Beyond the Standard Model

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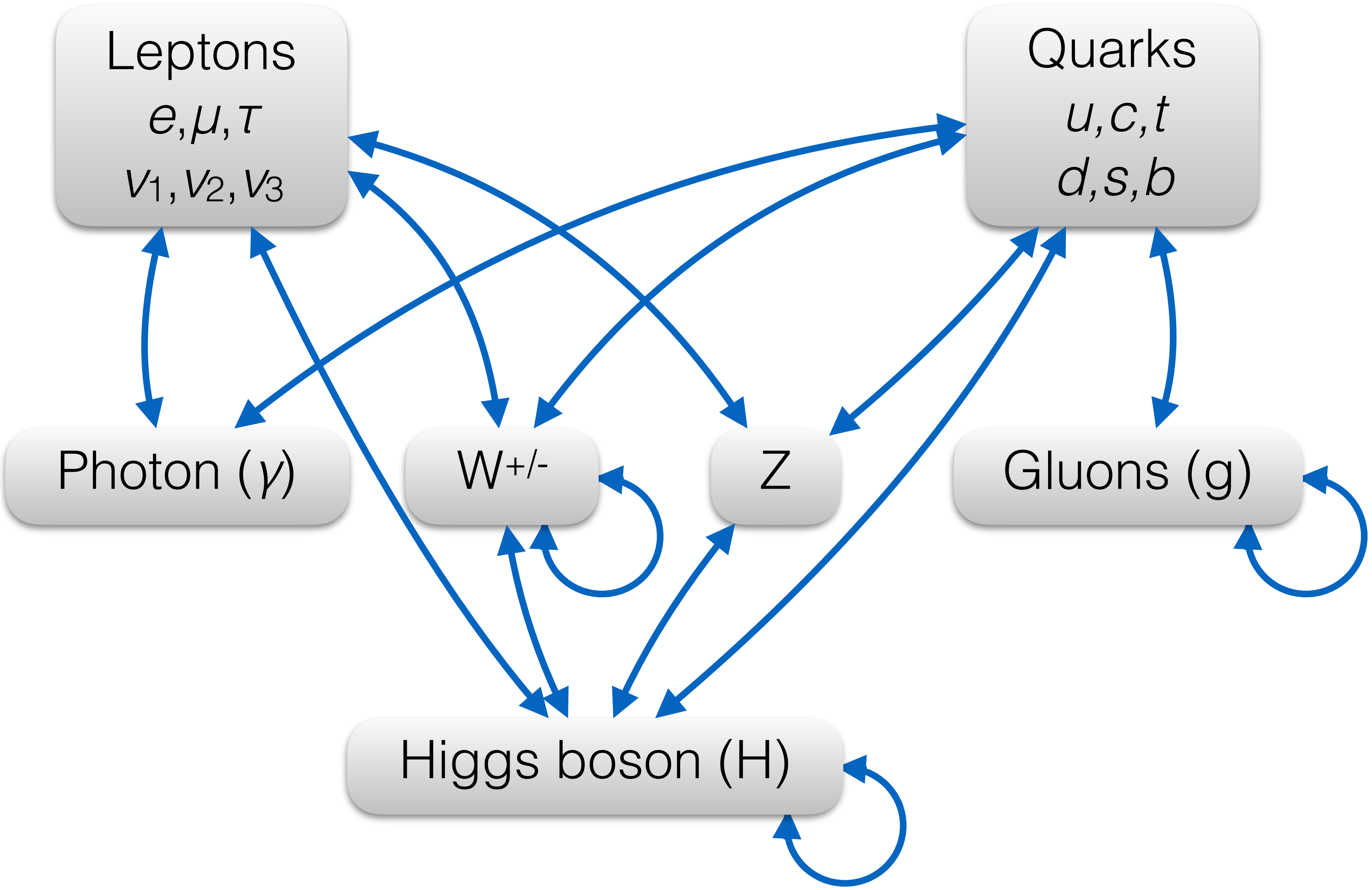
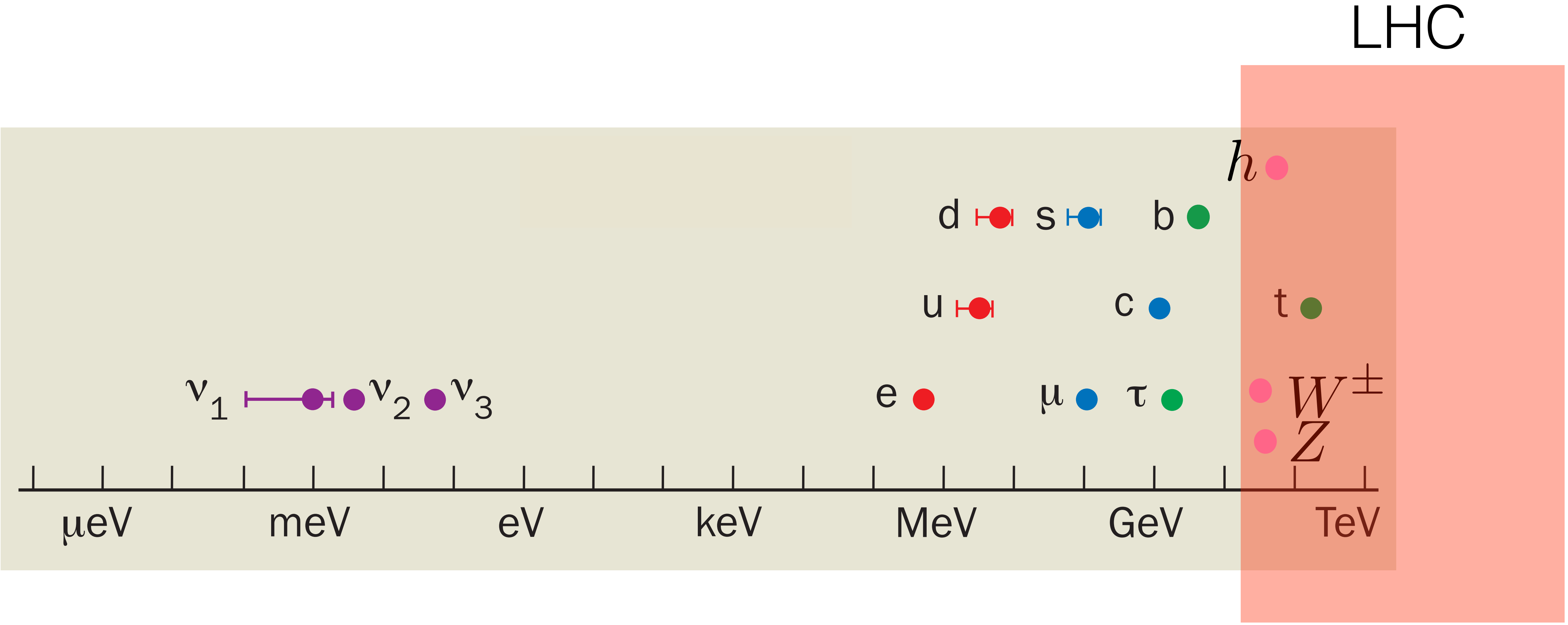
based in part on previous lectures
by A. Weiler & Y. Shadmi
at CERN ESHEP 2014
and by M. McCullough @ LP2015

The Standard Model



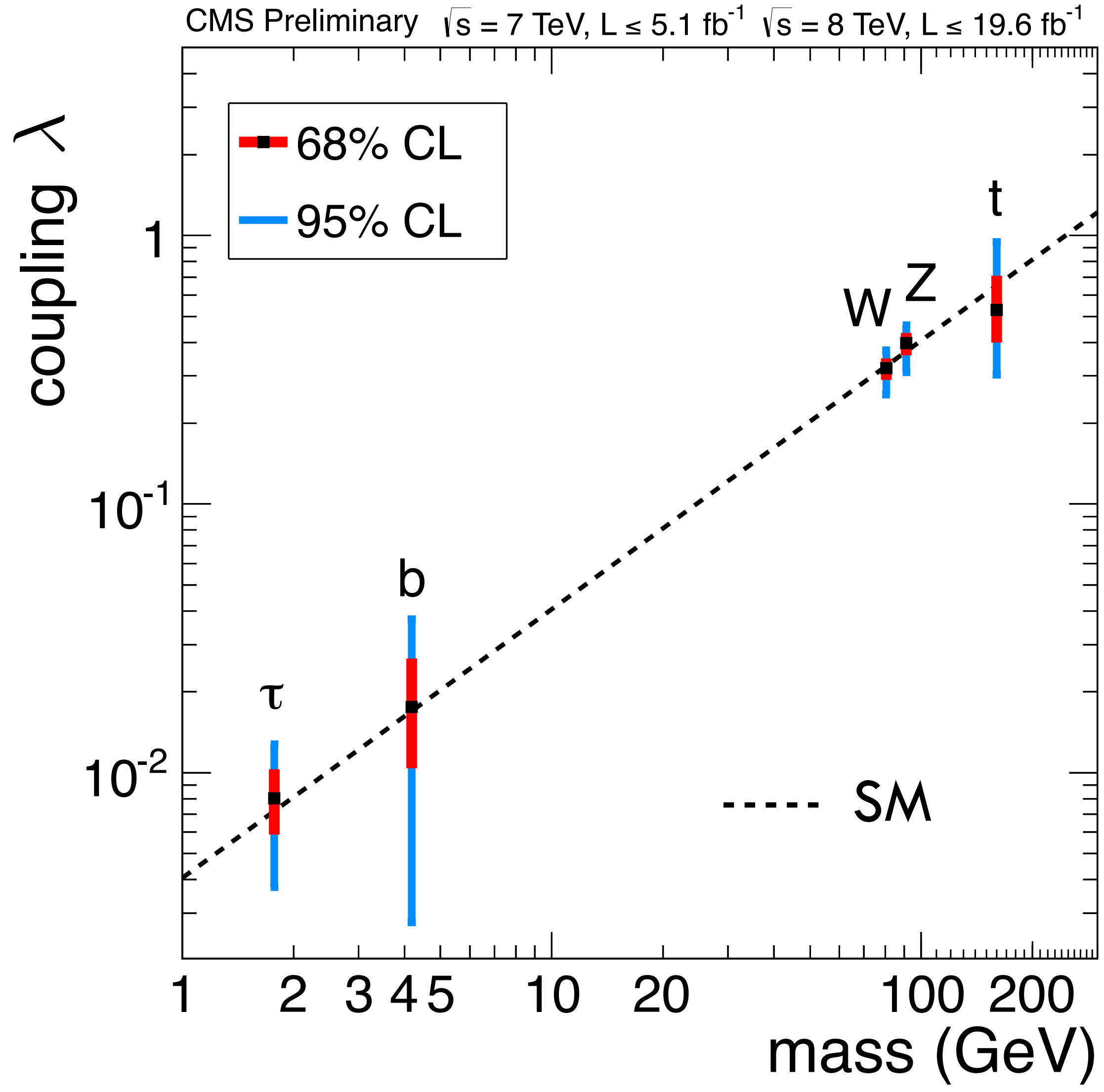
The energy frontier



What can we expect to discover?

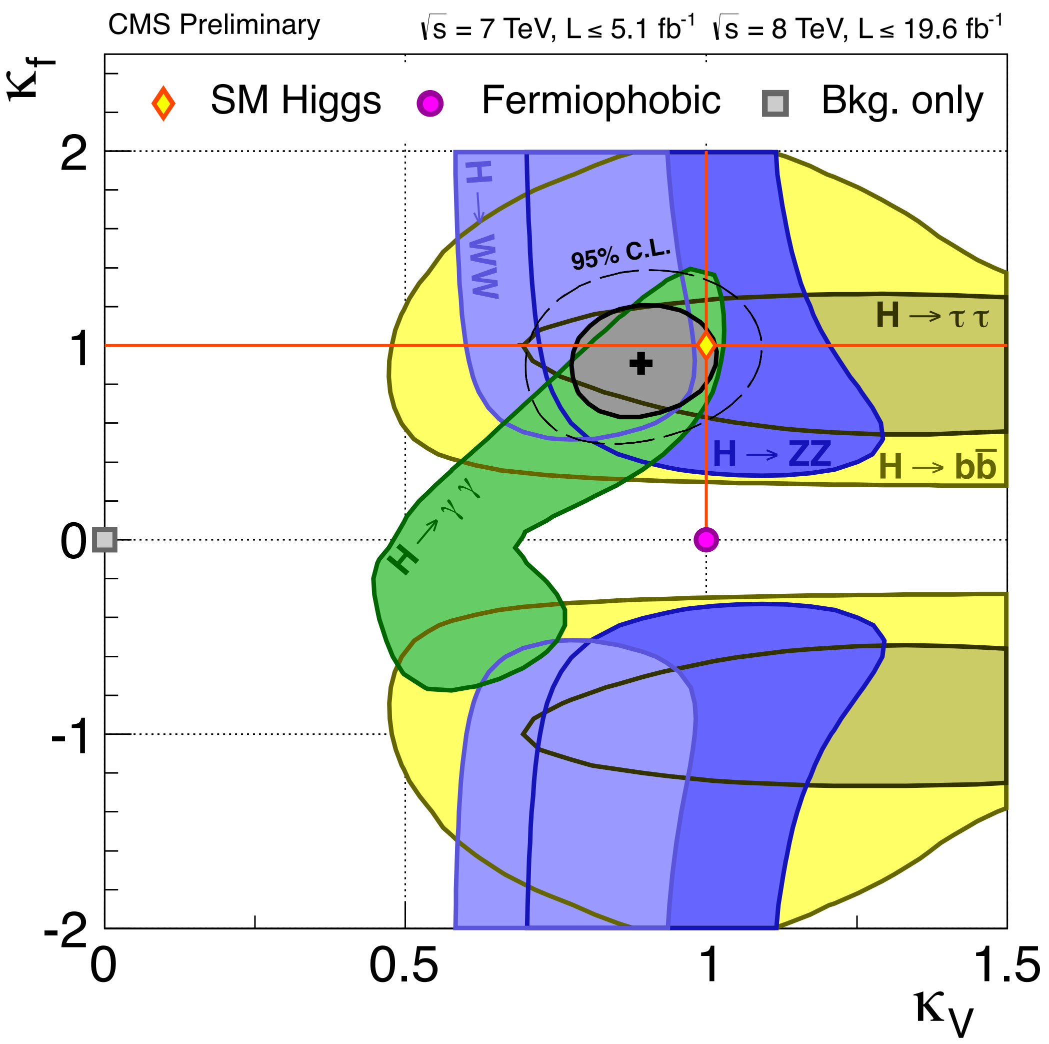
The Higgs boson

Related to EWSB

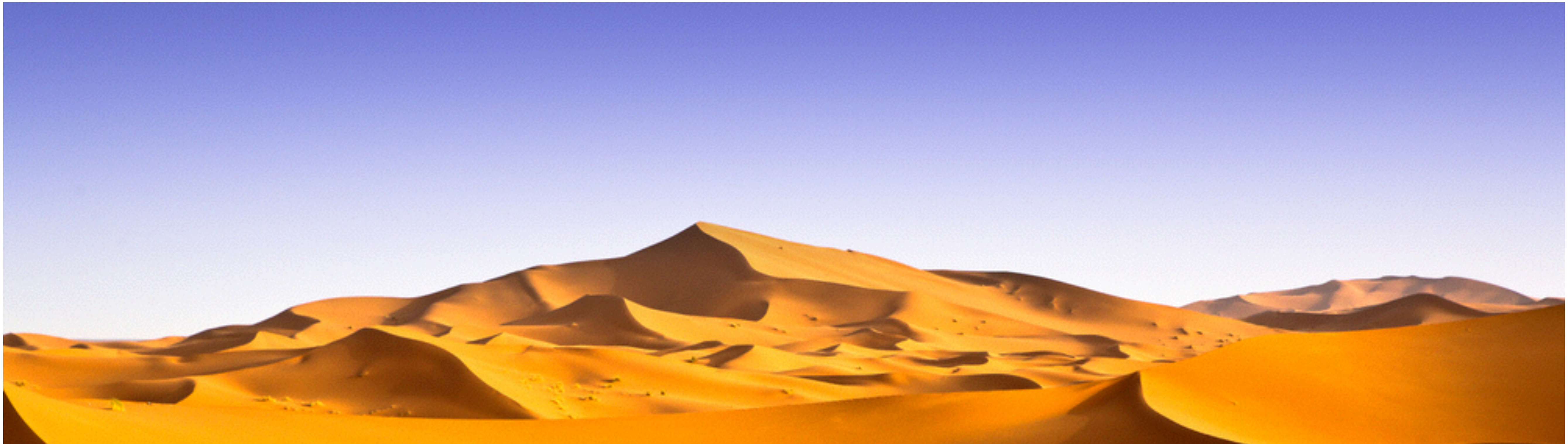


$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

Overall compatible with SM



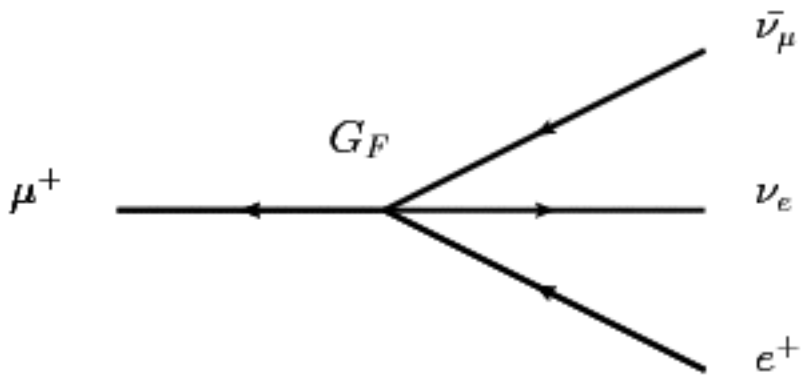
Why still expect NP@LHC



Fermi theory

G_F

$$\boxed{\frac{g^2}{m_W^2}}\bar{\nu}\gamma_\mu P_L \mu \bar{e}\gamma^\mu P_L \nu$$

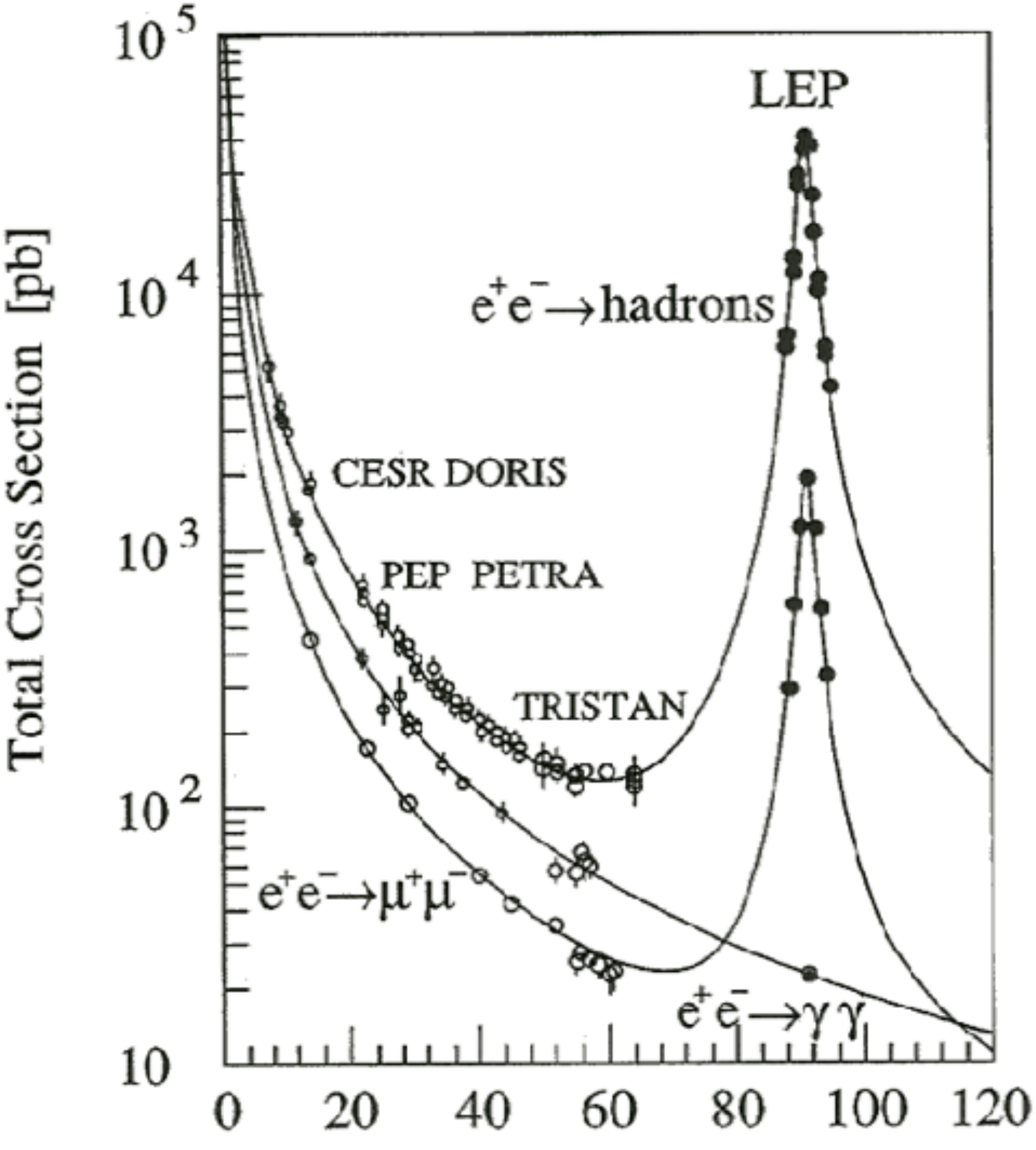


Scale!

Dimensional analysis: $\sigma \propto \frac{g^4}{m_W^4} E^2$

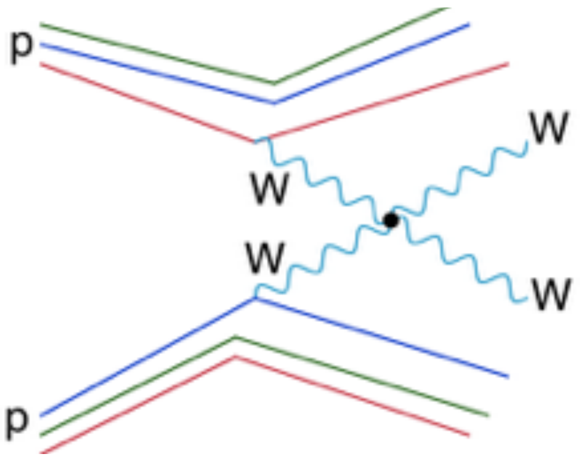
Something interesting will happen around E ~ m_W!

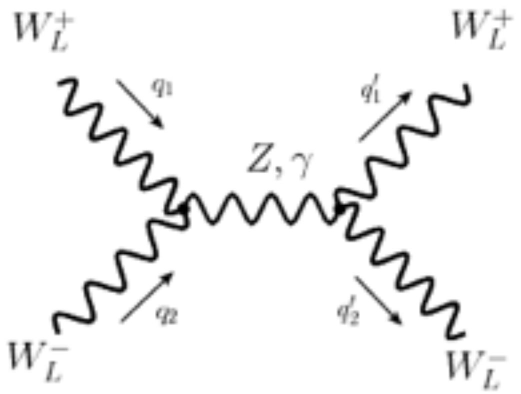
LEP

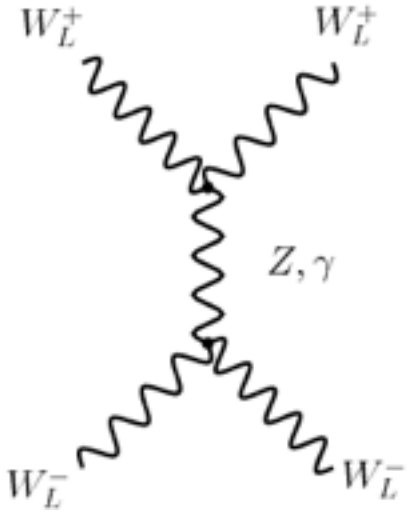

Total Cross Section [pb]
10^5
10^4
10^3
10^2
10
0
20
40
60
80
100
120
Centre of Mass Energy [GeV]
LEP
$e^+e^- \rightarrow$ hadrons
CESR DORIS
PEP PETRA
TRISTAN
$e^+e^- \rightarrow \mu^+\mu^-$
$e^+e^- \rightarrow \gamma\gamma$

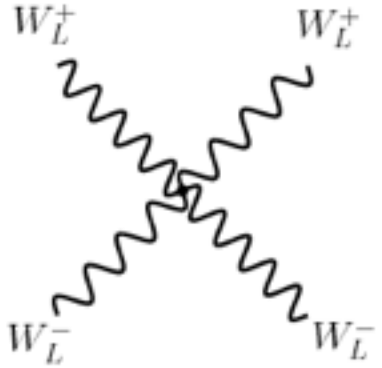
SM without Higgs

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\cancel{h}^0, A_\mu, W_\mu^\pm, Z_\mu, G_\mu, q, \ell)$$









$\sim E^2 + \ldots$

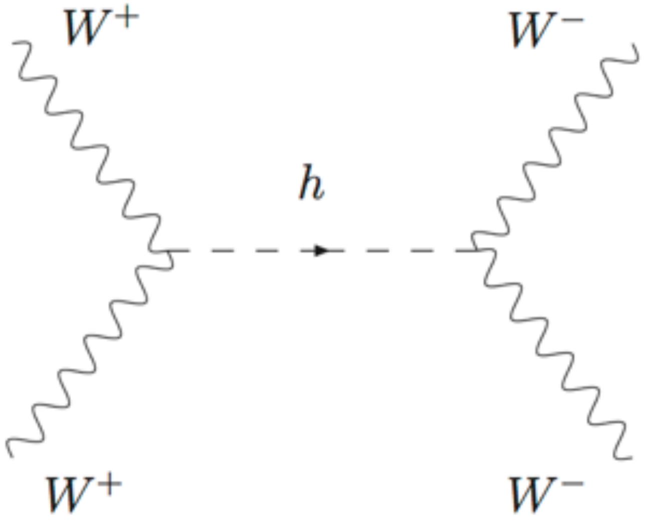
$\sim \cancel{E}^4 + E^2 + \ldots$

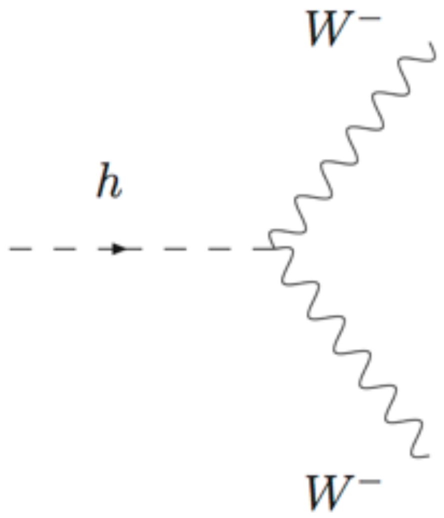
$\sim \cancel{E}^4 + E^2 + \ldots$

$\Lambda \approx 4\pi v \approx 3\text{TeV}$ NP to show up before this scale

SM-like Higgs

What if it couples only approximately like the SM Higgs?





$$a\, g_{VVh}^{\mathrm{SM}}$$

W_L W_L scattering fully unitarized? $\Lambda \approx 4\pi v \to \dfrac{4\pi v}{\sqrt{1-a^2}}$

Even if we measure a < 1, current limits do not guarantee new physics in reach of LHC: a ~ 0.8-0.9, Λ > 6…8 TeV

Where is the next scale?

- 13/14 TeV enough to reveal fundamental physics?
- First time in history without nearby new scale: all couplings dimensionless (marginal) or of positive mass dimension (relevant)
- Remaining hopes?
    - Landau pole of hyper-charge $U(1)_Y$
    - Gravity scale (M_{Planck})

SM hyper-charge

Hyper-charge is not asymptotically free, will blow up at (very) high energies — Landau Pole

$$1/\alpha_Y(M_Z) = 1/\alpha_Y(\Lambda) + \frac{b_Y}{2\pi}\ln\frac{\Lambda}{M_Z} \qquad\qquad b_Y = \frac{41}{10}$$

$$\Lambda \sim M_Z\, e^{2\pi/\alpha_Y b_Y} \sim 10^{41}\,\mathrm{GeV}$$

Gravity

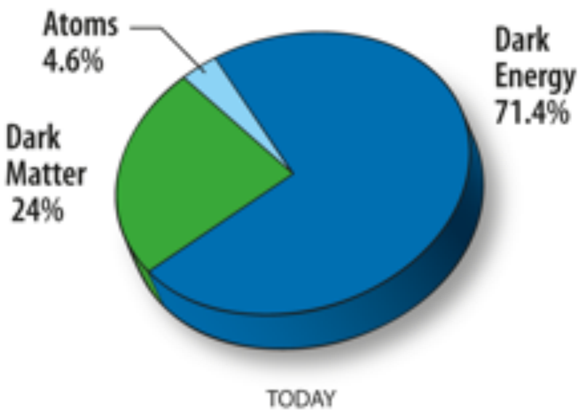
Strong coupling problem, e.g. graviton-graviton scattering

$$\sigma \sim \frac{E^n}{M_{pl}^{n+2}} \qquad\qquad M_{pl} \simeq 10^{19}\ \mathrm{GeV}$$

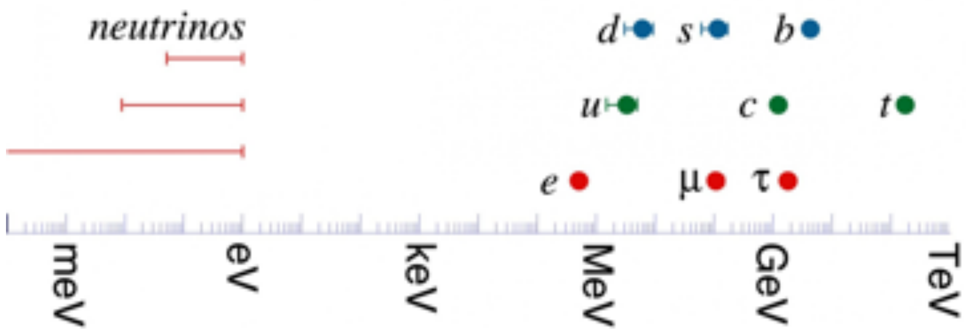
Open questions of the SM

SM is incomplete:

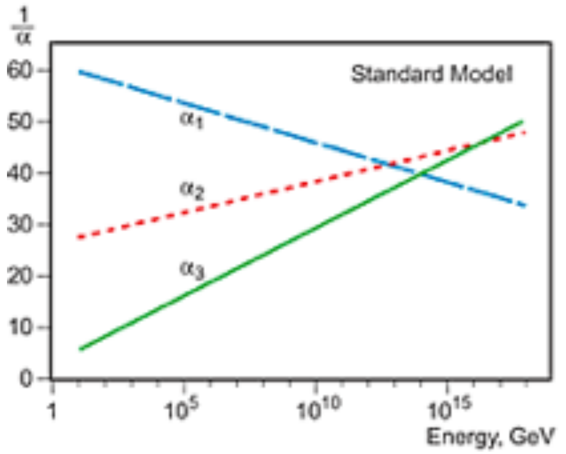
Dark matter?



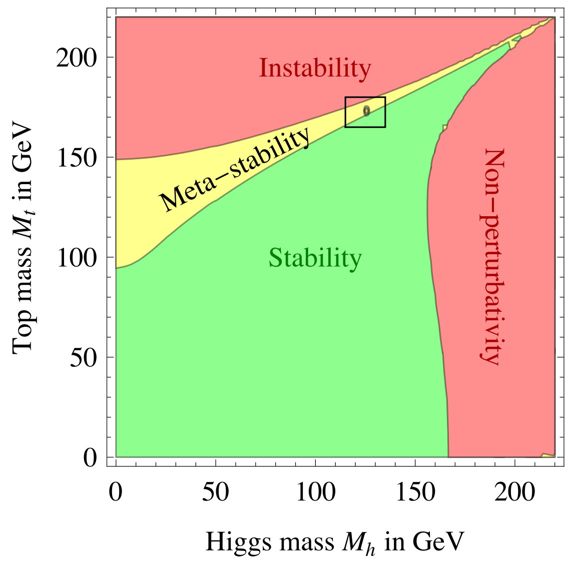
Origin of SM flavor & lepton mass hierarchy?



Unification of forces?



Stability of Higgs potential?



Stability of Higgs potential

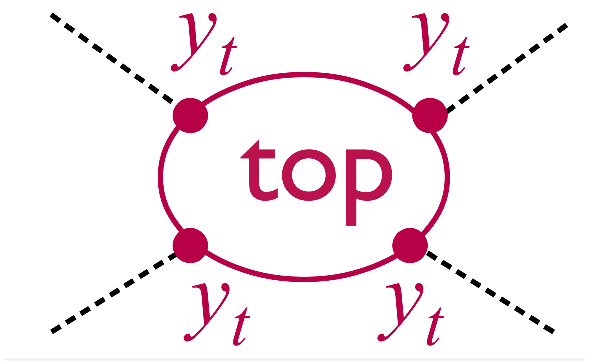
Tree level:

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

What happens at $|\phi| \gg v$? Focus on λ, $\mu^2 \ll |\phi|^2$

Quantum fluctuations change potential

$$V \simeq \lambda(|\phi|)|\phi|^4$$

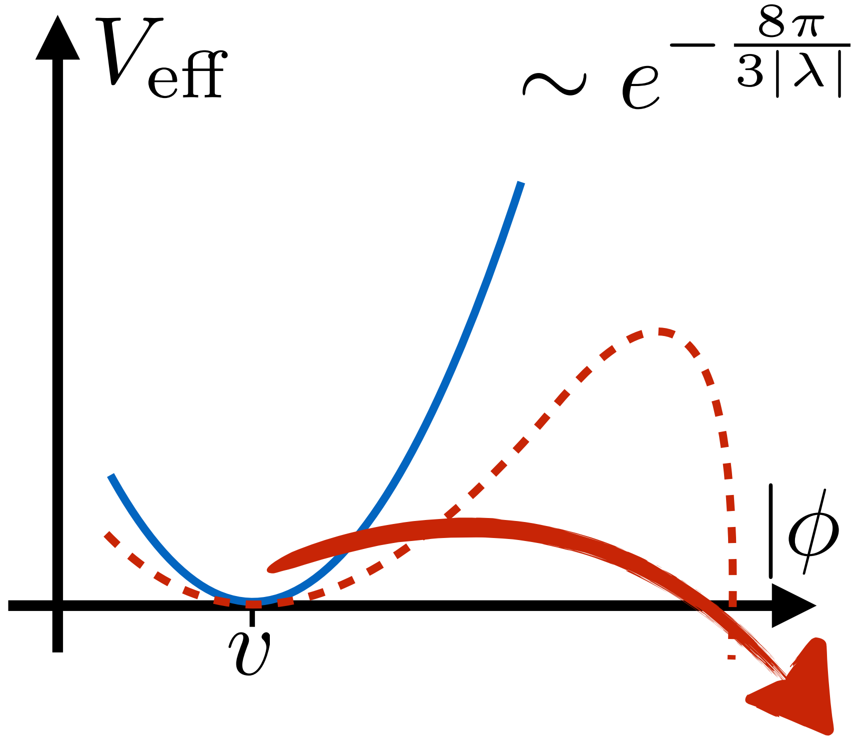


decreasing
at large Energies

➤➤➤➤➤➤➤➤

Tunneling

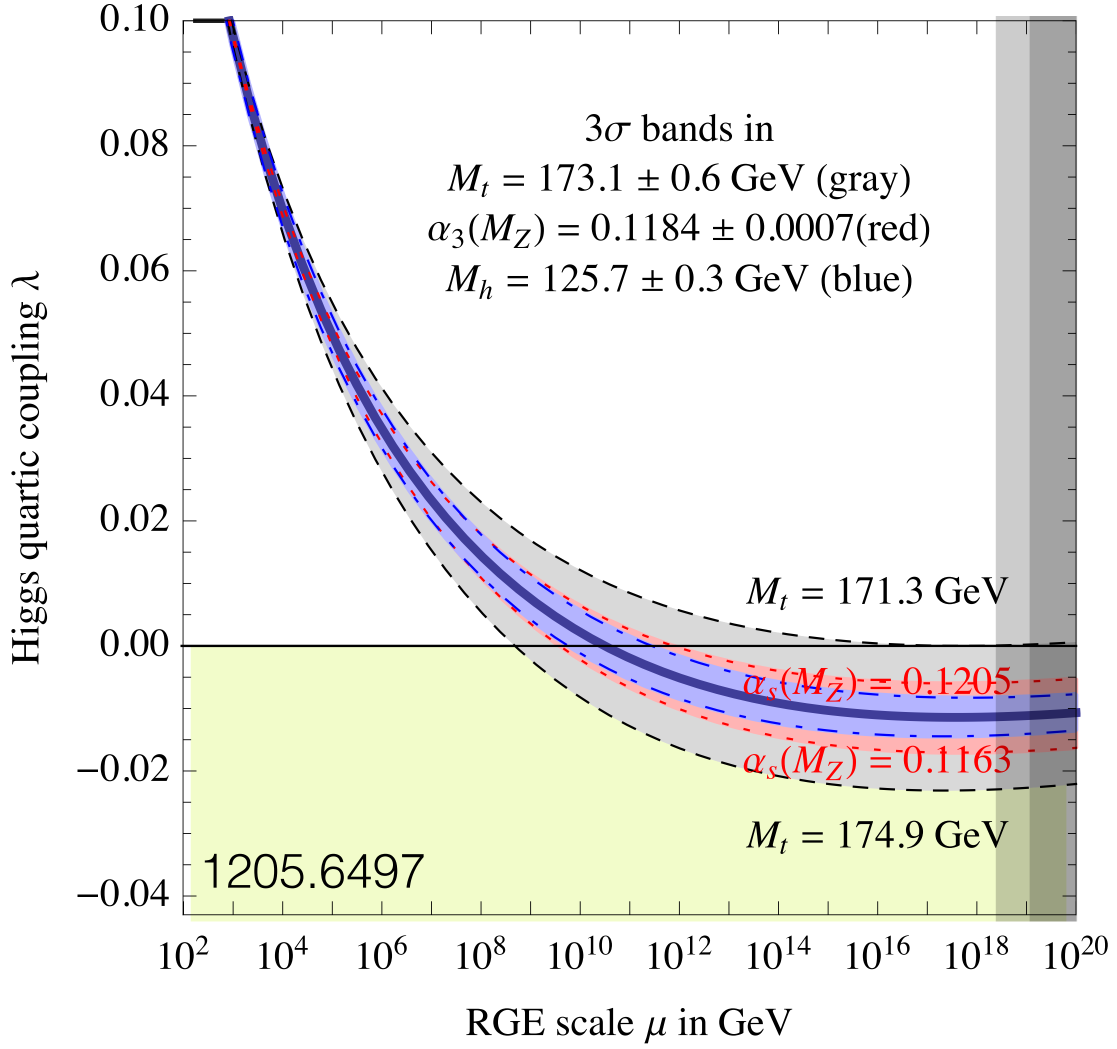
$\sim e^{-\frac{8\pi}{3|\lambda|}}$



Stability & meta-stability

SM vacuum is unstable but sufficiently long-lived

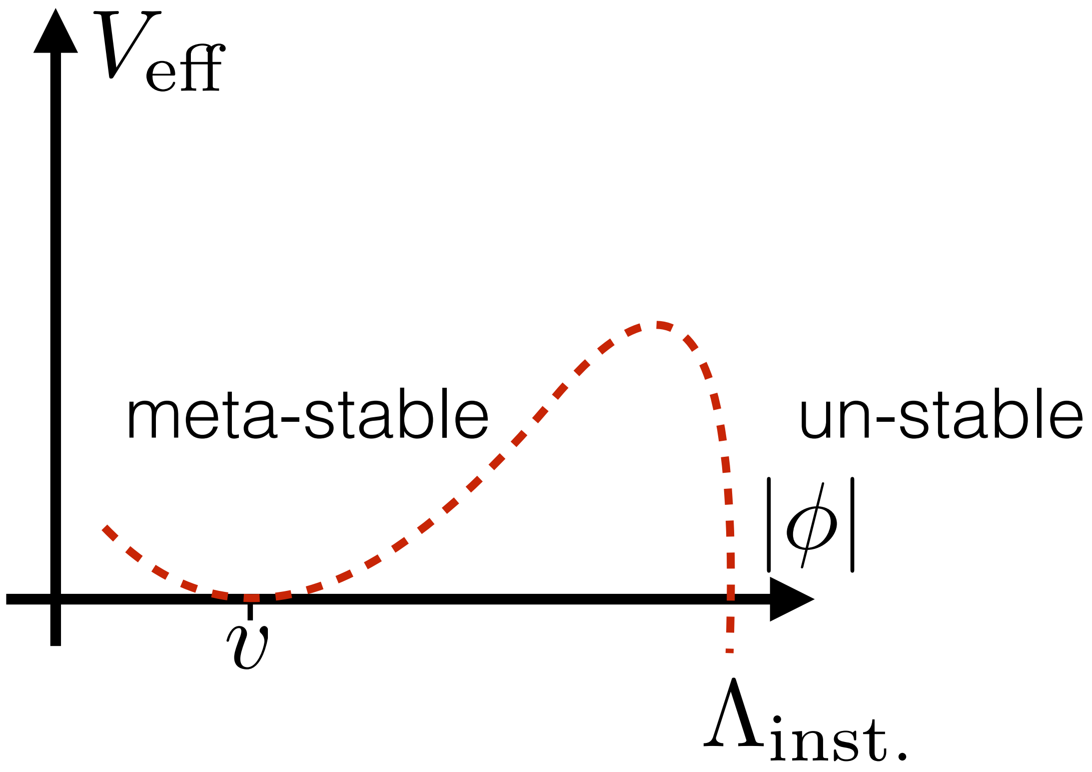
(depends on m_t, m_h)



Unlikely the full story, assumes nothing but SM up to the Planck scale…

Stability & meta-stability

If metastable: How did we end up in the energetically disfavoured vacuum?



Universe is overwhelmingly likely to evolve to wrong minimum

Fine-tunning of initial conditions?

$\sim \Lambda_{\text{inst.}}/M_{\text{Planck}}$

For $\Lambda_{\text{inst.}} \sim 10^{10}\,\text{GeV} \rightarrow \sim 10^{-8}$ tunning needed

Stability of EW scale

Quantum fluctuations destabilize Higgs mass^2 term:

$$V(\phi) = -\boxed{\mu^2|\phi|^2} + \lambda|\phi|^4$$

Effective field theory

An approximate field theory which works up to a certain energy scale (Λ), using only degrees of freedom with $m \ll \Lambda$.

Example: QED (e, γ), for $E \ll m_W$

Is the SM an EFT?

Yes! Breaks down latest at the gravity scale (details unknown).

UV insensitivity

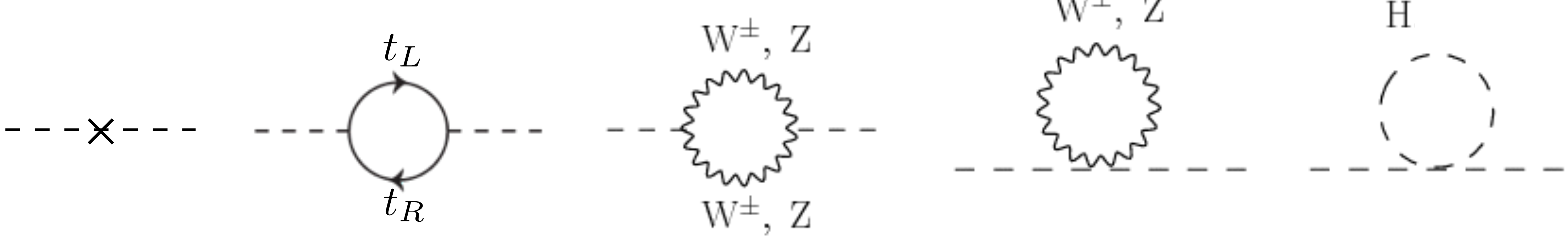
Naturalness : absence of special conspiracies between phenomena occurring at very different length scales.

Planets do not care about QED.

QED at E ~ m_e does not care about the Higgs.

Hierarchy problem

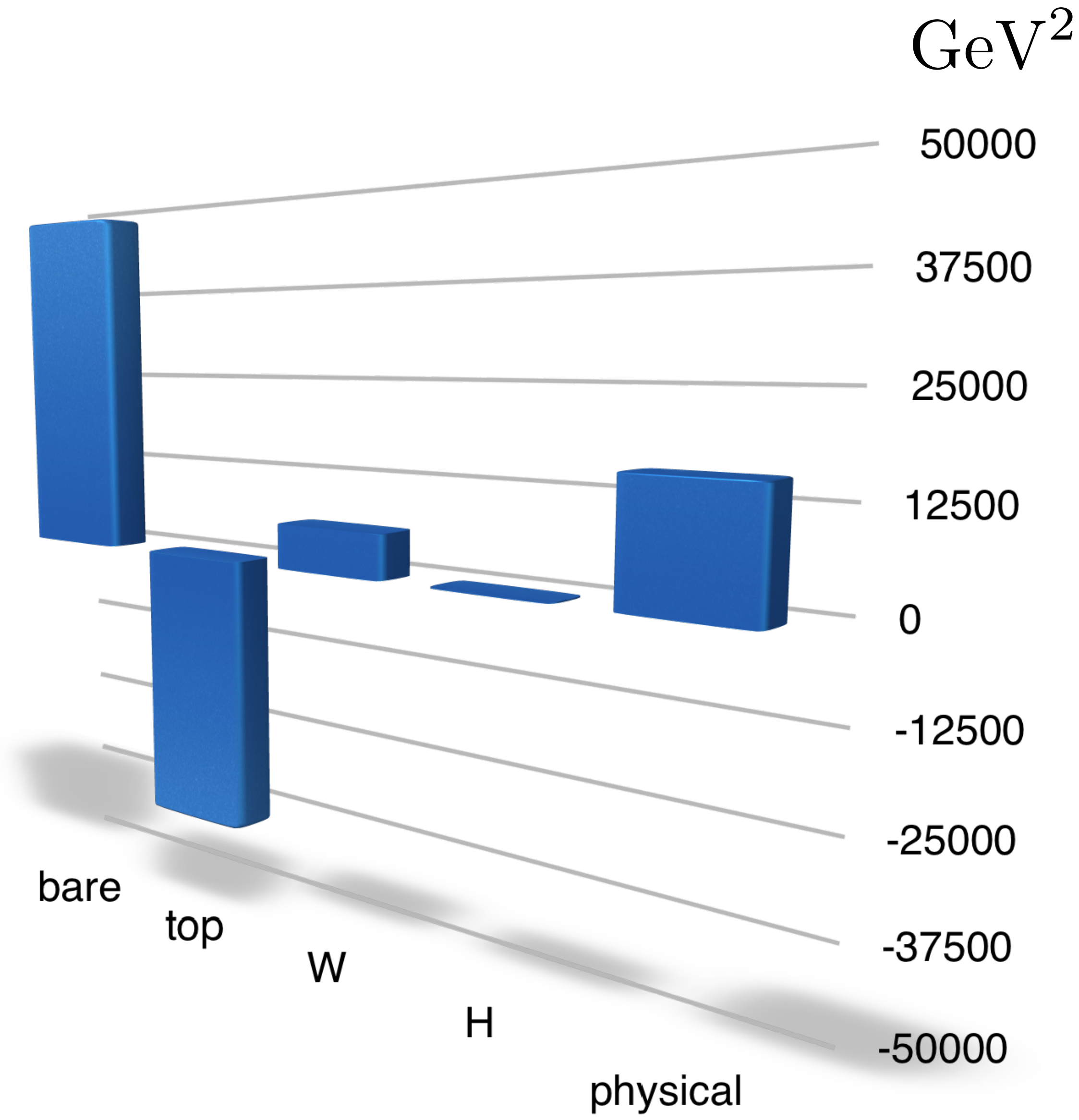
- Higgs mass sensitive to thresholds (GUT, gravity)
- Quantum corrections due to heavy NP exceed Higgs mass (EW scale) physical value, need to fine-tune parameters



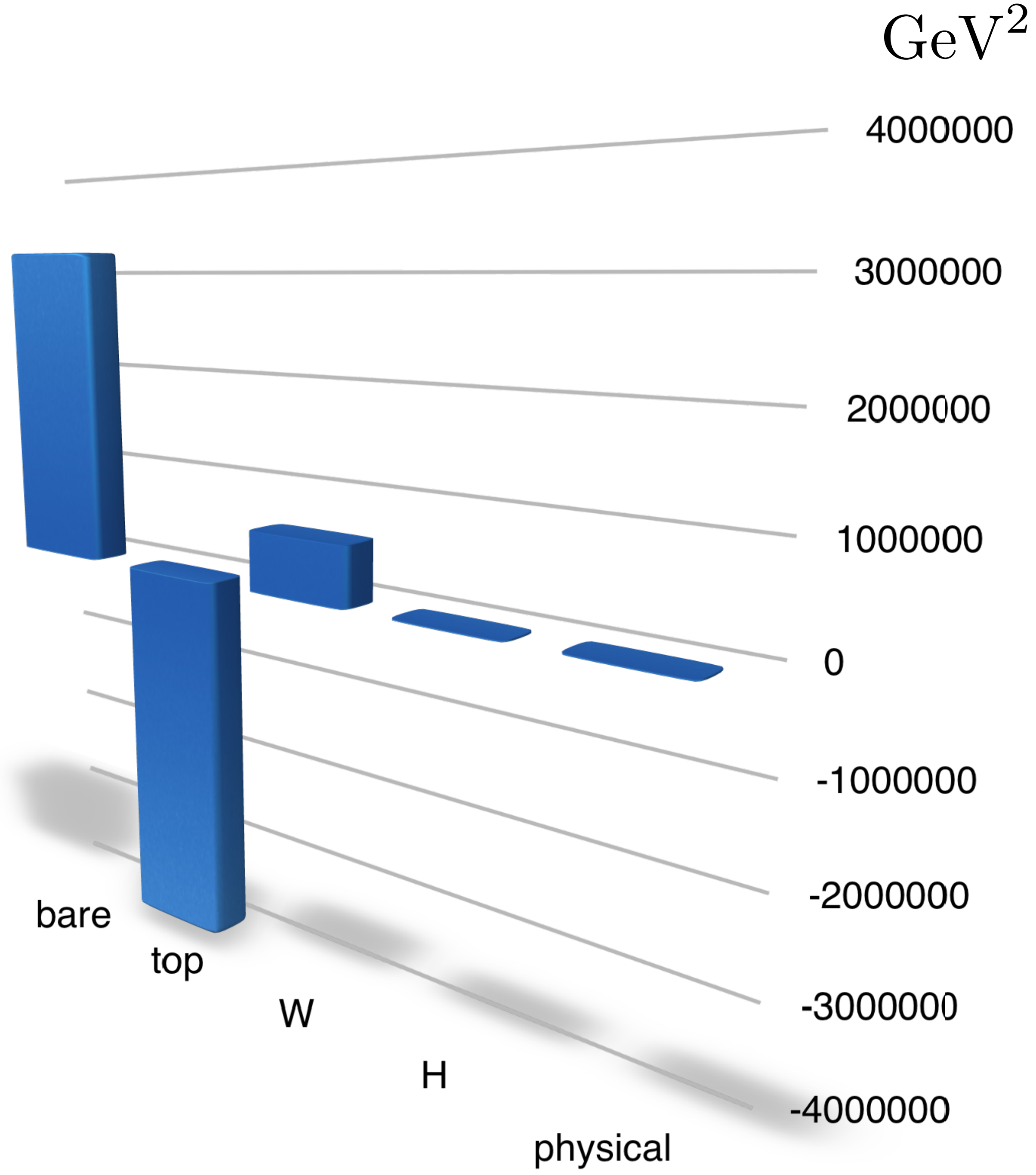
$m_h^2(\text{bare})$ $\quad -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$ $\quad \frac{9}{64\pi^2}g^2\Lambda^2$ $\quad \frac{1}{16\pi^2}\lambda^2\Lambda^2$

$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i\Lambda^2$$

$\Lambda = 1\,\mathrm{TeV}$

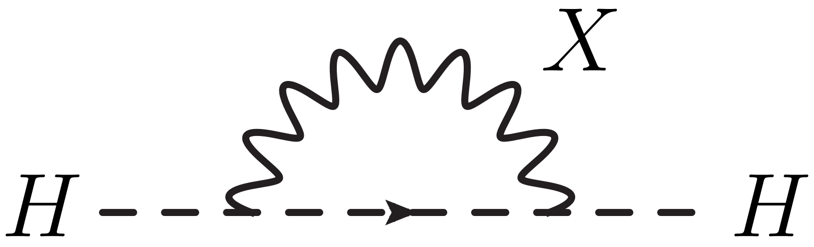


$\Lambda = 10\,\mathrm{TeV}$



Comments

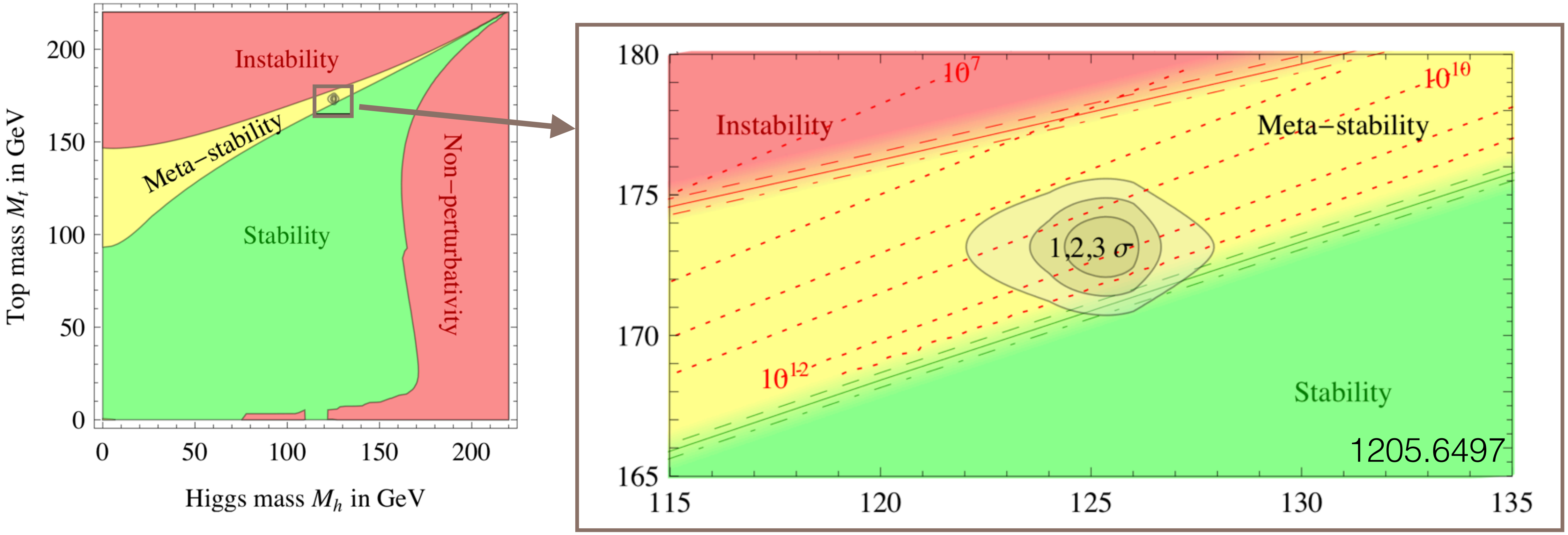
- The ‘cancelation of divergencies’ is not the question
- Rather: parameters in the effective theory are strongly sensitive to fundamental ones (e.g. GUT)



$$\Delta m_H^2 \sim \frac{g_{\rm GUT}^2}{16\pi^2} M_X^2 \sim (10^{15}{\rm GeV})^2$$

- The hierarchy problem needs a ‘hierarchy of scales’.
- The SM alone (no gravity, nothing else) is fine
  → no hierarchy, no problem!

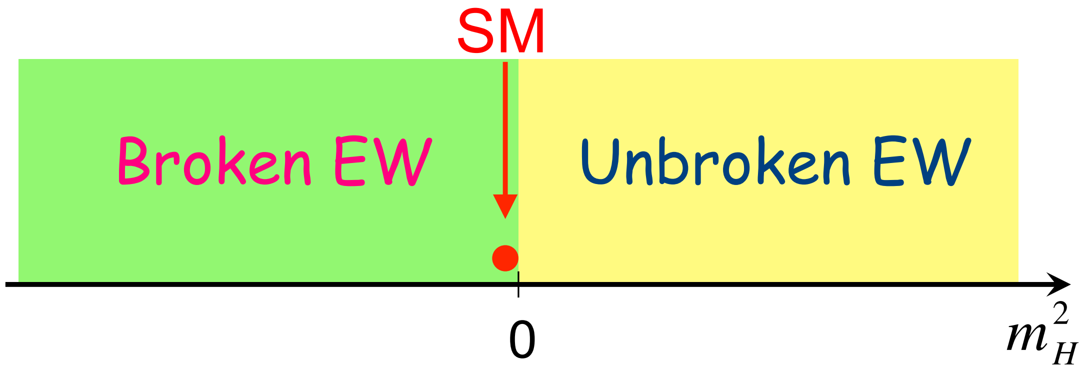
Only the SM?



1205.6497

We seem to be living close to a critical condition

Similar with Planck-Weak hierarchy

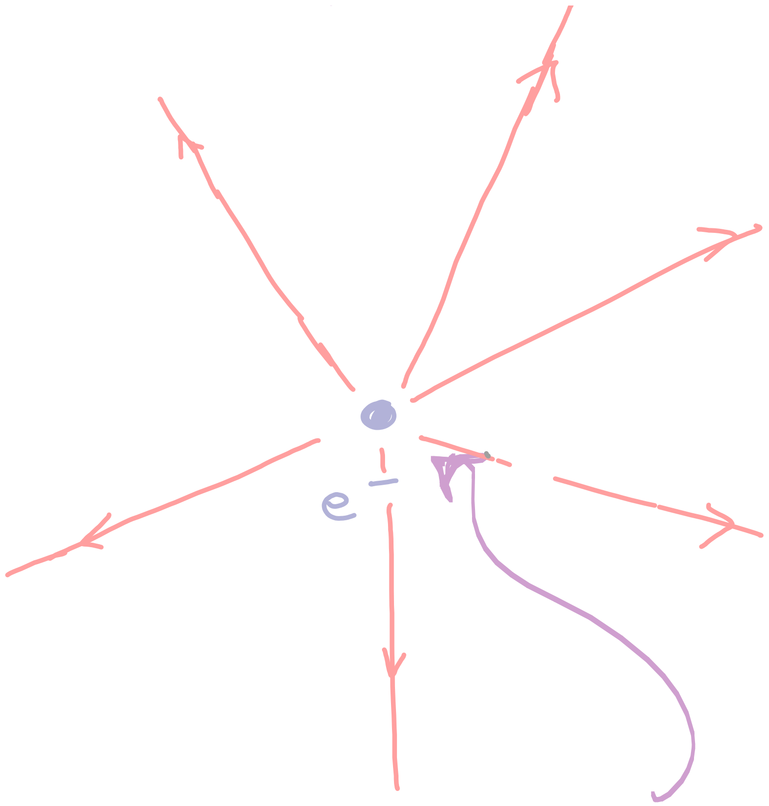


Fine-tuning not an inconsistency of physics since we can always cancel bare vs. quantum.

However, it might help us understand where new physics could set in.

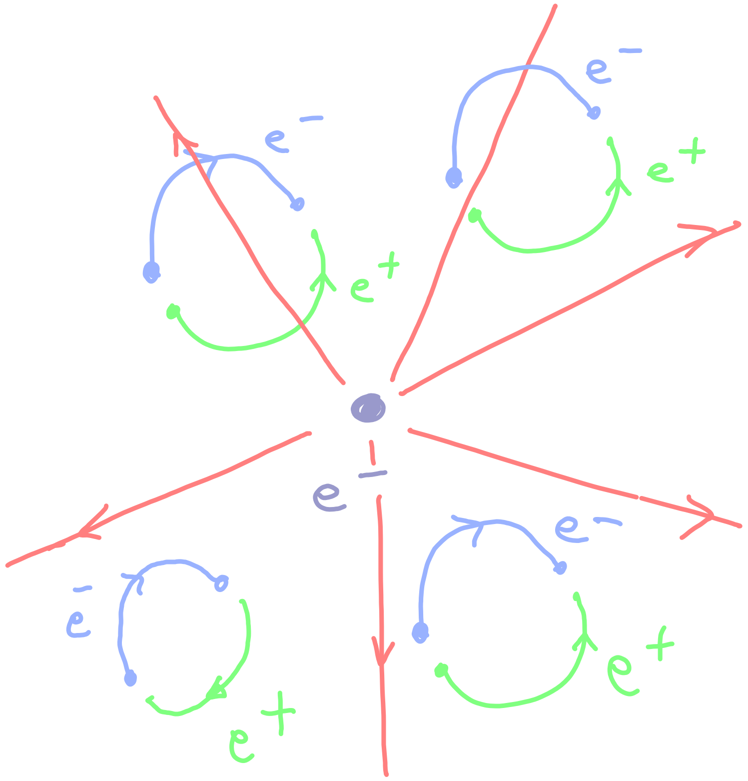
Electron mass

Example: divergent energy of electric field + positron



Classically

$$\int_{r=1/\Lambda} d^3r\vec{E}^2 \simeq \alpha\Lambda$$



Extend space-time symmetry, relativity + QM:

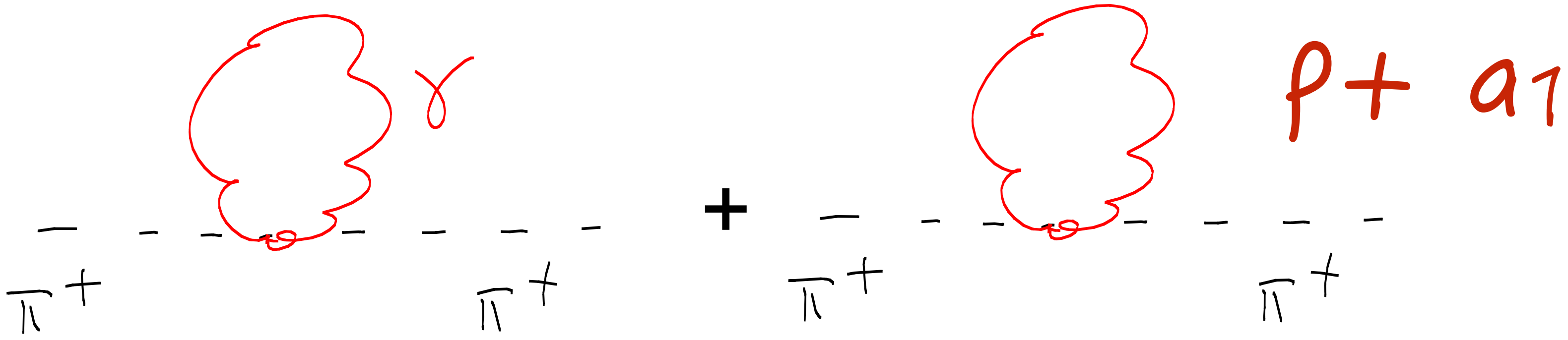
$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$

→ natural electron mass

→ predict positron

Pion mass

Example: neutral-charged pion mass difference



$$\delta m_{\pi^+}^2 \sim \frac{3\alpha}{4\pi}\Lambda^2 < (m_{\pi^+}^2 - m_{\pi^0}^2)_{\text{exp}} \simeq (4\text{MeV})^2$$

Expect $\Lambda < 850\,\text{MeV}$

‘New physics’: comes in at $m_\rho = 770\,\text{MeV}$

$$m_\pm^2 - m_{\pi^0}^2 \simeq \frac{3\alpha_{\text{em}}}{4\pi}\frac{m_\rho^2 m_{a_1}^2}{m_{a_1}^2 - m_\rho^2}\log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$

$$(m_\pm - m_{\pi^0})_{\text{th}} \simeq 5.8\,\text{MeV}$$

Famous naturalness disaster

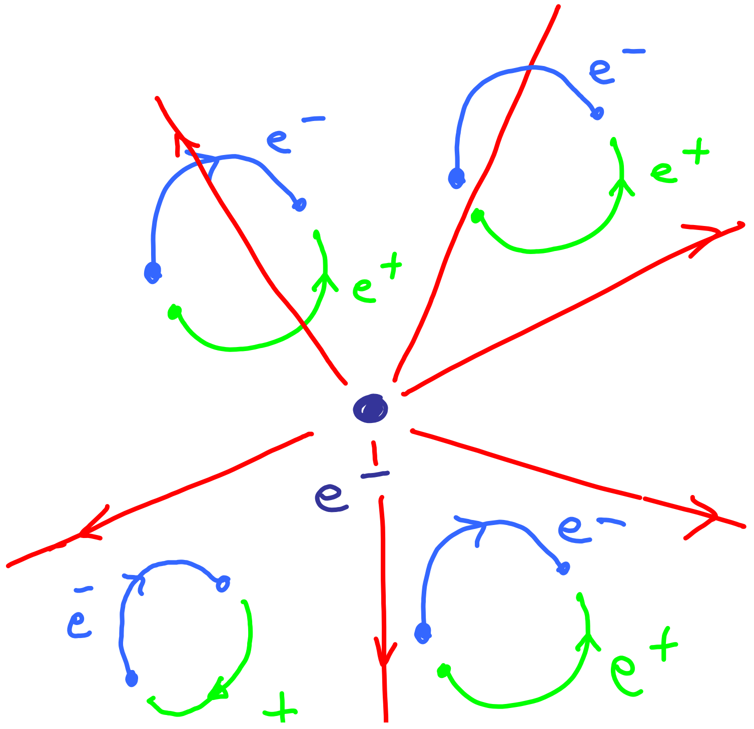
We don’t understand the cosmological constant

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R-\Lambda_0)$$

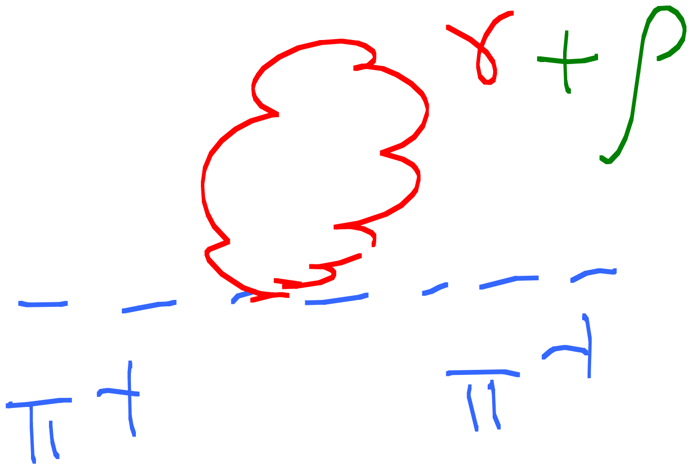
$$\mathrm{CC} = \Lambda_0 \approx \left(10^{-3}\mathrm{eV}\right)^4$$

$\delta\Lambda_0 \approx \Lambda^4$ - New physics at the scale of few mm?

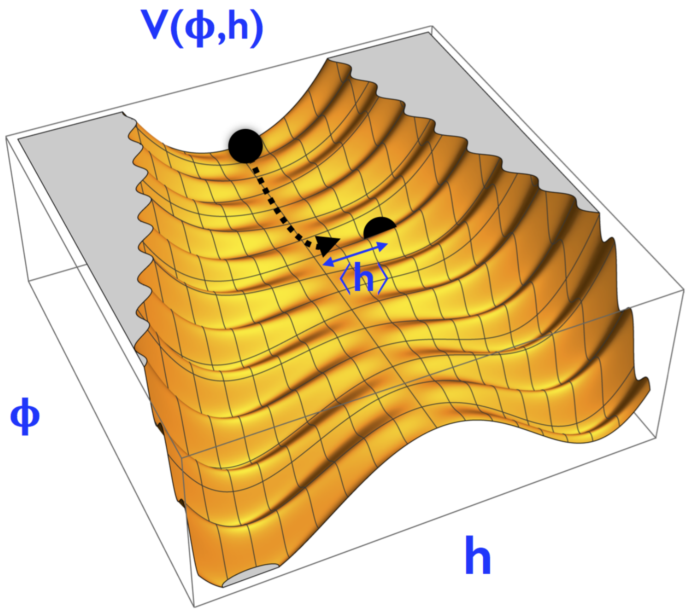
Environmental selection? (antropics, relaxation)



Supersymmetry
(new space-time symmetry)

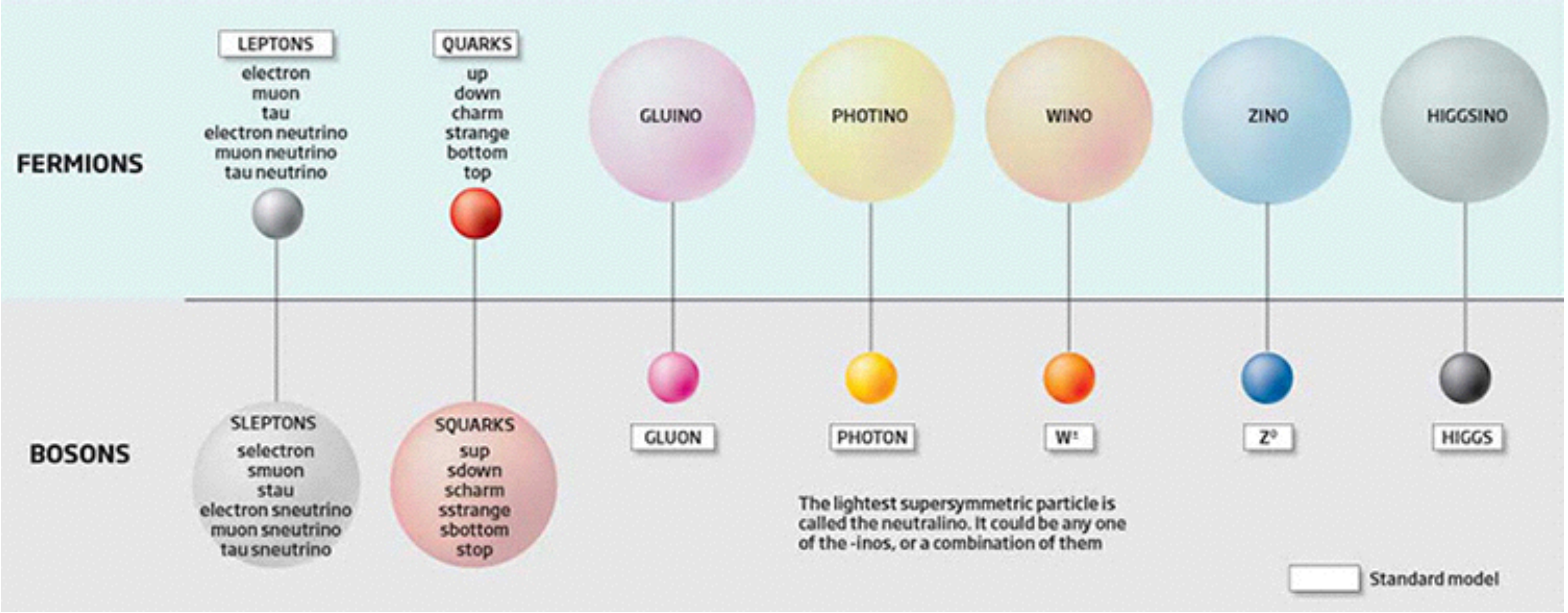


Composite Higgs



Cosmological relaxation

Supersymmetry



What is supersymmetry?

Space-time symmetry:

$$Q\,|Fermion\rangle \;=\; |Boson\rangle$$ and vice versa

Non-factorizable extension of Poincare symmetry

$$[Q, P_\mu] = 0 \quad , \quad [Q, G] = 0 \quad , \quad [Q, M_{\mu\nu}] \neq 0\ .$$

(translations) (internal symmetries) (Lorentz transformations)

Particles appear in super-multiplets:

- equal mass
- equal q-numbers
- different spin

Invariance under general covariant transformations

→Local SUSY: $\{Q, \bar{Q}\} \sim P_\mu$ (Supergravity)

Number of SUSY generators N

→particles with spin at least N/4

For local interacting theories: N_{max}=4 (w/o gravity)

(in d=4) N_{max}=8 (with gravity)

Most general symmetry of S-matrix

$$\text{SuperPoincaré} \times \text{Internal Symmetries}$$

Haag–Lopuszanski–Sohnius

‘Minimal’ SUSY model

Free theory:
- 1 massive (Dirac) fermion ψ of mass m,
- 2 complex scalars ϕ_+, ϕ_- of mass m

$$\mathcal{L} = \partial^\mu \phi_+^* \, \partial_\mu \phi_+ - m^2 \, |\phi_+|^2 + \partial^\mu \phi_-^* \, \partial_\mu \phi_- - m^2 \, |\phi_-|^2 + \bar{\psi}(i\partial\!\!\!/ - m)\psi$$

Decompose 4-spinors in terms of 2-components

$$\rightarrow \psi = \begin{pmatrix} \psi_+ \\ -\varepsilon \psi_-^* \end{pmatrix} \qquad \psi_L = \psi_+, \, \psi_R = -\varepsilon \psi_-^* \qquad \varepsilon \equiv -i\sigma^2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} &= \partial^\mu \phi_+^* \, \partial_\mu \phi_+ + \psi_+^\dagger i \bar{\sigma}^\mu \partial_\mu \psi_+ \\ &+ \partial^\mu \phi_-^* \, \partial_\mu \phi_- + \psi_-^\dagger i \bar{\sigma}^\mu \partial_\mu \psi_- \\ &- m^2 \, |\phi_-|^2 - m^2 \, |\phi_+|^2 - m(\psi_+^T \varepsilon \psi_- + \mathrm{hc}) \end{aligned}$$

$$
\begin{aligned}
\mathcal{L} &= \partial^\mu \phi_+^* \, \partial_\mu \phi_+ + \psi_+^\dagger i \bar{\sigma}^\mu \partial_\mu \psi_+ \\
&+ \partial^\mu \phi_-^* \, \partial_\mu \phi_- + \psi_-^\dagger i \bar{\sigma}^\mu \partial_\mu \psi_- \\
&- m^2 \, |\phi_-|^2 - m^2 \, |\phi_+|^2 - m(\psi_+^T \varepsilon \psi_- + \mathrm{hc})
\end{aligned}
$$

The model supports extended space-time symmetry:
take a constant (anti-commuting) 2-component (L) spinor ξ

$$
\begin{aligned}
\delta_\xi \phi_+ &= \sqrt{2} \, \xi^T \varepsilon \psi_+ \\
\delta_\xi \psi_+ &= \sqrt{2} \, i \sigma^\mu \varepsilon \xi^* \partial_\mu \phi_+ - m \xi \phi_-^*
\end{aligned}
$$

and similarly for + → –

transforms fermions into bosons & vice versa

This is supersymmetry!

Vacuum energy

Global symmetries → Noether currents

$$Q = \int d^3x j^0(x) \quad \text{with} \quad \frac{d}{dt}Q = 0$$

translations: conserved charge = Hamiltonian *H*

$$\{\mathrm{SUSY}, \mathrm{SUSY}\} \propto H$$

consider the vacuum expectation value of this:

$$\langle 0| \{\mathrm{SUSY}, \mathrm{SUSY}\} |0\rangle \propto \langle 0|H|0\rangle$$

if SUSY unbroken: $\mathrm{SUSY}|0\rangle = 0$

therefore $\langle 0|H|0\rangle = 0$

The vacuum energy vanishes!

Why we don't worry about electron mass

There is no quadratic divergence in fermion mass

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\partial\!\!\!/ - m_0)\psi \\ &= \bar{\psi}(i\partial\!\!\!/)\psi - m_0(\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L)\end{aligned}$$

with $m_0 = 0$ we have 2 different species: $\psi_{L,R}$

$U(1)_L \times U(1)_R$ chiral symmetry

breaking needs to be proportional to m_0

UV physics can only enter as $\delta m \propto m_0 \log \frac{m_0}{\Lambda}$

SUSY-Chiral protection of scalar mass

No scalar electron → SUSY broken

In (softly) broken SUSY: ${m_0}^2_{scalar} = {m_0}^2_{fermion} + \tilde{m}^2$

UV sensitivity of scalar mass:

$$\delta m^2_{scalar} = \xcancel{\#\Lambda}^2 + \#{m_0}^2_{scalar} \log \frac{{m_0}^2_{scalar}}{\Lambda^2}$$

for: $\tilde{m}^2 = 0$ SUSY restored:

Λ^2 term must be proportional to $\tilde{m}^2$

‘Minimal’ SUSY model revisited

$$\begin{aligned}\mathcal{L} &= \partial^\mu \phi_+^* \, \partial_\mu \phi_+ + \partial^\mu \phi_-^* \, \partial_\mu \phi_- + \partial^\mu h^* \, \partial_\mu h \\ &+ \psi_+^\dagger i\bar{\sigma}^\mu \partial_\mu \psi_+ + \psi_-^\dagger i\bar{\sigma}^\mu \partial_\mu \psi_- + \tilde{h}^\dagger i\bar{\sigma}^\mu \partial_\mu \tilde{h} \\ &+ \mathcal{L}_{int}\end{aligned}$$

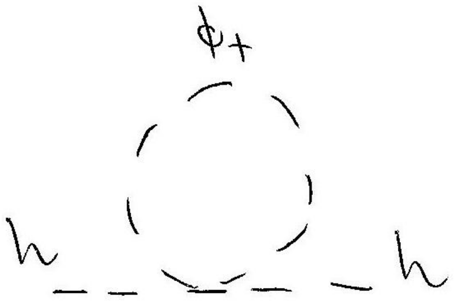
Added complex scalar h (+ SUSY partner) & set *m*=0

(SUSY) Yukawa interactions:

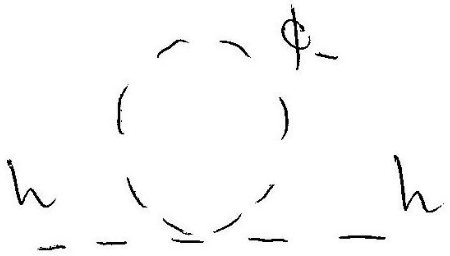
$$\begin{aligned}\mathcal{L}_{int} = &- y\,(h\psi_+^T \varepsilon \psi_- + \phi_+ \tilde{h}^T \varepsilon \psi_- + \phi_- \tilde{h}^T \varepsilon \psi_+ + \mathrm{hc}) \\ &- |y|^2 [|\phi_+|^2 \, |\phi_-|^2 + |h|^2 \, |\phi_-|^2 + |h|^2 \, |\phi_+|^2]\end{aligned}$$

Consider loop contributions to h mass (including soft ~~SUSY~~)

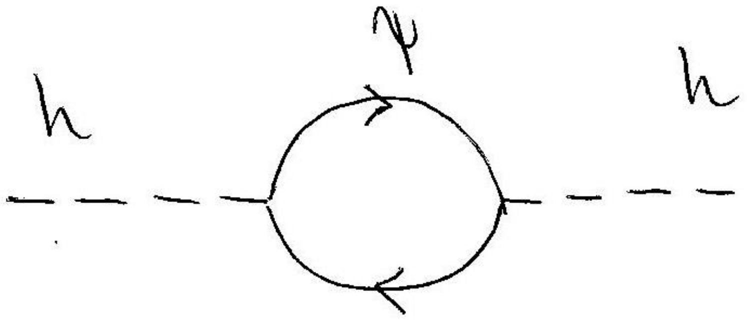
‘stop$_L$’



‘stop$_R$’



‘top’



$$|y|^2 \int \frac{d^4p}{(2\pi)^4}\left[-\frac{1}{p^2-\tilde{m}_+^2}\right] \qquad |y|^2 \int \frac{d^4p}{(2\pi)^4}\left[-\frac{1}{p^2-\tilde{m}_-^2}\right] \qquad 2|y|^2 \int \frac{d^4p}{(2\pi)^4}\frac{1}{p^2}$$

$$\delta m_h^2 \;\propto\; |y|^2\,\tilde{m}_1^2 \int \frac{d^4p}{(2\pi)^4}\,\frac{1}{p^2(p^2-\tilde{m}_+^2)} + (\tilde{m}_+^2 \to \tilde{m}_-^2)$$

h mass log divergent, proportional to $\tilde{m}_\pm^2$

requires equal couplings of bosons & fermions (y)!

SUSY only broken by masses

Small scalar mass implies additional
light scalar (top) partners!

SUSY SM ~ MSSM

Field content: gauge

- $SU(3)_C$: gluon + gluino
- $SU(2)_L$: W + wino
- $U(1)_Y$: B + bino

matter (L-fermions)

- (doublet) quark q + squark $\tilde{q}$
- (singlet) up-quark u^c + up squark $\tilde{u}^c$
- (singlet) down-quark d^c + down squark $\tilde{d}^c$
- (doublet) lepton l + slepton $\tilde{l}$
- (singlet) lepton e^c + slepton $\tilde{e}^c$

All interactions fixed by gauge - and supersymmetry

No Higgs yet…

SUSY SM with single Higgs doublet has several problems

- EWSB generates negative SUSY breaking terms for squarks & sleptons
  → color & charge breaking minima
- massless chiral fermion Higgsino
  → SM gauge symmetry anomalous
- combined up- and down-quark / charged lepton yukawas break SUSY

All above problems fixed by adding 2 Higgs doublets

$$H_{U,D} \sim (1,2)_{\pm 1}$$

In unbroken SUSY $\langle H_U \rangle = \langle H_D \rangle$

Quartic in Higgs potential fixed by gauge symmetry (g_2,g_Y)!

MSSM Higgs spectrum

2 complex doublets: 8 d.o.f.s

in EW vacuum:

$$\langle H_U \rangle = \begin{pmatrix} v_U \\ 0 \end{pmatrix} \qquad \langle H_D \rangle = \begin{pmatrix} 0 \\ v_D \end{pmatrix}$$

$$\sqrt{v_u^2 + v_d^2} \equiv v \simeq 246\,\mathrm{GeV} \qquad \tan\beta \equiv v_U / v_D$$

3 GBs eaten by W,Z

remaining physical scalars

2 charged ($H^\pm$) + 3 neutral (H^0,h^0,A^0) scalars

In MSSM @ tree level (in terms of $\delta V = B\mu H_U H_D$, β & masses)

$$H^{\pm} \quad : \quad M_W^2 + M_A^2 \qquad (\mathrm{SUSY}: M_W^2)$$

$$H^0 \quad : \quad \frac{1}{2}(M_Z^2 + M_A^2) + \frac{1}{2}\sqrt{(M_Z^2 + M_A^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}$$

$$(\mathrm{SUSY}: M_Z^2)$$

$$A^0 \quad : \quad M_A^2 = B\mu(\cot\beta + \tan\beta) \qquad (\mathrm{SUSY}: 0)$$

For the light Higgs (SUSY: 0)

$$m_h^2 = \frac{1}{2}(M_Z^2 + M_A^2) - \frac{1}{2}\sqrt{(M_Z^2 + M_A^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}$$

Prediction:

$$\underset{\substack{\uparrow \\ 125\text{ GeV}}}{m_h} \leq m_Z|\cos 2\beta| \leq \underset{\substack{\uparrow \\ 90\text{ GeV}}}{M_Z}$$

Higgs mass @ 1-loop

Large 1-loop SUSY corrections possible

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^2}{4\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\right]$$

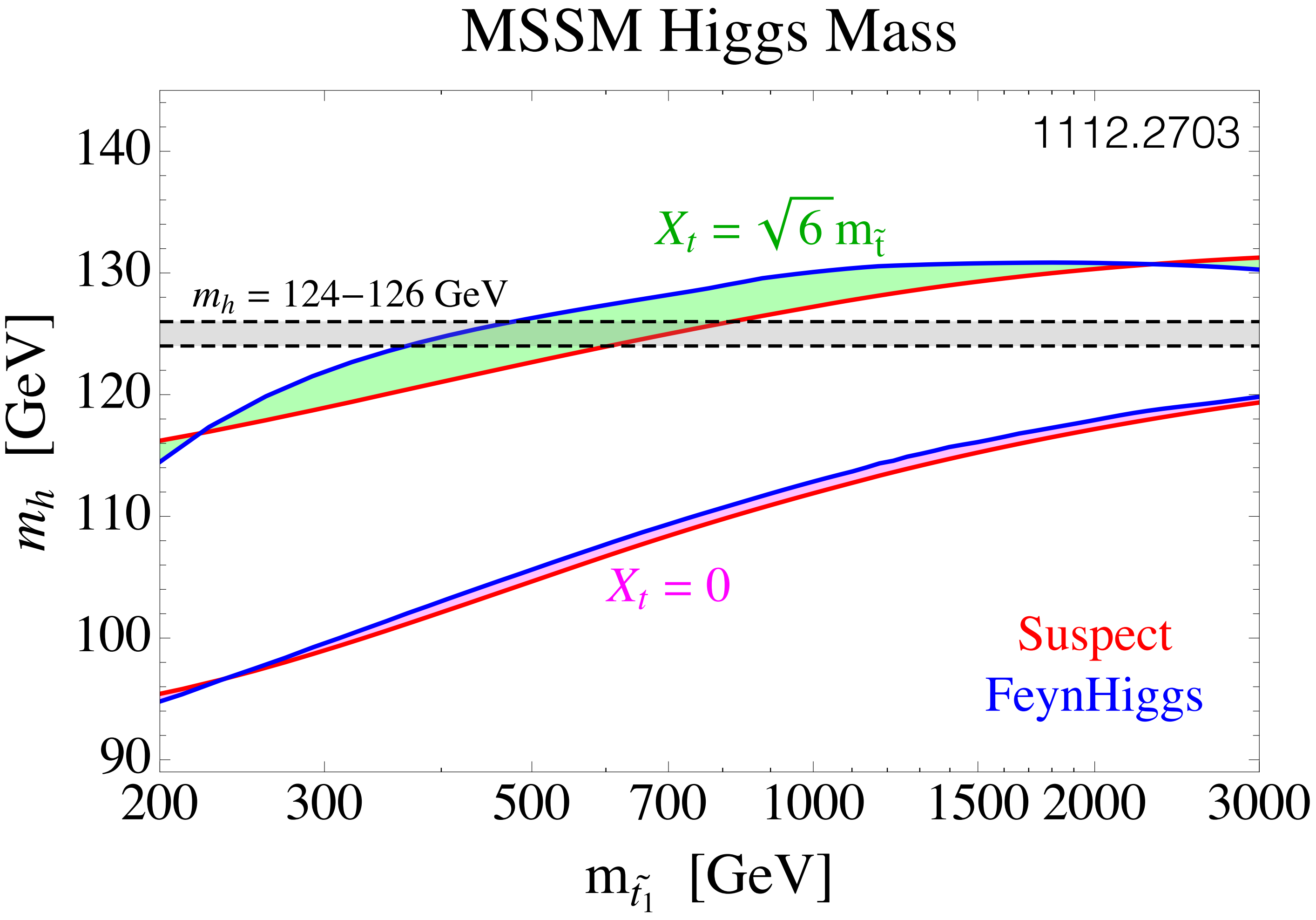
Where

$$X_t = A_t - \mu \cot\beta$$

(L-R stop mixing)

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

(geometric mean stop mass)

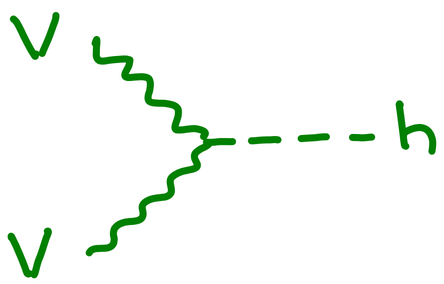


Implies heavy SUSY partners: little-hierarchy problem

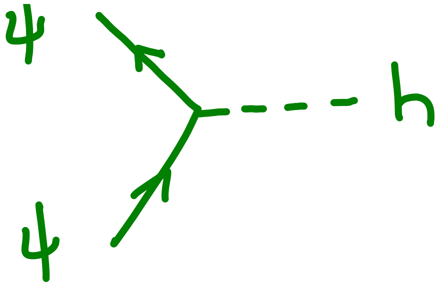
Deviations from SM Higgs

MSSM with heavy spectrum (≫100 GeV)

Main effects from the 2nd Higgs doublet:



$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

$$a \sim \frac{v^4}{M_H^4}$$

$$c \sim \frac{v^2}{M_H^2}$$

Dominant effect!

Corrections to Higgs couplings to fermions:

1) MSSM (with no mixing)

$$c_b \approx 1 + \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2}\,,$$

$$c_t \approx 1 - (\cot\beta)^2 \frac{m_h^2 - m_Z^2 \cos 2\beta}{m_H^2}$$

2) MSSM (large LR mixing)

$$c_b \approx 1 + 2\frac{m_h^2}{m_H^2}\frac{t_\beta^2}{t_\beta^2 - 1}$$

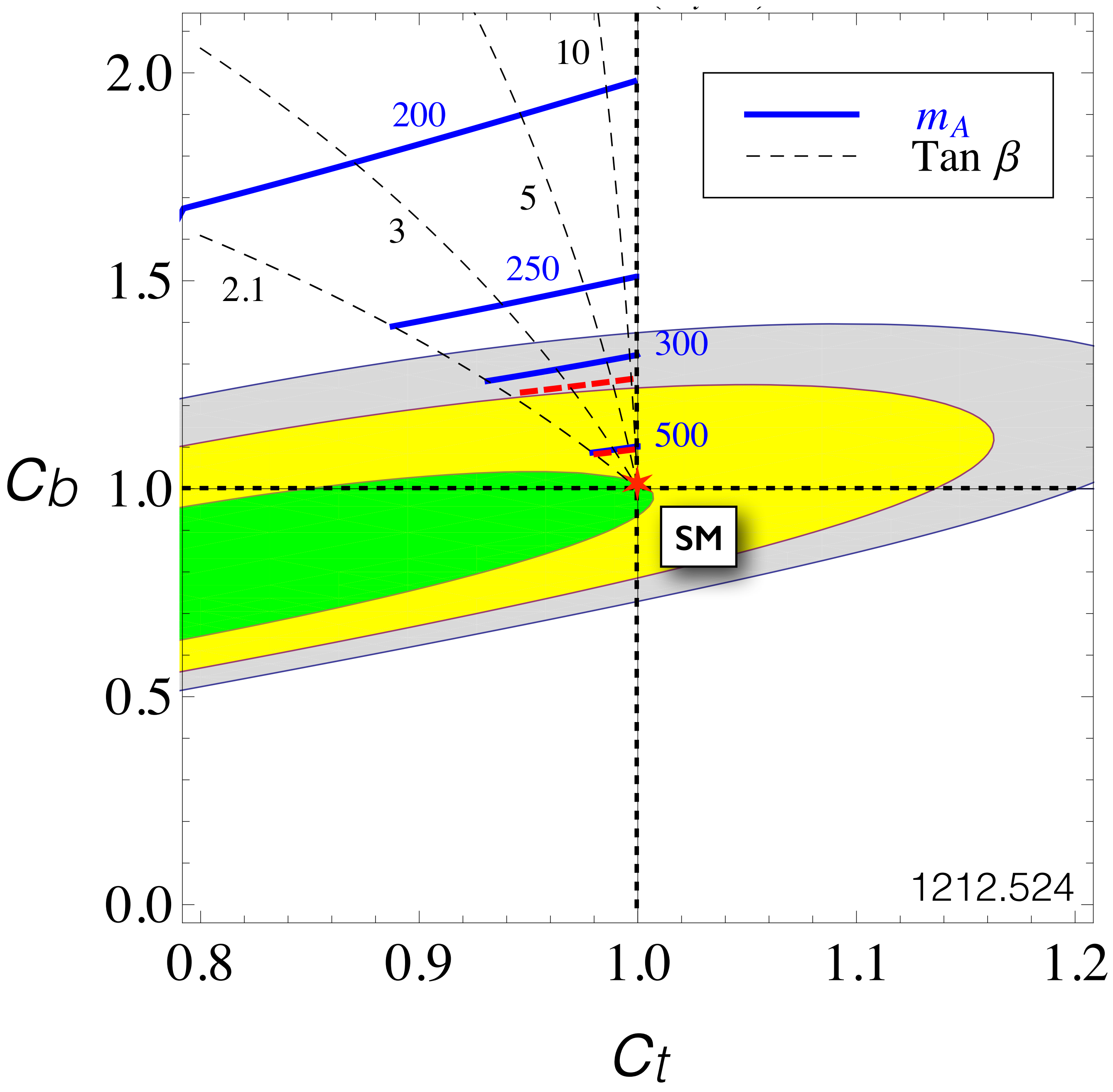
$$c_t \approx 1 - 2\frac{m_h^2}{m_H^2}\frac{1}{t_\beta^2 - 1}$$

3) NMSSM (with heavy singlet & light stops)

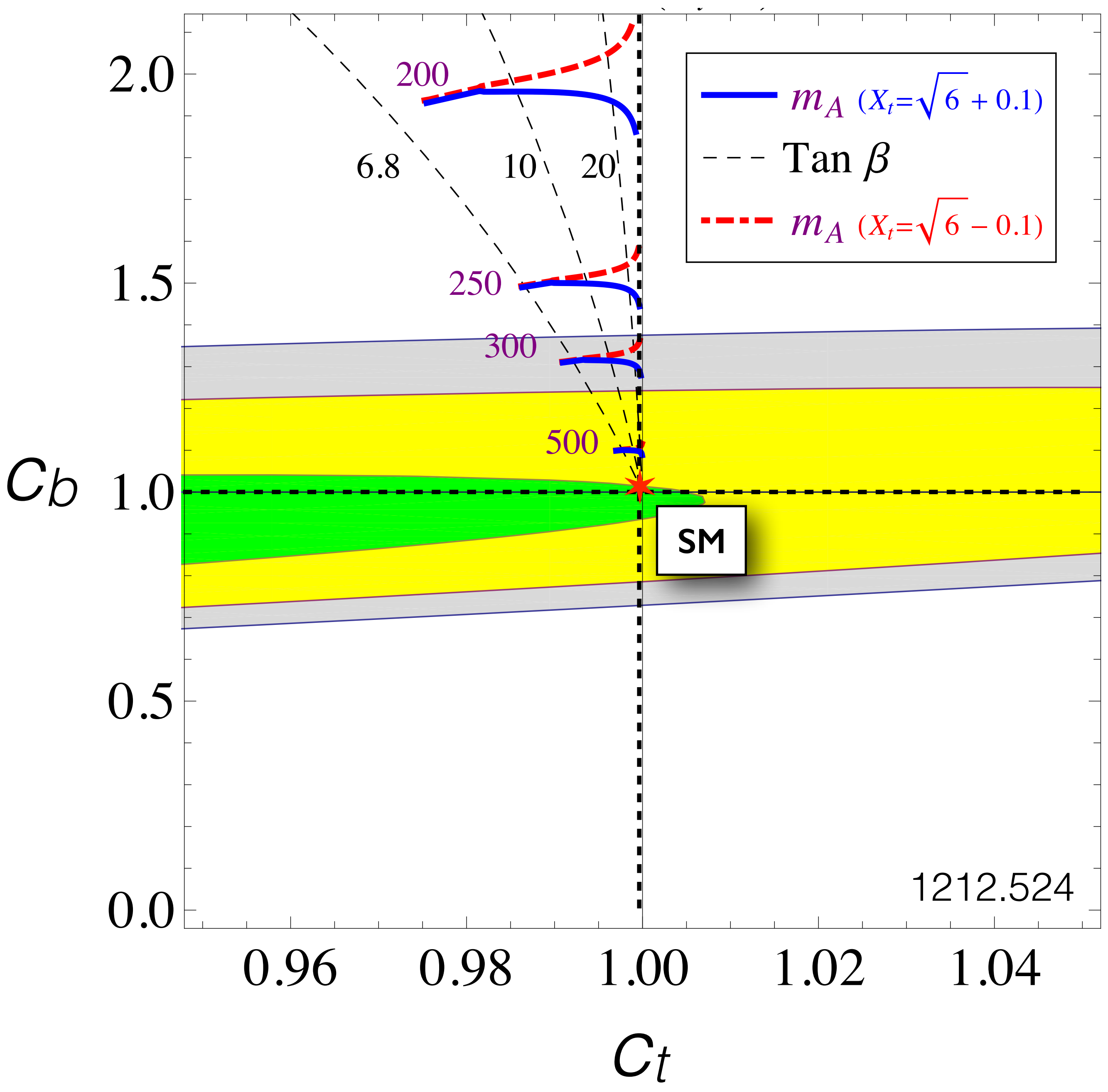
$$c_b \approx 1 - \frac{t_\beta^2 - 1}{2}\frac{m_h^2 - m_Z^2}{m_H^2}$$

$$c_t \approx 1 + \frac{t_\beta^2 - 1}{2t_\beta^2}\frac{m_h^2 - m_Z^2}{m_H^2}$$

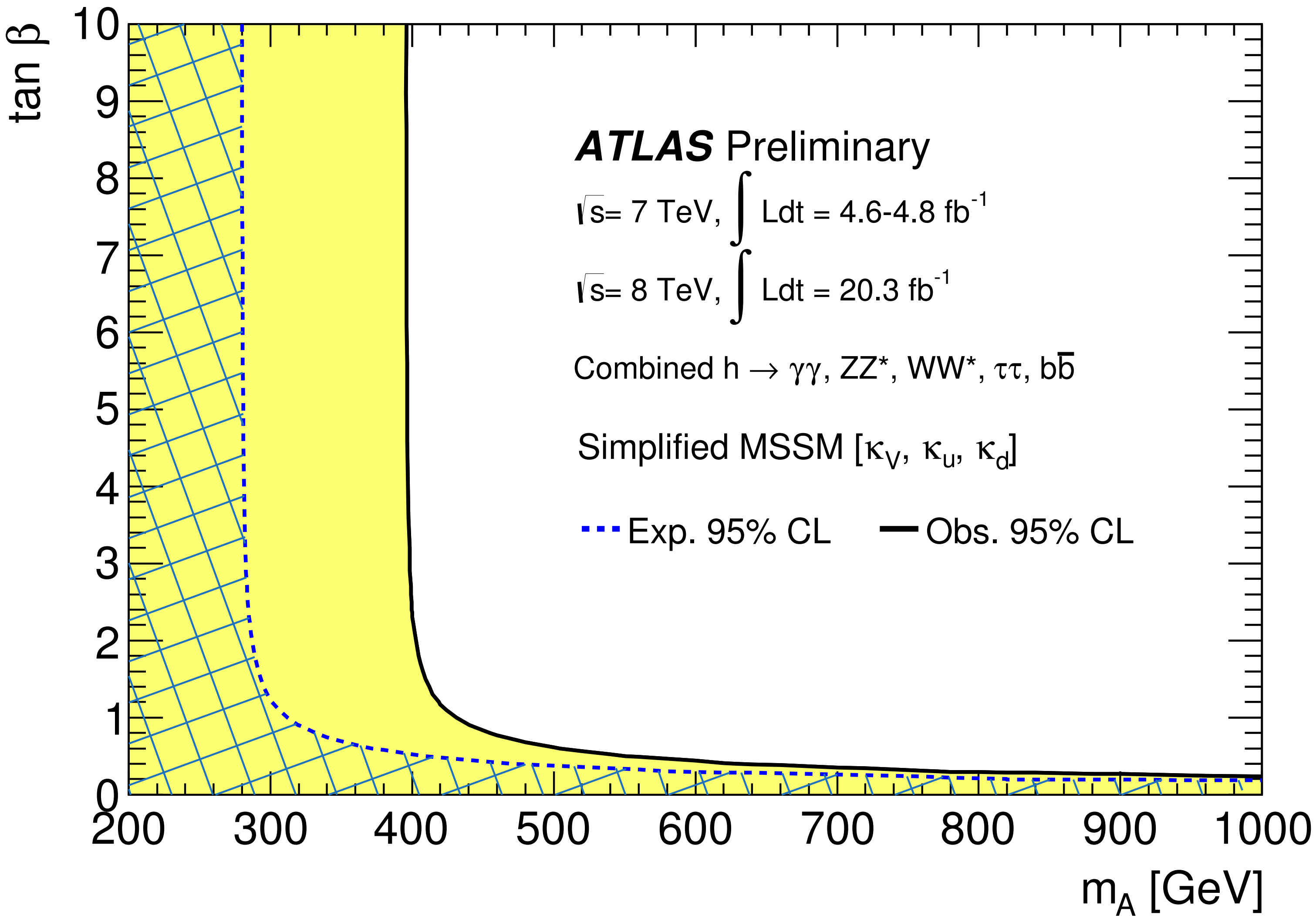
MSSM with X_t=0



MSSM with $X_t \neq 0$



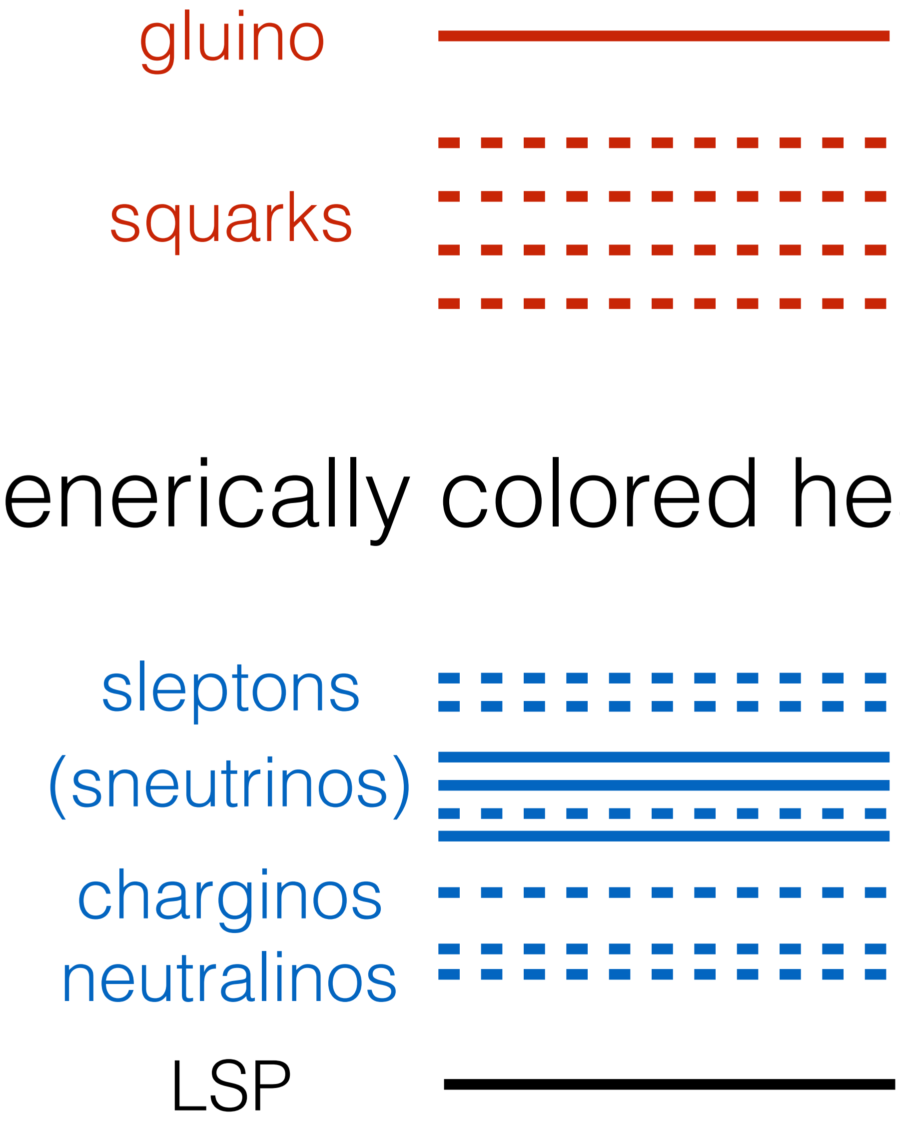
Higgs coupling measurements ruling out MSSM-parameter space



Complementary to direct searches
(i.e. for stops & gluinos)

MSSM @ LHC

General considerations: Spectrum



gluino

squarks

Depends on
~~SUSY~~ details

Generically colored heavier (RGE's)

sleptons

(sneutrinos)

charginos

neutralinos

Also (flavor)
model dependence

LSP

Stable or decaying?

(& neutral)

Focus on EW hierarchy solution

$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

↑

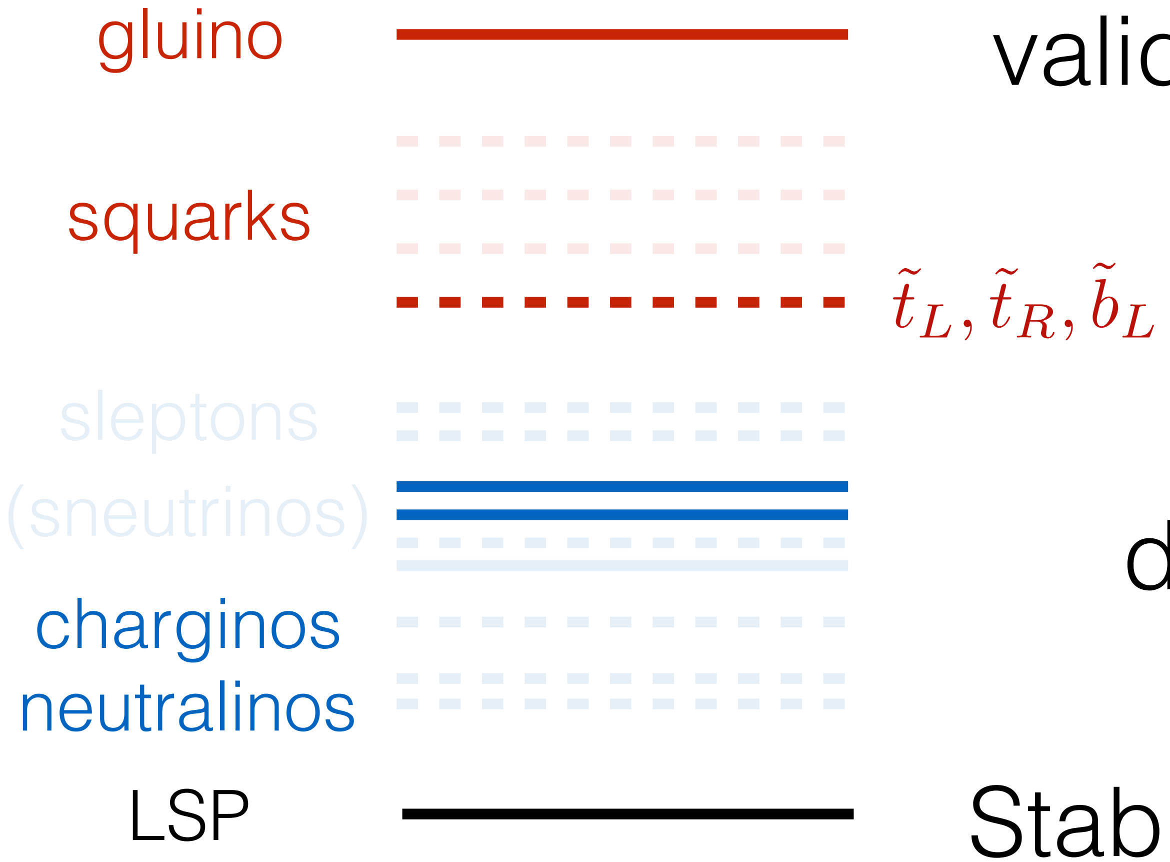
Higgsino mass

$$\delta m_H^2|_{\rm stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\rm TeV}\right)$$

$$\delta m_H^2|_{\rm gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\rm TeV}\right)$$

~~SUSY~~

valid beyond MSSM



model dependence

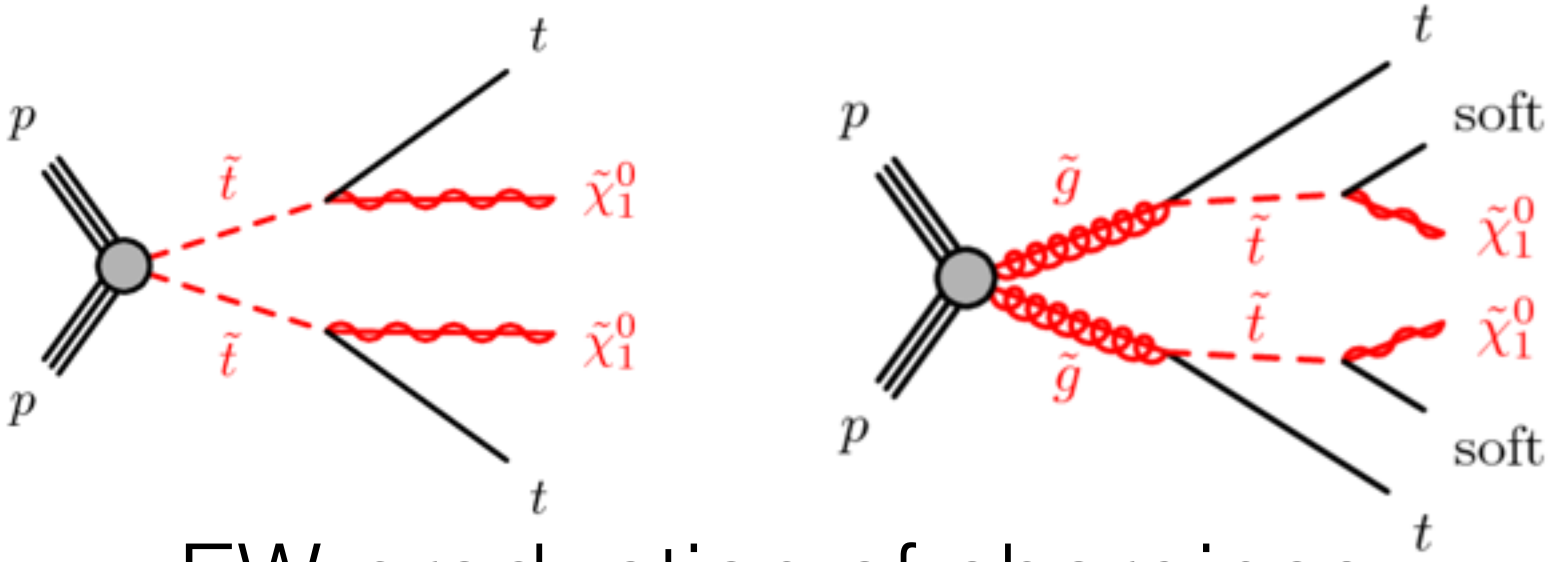
↓

Stable or decaying?

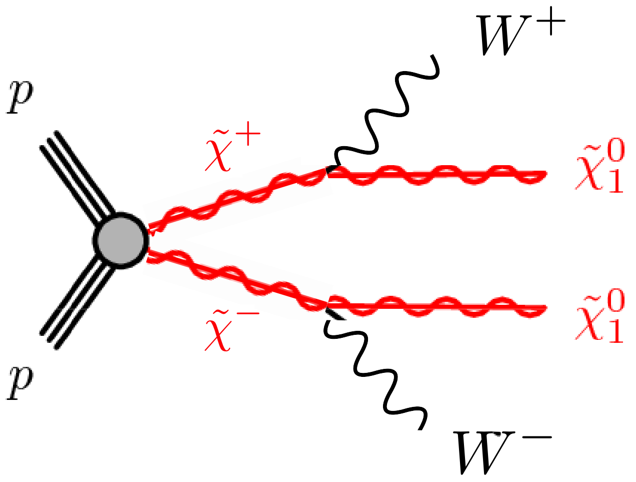
(& neutral)

Natural SUSY @ LHC

Colored partner production dominates

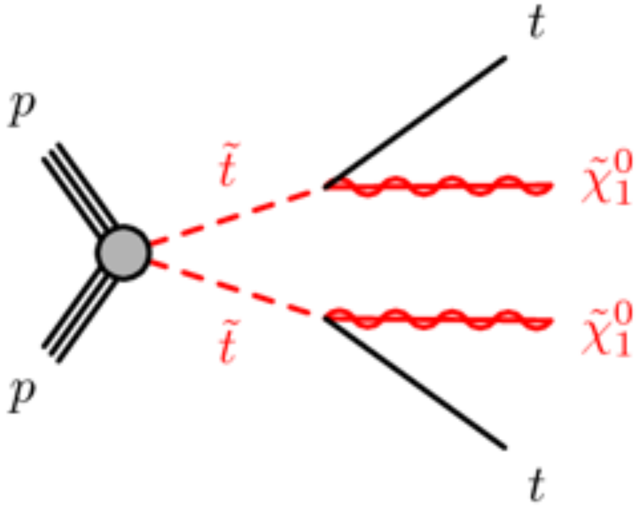


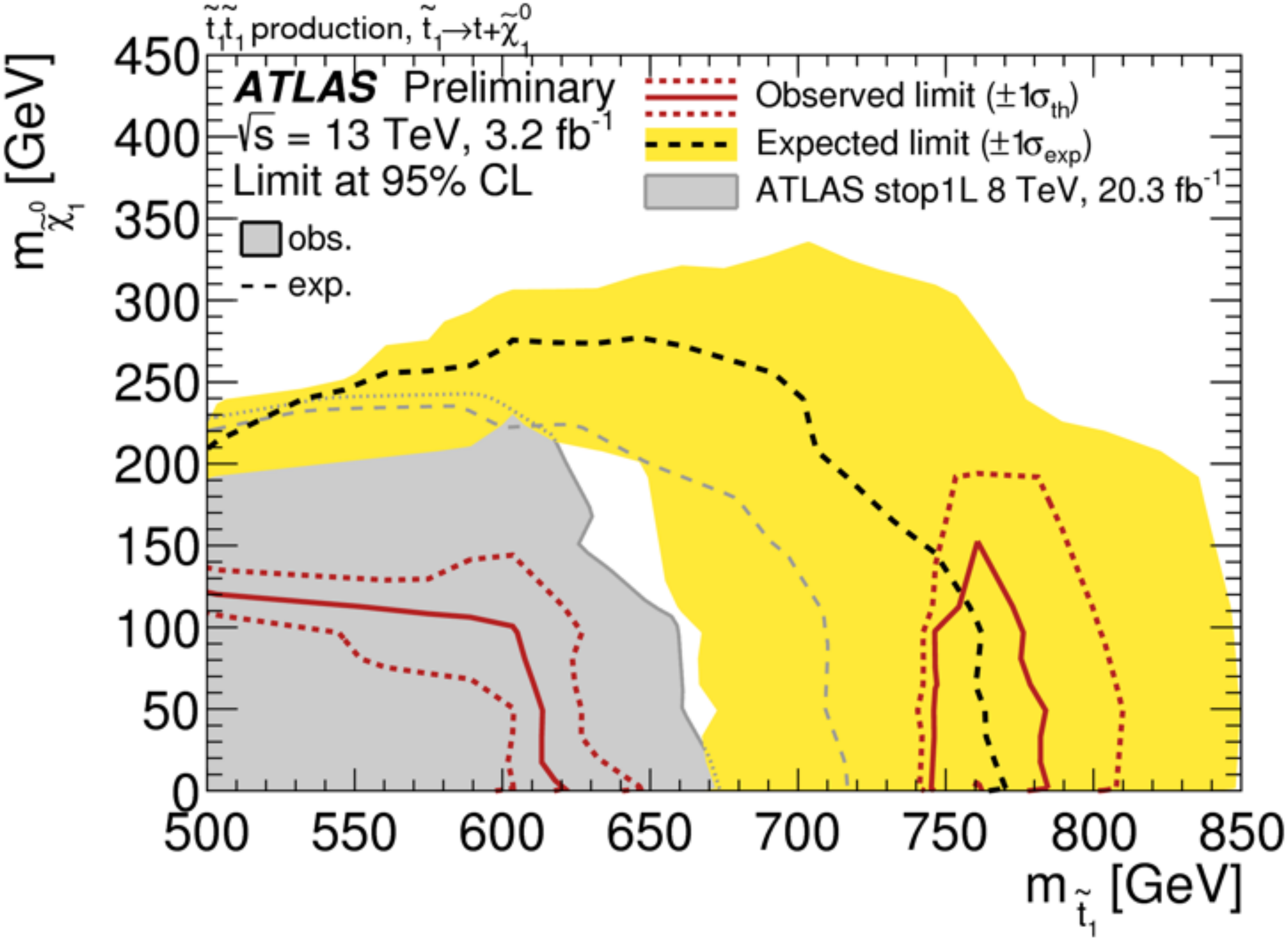
EW production of charginos



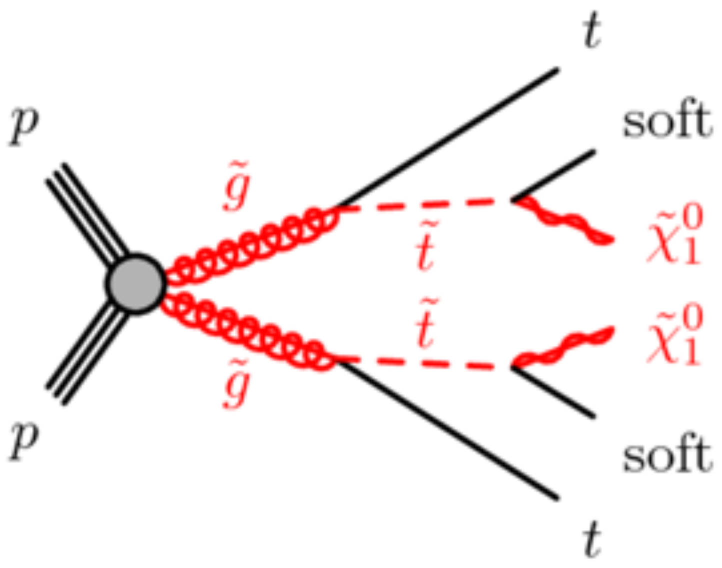
Assume stable LSP: escapes detectors, registered as missing (transverse) energy

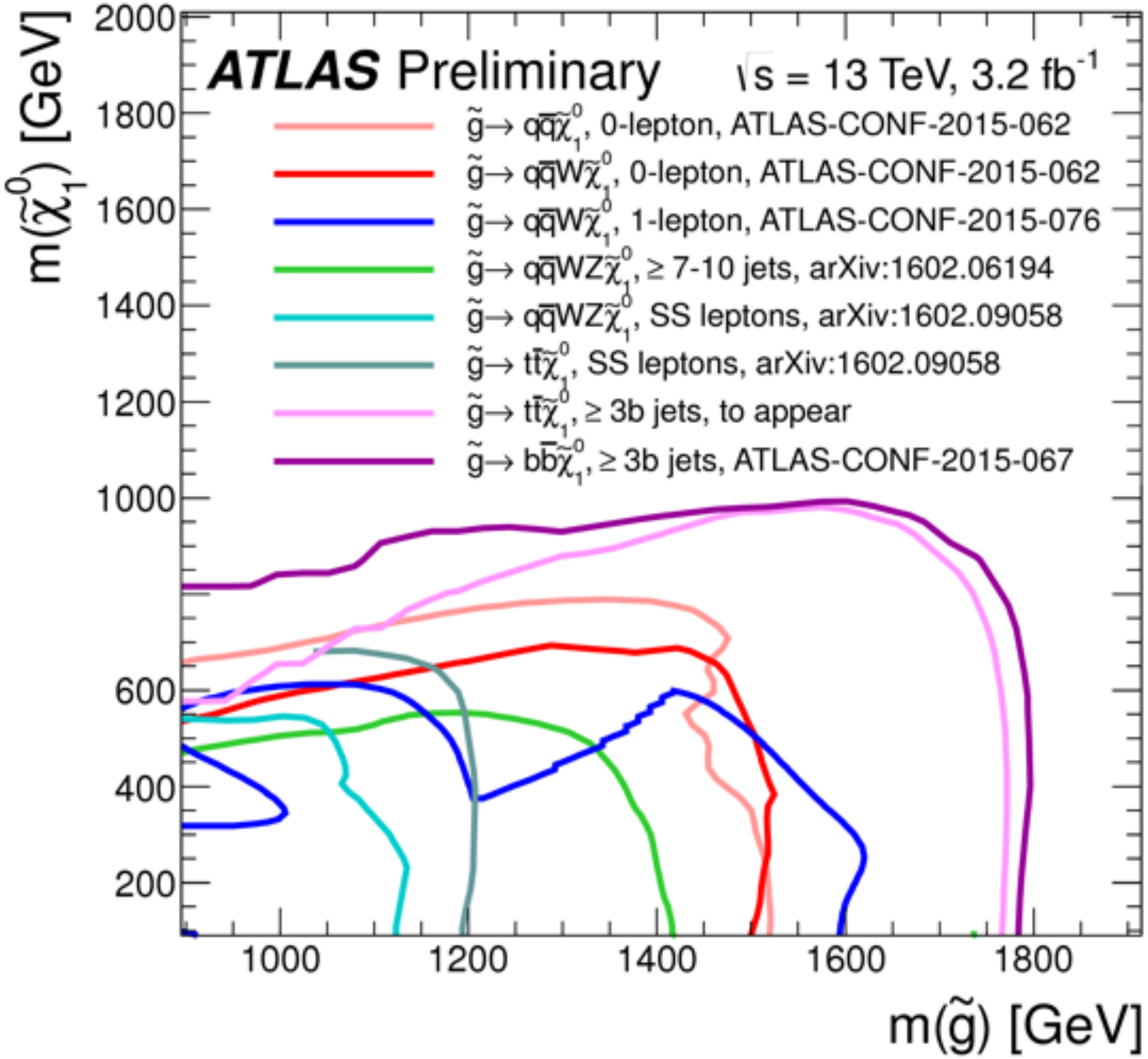
stops


p
p
$\tilde{t}$
$\tilde{t}$
t
t
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

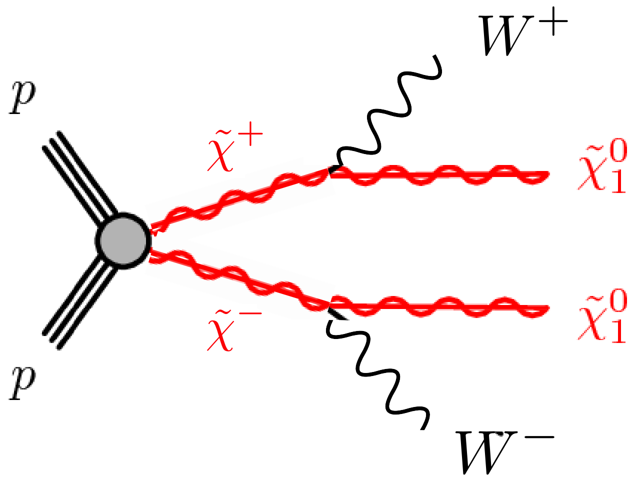

$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t+\tilde{\chi}_1^0$
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Limit at 95% CL
obs.
exp.
Observed limit ($\pm 1\sigma_{th}$)
Expected limit ($\pm 1\sigma_{exp}$)
ATLAS stop1L 8 TeV, 20.3 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850

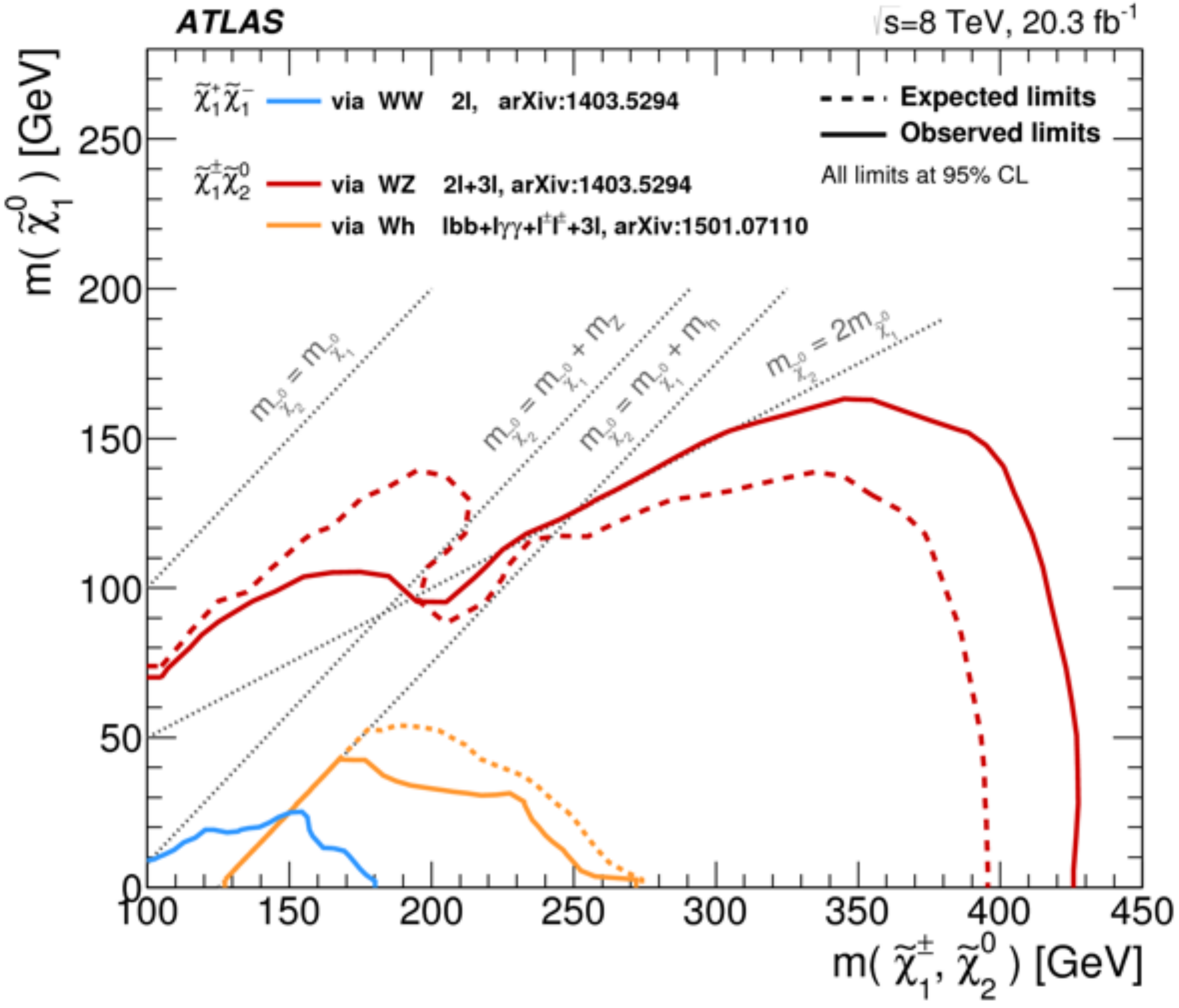
gluino


t
soft
p
$\tilde{g}$
$\tilde{t}$
$\tilde{\chi}_1^0$
$\tilde{t}$
$\tilde{\chi}_1^0$
$\tilde{g}$
p
soft
t

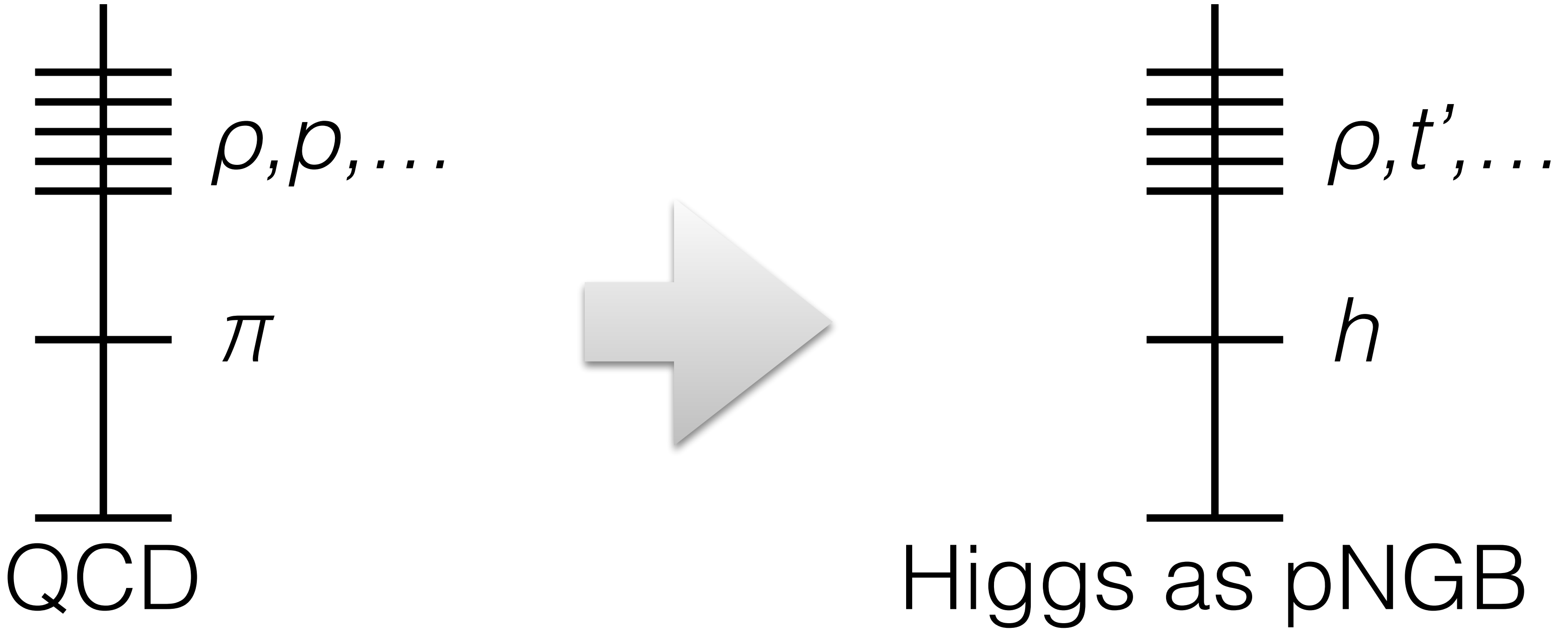

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2015-062
$\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$, 0-lepton, ATLAS-CONF-2015-062
$\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$, 1-lepton, ATLAS-CONF-2015-076
$\tilde{g} \to q\bar{q}WZ\tilde{\chi}_1^0$, ≥ 7-10 jets, arXiv:1602.06194
$\tilde{g} \to q\bar{q}WZ\tilde{\chi}_1^0$, SS leptons, arXiv:1602.09058
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$, SS leptons, arXiv:1602.09058
$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$, ≥ 3b jets, to appear
$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$, ≥ 3b jets, ATLAS-CONF-2015-067
$m(\tilde{\chi}_1^0)$ [GeV]
2000
1800
1600
1400
1200
1000
600
400
200
1000
1200
1400
1600
1800
$m(\tilde{g})$ [GeV]

charginos


W^+
p
$\tilde{\chi}^+$
$\tilde{\chi}_1^0$
$\tilde{\chi}^-$
$\tilde{\chi}_1^0$
p
W^-


ATLAS
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ via WW 2l, arXiv:1403.5294
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ 2l+3l, arXiv:1403.5294
via Wh lbb+lγγ+l$^\pm$l$^\pm$+3l, arXiv:1501.07110
Expected limits
Observed limits
All limits at 95% CL
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_h$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
m($\tilde{\chi}_1^0$) [GeV]
0
50
100
150
200
250
100
150
200
250
300
350
400
450
m($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$) [GeV]

Strong EWSB (Composite Higgs)



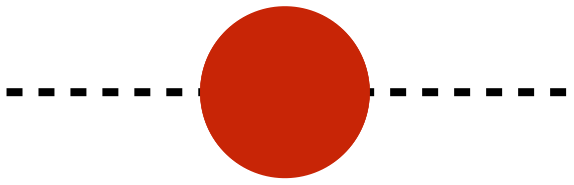
Why is the Higgs light?

Inspired by QCD: (pseudo) scalar pion is the lightest state

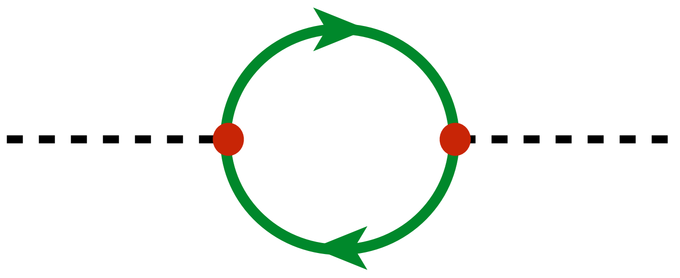
Shift symmetry $\pi \rightarrow \pi + \alpha$ protects its mass.

Interactions are perturbative for $E \ll 4\pi f$

No pure composite effects due to Goldstone symmetry



Shift symmetry broken by elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

Supersymmetry is a weakly coupled solution to the hierarchy problem.We can extrapolate physics to the Planck scale, complete the MSSM in a GUT.

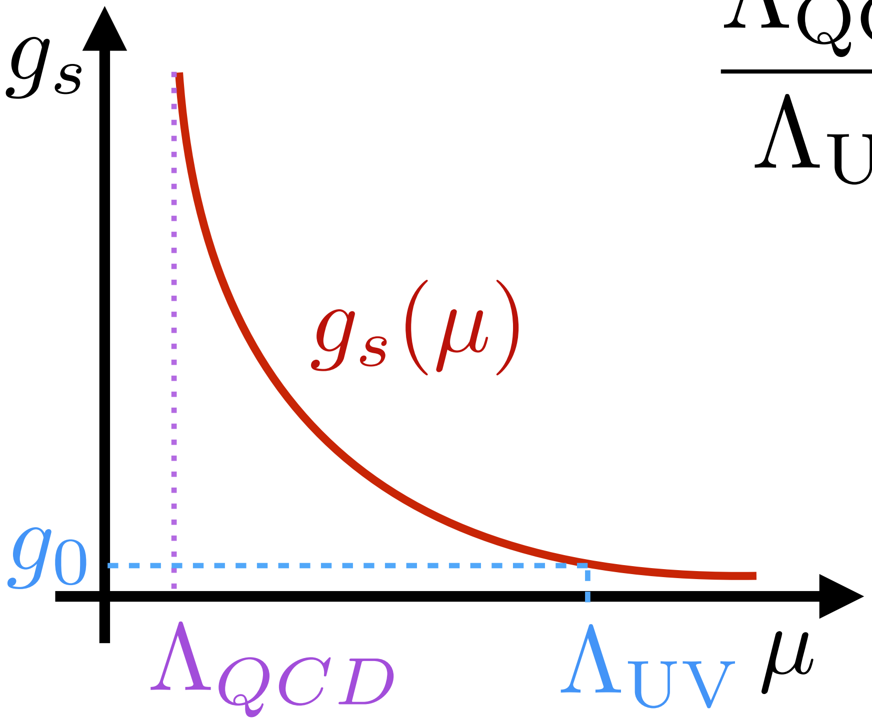
There is another way and it’s already in use.

Nature already employs a strongly coupled mechanism to explain why

$$\Lambda_{QCD} \ll M_{\text{Planck}}$$

$$\sim 1\,\text{GeV} \qquad \sim 10^{19}\,\text{GeV}$$

QCD

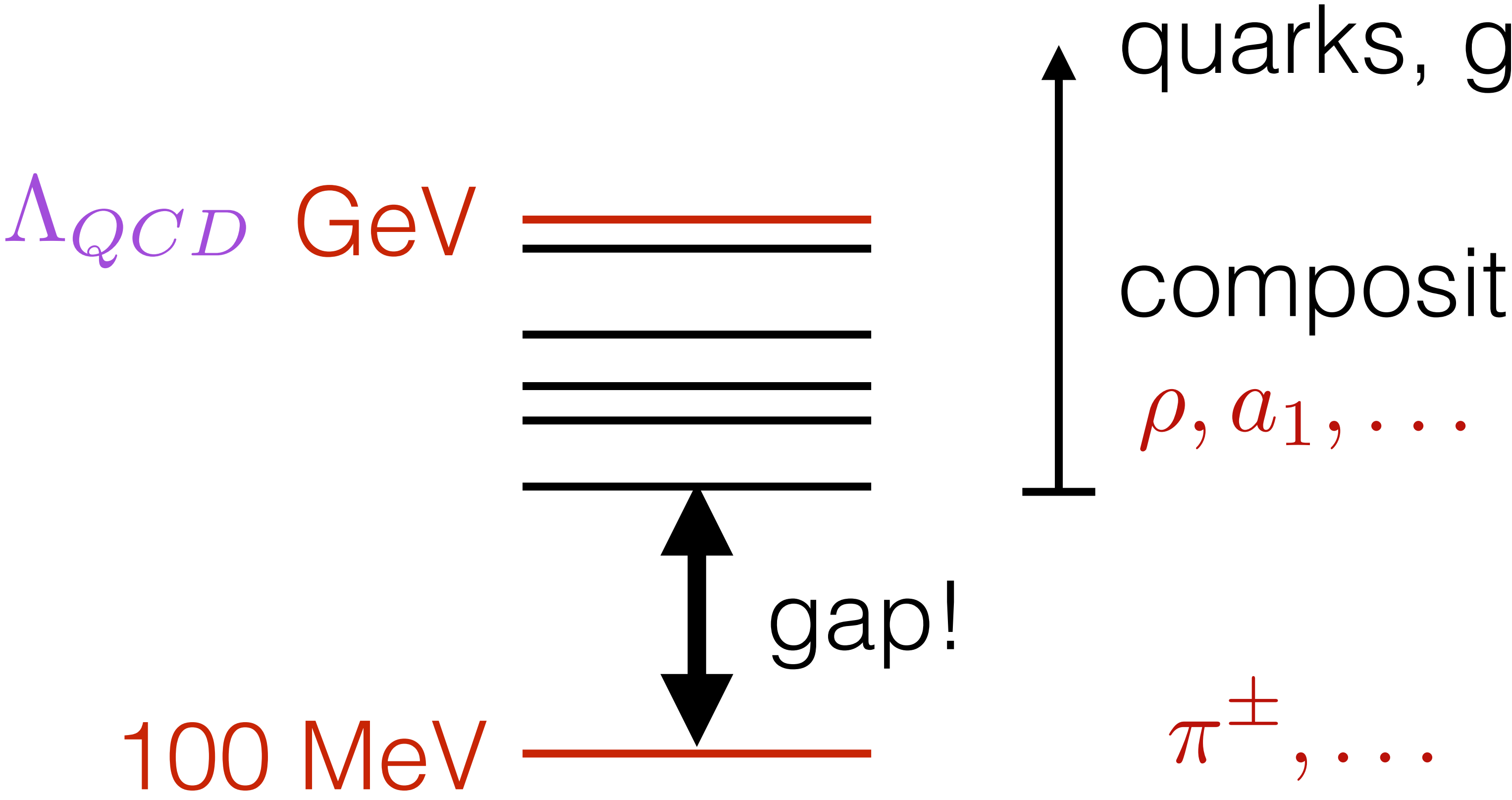


$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \ \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$

Asymptotic freedom

QCD:
composite bound states



quarks, gluons

Λ_{QCD} GeV

composite resonances

$\rho, a_1, \ldots$

gap!

100 MeV

$\pi^{\pm}, \ldots$

At strong coupling, new resonances are generated

QCD & EWSB

QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\langle \bar{q}_L q_R \rangle \simeq \Lambda^3_{\mathrm{QCD}} \sim (\mathrm{GeV})^3$$

The QCD masses of W/Z are small

$$m_{\mathrm{W,Z}} \sim \frac{g}{4\pi} \Lambda_{\mathrm{QCD}} \sim 100\ \mathrm{MeV}$$

Longitudinal components of W & Z have tiny admixture of pions...

Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \simeq \Lambda^3_{\rm TC} \sim ({\rm TeV})^3$$

Technicolor, doesn't have a Higgs ...

*125 GeV dilaton as the last bastion

Composite Higgs

- Want to copy QCD, but extend pion sector
- Higgs as a (pseudo) Goldstone boson

Quantum Protection

Symmetries can soften quantum behaviour

$$\mathcal{L} = |\partial_\mu \phi|^2 + \enclose{circle}{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

breaks SUSY → corrections must be proportional to SUSY breaking

Shift symmetry

Symmetries can soften quantum behaviour

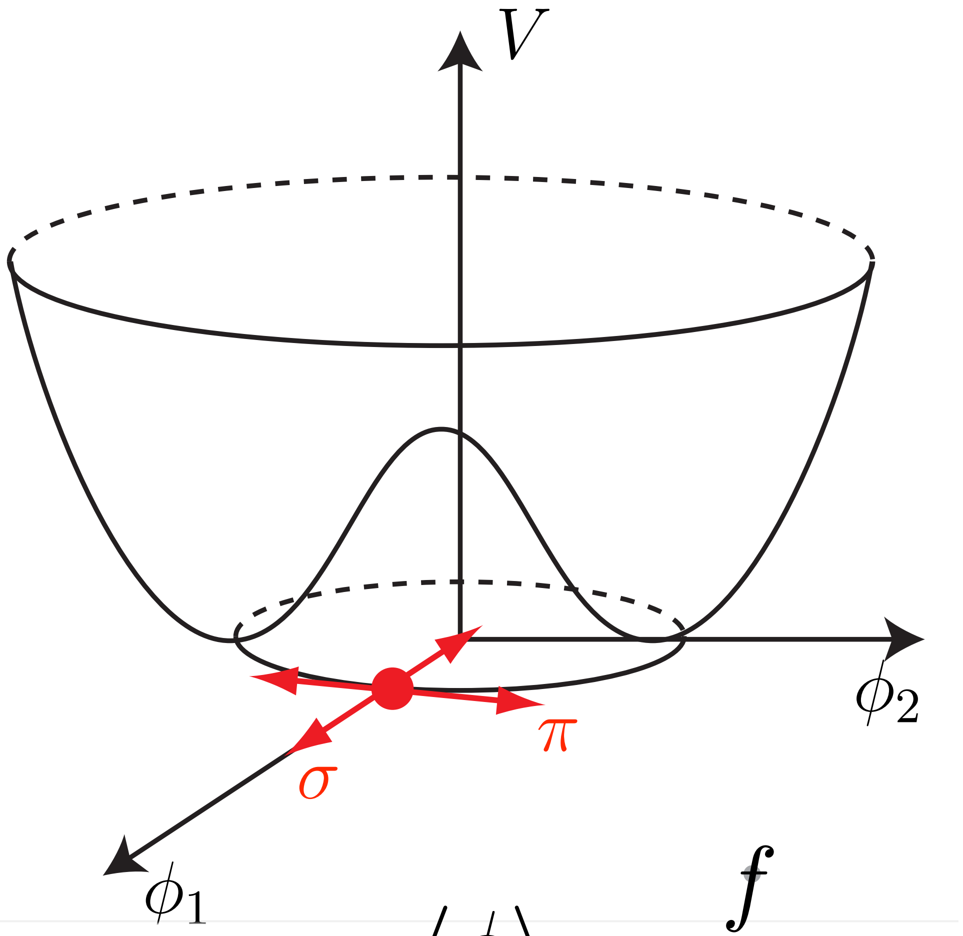
$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

- $\phi \to e^{i\alpha}\phi$ does not forbid the mass^2 term
- $\phi \to \phi + \alpha$ works!

Can we make the Higgs transform this way ?

Spontaneous breaking of U(1)

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$



$$\langle \phi \rangle = \frac{f}{\sqrt{2}}$$

Instead using complex field

$$\phi = \phi_1 + i\phi_2$$

use alternative parametrisation

$$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} [f + \sigma(x)]$$

‘phase’ ‘modulus’

$$\mathcal{L} = |\partial_\mu \phi|^2 + \overbrace{\mu^2|\phi|^2 - \lambda|\phi|^4}^{-V(|\phi|^2)} + \ldots$$

use $\phi(x) = \frac{1}{2} e^{i\pi(x)/f}[f + \sigma(x)]$

$$\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2}(1 + \sigma/f)^2 \frac{1}{2}\partial^\mu \pi \partial_\mu \pi$$

$$V(|\phi(x)|^2) = V(\sigma(x))$$

No mass term

No dependence on $\pi(x)$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2\frac{1}{2}\partial^\mu\pi\partial_\mu\pi+\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma-V(\sigma(x))$$

Using this parameterization a new symmetry is visible:

$$\pi(x)\to\pi(x)+\alpha$$

because $\pi(x)$ has only ‘derivative interactions’

$$\partial_\mu(\pi(x)+\alpha)=\partial_\mu\pi(x)$$

But what happened to the U(1) symmetry? σ,π are real…

What happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}[f+\sigma(x)] \to e^{i\alpha}e^{i\pi(x)/f}[f+\sigma(x)]$$

……

$$\sigma(x) \to \sigma(x)$$

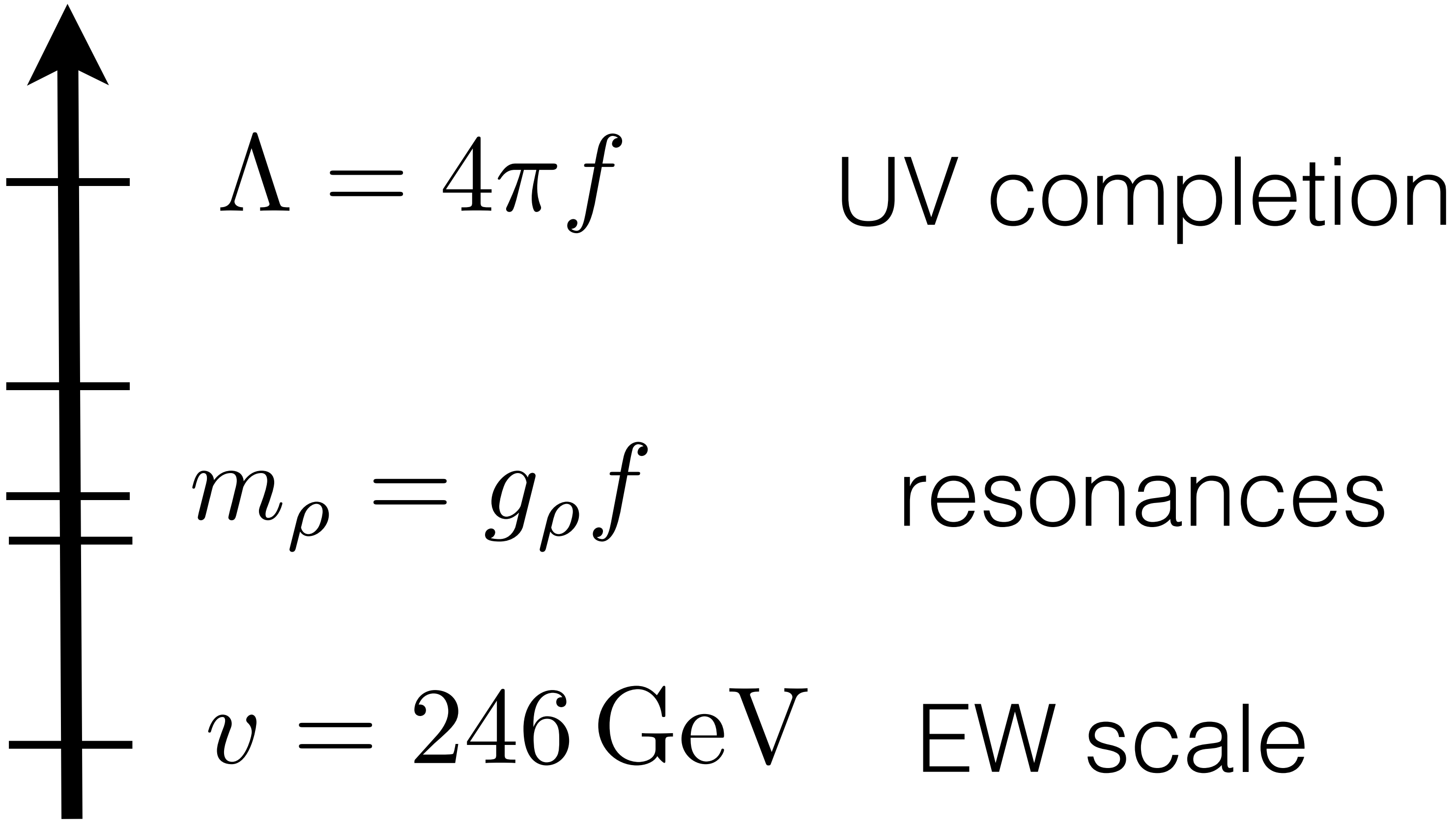
$$\pi(x) \to \pi(x) + \alpha$$

Phase rotation becomes shift symmetry

$\pi(x)$ is massless but also no

- gauge couplings
- potential
- yukawas

Semi-realistic model



$\Lambda = 4\pi f$ UV completion

$m_\rho = g_\rho f$ resonances

$v = 246\,\mathrm{GeV}$ EW scale

pGB Higgs

$SU(3) \to SU(2)$

Break symmetry using $\langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

Goldstone bosons = # broken generators

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

$$\Phi = \frac{1}{\sqrt{2}}\, e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f+\sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

Expand: $\Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} + \ldots$

Contains a Higgs: $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

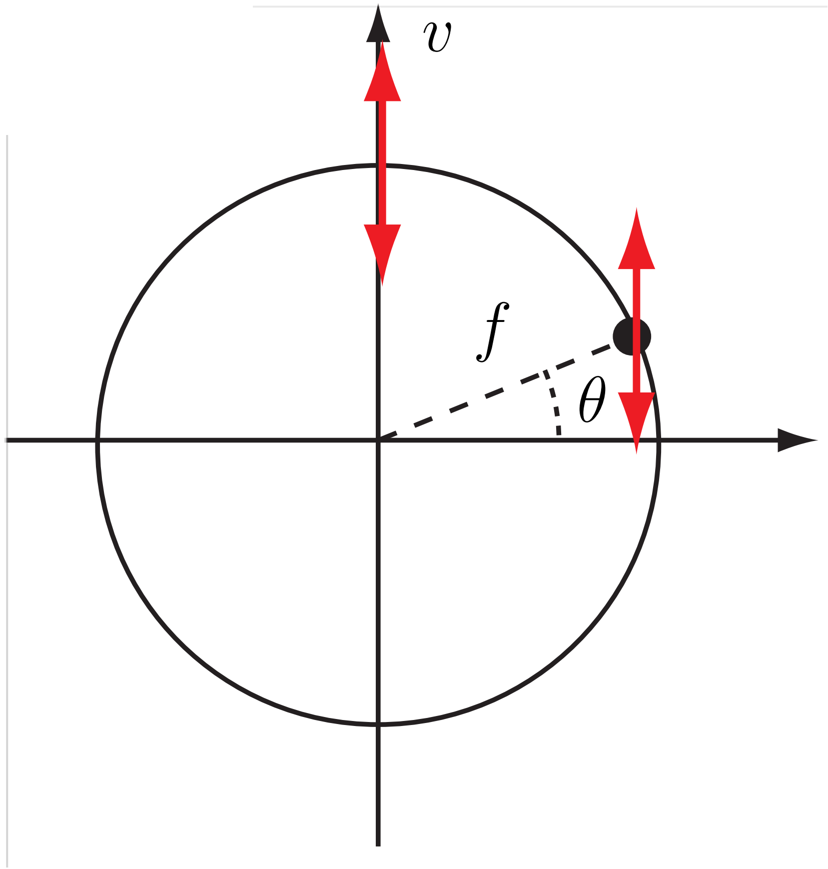
pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates ‘vacuum misalignment’

$SU(2)_L$ vs. $SU(2)$

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix}$$ $SU(2)_L$

EW symmetry broken



$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} \boxed{\begin{matrix} 0 \\ \sin\theta \end{matrix}} \\ \cos\theta \end{pmatrix}$$ $SU(2)_L$

electro-weak scale: $v = f \sin\theta$

f ~ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ SM limit

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Collective breaking

Add a yukawa coupling to give mass to the top quark

$\lambda_t \bar{Q}_i H_i^c t_R$ [*i* : sum over *SU*(2)$_L$]

Fundamental field is a triplet

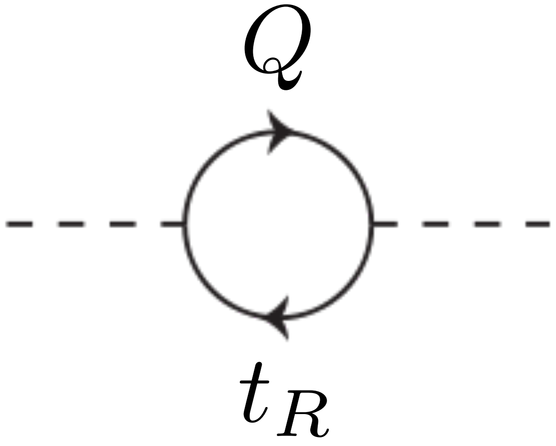
$$\phi = \exp\left\{ i \begin{pmatrix} & & h_1 \\ & & h_2 \\ h_1^* & h_2^* & \end{pmatrix} \right\} \begin{pmatrix} \\ \\ f \end{pmatrix}$$

Top yukawa: 1st try

$$\sum_i^2 y_t \phi_i^c \bar{Q}_i t_R$$

works, gives mass to the top

... but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:



$$\sim \frac{\lambda_t^2}{16\pi^2}\Lambda^2$$

We have accomplished nothing!

2nd try: Collective breaking

Example: $SU(3) \to SU(2)$ [Ignore *U*(1)$_Y$ again]

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

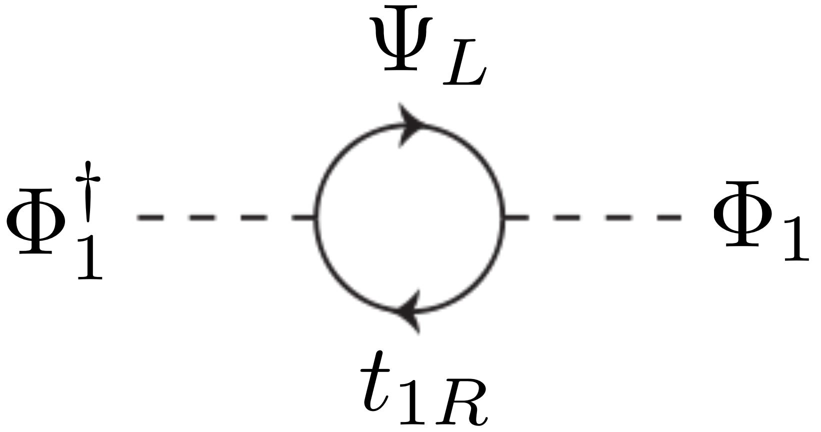
Gauge full *SU*(3) - exact symmetry

$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\, t_{2R},\, b_R$$

$$\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

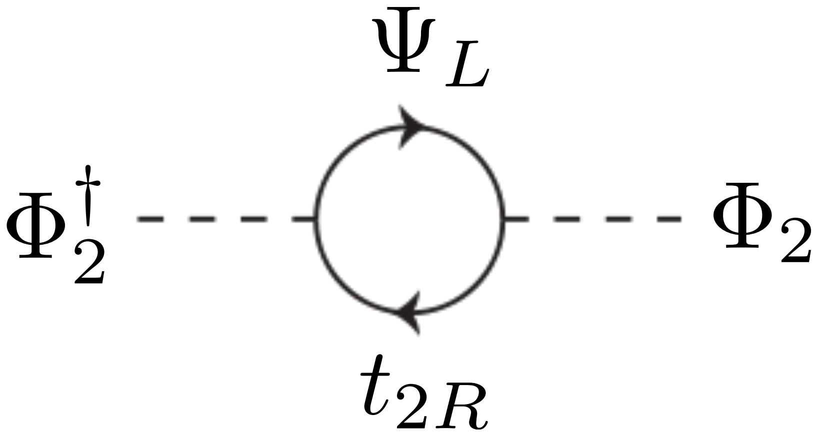
y_1: preserves $SU(3)_2 \to SU(2)_2$ and vice versa

Both $y_1, y_2 \neq 0$ required for non-derivative couplings of pNGB Higgs!



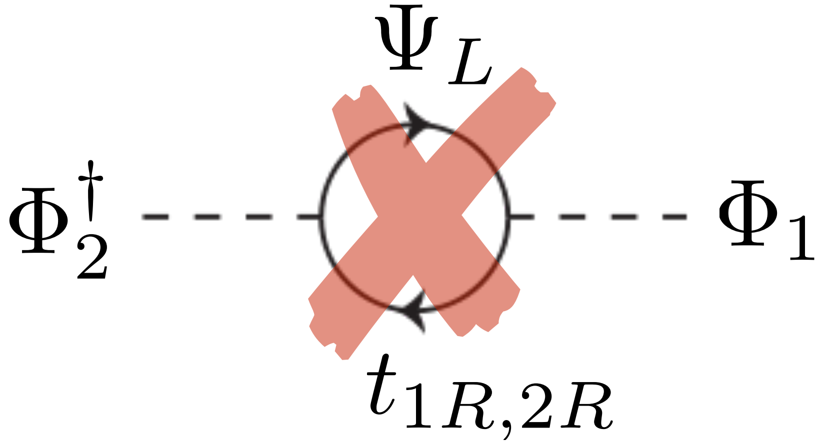
$$\sim \frac{y_1^2}{16\pi^2}\Lambda^2$$

Preserves $SU(3)_2 \to SU(2)_2$: no pNGB Higgs mass



$$\sim \frac{y_2^2}{16\pi^2}\Lambda^2$$

Preserves $SU(3)_1 \to SU(2)_1$: no pNGB Higgs mass



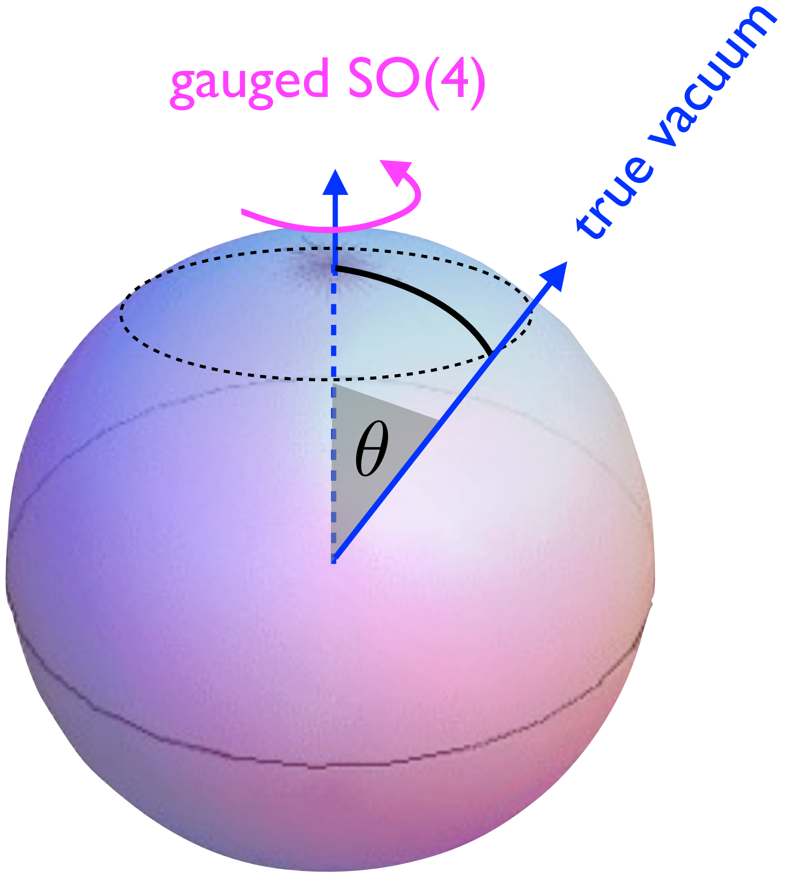
Not allowed.

Predicts top partners!

hep-ph/0412089
…

Minimal composite Higgs

$SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$



$SO(5)/SO(4)$

Tree level: gauge SO(4) aligned

Higgs

$$\phi = e^{i\pi^{\hat{a}}T^{\hat{a}}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat{\pi}^1\\\hat{\pi}^2\\\hat{\pi}^3\\\hat{\pi}^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\;\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

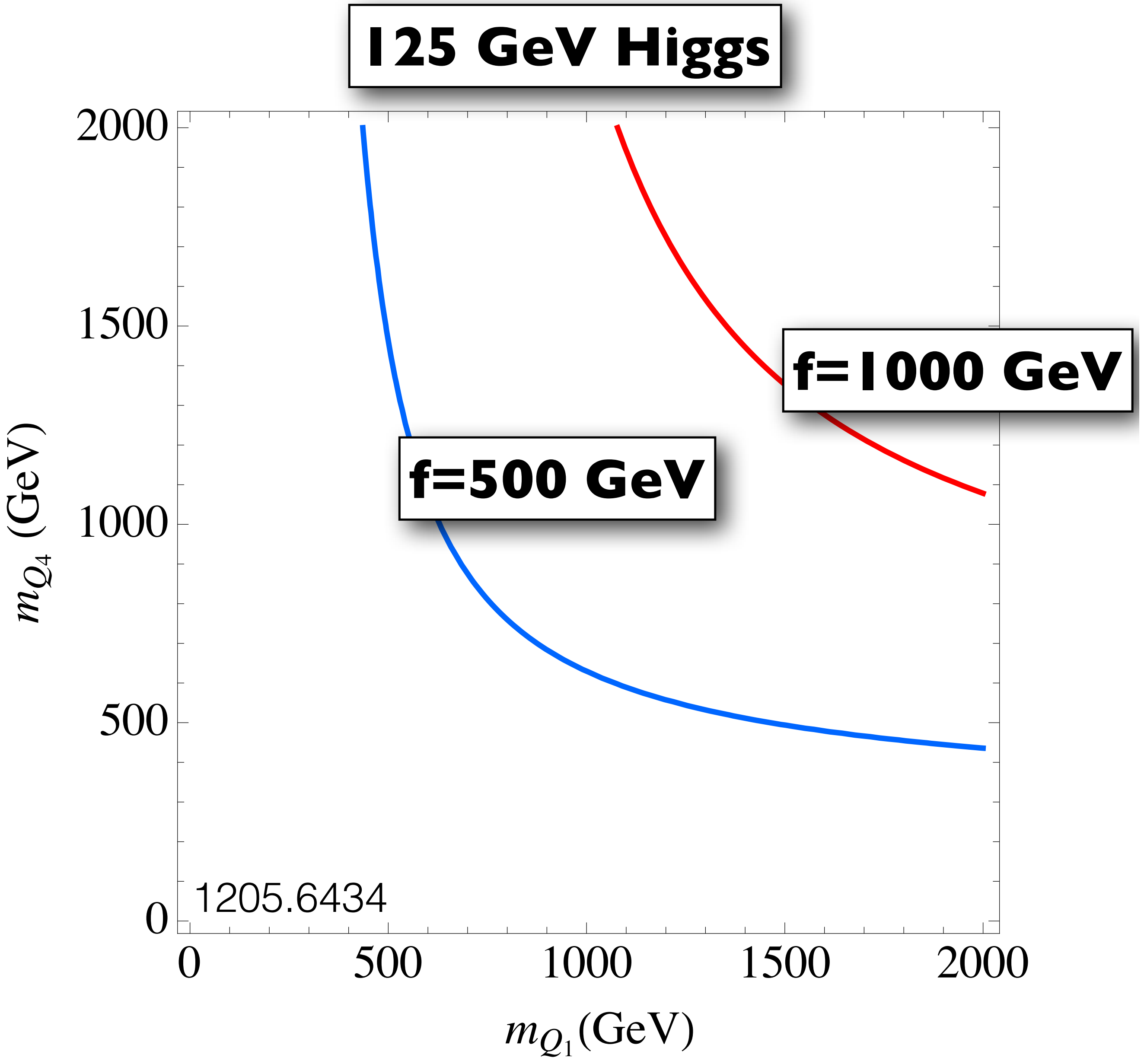
1-loop $\langle\phi(x)\rangle = \theta\cdot f$

eaten by W_L, Z_L

Light Higgs implies light fermionic top partners

SO(5)/*SO*(4): 5 = 4 + 1

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$



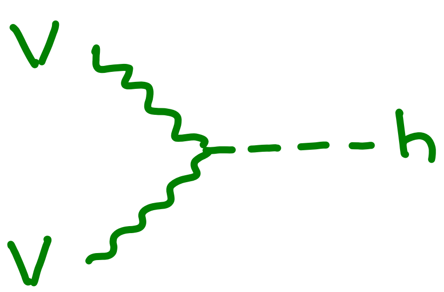
Q_4, Q_1

colored fermions
with EM charges
5/3, 2/3,-1/3

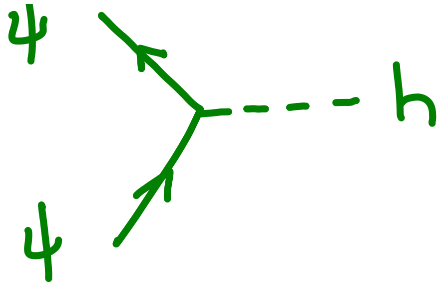
Deviations from SM Higgs

Goldstone boson nature

$$f^2\left|\partial_\mu\, e^{i\pi/f}\right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2}\left[\partial_\mu(H^\dagger H)\right]^2 + \frac{c'_H}{2f^4}(H^\dagger H)\left[\partial_\mu(H^\dagger H)\right]^2 + \ldots$$

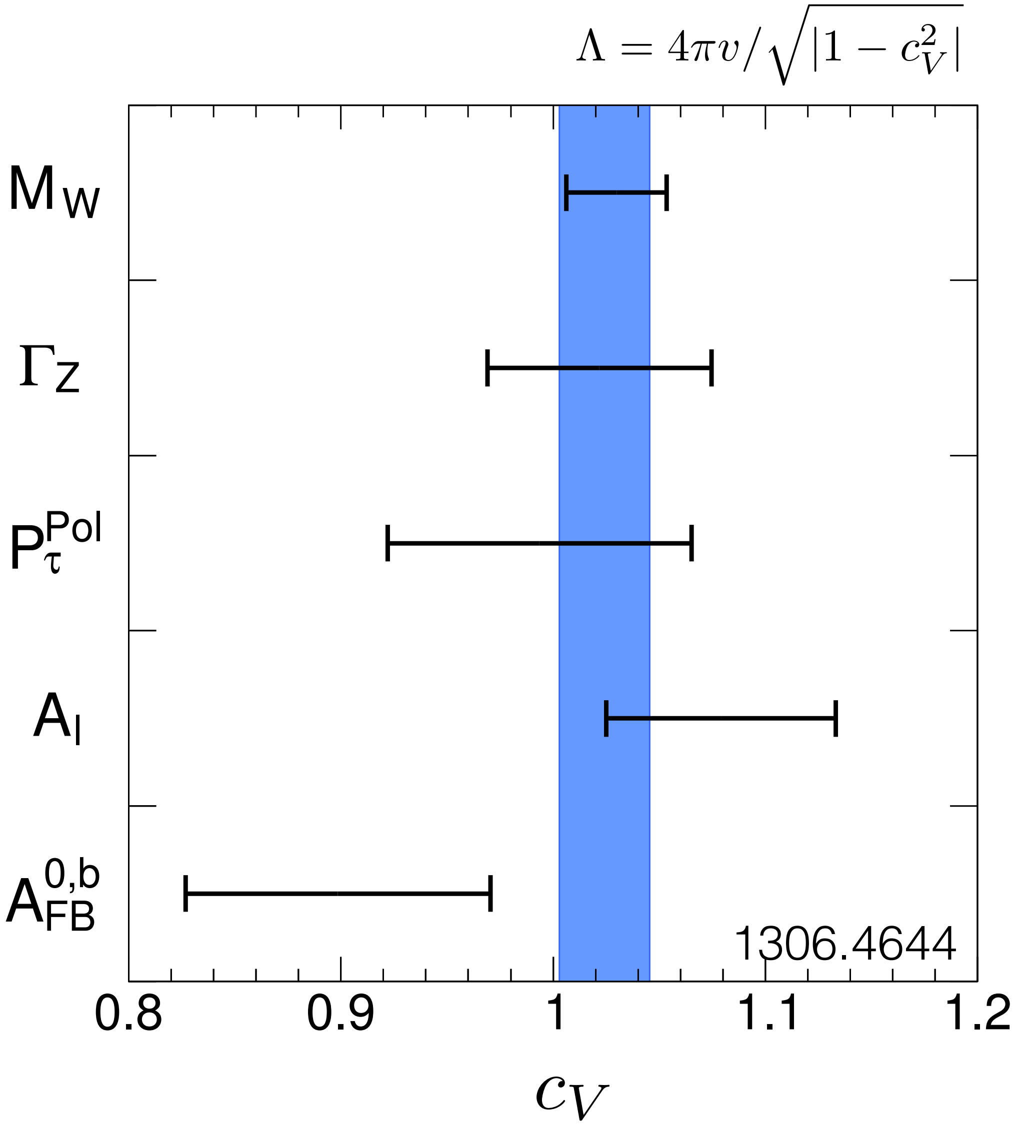


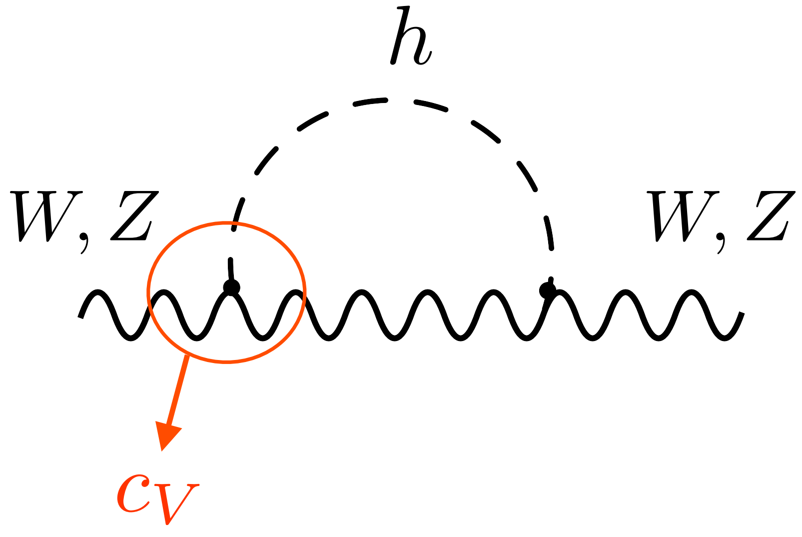
$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

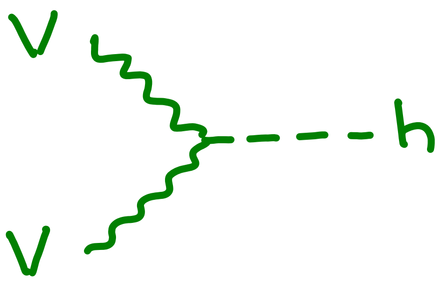
EW precision tests



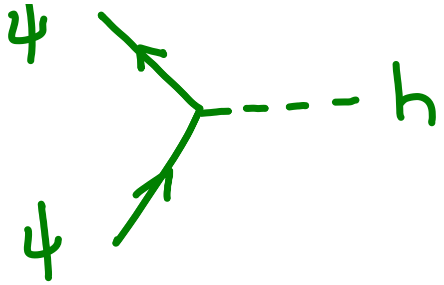


Higgs couplings

Have been measured to 20-30% precision



$a\, g^{SM}_{hVV}$

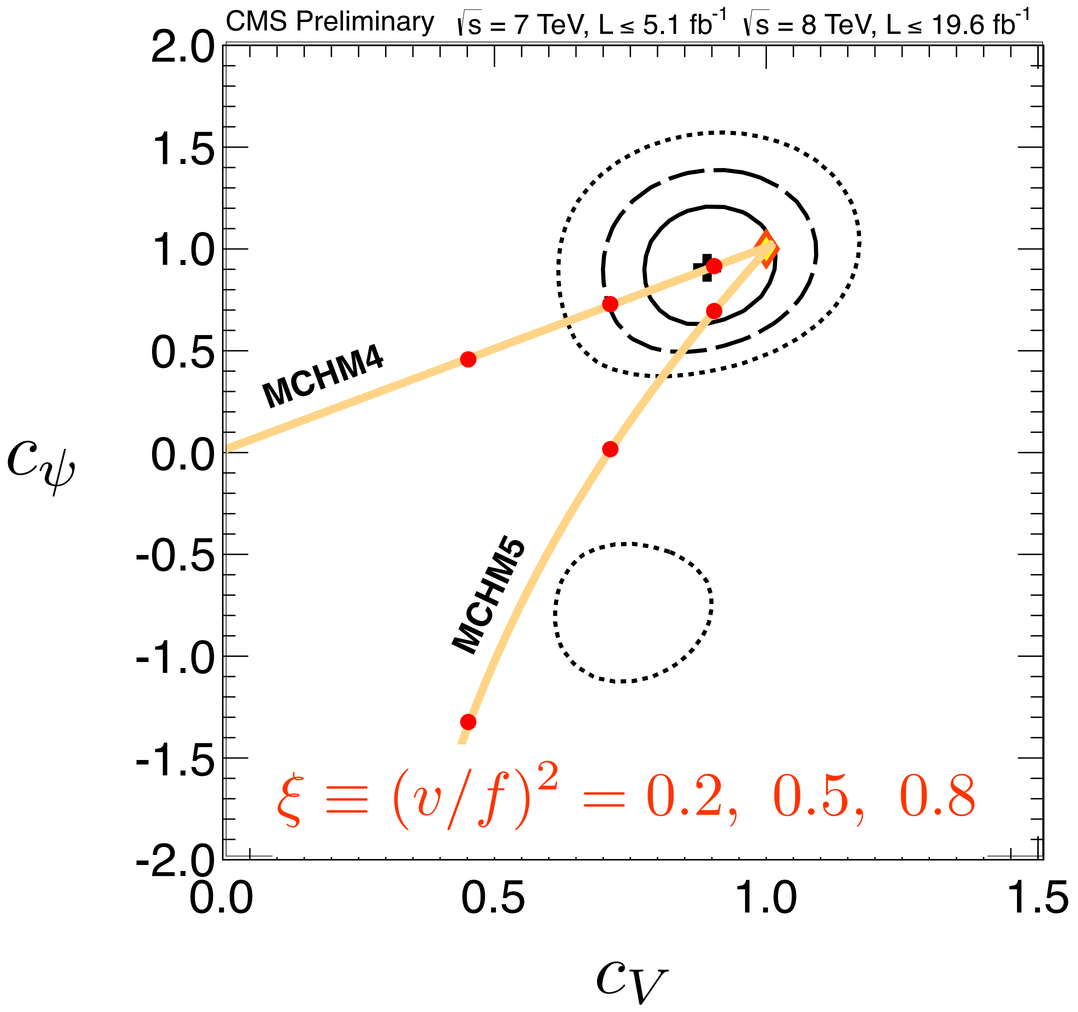


$c\, h^{SM}_{\psi\psi h}$

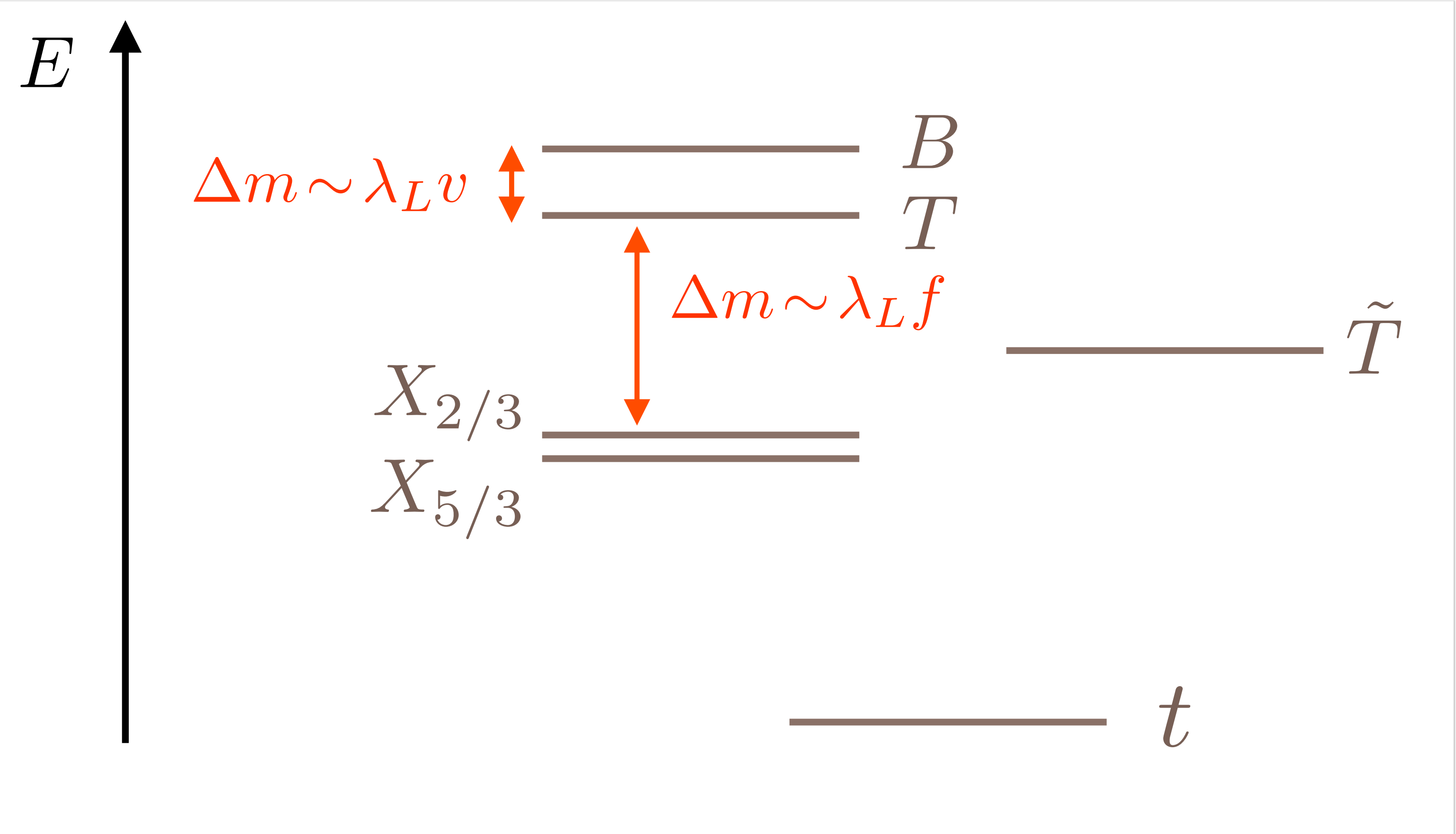
Expect deviations $\sim \xi \equiv \left(\frac{v}{f}\right)^2$

$$a = \sqrt{1-\xi}$$

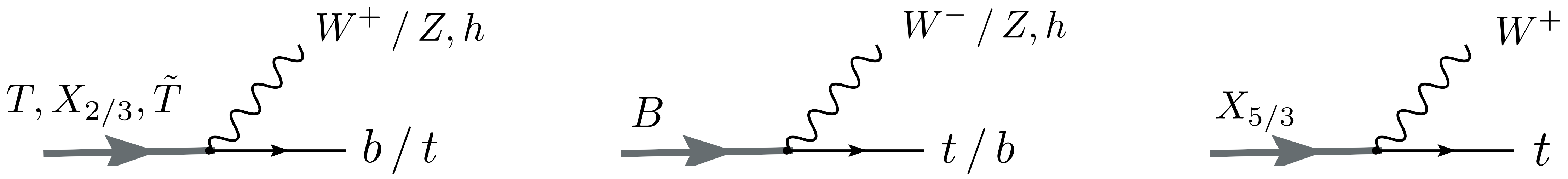
$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$



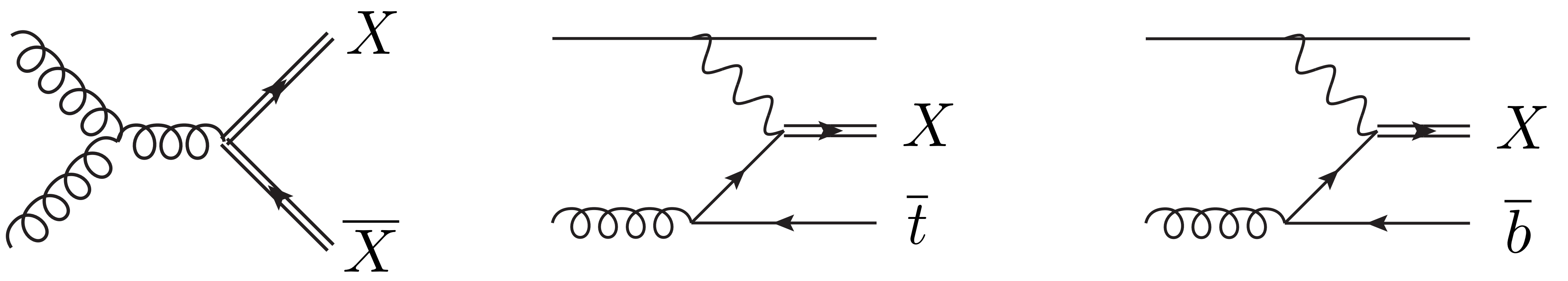
Top partners



Decay modes



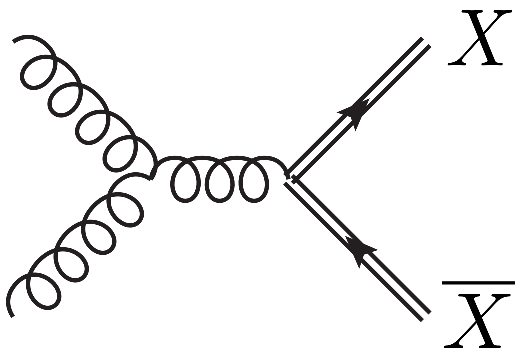
Production modes

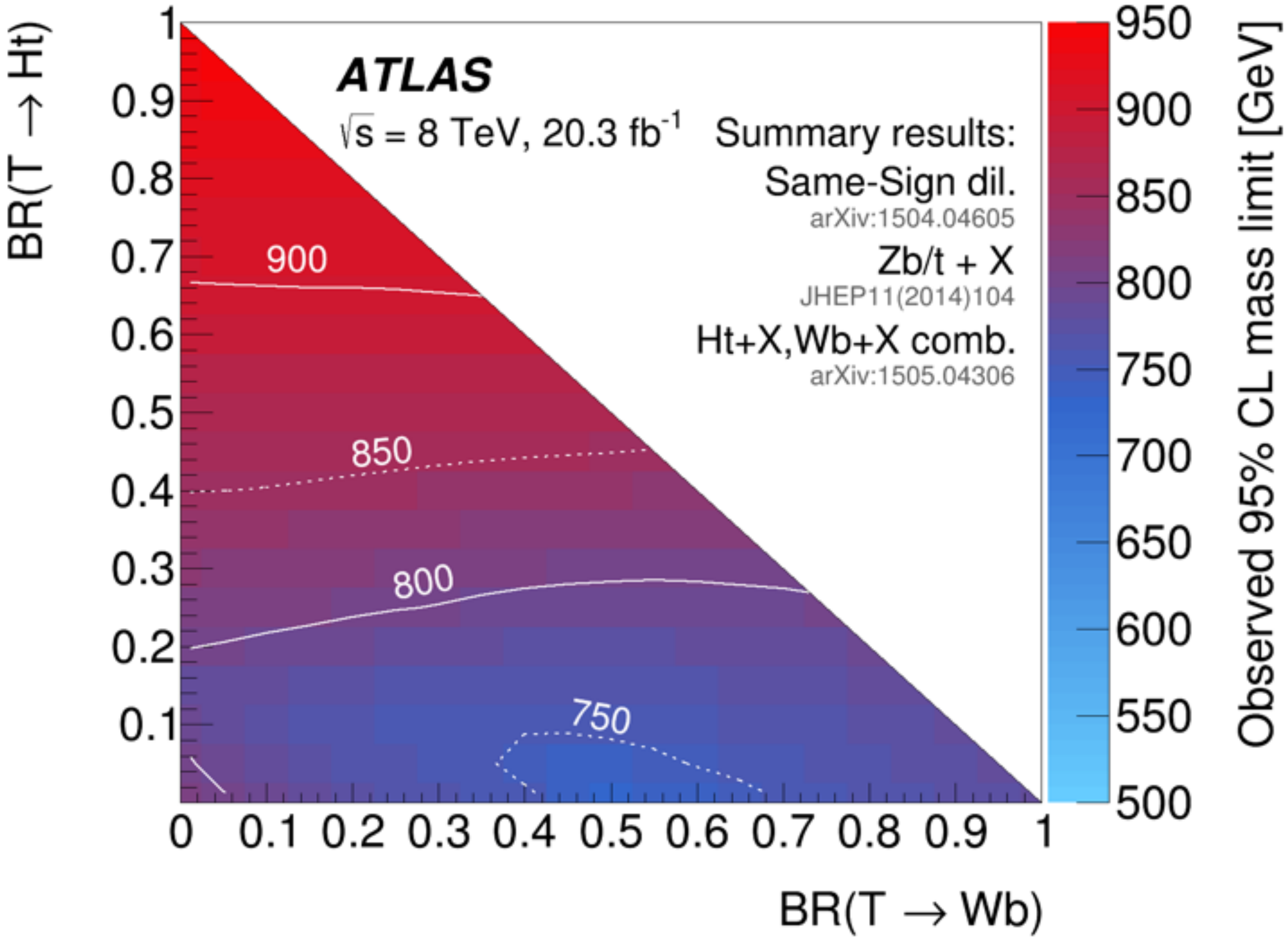


model independent
dominates at small m_X

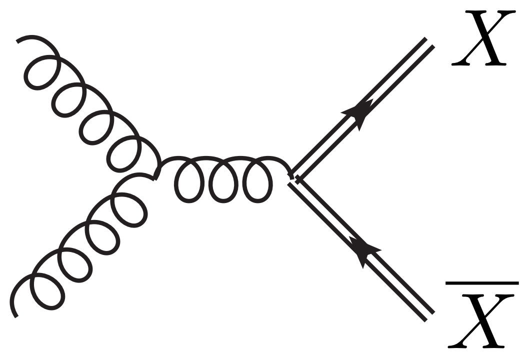
depend on yukawa structure
if present, dominate for large m_X

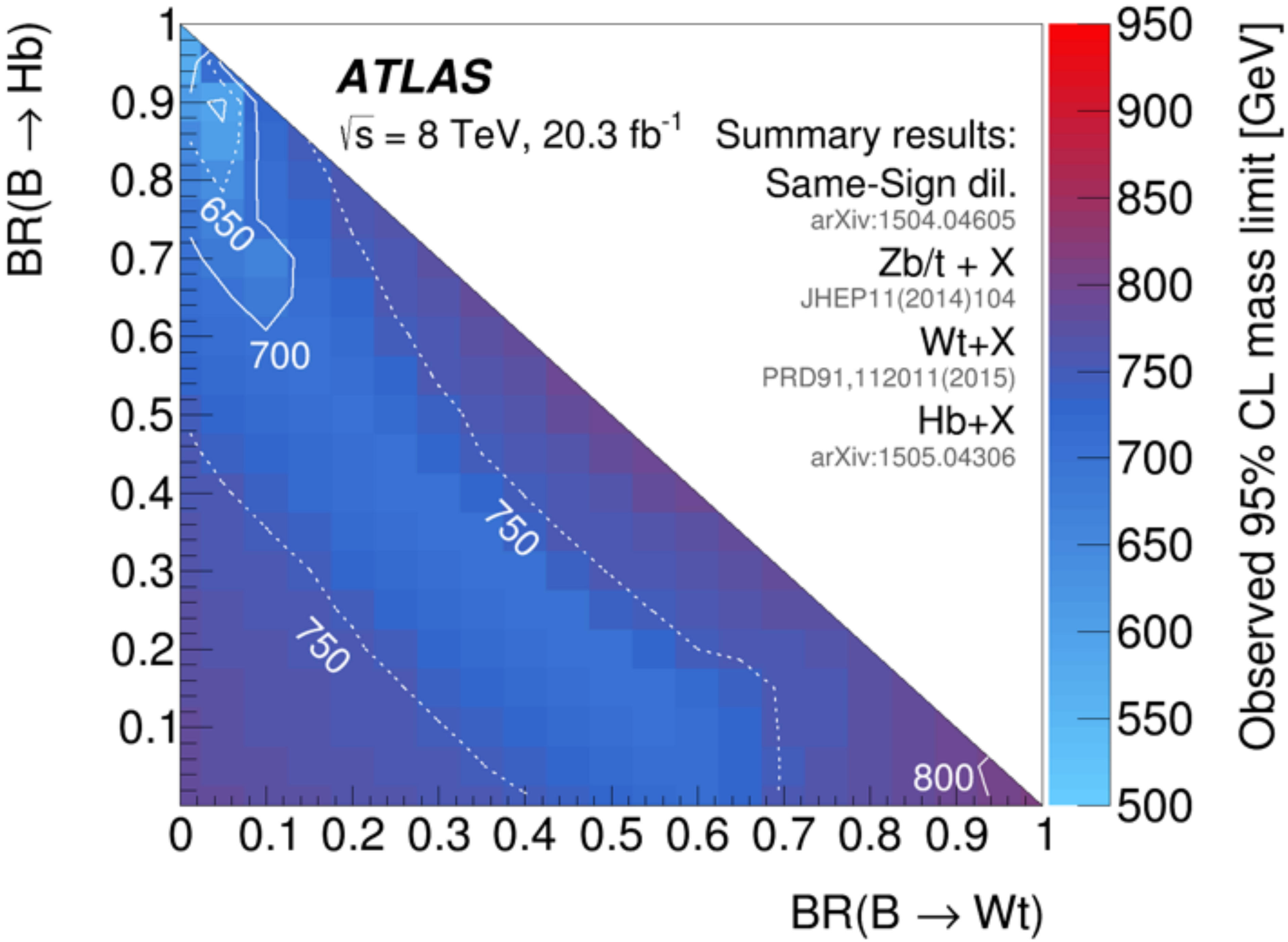
T-partner


X
$\overline{X}$

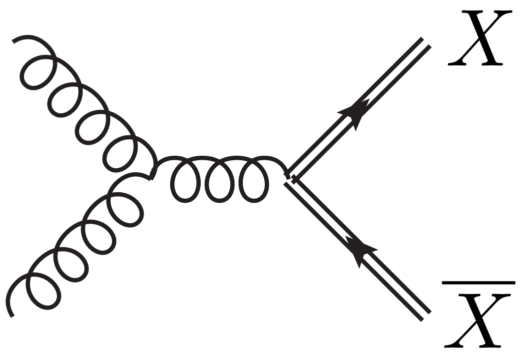

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Summary results:
Same-Sign dil.
arXiv:1504.04605
Zb/t + X
JHEP11(2014)104
Ht+X,Wb+X comb.
arXiv:1505.04306
900
850
800
750
BR(T → Ht)
BR(T → Wb)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Observed 95% CL mass limit [GeV]
500
550
600
650
700
750
800
850
900
950

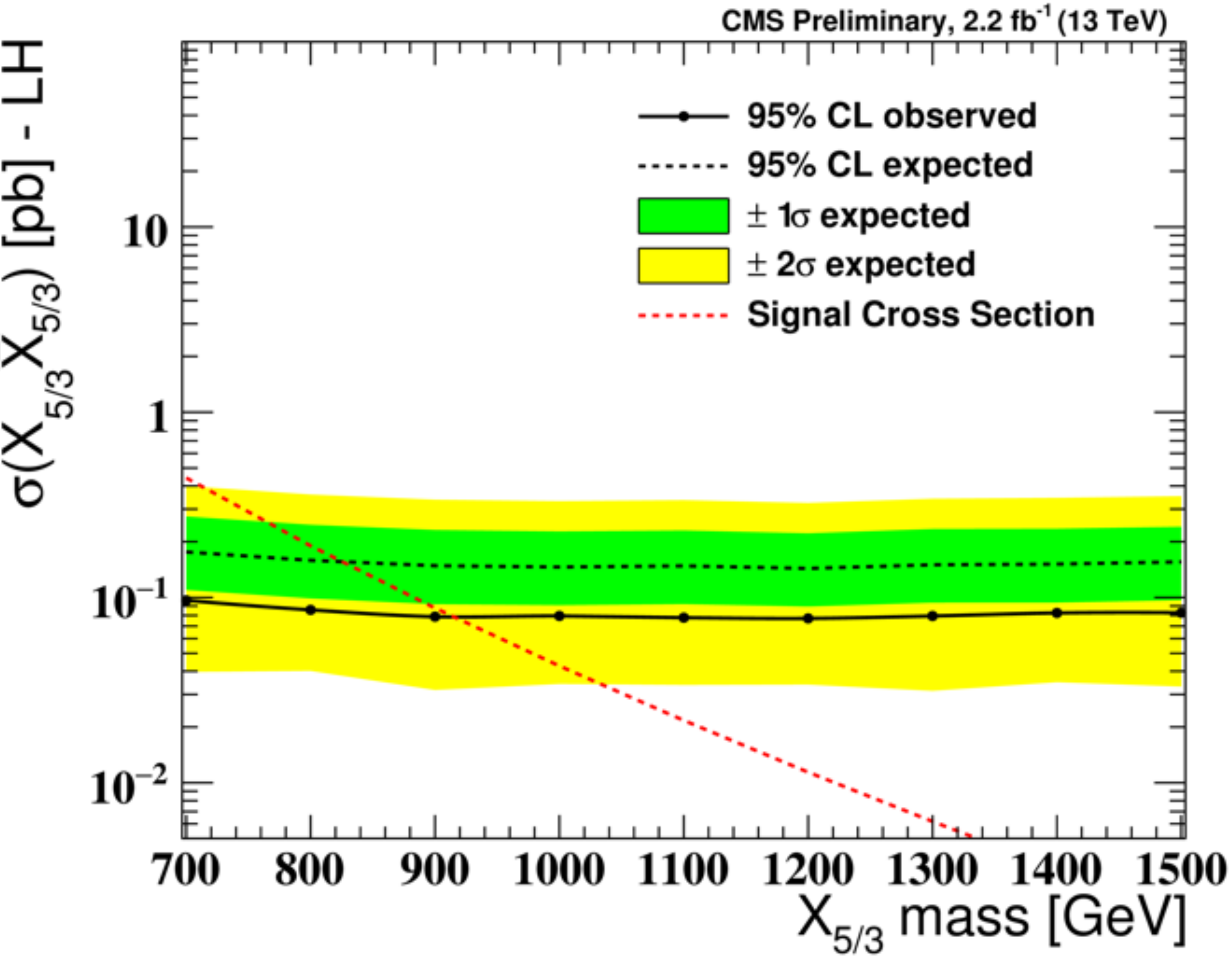
B-partner


X
$\overline{X}$


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Summary results:
Same-Sign dil.
arXiv:1504.04605
Zb/t + X
JHEP11(2014)104
Wt+X
PRD91,112011(2015)
Hb+X
arXiv:1505.04306
BR(B → Hb)
BR(B → Wt)
Observed 95% CL mass limit [GeV]
650
700
750
750
800
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
550
600
650
700
750
800
850
900
950

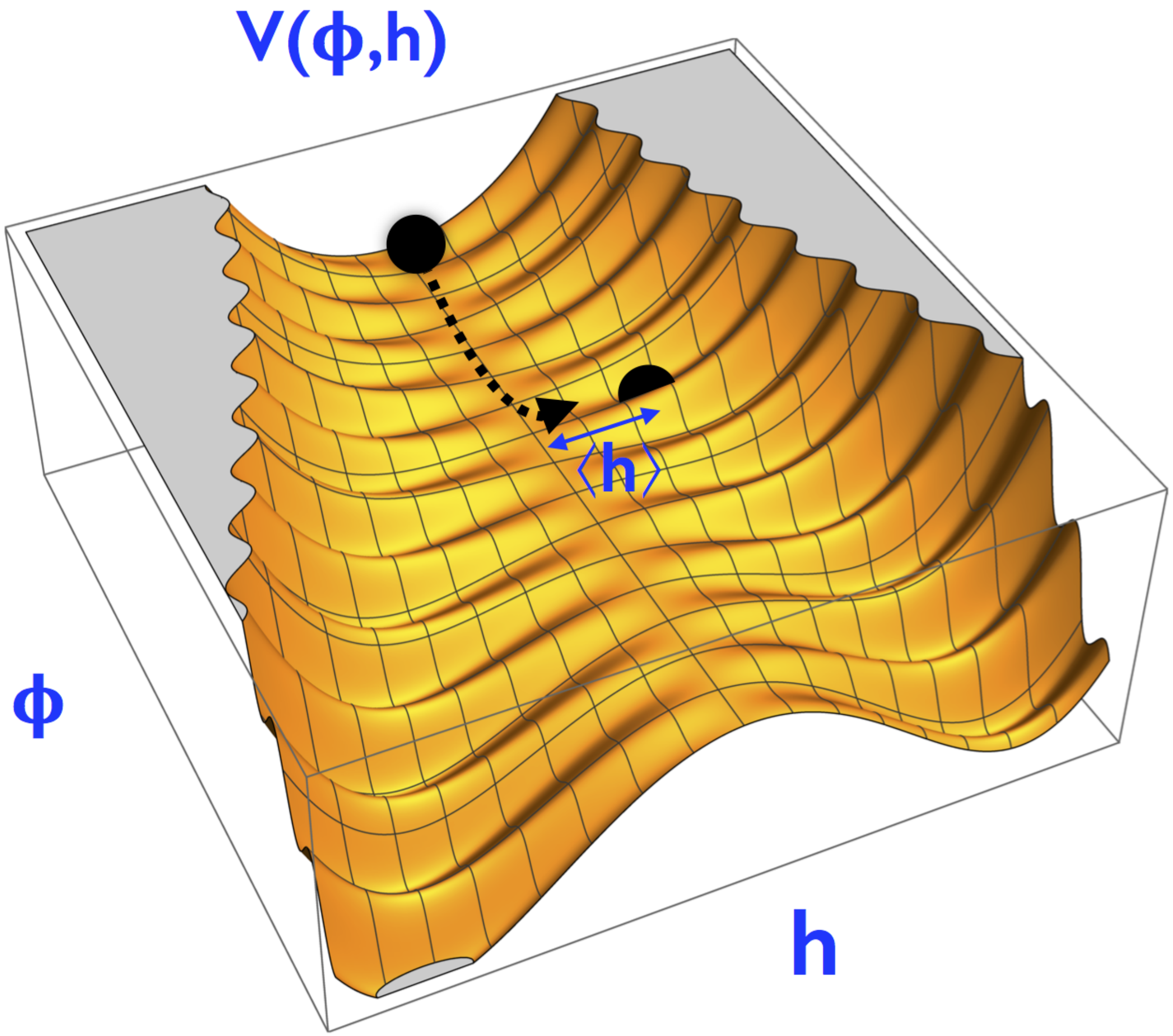
$X_{5/3}$-partner


X
X̄


CMS Preliminary, 2.2 fb^{-1} (13 TeV)
95% CL observed
95% CL expected
± 1σ expected
± 2σ expected
Signal Cross Section
σ($X_{5/3}\overline{X}_{5/3}$) [pb] - LH
10
1
10^{-1}
10^{-2}
700
800
900
1000
1100
1200
1300
1400
1500
$X_{5/3}$ mass [GeV]

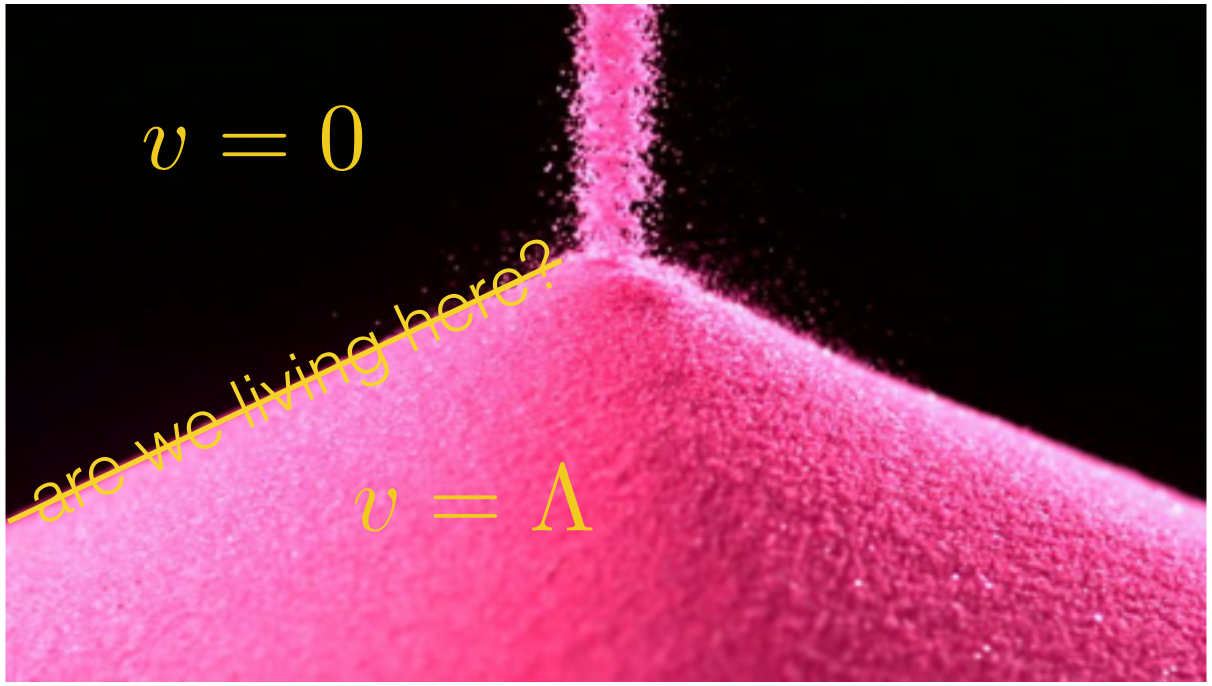
1504.07551
…

Relaxing the EW scale



Self-organized criticality

What if the current fine-tuned value of EW scale is a result of a dynamical process taking place early universe evolution



Basic idea

in fundamental theory (bare) $m_H \sim \Lambda$

dynamical mechanism ‘scans’ (in time)
different values of physical m_H

change of sign in m_H triggers break in scan

Note: fundamentally different from antropics - observed value of m_H is selected dynamically, (mostly) not random process

Higgs Scanner

Scalar field with approximate shift symmetry

$$\phi \to \phi + \alpha$$

breaking controlled by tiny coupling (g)

- couples to Higgs $\mathcal{L} \sim (\Lambda^2 - g\phi)|H|^2$

  $$(m_H^2)_{\text{eff}} = \Lambda^2 - g\langle\phi\rangle$$

- slowly (classically) rolls: $-g\phi\Lambda^2$

  $$\langle\phi\rangle(t) = \langle\phi\rangle(0) - g\Lambda^2 t/3H_I$$

$\uparrow$

Hubble friction during Inflation

Axion Brake

Axions - NGBs of anomalous approximate chiral symmetries

(introduced to solve the strong CP problem of QCD)

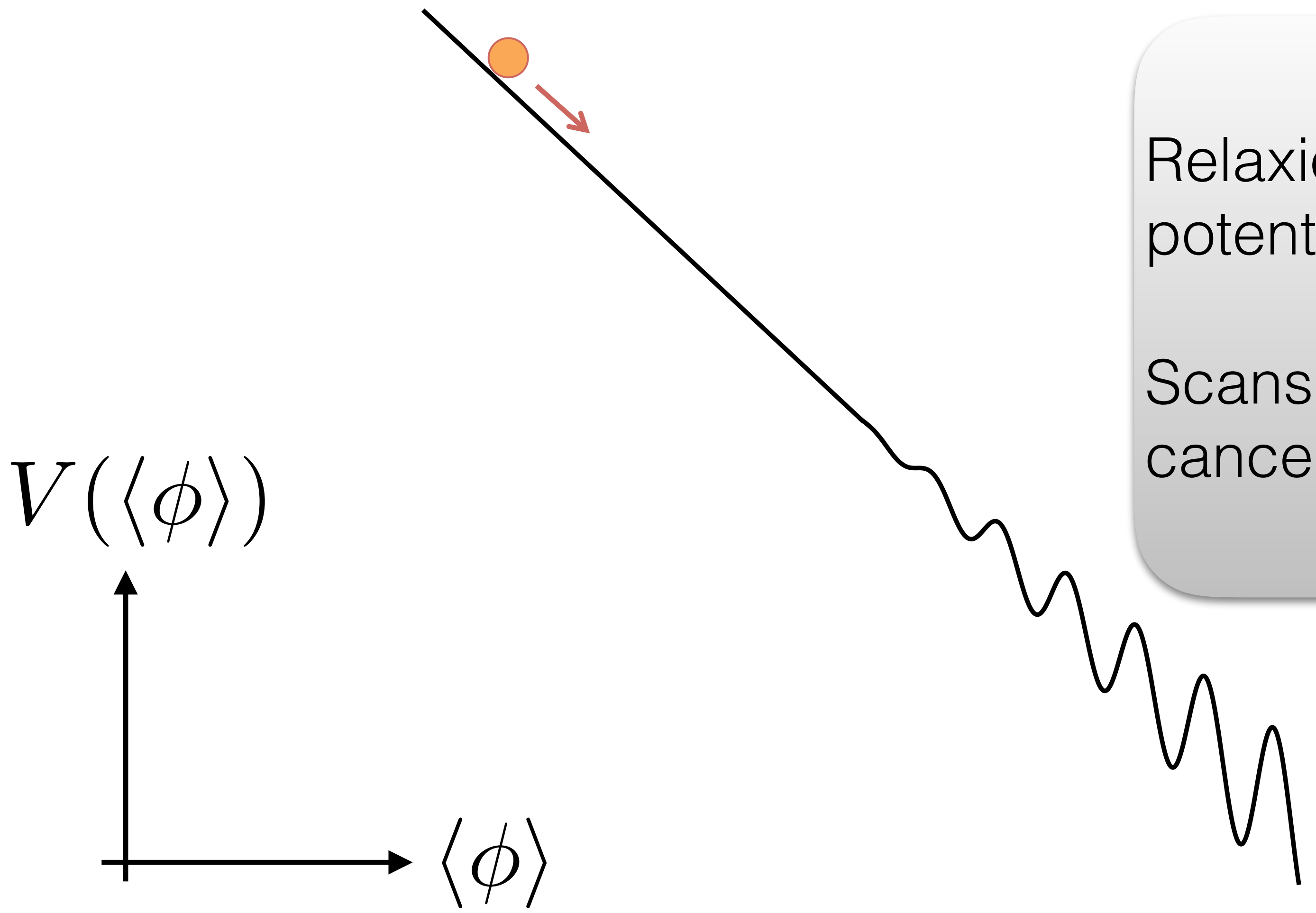
their shift symmetry broken by non-perturbative (QCD) dynamics

$$\frac{\phi}{32\pi^2 f}\tilde{G}G \to\sim \Lambda_G^3 m_q \cos\left(\frac{\phi}{f}\right) \sim \Lambda_G^3 \langle H \rangle y_q \cos\left(\frac{\phi}{f}\right)$$

can be related to phase of fermion (quark) mass matrix

which is sourced by the Higgs vev

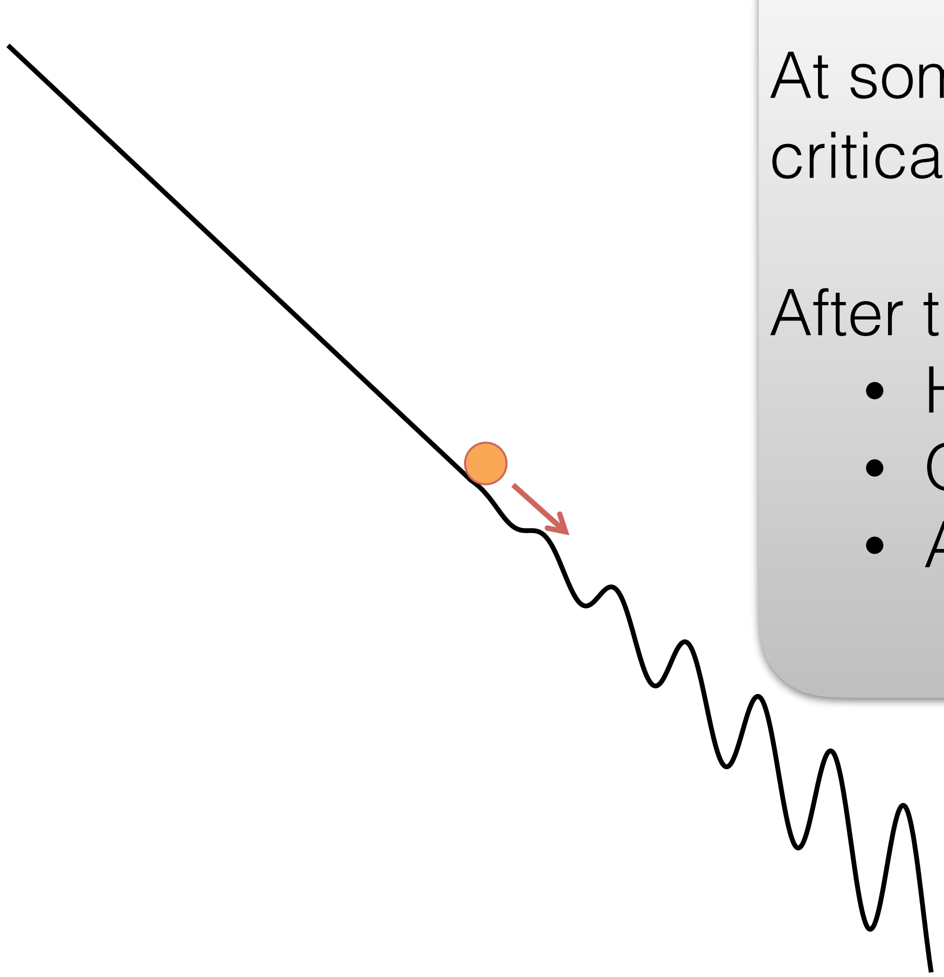
Cosmological evolution



Relaxion starts at the top of potential. Starts rolling down.

Scans m_H^2 while it rolls, slowly cancelling against large Λ^2.

Cosmological evolution

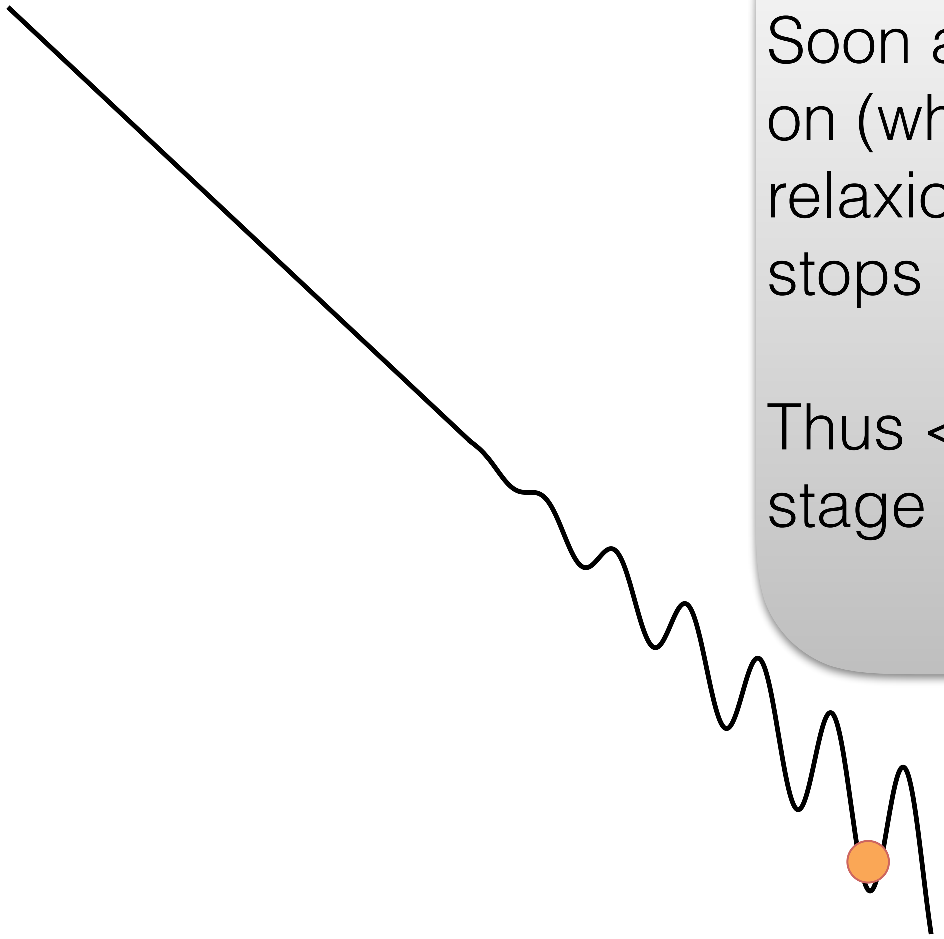


At some point relaxion crosses critical value at which m_H^2=0.

After this m_H^2 becomes negative:

- Higgs gets a vev (<H>)
- Quarks get mass
- Axion potential turns on

Cosmological evolution



Soon after axion potential turns on (while <H> is still very small), relaxion becomes trapped and stops rolling.

Thus <H> becomes stuck at this stage too.

Large Λ/v hierarchy generated dynamically in early Universe.

Requires distinct inflationary period:

- Long-lasting $N_e \gtrsim \frac{H_I^2}{g^2\Lambda^2}$
- Tightly constrained Hubble scale

$$\frac{\Lambda^2}{M_{\text{Planck}}} < H_I < \Lambda_G,\ g^{1/3}\Lambda$$

<relaxion> < <inflaton>

classical roll dominates
over quantum fluctuations

axion barriers
high enough

Absolute bound on $\Lambda < 10^8\ \text{GeV}$

CP problem redux

At min of potential, where relaxion comes to rest:

$$\frac{\partial V}{\partial \phi} \sim g\Lambda^3 - \frac{\Lambda_G^3 m_q}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

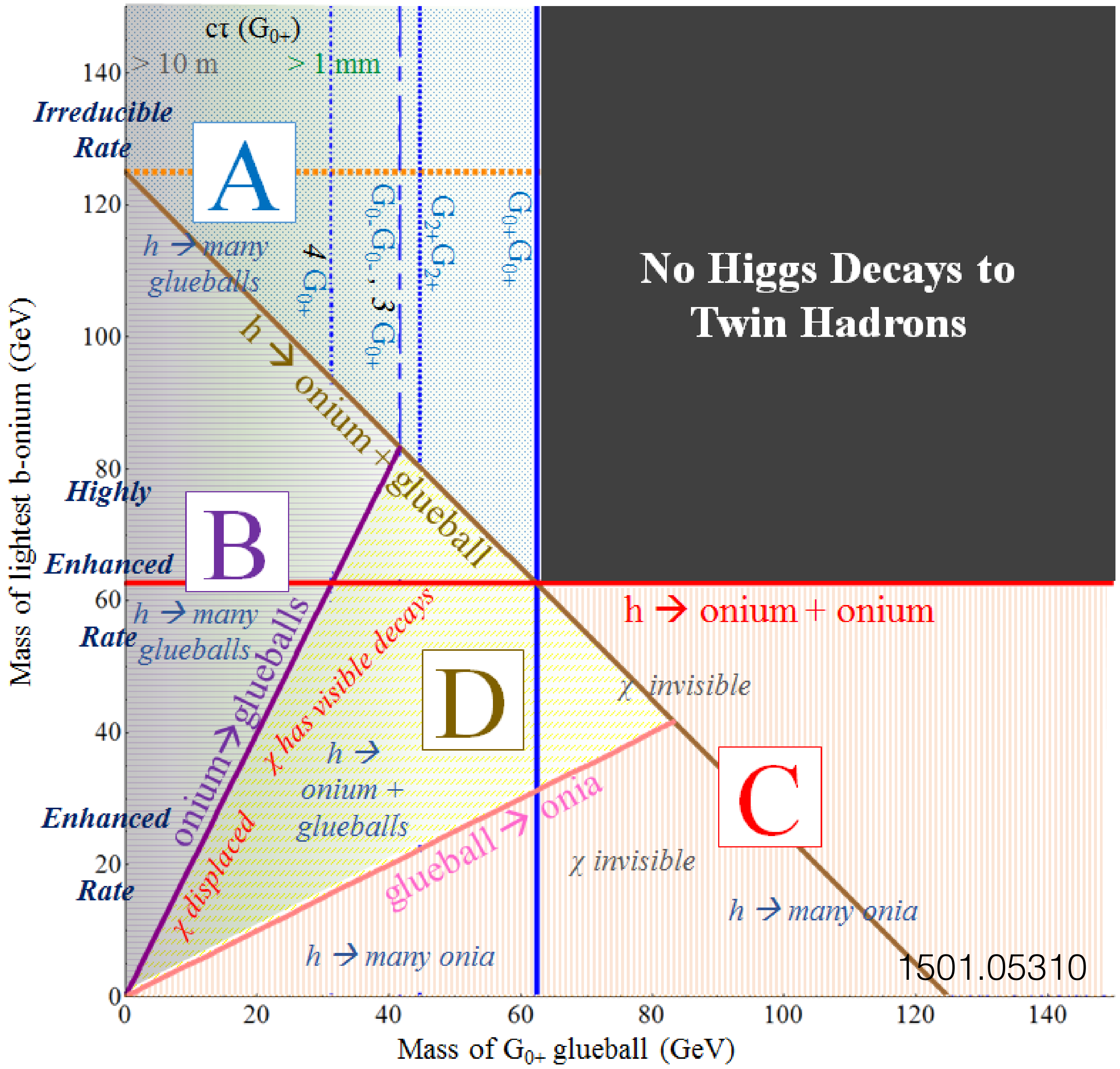
If G=QCD we have strong CP angle $\langle \phi \rangle \neq 0$

Measurements of neutron EDM: $\langle \phi \rangle < 10^{-10}$

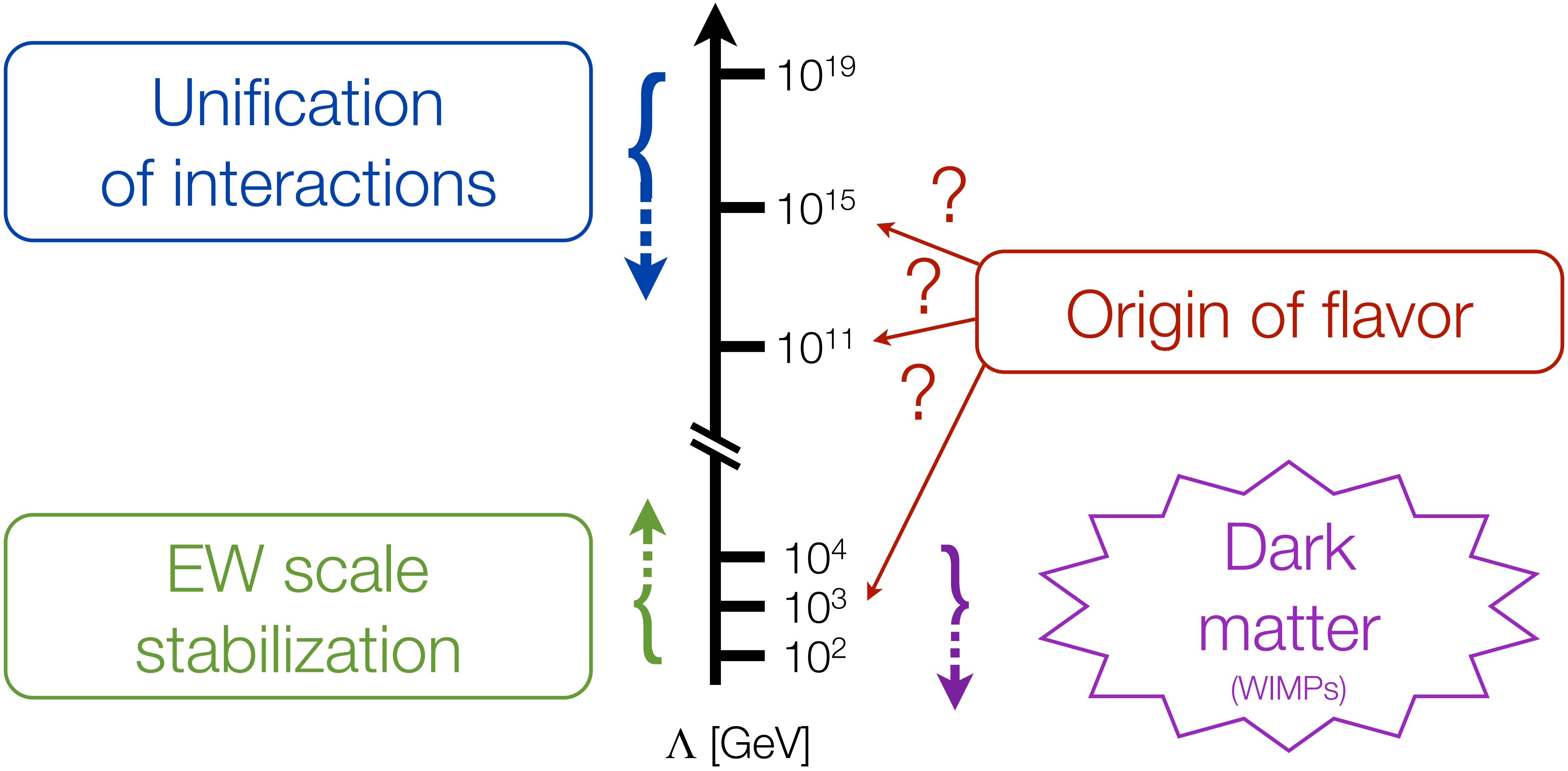
Solution: G new confining dynamics,
q’ - new fermions

Λ_G, $m_{q'}$ need to be close to v
hidden QCD coupled to Higgs @ LHC

Λ_G, $m_{q'}$ need to be close to v hidden QCD coupled to Higgs @ LHC (twin)



The NP flavour puzzle



SM as EFT

valid below cut-off scale Λ

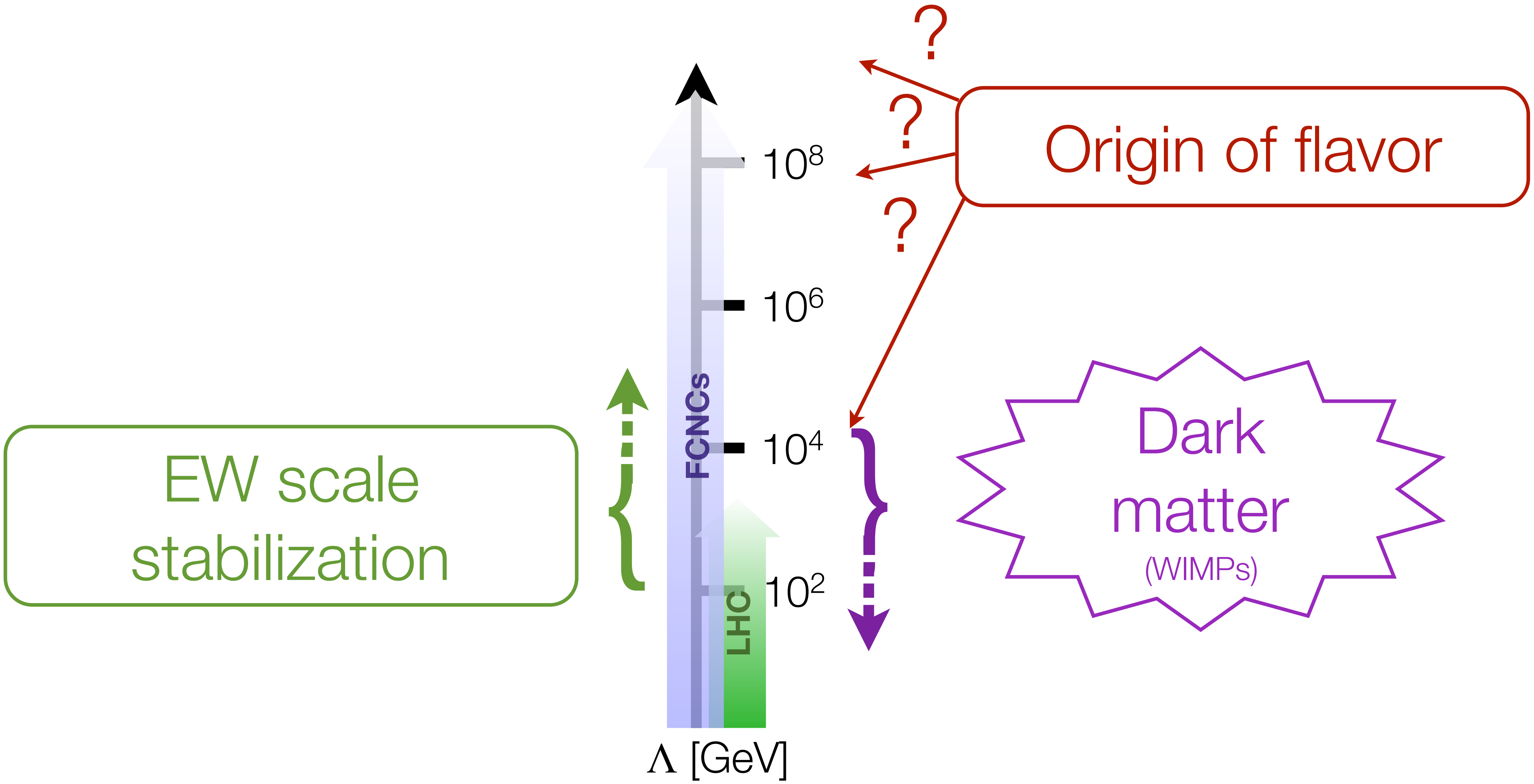
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{n} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)} \, .$$

for natural theory: $c_n^{(d)} \sim \mathcal{O}(1)$

NP flavour puzzle:
If there is NP at the TeV scale, why haven't we seen its effects in flavour observables?

Flavour probes of BSM

indirect probe of BSM physics beyond direct reach



Flavour in SM

Higgs Yukawa interactions

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i\phi E^j_R + \text{h.c.}\,,$$

after EWSB $\tilde{\phi} = i\sigma_2\phi,$

$${\rm Re}(\phi^0) \to (v+h)/\sqrt{2}, \qquad M_q = \frac{v}{\sqrt{2}}Y_q\,.$$

Mass basis: $Q_L \to V_Q Q_L\,,\ U_R \to V_U U_R\,,\ D_R \to V_D D_R$

since $[M_u, M_d] \neq 0,\ \ V_Q^u V_Q^{d\dagger} \equiv V_{\rm CKM} \neq 1$

Cabibbo, Kobayashi & Maskawa

SM flavour Lagrangian

$$\mathcal{L}_m^F = \left(\bar{q}_i \not{D} q^j \delta_{ij}\right)_{\mathrm{NC}} + \frac{g}{\sqrt{2}} \bar{u}_L^i \not{W}^+ V_{\mathrm{CKM}}^{ij} d_L^j \\ + \bar{u}_L^i \lambda_u^{ij} u_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \bar{d}_L^i \lambda_d^{ij} d_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \mathrm{h.c.}\,,$$

NC = neutral currents (g,γ,Z)

$$(u_L^i, d_L^i) \equiv Q_L^T$$

Flavour conversion in SM

- fully parametrized by 3 CKM angles
- mediated by charged current weak interactions
- these involve left-handed fields only

(Over)constraining SM flavor

$\mathcal{L}_{\mathrm{SM}}$

Λ_{weak}
[~100 GeV]

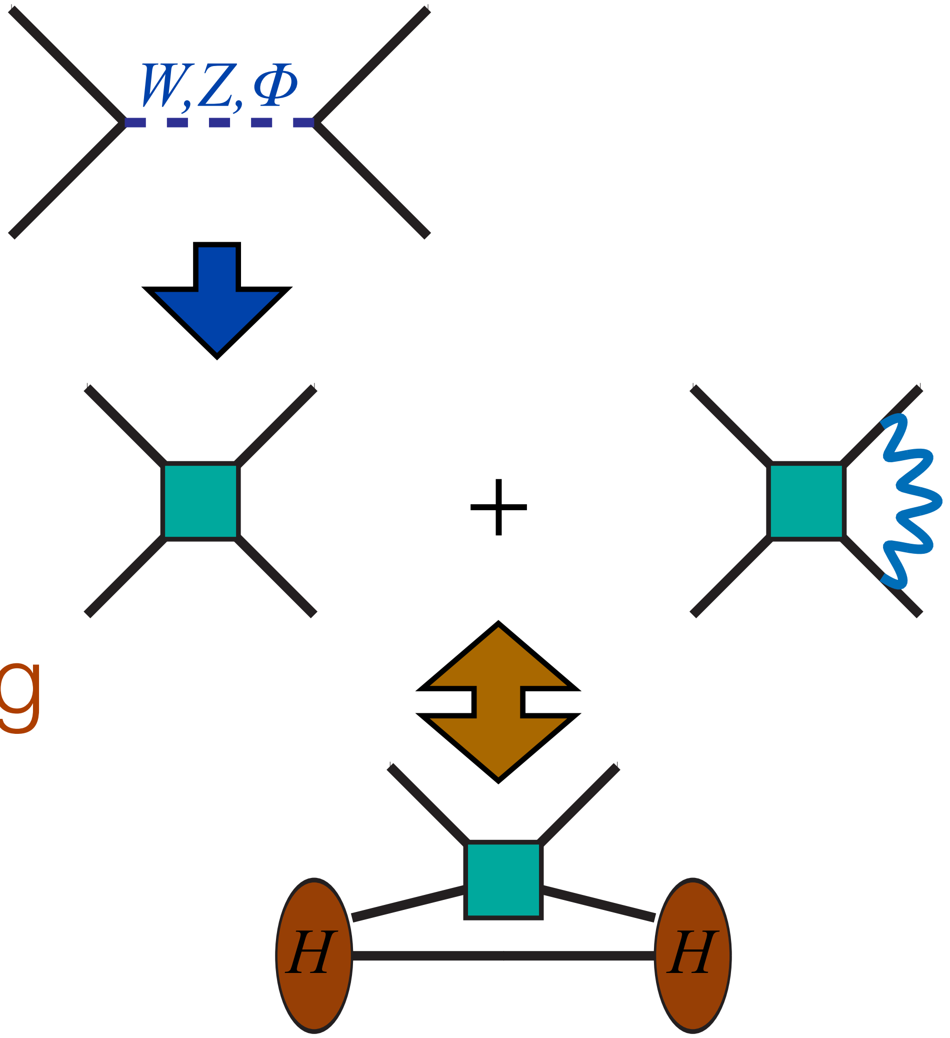
Weak scale operators

$\mathcal{L}^{\mathrm{eff}}_{\mathrm{weak}}(\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$

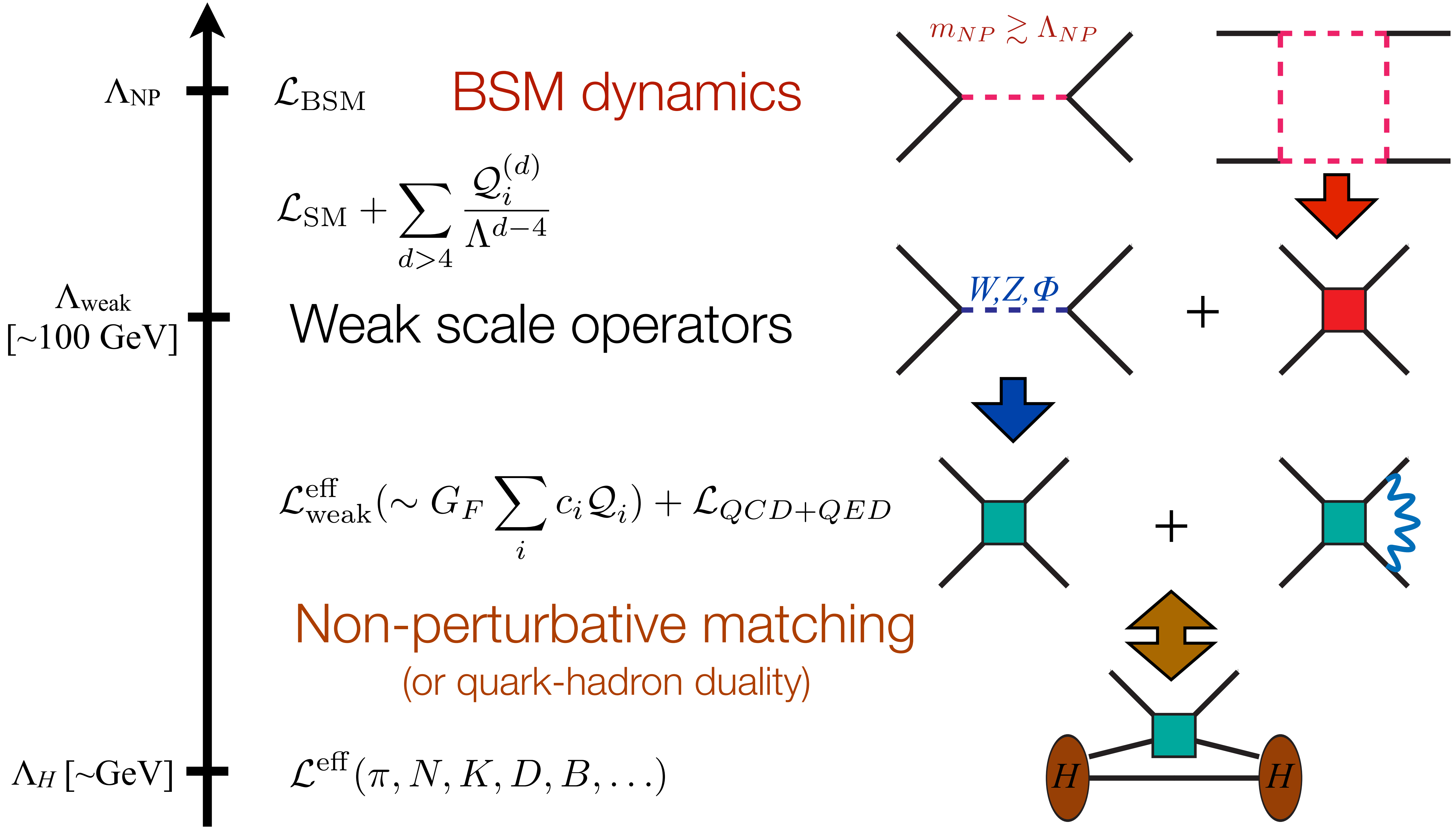
Non-perturbative matching
(or quark-hadron duality)

Λ_H [~GeV]

$\mathcal{L}^{\mathrm{eff}}(\pi, N, K, D, B, \ldots)$



(Over)constraining NP flavor



$\Lambda_{\rm NP}$ $\mathcal{L}_{\rm BSM}$ BSM dynamics

$$\mathcal{L}_{\rm SM} + \sum_{d>4} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$

$\Lambda_{\rm weak}$ [~100 GeV] Weak scale operators

$$\mathcal{L}_{\rm weak}^{\rm eff} (\sim G_F \sum_i c_i \mathcal{Q}_i) + \mathcal{L}_{QCD+QED}$$

Non-perturbative matching

(or quark-hadron duality)

Λ_H [~GeV] $\mathcal{L}^{\rm eff}(\pi, N, K, D, B, \ldots)$

Neutral meson mixing

Focus on the neutral B meson system: flavour states

$$B^0 \sim \bar{b}d \qquad\qquad \bar{B}^0 \sim b\bar{d}.$$

$$CP|B^0\rangle = e^{i\xi_B}|\bar{B}^0\rangle \, ,$$
$$CP|\bar{B}^0\rangle = e^{-i\xi_B}|B^0\rangle \, .$$

Time evolution

$$|\psi(0)\rangle = a(0)|B^0\rangle + b(0)|\bar{B}^0\rangle$$
$$|\psi(t)\rangle = a(t)|B^0\rangle + b(t)|\bar{B}^0\rangle + c_1(t)|f_1\rangle + c_2(t)|f_2\rangle + \dots \, ,$$

B decay products

If only interested a(t), b(t):

$$i\frac{d}{dt}\begin{pmatrix}a(t)\\b(t)\end{pmatrix}=H\begin{pmatrix}a(t)\\b(t)\end{pmatrix}\,,\qquad \mathcal{H}=M+i\frac{\Gamma}{2}$$

- M & Γ: time-independent, Hermitian 2 × 2 matrices,
- M-oscillations (dispersive); Γ-decays (absorptive)

H eigenvectors

$$|B_{L,H}\rangle = p_{L,H}|B^0\rangle \pm q_{L,H}|\bar{B}^0\rangle$$

$$|p_{L,H}|^2 + |q_{L,H}|^2 = 1$$

CP conserving oscillation parameters:

$$m \equiv \frac{M_L + M_H}{2}\,, \qquad \Gamma \equiv \frac{\Gamma_L + \Gamma_H}{2}\,,$$

$$\Delta m \equiv M_H - M_L\,, \qquad \Delta\Gamma \equiv \Gamma_H - \Gamma_L\,,$$

($x \equiv \Delta m/\Gamma$,
$y \equiv \Delta\Gamma/2\Gamma$)

- If CPT: $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$,
  $\Rightarrow p_L = p_H \equiv p$, $q_L = q_H \equiv q$

- If CP: Arg(M_{12}) = Arg(Γ_{12})
  $\Rightarrow |q/p| = 1$

In SM:($M = K^0,\ B^0,\ B_s$)

$$M_{12}^{\mathrm{SM}} = \underbrace{\frac{G_F^2 m_t^2}{16\pi^2}\,(V_{ti}^* V_{tj})^2}_{\frac{(Y_u Y_u^*)_{ij}^2}{128\pi^2 m_t^2}} \langle \bar{M} | (\bar{d}_L^i \gamma_\mu d_L^j)^2 | M \rangle F\left(\frac{m_t^2}{m_W^2}\right) + \ldots\,,$$

$$F(x) \sim \mathcal{O}(1)$$
$$F(\infty) = 1$$

Hadronic matrix elements:

$$\langle \bar{M} | (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{d}_L^i \gamma^\mu d_L^j) | M \rangle = \frac{2}{3} f_M^2 m_M^2 \hat{B}_M \quad \hat{B}_M \sim \mathcal{O}(1)$$

$$\langle 0 | d^i \gamma_\mu \gamma_5 d^j | M(p) \rangle \equiv i p_\mu f_M$$

tremendous progress in past 30 yrs - Lattice QCD

SM in ΔF=2

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

SM ($\Lambda_{\rm SM} \approx v$)

$$\Im(z_{sd}^{\rm SM}) \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{ts}^*|^2 \sim 10^{-10}$$

$$\Re(z_{sd}^{\rm SM}) \sim \frac{\lambda_c^2}{64\pi^2}|V_{cd}V_{cs}^*|^2 \sim 5 \times 10^{-9}$$

$$|z_{bd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{tb}^*|^2 \sim 9 \times 10^{-8}$$

$$|z_{bs}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{ts}V_{tb}^*|^2 \sim 3 \times 10^{-6}$$

Generic BSM flavour

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda^2_{\text{NP}}}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda^2_{\text{NP}}}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda^2_{\text{NP}}}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda^2_{\text{NP}}}(\overline{s_L}\gamma_\mu b_L)^2 .$$

CPC NP

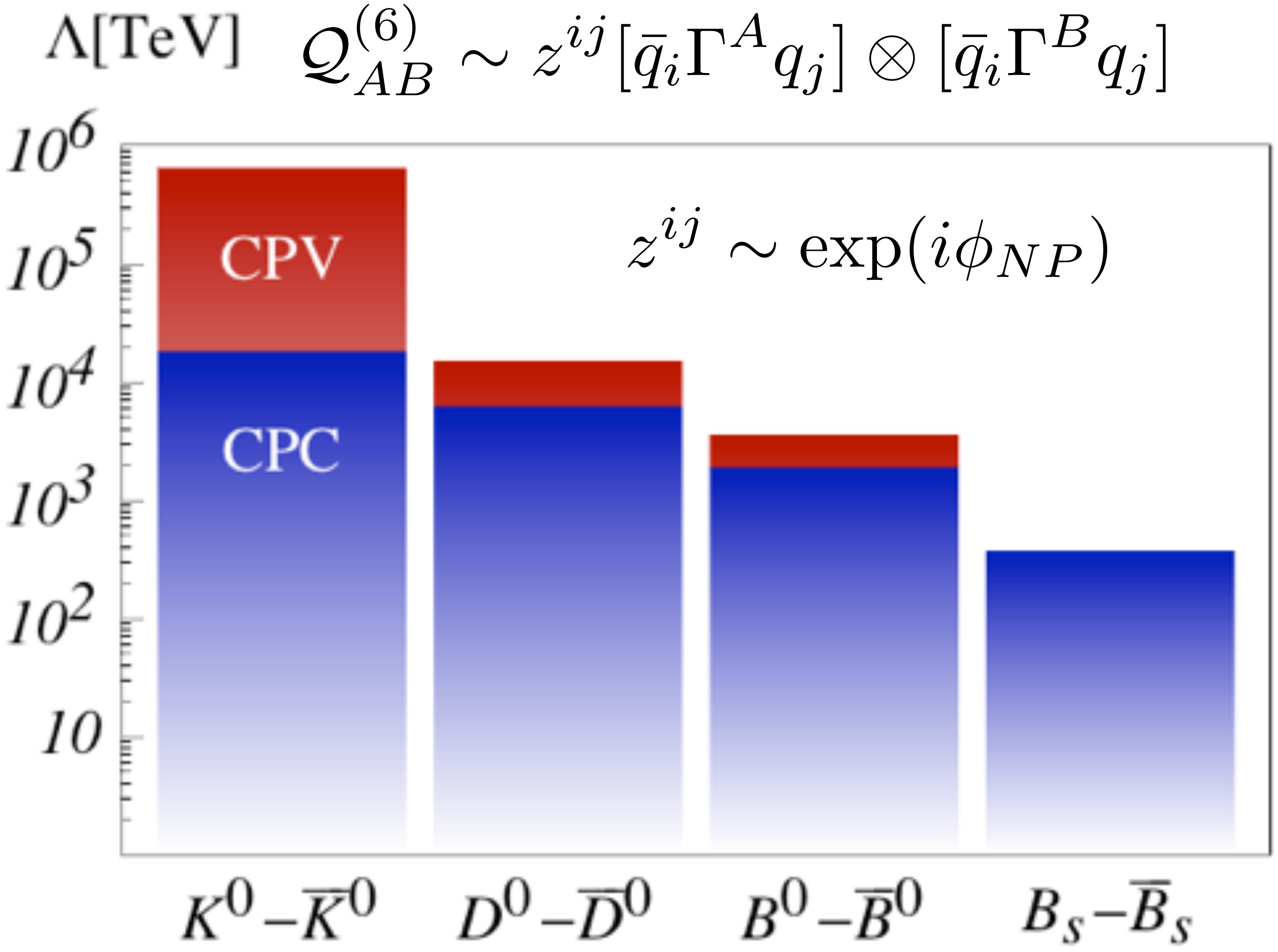
$$\begin{aligned} \Delta m_K/m_K &\sim 7.0\times 10^{-15}, \\ \Delta m_D/m_D &\sim 8.7\times 10^{-15}, \\ \Delta m_B/m_B &\sim 6.3\times 10^{-14}, \\ \Delta m_{B_s}/m_{B_s} &\sim 2.1\times 10^{-12}, \end{aligned} \quad \Rightarrow \Lambda_{\text{NP}} \gtrsim \begin{cases} \sqrt{z_{sd}}\; 1\times 10^3\ \text{TeV} & \Delta m_K \\ \sqrt{z_{cu}}\; 1\times 10^3\ \text{TeV} & \Delta m_D \\ \sqrt{z_{bd}}\; 4\times 10^2\ \text{TeV} & \Delta m_B \\ \sqrt{z_{bs}}\; 7\times 10^1\ \text{TeV} & \Delta m_{B_s} \end{cases}$$

CPV NP

$$\begin{aligned} \epsilon_K &\sim 2.3\times 10^{-3}, \\ A_\Gamma/y_{\text{CP}} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm 0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad \Rightarrow \Lambda_{\text{NP}} \gtrsim \begin{cases} \sqrt{z_{sd}}\; 2\times 10^4\ \text{TeV} & \epsilon_K \\ \sqrt{z_{cu}}\; 3\times 10^3\ \text{TeV} & A_\Gamma \\ \sqrt{z_{bd}}\; 8\times 10^2\ \text{TeV} & S_{\psi K} \\ \sqrt{z_{bs}}\; 7\times 10^1\ \text{TeV} & S_{\psi\phi} \end{cases}$$

NP with a generic flavour structure is irrelevant for EW hierarchy

$$\mathcal{Q}^{(6)}_{AB} \sim z^{ij}[\bar{q}_i \Gamma^A q_j] \otimes [\bar{q}_i \Gamma^B q_j]$$



Flavour of TeV NP

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2.$$

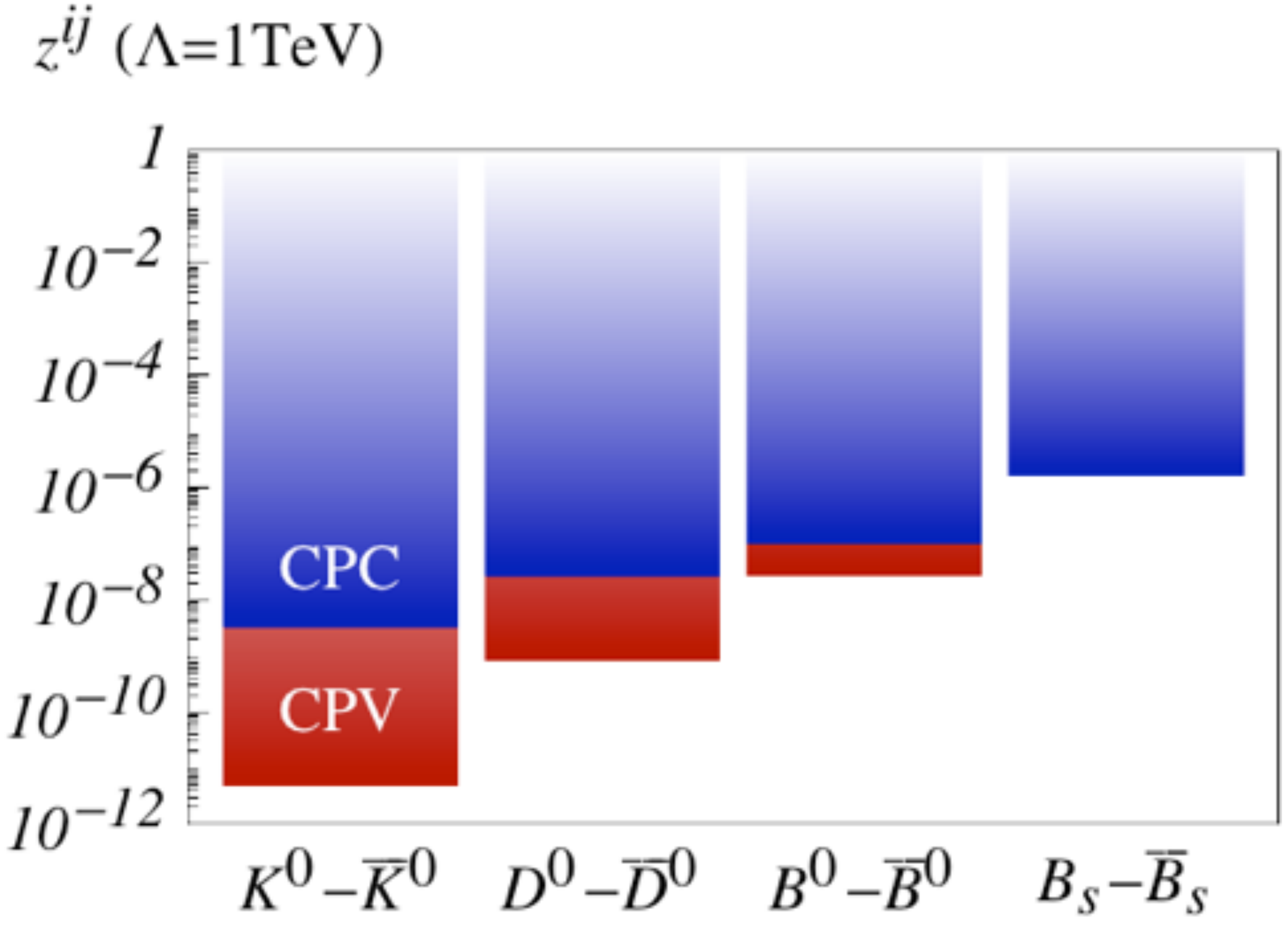
CPC NP

$$\begin{aligned} \Delta m_K/m_K &\sim 7.0\times 10^{-15}, \\ \Delta m_D/m_D &\sim 8.7\times 10^{-15}, \\ \Delta m_B/m_B &\sim 6.3\times 10^{-14}, \\ \Delta m_{B_s}/m_{B_s} &\sim 2.1\times 10^{-12}, \end{aligned} \quad \Rightarrow \quad \begin{aligned} z_{sd} &\lesssim 8\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{cu} &\lesssim 5\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bd} &\lesssim 5\times 10^{-6}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bs} &\lesssim 2\times 10^{-4}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \end{aligned}$$

CPV NP

$$\begin{aligned} \epsilon_K &\sim 2.3\times 10^{-3}, \\ A_\Gamma/y_{\rm CP} &\lesssim 0.2, \\ S_{\psi K_S} &= 0.67\pm 0.02, \\ S_{\psi\phi} &\lesssim 1. \end{aligned} \quad \Rightarrow \quad \begin{aligned} z_{sd}^I &\lesssim 6\times 10^{-9}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{cu}^I &\lesssim 1\times 10^{-7}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bd}^I &\lesssim 1\times 10^{-6}\,(\Lambda_{\rm NP}/{\rm TeV})^2, \\ z_{bs}^I &\lesssim 2\times 10^{-4}\,(\Lambda_{\rm NP}/{\rm TeV})^2. \end{aligned}$$

in case of TeV NP, flavour structure needs to be far from generic



z^{ij} (Λ=1TeV)
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
CPC
CPV
$K^0-\overline{K}^0$
$D^0-\overline{D}^0$
$B^0-\overline{B}^0$
$B_s-\overline{B}_s$

NP in Δ*F*=1

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

SM ($\Lambda_{SM} \approx v$)

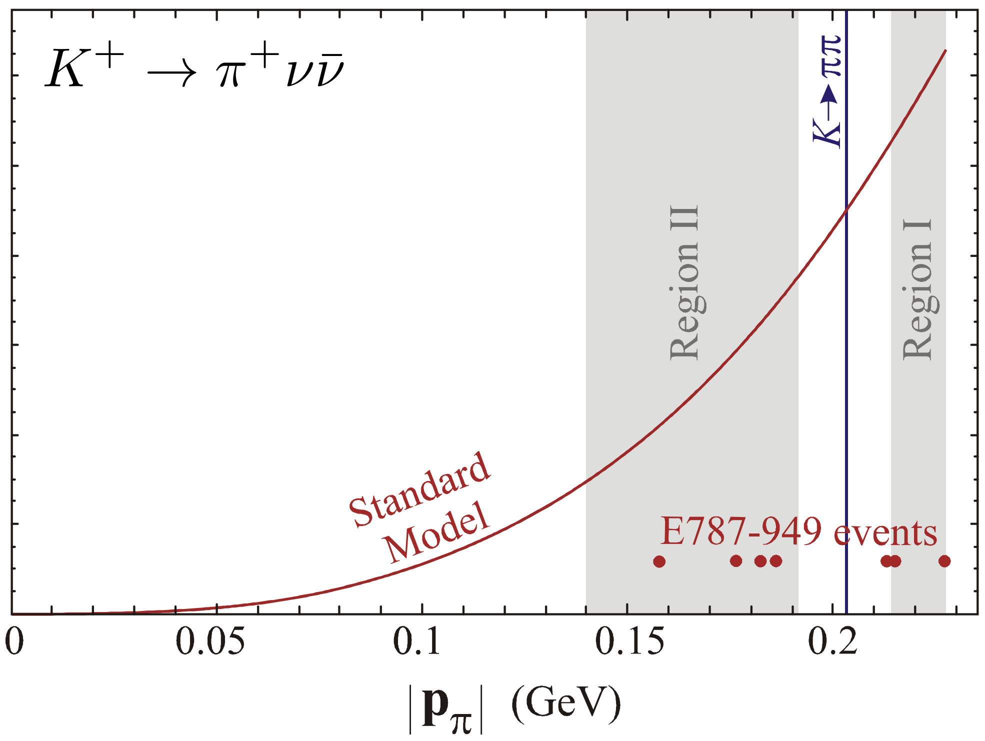
$$|y_{sd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{ts}^*| \sim 5\times 10^{-7}$$
$$|y_{bd}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{td}V_{tb}^*| \sim 10^{-5}$$
$$|y_{bs}^{\rm SM}| \sim \frac{\lambda_t^2}{64\pi^2}|V_{ts}V_{tb}^*| \sim 6\times 10^{-5}$$

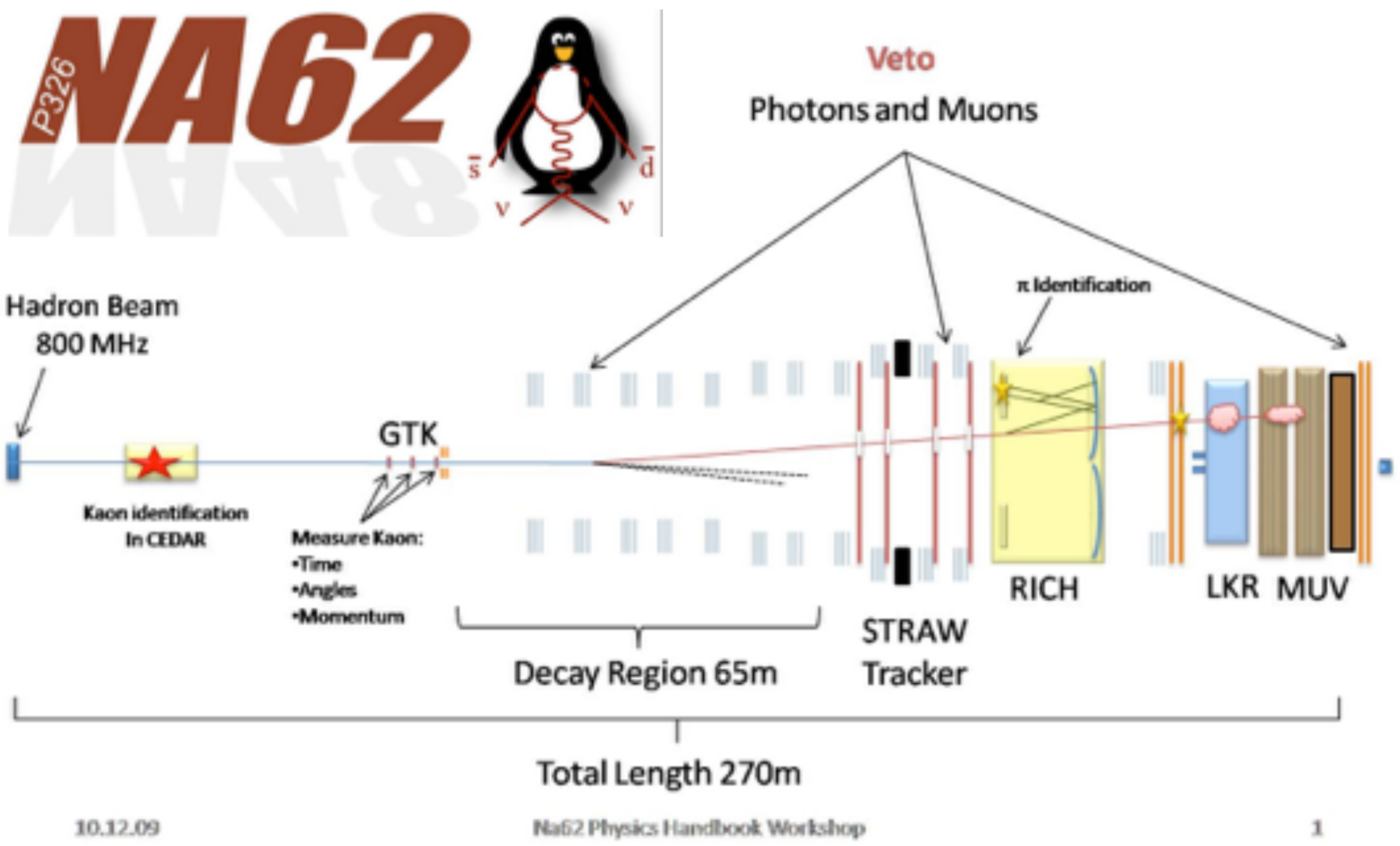
$\Rightarrow$

$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu}) \sim 8\times 10^{-11}\,,$$
$$\mathcal{B}(B_d\to\mu^+\mu^-) \sim 10^{-10}\,,$$
$$\mathcal{B}(B_s\to\mu^+\mu^-) \sim 4\times 10^{-9}\,.$$

Rare Kaon decays

$$\mathcal{L}_{\Delta F=1} = \boxed{y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L} + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L$$

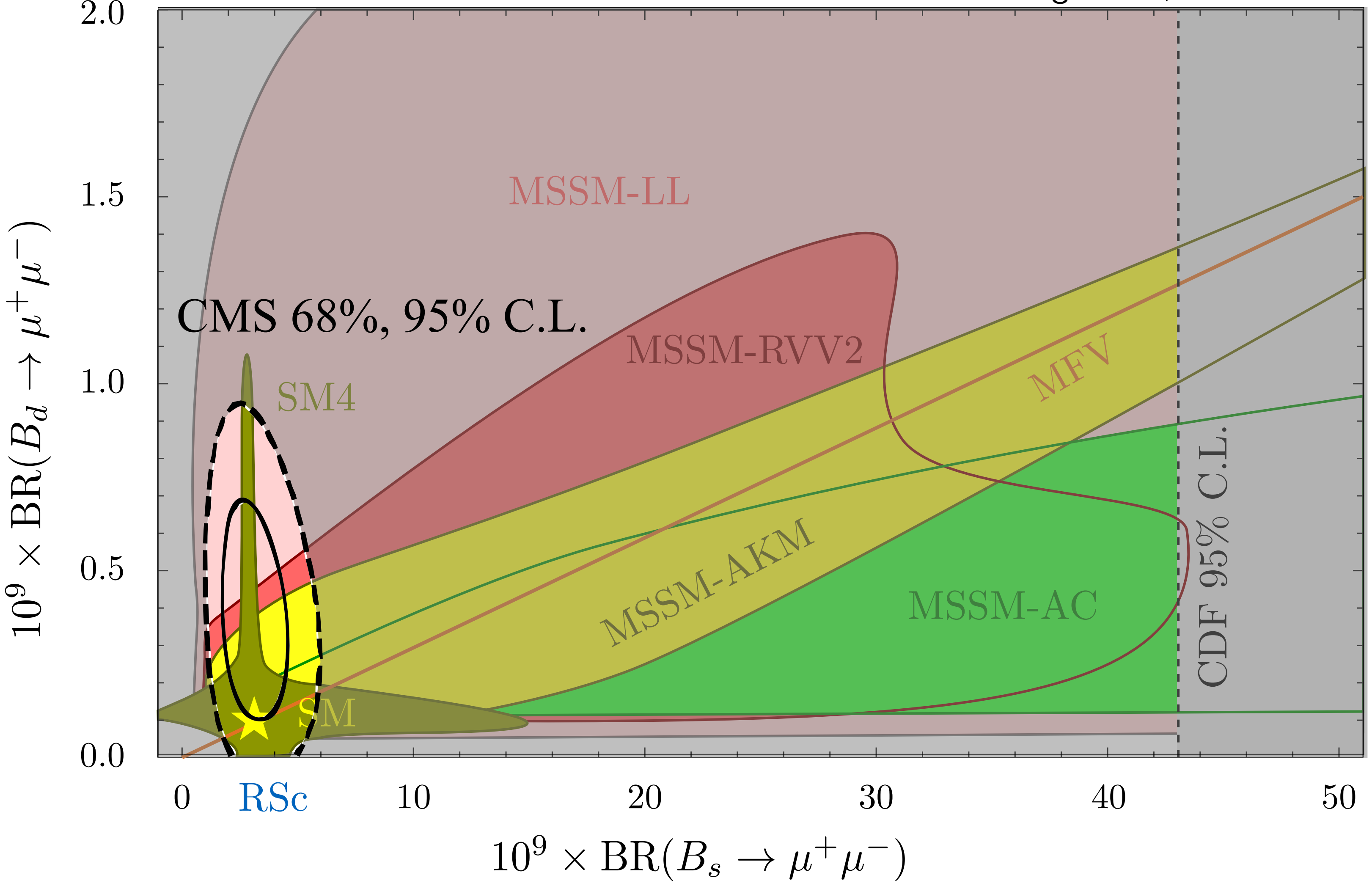




$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{Exp}} = 17.3^{+11.5}_{-10.5} \times 10^{-11} \Rightarrow \Lambda_{NP} \gtrsim \sqrt{y_{sd}}\, 2 \times 10^2 \ \mathrm{TeV}$$

Rare B decays

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + \boxed{y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L}$$

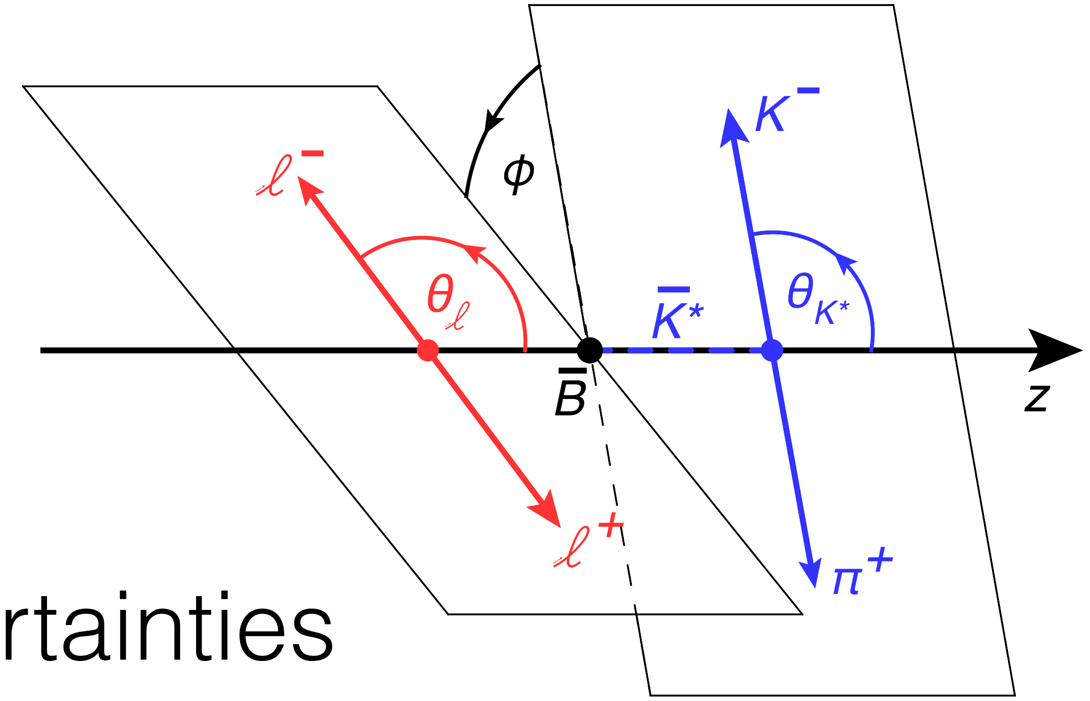


update of Straub, 1012.3893
using CMS, 1307.5025

B flavour anomalies

$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + \boxed{y_{bs}\frac{v^2}{\Lambda^2_{NP}}\frac{g}{c_W}\bar{s}_L \not{Z} b_L}$$

$$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$$



- differential rate analysis
- challenging theory uncertainties

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\Gamma)}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell$$

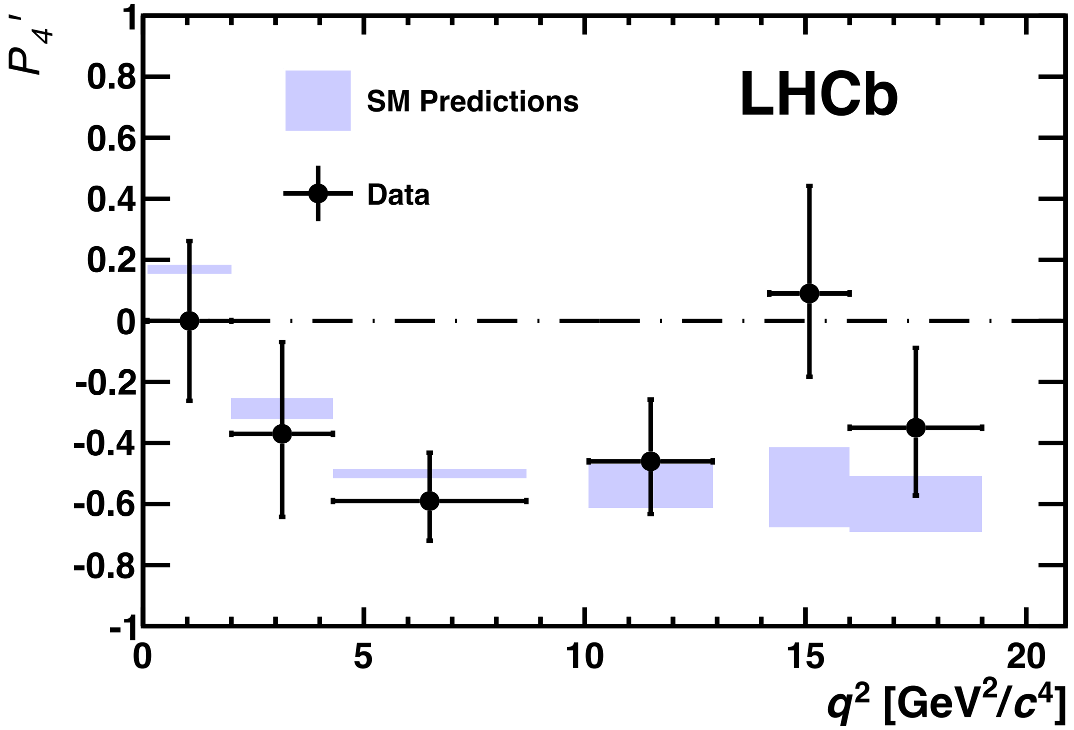
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi$$

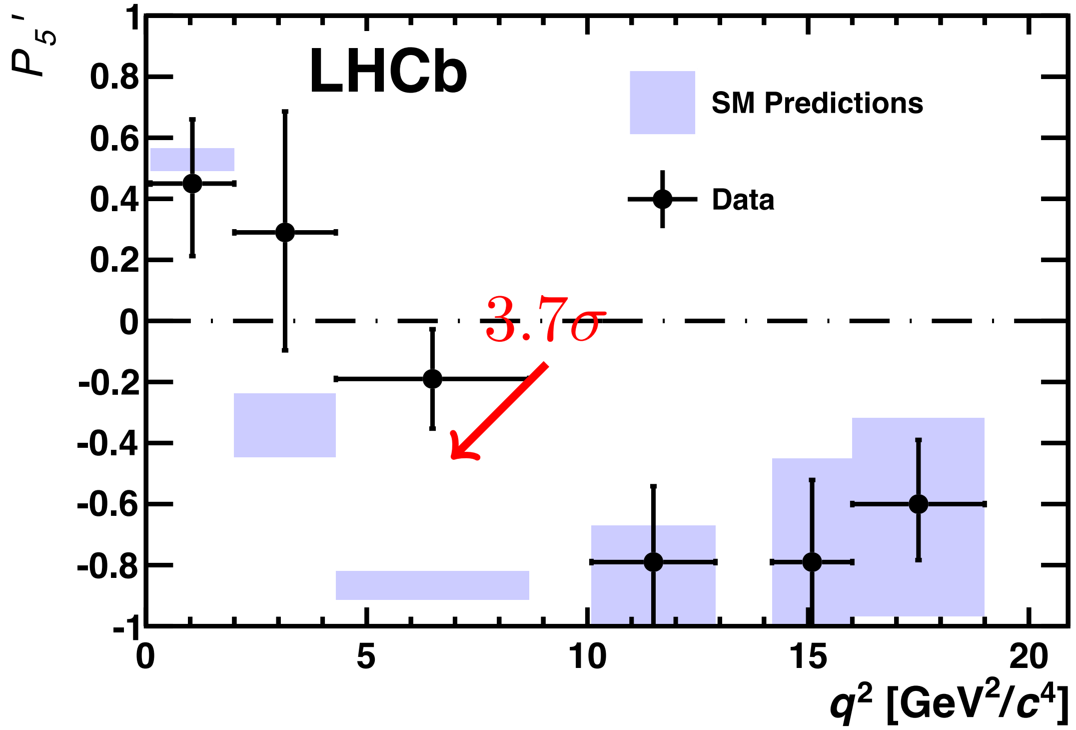
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi$$

$$+ \tfrac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi$$

$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Big]$$

P_5'





$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

[PRL 111, 191801 (2013)]

LFU

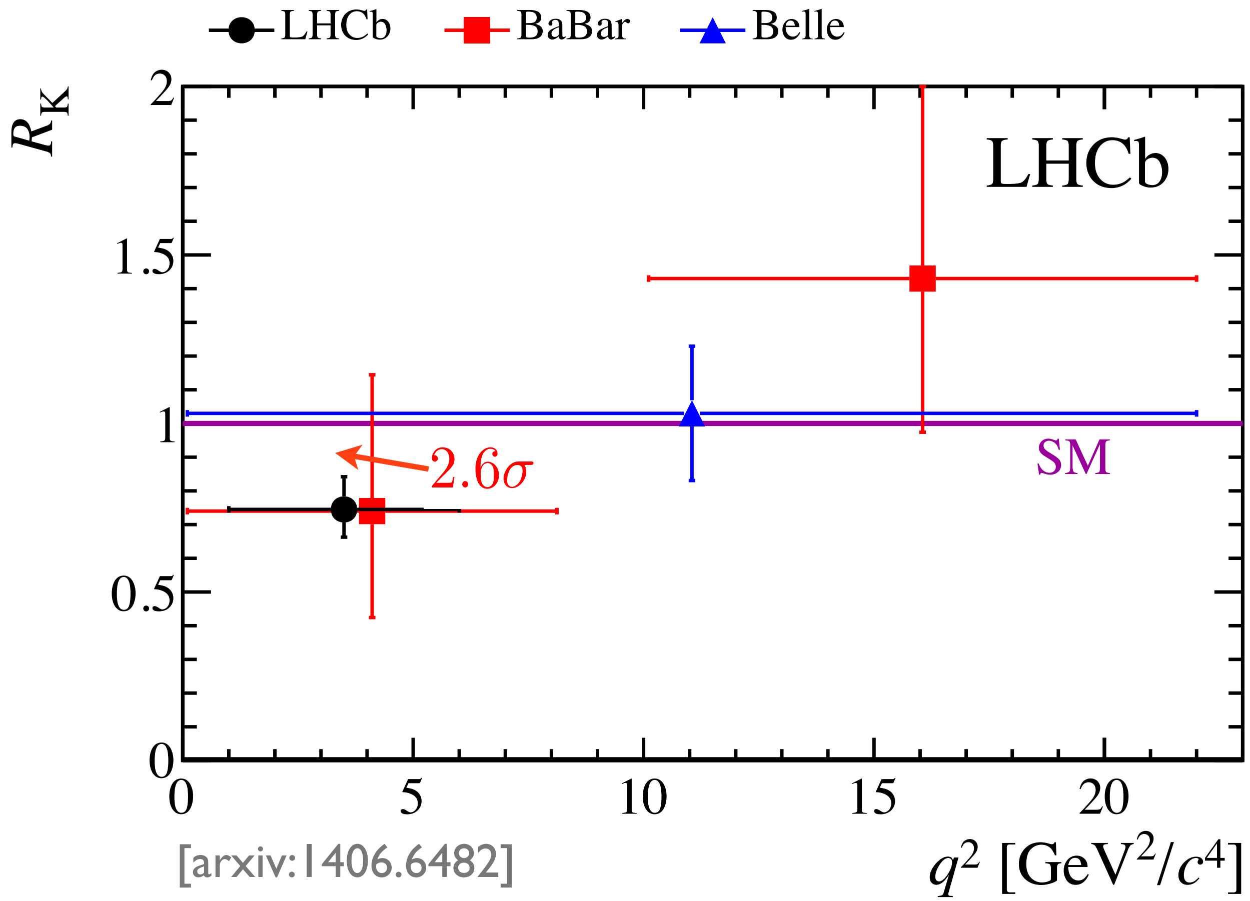
$$\mathcal{L}_{\Delta F=1} = y_{sd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} s_L + y_{cu}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{u}_L \not{Z} c_L + y_{bd}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{d}_L \not{Z} b_L + \boxed{y_{bs}\frac{v^2}{\Lambda_{NP}^2}\frac{g}{c_W}\bar{s}_L \not{Z} b_L}$$

$$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^- \qquad B^\pm \to K^\pm\mu^+\mu^-$$

- differential rate analysis
- lepton flavour universality tests

$\mathcal{R}_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in the SM

R_K



[arxiv:1406.6482]

NP in Flavour

Example: Supersymmetry

- SUSY models in general provide new sources of flavor violation
  - supersymmetry breaking soft mass terms for squarks and sleptons
  - trilinear couplings of a Higgs field with a squark-antisquark or slepton-antislepton pairs

$$\tilde{q}^*_{Mi}(M^2_{\tilde{q}})^{MN}_{ij}\tilde{q}_{Nj} = (\tilde{q}^*_{Li}\ \tilde{q}^*_{Rk})\begin{pmatrix} (M^2_{\tilde{q}})_{Lij} & A^q_{il}v_q \\ A^q_{jk}v_q & (M^2_{\tilde{q}})_{Rkl} \end{pmatrix}\begin{pmatrix} \tilde{q}_{Lj} \\ \tilde{q}_{Rl} \end{pmatrix}$$

SUSY in ΔF=2

MSSM contributions to neutral meson mixing

$$M_{12}^{D}=\frac{\alpha_s^2 m_D f_D^2 B_D \eta_{\rm QCD}}{108 m_{\tilde{u}}^2}[11\tilde{f}_6(x_u)+4x_u f_6(x_u)]\frac{(\Delta m_{\tilde{u}}^2)^2}{m_{\tilde{u}}^4}(K_{21}^{u}K_{11}^{u*})^2,$$

$$M_{12}^{K}=\frac{\alpha_s^2 m_K f_K^2 B_K \eta_{\rm QCD}}{108 m_{\tilde{d}}^2}[11\tilde{f}_6(x_d)+4x_d f_6(x_d)]\frac{(\Delta \tilde{m}_{\tilde{d}}^2)^2}{\tilde{m}_{d}^4}(K_{21}^{d*}K_{11}^{d})^2.$$

Experimental bounds on

$$(\delta_{ij}^q)_{MM}=\frac{\Delta\tilde{m}^2_{q_j q_i}}{\tilde{m}_q^2}(K_M^q)_{ij}(K_M^q)^*_{jj}\,,$$

for $m_{\tilde{q}}=1\ \mathrm{TeV}\,,\ \mathrm{x_i}=1$

q	ij	$(\delta_{ij}^q)_{MM}$
d	12	0.03
d	13	0.2
d	23	0.6
u	12	0.1

$$(\delta^q_{ij})_{MM} = \frac{\Delta\tilde{m}^2_{q_j q_i}}{\tilde{m}^2_q}(K^q_M)_{ij}(K^q_M)^*_{jj}\,,$$

Ways to avoid stringent exp. bounds on 1↔2 mixing

- Heaviness: $m_{\tilde{q}} \gg \mathrm{TeV}$
- Degeneracy: $\Delta m^2_{\tilde{q}} \ll m^2_{\tilde{q}}.$
- Alignment: $K^{d,u}_{21} \ll 1.$

Minimal Flavour Hypothesis

hep-ph/0207036

- flavour-violating interactions are linked to known Yukawa couplings also beyond SM

  (i) flavour symmetry: *SU*(3)^3

  (ii) set of symmetry-breaking terms:

$$Y_u \sim (3, \bar{3}, 1) \ , \qquad Y_d \sim (3, 1, \bar{3}) \ .$$

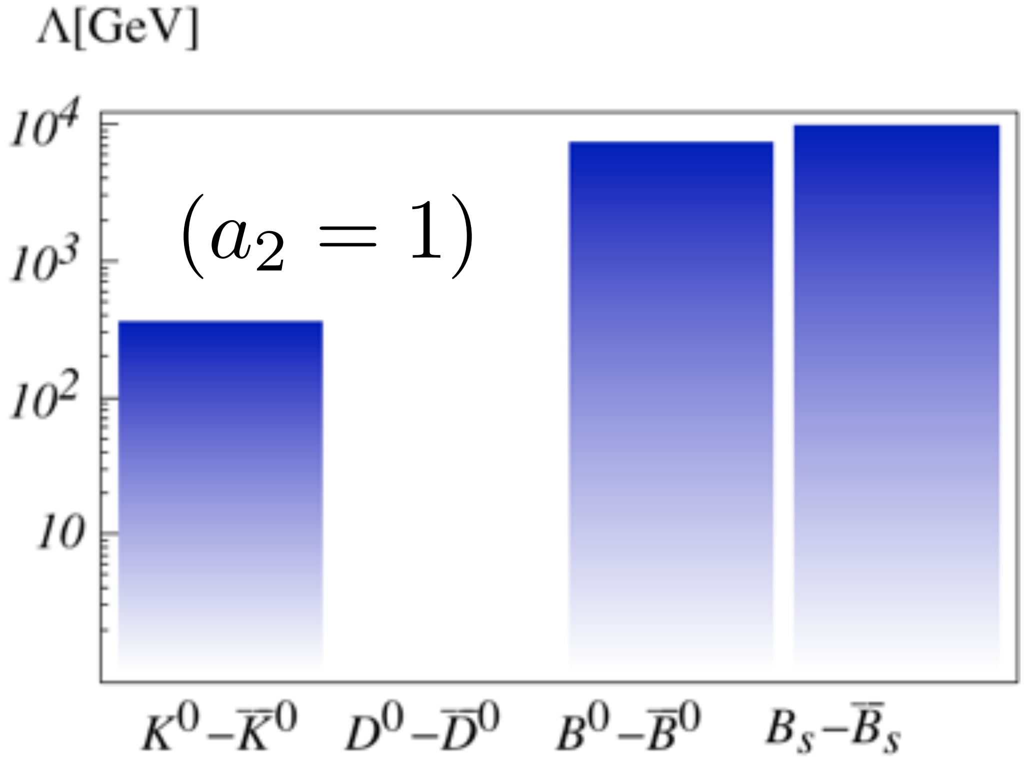
- tractable due to peculiar structure of SM flavour

$$\left[Y_u (Y_u)^\dagger \right]^n_{i \neq j} \ \approx \ y_t^n V_{it}^* V_{tj} \ .$$

MFV NP

leading ΔF = 2 and ΔF = 1 FCNC amplitudes

$$\begin{aligned}\mathcal{A}(d^i \to d^j)_{\rm MFV} &= (V_{ti}^* V_{tj})\ \mathcal{A}_{\rm SM}^{(\Delta F=1)} \left[1 + a_1 \frac{16\pi^2 M_W^2}{\Lambda^2}\right] , \\ \mathcal{A}(M_{ij} - \bar{M}_{ij})_{\rm MFV} &= (V_{ti}^* V_{tj})^2 \mathcal{A}_{\rm SM}^{(\Delta F=2)} \left[1 + a_2 \frac{16\pi^2 M_W^2}{\Lambda^2}\right] .\end{aligned}$$



MFV SUSY

squark masses

$$
\begin{aligned}
\tilde{m}^2_{Q_L} &= \tilde{m}^2 \left(a_1 1\!\!1 + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger + b_3 Y_d Y_d^\dagger Y_u Y_u^\dagger + \ldots \right) \,, \\
\tilde{m}^2_{U_R} &= \tilde{m}^2 \left(a_2 1\!\!1 + b_5 Y_u^\dagger Y_u + \ldots \right) \,, \\
A_U &= A \left(a_3 1\!\!1 + b_6 Y_d Y_d^\dagger + \ldots \right) Y_d \,, \\
&\ldots
\end{aligned}
$$

combination of degeneracy & alignment

Conclusions

LHC14 will be exciting (tuning ~ E^2).

Could also deepen or elucidate flavour puzzle.

Keep an eye on some recent anomalies both at high pT and in flavour.

Let’s be prepared and leave no stone unturned.