Higgs Physics beyond the Standard Model: the case for heavy Higgs bosons and vector-like quarks

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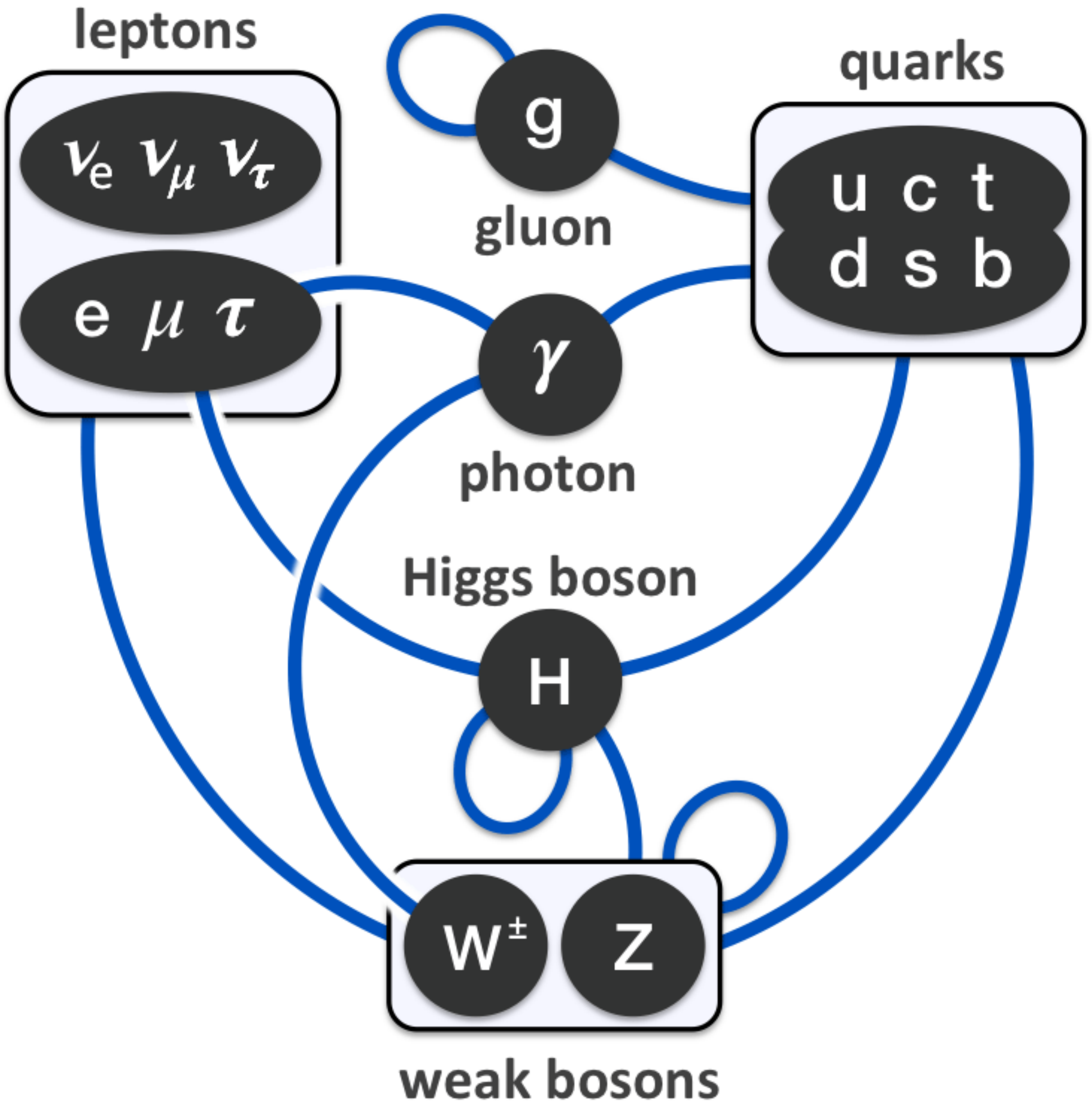
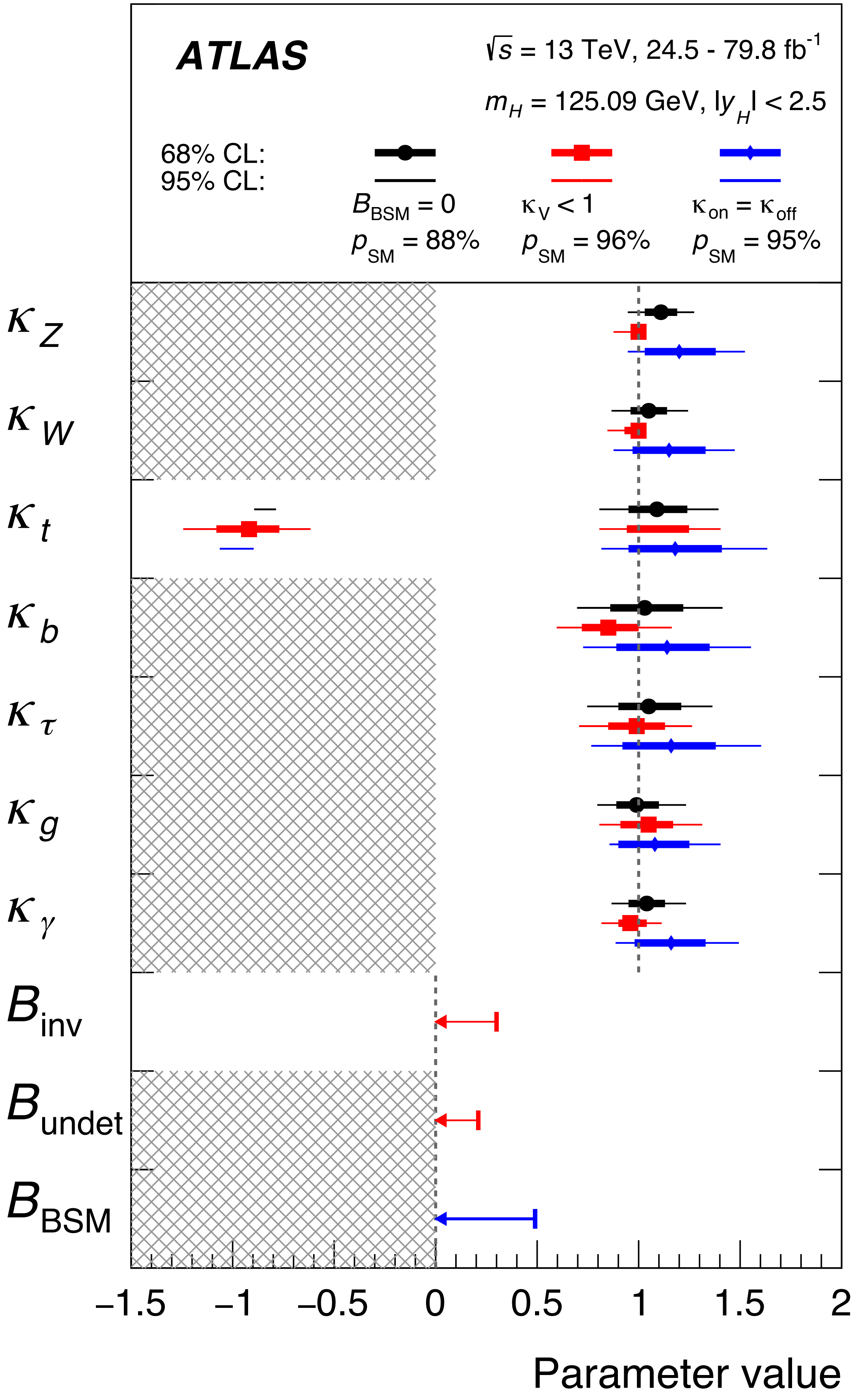
Outline

- The Standard Model and beyond
- Common denominator: Extended Higgs and matter sectors
- Cascade decays at the LHC - Based on collaboration with R. Dermisek, E. Lunghi, and S. Shin
- Understanding parameters in the SM within the MSSM with a vector-like family - Based on collaboration with R. Dermisek

The Standard Model



$$
\begin{gathered}
\mathcal{L}_{\mathrm{StandardModel}} = \\
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g^2_s (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c^2_w} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2} g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s^2_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \\
\bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s^2_w - \\
1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s^2_w - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + \\
m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u^\kappa_j] - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
\tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c^2_w}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w} \bar{X}^0 X^0 H] + \\
\tfrac{1-2c^2_w}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0].
\end{gathered}
$$



$$\Gamma_H(\kappa, B_{inv}, B_{undet}) = \kappa_H^2(\kappa, B_{inv}, B_{undet})\Gamma_H^{SM}$$

$$\kappa_H^2(\kappa, B_{inv}, B_{undet}) = \frac{\sum_j B_f^{SM}\kappa_j}{(1 - B_{inv} - B_{undet})}$$

From: ATLAS

- arXiv:1909.02845

Are we done?

Are we done?

- Hierarchy problems: Yukawa couplings, mixings, Higgs mass
- Number of fermions generations
- Neutrino masses
- Dark Matter
- muon g-2
- Higgs self-interactions
- …

Abundance of Models beyond the SM

- Supersymmetry
- Composite Higgs
- Randall-Sundrum/ extra dimensions
- Twin Higgs
- GUTs
- …

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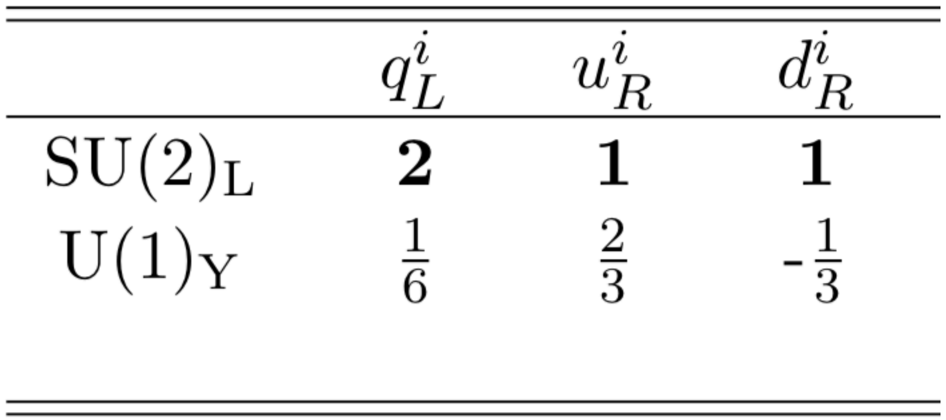
Common features in most cases: Heavy Higgs bosons and vector-like fermions

Common denominator: Extended Higgs and matter sectors

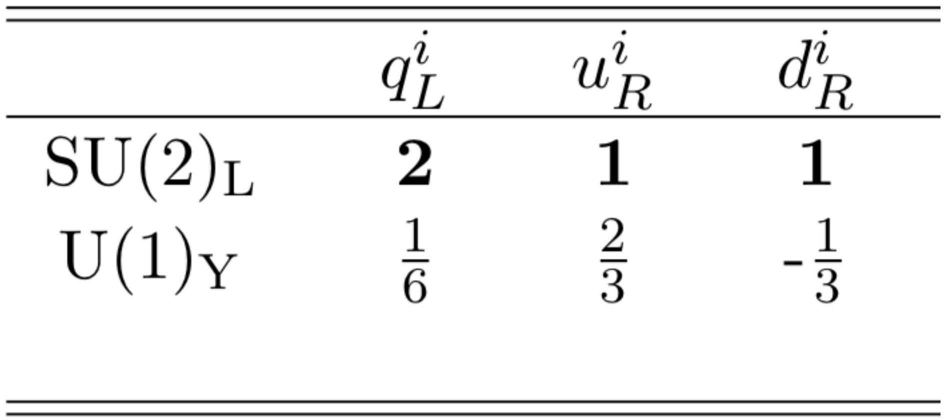
SM quarks



	q_L^i	u_R^i	d_R^i
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	-$\frac{1}{3}$

Common denominator: Extended Higgs and matter sectors

SM quarks

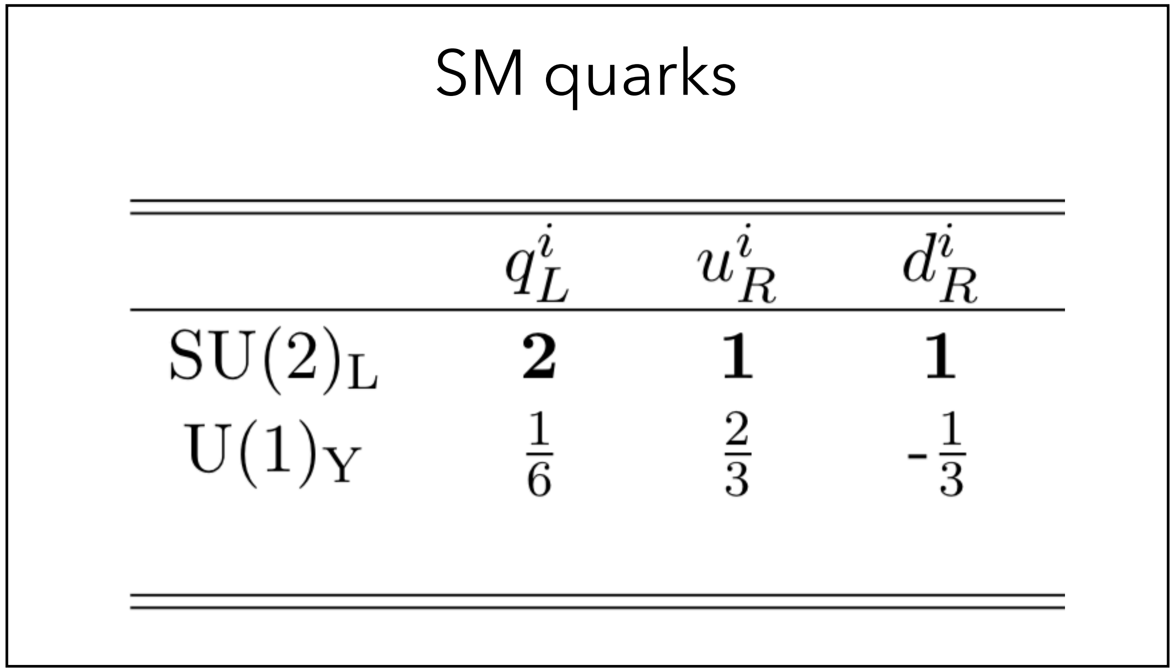


	q_L^i	u_R^i	d_R^i
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$

$\longrightarrow$

$$\mathscr{L} \supset \psi_L \psi_R$$

Common denominator: Extended Higgs and matter sectors



SM quarks

	q_L^i	u_R^i	d_R^i
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	-$\frac{1}{3}$

→

$$\mathscr{L} \cancel{\supset \psi_L \psi_R}$$

$$\mathscr{L} \supset \psi_L \psi_R H$$ ✓

Common denominator: Extended Higgs and matter sectors

SM quarks

	q_L^i	u_R^i	d_R^i
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
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→

$$\cancel{\mathscr{L} \supset \psi_L \psi_R}$$

$$\mathscr{L} \supset \psi_L \psi_R H$$ ✓

Vector-like quarks

$Q_{L,R}$	$T_{L,R}$	$B_{L,R}$
$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$\frac{1}{6}$	$\frac{2}{3}$	-$\frac{1}{3}$

$$\mathscr{L} \supset Q_L Q_R$$ ✓

Common denominator: Extended Higgs and matter sectors

Many choices for extended Higgs sectors:

- Singlets

- Doublets

Good choice common for interesting pheno and BSM models:
2HDM

H_d	H_u
$\mathbf{2}$	$\mathbf{2}$
$\frac{1}{2}$	-$\frac{1}{2}$

Vectorlike leptons also possible, many studies available:

- R. Dermisek, E. Lunghi, S. Shin - JHEP 1610 (2016) 081
- R. Dermisek, E. Lunghi, S. Shin - JHEP 1605 (2016) 148
- R. Dermisek, E. Lunghi, S. Shin - JHEP 1602 (2016) 119

2HDM & Higgs decays

- R. Dermisek, A. Raval, S. Shin - Phys.Rev. D90 (2014) no.3, 034023
- R. Dermisek, A. Raval - Phys.Rev. D88 (2013) 013017

g-2 anomaly &
Collider pheno

- P. Bhattiprolu, S. Martin - Phys.Rev. D100 (2019) no.1, 015033
- N. Kumar, S. Martin - Phys.Rev. D92 (2015) no.11, 115018

Collider pheno w VLL

Model for this presentation:

	q_L^i	u_R^i	d_R^i	$Q_{L,R}$	$T_{L,R}$	$B_{L,R}$	H_d	H_u
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{Z_2}$	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$+$

Model for this presentation:

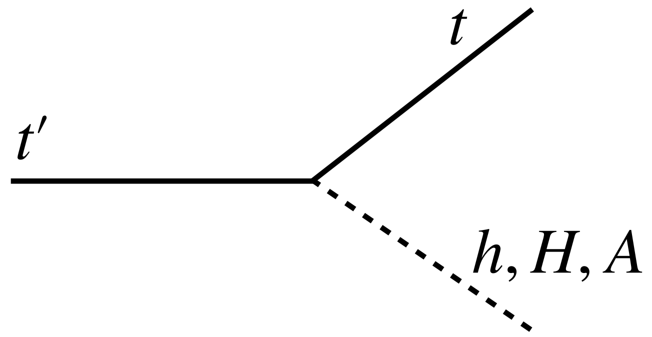
	q_L^i	u_R^i	d_R^i	$Q_{L,R}$	$T_{L,R}$	$B_{L,R}$	H_d	H_u
$\mathrm{SU(2)_L}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{Z_2}$	$+$	$+$	$-$	$+$	$+$	$-$	$-$	$+$

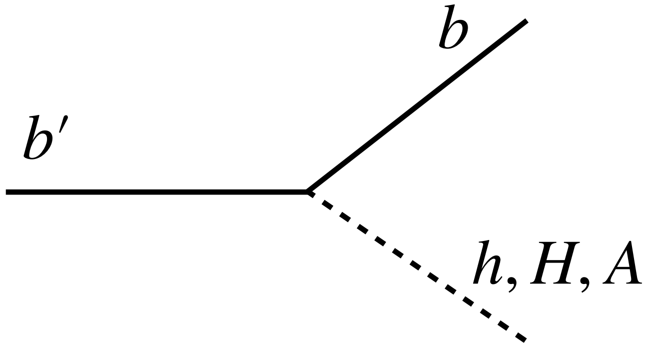
Most general Lagrangian under these assumptions:

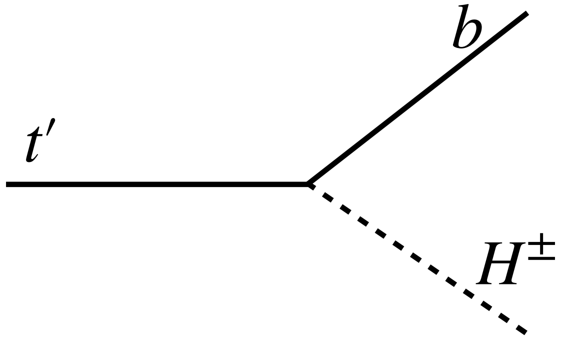
$$
\begin{aligned}
\mathcal{L} \supset\; & - y_d^{ij} \bar{q}_L^i d_R^j H_d - \lambda_B^i \bar{q}_L^i B_R H_d - \lambda_Q^j \bar{Q}_L d_R^j H_d - \lambda \bar{Q}_L B_R H_d - \bar{\lambda} H_d^\dagger \bar{B}_L Q_R \\
& - y_u^{ij} \bar{q}_L^i u_R^j H_u - \kappa_T^i \bar{q}_L^i T_R H_u - \kappa_Q^j \bar{Q}_L u_R^j H_u - \kappa \bar{Q}_L T_R H_u - \bar{\kappa} H_u^\dagger \bar{T}_L Q_R \\
& - M_Q \bar{Q}_L Q_R - M_T \bar{T}_L T_R - M_B \bar{B}_L B_R + \text{h.c.}\;,
\end{aligned}
$$

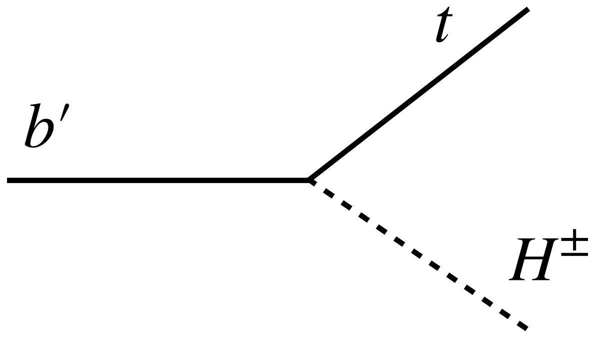
See: Dermisek, Lunghi, and Shin JHEP 1904 (2019) 019, for more details

Mixing induced decays:

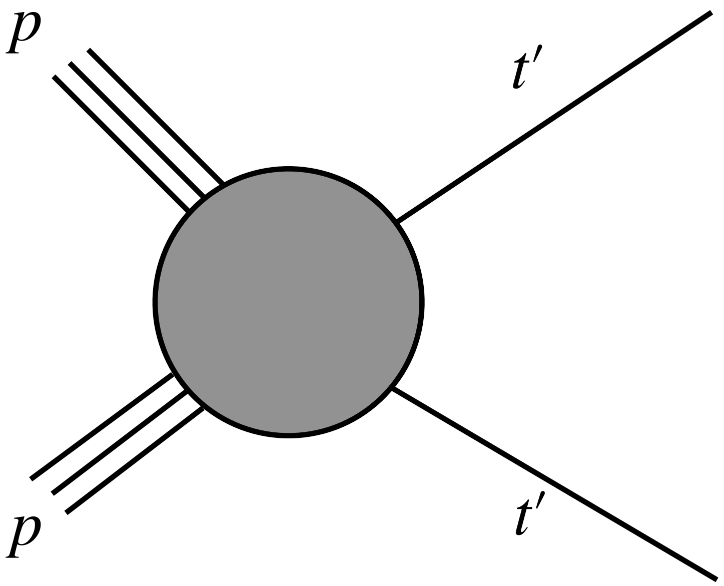


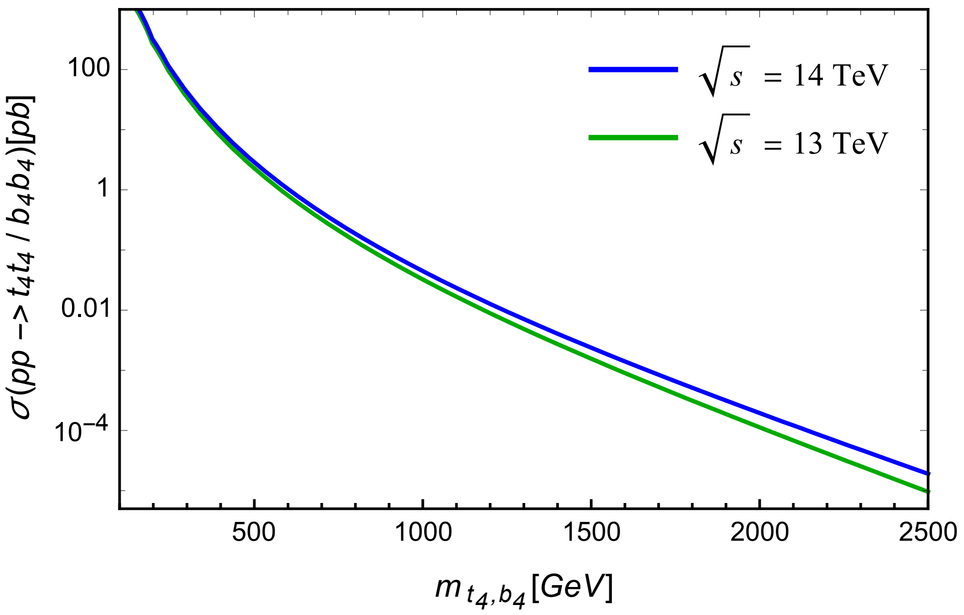




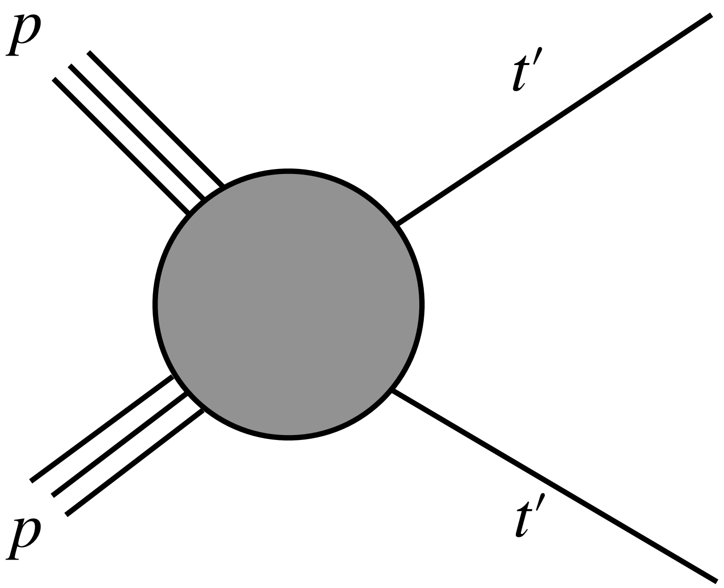


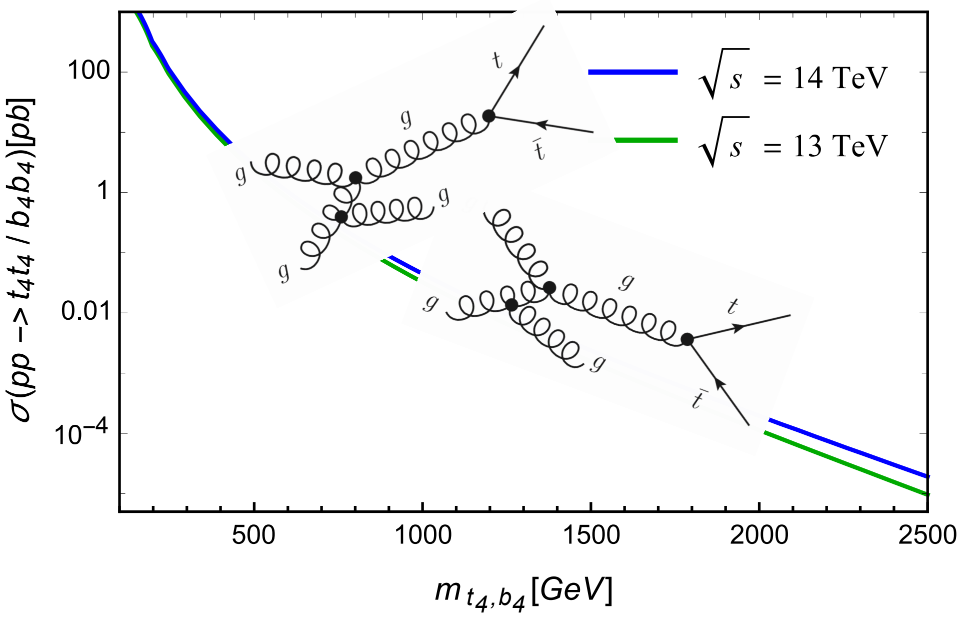
New opportunities to search for VLQ at LHC:



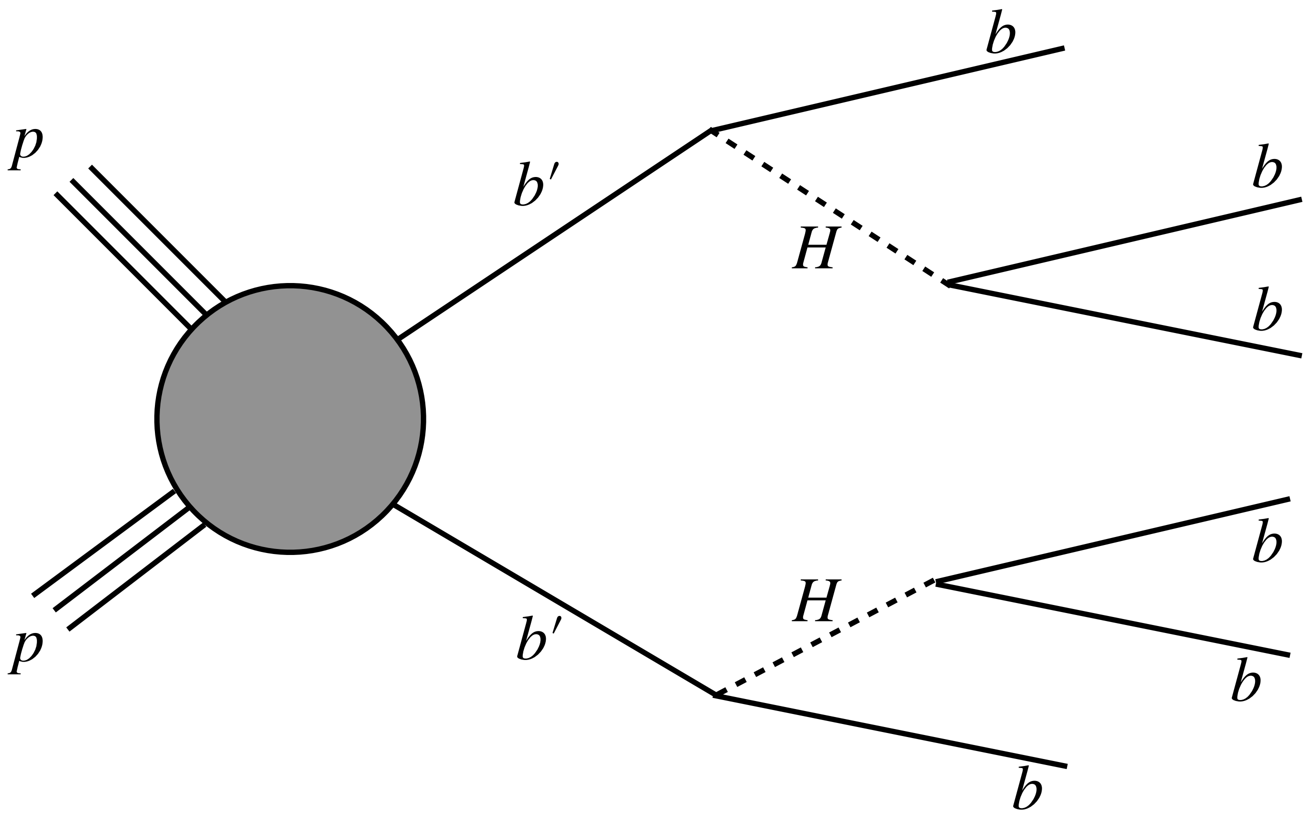


New opportunities to search for VLQ at LHC:



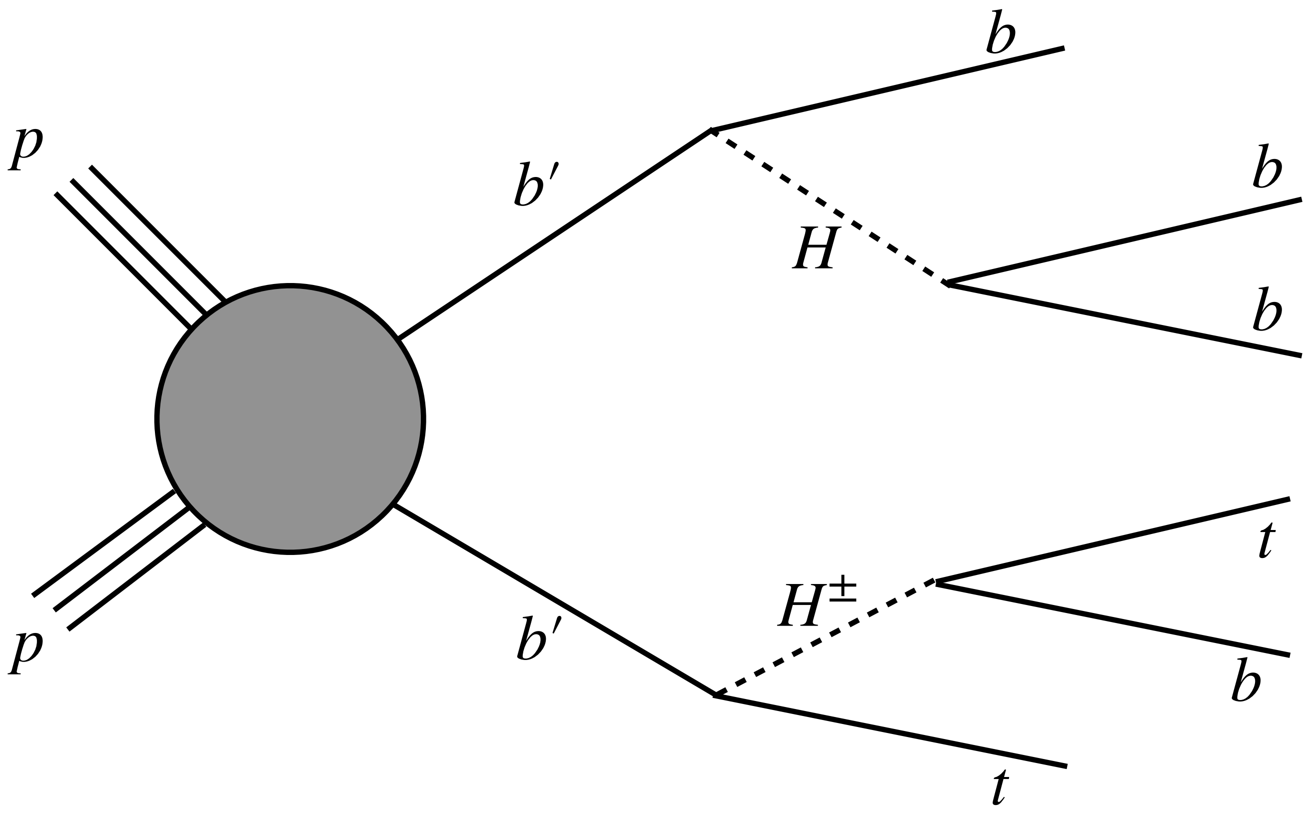


New opportunities to search for VLQ at LHC:

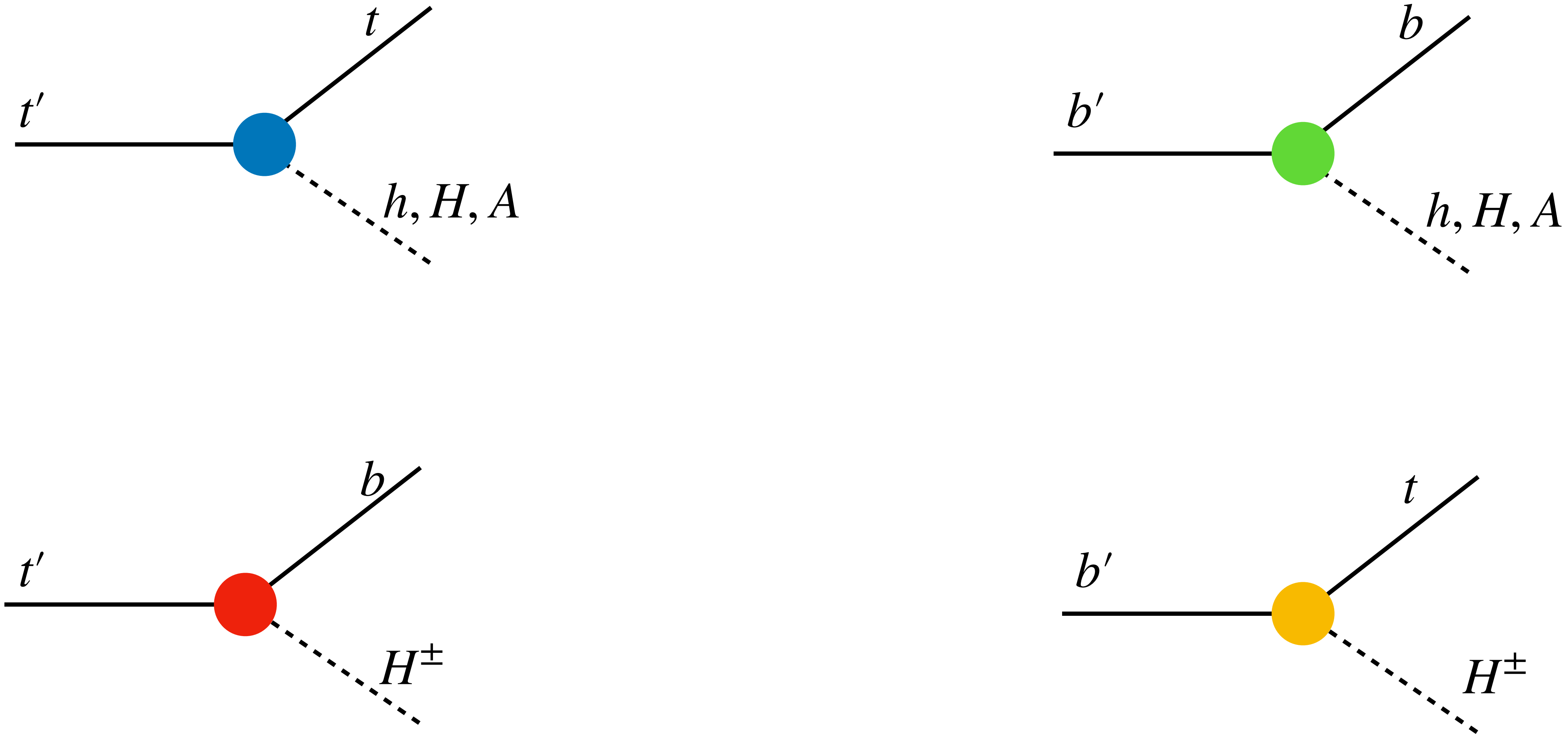


Similar signal for 6 tops, see: T. Tait et. al. - JHEP 1910 (2019) 008

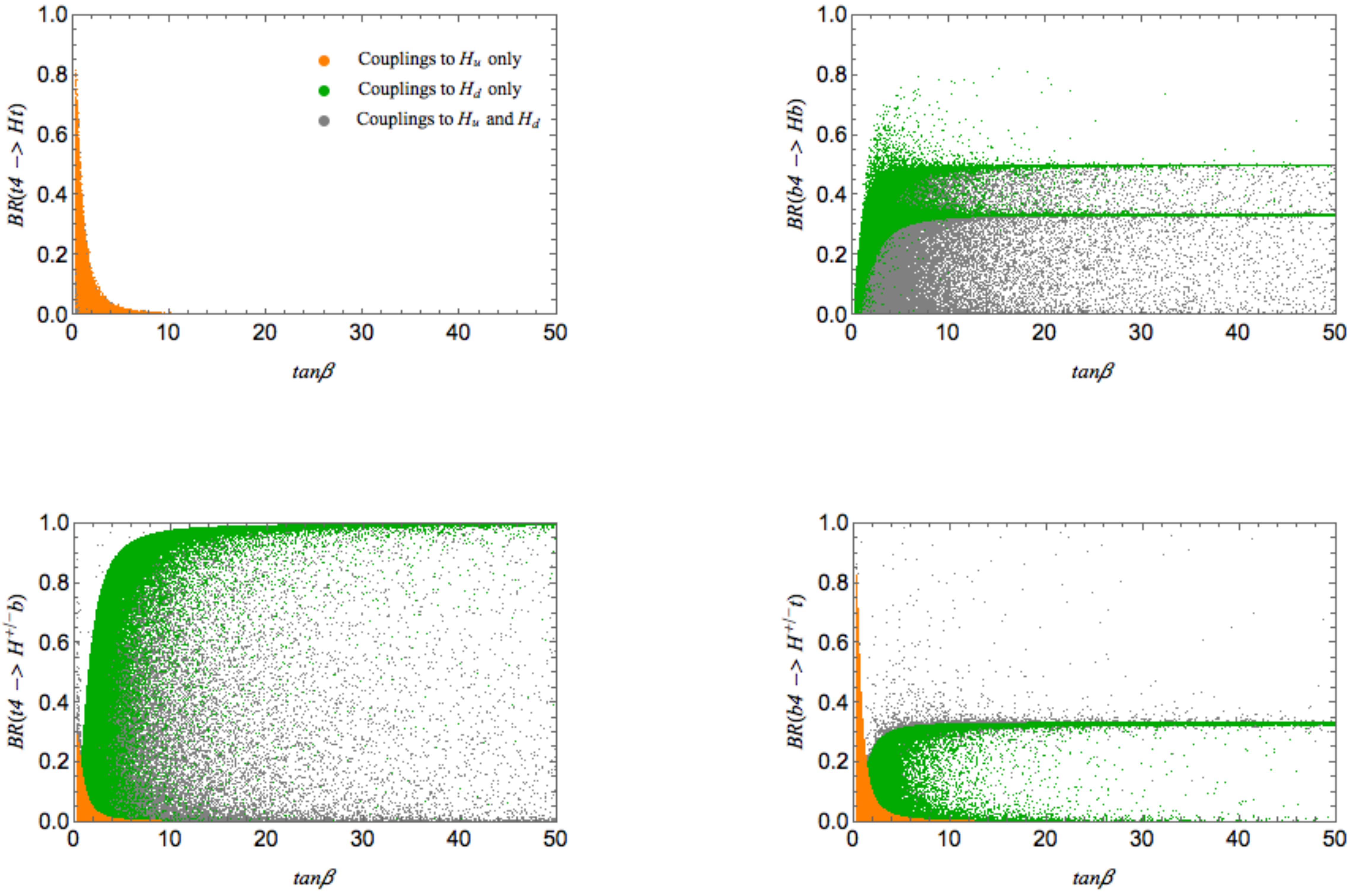
New opportunities to search for VLQ at LHC:



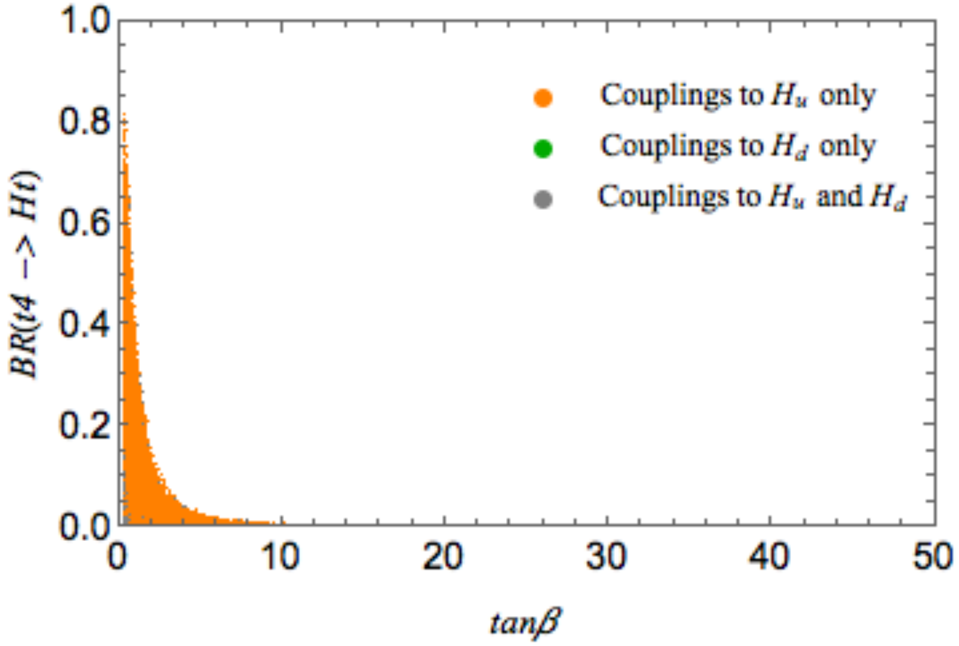
Branching ratios?

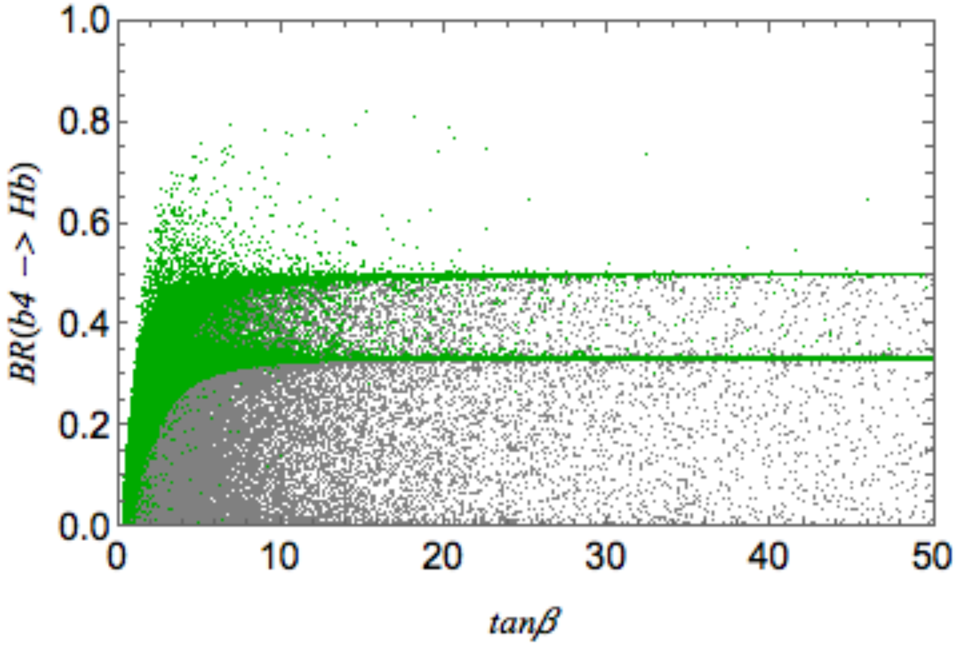


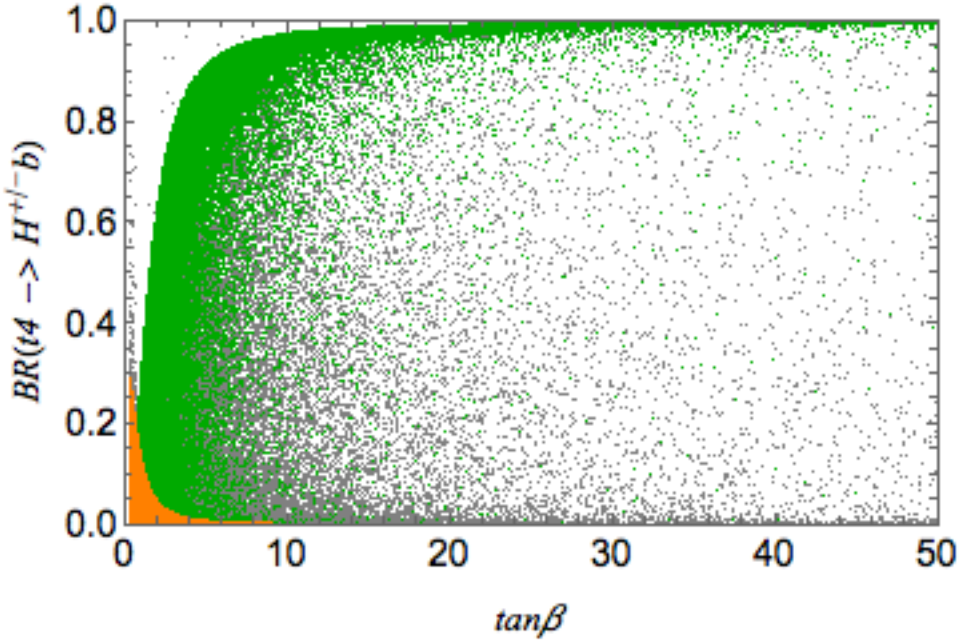
$BR =$ (🔴 + 🔵 + Z + W) / Γ

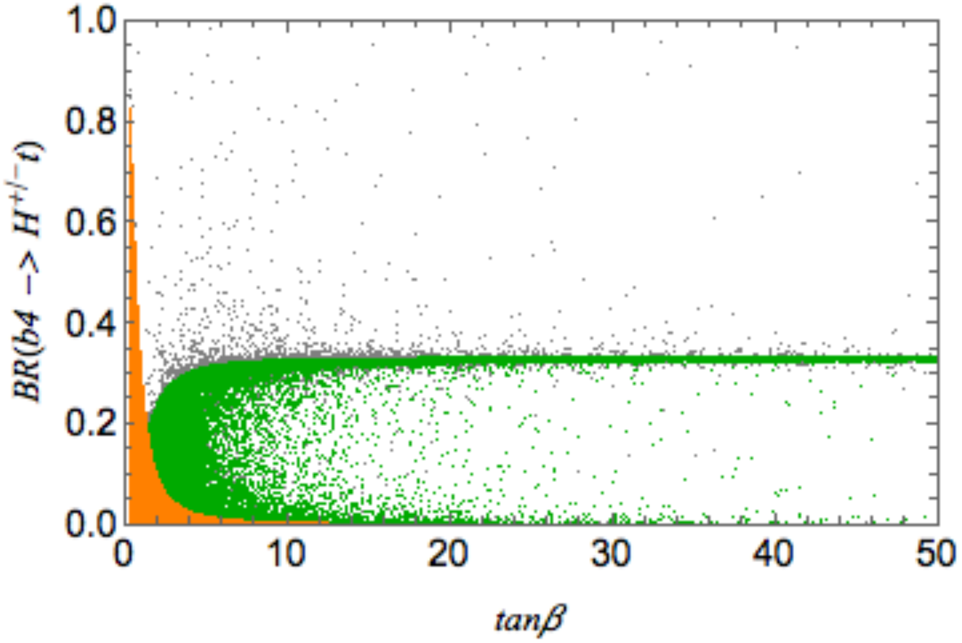


$t_4, b_4 \rightarrow$ Any Higgs Allowed



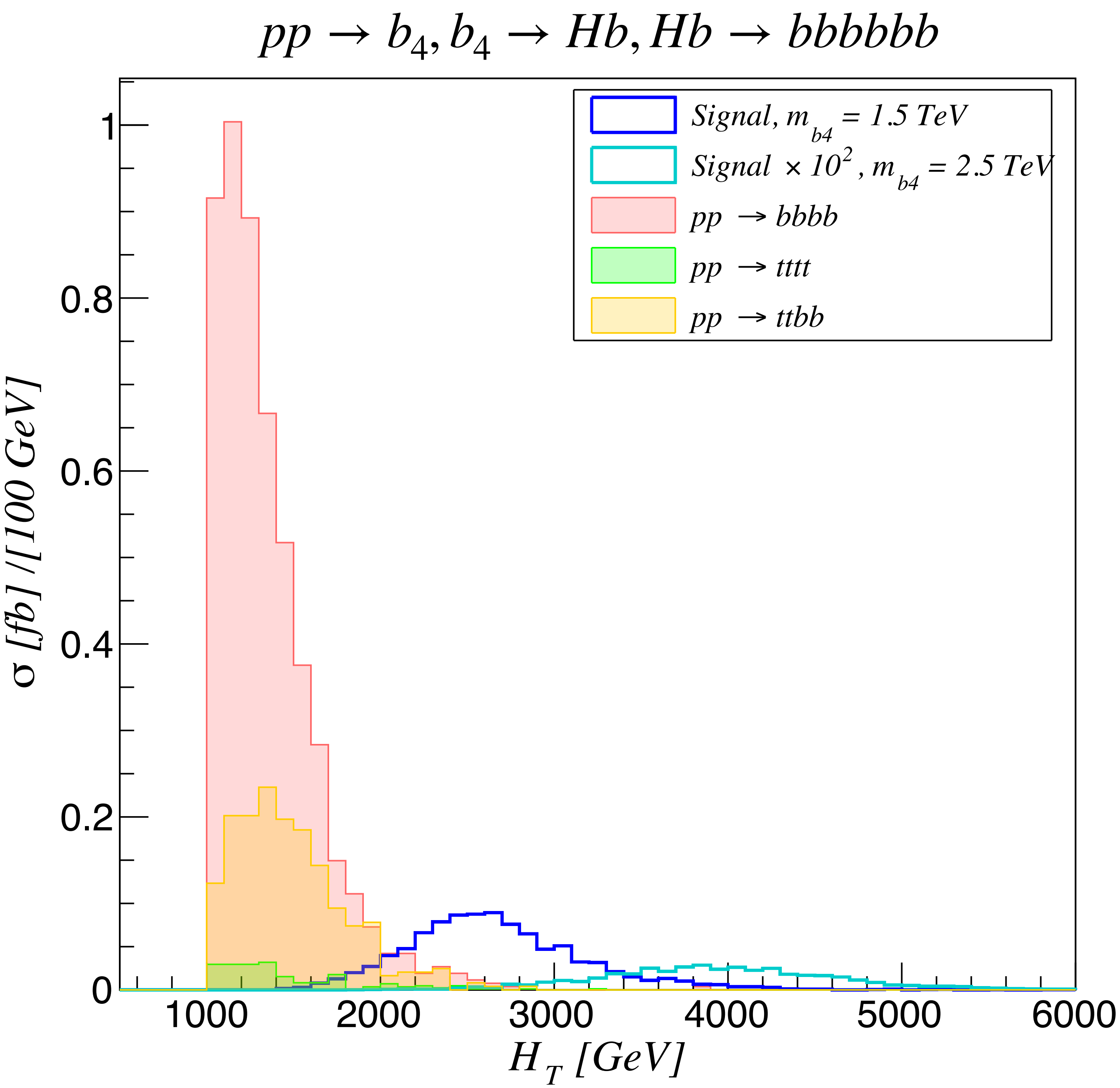






Limits on t_4 pair production strongly constrained by multi-lepton searches.

VL - b quarks less so….



$$H_T = \sum_{visible} |P_T|$$

SUSY Models with VL fermions

- Extending MSSM to raise the Higgs mass
  - S. Martin - Phys.Rev. D81 (2010) 035004
  - K. Babu, et. al. - Phys.Rev. D78 (2008) 055017

    - Yukawa couplings of VLM coupled to Higgs can help raise m_h in SUSY

    - focused on perturbative unification: MSSM + $5 \oplus \overline{5}$, or MSSM + $10 \oplus \overline{10}$,

    $\Rightarrow \beta_{\alpha_3} < 0$

  - Dermíšek - Phys.Rev. D95 (2017) no.1, 015002

    - Mixing with MSSM scalars can raise m_h without the need for heavy stops

Extending models with VL fermions offers scenarios where low energy parameters can be understood from particle content

In MSSM + 1VF, the seven largest couplings of the SM

$$\alpha_{1,2,3}, y_{t,b,\tau}, \lambda_H$$

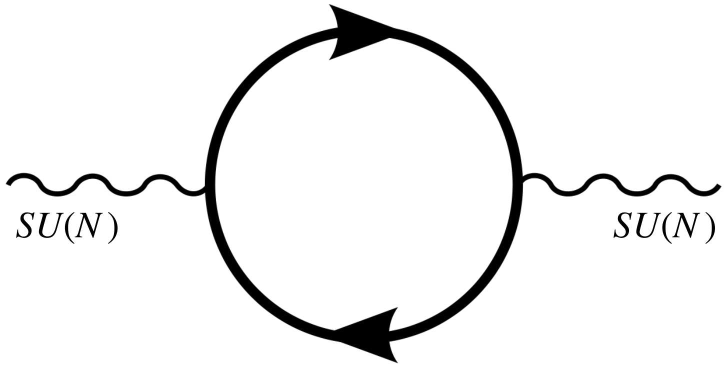
can be understood from IR fixed points of the model

Based on Dermisek & NM: Phys.Rev. D97 (2018) no.5, 055009, Phys.Rev. D99 (2019) no.3, 035033, Phys.Rev.Lett. 122 (2019) no.18, 181803

Alternatives to GUTs:

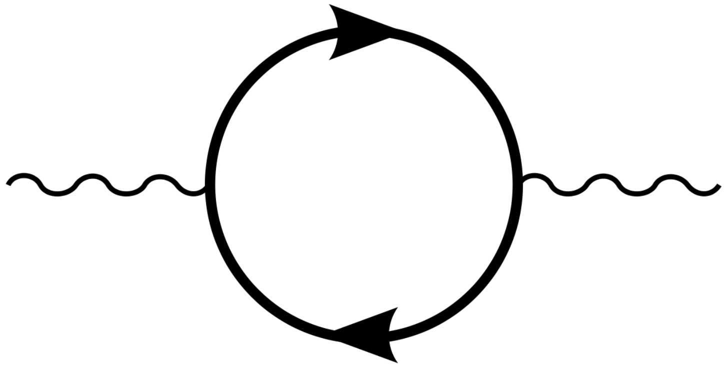
- Pattern of low energy couplings emerges from the structure of RG flow, depending very little on BC’s from high scale physics
  - Maiani, Parisi, Petronzio (1978) ~ gauge couplings in EW
  - Pendleton-Ross/Hill fixed point (1981) ~ fermion masses in SM/2HDM
  - Bardeen, Carena, Pokorski, Wagner (1994) ~ top mass in MSSM

Weak scale parameters from IR fixed points:



$\propto n_F$

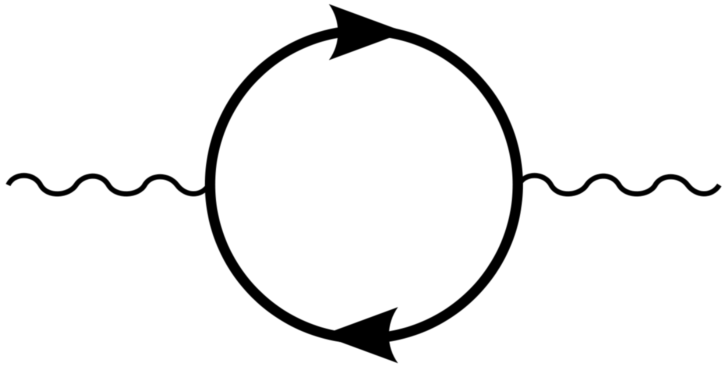
Weak scale parameters from IR fixed points:



$\propto n_F$

$$\beta^{1l}(g) = \frac{g^3}{16\pi^2}\left(-\frac{11}{3}N + \frac{2}{3}n_F\right)$$

Weak scale parameters from IR fixed points:



$\propto n_F$

$$\beta^{1l}(g) = \frac{g^3}{16\pi^2}\left(-\frac{11}{3}N + \frac{2}{3}n_F\right)$$

$$n_F > \frac{11}{2}N \quad \Rightarrow \quad \beta^{1l}(g) > 0$$

Weak scale parameters from IR fixed points: gauge couplings

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha^{-1}(M_G)$$

$$\alpha_i = \frac{g_i^2}{2\pi}$$

Weak scale parameters from IR fixed points: gauge couplings

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \cancelto{\sim 0}{\alpha^{-1}(M_G)}$$

$$\frac{\alpha_i(M_Z)}{\alpha_j(M_Z)} \simeq \frac{b_j}{b_i}$$

$$\alpha_i = \frac{g_i^2}{2\pi}$$

Weak scale parameters from IR fixed points: gauge couplings

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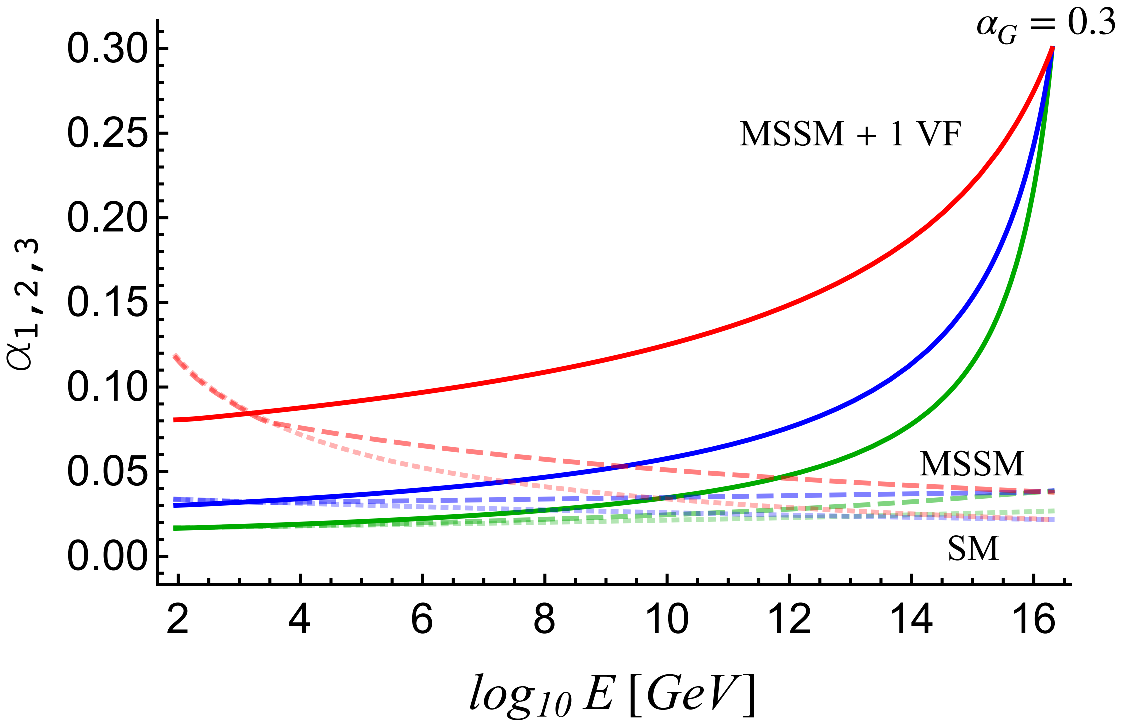


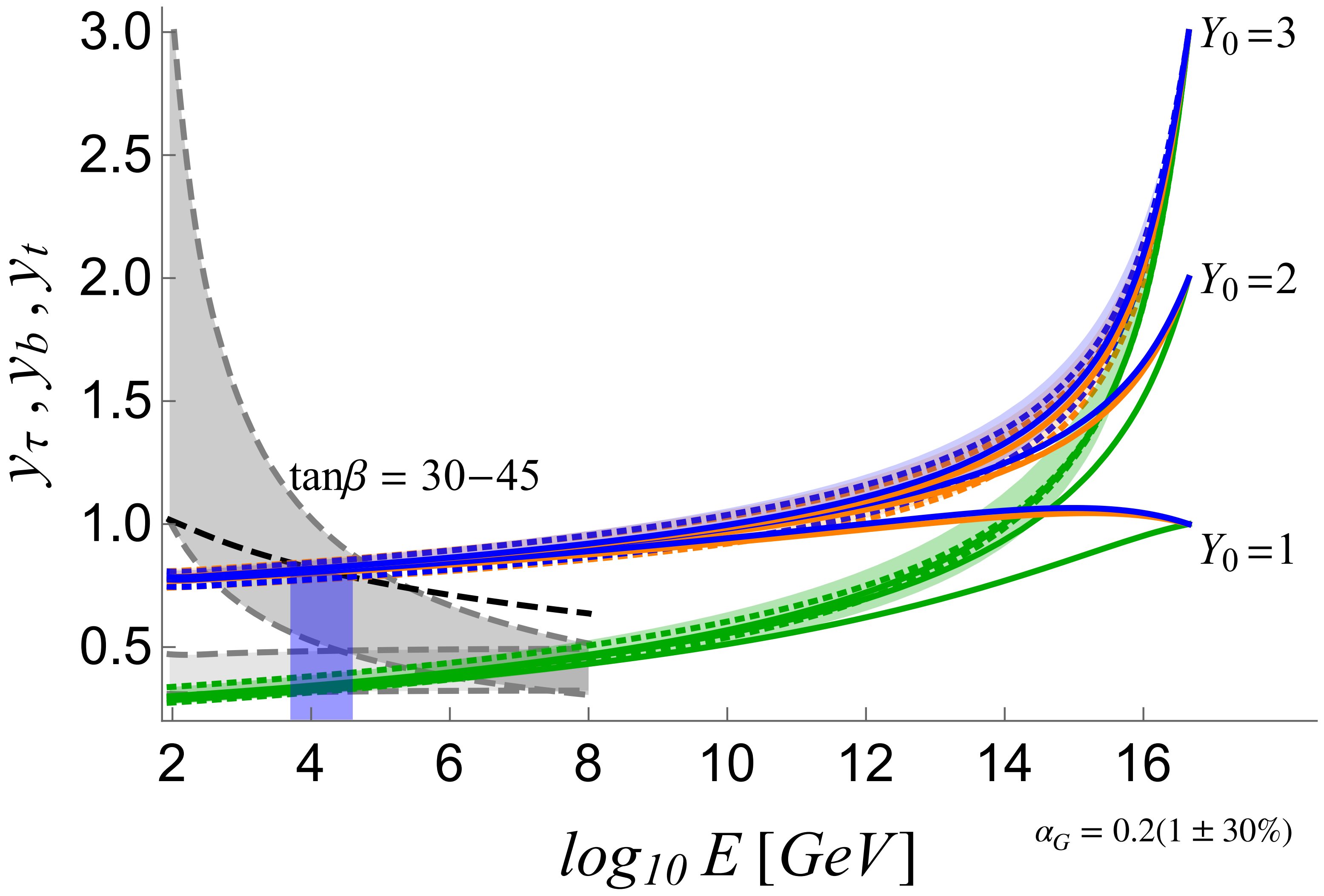
For MSSM + 1 VL family: $W \supset M_V 16\overline{16}$

$$\sin^2\theta_W \equiv \frac{\alpha'}{\alpha_2+\alpha'} \simeq \frac{b_2}{b_2+b'} = 0.2205$$

$$\alpha_i = \frac{g_i^2}{2\pi}$$

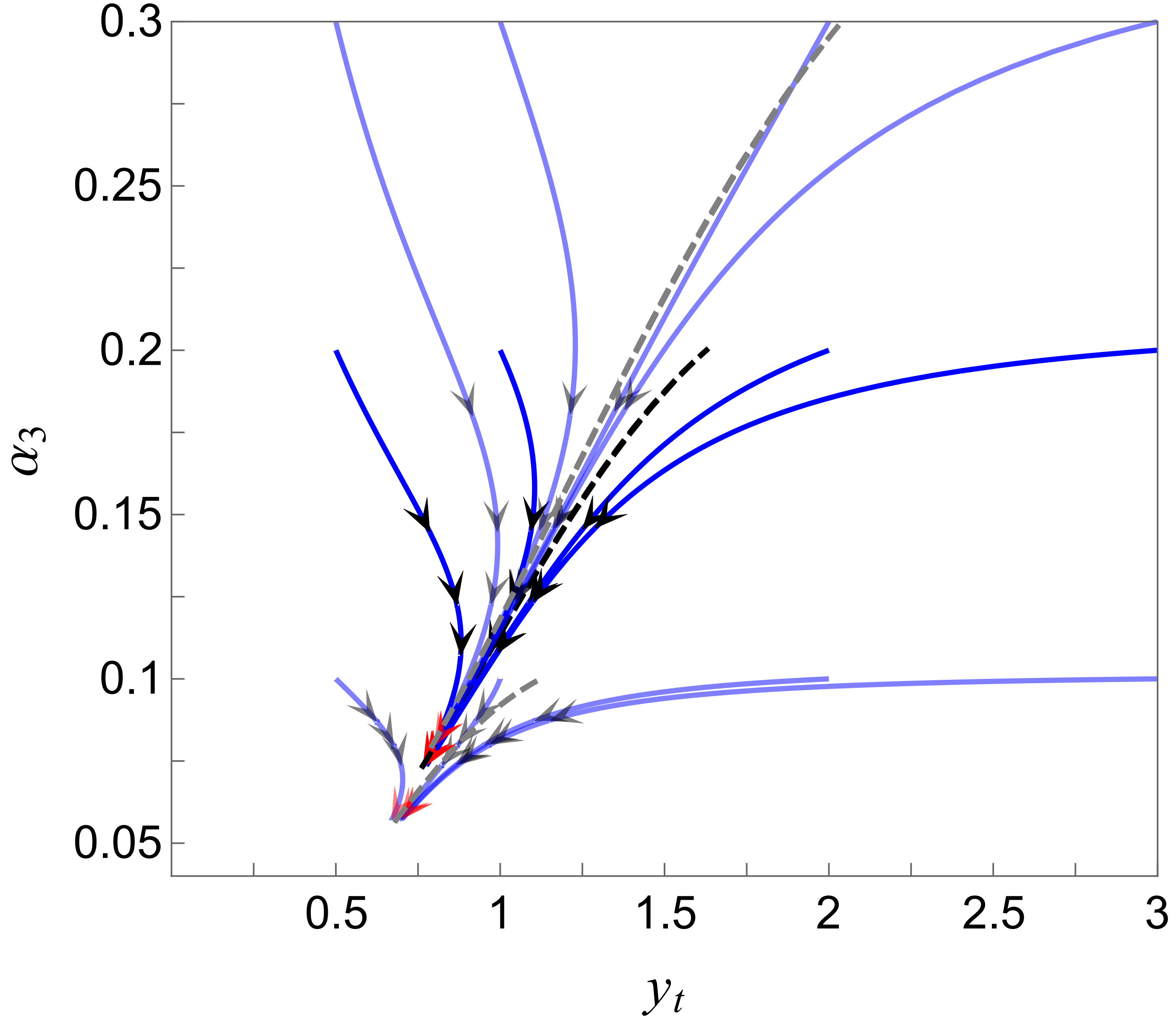
Weak scale parameters from IR fixed points: Yukawa couplings

$$W \supset Y_0 16_3 10_H 16_3 + Y_V 16 10_H 16 + \bar{Y}_V \bar{16} 10_H \bar{16} + M_V 16 \bar{16}$$



Weak scale parameters from IR fixed points: Yukawa couplings

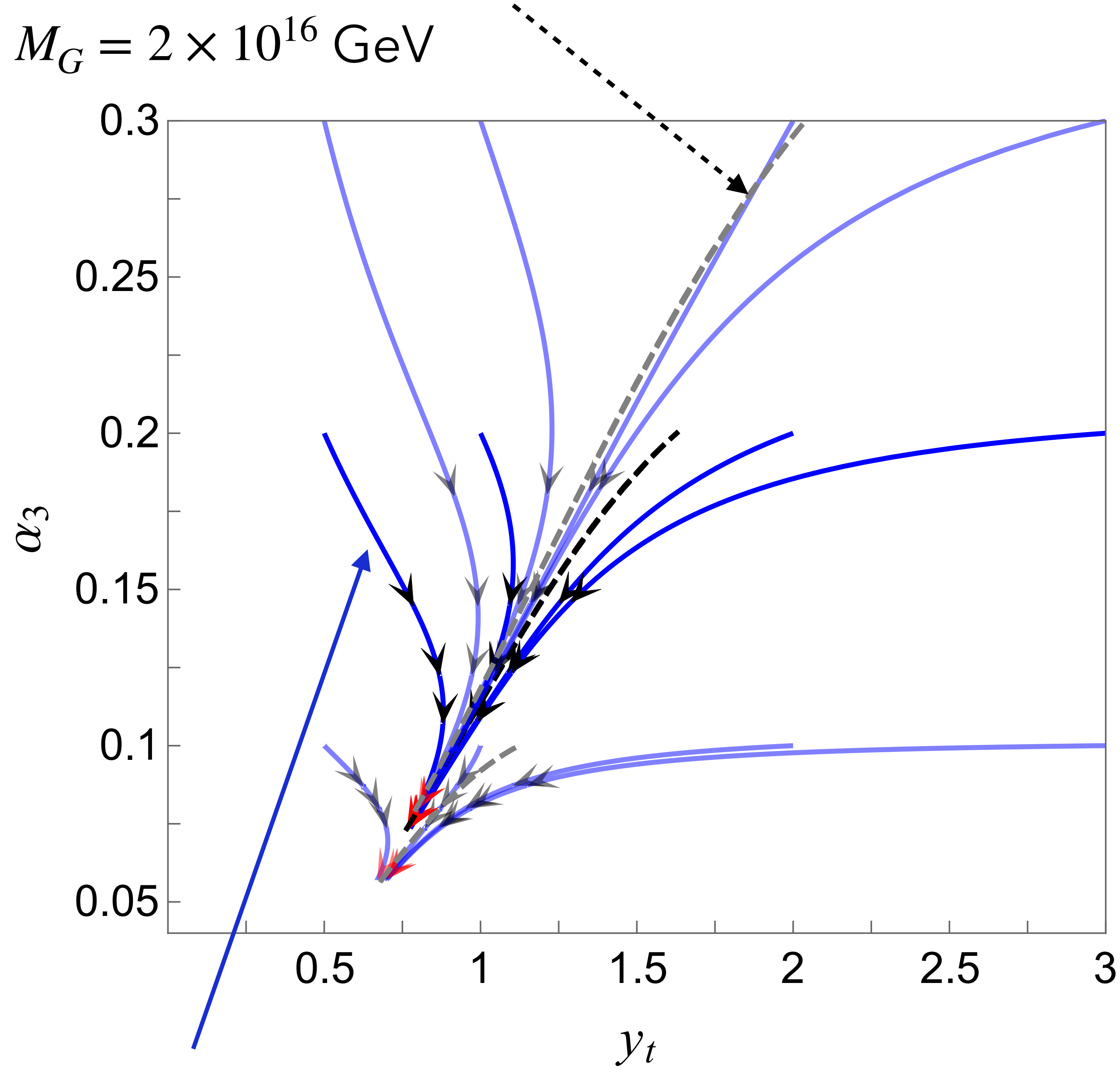
$$\frac{dy_{t,IR}^2/\alpha_3}{dt} \equiv 0$$



Weak scale parameters from IR fixed points: Yukawa couplings

$$\frac{dy_{t,IR}^2/\alpha_3}{dt} \equiv 0$$

$$\left(\frac{y_{t,IR}^2}{g_3^2}\right) = \frac{16+3b_3}{3a}$$

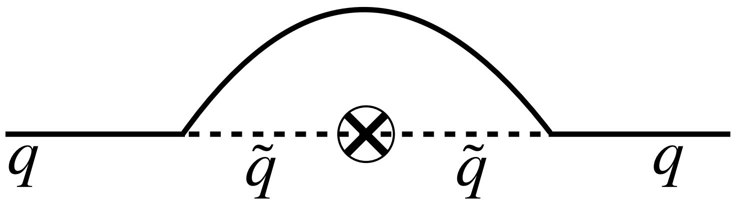


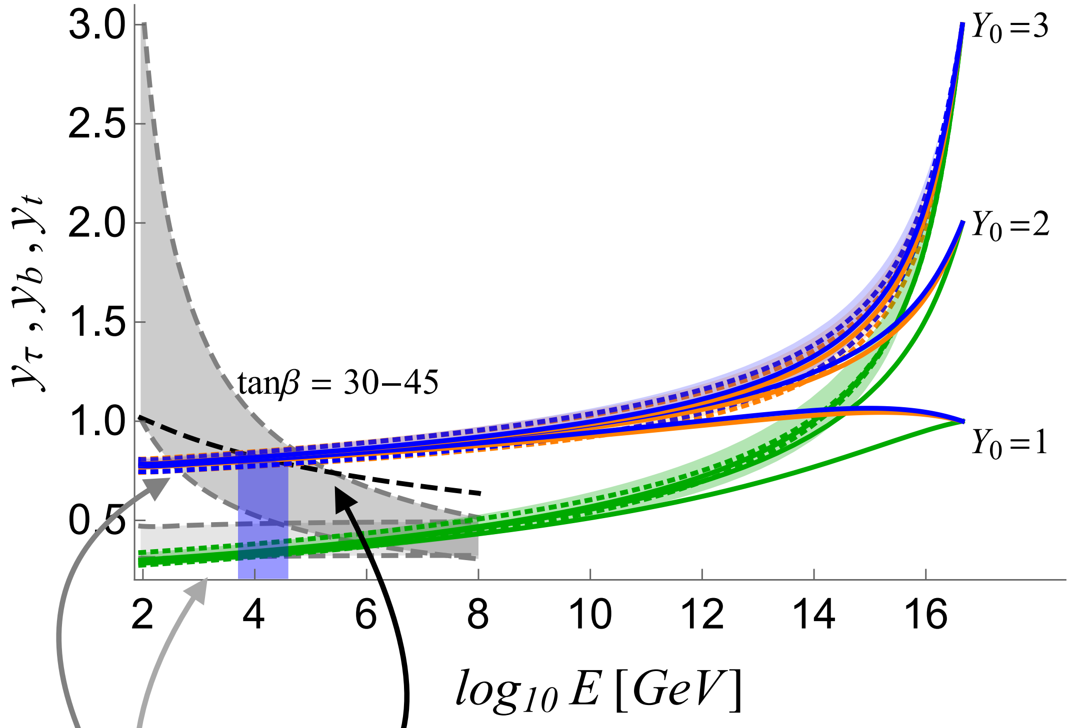
$M_G = 2 \times 10^{16}$ GeV

$y_{t,IR}(t)$ w/ two-loop corrections

Numerical

Threshold effects:

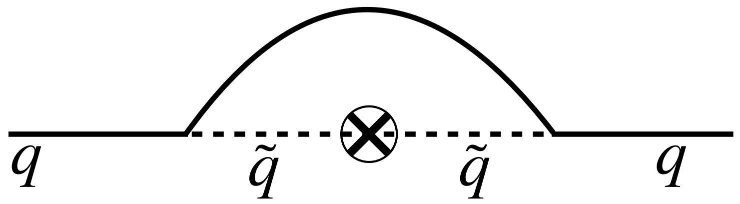


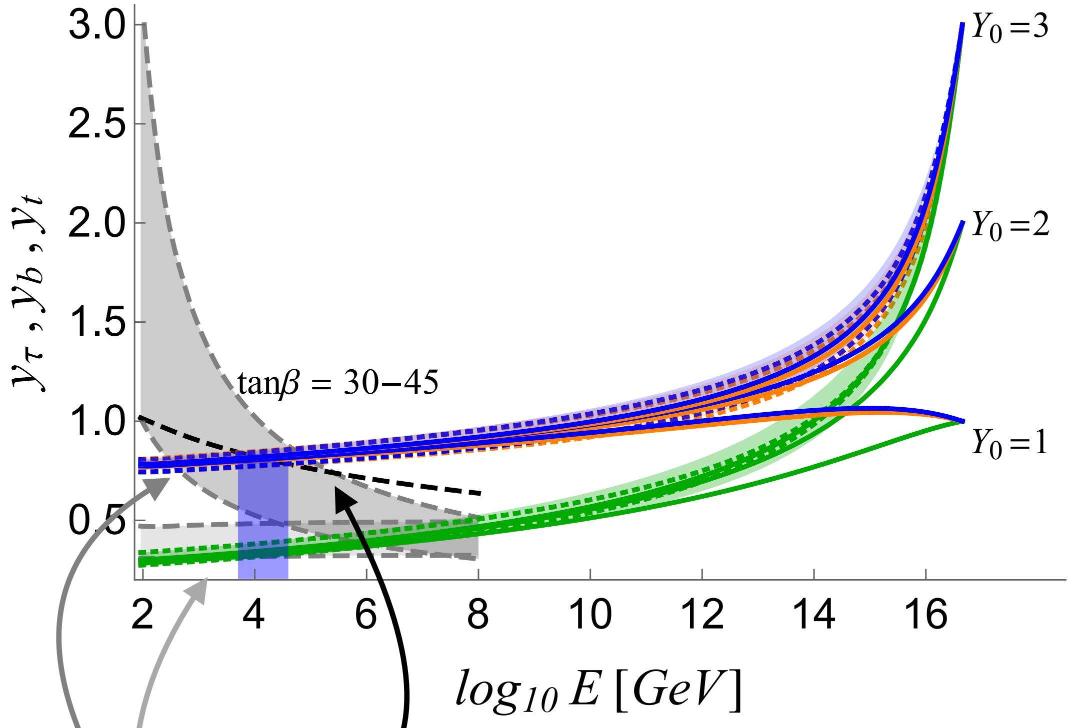


$$(y_t)_{SM} = y_t(1 + \epsilon_t)\sin\beta$$

$$(y_b)_{SM} = y_b(1 + \epsilon_b)\cos\beta$$

$$(y_\tau)_{SM} = y_\tau(1 + \epsilon_\tau)\cos\beta$$





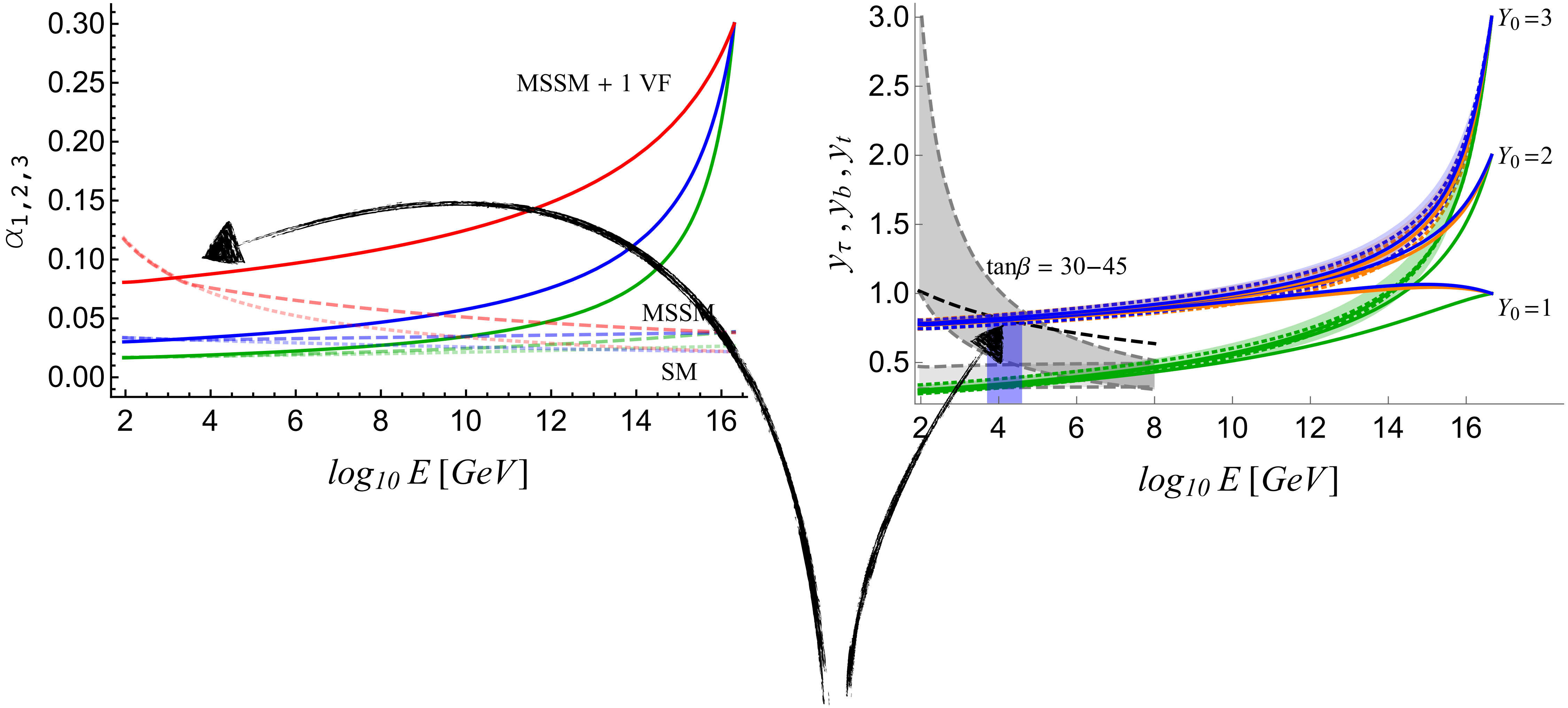
$$(y_t)_{SM} = y_t(1 + \epsilon_t)\sin\beta$$

$$(y_b)_{SM} = y_b(1 + \epsilon_b)\cos\beta$$

$$(y_\tau)_{SM} = y_\tau(1 + \epsilon_\tau)\cos\beta$$

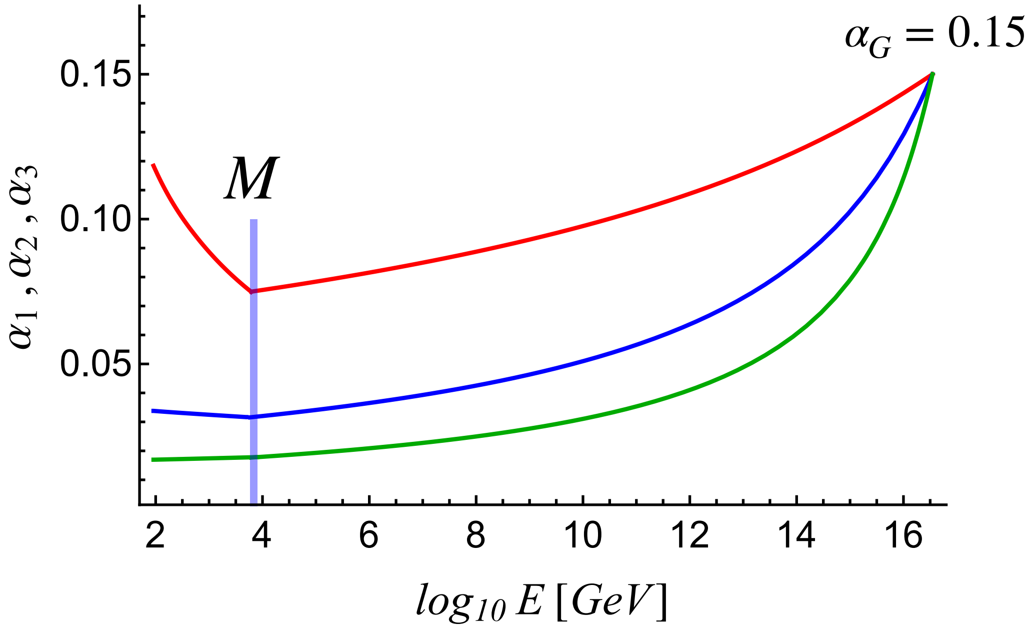
Threshold effects will depend on $\tan\beta, \mu, M_S$

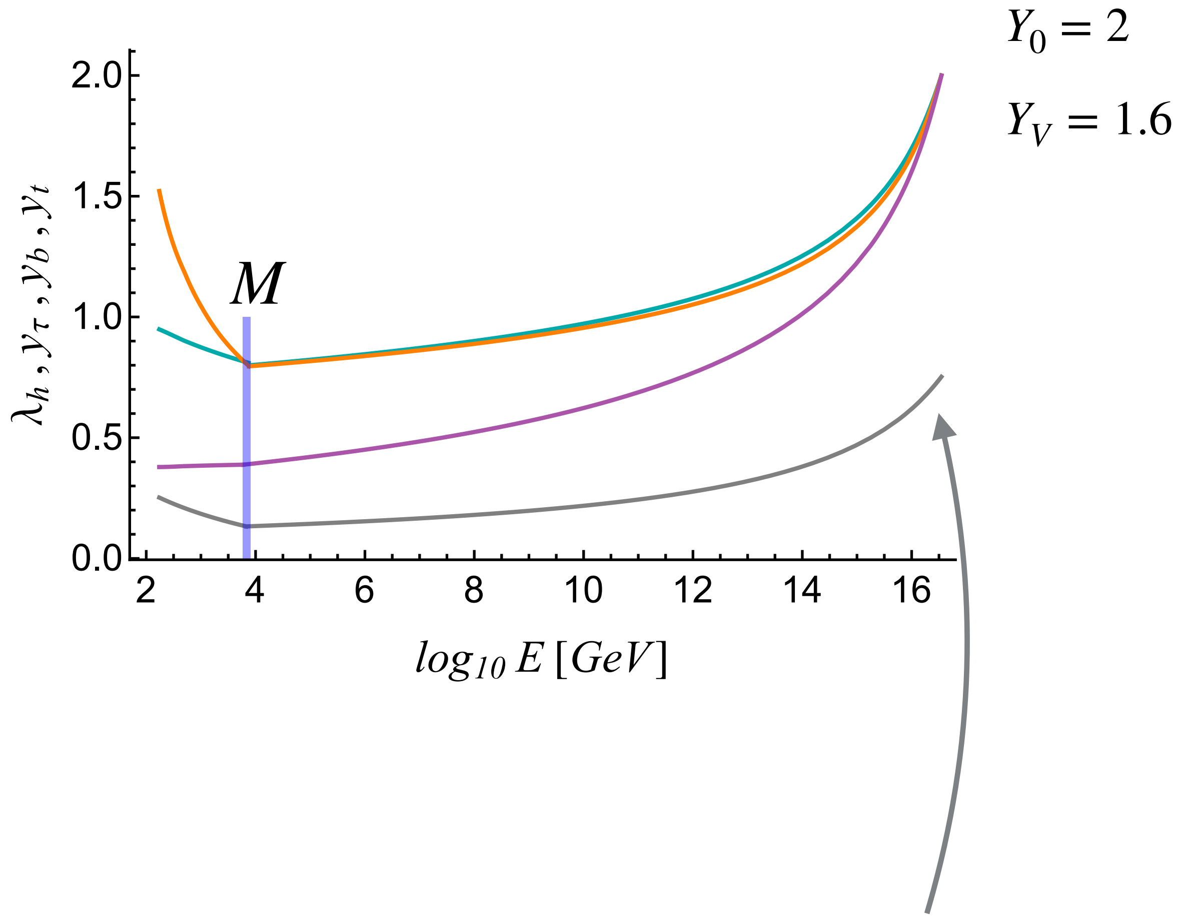
For details see:



$M_{SUSY} \sim M_{VF}$ ~ multi-TeV

Fixed points in unified models:





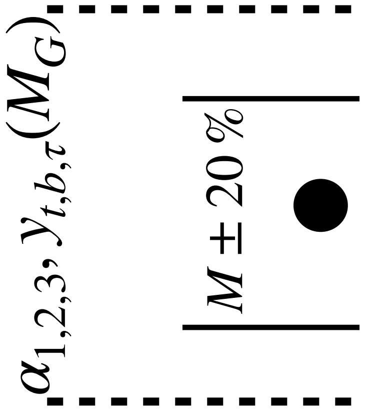
$$\lambda = \frac{1}{4}\left(g_2^2 + \frac{3}{5}g_1^2\right)\cos 2\beta$$

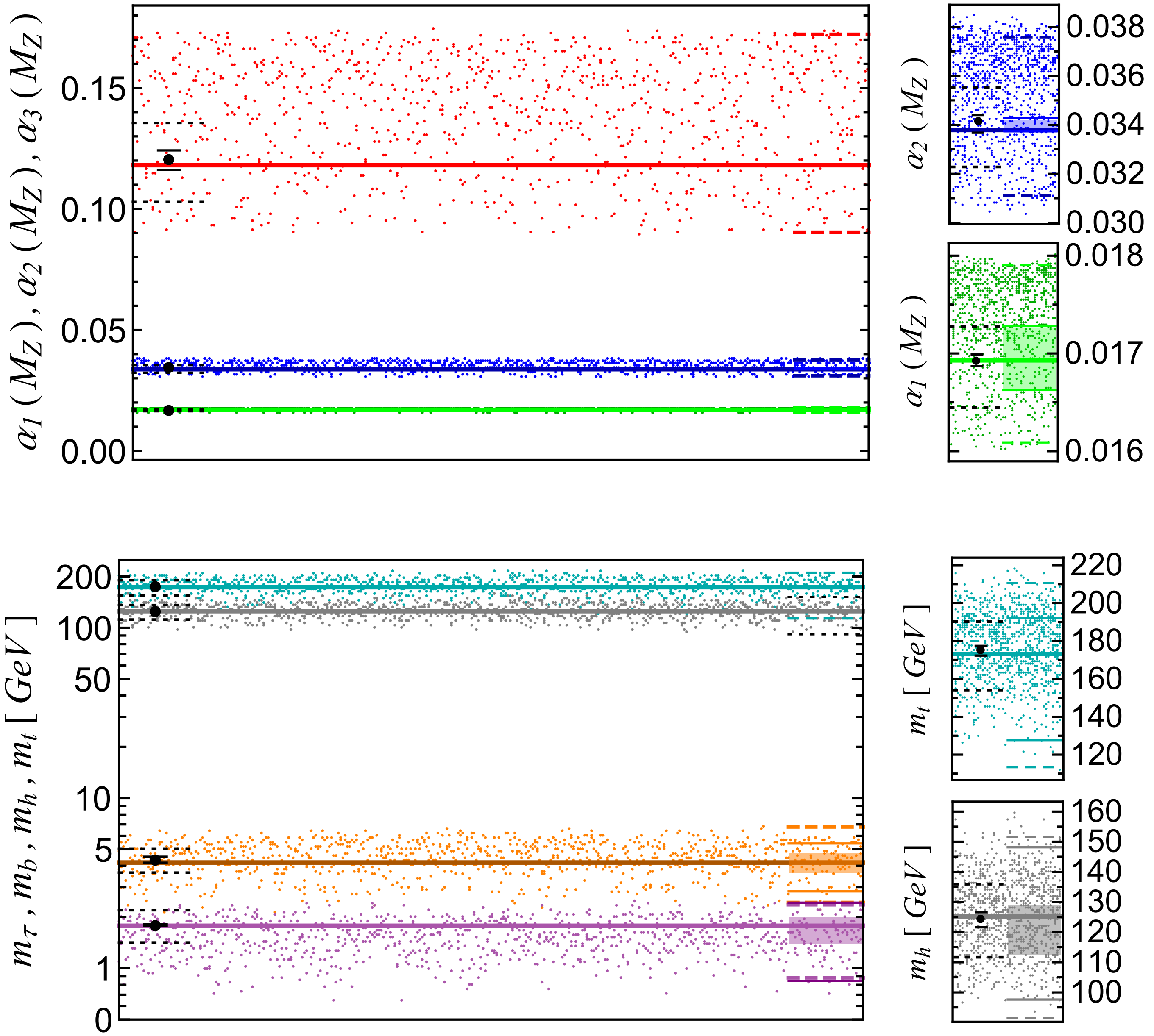
Assuming:

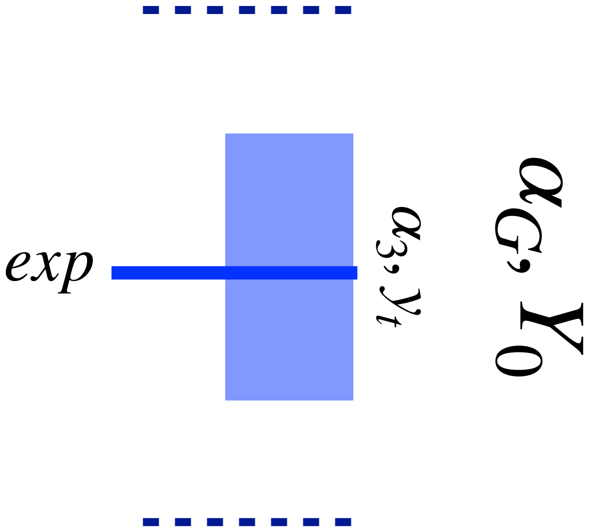
- $M_S = M_V = M$
- $\tan\beta = 40$
- $\mu = -\sqrt{2}M$

Low energy predictions of IR fixed points

$\alpha_{1,2,3} \in [0.1,0.3]$ $Y_0, Y_V \in [1,3]$





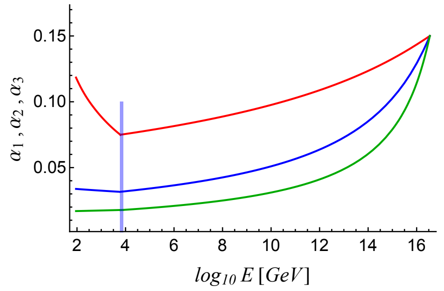


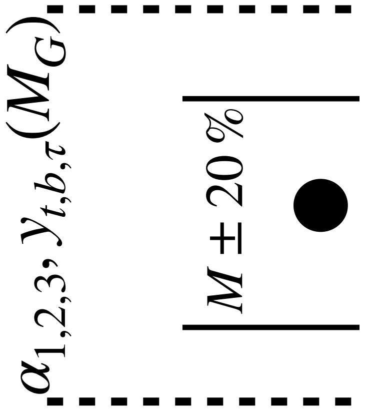
Correct hierarchical pattern emerges from RG flow and <u>single</u> scale of NP

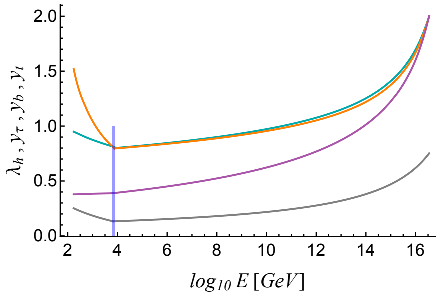
Low energy predictions of IR fixed points

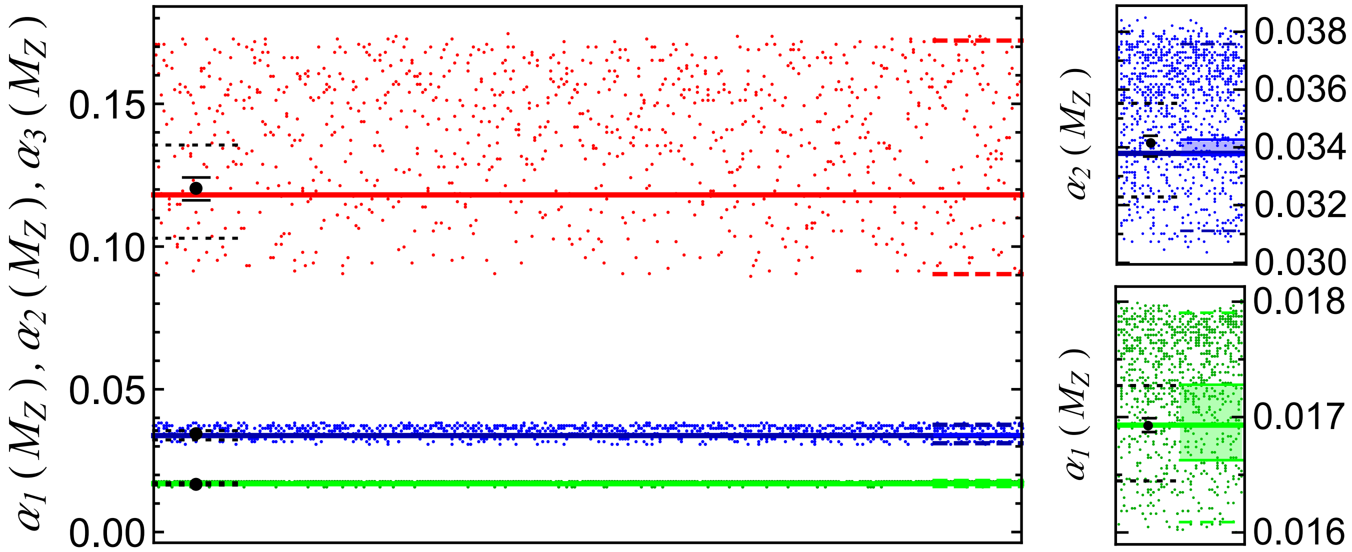
$M \sim \mathcal{O}(10) TeV$

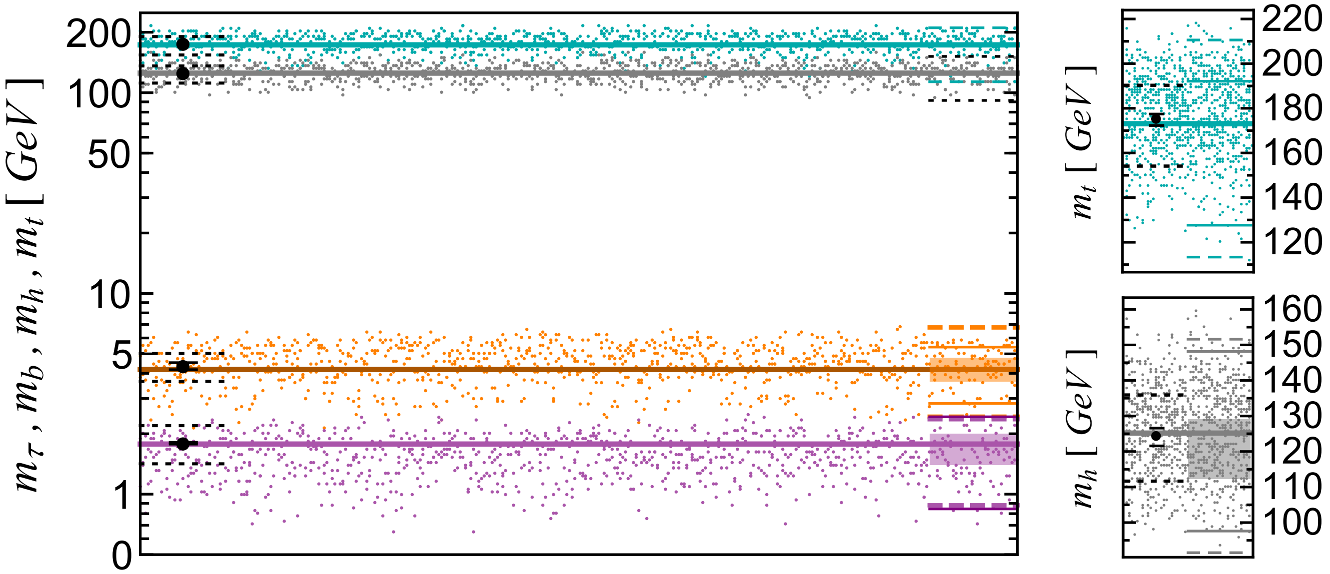
$\alpha_{1,2,3} \in [0.1,0.3]$ $Y_0, Y_V \in [1,3]$

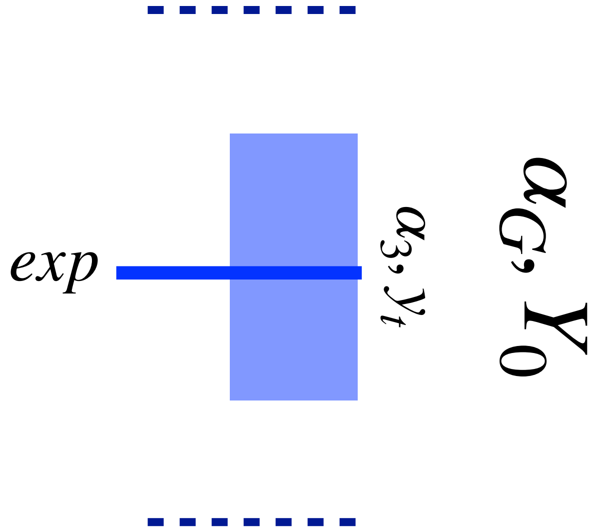




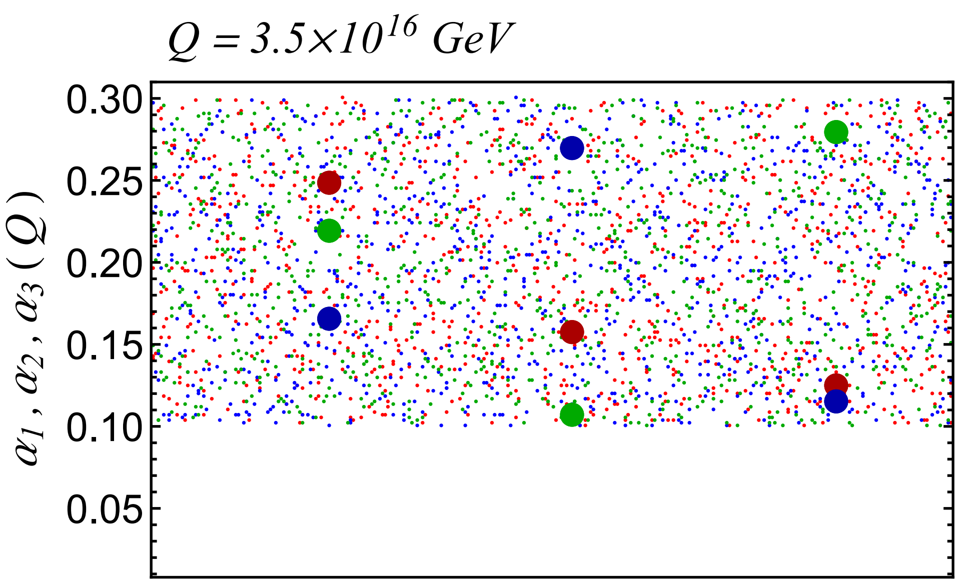


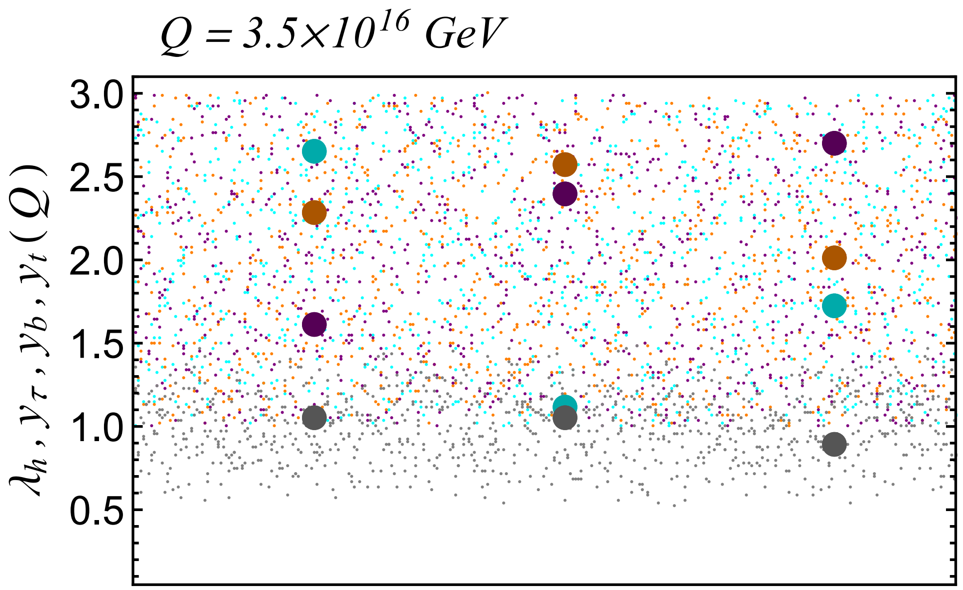


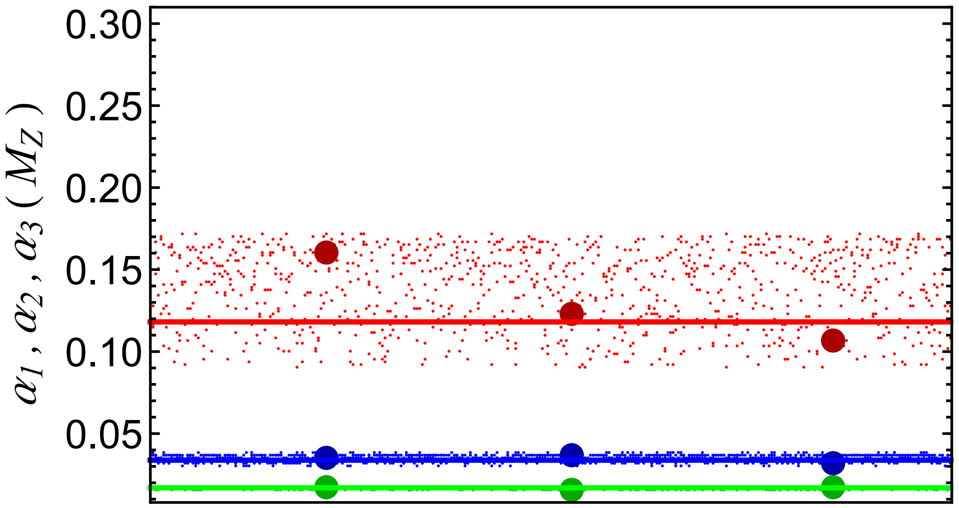


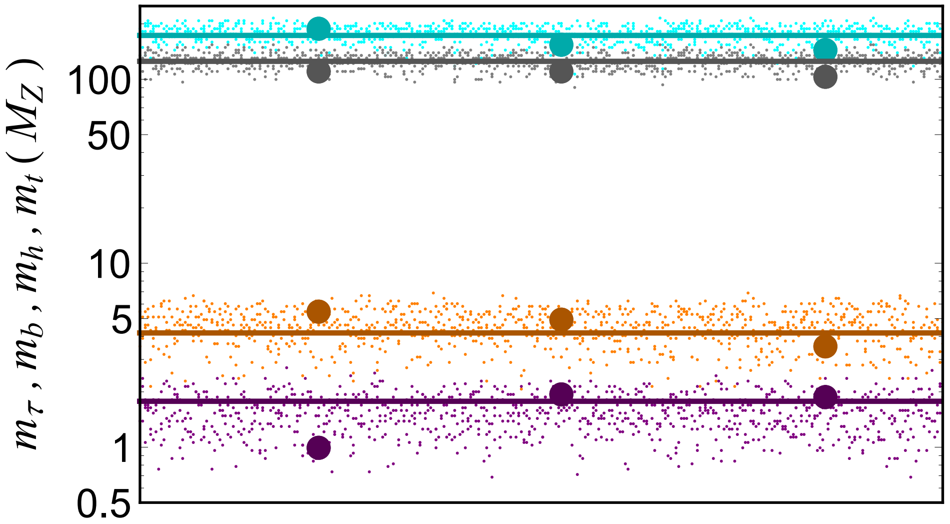


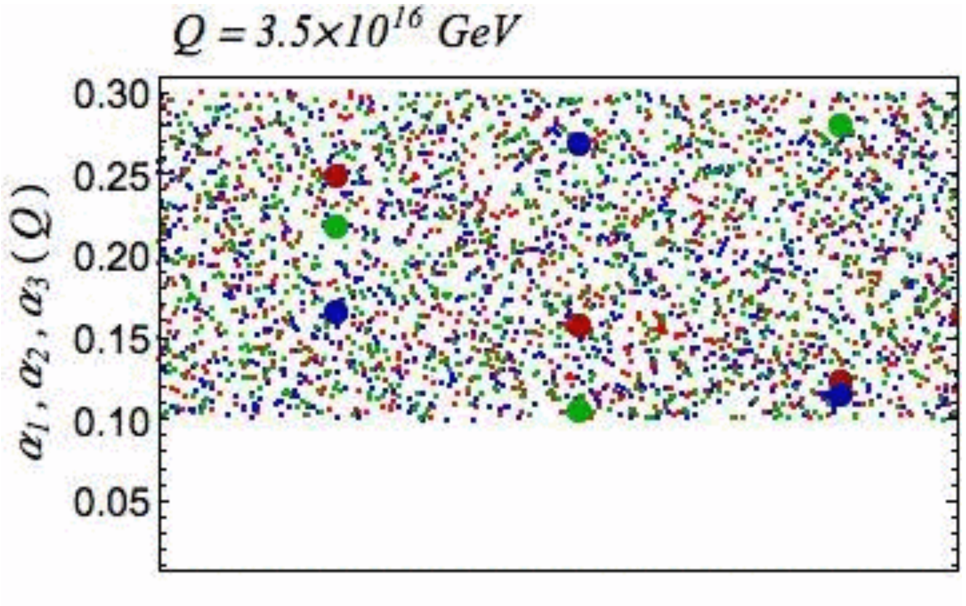
Correct hierarchical pattern emerges from RG flow and single scale of NP

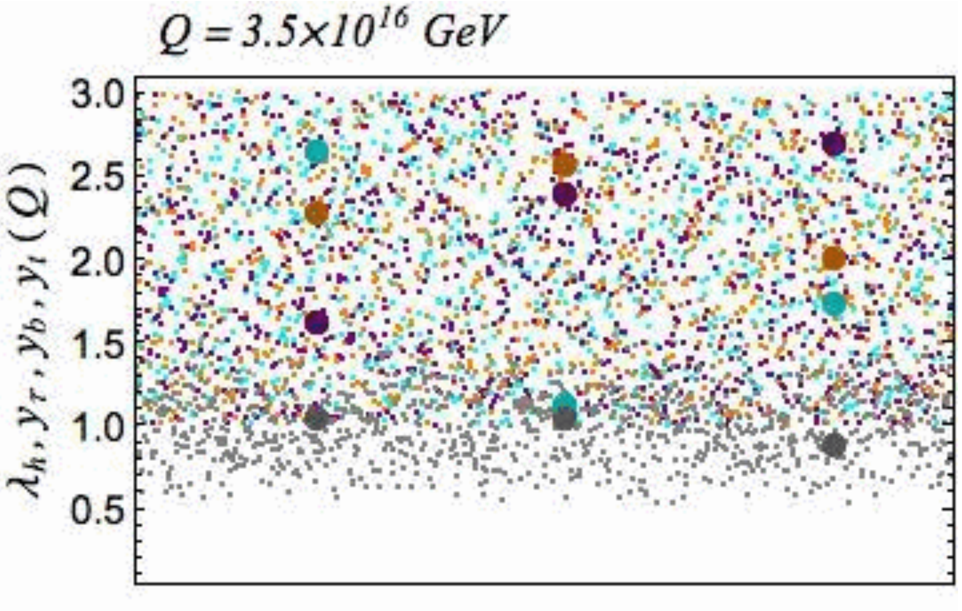

$Q = 3.5\times10^{16}$ GeV
$\alpha_1, \alpha_2, \alpha_3\,(Q)$
0.30
0.25
0.20
0.15
0.10
0.05


$Q = 3.5\times10^{16}$ GeV
$\lambda_h, y_\tau, y_b, y_t\,(Q)$
3.0
2.5
2.0
1.5
1.0
0.5


$\alpha_1, \alpha_2, \alpha_3\,(M_Z)$
0.30
0.25
0.20
0.15
0.10
0.05


$m_\tau, m_b, m_h, m_t\,(M_Z)$
100
50
10
5
1
0.5


$Q = 3.5\times10^{16}$ GeV
$\alpha_1 , \alpha_2 , \alpha_3 (Q)$
0.30
0.25
0.20
0.15
0.10
0.05


$Q = 3.5\times10^{16}$ GeV
$\lambda_h , y_\tau , y_b , y_t (Q)$
3.0
2.5
2.0
1.5
1.0
0.5

Fin

- Extending the MSSM w/ 1VF offers a scenario where the largest features of the SM can be understood from the scale of new physics
  - pattern of low energy couplings emerges from RG flow of couplings to IR fixed points
  - Details of parameters at M_G irrelevant, GUT BC's look the same as completely random
- Number of couplings at M_G irrelevant, similar scenarios can be considered in "non-minimal" GUTs, e.g. Flipped SU(5), Pati-Salam, etc.
- Interesting models to explore, details offer rich phenomenology
  - Higgs cascade decay channels offer promising discovery channels

Thanks!