The Standard Model

CSU-NUPAX/CERN IRES Program

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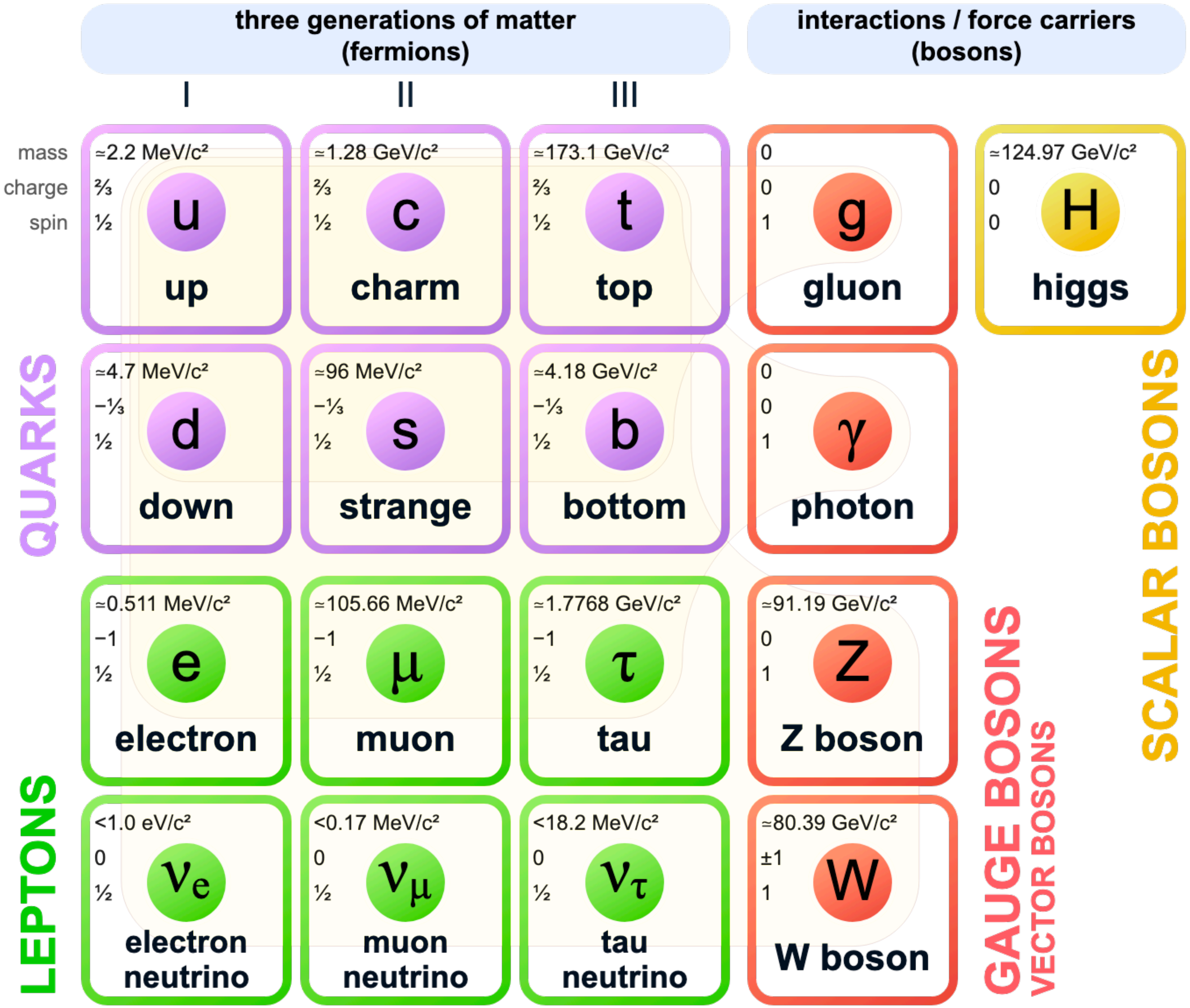
March 8th and 10th, 2022

Standard Model of Elementary Particles



Standard Model Symmetries

$U(1) \times SU(2)_L \times SU(3)$ **->** $U(1)_{QED} \times SU(3)_C$

- $U(1) \times SU(2)_L$ represents Electroweak symmetry
  — 4 degrees of freedom -> electroweak symmetry breaking -> 3 leftover
  — Goldstone bosons -> physical bosons
  — Higgs ‘eats’ a degree of freedom

- $SU(3)$ represent Quantum Chromo Dynamics (QCD, aka strong force)
  — No symmetry breaking
  — Decoupled from Electroweak sector

Lorentz Group

Lorentz boost (x *direction*)

$$t' = \gamma\left(t - \frac{vx}{c^2}\right)$$
$$x' = \gamma\left(x - vt\right)$$
$$y' = y$$
$$z' = z$$

- Set of all Lorentz transformations
  — Invariant physics in 4-dimensional spacetime
  — 3 degrees of freedom for rotations
  — 3 degrees of freedom for translations (boosts)
  — 3+3=6 *generators* of group

- SO(4): Special Ordinary Group of Rank 4
  — Happens to have 6 generators
  — Turns out SO(4)=SU(2)xSU(2) -> Left/Right-Handed
  — Useful since respects Lorentz Invariance, and lines up with evidence of ‘handed-ness’ of physics (see Wu and Goldhaber experiments in 1950’s)

Writing Down a Lagrangian

- For each Gauge-Symmetry -> Field Tensor $F^{\mu\nu}$
  - SU(3) -> G_μ^a (x8)
  - SU(2) -> W_μ^i (x3)
  - U(1) -> B_μ (x1)
- Total derivative involves all field tensors
- Introduce chiral (handed) fermions
  - LH: Doublets; RH: Singlets (Y==0)

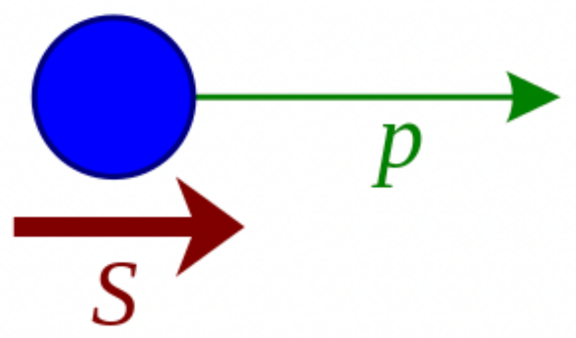
Couplings

$$D_\mu = \partial_\mu - i g_C \lambda_\alpha G^\alpha_\mu - i g_L T_j W^j_\mu - \frac{i}{2} g_Y Y \; B_\mu$$

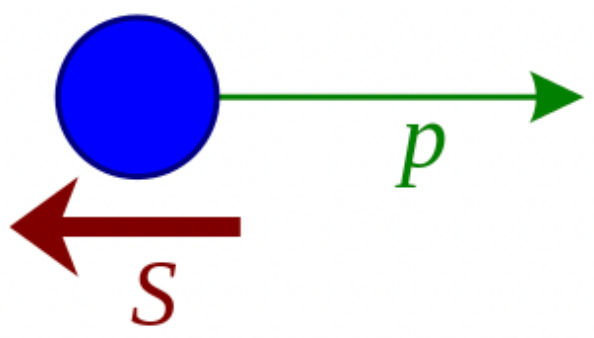
Weak Hyperspin

Weak Hypercharge

Right-handed:



Left-handed:



$$L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad Q_{L_a} = \begin{pmatrix} u_a \\ d_a \end{pmatrix}_L$$

Lagrangian of the Standard Model

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + H.C. \text{ (Kinetics and Gauge-Interactions)}$$

$$+ |D_\mu\phi|^2 + V(\phi) \text{ (Higgs)}$$

$$+ \psi_i y_{ij}\psi_j\phi + H.C. \text{ (Yukawa)}.$$

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No mass terms!! Everything is massless!!!!

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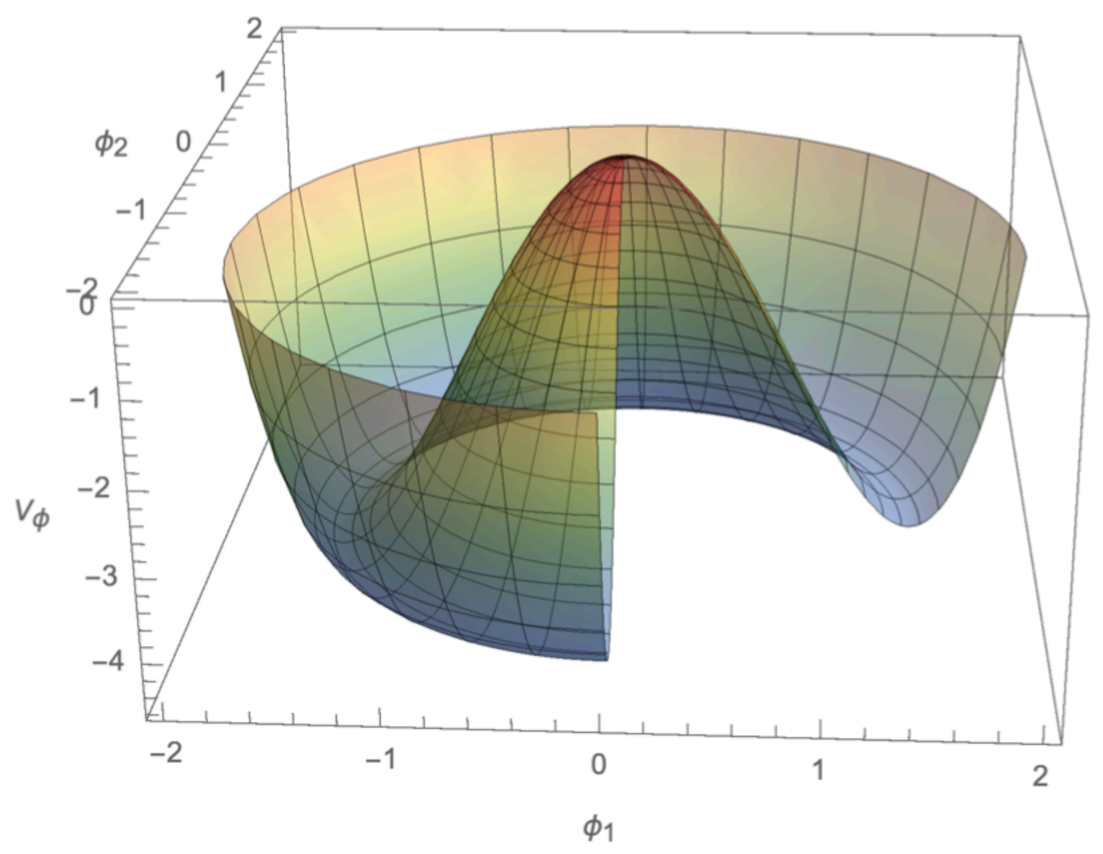
Higgs Sector -> Leads to effective mass terms (Yukawa)

The Higgs Potential

- Where we start: $SU(2)_L \otimes U(1)_Y$ => $(W_\mu^{1,2,3}, B_\mu)$ four generators

- Higgs potential: $V(\phi) = -\frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$



$|\lambda| > 0$ and $|\mu| < 0$

- Minimum defines Vacuum Expectation Value

$$\text{VEV} \equiv v \equiv \frac{\mu^2}{\lambda} \text{ such that } \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v\end{pmatrix}$$

- Choose representation of scalar field as

$$\phi = \begin{pmatrix}\phi_1\\\phi_2\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v+h\end{pmatrix}$$

Electroweak Symmetry Breaking

Expanding the Total Derivative

$$(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{v^2}{8}\left|\begin{pmatrix} g_L W_\mu^1 - i g_L W_\mu^2 \\ -g_L W_\mu^3 + g_Y B_\mu \end{pmatrix}\right|^2 = \frac{v^2}{8}\left(g_L^2\left(\left(W_\mu^1\right)^2 + \left(W_\mu^2\right)^2\right) + g_Y\left(W_\mu^3 - g_Y B_\mu\right)^2\right)$$

We can measure VEV
v=246 GeV

$$W_\mu^\pm \equiv \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right) \text{ such that } m_W = \frac{g_L v}{2},$$

$$Z_\mu \equiv \frac{1}{\sqrt{g_L^2 + g_Y^2}}\left(g_Y W_\mu^3 + g_L B_\mu\right) \text{ such that } m_Z = \frac{v}{2}\sqrt{g_L^2 + g_Y^2},$$

$$A_\mu \equiv \frac{1}{\sqrt{g_L^2 + g_Y^2}}\left(g_Y W_\mu^3 + g_L B_\mu\right) \text{ such that } m_A = 0.$$

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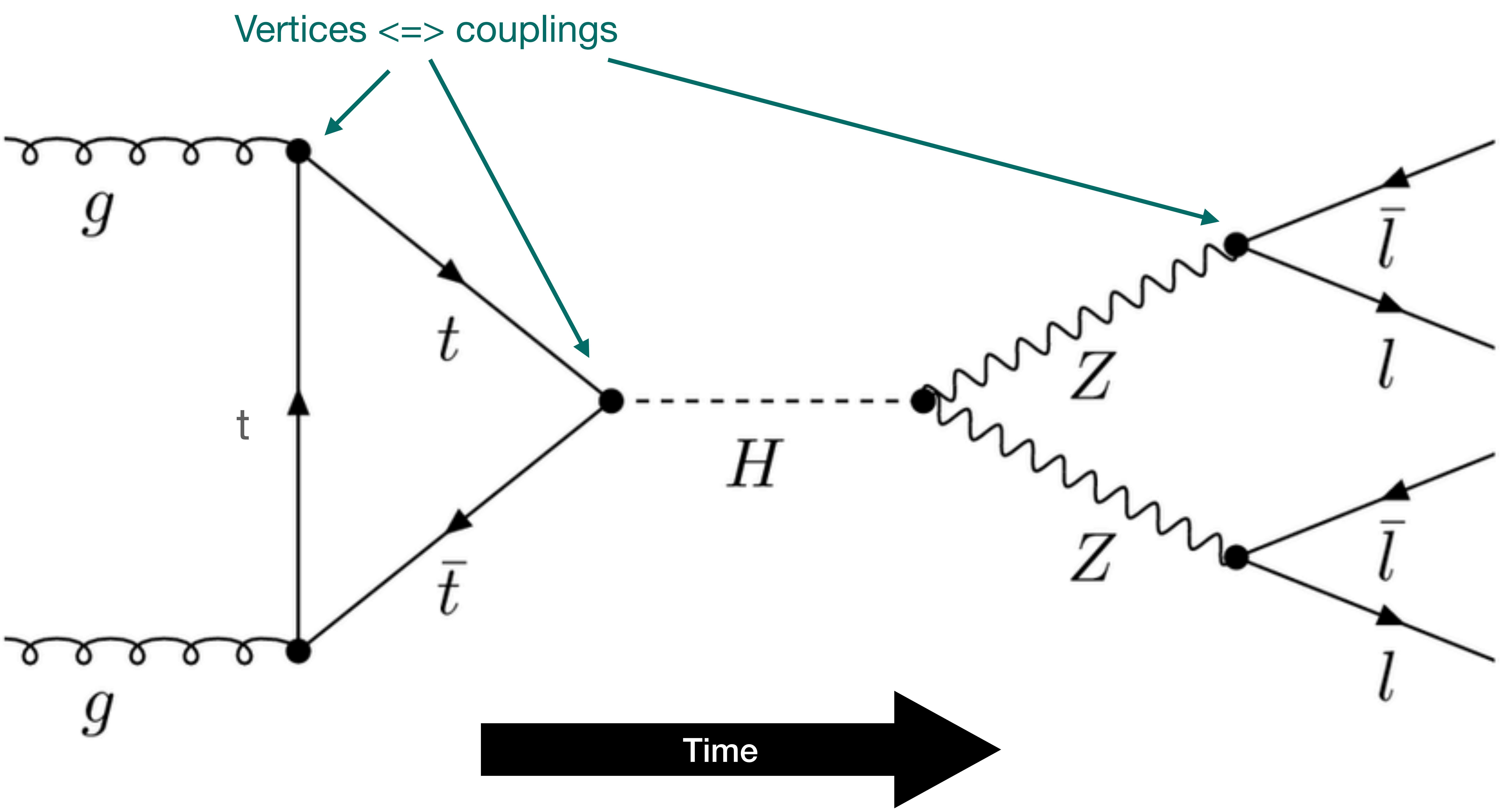
Higgs Sector -> Leads to effective mass terms (Yukawa)

Quantum Numbers of the Standard Model

Type	Mass	Lifetime	Q	J	Y	P	Color
e	0.511 MeV	stable	-1	$1/2$	$-\frac{1}{2}$	$-1/2$	0
ν_e	small	oscillates	0	$1/2$	$-\frac{1}{2}$	$+1/2$	0
μ	106 MeV	$\mathcal{O}(10^{-6})s$	-1	$1/2$	$-\frac{1}{2}$	$-1/2$	0
ν_μ	small	oscillates	0	$1/2$	$-\frac{1}{2}$	$+1/2$	0
τ	1776 MeV	$\mathcal{O}(10^{-13})s$	-1	$1/2$	$-\frac{1}{2}$	$-1/2$	0
ν_τ	small	oscillates	0	$1/2$	$-\frac{1}{2}$	$+1/2$	0
u	2.2 MeV	stable	$+2/3$	$1/2$	$+1/3$	$+\frac{1}{2}$	r/g/b
d	4.7 MeV	$\mathcal{O}(10^{-8})$s	$-1/3$	$1/2$	$+1/3$	$-\frac{1}{2}$	r/g/b
s	95 MeV	$\mathcal{O}(10^{-8})$s	$-1/3$	$1/2$	$+1/3$	$-\frac{1}{2}$	r/g/b
c	1.275 GeV	$\mathcal{O}(10^{-12})$s	$+2/3$	$1/2$	$+1/3$	$+\frac{1}{2}$	r/g/b
b	4.18 GeV	$\mathcal{O}(10^{-12})$s	$-1/3$	$1/2$	$+1/3$	$-\frac{1}{2}$	r/g/b
t	173 GeV	$\mathcal{O}(10^{-25})$s	$+2/3$	$1/2$	$+1/3$	$+\frac{1}{2}$	r/g/b
γ	0	stable	0	1	0	0	0
$W^\pm$	80.4 GeV	$\mathcal{O}(10^{-25})$s	±1	1	0	±1	0
Z	91.2 GeV	$\mathcal{O}(10^{-25})$s	0	1	0	0	0
g	0	-	0	1	0	0	double ($c\bar{c}$)
H	125 GeV	$\mathcal{O}(10^{-22})$s	0	0	+1	$-\frac{1}{2}$	0

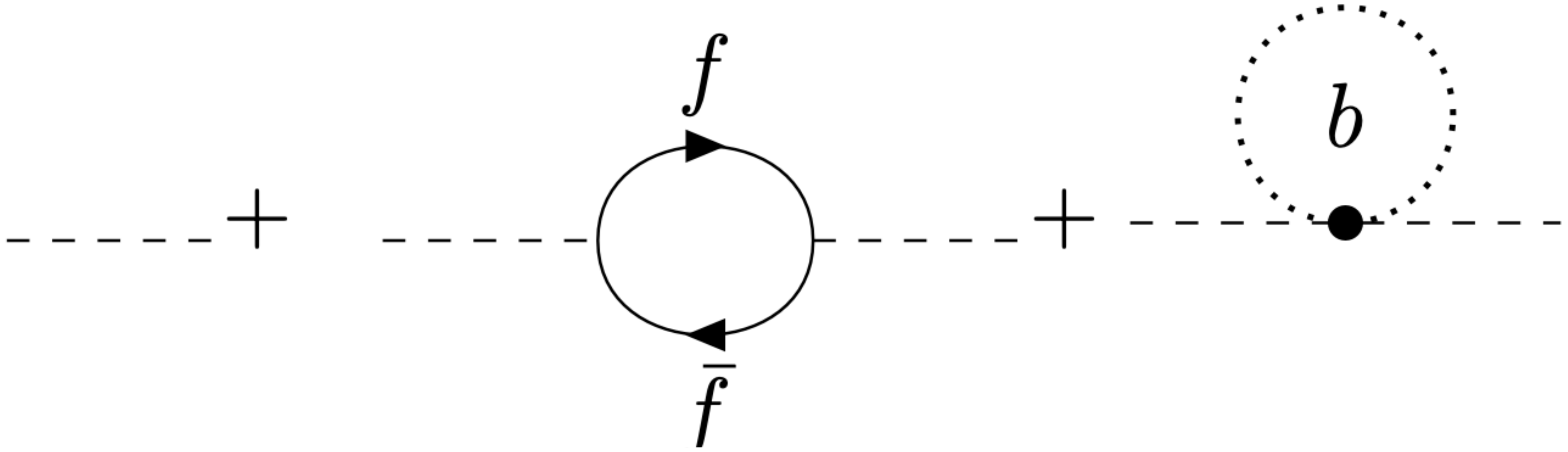
Feynman Diagrams



Naturalness in the Standard Model

$$m^2_{h,phys} = 2\mu^2 = m^2_{h,\ bare} + \sum_{Fermions} k_f m_f^2 + \sum_{Bosons} k_b m_b^2$$

=



$$= m^2_{H,bare} - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2_{UV} + \frac{|\lambda_b|^2}{8\pi^2}\Lambda^2_{UV}$$

Left Side: Measured at 125 GeV

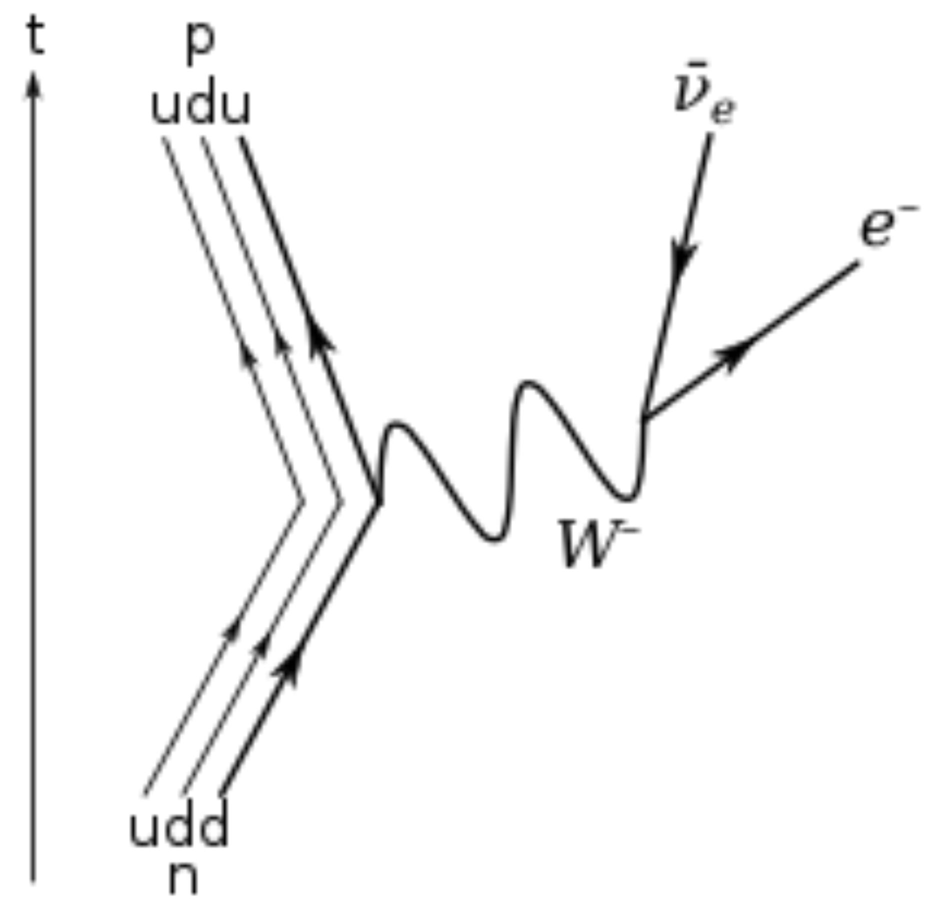
Right Side: (Bare Mass) + (User Defined Scale)

Beyond the Standard Model

Questions to Think About

- Is the Higgs really fundamental?
- Could there be new physics to help with quadratic divergence of Higgs mass?
- Why is gravity so weak? Can it be easily integrated into the SM?
- What about Dark Matter?
- Is lepton universality really true?
- Where did all the anti-matter go?

Johan HW: Quantum Number for Quarks



Q/e	$L_e = -1$	$L_\mu = -1$	$L_\tau = -1$
0 +1	$\begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix}$	$\begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix}$	$\begin{pmatrix} \bar{\nu}_\tau \\ \tau^+ \end{pmatrix}$
Q/e	$L_e = 1$	$L_\mu = 1$	$L_\tau = 1$
0 −1	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$

- Lepton Number (Historically)

  $\bar{\nu} + n \to p + e^-$ does not occur

  $\bar{\nu} + p \to n + e^+$ does

- Baryon Number (Historically)

  $p^+ \to e^+ + \pi^0$

  $\quad\quad\quad\quad\quad \llcorner\!\to 2\gamma$

  $n \to e^+ + e^-$

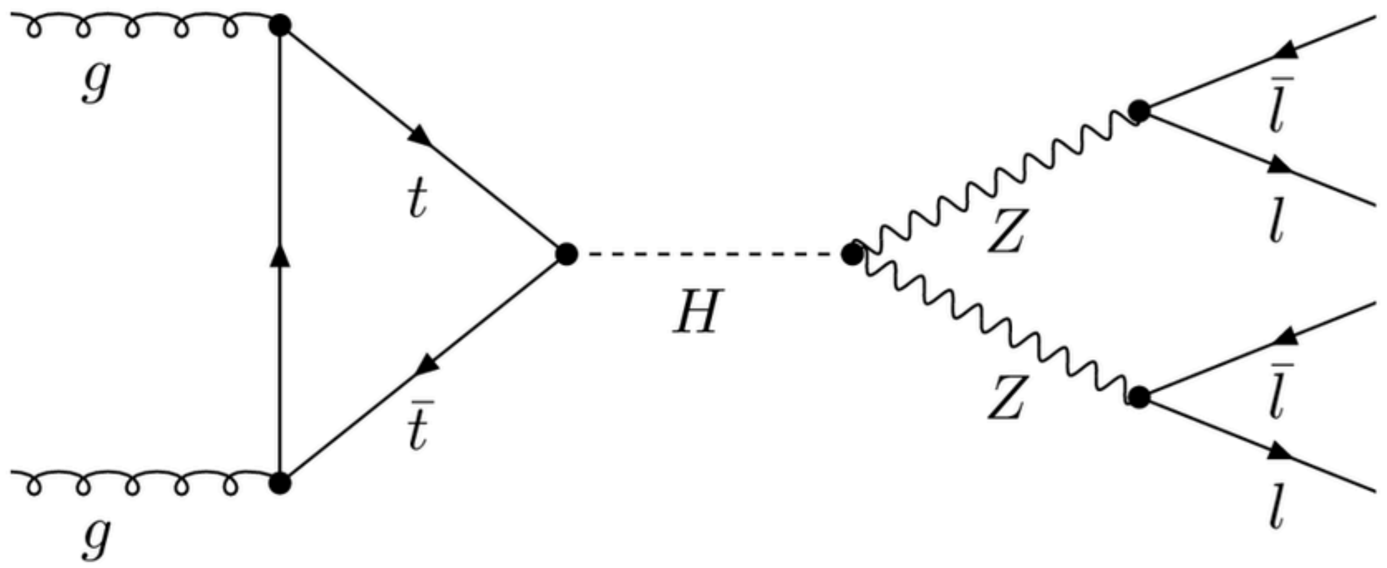
  Neither occur! People have been looking!

- Baryon and Lepton number are accidental symmetries of the Stadard Model — So is B-L (motivates many GUT models)

- Baryon number is defined for quarks: +1/3 quarks, -1/3 anti-quarks

Johan HW: Electrons in Higgs Production

- Substitute t -> e/mu/tau, is it allowed?
  - — Electron/muon/tau have no color
  - — Gluons are electrically neutral
  - — Vertex would be 0, so NO
- What is instead we had photons?
  - — Yes, you can produce Higgs
  - — Ultraperipheral collisions
  - — Can technically make a electron loop
- Electrons can indirectly ‘interact’ with gluons
  - — Via intermediary quarks
- Electron/muon colliders can be Higgs factories



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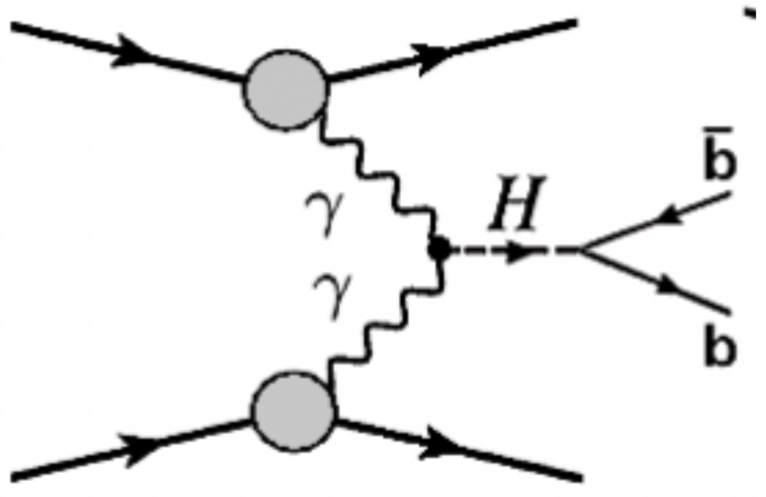
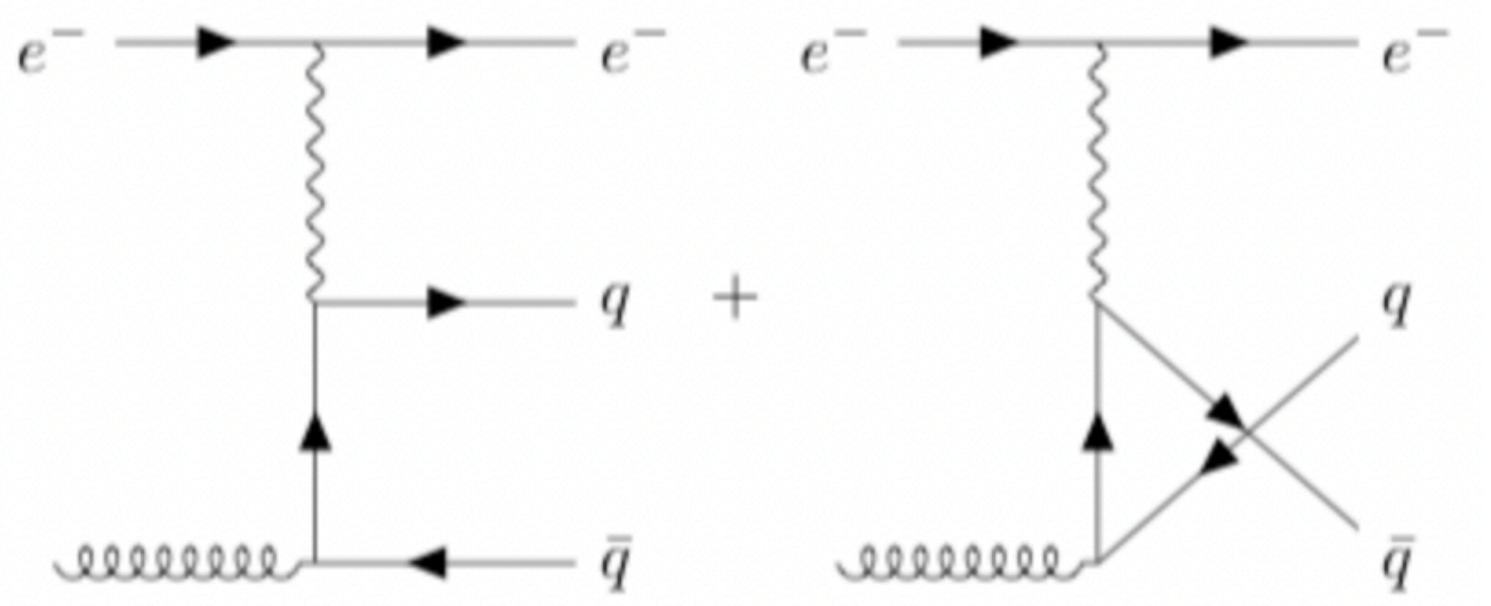
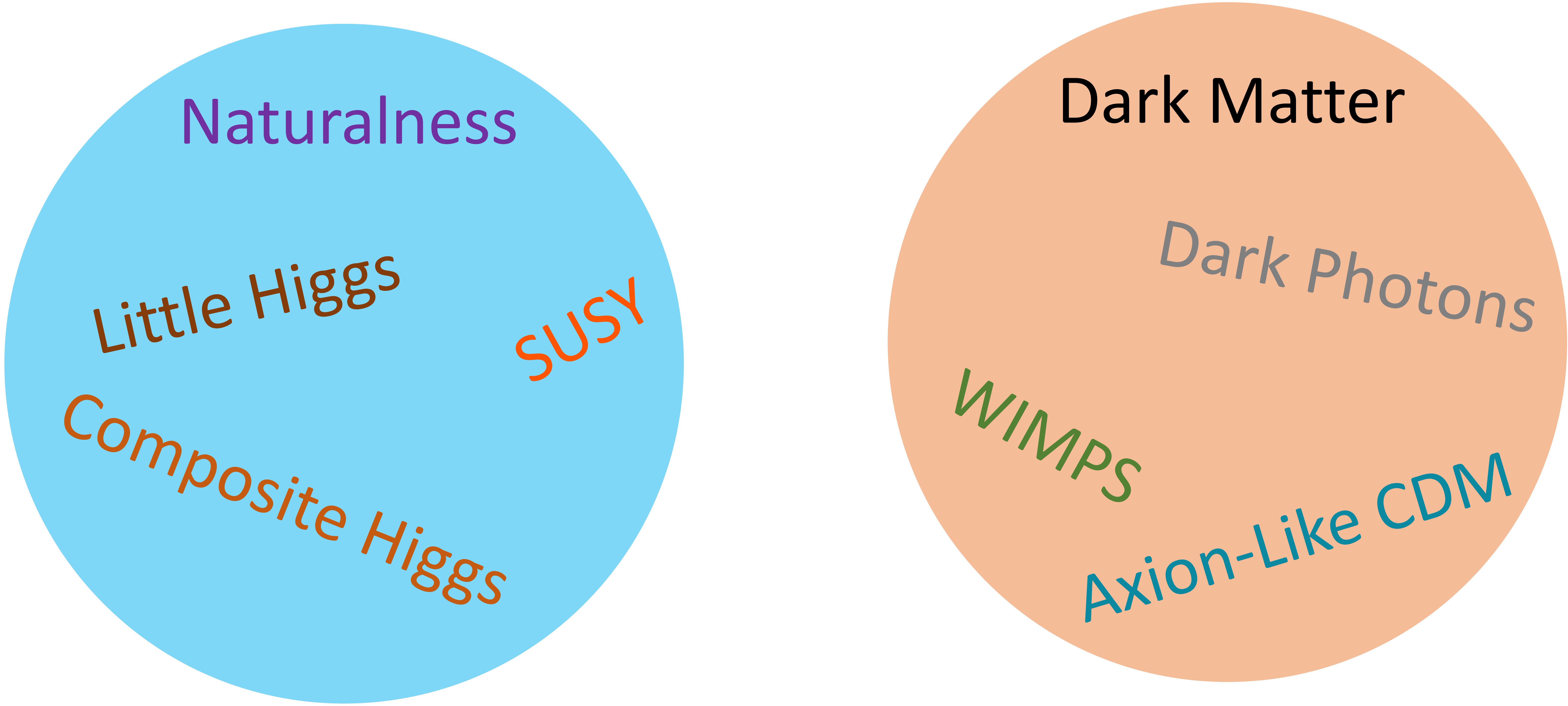




Beyond the Standard Model

Some Solutions



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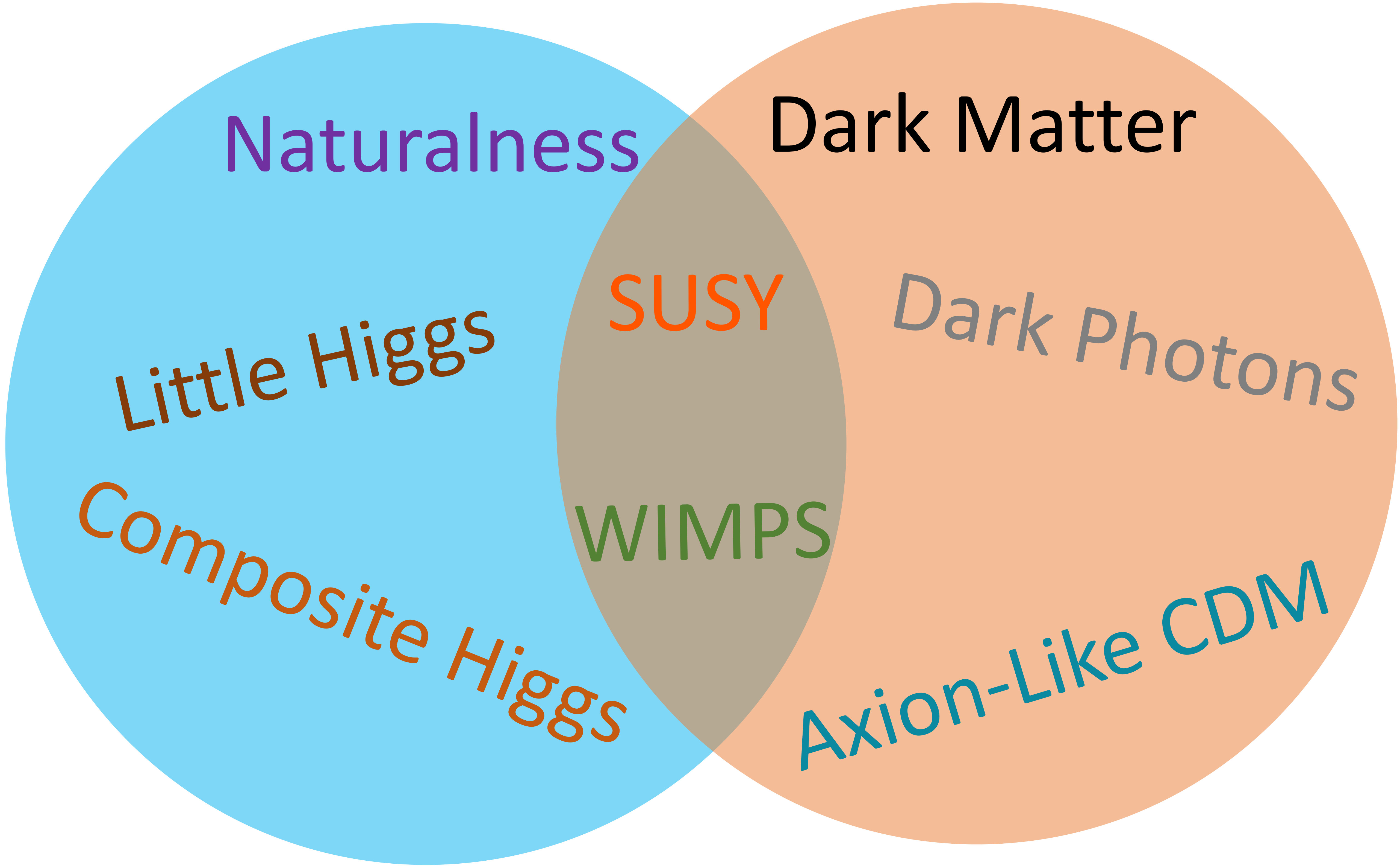
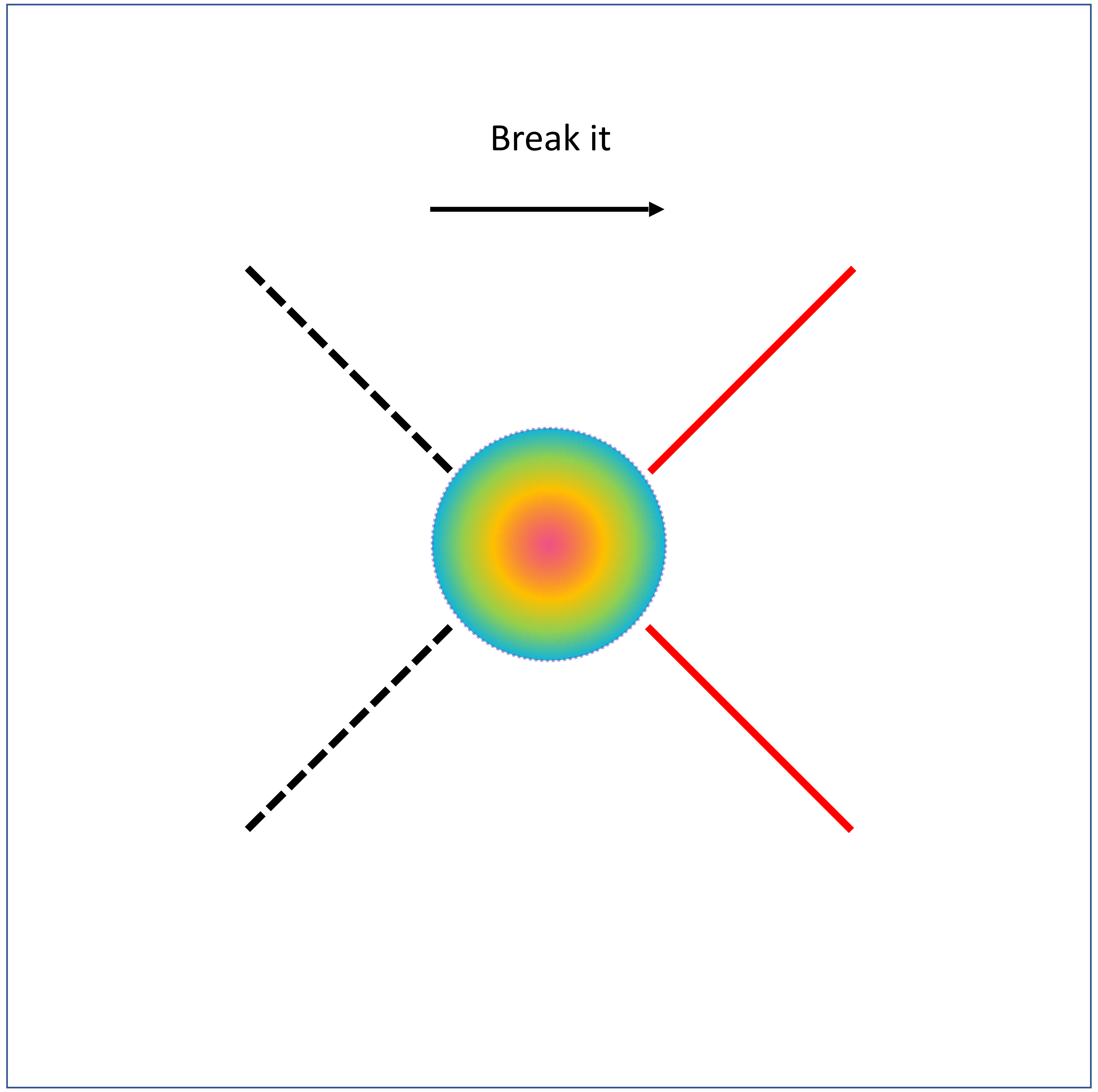


Finding Dark Matter

- “Break” it (DM annihilation)
  - Backdoors between SM and Dark sectors
  - Experiment: Space (cold, large)
- “Shake” it (DM sensing)
  - Sensitive to any interaction
  - Experiment: Pure substance (warm, dense)
- “Make” it (DM creation)
  - Tunable SM initial state
  - Experiment: LHC and other colliders



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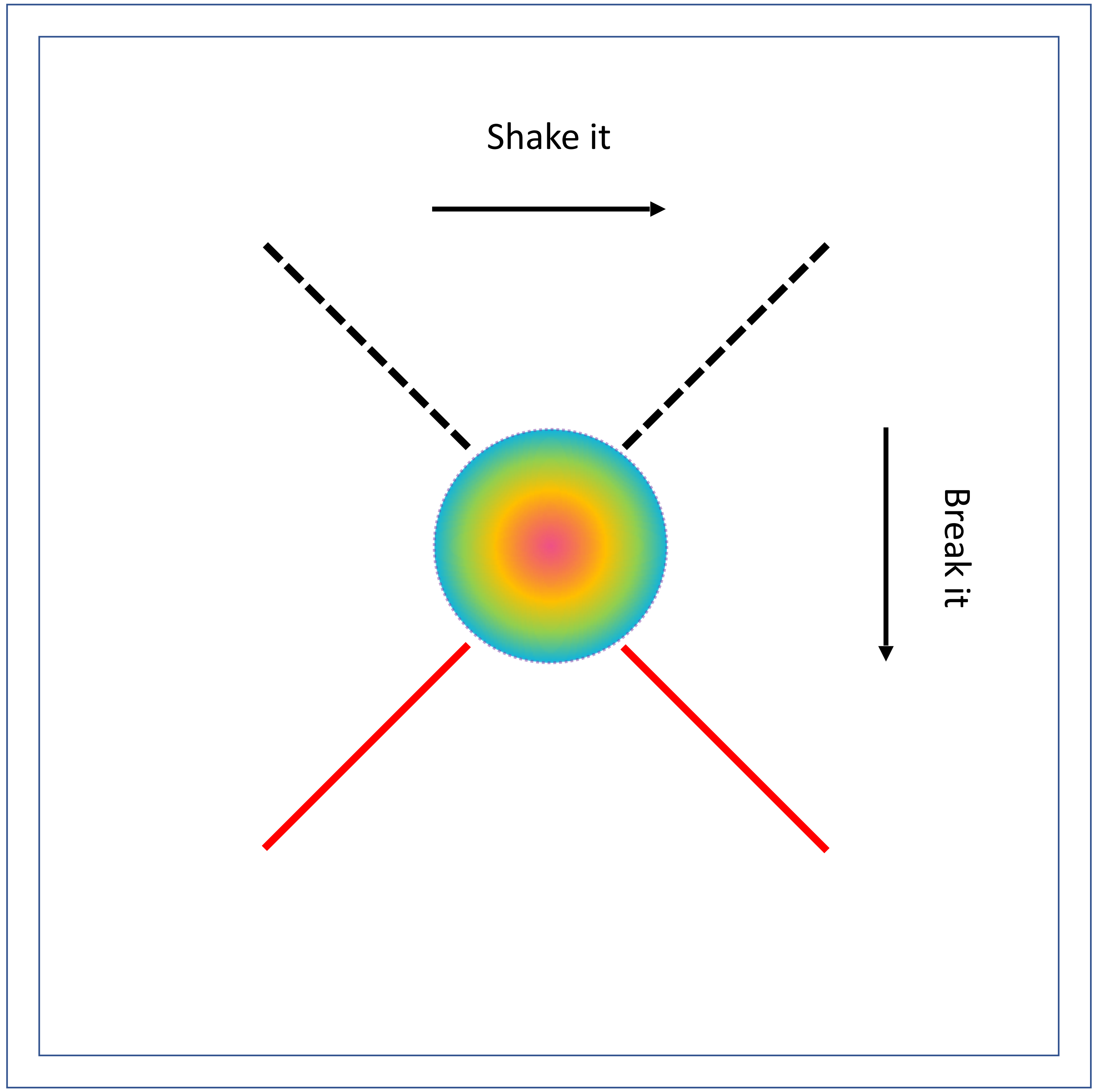

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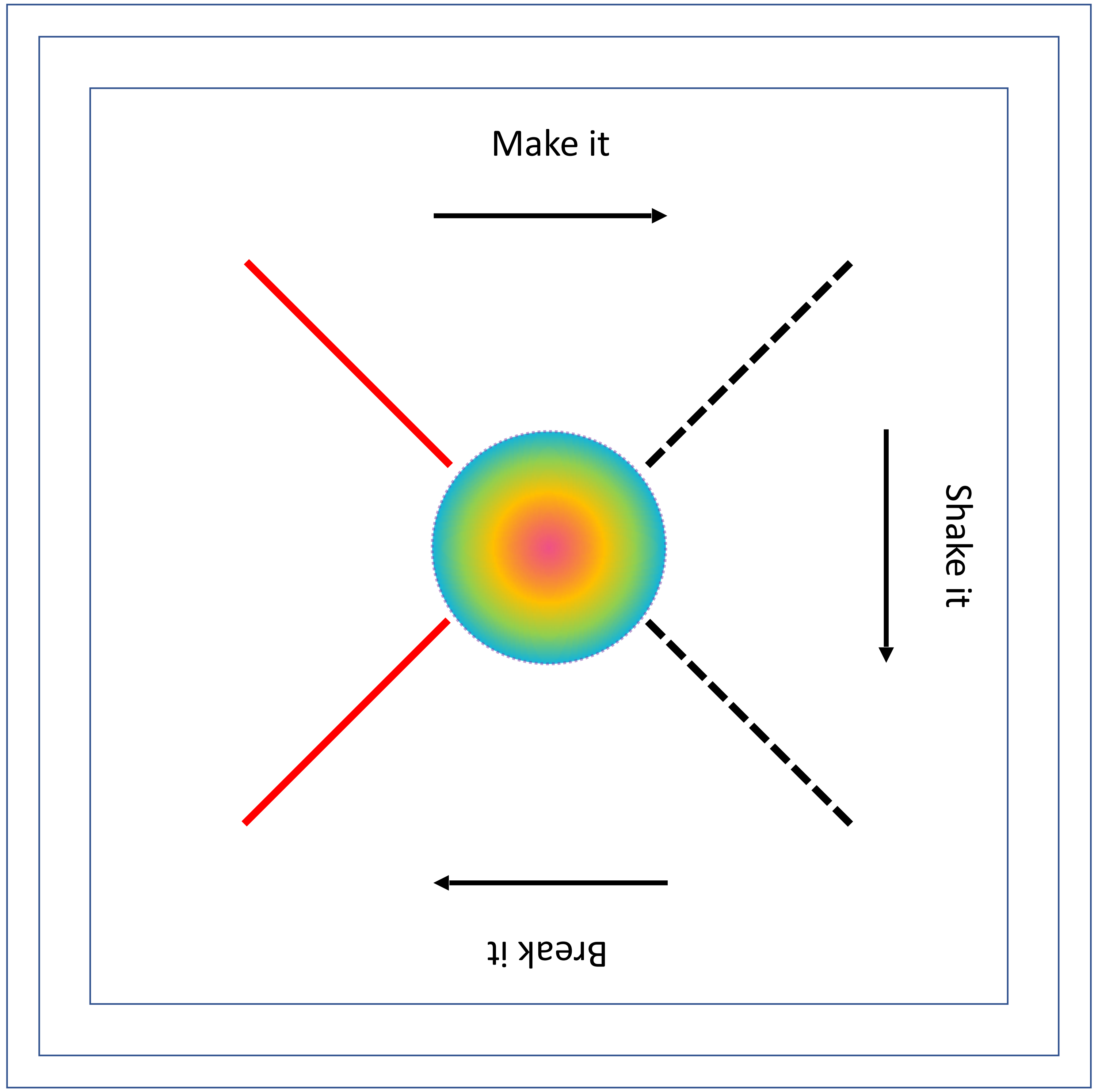


Supersymmetry

Bosons

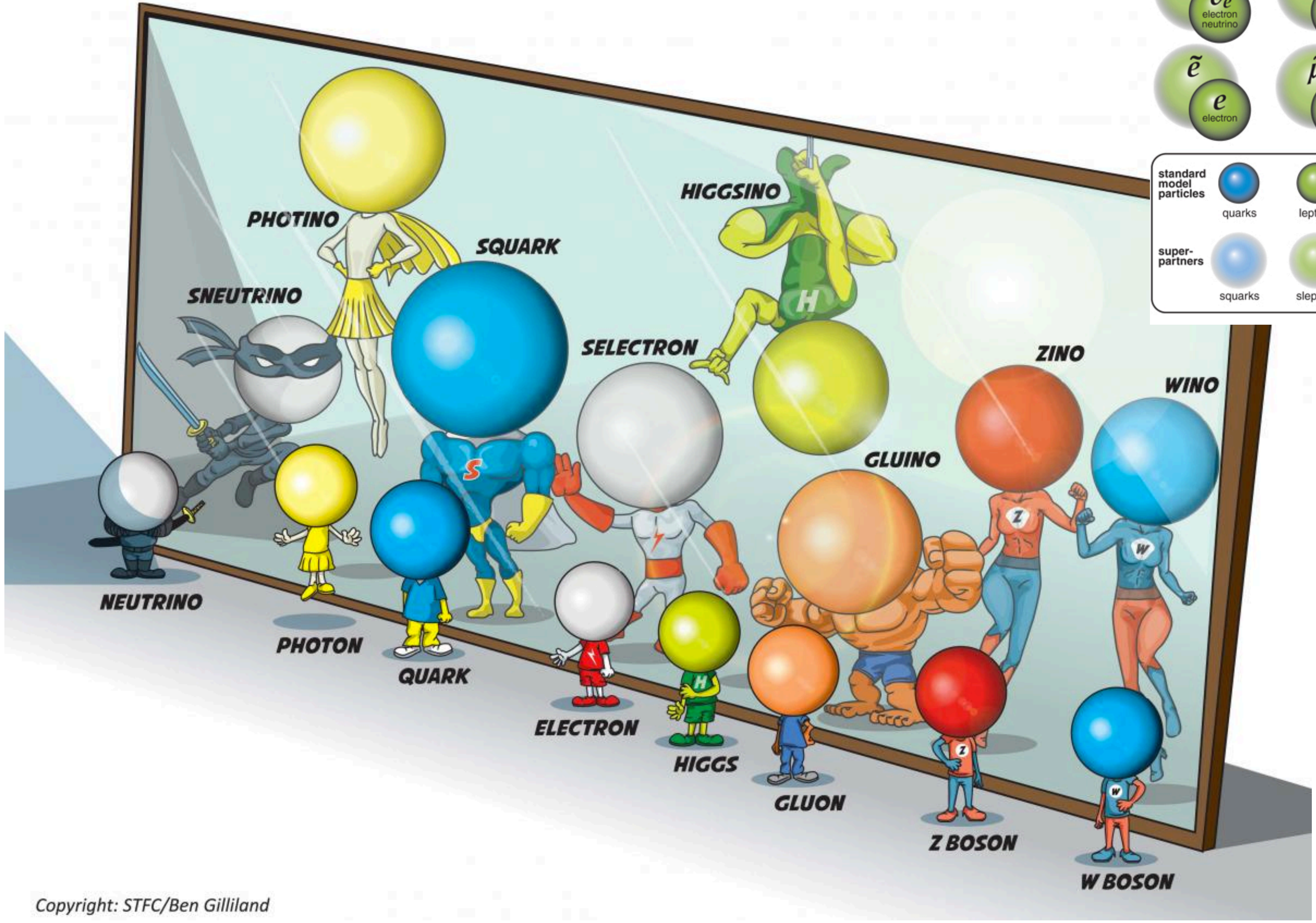
Partners

Fermions

SUSY

Partners

SM



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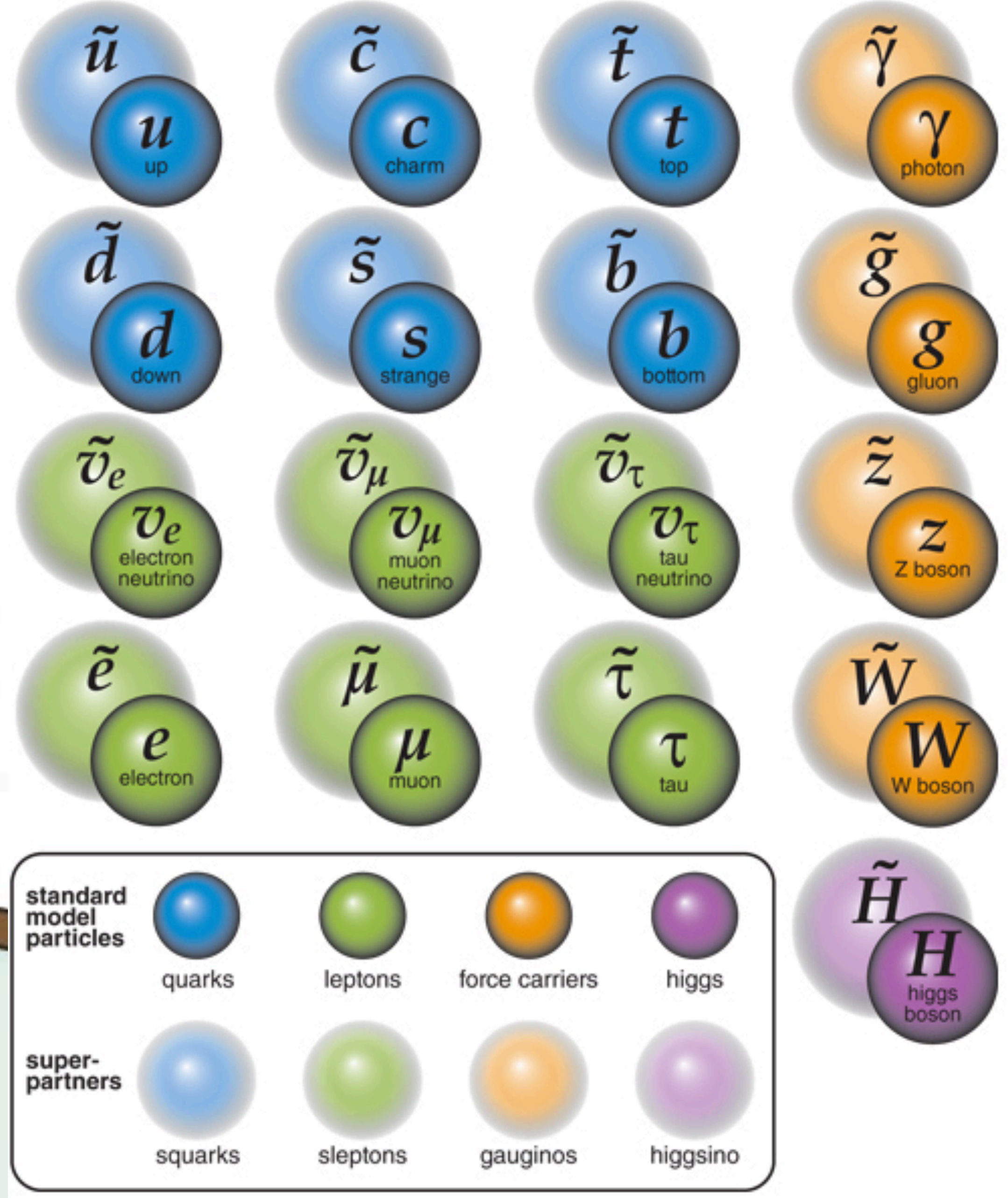

American Scientist

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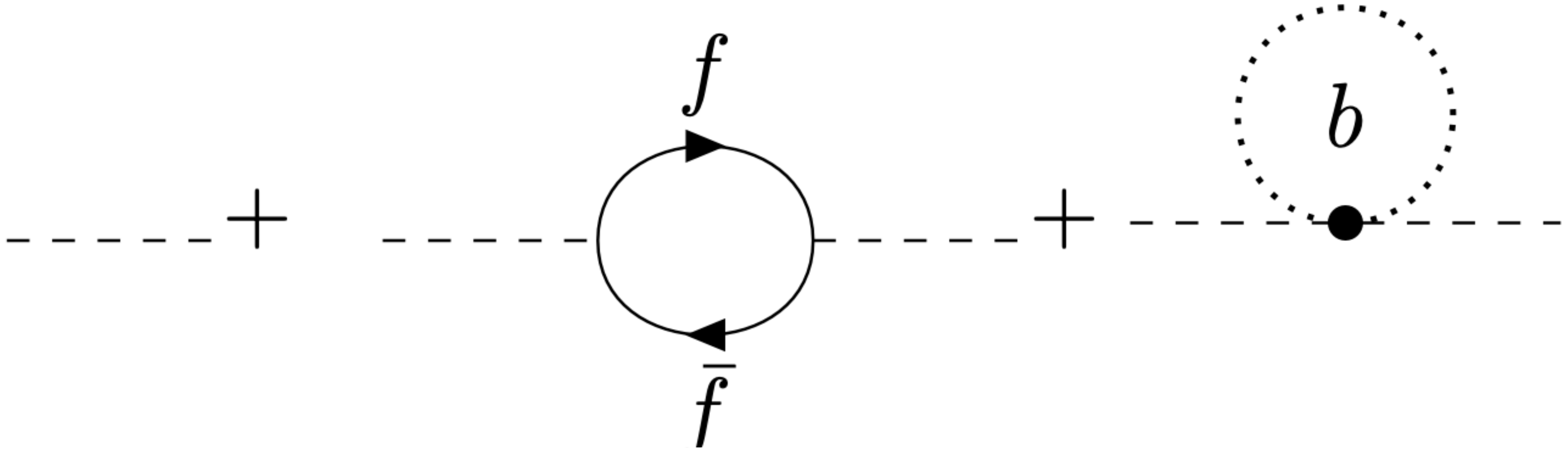
$=$ 

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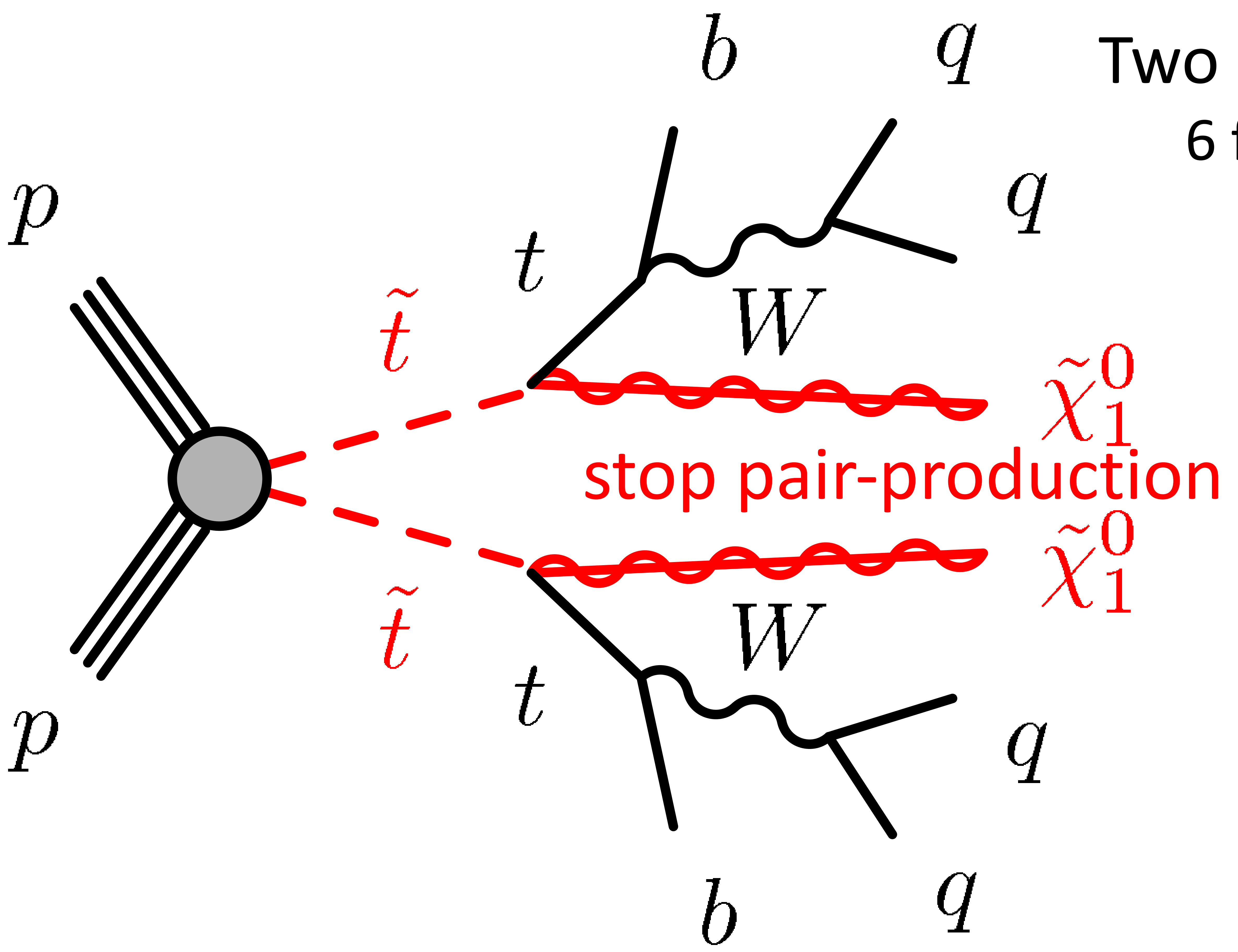
Experimental Signature

Pair-Produced, R-Parity Conserving stop ($\tilde{t}$)



Two hadronically decaying tops

6 final state quarks (>=4 jets)

Visible!

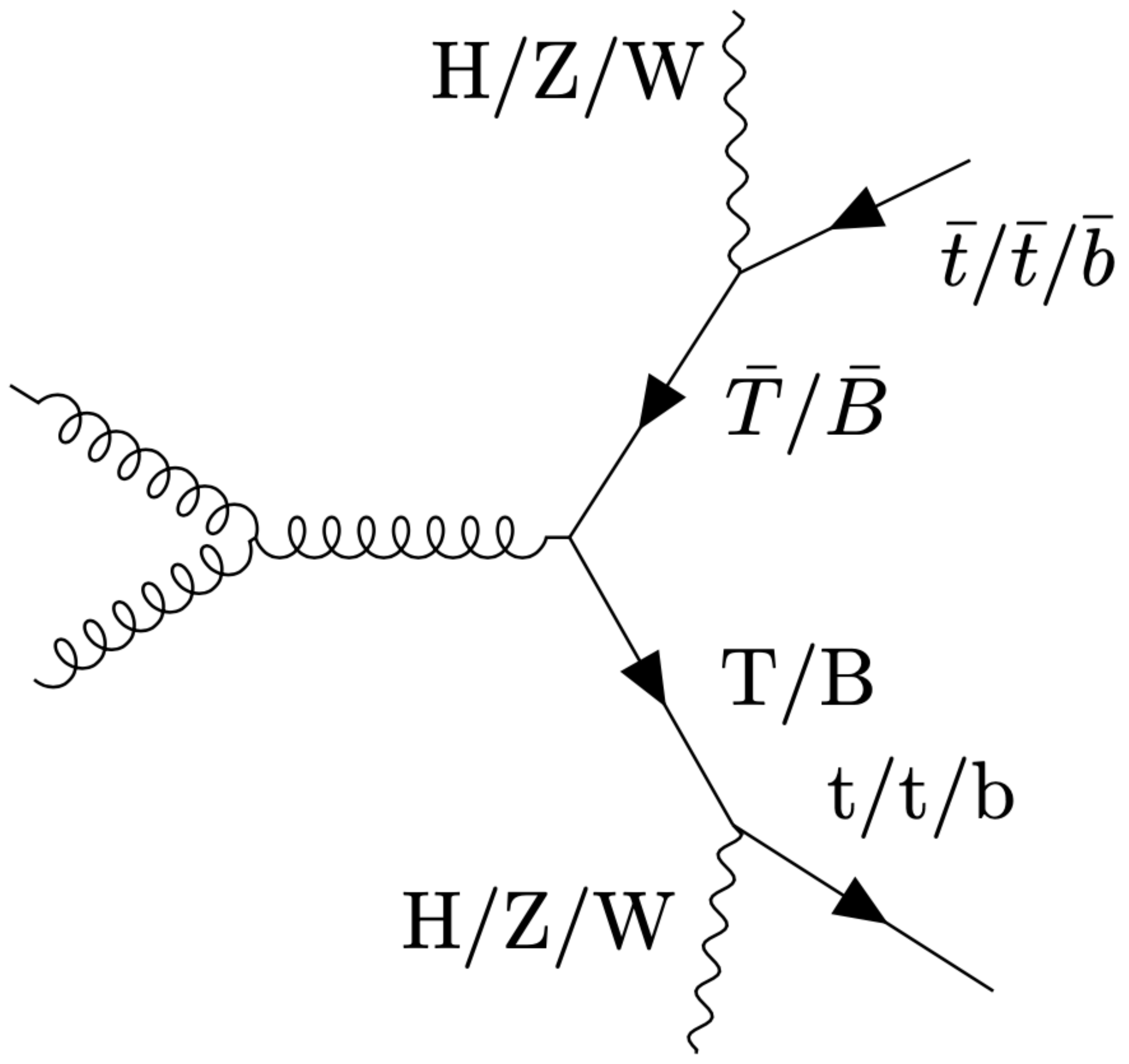
Stable Neutralino

(Missing Energy)

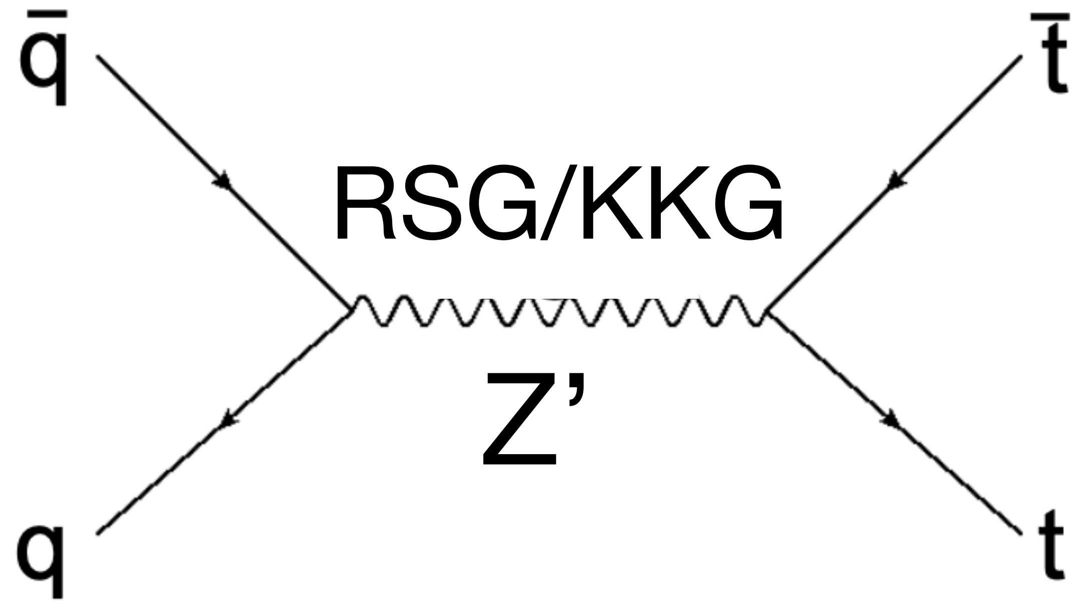
Possible Dark Matter Candidate!

The Top Quark: Possible Portal to New Physics

Evading Exclusions of Higgs Measurements



- Stops can be excluded up to ~1250 GeV
  - —Not the end of SUSY, not by a long shot!
  - —SUSY need not conserve R-parity (long-lived)
- Other chiral fermions (new 3rd, or 4th gen. quarks)
  - — Excluded by Higgs cross-section measurements
  - — Also by direct searches
- There are other BSM models to consider:
  - — The 125 GeV Higgs may not be fundamental
  - — Vector-Like Quarks (T/B) not excluded by Higgs measurements
  - — Can still be new high energy resonances with SM ttbar

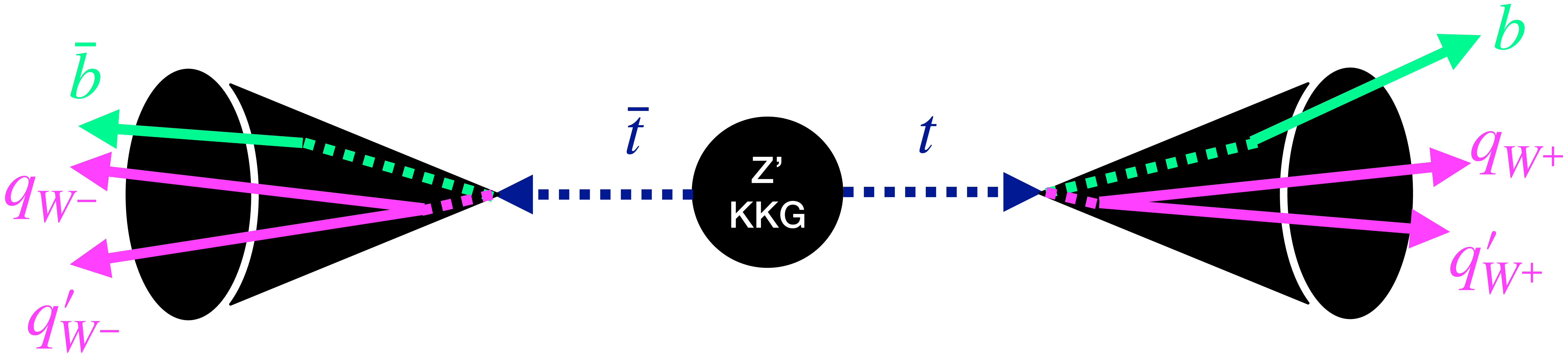


One Analyzer's Background is Another's Signal

Searching for New Physics in ttbar Resonance

- Extending the SM with additional SU(2) symmetries give rise to heavier analogs of EW bosons (W'/Z')
  - — Kaluza-Klein Graviton
  - — Randall Sundrum Bulk Graviton

- ttbar resonance mass used as discriminating observable
  - — Pivotal aspect of search is choice of top tag



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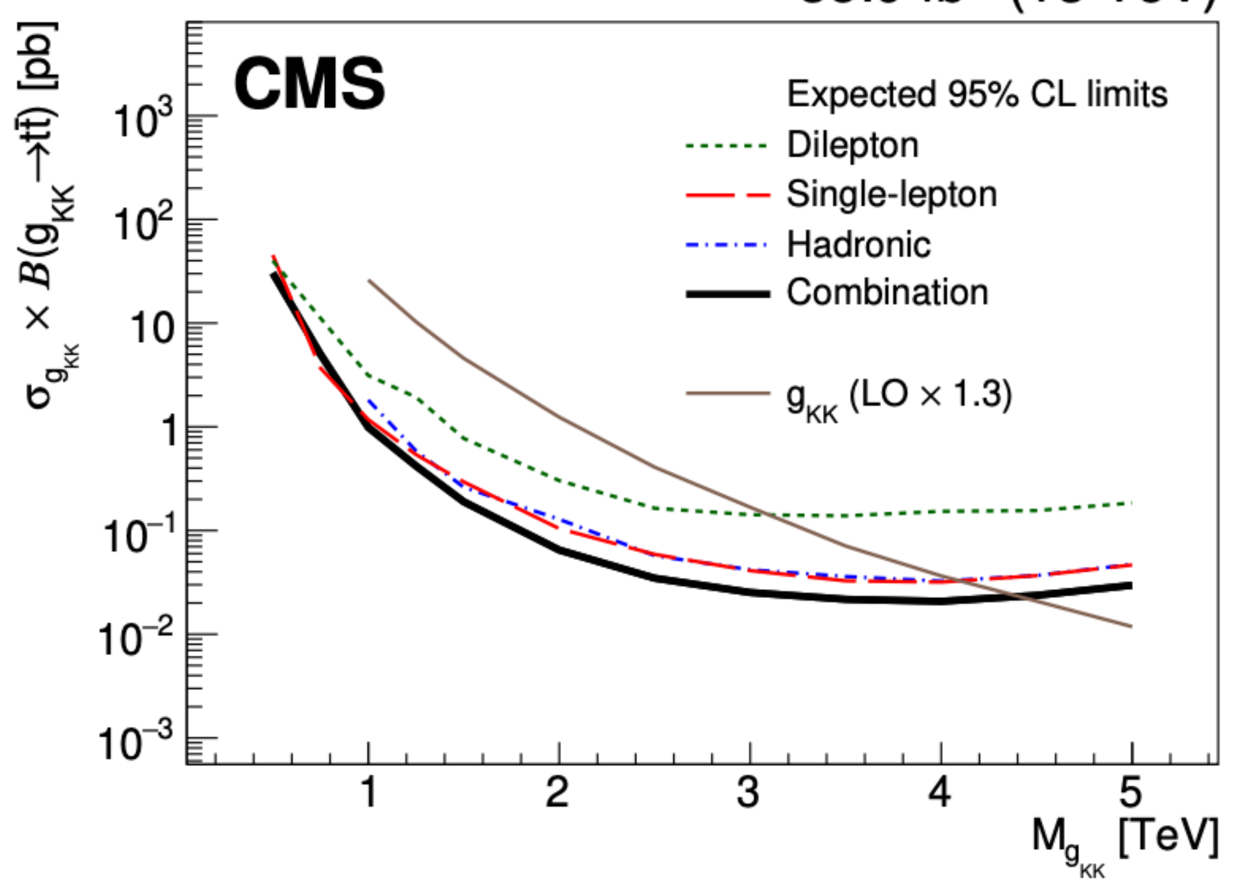

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