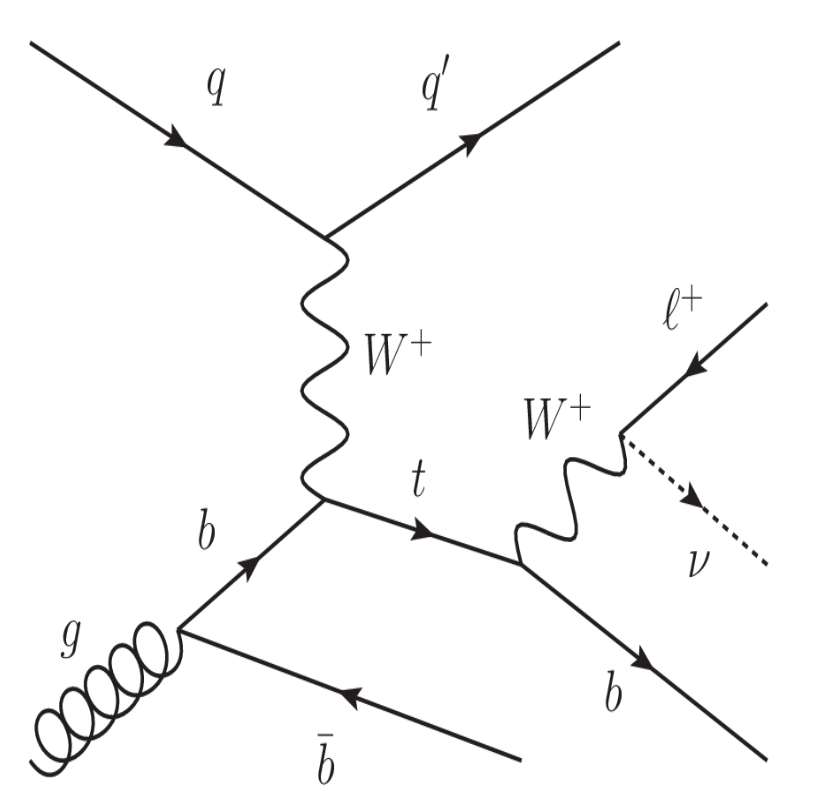
As it can be measured as:

$$D = -3\langle\cos\phi\rangle$$

where $\langle\cos\phi\rangle$ is the average value of the cosine of the angle between charged-lepton direction in their parent tops rest frame.
The new condition for entanglement, following Peres-Horodecki criteria, is:

$$\boxed{D < -1/3} \Longrightarrow t\bar{t} \text{ spin entanglement}$$

Single t quark decays



- t-channel has the largest rate among all single-top production channels
- Top quark produced via weak interaction -> preserves polarization *J. High Energ. Phys.* 2022, 40 (2022)
- Great laboratory for testing SM through Effective Field Theories (EFT) -> Mariam's talk just before arXiv:2510.23372

4 angle framework: Amplitudes from the M-function coefficients

$$c^{00}_{00} = \frac{1}{4\pi}\,,$$

$$c^{10}_{00} = \frac{1}{4\sqrt{3}\pi} P_z \left[|a_{1\,\frac{1}{2}}|^2 - |a_{0\,\frac{1}{2}}|^2 + |a_{0\,-\frac{1}{2}}|^2 - |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{10}_{10} = -(c^{10}_{-10})^* = -\frac{1}{4\sqrt{6}\pi} (P_x + iP_y) \left[|a_{1\,\frac{1}{2}}|^2 - |a_{0\,\frac{1}{2}}|^2 + |a_{0\,-\frac{1}{2}}|^2 - |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{01}_{00} = \lambda \frac{\sqrt{3}}{8\pi} \left[|a_{1\,\frac{1}{2}}|^2 - |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{11}_{00} = \lambda \frac{1}{8\pi} P_z \left[|a_{1\,\frac{1}{2}}|^2 + |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{11}_{10} = -(c^{11}_{-10})^* = -\lambda \frac{1}{8\sqrt{2}\pi} (P_x + iP_y) \left[|a_{1\,\frac{1}{2}}|^2 + |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{11}_{01} = (c^{11}_{0-1})^* = \lambda \frac{1}{4\sqrt{2}\pi} P_z \left[a_{0\,\frac{1}{2}}\, a^*_{1\,\frac{1}{2}} + a_{-1\,-\frac{1}{2}}\, a^*_{0\,-\frac{1}{2}} \right] / \mathcal{N}\,,$$

$$c^{11}_{11} = -(c^{11}_{-1-1})^* = -\lambda \frac{1}{8\pi} (P_x + iP_y) \left[a_{0\,\frac{1}{2}}\, a^*_{1\,\frac{1}{2}} + a_{-1\,-\frac{1}{2}}\, a^*_{0\,-\frac{1}{2}} \right] / \mathcal{N}\,,$$

$$c^{11}_{1-1} = -(c^{11}_{-11})^* = -\lambda \frac{1}{8\pi} (P_x + iP_y) \left[a_{1\,\frac{1}{2}}\, a^*_{0\,\frac{1}{2}} + a_{0\,-\frac{1}{2}} a^*_{-1\,-\frac{1}{2}} \right] / \mathcal{N}\,,$$

$$c^{02}_{00} = \frac{1}{8\sqrt{5}\pi} \left[|a_{1\,\frac{1}{2}}|^2 - 2|a_{0\,\frac{1}{2}}|^2 - 2|a_{0\,-\frac{1}{2}}|^2 + |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{12}_{00} = \frac{1}{8\sqrt{15}\pi} P_z \left[|a_{1\,\frac{1}{2}}|^2 + 2|a_{0\,\frac{1}{2}}|^2 - 2|a_{0\,-\frac{1}{2}}|^2 - |a_{-1\,-\frac{1}{2}}|^2 \right] / \mathcal{N}\,,$$

$$c^{12}_{10} = -(c^{12}_{-10})^* = -\frac{1}{8\sqrt{30}\pi} (P_x + iP_y) \left[|a_{1\,\frac{1}{2}}|^2 + 2|a_{0\,\frac{1}{2}}|^2 - 2|a_{0\,-\frac{1}{2}}|^2 - |a_{-1\,-\frac{1}{2}}| \right.$$

$$c^{12}_{01} = (c^{12}_{0-1})^* = \frac{1}{4\sqrt{10}\pi} P_z \left[a_{0\,\frac{1}{2}}\, a^*_{1\,\frac{1}{2}} - a_{-1\,-\frac{1}{2}}\, a^*_{0\,-\frac{1}{2}} \right] / \mathcal{N}\,,$$

$$c^{12}_{11} = -(c^{12}_{-1-1})^* = -\frac{1}{8\sqrt{5}\pi} (P_x + iP_y) \left[a_{0\,\frac{1}{2}}\, a^*_{1\,\frac{1}{2}} - a_{-1\,-\frac{1}{2}}\, a^*_{0\,-\frac{1}{2}} \right] / \mathcal{N}\,,$$

$$c^{12}_{1-1} = -(c^{12}_{-11})^* = -\frac{1}{8\sqrt{5}\pi} (P_x + iP_y) \left[a_{1\,\frac{1}{2}}\, a^*_{0\,\frac{1}{2}} - a_{0\,-\frac{1}{2}}\, a^*_{-1\,-\frac{1}{2}} \right] / \mathcal{N}\,.$$

Differential decay width

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} \quad = \quad & \frac{3}{64\pi^2}\frac{1}{\mathcal{N}}\left\{\left[|a_{1\,\frac{1}{2}}|^2\,(1+\lambda\cos\theta^*)^2 + 2|a_{0\,-\frac{1}{2}}|^2\sin^2\theta^*\right]\left(1+\vec{P}\cdot\vec{u}_L\right)\right. \\
& + \left[2|a_{0\,\frac{1}{2}}|^2\sin^2\theta^* + |a_{-1\,-\frac{1}{2}}|^2\,(1-\lambda\cos\theta^*)^2\right]\left(1-\vec{P}\cdot\vec{u}_L\right) \\
& + \lambda 2\sqrt{2}\left[\mathrm{Re}(a_{0\,\frac{1}{2}}a^*_{1\,\frac{1}{2}}e^{-i\phi^*})(1+\lambda\cos\theta^*)\right. \\
& \left. + \mathrm{Re}(a_{-1\,-\frac{1}{2}}a^*_{0\,-\frac{1}{2}}e^{-i\phi^*})(1-\lambda\cos\theta^*)\right]\sin\theta^*\vec{P}\cdot\vec{u}_T \\
& + \lambda 2\sqrt{2}\left[\mathrm{Im}(a_{0\,\frac{1}{2}}a^*_{1\,\frac{1}{2}}e^{-i\phi^*})(1+\lambda\cos\theta^*)\right. \\
& \left.\left. + \,\mathrm{Im}(a_{-1\,-\frac{1}{2}}a^*_{0\,-\frac{1}{2}}e^{-i\phi^*})(1-\lambda\cos\theta^*)\right]\sin\theta^*\vec{P}\cdot\vec{u}_N\right\}\,.
\end{aligned}
$$

The fully differential top decay distribution

Eur. Phys. J. C 77, 200 (2017)

The **differential decay width** can be **expanded** in a **orthonormal basis** of so-called M-**functions**, (in the narrow width limit, and helicity basis, quantizing spin in the direction of motion of particles):

$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \sum_{j_1 j_2 m' m} c^{j_1 j_2}_{m'm} M^{j_1 j_2}_{m'm}(\theta, \phi, \theta^*, \phi^*)}$$

that are related with Wigner D functions E. P. Wigner:

$$M^{j_1 j_2}_{m'm}(\theta, \phi, \theta^*, \phi^*) \propto D^{j_1}_{m'm}(\phi, \theta, 0) D^{j_2}_{m0}(\phi^*, \theta^*, 0)$$

Coefficients $c^{j_1 j_2}_{m'm}$ are combinations of 2-body decay amplitudes $a_{\lambda_1 \lambda_2}$ in the helicity basis, of $t \to Wb \to \ell\nu b$ process, and $c^{j_1 j_2}_{m'm} = \langle (M^{j_1 j_2}_{m'm})^* \rangle$

Full quantum tomography of top quark decays

Phys. Let. B 855 (2024) 138849

- We can reconstruct the full 54-dim density matrix of the $t \to Wb$ decays, including the angular momentum L, ρ_{LWb}.
- It is no trivial as measuring the decay width of top quarks (experimental measure) projects ρ_L like $d\Gamma \sim \langle\Omega|\rho_L|\Omega\rangle$, so $d\Gamma$ involves products of two spherical harmonics that are **not** orthogonal. So several ρ_L can lead to the same result.
- The "canonical" amplitudes could release this angular dependence, allowing the addition of the angular momentum without degeneracies to the density matrix of the system $t \to Wb$.

Adding the angular momentum to helicity amplitudes

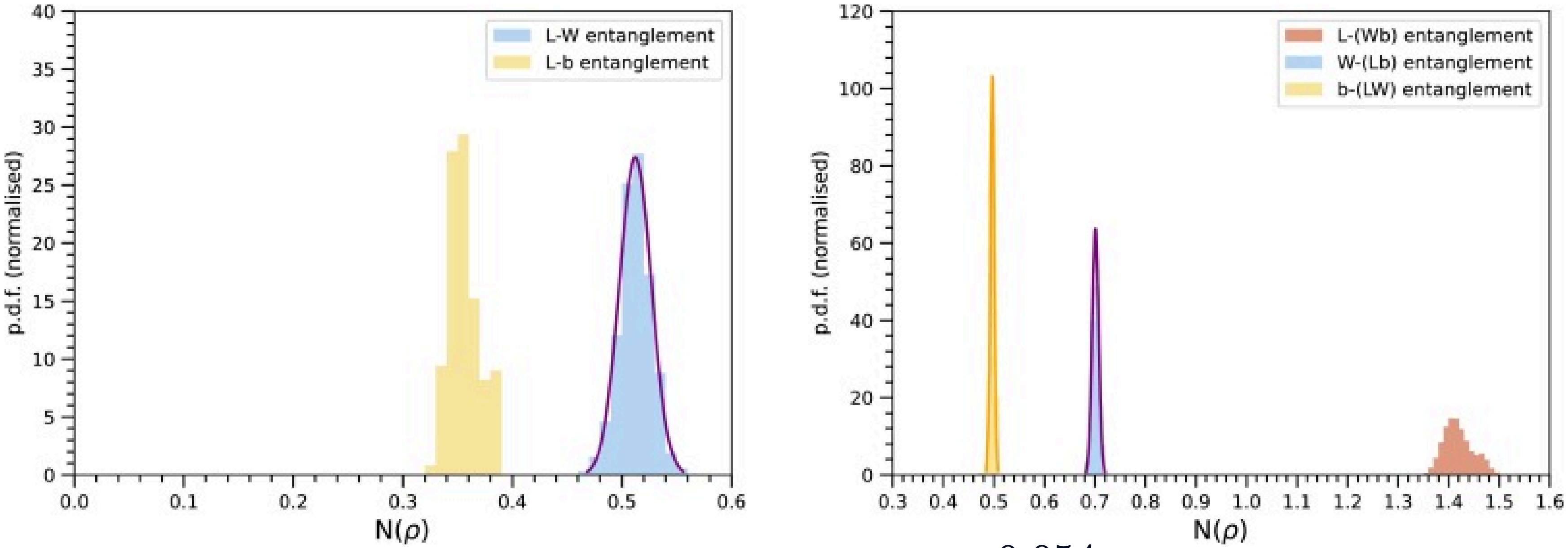
- The approach is using helicity amplitude framework of Jacob and Wick Annals of Phys. Vol. 7 4 (1959):

$$A^h_{M\lambda_1\lambda_2}(\theta,\phi) = a_{\lambda_1\lambda_2} D^{1/2*}_{M\lambda}(\phi,\theta,0)$$

- These can be measured with the 4-angle framework explained in the slides before.
- Then, performing a change of basis for the b spinors and W polarization vectors, and expanding in terms of spherical harmonics $\langle\Omega|lm\rangle = Y_l^m(\Omega)$, we get the "canonical amplitudes", $A_{Ms_1s_2;lm}$

Fenomenological prediction

Phys. Let. B 855 (2024) 138849



$$N(\rho_{LW}) = 0.512 \pm 0.015\ (\text{stat})^{+0.054}_{-0.057}\ (\text{syst}), > 5\sigma$$
$$N(\rho_{Lb}) = 0.356 \pm 0.014\ (\text{stat})^{+0.008}_{-0.11}\ (\text{syst}), \sim 3.2\sigma$$
$$N(\rho_{L[Wb]}) = 1.42 \pm 0.03\ (\text{stat})^{+0.13}_{-0.09}\ (\text{syst}), > 5\sigma$$