

*Beyond the SM
Physics*

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Karlsruhe Institute of Technology

VSOP-28: July 24 - August 5, 2022
ICISE, Quy Nhon, Viet Nam

Outline

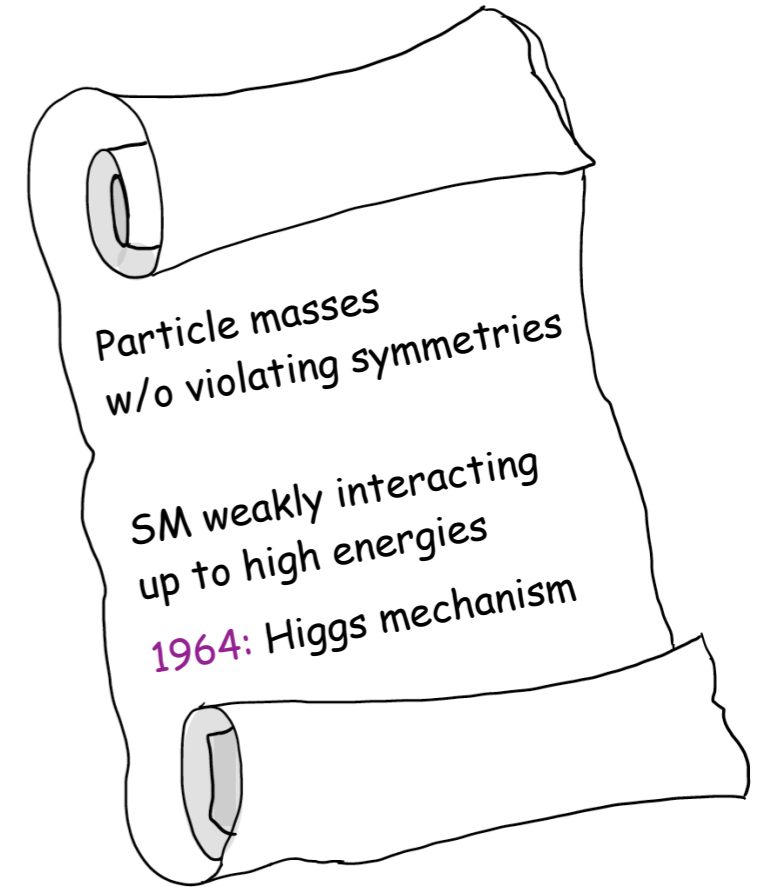
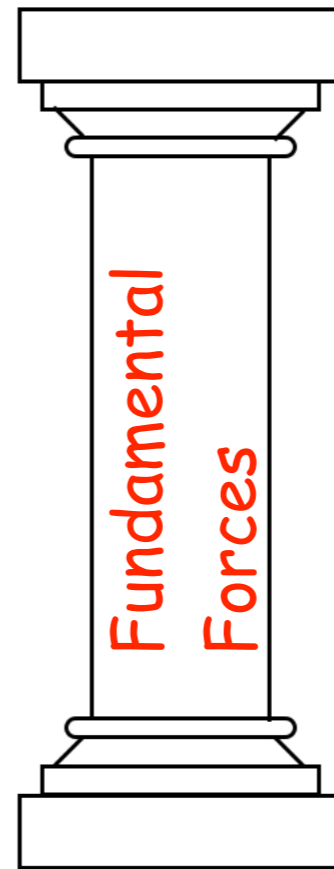
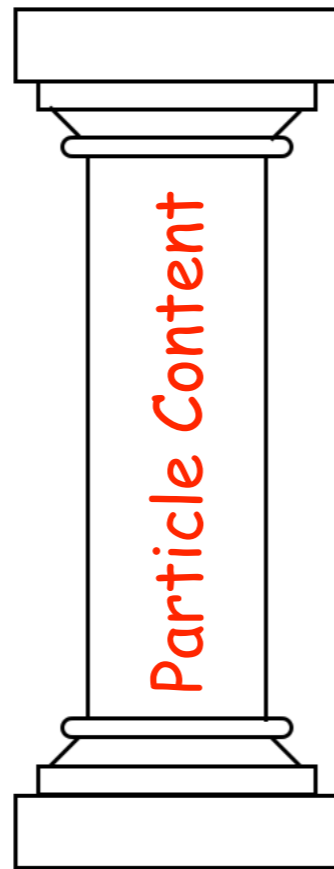
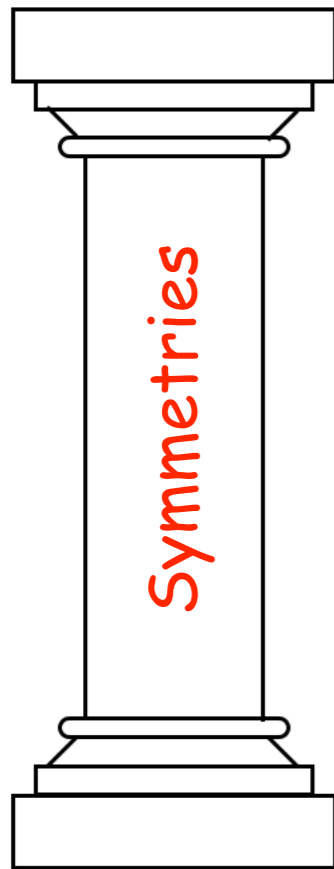
- ✦ Status
- ✦ New Physics Extensions: general remarks
- ✦ Specific New Physics extensions: guidelines, constraints
- ✦ The 2-Higgs Doublet Model: the Higgs sector
- ✦ Coming back to the constraints: detailed discussion
- ✦ A little bit of Higgs phenomenology: Higgs production and decay channels
- ✦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

Status

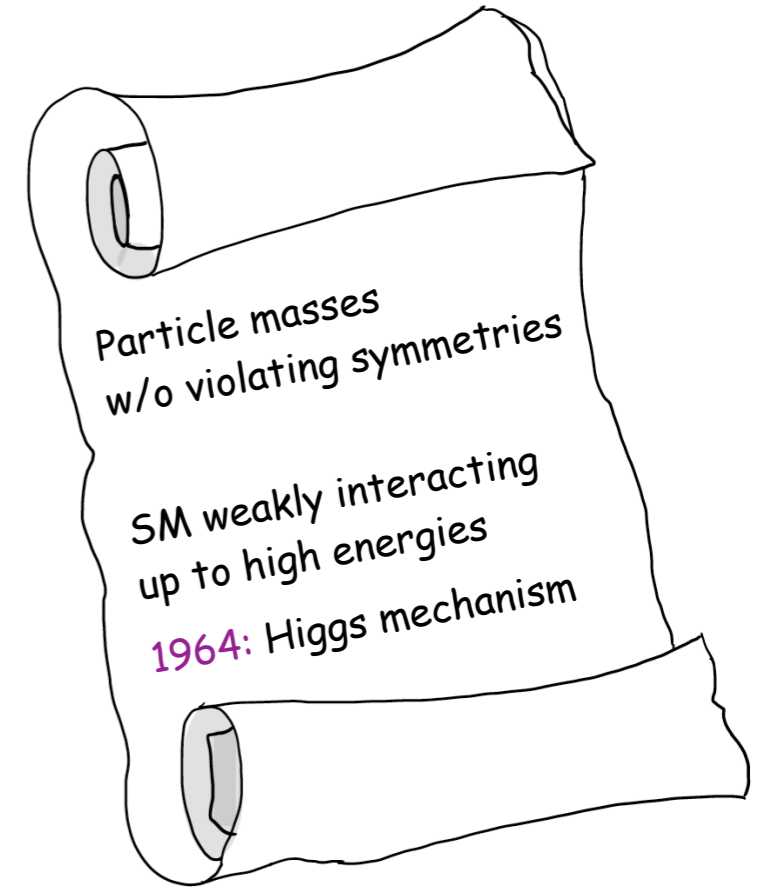
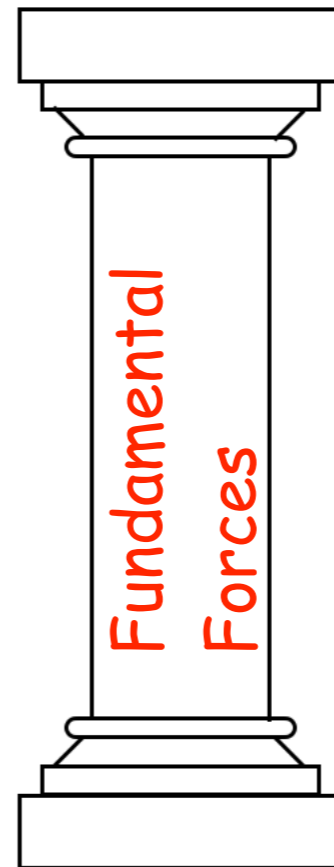
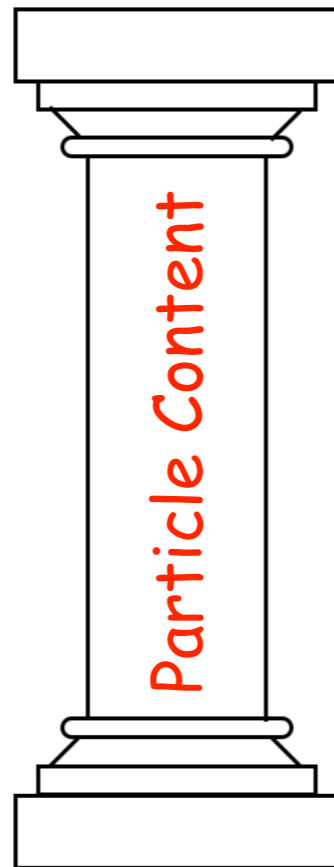
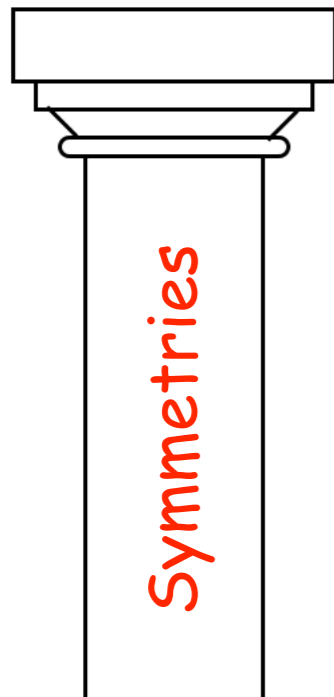


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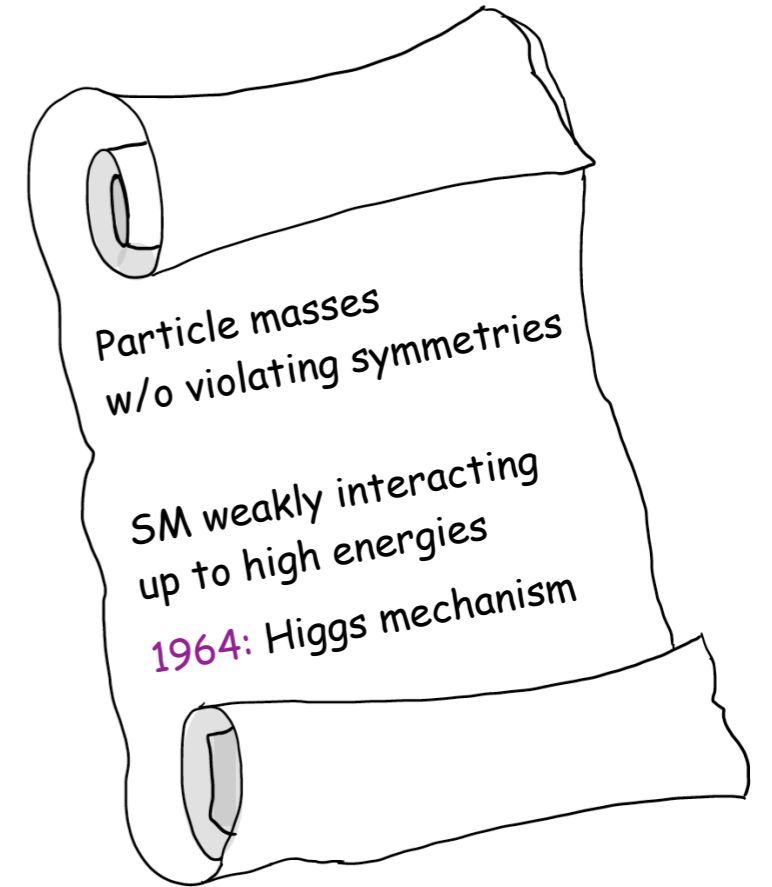
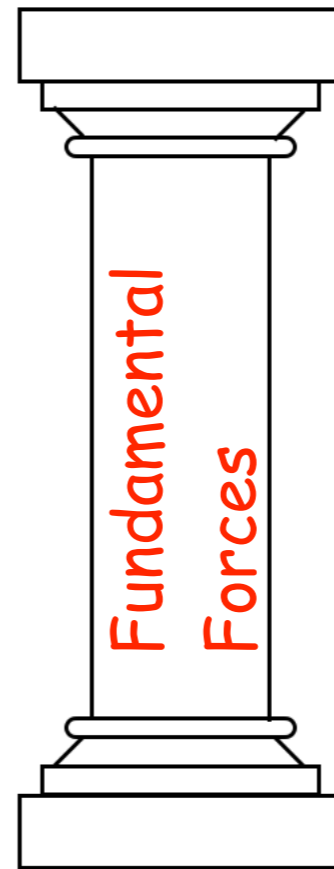
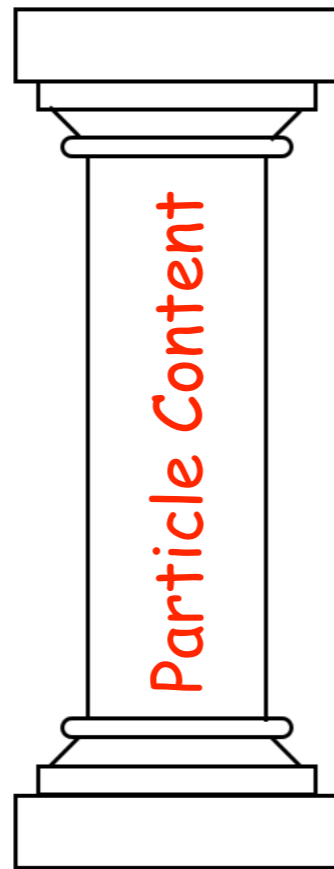
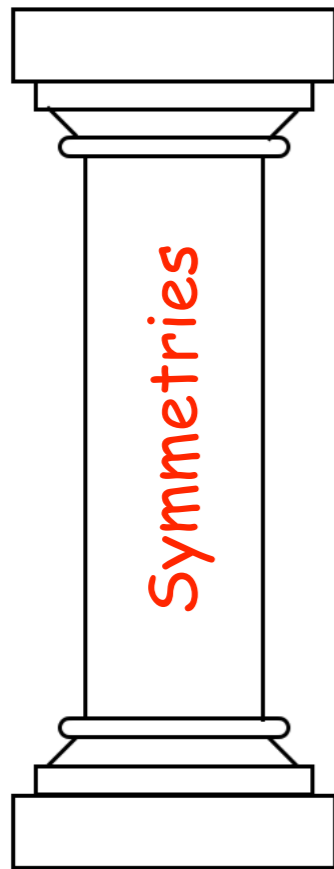
The Four Pillars of the Standard Model



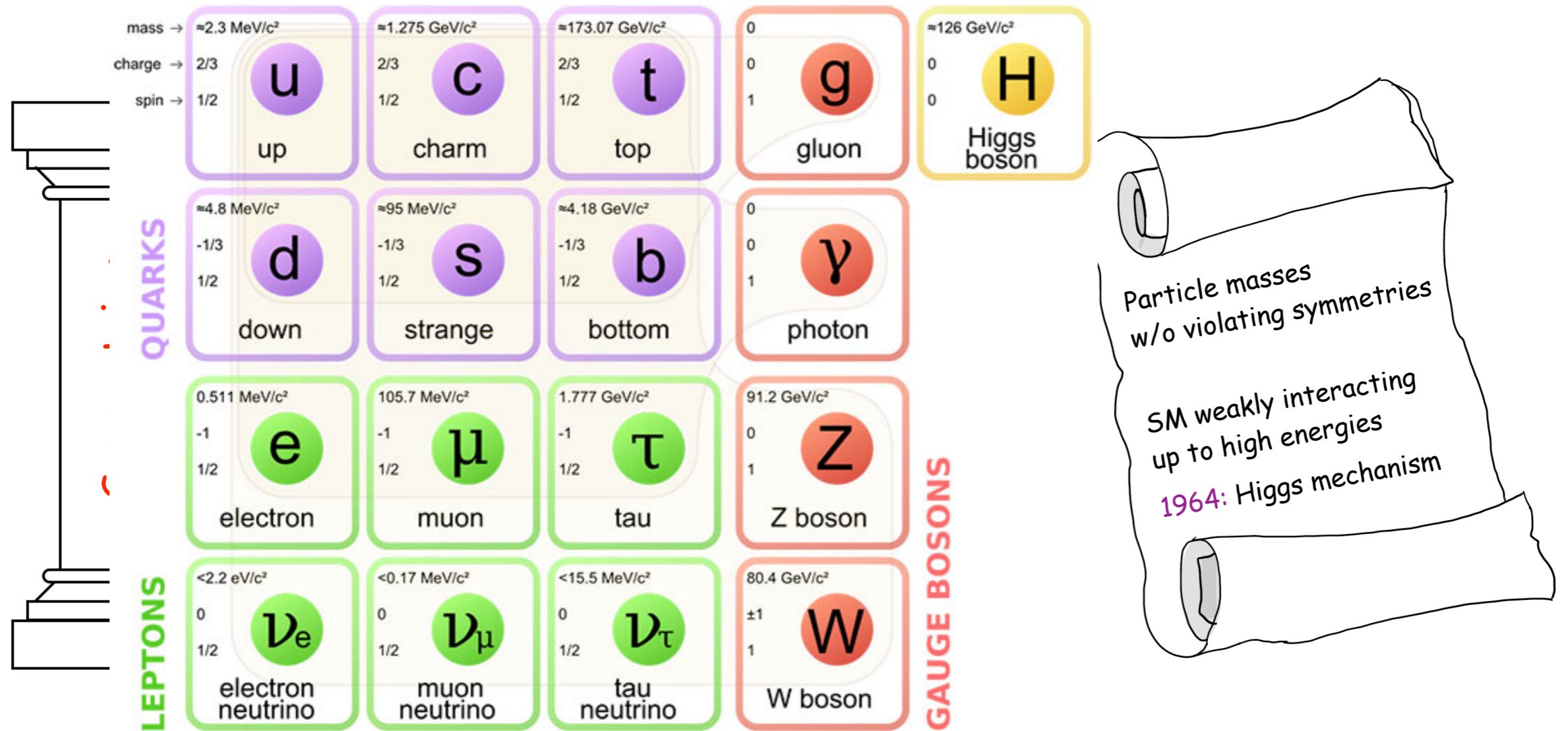
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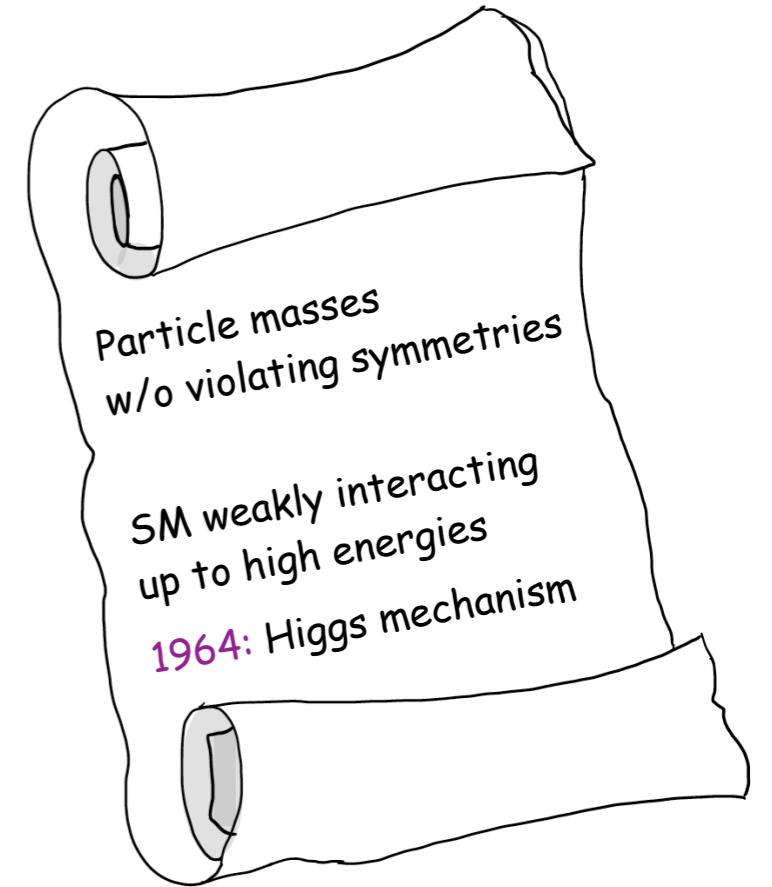
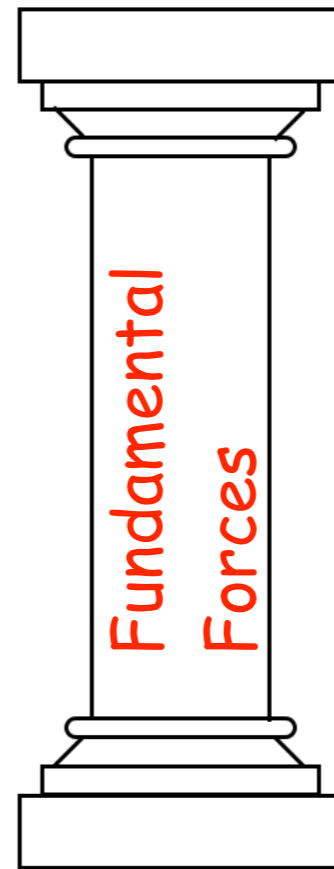
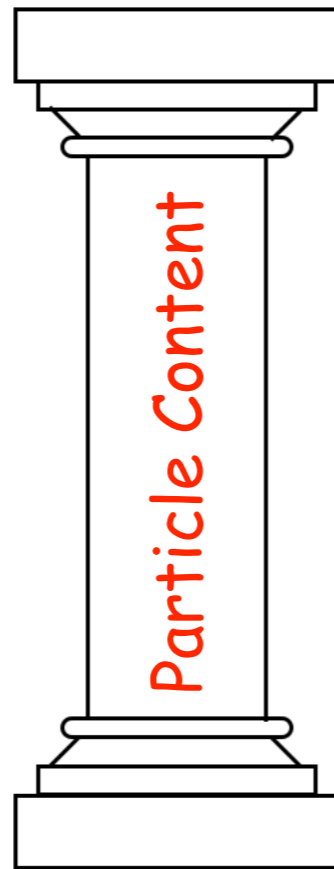
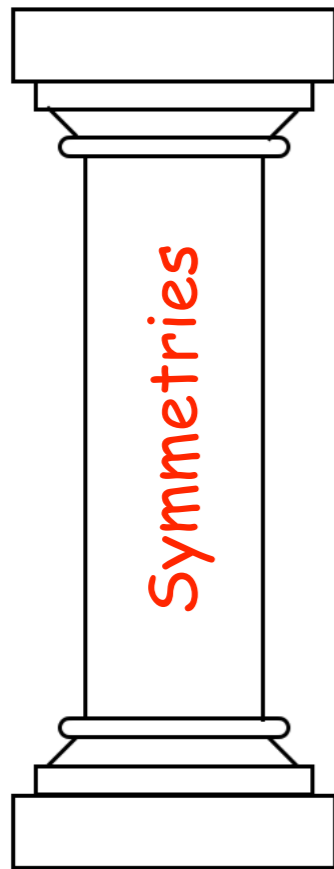
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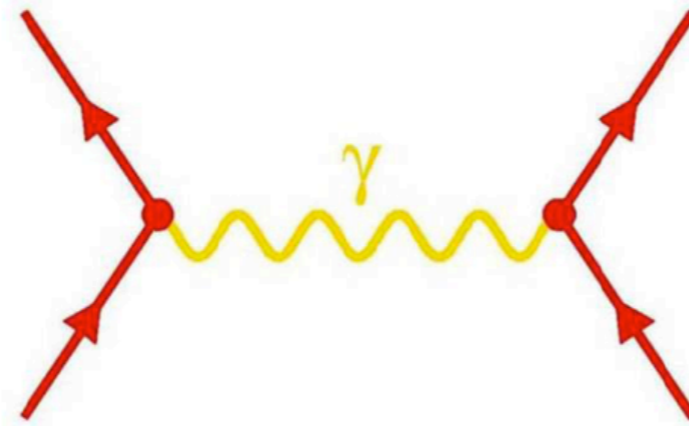
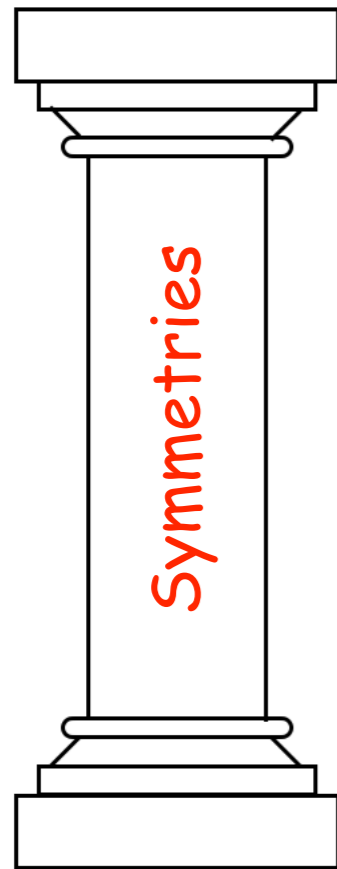
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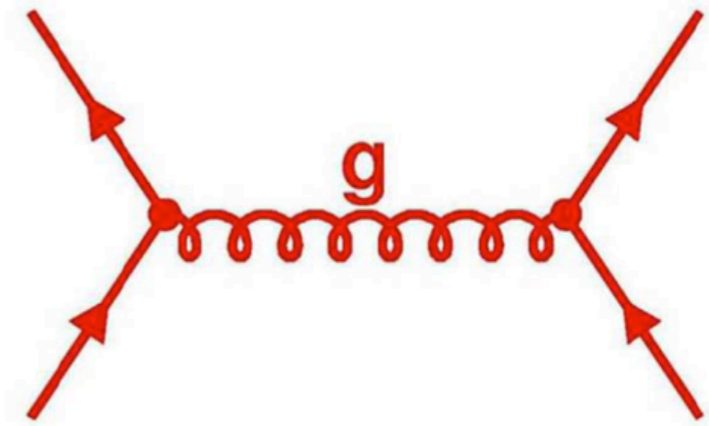
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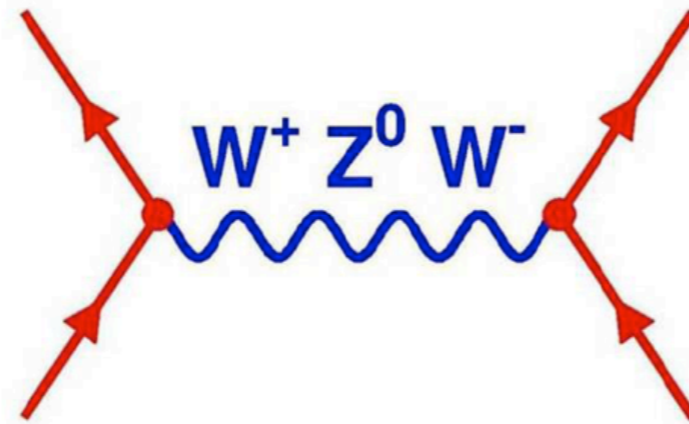
The Four Pillars of the Standard Model



elektromagn. Kraft



starke Kraft



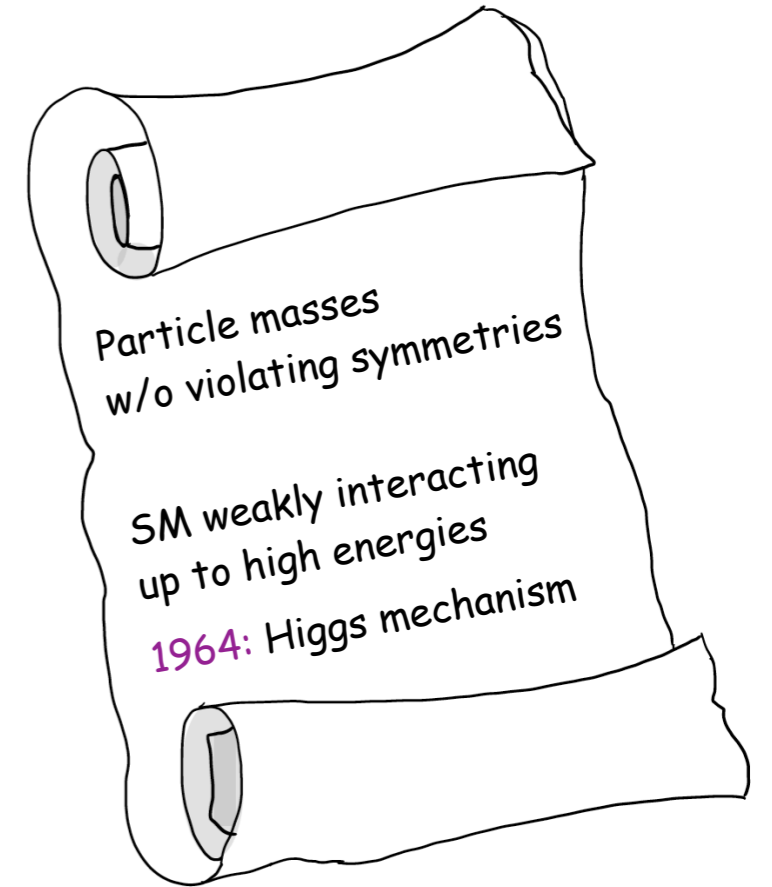
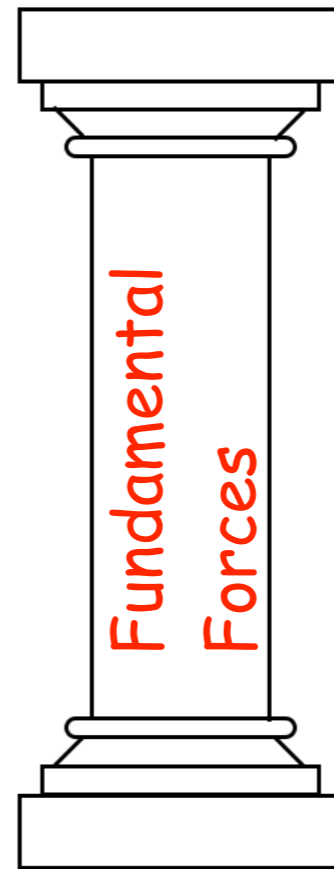
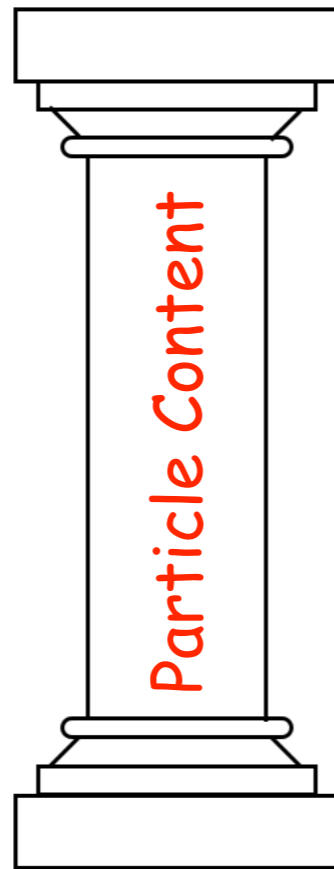
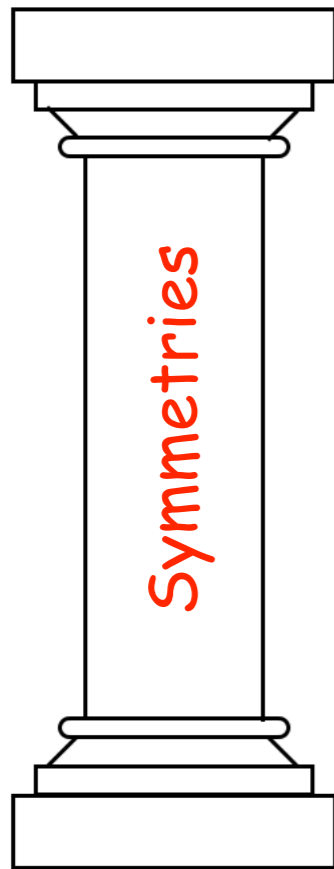
schwache Kraft



Gravitation

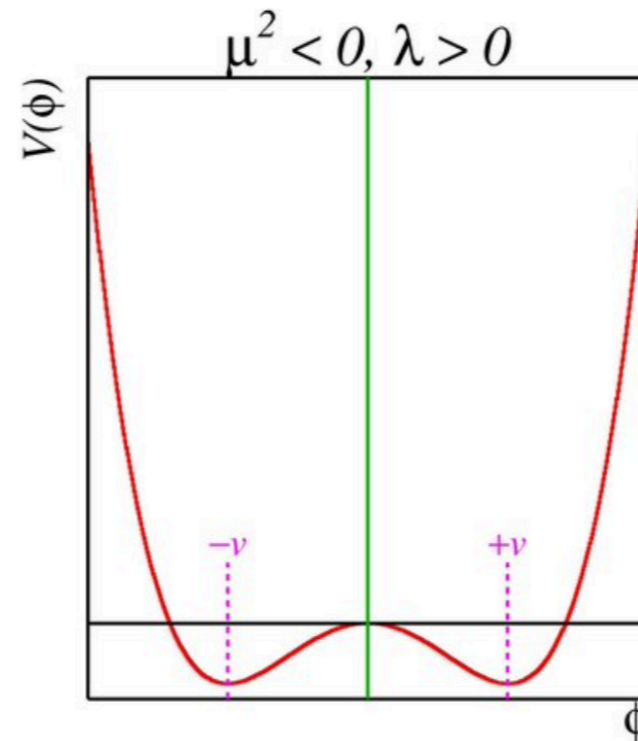


The Four Pillars of the Standard Model



Higgs Mechanism

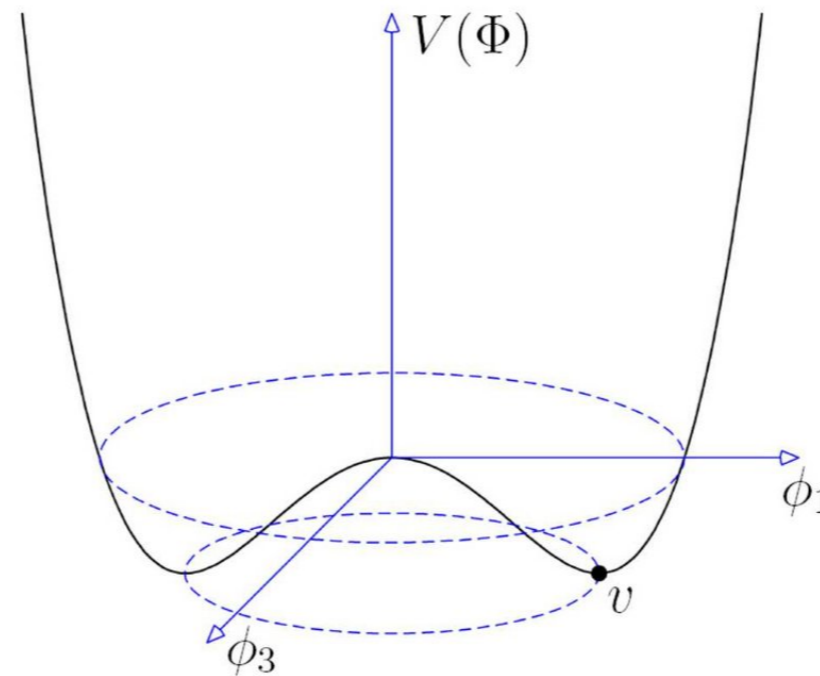
- ♦ **Higgs potential:** non-vanishing vacuum expectation value



- ♦ **Generation of particle masses:** particles couple with Higgs boson in the ground state
mass $\sim g \cdot v$
- ♦ **Spontaneous symmetry breaking:** SM symmetry broken by the ground state
- ♦ **Existence of Higgs particle H**

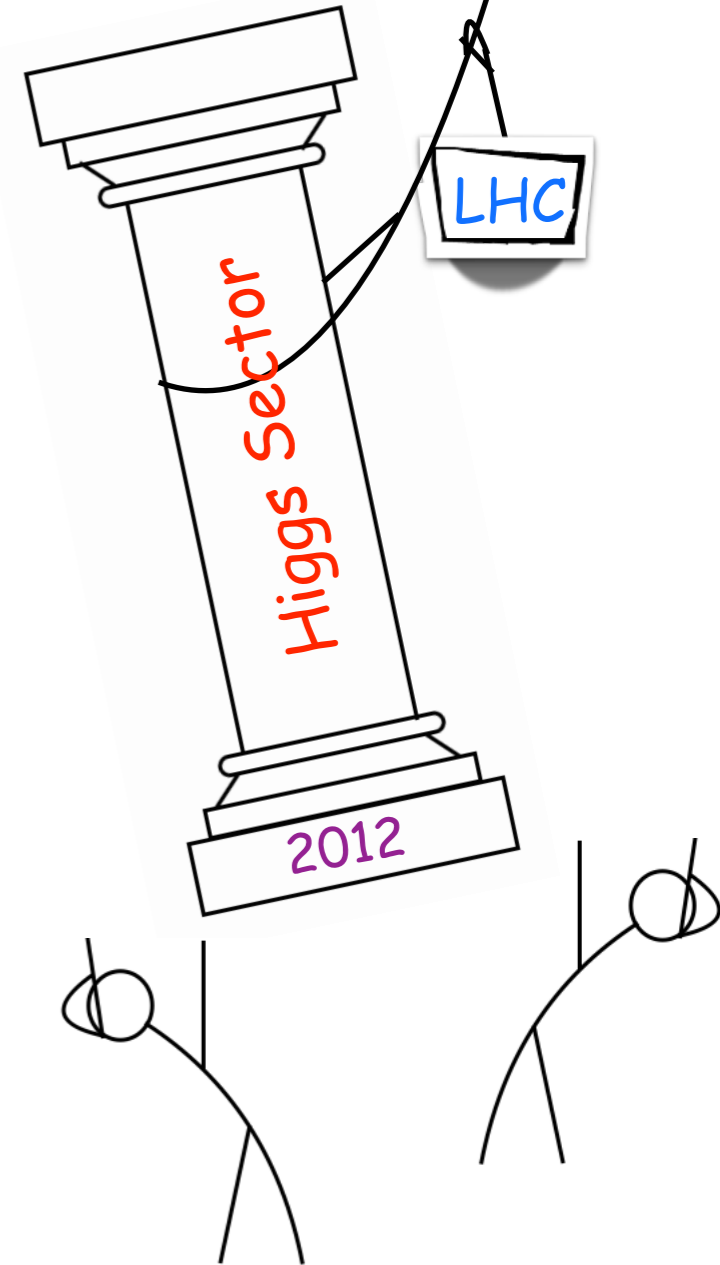
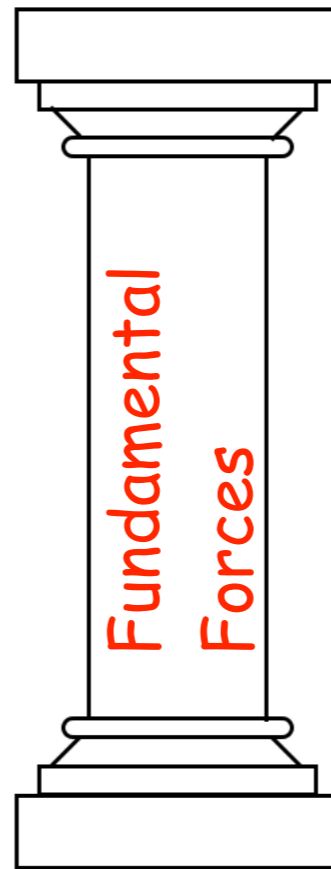
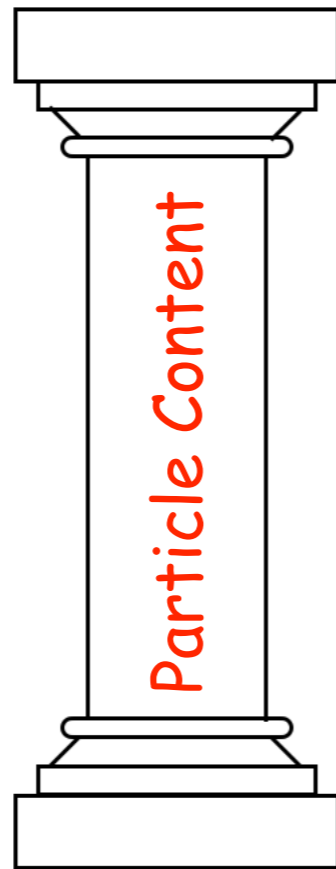
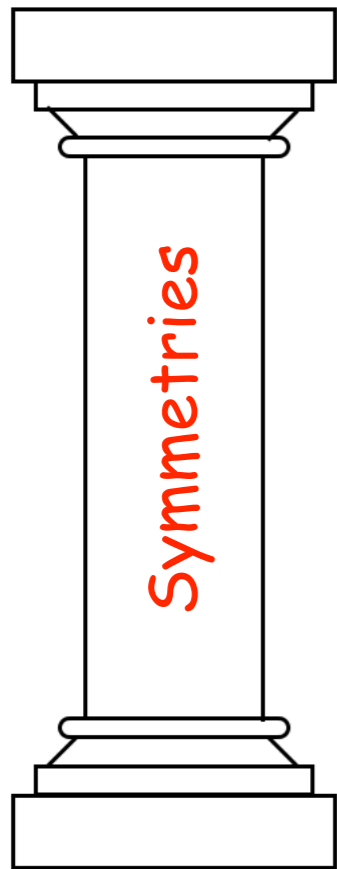
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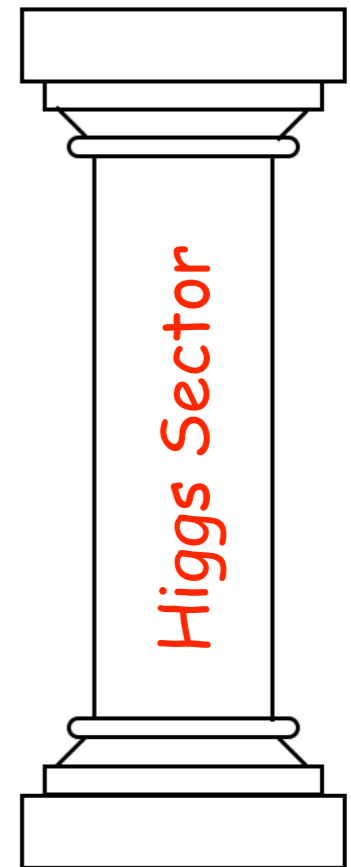
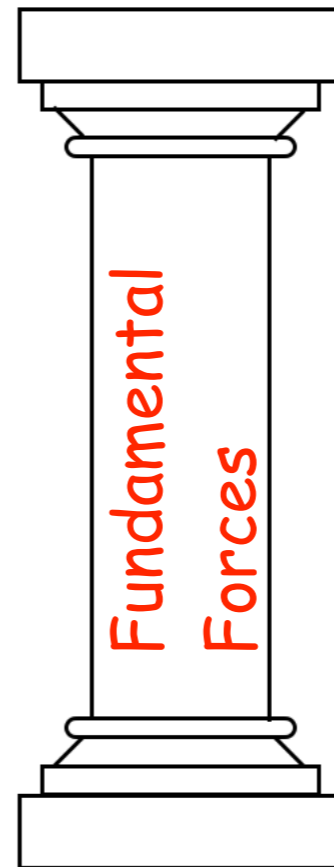
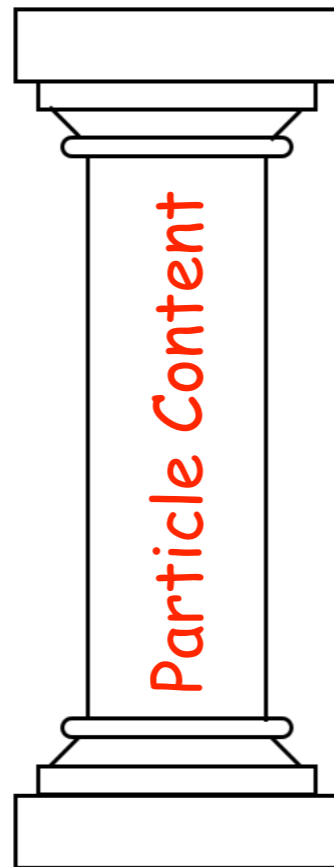
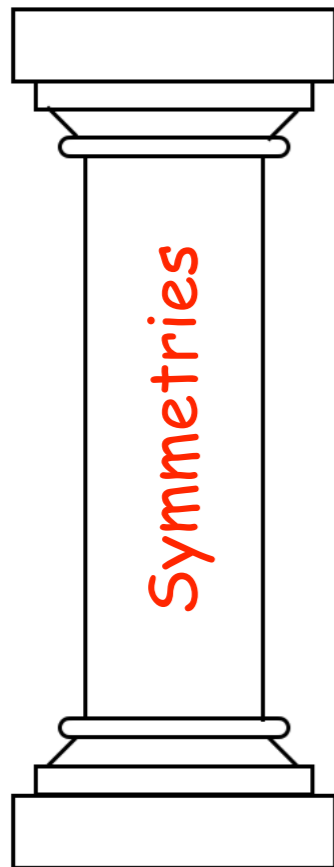


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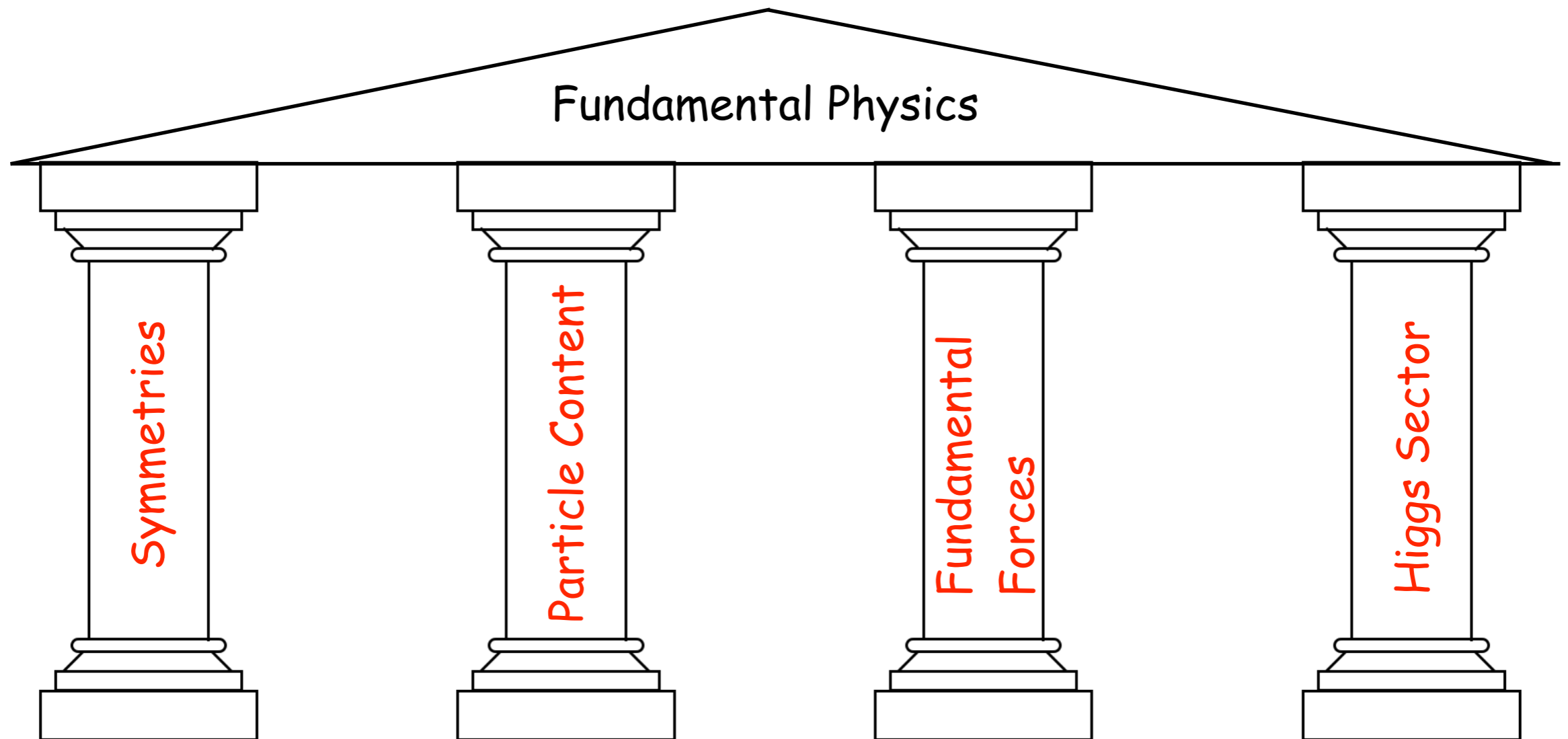
The Four Pillars of the Standard Model



The Four Pillars of the Standard Model



The Standard Model is Structurally Complete



Higgs Discovery: 4.7.2012

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

14 Mar 2013

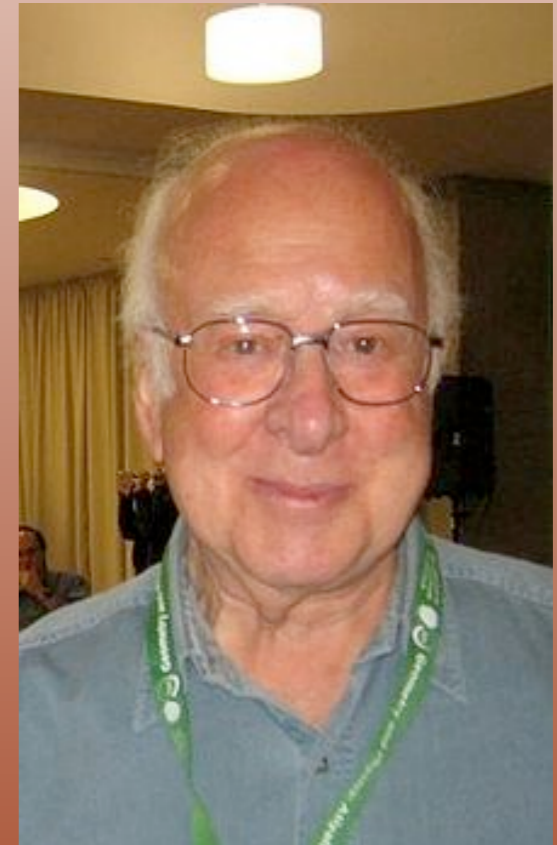
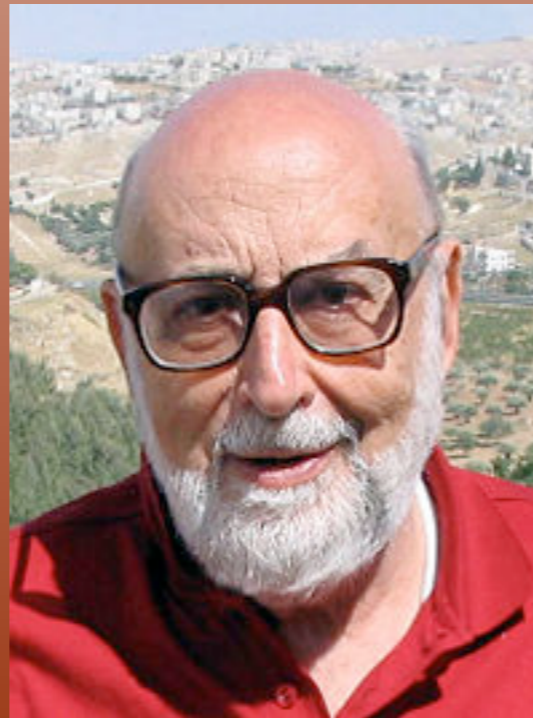
Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN¹'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery 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

The Higgs Mechanism

1964

Brout-Englert-Higgs-Mechanismus



The Higgs Mechanism

1964

Brout-Englert-Higgs-Mechanismus

Physik Nobelpreis 2013



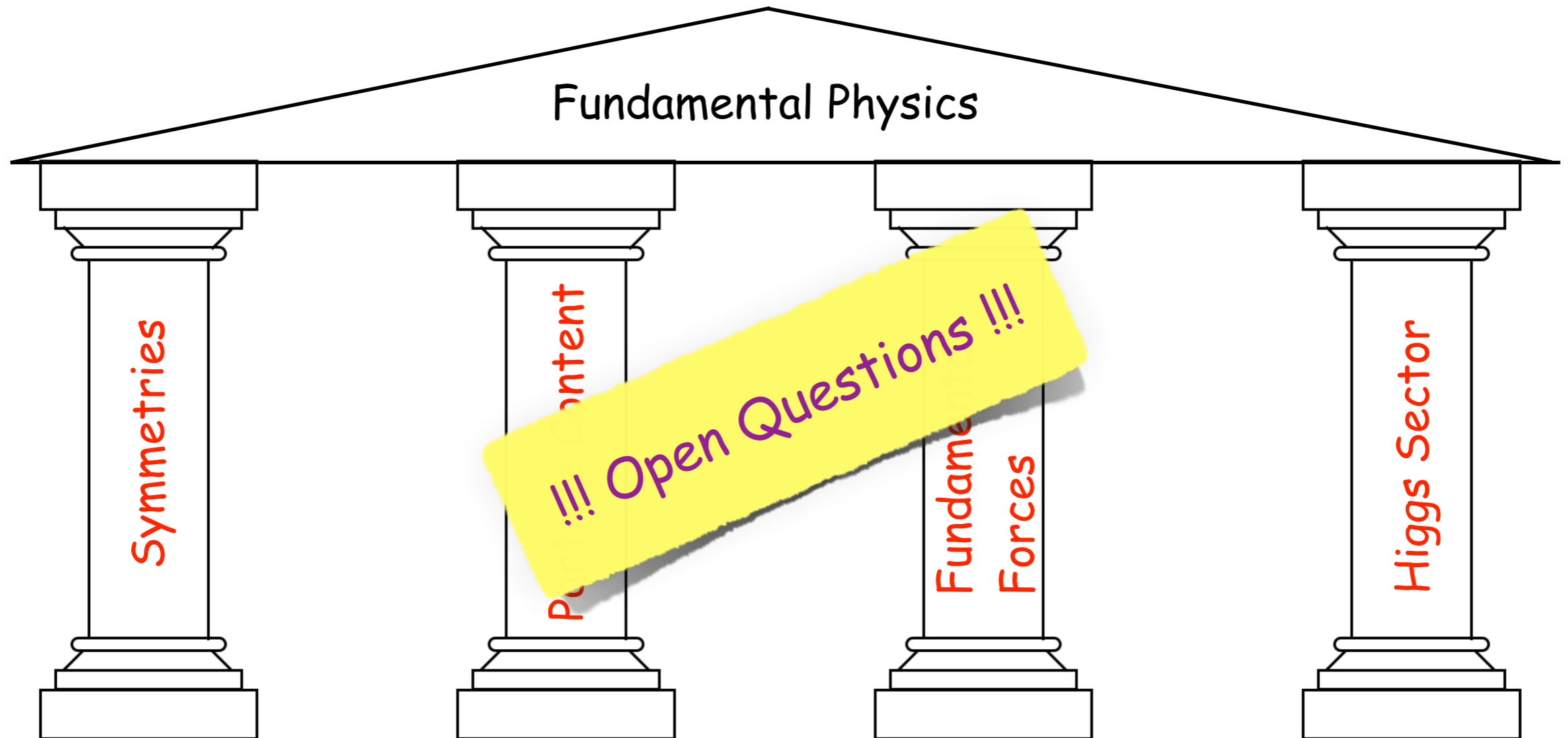
Higgs 10th Birthday!

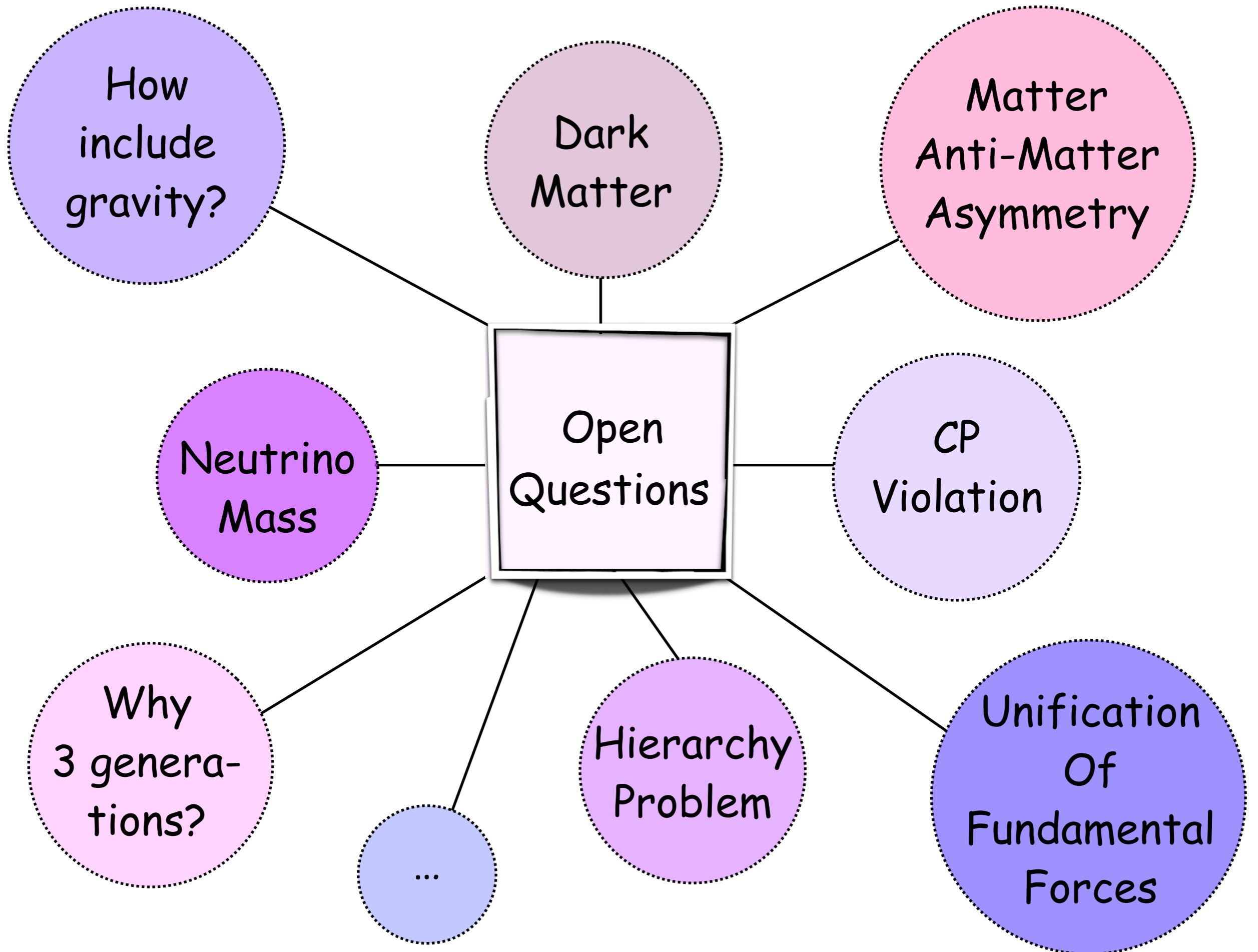


Higgs 10th Birthday!



The Standard Model is Structurally Complete - But





Hierarchy Problem

Consider QED

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

with the covariant derivative

$$D_{\mu} = \partial_{\mu} + ieA_{\mu}(x) \quad (2)$$

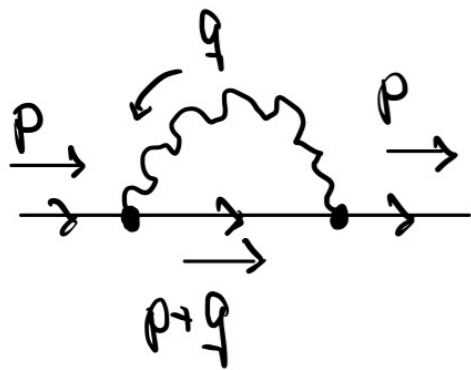
↑ Vector potential
↑ coupling constant

field strength tensor

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

Quantum corrections to the fermion mass:

Λ cut-off scale ; $\alpha = \frac{e^2}{4\pi}$



$$\delta m \sim \alpha \int \frac{d^4q}{(2\pi)^4} \frac{(p+q)}{q^2 (p+q)^2} \sim \alpha \int |q|^3 dq \frac{1}{q^3} \sim \alpha \int dq \sim \alpha \Lambda \quad (4)$$

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

Hierarchy Problem

Why is $\delta m \sim m$?

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

$$\psi \rightarrow e^{i\alpha\gamma_5}\psi, \quad \bar{\psi} \rightarrow \bar{\psi}e^{-i\alpha\gamma_5} \quad (6)$$

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

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

$$\leadsto m\bar{\psi}\psi \rightarrow m\bar{\psi}e^{i\alpha\gamma_5}\psi \quad (8)$$

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

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

Symmetry protects mass against large radiative corrections.

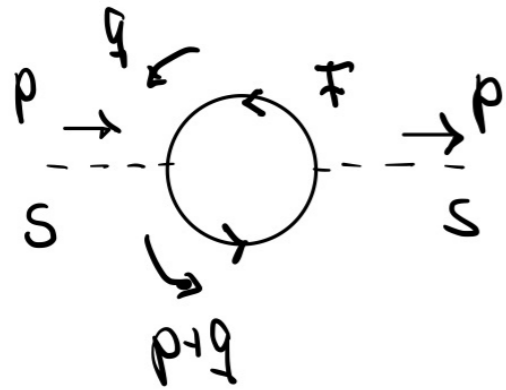
Hierarchy Problem

What about scalars?

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

$$\not{\partial} = \gamma^{\mu}\partial_{\mu}, \quad S \text{ scalar}$$

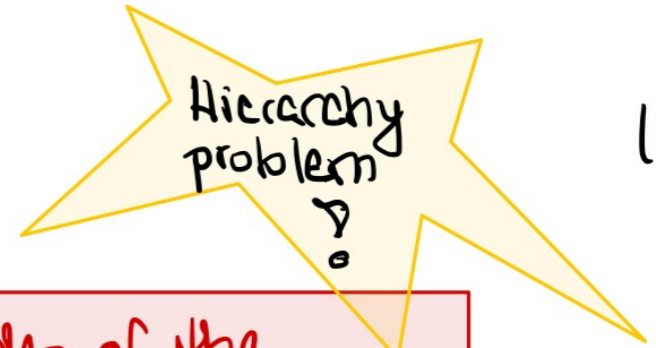
quantum correction to scalar mass: dimensional analysis



$$\sim \frac{\lambda^2}{F} \int \frac{d^4q}{(2\pi)^4} \frac{q(p+q)}{q^2(p+q)^2} \sim \frac{\lambda^2}{F} \int |q|^3 dq \frac{1}{q^2} \sim \frac{\lambda^2}{F} \int dq q \quad (10)$$

$$\sim \frac{\lambda^2}{F} \Lambda^2$$

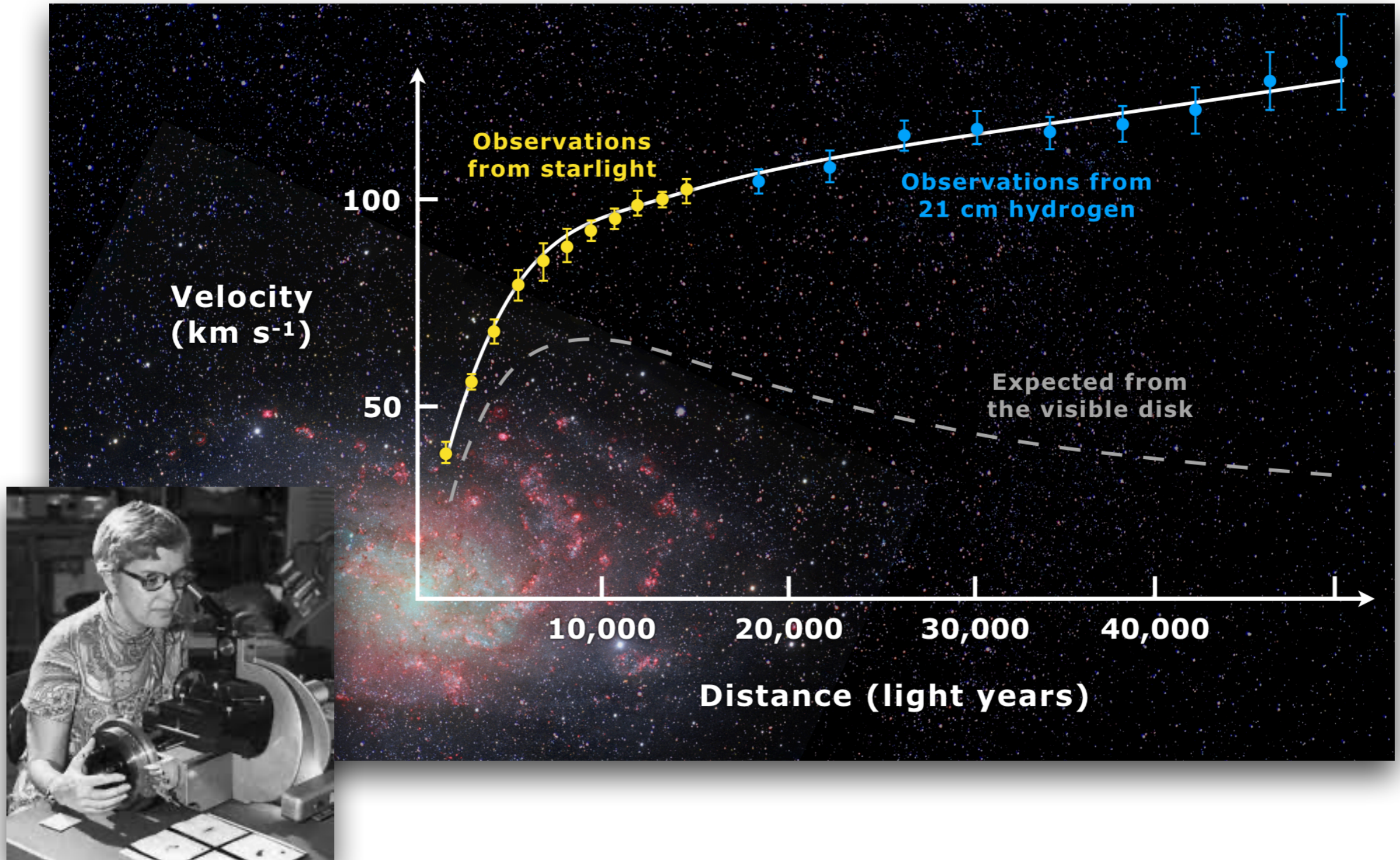
$$\delta m_S^2 \sim \frac{\lambda^2}{F} \Lambda^2 \quad \text{quadratic divergence}$$



(11)

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?

Dark Matter



Dark Matter

Expectation:

centripetal force = gravitational force

$$\frac{mv_p^2}{r} = G \frac{M_p m}{r^2} \quad \leadsto \quad v_p^2 = G \frac{M_p}{r} \quad (1)$$

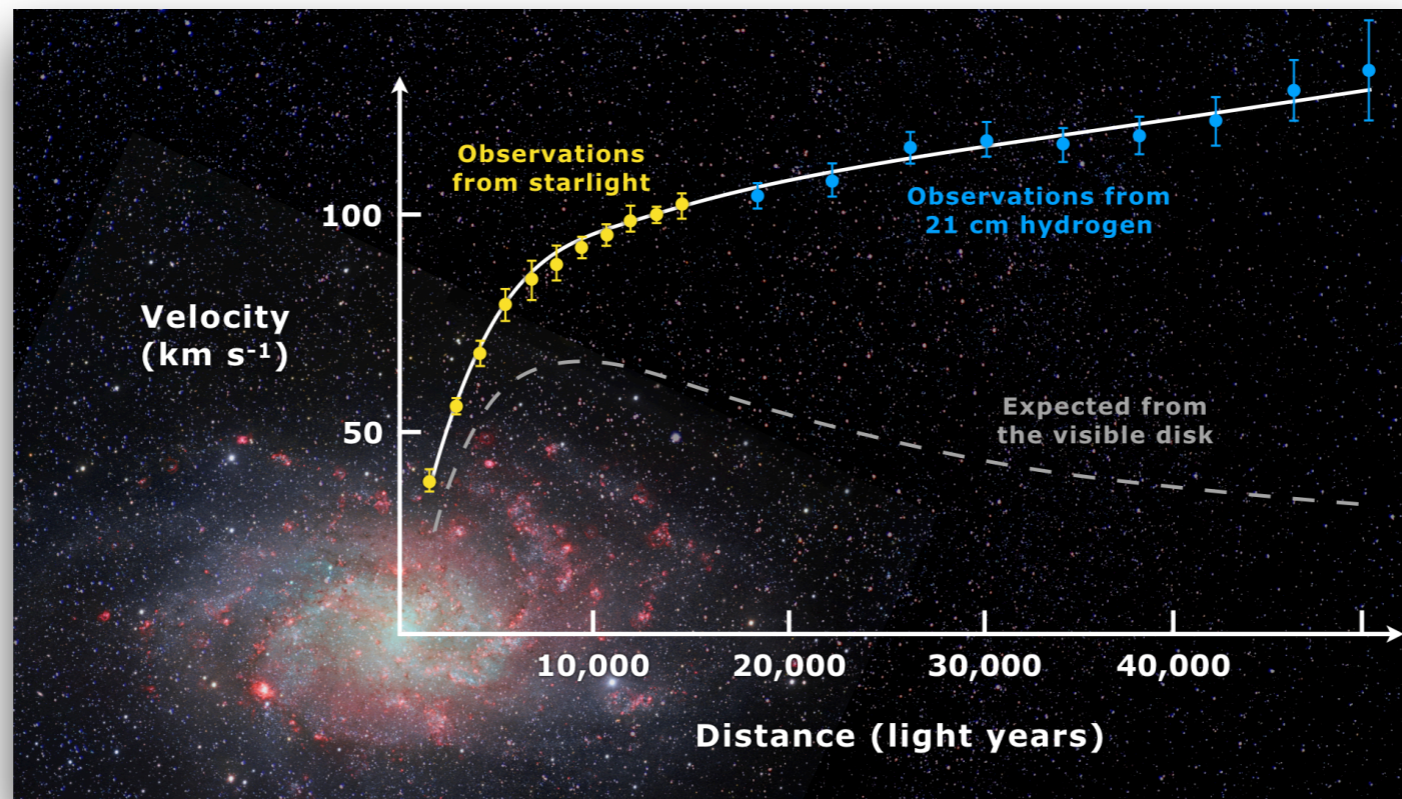
$$\leadsto \quad v_p = \sqrt{\frac{GM_p}{r}} \quad \leadsto \quad v_p \sim \frac{1}{\sqrt{r}} \quad (2)$$

Observation:

$v_p (r \geq R_0) \simeq \text{const.}$

(3)

$\leadsto M_p \sim r$



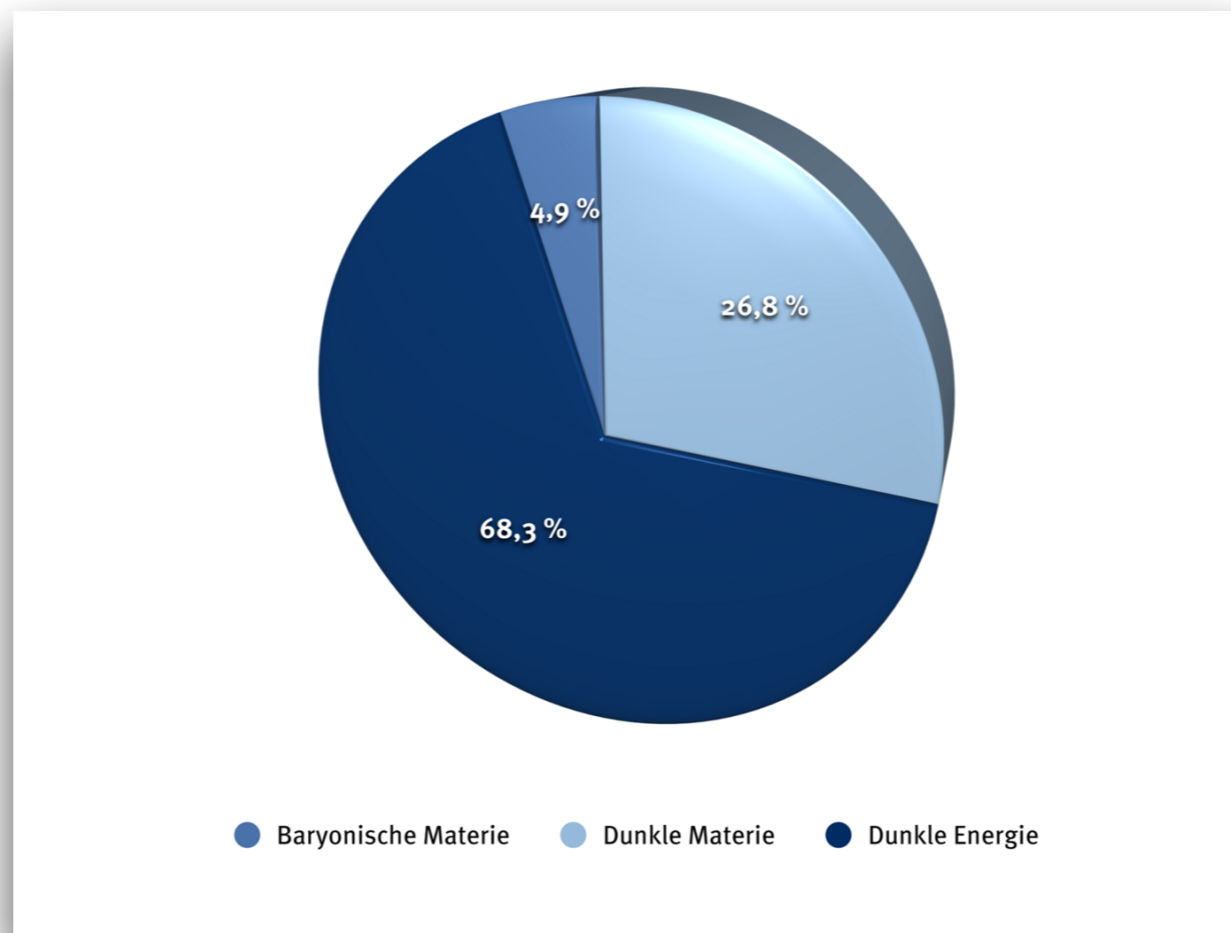
Relic Abundance

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

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**



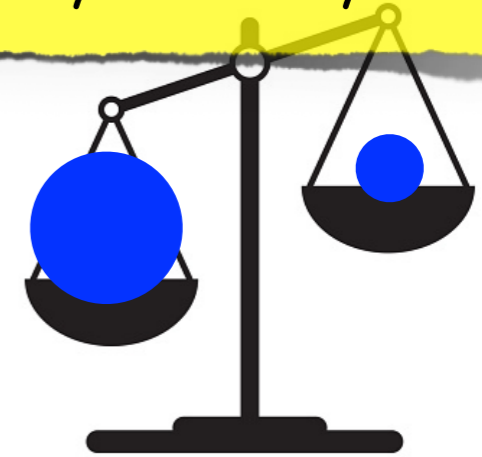
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Why must there obviously be an asymmetry?



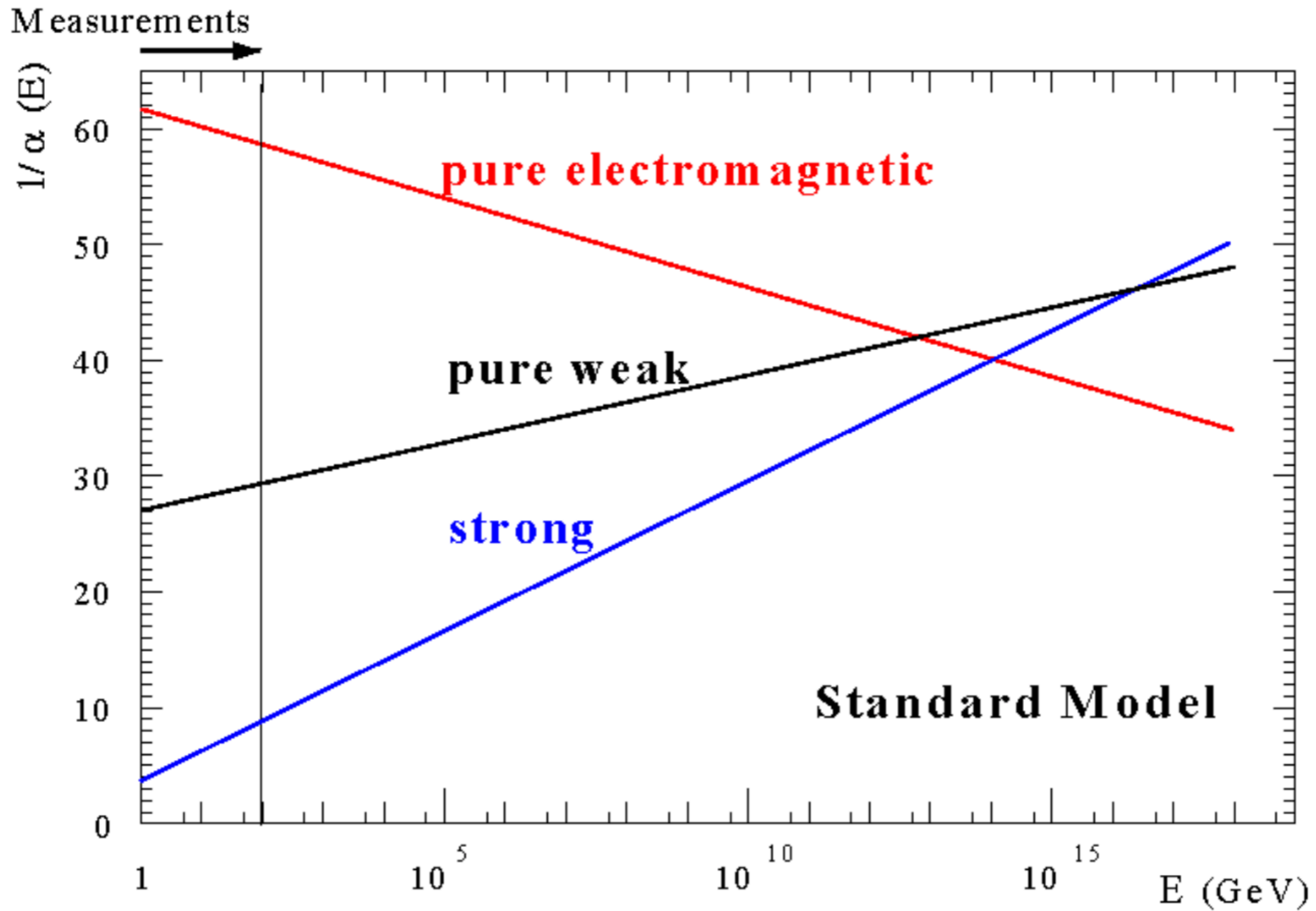
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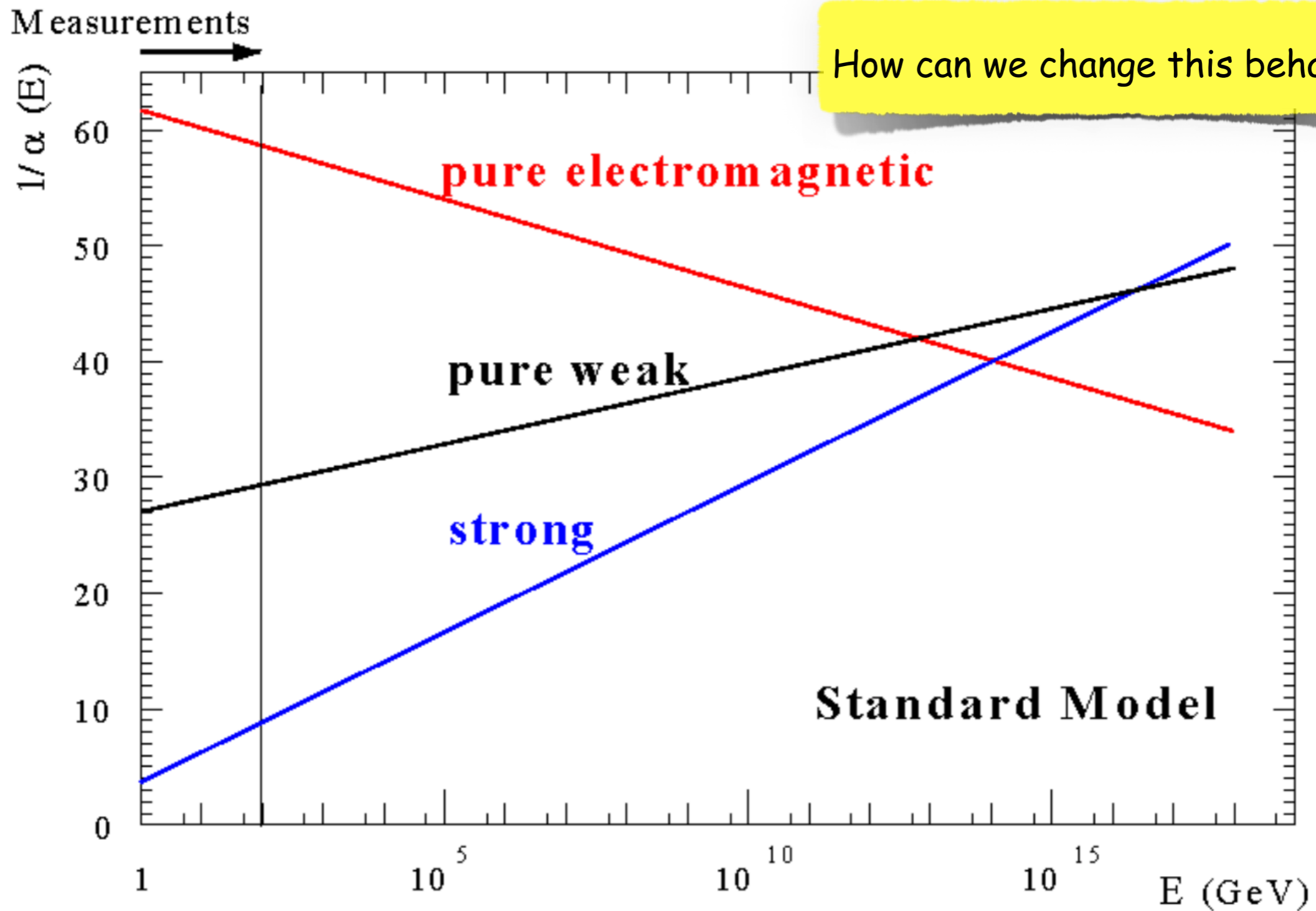
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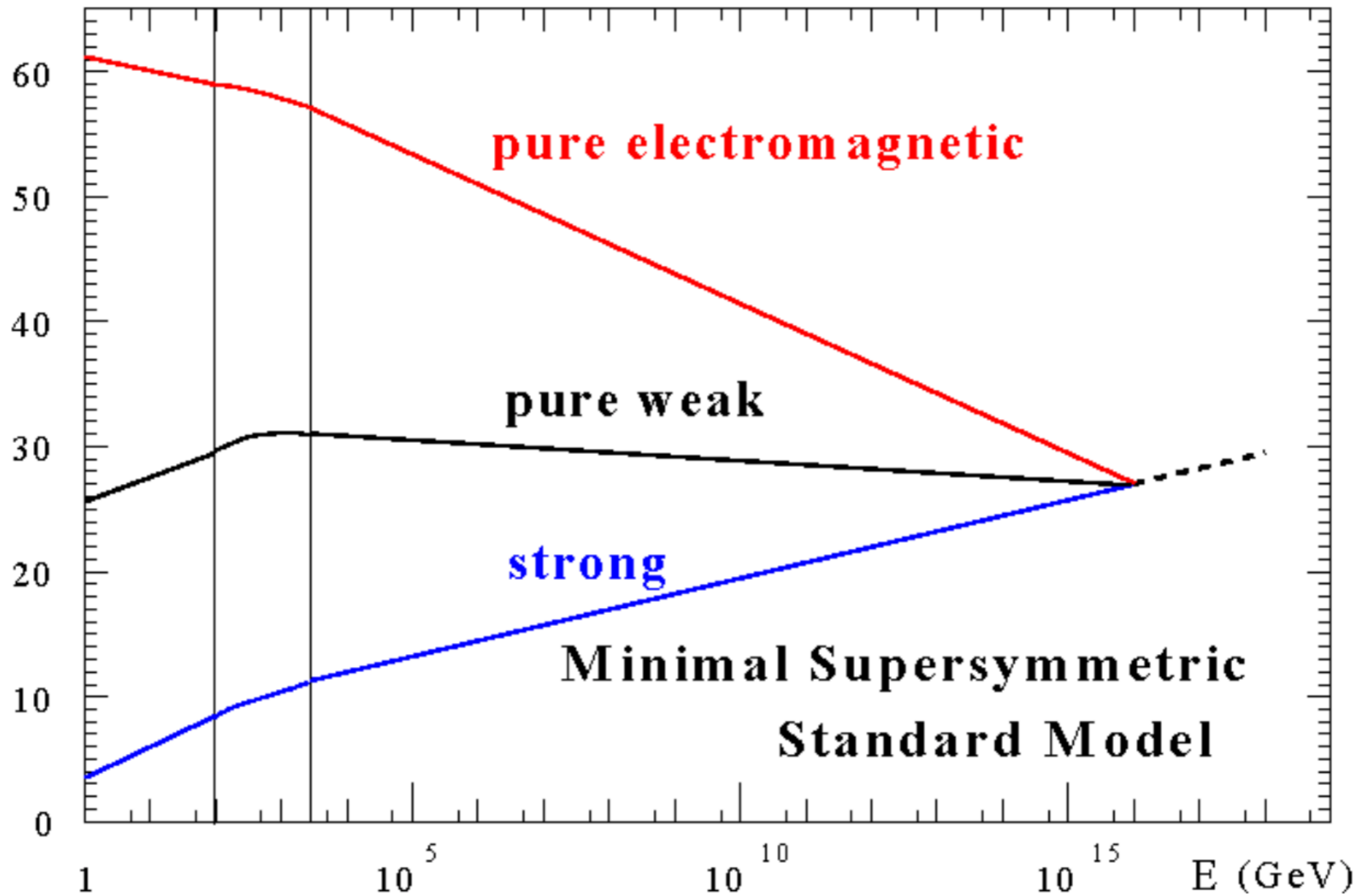
Unification of Fundamental Forces!

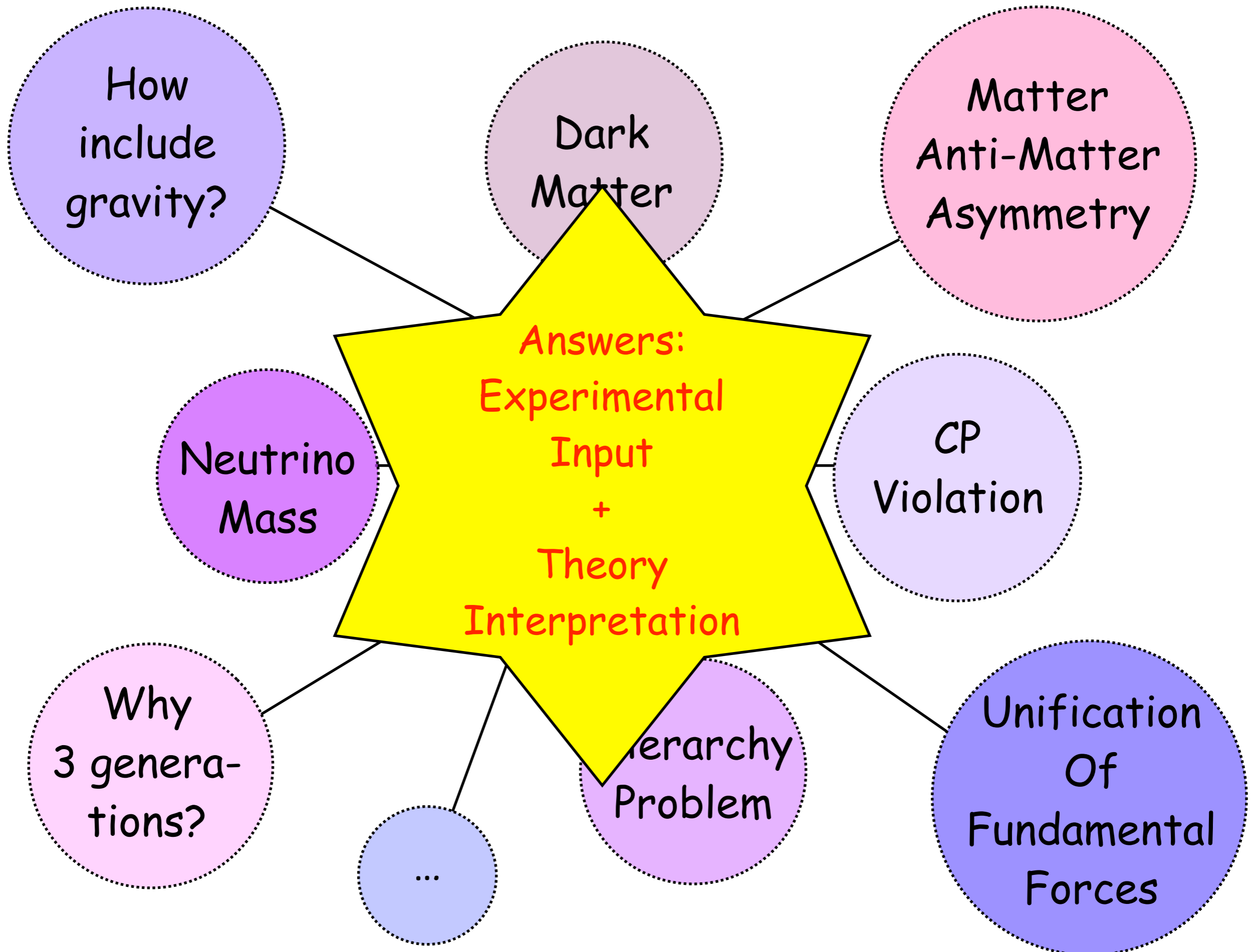


Unification of Fundamental Forces!



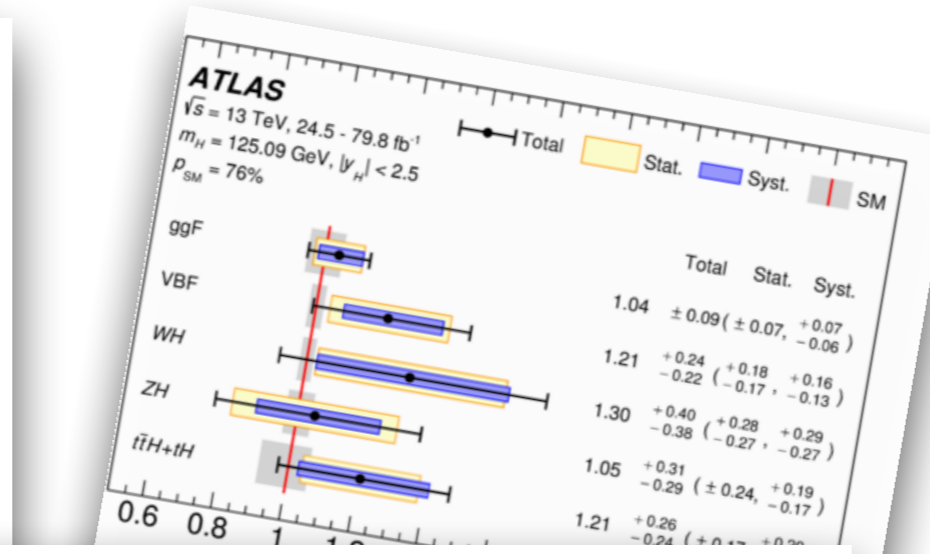
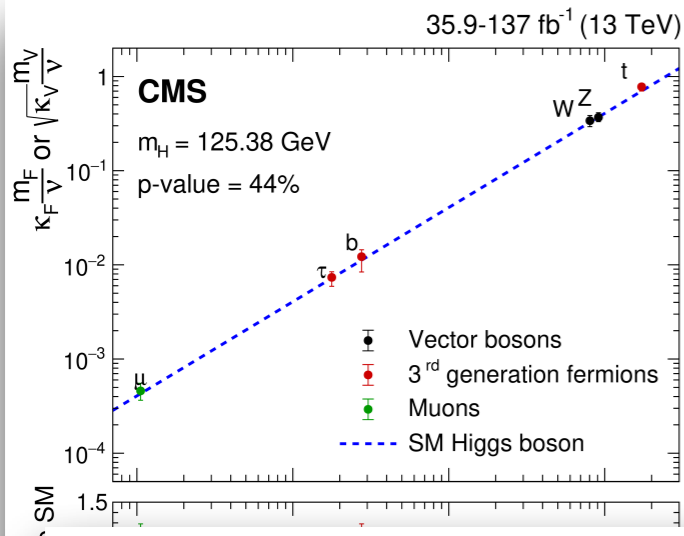
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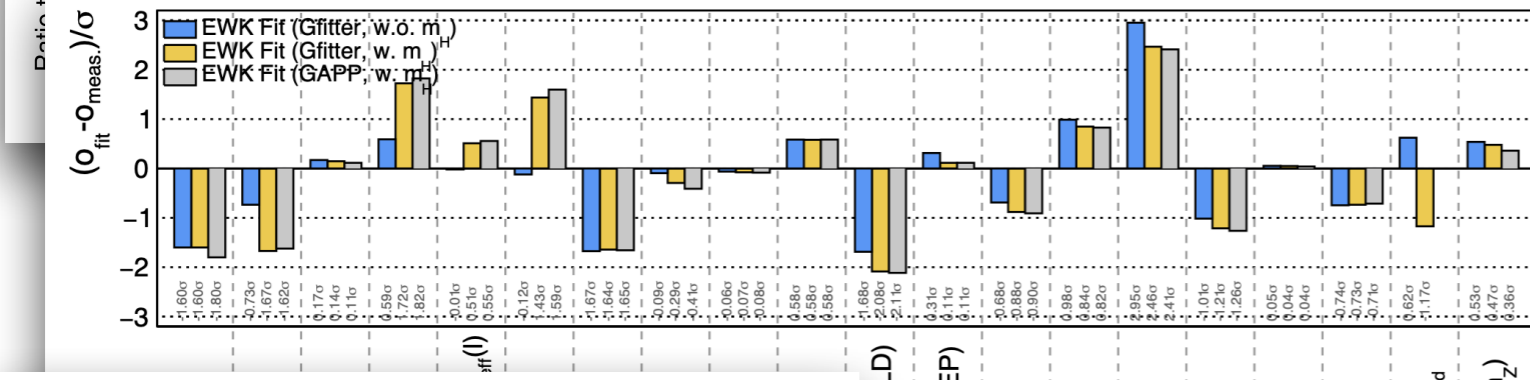




Status



Discovered Higgs Boson behaves very SM-like



Consistency Test of the SM at the quantum level

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
 Status: July 2021

Model	f, γ	Jets	E_{miss}	Limit	Reference	
ADD $G_{UV} + g/g$	$0, e, \mu, \tau, \gamma$	1-4	Yes	$M_{Pl} > 11.2 \text{ TeV}$	2102.10874	
ADD non-resonant $\gamma\gamma$	$2, \gamma$	-	Yes	$M_{Pl} > 8.8 \text{ TeV}$	1702.04147	
ADD QSH	-	2	-	$M_{Pl} > 8.9 \text{ TeV}$	1703.09127	
ADD BH multijet	-	-	-	$M_{Pl} > 8.9 \text{ TeV}$	1612.05586	
RS1 $G_{UV} \rightarrow \gamma\gamma$	$2, \gamma$	-	Yes	$M_{Pl} > 11.2 \text{ TeV}$	2102.10874	
Bulk RS $G_{UV} \rightarrow WW/ZZ$	multi-channel	-	Yes	$M_{Pl} > 11.2 \text{ TeV}$	1608.02080	
Bulk RS $G_{UV} \rightarrow WZ$	$1, e, \mu$	2/1/1	Yes	$M_{Pl} > 11.2 \text{ TeV}$	2004.14636	
Bulk RS $G_{UV} \rightarrow \tau\tau$	$1, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{Pl} > 11.2 \text{ TeV}$	1804.10623	
UED (RPV)	$1, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{Pl} > 11.2 \text{ TeV}$	1602.06273	
SSM $Z' \rightarrow \tau\tau$	$2, e, \mu$	-	Yes	$M_{Z'} > 2.42 \text{ TeV}$	1902.06248	
SSM $Z' \rightarrow \tau\tau$	$2, \tau$	-	Yes	$M_{Z'} > 2.1 \text{ TeV}$	1709.07262	
Leptophobic $Z' \rightarrow \tau\tau$	$2, \tau$	-	Yes	$M_{Z'} > 2.1 \text{ TeV}$	1805.09239	
Leptophobic $Z' \rightarrow \tau\tau$	$0, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{Z'} > 2.1 \text{ TeV}$	2005.09138	
SSM $W' \rightarrow \nu\nu$	$1, e, \mu$	-	Yes	$M_{W'} > 4.4 \text{ TeV}$	1905.09239	
SSM $W' \rightarrow \nu\nu$	$1, \tau$	-	Yes	$M_{W'} > 4.4 \text{ TeV}$	ATLAS-CONF-2021-025	
SSM $W' \rightarrow \nu\nu$	$1, e, \mu, \tau$	1/1/1	Yes	$M_{W'} > 4.4 \text{ TeV}$	ATLAS-CONF-2021-043	
HVT $W' \rightarrow WZ$	$1, e, \mu$	2/1/1	Yes	$M_{W'} > 4.3 \text{ TeV}$	2004.14636	
HVT $Z' \rightarrow ZH$ model B	$0, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{Z'} > 3.2 \text{ TeV}$	ATLAS-CONF-2020-043	
HVT $W' \rightarrow WZ$ model B	$0, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{W'} > 3.2 \text{ TeV}$	2007.02052	
LRSM $W_2 \rightarrow \mu\nu$	$2, \mu$	1	-	$M_{W_2} > 5.0 \text{ TeV}$	1904.12879	
Cl eeee	$2, e, \mu$	2	-	$M_{Cl} > 370 \text{ GeV}$	1702.09127	
Cl eeee	$2, e, \mu$	1	-	$M_{Cl} > 2.0 \text{ TeV}$	2006.12546	
Cl eeee	$2, e, \mu$	1b	-	$M_{Cl} > 2.0 \text{ TeV}$	2105.13847	
Cl eeee	$2, e, \mu$	1b	-	$M_{Cl} > 2.0 \text{ TeV}$	2105.13847	
Cl tttt	$> 1, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{Cl} > 2.0 \text{ TeV}$	1811.02395	
DM	Axial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	$M_{DM} > 370 \text{ GeV}$	2102.10874
DM	Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	$M_{DM} > 370 \text{ GeV}$	2102.10874
DM	Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	$M_{DM} > 370 \text{ GeV}$	ATLAS-CONF-2021-026
DM	Pseudo-scalar med. 2HDMa	multi-channel	-	Yes	$M_{DM} > 370 \text{ GeV}$	ATLAS-CONF-2021-026
DM	Scalar reson. $\phi \rightarrow \tau\tau$ (Dirac DM)	$0, e, \mu, \tau, \gamma$	1b, 0-1	Yes	$M_{DM} > 370 \text{ GeV}$	ATLAS-CONF-2021-026
LO	Scalar LQ 1 st gen	$2, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	2006.05872
LO	Scalar LQ 2 nd gen	$2, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	2006.05872
LO	Scalar LQ 3 rd gen	$1, \tau$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	ATLAS-CONF-2021-026
LO	Scalar LQ 3 rd gen	$0, e, \mu$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	2004.14660
LO	Scalar LQ 3 rd gen	$> 2, e, \mu, \tau, \gamma$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	2103.11582
LO	Scalar LQ 3 rd gen	$0, e, \mu, \tau, \gamma$	$> 1b, > 1\tau$	Yes	$M_{LQ} > 1.2 \text{ TeV}$	2101.12827
Heavy Quarks	VLO $T \rightarrow Z + X$	$2e, 2\mu, 2\tau, \gamma, 1b, > 1\tau$	-	Yes	$M_T > 1.4 \text{ TeV}$	ATLAS-CONF-2021-024
Heavy Quarks	VLO $B \rightarrow W + X$	multi-channel	-	Yes	$M_B > 1.4 \text{ TeV}$	1905.02053
Heavy Quarks	VLO $T \rightarrow W + X$	$2e, 2\mu, 2\tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_T > 1.4 \text{ TeV}$	1807.19883
Heavy Quarks	VLO $T \rightarrow W + X$	$1, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_T > 1.4 \text{ TeV}$	ATLAS-CONF-2021-040
Heavy Quarks	VLO $Y \rightarrow W + X$	$1, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_Y > 1.4 \text{ TeV}$	1812.07343
Heavy Quarks	VLO $B \rightarrow W + X$	$0, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_B > 1.4 \text{ TeV}$	ATLAS-CONF-2021-018
Exotic fermions	Excluded quark $q \rightarrow q\gamma$	$1, \gamma$	-	Yes	$M_q > 1.7 \text{ TeV}$	1910.20447
Exotic fermions	Excluded quark $q \rightarrow q\gamma$	$1, \gamma$	-	Yes	$M_q > 1.7 \text{ TeV}$	1709.10440
Exotic fermions	Excluded quark $q \rightarrow q\gamma$	$1, \gamma$	-	Yes	$M_q > 1.7 \text{ TeV}$	1805.09239
Exotic fermions	Excluded lepton $l \rightarrow l\gamma$	$3, e, \mu, \tau$	-	Yes	$M_l > 1.6 \text{ TeV}$	1411.2921
Exotic fermions	Excluded lepton $l \rightarrow l\gamma$	$3, e, \mu, \tau$	-	Yes	$M_l > 1.6 \text{ TeV}$	1411.2921
Other	Type III Seesaw	$2, 3, 4, e, \mu, \tau, \gamma, 1b, > 1\tau$	-	Yes	$M_{\nu} > 910 \text{ GeV}$	ATLAS-CONF-2021-023
Other	LRSM Majorana	$2, 3, 4, e, \mu, \tau, \gamma, 1b, > 1\tau$	-	Yes	$M_{\nu} > 300 \text{ GeV}$	2101.11961
Other	Higgs triplet $H^{\pm\pm} \rightarrow W^+W^+$	$2, 3, 4, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_{H^{\pm\pm}} > 870 \text{ GeV}$	1710.00748
Other	Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$2, 3, 4, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_{H^{\pm\pm}} > 870 \text{ GeV}$	1411.2921
Other	Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$2, 3, 4, e, \mu, \tau, \gamma, 1b, > 1\tau$	Yes	Yes	$M_{H^{\pm\pm}} > 870 \text{ GeV}$	1812.07343
Other	Multi-charged particles	-	-	Yes	$M_{MC} > 1.22 \text{ TeV}$	1905.10130
Other	Magnetic monopoles	-	-	Yes	$M_{MP} > 3.7 \text{ TeV}$	1905.10130

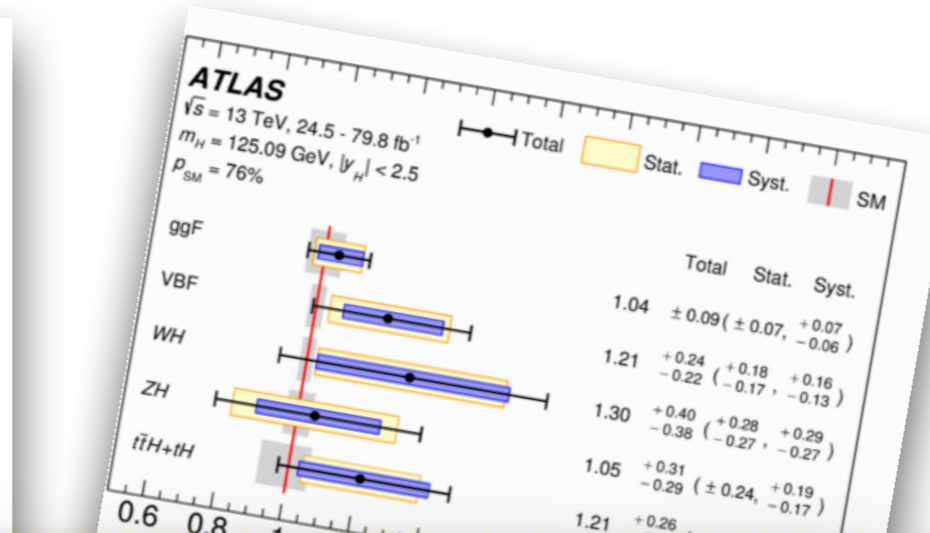
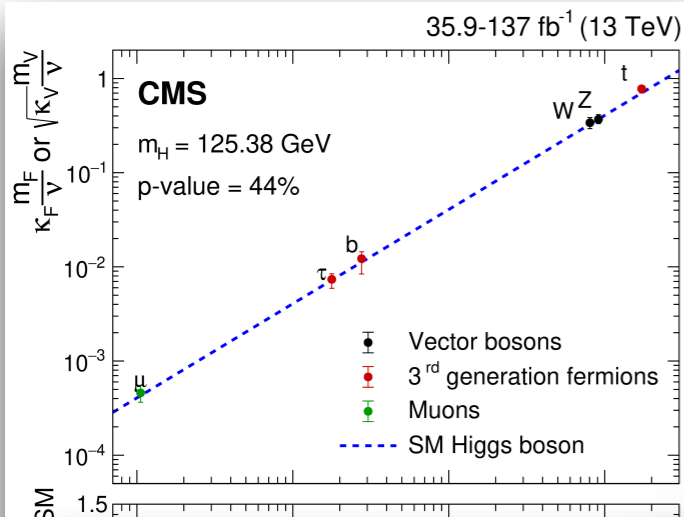
ATLAS Preliminary
 $\sqrt{s} = 8, 13 \text{ TeV}$

Model	Limit	Reference
$A(SLD)$	$M_{S} > 21.8 \text{ TeV}$	1702.09127
$A(LEP)$	$M_{S} > 2.0 \text{ TeV}$	2006.12546
O_1	$M_{O_1} > 2.0 \text{ TeV}$	2105.13847
$A_{FB}^{0,1}$	$M_{A_{FB}^{0,1}} > 2.0 \text{ TeV}$	1811.02395
$A_{FB}^{0,c}$	$M_{A_{FB}^{0,c}} > 2.0 \text{ TeV}$	1811.02395
$A_{FB}^{0,b}$	$M_{A_{FB}^{0,b}} > 2.0 \text{ TeV}$	1811.02395
R_1^0	$M_{R_1^0} > 2.0 \text{ TeV}$	1811.02395
R_c^0	$M_{R_c^0} > 2.0 \text{ TeV}$	1811.02395
R_b^0	$M_{R_b^0} > 2.0 \text{ TeV}$	1811.02395
$\Delta\alpha_{had}^{(5)}$	$M_{\Delta\alpha_{had}^{(5)}} > 2.0 \text{ TeV}$	1811.02395
$\alpha_s(m_Z)$	$M_{\alpha_s(m_Z)} > 2.0 \text{ TeV}$	1811.02395

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSP's unless stated otherwise. The quantities ΔM and δ represent the absolute mass difference between the primary particle and the LSP, and the difference between the intermediate particle and the LSP relative to ΔM , respectively, values indicated otherwise.

No direct discovery of New Physics so far

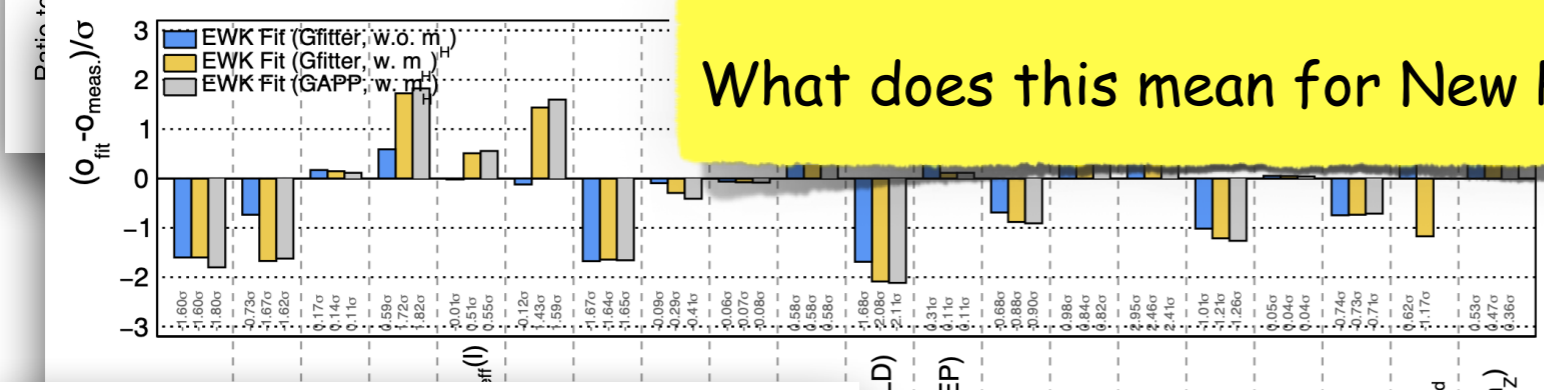
Status



Discovered Higgs Boson behaves very SM-like

What does this mean for New Physics?

Consistency Test of the SM at the quantum level

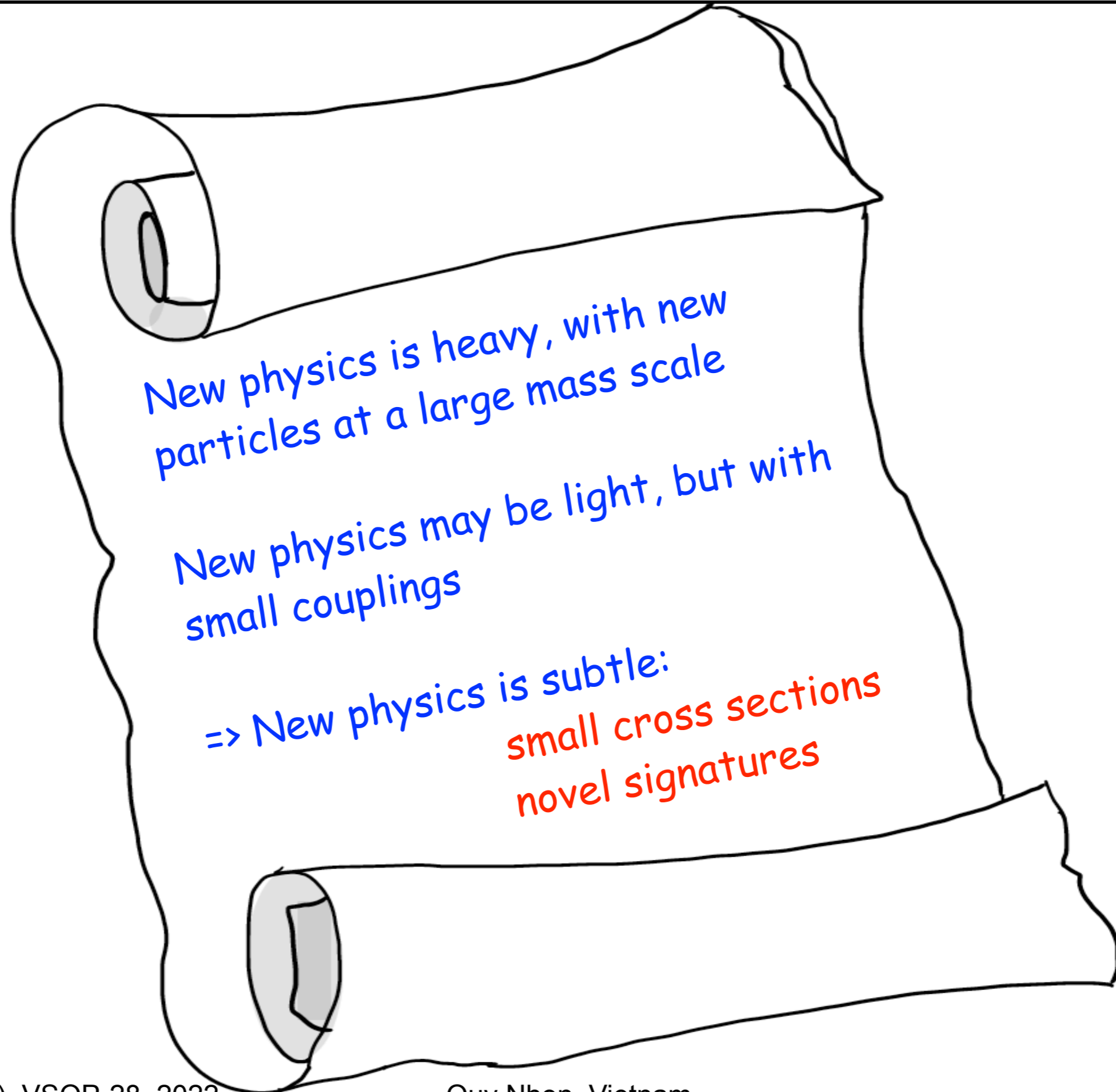


Model	f, γ	Jets	E_{miss}	Limit	Reference
ADD $G_{UV} + g/g$	$0, e, \mu, \tau, \gamma$	1-4	Yes	11.2 TeV	2102.10874
ADD non-resonant $\gamma\gamma$	$2, \gamma$	-	Yes	8.8 TeV	1702.04147
ADD QSH	-	2j	-	37.0 TeV	1703.09127
ADD BH multijet	-	-	-	8.9 TeV	1612.05586
RS1 $G_{UV} \rightarrow \gamma\gamma$	$2, \gamma$	-	Yes	8.9 TeV	2102.13495
Bulk RS $G_{UV} \rightarrow WW/\gamma Z$	multi-channel	-	Yes	2.3 TeV	1608.02380
Bulk RS $G_{UV} \rightarrow WW \rightarrow f\nu_{qg}$	$1, e, \mu$	2j/1j	Yes	2.0 TeV	2004.14636
Bulk RS $G_{UV} \rightarrow \tau\tau$	$1, e, \mu$	$>1b, >1Z$	Yes	3.1 TeV	1804.10823
UED/RSPP	$1, e, \mu$	$>2b, >2j$	Yes	1.3 TeV	1602.06273
SSM $Z' \rightarrow \tau\tau$	$2, e, \mu$	-	Yes	2.42 TeV	1902.06248
SSM $Z' \rightarrow \tau\tau$	$2, \tau$	-	Yes	2.1 TeV	1709.07262
Leptophobic $Z' \rightarrow bb$	$0, e, \mu$	$>1b, >2j$	Yes	4.1 TeV	1605.06259
Leptophobic $Z' \rightarrow \tau\tau$	$0, e, \mu$	$>1b, >2j$	Yes	4.1 TeV	2005.05138
SSM $W' \rightarrow \nu\nu$	$1, \nu$	-	Yes	6.0 TeV	1605.06259
SSM $W' \rightarrow \nu\nu$	$1, \nu$	-	Yes	5.9 TeV	ATLAS-CONF-2021-025
SSM $W' \rightarrow \nu\nu$	$1, \nu$	$>1b, >1j$	Yes	4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow f\nu_{qg}$ model B	$1, e, \mu$	2j/1j	Yes	4.3 TeV	2004.14636
HVT $Z' \rightarrow ZH$ model B	$0, e, \mu$	$>1b, >2j$	Yes	3.2 TeV	ATLAS-CONF-2020-043
HVT $W' \rightarrow WH$ model B	$0, e, \mu$	$>1b, >2j$	Yes	3.2 TeV	1602.06252
LRSM $W_2 \rightarrow \mu\nu_e$	$2, \mu$	1j	-	5.0 TeV	1904.12879
Cl eeee	$2, e, \mu$	2j	-	37.0 TeV	1702.09127
Cl ee $\tau\tau$	$2, e, \mu$	1b	-	1.0 TeV	2006.15946
Cl ee $\mu\tau$	$2, e, \mu$	1b	-	2.0 TeV	2105.13847
Cl ee $\tau\tau$	$>1, e, \mu$	$>1b, >1j$	Yes	2.57 TeV	1811.02395
Axisial-vector med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	376 GeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0, e, \mu, \tau, \gamma$	1-4	Yes	376 GeV	2102.10874
Vector med. Z' -2HDM (Dirac DM)	$0, e, \mu, \tau$	2b	Yes	3.1 TeV	ATLAS-CONF-2021-026
Pseudo-scalar med. 2HDMa	multi-channel	-	Yes	590 GeV	ATLAS-CONF-2021-026
Scalar reson. $\phi \rightarrow \tau\tau$ (Dirac DM)	$0, e, \mu, \tau$	1b, 0-1j	Yes	3.4 TeV	ATLAS-CONF-2021-026
Scalar LQ 1 st gen	$2, e, \mu$	$>2j$	Yes	1.2 TeV	2006.05872
Scalar LQ 2 nd gen	$2, e, \mu$	$>2j$	Yes	1.2 TeV	2006.05872
Scalar LQ 3 rd gen	$0, e, \mu$	$>2j$	Yes	1.2 TeV	ATLAS-CONF-2021-026
Scalar LQ 3 rd gen	$0, e, \mu$	$>2j, >2b$	Yes	1.2 TeV	2004.14660
Scalar LQ 3 rd gen	$>2, e, \mu, \tau$	$>1b, >1j$	Yes	1.42 TeV	2101.11582
Scalar LQ 3 rd gen	$0, e, \mu, \tau$	$>1, 0-2j, >2b$	Yes	1.26 TeV	2101.12827
VLO $TT \rightarrow Z + X$	$2e, 2\mu, 2\tau, >1b, >1j$	-	Yes	1.4 TeV	ATLAS-CONF-2021-024
VLO $BB \rightarrow WZ, Z\gamma + X$	multi-channel	-	Yes	1.4 TeV	1605.02043
VLO $T_{3/2} T_{3/2} \rightarrow W + X$	$2(5S)/3 \text{ eq. } >1b, >1j$	Yes	Yes	1.6 TeV	1807.19883
VLO $T \rightarrow H/Z$	$1, e, \mu, \tau$	$>1b, >1j$	Yes	1.5 TeV	ATLAS-CONF-2021-040
VLO $V \rightarrow W\phi$	$1, e, \mu, \tau$	$>1b, >1j$	Yes	1.85 TeV	1812.07343
VLO $B \rightarrow H\phi$	$0, e, \mu, \tau$	$>2b, >1j, >2j$	Yes	2.9 TeV	ATLAS-CONF-2021-018
Excluded quark $q' \rightarrow qq$	$1, \gamma$	1j	-	3.7 TeV	1910.26447
Excluded quark $q' \rightarrow q\gamma$	$1, \gamma$	1b, 1j	-	3.7 TeV	1709.10440
Excluded quark $q' \rightarrow qg$	$3, e, \mu, \tau$	-	-	3.1 TeV	1605.06269
Excluded lepton l'	$3, e, \mu, \tau$	-	-	3.0 TeV	1411.2921
Excluded lepton ν'	$3, e, \mu, \tau$	-	-	1.6 TeV	1411.2921
Type III Seesaw	$2.3, e, \mu$	$>2j$	Yes	910 GeV	ATLAS-CONF-2021-023
LRSM Majorana	$2.3, e, \mu$	various	Yes	350 GeV	2101.11991
Higgs triplet $H^{\pm\pm} \rightarrow W^+W^+$	$2.3, e, \mu$	(SS) various	Yes	870 GeV	1710.00148
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$2.3, e, \mu$	(SS) various	Yes	870 GeV	1411.2921
Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3, e, \mu, \tau$	-	-	400 GeV	1812.05273
Multi-charged particles	-	-	-	1.22 TeV	1905.10130
Magnetic monopoles	-	-	-	2.37 TeV	-

$A(SLD)$	$A(LEP)$	O_1	$A_{FB}^{0,1}$	O_1^c	$A_{FB}^{0,c}$	O_1^b	$A_{FB}^{0,b}$	R_1^0	R_1^c	R_1^b	$\Delta\alpha_{had}^{(5)}$	$\alpha_s(m_Z)$
1.000 ± 0.005	1.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005	0.000 ± 0.005

No direct discovery of New Physics so far

Where is New Physics?



New physics is heavy, with new particles at a large mass scale

New physics may be light, but with small couplings

=> New physics is subtle:
small cross sections
novel signatures



*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:

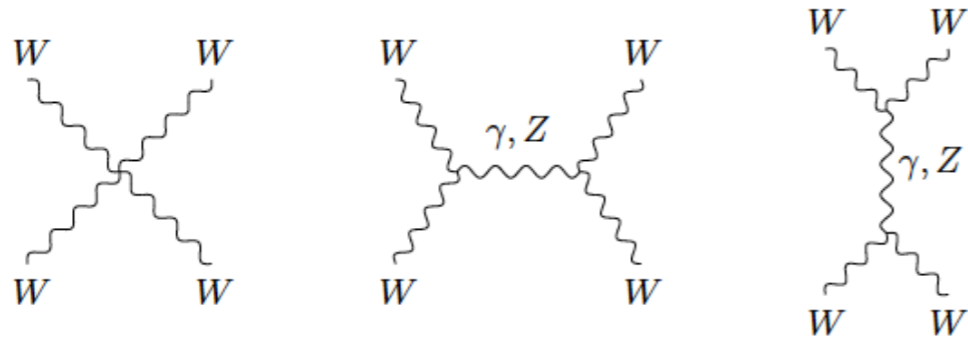
- * weakly interacting (extended Higgs sectors, supersymmetry)
- * strongly interacting (composite Higgs)

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

Intermezzo: Higgs as UV regulator

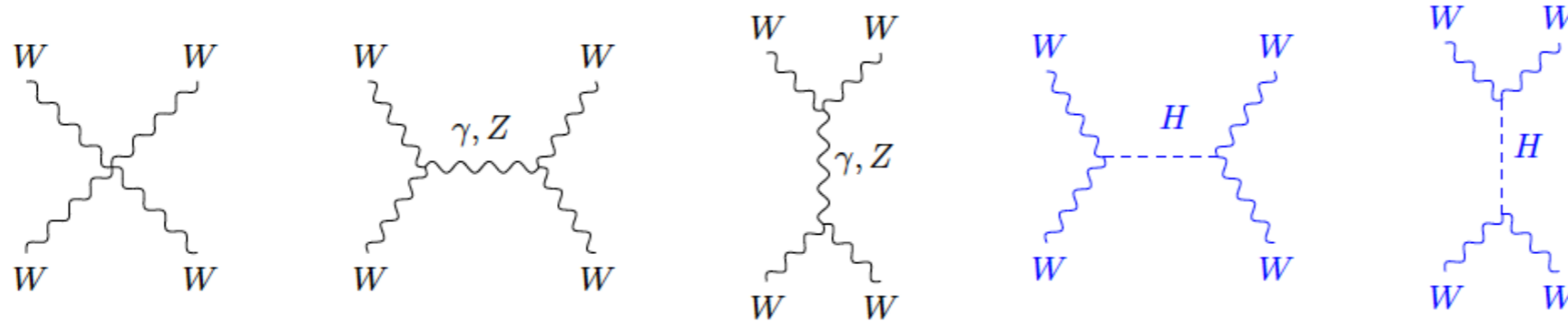
Scattering of longitudinally polarized W bosons



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

Intermezzo: Higgs as UV regulator

Scattering of longitudinally polarized W bosons

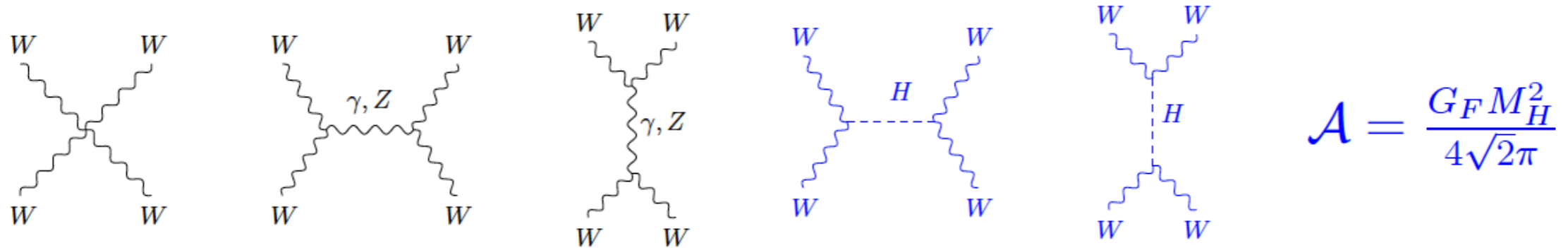


$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

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

Intermezzo: Higgs as UV regulator

Scattering of longitudinally polarized W bosons



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

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
 \Rightarrow non-Abelian gauge theories with spontaneous symmetry breaking.

Physics beyond the Standard Model

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