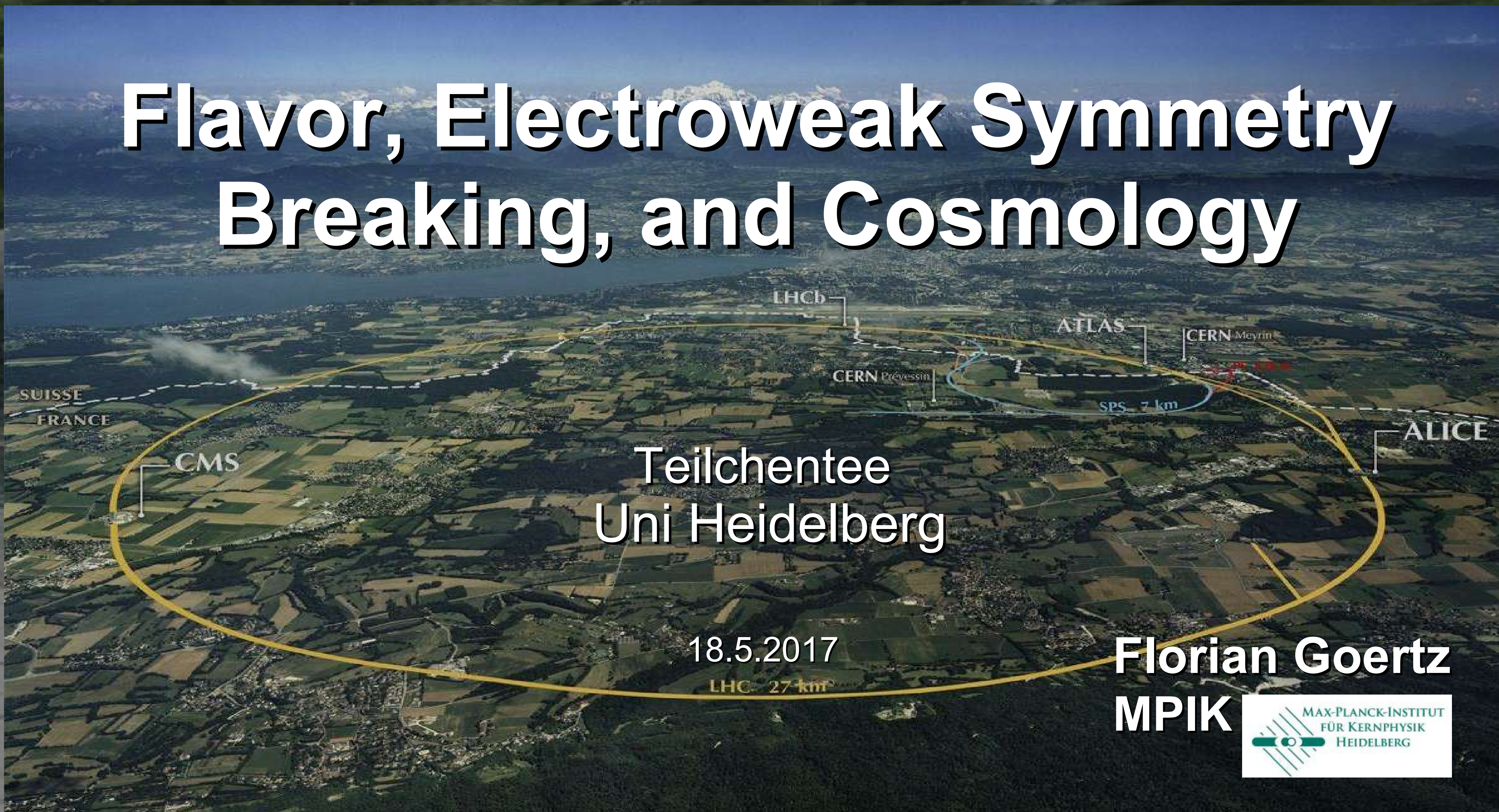
Flavor, Electroweak Symmetry Breaking, and Cosmology



Teilchentee
Uni Heidelberg

18.5.2017

Florian Goertz
MPIK
Max-Planck-Institut für Kernphysik Heidelberg

Introduction

The Standard Model of Particle Physics

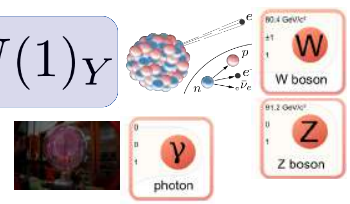
– Renormalizable QFT –

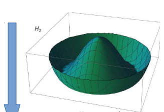
Various Nobel Prizes

Glashow, Weinberg, Salam '79
Rubbia, van der Meer '84
't Hooft, Veltman '99
Gross, Politzer, Wilczek '04
Nambú, Kobayashi, Maskawa'08
Englert, Higgs '13, ...

Local 'Gauge' Symmetries → Forces

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





ground state

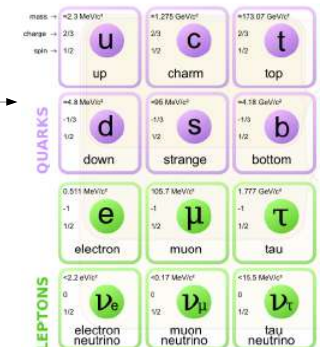
$SU(3)_c \times U(1)_{EM}$

Higgs Boson h

Brout, Englert, Higgs, Guralnik, Hagen, Kibble,...

Matter Content

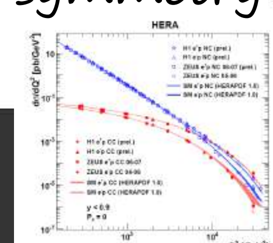
massive

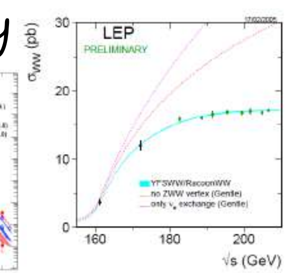


3 different flavors

- Tested extremely well up to weak scale $M_w \sim 100\,\mathrm{GeV}$ (currently going beyond: )

- Many non-trivial predictions from (hidden) gauge symmetry
- Renormalizable: $\mathcal{O}_{SM} \subset \mathcal{L}_{\mathrm{SM}} \rightarrow d[\mathcal{O}_{SM}] \leq 4$



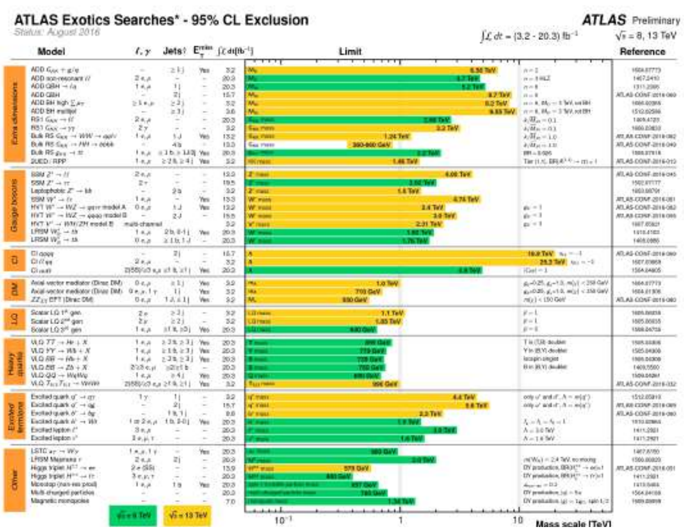


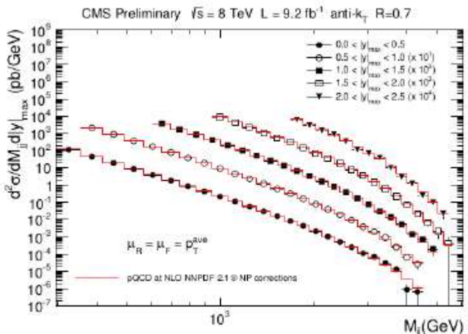
Introduction

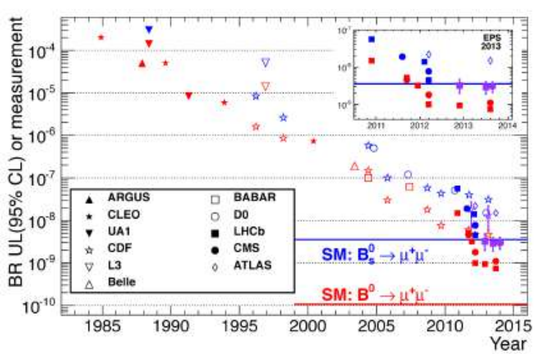
The Standard Model of Particle Physics

- A Success Story -

New Physics should be rather heavy (or very weakly coupled to the SM)

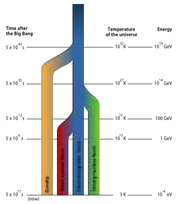




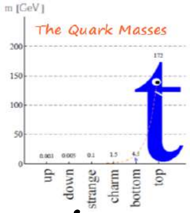


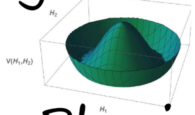
Physics Beyond the SM

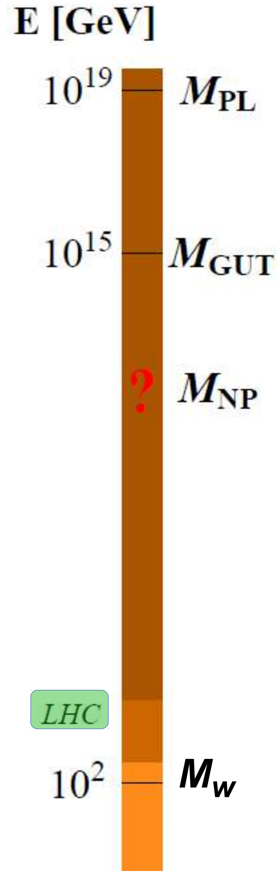
However: SM explains by far not everything!



- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h \ll M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- Some Hints in Flavor/Precision Physics
- ...

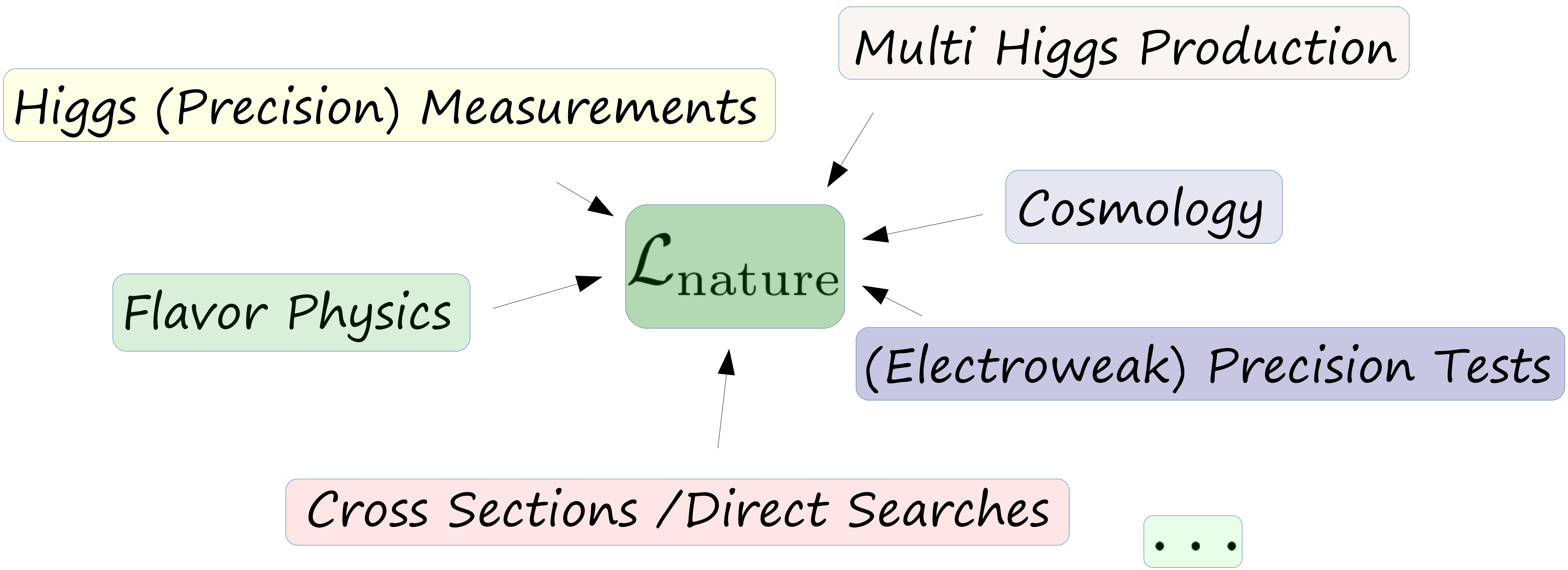






→ Extension of SM at short distances → How could extension look like? / How to probe SM/NP? → $\mathcal{L}_{\text{nature}}$

Combined Effort



- Interconnected Questions, Interconnected Fields → Synergies
  e.g.: Higgs-Matter couplings ↔ Flavor Physics, Higgs Potential/hh Prod., Vacuum Stability,...

Combined Effort

Multi Higgs Production

Higgs (Precision) Measurements

Cosmology

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

Flavor Physics

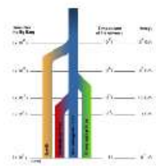
(Electroweak) Precision Tests

Cross Sections /Direct Searches

. . .

- Interconnected Questions, Interconnected Fields → Synergies
  e.g.: Higgs–Matter couplings ↔ Flavor Physics, Higgs Potential/hh Prod., Vacuum Stability,...

Physics Beyond the SM



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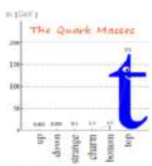

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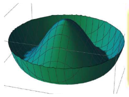
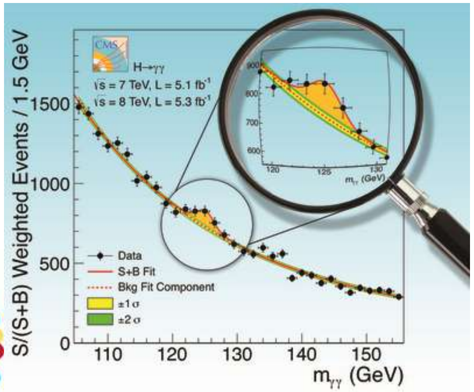
Many links to Higgs Sector



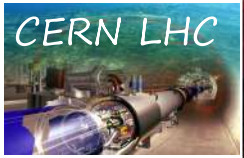
still least understood...

Use the Higgs Sector as a unique window to NP!

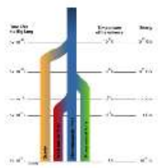
One of the biggest discoveries of mankind



BREAKTHROUGH OF THE YEAR



Physics Beyond the SM



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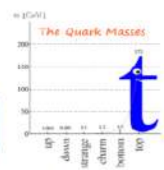

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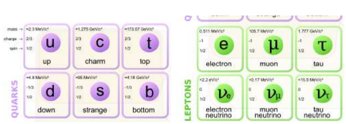
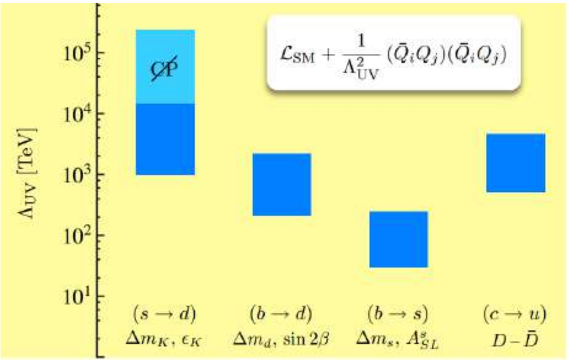
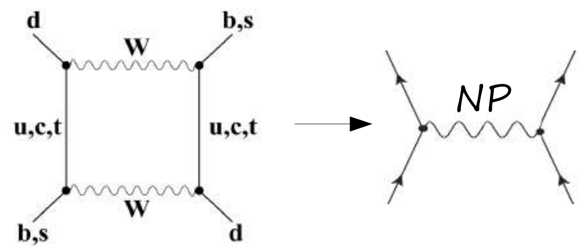
And to Flavor!!



Flavor Physics allows to test enormous mass scales …



Neubert, EPS 2011



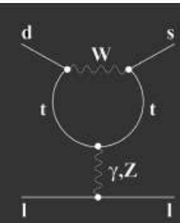
$\sim \frac{g_*^2}{M_{NP}^2}$

suppressed in SM → large sensitivity to NP

$g_* \sim 1; \boxed{M_{NP} \gg v}$

… or very small NP couplings

→ ΔF=1 decays $\boxed{g_* \ll 1}; M_{NP} \ll v$



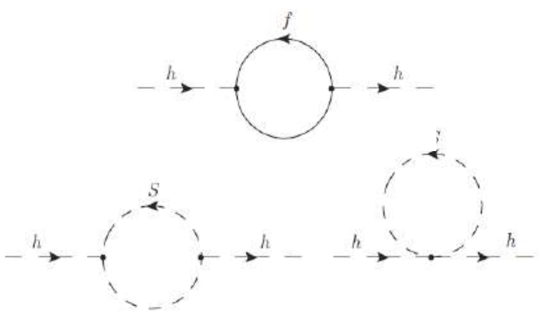
The Hierarchy Problem

$$\mathcal{L} \supset \boxed{m_H^2} |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2}$$

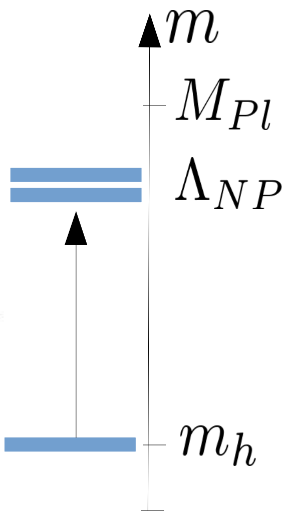
$\Lambda^2 \gg m_H^2 \quad (??)$

$\mathrm{m}_H \sim 100\,\mathrm{GeV}$

$m_H \ll \Lambda \sim M_{Pl,GUT}$ → Hierarchy Problem



$\rightarrow \Delta m_h^2 \sim \Lambda_{NP}^2$



Expect coefficient of unprotected D=2 operator H^2 to reside at cutoff: $m_H^2 \sim \Lambda^2 \gg 100\,\mathrm{GeV}$

$\Lambda^2 \sim M_{GUT}^2 \rightarrow$ Fine tuning 1 in 10^{26}

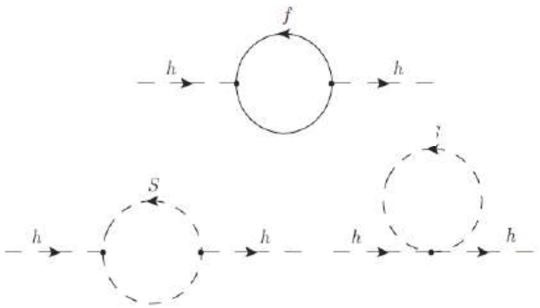
Allowed from laws of nature...
... though puzzling

The Hierarchy Problem

$$\mathcal{L} \supset \boxed{m_H^2} |H|^2 + \frac{\mathcal{O}^{(6)}}{\Lambda^2}$$

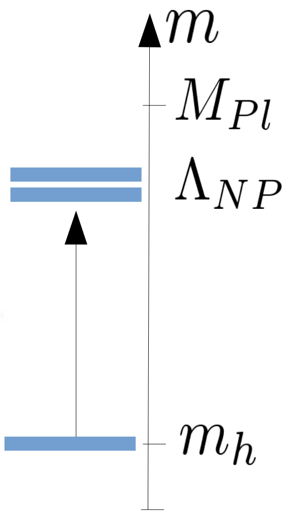
$\Lambda^2 \gg m_H^2 \quad (??)$

$\mathrm{m}_H \sim 100\,\mathrm{GeV}$



$m_H \ll \Lambda \sim M_{Pl,GUT}$ → Hierarchy Problem

$\rightarrow \Delta m_h^2 \sim \Lambda_{NP}^2$



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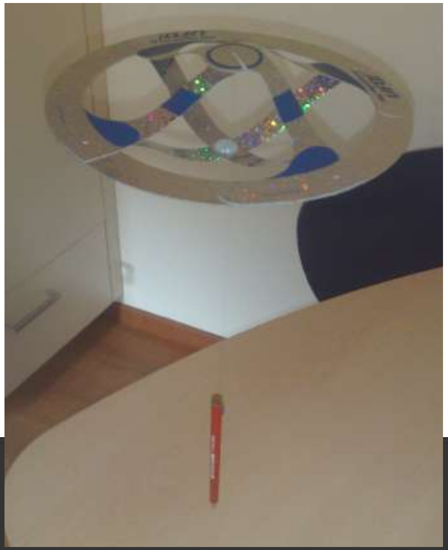
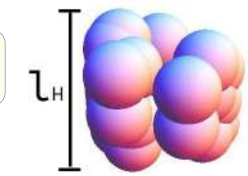


An Explicit Solution: Composite Higgs

Kaplan, Georgi, Dimopoulos,. . .

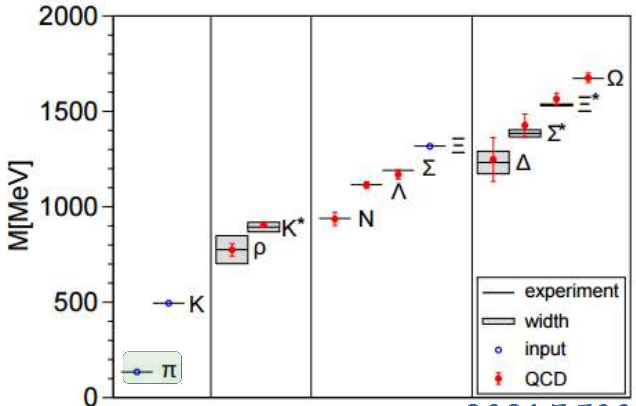
- Higgs is composite at small distances

  ➡ m_H saturated in IR ➡ Hierarchy Problem solved

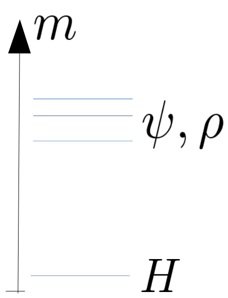


- Higgs = (pseudo) Goldstone Boson ➡ $m_H << m_\rho$

  like pions in QCD



0906.3599



- Minimal models: SO(5)→SO(4) Contino, Nomura, Pomarol, ph/0306259 Agashe, Contino, Pomarol, ph/0412089

→ 4 Goldstone dof, custodial symmetry

Naturally address

- Hierarchical Flavor Structure
- Dynamical EWSB
- Tiny Neutrino Masses

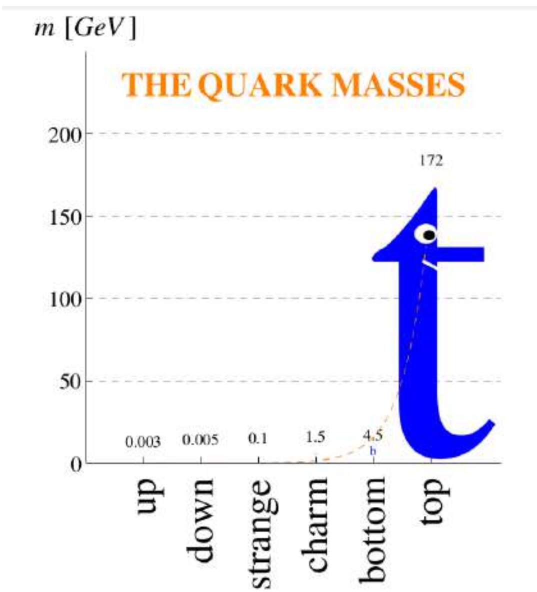
- Dark Matter
- Baryogenesis ...

Probe nature of Higgs → Learn about such models

EWSB $\leftrightarrow$ Flavor

The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.23$$

NuFIT 3.0 (2016)

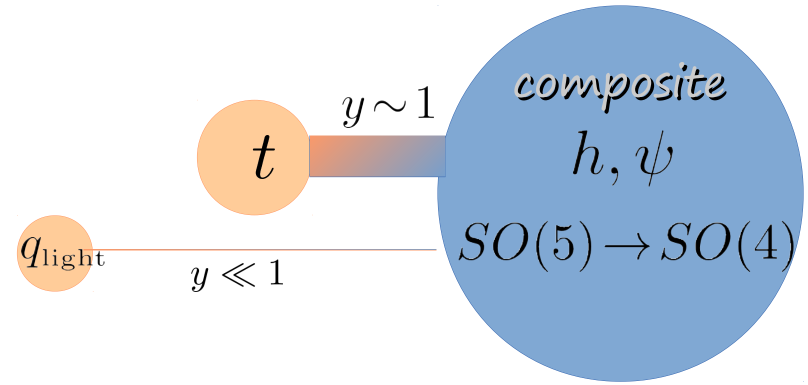
$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Model of Flavor: Partial Compositeness

- Addresses the flavor puzzle:

$$y^q_{L,R} \leftrightarrow D[\mathcal{O}^q_{L,R}],\ \langle 0|\mathcal{O}^q_{L,R}|\Psi^{Q,q}\rangle \neq 0$$

→ Hierarchies generated naturally

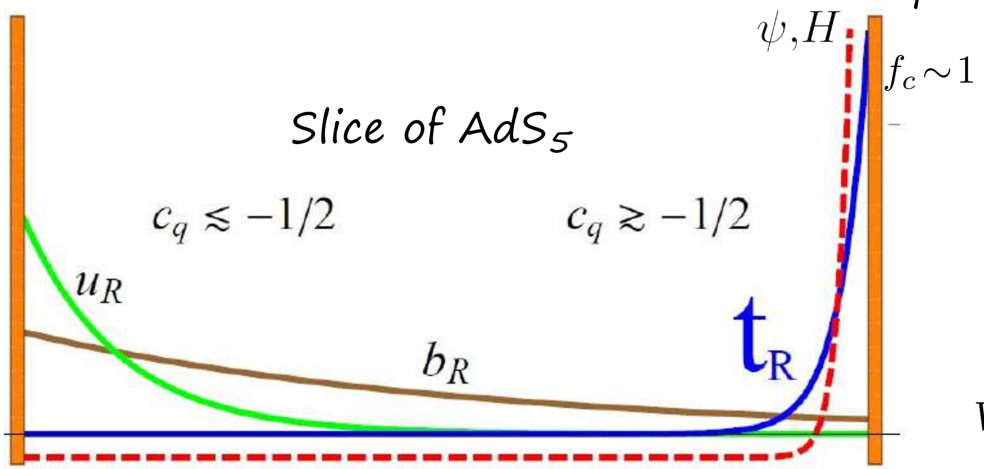


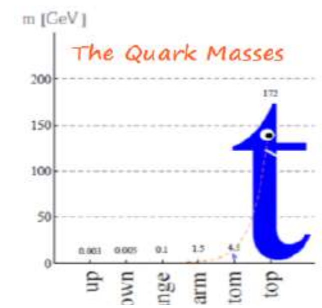
- FCNC protection via GIM-like mechanism

Dual picture:
Extra Dimension

TeV brane:
Composites (Higgs,...)

Planck brane:
elementary
sector



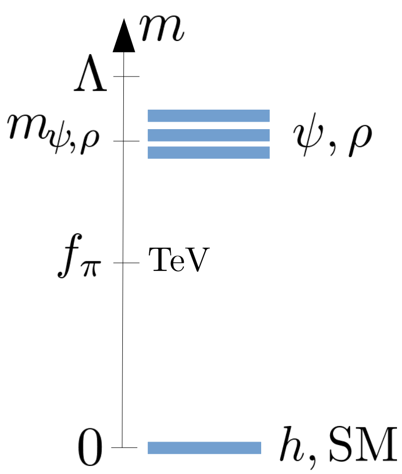


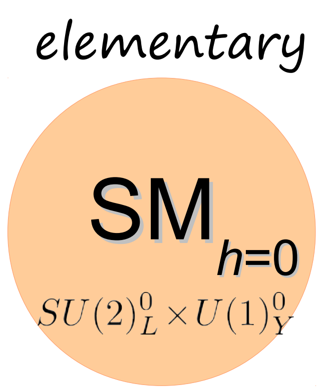
$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

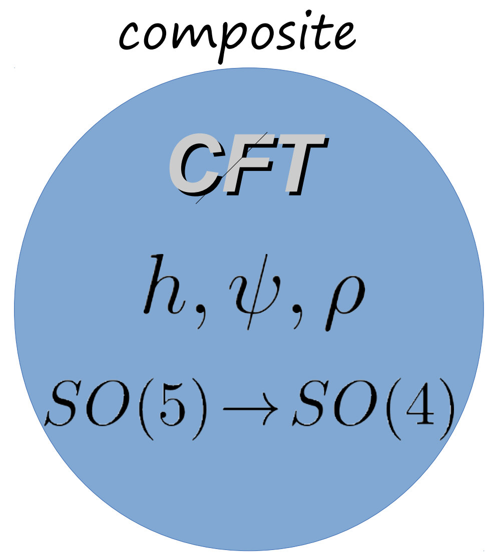
Mass matrices follow Froggatt-Nielsen-like
structure → see later

Dynamical EWSB

- Higgs boson = Goldstone of $SO(5) \to SO(4)$
  → massless w/o explicit SO(5) breaking
- Couplings to SM break SO(5) → 1-loop Coleman-Weinberg Potential







$$\Sigma = e^{i\frac{\sqrt{2}}{f_\pi} h_{\hat{a}} T^{\hat{a}}} \Sigma_0$$

$$\Sigma_0 = (0,0,0,0,f_\pi)^T$$

$$T^{\hat{a}} : SO(5)/SO(4)$$

$$V(h) \propto 0$$

Higgs potential ↔ Flavor

Dynamical EWSB

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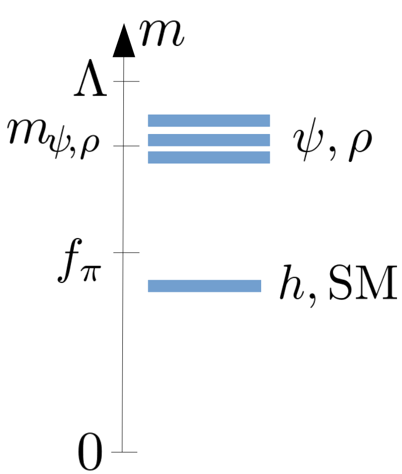
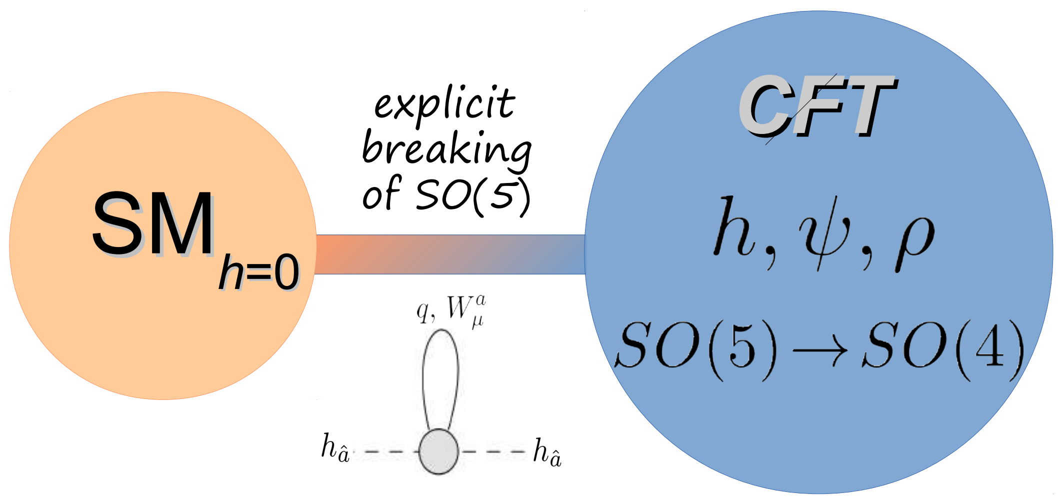




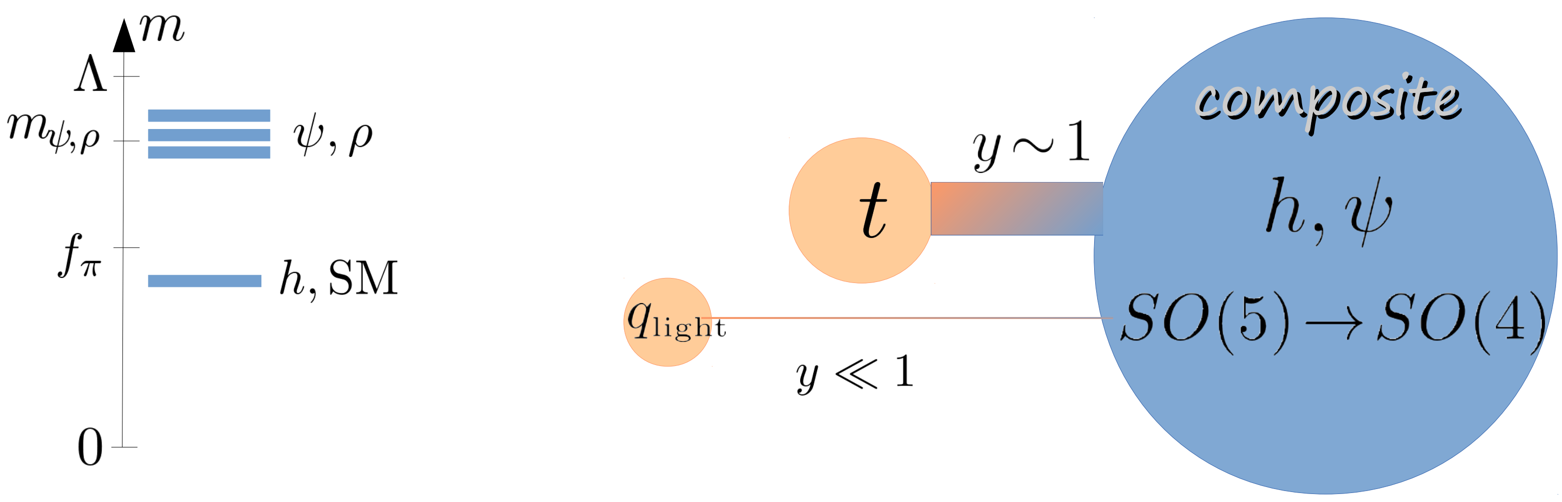
$$\longrightarrow V(h) \approx \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi) \cos^2(h/f_\pi)$$

Higgs potential ↔ Flavor

Dynamical EWSB

- Higgs boson = Goldstone of $SO(5) \to SO(4)$
  $\to$ massless w/o explicit SO(5) breaking

- Couplings to SM break SO(5) $\to$ *1-loop Coleman-Weinberg Potential*



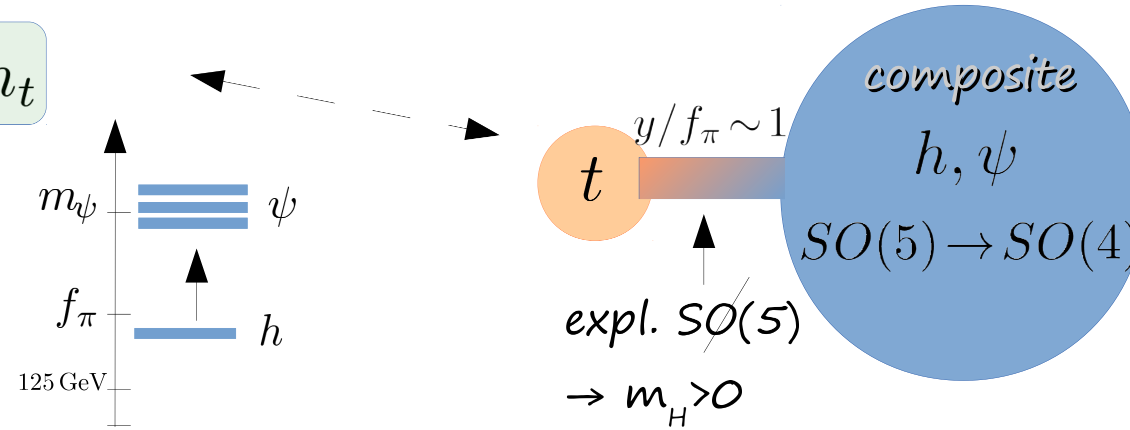
- *Most important SO(5) breaking: top quark*

Higgs potential $\leftrightarrow$ Flavor

Light Top Partners in CH

- Large top yukawa → large m_h

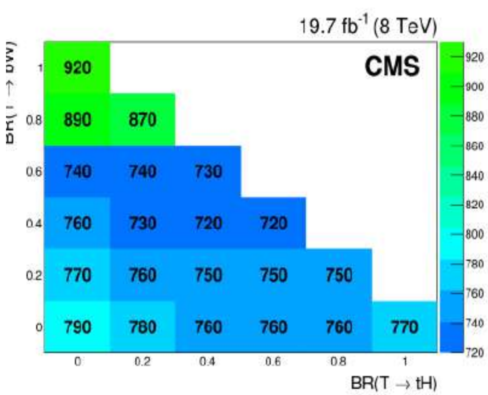
$$\boxed{m_H} \sim y_t^2\, v \sim \boxed{m_{2/3}^{\min}/f_\pi\; m_t}$$

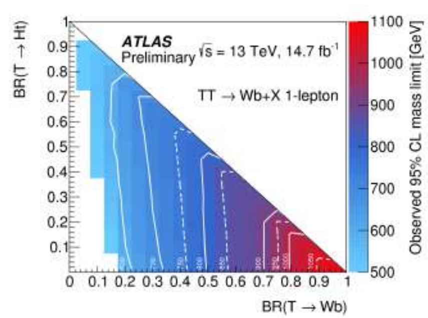


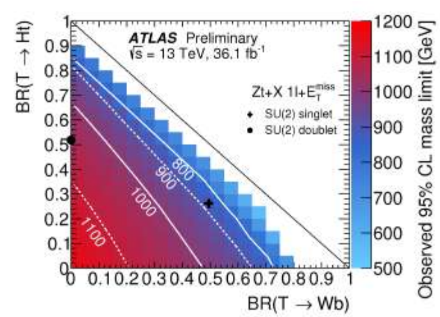
=> <u>light top partners</u>:

$$\boxed{m_{2/3}^{\min} << f_\pi} \sim \boxed{\text{TeV}}$$

LHC Searches







Matsedonskyi, Panico, Wulzer, 1204.6333;
Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954;
De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434

(Too) Light Top Partners in CH

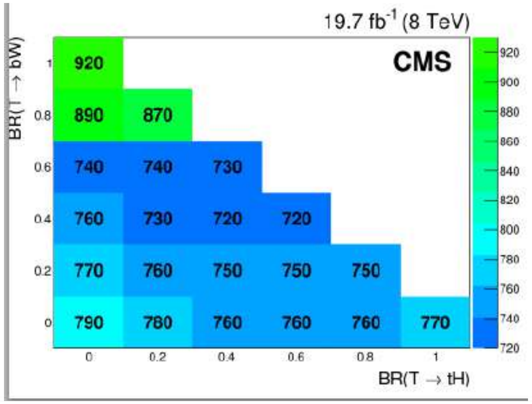
- Large top yukawa → large m_h

$$\boxed{m_H} \sim y_t^2\, v \sim \boxed{m_{2/3}^{\min}/f_\pi\; m_t}$$

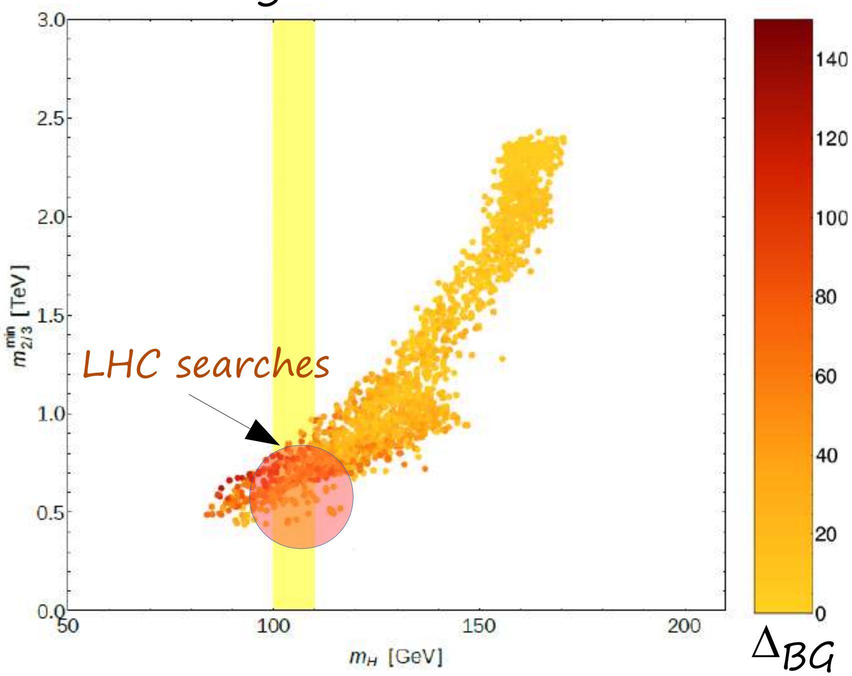
=> light top partners:

$$\boxed{m_{2/3}^{min} << f_\pi} \sim \boxed{\text{TeV}}$$

LHC Searches



MCHM$_5$



Carmona, FG, JHEP (1410.8555)

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Light Top Partners

Interesting new class of solutions:

- New minimal models of the lepton sector, unifying RH leptons in single SO(5) rep.

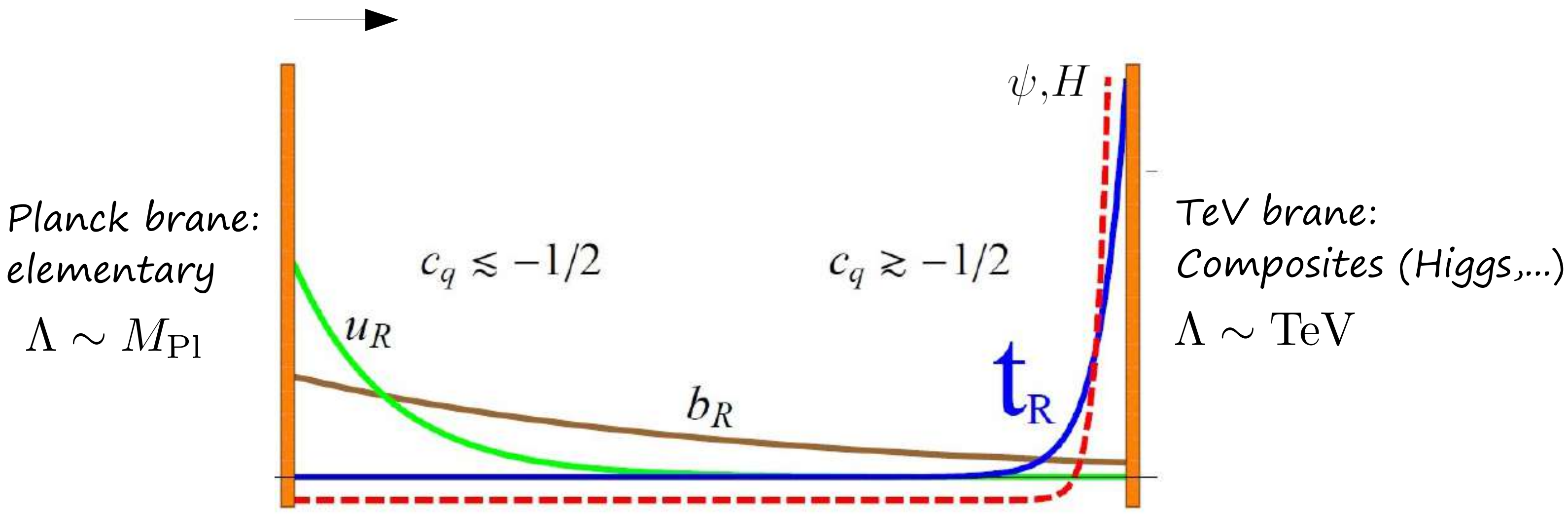
$$\xi_{2\tau} = \tau_2'[-,-] \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix} \oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$ Type-III seesaw

Carmona, FG, JHEP (1410.8555)

Light Top Partners

Interesting new class of solutions:

- New minimal models of the lepton sector, unifying RH leptons in single SO(5) rep.
- $M_{\rm GUT} \ll M_{\rm PL}$ ➡ compositeness of seesaw fields ➡ compos. of charged leptons → V_H



Light Top Partners

Interesting new class of solutions:

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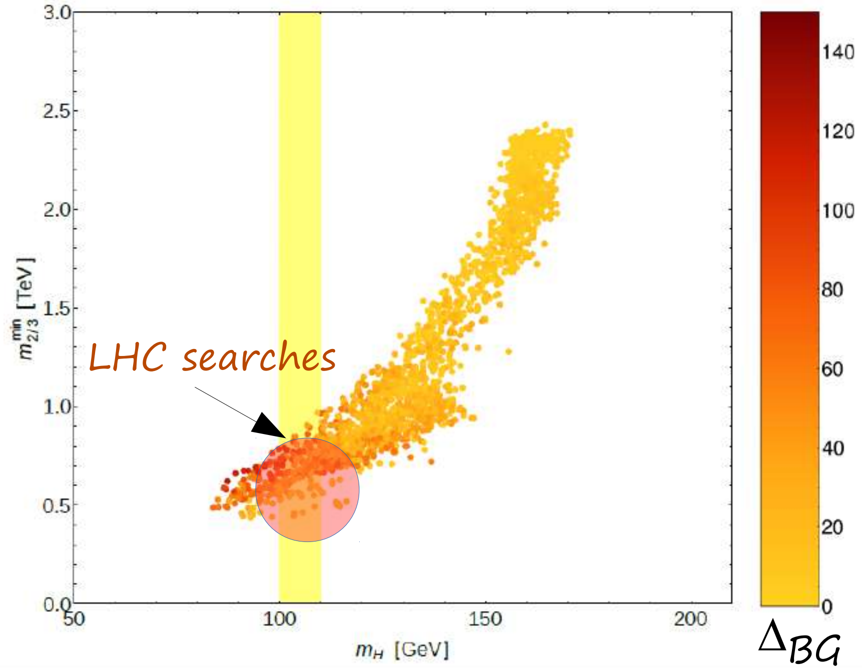
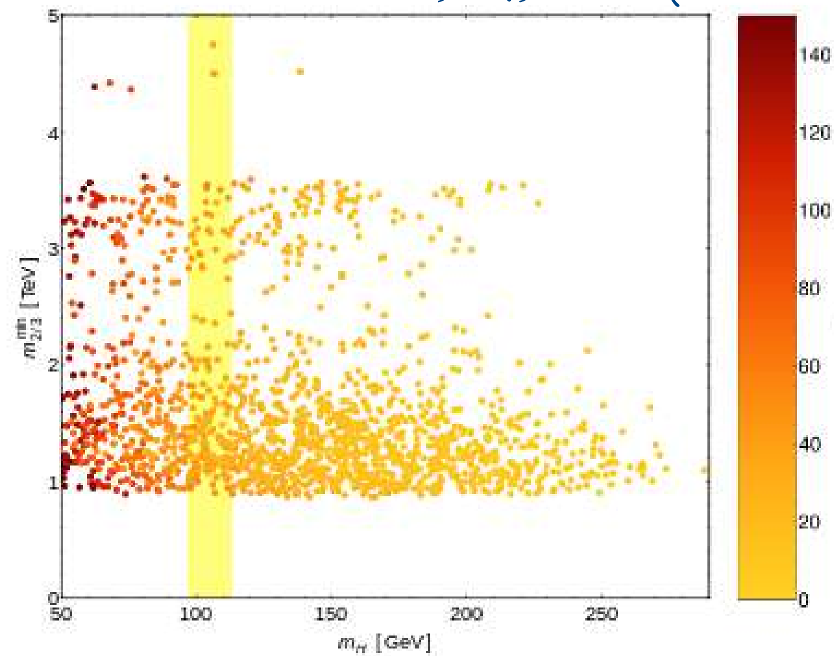
➡ top-partners lifted

MCHM$_5$



Carmona, FG, JHEP (1410.8555)

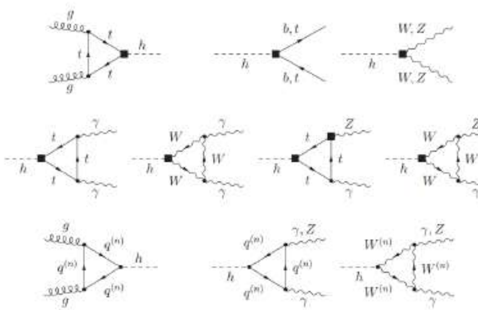


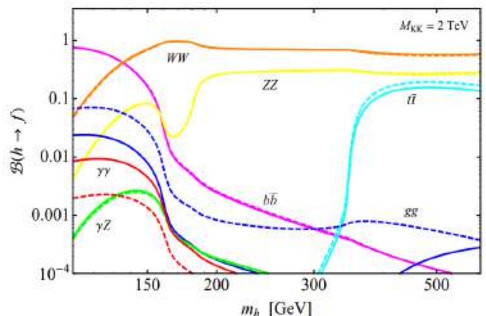
Higgs potential ↔ neutrino physics (see saw)

$f_\pi = 800\,\mathrm{GeV}$

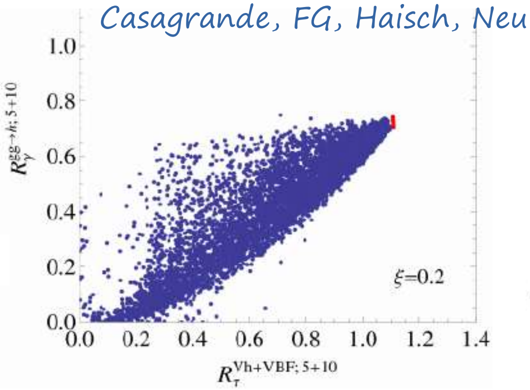
Indirect Signatures of Compositeness

Higgs Rates

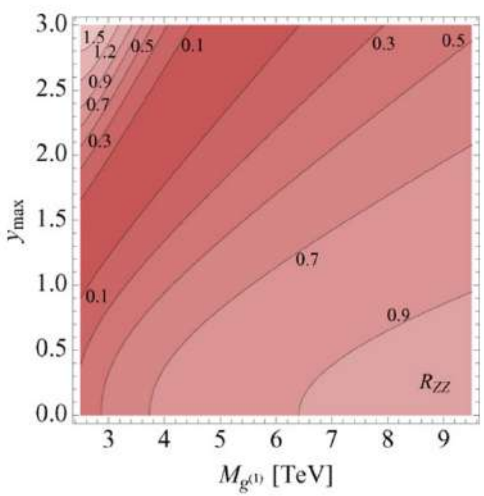




Casagrande, FG, Haisch, Neubert, Pfoh, JHEP (1005.4315), ...

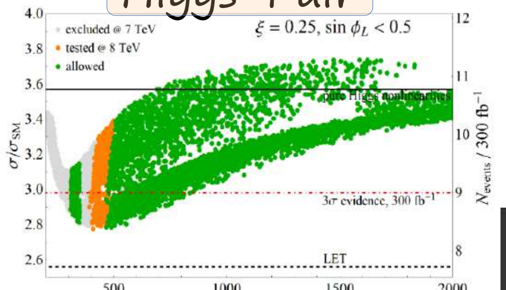


Carmona, FG, JHEP (1301.5856)



FG, Haisch, Neubert, PLB (1112.5099)
Carena, Casagrande, FG, Haisch, Neubert, JHEP (1204.0008)

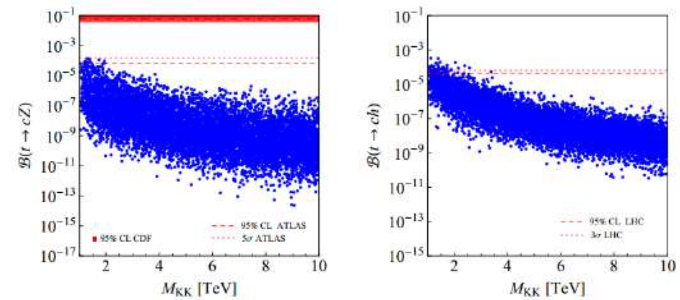
Higgs-Pair



$$R_f = \frac{[\sigma(pp \to h) Br(h \to f)]_{NP}}{[\sigma(pp \to h) Br(h \to f)]_{SM}}$$

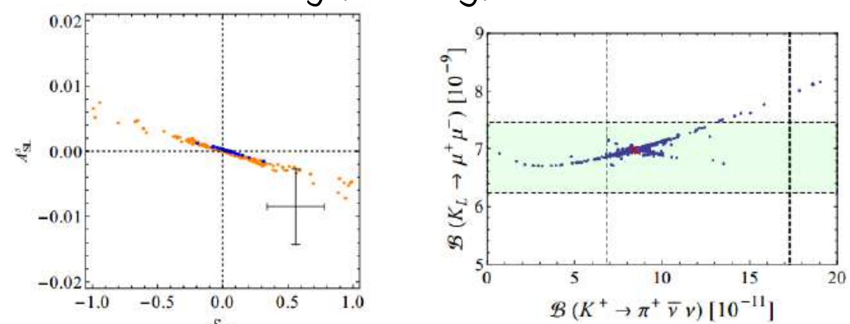
Gillioz, et al 1206.7120 Contino, et al 1205.5444

Flavor Physics



Casagrande, FG, Haisch, Neubert, Pfoh, JHEP (0807.4937), JHEP (1005.4315), ...

K and B Decays, Mixing, Correlations...



FG, Pfoh, PRD (1105.1507)
Agashe, Bauer, FG, Lee, Vecchi, Wang, Yu (1310.1070)

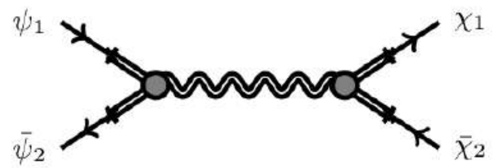
Reach beyond the TeV scale!

+ Azatov, et al, 1006.5939; Carena, et al, JHEP (1402.2987), Blanke, et al, JHEP (0809.1073) Blanke, et al, JHEP (0812.3803), Bauer, et al, JHEP (0912.1625), Csaki, et al, 0804.1954, ...

Interesting Predictions in Flavor Physics

- Very interesting predictions due to different compositeness of RH charged-leptons → Lepton-Flavor Universality violation

Carmona, FG, PRL (1510.07658)
Carmona, FG, 1610.05766



- In particular noteworthy given the LHCb result

$$R_K = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to K e^+ e^-)}\right|^{\exp}_{q^2\in[1,6]\,\mathrm{GeV}}$$

$$= 0.745^{+0.090}_{-0.074} \pm 0.036 < 1$$

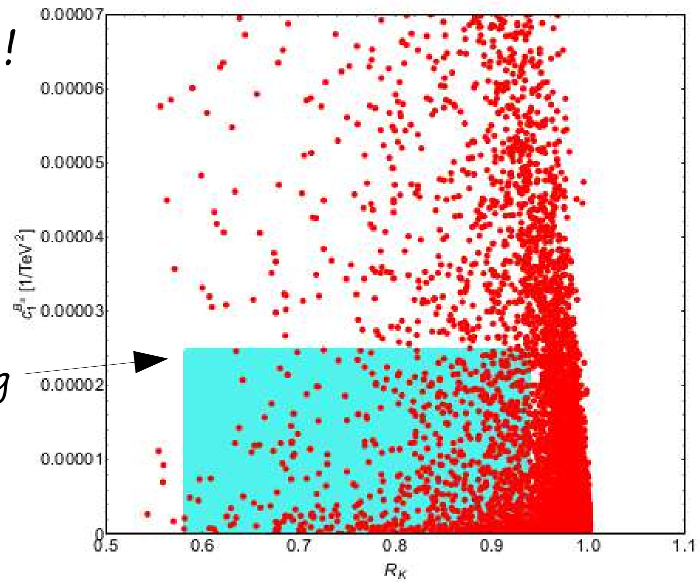
$$\mathcal{O}_{qe}^{32\ell\ell} = (q_L^2\gamma_\mu q_L^3)(\ell_R\gamma^\mu\ell_R)$$

$$\mathcal{O}_{qe}^{32\ell\ell} = (q_R^2\gamma_\mu q_R^3)(\ell_R\gamma^\mu\ell_R)$$

$$\to \mathcal{O}_9 + \mathcal{O}_{10};\ \mathcal{O}_9' + \mathcal{O}_{10}'$$

- Model predicts R_K<1!

- 2σ constraint from B_s-mixing
- Points in agreement with constraints from B_s->μμ and on 4e operators



Higgs potential ↔ Flavor Physics

$f_\pi = 1.2\,\mathrm{TeV}$

Interesting Predictions in Flavor Physics

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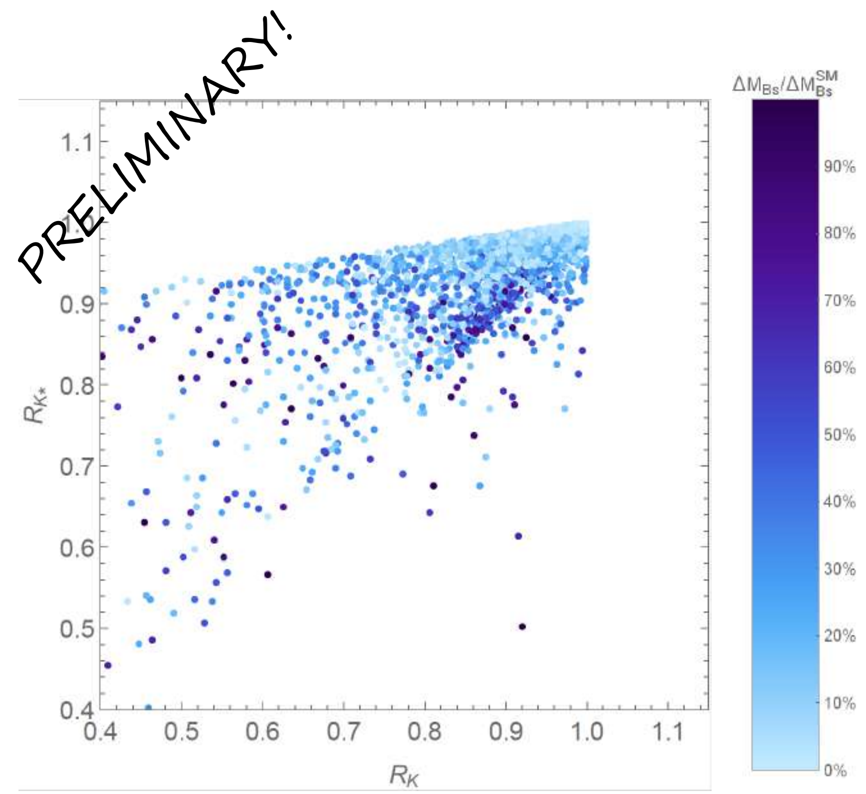
Carmona, FG, 1610.05766

- New LHCb result:

$$R_{K^*} = \left.\frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}\right|^{\text{exp}}_{q^2 \in [1.1,6]\text{GeV}}$$

$$= 0.685^{+0.113}_{-0.069} \pm 0.047$$



Carmona, FG, in preparation

Higgs potential ↔ Flavor Physics

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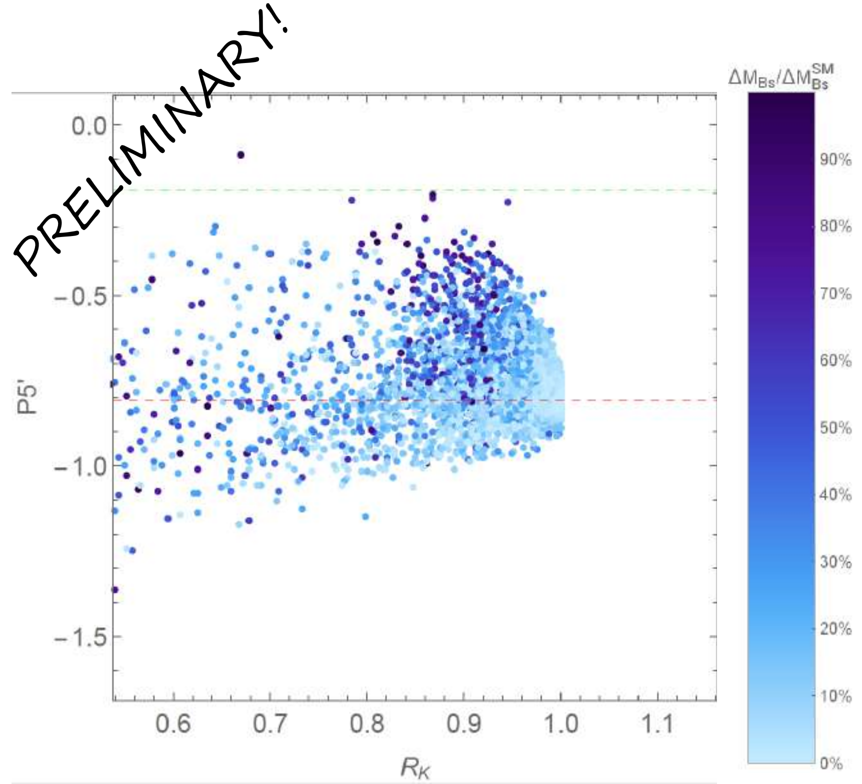
Flavor as a first window on the composite Higgs... ?

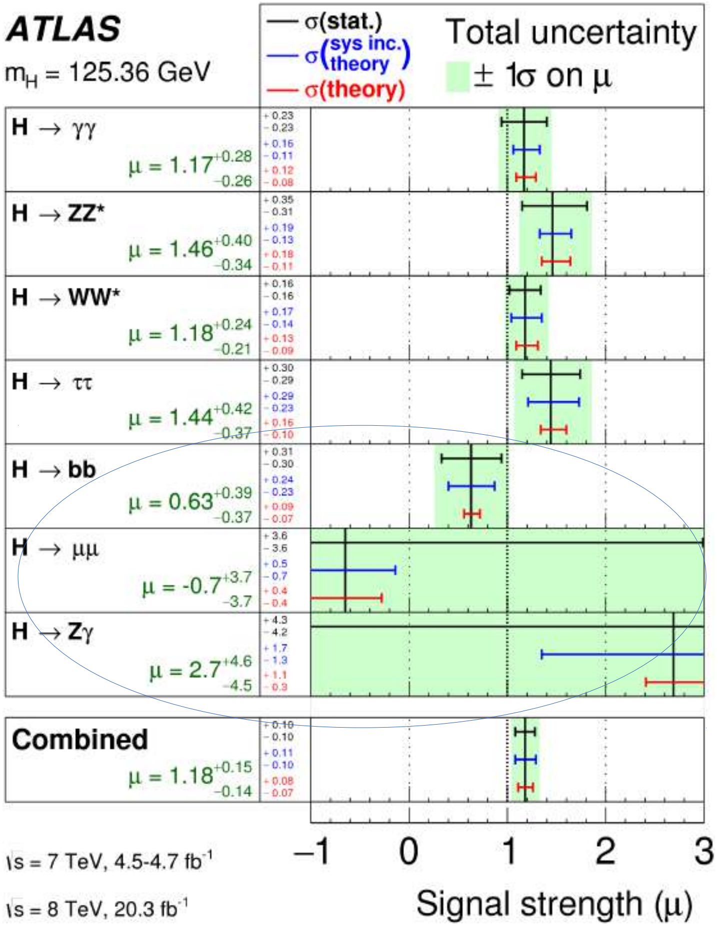


Carmona, FG, in preparation

In general: Higgs ↔ Flavor

... still much to learn about H!

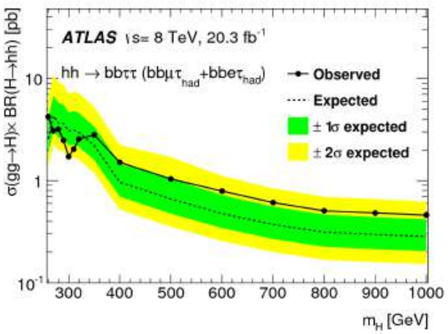
bunch of challenging, though important, measurements:



hh production → V(H)

σ(gg→hh)<700fb → 70X SM

ATLAS 1509.04670, 1606.04782, CMS-PAS-HIG-16-026,24,32,-15-013



Yukawa couplings (↔ Dynamical EWSB?)

→ fermion-mass generation (1^{st}+2^{nd} generation?)

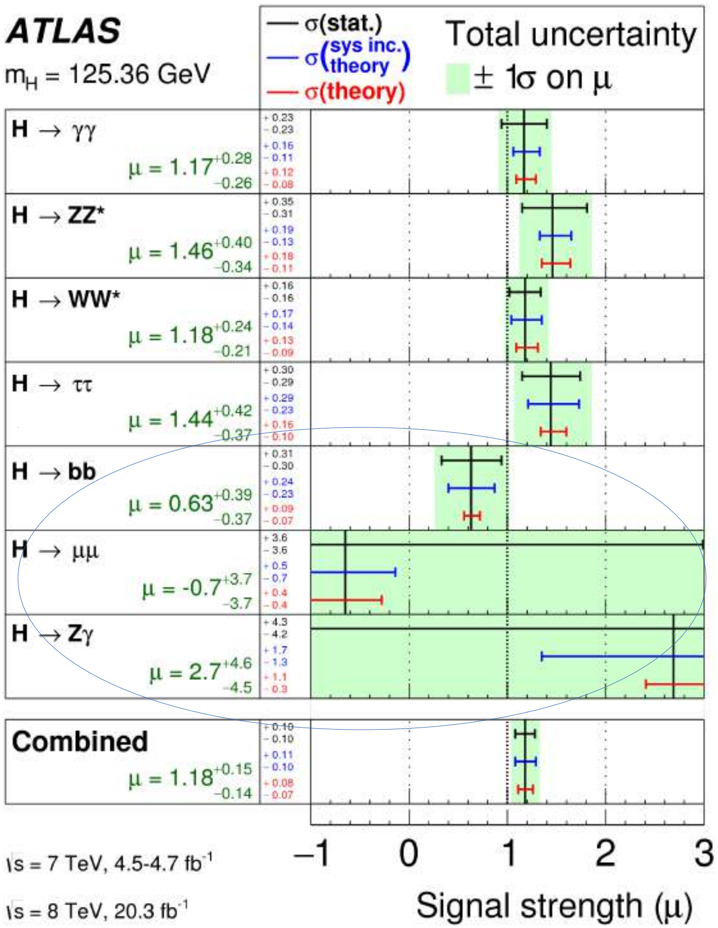
H→Zγ : New Physics hiding in the loop?

Interesting probes of many NP scenarios (SUSY, composite,...)

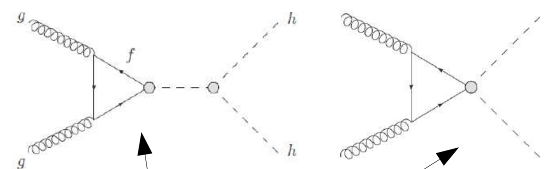
Higgs ↔ Flavor

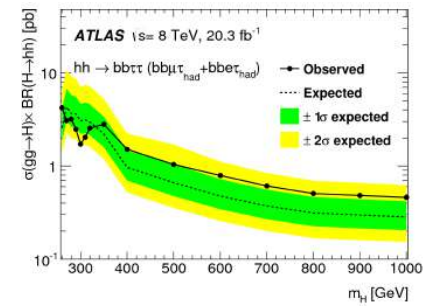
… still much to learn about H!

Connections with flavor are ubiquitous



hh production → V(H)





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Higgs ↔ Flavor

… still much to learn about H!

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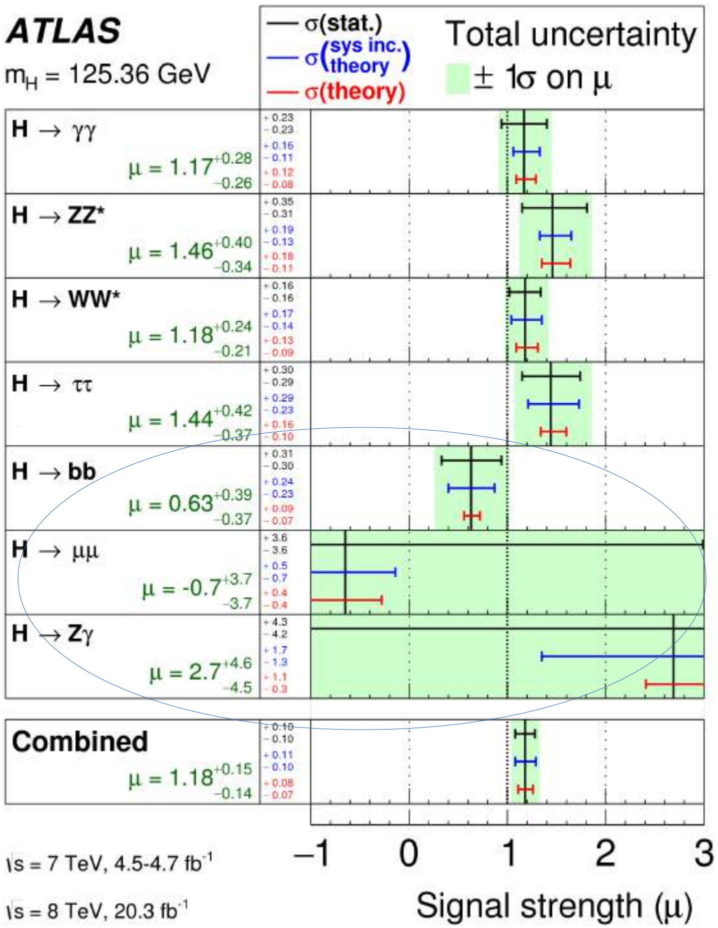
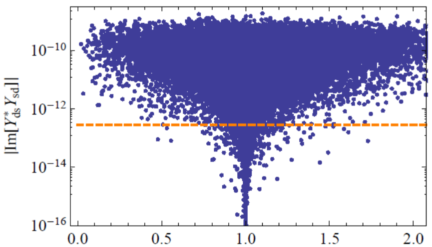


Yukawa couplings (↔ Dynamical EWSB?)

→ fermion-mass generation (1^{st}+2^{nd} generation?)

Large changes in y ↔ FCNCs



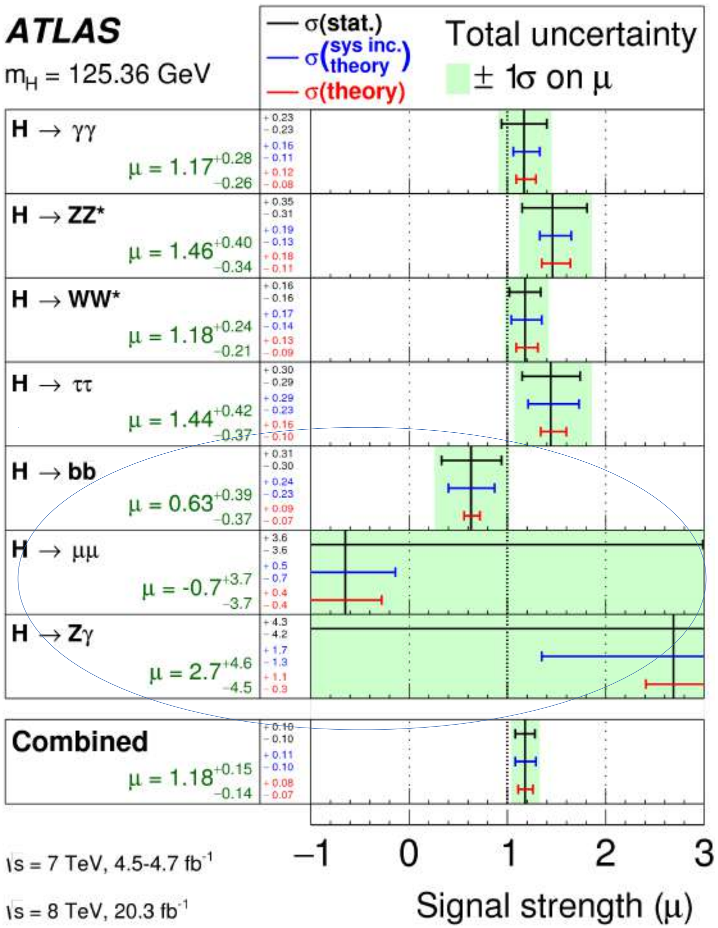
$0.4 \lesssim |Y_d/Y_d^{SM}| \lesssim 1.7$

FG, PRL (1406.0102)

Higgs ↔ Flavor

... still much to learn about H!

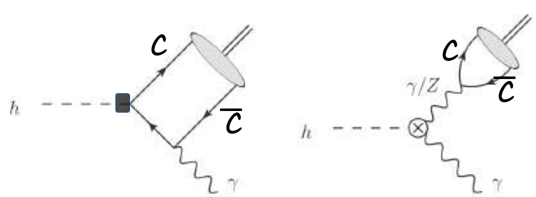
Connections with flavor are ubiquitous

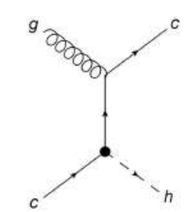


Yukawa couplings (↔ Dynamical EWSB?)

→ fermion-mass generation (1^{st}+2^{nd} generation?)

So far no direct evidence for second generation yukawas; next frontier: y_c





$h \to MV \quad (+h \to c\bar{c})$

$pp \to hc$

Bodwin, et al, 1306.5770, Kagan et al, 1406.1722, Grossman, et al, 1501.06569, Perez, et al, 1503.00290, 1505.06689,...

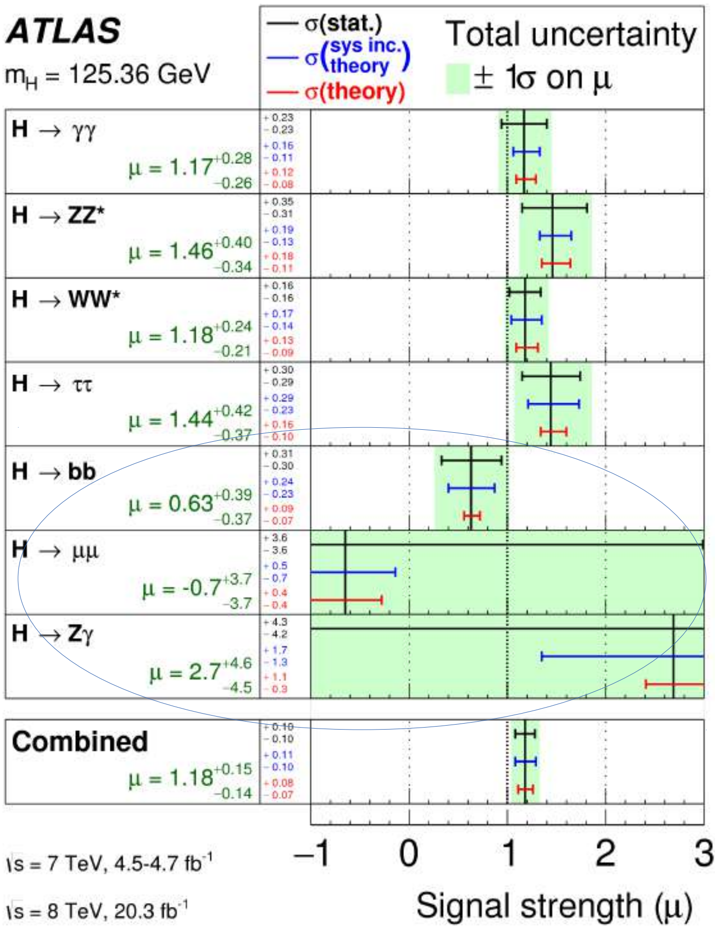
Brivio, FG, Isidori, PRL (1507.02916)

$\Rightarrow |\kappa_c| < \mathcal{O}(\text{few})$

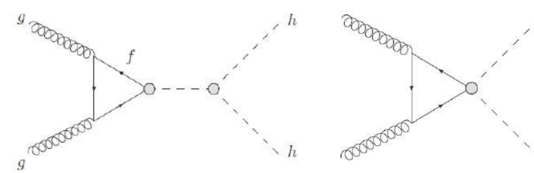
Higgs physics ↔ Flavor Physics

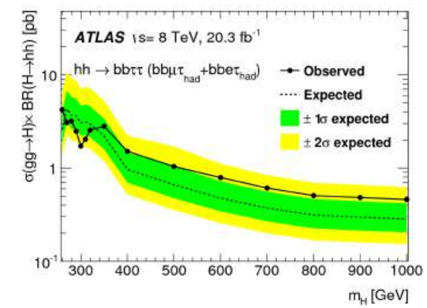
Higgs ↔ Cosmology

… still much to learn about H!

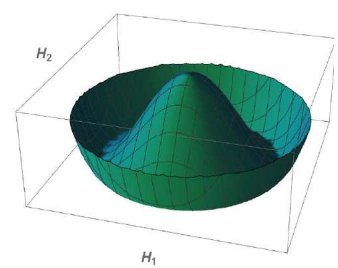


hh production → V(H)





How is electroweak symmetry broken?

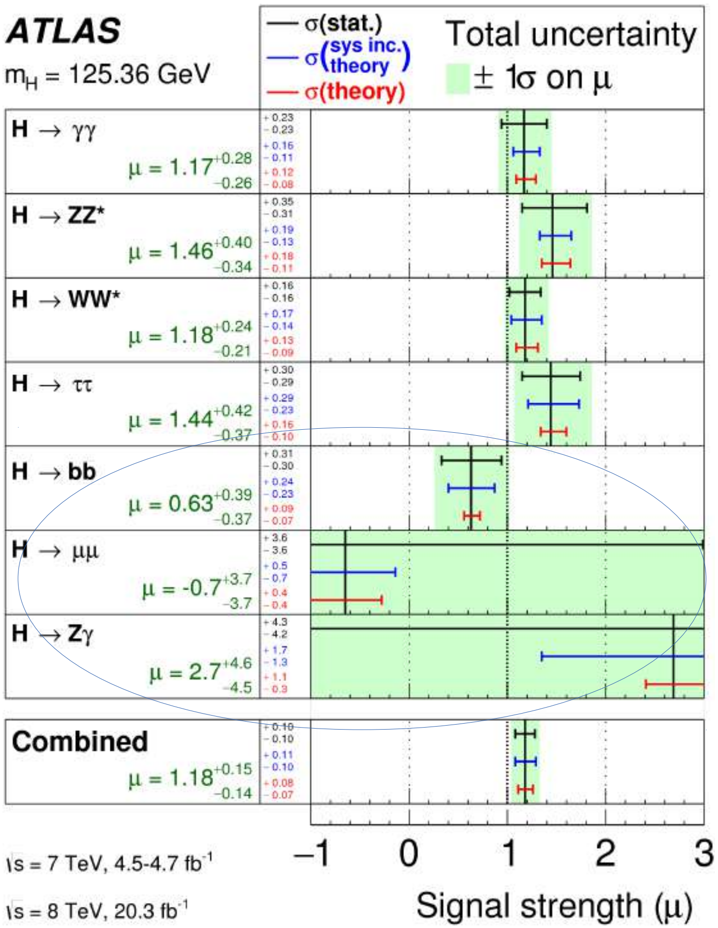


$$V(H) = \mu^2 \, |H|^2 + \lambda \, |H|^4 + \boxed{\frac{c_6}{\Lambda^2} \lambda |H|^6}$$

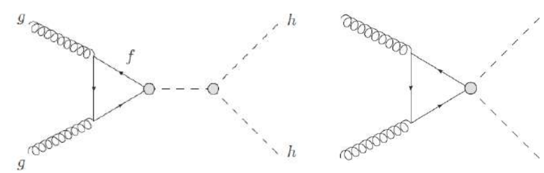
- Vacuum Stability
- Origin of the Potential (↔ flavor)
- Dark Matter
- Portal
- Baryogenesis
- Hierarchy Problem …

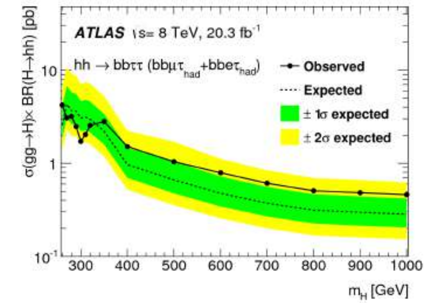
Higgs ↔ Cosmology

… still much to learn about H!

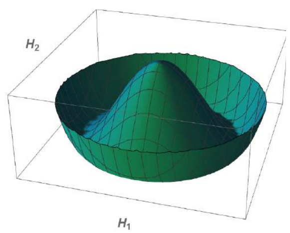


hh production → V(H)





How is electroweak symmetry broken?

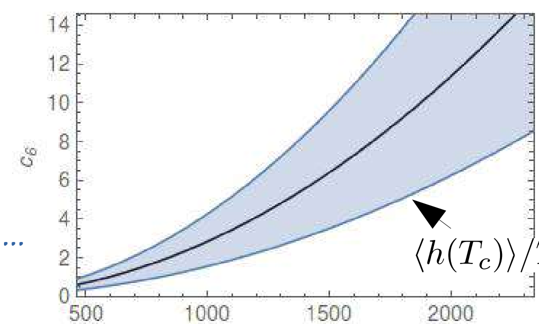


$$V(H) = \cancel{\mu^2}|H|^2 + \lambda|H|^4 + \boxed{\frac{c_6}{\Lambda^2}}\lambda|H|^6$$

?

FG, PRD (1504.00355)

Grojean, Servant, Wells …



appropriate 1st order PT for Baryogen.

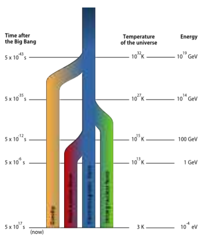
Higgs Physics ↔ Cosmology

Flavor ↔ Cosmology

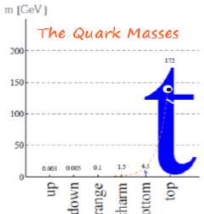
Flavor in the Sky:
The Axiflavon

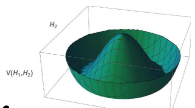
Physics Beyond the SM

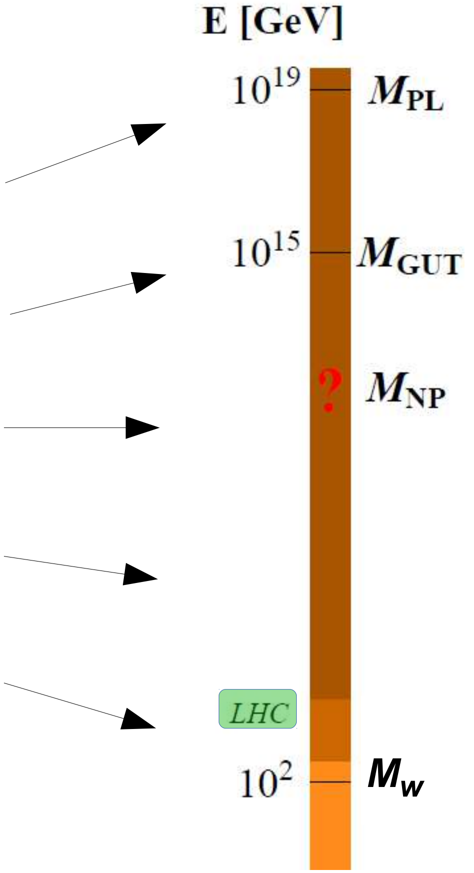
Three of the Major Open Questions in Particle Physics



- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h \ll M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- ...



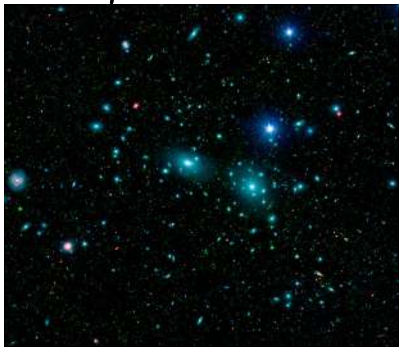




Dark Matter

- Luminous matter cannot explain many observations

- luminous matter not sufficient to keep clusters bound



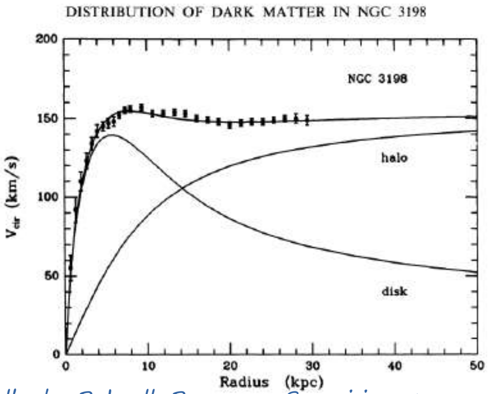
Coma Cluster, NASA, Zwicky

- Bullet Cluster:

Optical observation (x-ray) vs. grav. lensing

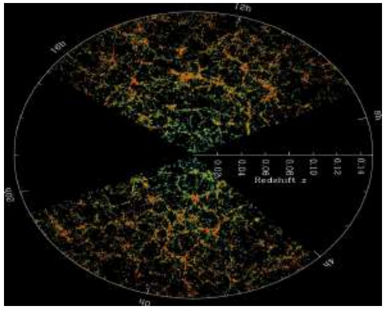
NASA, ...

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

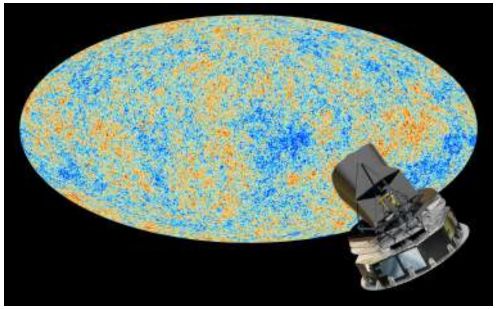
- large-scale structure formation



Sloan Digital Sky Survey

+ BBN, Lyman-α forest, ...

- CMB

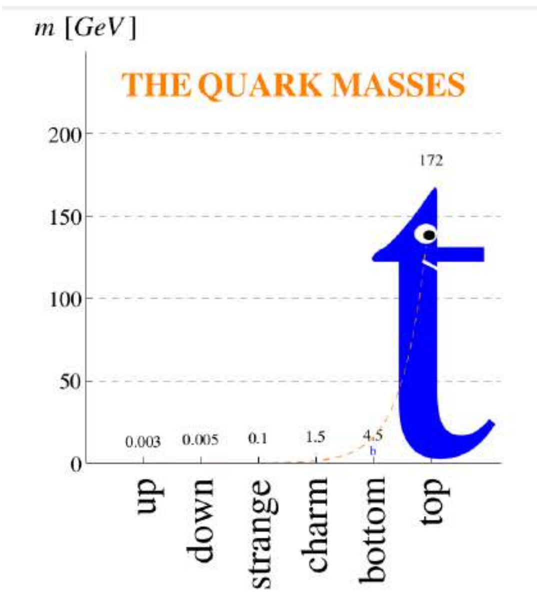


ESA

- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

The Flavor Puzzle

- Large hierarchies in quark + lepton masses
  and in CKM matrix



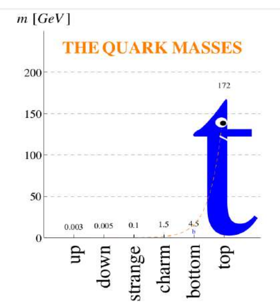
$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$\lambda \sim 0.23$

NuFIT 3.0 (2016)

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

Basic Solution to The Flavor Puzzle



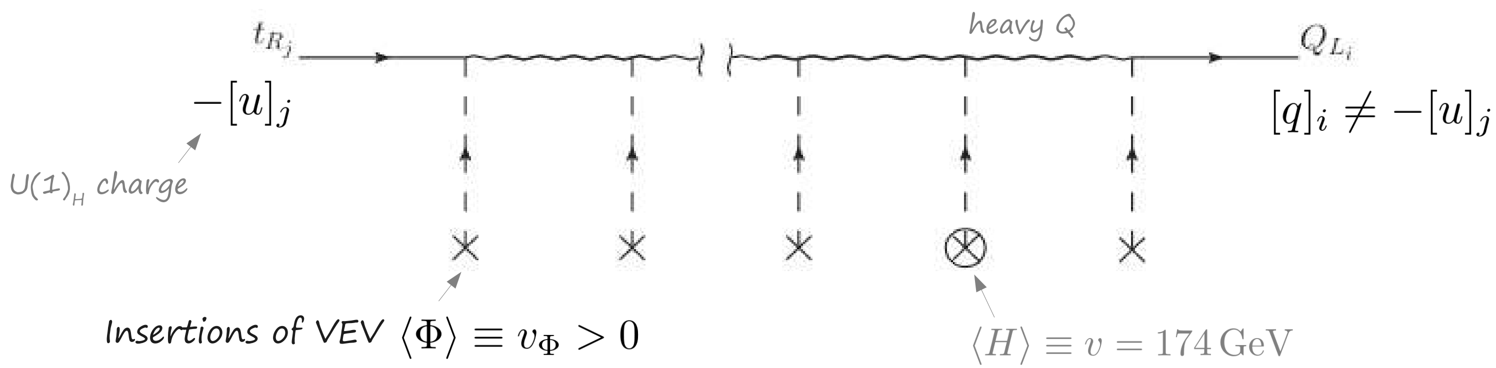
- Large hierarchies in quark + lepton masses and in CKM matrix ...

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

... can be addressed via 'horizontal' $U(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...

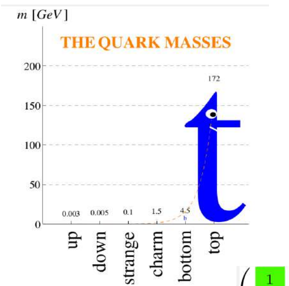
- SM LH and RH fermions feature different $U(1)_H$ charges
- Mass terms only after $U(1)_H$ broken via VEV of scalar field: **flavon** Φ



$Q_{U(1)_H}(\Phi) = -1$ → suppression by $v_\Phi/m_Q \ll 1$

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...



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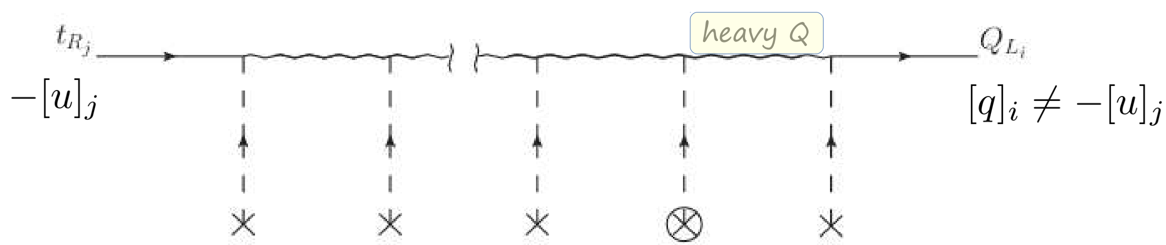
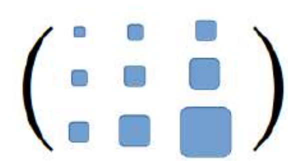


Integrate out heavy Q → $\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\,(\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$ flavon Φ

$m_Q \sim \Lambda \gtrsim v_\Phi$

a^q_{ij} : O(1) coefficient; all flavor structure comes from

Yukawa couplings $y^{u,d,e}_{ij} = a^{u,d,e}_{ij}\,\epsilon^{[L]_i+[R]_j}$ $\quad \epsilon \equiv v_\Phi/\Lambda$



$[L]_i = [q]_i, [R]_i = [u]_i, [d]_i$ (quarks)

$[L]_i = [l]_i, [R]_i = [e]_i$ (leptons)

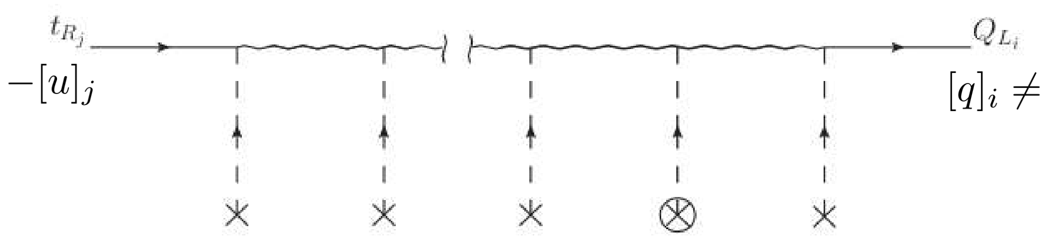
$[L]_i, [R]_i > 0$

Solution to The Flavor Puzzle

- Large hierarchies in quark + lepton masses and in CKM matrix ...

... can be addressed via horizontal $U(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...



Yukawa couplings $\boxed{y_{ij}^{u,d,e} = a_{ij}^{u,d,e}\,\epsilon^{[L]_i+[R]_j}}$

LO in ε

$$m_n = \frac{v}{\sqrt{2}} \frac{\left|\det \boldsymbol{a}_f^{(n)}\right|}{\left|\det \boldsymbol{a}_f^{(n-1)}\right|}\,\epsilon^{[L]_n+[R]_n}$$

Hierarchical structure:

$$\boxed{m_i/m_j \sim \epsilon^{[L]_i+[R]_i-[L]_j-[R]_j}}$$

$$\epsilon \equiv v_\Phi/\Lambda \sim \lambda \sim 0.23$$

LH rotations

$$\boldsymbol{U}_f = (u_f)_{ij}\,\epsilon^{|[L]_i-[L]_j|}$$

$$\boldsymbol{u}_f = \begin{pmatrix} 1 & \frac{(M_f)_{21}}{(M_f)_{11}} & \frac{(a_f)_{13}}{(a_f)_{33}} \\ -\frac{(M_f)_{21}^*}{(M_f)_{11}^*} & 1 & \frac{(a_f)_{23}}{(a_f)_{33}} \\ \frac{(M_f)_{31}^*}{(M_f)_{11}^*} & -\frac{(a_f)_{23}^*}{(a_f)_{33}^*} & 1 \end{pmatrix}$$

$$\boxed{(V_{\rm CKM})_{ik} = \sum_{j=1}^{3} \left(U_u^\dagger\right)_{ij} (U_d)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}}$$

$\boldsymbol{a}_f^{(n)}$: remove rows + columns with i,j>n from $\boldsymbol{a}_f \equiv (a_{ij}^f)$

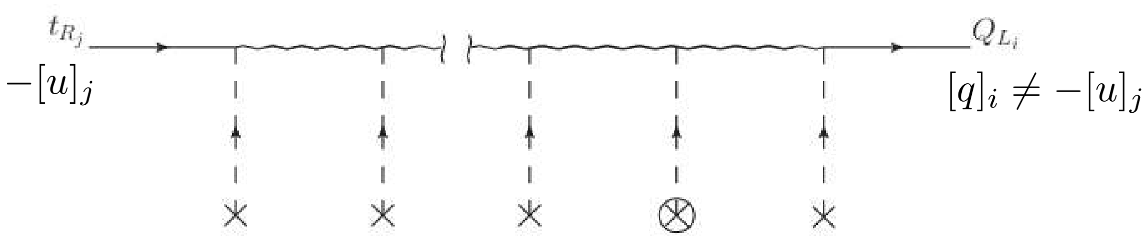
$(M_q)_{ij}$: minors of $\boldsymbol{a}_f$

Solution to The Flavor Puzzle

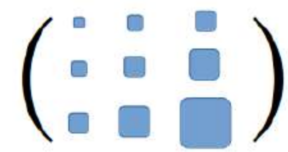
- Large hierarchies in quark + lepton masses and in CKM matrix ...

... can be addressed via horizontal $U(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...

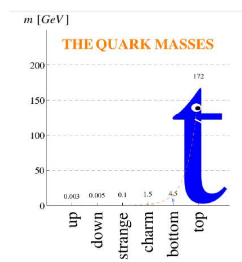


Yukawa couplings $y_{ij}^{u,d,e} = a_{ij}^{u,d,e}\,\epsilon^{[L]_i+[R]_j}$



Hierarchical structure:

$$m_i/m_j \sim \epsilon^{[L]_i+[R]_i-[L]_j-[R]_j}$$



$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

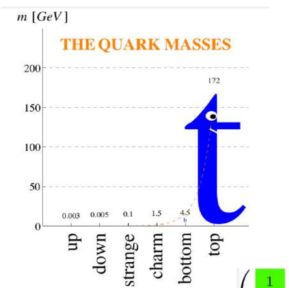
$$(V_{\mathrm{CKM}})_{ik} = \sum_{j=1}^{3} \left(U_u^\dagger\right)_{ij} \left(U_d\right)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}$$

Fit to fermion masses and mixings → $[L]_i, [R]_i$

uncertainties due to a_{ij}^f, overall normalization

Solution to The Flavor Puzzle

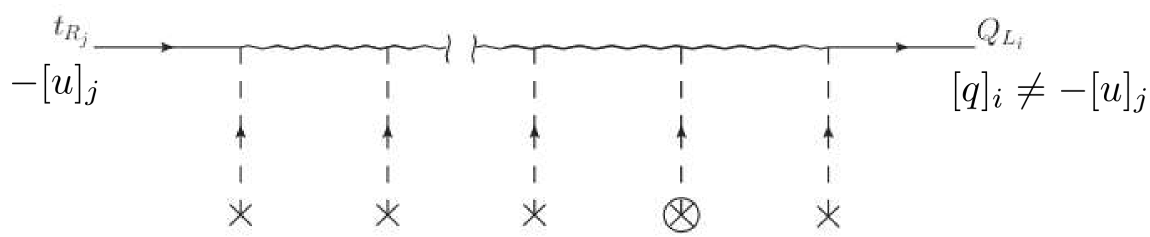
- Large hierarchies in quark + lepton masses and in CKM matrix ...



$$V_{\rm CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

... can be addressed via horizontal $U(1)_H$ symmetry:

Froggatt-Nielsen mechanism: NPB 147, 277,...



Yukawa couplings $y_{ij}^{u,d,e} = a_{ij}^{u,d,e}\,\epsilon^{[L]_i+[R]_j}$

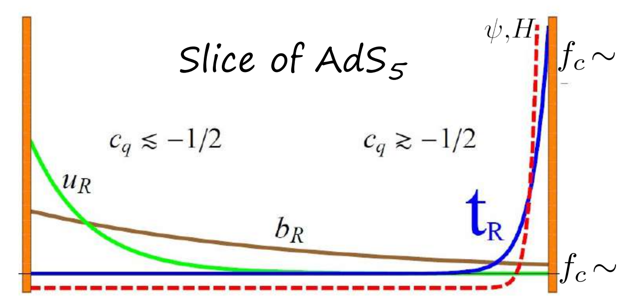
Hierarchical structure:

$$m_i/m_j \sim \epsilon^{[L]_i+[R]_i-[L]_j-[R]_j}$$

$$\epsilon \equiv v_\Phi/\Lambda \sim \lambda \sim 0.23$$

$$(V_{\rm CKM})_{ik} = \sum_{j=1}^{3} \left(U_u^\dagger\right)_{ij} \left(U_d\right)_{jk} \sim \epsilon^{|[L]_i-[L]_k|}$$

Naturally realized in warped extra dimensions/composite Higgs



$$y \sim f_{c_L} f_{c_R}$$

Strong CP Problem

Why is the coefficient of the $\cancel{CP}$ operator $\mathcal{L}_{\rm SM} \supset \bar\theta\, \frac{\alpha_s}{8\pi} G_{a\mu\nu}\tilde{G}_a^{\mu\nu}$ so tiny?

- Limits on Neutron EDMs:

$$d_n \approx 3.6 \times 10^{-16}\bar\theta\, e\,{\rm cm}$$
$$|d_n| < 2.9 \times 10^{-26} e\,{\rm cm}\ (95\%{\rm CL})$$

$\Rightarrow$ $|\bar\theta| \lesssim 10^{-10}$

Crewther, Vecchia, Veneziano, Witten, PLB 88, 123-127 (1979)
Baker et. al., hep-ex/0602020

- θ receives ($\mathcal{O}(1)$) contributions from two different sectors:

$$\bar\theta = \theta + \arg\det(M_u M_d)$$

Theta-vacua of QCD   Electroweak Sector

$|\bar\theta| \lesssim 10^{-10}$ $\Rightarrow$ Fine-tuning problem!

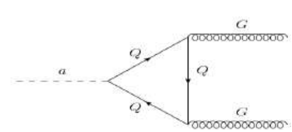
No anthropic reasoning or the like:
$\bar\theta \sim 0.01$ would be perfectly fine

Peccei-Quinn Axion Solution

Why is the coefficient of the $\not{CP}$ operator $\mathcal{L}_{\rm SM} \supset \bar\theta \, \frac{\alpha_s}{8\pi} G_{a\mu\nu}\tilde{G}^{\mu\nu}_a$ so tiny?

- Promote $\bar\theta$ from parameter to dynamical variable:
  axion a = PNGB of spontaneously broken $U(1)_{PQ}$ symmetry $\quad \sigma \sim \frac{f}{\sqrt{2}} e^{ia/f}$
  → solves strong CP problem:

- $$\mathcal{L} \supset \theta_0 \frac{\alpha_s}{8\pi} G\tilde{G} + \frac{\alpha_s}{4\pi} N \frac{a}{f} G\tilde{G}$$
  Potential induced by QCD instantons
  → minimum CP conserving $\langle a \rangle = -af/(2N)\theta_0$ → $G\tilde{G}$ term vanishes
  Peccei, Quinn, PRL 38, 1440, Vafa, Witten, PRL 53, 535

- axion coupled to $G\tilde{G}$ via chiral anomaly  → $a\,G\tilde{G}$

Wilczek, PRL 40, 279 (1978), Weinberg, PRL 40, 223 (1978)

A Unified Solution: The Axiflavon

- Can both frameworks be *unified*: 'single' solution for two problems?

$$\boxed{U(1)_H \leftrightarrow U(1)_{PQ}}$$

➡ embed **axion** and **flavon** in same complex scalar (single U(1))

don't gauge $U(1)_H$ of FN mech. ...

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{\boxed{ia}/v_\Phi}$$

flavon

axiflavon

Calibbi, FG, Redigolo, Ziegler, Zupan, PRD (1612.08040)

→ Solves strong CP problem: axiflavon $\hat{=}$ axion + solves flavor puzzle

$m_\phi \sim \mathcal{O}(v_\Phi)$ flavon heavy → integrate out

$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}}{f_a}\right) \ll m_\Phi$ axiflavon = light PNGB, small mass induced by anomaly

di Cortona, Hardy, Pardo Vega, Villadoro, 1511.02867

$f_a = v_\Phi/2N$

see also: Ema, Hamaguchi, Moroi, Nakayama, 1612.05492, Wilczek, PRL 49, 1549 (1982), ...

The Axiflavon: Very Predictive

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{i\boxed{a}/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\ Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- **axiflavon** couplings to fermions $\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.}$

non-universal (generation-dependent charges) → FCNCs

$$\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}$$

$$y^{u,d,e}_{ij} = a^{u,d,e}_{ij}\epsilon^{[L]_i+[R]_j}$$

- **axiflavon** couplings to gluons/photons $\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F}$

  N = color anomaly

  E = electromagnetic anomaly

  $f_a = v_\Phi/2N$

$$N\delta_{ab} = \mathrm{Tr}\lambda_a\lambda_b Q_{PQ}$$

$$E = \mathrm{Tr}Q_{PQ}Q^2_{\rm em}$$

The Axiflavon: Flavor Constraints

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{i\boxed{a}/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- ***axiflavon*** *couplings to* ***fermions***

$$\boxed{\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.}}$$

non-universal (generation-dependent charges) → FCNCs

$$\boxed{\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}}$$

- *strong bounds from* ***Kaon Physics*** *($a\bar{s}d$ transitions):*

$$\Gamma(K^+ \to \pi^+ a) \simeq \frac{m_K}{64\pi}|\lambda^d_{21} + \lambda^{d*}_{12}|^2 B_s^2 \left(1 - \frac{m_\pi^2}{m_K^2}\right)$$

stringent limit: $\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$

E787, E949

Kamenik, Smith, 1111.6402

$$\Rightarrow \boxed{\frac{1}{2}|\lambda^d_{21} + \lambda^{d*}_{12}| < 1.4 \cdot 10^{-13}}$$

define $|\lambda^d_{21} + \lambda^{d*}_{12}| \equiv 2\kappa_{sd}\sqrt{m_d m_s}/(2N f_a)$ $\Rightarrow$ $\boxed{f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}}$ $\left(m_a \lesssim \frac{N}{\kappa_{sd}} \times 7.6 \cdot 10^{-5}\,\mathrm{eV}\right)$

O(1) [model dependent]

$B_s = 4.6(8)$

NA62: O(10) improvement

The Axiflavon: Flavor Constraints

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

- **axiflavon** couplings to <u>fermions</u> $\boxed{\mathcal{L}_{aff} = \lambda^f_{ij} a F_i F^c_j + \text{h.c.}}$

non-universal (generation-dependent charges) → FCNCs

$$\boxed{\lambda^{u,d,e}_{ij} = i([L]_i + [R]_j)\frac{v}{v_\Phi} y^{u,d,e}_{ij}}$$

- further bounds from **B-Physics** ($a\bar{b}s$ transitions):

$$\Gamma(B^+ \to K^+ a) \simeq \frac{m_B}{64\pi}|\lambda^d_{32} + \lambda^{d*}_{23}|^2 \left(f_0^K(0)\right)^2 \left(\frac{m_B}{m_b - m_s}\right)^2 \left(1 - \frac{m_K^2}{m_B^2}\right)^3$$

define $|\lambda^d_{32} + \lambda^{d*}_{23}| \equiv 2\kappa_{bs}\sqrt{m_b m_s}/(2Nf_a)$ ➡ $\text{BR}(B^+ \to K^+ a) \lesssim 10^{-6\div 8}$ $\rightarrow$ $\boxed{m_a \lesssim \frac{N}{\kappa_{bs}} 10^{-1\div 2}\,\text{eV}}$

Belle-II

- Axion couplings as window to flavor dynamics (Kaon decay part. interesting)

$f_0^K(0) = 0.331$

The Axiflavon: Photon Couplings

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\, (\Phi/\Lambda)^{[q]_i + [u]_j} + \dots$$

- ***axiflavon** couplings to gluons/photons*

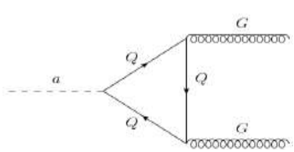
$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a} F\tilde{F}$$

$$f_a = v_\Phi/2N$$

$$N = \frac{1}{2}\sum_i 2[q]_i + [u]_i + [d]_i$$

$$E = \sum_i \frac{4}{3}\left([q]_i + [u]_i\right) + \frac{1}{3}\left([q]_i + [d]_i\right) + [l]_i + [e]_i$$

N,E determined completely in terms of $U(1)_H$ charges



- *Can be directly related to fermion mass matrices:*

Froggatt, Nielsen: NPB 147, 277,...

$$\det m_u \det m_d = \alpha_{ud}\, v^6 \epsilon^{2N}$$
$$\det m_d / \det m_e = \alpha_{de}\, \epsilon^{\frac{8}{3}N - E}$$

$\det m_u \det m_d / v^6 \approx 5 \cdot 10^{-20}$; $\det m_d/\det m_e \approx 0.7$ ➡ $E \approx 8/3N$

Masses at μ=10⁹ GeV from Xing, Zhang, Zhou, 0712.1419

$$\alpha_{ud} = \det a_u \det a_d$$
$$\alpha_{de} = \det a_d / \det a_e$$

- *somewhat similar to DFSZ axion*

The Axiflavon: Photon Couplings

$$\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \boxed{\phi})e^{i\boxed{a}/v_\Phi}$$

flavon

axiflavon

$$\mathcal{L} = a^u_{ij}\; Q_i U^c_j\, H\,(\Phi/\Lambda)^{[q]_i+[u]_j} + \dots$$

- ***axiflavon*** *couplings to* *gluons/photons* $\boxed{\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F}}$ $f_a = v_\Phi/2N$

$$N = \frac{1}{2}\sum_i 2[q]_i + [u]_i + [d]_i$$

$$E = \sum_i \frac{4}{3}\left([q]_i + [u]_i\right) + \frac{1}{3}\left([q]_i + [d]_i\right) + [l]_i + [e]_i$$

N,E determined completely in terms of $U(1)_H$ charges

- *Can be directly related to fermion mass matrices:*

$$\frac{E}{N} = \frac{8}{3} - 2\frac{\log\frac{\det m_d}{\det m_e} - \log\alpha_{de}}{\log\frac{\det m_u \det m_d}{v^6} - \log\alpha_{ud}} \xrightarrow[99.9\%]{|a_{ij}|\in[1/3,3]} \boxed{\frac{E}{N} \in [2.4, 3.0]}\,,\quad \boxed{g_{a\gamma\gamma} \in \frac{[1.0, 2.2]}{10^{16}}\frac{m_a}{\mu\mathrm{eV}}}$$

Rather sharp prediction for photon coupling, not too sensitive to O(1) changes in a_{ij}
(nor to explicit charge assignments)

$$\mathcal{L} \supset \frac{1}{4}g_{a\gamma\gamma}aF\tilde{F}$$

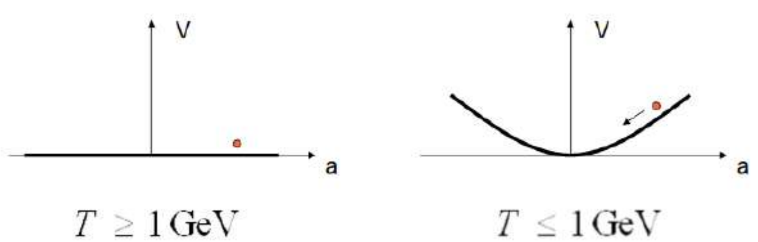
Axiflavon in the Sky: Dark Matter

- $U(1)_H$-breaking before inflation → vacuum realignment mechanism

  → axions as cold dark matter $\boxed{\Omega_{\rm DM} h^2 \approx 1 \times 10^{-7} \left(\frac{\rm eV}{m_a}\right)^{7/6} \theta^2}$

  misalignment angle

- Require $\Omega_{\rm DM} h^2 \approx 0.12$ → always possible (with $\theta<\pi$) if $\boxed{m_a \lesssim 10^{-5} - 10^{-4}\,\rm eV}$



vacuum realignment

Sandbox Studio, Chicago with Ana Kova

axion-string density diluted by inflation

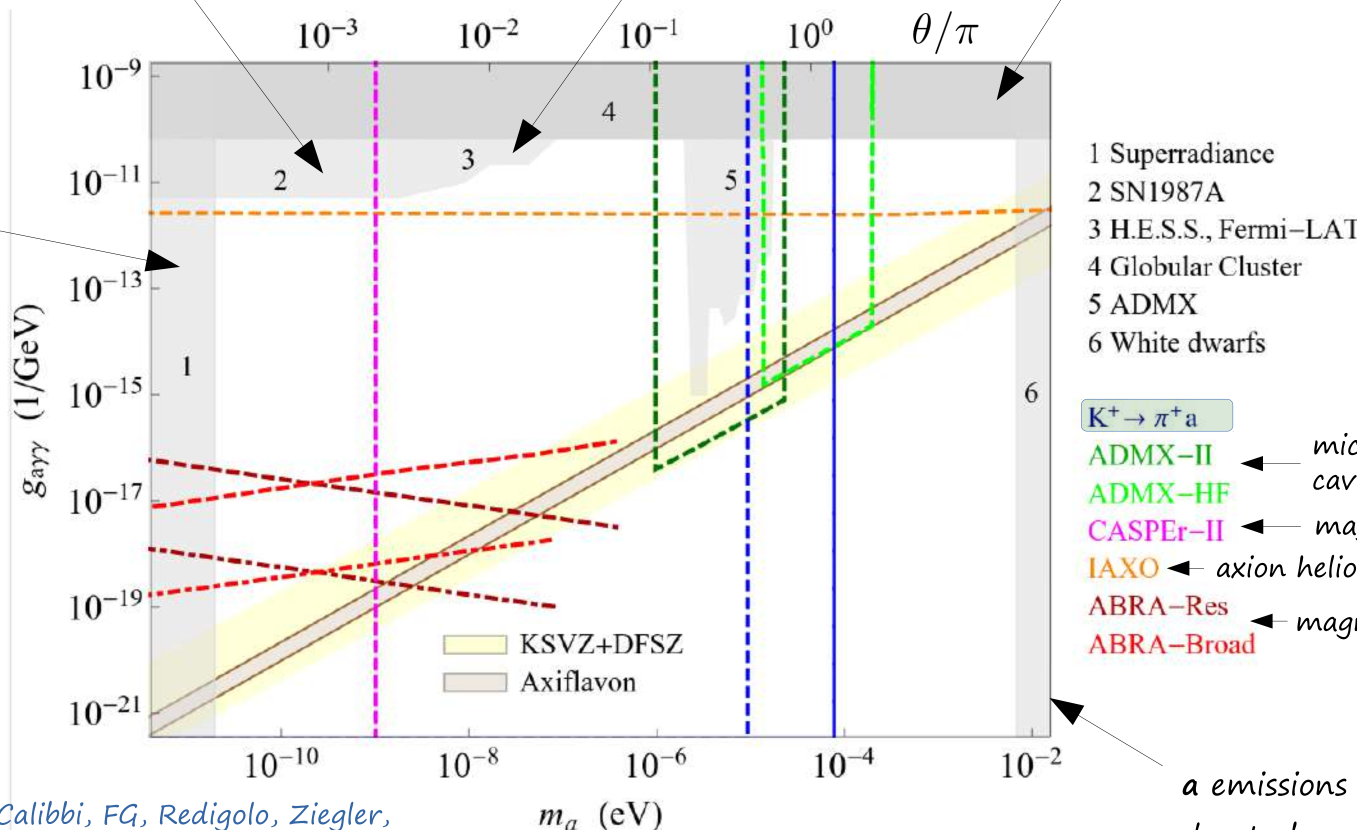
Summary of Constraints

Primakoff production of **a** in core of SN: $\gamma + Ze \leftrightarrow Ze + a$, converted to photons in galactic B field → gamma rays (SMM satellite)

Telescopes, searching for irregularities in γ-ray spectrum (γ-**a** oscil.)

Primakoff **a** losses affect stellar evolution (Globular Cluster)

a affects gravitational wave emission of rotating BH (rotating BEC of axions), imprint in spin vs. mass plots



ADMX-II, ADMX-HF ← microwave signal in cavity (strong B-field)

CASPEr-II ← magnetic resonance exp.

IAXO ← axion helioscope (**a**->γ in B-field)

ABRA-Res, ABRA-Broad ← magn. flux in superc. loop

Calibbi, FG, Redigolo, Ziegler, Zupan, PRD (1612.08040)

← 'natural' axiflavon DM →

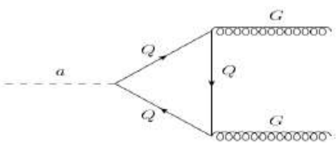
a emissions in white dwarfs due to bremsstrahlung → $a\bar{e}e$ coupling (WD cooling)

KSVZ, DFSZ: $|\frac{E}{N} - 1.92| \in [0.07, 7]$

PDG (2010)

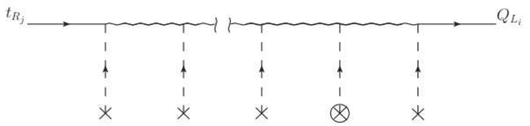
The Axiflavon

- Strong CP Problem



$\rightarrow a G\tilde{G}$

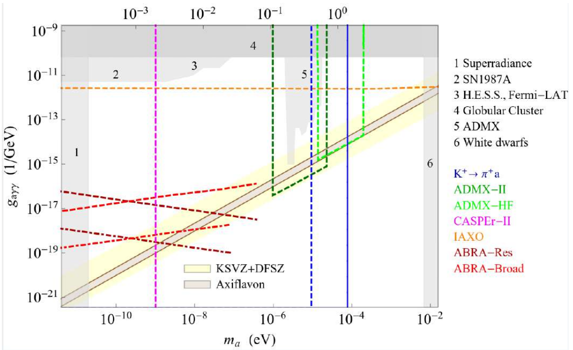
- Flavor Puzzle



$$\mathcal{L} = a^u_{ij}\, Q_i U^c_j\, H\,(\Phi/\Lambda)^{[q]_i+[u]_j} + \ldots$$

Axiflavon $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$

- Dark Matter



Complementary information from flavor, cosmology, axion searches: probing interesting parameterspace in the future and potentially telling apart general axion solution from axiflavon

$K^+ \to \pi^+ a$ search with a almost massless is a new challenge for NA62

Strong CP $\leftrightarrow$ Flavor $\leftrightarrow$ Cosmology

Conclusions

- Interesting interplay between Flavor Physics, Higgs Physics, and Cosmology emerges in well motivated extensions of the SM
- Solutions to several problems of the SM at a time!
- Correlations provide new handle to probe BSM scenarios
- Axion → window to generation of flavor hierarchies?
- Lepton-flavor non universality as a first hint for compositeness?

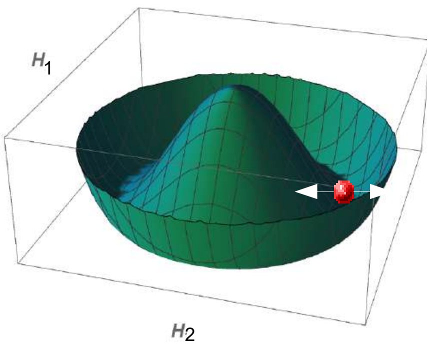

Backup:

Unveil the Higgs Potential

Very important test of nature: measure Higgs potential

→ How is electroweak symmetry broken?

EFT approach: parametrize NP generically via operators with D>4
Validity, see e.g. Contino, Falkowski, FG, Grojean, Riva, JHEP (1604.06444)



SM: $\mu^2 < 0$

$$V(H) = \mu^2\,|H|^2 + \lambda\,|H|^4 + \boxed{\frac{c_6}{\Lambda^2}\lambda|H|^6}$$

$$\downarrow H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad v \leftarrow \langle |H| \rangle$$

$$V(h) = \frac{1}{2}\boxed{m_h^2}\,h^2 + \boxed{\lambda_{3h}}\,v h^3 + \frac{\lambda_{4h}}{4}\,h^4 \quad (+\cdots)$$

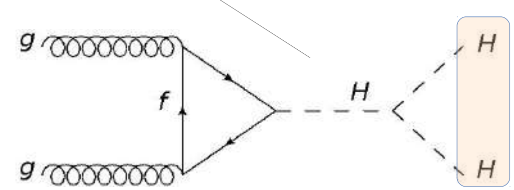
m_h^2: $(125\,\mathrm{GeV})^2$

→ self couplings

SM (c_6=0): $\lambda_{3h} = \lambda_{4h} = m_h^2/2v^2$

APS/Alan Stonebraker

- Vacuum Stability
- Origin of the Potential (↔ flavor)
- Dark Matter
- Portal
- Baryogenesis
- Hierarchy Problem ...



$\lambda_{3h}(c_6)$ accessible in Higgs pair production

Higgs Potential

- Can also test presence/size of μ-term

(significant perturbation from the SM)

$$V(H) = \cancel{\mu}^2\,|H|^2 + \lambda\,|H|^4 + \boxed{c_6}\frac{}{\Lambda^2}\lambda|H|^6$$

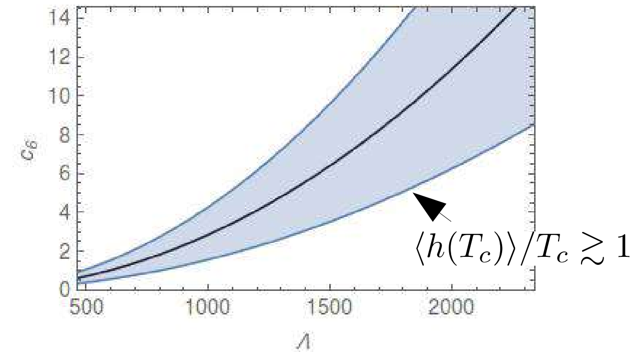
?

Extreme scenario, not entertained before:

- Even μ=0 phenomenologically viable?
- Yes! Due to the lightness of the Higgs Boson!

$$\lambda = -\frac{m_h^2}{2v^2} \approx -0.13\,, \quad c_6\lambda = \frac{2m_h^2}{3v^2}\frac{\Lambda^2}{v^2} \approx \boxed{2.8\,\frac{\Lambda^2}{\mathrm{TeV}^2}}$$

FG, PRD (1504.00355)



- appropriate 1st order PT possible

→ Find (approximate) UV completion

Higgs Physics ↔ Cosmology

Testable at LHC in hh production!

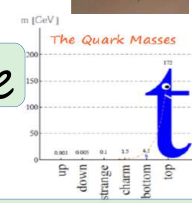
New Approaches to BSM Physics

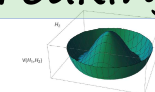
Measuring properties of nature in a general framework is important, however in the end seek a full model that addresses questions left open in the SM

- Two novel models that address many open questions in a unified way

Calibbi, FG, Redigolo, Ziegler, Zupan, 1612.08040 Carmona, FG, JHEP (1410.8555), PRL (1510.07658)

- Hierarchy Problem: $m_h << M_{PL}$
- Tiny Neutrino Masses
- Hierarchical Flavor Structure
- Dark Matter $\notin$ SM
- Trigger for Symmetry-Breaking Potential?
- Strong CP Problem
- Some Hints in Flavor/Precision Physics





Backup: SM, Higgs

The Standard Model of Particle Physics:

renormalizable QFT, defined by...

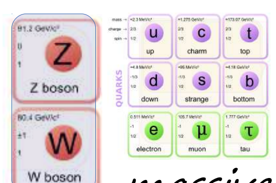
... Local 'Gauge' Symmetries

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

SM solution →

'Electroweak' Symmetry **hidden** in ground state

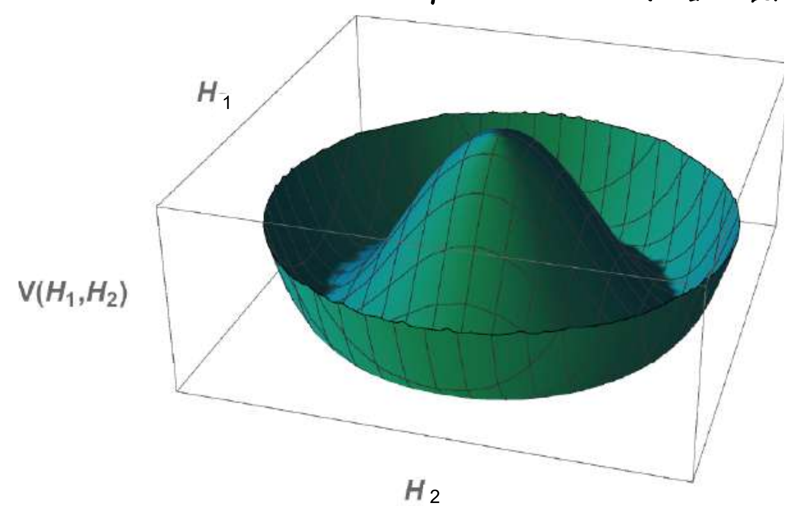
$$SU(3)_c \times U(1)_{EM}$$



massive

Higgs field $H = (H_1, H_2)$

with non-trivial potential $V(H_1, H_2)$



V is $SU(2)_L \times U(1)_Y$ symmetric

Backup: SM, Higgs

The Standard Model of Particle Physics

defined by...

... Local *'Gauge' Symmetries*

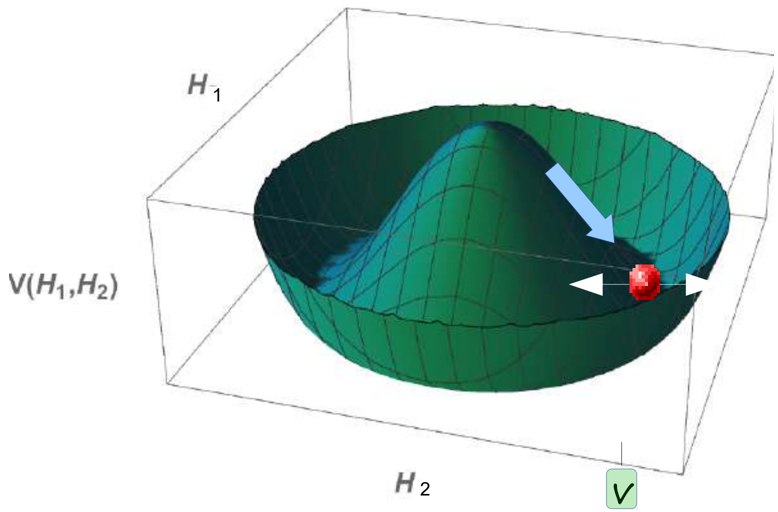
$$SU(3)_c \times \boxed{SU(2)_L \times U(1)_Y}$$

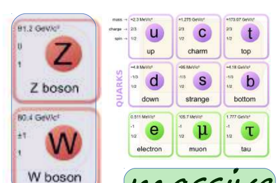
'Electroweak' Symmetry **hidden** in ground state

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

expand around ground state:

H =(H1,H2) = (H1, v + h + iϕ)





Gauge

massive

Yukawa

coupling to H = (H1, v + h + iϕ)

h: Higgs Boson

Brout, Englert, Higgs, Guralnik, Hagen, Kibble,...

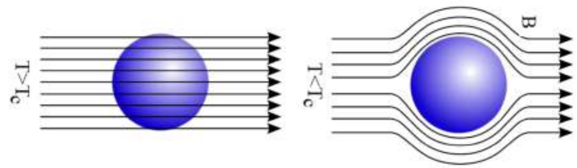
Higgs Mechanism

Analogy: Superconductivity

Anderson '62

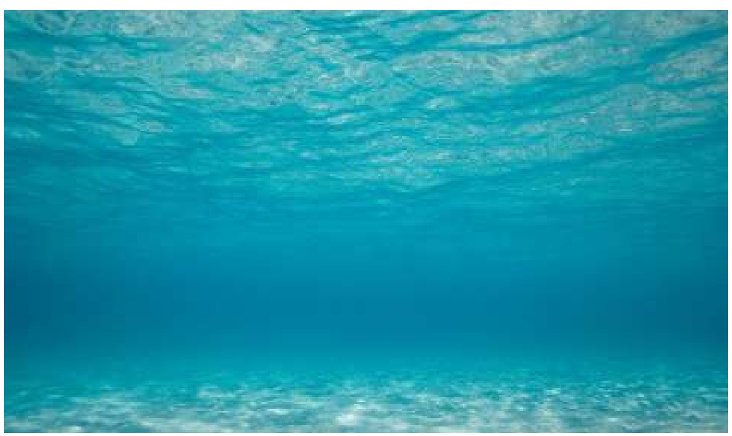
- Finite penetration depth of magnetic field

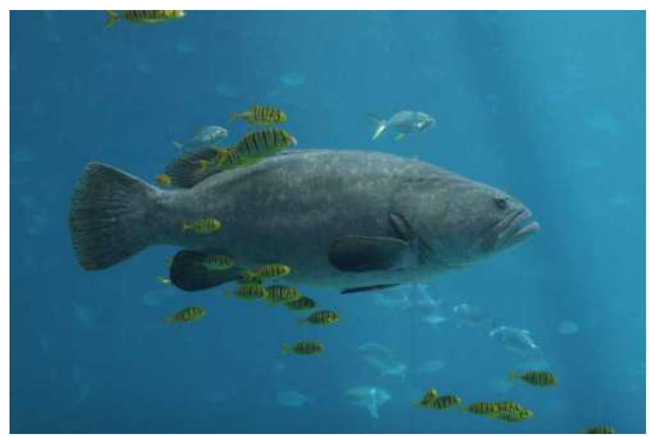
Meißner-Ochsenfeld effect



$\leftrightarrow$ effective photon mass $\lambda = \dfrac{\hbar}{Mc}$

- Cooper-pairs $\langle e^- e^- \rangle \neq 0$ → breaking of gauge invariance





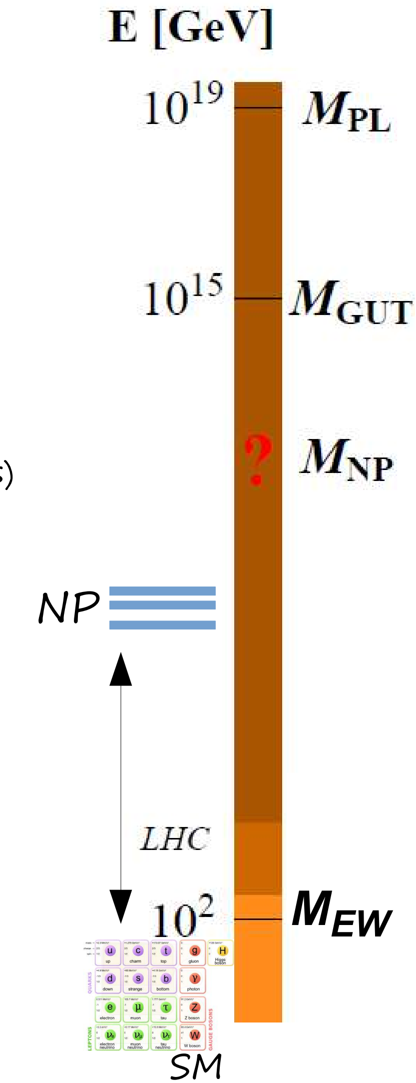
$$\langle |\mathcal{H}| \rangle = v > 0$$

Variety of Models → Effective Field Theory Approach to NP

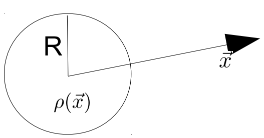
- NP at $\Lambda \gg M_{EW}$, not directly accessible
  → described generically by operators with $d[\mathcal{O}] > 4$

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{D\,\leq\,4} + \boxed{\sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{D=6}} + \mathcal{O}(E^4/\Lambda^4)$$

local operators = New Physics (SM field content + gauge symmetries)

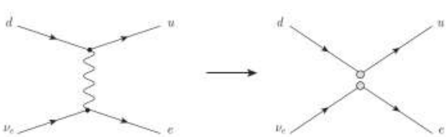


c.f. multipole expansion, Fermi Theory



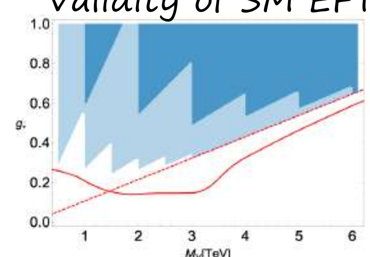
$|\vec{x}| \gg R$:

$$\phi(\vec{x}) = \frac{1}{4\pi}\left(\frac{q}{|\vec{x}|} + \vec{p}\cdot\frac{\vec{x}}{|\vec{x}|^3} + \frac{1}{2}\sum_{i,j} Q_{ij}\frac{x_i x_j}{|\vec{x}|^5} + \cdots\right)$$



$$\mathcal{L}_{eff} = -\frac{g^2}{8m_W^2} C_1(\mu)(\bar{e}\,\nu_e)_{V-A}(\bar{u}\,d)_{V-A}$$

Validity of SM EFT



Contino, Falkowski, FG, Grojean, Riva, JHEP (1604.06444)

+ Handbook of LHC Higgs Cross Sections 4,...

- allows for gradual progress: Fermi Theory → SM → 'New SM'

Weinberg, Wilson, Callen, Coleman, Wess, Zumino, ...

$\hbar = c = 1$

'Higgs Physics' EFT

- Neglecting operators strongly constrained from precision tests

See e.g.: Corbett, Eboli, Gonzalez-Fraile, Gonzalez-Garcia 1207.1344;
Elias-Miro, Espinosa, Masso, Pomarol, 1308.1879;
Pomarol, Riva, 1308.2803; ...

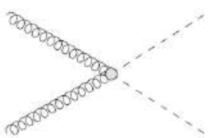
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda |H|^6$$

Pure Higgs

Yukawa type

$$- \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar{L}_L H \tau_R + \text{h.c.} \right)$$

$$+ \frac{\alpha_s c_g}{4\pi\Lambda^2} |H|^2 G^a_{\mu\nu} G_a^{\mu\nu} + \frac{\alpha' \, c_\gamma}{4\pi\Lambda^2} |H|^2 B_{\mu\nu} B^{\mu\nu}$$



$$+ \frac{i\, c_{WW}}{16\pi^2\Lambda^2} \mathcal{O}_{WW} \; (+\mathcal{L}_{\rm CP} + \mathcal{L}_{\rm 4f})$$

Buchmuller, Wyler, NPB 268(1986)621-653
Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

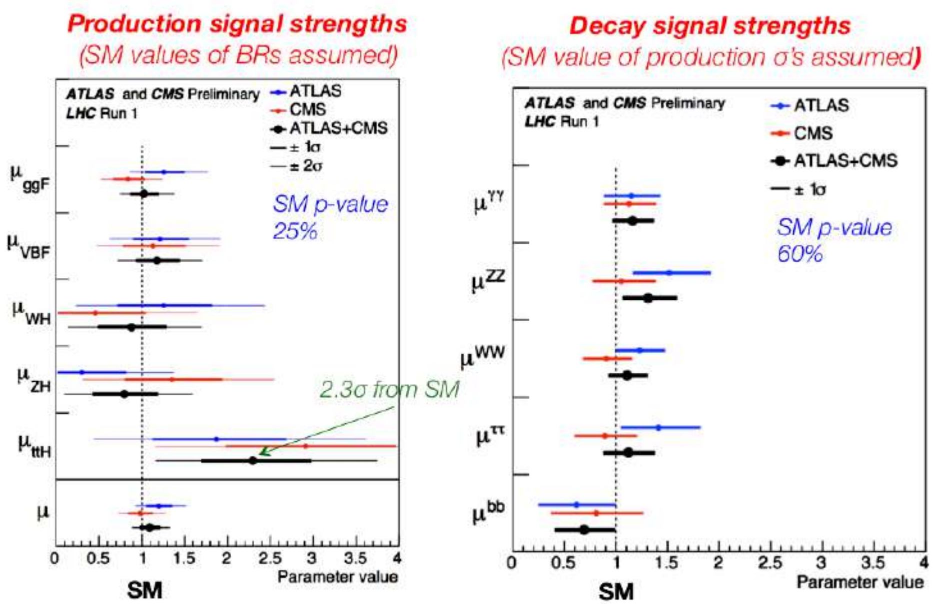
For non-linear realization, see Grinstein, Trott 0704.1505
Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

Use The Higgs Sector...

Combine with slide before

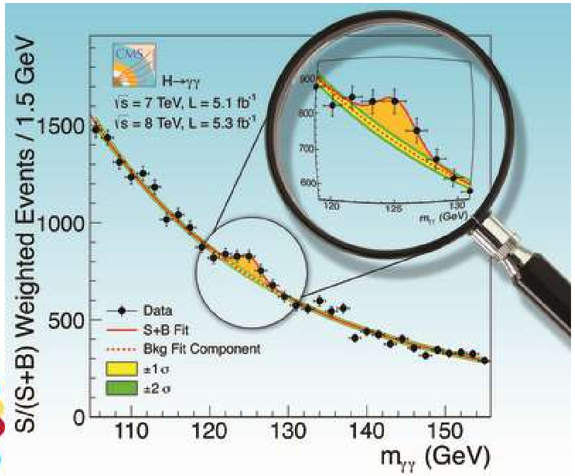
- ... as a unique window to NP.

Is it the SM-Higgs Boson?

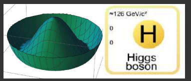


ATLAS + CMS combination

One of the biggest discoveries of mankind



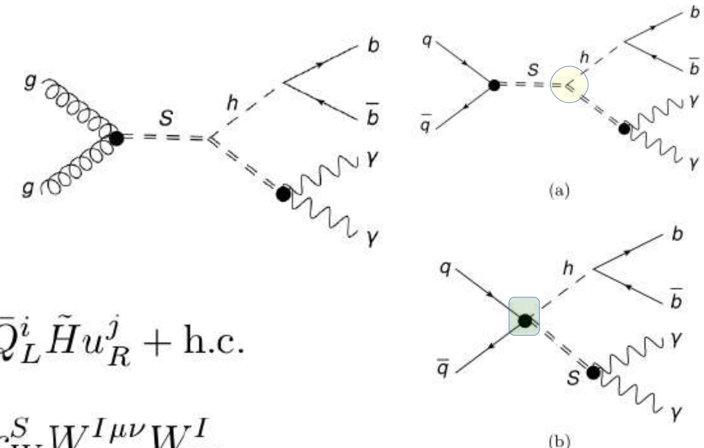
BREAKTHROUGH OF THE YEAR



still least understood...

Di-Scalar Production: hS

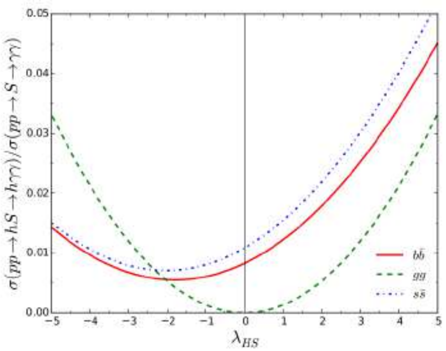
Important probe of (extended) scalar sector:
Associated Production of scalar with Higgs



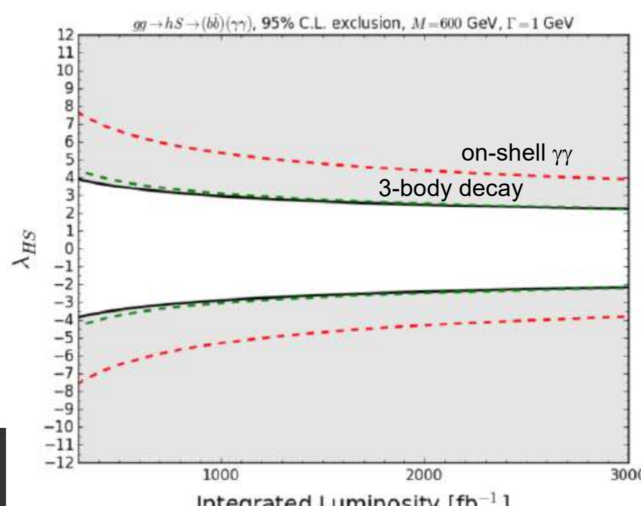
→ Portal coupling, ...

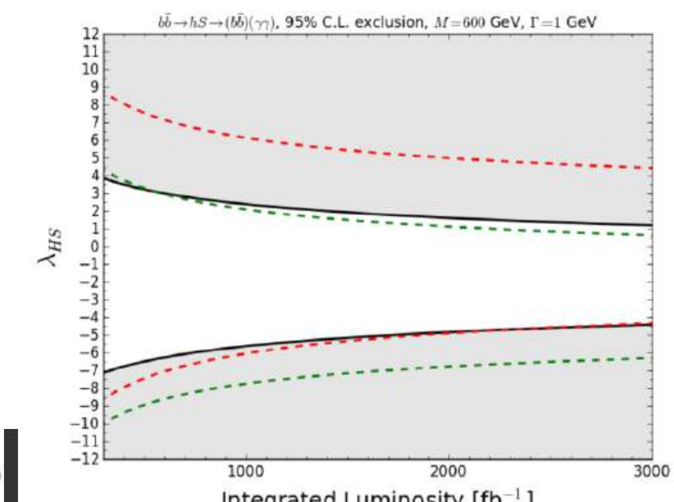
$$\mathcal{L}_{\rm eff}^{SM+S} \supset \frac{1}{2}\partial_\mu \mathcal{S}\partial^\mu \mathcal{S} - \frac{1}{2}\mu_S^2\mathcal{S}^2 - \boxed{(y_d^S)^{ij}\frac{\mathcal{S}}{\Lambda}\bar{Q}_L^i H d_R^j} - (y_u^S)^{ij}\frac{\mathcal{S}}{\Lambda}\bar{Q}_L^i \tilde{H} u_R^j + \text{h.c.} - \frac{\mathcal{S}}{\Lambda}\frac{1}{16\pi^2}\left[g'^2 c_B^S B_{\mu\nu}B^{\mu\nu} + g^2 c_W^S W^{I\mu\nu}W^I_{\mu\nu} + g_S^2 c_G^S G^{a\mu\nu}G^a_{\mu\nu}\right] - \boxed{\lambda_{HS}|H|^2\mathcal{S}^2} - \frac{\lambda_S}{4}\mathcal{S}^4 \,.$$

scalar singlet



Carmona, FG, Papaefstathiou, 1606.02716





assumed
$\sigma(pp\to S\to\gamma\gamma) = 10\,\text{fb}$

motivated by S=S(750), however rather general analysis

EFT Approach to New Physics

- Full set of non-redundant operators (i.e., basis):

59 D=6 operators (2499 including full flavor structure)

[assuming B&L conservation]

Buchmuller, Wyler, NPB 268(1986)621-653

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

Alonso, Jenkins, Manohar, Trott, 1312.2014

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Table 3: Four-fermion operators.

- Constrain coefficients of these operators

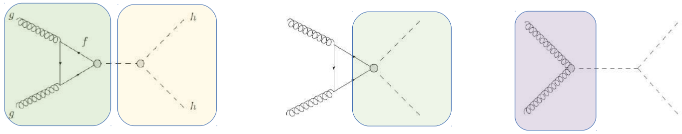
[One way to go, given the lack of evidence in favor of concrete models]

For non-linear realization, see Grinstein, Trott 0704.1505

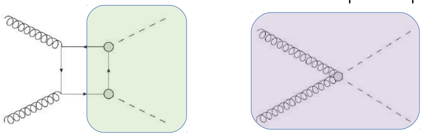
Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

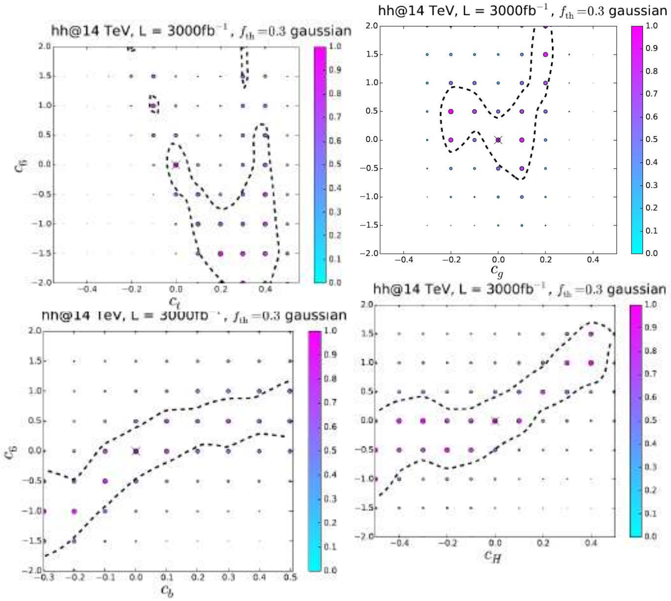
Di-Higgs Production in full D=6 Extension of SM

Many more contributions in full EFT...



$$\left.\frac{d\hat{\sigma}(gg\to hh)}{d\hat{t}}\right|_{\rm EFT} = \frac{G_F^2\alpha_s^2}{256(2\pi)^3}\left\{\left|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)\;+2c_g C_\triangle\right.\right.$$
$$\left.\left.+C_\Box F_\Box(1-c_H+2c_t)+2c_g C_\Box\right|^2+\left|C_\Box G_\Box\right|^2\right\}$$





FG, Papaefstathiou, Yang, Zurita, JHEP (1410.3471)

Expected 1σ constraints at the 14 TeV LHC in full model, assuming f_{th} = 30%

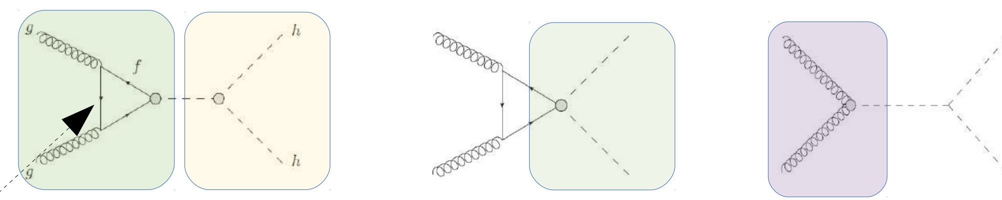
model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full (**future**)	$c_6 \in (-0.8, 0.9)$	$c_6 \in (-0.6, 0.6)$

FG, Papaefstathiou, Yang, Zurita, JHEP (1410.3471)

See also Azatov, Contino, Panico, Son 1502.00539

Di-Higgs Production in full D=6 Extension of SM

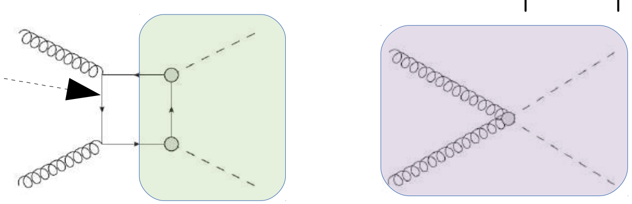
Many more contributions in full EFT...

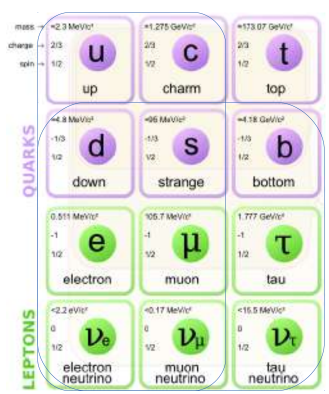


$$\left.\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}}\right|_{\mathrm{EFT}} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \Big\{ \Big| C_\triangle F_\triangle (1 - 2c_H + c_t + c_6) + 3F_\triangle(3c_t - c_H) \; + 2c_g C_\triangle$$

$$+ C_\Box F_\Box (1 - c_H + 2c_t) + 2c_g C_\Box \Big|^2 + \Big| C_\Box G_\Box \Big|^2 \Big\}$$

Need to consider light generations?



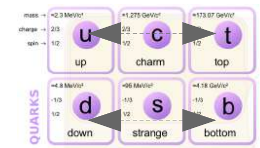


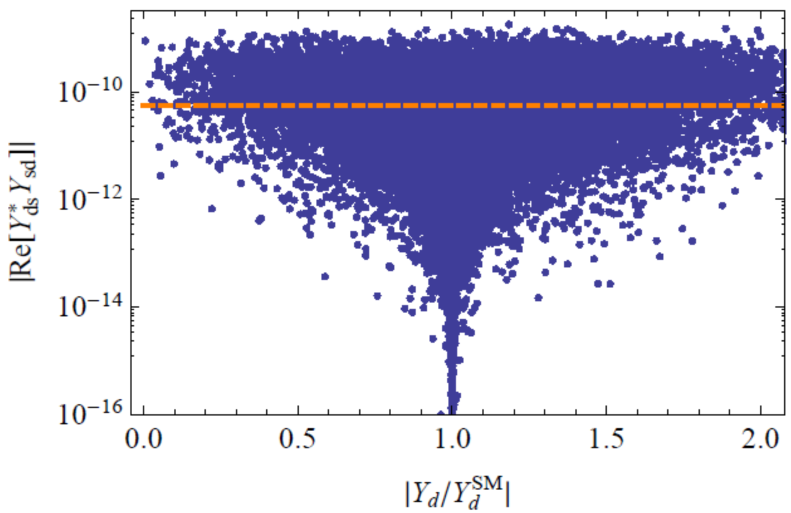
See also Azatov, Contino, Panico, Son 1502.00539

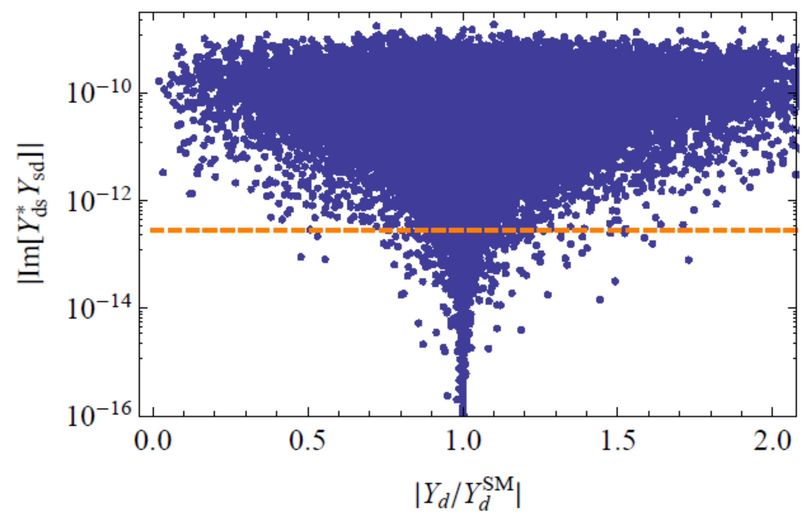
Strong Correlation $\Delta Y \leftrightarrow$ FCNCs

e.g.: Bounds from K^0-oscillation

Flavor changing neutral current (FCNC)



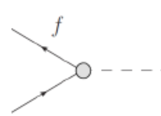




FG, PRL 113, 261803

$$0.4 \lesssim |Y_d/Y_d^{\mathrm{SM}}| \lesssim 1.7$$ ← Best handle on Y_d

Need to consider light generations?

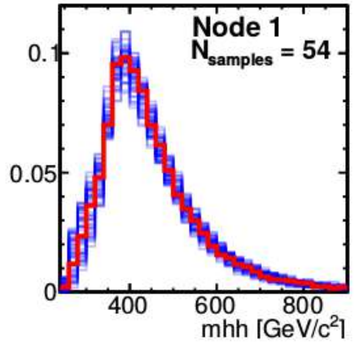


Motivated to neglect them

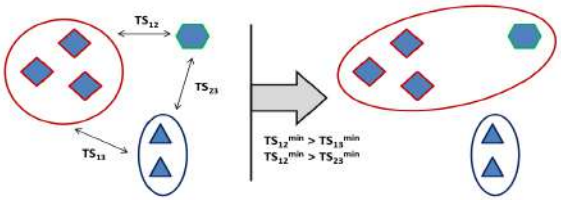
Higgs-Matter couplings ↔ Flavor Physics

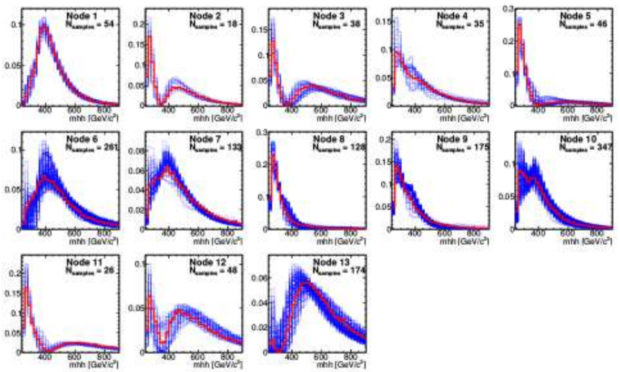
Enhance Sensitivity: Consider Distributions

- Optimize hh analysis to kinematical properties
  [Collaboration with Experimentalists started (CMS)]
  Dall'Osso, Dorigo, FG, Gottardo, Oliveira, Tosi, 1507.02245 (JHEP)



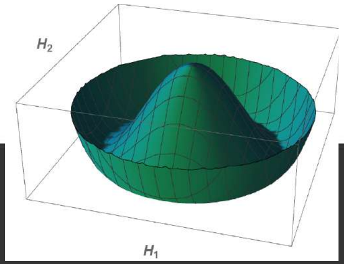
- Huge task to probe full parameter space!!
  → Cluster with respect to resulting distributions...





Leading contributions to unravel V(H)

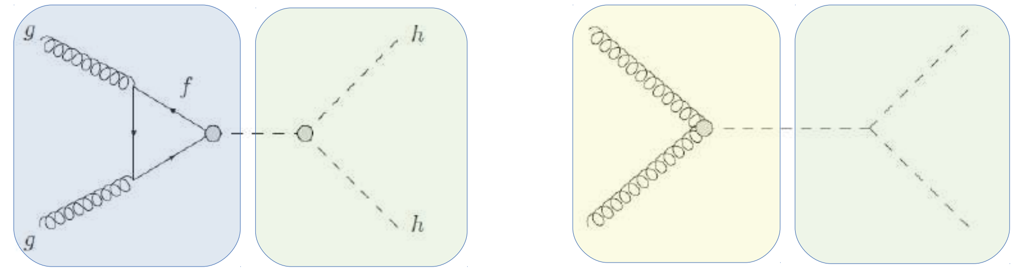
Still a lot to explore
in the future!



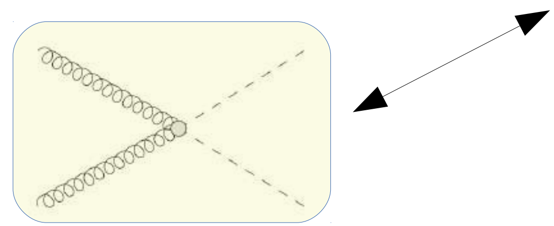
Higgs-Pair Production in gg-fusion

EWSB → Relevant Terms:

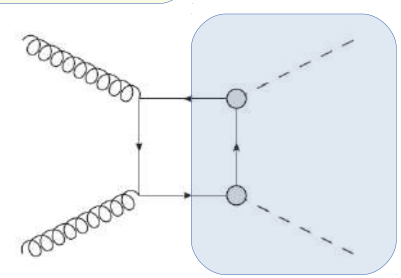
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right) h^3$$



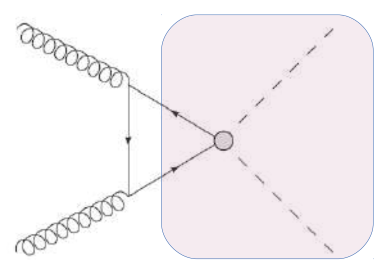
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G_a^{\mu\nu}$$



$$-\left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \text{h.c.}\right]$$



$$-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$



$c_i \to c_i\, \Lambda^2/v^2$

Higgs Decays in D=6 EFT

Mode	tree	1 loop QCD	1 loop
$h \to bb$	$c_H,\ c_b$	$\cancel{c_H,\ c_b}$	c_H, c_b, c_t, c_6, c_W
$h \to \tau\tau$	$c_H,\ c_\tau$	-	c_H, c_τ, c_6, c_W
$h \to \gamma\gamma$	c_γ		$c_H, c_b, c_t, c_\tau, c_W$
$h \to WW$	$c_H,\ \cancel{c_{HW},\ c_W}$	-	$c_H, c_W, c_b, c_t, c_\tau, c_6$
...			
$gg \to hh$	c_g	$c_t,\ c_b$	$c_t,\ c_b,\ c_H,\ c_6$
$gg \to h$	c_g	$c_t,\ c_b,\ c_H$	$c_t,\ c_b\ ,c_H$

Loop + $1/\Lambda^2$ suppressed wrt SM

Bold coefficients included in FG, Papaefstathiou, Yang, Zurita, 1410.3471

Don't include suppressed (loop) operators in loop topologies

Focus on

$\boxed{hh \to b\bar{b}\tau^+\tau^-}$ → 6 Parameters: $\{c_6, c_H, c_t, c_b = c_\tau, c_g, c_\gamma\}$

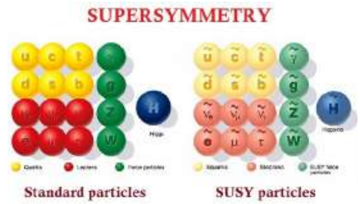
@LHC14

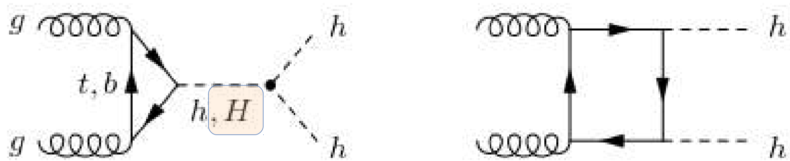
Unique accessibility in hh production!

$\mathcal{O}_{W,B,HW,HB} \in \mathcal{O}_{WW}$

New Physics in HH Production

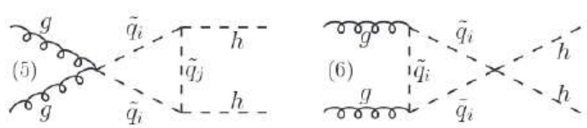
- SUSY





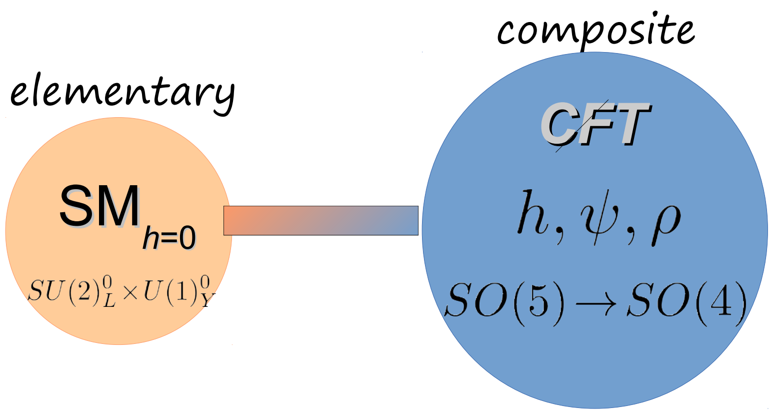
$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta+\alpha) + 3\frac{\epsilon}{m_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha,$$

$$\lambda_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha\cos(\beta+\alpha) + 3\frac{\epsilon}{m_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha,$$

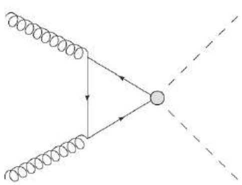


case	model	$\tan\beta$	m_h (GeV)	A (TeV)	μ (TeV)	σ (fb)	dominant mode
1	MSSM	3	104	+1	−1	2000	$gg \to H \to hh$
2	MSSM	3	100	+1	−1	20	$gg \to hh$
3	MSSM	50	105	+1	+1	5000	$gg \to hh$
4	SM	-	105	-	-	40	$gg \to hh$

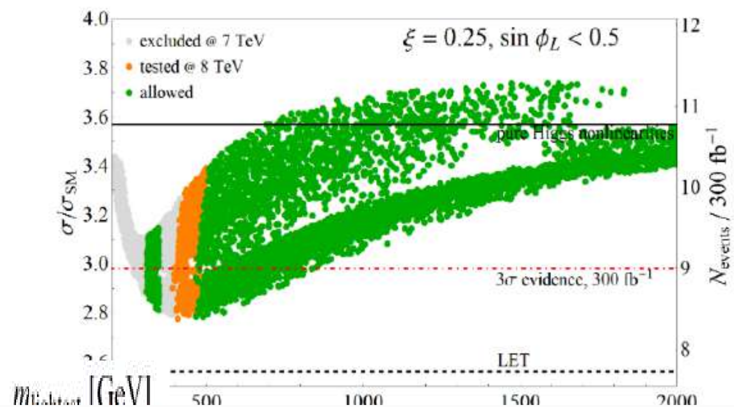
- Composite Higgs



$$\Sigma = U\,\Sigma_0\,,\ U = e^{i\frac{\sqrt{2}}{f_\pi}h_{\hat a}T^{\hat a}}$$



...



- etc...

Plehn, Spira, Zerwas, ph/9603205,
Djouadi, Kilian, Muhlleitner, Zerwas, ph/9904287,
Lafaye, Miller, Muhlleitner, Moretti, ph/0002238,
Cao, Heng, Shang, Wan, Yang, 1301.6437, ...

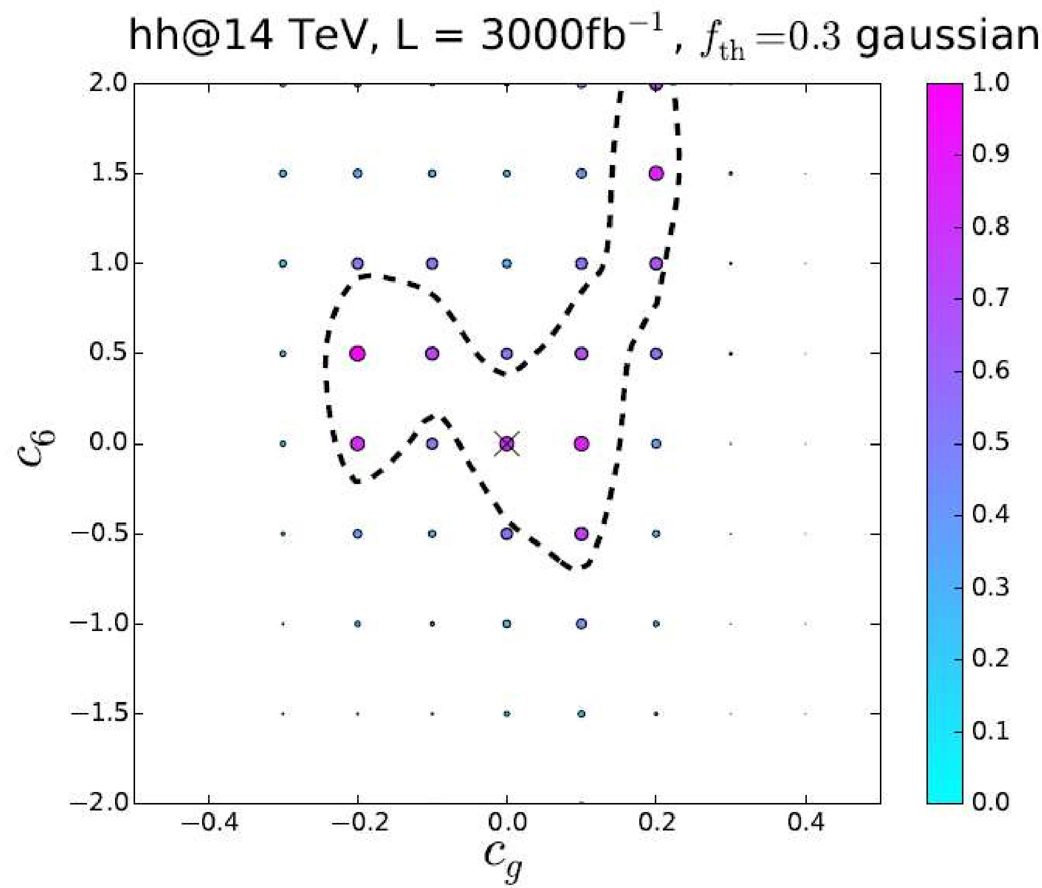
Gillioz, Grober, Grojean, Muhlleitner, Salvioni, 1206.7120,
Contino, Grojean, Moretti, Piccinini, Rattazzi, 1002.1011,
Grober, Muhlleitner, 1012.1562,
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, 1205.5444, ...

Backup: The H-Potential

$\boxed{\frac{c_6}{\Lambda^2}\lambda|H|^6}$ enters Higgs potential $\Rightarrow$ self couplings

$$V(h) = \frac{\mu^2}{2}(2hv + h^2) + \frac{\lambda}{4}(4hv^3 + 6h^2v^2 + 4h^3v + h^4)$$
$$+ \boxed{\frac{c_6\lambda}{8\Lambda^2}}(6hv^5 + 15h^2v^4 + 20h^3v^3 + 15h^4v^2) + \ \ldots$$

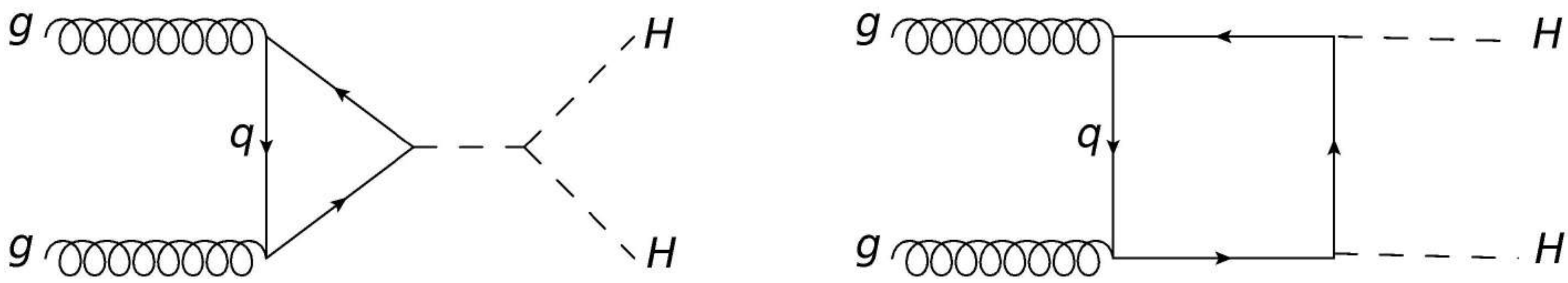
Backup: c_g-c_6



- Again compensation of effects from different operators possible
  → range for c_6 depends significantly on other coefficients

Backup: hh @ LHC

- Most important mechanism: $gg \to hh$



Eboli, Marques, Novaes, Natale, PLB 197(1987)269
Glover, van der Bij, NPB 309(1988)282
Dawson, Dittmaier, Spira, PRD 58(1998)115012
Grigo, Hoff, Melnikov, Steinhauser, 1305.7340
de Florian, Mazzitelli, 1305.5206, 1309.6594
see also Maltoni, Vryonidou, Zaro, 1408.6542

$$\sigma(gg \to hh)_{\mathrm{LO}} \sim 17\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NLO}} \sim 33\,\mathrm{fb}$$
$$\sigma(gg \to hh)_{\mathrm{NNLO}} \sim 40\,\mathrm{fb}$$

Theoretical error (NNLO): $f_{th} \sim$ 10% (scale) + 10% (pdf+α_s) + 10% (m_t^{-1})

LHC@14TeV
m_h ~125 GeV

Backup: The Higgs Potential

$$V(h) \approx \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi)\cos^2(h/f_\pi)$$

$$\boxed{\mathrm{EWSB} : \alpha - \beta = -2\beta \sin^2(v/f_\pi)}$$

→ general tuning: $\boxed{\Delta^{-1} \sim v^2/f_\pi^2}$
(a priori)

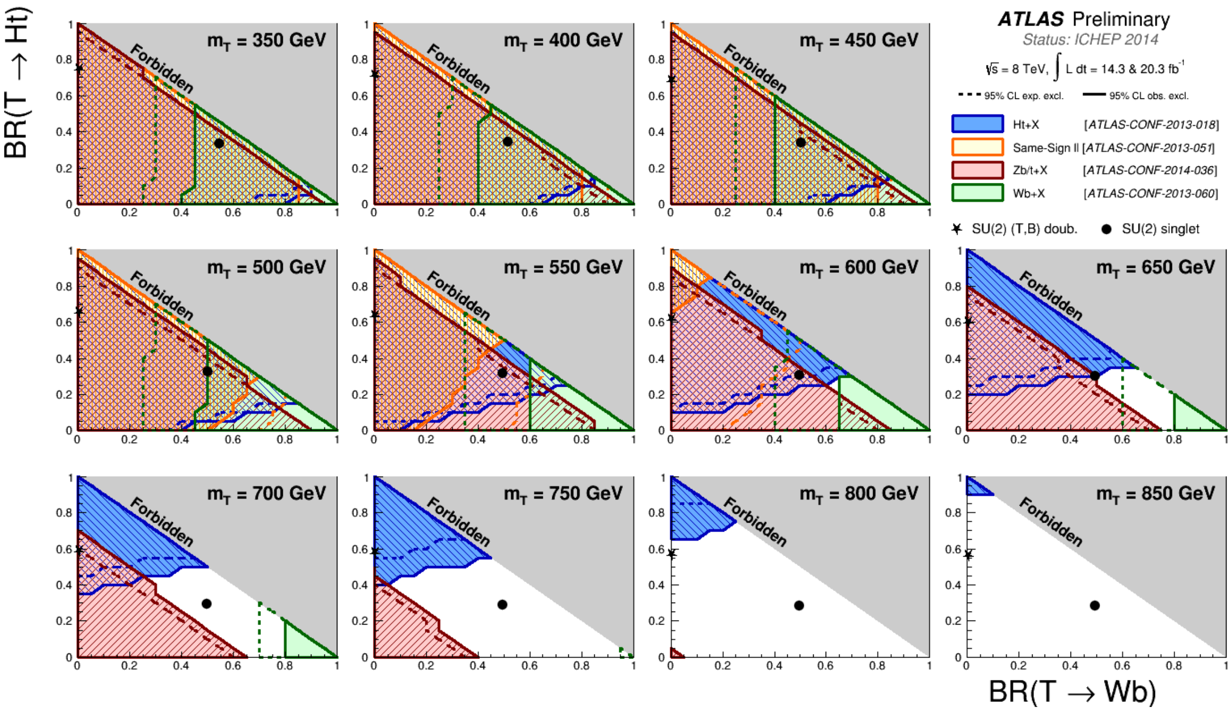
$v \approx 246\,\mathrm{GeV}$

$f_\pi \sim 1\,\mathrm{TeV}$

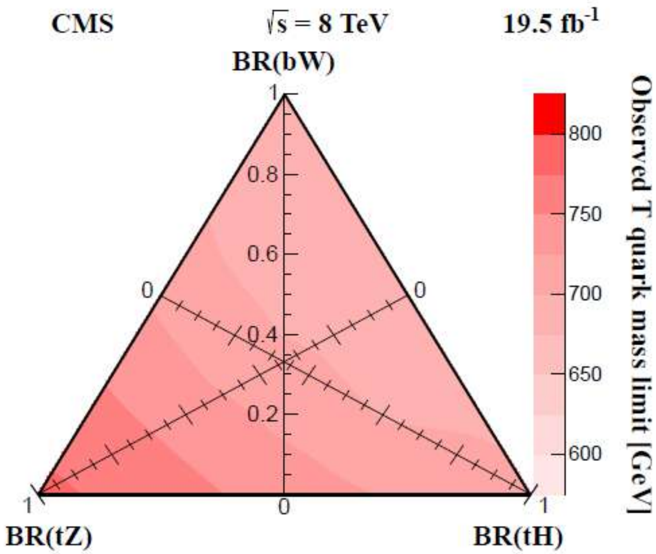
$$\boxed{m_H^2} = \frac{8}{f_\pi^2} \cos^2(v/f_\pi) \sin^2(v/f_\pi) \boxed{\beta}$$

$\beta_{\mathrm{gauge}} \approx 0$

Backup: Direct Searches



$m_{2/3}^{min} > 600$ GeV



Backup: Impact of Leptons

Motivation for large representation: 14_R ?

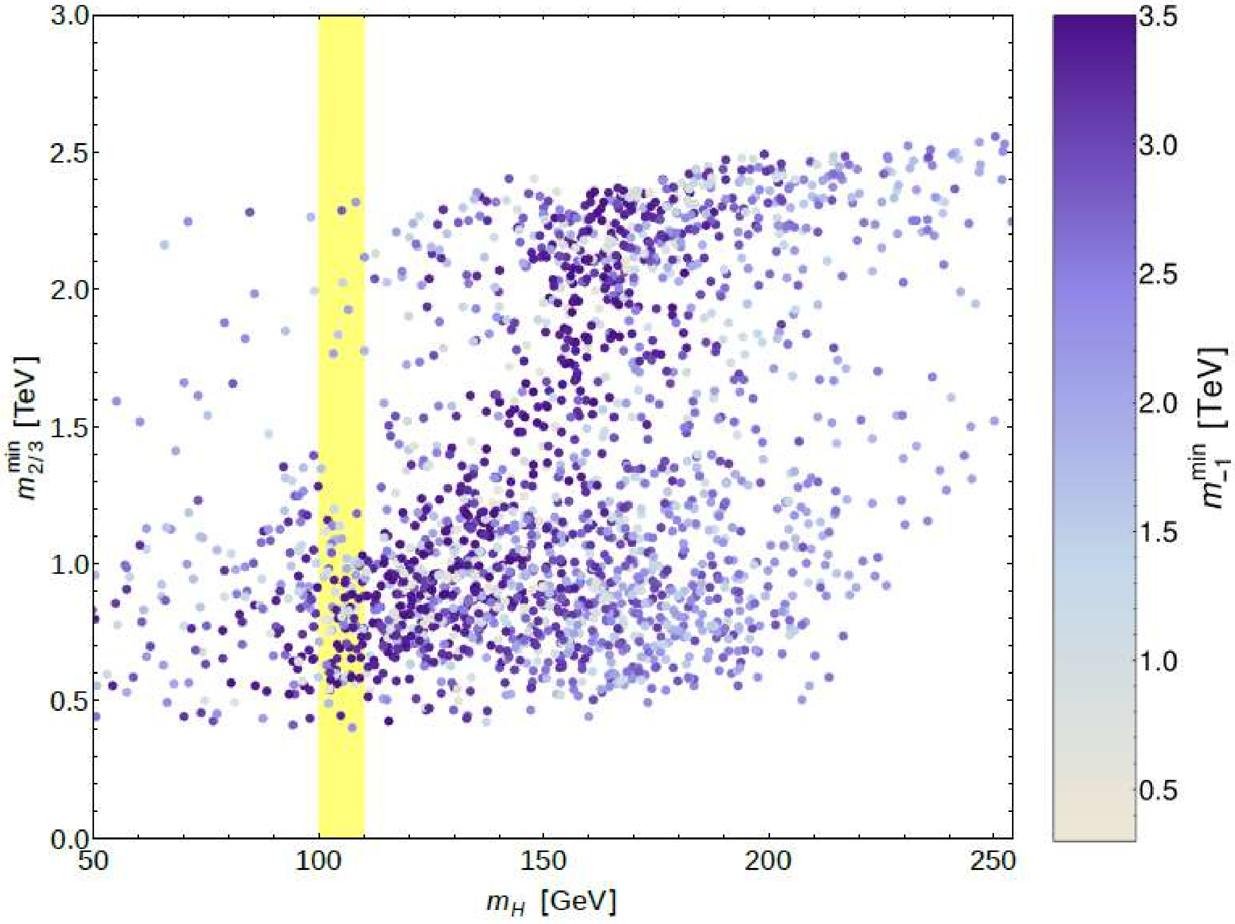
- Tiny neutrino masses → seesaw
- Type-III: $\ell_R \sim \mathbf{1_{-1}},\ l_L \sim \mathbf{2_{-1/2}},\ \Sigma_R \sim \mathbf{3_0}$

$$\xi_{2\tau} = \tau_2'[-,-] \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix} \oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

- Unification of RH lepton sector, compositeness dictated by seesaw!! $\mathrm{mMCHM^{III}}$

No such unification possible with type-I

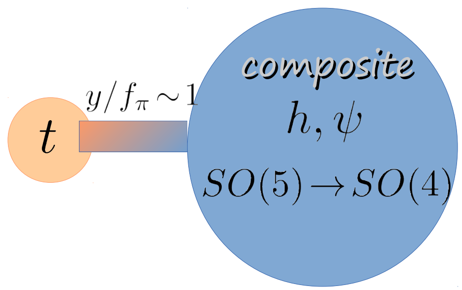
Backup: Tau Partner Mass

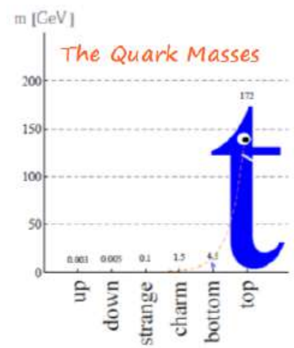


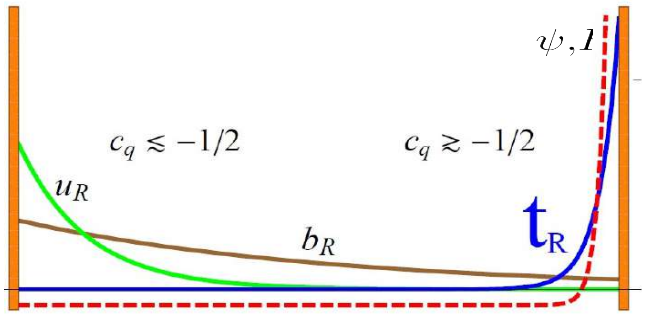
$$\mathrm{MCHM}_5^{5-14} \text{ with } f_\pi = 800\,\mathrm{GeV},\;\; Y_*^q = 0.7, Y_*^l = 0.35$$

Backup: (Indirect) Signatures of Composite/Warped Models

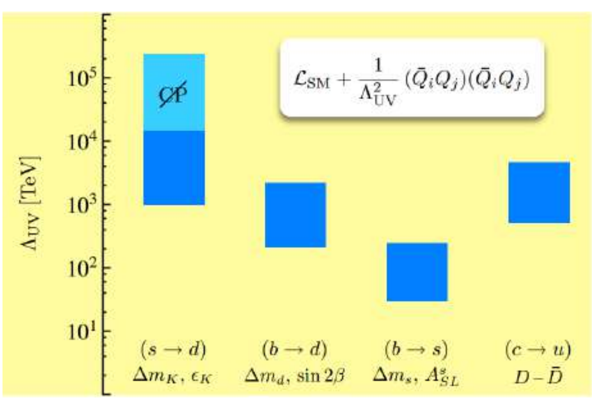
- Interesting signatures in Higgs Physics and Flavor Physics (3^{rd} generation!)







Neubert, EPS 2011



Flavor

- Provides portal to very high energies!
- Closely related to Higgs Sector