Beyond the SM Physics

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ICISE, Quy Nhon, Viet Nam

Outline

- Status
- New Physics Extensions: general remarks
- Specific New Physics extensions: guidelines, constraints
- The 2-Higgs Doublet Model: the Higgs sector
- Coming back to the constraints: detailed discussion
- A little bit of Higgs phenomenology: Higgs production and decay channels
- Supersymmetry: Basics


Status
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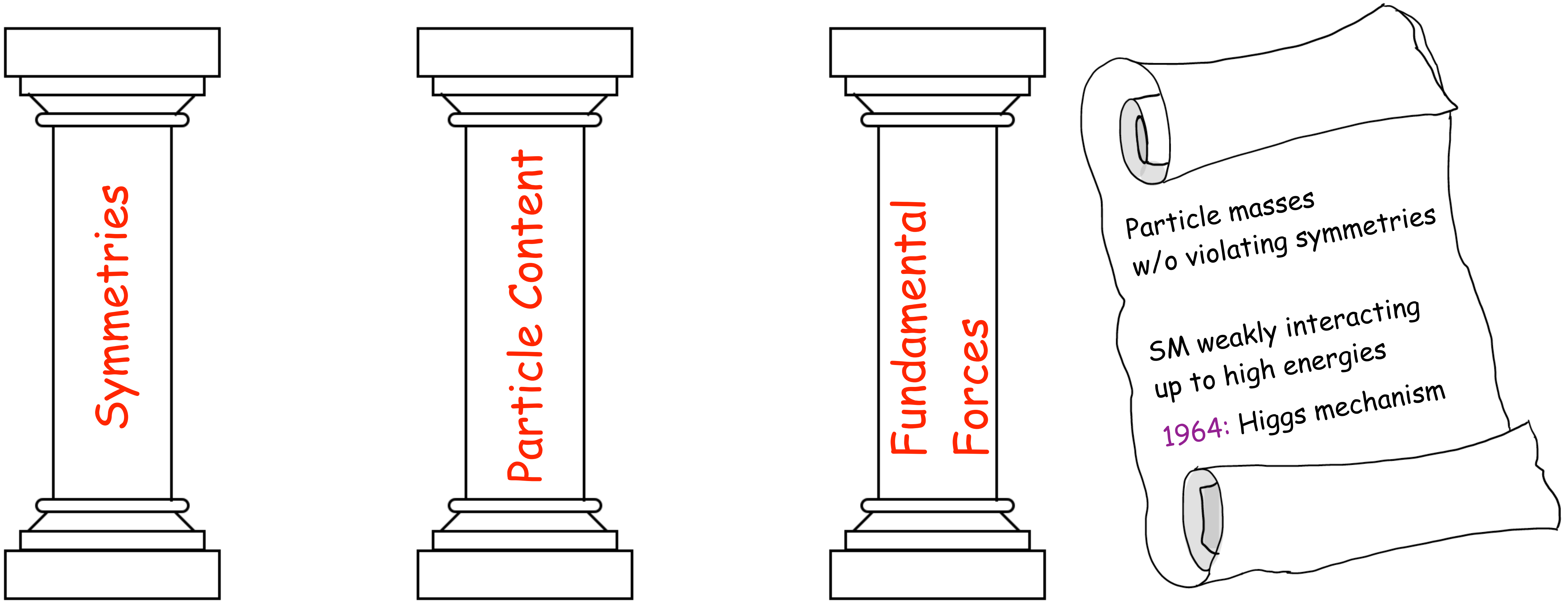
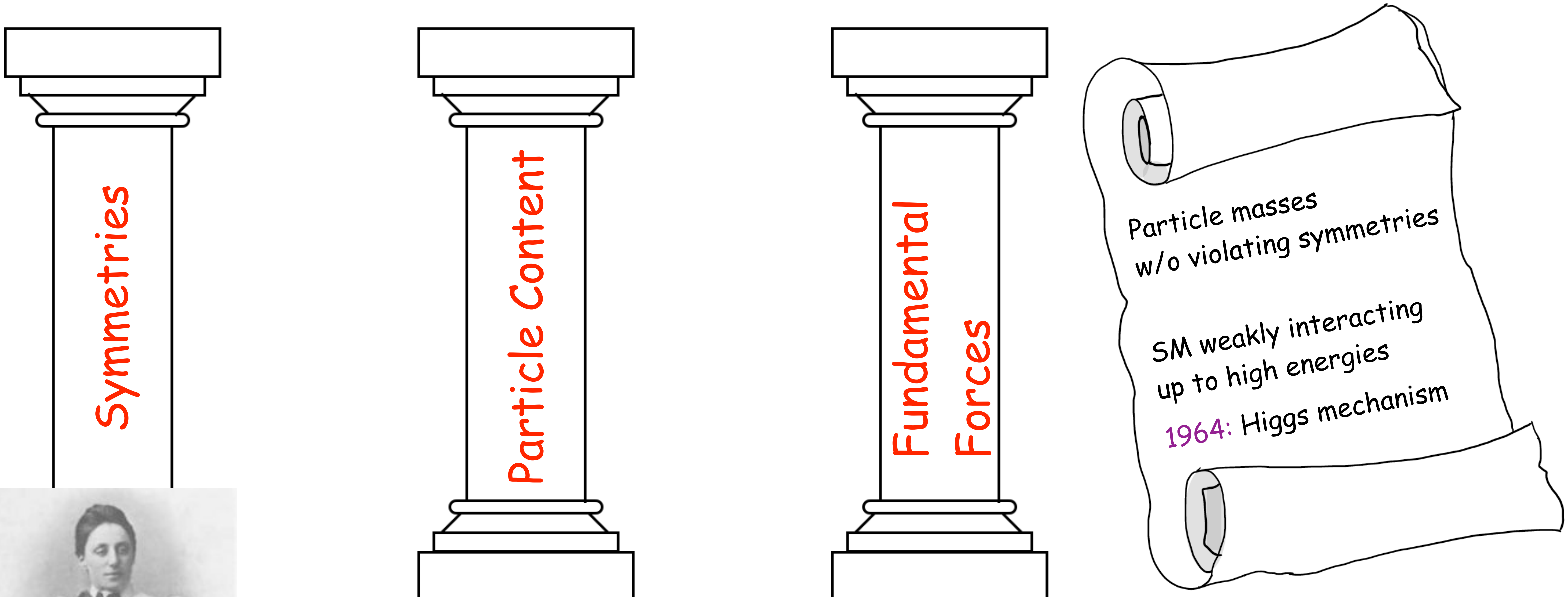
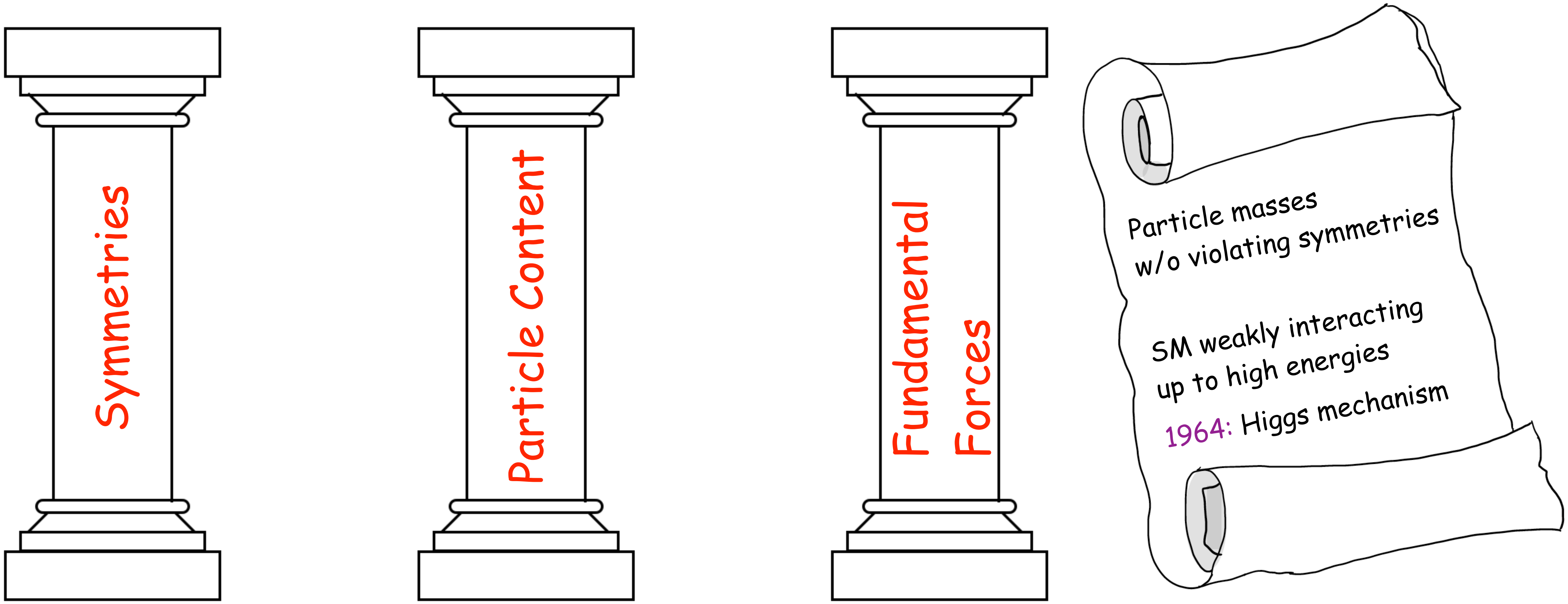
The Four Pillars of the Standard Model




Symmetries
Particle Content
Fundamental Forces
Particle masses
w/o violating symmetries
SM weakly interacting
up to high energies
1964: Higgs mechanism

The Four Pillars of the Standard Model



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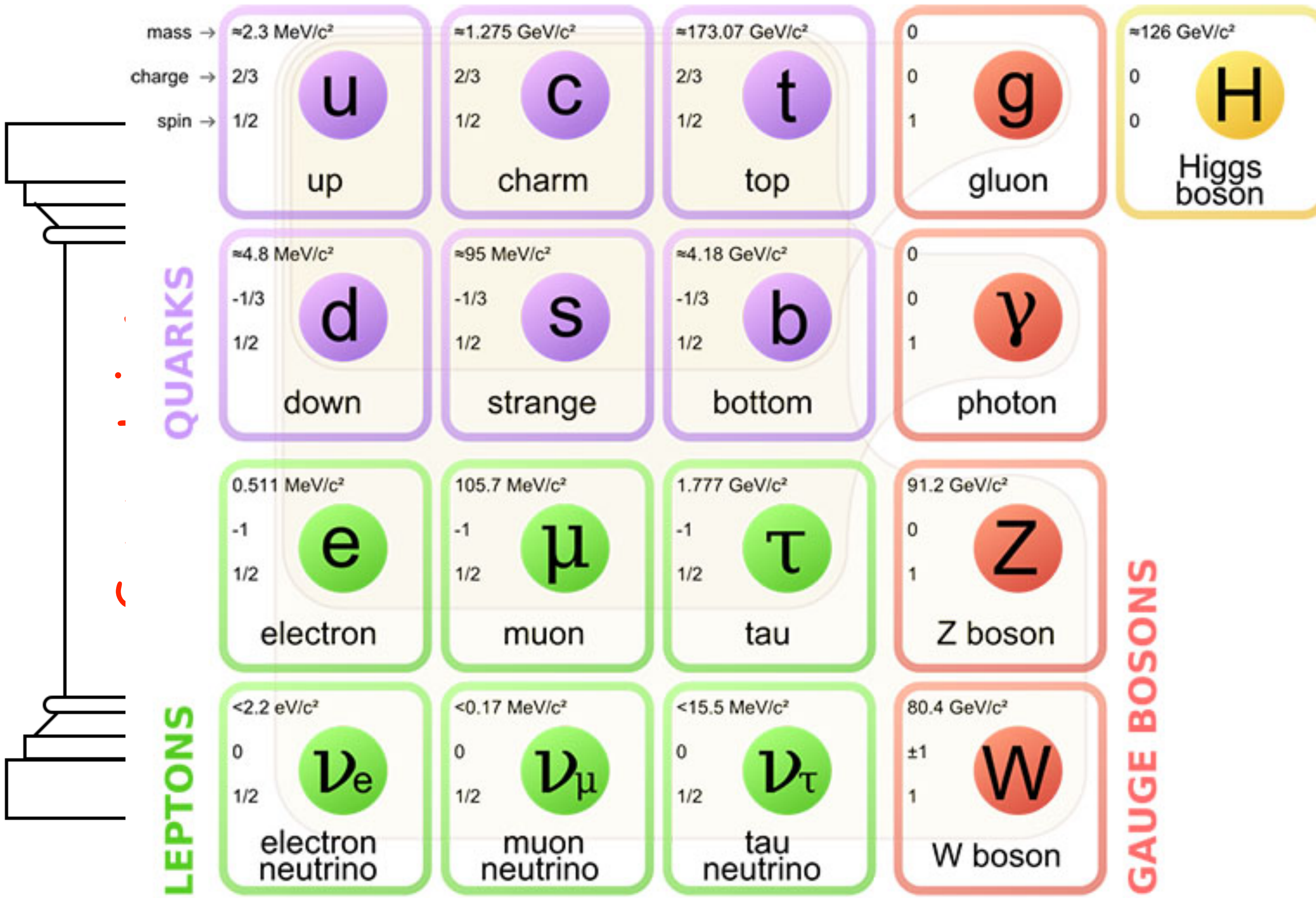

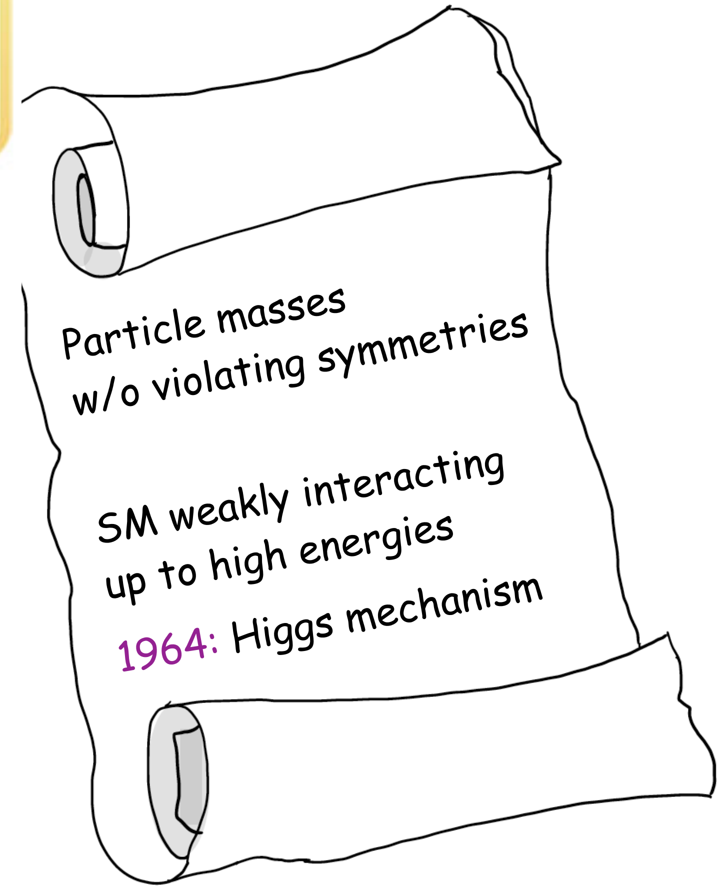

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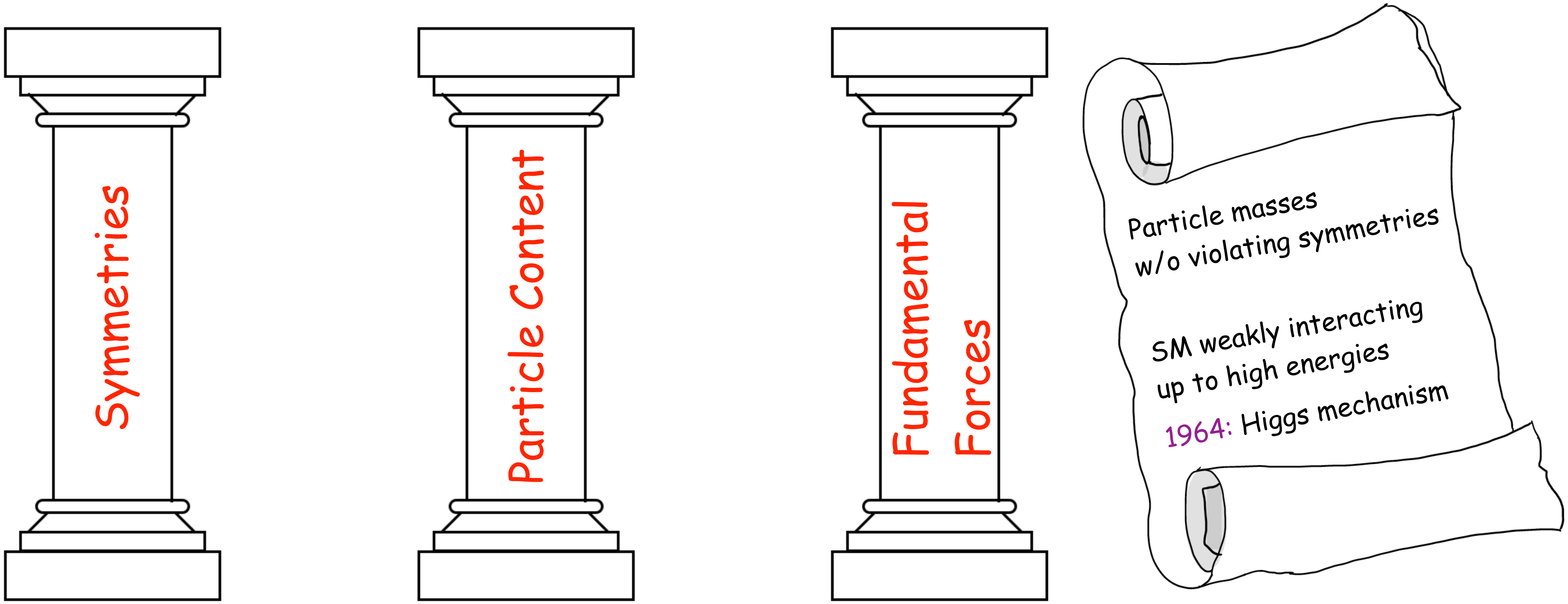

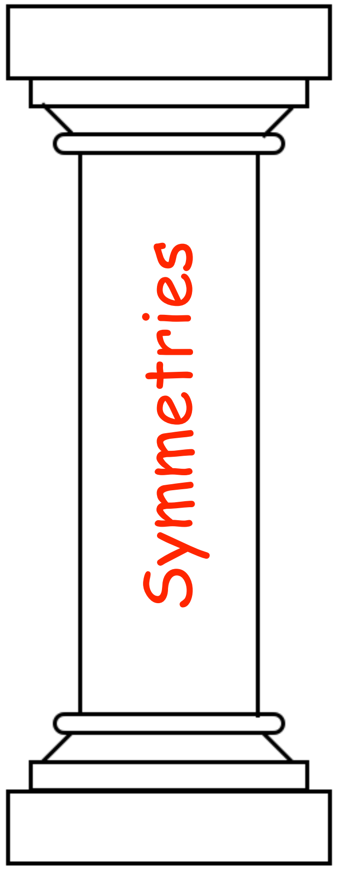
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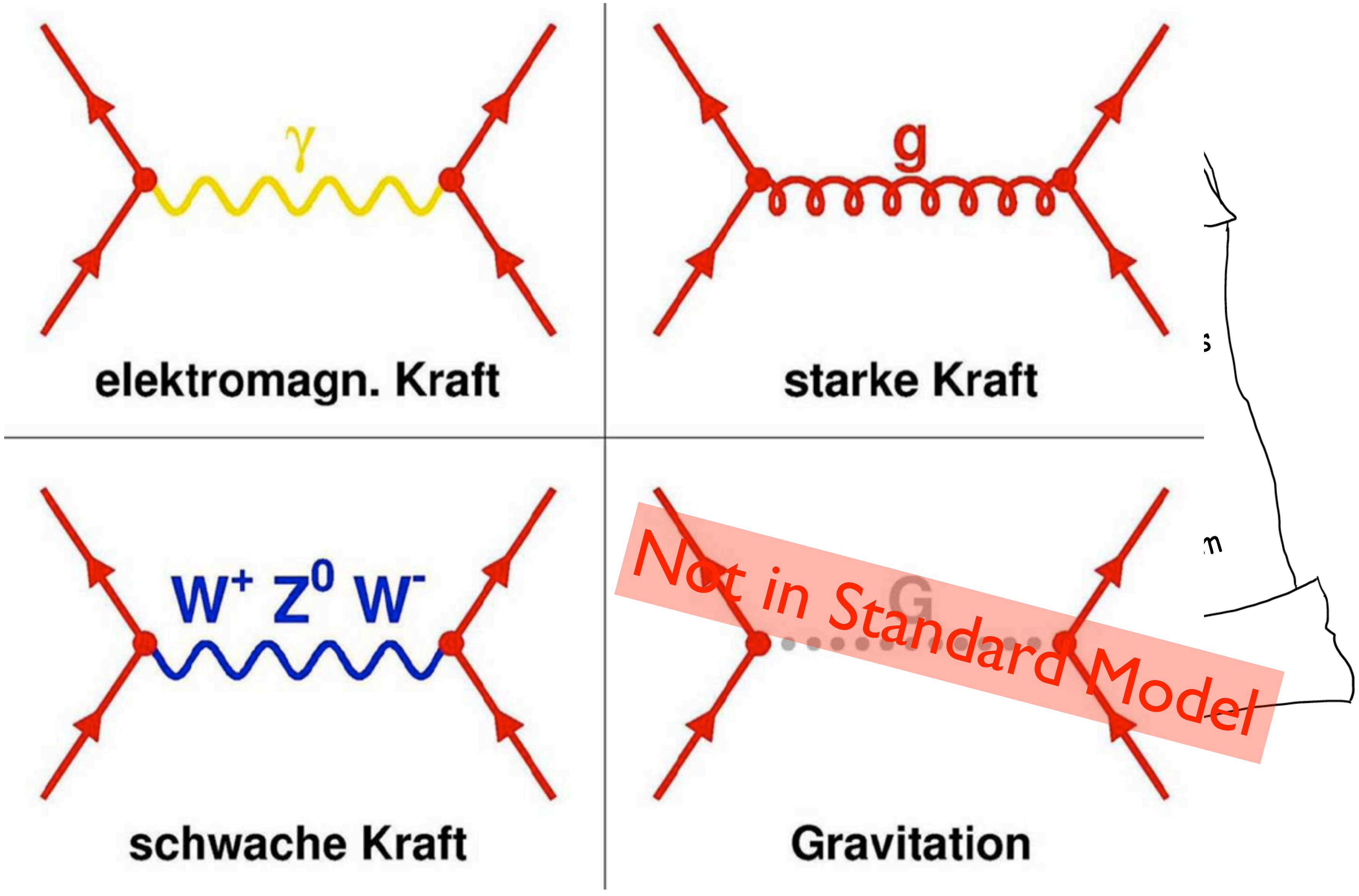
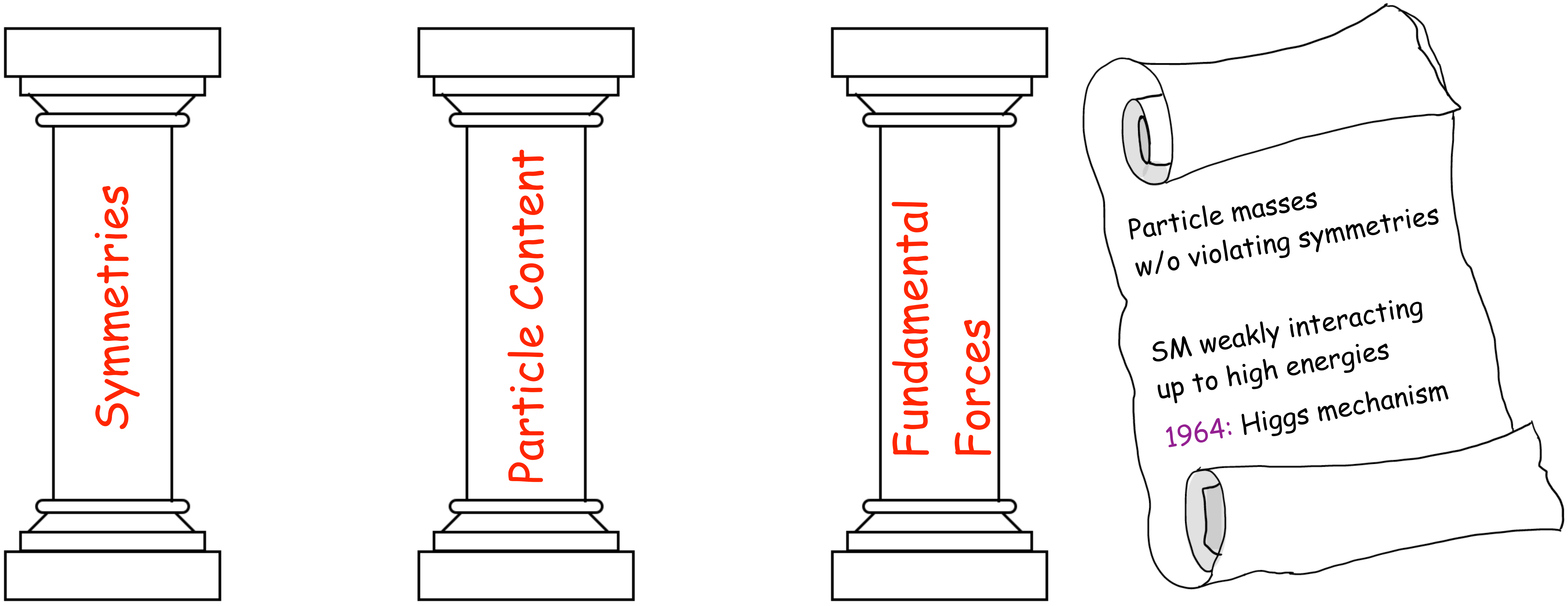
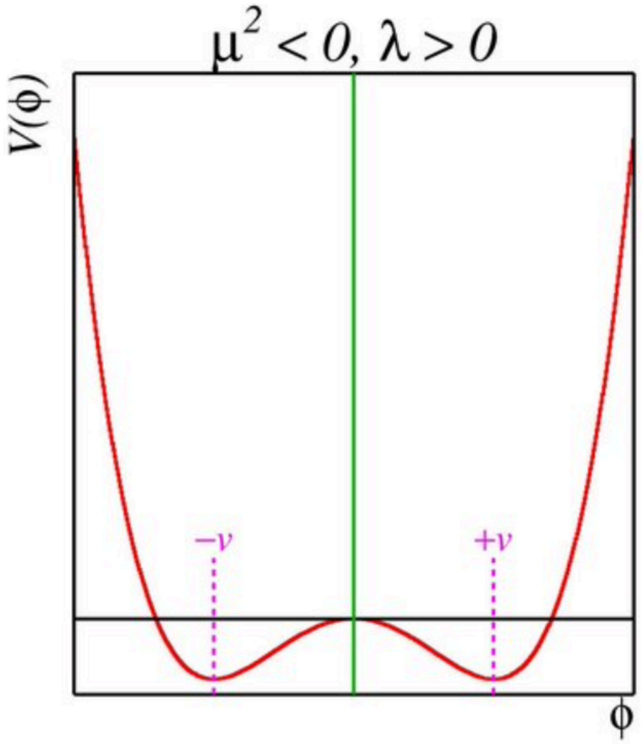

γ
elektromagn. Kraft
g
starke Kraft
W⁺ Z⁰ W⁻
schwache Kraft
G
Gravitation
Not in Standard Model

The Four Pillars of the Standard Model



✦ Higgs potential: non-vanishing vacuum expectation value



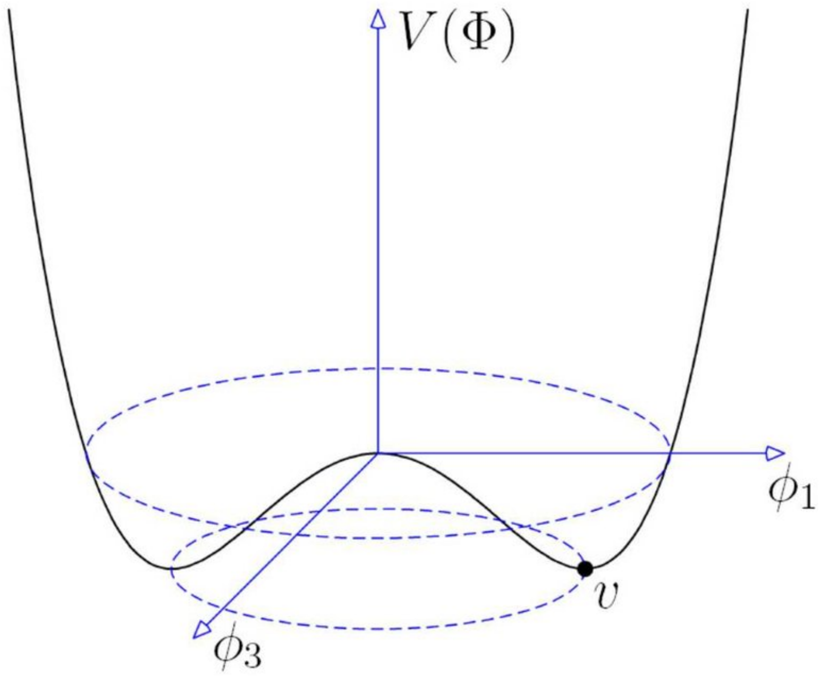
✦ Generation of particle masses: particles couple with Higgs boson in the ground state

mass $\sim g * v$

✦ Spontaneous symmetry breaking: SM symmetry broken by the ground state

✦ Existence of Higgs particle H

✦ Higgs potential: non-vanishing vacuum expectation value



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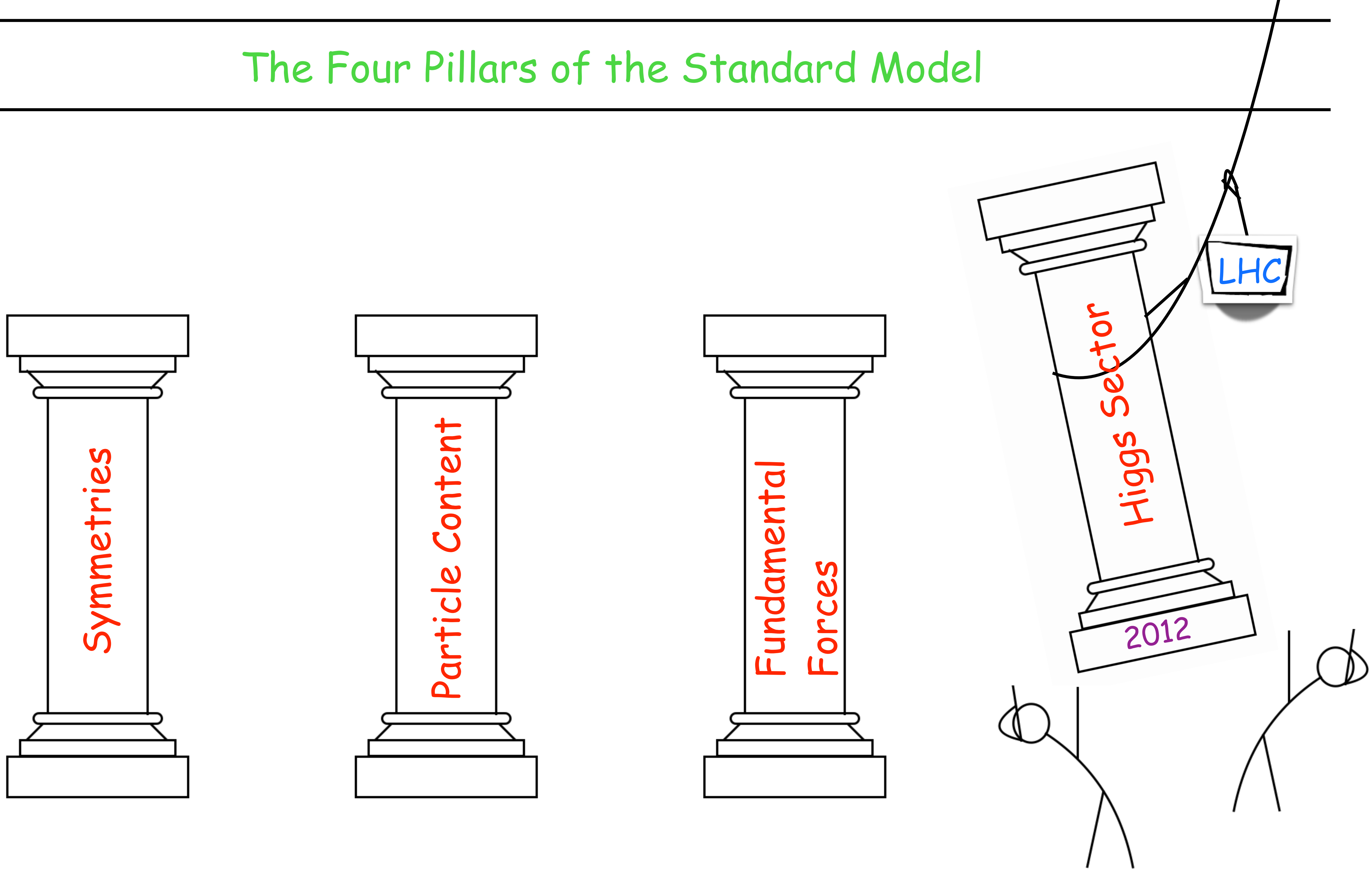
The Four Pillars of the Standard Model



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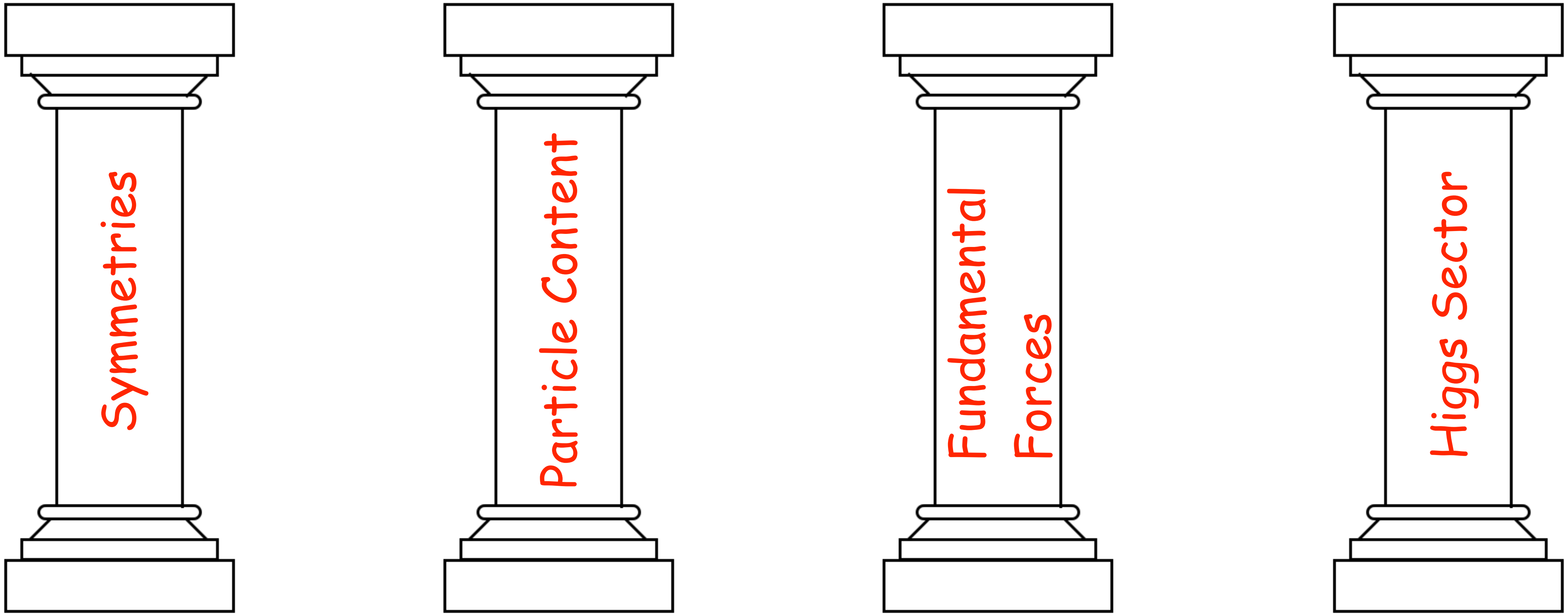
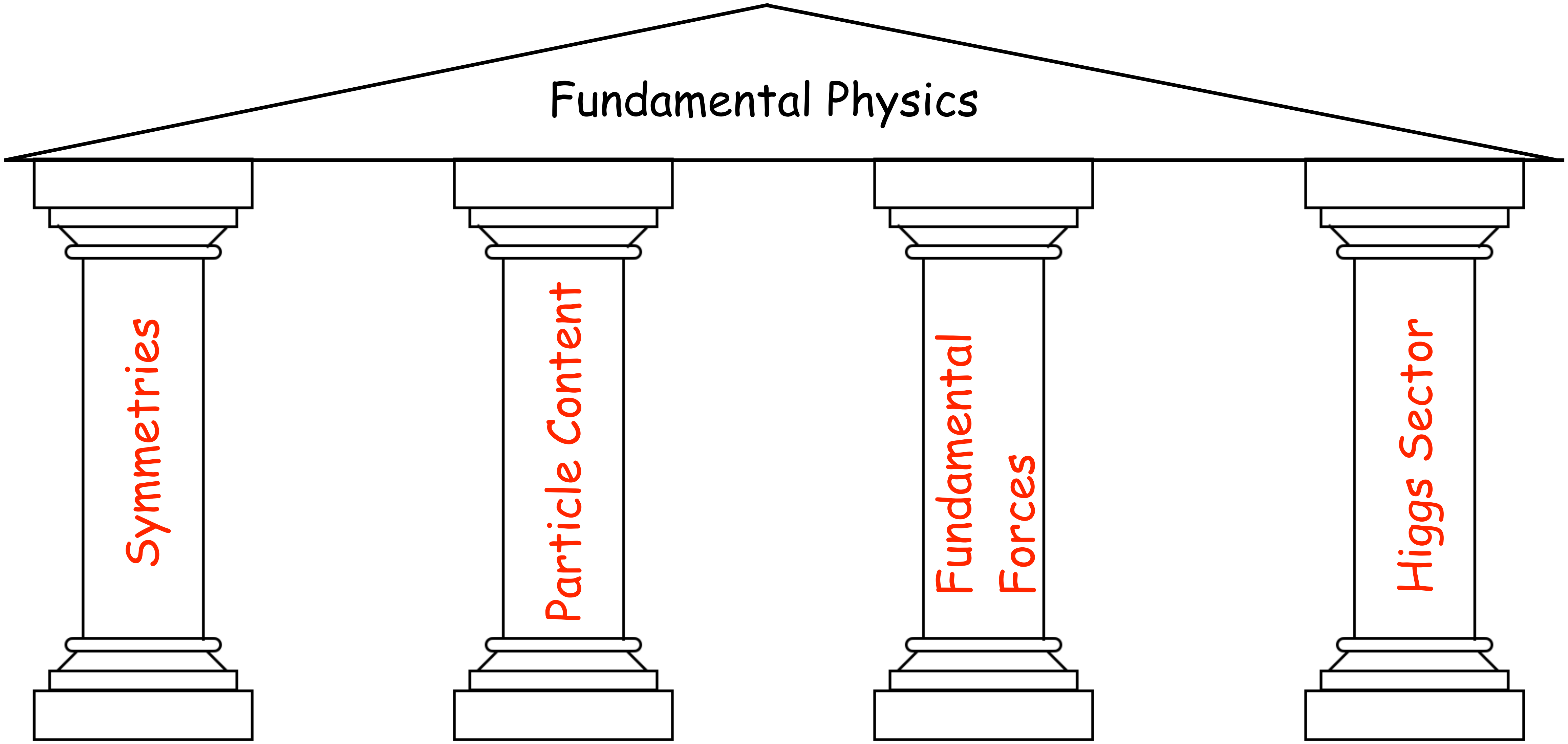


The Standard Model is Structurally Complete



Higgs Discovery: 4.7.2012

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Discovered Particle is the Higgs Boson

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New results indicate that particle discovered at CERN is a Higgs boson

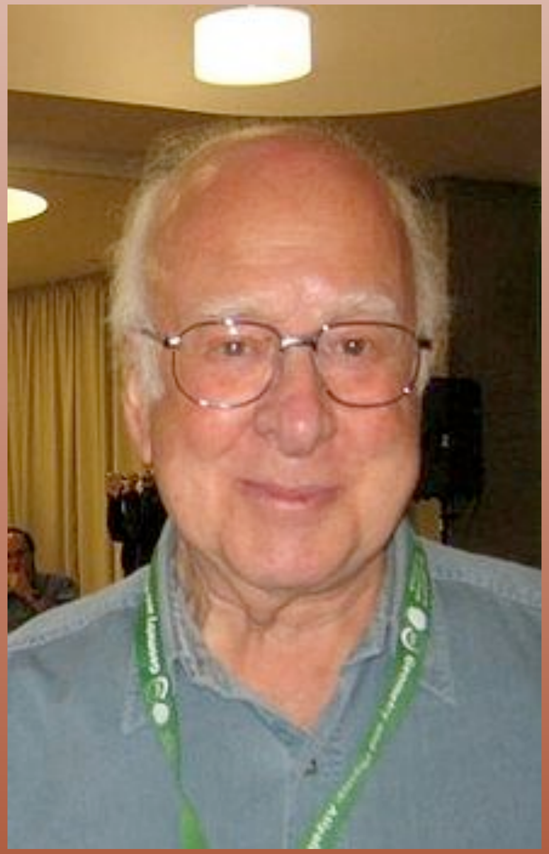
14 Mar 2013

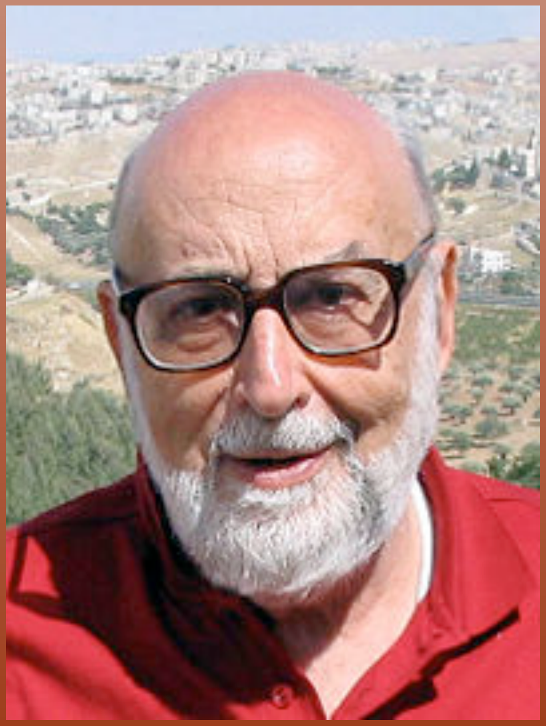
Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Whether or not it is a Higgs boson is demonstrated by how it interacts with other

1964

Brout-Englert-Higgs-Mechanismus





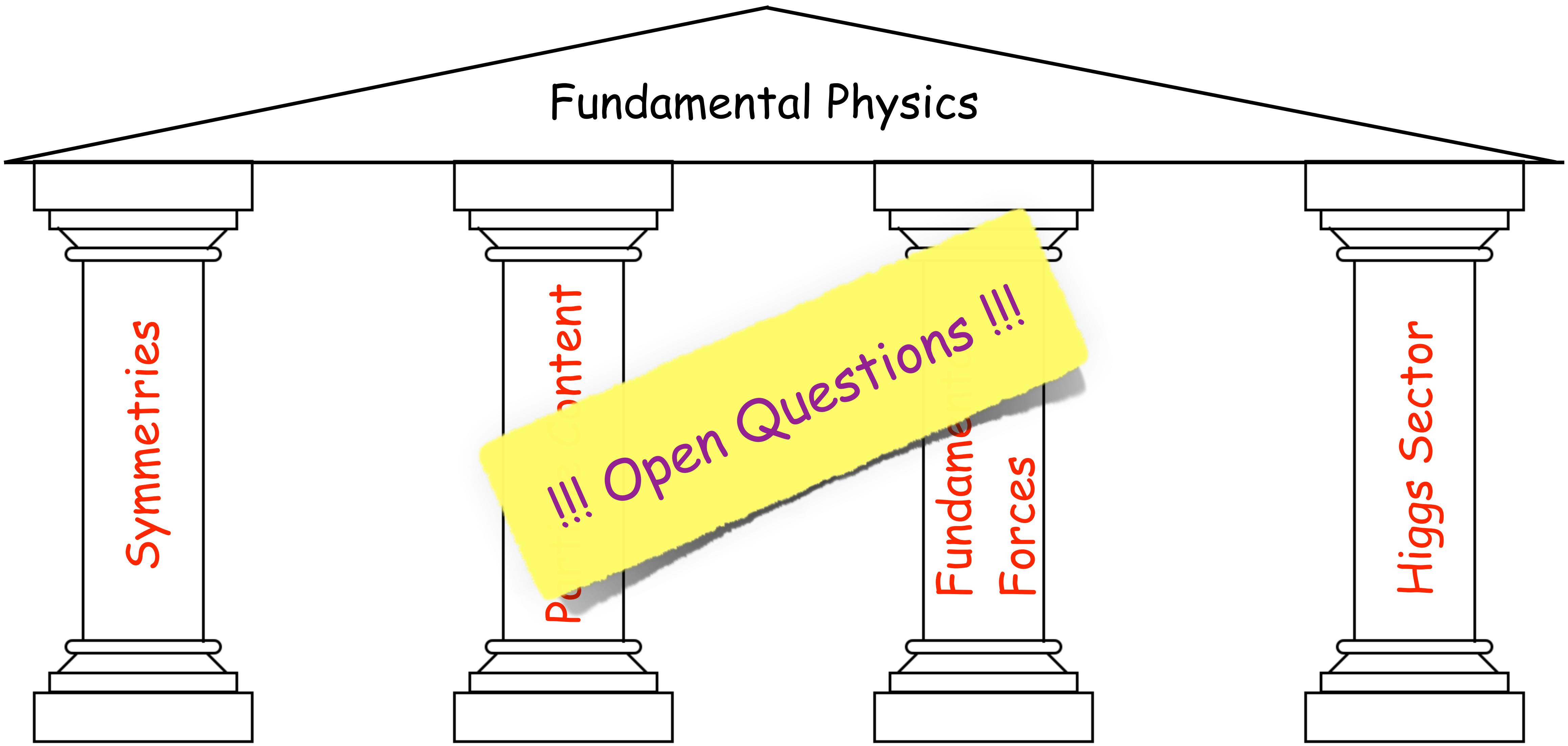
1964
Brout-Englert-Higgs-Mechanismus

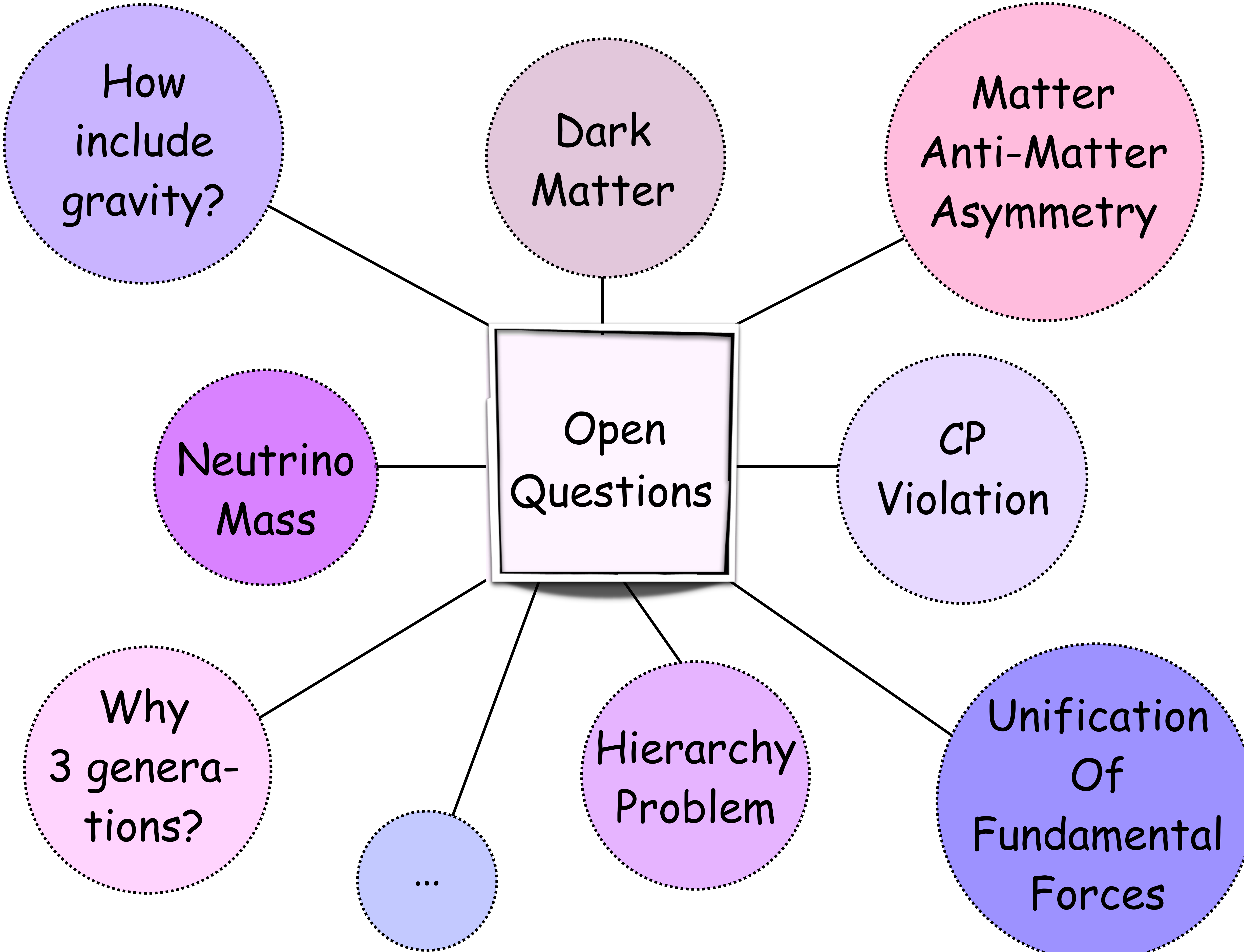
Physik Nobelpreis 2013

Higgs 10th Birthday!

Higgs 10th Birthday!

The Standard Model is Structurally Complete - But




Open Questions
How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
CP Violation
Why 3 genera-tions?
...
Hierarchy Problem
Unification Of Fundamental Forces

Hierarchy Problem

Consider QED

$$\mathcal{L} = i\bar{\Psi}\gamma_\mu D^\mu \Psi - m\bar{\Psi}\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad (1)$$

with the covariant derivative

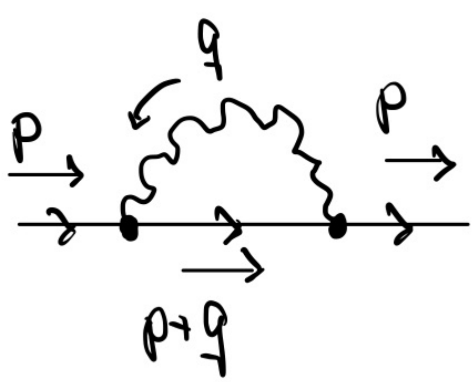
$$D_\mu = \partial_\mu + ieA_\mu(x) \qquad (2)$$

↑ └ Vector potential
coupling constant

field strength tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad (3)$$

Quantum corrections to the fermion mass: Λ cut-off scale ; $\alpha = \frac{e^2}{4\pi}$



$$\delta m \sim \alpha \int^\Lambda \frac{d^4q}{(2\pi)^4} \frac{(\not{p}+\not{q})}{q^2 (p+q)^2} \sim \alpha \int^\Lambda |q|^3 dq \frac{1}{q^3} \sim \alpha \int^\Lambda dq \sim \alpha\Lambda \qquad (4)$$

exact calculation: $\delta m \sim \alpha m \ln \Lambda$ (5)

Why is $\delta m \sim m$?

Reason: QED Lagrangian has chiral symmetry for $m \to 0$:

$$\psi \to e^{i\alpha\gamma_5}\psi \quad , \quad \psi^\dagger \to \psi^\dagger e^{-i\alpha\gamma_5} \qquad (6)$$

is violated by $m\bar{\psi}\psi$ as:

$$\bar{\psi} = \psi^\dagger\gamma_0 \to \psi^\dagger e^{-i\alpha\gamma_5}\gamma_0 = \bar{\psi}e^{i\alpha\gamma_5} \quad \text{since } \gamma_0\gamma_5 = -\gamma_5\gamma_0 \qquad (7)$$

$$\rightsquigarrow \quad m\bar{\psi}\psi \to m\bar{\psi}e^{i2\alpha\gamma_5}\psi \qquad (8)$$

$\Rightarrow$ all radiative corrections to m vanish as $m \to 0$ (photon cannot flip the helicity)

$$\Rightarrow \quad \delta m \sim m \ln\frac{\Lambda}{m}$$

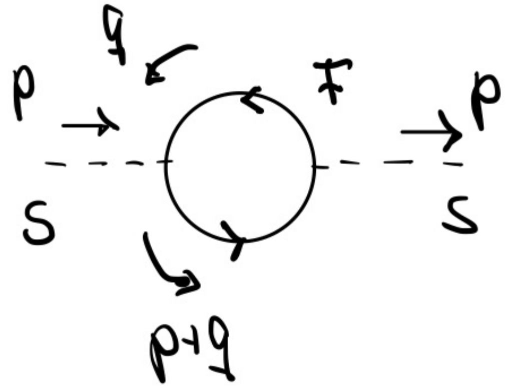
Symmetry protects mass against large radiative corrections.

What about scalars?

$$\mathcal{L} = \bar\Psi(i\not\partial - m_f)\Psi + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_f}{2}\bar\Psi\Psi S \qquad (9)$$

$\not\partial = \partial_\mu \gamma^\mu$, S scalar

quantum correction to scalar mass: dimensional analysis



$$\sim \lambda_f^2 \int^\Lambda \frac{d^4q}{(2\pi)^4} \frac{\not q(\not p + \not q)}{q^2(p+q)^2} \sim \lambda_f^2 \int^\Lambda |q|^3 dq \, \frac{1}{q^2} \sim \lambda_f^2 \int^\Lambda dq \, q$$

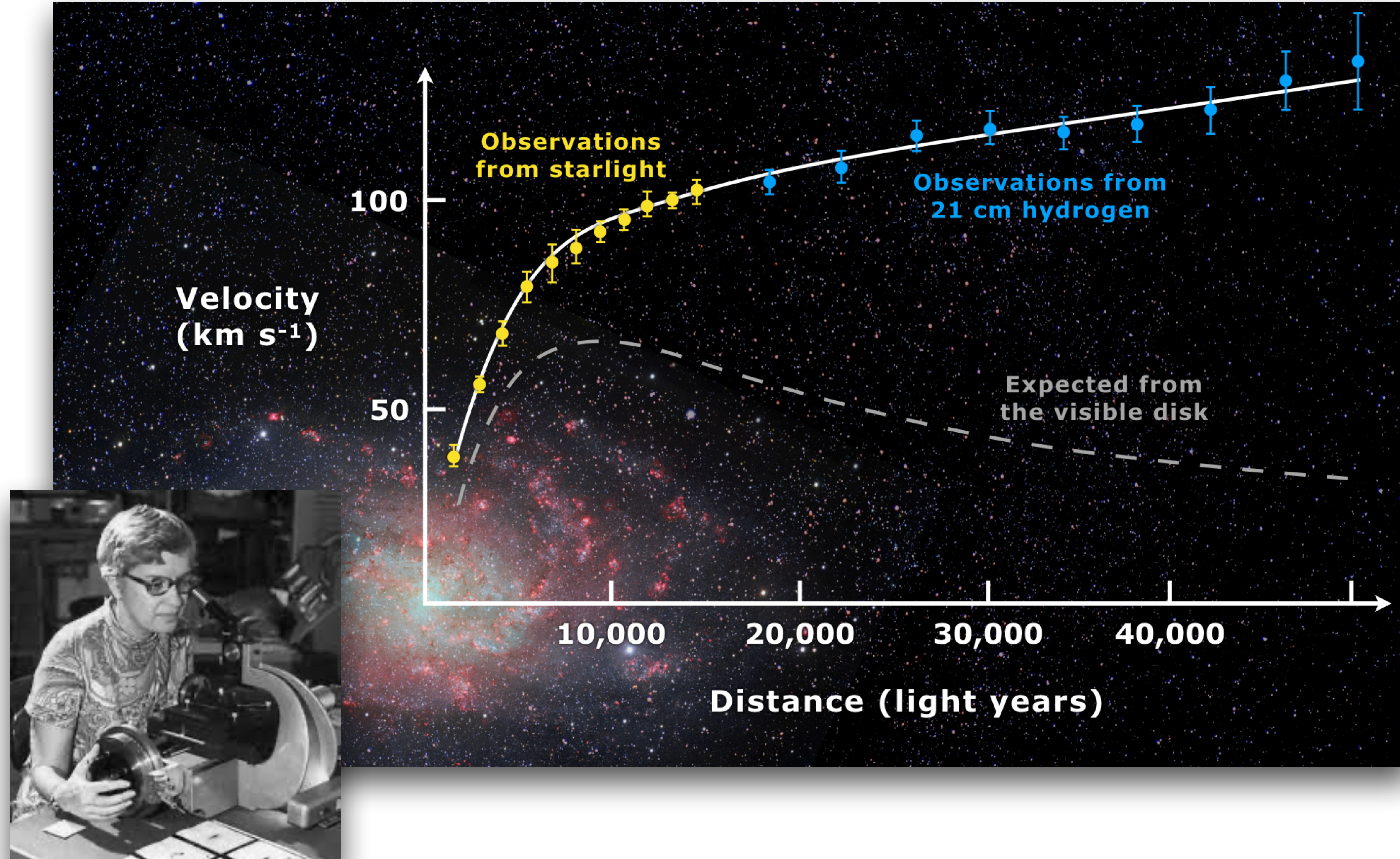
$$\sim \lambda_f^2 \Lambda^2 \qquad (10)$$

$$\delta m_S^2 \sim \lambda_f^2 \Lambda^2 \qquad (11)$$

quadratic divergence

Hierarchy problem?

How can the Higgs boson mass remain of the order of the electroweak scale in the presence of high-energy scales Λ, e.g. the Planck scale in case the SM remains valid up to the Planck scale?



Observations from starlight
Observations from 21 cm hydrogen
100
50
Velocity (km s⁻¹)
Expected from the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

Dark Matter

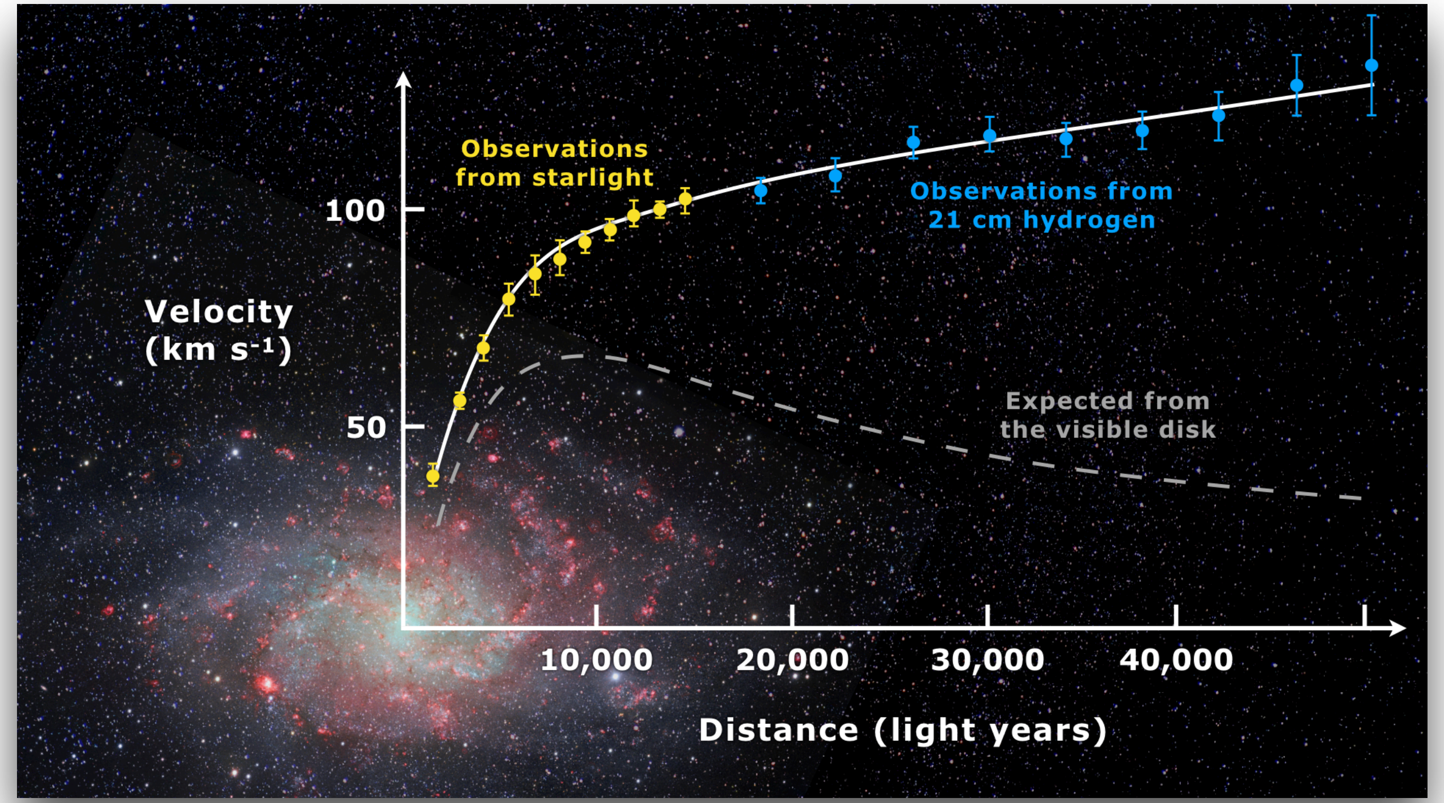
Expectation: centripetal force = gravitational force

$$\frac{m v_r^2}{r} = G \frac{M_r m}{r^2} \quad \rightsquigarrow \quad v_r^2 = G \frac{M_r}{r} \qquad (1)$$

$$\rightsquigarrow \quad v_r = \sqrt{\frac{G M_r}{r}} \quad \rightsquigarrow \quad v_r \sim \frac{1}{\sqrt{r}} \qquad (2)$$

Observation: $v_r (r \geq R_0) \simeq \text{const.}$

$$\rightsquigarrow \quad M_r \sim r \qquad (3)$$

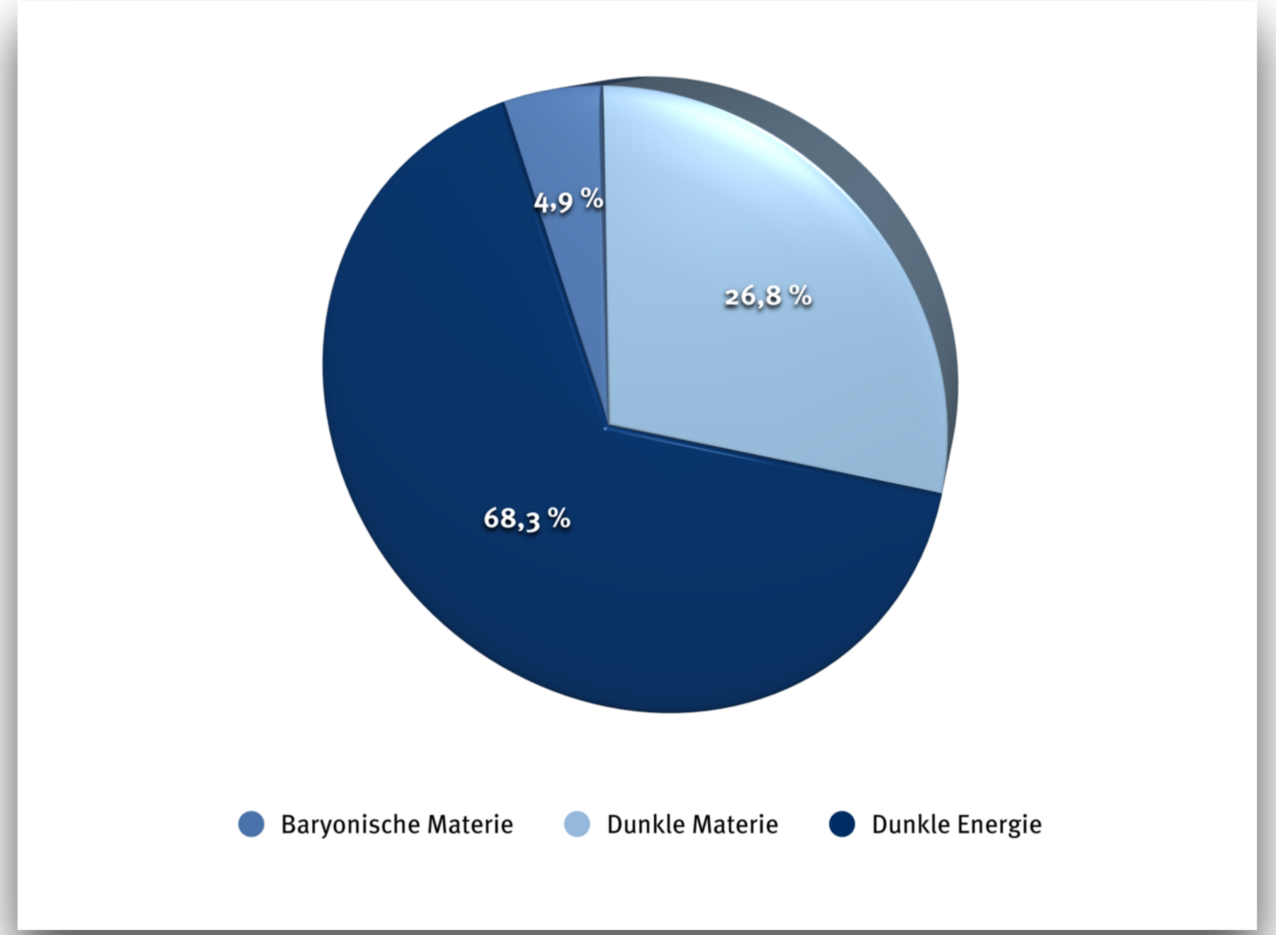


Relic abundance:

Measure for the present quantity of the DM particle remaining from the Big Bang

How much DM do we have?

Dark Matter makes up for 27% of the energy density of the universe,
usual baryonic matter makes up for only 5%!



Matter-Antimatter asymmetry:

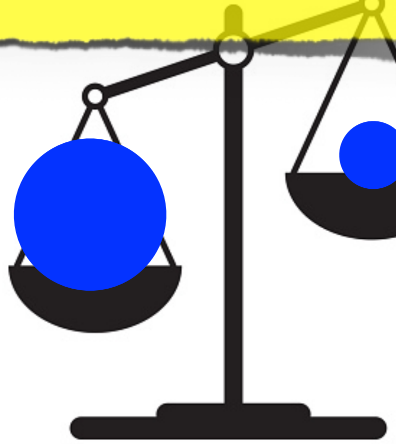
Observation: Dominance of matter over antimatter
=> baryon asymmetry of the Universe (BAU)
Tiny asymmetry: 1 particle more per
1 billion matter-antimatter particles

What is the reason?

- Accidental initial condition of the universe?
  Improbable
- More probable:
  Same amount of matter and antimatter at the beginning of the universe;
  asymmetry was generated **dynamically** during the evolution of the universe
  Theory models for this: **Baryogenesis**

Matter-Antimatter Asymmetry

Why must there obviously be an asymmetry?



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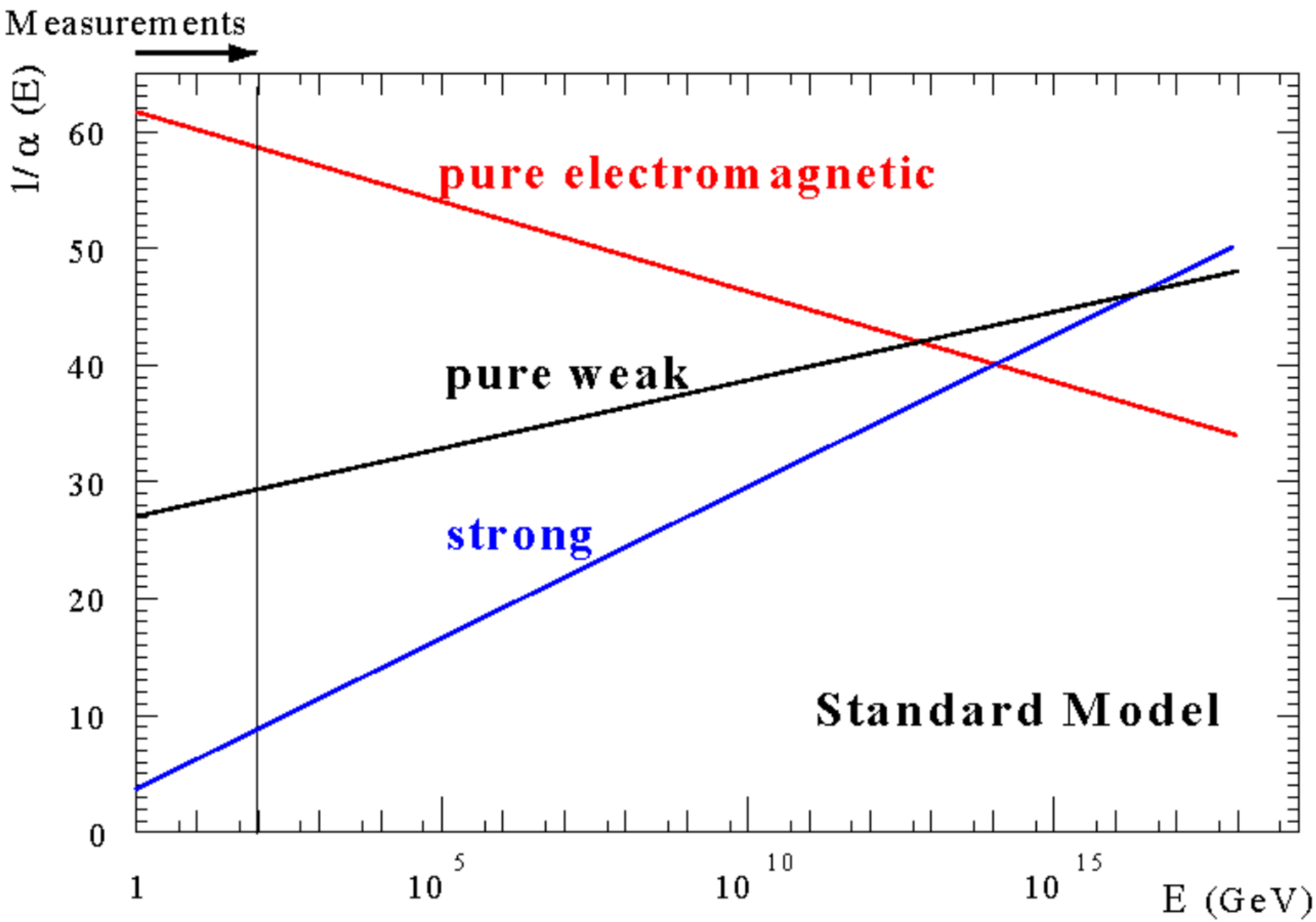
Unification of Fundamental Forces!



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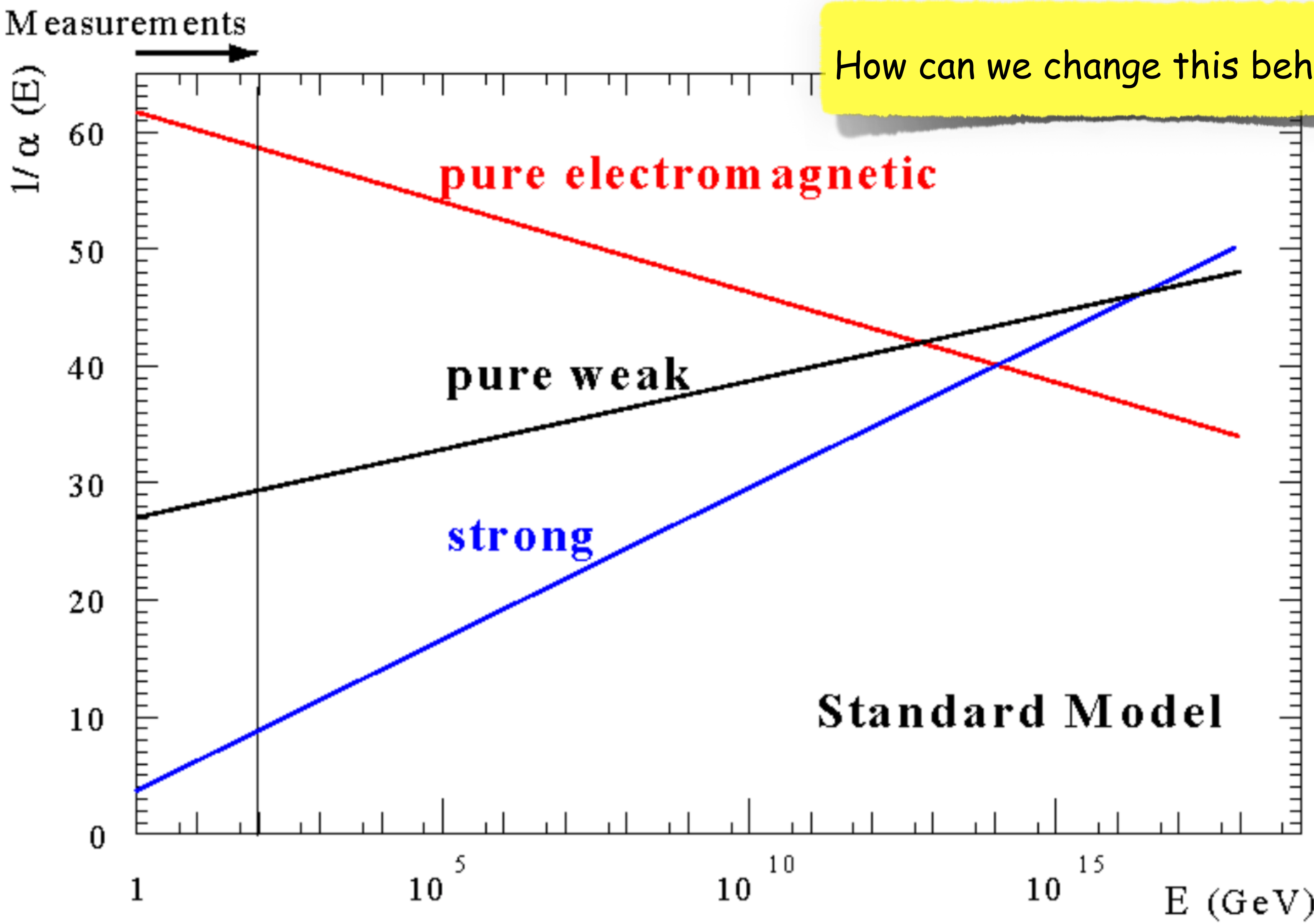
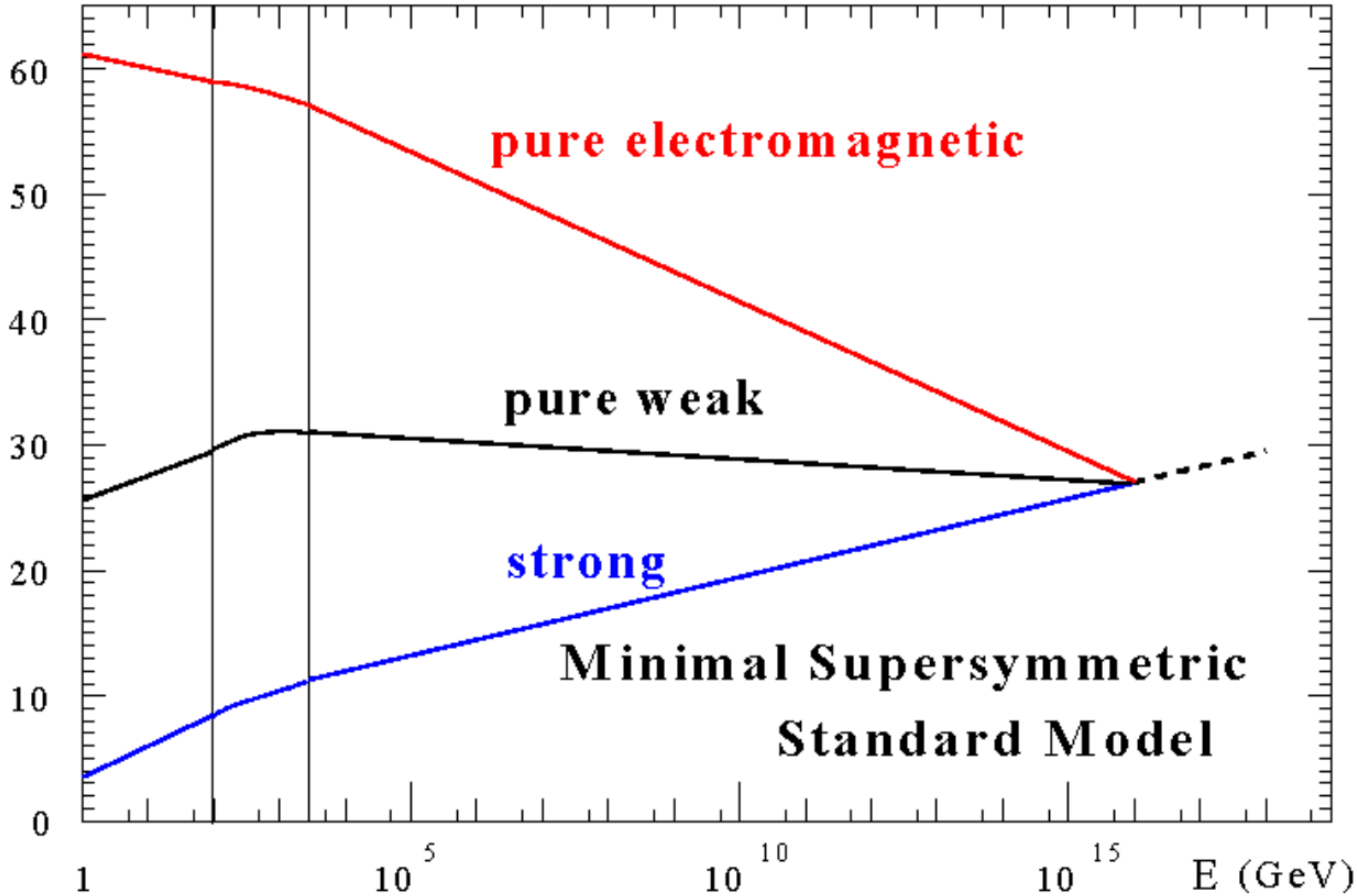
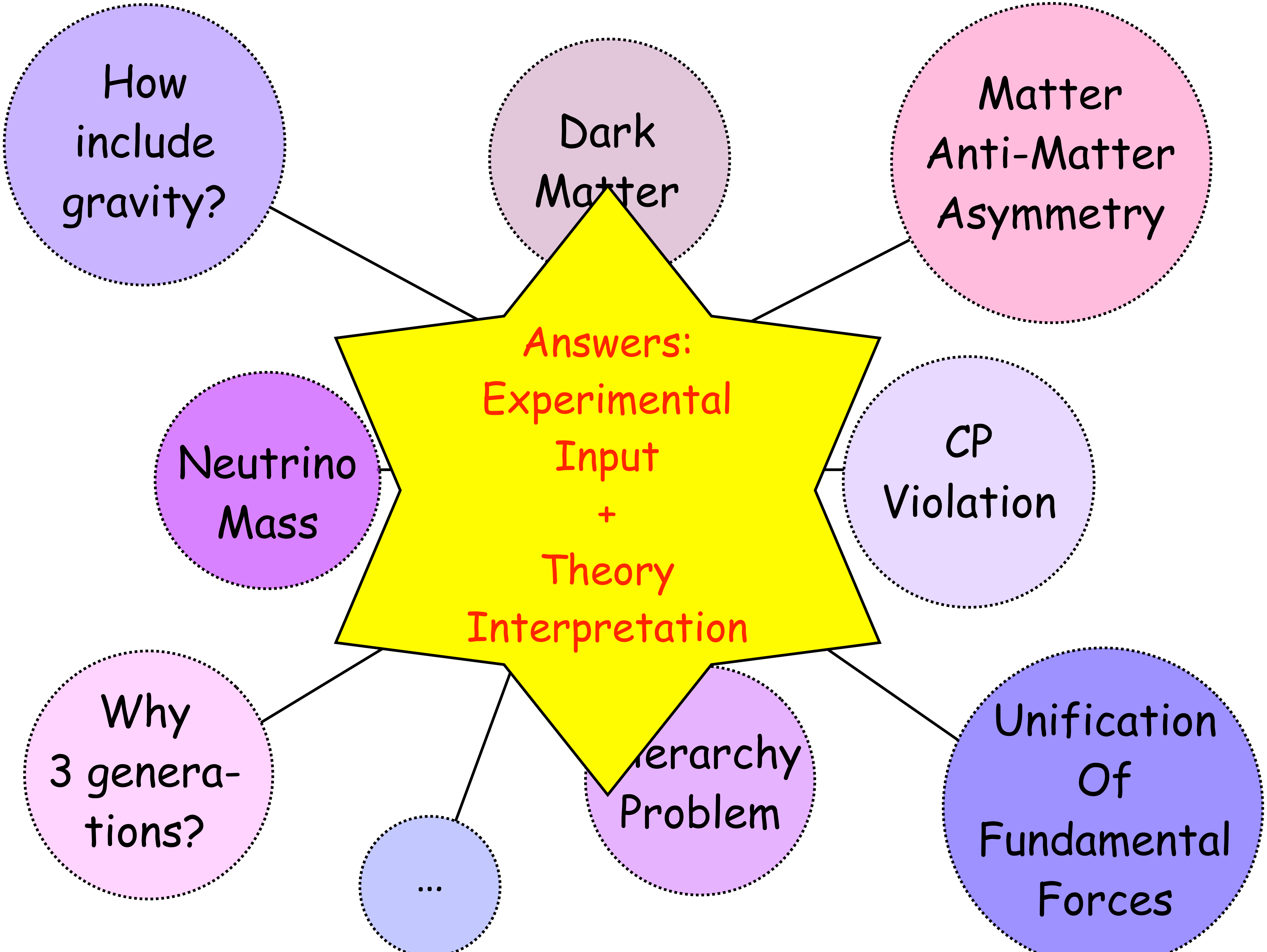
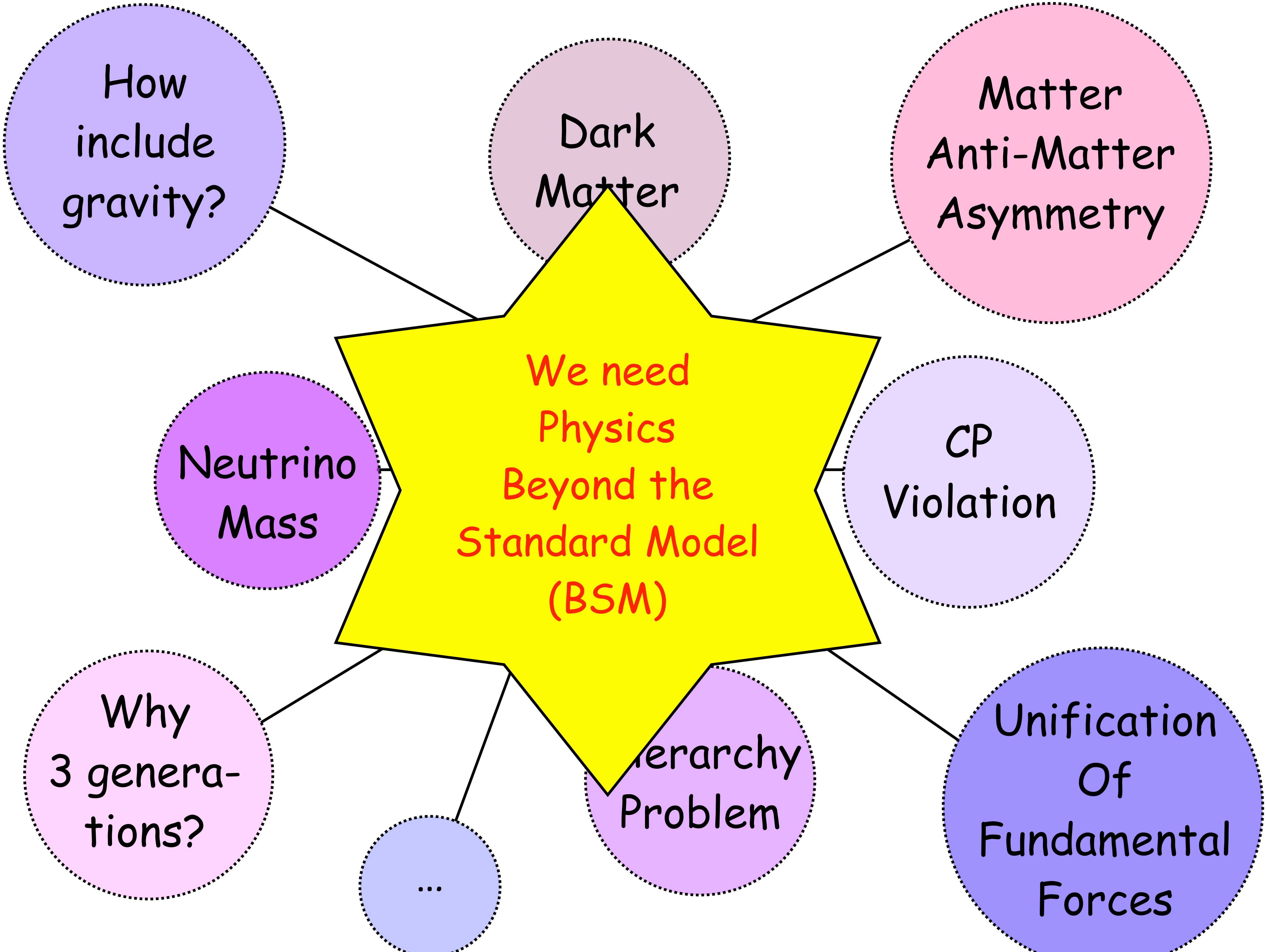


How can we change this behavior?

Unification of Fundamental Forces!




How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
Answers: Experimental Input + Theory Interpretation
CP Violation
Why 3 genera-tions?
...
ierarchy Problem
Unification Of Fundamental Forces



How include gravity?
Dark Matter
Matter Anti-Matter Asymmetry
Neutrino Mass
We need Physics Beyond the Standard Model (BSM)
CP Violation
Why 3 genera-tions?
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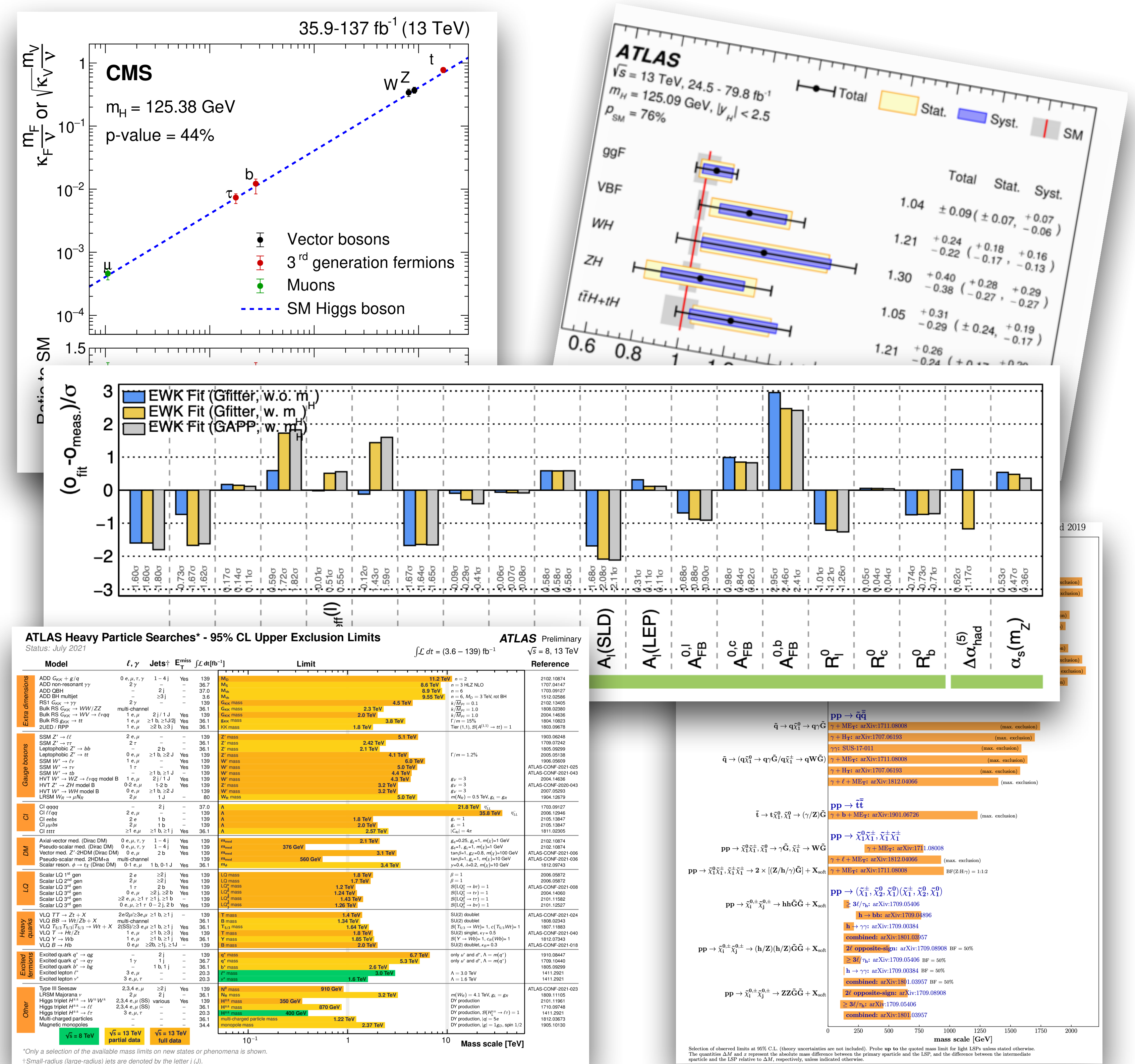
Unification Of Fundamental Forces

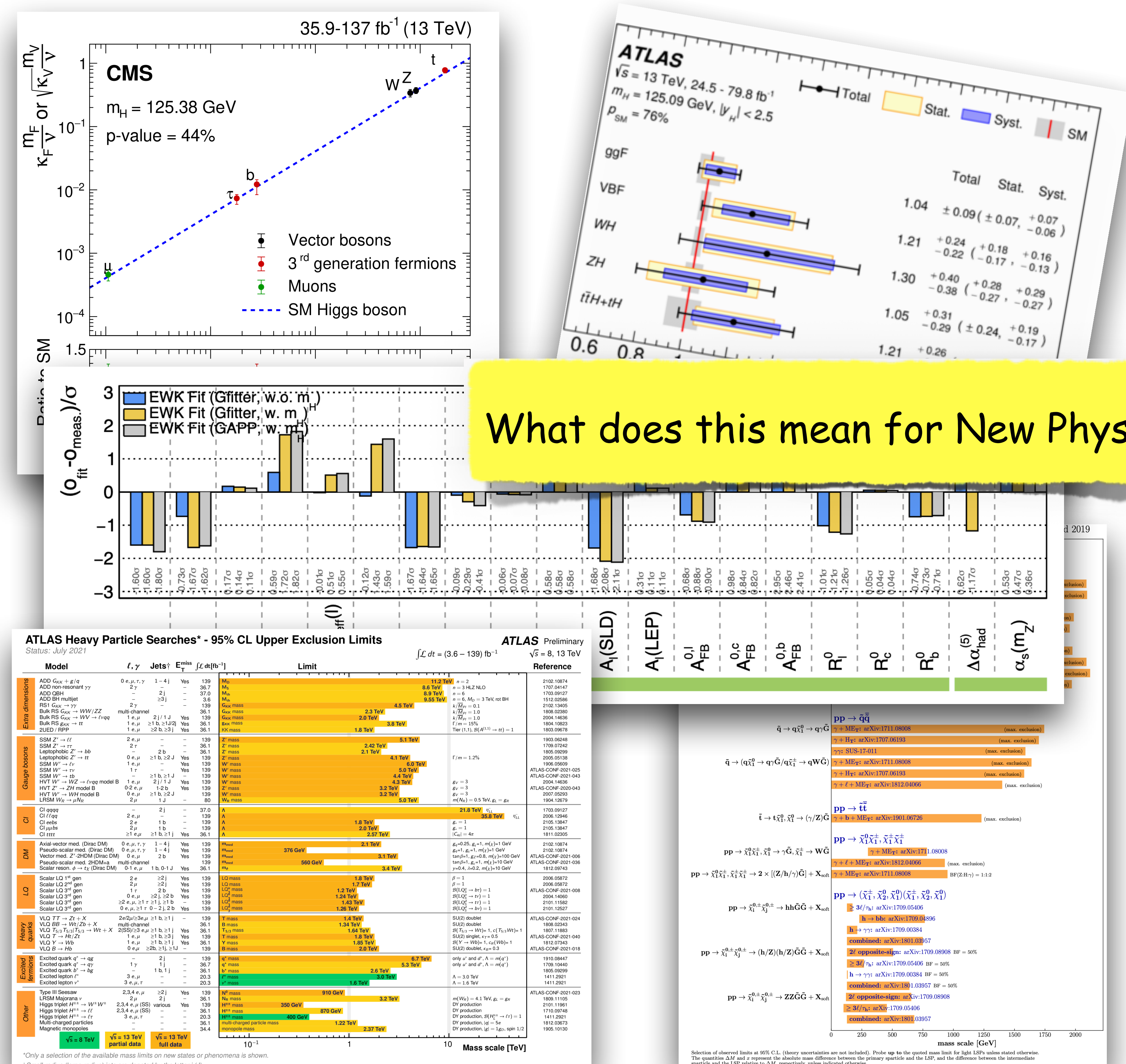
Status



Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far



What does this mean for New Physics?

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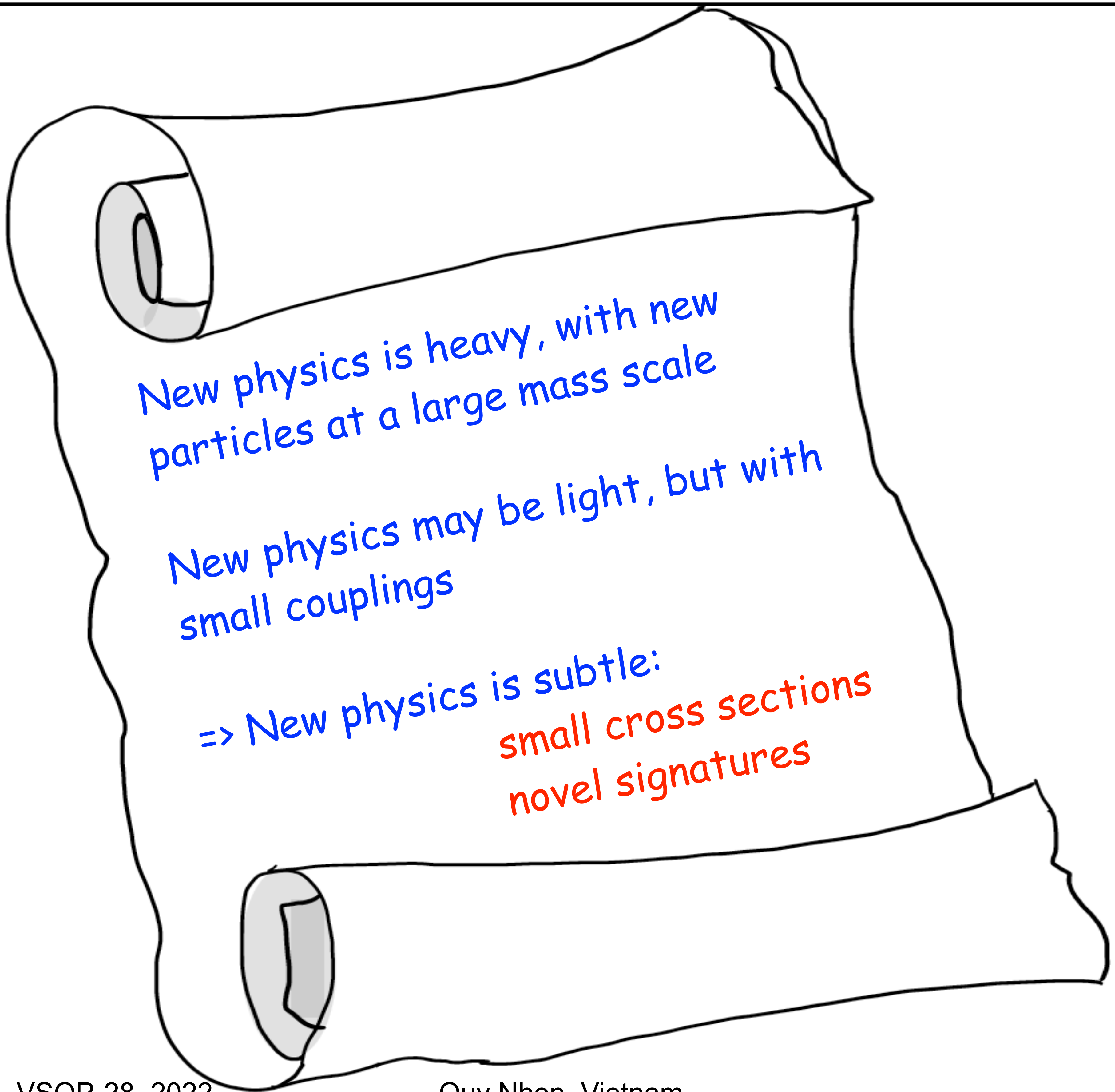
Where is New Physics?



New Physics Extensions

Physics beyond the Standard Model

Guidelines for model selection

* simplicity
* compatibility with relevant experimental and theoretical constraints
* solve (some of the) flaws of the SM
* testable in experiment

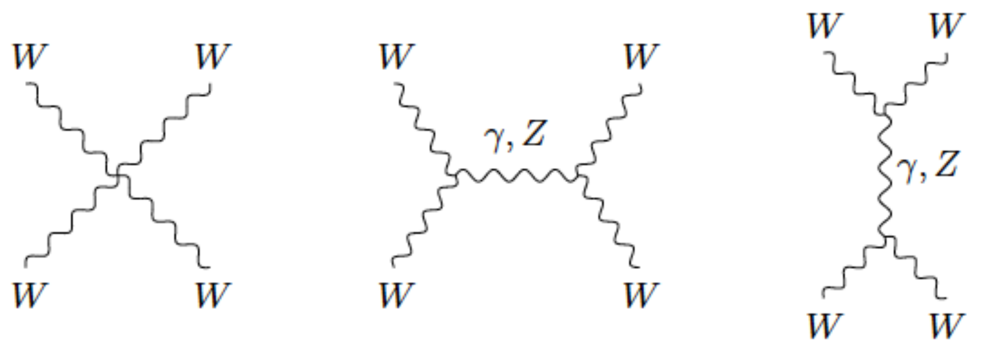
New Physics extensions:

* weakly interacting (extended Higgs sectors, supersymmetry)
* strongly interacting (composite Higgs)

Implications:

* new non-SM particles (search for them; can modify electroweak precision observables (EWPO), B-physics observables, low-energy observables; break symmetries, be DM candidate, ...)
* modify properties of discovered Higgs boson, which behaves very SM-like

Scattering of longitudinally polarized W bosons



$$\mathcal{A} = \frac{G_F s}{8\pi\sqrt{2}}$$

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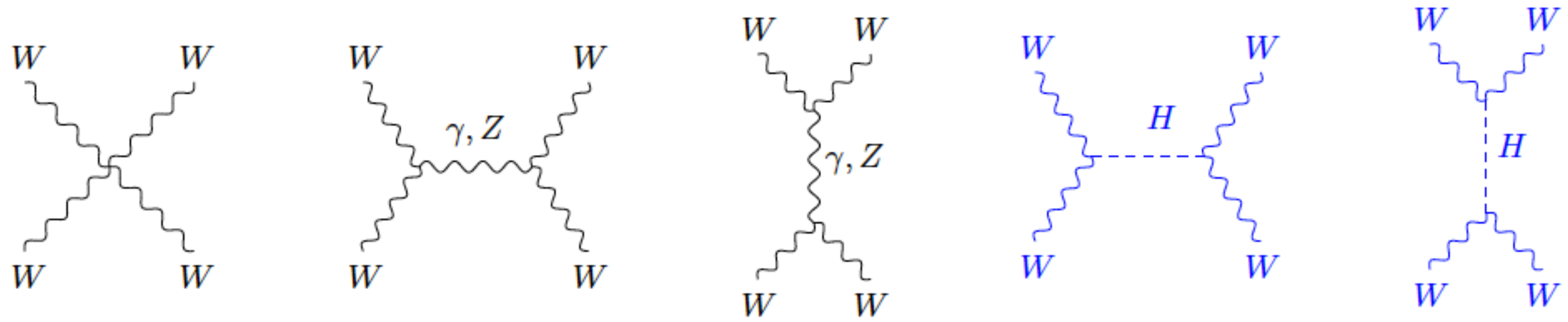

$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs ensures unitarity of longitudinally polarized W boson scattering provided coupling $g(HWW) \sim m_W^2$

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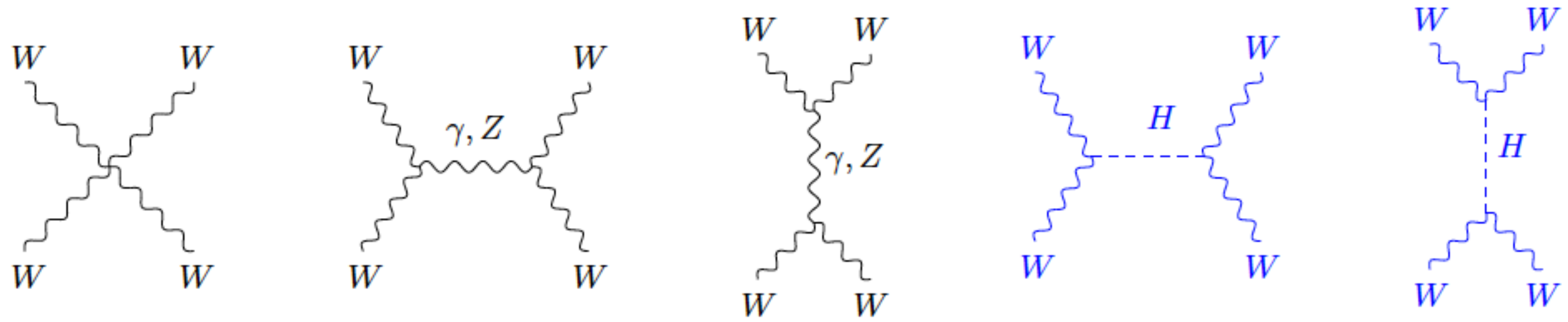

$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs ensures unitarity of longitudinally polarized W boson scattering provided coupling g(HWW) ~ m_W^2

A theory of massive gauge bosons and fermions, that are weakly interacting up to very high energies, demands - for unitarity reasons - the existence of a Higgs particles. The Higgs particle is a scalar 0+ (electrically neutral, CP-even) particle, that couples proportional to the mass/mass squared of the particle
=> non-Abelian gauge theories with spontaneous symmetry breaking.

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