ATLAS EXPERIMENT

The Frontier of Collider Physics

Navin McGinnis

THE UNIVERSITY OF ARIZONA

Science Week 2025

July 28th — July 31st

ATLAS EXPERIMENT

Caveat:

~~The~~ A Frontier of Collider Physics

Based on my perspective, oriented towards high-energy colliders
and the search for new physics beyond the Standard Model

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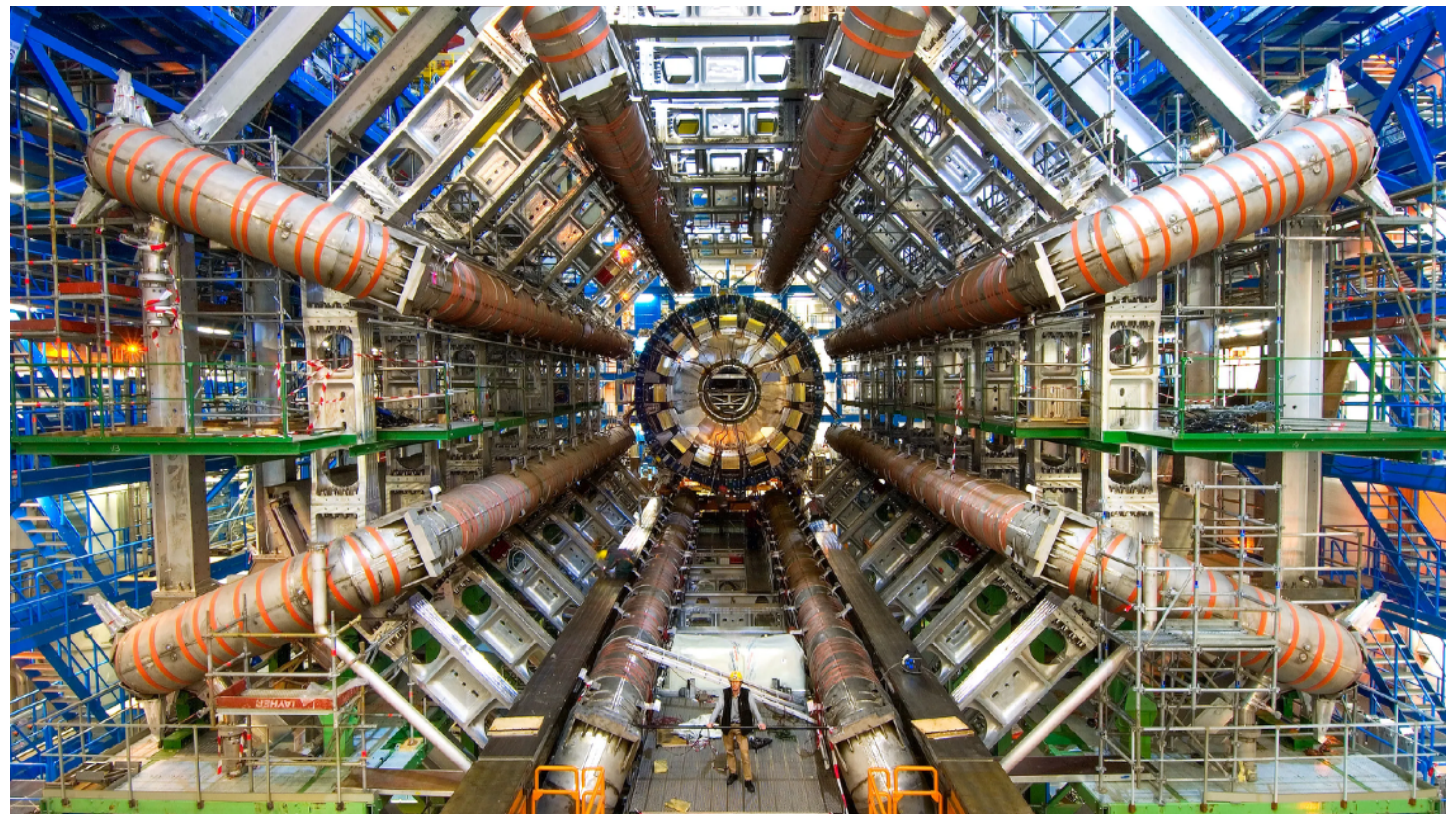
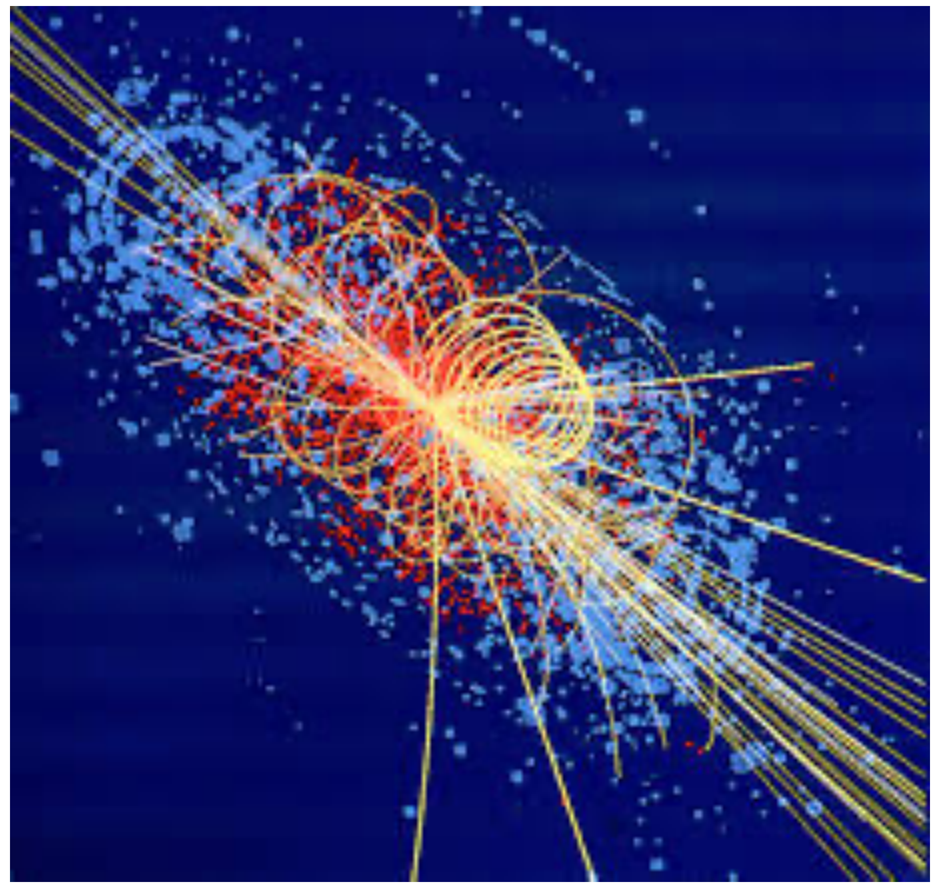
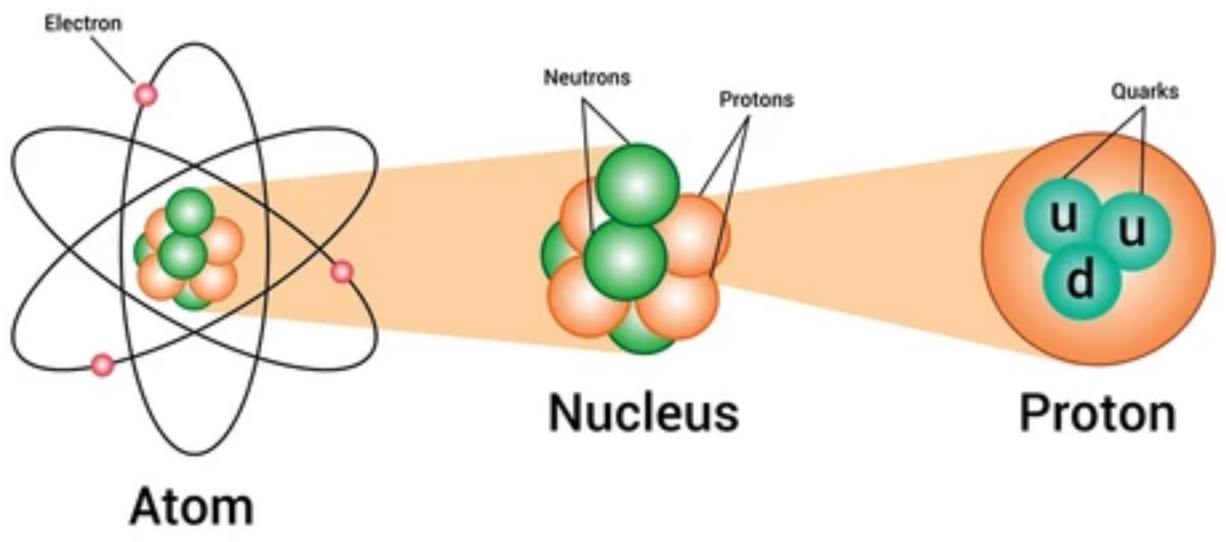
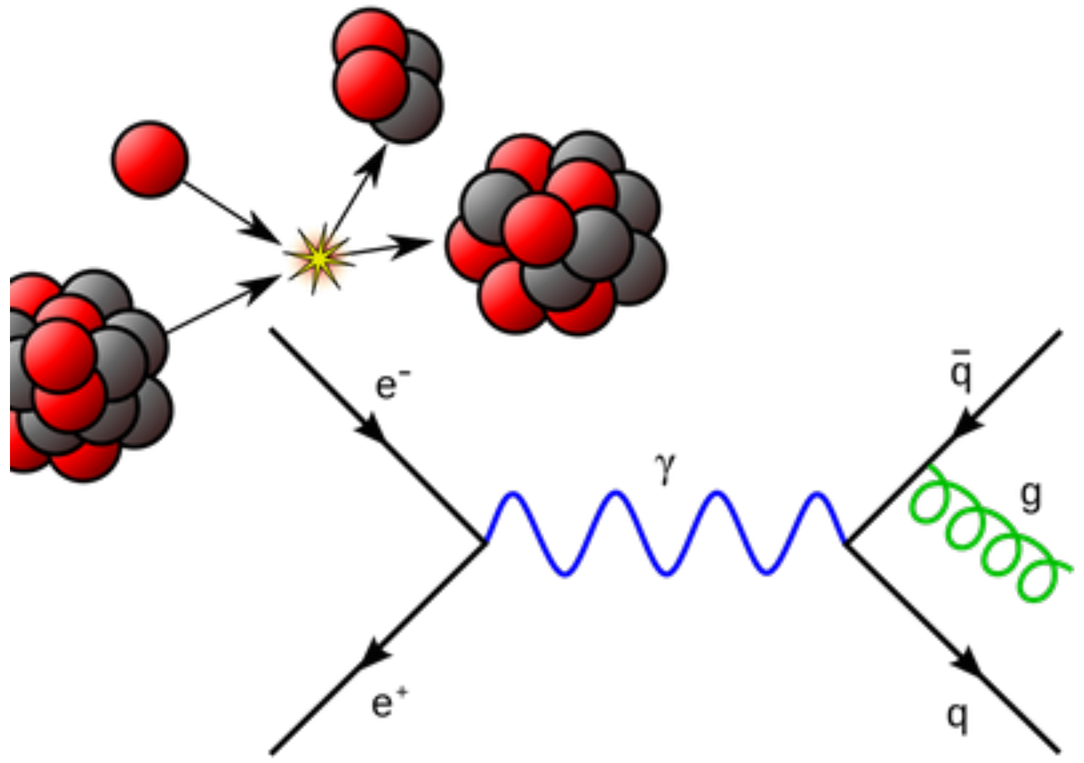
Collider physics is the modern tool for studying one of the oldest questions in history



What is the universe made of?







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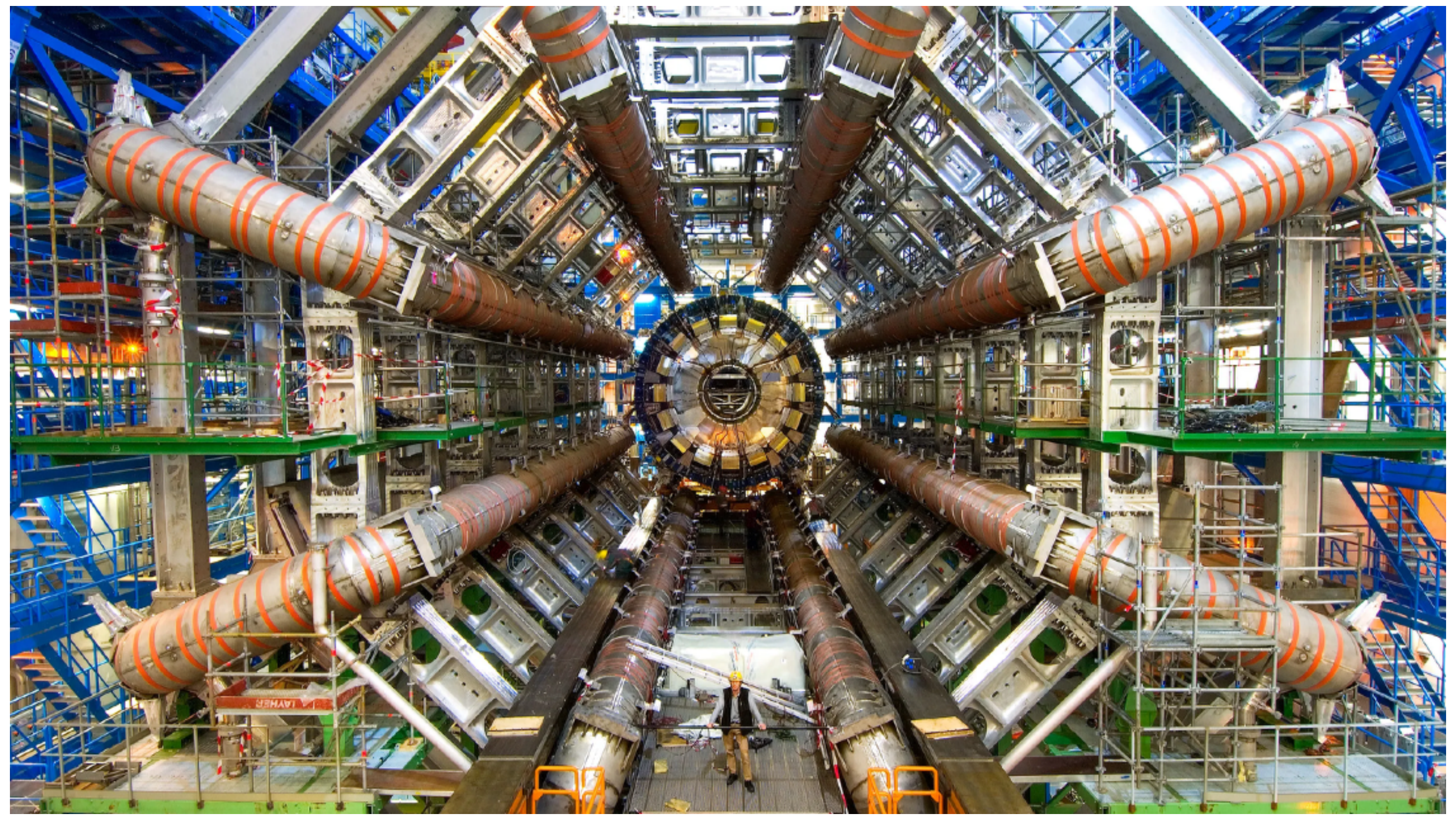

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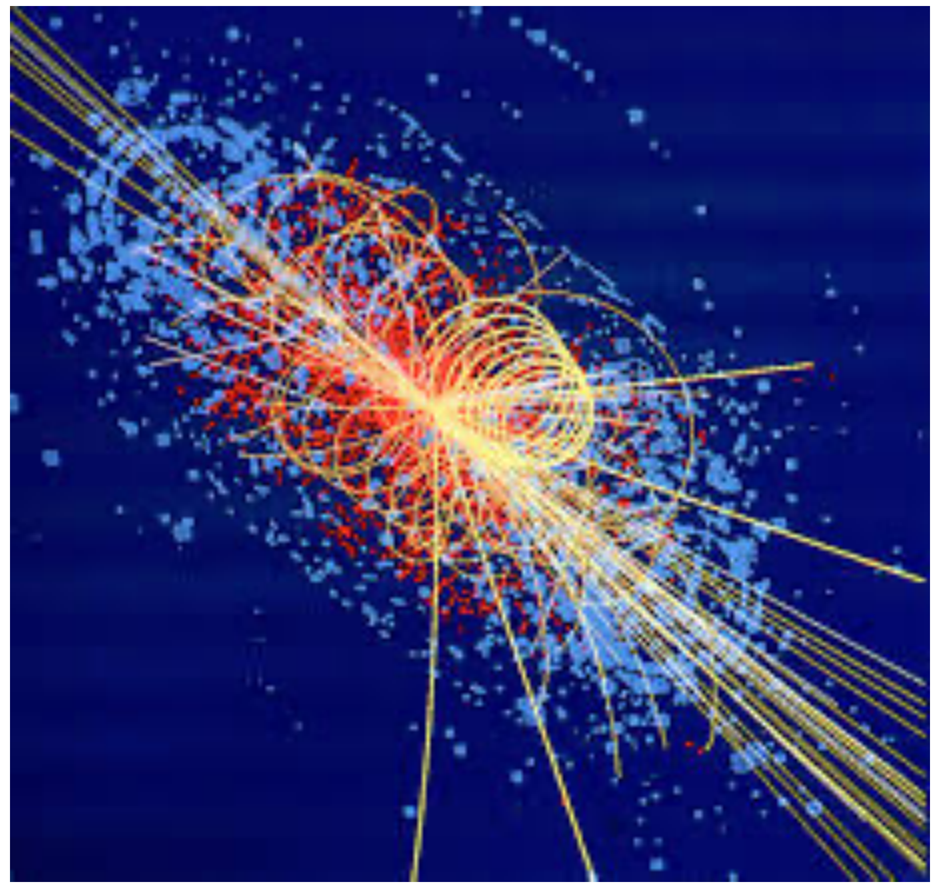
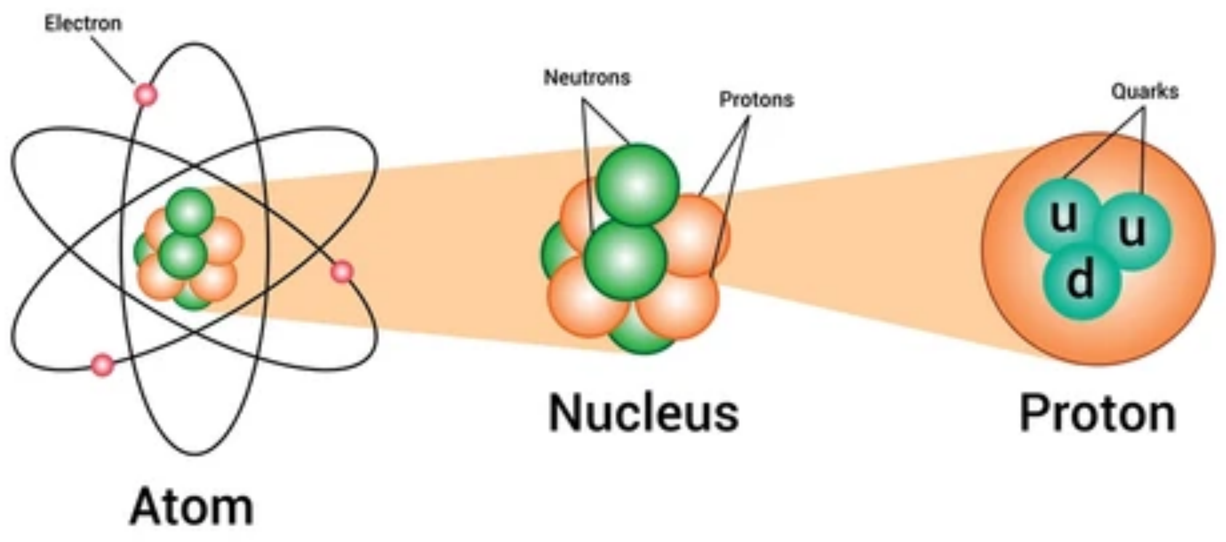
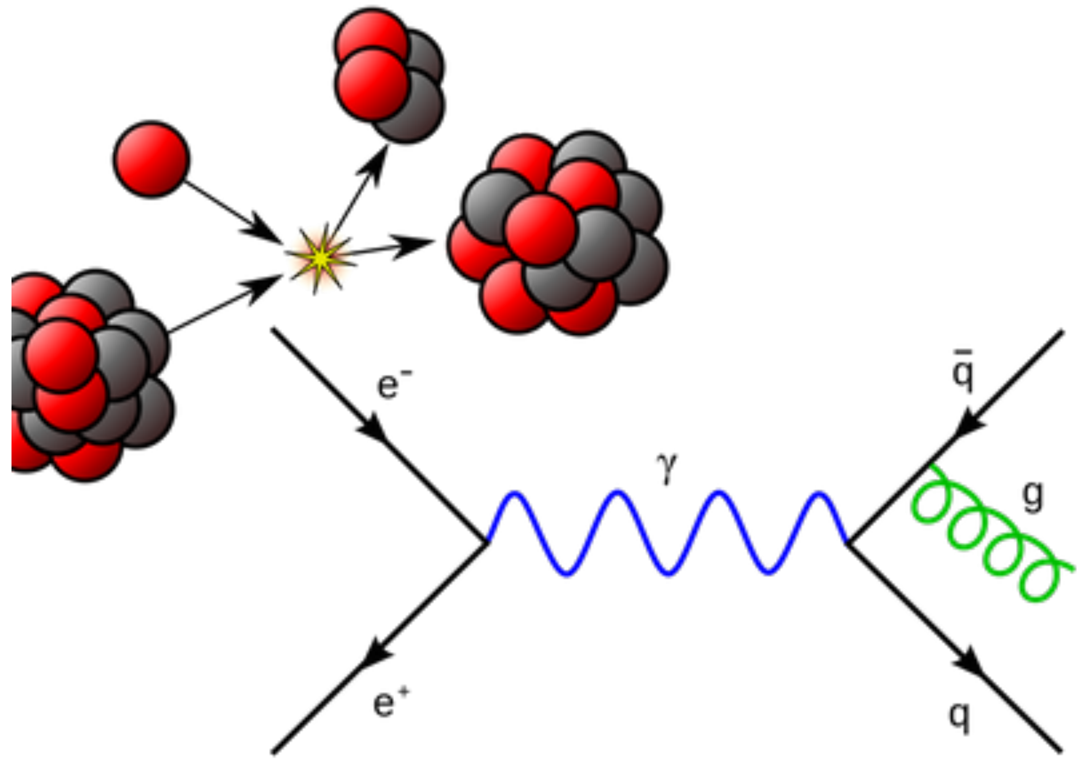
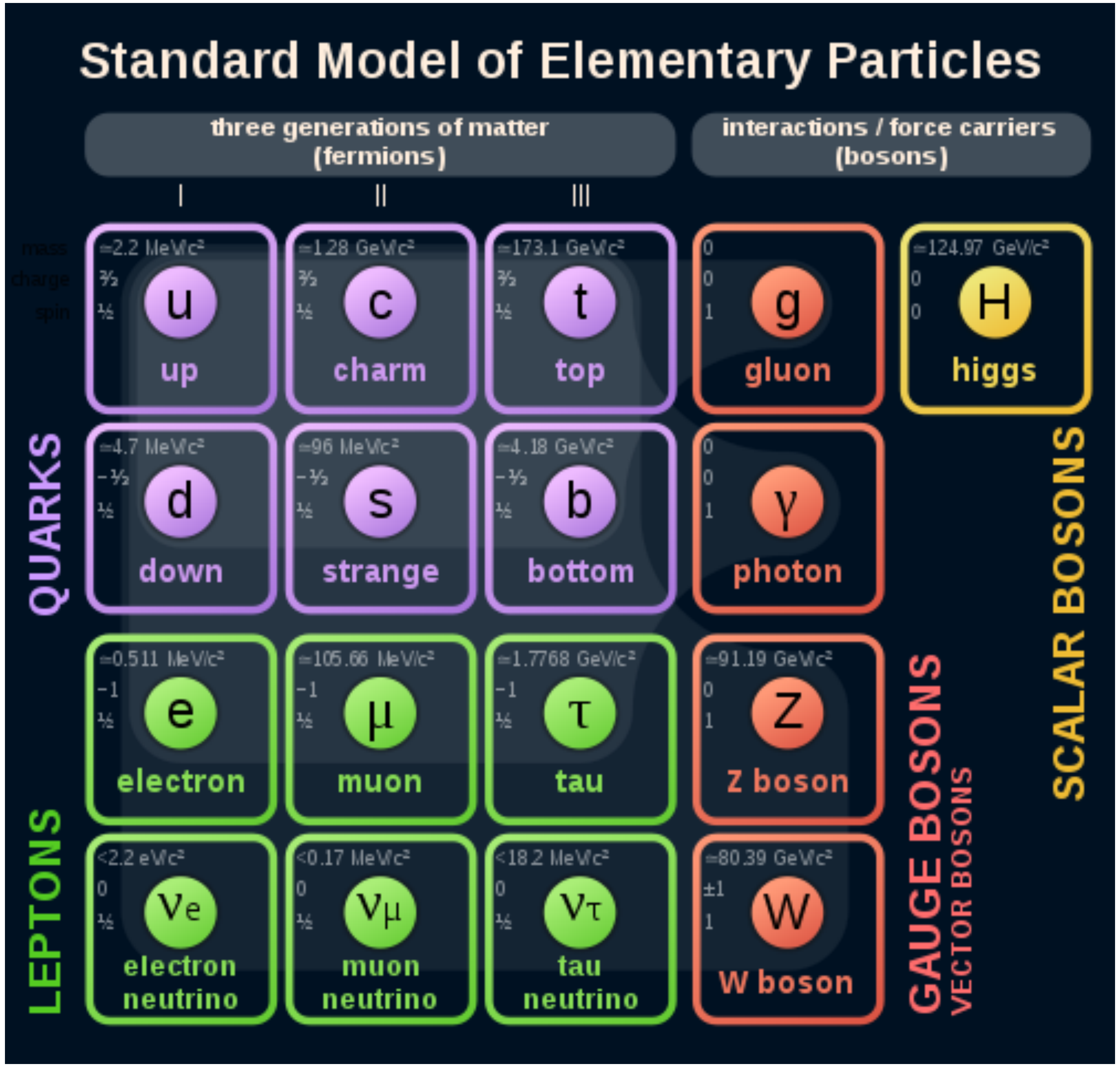






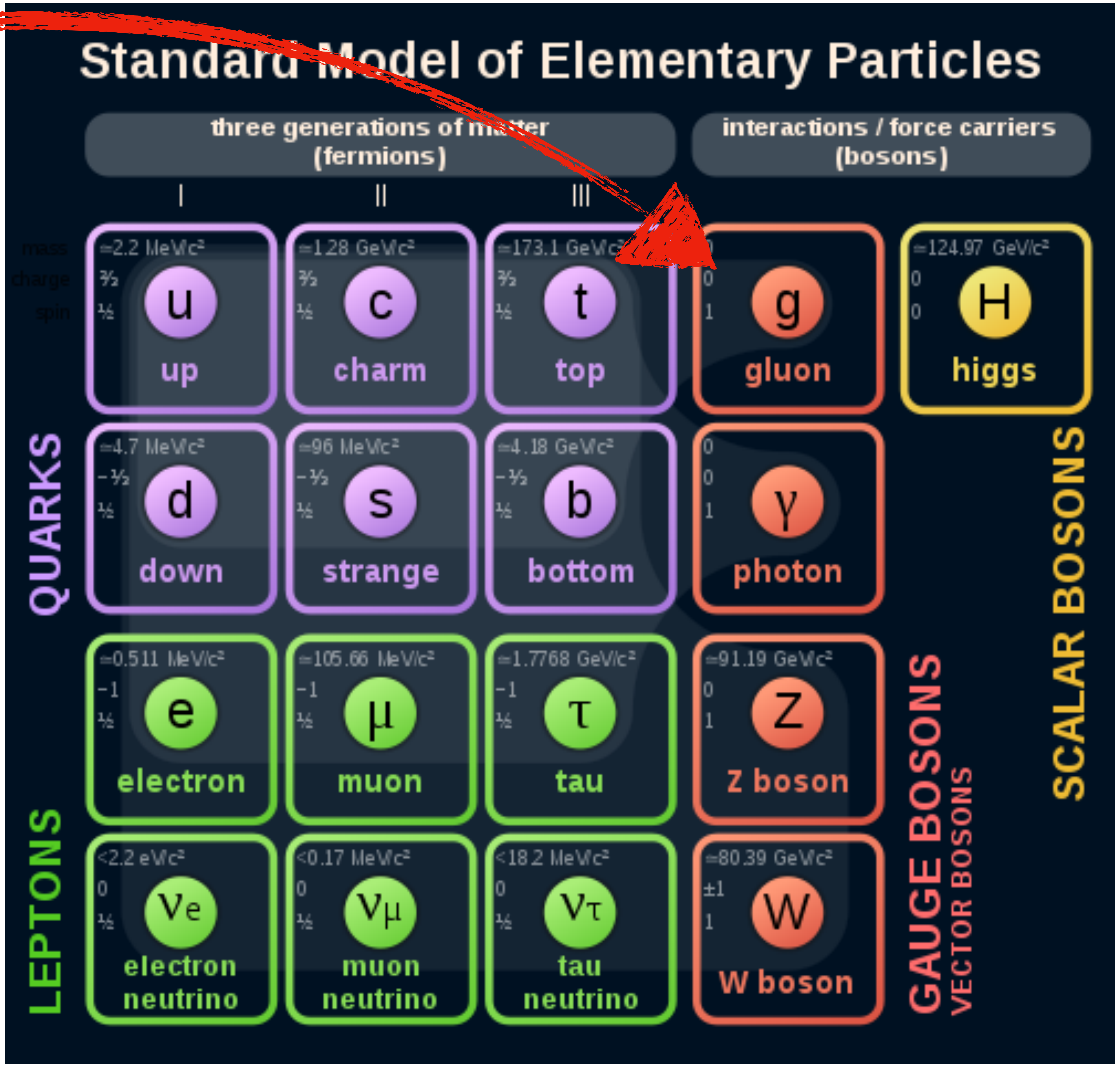
Where are we now?



Where are we now?

Three (particle) forces of nature

- Strong force



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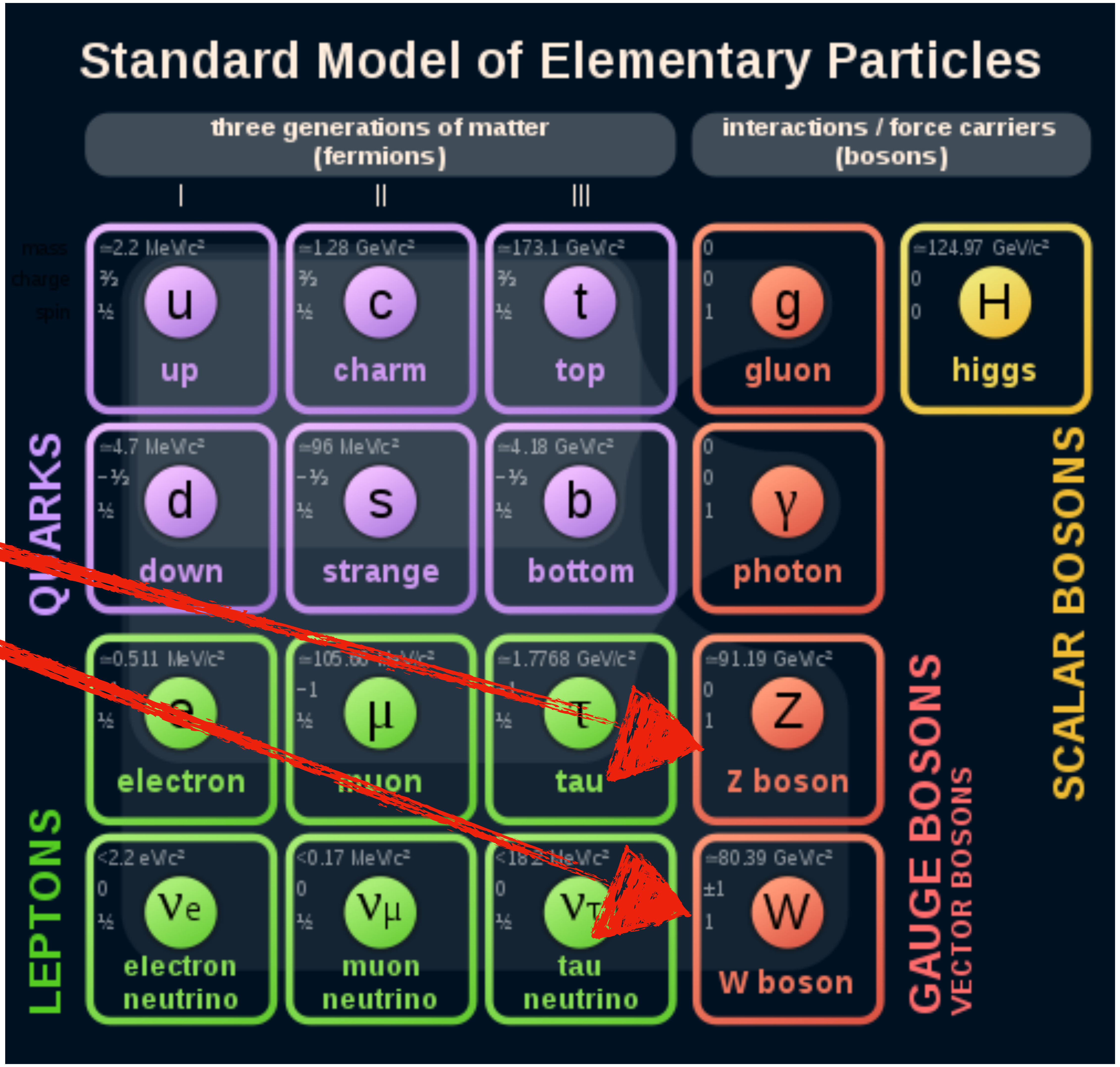
Three (particle) forces of nature

- Strong force
- Weak force



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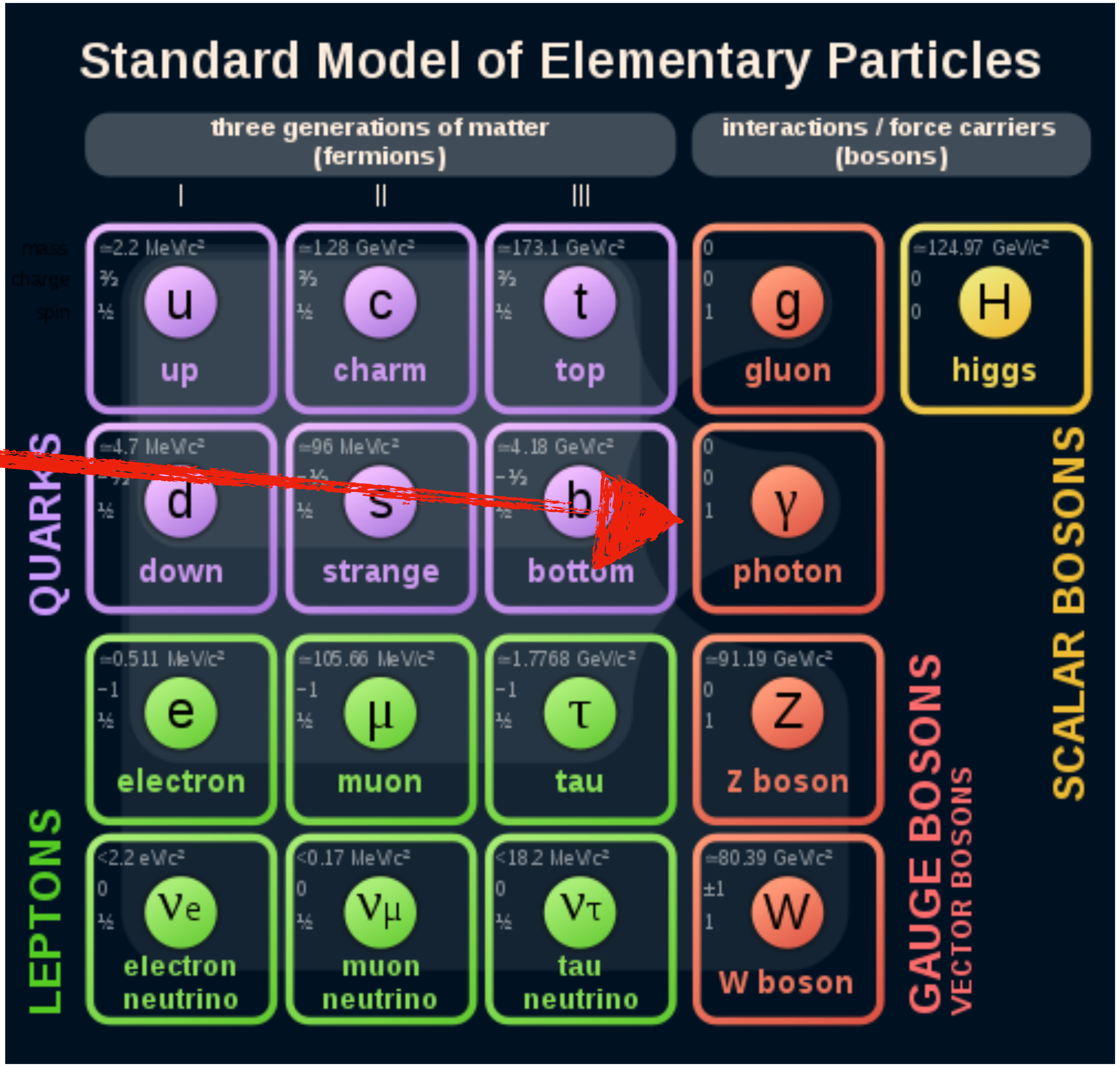
- Weak force
- Electromagnetism



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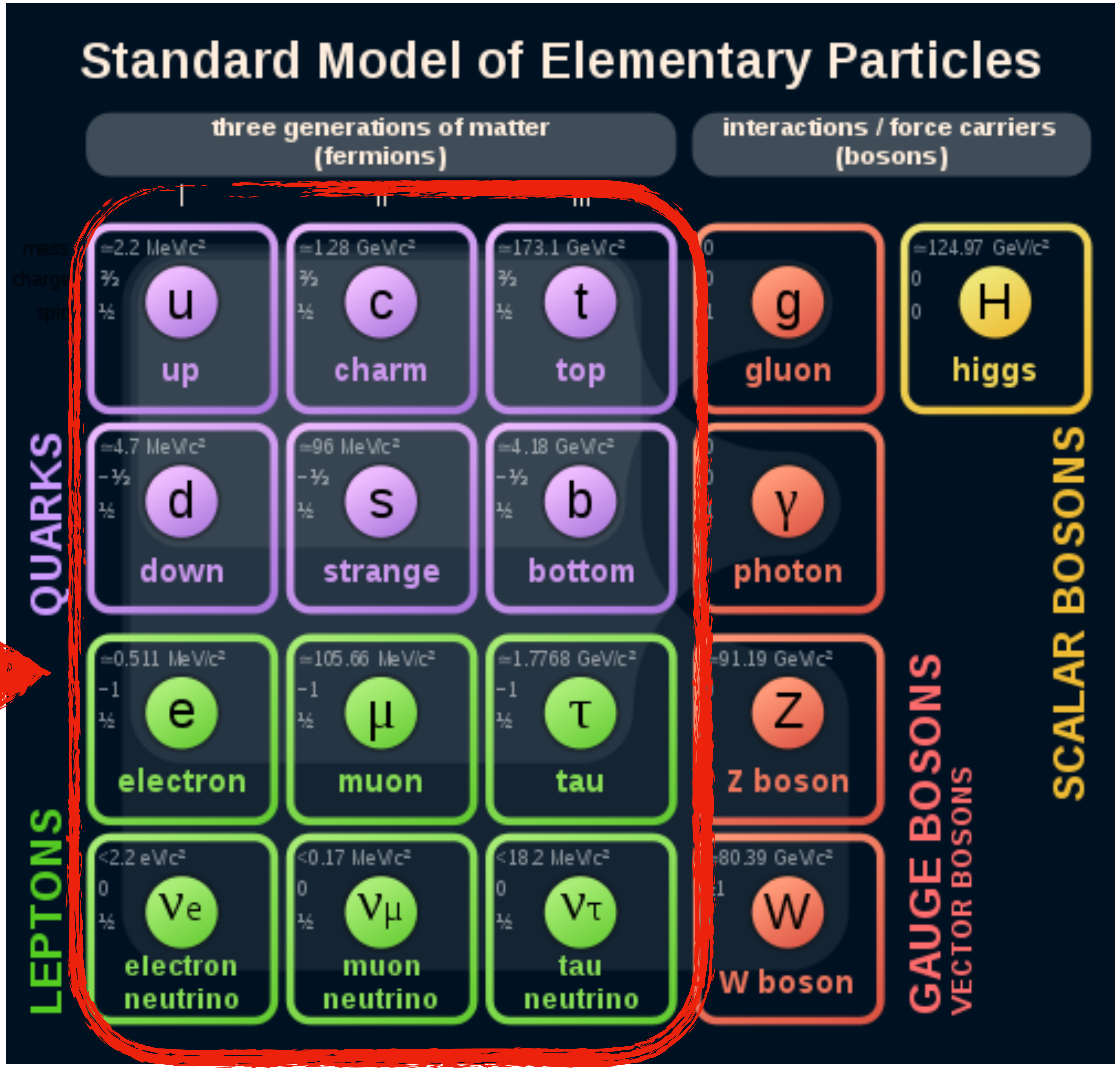
Matter particles



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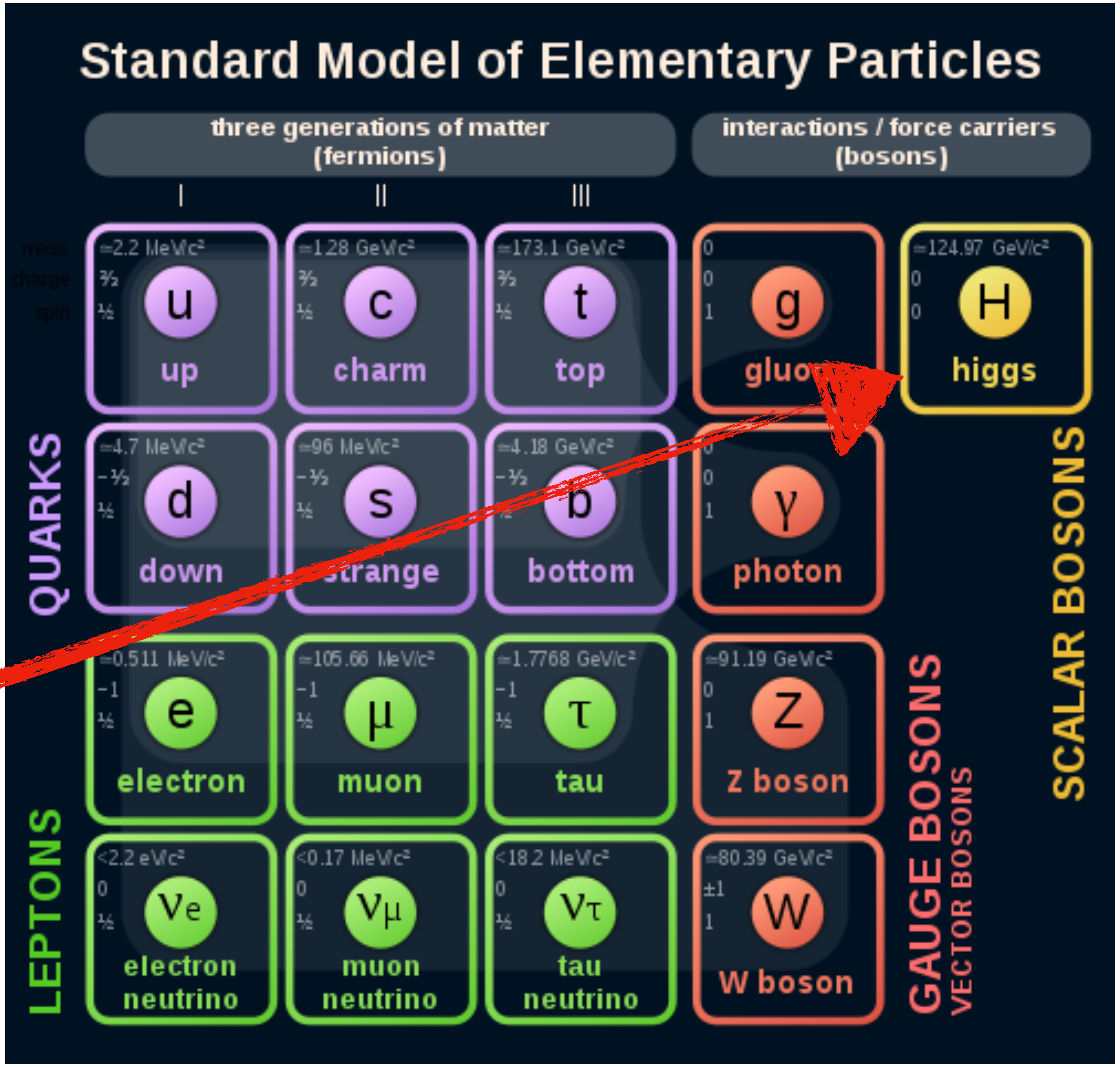


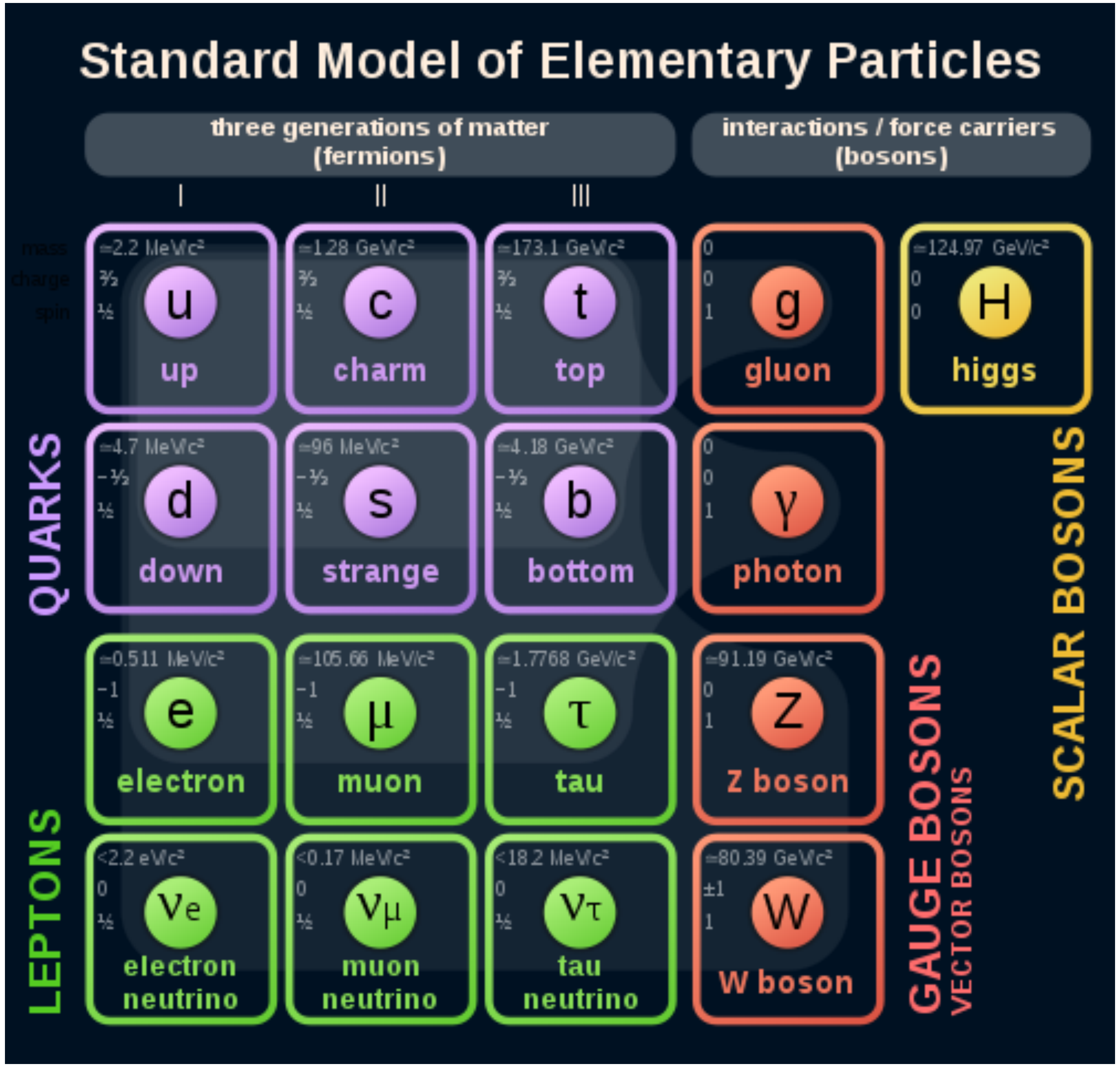
Matter particles

Higgs particle

Where are we now?

Λ

7-8 TeV	CERN (ATLAS/CMS run 1), 2012: H
2 TeV	Tevatron, 1995: t
546 GeV	CERN (UA1/UA2), 1983: $W^{\pm}, Z$
10-30 GeV	PETRA, 1979: g
38 GeV	Fermilab, 1974: b
4-8 GeV	SLAC, 1974: τ
6-7 GeV	SLAC, 1974: c
1-20 GeV	SLAC, 1968: proton=qqq



Non-collider discoveries, 1897 - 1964: $e^{\pm}, \mu^{-}, \nu_{e,\mu}, s$

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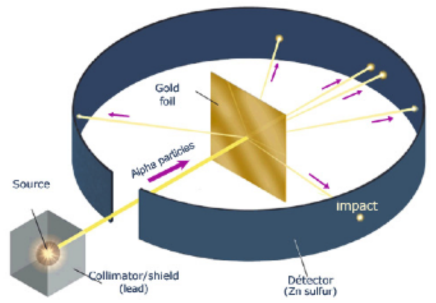
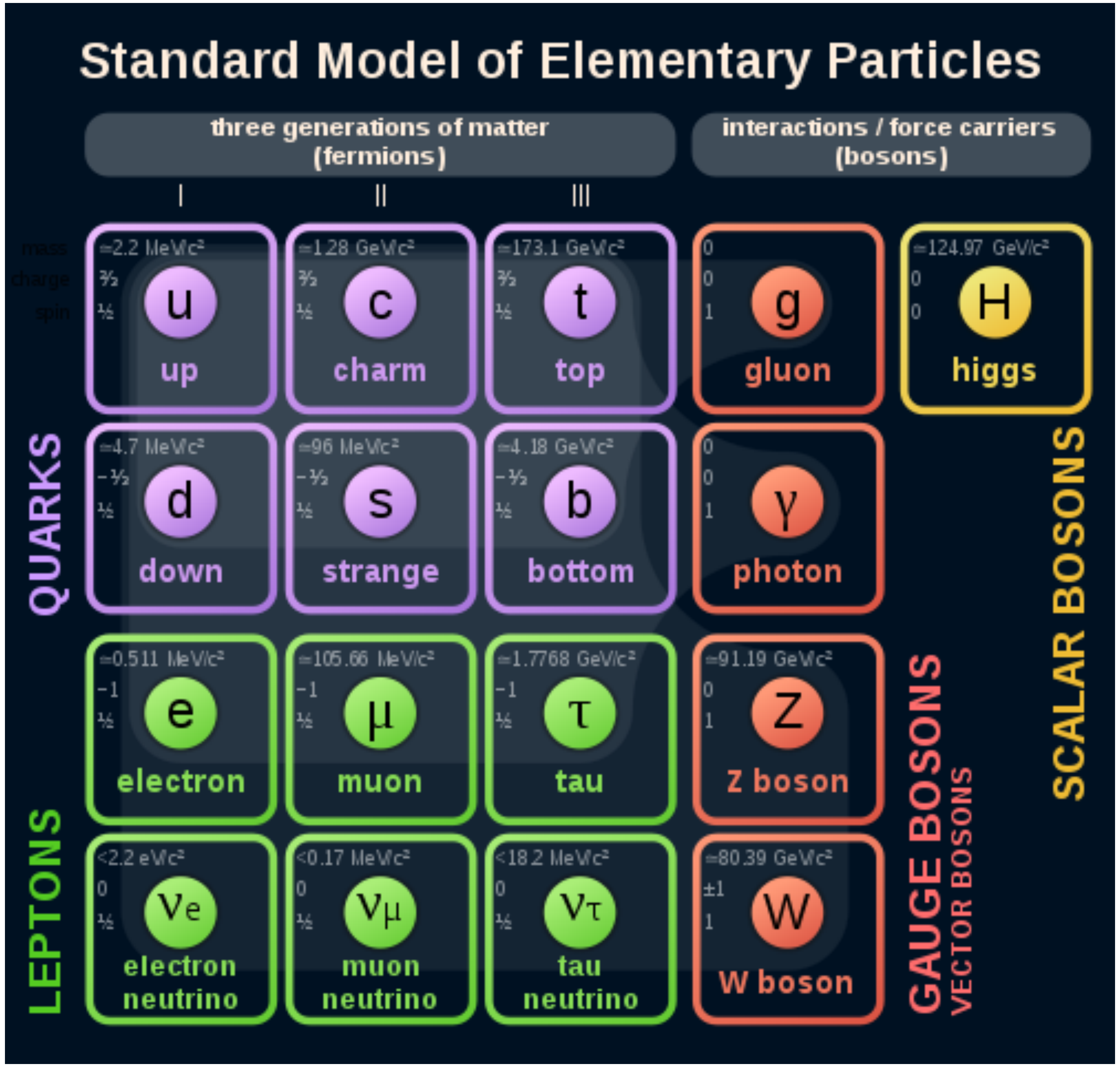


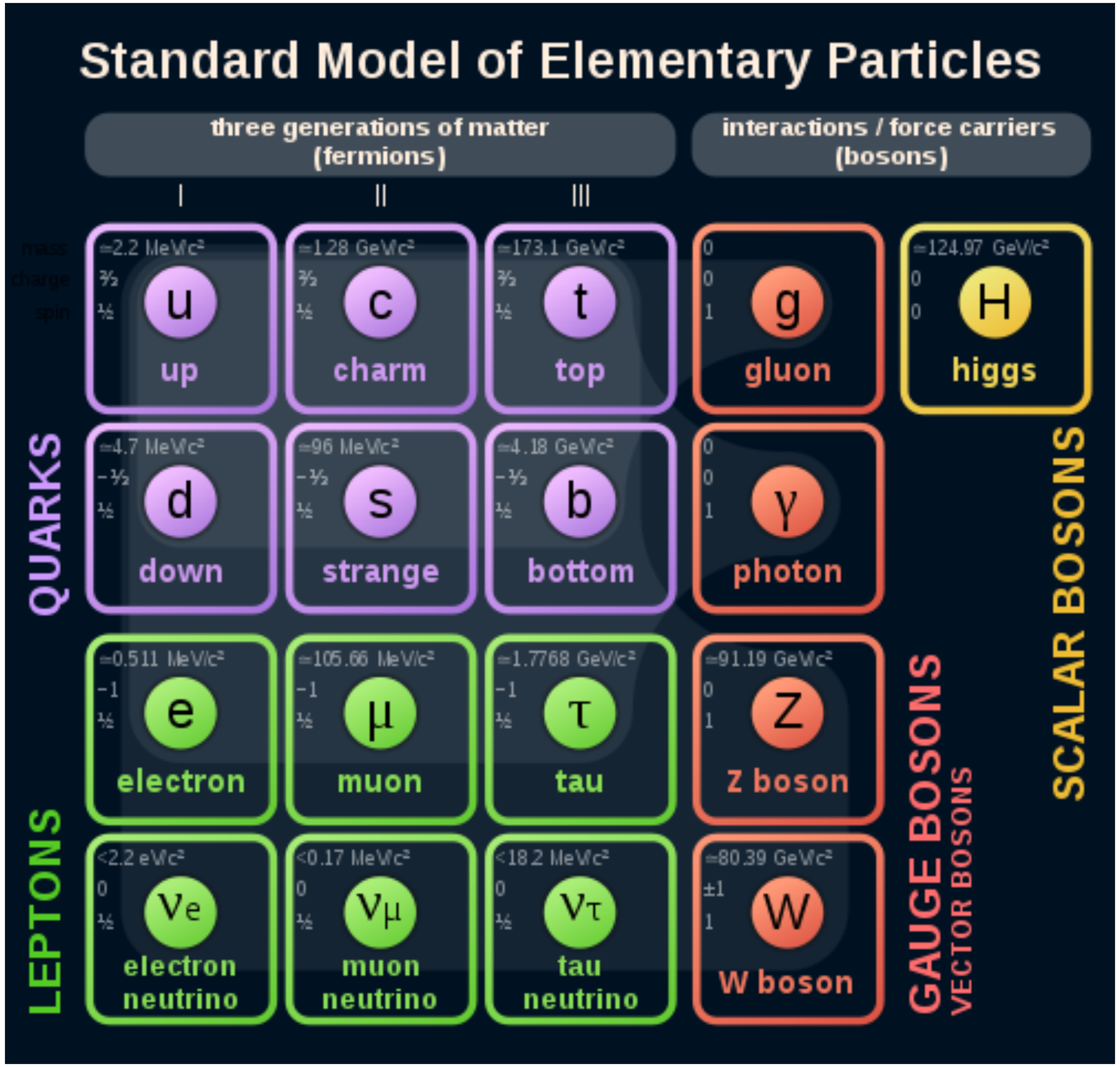
Rutherford, 1906: Atomic substructure

Non-collider discoveries, 1897 - 1964: $e^{\pm}$, μ^{-}, $\nu_{e,\mu}$, s

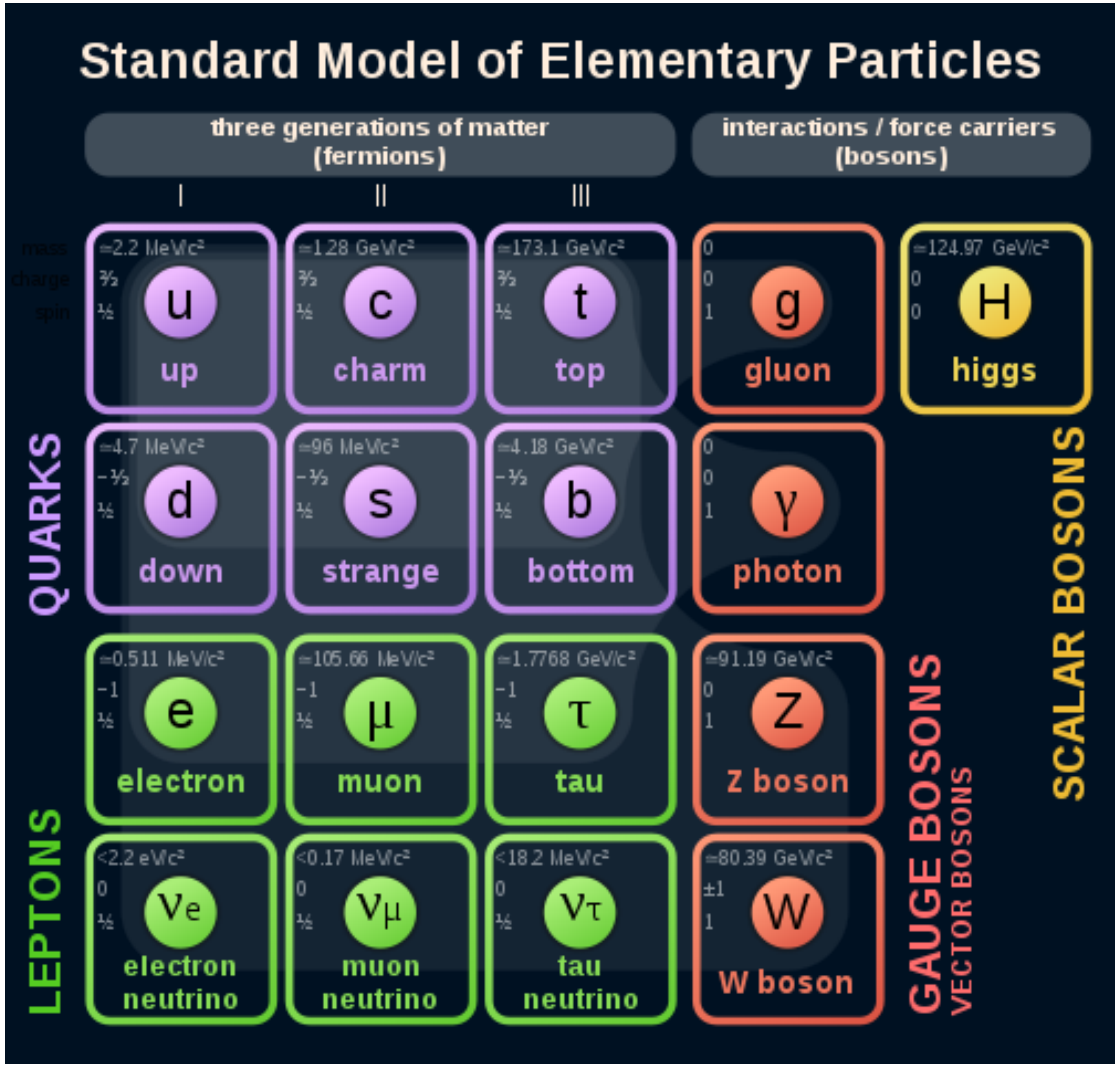


Where are we now?

- Why build another collider(s)?
- Which collider(s) to build?



What do we still need to know?



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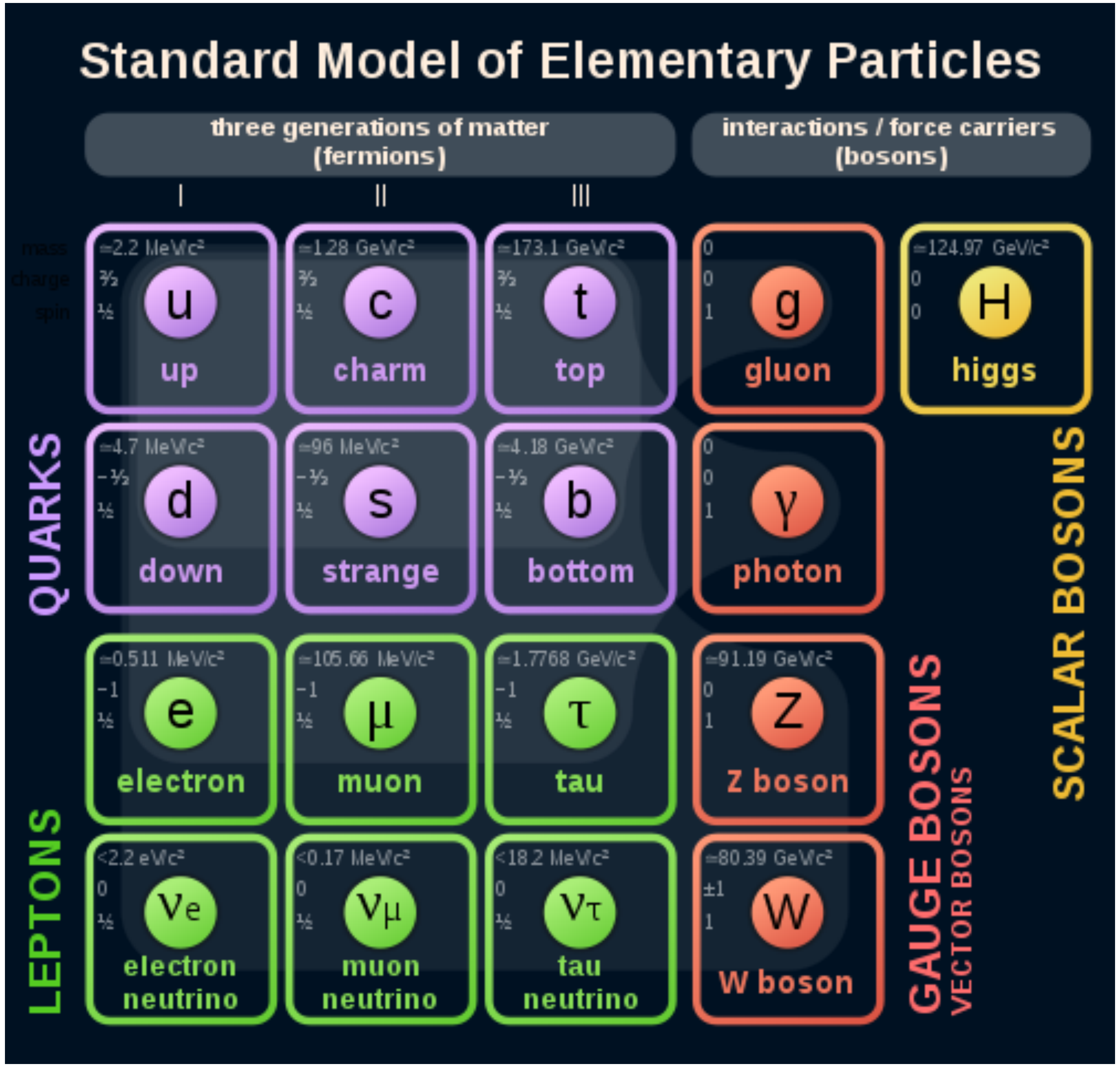

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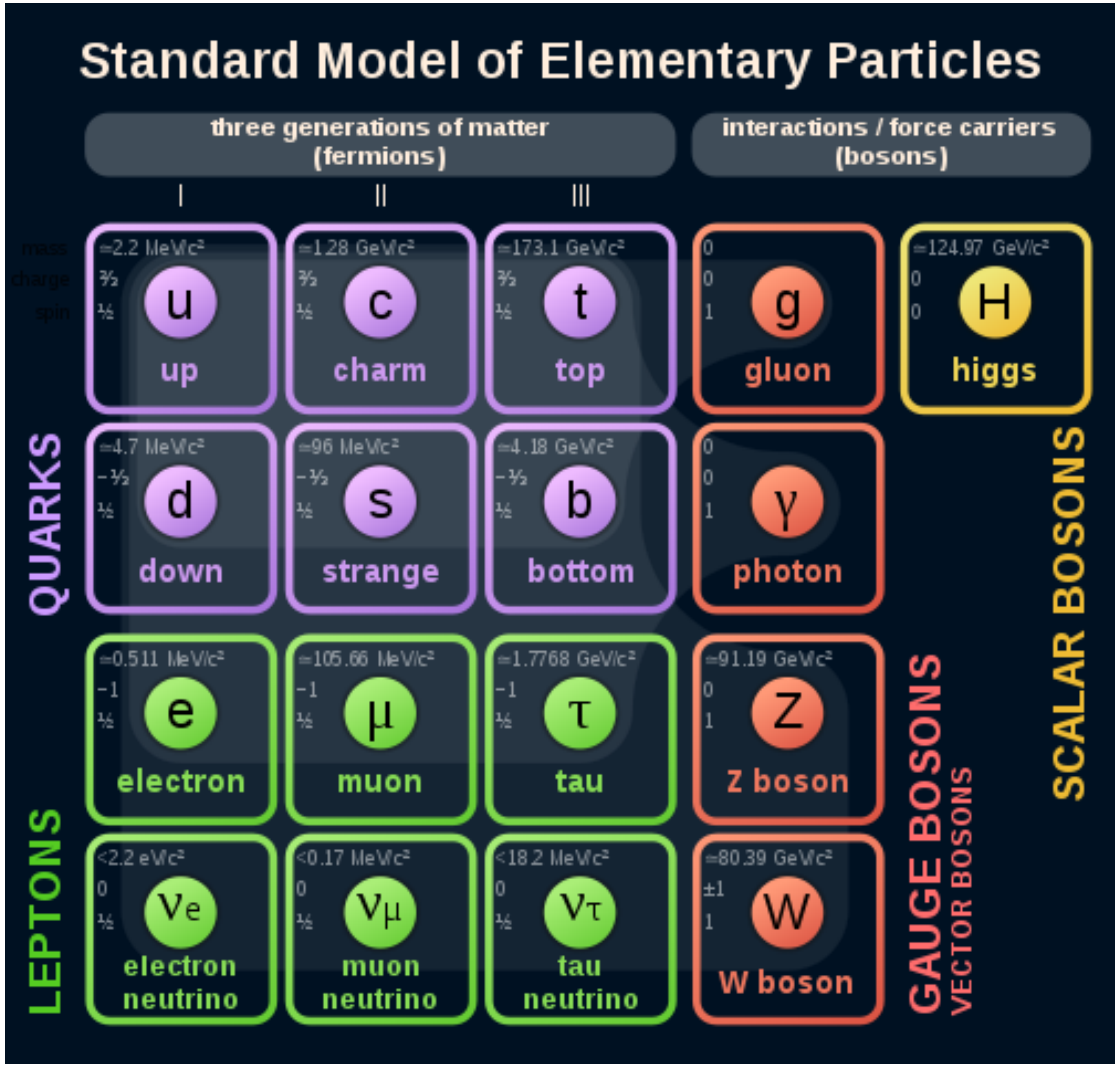

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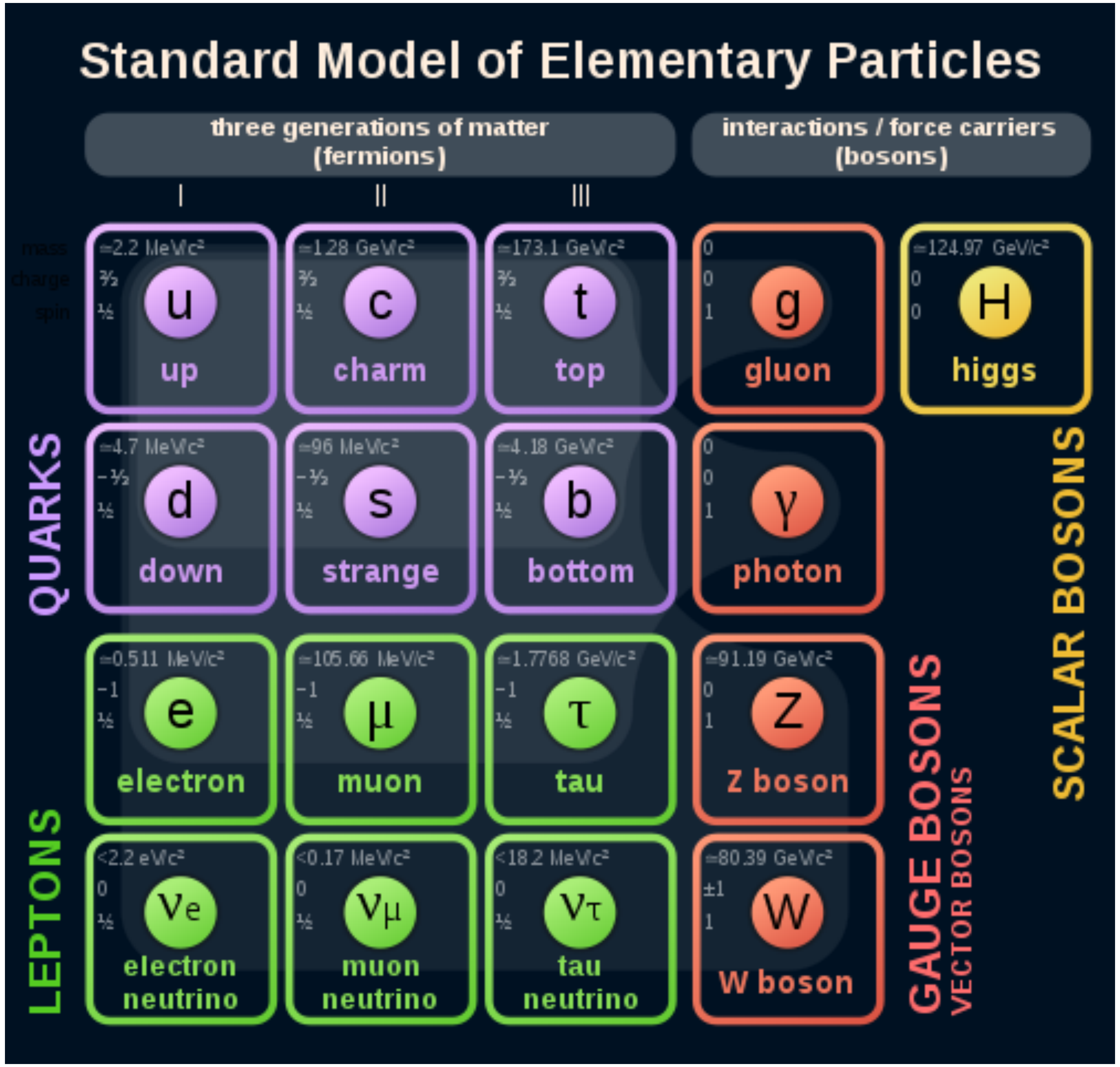

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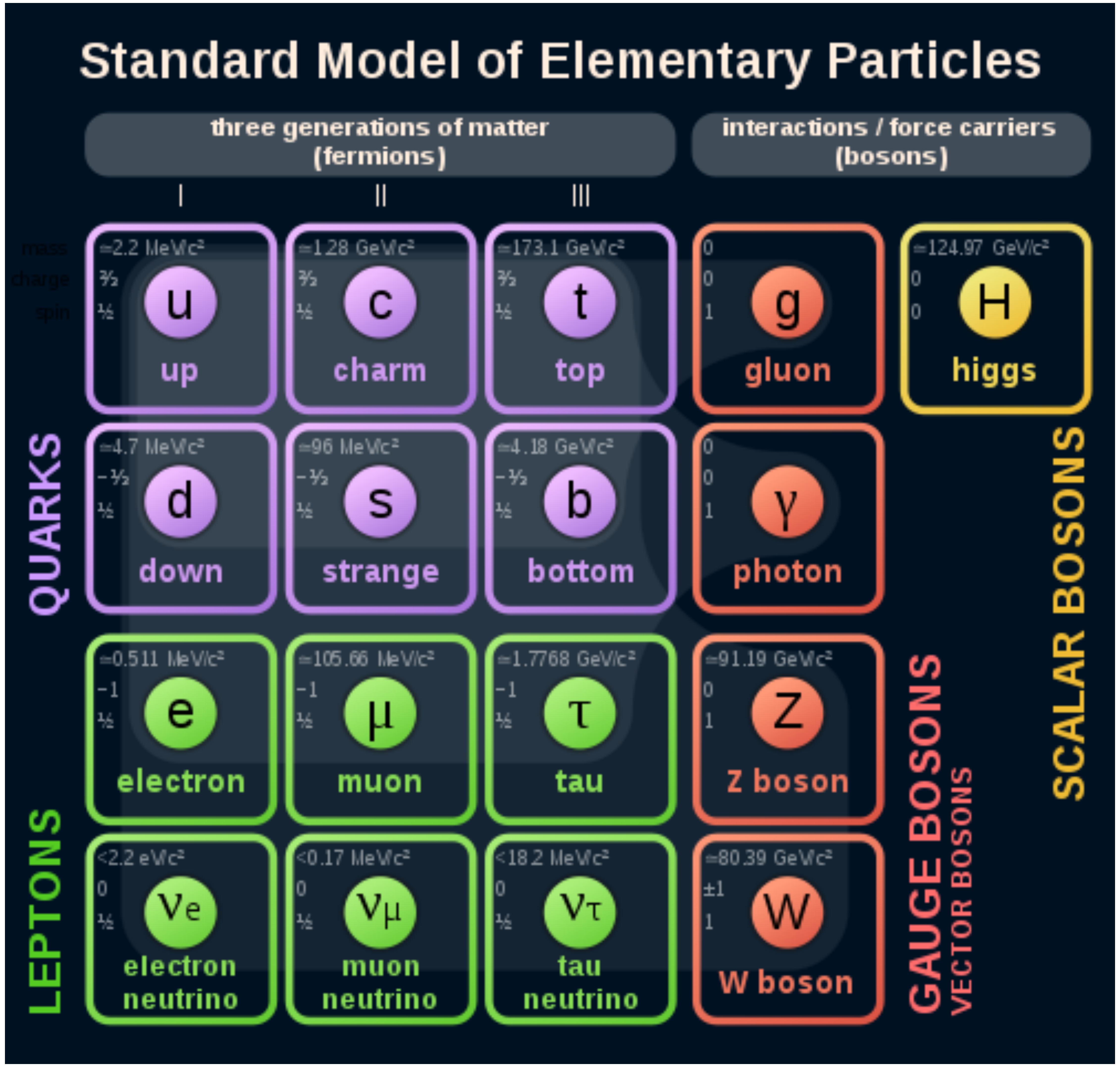
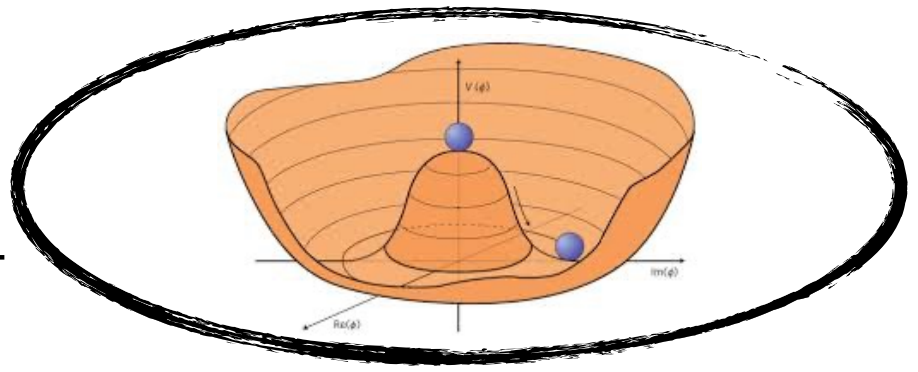


$$V(\phi) = -m^2\phi^2 + \lambda\phi^4$$



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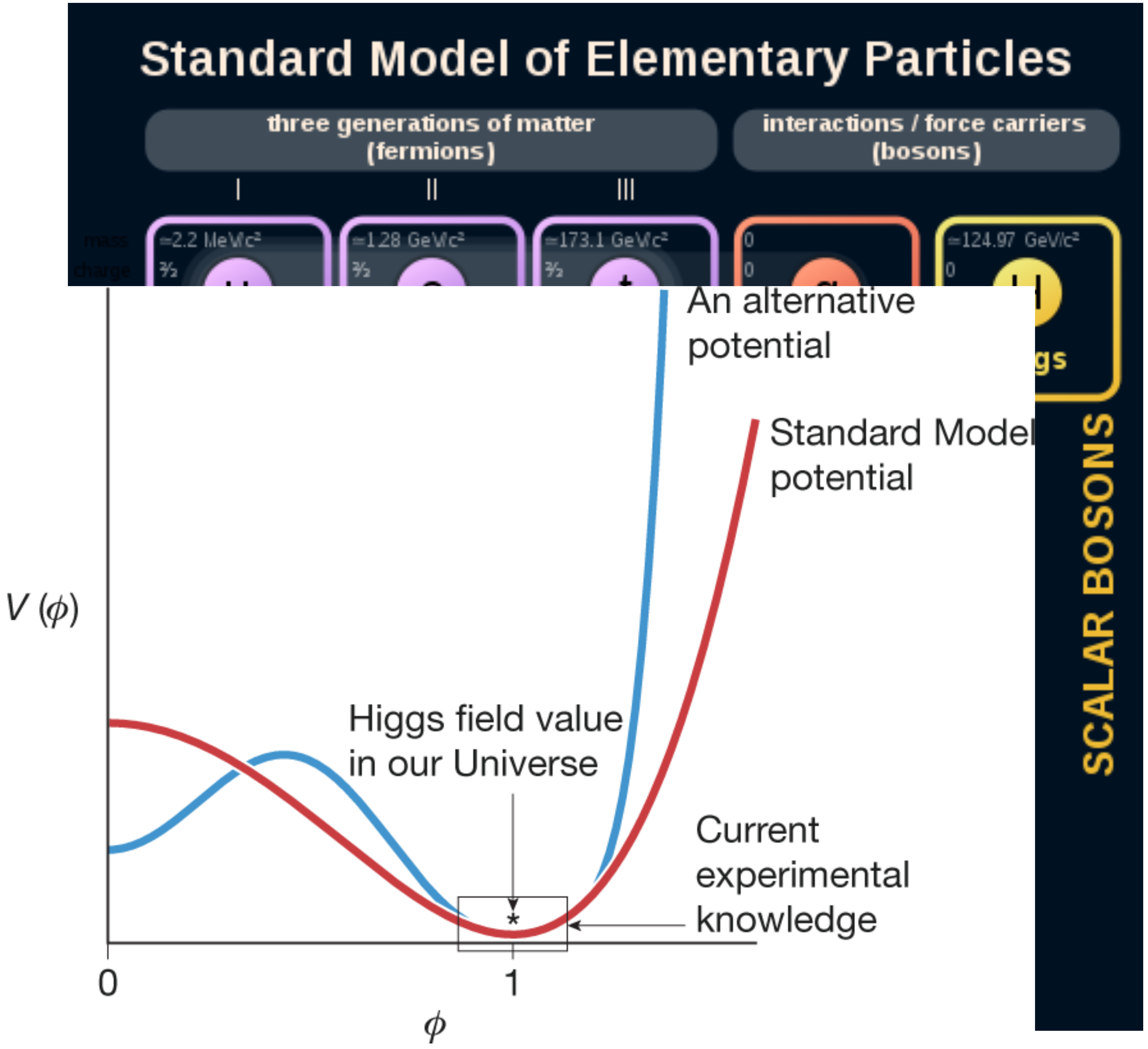

https://www.nature.com/articles/d41586-022-01862-1

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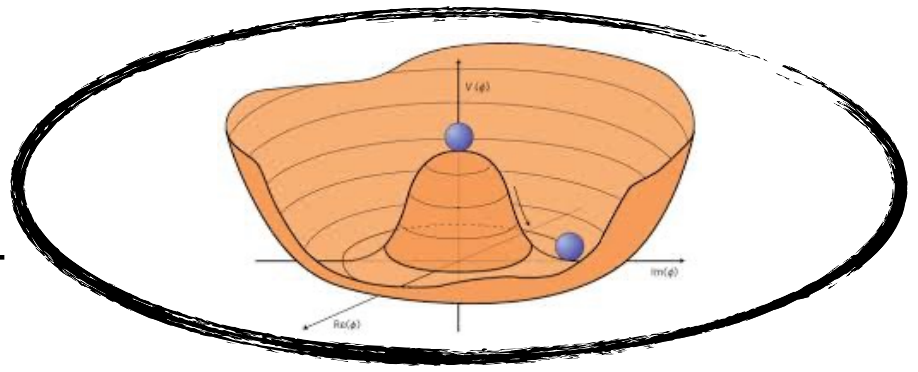


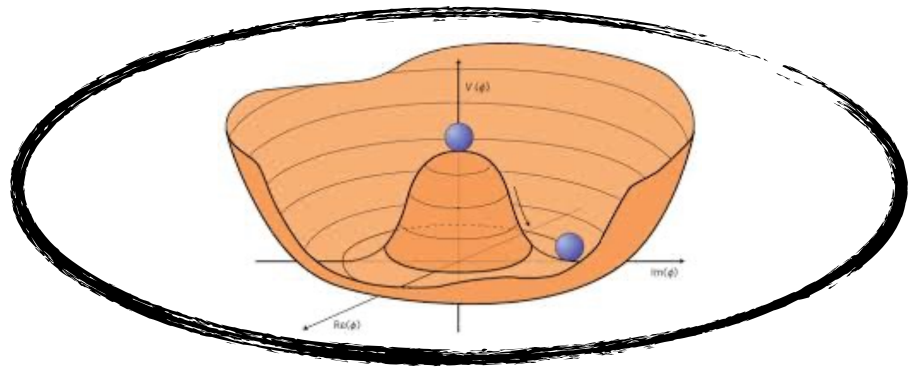
From the P5 report

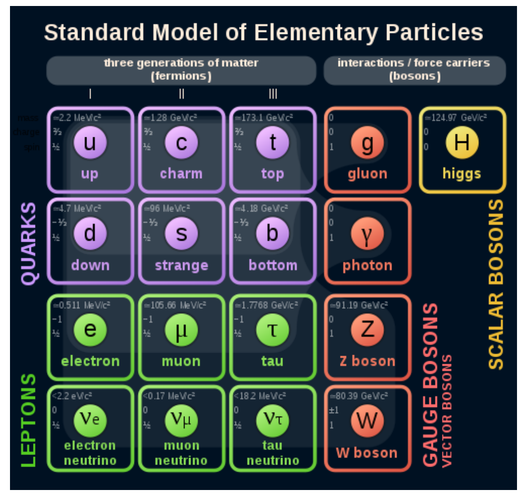
https://www.usparticlephysics.org/2023-p5-report/decipher-the-quantum-realm.html#32reveal-the-secrets-of-the-higgs-boson

3.2

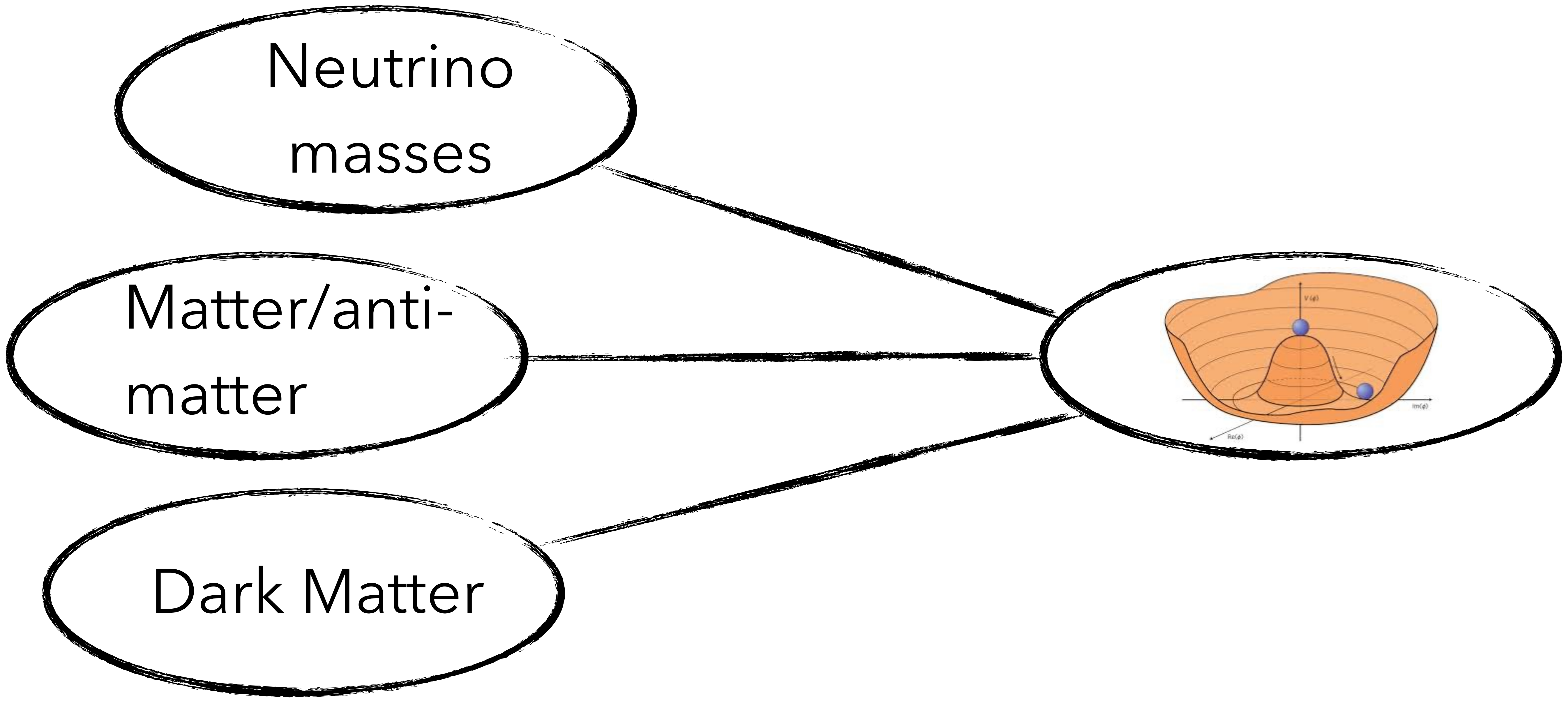
Illustration by Abigail Malate for U.S. Particle Physics

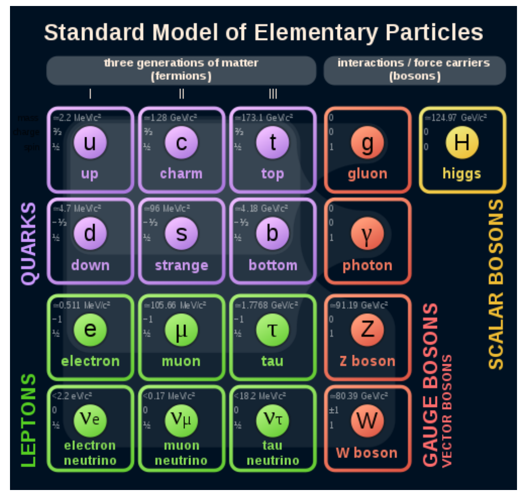
Reveal the Secrets of the Higgs Boson





Major questions remain about the nature of the Higgs boson. We do not know if the Higgs field is a fundamental field, or if it is actually a composite field made from other constituents. We do not know if there is only one Higgs boson, or if there is a richer sector containing related particles with new dynamics. We do not know why the Higgs boson mass should be as low as it is in the absence of additional particles with similar masses that would stabilize it, or why the mass is not zero in the first place. We do not know if the Higgs boson can decay to non-Standard Model particles. The interactions of the Higgs boson with the matter particles—the generation of fermion masses and mixings—involve the largest number of experimentally measured Standard Model parameters whose values and pattern are not predicted by any theory. Understanding this pattern may shed light on important questions such as the matter-antimatter asymmetry and the origin of neutrino masses.





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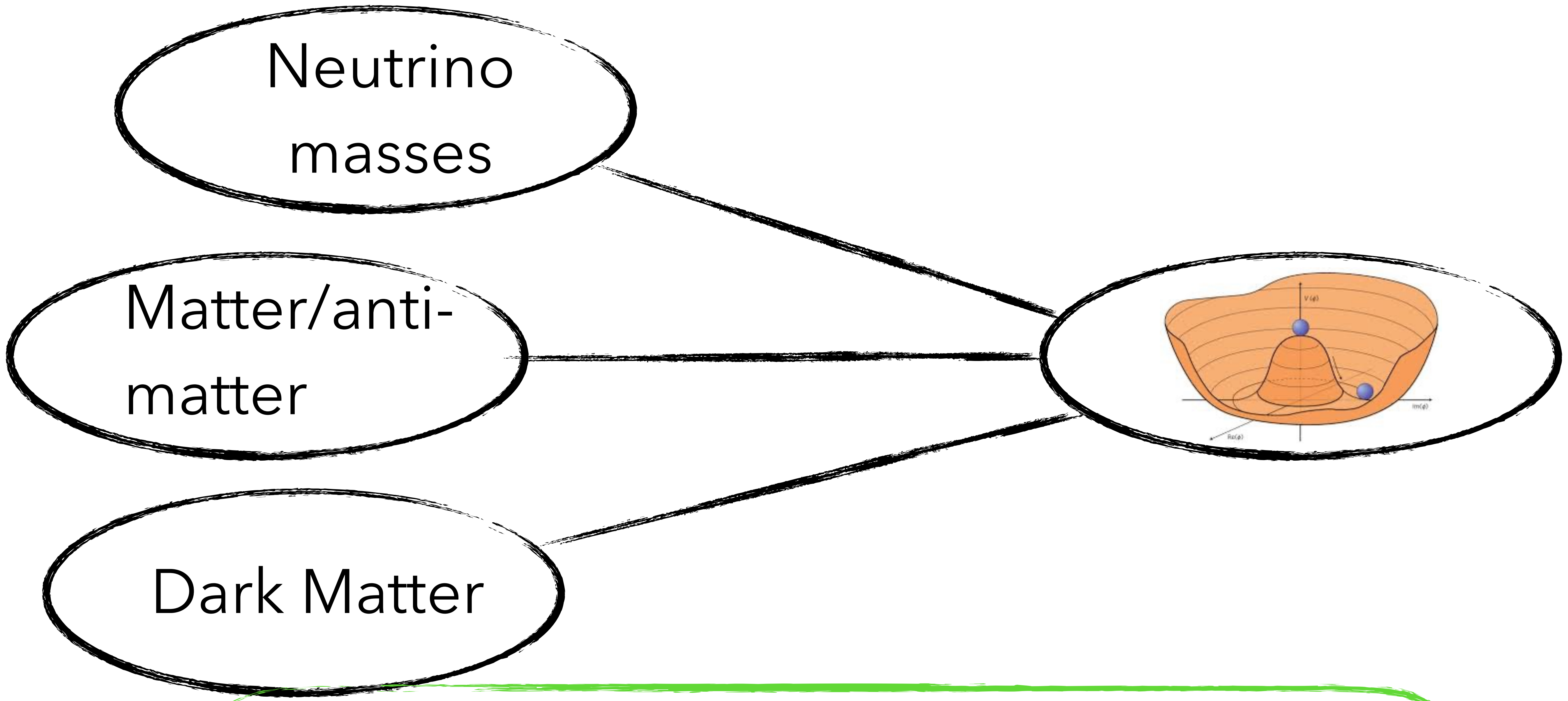
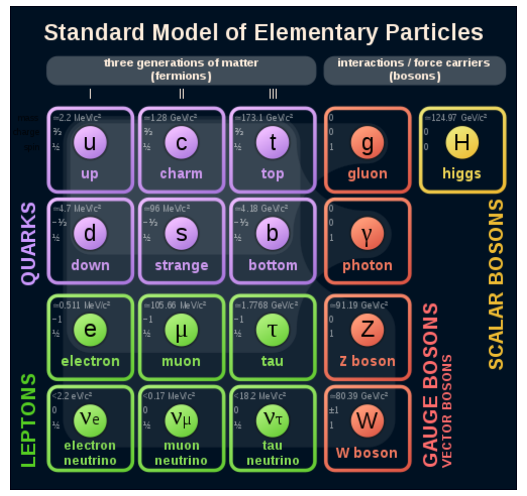
Reveal the Secrets of the Higgs Boson

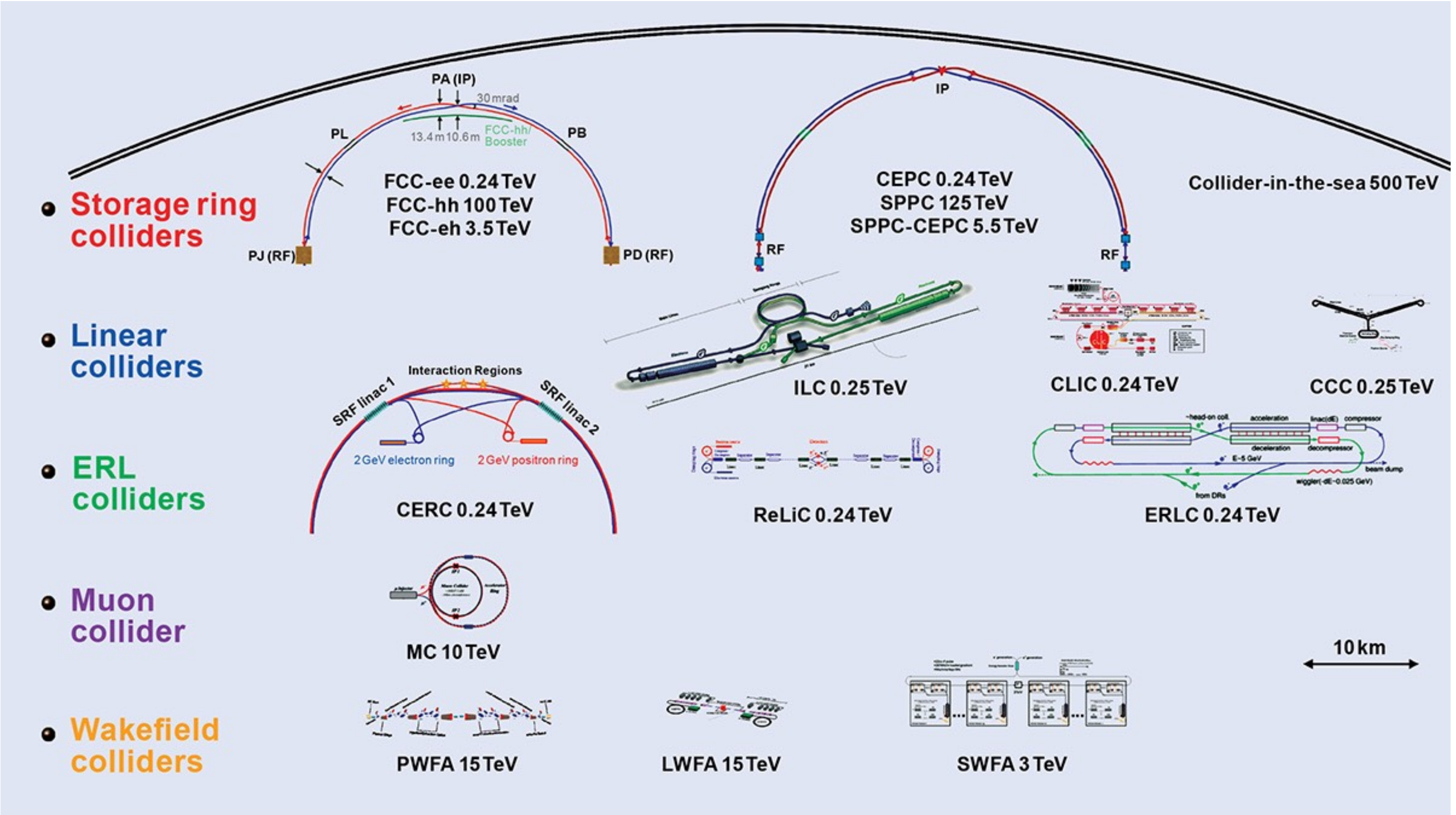
Higgs boson physics can only be studied at high-energy collider experiments, which are currently limited to the LHC and HL-LHC. Longer-term, future colliders, described below, will further our understanding of the Higgs boson by testing its couplings to lighter quarks, by improving the precision of the Higgs couplings, and by measuring the Higgs potential. Advances in theoretical calculations of Higgs properties will be required to fully understand the experimental results.



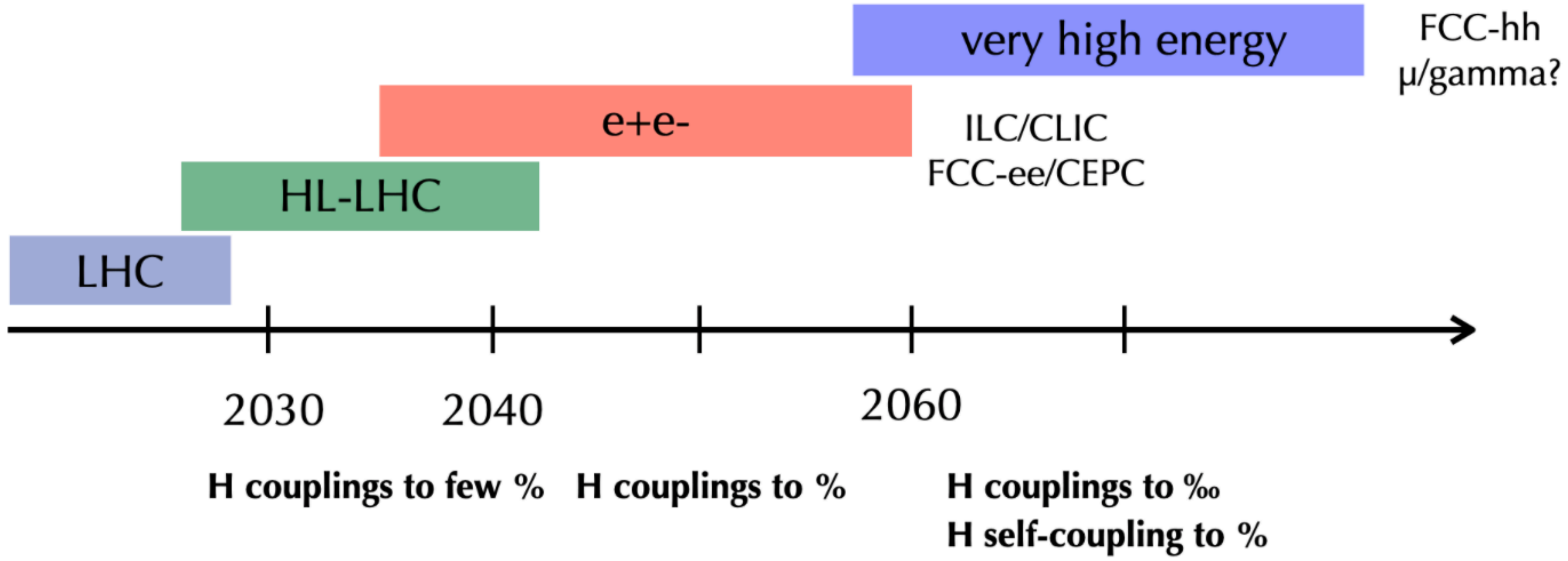


Although the Standard Model agrees well with data across a large range of energy scales, we <u>do not</u> yet have a <u>complete</u> theory of particle physics. A new collider is <u>necessary</u> to explore answers

Future collider proposals



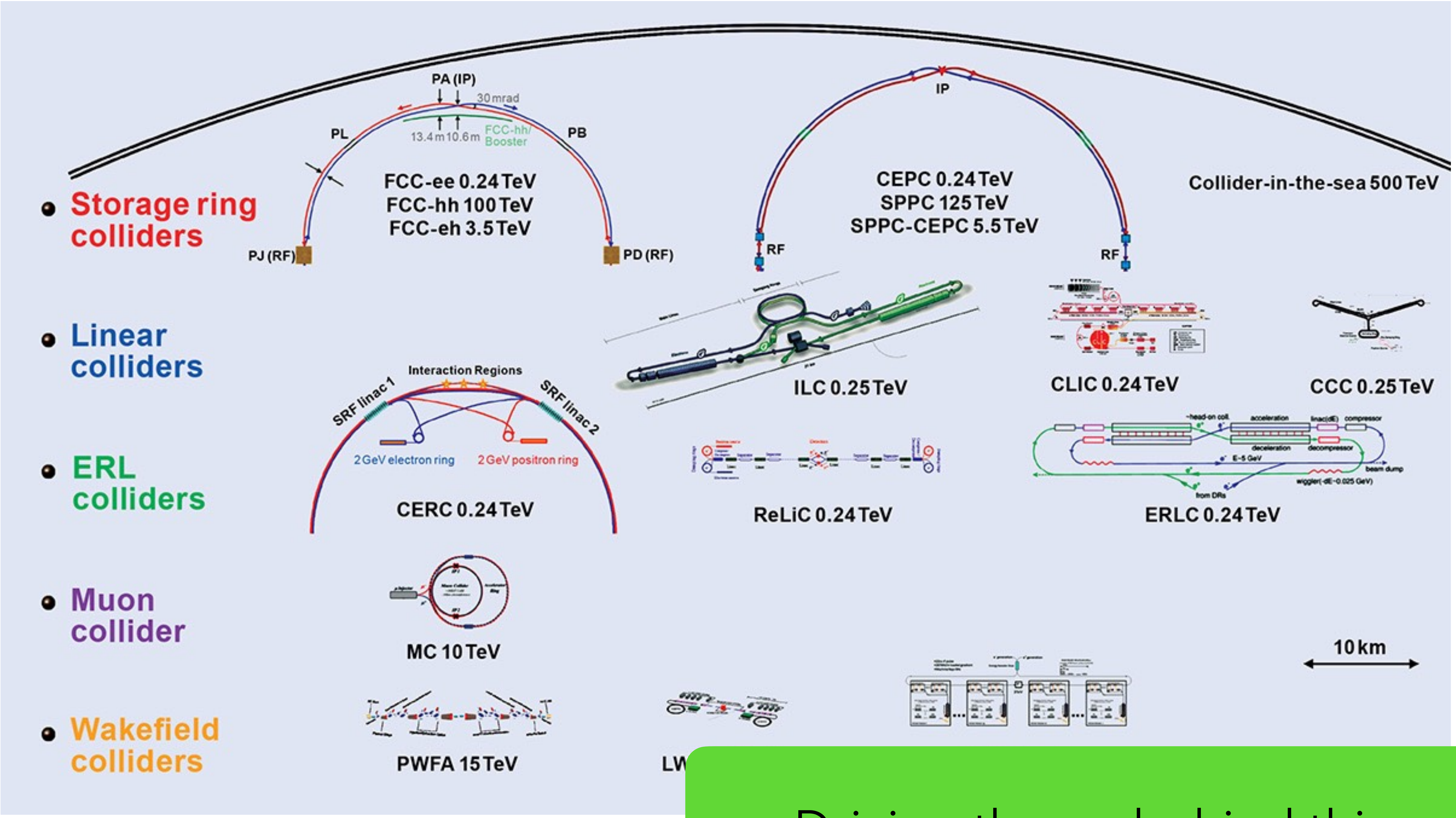
https://cerncourier.com/a/music-city-tunes-in-to-accelerators/



https://ep-news.web.cern.ch/higgs-physics-future-colliders

Note: H self-coupling @ HL-LHC to ~50%

Future collider proposals



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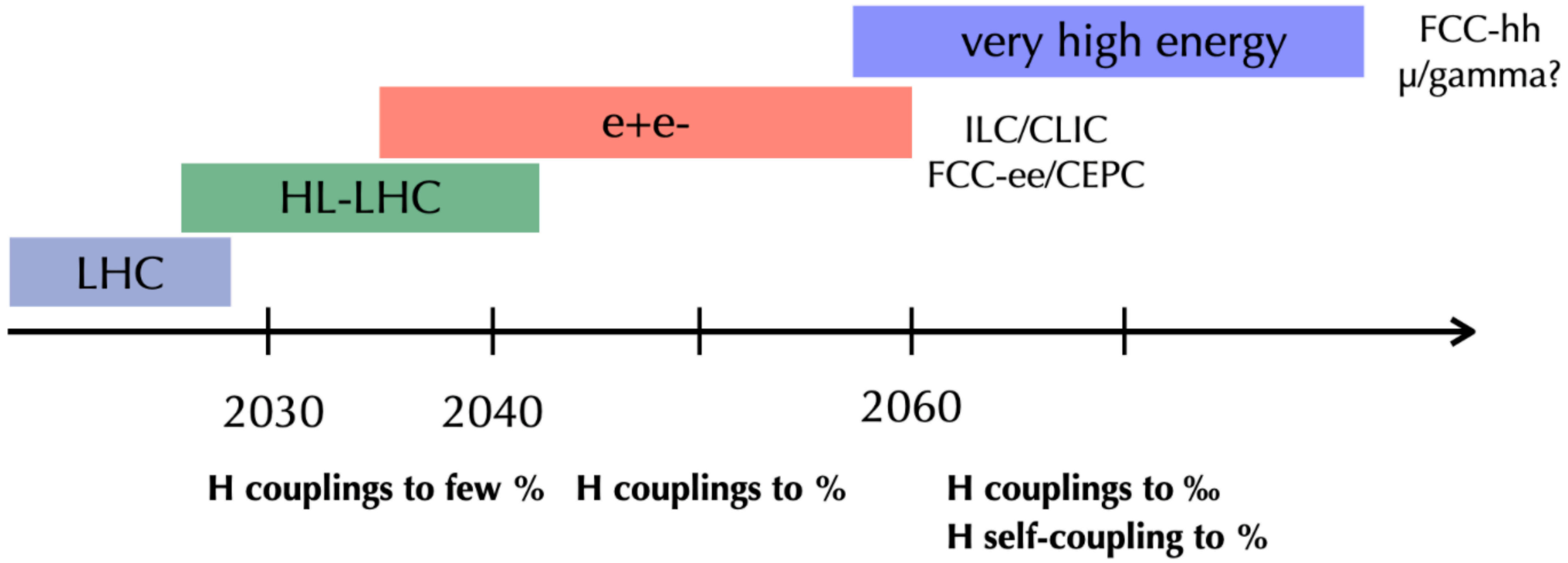

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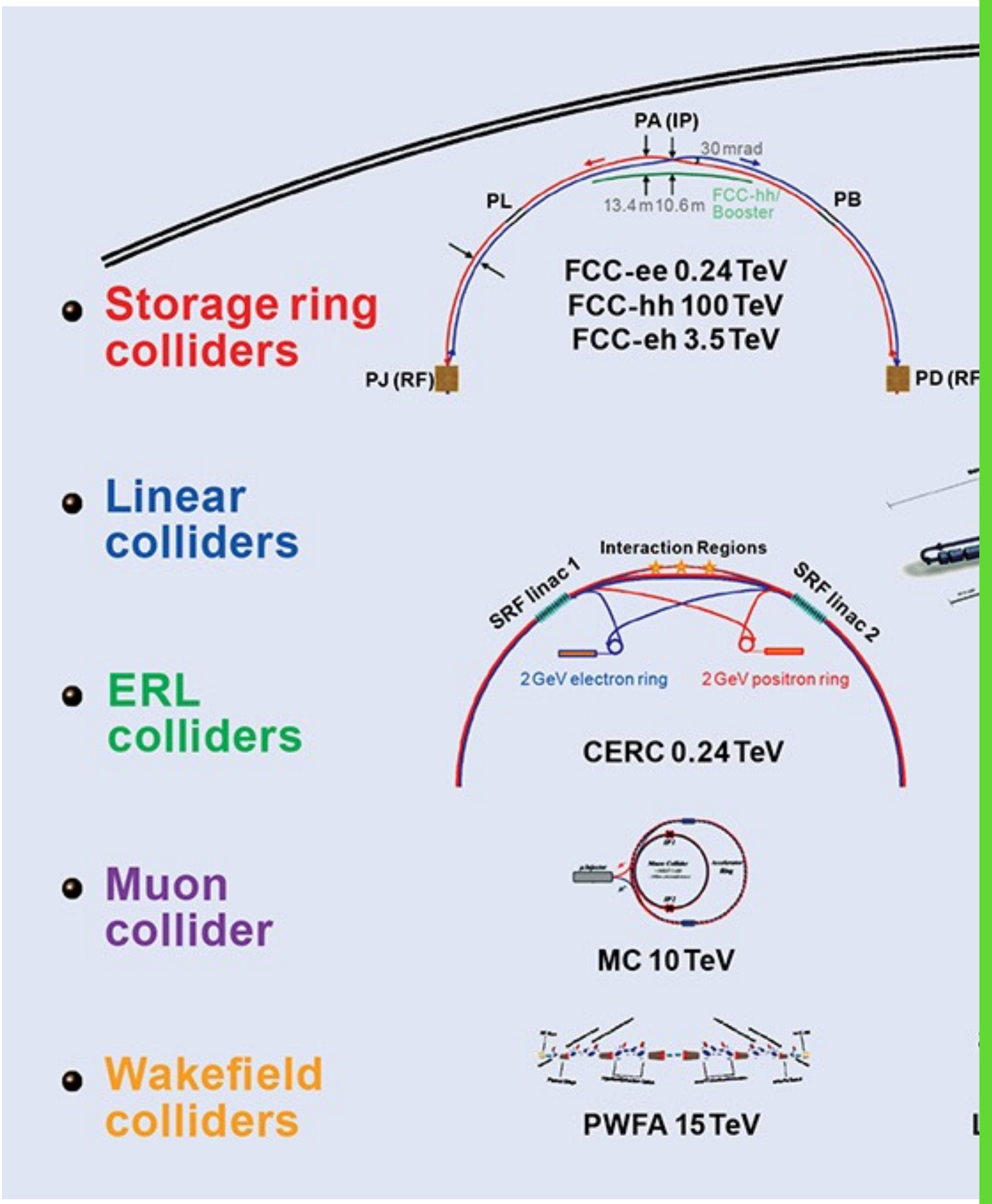
Driving theme behind this community planning:

Complementarity with energy vs precision measurements of fundamental interactions

Future collider proposals



https://cerncourier.co

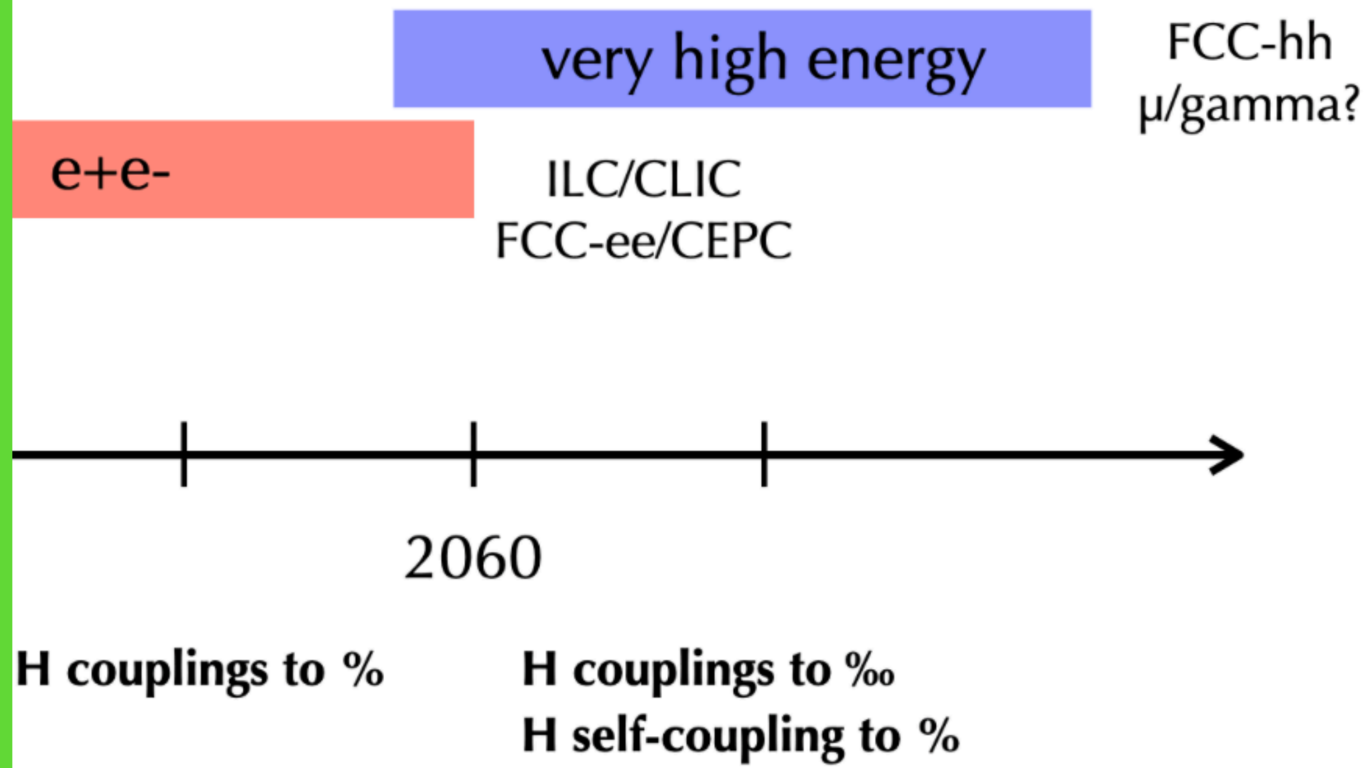
My take

The next generation of high-energy colliders (post HL-LHC) is decades in the making

It's critical in the meantime to continue to develop new skills and perspectives to make the most of of the remaining data taking at the LHC and for whatever comes next

One way is to draw inspiration from other fields, e.g. Machine Learning (see talk later in this session by W. Fedorko)

Recently, a lot of activity in bringing in tools from **Quantum Information**



ern.ch/higgs-physics-future-colliders

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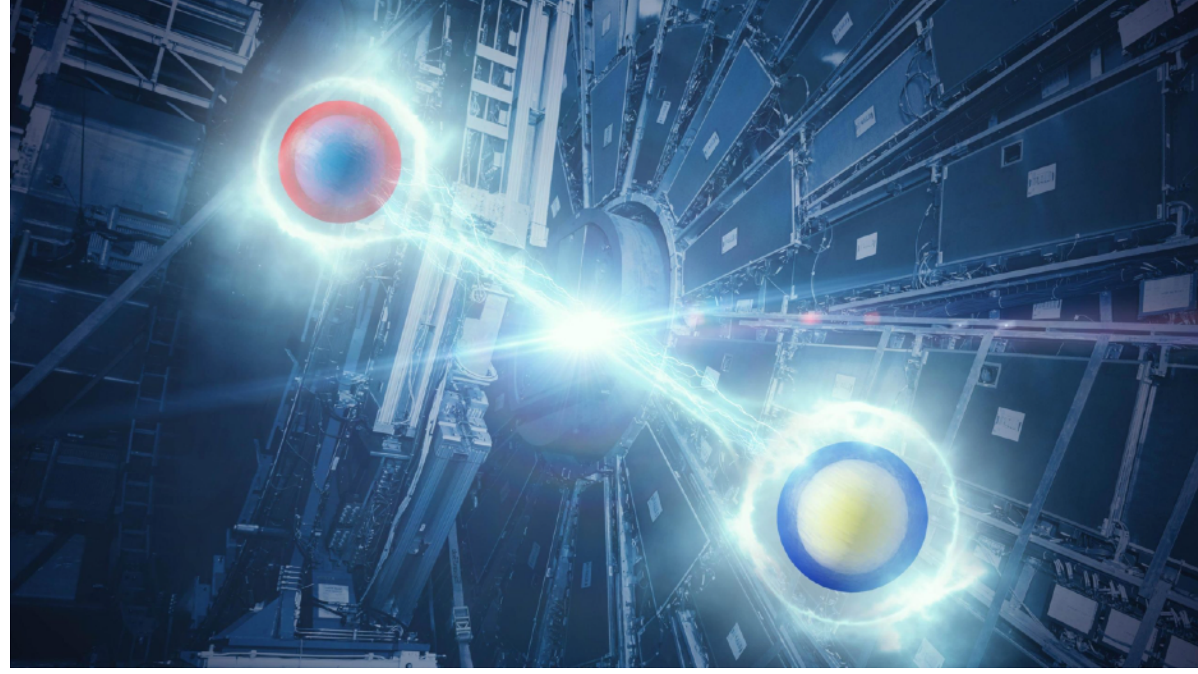
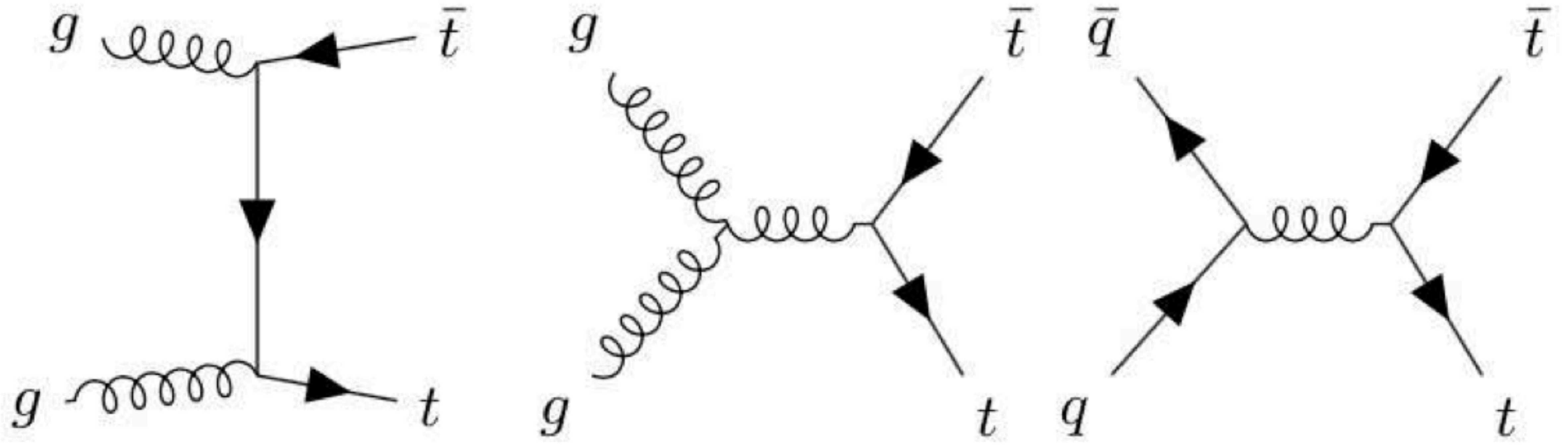
A quantum lens on collider physics



Very recent development in high-energy colliders:
2020, Y. Avid & J. De Nova: *Eur.Phys.J.Plus* 136 (2021) 9, 907

Entanglement is a key prediction of quantum mechanics and now understood as a fundamental aspect of nature. Has been experimentally established in low-energy systems (2022 Nobel prize). Can we measure it in a high-energy collider?

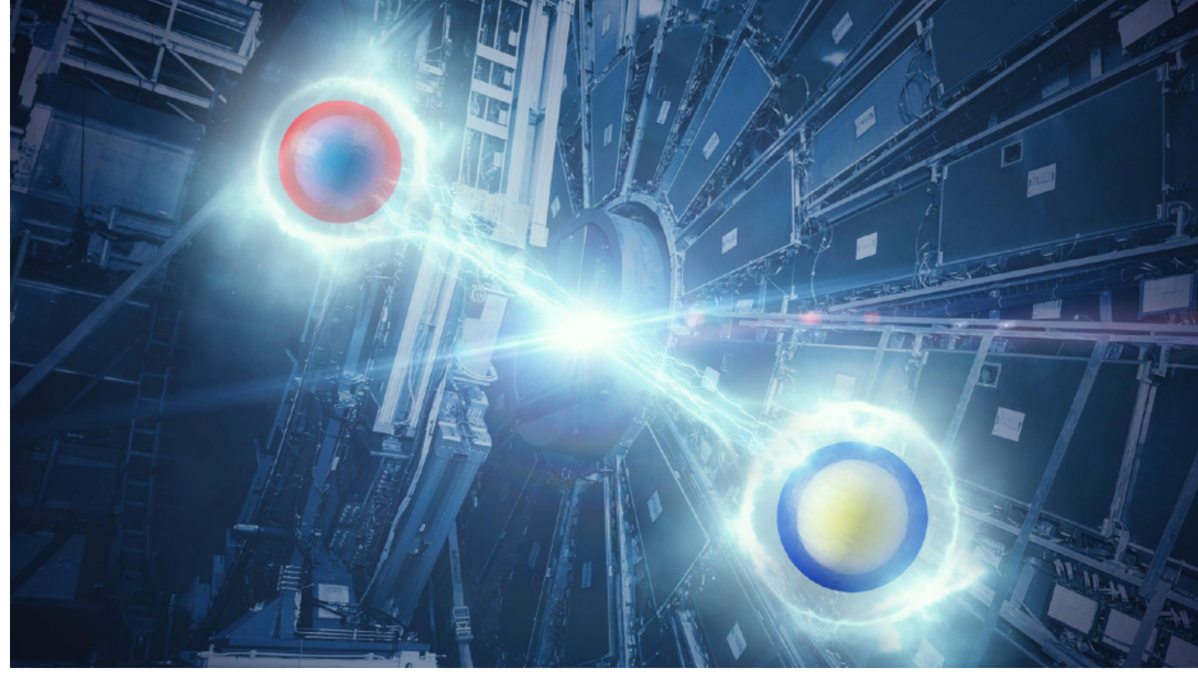


$$|t> \sim \alpha|\uparrow> + \beta|\downarrow>$$

$$|\bar{t}> \sim \gamma|\uparrow> + \delta|\downarrow>$$

$|t\bar{t}> \sim$ Entangled state

A quantum lens on collider physics



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

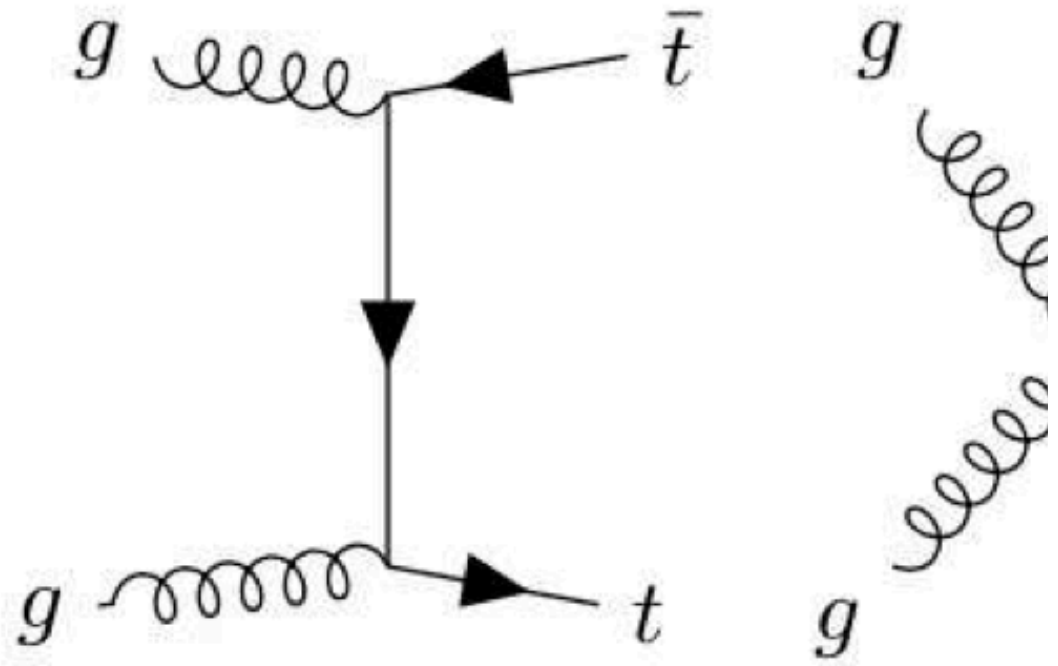
Nature 633 (2024) 542
DOI: 10.1038/s41586-024-07824-z

CERN-EP-2023-230
October 3, 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Entanglement is a key feature of quantum mechanics [1–3], with applications in fields such as metrology, cryptography, quantum information, and quantum computation [4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic [9–13] to the macroscopic [14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a center-of-mass energy of $\sqrt{s}$ = 13 TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modeling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) ± 0.019 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

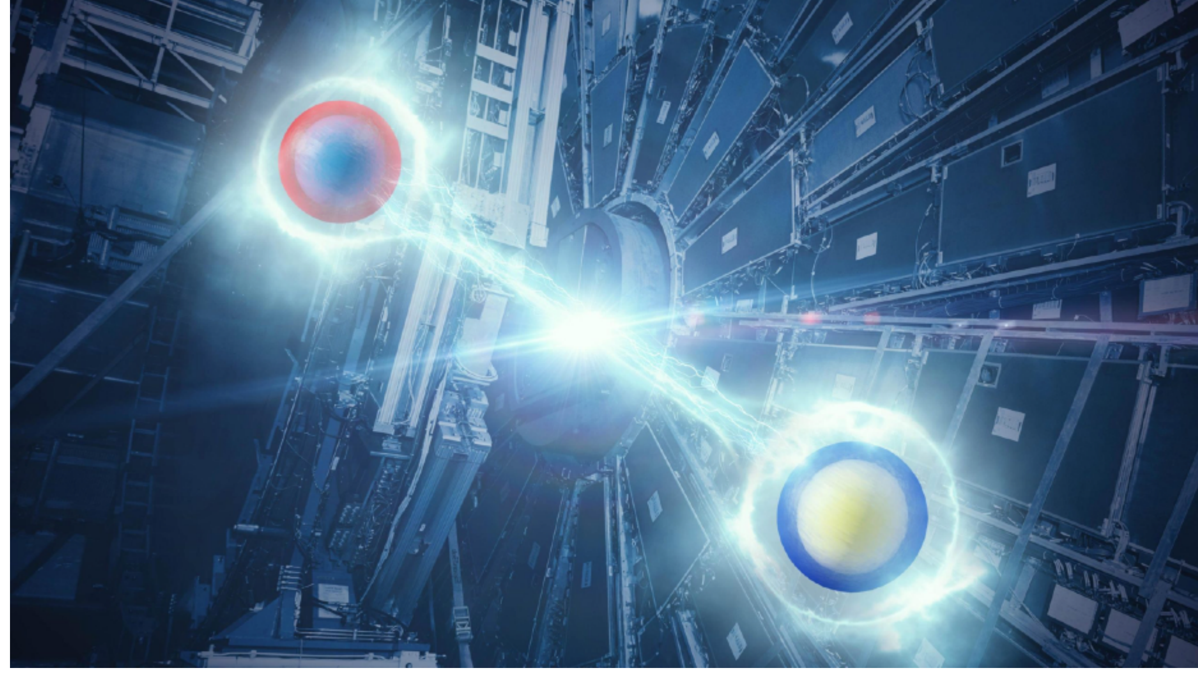


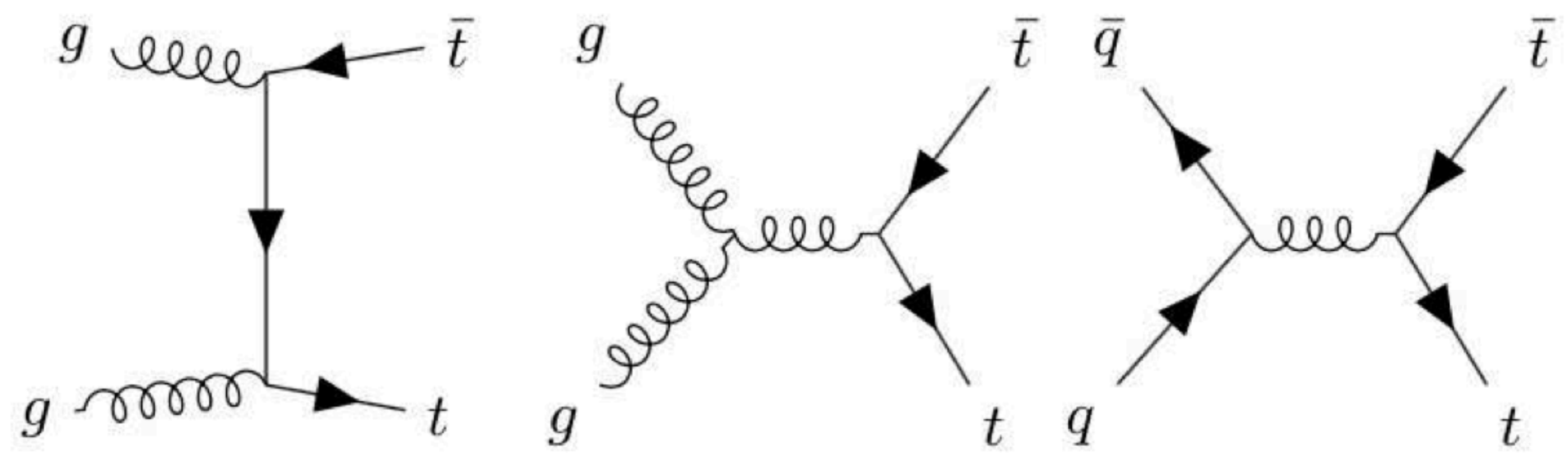
$$> \sim \alpha | \uparrow > + \beta | \downarrow >$$

$$> \sim \gamma | \uparrow > + \delta | \downarrow >$$

Entangled state

A quantum lens on collider physics





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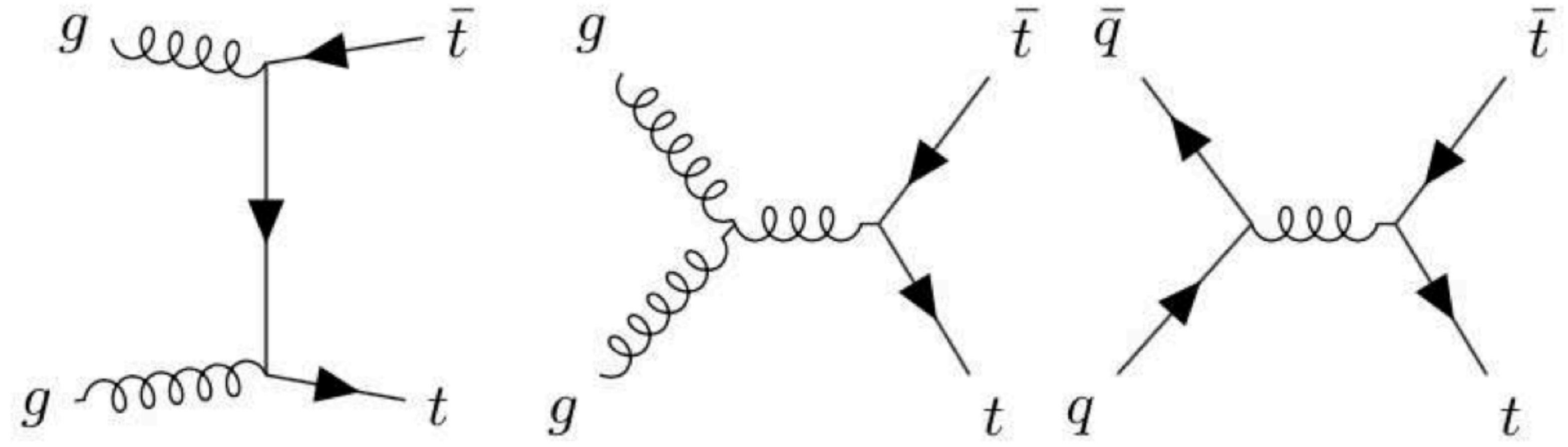
Spin ↑, ↓ of elementary particles ↔ fundamentally the same as logical qubits, $|0>, |1>$

A quantum lens on collider physics



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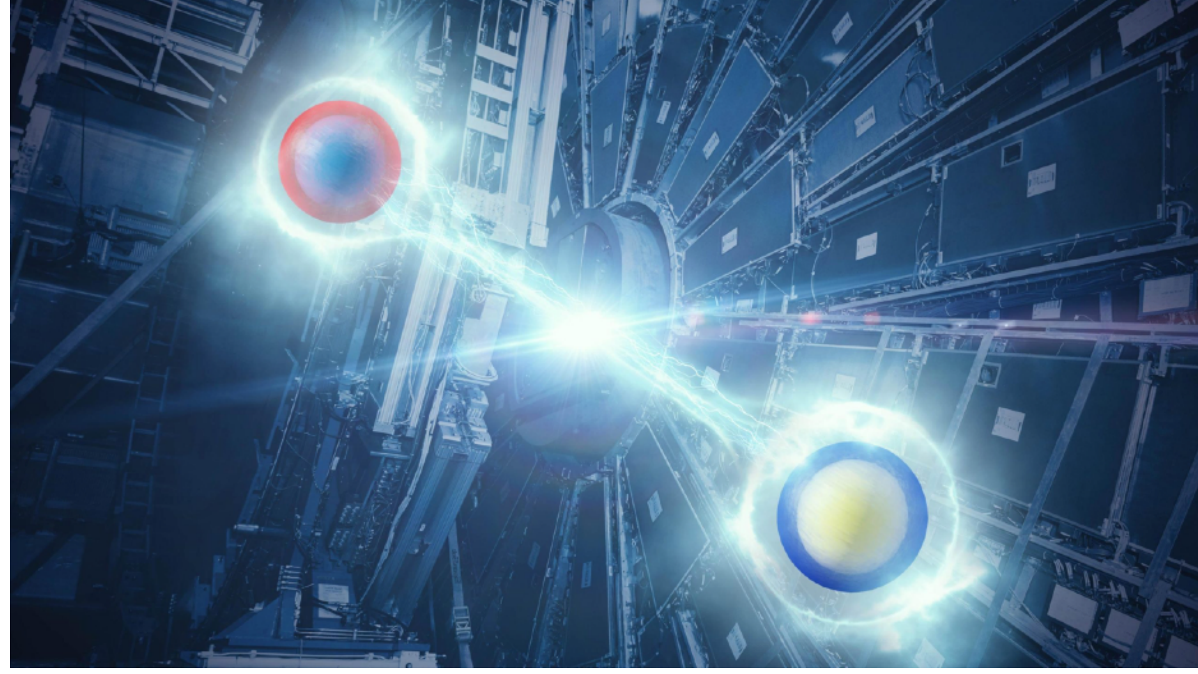
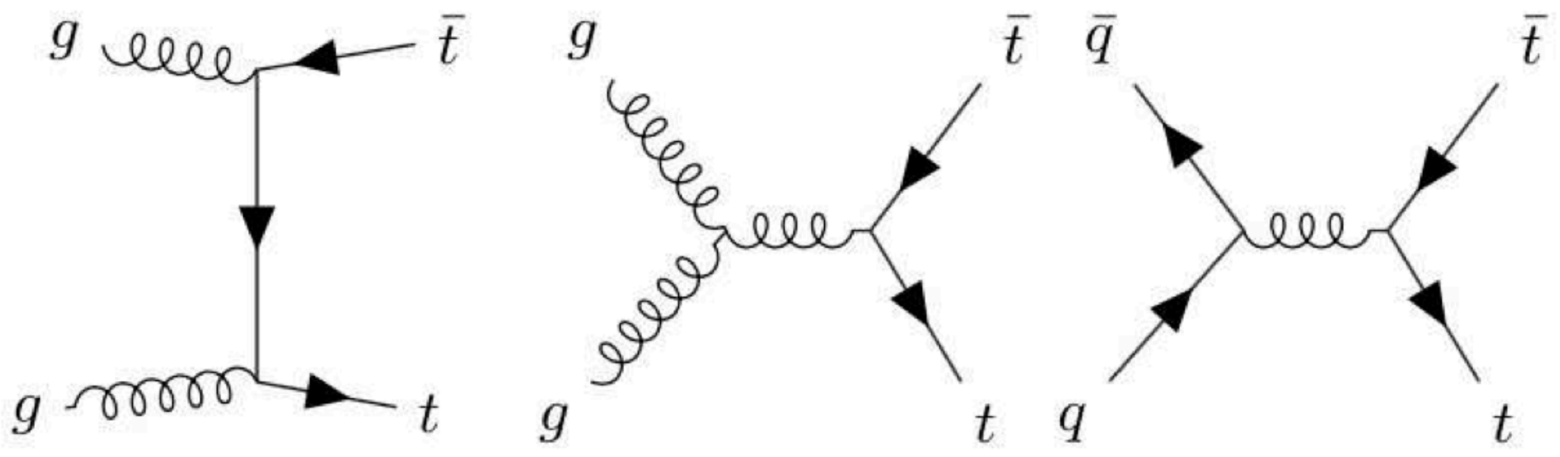
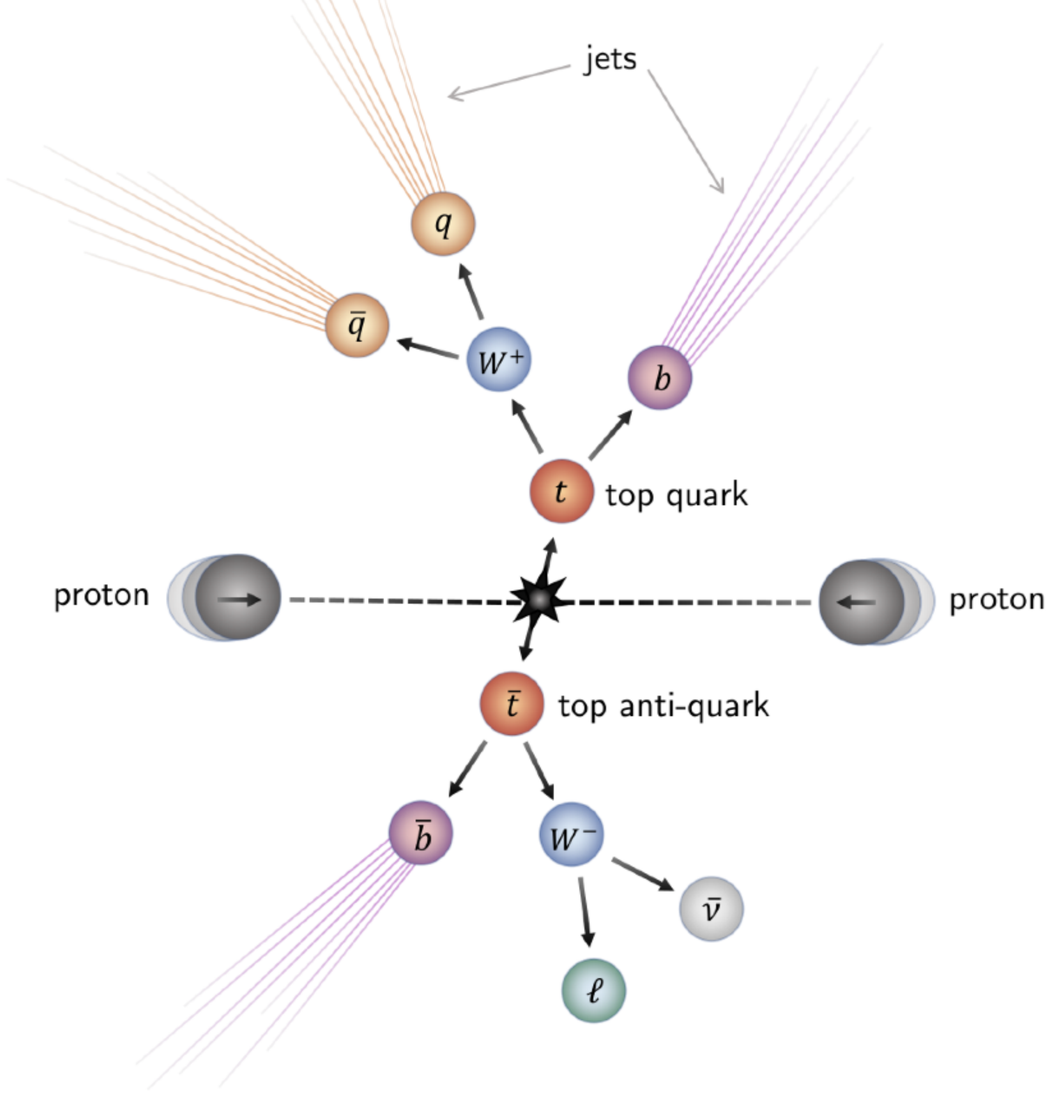


Spin $\uparrow, \downarrow$ of elementary particles $\leftrightarrow$ fundamentally the same as logical qubits, $|0>, |1>$

Reconstructing spin polarization

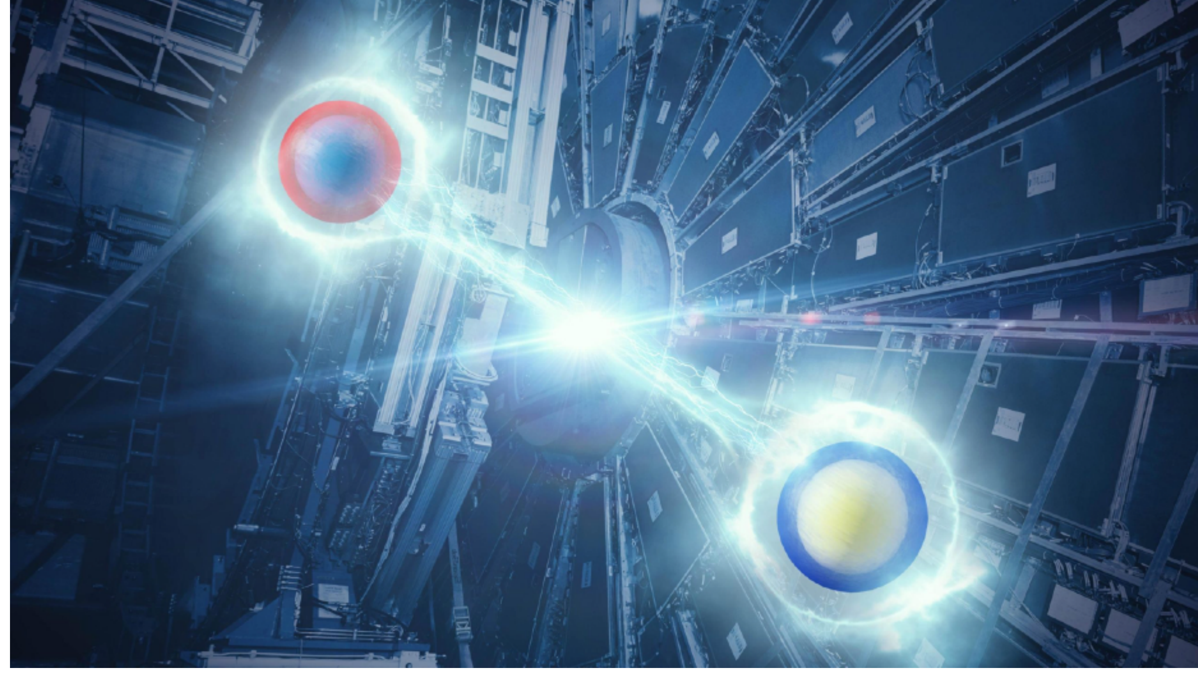


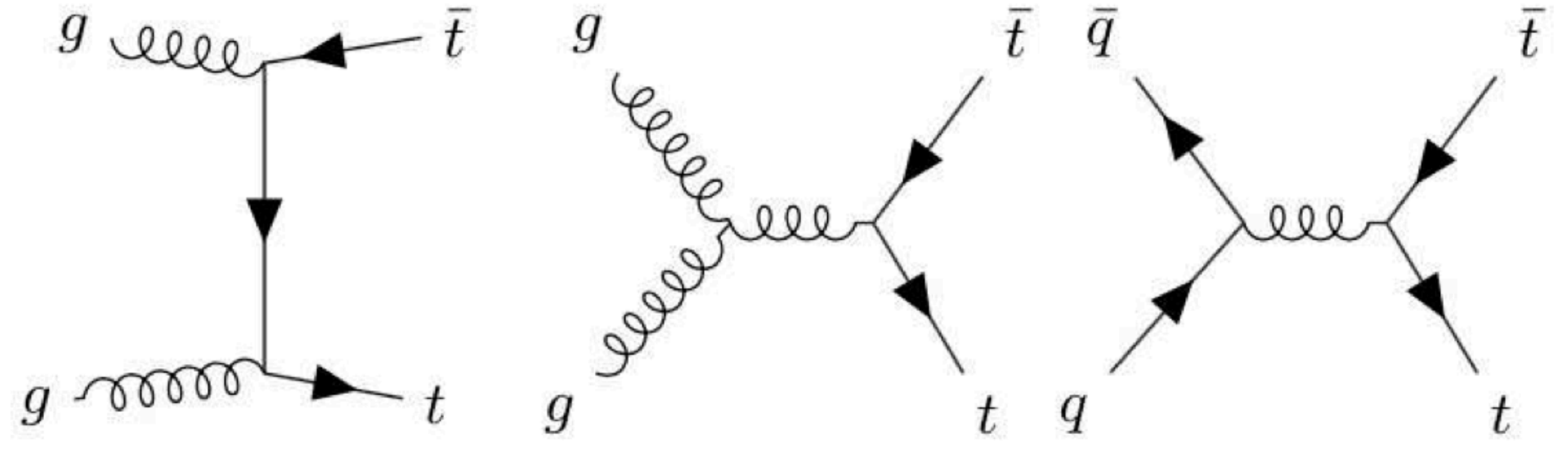


Captures quantum information properties of particle collisions, parameterized by all possible 'bits' of $|01>$

$$\rho = \frac{1}{4}\Big[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^{+}(\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^{-}(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\Big]$$

A quantum lens on collider physics





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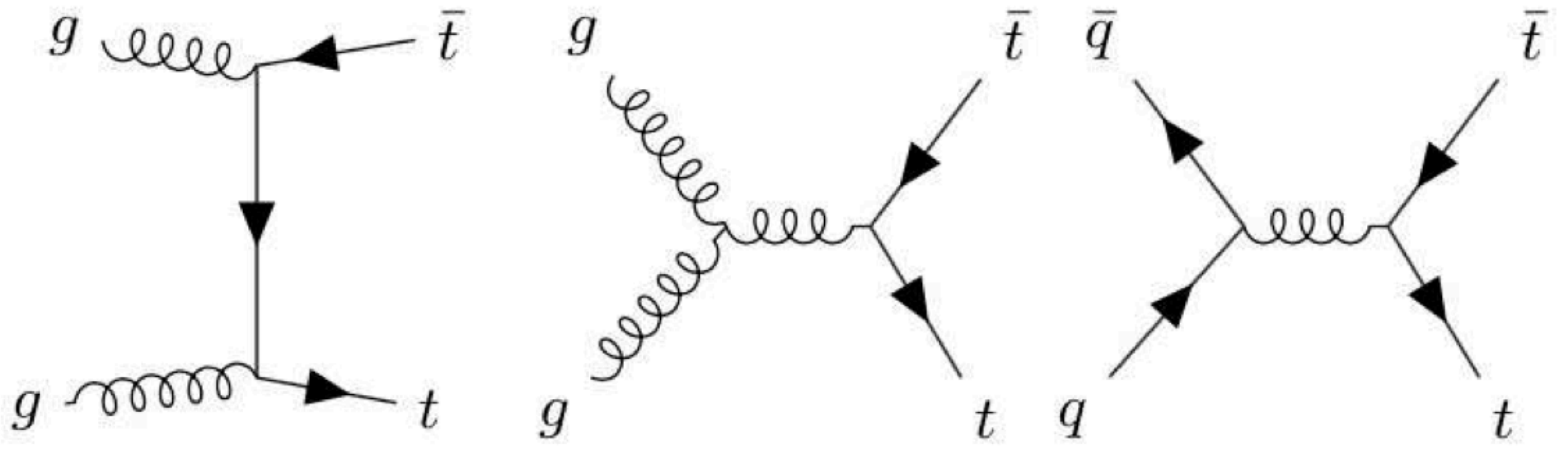
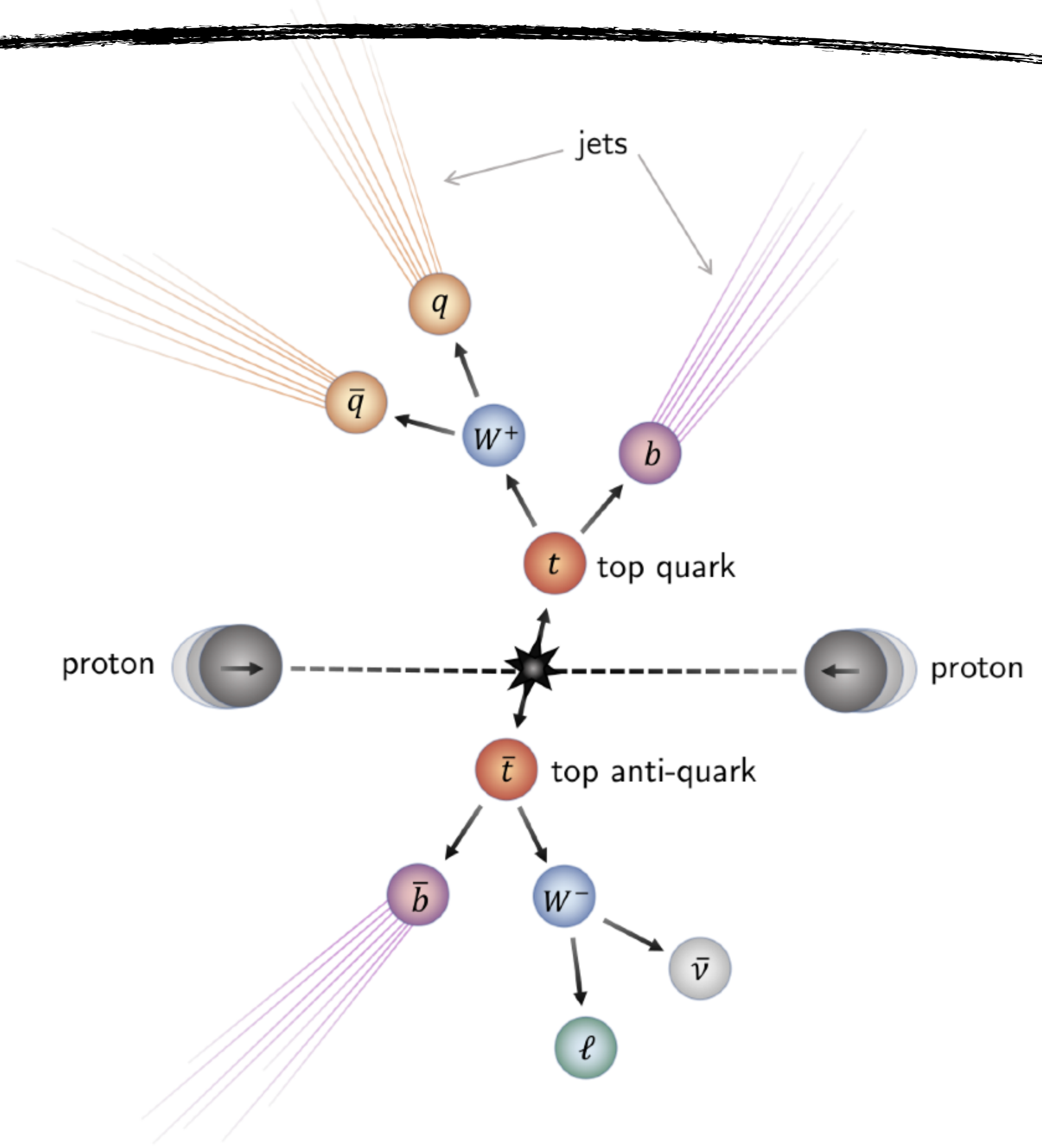
Spin ↑, ↓ of elementary particles ↔ fundamentally the same as logical qubits, $|0>, |1>$

Reconstructing spin polarization



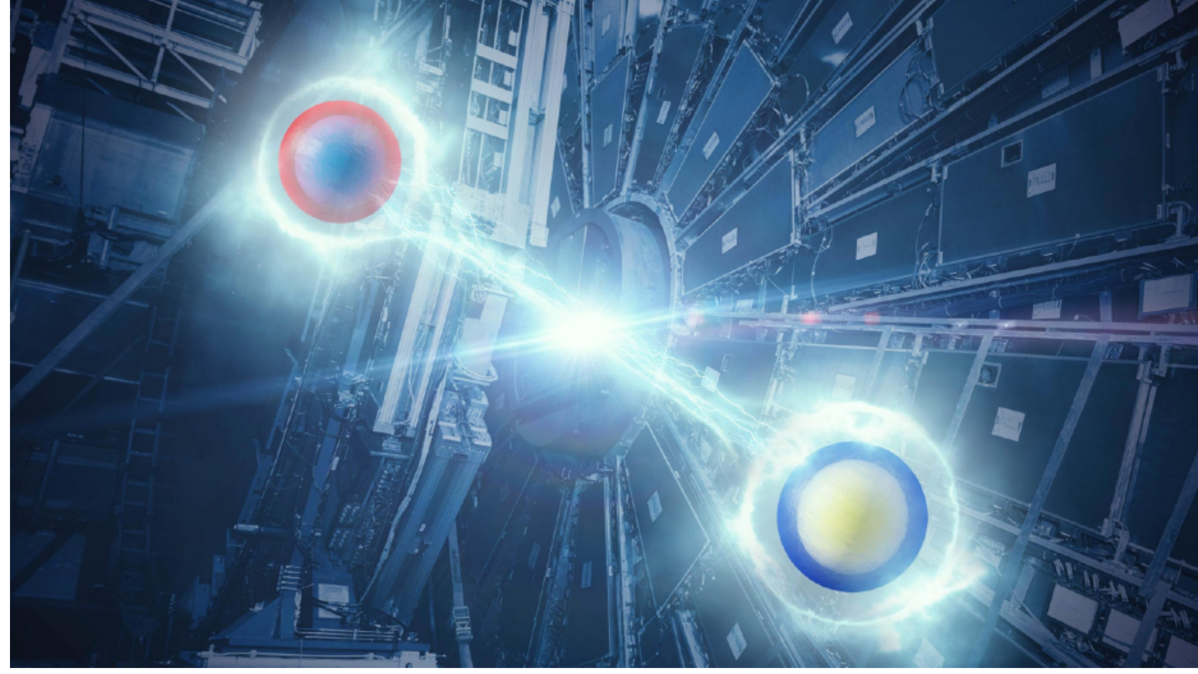


Captures quantum information properties of particle collisions, parameterized by all possible 'bits' of $|01>$

$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+ (\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^- (\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij} (\sigma_i \otimes \sigma_j)\right]$$

Quantum tomography: QI technique of reconstructing full information of correlations

A quantum lens on collider physics

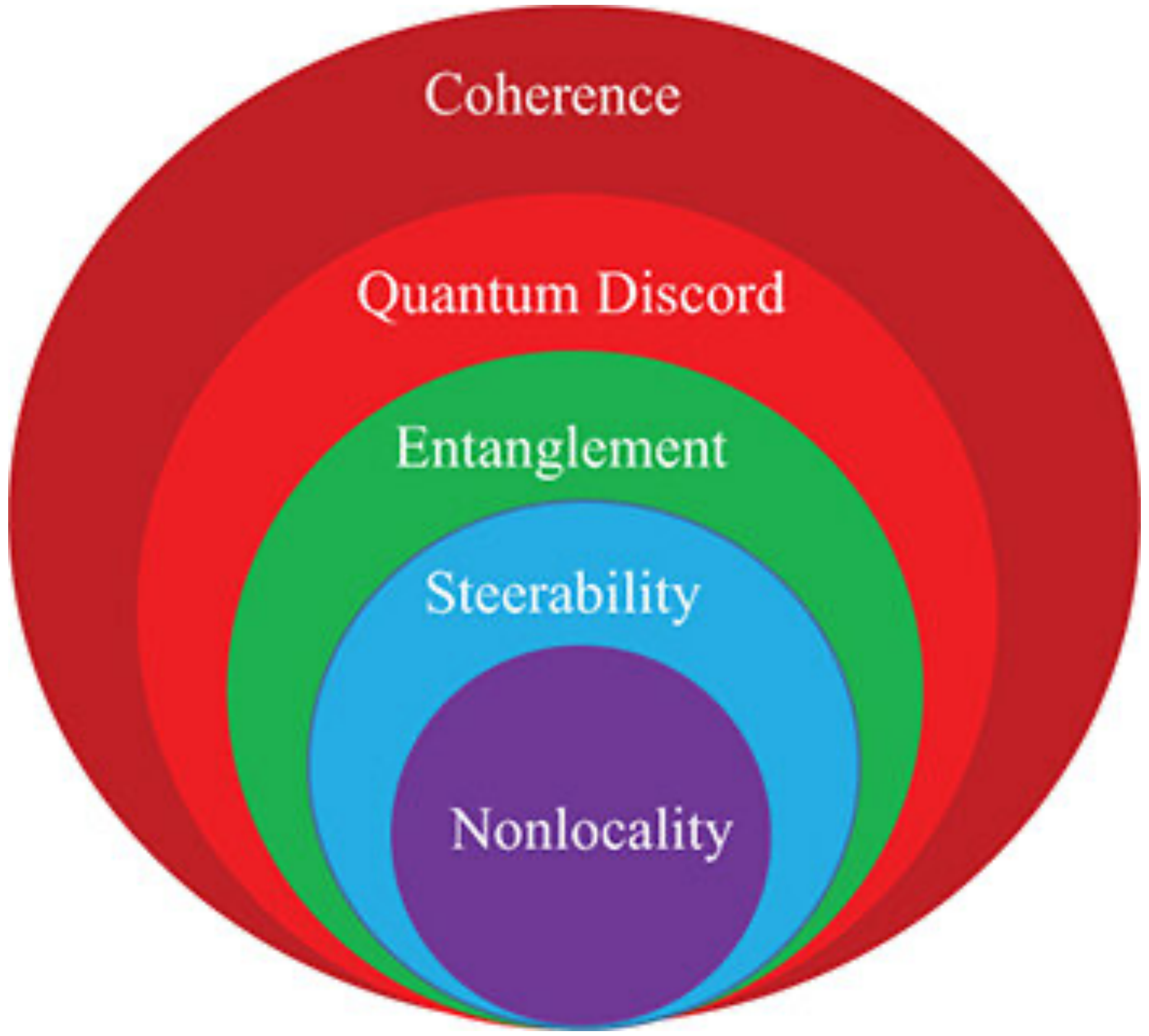


$$|t> \sim \alpha|\uparrow> + \beta|\downarrow>$$

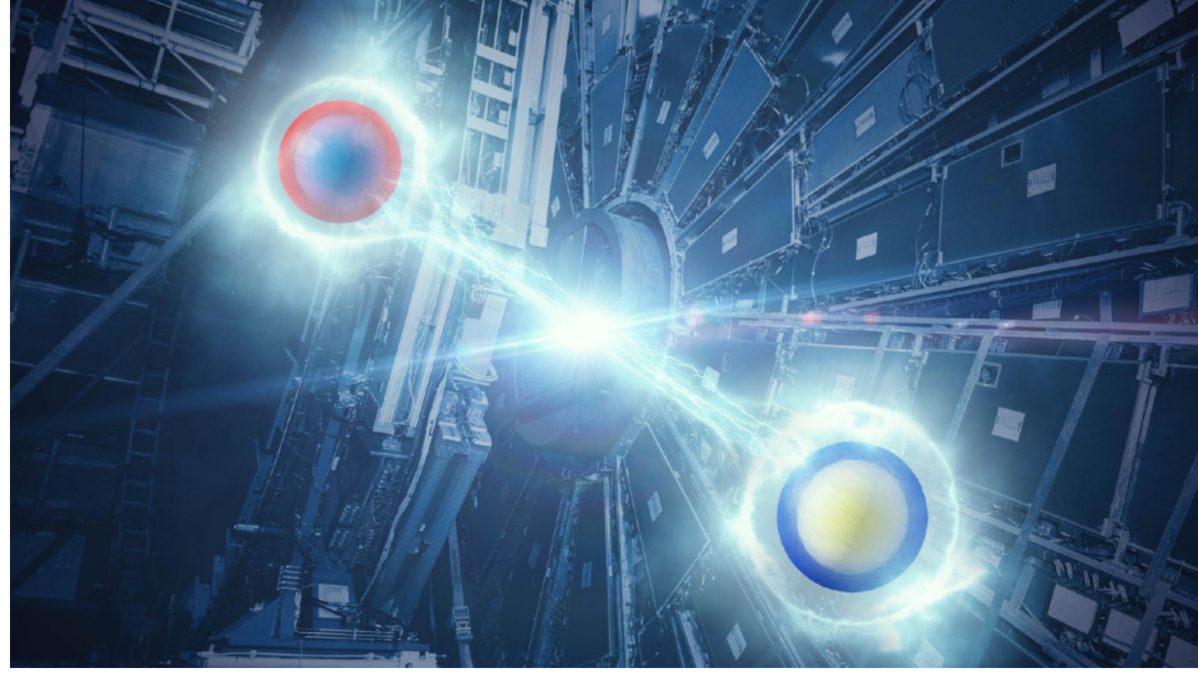
$$|\bar{t}> \sim \gamma|\uparrow> + \delta|\downarrow>$$

$$\rho = \frac{1}{4}\Big[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+(\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^-(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\Big]$$

"New" properties of nature to measure and understand better



A quantum lens on collider physics



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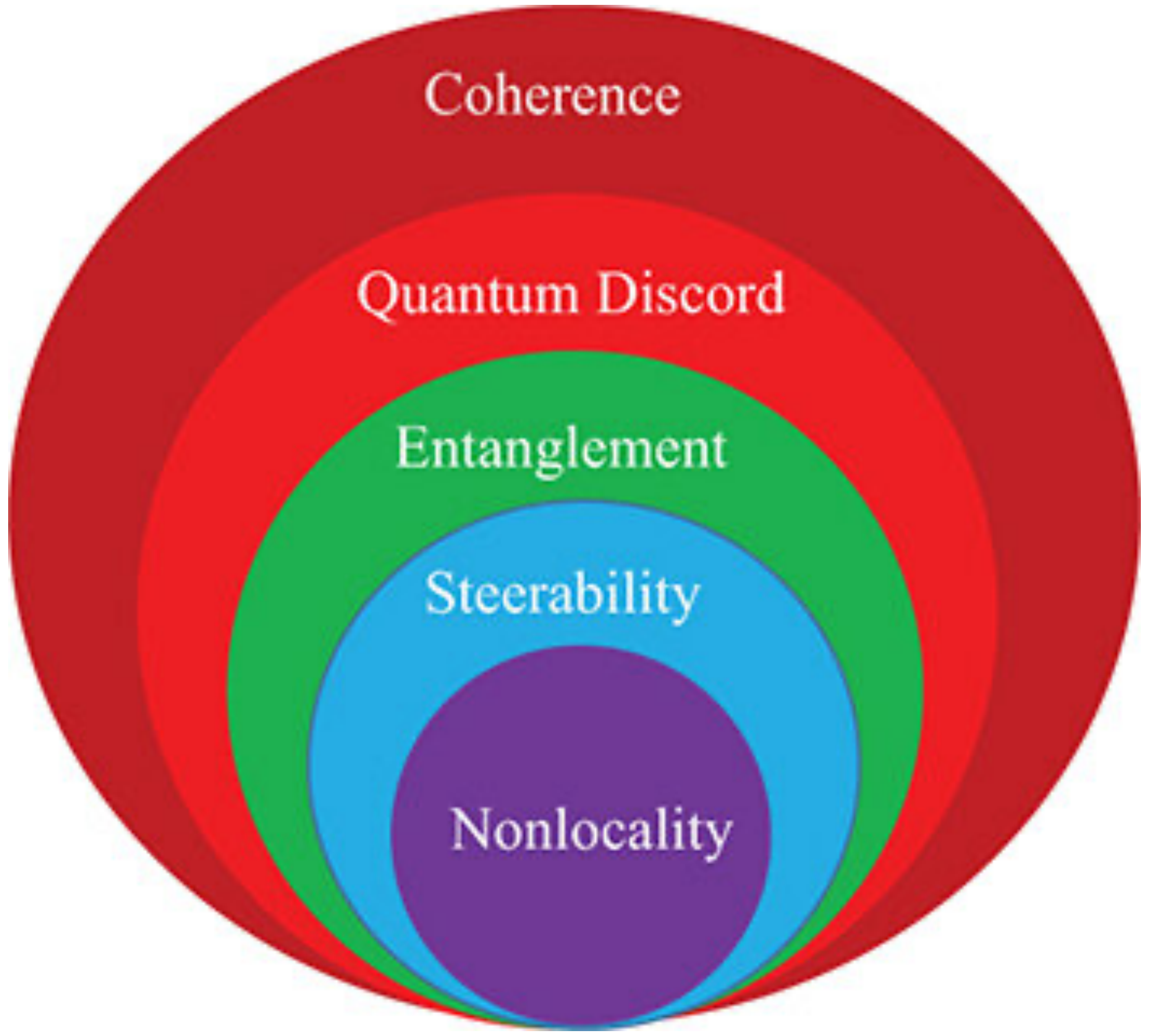
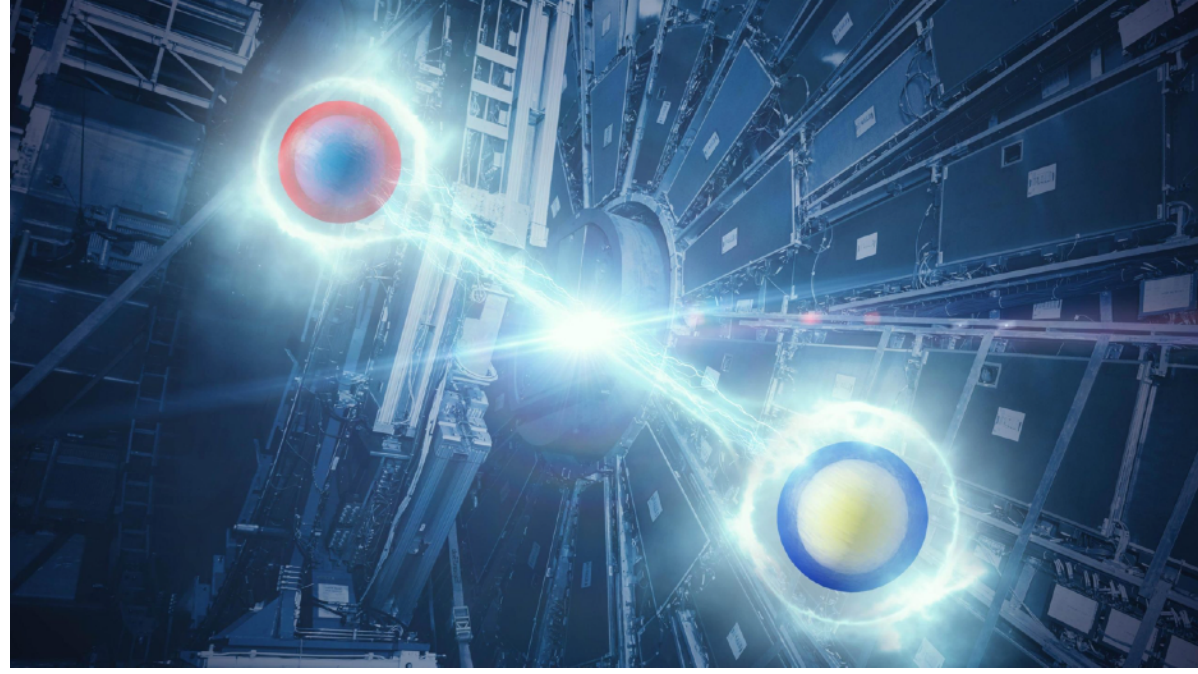


Until recently, LHC measurements of fundamental interactions have probed coherent correlations

A quantum lens on collider physics



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“New” properties of nature to measure and understand better

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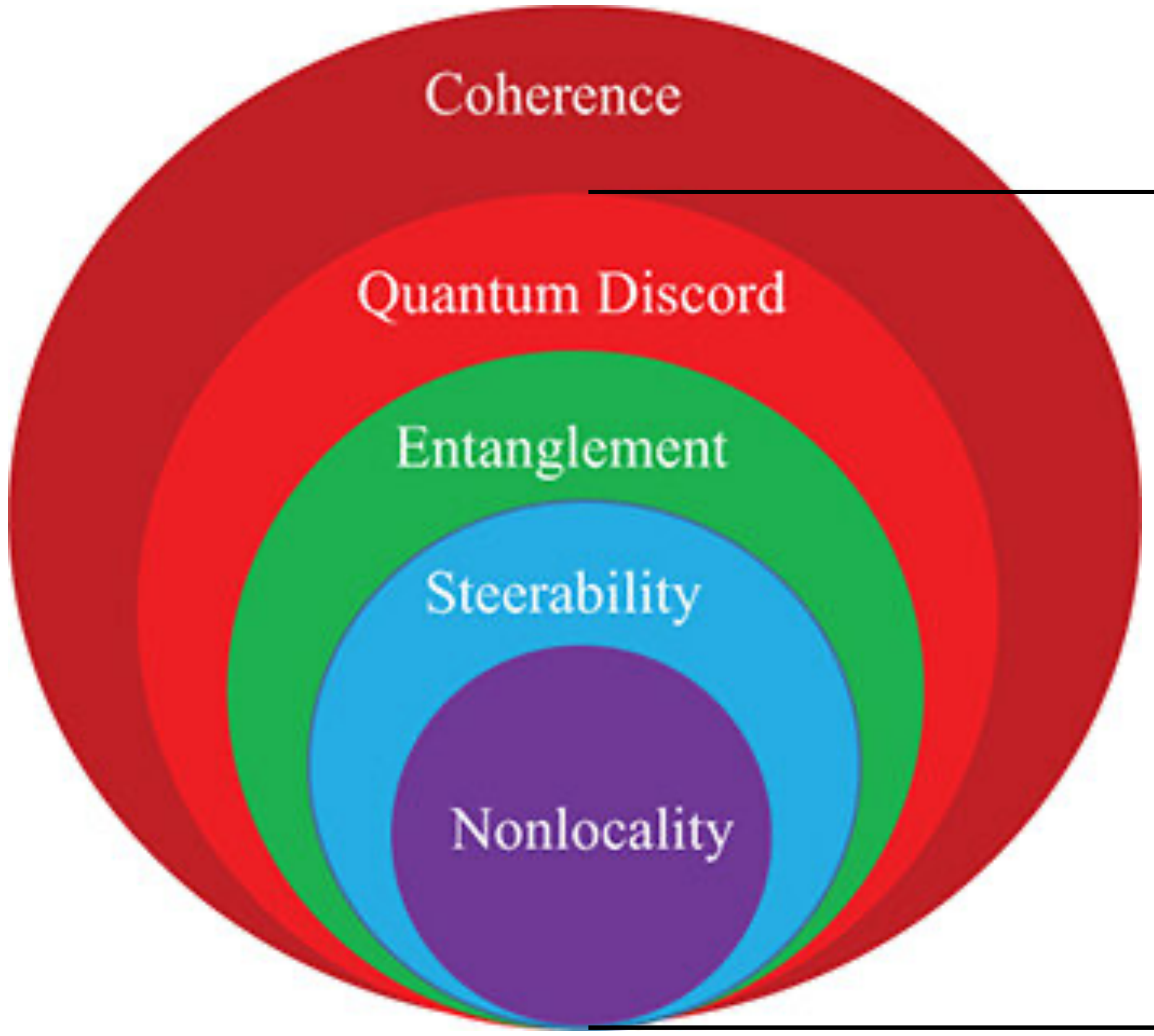
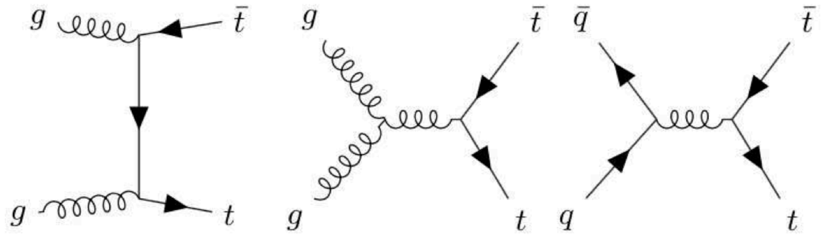
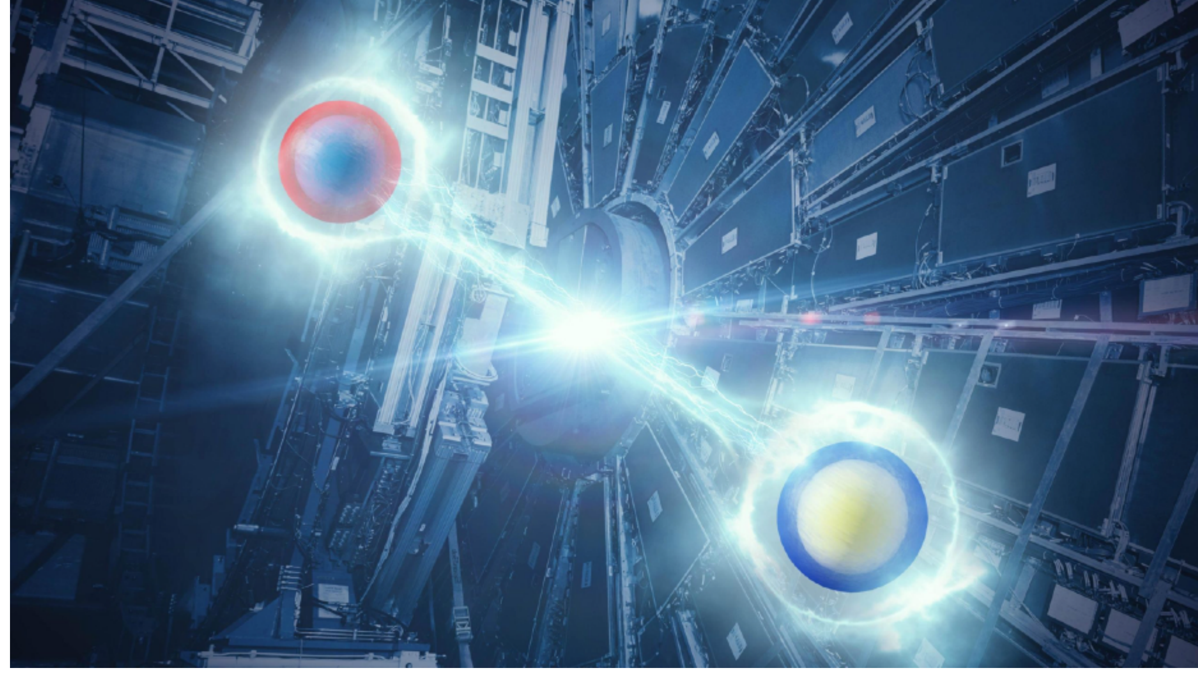




New observables for collider physics!

$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+ (\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^- (\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij} (\sigma_i \otimes \sigma_j)\right]$$

A quantum lens on collider physics

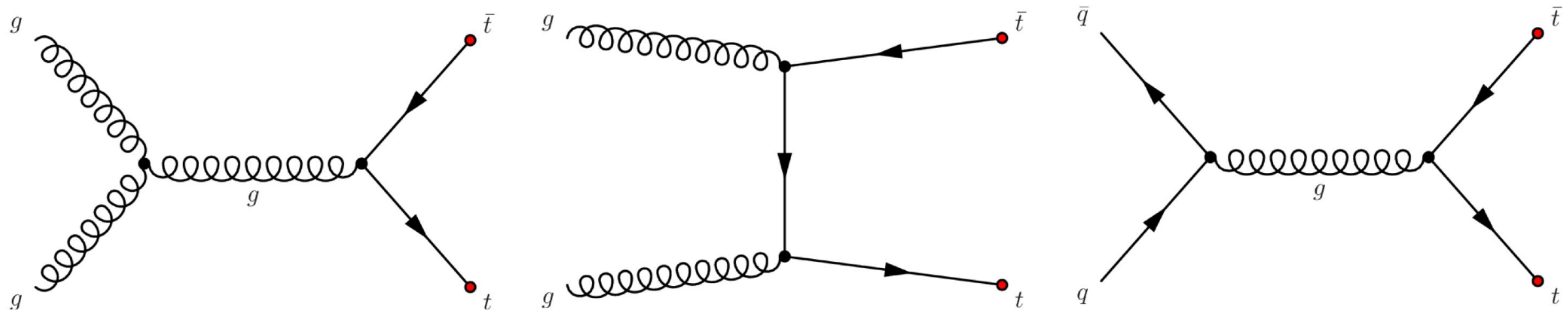


Case study:

Probing new physics in the top sector using quantum information

Rafael Aoude[a1], Hannah Banks[b2], Chris D. White[c3] and Martin J. White[d4]

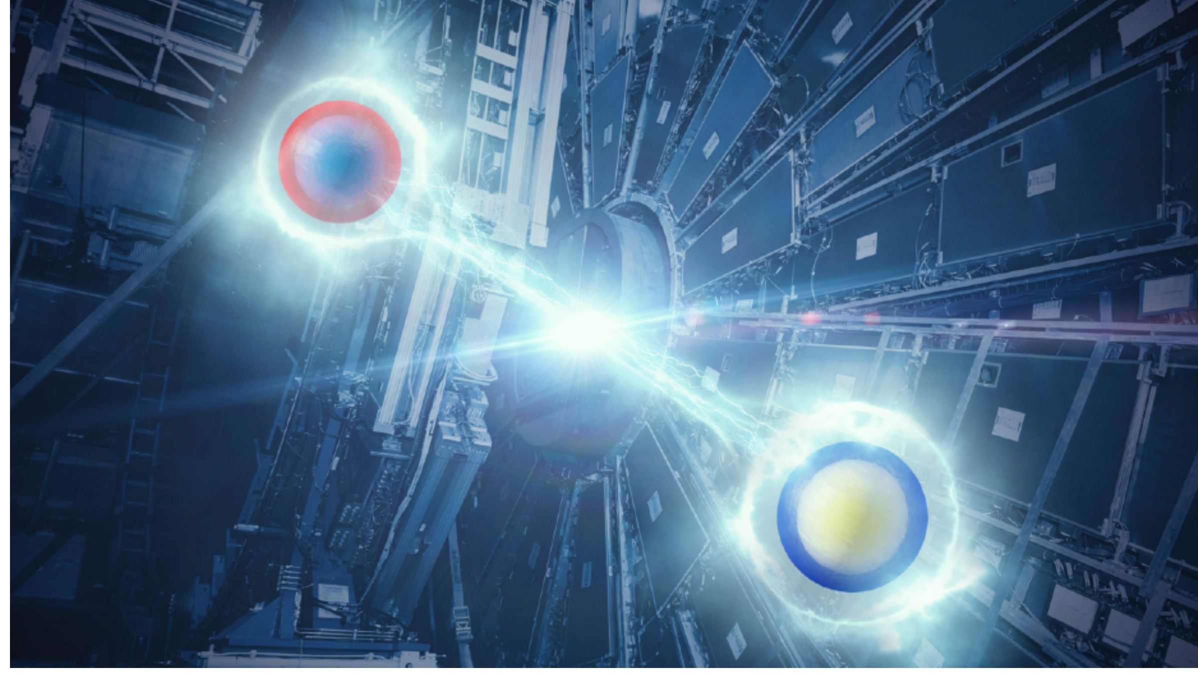
arXiv:2505.12522 **[hep-ph]**



$$\mathscr{L}_{SM} \longrightarrow \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{O}$$

Additional interactions due to new physics beyond the Standard Model, effects parameterized by hypothetical new scale in Nature Λ, an be systematically studied using method of effective field theory

A quantum lens on collider physics



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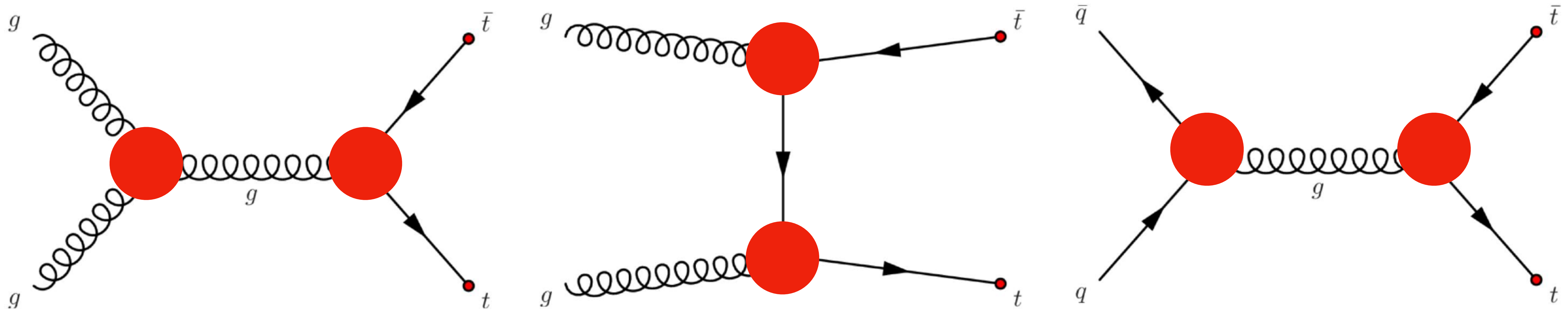
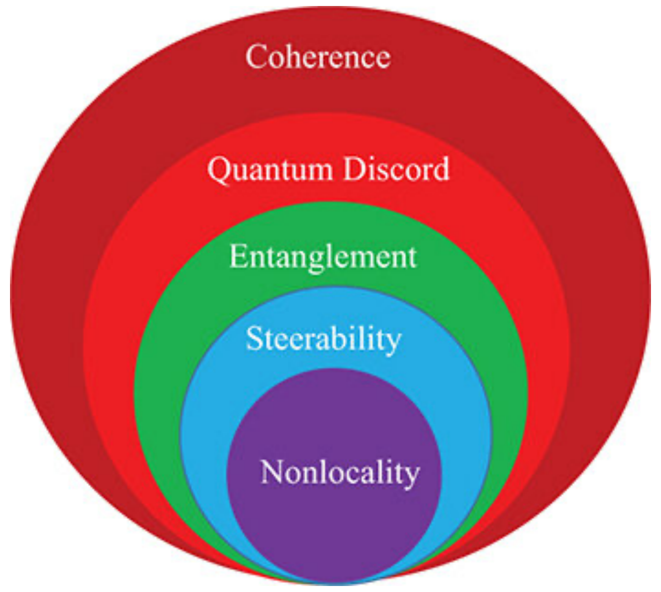
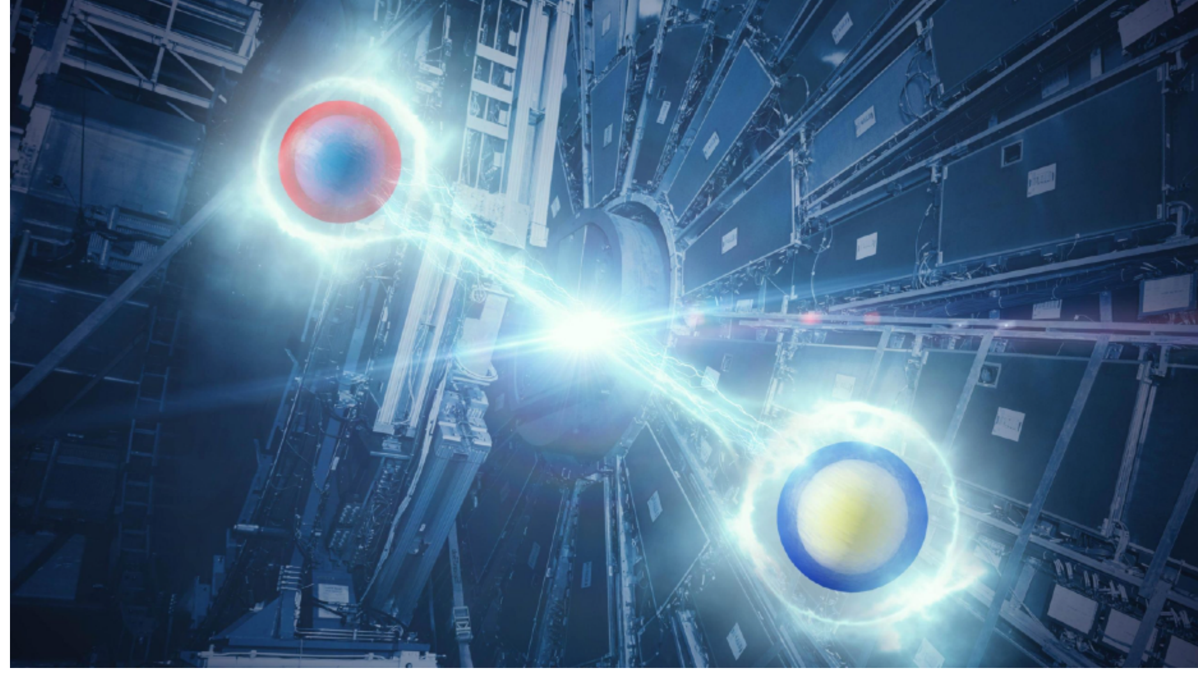


$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^{+}(\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^{-}(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\right]$$



Although effective interactions may be small, can imprint distinct changes in spin/kinematic distributions. A new precision tool for new physics signatures

A quantum lens on collider physics



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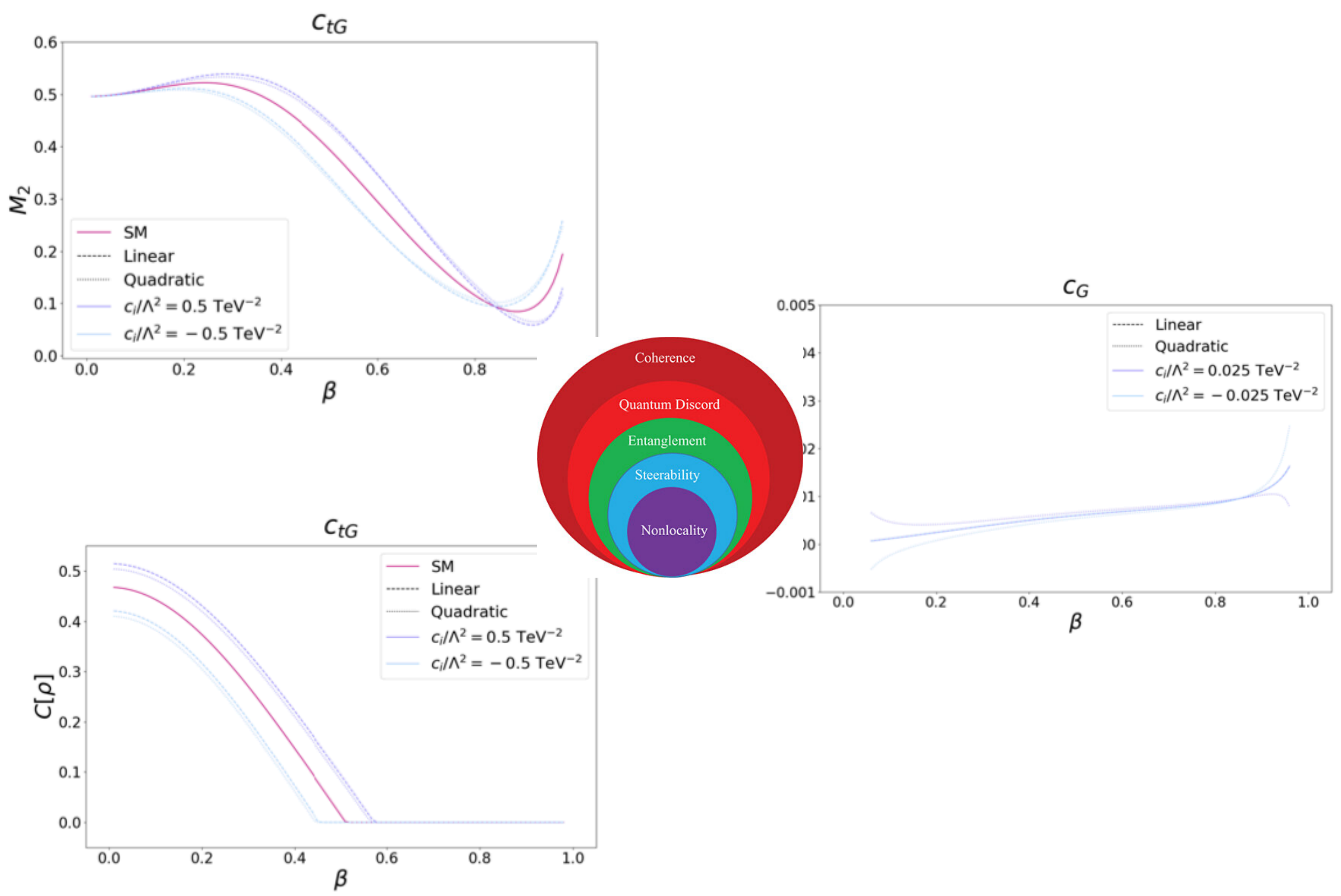
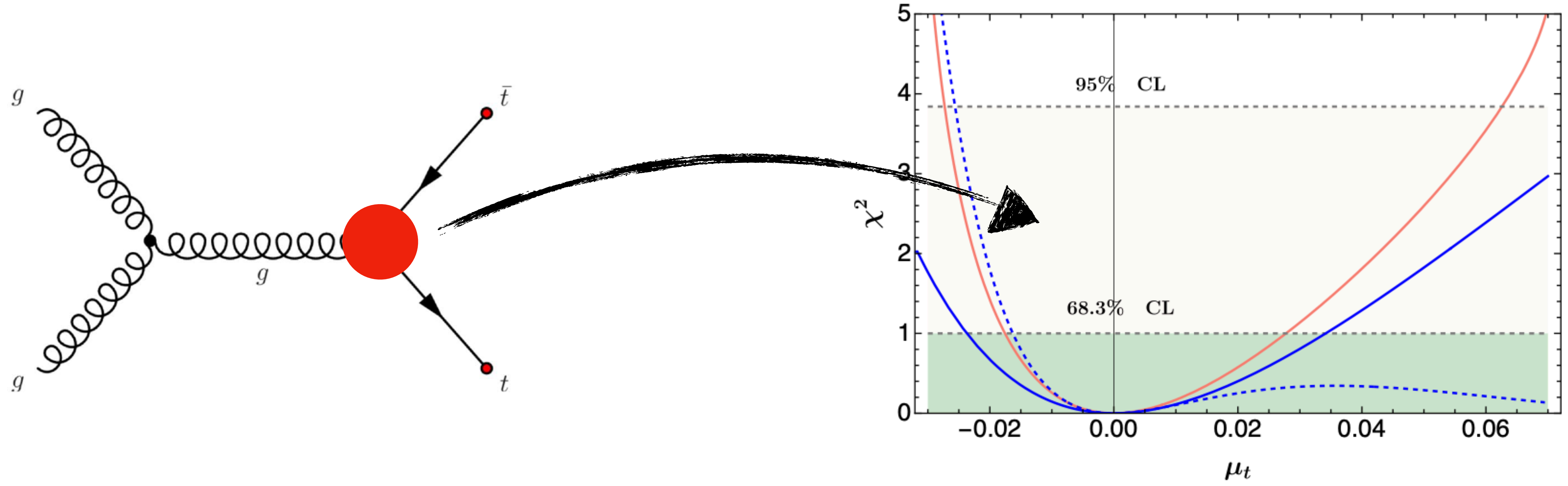
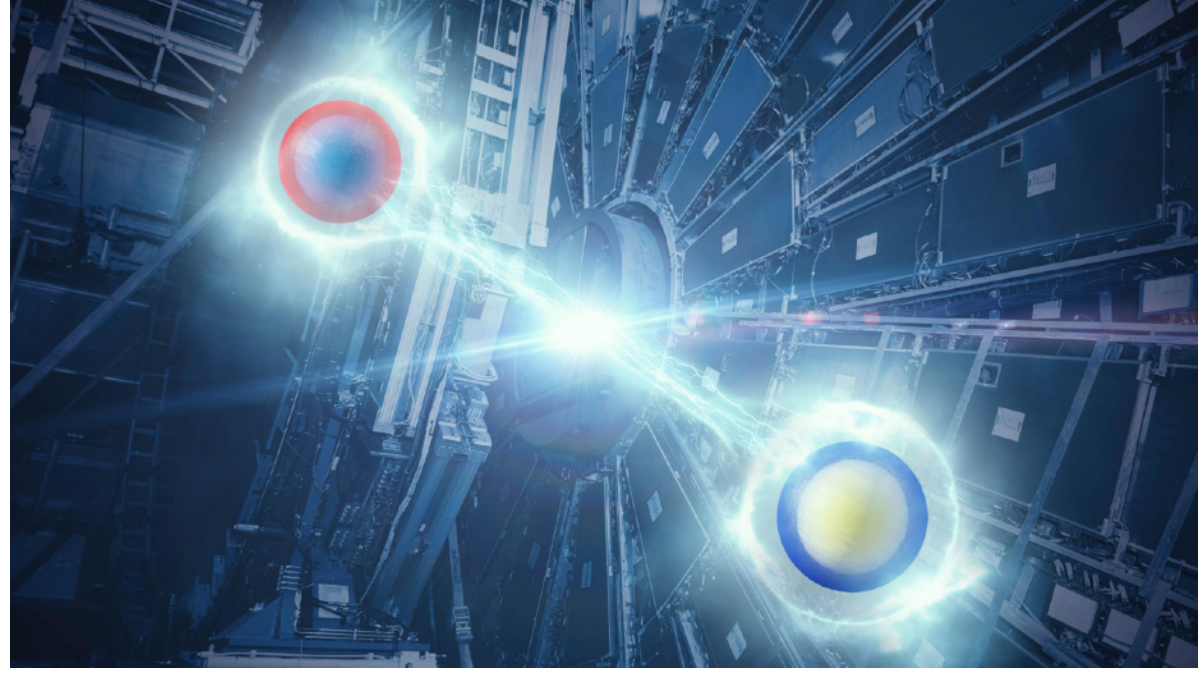


Different QI measures can capture more refined picture in the structure of fundamental interactions



M. Fabbrichesi, M. Low, L. Marzola Phys.Rev.D 112 (2025) 1, 013003

A quantum lens on collider physics



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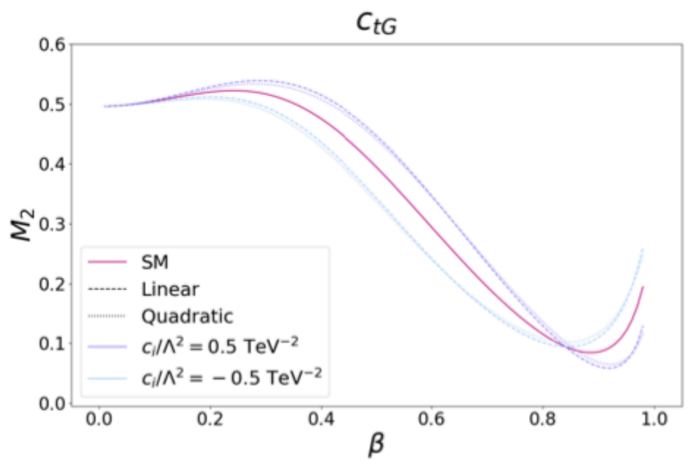
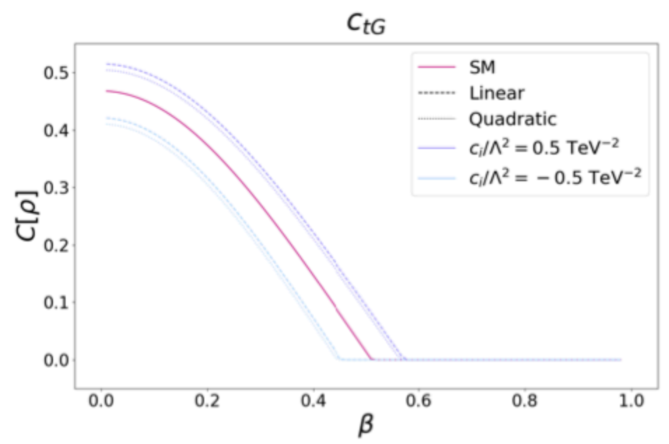
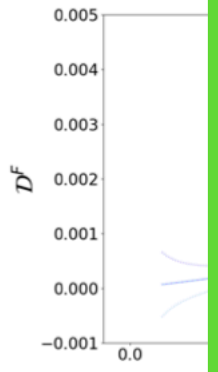


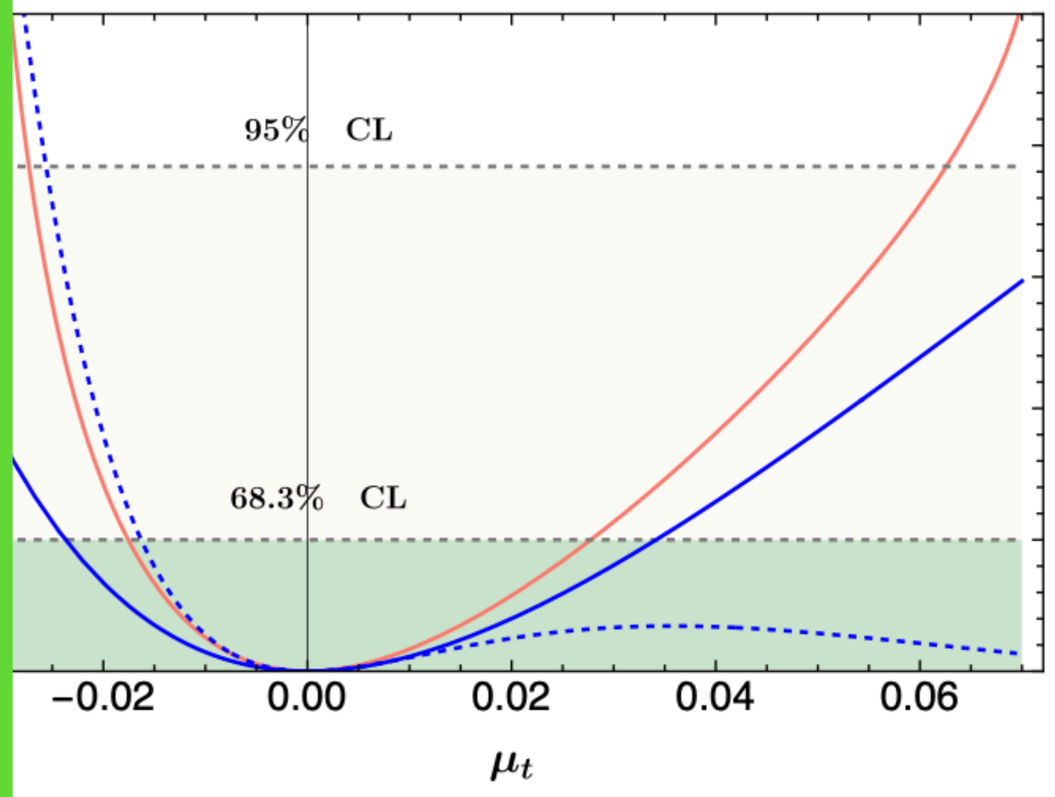




Big picture

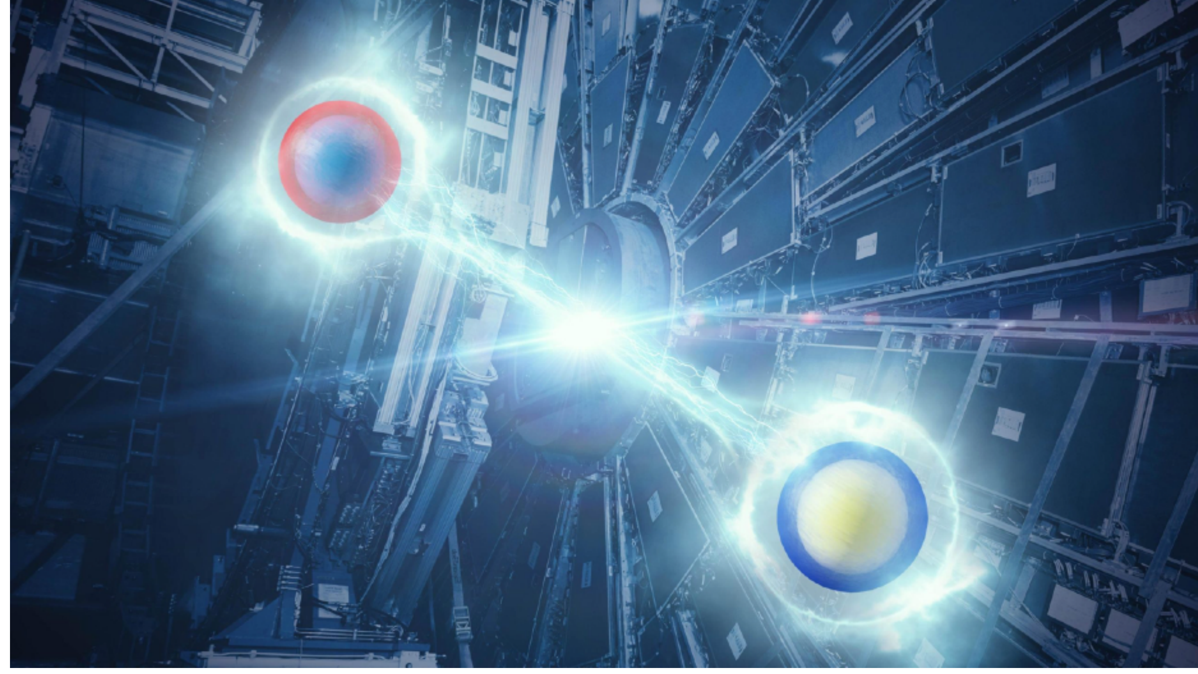
QI presents new tools to study fundamental interactions at colliders. Known case studies showing promising results, achieving superior precision over traditional observables.

A lot of work still to do to develop these tools!



M. Fabbrichesi, M. Low, L. Marzola Phys.Rev.D 112 (2025) 1, 013003

A quantum lens on collider physics



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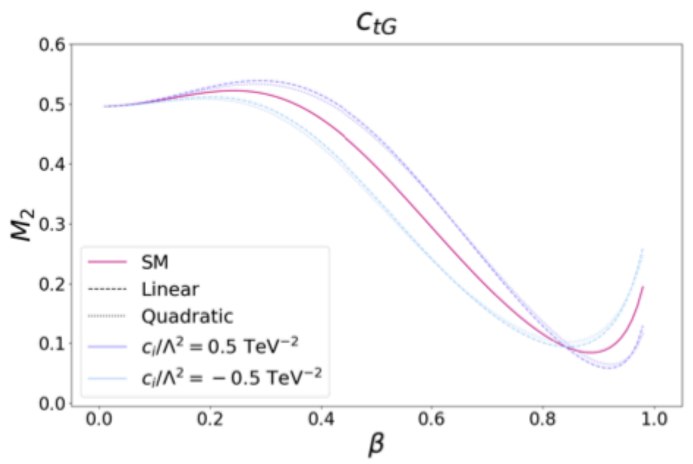

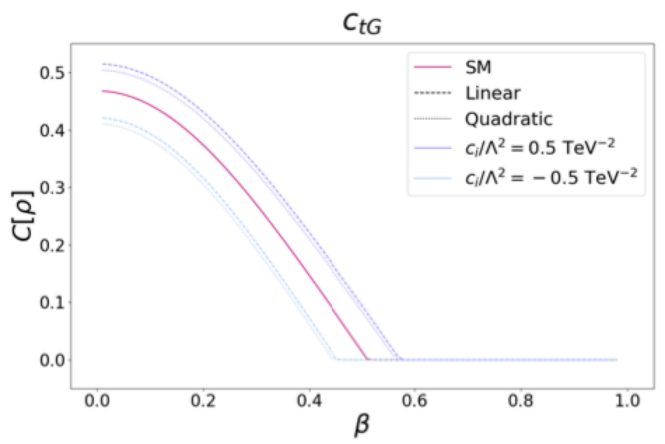

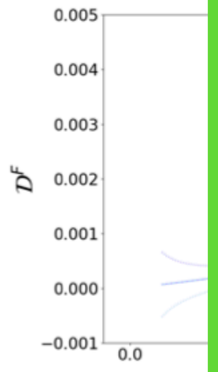

Big picture

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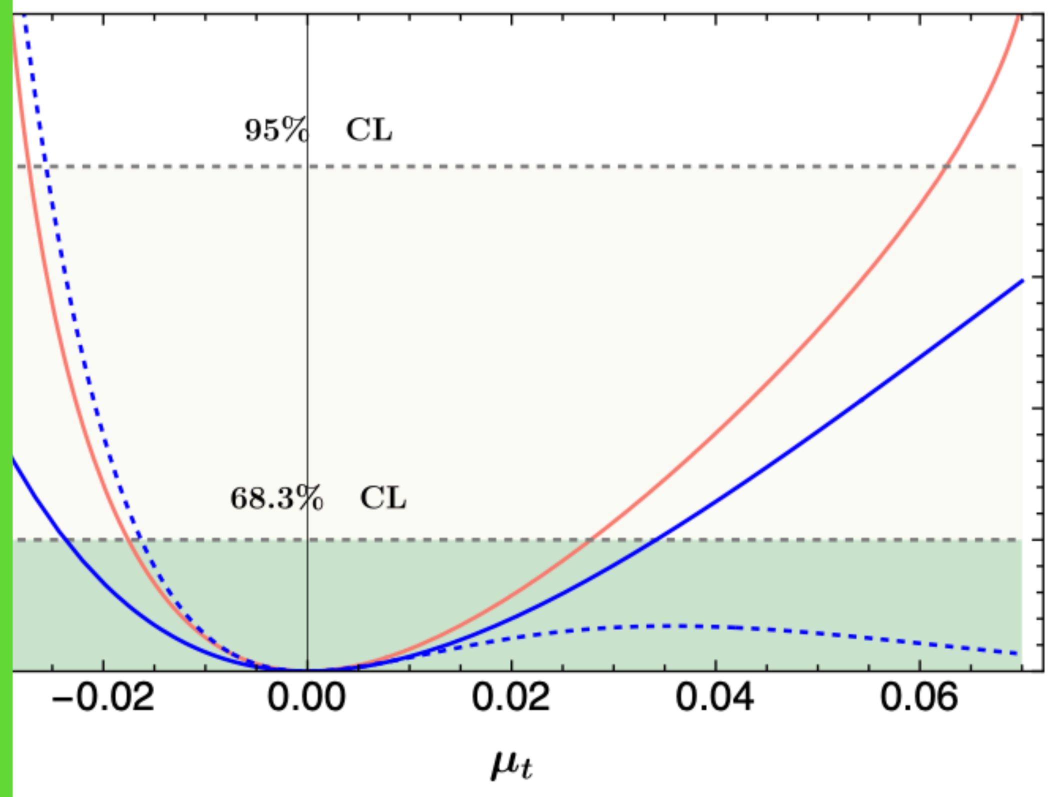
A lot of work still to do to develop these tools!

Building new territory to explore principles of QI, interesting/useful scientific effort itself



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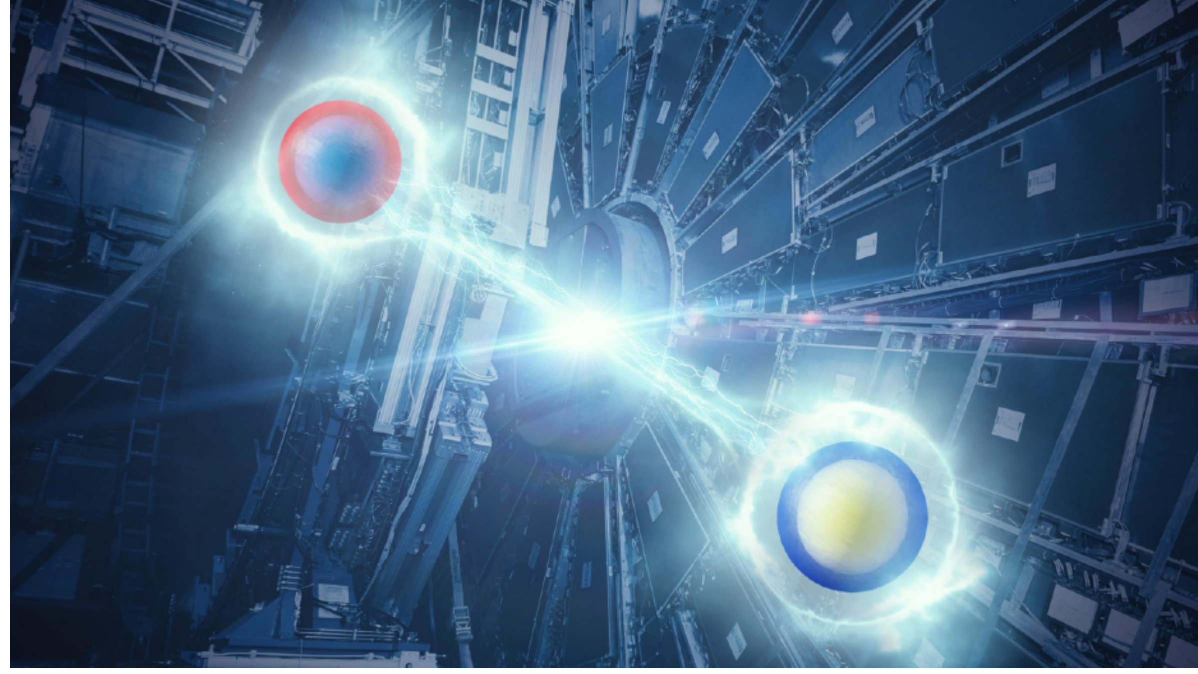


Experimental status:

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Nature 633 (2024) 542
DOI: 10.1038/s41586-024-07824-z

CERN-EP-2023-230
October 3, 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration

Entanglement is a key feature of quantum mechanics [1–3], with applications in fields such as metrology, cryptography, quantum information, and quantum computation [4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic [9–13] to the macroscopic [14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a center-of-mass energy of $\sqrt{s}$ = 13 TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modeling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) $\pm$ 0.019 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

CMS

CMS-TOP-23-001

CERN-EP-2024-137
2024/10/30

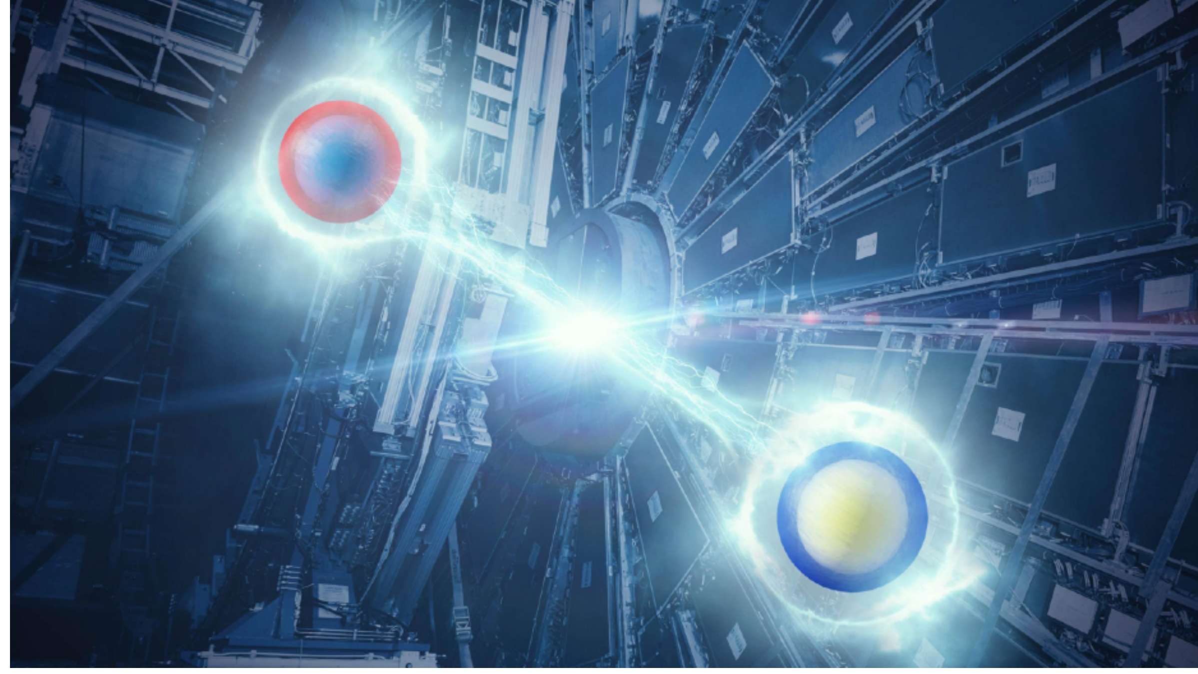
Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

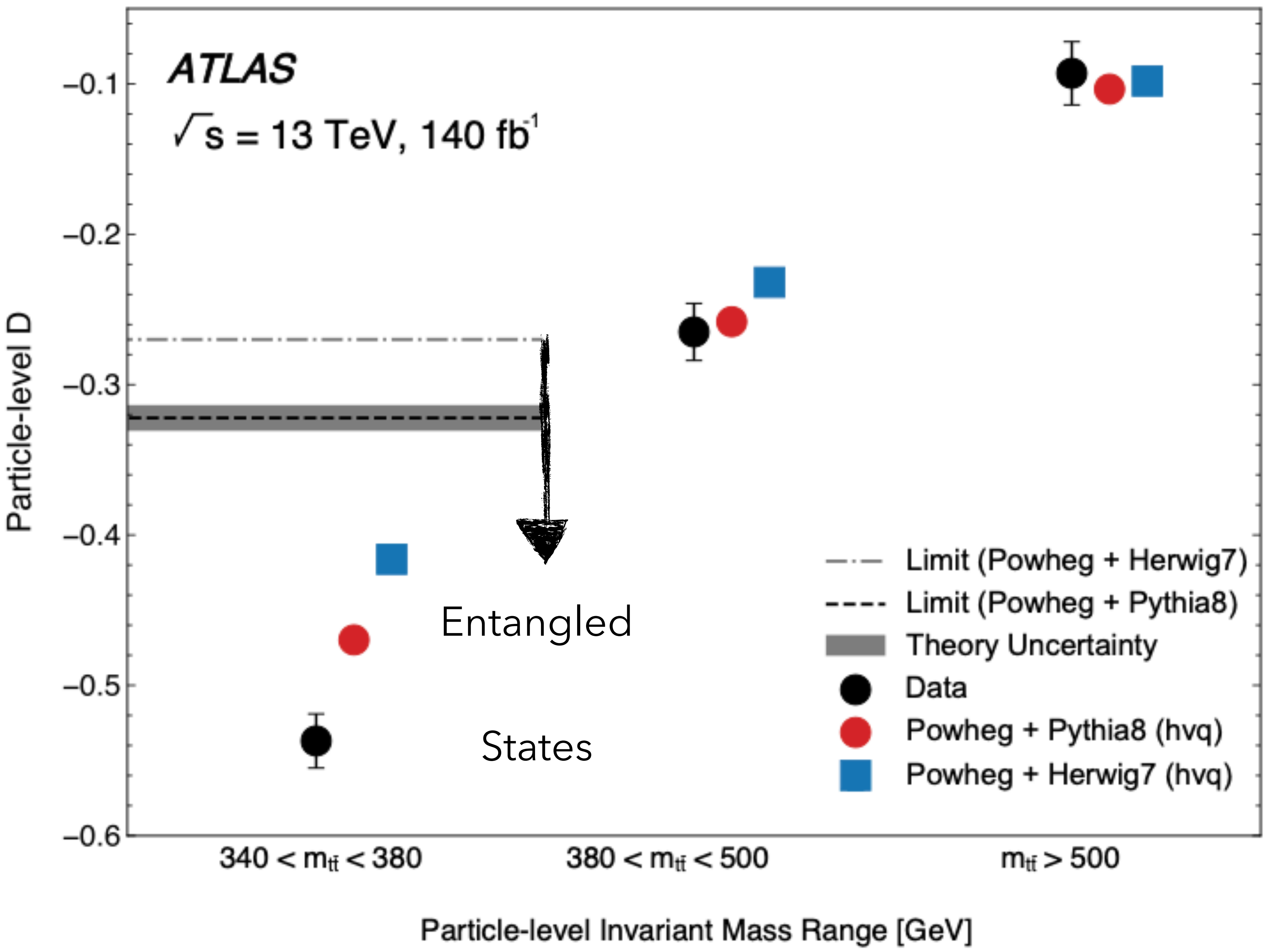
Entanglement is an intrinsic property of quantum mechanics and is predicted to be exhibited in the particles produced at the Large Hadron Collider. A measurement of the extent of entanglement in top quark-antiquark ($t\bar{t}$) events produced in proton-proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of 36.3 fb^{-1}. The events are selected based on the presence of two leptons with opposite charges and high transverse momentum. An entanglement-sensitive observable D is derived from the top quark spin-dependent parts of the $t\bar{t}$ production density matrix and measured in the region of the $t\bar{t}$ production threshold. Values of $D < -1/3$ are evidence of entanglement and D is observed (expected) to be $-0.480^{+0.026}_{-0.029}$ ($-0.467^{+0.026}_{-0.029}$) at the parton level. With an observed significance of 5.1 standard deviations with respect to the non-entangled hypothesis, this provides observation of quantum mechanical entanglement within $t\bar{t}$ pairs in this phase space. This measurement provides a new probe of quantum mechanics at the highest energies ever produced.

A quantum lens on collider physics

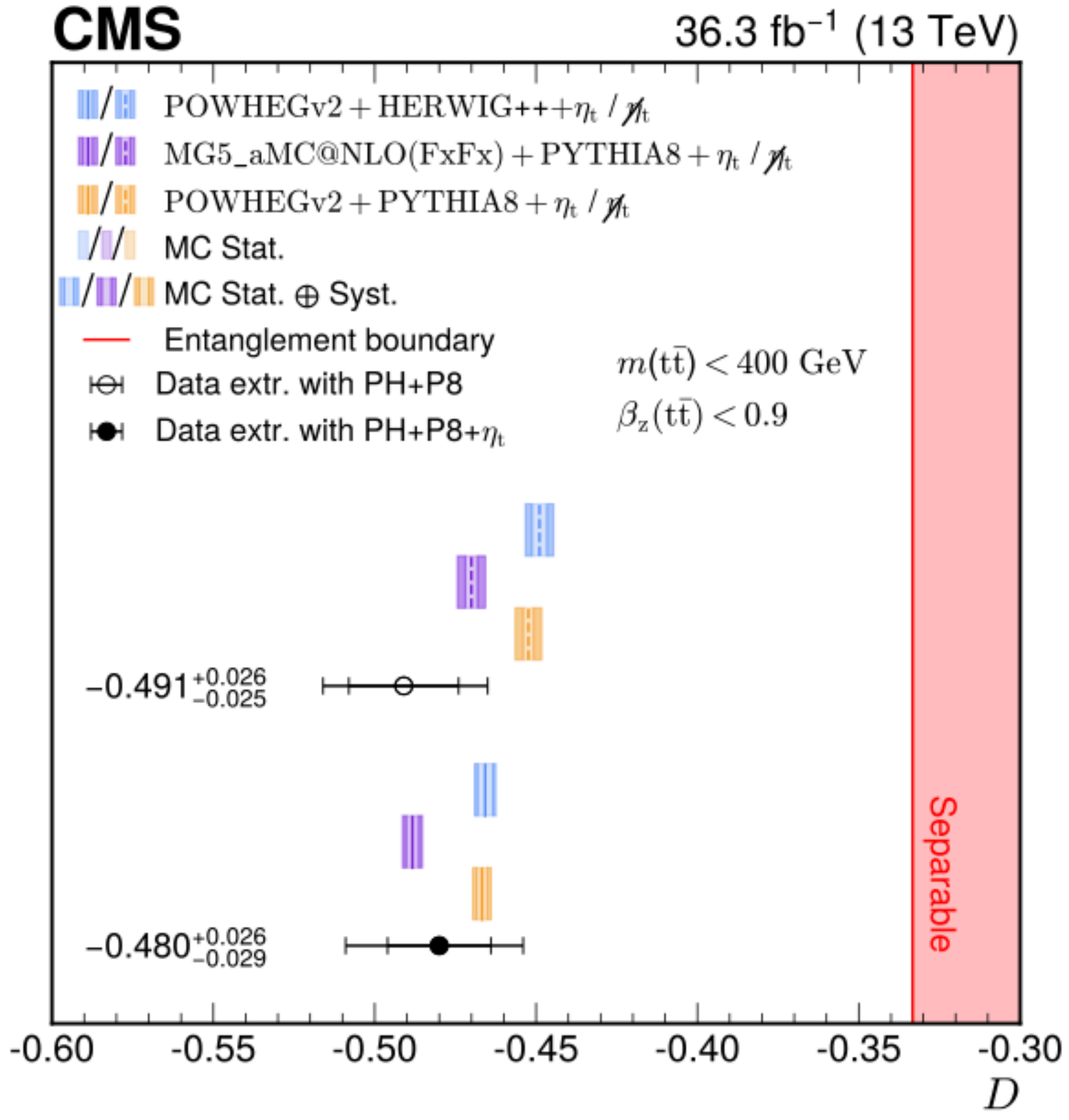


Experimental status:

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



CERN-EP-2024-137
2024/10/30



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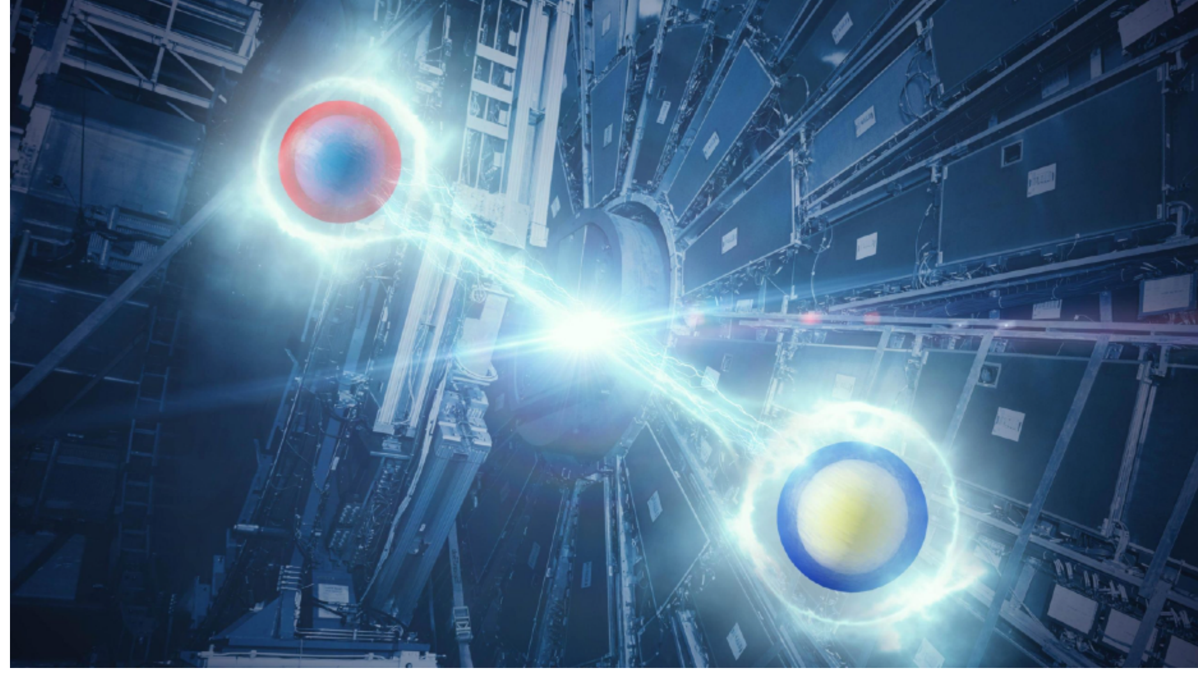


For anyone interested:

- **Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics,** arXiv:2504.00086 [hep-ph]

- **Quantum entanglement and Bell inequality violation at colliders,** arXiv:2402.07972 [hep-ph]

$pp \to t\bar{t}$ (Primary focus so far)

$pp \to \tau\bar{\tau}$

$pp \to W^+W^-, ZZ$

$pp \to h \to \gamma\gamma$

Many other works already exploring possibilities for proposed future colliders!

Many fundamental questions remain in the Standard Model

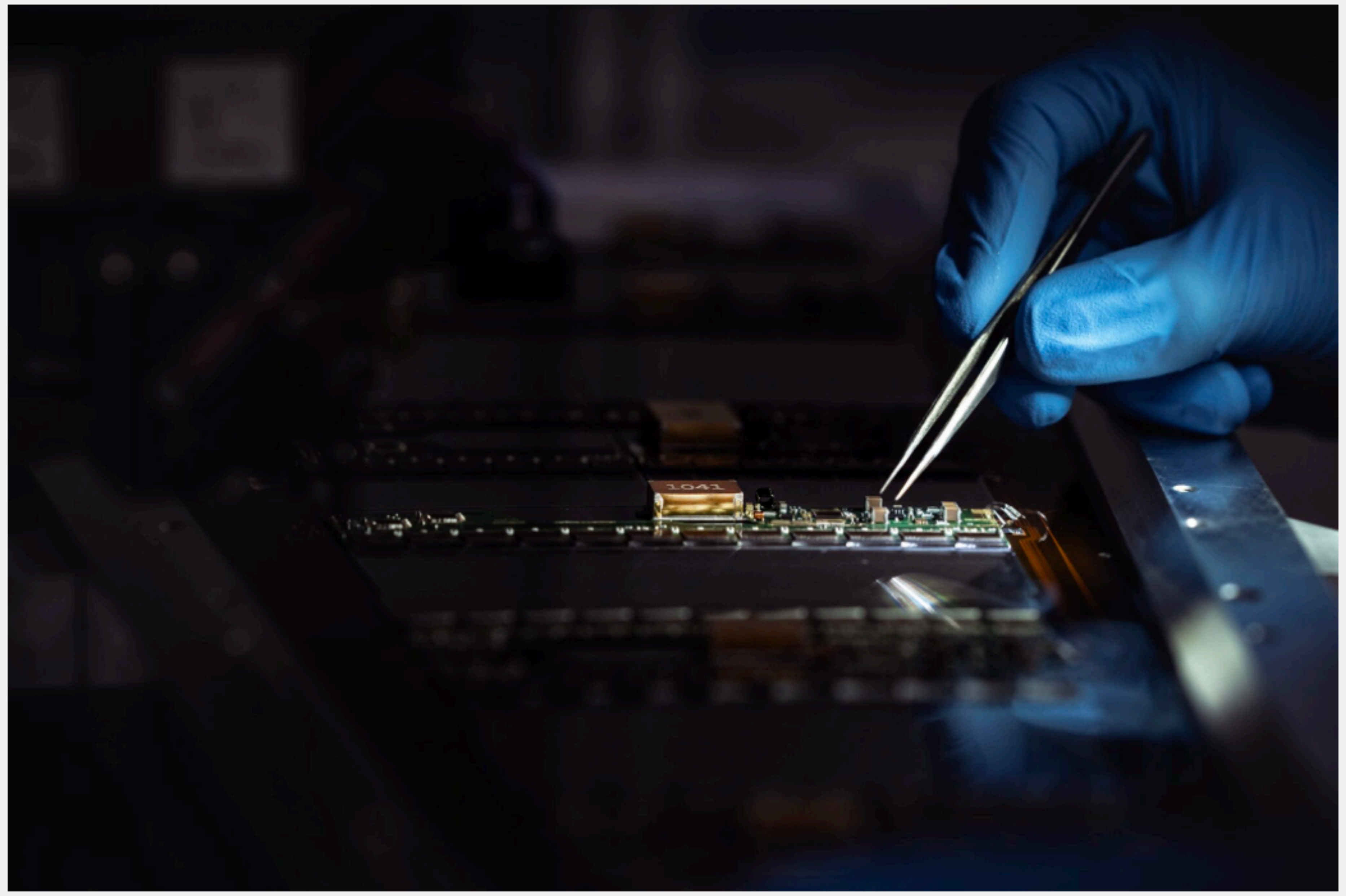
- Answering some of those questions will require a new generation of high-energy colliders, but this program is decades in the making

- In the meantime, should explore new ideas to make the most out of our time and efforts, ML, QI, etc.

- Many directions to develop, exciting time to do ground-floor work!

TRIUMF-ATLAS team shares in major Breakthrough Prize in Fundamental Physics

April 10, 2025 | Stu Shepherd



https://triumf.ca/2025/04/10/triumf-atlas-team-shares-in-major-breakthrough-prize-in-fundamental-physics/