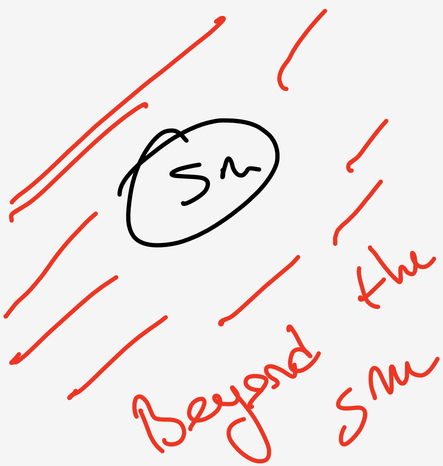
Beyond the Standard Model Physics



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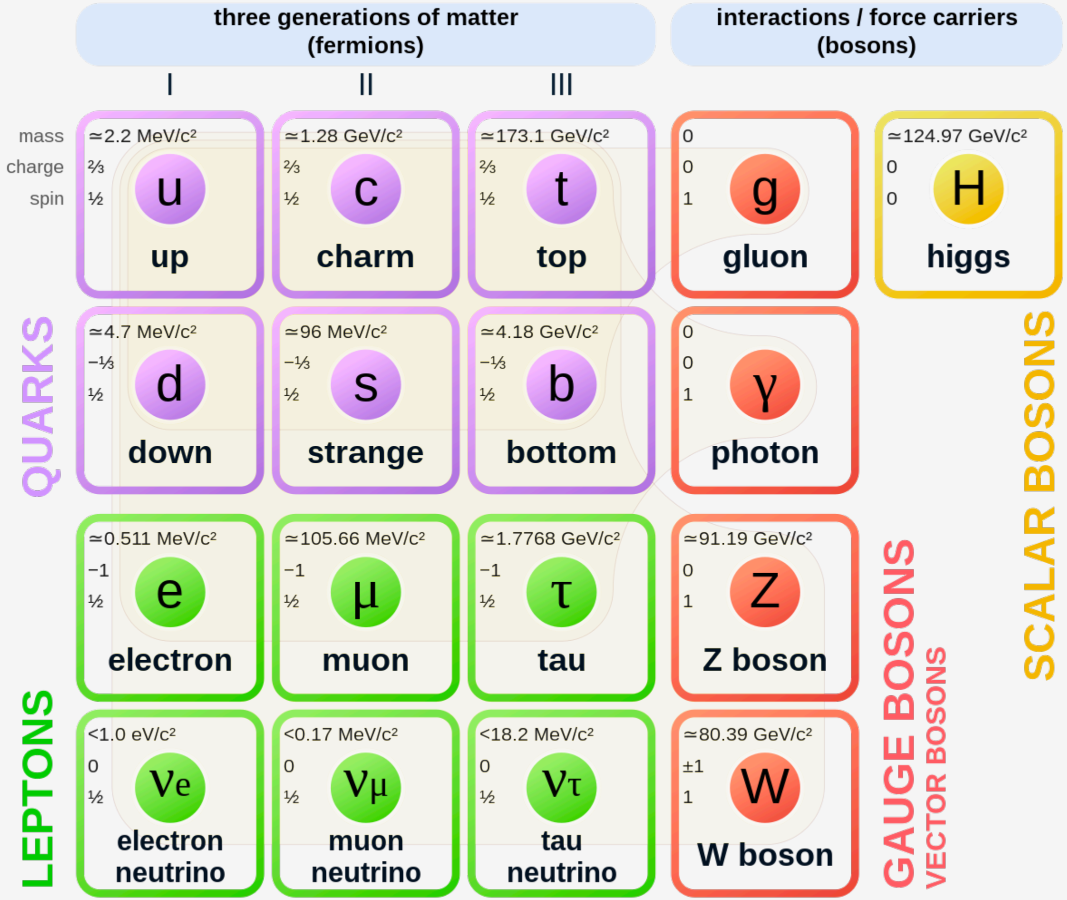
Carleton University

TRISEP 2022

Standard Model of Elementary Particles



$\mathcal{L}'$. Hereafter we will consider only the case of (A, C). The first one is to introduce another scalar doublet field ϕ. Then, we may consider an interaction with this new field

1

$$\mathcal{L}' = \bar{q}\phi C \frac{1-\gamma_5}{2} q + \text{h.c.}, \tag{11}$$

$$\phi \equiv \begin{pmatrix} \bar{\phi}^0 & \phi^+ & 0 & 0 \\ -\phi^- & \phi^0 & 0 & 0 \\ 0 & 0 & \bar{\phi}^0 & \phi^+ \\ 0 & 0 & -\phi^- & \phi^0 \end{pmatrix}, \qquad C \equiv \begin{pmatrix} c_{11} & 0 & c_{12} & 0 \\ 0 & d_{11} & 0 & d_{12} \\ c_{21} & 0 & c_{22} & 0 \\ 0 & d_{21} & 0 & d_{22} \end{pmatrix},$$

where c_{ij} and d_{ij} are arbitrary complex numbers. Since we have already made use of the gauge transformation to get rid of the CP-odd part from the quartet mass term, there remains no such arbitrariness. Furthermore, we note that an arbitrariness of the phase of ϕ cannot absorb all the phases of c_{ij} and d_{ij}. So, this interaction can cause a CP-violation.

u, d, s, c

$SU(2)_L$ $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}$

2 generations "known"

CP violation

Kaons

weak interactions

No CP violation

w/ 4 quarks!

2

Another one is a possibility associated with the strong interaction. Let us consider a scalar (pseudoscalar) field S which mediates the strong interaction. For the interaction to be renormalizable and $SU_{\text{weak}}(2)$ invariant, it must belong to a $(4, 4^*) + (4^*, 4)$ representation of chiral $SU(4) \times SU(4)$ and interact with q through scalar and pseudoscalar couplings. It also interacts with φ and possible renormalizable forms are given as follows:

$$\begin{aligned} &\text{tr}\{G_0 S^+ \boldsymbol{\varphi}\} + \text{h.c.}, \\ &\text{tr}\{G_1 S^+ \boldsymbol{\varphi} G_2 \boldsymbol{\varphi}^+ S\} + \text{h.c.}, \\ &\text{tr}\{G_1' S^+ \boldsymbol{\varphi} G_2' S^+ \boldsymbol{\varphi}\} + \text{h.c.}, \end{aligned} \tag{12}$$

with

$$\boldsymbol{\varphi} \equiv \begin{pmatrix} \bar{\varphi}^0 & \varphi^+ & 0 & 0 \\ -\varphi^- & \varphi^0 & 0 & 0 \\ 0 & 0 & \bar{\varphi}^0 & \varphi^+ \\ 0 & 0 & -\varphi^- & \varphi^0 \end{pmatrix},$$

where G_i is a 4×4 complex matrix and we have used a 4×4 matrix representation for S. It is easy to see that these interaction terms can violate CP-conservation.

M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973), 652.

③

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

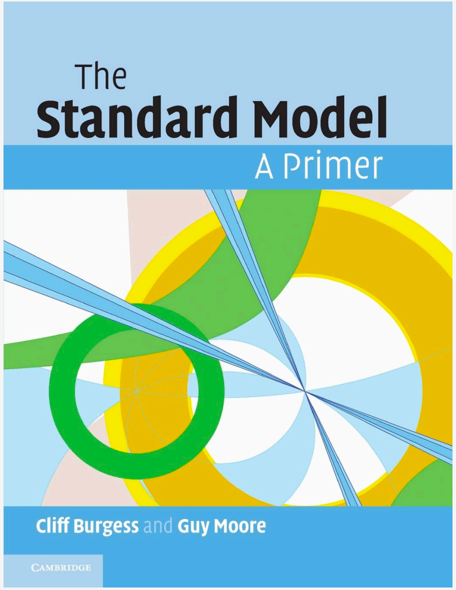
$$\underbrace{\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}}_{\text{Calibbo - Kobayashi - Maskawa (CKM) matrix}}.$$

CP phase

Model ③:

6 quark (3 generations):

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$



$$\boxed{SU(3)_c \times SU(2)_L \times U(1)_Y}$$

$$\Big\downarrow \text{Higgs}$$

$$SU(3)_c \times U(1)_{EM}$$

$H \quad (1, 2, 1/2)$

↑ Higgs

+ gauge fields

$Q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	$(3, 2, -1/6)$	quarks
U_R^i	$(3, 1, 2/3)$	
D_R^i	$(3, 1, -1/3)$	
$L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	$(1, 2, 1/2)$	leptons
E_R^i	$(1, 1, -1)$	

$i = 1, 2, 3$

SM is very compact now that we have time to digest it:

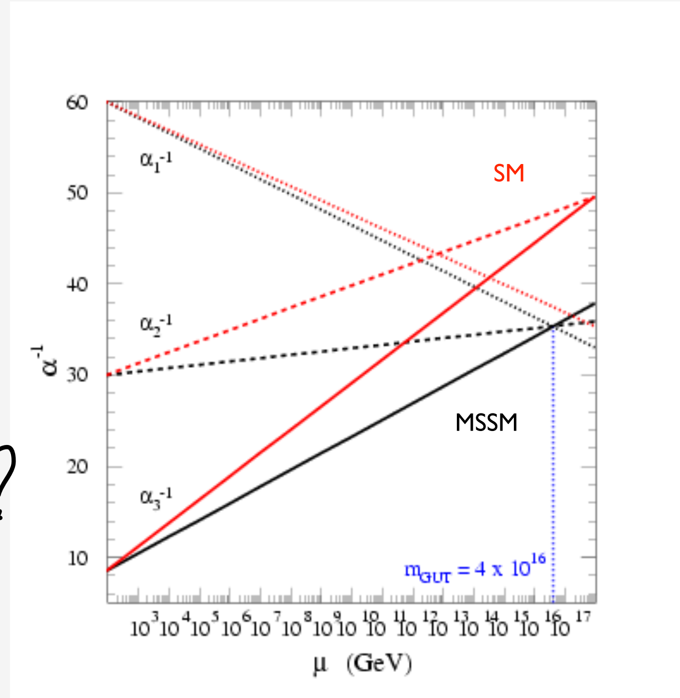
$$\mathcal{L}_{SM} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} G^\alpha_{\mu\nu} G^{\alpha\mu\nu}$$

$$+ \bar{L}^i \not{D} L^i + \bar{E}^i_R \not{D} E^i_R + \bar{Q}^i \not{D} Q^i + \bar{U}^i_R \not{D} U^i_R + \bar{D}^i_R \not{D} D^i_R$$

$$+ \mathcal{L}_{Higgs}$$

gauge structure is <u>not</u> minimal

gauge couplings do not unify in the SM



Grand Unified Theories?
(GUTs)

$SO(10), SU(5), \ldots$ above M_{GUT}

$\Downarrow$ symmetry breaking

$SU(3) \times SU(2) \times U(1)$ SM in the "IR"

Why are there 3 generations?

For a fun BSM paper, read:

"A Universe w/o weak interactions"

$\boxed{\begin{array}{ll} u, d, s & \text{quarks} \\ e & \text{lepton} \\ \text{no weak interactions} & \end{array}}$

A Universe Without Weak Interactions, Fox, Harnik, Kribs, arXiv: hep-ph/0604027 up quark $\simeq 2$ MeV

top quark $\simeq 173$ GeV

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

e, μ, τ

$\nu_e \quad \nu_\mu \quad \nu_\tau$

Froggatt - Nielsen

$$\mathcal{L} \ni y_i \Big(\underbrace{\frac{S}{\Lambda}}_{}\Big)^{n_i} \bar{e}_R^i \phi^* L^i$$

flavon

$$\epsilon = \frac{\langle S \rangle}{\Lambda} \sim 0.2$$

$$n_e = 9, \quad n_\tau = 3, \quad n_\mu = ?$$

TASI Lectures by Babu, arXiv: 0910.2948

Observations that cannot be explained by the SM.

neutrino masses!

$y_e \bar{\ell}_R^i H L^i$

not observed

$y_\nu \bar{L} \epsilon H^* N_R$

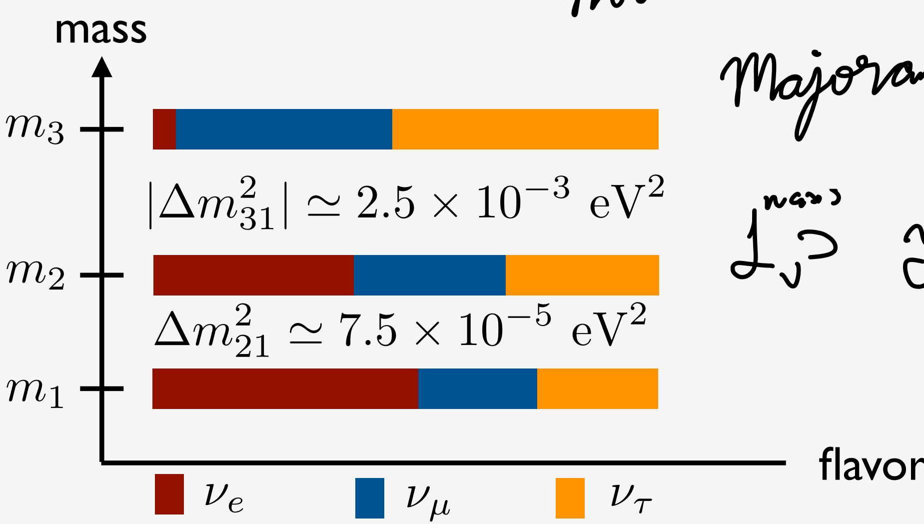
not allowed

$N_R : (1, 1, 0)$

$y_\nu \sim 10^{-12}$

Majorana neutrinos

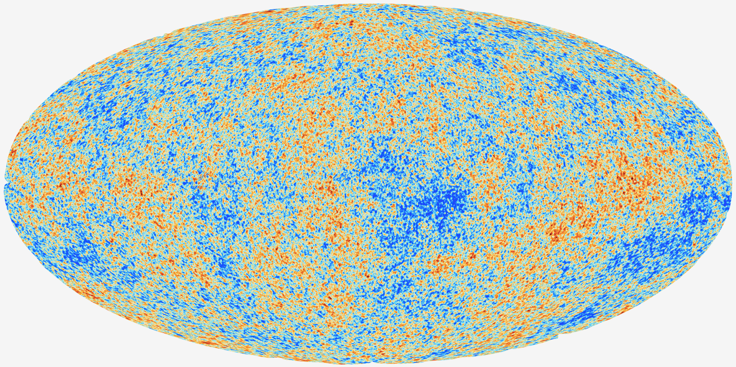
$\mathcal{L}_\nu^{\text{mass}} \supset y_\nu \bar{L} \epsilon H^* N_R + \underbrace{M_R N_R N_R}_{\text{majorana mass}}$



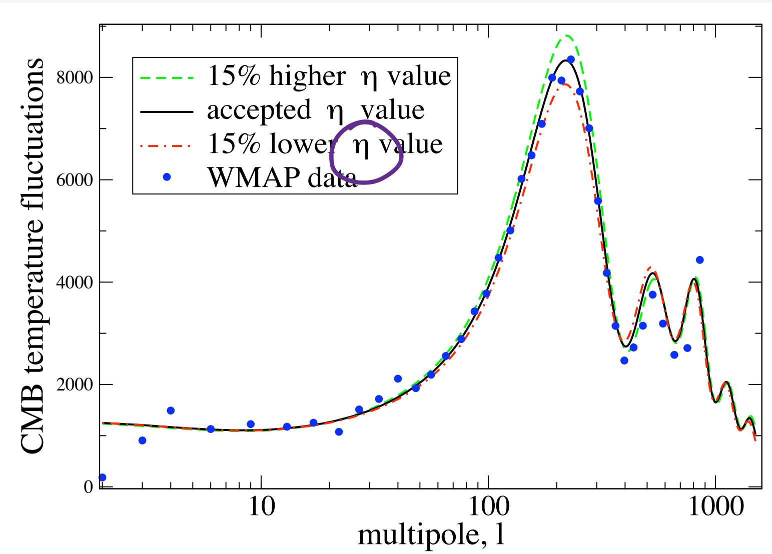
seesaw scale

$M_R \sim 10^{12}$ GeV

More matter than antimatter in the Universe!

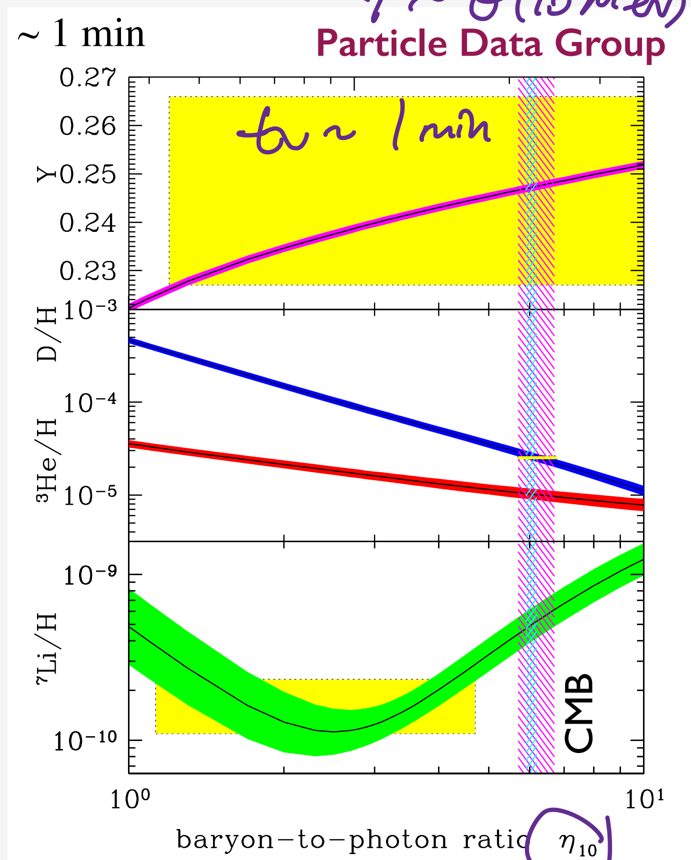


CMB



Primordial light element abundances

$T \sim \mathcal{O}(10\,\mathrm{MeV})$



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6\times10^{-10}$$ (sometimes $\frac{n_B - n_{\bar{B}}}{s}$ is used)

Sakharov Conditions (Andrei Sakharov '67)

1. Baryon number violation

$$B(q) = 1/3 \quad , \quad B(\bar{q}) = -1/3$$

SM interactions: $\underbrace{\bar{Q}\not{D}Q}_{B=0}$, $\underbrace{\bar{Q}Hu_R}_{B=0}$, ...

$\Delta_B = n_B - n_{\bar{B}}$

initially symmetric: $\Delta_B = 0$

2. C and CP violation

3. A process that is out of thermodynamic equilibrium

Let's look at the SM

1 $\int d^4x\, \mathcal{L}$: B-number conserved.

$SU(2)_L$ only left-handed fermions

$\bar{\psi}_L^i \not{D} \psi_L^i \longleftarrow$ 2 symmetries

$\psi_L \to e^{i\theta} \psi_L$

$\psi_L \to e^{i\theta\gamma_5} \psi_L$

Noether's theorem $\Rightarrow$ conserved currents

$$j^\mu = \bar{\psi} \gamma^\mu \psi \qquad j_5^\mu = \bar{\psi} \gamma^\mu (1-\gamma_5) \psi$$

However, the partition violates this symmetry because the measure is not invariant.

$$Z = \int d\psi\, d\bar{\psi}\, dA\, e^{-\int d^4x \mathcal{L}}$$

As a result we have

$$\int d^4x\, \partial_\mu j^{5\mu} = \frac{\alpha_W}{4\pi} \int d^4x\, Tr\left(W^a_{\mu\nu} \tilde{W}^{a,\mu\nu}\right) = \underset{\text{integer}}{n}$$

$$\tilde{W}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} W_{\alpha\beta}$$

→ Chern-Simons current

In the SM:

$(B-L)$ is conserved

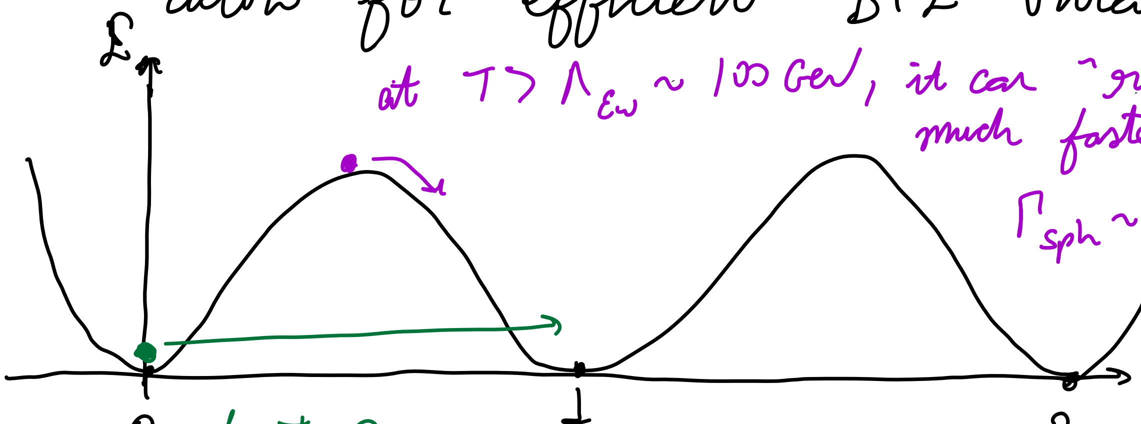
$\boxed{B+L \text{ is violated}}$ through an anomaly

→ sphalerons

gauge field configurations that allow for efficient $B+L$ violation

at $T > \Lambda_{EW} \sim 100$ GeV, it can "roll over" much faster

$\Gamma_{sph} \sim 30\, \alpha_W^5 T^4$



at $T=0$, universe needs to tunnel to change $B+L$ number

$\Gamma \sim e^{-4\pi/\alpha_W} \sim e^{-160}$!

(2) SM has CP violation due to a phase in the CKM matrix

How does this phase enter the production of a baryon asymmetry?

detailed calculations can be found in:

Gavela, et al CERN 93/7081

Back of the envelope estimate:

$$\eta_{CKM} \propto \prod_{i=\text{quarks}} \left(\frac{m_i}{T_{EW}}\right)^2 \sim 10^{-20}$$

Observed asymmetry:

$$\eta_{obs} \simeq 10^{-10}$$

There is not enough CP violation in the SM!

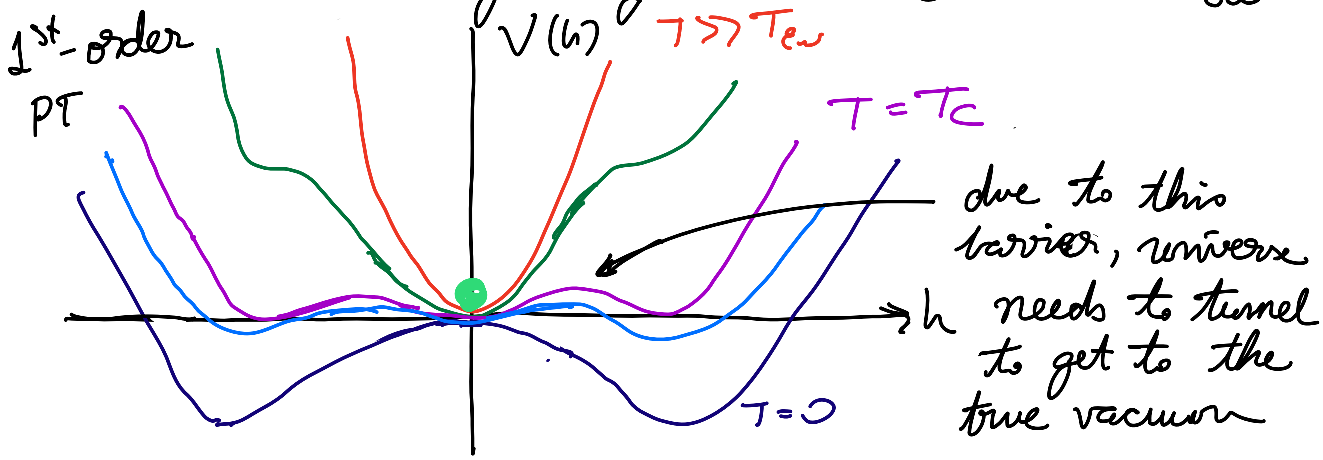
③ The expansion of our universe allows for interactions to fall out of equilibrium.

In order to decide if a process is in equilibrium or not, we compare its rate to the Hubble rate:

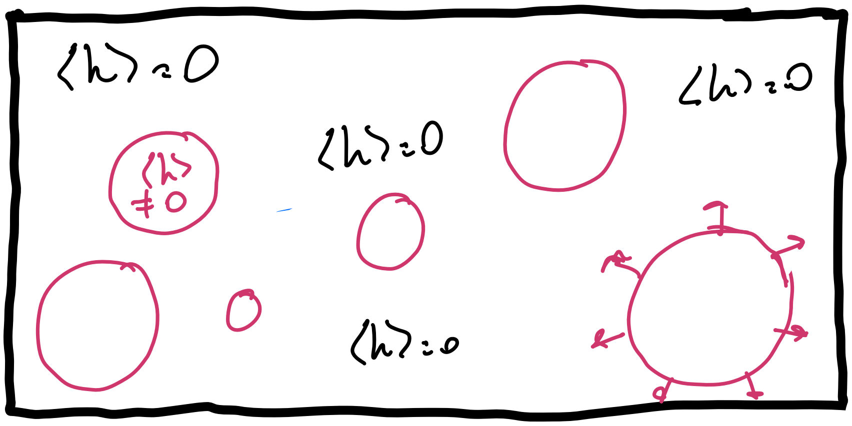
$$\Gamma(T) \text{ vs } H(T)$$

In the SM, even the weak interactions are still large enough to equilibrate the SM particles. The only possibility of an out-of-equilibrium process identified in the SM was through a 1^{st}-order EW phase transition.

At $T=0$, the Higgs potential is the well-known Mexican-hat potential w/ a minimum at $v = 246$ GeV. But it gets finite-temperature corrections in the early universe. These corrections result in EW symmetry restoration at $T > T_{EW}$.



A 1^{st}-order PT proceeds through "bubble nucleation". Below a critical temperature T_c, regions of true vacuum starts forming. Some of these bubbles collapse, some expand and collide and fill the whole universe.



this can produce gravitational waves!

This 1^{st}-order PT would only happen if

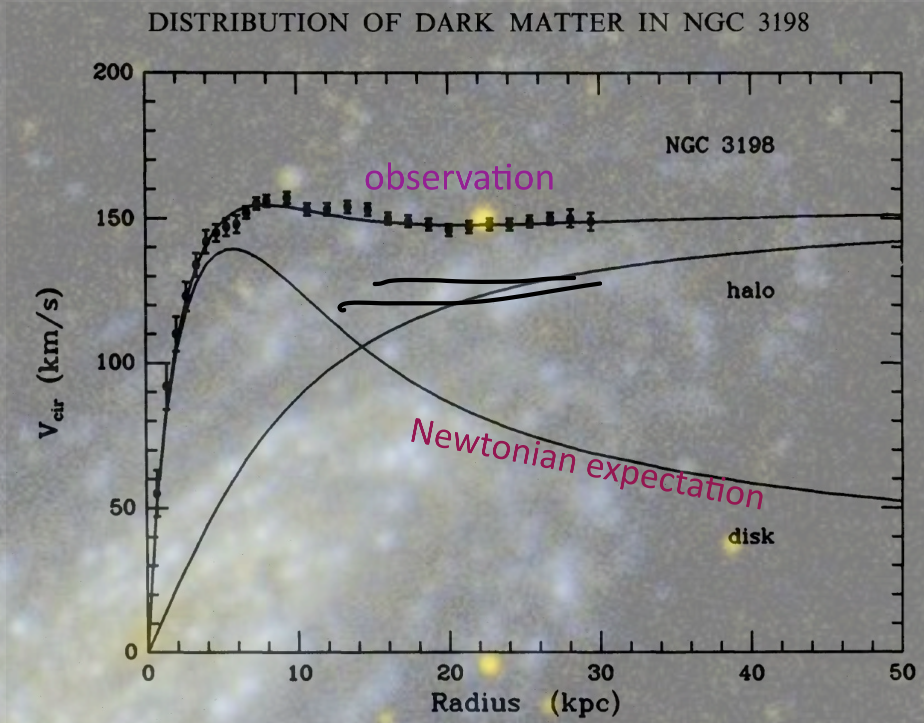
$m_h \lesssim 60$ GeV, but it is not!

In the SM, the EW transition is a "crossover". There is never a barrier seperating the false vacuum from the true vacuum. It is always in-equilibrium.

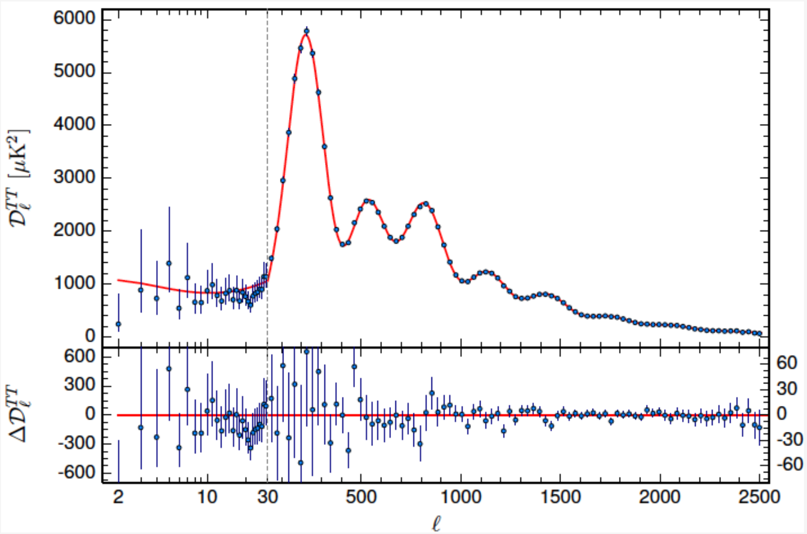
SM can not explain the baryon asymmetry of the universe!

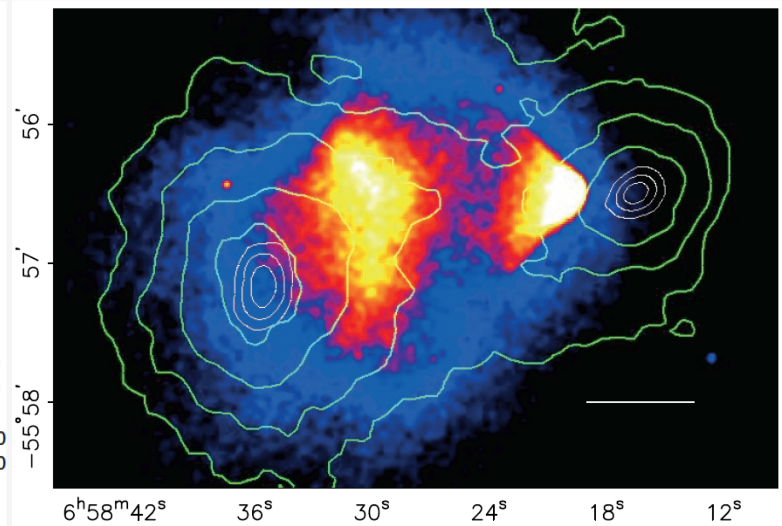
DARK MATTER

Vera Rubin
(1928 - 2016)



Astrophys J, 295, 305 (1985)





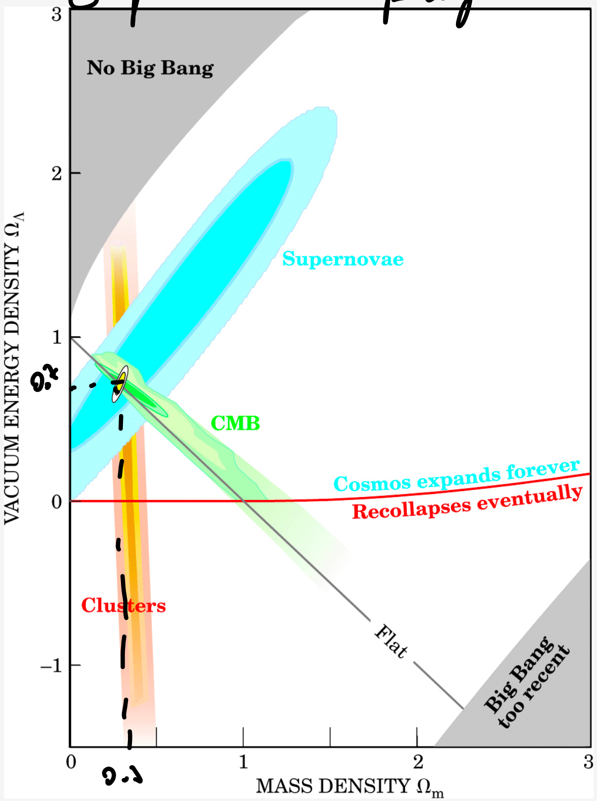
bullet cluster

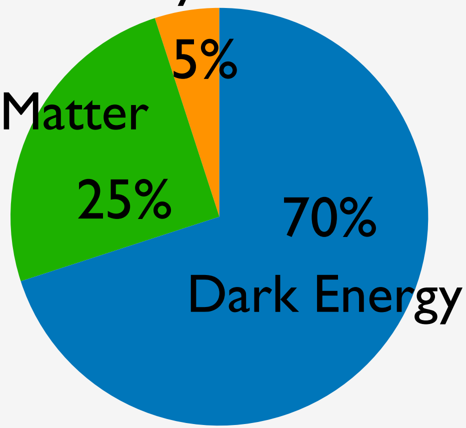
$$\Omega_d \sim 0.27$$

$$\Omega_b \sim 0.04$$

You will have lectures on dark matter

Supernova project





Cosmological constant problem

$$\langle 0 | S_M | 0 \rangle \propto \Lambda^4$$

$$\Lambda_{SM} - \Lambda = \Lambda_{obs}$$

$$\Lambda \sim M_{pl}$$

& very precise cancellation

No gravity
in the SM!

CP Violation in the strong sector?

QCD Lagrangian is allowed to have a term like:

$$\mathcal{L} \supset \theta \frac{g_s}{16\pi^2} G^{\alpha}_{\mu\nu} \tilde{G}^{\alpha\mu\nu} \qquad \tilde{G}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$$

This term actually can be rewritten as a total derivative:

$$G\tilde{G} = \partial_\mu J^\mu$$

where $$J^\mu = \epsilon^{\mu\nu\alpha\beta}\left(A_\nu G_{\alpha\beta} - \frac{2}{3} A_\nu A_\alpha A_\beta\right)$$

Total derivatives do not affect equations of motion and we mostly ignore them.

Fujikawa, Phys. Rev. Lett. 42, 1195 (1979)

But this one has non-perturbative effects!

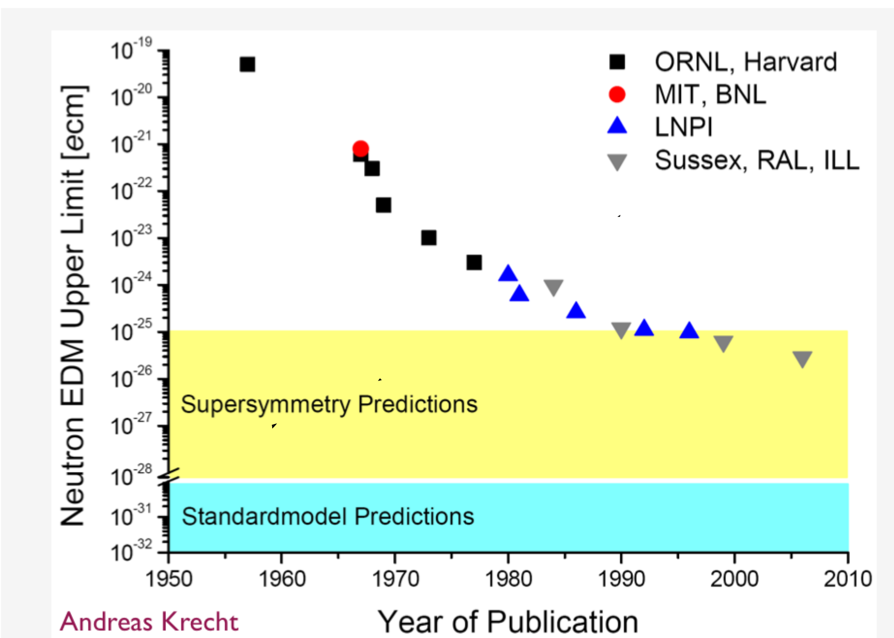
Attiyah-Singer theorem:

$$\frac{\alpha_s}{4\pi}\int d^4x\, G\tilde{G} = \frac{\alpha_s}{4\pi}\int dS_\mu\, j^\mu = n$$

↑ integer

This θ term violates CP and generates an electric dipole moment (EDM) for the neutron

$$\frac{d_n}{e} = \frac{\theta}{\Lambda_{QCD}^2}\,\frac{m_u m_d}{m_u + m_d} < 3\times 10^{-26}\ cm$$



$\theta < 10^{-11}$

why so small?

Is there a symmetry behind the smallness of this dimensionless parameter θ?

axions might be the answer! Also could be dark matter!

The Hierarchy Problem!

naturalness problem

of the Higgs mass

Let's talk about symmetries

$$\mathcal{L}_{SM} \supset y_e \bar{L} H e_R - i\bar{L}\not{D}L - i\bar{e}_R \not{D} e_R$$

If $y_e = 0$, we recover a continuous symmetry:

$$L \to e^{i\theta} L$$
$$e_R \to e^{i\theta} e_R$$

chiral symmetry

Due to this would-be symmetry, all quantum corrections to the electron mass will be proportional to y_e:

$$\delta m_e \propto y_e$$

$y_e \simeq 10^{-5}$: a "small" number, but it is technically natural. Protected by a symmetry

Let's look at a toy scalar Lagrangian

$$\mathcal{L} \supset -|\partial\phi|^2 + M_\phi^2 |\phi|^2$$

When $M_\phi^2 = 0$: we recover a shift symmetry:

$$\phi \to \phi + c$$

So, we expect the same "protection" from quantum corrections:

$$\delta M_\phi^2 \propto M_\phi^2 \times (\text{loop integrals})$$

(There is another symmetry for $M_\phi^2 = 0$: scale invariance. It is more subtle and is actually broken by quantum corrections!)

In the SM:

- $\lambda |H|^4$
- $\underline{y_t}$ $\bar{Q} H U$ ← top yukawa is largest
- $H W^+ W^-$, $H Z^0 Z^0$

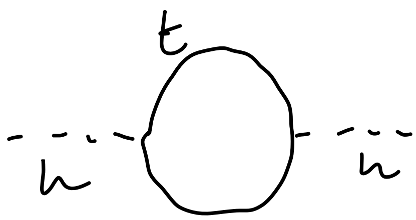
} break the shift symmetry

Quantum corrections to the Higgs mass:

$$\delta m^2 \sim \left(\frac{y_t}{4\pi}\right)^2 \Lambda^2$$

↳ some cutoff scale

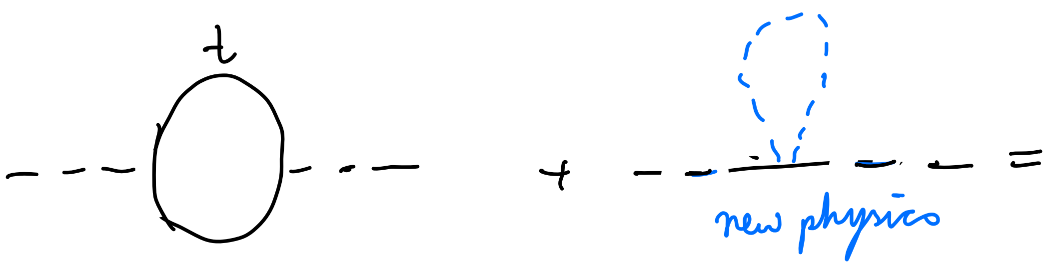
new physics?



$m_h = 125$ GeV

We usually don't want the would-be quantum corrections larger than $\sim m_h$ itself, which means:

$$\Lambda \sim \mathcal{O}(\text{TeV})$$



= correct higgs mass

If you are canceling two independent terms (up to a good precision), you want a symmetry reason for it.

Otherwise you will have

fine-tuning

Now consider:

$$-\mathcal{L} \supset -|\partial\phi|^2 + M_\phi^2|\phi|^2 - i\bar{\psi}\,\partial\!\!\!/\,\psi + M_\psi\bar{\psi}\psi$$

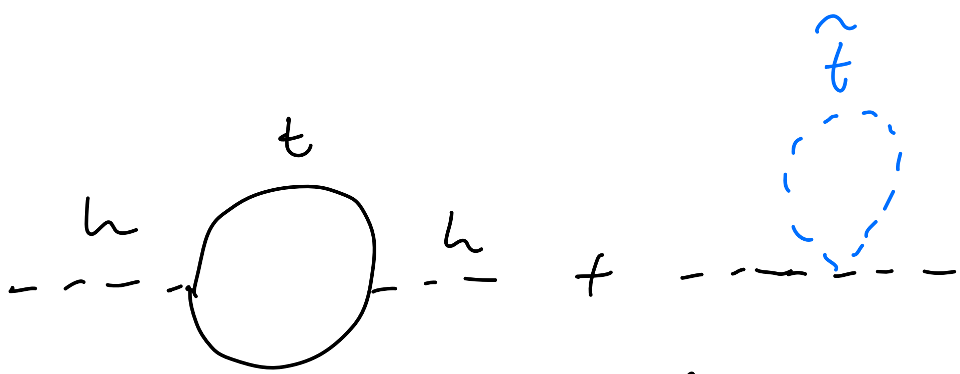
There is a curious symmetry when

$$\boxed{M_\phi = M_\psi}$$

$$\phi \to Q\psi$$
$$\psi \to \tilde{Q}\phi$$

scalar $\Longleftrightarrow$ fermion

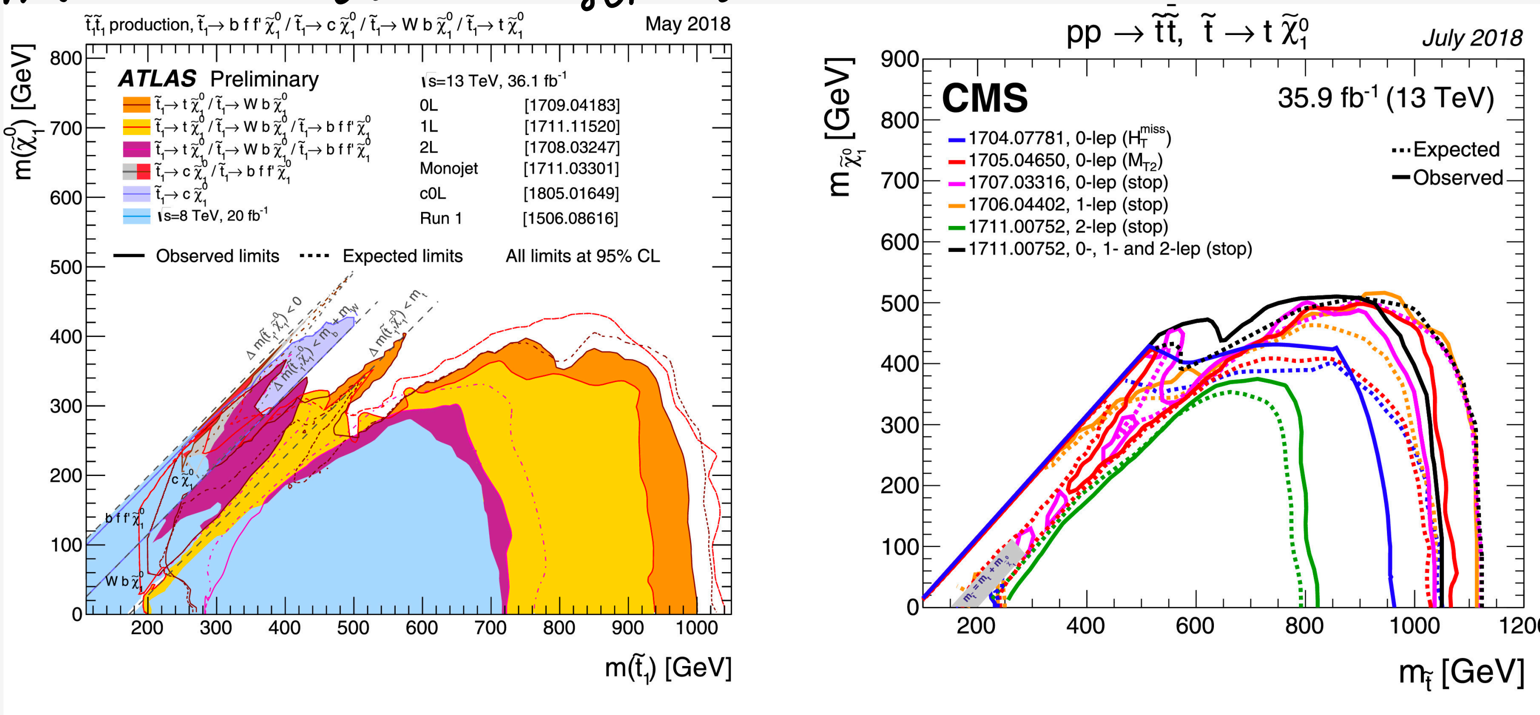
$\Rightarrow$ SUPERSYMMETRY!



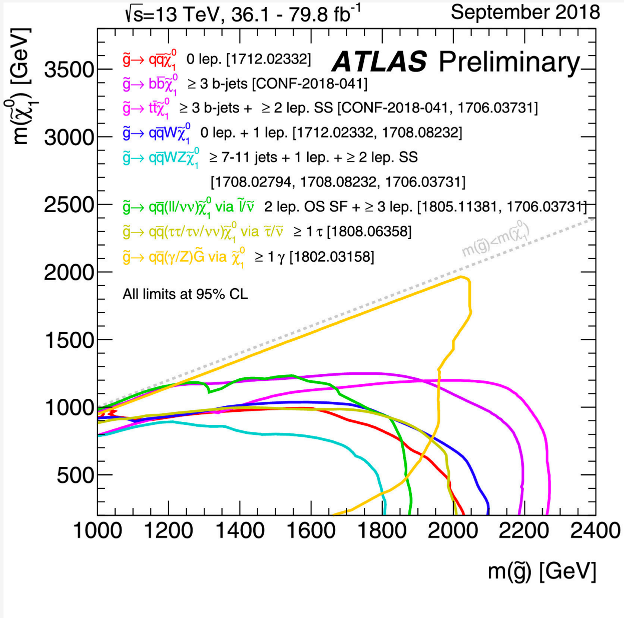
$$\propto \frac{M_h^2}{16\pi^2}\log\left(\frac{M_Z}{M_{\tilde{t}}}\right)$$

stops $< \mathcal{O}(\text{TeV})$

Since we haven't observed superpartners w/ equal masses to SM particles, we say SUSY must be broken somehow

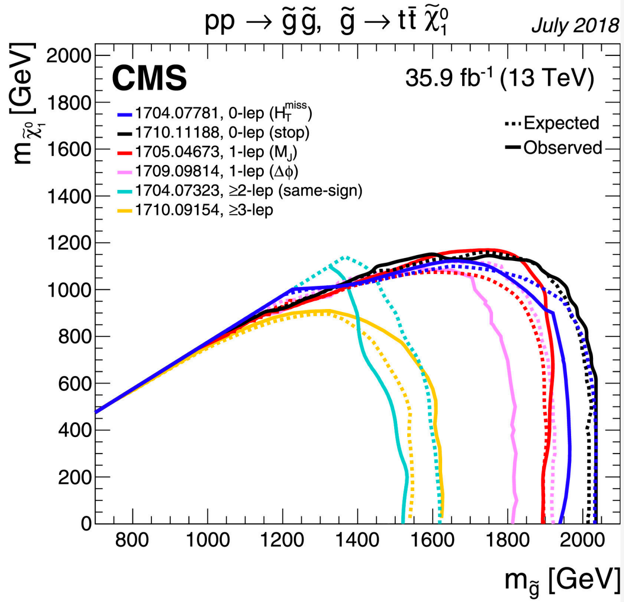


(a) (b)



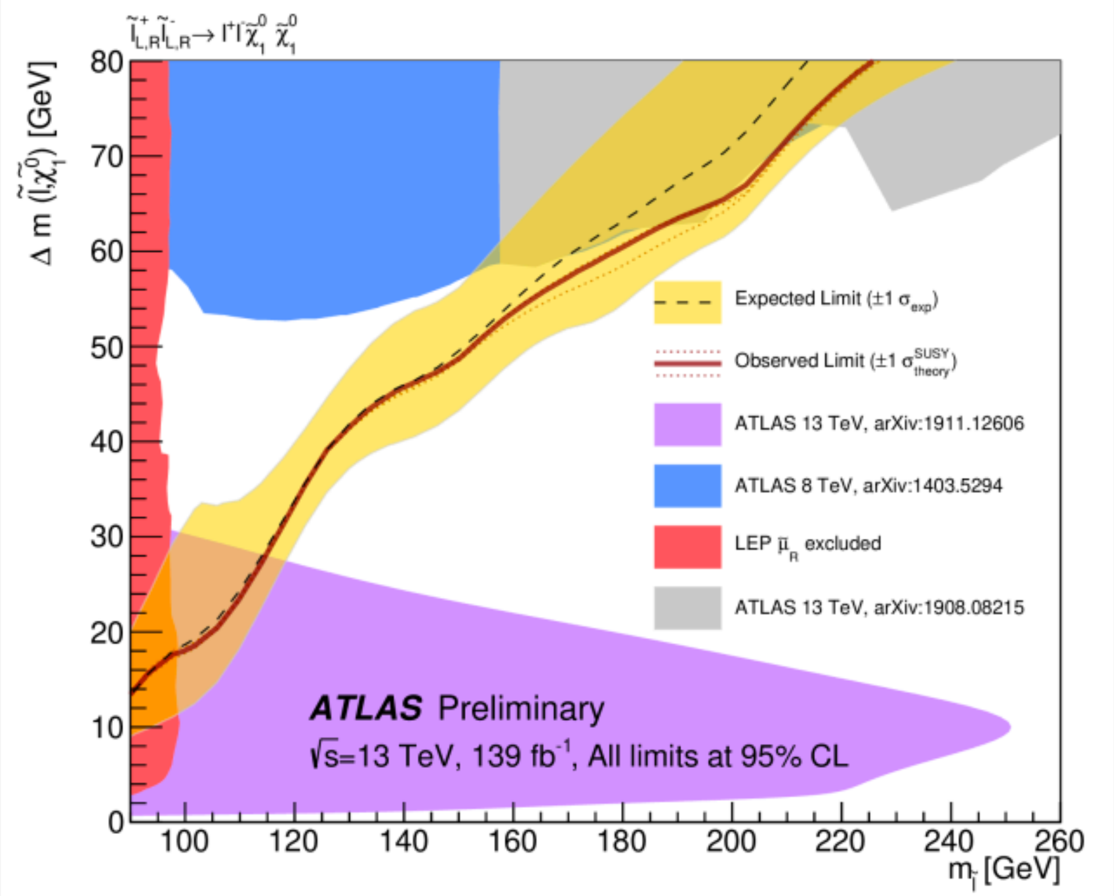
√s=13 TeV, 36.1 - 79.8 fb-1
September 2018
ATLAS Preliminary
g̃→ qq̄χ̃10 0 lep. [1712.02332]
g̃→ bb̄χ̃10 ≥ 3 b-jets [CONF-2018-041]
g̃→ tt̄χ̃10 ≥ 3 b-jets + ≥ 2 lep. SS [CONF-2018-041, 1706.03731]
g̃→ qq̄Wχ̃10 0 lep. + 1 lep. [1712.02332, 1708.08232]
g̃→ qq̄WZχ̃10 ≥ 7-11 jets + 1 lep. + ≥ 2 lep. SS
[1708.02794, 1708.08232, 1706.03731]
g̃→ qq̄(ll/νν)χ̃10 via l̃/ν̃ 2 lep. OS SF + ≥ 3 lep. [1805.11381, 1706.03731]
g̃→ qq̄(ττ/τν/νν)χ̃10 via τ̃/ν̃ ≥ 1 τ [1808.06358]
g̃→ qq̄(γ/Z)G̃ via χ̃10 ≥ 1 γ [1802.03158]
All limits at 95% CL
m(g̃)<m(χ̃10)
m(χ̃10) [GeV]
m(g̃) [GeV]

(a)



pp → g̃g̃, g̃ → tt̄χ̃10
July 2018
CMS
35.9 fb-1 (13 TeV)
1704.07781, 0-lep (HTmiss)
1710.11188, 0-lep (stop)
1705.04673, 1-lep (MJ)
1709.09814, 1-lep (Δϕ)
1704.07323, ≥2-lep (same-sign)
1710.09154, ≥3-lep
Expected
Observed
mχ̃10 [GeV]
mg̃ [GeV]

(b)


$\tilde{l}^+_{L,R}\tilde{l}^-_{L,R} \rightarrow l^+l^-\tilde{\chi}^0_1\tilde{\chi}^0_1$
$\Delta m(\tilde{l},\tilde{\chi}^0_1)$ [GeV]
$m_{\tilde{l}}$ [GeV]
Expected Limit ($\pm 1\ \sigma_{exp}$)
Observed Limit ($\pm 1\ \sigma^{SUSY}_{theory}$)
ATLAS 13 TeV, arXiv:1911.12606
ATLAS 8 TeV, arXiv:1403.5294
LEP $\tilde{\mu}_R$ excluded
ATLAS 13 TeV, arXiv:1908.08215
ATLAS Preliminary
$\sqrt{s}$=13 TeV, 139 fb^{-1}, All limits at 95% CL

Another way to have a light scalar is to have it as a (pseudo-) Nambu–Goldstone boson.

If a global symmetry is spontaneously broken, there will be a massless scalar – NG boson

If that symmetry is explicitly broken, the scalar is massive, but can be light.

The SM example: pions! QCD confinement breaks $SU(2)_L \times SU(2)_R \to SU(2)_{\text{diagonal}}$

This symmetry is also broken explicitly due to quark masses. The pNGB's are the pions and it is "natural" for them to be lighter than the QCD scale $\sim \mathcal{O}(\text{GeV})$

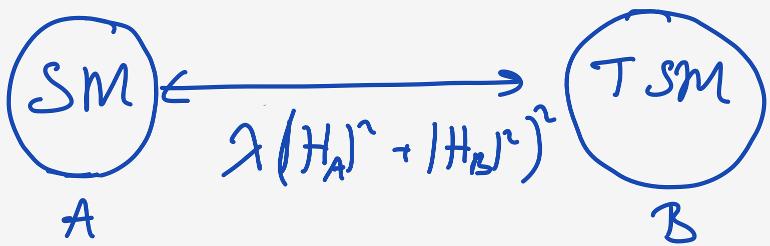
- Composite Higgs models
  e.g. technicolor

- Little Higgs models
  Spontaneous symmetry breaking

w/ ever-growing $SU(N)$ groups

e.g. $SU(3) \to SU(2)$

- Twin Higgs models (hep-ph/0506256)



↑ has an $SU(4)$ symmetry which can be spontaneously broken by a higgs vev.

e.g $SU(4) \to SU(3)$

- Extra dimensions

There are a lot of particle physics experiments at the LHC and elsewhere

FASER, MATHUSLA, CODEX-b, SHiP, ...

BaBar, Belle, ...

DUNE, ...

XENON-1T, ADMX, ...

Fermi-LAT, ...

⋮

Flavor Anomalies

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

SM gauge interactions are flavor universal

$$\bar{Q}^i \not{D} Q^i \,, \quad \bar{L}^i \not{D} L^i \,, \ldots$$

The only difference between flavors:

$$y_\ell^i \, \bar{L}^i H E_R^i$$

Tests of LFU: $\qquad M^\pm \longrightarrow \ell^\pm \nu_\ell$

$M = \pi, B, K, D$

$\ell = e, \mu, \tau$

e.g. $\pi^\pm \longrightarrow \mu^\pm \nu_\mu$ $\quad$ $(e^\pm \nu_e)$ channel is helicity suppressed

CKM element

$$\Gamma_{SM}(M^\pm \to \ell^\pm \nu) = \frac{G_F^2\, m_M\, m_\ell^2}{8\pi}\, \underbrace{f_M^2}_{\text{meson decay constant}} |V_{qq'}| \underbrace{\left(1 - \frac{m_\ell^2}{m_M^2}\right)^2}_{\text{phase space suppression}}$$

e.g. $K^\pm \longrightarrow \ell^\pm \nu$

$$R_K^{SM} = \frac{\Gamma_{SM}(K^\pm \longrightarrow e^\pm \nu)}{\Gamma_{SM}(K^\pm \longrightarrow \mu^\pm \nu)}$$

$$= \frac{m_e^2}{m_\mu^2}\left(\frac{M_K^2 - m_e^2}{M_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{QED})$$

EM corrections

Taking ratios is good because you get rid of a lot of hadronic physics which can be non-perturbative.

What is expected from the SM:

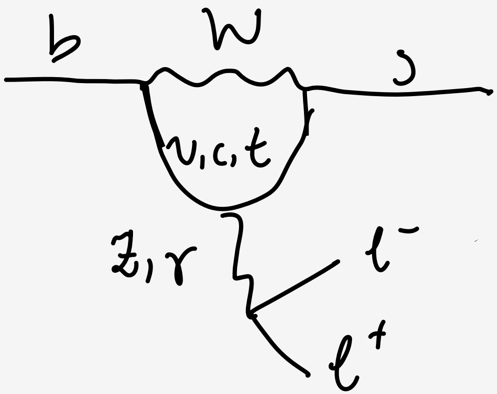
$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

What is measured by experiments (NA62 + KLOE)

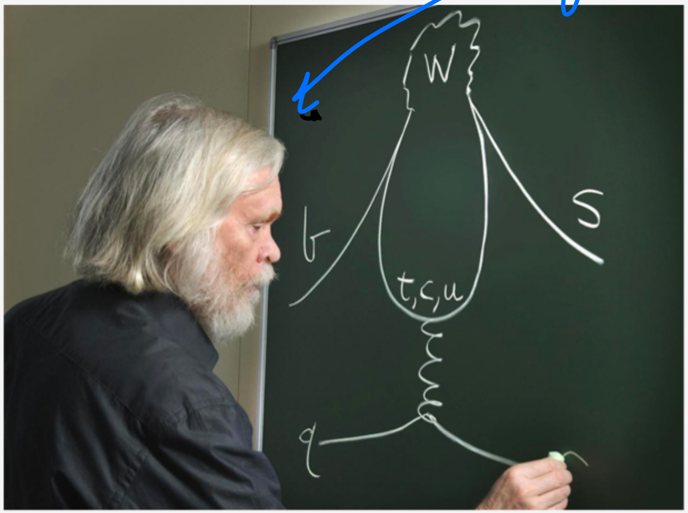
$$R_K^{meas.} = (2.488 \pm 0.0\underline{09}) \times 10^{-5}$$

needs work to bring the uncertainties down to the theory level

$b \to s\, l^+ l^-$ penguin diagrams!

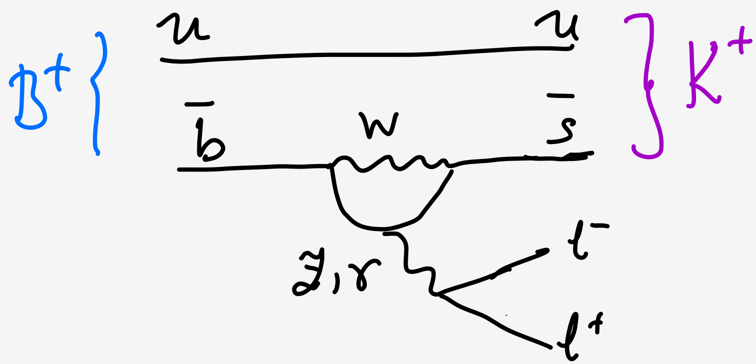


John Ellis



An interesting decay to look at is

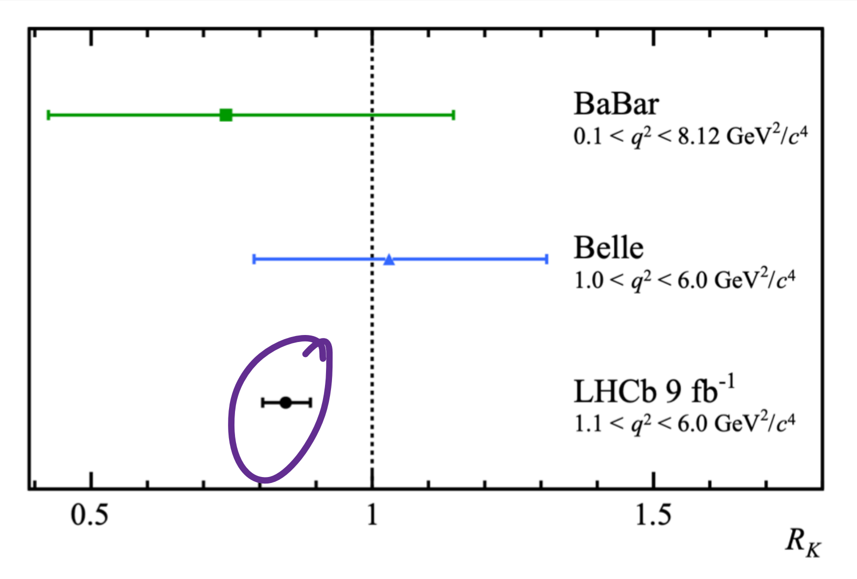
$$B^+ \longrightarrow K^+ l^+ l^-$$



Again, it is better to look at the ratio of states w/ different lepton flavors:

$$R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)}$$

The SM expectation: $R_K^{SM} = 1$.



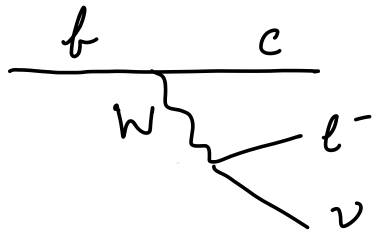
there is an anomaly!

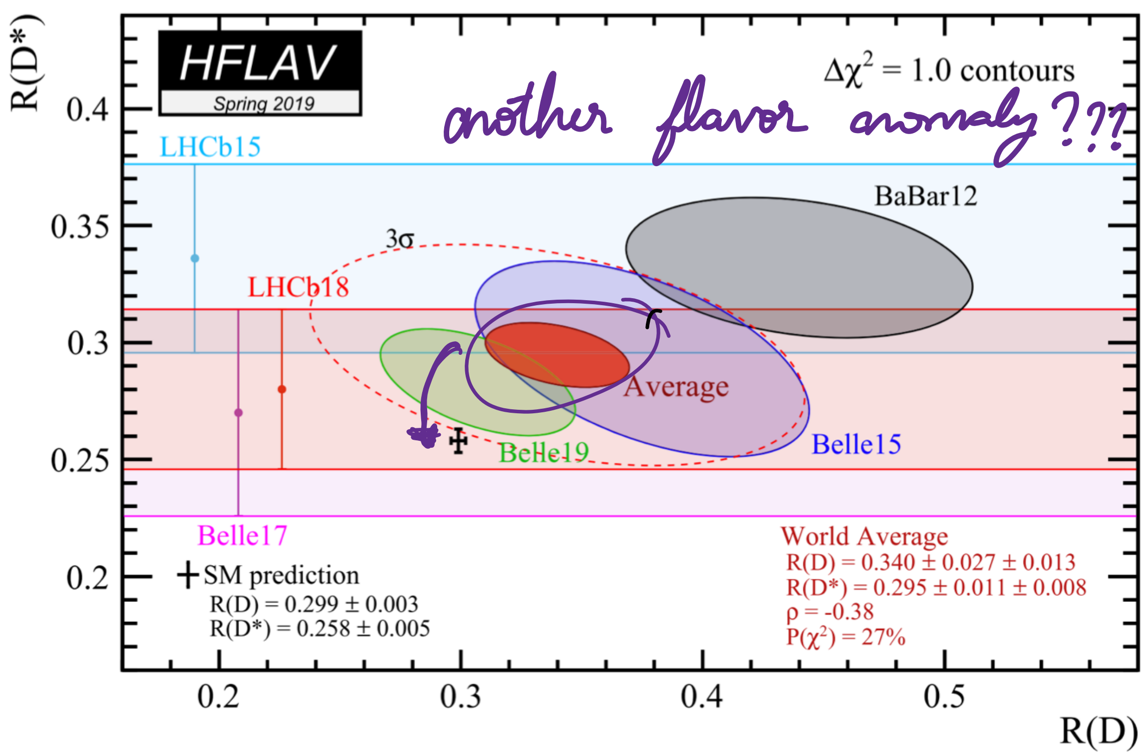
Another such flavor observable:

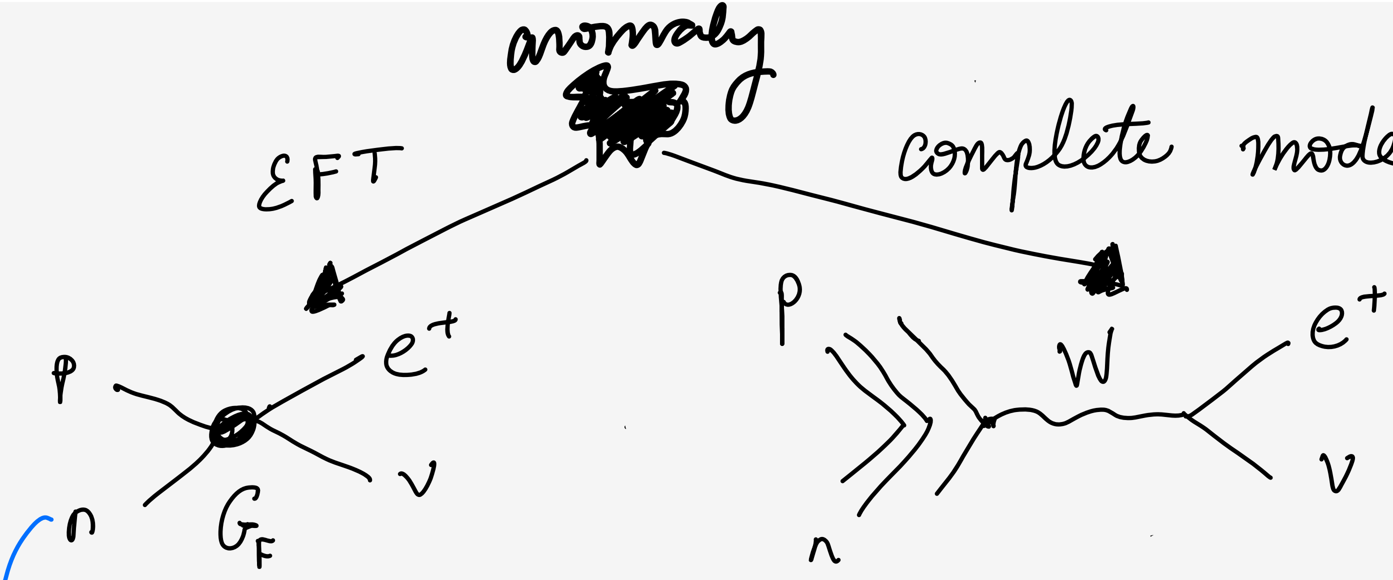
$$R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)} \tau^- \nu)}{Br(\bar{B} \to D^{(*)} \ell^- \nu)}$$

$\ell = e, \mu$

This happens at tree level in the SM through $b \to c\, \ell^- \nu$:







Fermi constant $G_F = \dfrac{\sqrt{2}\, g_2^2}{8\, m_W^2}$: scale of interactions

4-fermion contact interaction
dimension - 6

Without knowing what kind of new physics could be involved, we can write the

$$b \longrightarrow s\,\ell^+\ell^-$$

decay in terms of dim-6 effective operators.

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i=1}^{12} C_i\, \mathcal{O}_i$$

Wilson coefficients

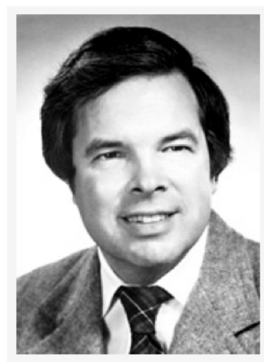
$$\mathcal{O}_7 = \frac{m_t}{e} \left(\bar{s}\, \sigma_{\mu\nu} \underset{L}{P_R}\, b\right) F^{\mu\nu}$$

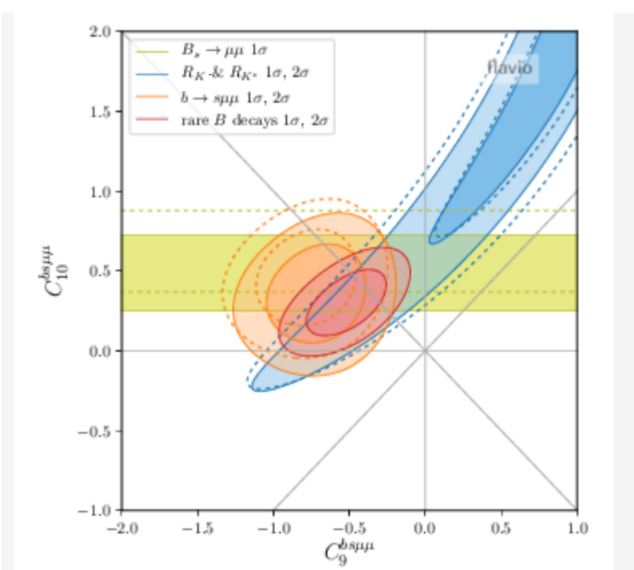
$$\mathcal{O}_{q\ell} = \left(\bar{s}\, \gamma_\mu \underset{R}{P_L}\, b\right)\left(\bar{\ell}\, \gamma^\mu \ell\right)$$

$$\mathcal{O}_{S\ell} = \left(\bar{s}\, \underset{L}{P_R}\, b\right)\left(\bar{\ell}\, \ell\right)$$

$$\mathcal{O}_{T\ell} = \left(\bar{s}\, \sigma_{\mu\nu} b\right)\left(\bar{\ell}\, \sigma^{\mu\nu} \ell\right)$$

$$\vdots$$





All the information about heavy degrees of freedom are in the Wilson coefficients. These coefficients can be measured or constrained.

For a given (mass) dimension, finding the allowed effective operators is an interesting problem! I think there are Mathematica packages that do that.

Effective Field Theories (EFT)

? ? ? ? ? ?

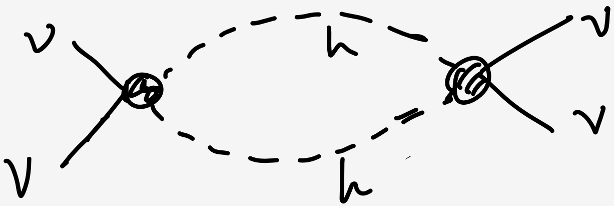
Any new degrees of freedom?

q, g, l, γ, W, Z	the Standard Model
q, g, l, γ	4-fermi interactions
π, p, n, l, γ	Chiral perturbation theory

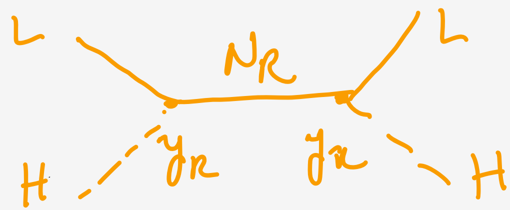
There is a dim-5 operator in the SM:

$$\underbrace{\frac{C}{\Lambda}}_{\text{Wilson coefficient}} (\bar{L} H)(L^c H) \quad : \text{Weinberg operator}$$

leads to ν-ν scattering:



One UV-completion:



$$\frac{C}{\Lambda} \iff \frac{|y|^2}{M_R}$$

<u>Exercise</u>: Calculate this loop.

It goes like $\left(\frac{C}{\Lambda}\right)$

Λ can be different than the mass of the new heavy particles

For a dim-d operator, corresponding scattering amplitude goes like
$$\left(\frac{E}{\Lambda}\right)^d$$
blows up for $E \sim \Lambda$!

$\mathcal{O}^{d<4}$: relevant

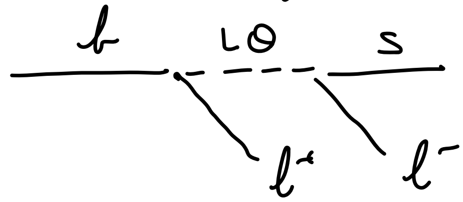
$\mathcal{O}^{d=4}$: marginal

$\mathcal{O}^{d>4}$: "irrelevant" for $E \ll \Lambda$

flavor observables can probe new probe new physics scales much higher than the reach of the LHC.

For $b \to s \ell^+ \ell^-$:
$$\Lambda_{NP} \simeq \frac{35\ \text{TeV}}{\sqrt{C_i}}$$

Possible UV completions for flavor anomalies?

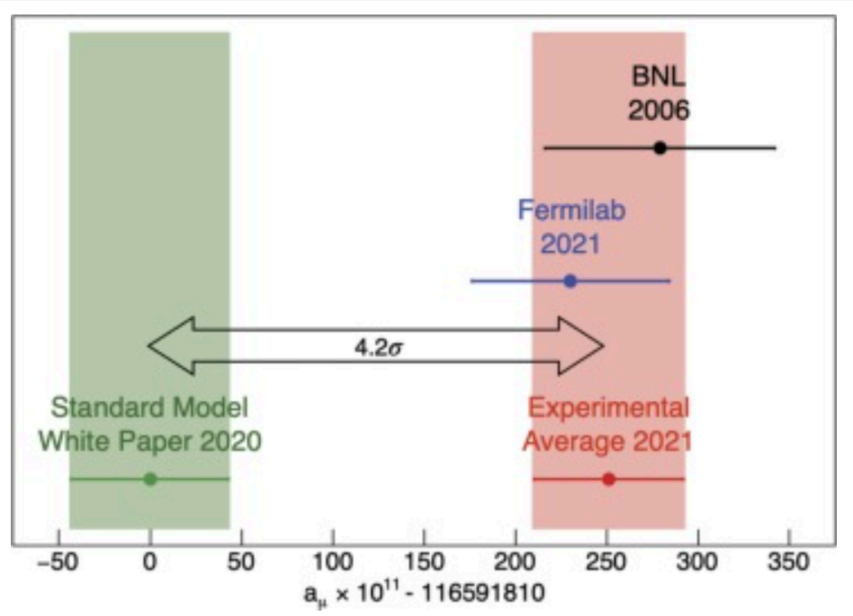
- leptoquarks : 

- Z', W' (from a gauged $U(1)_{\mu-\tau}$?)

$b \to s \ell^+ \ell^-$ $\quad$ $b \to c \ell^- \nu$

Muon g-2 anomaly?

SM prediction might be off. New lattice results show better agreement w/ data



Neutron lifetime anomaly

Two different methods for measuring the neutron lifetime have been consistently showing different results.