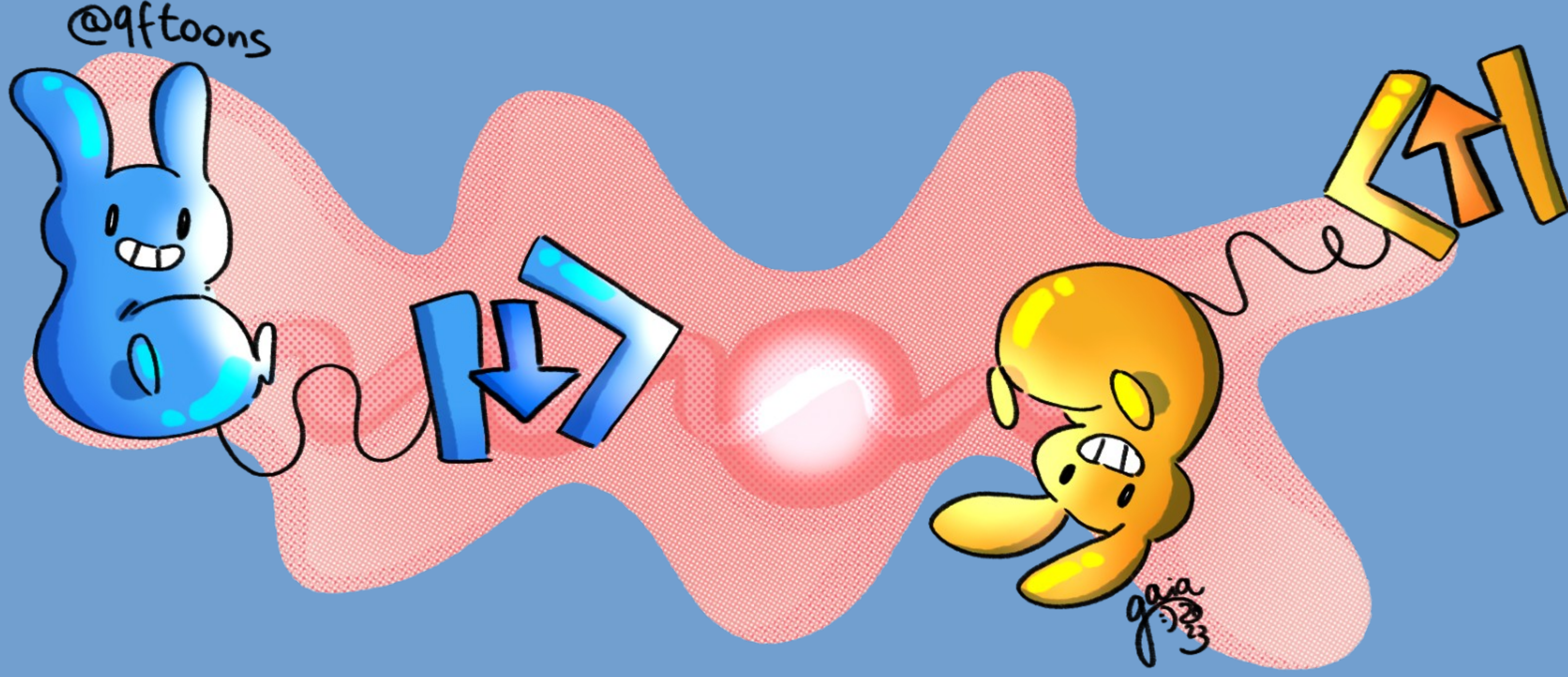
# Bell inequalities with top-quark pairs




*Drawings by Gaia Fontana @QFToons*

26/03/24 Claudio Severi - U. Manchester

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Nature

CERN-EP-2023-230
November 20, 2023

# Observation of quantum entanglement in top-quark pairs using the ATLAS detector

The ATLAS Collaboration

**nature reviews** physics

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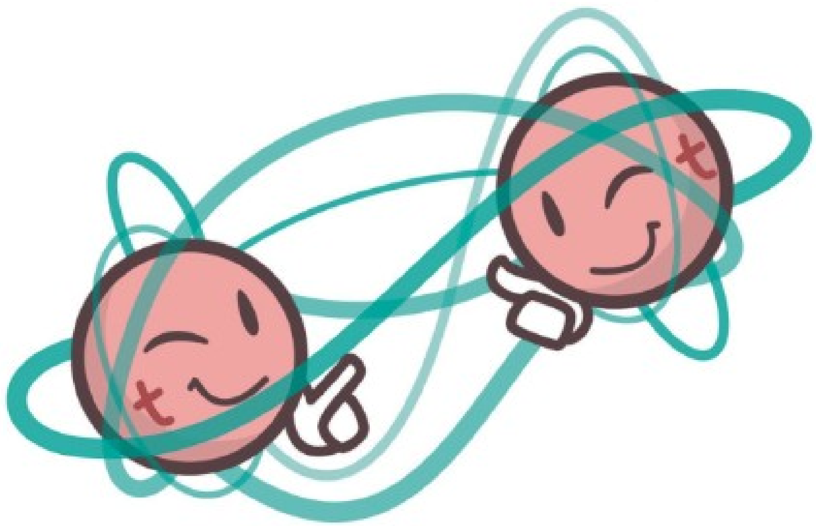
Editors' picks 2023 https://doi.org/10.1038/s42254-024-00695-3

# Entanglement between a pair of top quarks




Entanglement is a purely quantum phenomenon that has been studied extensively in low-energy systems to explore the foundations of quantum mechanics and for applications in quantum technologies. Would entanglement manifest at very high energies, in a relativistic regime with exotic interactions and symmetries? There is no reason to suspect that it wouldn't, but so far there has not been any experiment able to test this assumption. Now, the ATLAS Collaboration at CERN has used data from 13 TeV proton–proton collisions at the Large Hadron Collider to observe for the first time entanglement between a pair of top quarks.

This is the highest-energy measurement of entanglement to date and could open a new experimental program of investigating quantum mechanics and quantum information in a completely unexplored regime.

The top quark is a spin 1/2 fermion and the heaviest of all elementary particles. Being so massive, it is also unstable, with a lifetime of $10^{-25}$ s. This short lifetime makes the top quark ideal for studying entanglement, because when it decays, it transfers its spin to its decay particles, which can be detected and used to reconstruct the quantum state of the original top quark. This is exactly what the ATLAS Collaboration did using collision data at 13 TeV collected between 2015 and 2018. These collisions produce top–antitop quark pairs, which are entangled. By measuring the angular distributions of their decay products, it is possible to estimate the value of an entanglement witness, which distinguishes between entangled and non-entangled states. This value is indeed what one would expect for an entangled state. The result exceeds the five standard deviation threshold required for an observation.

This study is not only interesting for observing entanglement at such high energies, but also for using data that had not originally been collected for this purpose. The success of this analysis suggests further studies of these top–antitop quark quantum states, for example by measuring quantum discord which quantifies the 'quantumness' of correlations. If there are any measurable deviations from low-energy quantum entanglement these might hint at new physics beyond the standard model.

**Iulia Georgescu**

**Original article:** ATLAS Collaboration. Observation of quantum entanglement in top-quark pair production using *pp* collisions of $\sqrt{s}$ = 13TeV with the ATLAS detector. ATLAS-CONF-2023-069 (2023)

**Related articles:** Afik, Y. & de Nova, J. R. M. Entanglement and quantum tomography with top quarks at the LHC. *Eur. Phys. J. Plus* **136**, 907 (2021); Afik, Y. & de Nova, J. R. M. Quantum discord and steering in top quarks at the LHC. *Phys. Rev. Lett.* **130**, 221801 (2023)

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Illustration by Sandbox Studio, Chicago

# Scientists measure entanglement at the LHC

12/18/23 | By Chiara Villanueva

Scientists on the ATLAS collaboration performed the highest-energy measurement of quantum entanglement.

On the smallest level, the universe operates in such a bizarre way that even Albert Einstein had a difficult time making sense of it. An example of the strangeness in the quantum realm—one that has no equivalent in the world as we experience it—is the phenomenon of quantum entanglement.

Entanglement is a purely quantum phenomenon that has been studied extensively in low-energy systems to explore the foundations of quantum mechanics and for applications in quantum technologies. Would entanglement manifest at very high energies, in a relativistic regime with exotic interactions and symmetries? There is no reason to suspect that it wouldn't, but so far there has not been any experiment able to test this assumption. Now, the ATLAS Collaboration at CERN has used data from 13 TeV proton–proton collisions at the Large Hadron Collider to observe for the first time entanglement between a pair of top quarks.

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Physics

# Large Hadron Collider turned into world's biggest quantum experiment

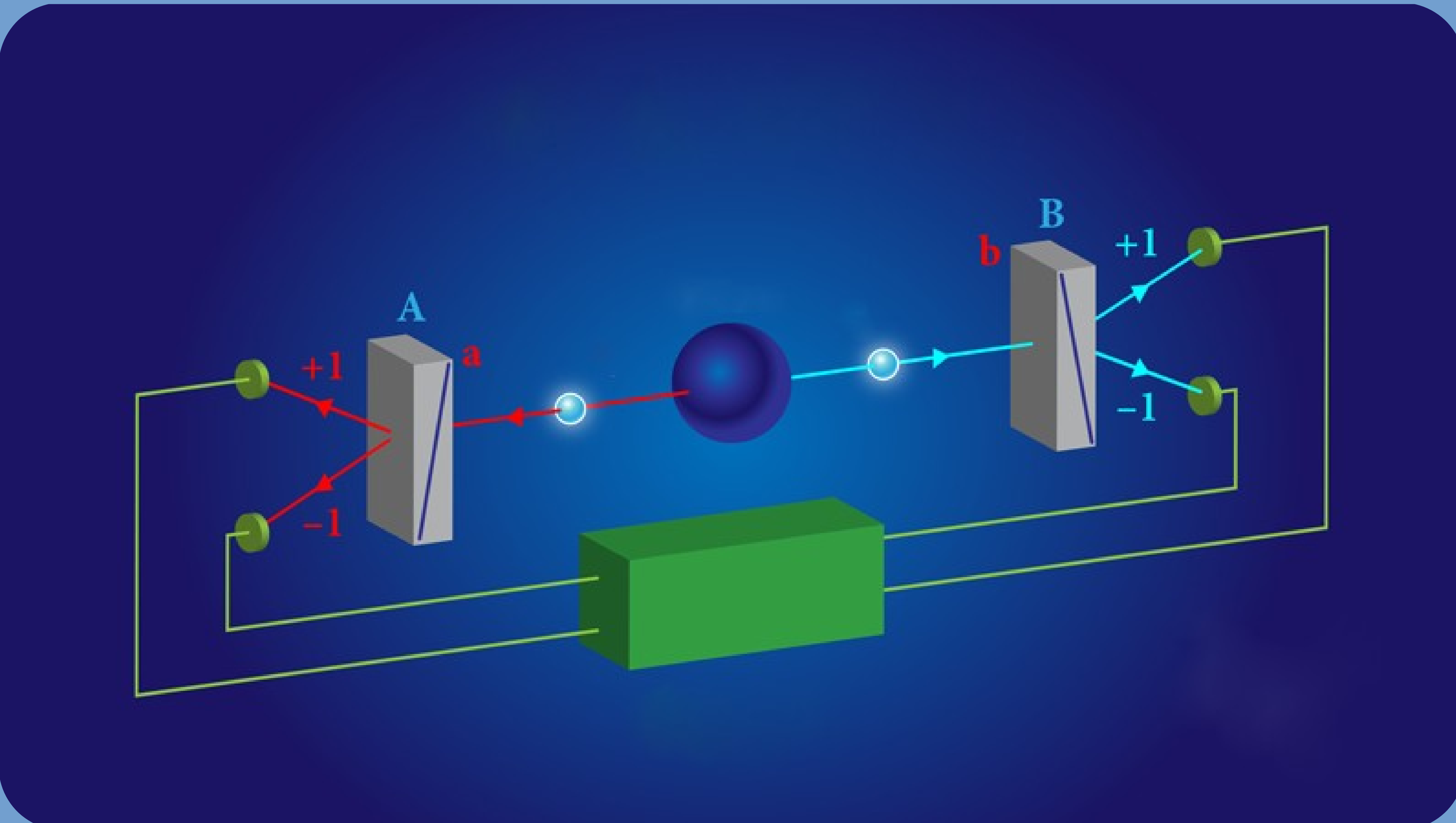
Physicists have used the famous particle smasher to investigate the strange phenomena of quantum entanglement at far higher energies than ever before

By Alex Wilkins

3 October 2023

26/03/24

# Bell inequalities



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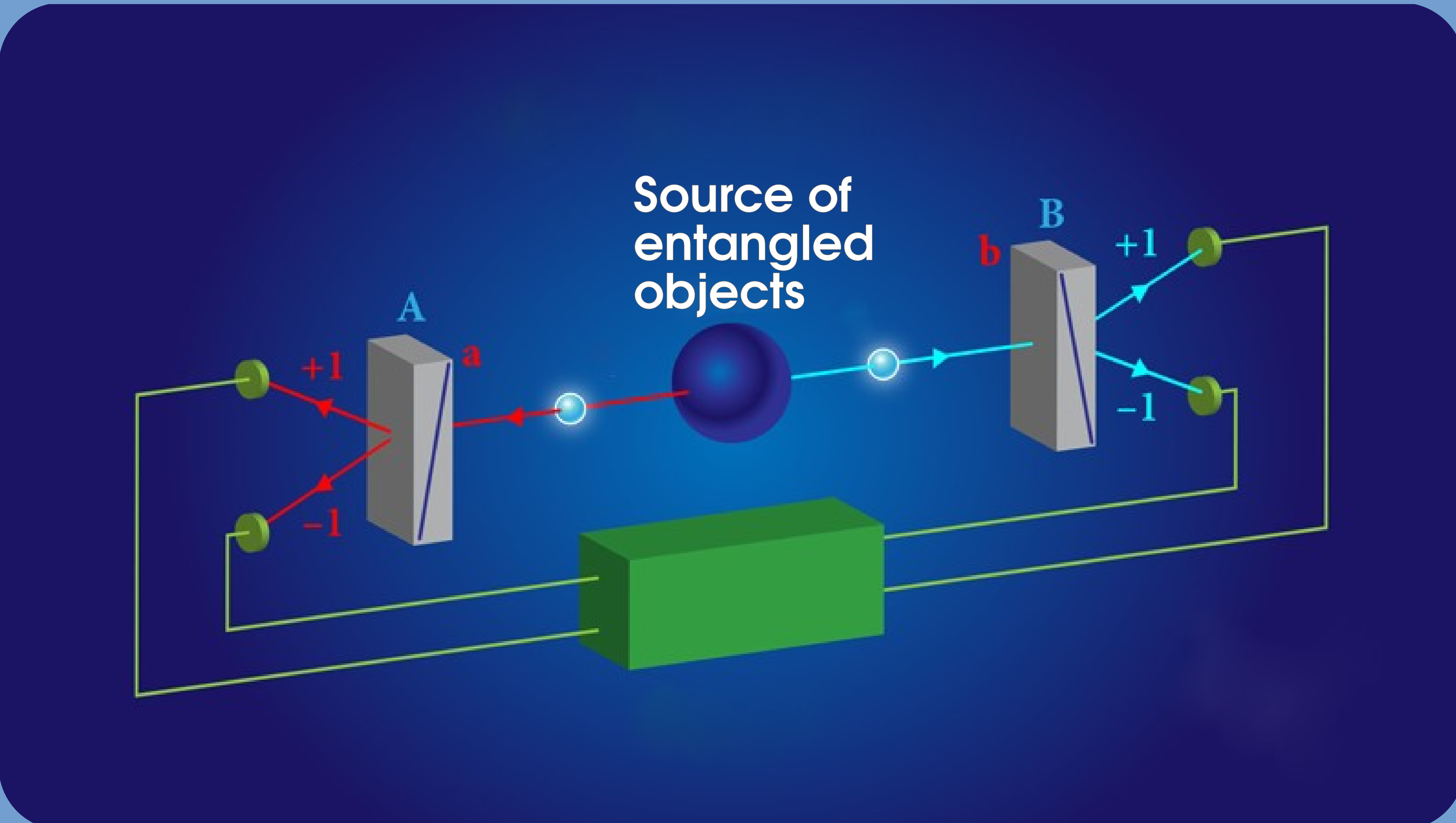

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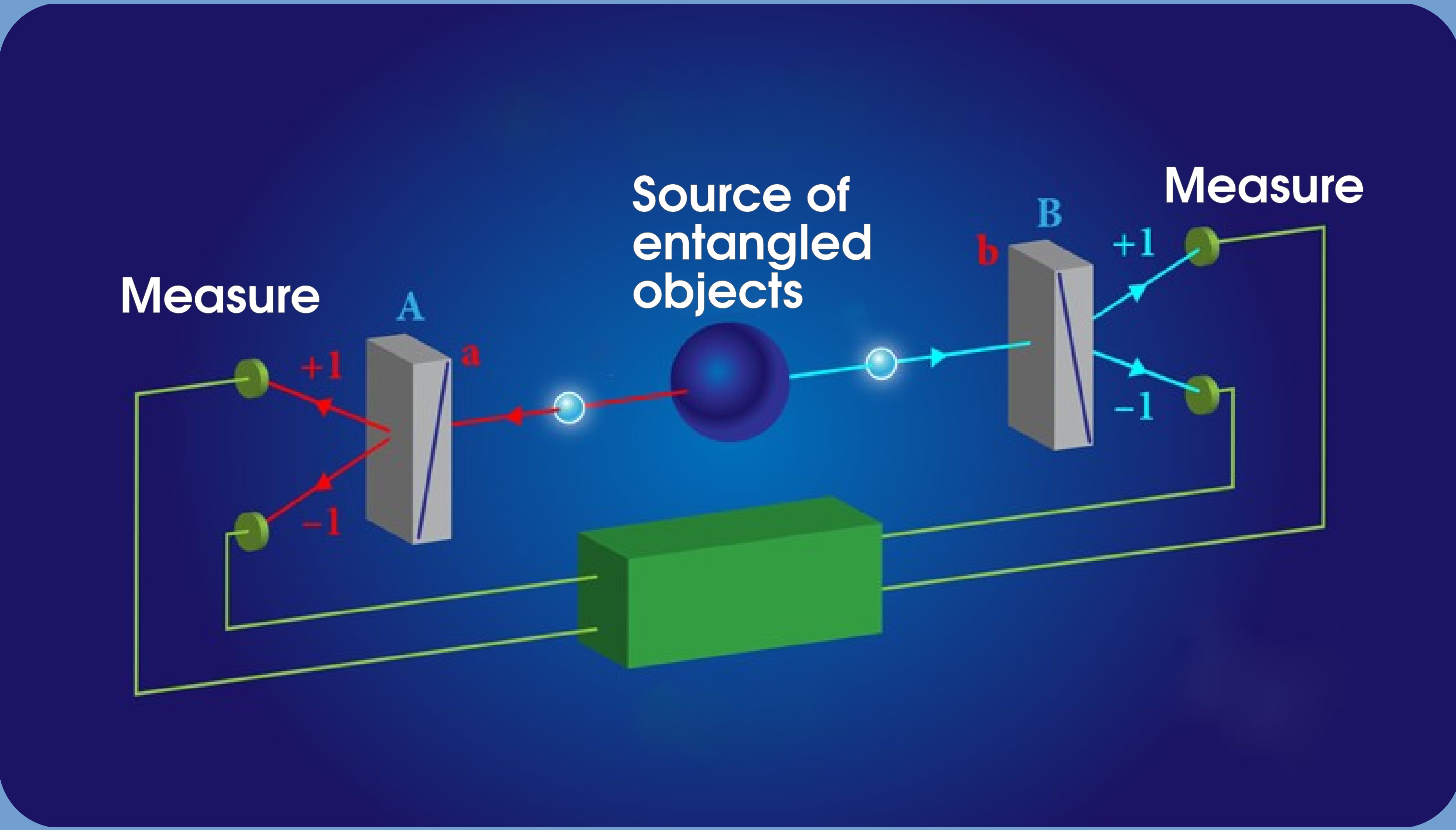

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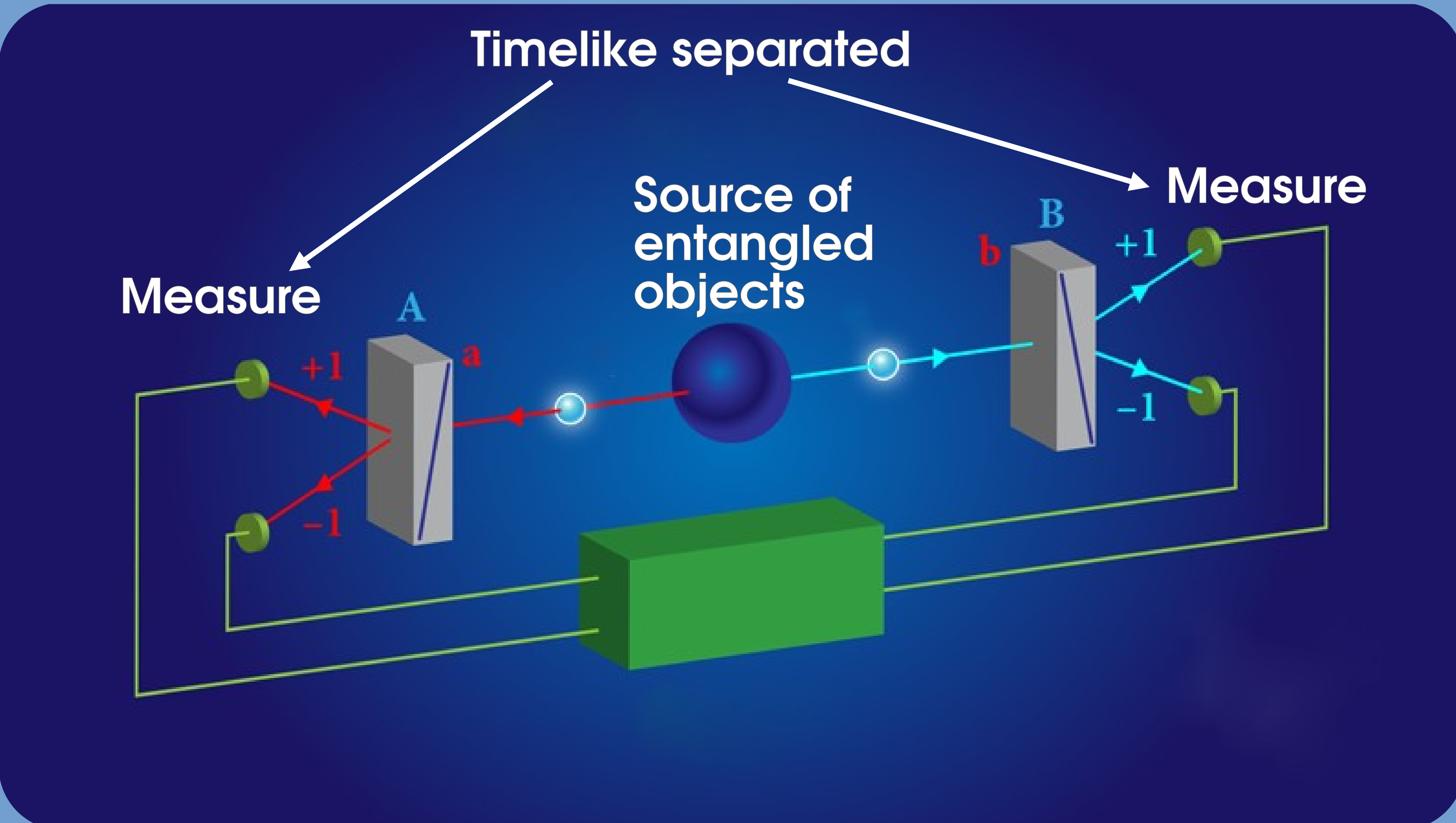

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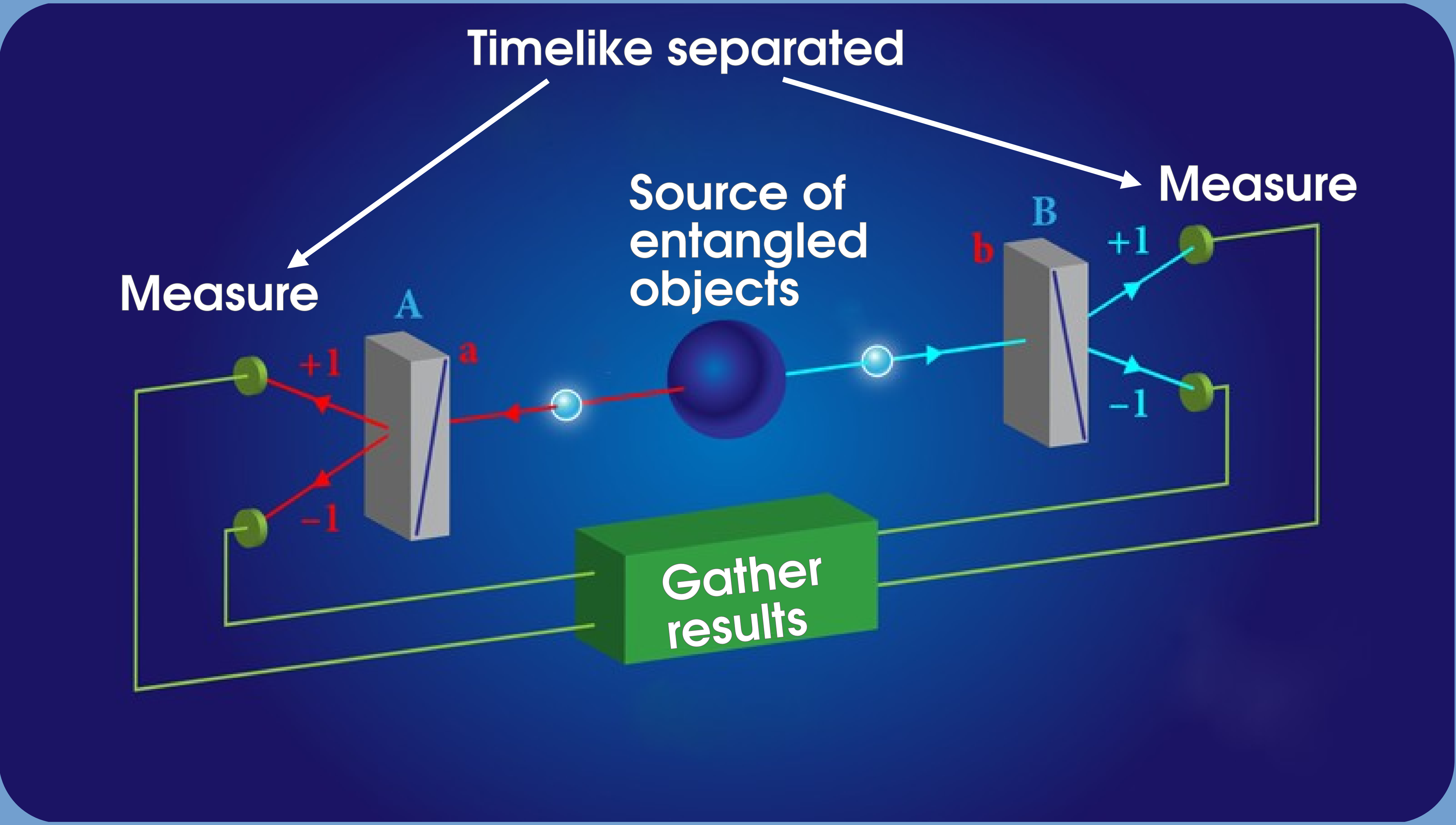

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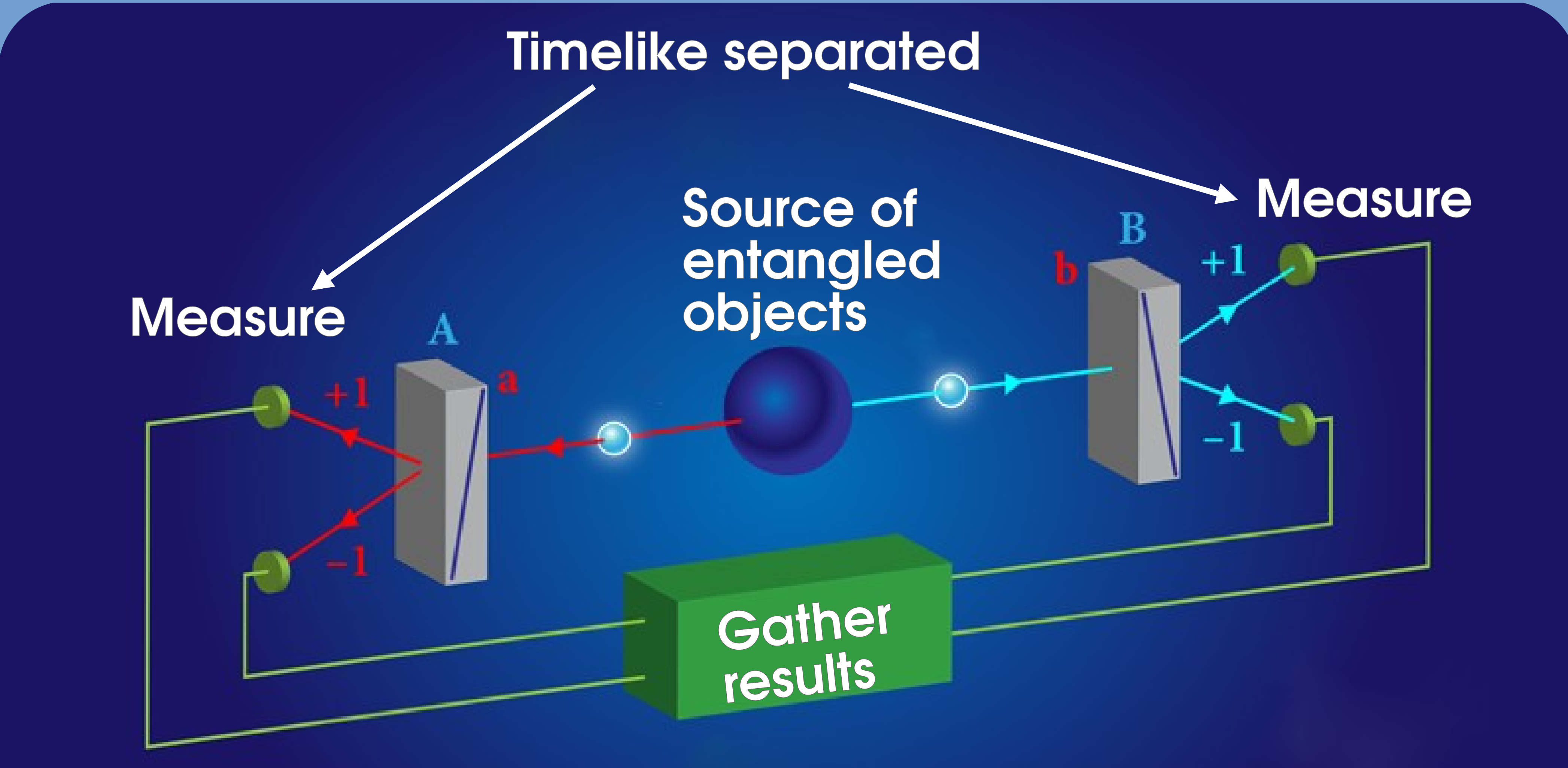


Compare results → find that correlations were so strong that they could not be explained classically

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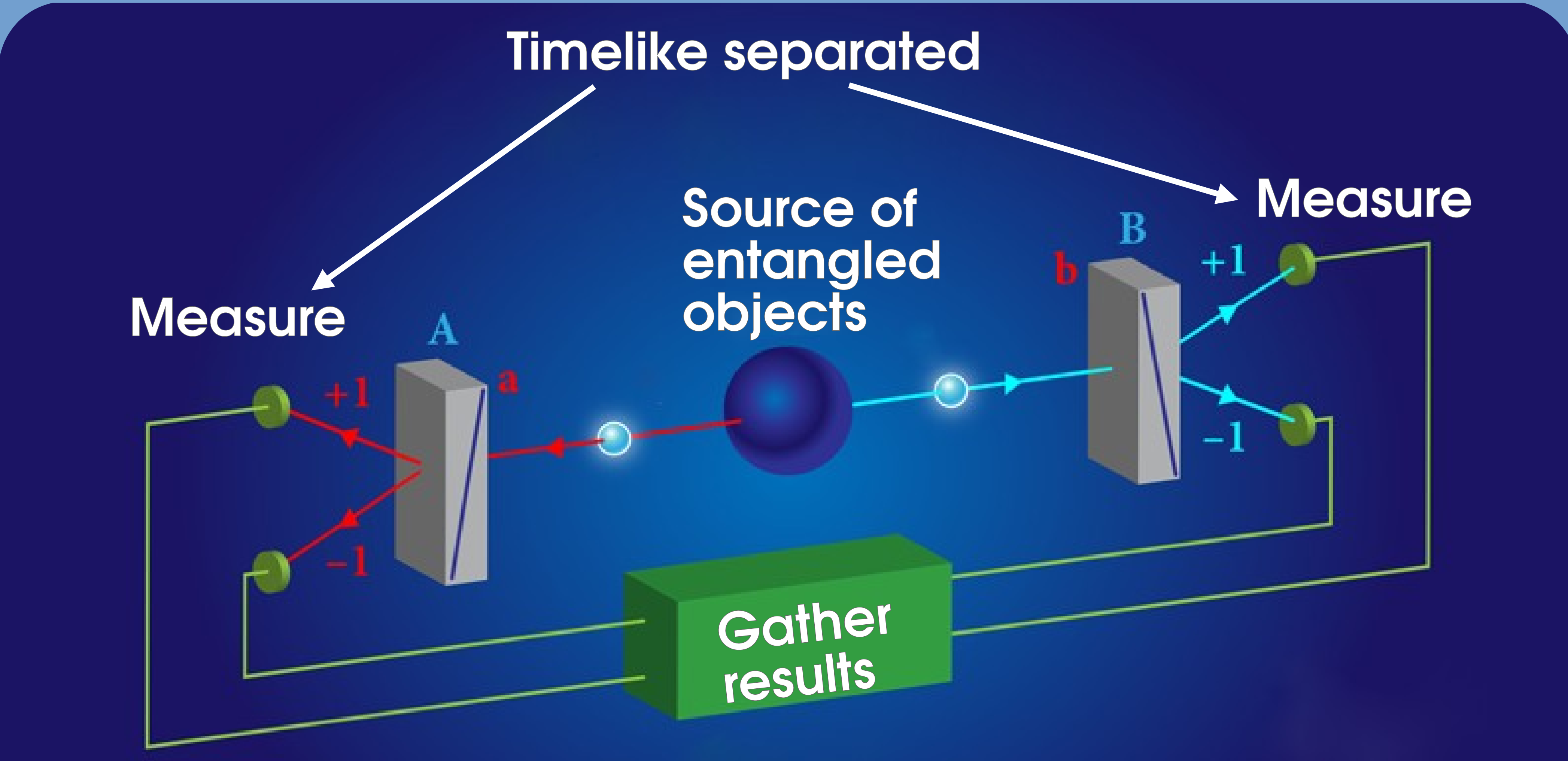


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$$|C(a_1, b_1) - C(a_1, b_2) + C(a_2, b_1) + C(a_2, b_2)| \leq 2$$

# Is there anything genuinely quantum to test in a collider?

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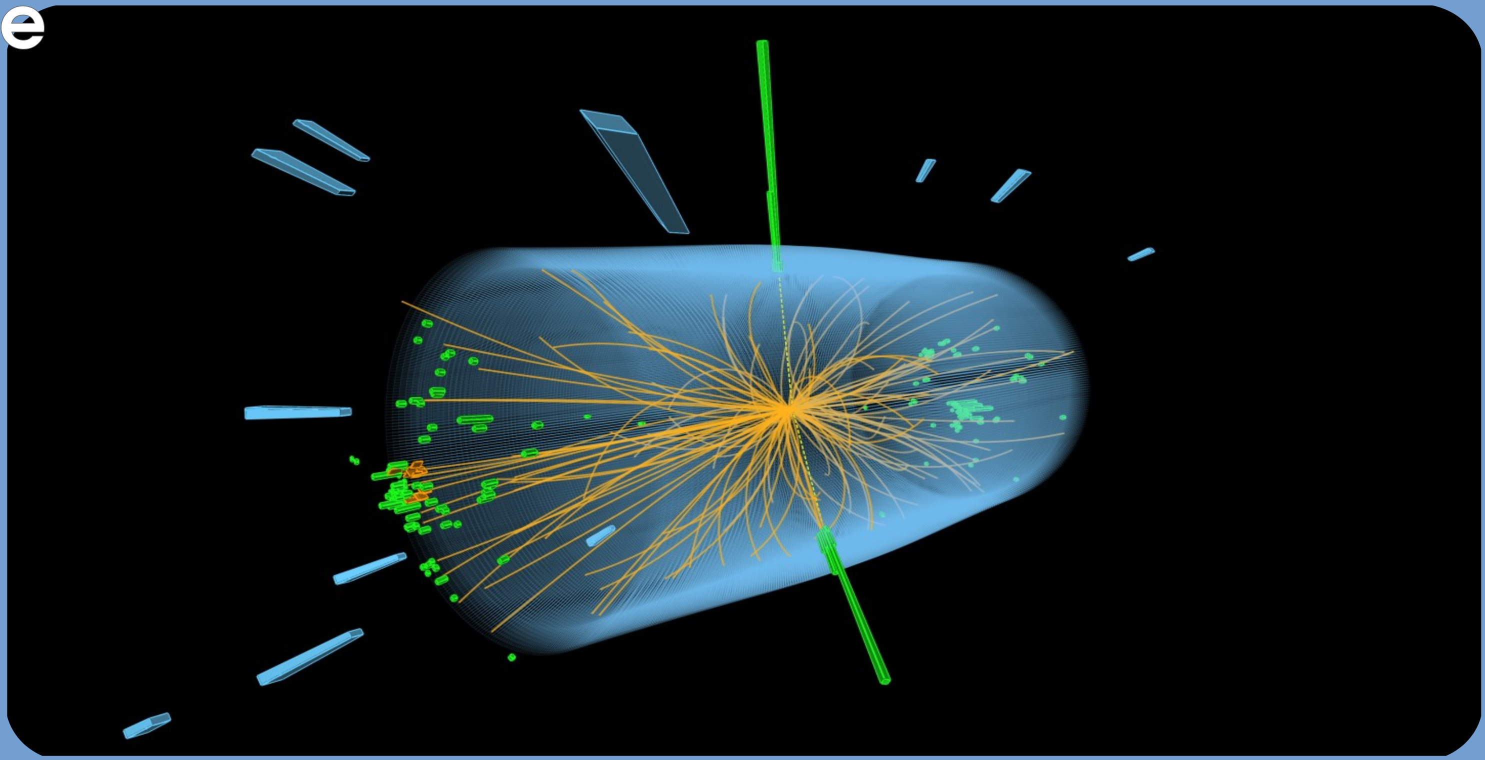

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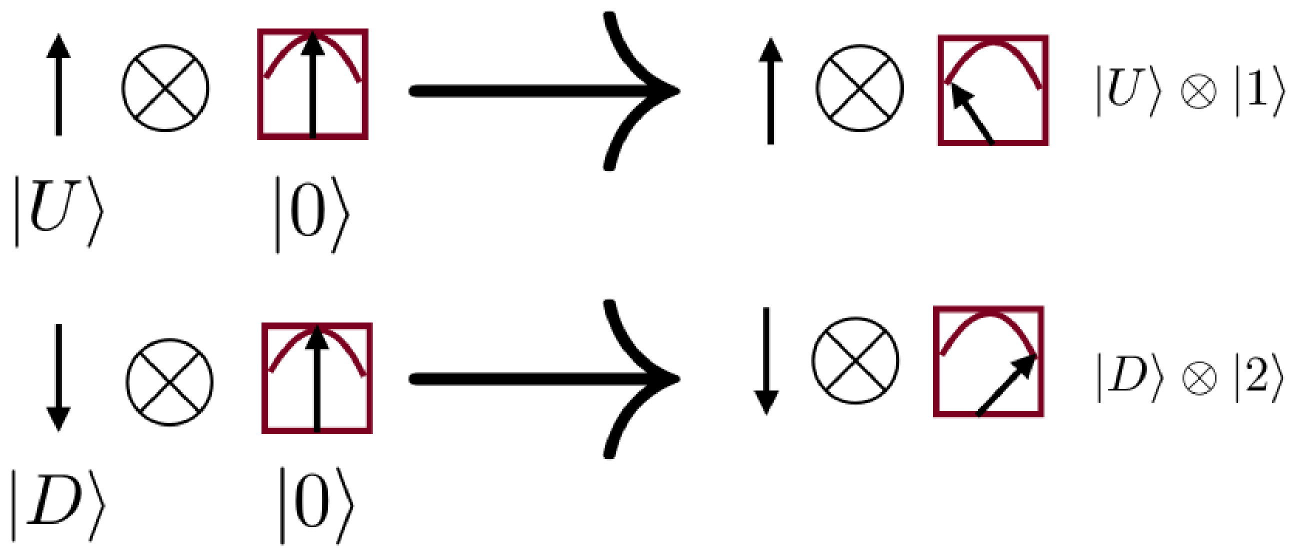
## What happens when I do a measurement?

How does this Human interact with a spin?

Toy Model of Human's Brain

Brain contains say M registers to deal with spins. Initially, all registers are in quantum state |o>

Interaction Hamiltonian between spin and Human: Register state changes




**Talk by Surjeet Rajendran, Pittsburgh, 8/3/24**

# Top spin correlations

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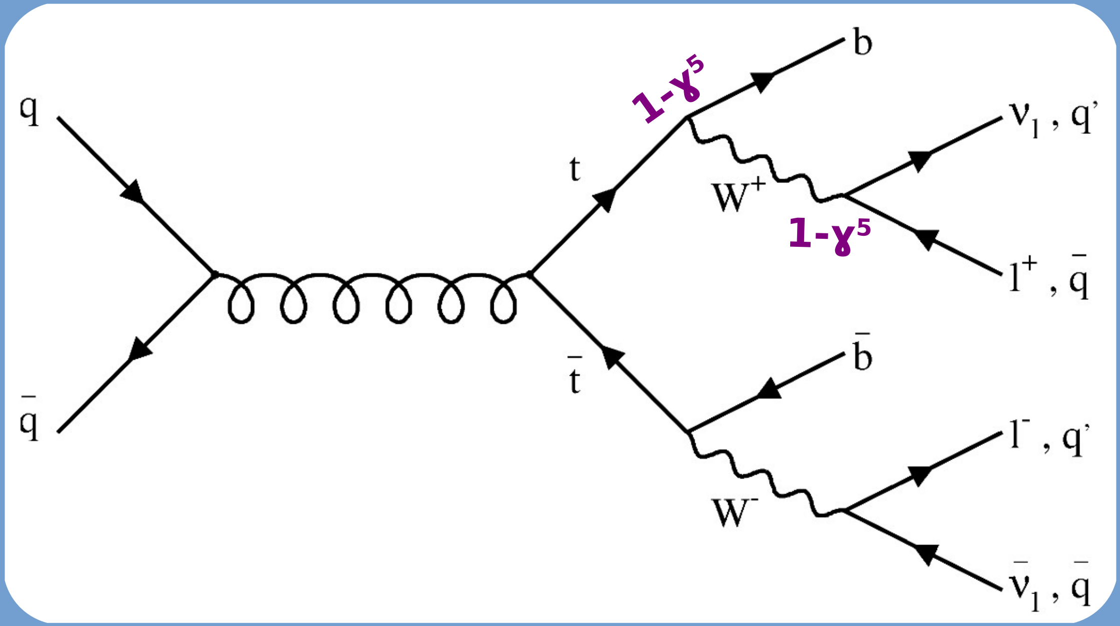
The weak decays
t → Wb, W → ℓ ν
transfer the spin state
to the decay products



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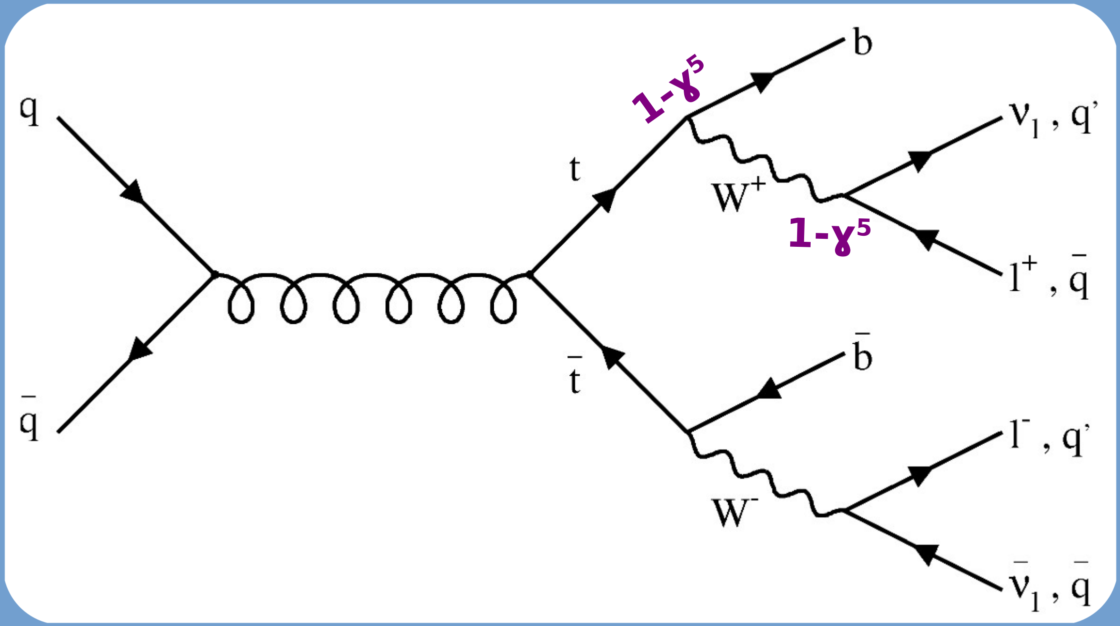


Tops decay before hadronizing,
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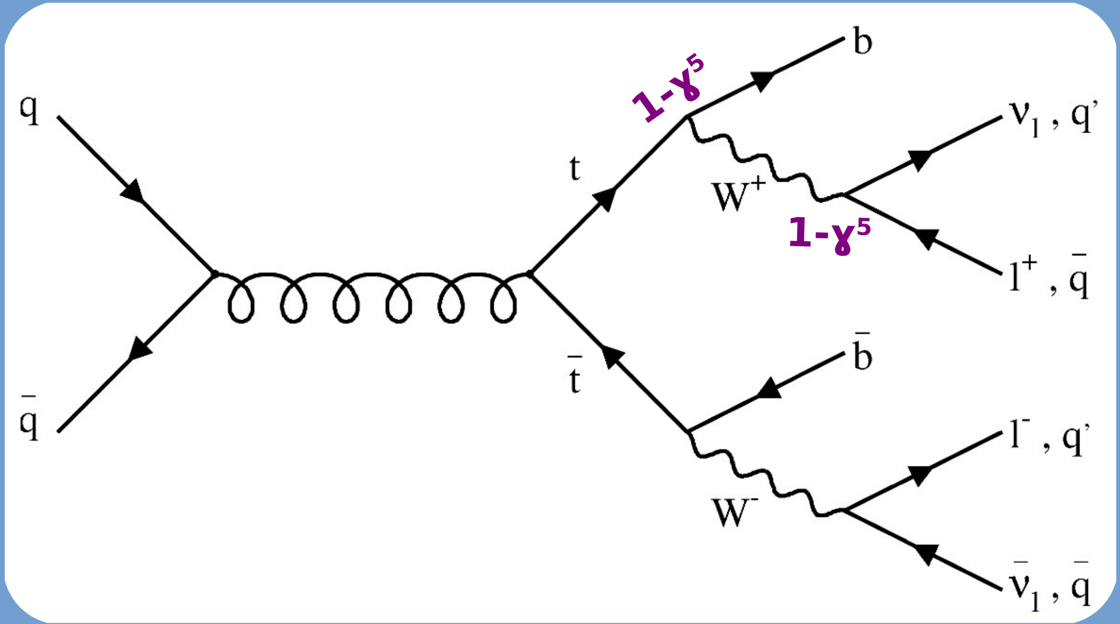


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ttbar = (almost) ideal pair of qubits

$$\rho = \frac{I_4 + \sum_i \left( B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

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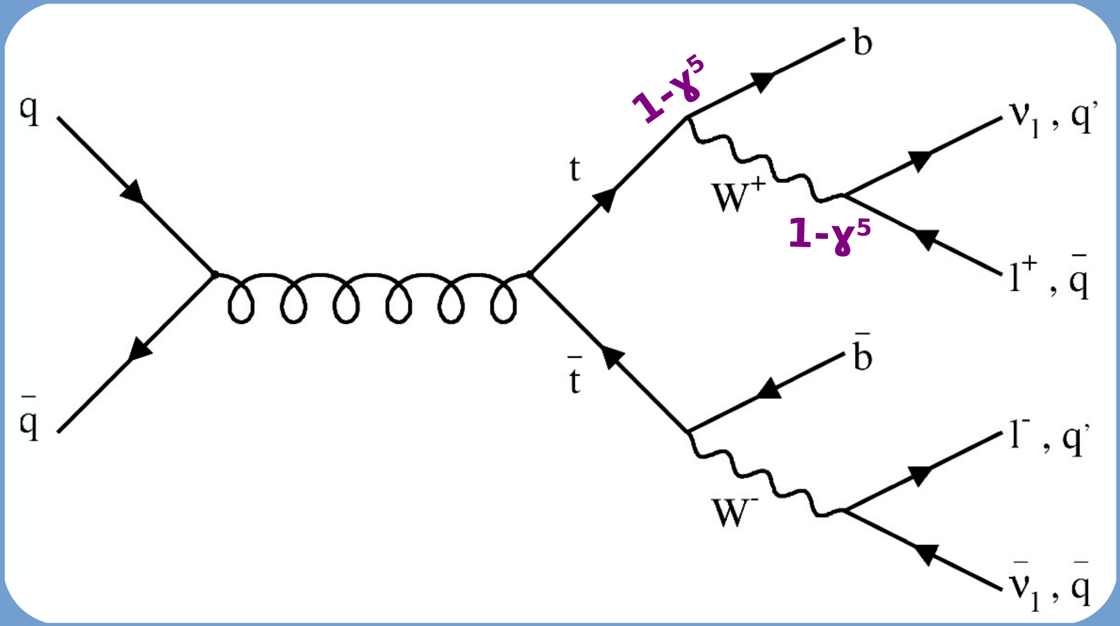


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**Entanglement**

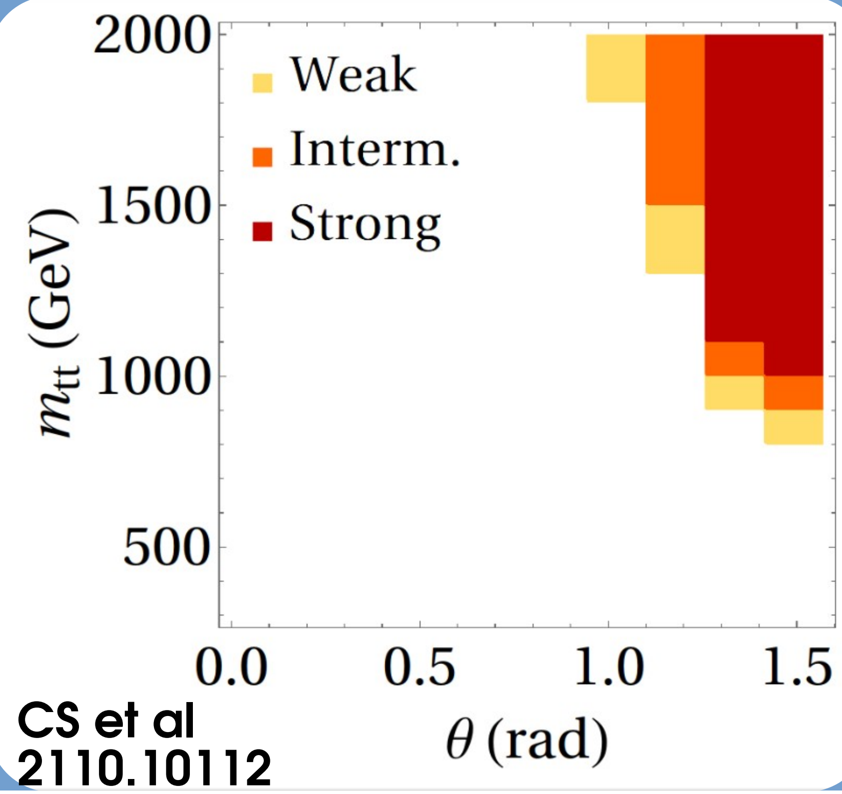
$$-C_{kk} - C_{rr} - C_{nn} > 1,$$

**Bell violation**

$$\sqrt{2}\left| -C_{rr} + C_{nn}\right| \leq 2,$$

# Some simulations

A series of studies have suggested a Bell beasurement
is doable at the HL-LHC




CS et al
2110.10112

| High-$p_T$ Selection | Cross section | CHSH on fixed axes, $\sqrt{2}|$ – Parton–level | Reconstructed [350 fb$^{-1}$] |
|---|---|---|---|
| Weak | 0.19 pb | 2.10 | $2.12 \pm 0.17$ |
| Intermediate | 0.10 pb | 2.18 | $2.20 \pm 0.30$ |
| Strong | 0.06 pb | 2.25 | $2.30 \pm 0.76$ |

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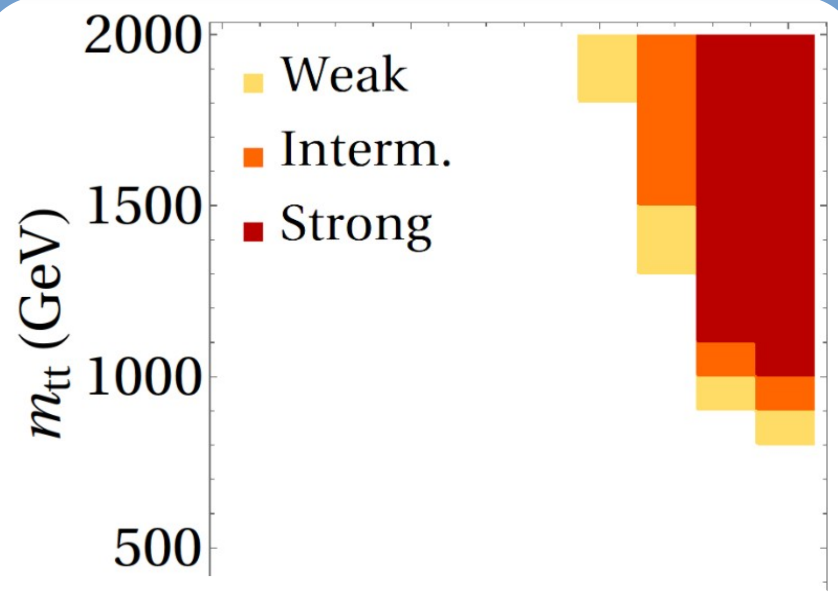


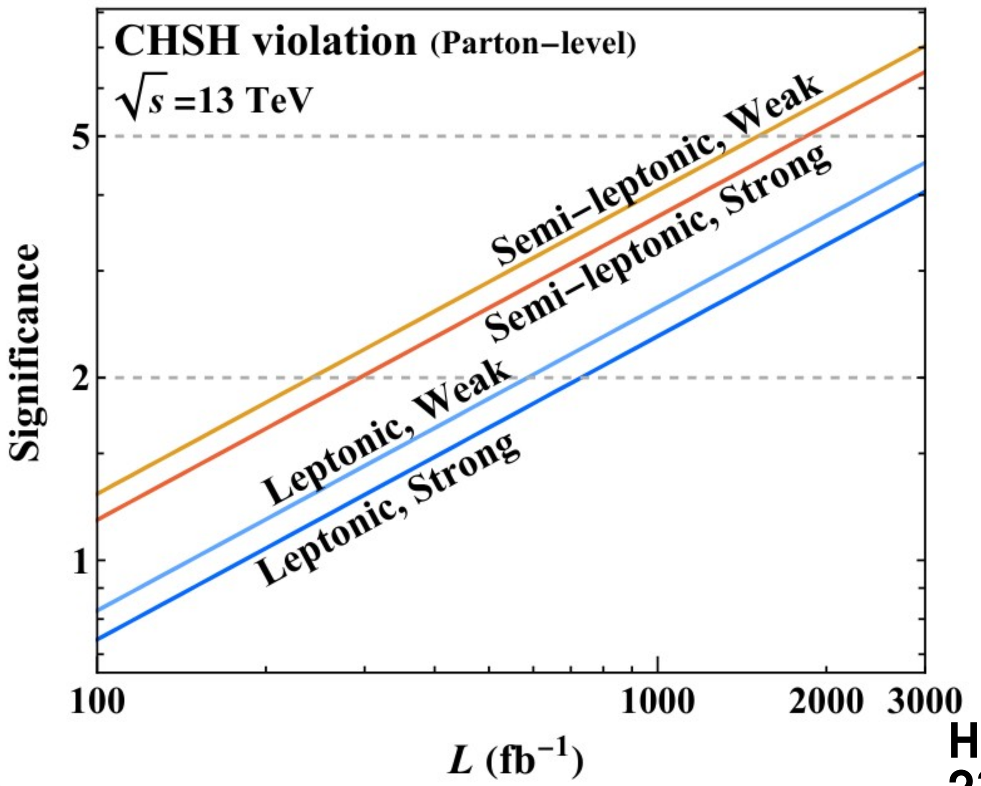


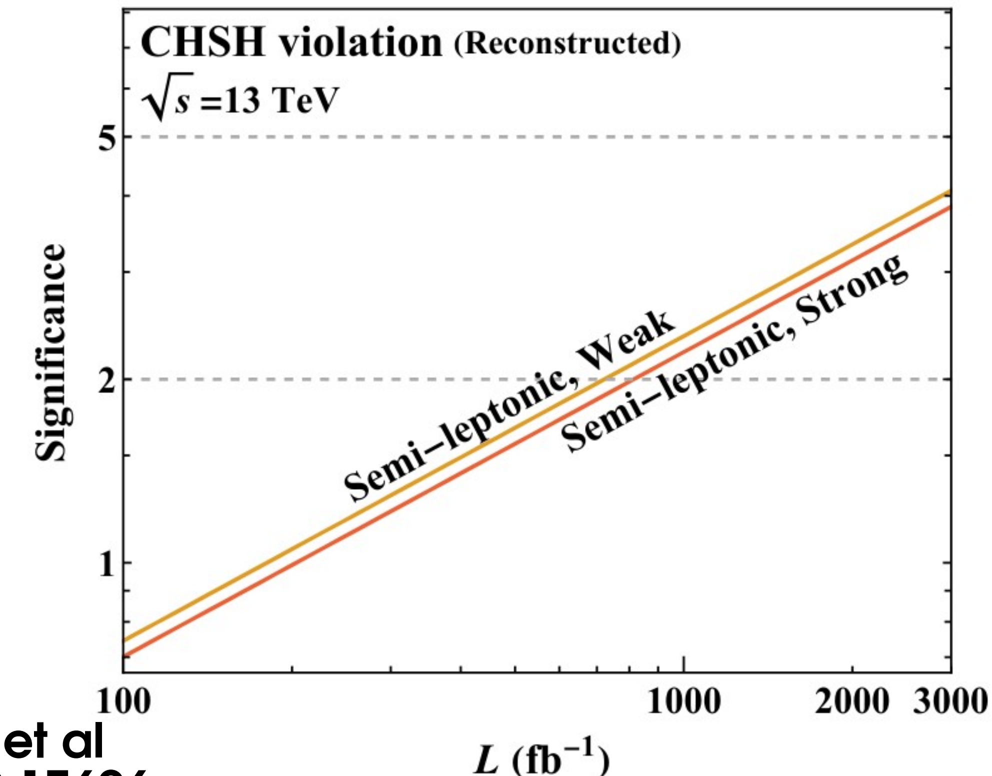


Han et al
2310.17696

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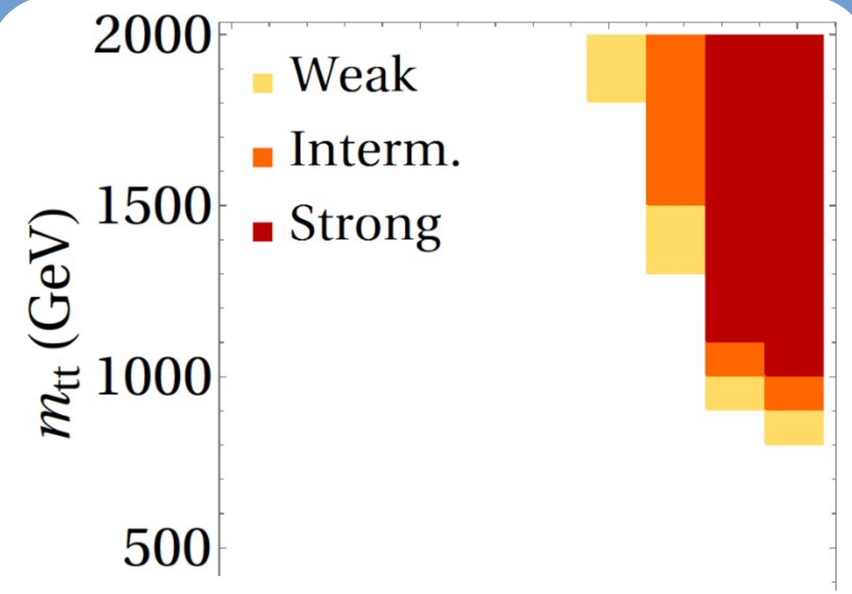


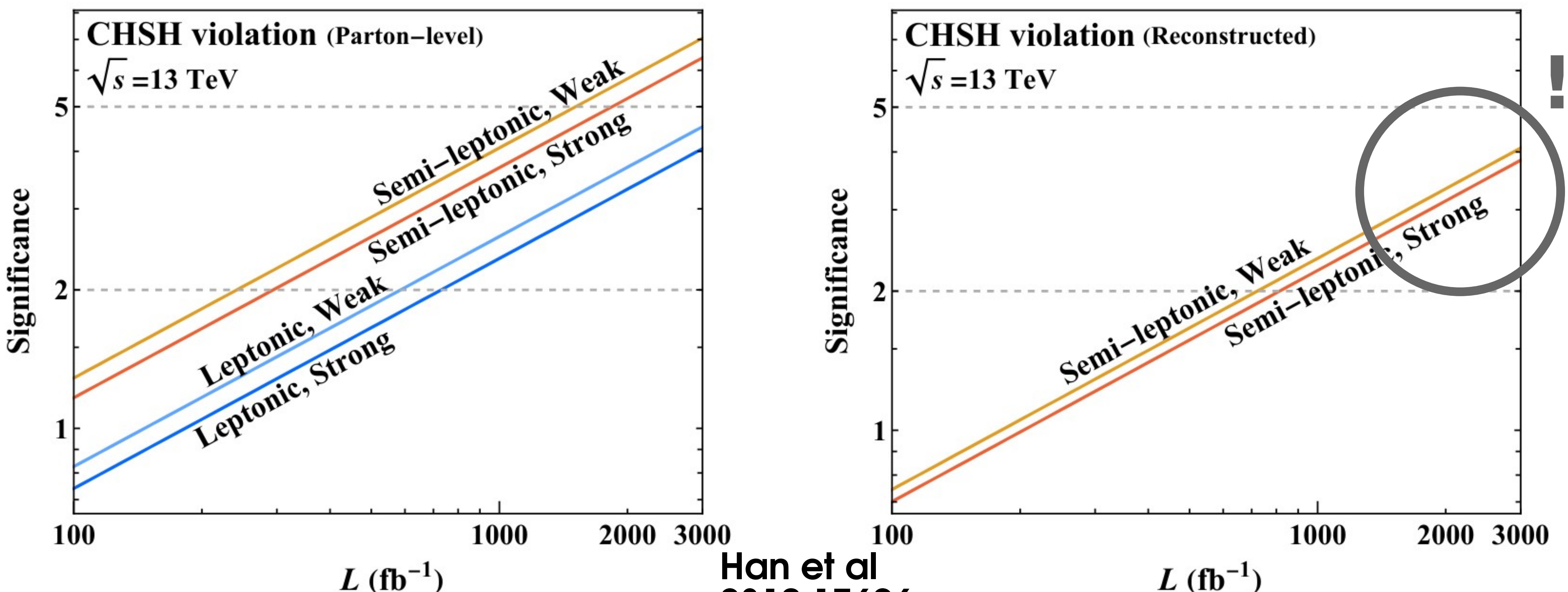


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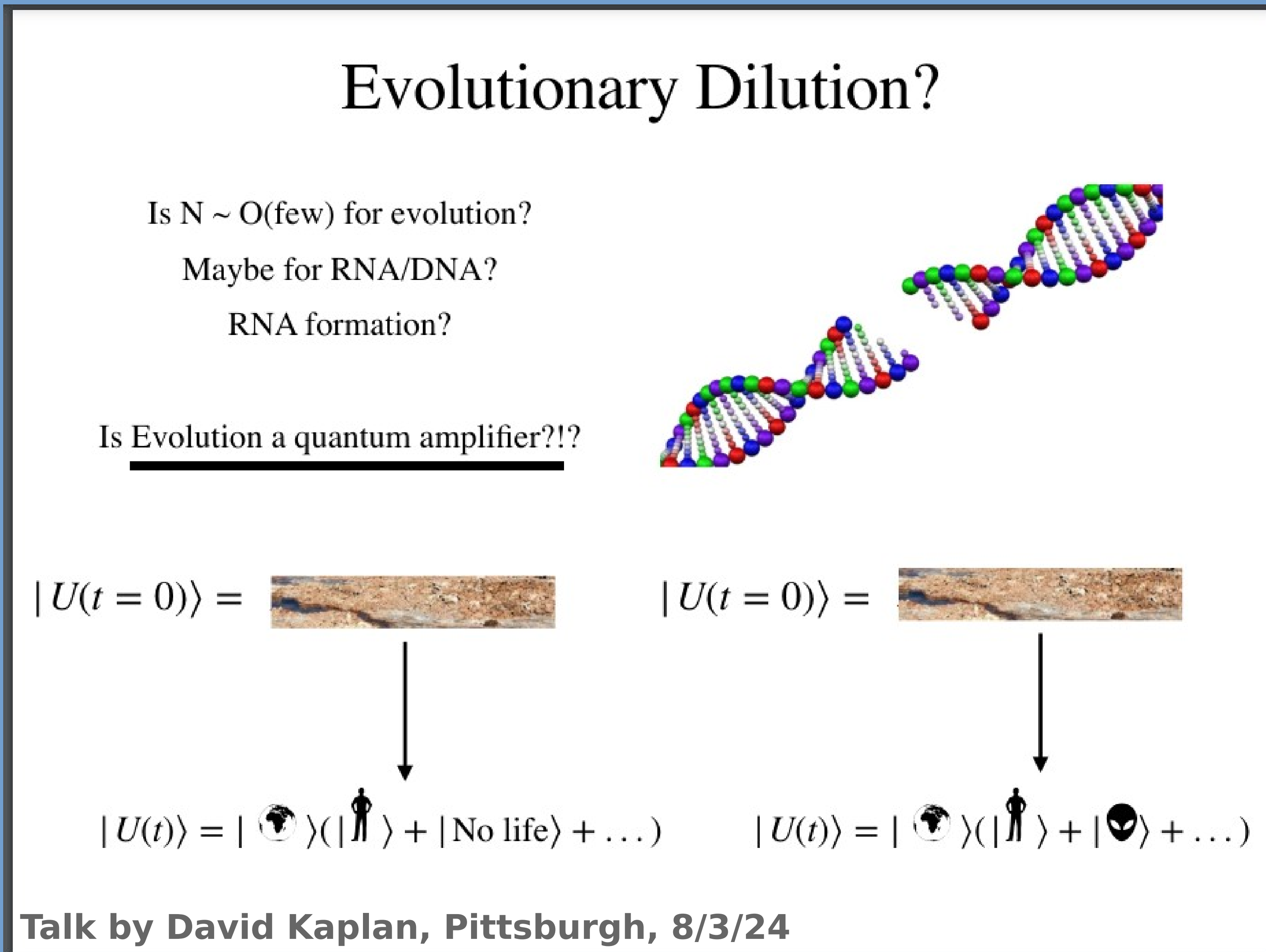

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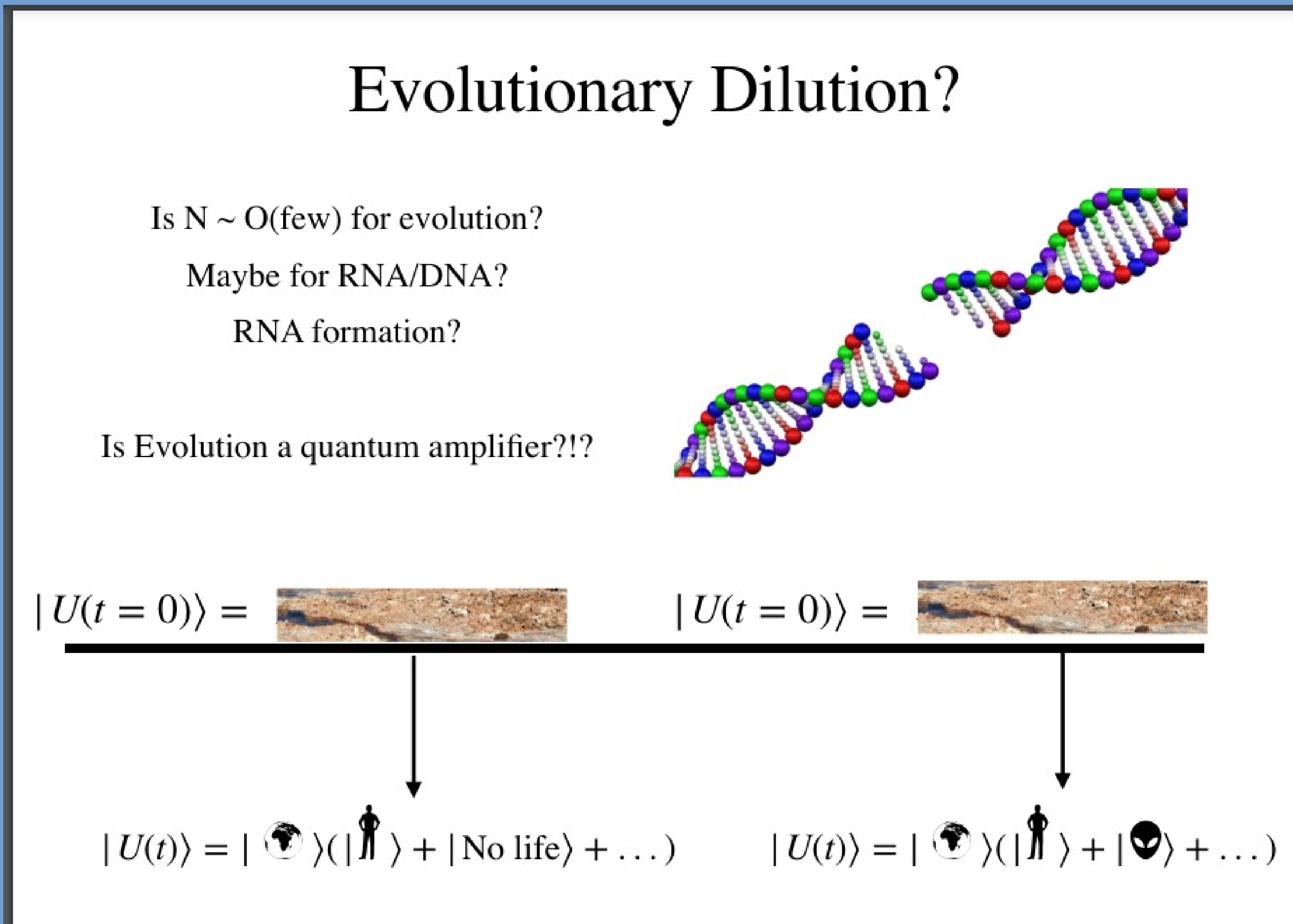


**Talk by David Kaplan, Pittsburgh, 8/3/24**

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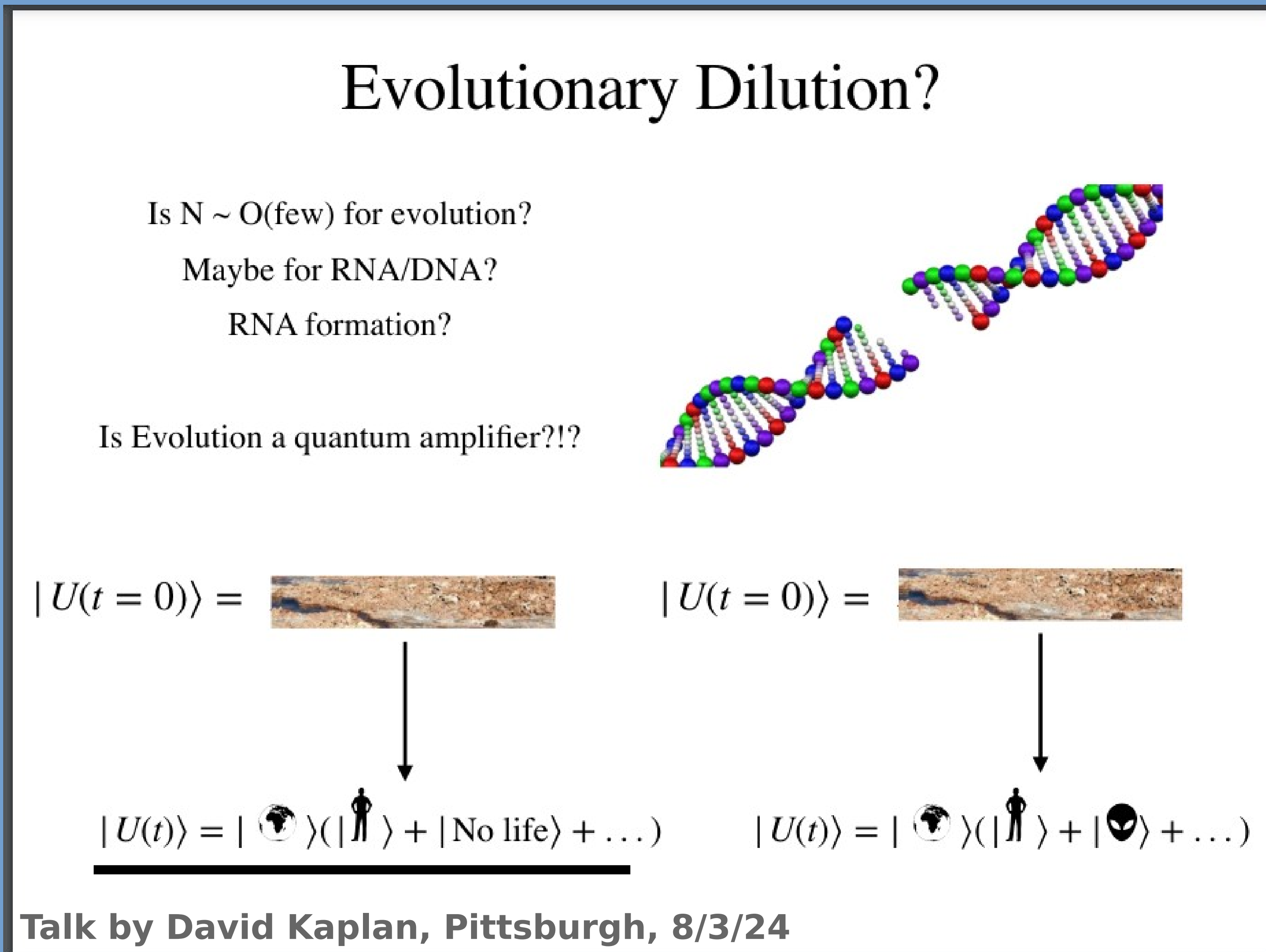

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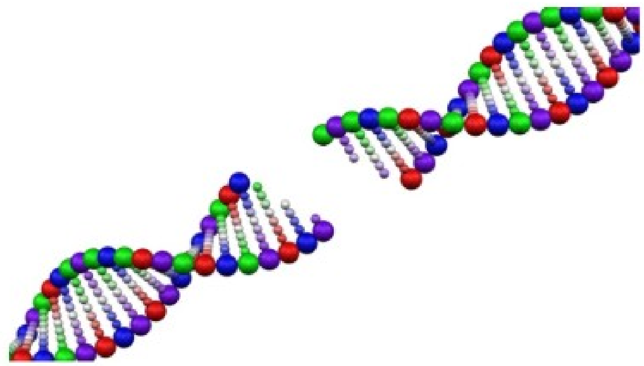
### Evolutionary Dilution?

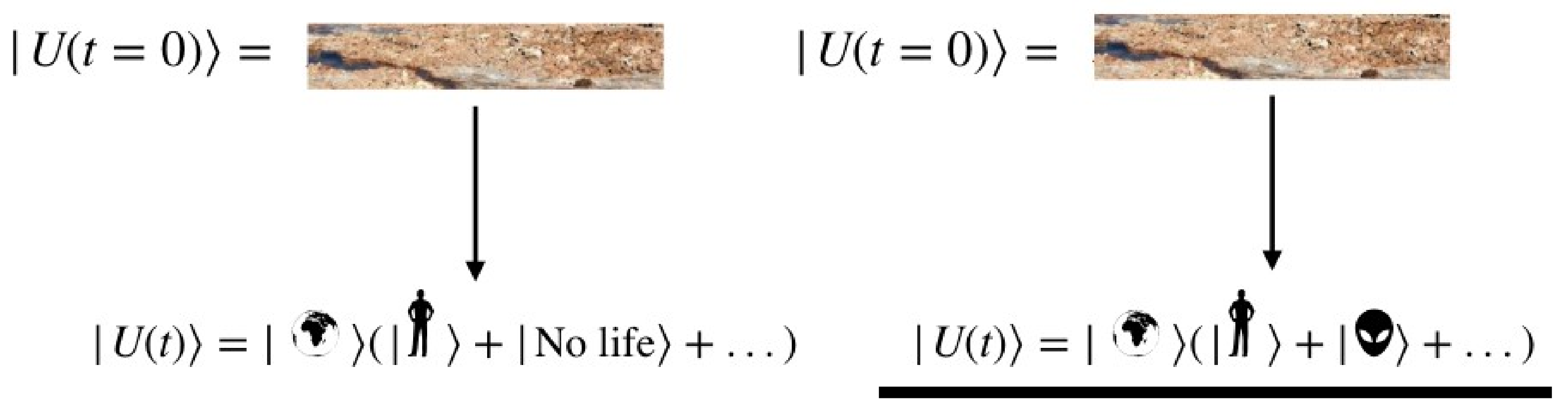
Is N ~ O(few) for evolution?

Maybe for RNA/DNA?

RNA formation?



Is Evolution a quantum amplifier?!?

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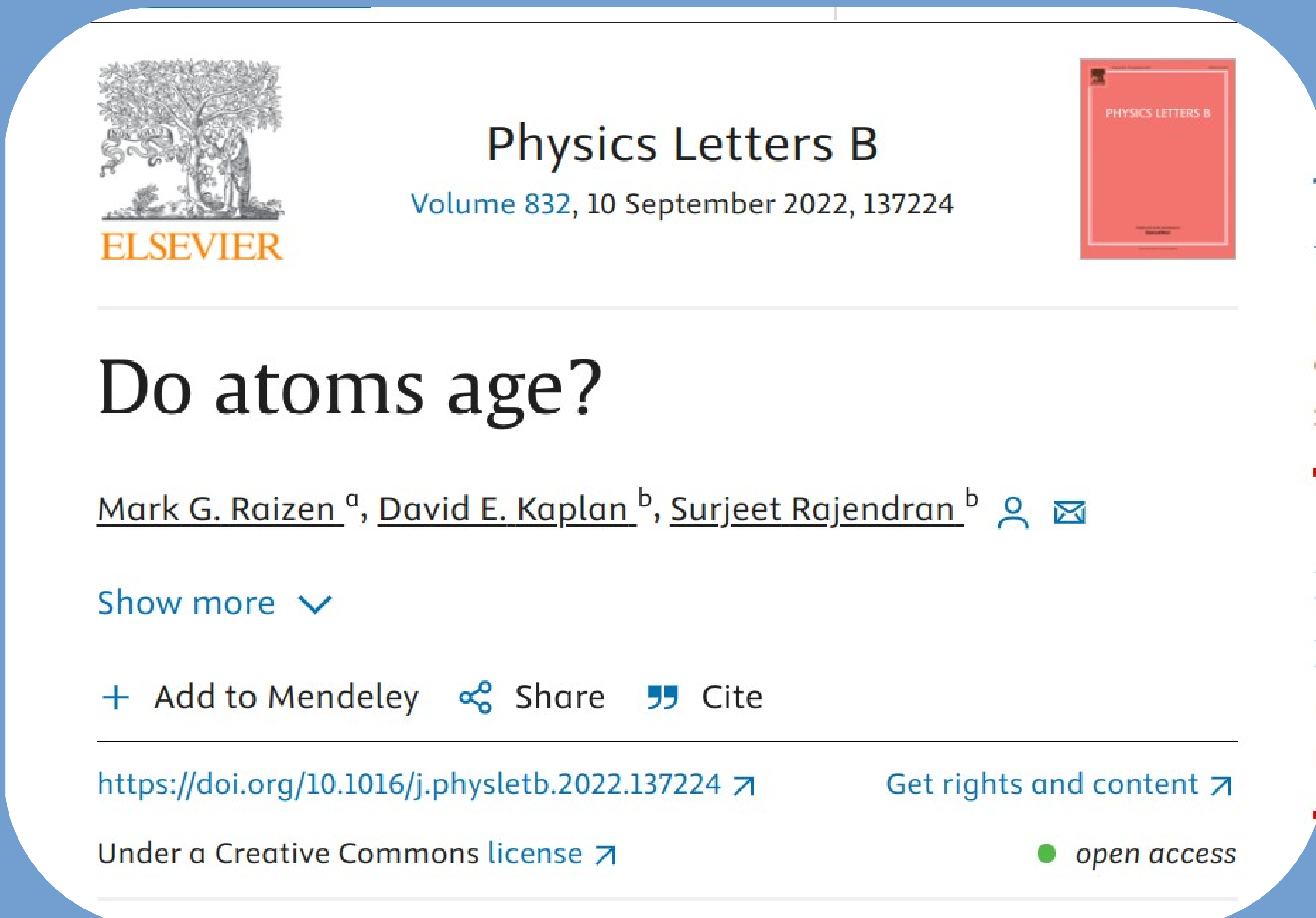
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# Do atoms age?

Mark G. Raizen [a], David E. Kaplan [b], Surjeet Rajendran [b]

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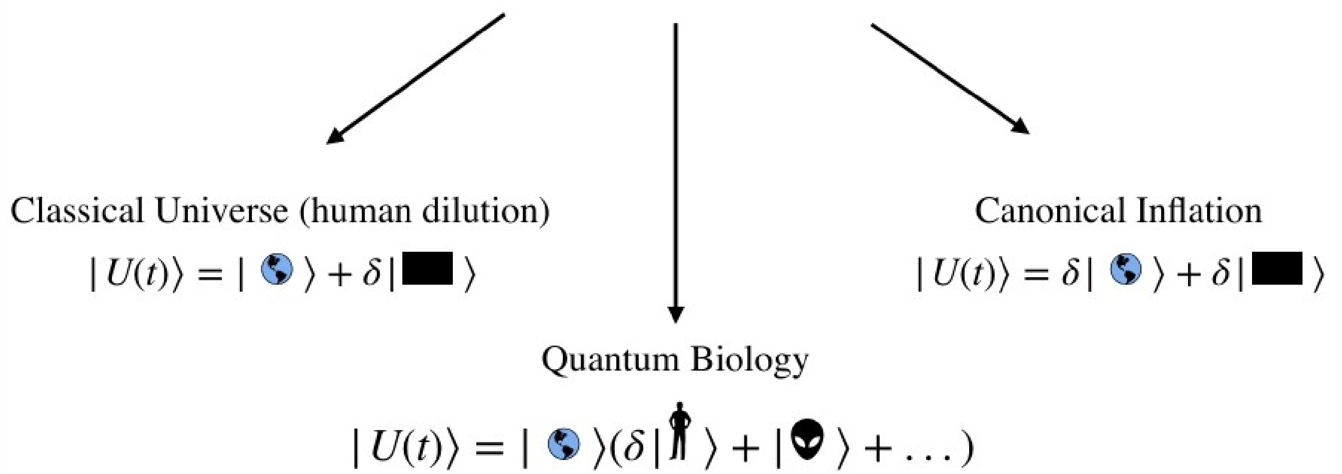
# Probes of Non-Linear Quantum Mechanics

Non-Linear effects deeply tied to unchangeable initial and evolution of total quantum state

Probe not just non-linear quantum mechanics but full evolutionary history of quantum state!

Three Scenarios

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"Quantum" observables provide complementary information to classical ones

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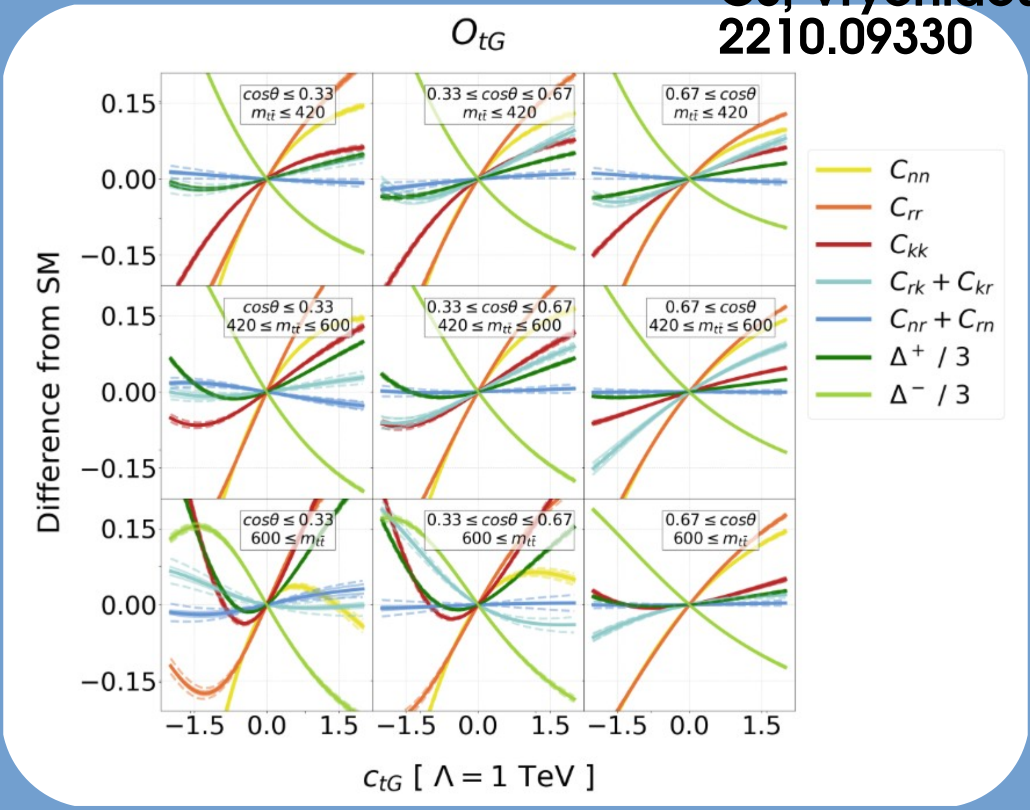
## Example 1: new physics searches

"Quantum" observables provide complementary information to classical ones

CS, Vryonidou
2210.09330



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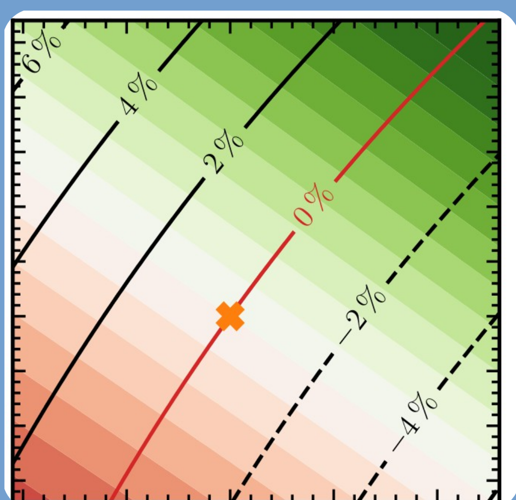


Aoude et al
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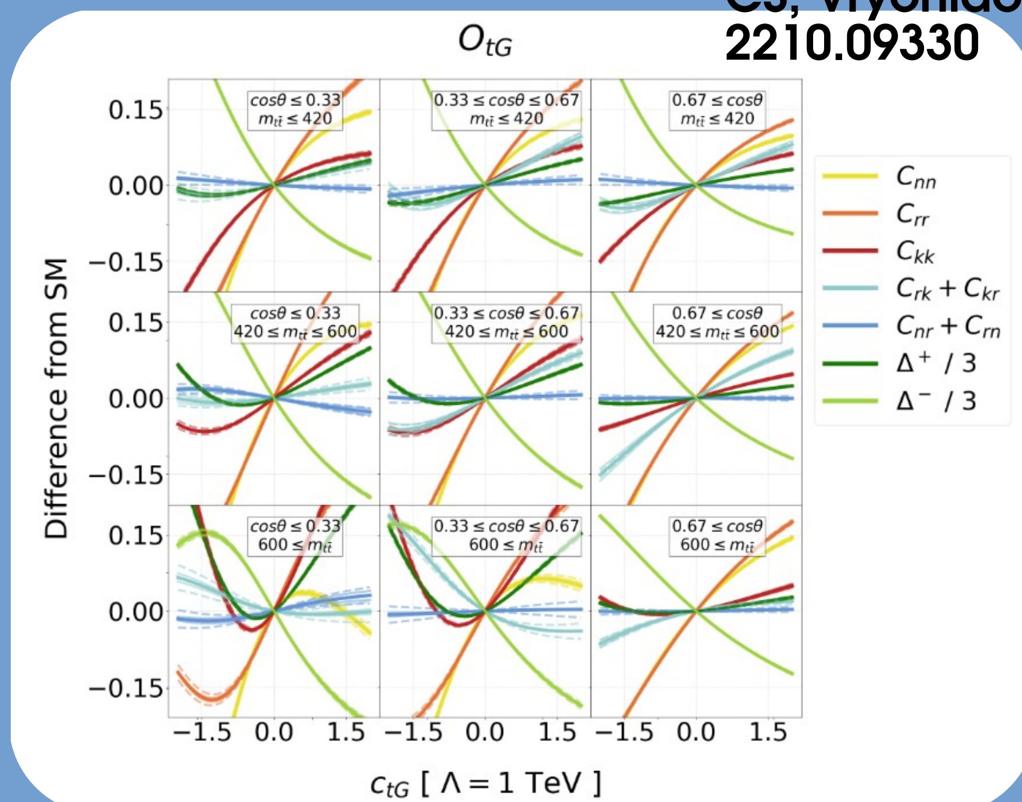

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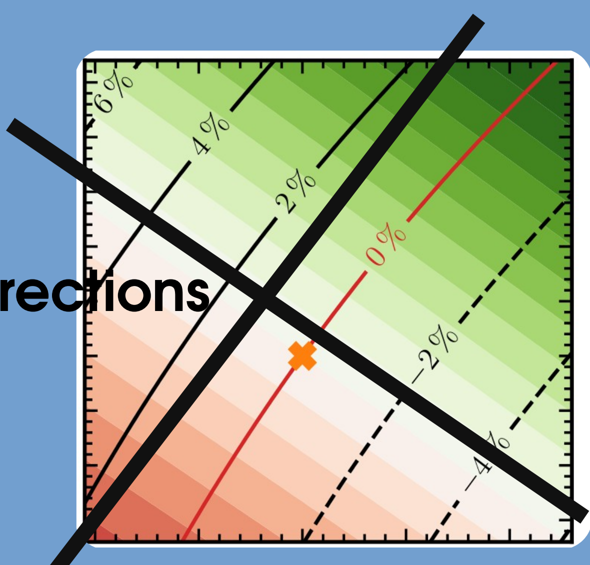
flat directions

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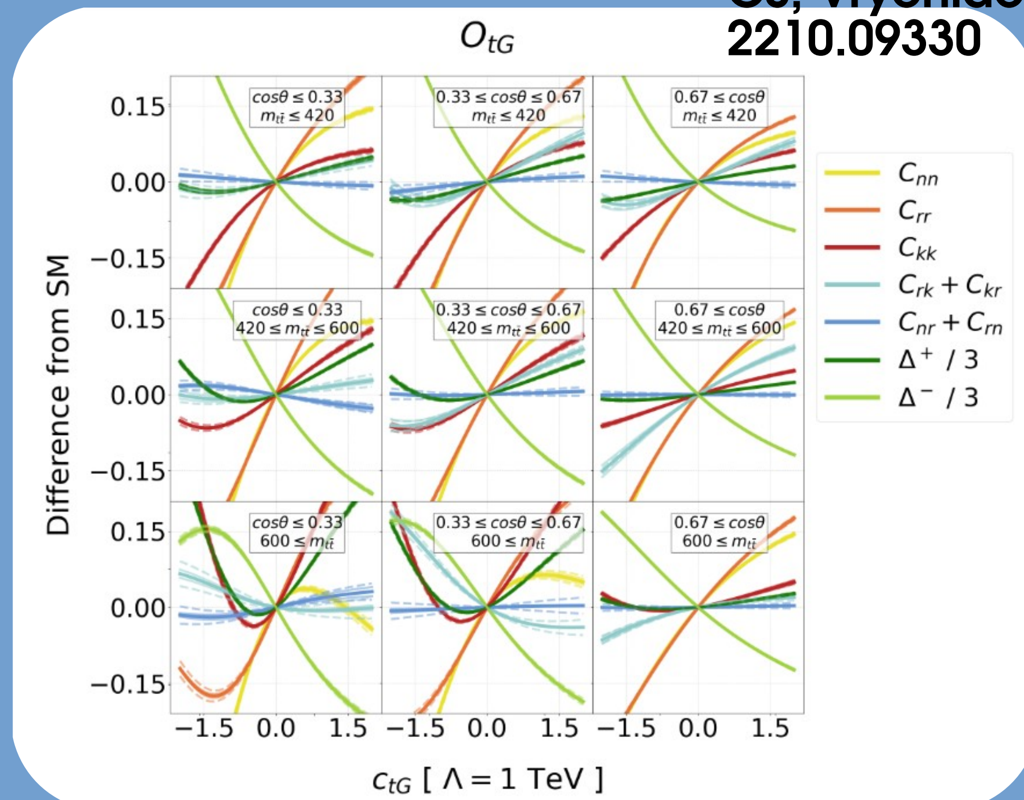

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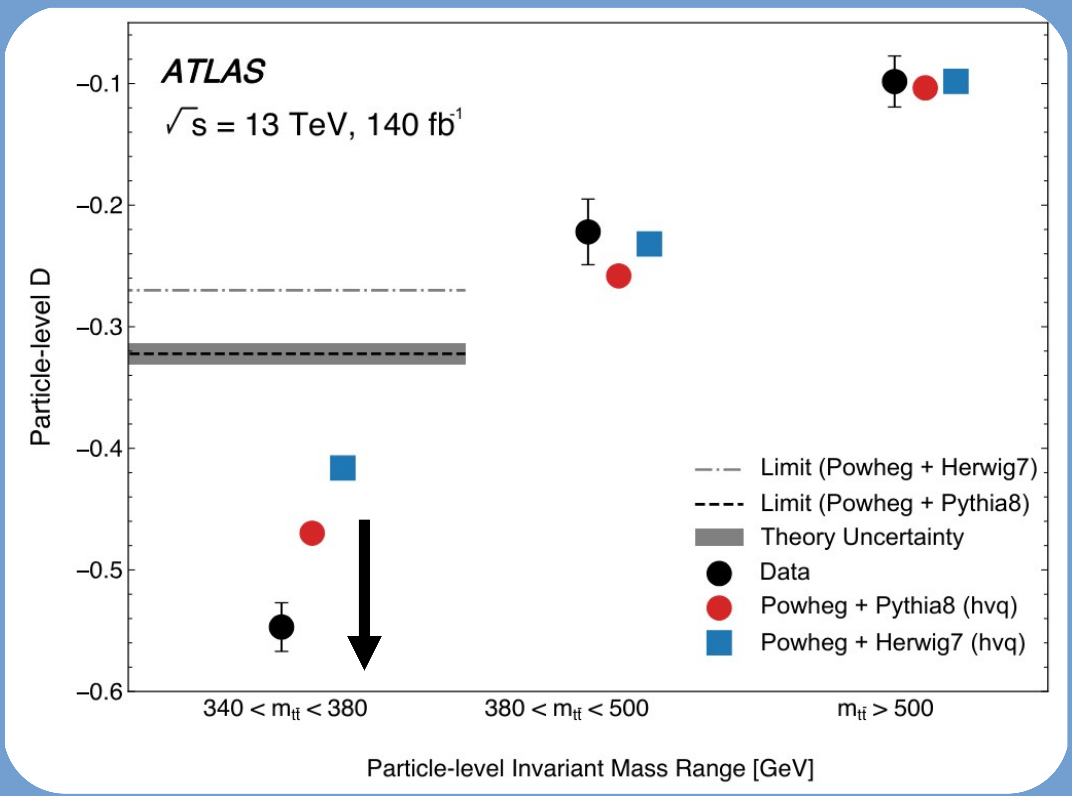
## Example 2: hidden SM effects

Toponium?

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Thank you :)