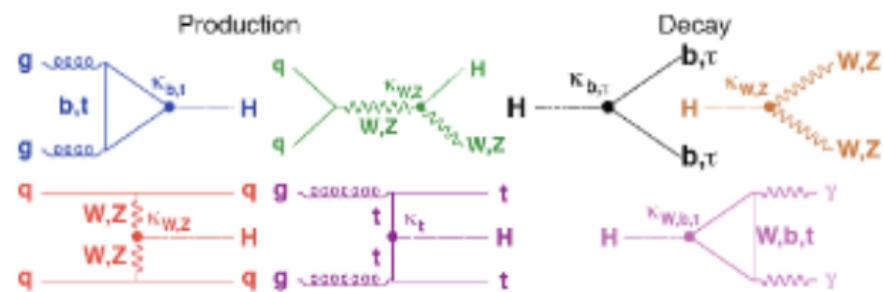


Vacuum stability bounds on Higgs couplings in the absence of new bosons



Kfir Blum (Weizmann)

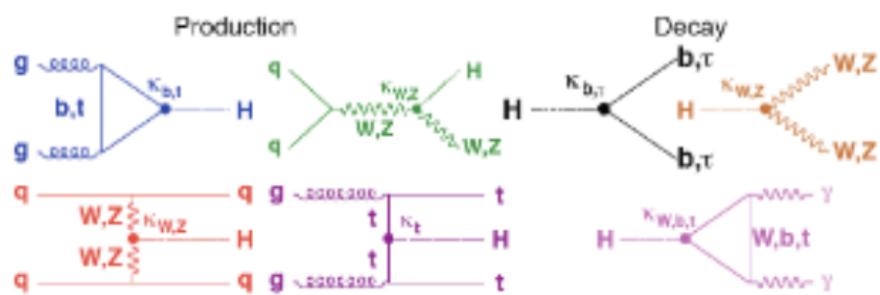
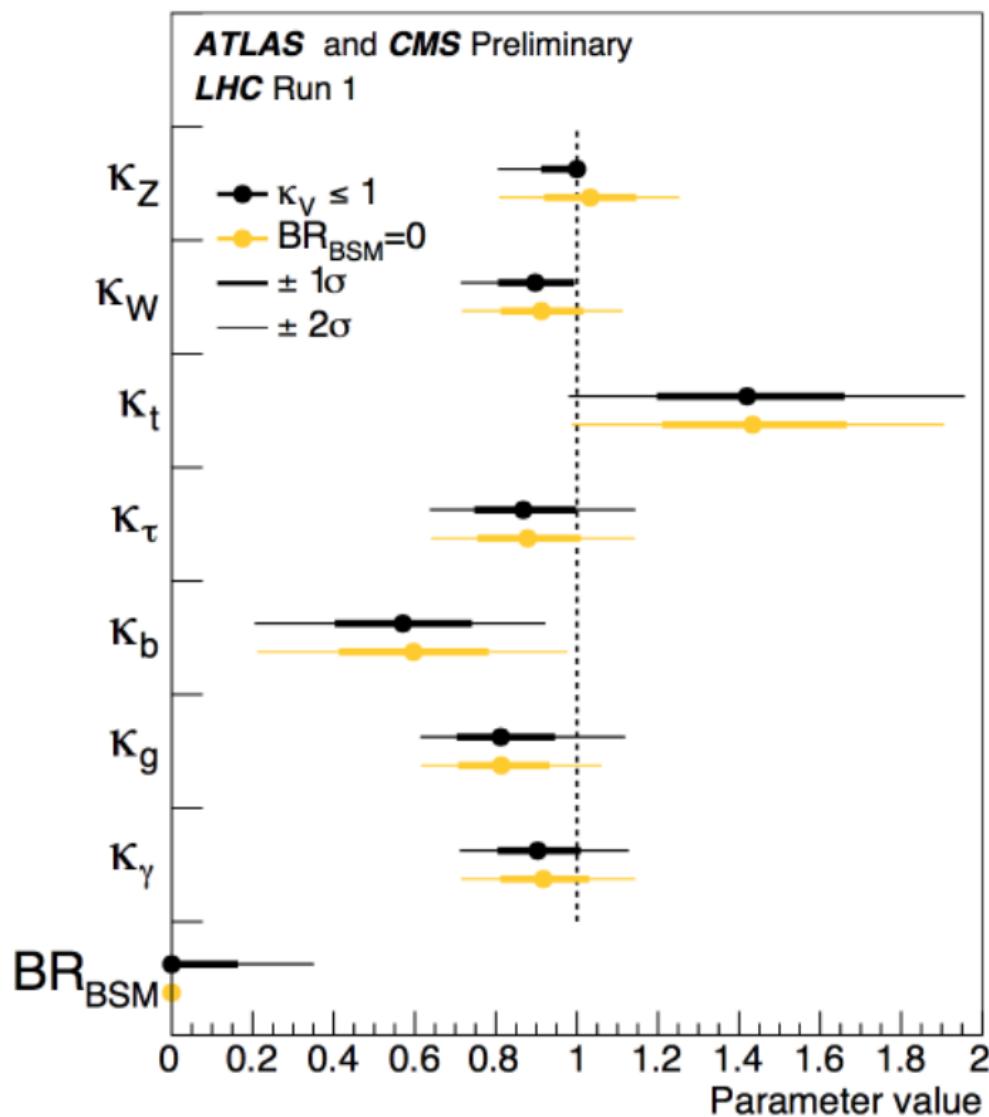
GGI 2015

1502.01045

With: Raffaele T. D'Agnolo, JiJi Fan

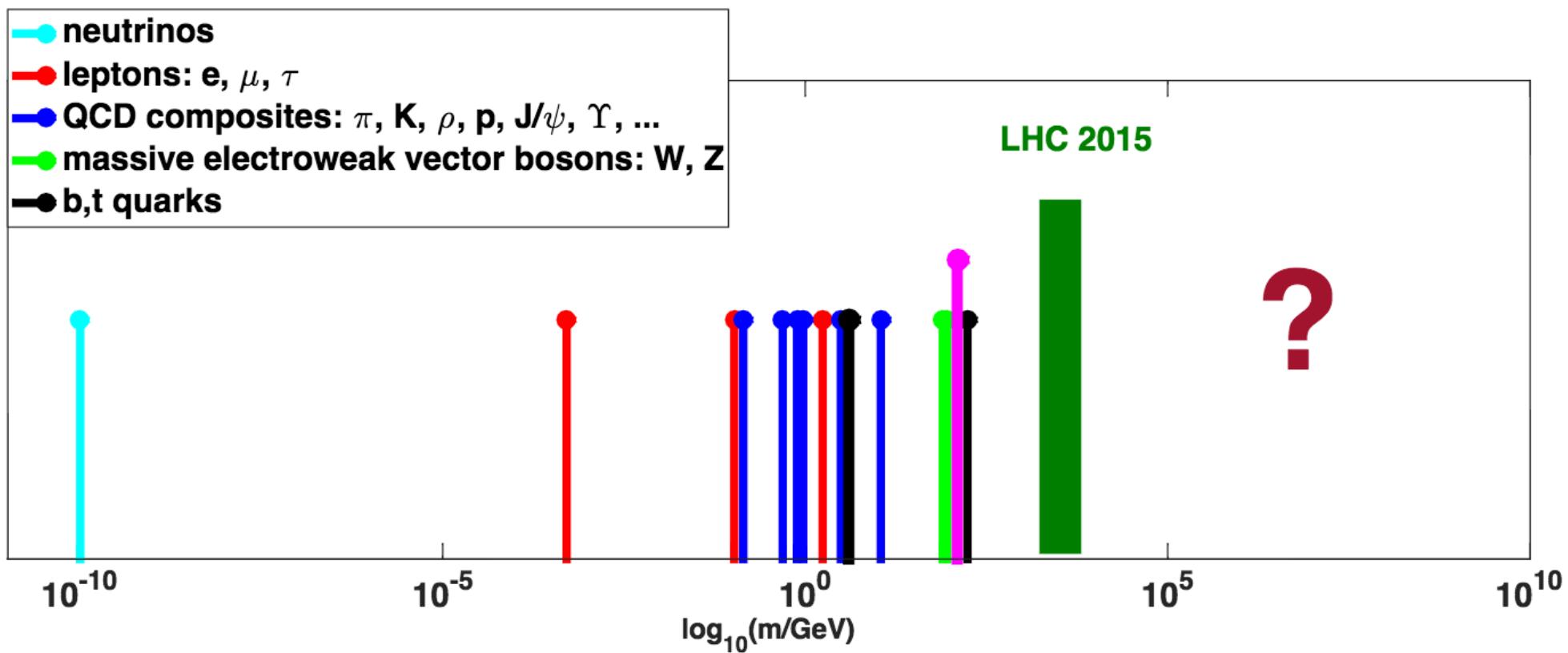


If Higgs couplings are off, what do we learn?



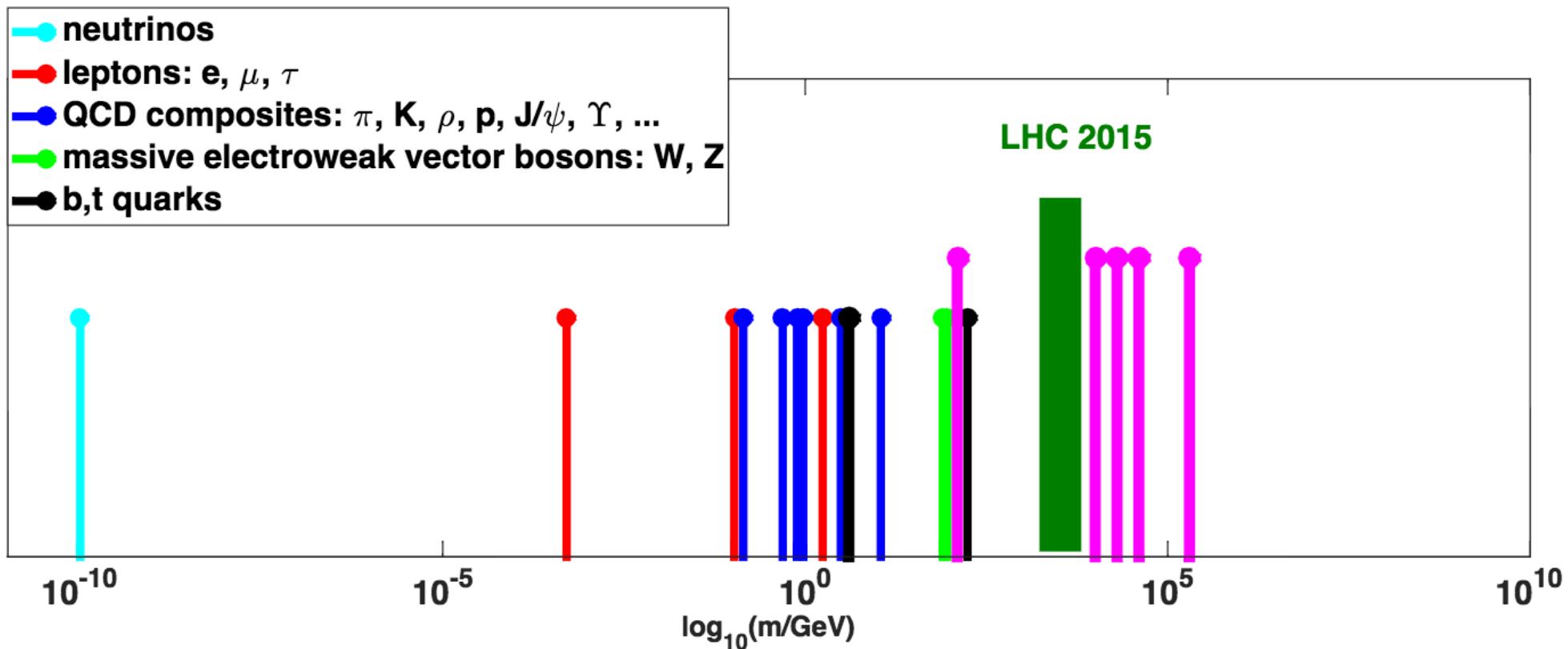
Is the Higgs the only scalar particle with $m \ll M_{Pl}$?

That would make it special.



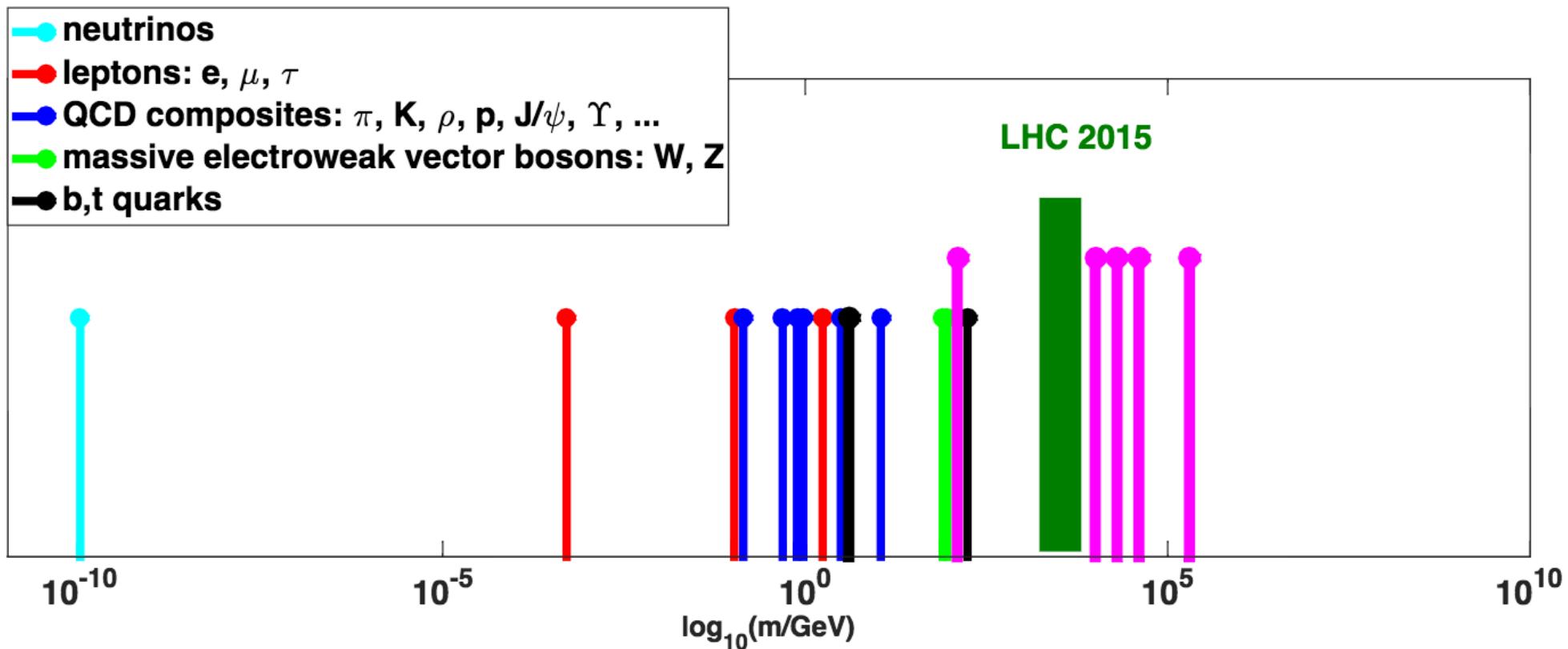
Is the Higgs the only scalar particle with $m \ll M_{Pl}$?

If there are more, would suggest generic stabilization.



Claim here:

Measurable deviations in Higgs couplings at the LHC imply new bosonic states



Consider new fermions but no new bosons up to high cut-off Λ

Certain things cannot be done:

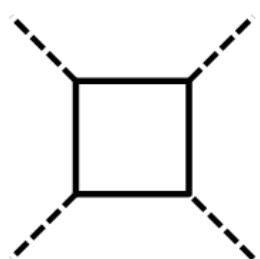
- No Higgs mixing

Certain things are fixed:

- Sign of leading fermion loops

Fermion loops drive the Higgs potential negative

Generic constraint from **vacuum stability**.



$$(4\pi)^2 \frac{d\lambda}{dt} = -4N_c \sum_i |y_i|^4 + \dots$$

Main observational channels

Htt , HWW , HZZ , $H\gamma\gamma$, HGG , Hbb , $H\tau\tau$

Imagine all the ways in which new fermions might modify them.

In most cases, $O(1)$ Yukawa couplings are needed if the LHC is to be sensitive to this.

Analog from days before top and/or Higgs discovery: stability bounds on m_t , m_H

Datta, Young, Zhang, Phys. Lett. B 385 (1996) 225,
Altarelli and Isidori, Phys. Lett. B 337 (1994) 141,
Casas, Espinosa, Quiros, Phys. Lett. B 342 (1995) 171,
Hung and Sher, Phys. Lett. B 374 (1996) 138,

...

Main observational channels

Htt , HWW , HZZ , $H\gamma\gamma$, HGG , Hbb , $H\tau\tau$

Imagine all the ways in which new fermions might modify them.

In most cases, $O(1)$ Yukawa couplings are needed if the LHC is to be sensitive to this.

Quantitatively, what happens if we add large Yukawa?

Example: vector-like quarks

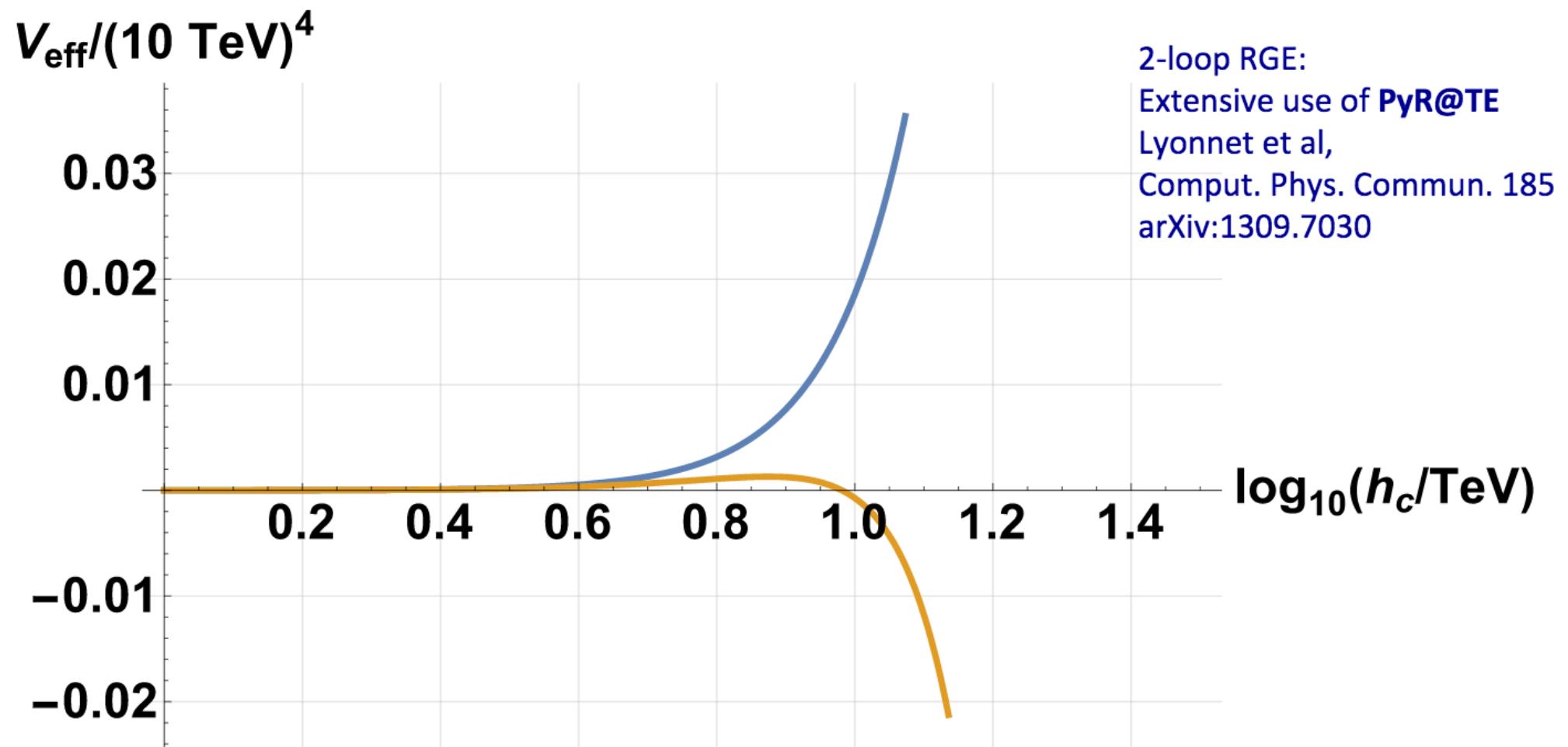
$$\begin{aligned} & Q(3, 2)_{\frac{1}{6}}, \quad Q^c(\bar{3}, 2)_{-\frac{1}{6}} \\ & D(3, 1)_{-\frac{1}{3}}, \quad D^c(\bar{3}, 1)_{\frac{1}{3}} \end{aligned}$$

$$\mathcal{V}_{NP} = Y_{QD^c} H^\dagger Q D^c + Y_{Q^c D} H^T \epsilon Q^c D + M_Q Q^T \epsilon Q^c + M_D D D^c + cc$$

e.g., “beautiful mirrors”,
Kearney, Pierce, Weiner 2012,
etc.

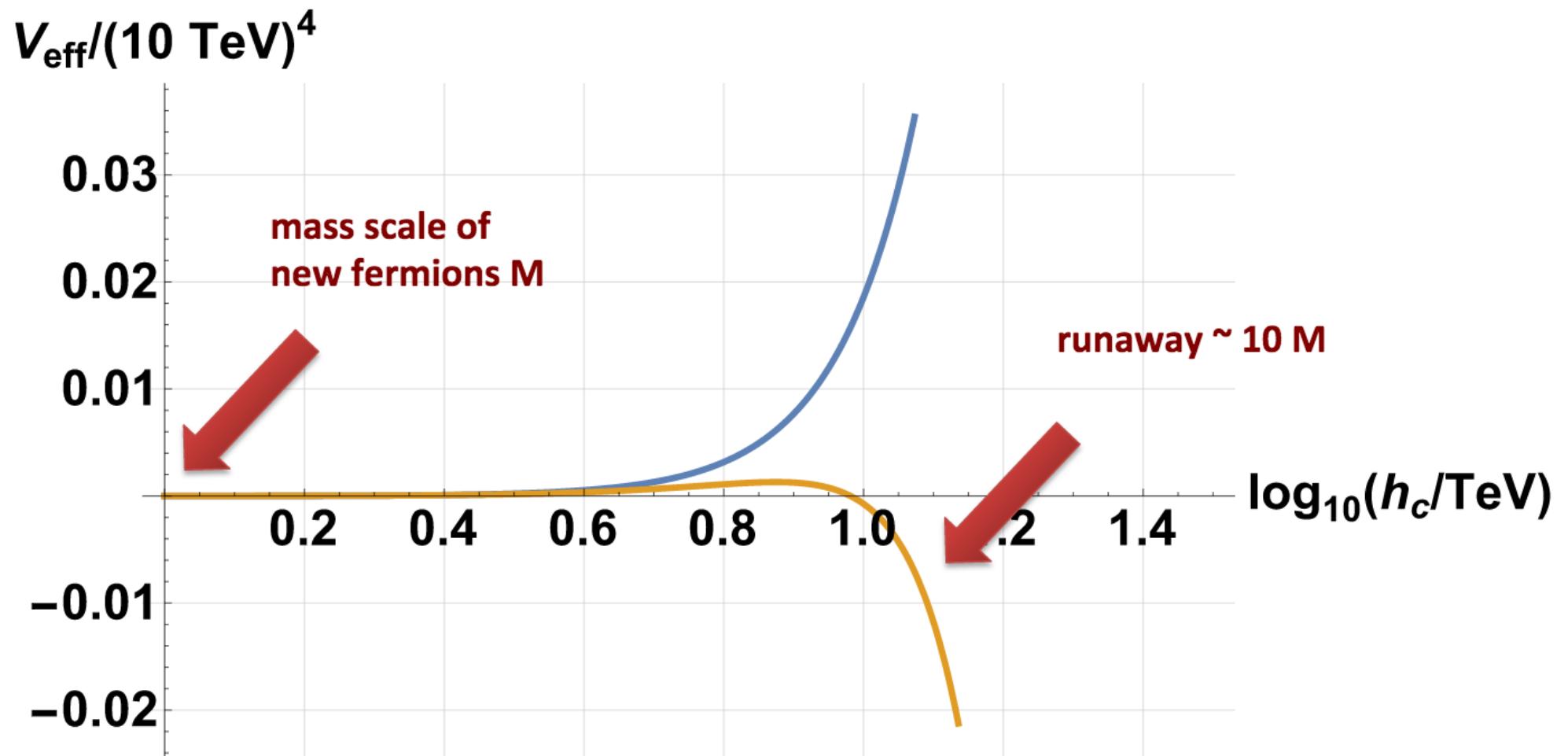
$$\begin{aligned} & Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ & D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}} \end{aligned}$$

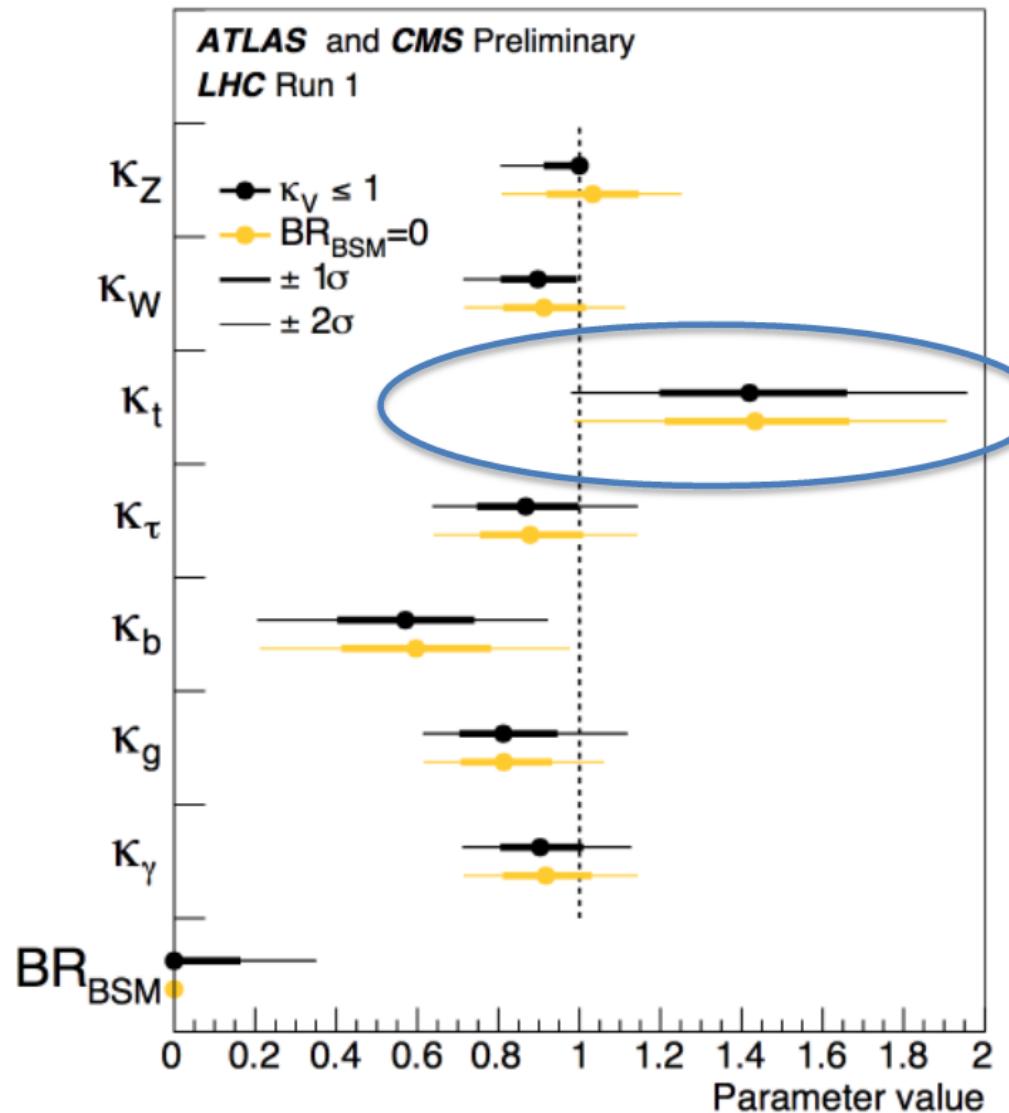
$$\begin{aligned} Y_{QD^c(1\text{TeV})} &= 0 \\ Y_{Q^cD(1\text{TeV})} &= 1.25 \end{aligned}$$



$$Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}}$$

$$Y_{QD^c(1\text{TeV})}=0 \\ Y_{Q^cD(1\text{TeV})}=1.25$$





Htt

	representation	$-\mathcal{L}_{NP}$
DI	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $D(3,1)_{-\frac{1}{3}}, D^c(\bar{3},1)_{\frac{1}{3}}$	$Y_{Qd^c} H^\dagger Q d^c + Y_{qD^c} H^\dagger q D^c + Y_{QD^c} H^\dagger Q D^c + Y_{Q^c D} H^T \epsilon Q^c D$ $+ M_Q Q^T \epsilon Q^c + M_D D D^c + cc$
DII	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D(3,1)_{-\frac{1}{3}}, D^c(\bar{3},1)_{\frac{1}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{qD^c} H^\dagger q D^c + Y_{Q'D^c} H^T \epsilon Q' D^c + Y_{Q'^c D} H^\dagger Q'^c D$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_D D D^c + cc$
DIII	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $D'(3,3)_{-\frac{1}{3}}, D'^c(\bar{3},3)_{\frac{1}{3}}$	$Y_{Qd^c} H^\dagger Q d^c + Y_{qD'^c} H^\dagger \sigma q \cdot D'^c + Y_{QD'^c} H^\dagger \sigma Q \cdot D'^c + Y_{Q^c D'} H^T \epsilon \sigma Q^c \cdot D'$ $+ M_Q Q^T \epsilon Q^c + M_{D'} D' \cdot D'^c + cc$
DIV	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D'(3,3)_{-\frac{1}{3}}, D'^c(\bar{3},3)_{\frac{1}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{qD'^c} H^\dagger \sigma q \cdot D'^c + Y_{Q'D'^c} H^T \epsilon \sigma Q' \cdot D'^c + Y_{Q'^c D'} H^\dagger \sigma Q'^c \cdot D'$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_{D'} D' \cdot D'^c + cc$
UI	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $U(3,1)_{\frac{2}{3}}, U^c(\bar{3},1)_{-\frac{2}{3}}$	$Y_{Qu^c} H^T \epsilon Qu^c + Y_{qU^c} H^T \epsilon q U^c + Y_{QU^c} H^T \epsilon QU^c + Y_{Q^c U} H^\dagger Q^c U$ $+ M_Q Q^T \epsilon Q^c + M_U U U^c + cc$
UII	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U(3,1)_{\frac{2}{3}}, U^c(\bar{3},1)_{-\frac{2}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{qU^c} H^T \epsilon q U^c + Y_{Q''U^c} H^\dagger Q'' U^c + Y_{Q''^c U} H^T \epsilon Q''^c U$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_U U U^c + cc$
UIII	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $U'(3,3)_{\frac{2}{3}}, U'^c(\bar{3},3)_{-\frac{2}{3}}$	$Y_{Qu^c} H^T \epsilon Qu^c + Y_{qU'^c} H^T \epsilon \sigma q \cdot U'^c + Y_{QU'^c} H^T \epsilon \sigma Q \cdot U'^c + Y_{Q^c U'} H^\dagger \sigma Q^c \cdot U'$ $+ M_Q Q^T \epsilon Q^c + M_{U'} U' \cdot U'^c + cc$
UIV	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U'(3,3)_{\frac{2}{3}}, U'^c(\bar{3},3)_{-\frac{2}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{qU'^c} H^T \epsilon \sigma q \cdot U'^c + Y_{Q''U'^c} H^\dagger \sigma Q'' \cdot U'^c + Y_{Q''^c U'} H^T \epsilon \sigma Q''^c \cdot U'$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_{U'} U' \cdot U'^c + cc$
DV	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D''(3,3)_{-\frac{4}{3}}, D''^c(\bar{3},3)_{\frac{4}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{Q'D''^c} H^\dagger \sigma Q' \cdot D''^c + Y_{Q'^c D''} H^T \epsilon \sigma Q'^c \cdot D''$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_{D''} D'' \cdot D''^c + cc$
UV	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U''(3,3)_{\frac{5}{3}}, U''^c(\bar{3},3)_{-\frac{5}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{Q''U''^c} H^T \epsilon \sigma Q'' \cdot U''^c + Y_{Q''^c U''} H^\dagger \sigma Q''^c \cdot U''$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_{U''} U'' \cdot U''^c + cc$

Htt

$\Upsilon t = O(1) \rightarrow$ need large new Yukawa to modify appreciably

$$Q(3,2)_{\frac{1}{6}}, \ Q^c(\bar{3},2)_{-\frac{1}{6}}, \ U(3,1)_{\frac{2}{3}}, \ U^c(\bar{3},1)_{-\frac{2}{3}}$$

$$\delta r_t \approx -v^2 \left(\frac{|Y_{qU^c}|^2}{2|M_U|^2} + \frac{|Y_{Qu^c}|^2}{2|M_Q|^2} + \frac{Y_{Q^c U} Y_{Qu^c} Y_{qU^c}}{M_Q M_U} \right)$$

Htt

$Y_t = O(1) \rightarrow$ need large new Yukawa to modify appreciably

$$Q(3,2)_{\frac{1}{6}}, \ Q^c(\bar{3},2)_{-\frac{1}{6}}, \ U(3,1)_{\frac{2}{3}}, \ U^c(\bar{3},1)_{-\frac{2}{3}}$$

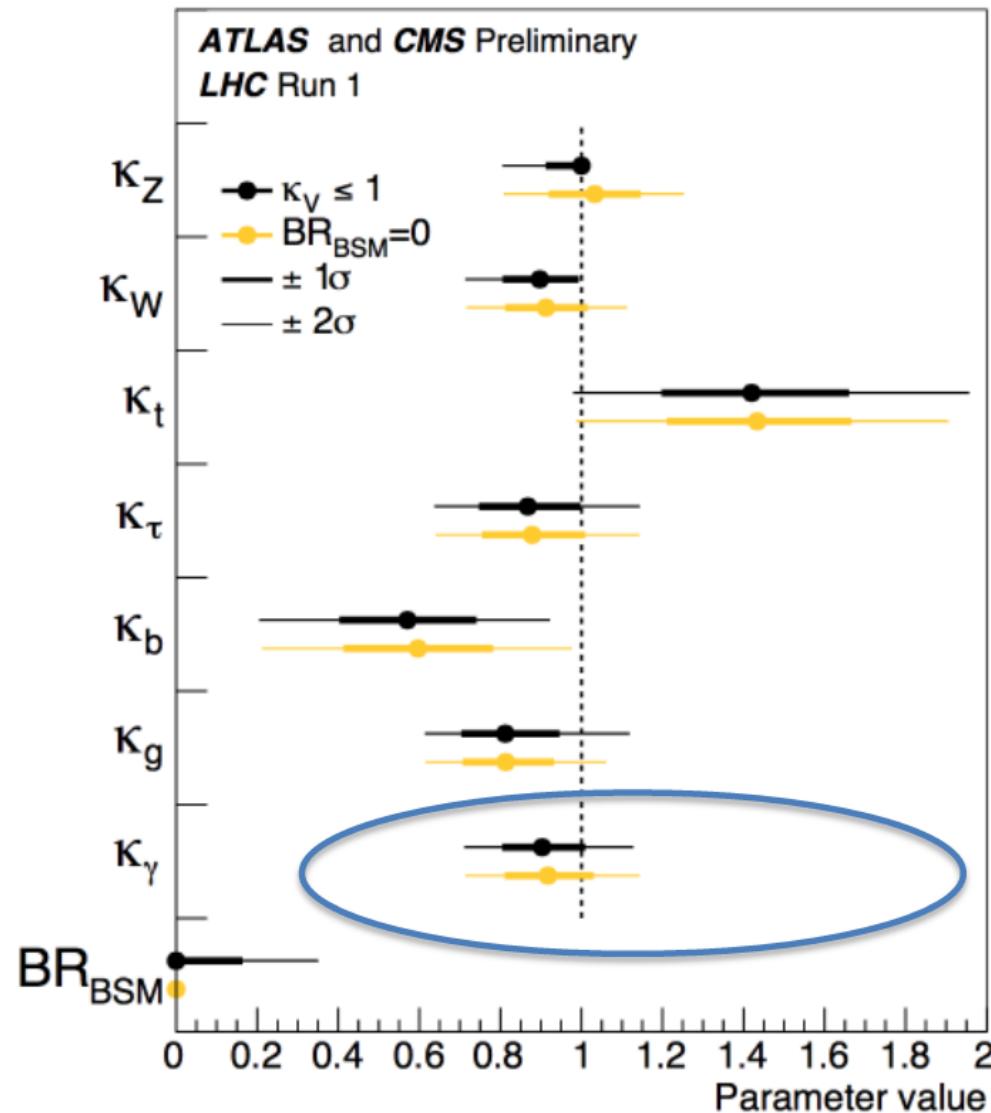
$$\delta r_t \approx -v^2 \left(\frac{|Y_{qU^c}|^2}{2|M_U|^2} + \frac{|Y_{Qu^c}|^2}{2|M_Q|^2} + \frac{Y_{Q^c U} Y_{Qu^c} Y_{qU^c}}{M_Q M_U} \right)$$



Turning all the knobs: $|\delta r_t| < 0.2$ for $\Lambda_{UV} > 100 \text{ TeV}$

Generic prediction: $|\delta r_t| \sim 0.1 \rightarrow \Lambda_{UV} = O(10 \text{ TeV})$

$H \rightarrow \text{diphoton}$

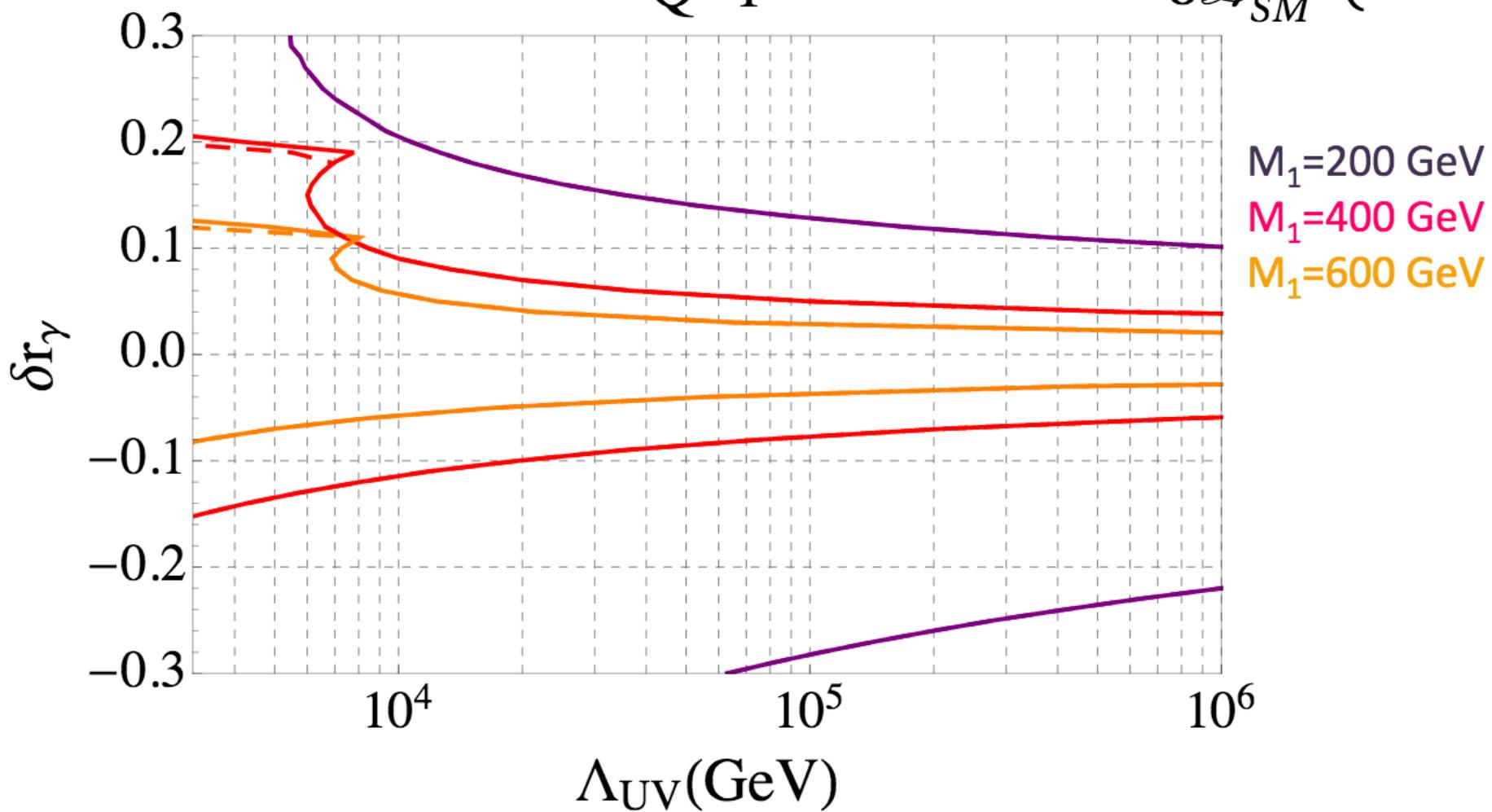


$L(1,2)_{-\frac{1}{2}}$	$L^c(1,2)_{\frac{1}{2}}$
$E(1,1)_{-1}$	$E^c(1,1)_1$

$H \rightarrow \text{diphoton}$

$$\delta r_\gamma \approx \frac{4Q^2 D}{3\mathcal{A}_{SM}^\gamma} \left(\frac{\partial \log \|M\|}{\partial \log \nu} \right)$$

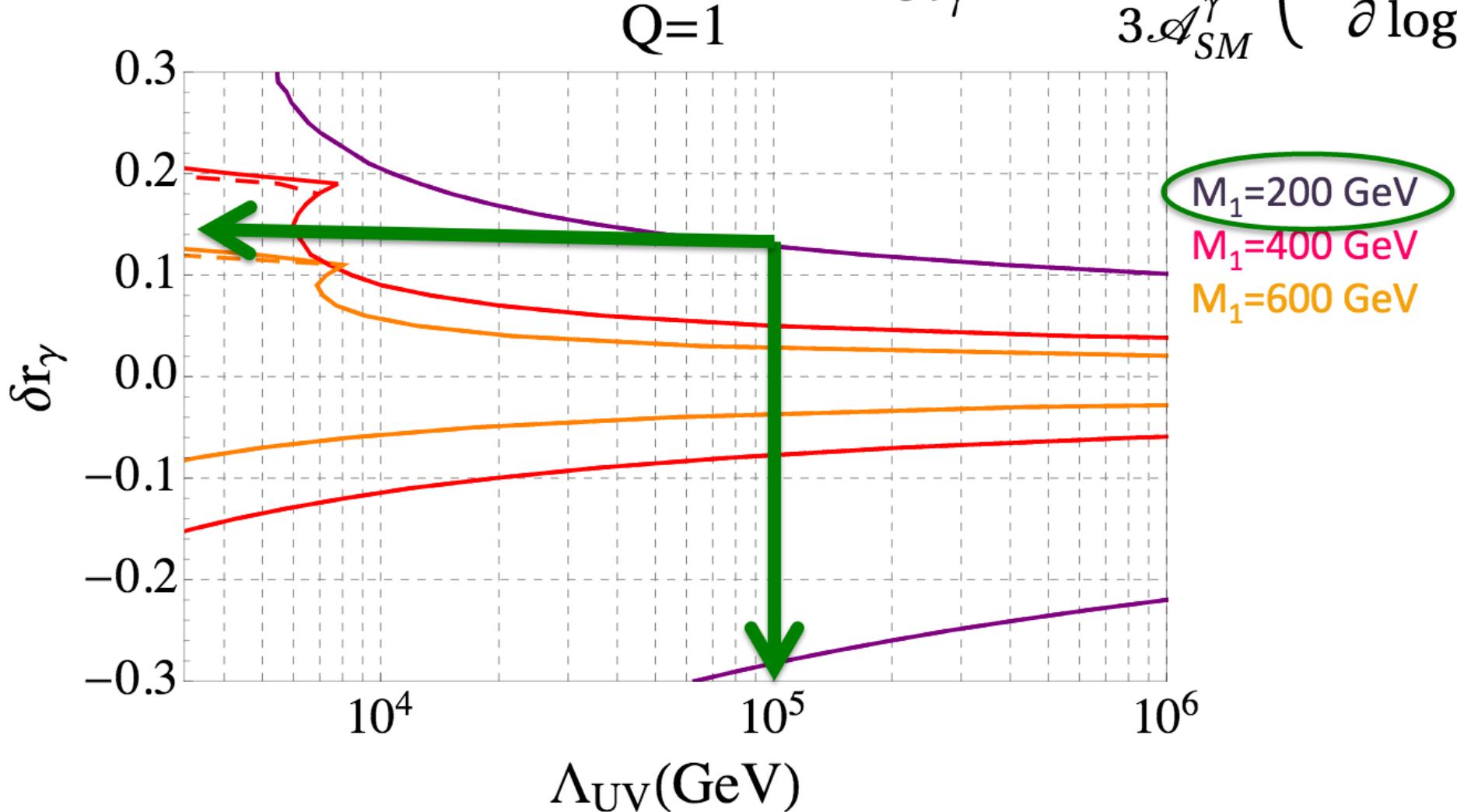
$Q=1$



$H \rightarrow \text{diphoton}$

$L(1,2)_{-\frac{1}{2}}$	$L^c(1,2)_{\frac{1}{2}}$
$E(1,1)_{-1}$	$E^c(1,1)_1$

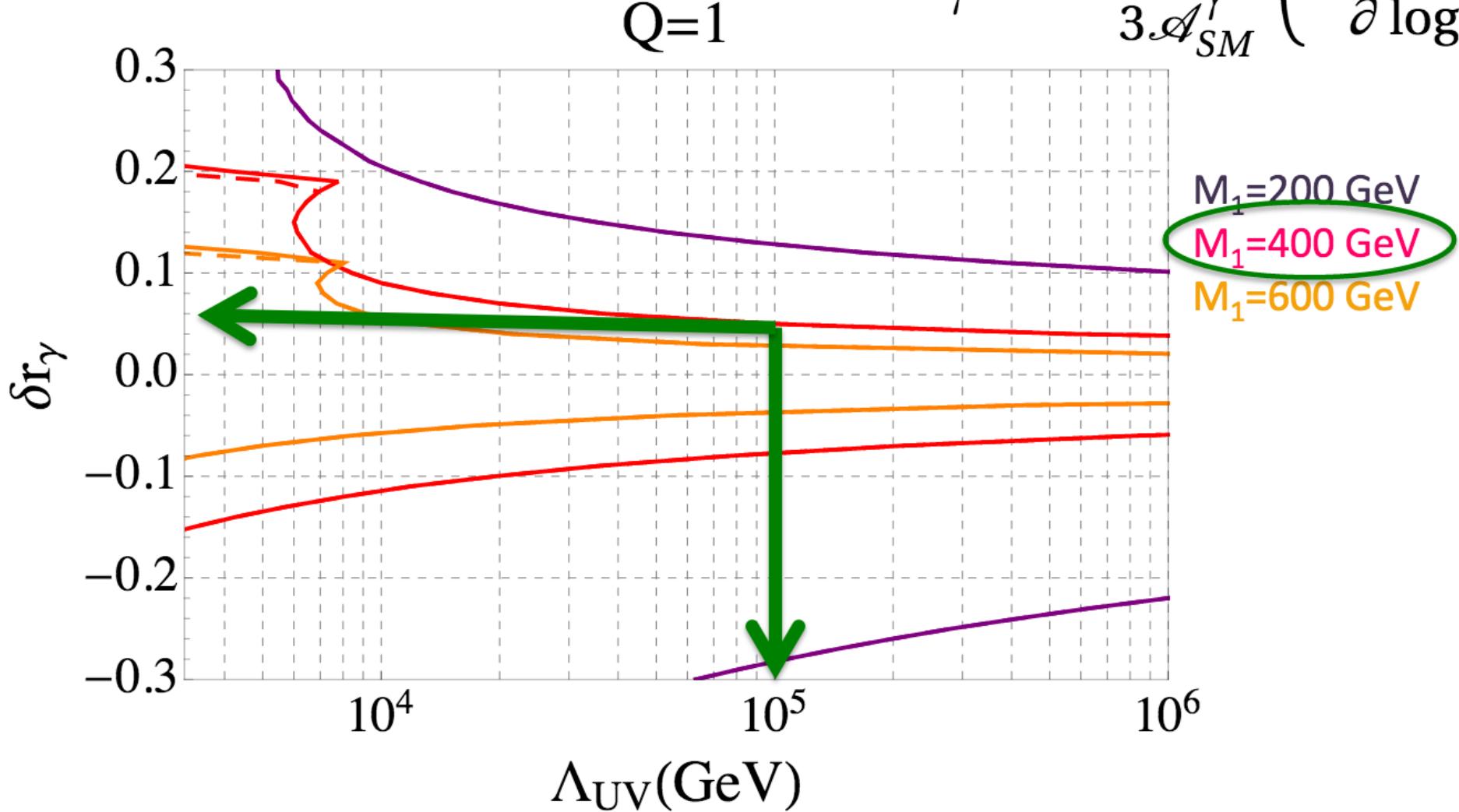
$$\delta r_\gamma \approx \frac{4Q^2 D}{3\mathcal{A}_{SM}^\gamma} \left(\frac{\partial \log ||M||}{\partial \log \nu} \right)$$



$L(1,2)_{-\frac{1}{2}}$	$L^c(1,2)_{\frac{1}{2}}$
$E(1,1)_{-1}$	$E^c(1,1)_1$

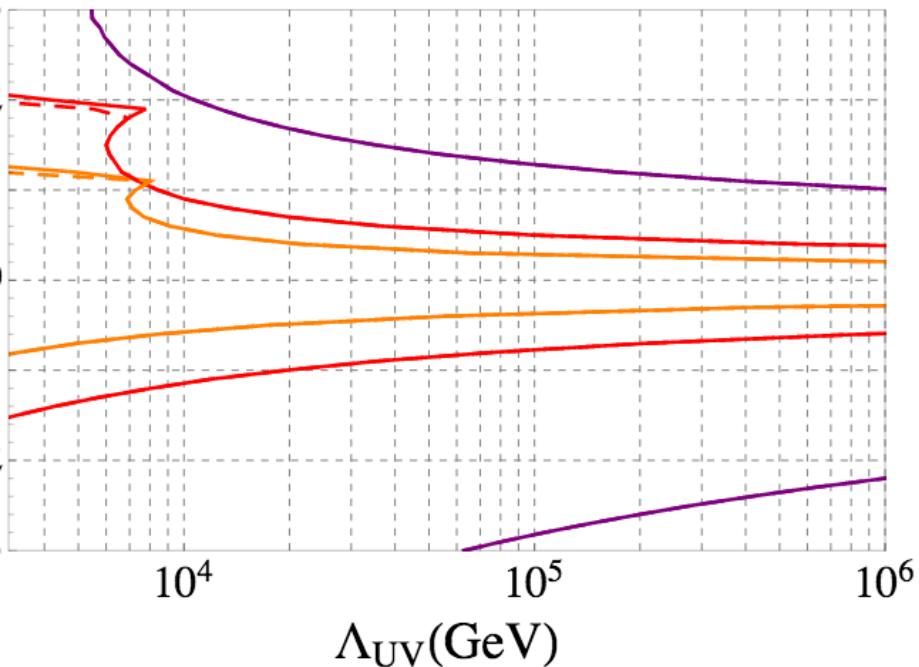
$H \rightarrow \text{diphoton}$

$$\delta r_\gamma \approx \frac{4Q^2 D}{3\mathcal{A}_{SM}^\gamma} \left(\frac{\partial \log \|M\|}{\partial \log \nu} \right)$$



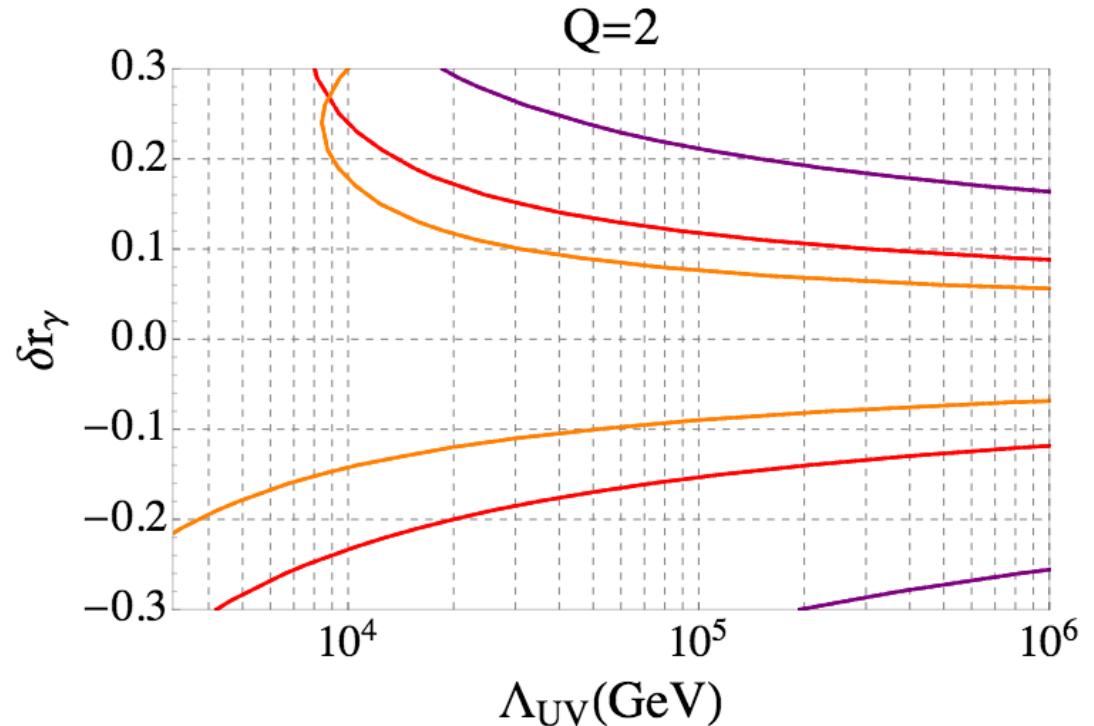
$H \rightarrow \text{diphoton}$

$Q=1$

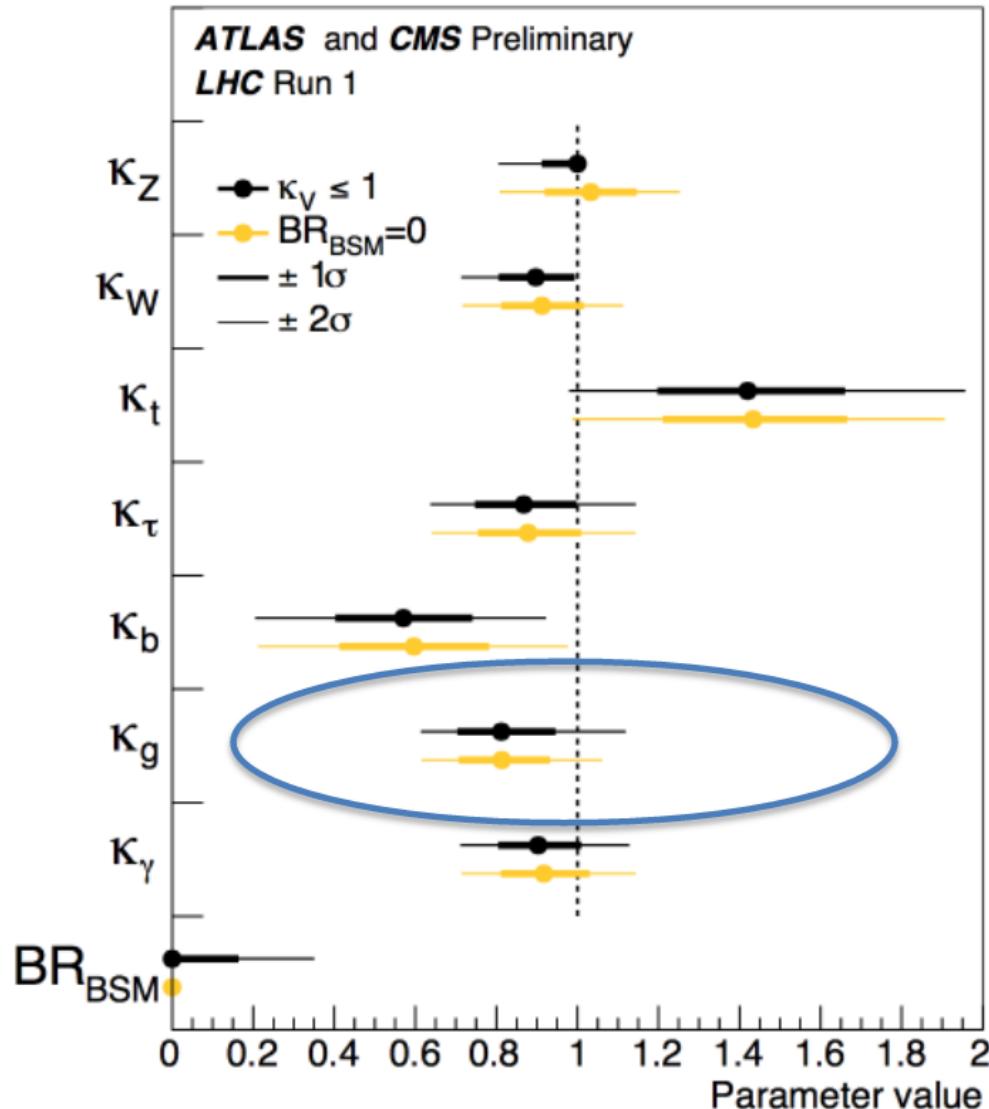


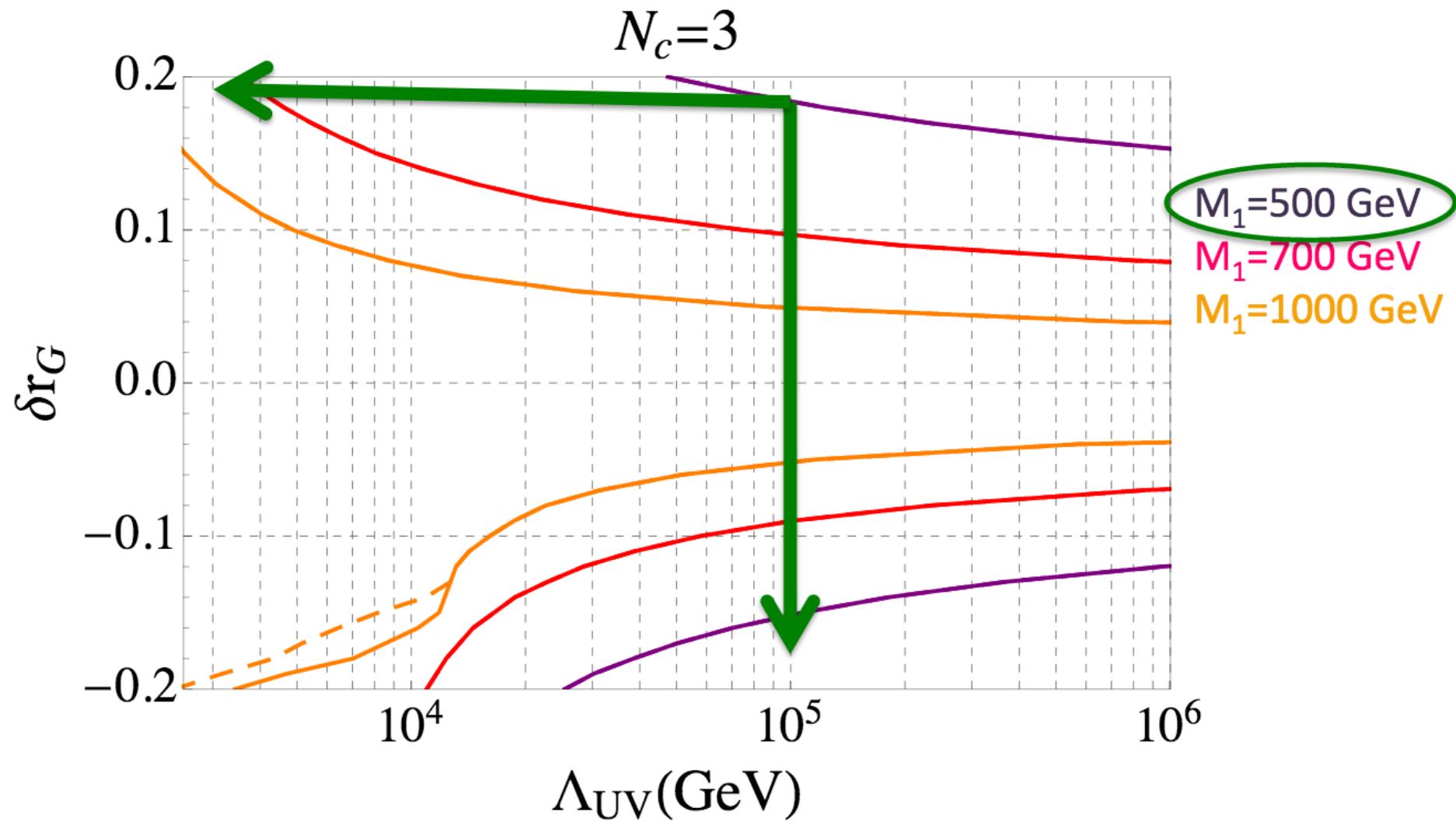
$M_1 = 200 \text{ GeV}, 400 \text{ GeV}, 600 \text{ GeV}$

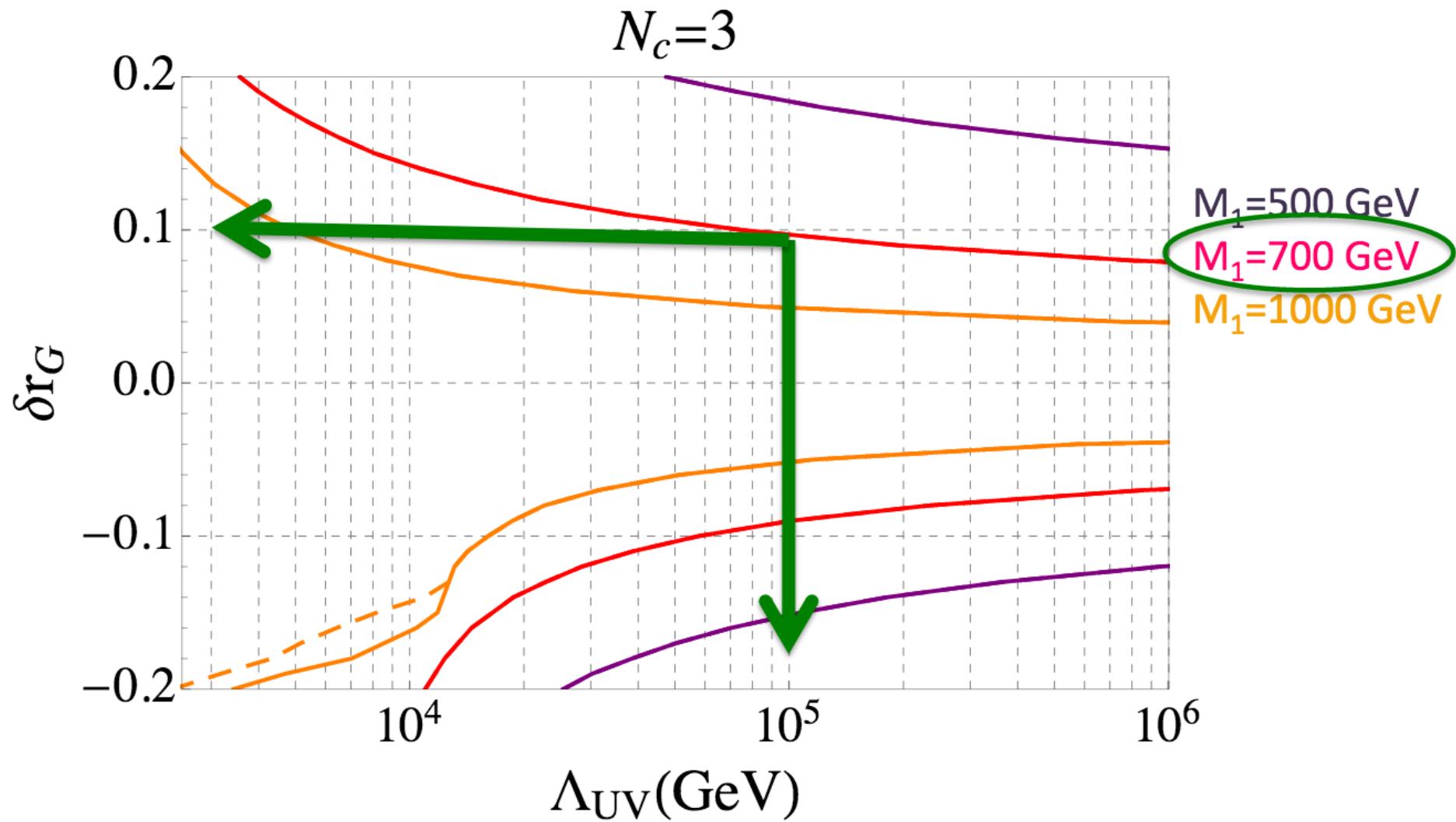
$Q=2$

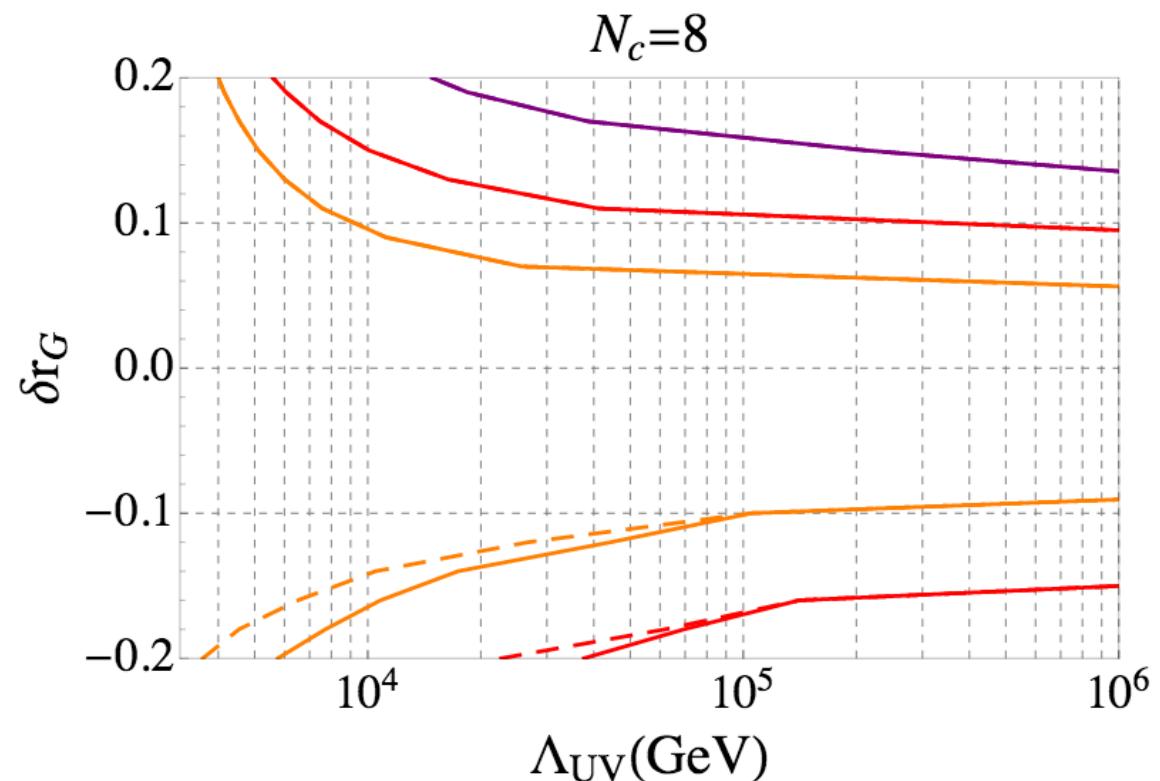
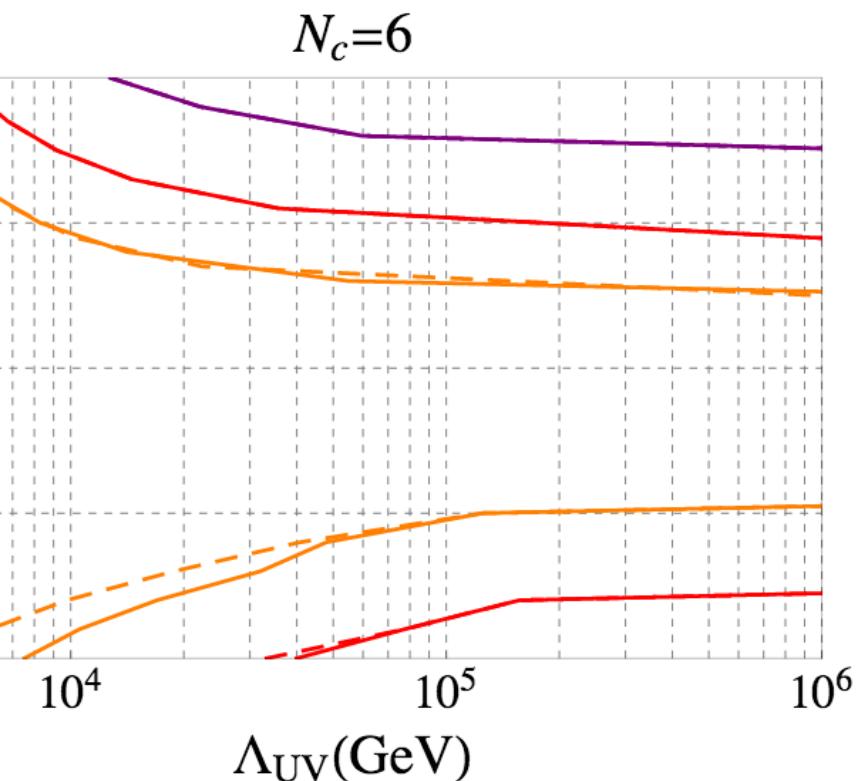


$M_1 = 400 \text{ GeV}, 600 \text{ GeV}, 800 \text{ GeV}$



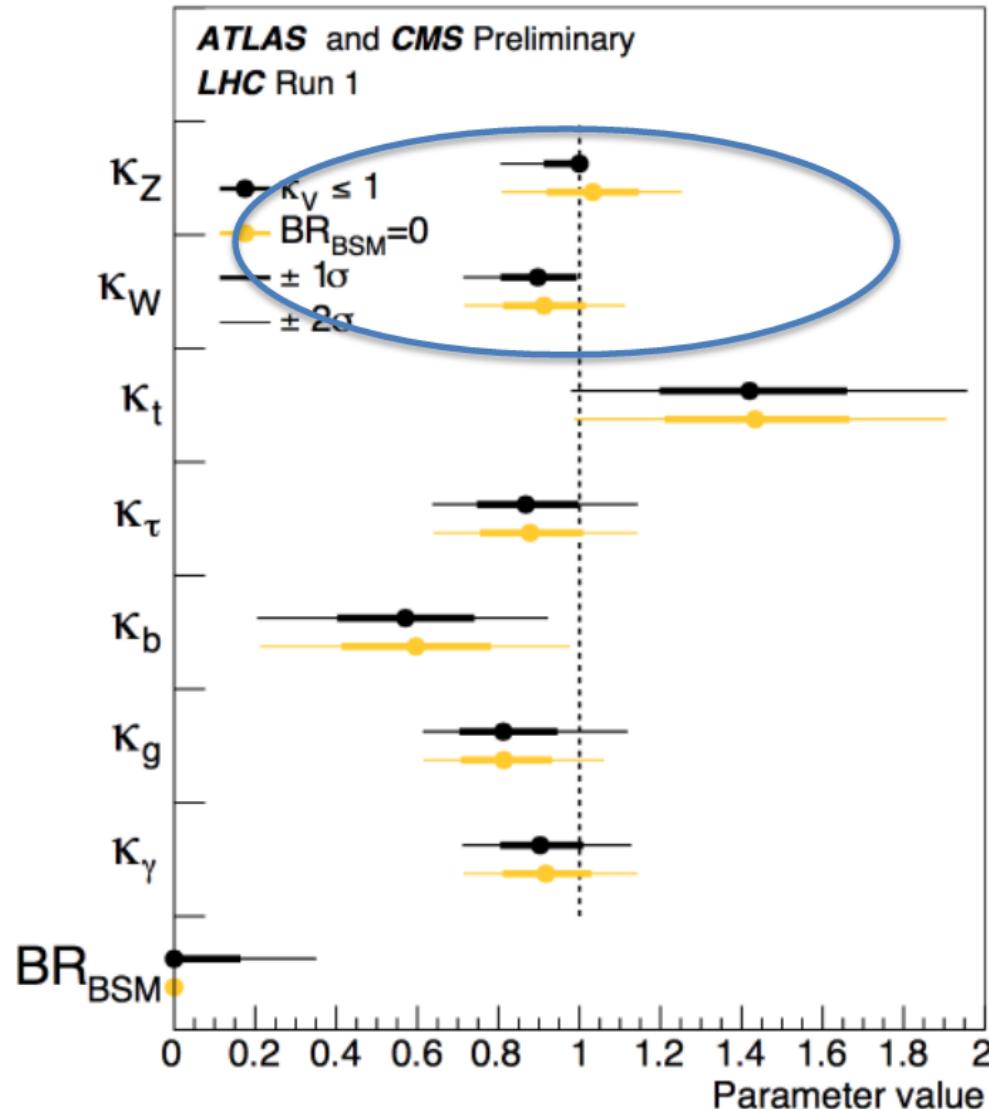






$M_1=1.2 \text{ TeV}, 1.5 \text{ TeV}, 2 \text{ TeV}$

HWW, HZZ



HWW, HZZ

Leading-log $\rightarrow c(h/v) W_{\mu\nu} W^{\mu\nu}$

$$c = \frac{8bg^2 D}{(4\pi)^2} \frac{d \log ||\mathcal{M}||}{d \log v} = -\frac{8bg^2 D}{(4\pi)^2} \frac{YY^c v^2}{M_1 M_2} \text{sign}(|\mathcal{M}|)$$

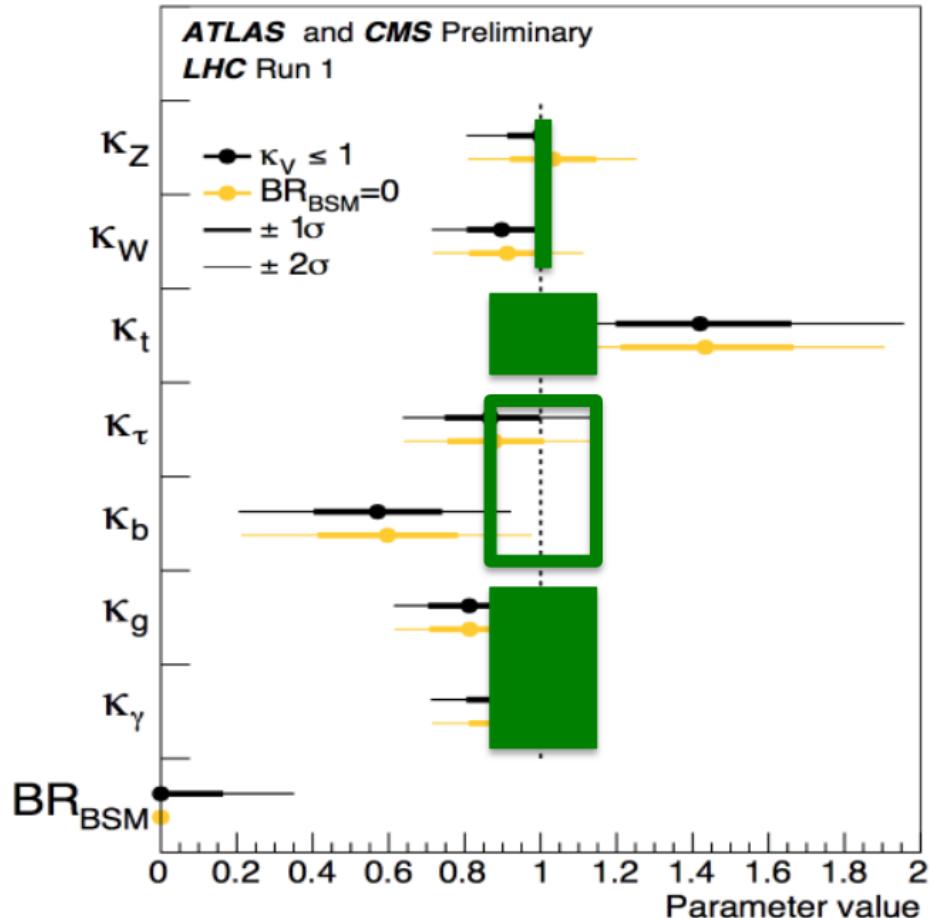
$$\rightarrow \delta r_W \sim \frac{|c|^2}{g^4} \lesssim 10^{-2} D^2 \left(\frac{M_1}{200 \text{ GeV}}\right)^{-4} |YY^c|^2$$

O(1%) deviation would imply new bosons nearby

Summary

1502.01045

- 1. Any of those → would imply new bosons < 10-100 TeV**
- 2. Run-II will sharpen this by placing new limits on (or detecting) new fermions**

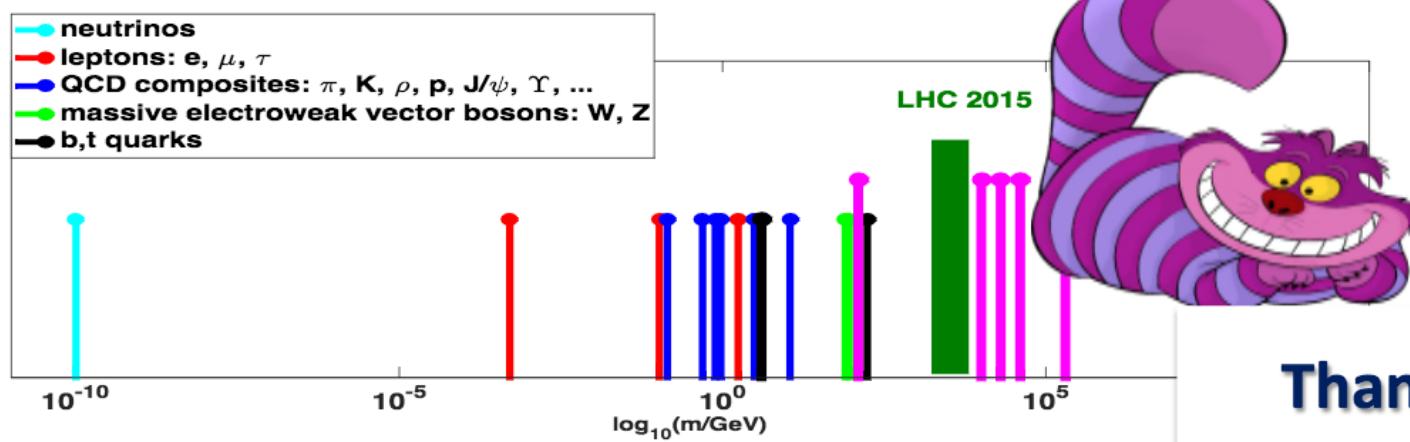
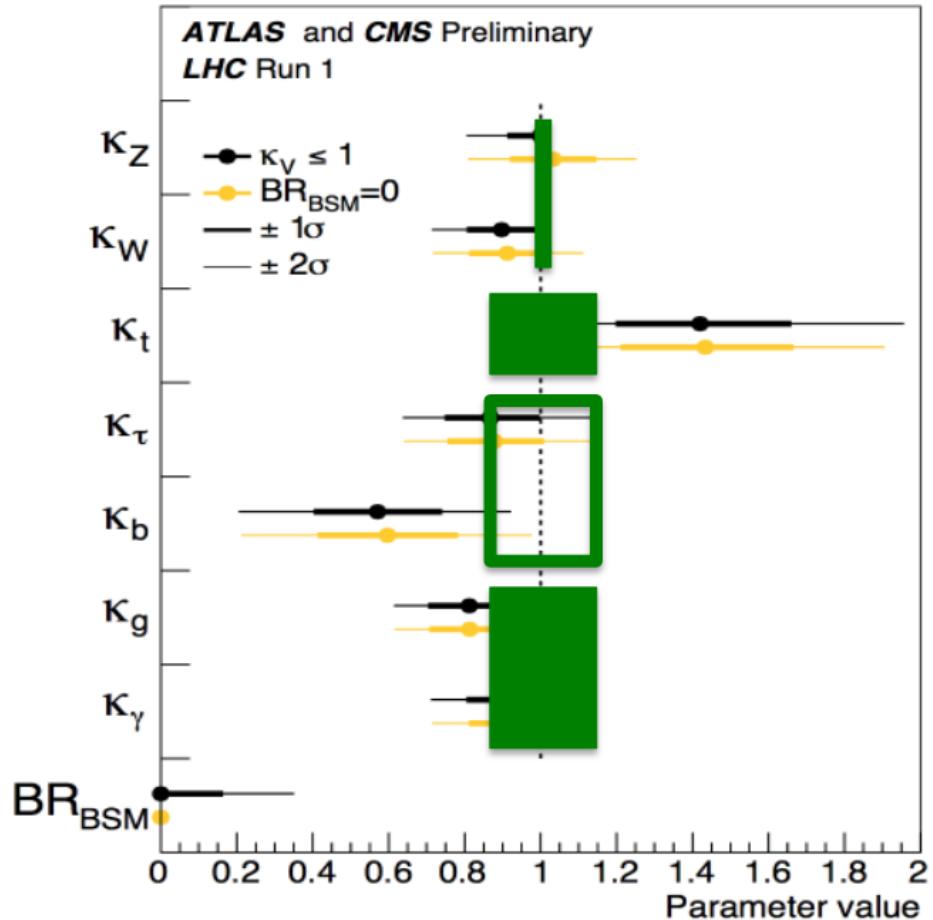


Summary

1502.01045

1. Any of those →
would imply
new bosons < 10-100 TeV

2. Run-II will sharpen this
by placing new limits on
(or detecting) new fermions



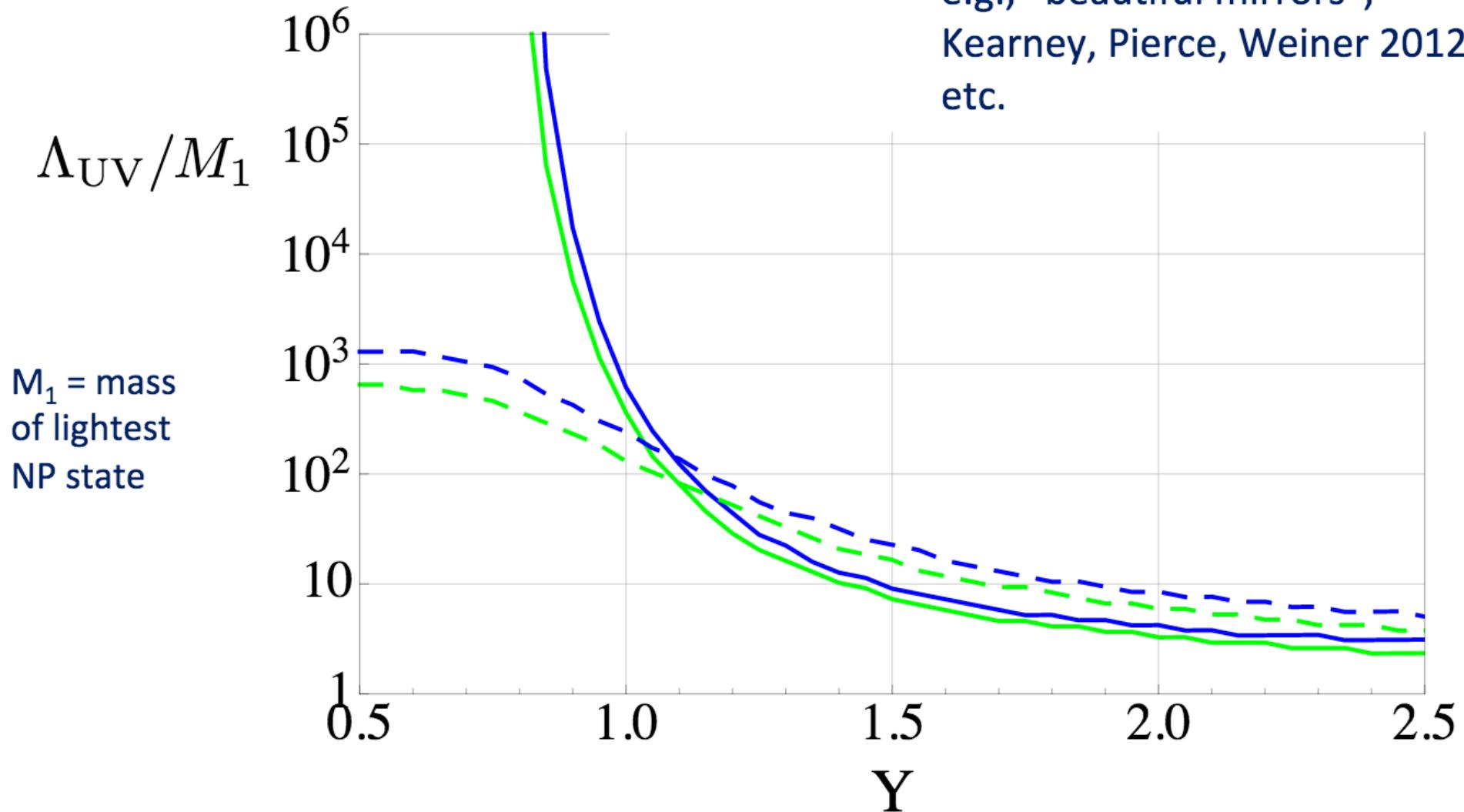
Thank you!

Xtra

$$Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}}$$

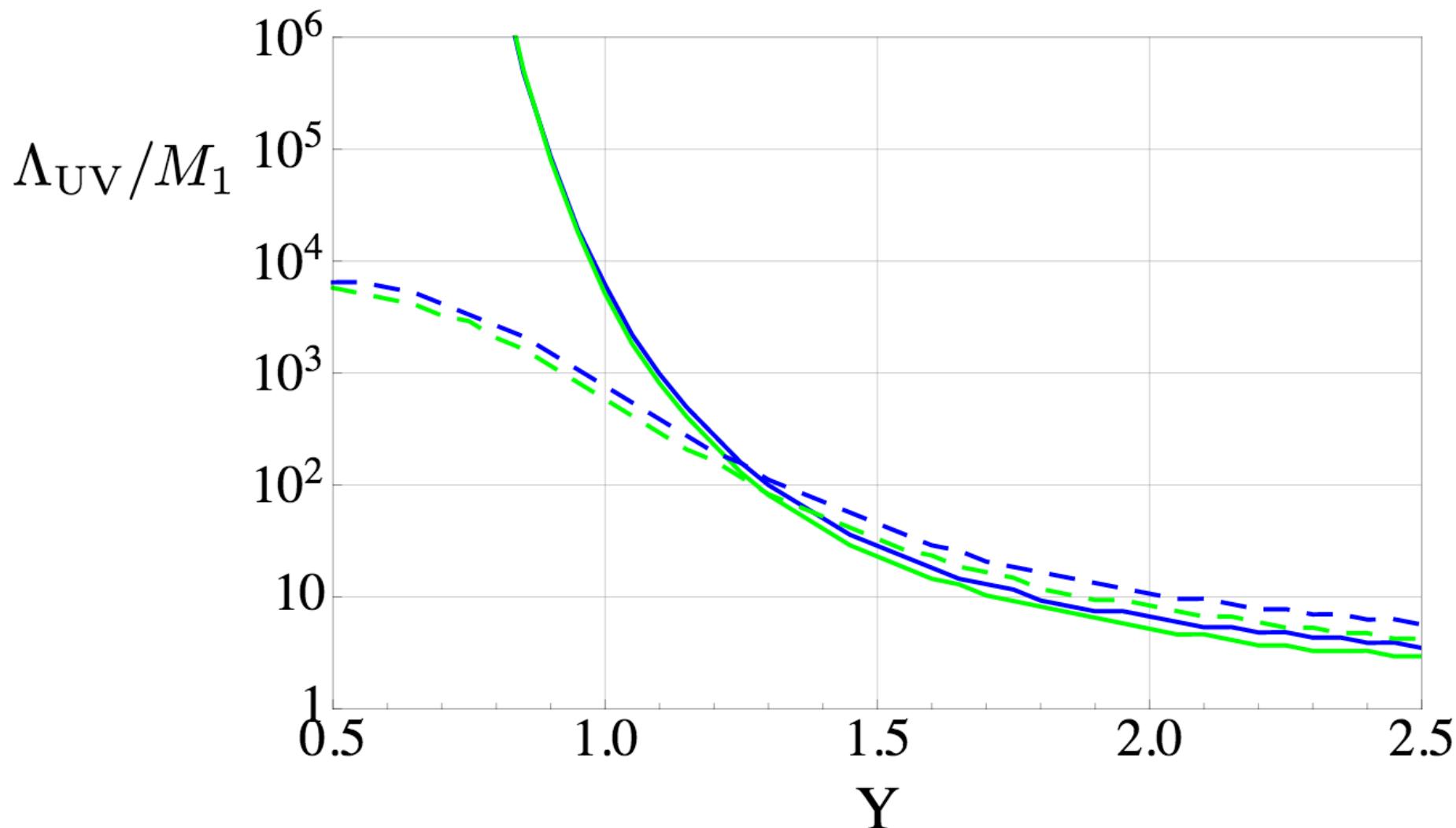
$\Upsilon \sim 1.2 \rightarrow \Lambda_{UV} \sim 10-100 M_1$
colored

e.g., “beautiful mirrors”,
 Kearney, Pierce, Weiner 2012,
 etc.



$$\begin{aligned} L(1,2)_{-\frac{1}{2}}, \quad &L^c(1,2)_{\frac{1}{2}} \\ E(1,1)_{-1}, \quad &E^c(1,1)_1 \end{aligned}$$

$\Upsilon \sim 1.5 \rightarrow \Lambda_{\text{UV}} \sim 10\text{-}100 M_1$
uncolored

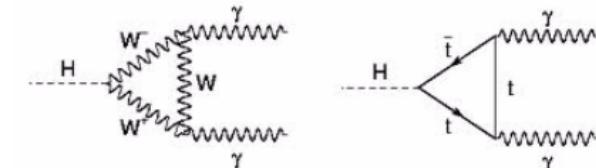


$$\delta r_\gamma \approx \frac{4Q^2 D}{3\mathcal{A}_{SM}^\gamma} \left(\frac{\partial \log |M|}{\partial \log v} \right)$$

Controlled by QED beta function

$$b = \begin{cases} +1/3 & \text{scalar} \\ +4/3 & \text{Dirac fermion} \\ -11/3 & \text{vector boson} \end{cases}$$

SM amplitude negative by W contribution $\mathcal{A}_{SM}^\gamma = -6.49$

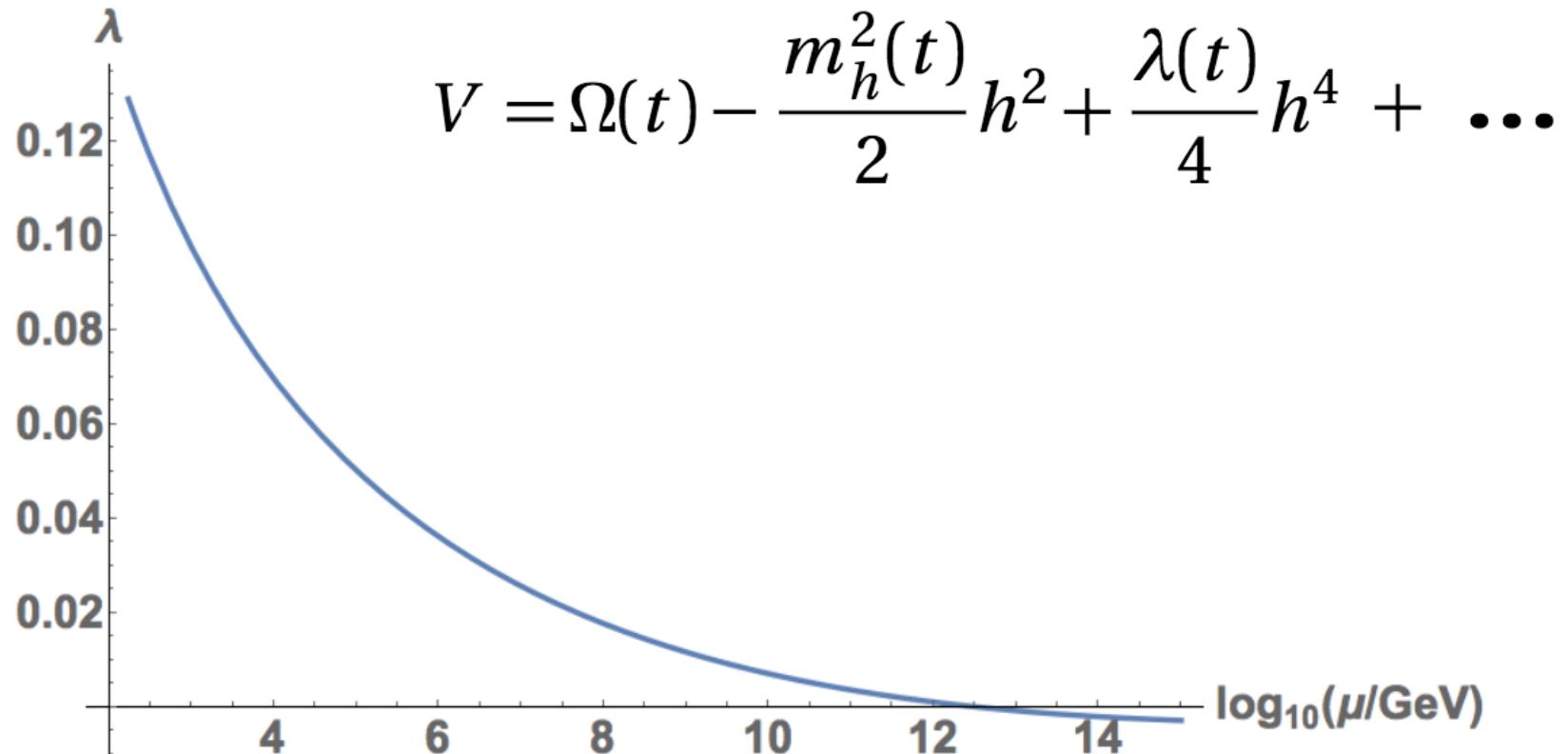


One basic structure (Arkani-Hamed, KB, D'Agnolo, Fan 2012)

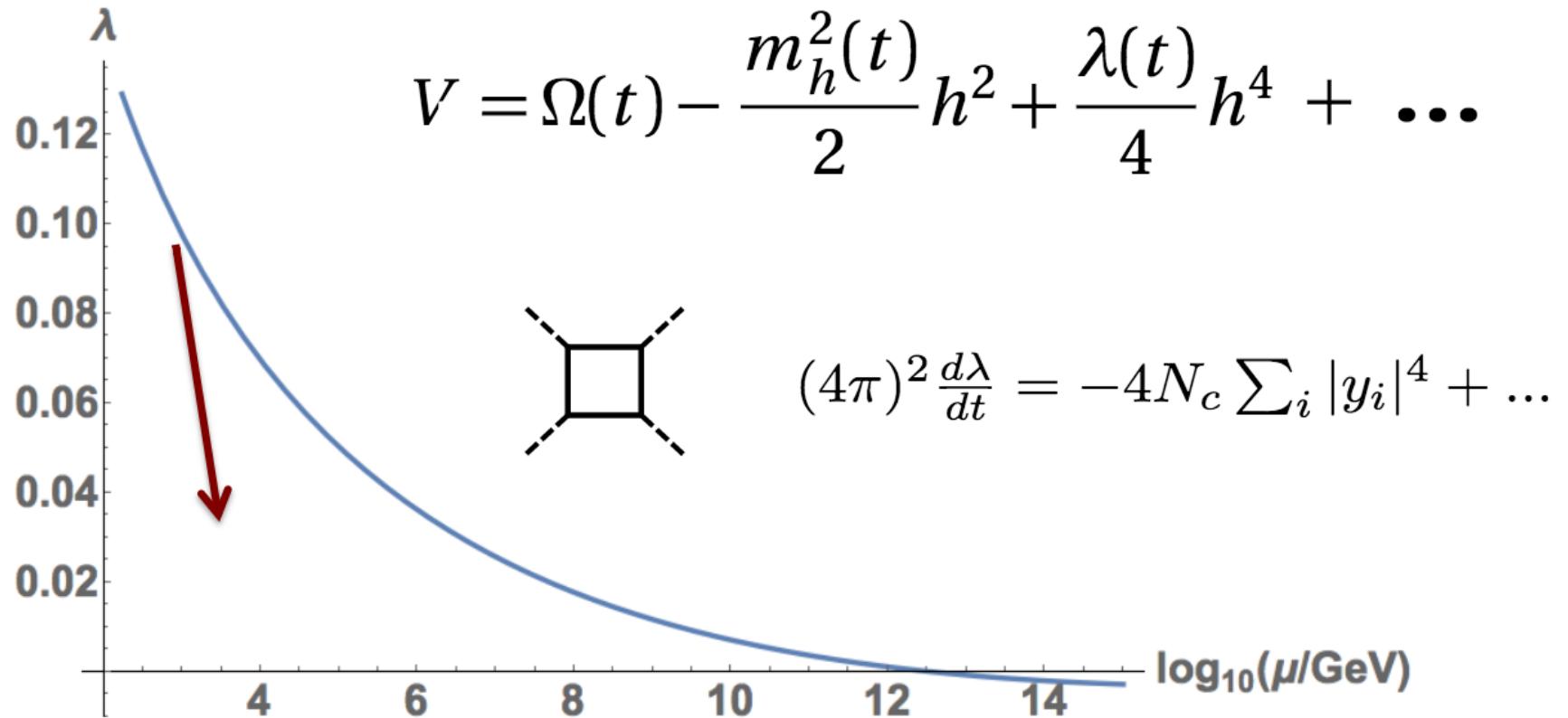
$$\psi(D,2)_{-Q+\frac{1}{2}}, \psi^c(\bar{D},2)_{Q-\frac{1}{2}}, \chi(\bar{D},1)_Q, \chi^c(D,1)_{-Q}$$

$$\gamma_{NP} = (\psi^{-Q} \chi^{c-Q}) \begin{pmatrix} \frac{Y\nu}{\sqrt{2}} & -m_\psi \\ m_\chi & -\frac{Y^c\nu}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \chi^{+Q} \\ \psi^{c+Q} \end{pmatrix} \xrightarrow{\text{orange arrow}} \left(\frac{\partial \log |M|}{\partial \log v} \right) = -\frac{YY^c\nu^2}{M_1M_2} \text{sign}(|M|)$$

SM Higgs quartic already dips below zero due to large top Yukawa coupling



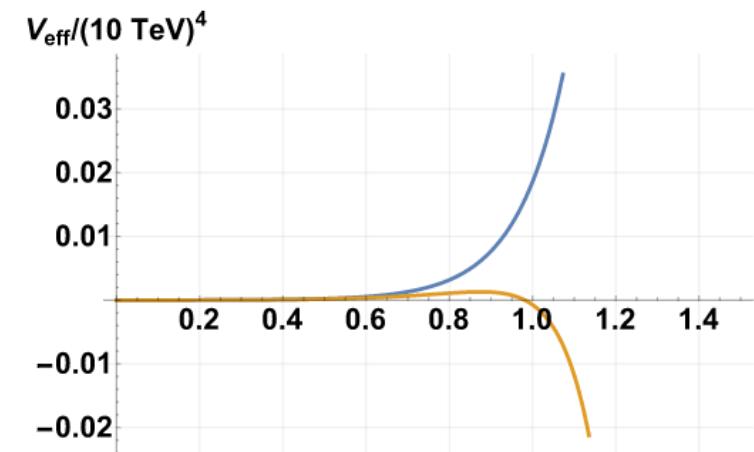
SM Higgs quartic already dips below zero due to large top Yukawa coupling



How to define the cut-off?

In a full (consistent) theory, this is straightforward via the tunneling action.

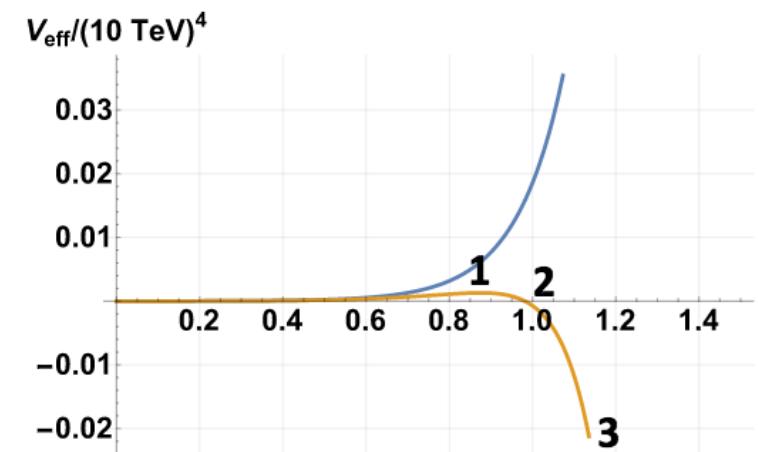
Here we often simply have a runaway...



How to define the cut-off?

In a full (consistent) theory, this is straightforward via the tunneling action.

Here we often simply have a runaway...



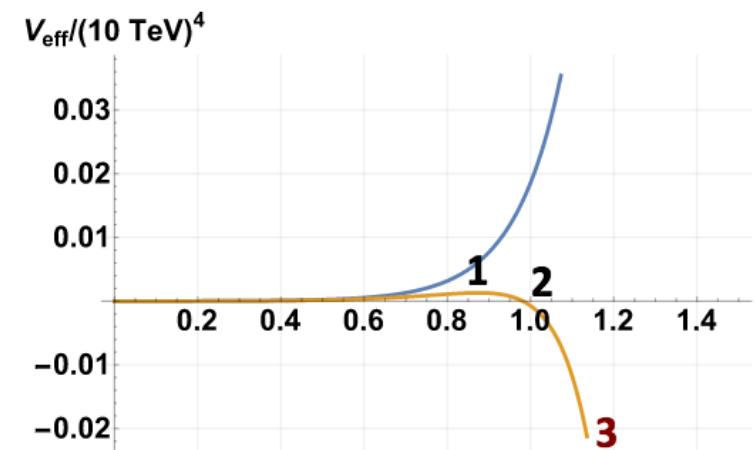
A number of possibilities, all scale similarly, and similarly agreeable for our purpose:

1. $\Lambda_{\text{UV}} \sim$ location of maximum of V_{eff}
2. $\Lambda_{\text{UV}} \sim$ location of $V_{\text{eff}}=0$
3. $\Lambda_{\text{UV}} \sim$ via approximate tunneling prob' using runaway quartic potential
4. ...

How to define the cut-off?

In a full (consistent) theory, this is straightforward via the tunneling action.

Here we often simply have a runaway...



A number of possibilities, all scale similarly, and similarly agreeable for our purpose:

1. $\Lambda_{\text{UV}} \sim \text{location of maximum of } V_{\text{eff}}$
2. $\Lambda_{\text{UV}} \sim \text{location of } V_{\text{eff}}=0$
3. $\Lambda_{\text{UV}} \sim \text{via approximate tunneling prob' using runaway quartic potential}$
4. ...

$$p \sim (\Lambda/H_0)^4 e^{-S} , \quad S = \frac{8\pi^2}{3|\lambda|} , \quad H_0 \sim 10^{-42} \text{ GeV}$$

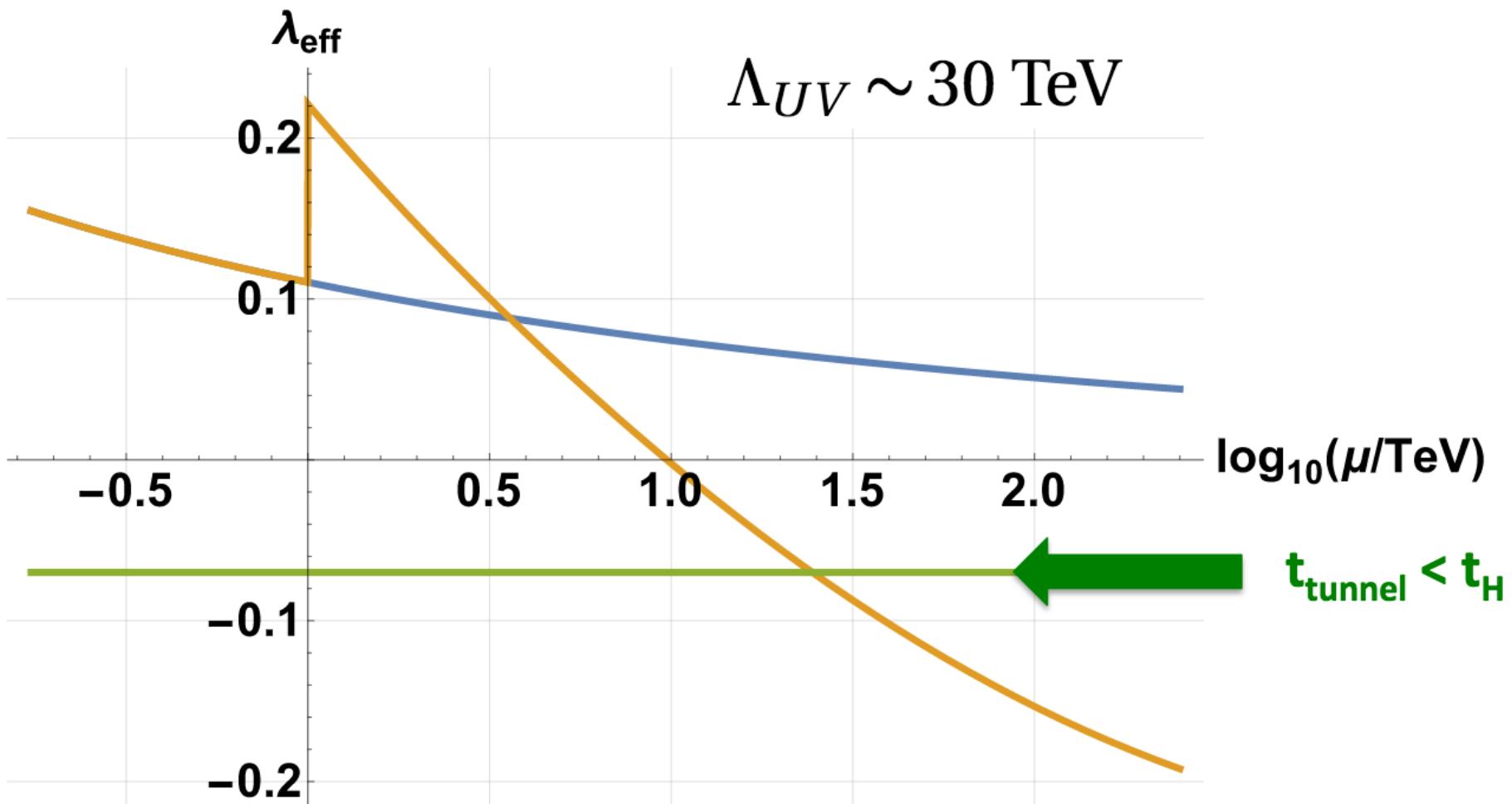
$$p = 1 \quad \rightarrow \quad \lambda \approx -0.065 (1 + 0.02 \log_{10}(\Lambda/1 \text{ TeV}))^{-1}$$

We take:

$$\lambda_{\text{eff}}(\Lambda_{\text{UV}}) = -0.07$$

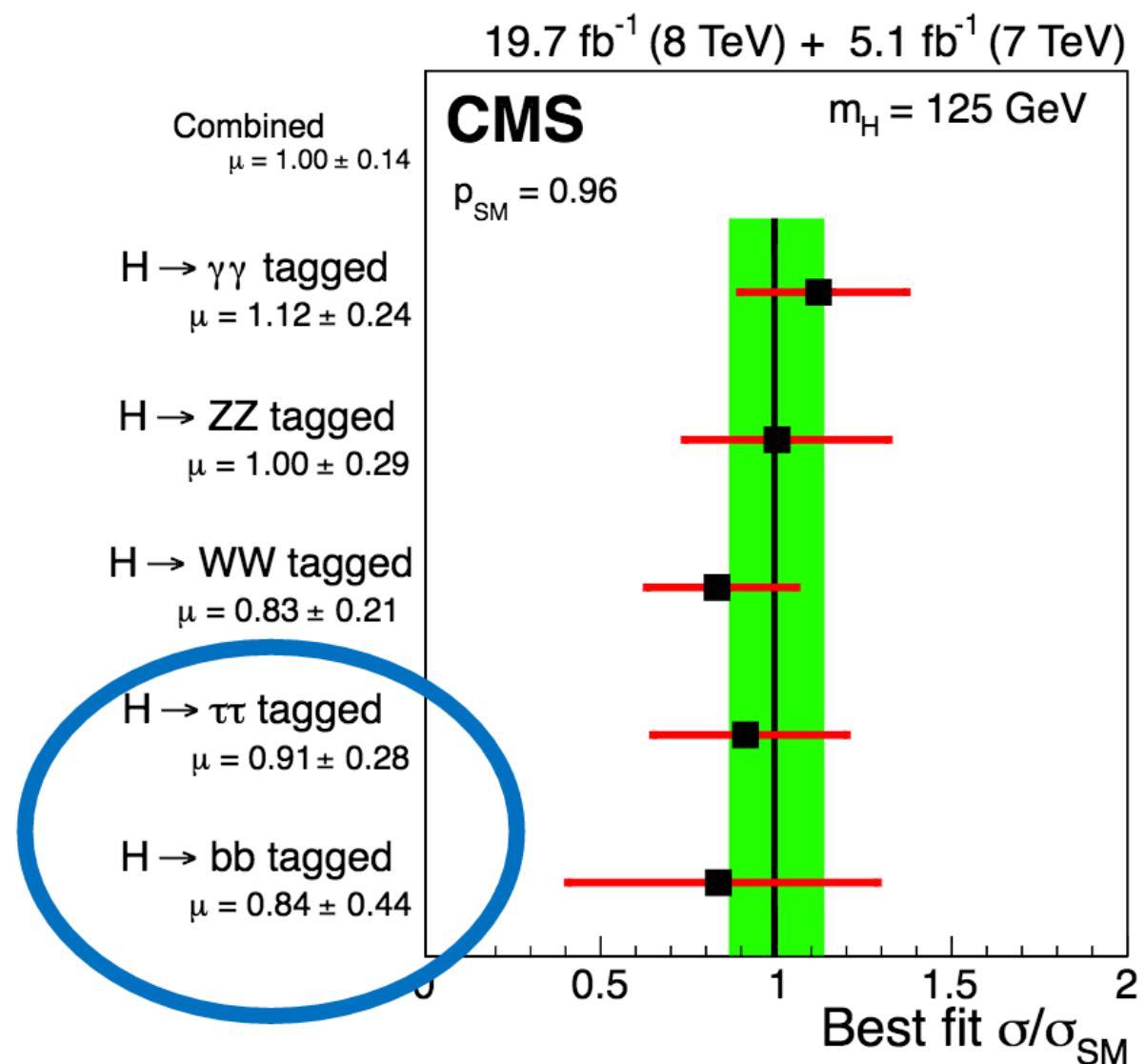
$$Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}}$$

$$Y_{QD^c(1\text{TeV})}=0 \\ Y_{Q^cD(1\text{TeV})}=1.25$$



Last:

H_{bb}, H_{ττ}



	representation	$-\mathcal{L}_{NP}$
DI	$Q(3,2)_{\frac{1}{6}}, Q^c(3,2)_{-\frac{1}{6}}$ $D(3,1)_{-\frac{1}{3}}, D^c(\bar{3},1)_{\frac{1}{3}}$	$Y_{Qd^c} H^\dagger Q d^c + Y_{qD^c} H^\dagger q D^c + Y_{QD^c} H^\dagger Q D^c + Y_{Q^c D} H^T \epsilon Q^c D$ $+ M_Q Q^T \epsilon Q^c + M_D D D^c + cc$
DII	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D(3,1)_{-\frac{1}{3}}, D^c(\bar{3},1)_{\frac{1}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{qD^c} H^\dagger q D^c + Y_{Q'D^c} H^T \epsilon Q' D^c + Y_{Q'^c D} H^\dagger Q'^c D$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_D D D^c + cc$
DIII	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $D'(3,3)_{-\frac{1}{3}}, D'^c(\bar{3},3)_{\frac{1}{3}}$	$Y_{Qd^c} H^\dagger Q d^c + Y_{qD'^c} H^\dagger \sigma q \cdot D'^c + Y_{QD'^c} H^\dagger \sigma Q \cdot D'^c + Y_{Q^c D'} H^T \epsilon \sigma Q^c \cdot D'$ $+ M_Q Q^T \epsilon Q^c + M_{D'} D' \cdot D'^c + cc$
DIV	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D'(3,3)_{-\frac{1}{3}}, D'^c(\bar{3},3)_{\frac{1}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{qD'^c} H^\dagger \sigma q \cdot D'^c + Y_{Q'D'^c} H^T \epsilon \sigma Q' \cdot D'^c + Y_{Q'^c D'} H^\dagger \sigma Q'^c \cdot D'$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_{D'} D' \cdot D'^c + cc$
UI	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $U(3,1)_{\frac{2}{3}}, U^c(\bar{3},1)_{-\frac{2}{3}}$	$Y_{Qu^c} H^T \epsilon Qu^c + Y_{qU^c} H^T \epsilon q U^c + Y_{QU^c} H^T \epsilon QU^c + Y_{Q^c U} H^\dagger Q^c U$ $+ M_Q Q^T \epsilon Q^c + M_U U U^c + cc$
UII	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U(3,1)_{\frac{2}{3}}, U^c(\bar{3},1)_{-\frac{2}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{qU^c} H^T \epsilon q U^c + Y_{Q''U^c} H^\dagger Q'' U^c + Y_{Q''^c U} H^T \epsilon Q''^c U$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_U U U^c + cc$
UIII	$Q(3,2)_{\frac{1}{6}}, Q^c(\bar{3},2)_{-\frac{1}{6}}$ $U'(3,3)_{\frac{2}{3}}, U'^c(\bar{3},3)_{-\frac{2}{3}}$	$Y_{Qu^c} H^T \epsilon Qu^c + Y_{qU'^c} H^T \epsilon \sigma q \cdot U'^c + Y_{QU'^c} H^T \epsilon \sigma Q \cdot U'^c + Y_{Q^c U'} H^\dagger \sigma Q^c \cdot U'$ $+ M_Q Q^T \epsilon Q^c + M_{U'} U' \cdot U'^c + cc$
UIV	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U'(3,3)_{\frac{2}{3}}, U'^c(\bar{3},3)_{-\frac{2}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{qU'^c} H^T \epsilon \sigma q \cdot U'^c + Y_{Q''U'^c} H^\dagger \sigma Q'' \cdot U'^c + Y_{Q''^c U'} H^T \epsilon \sigma Q''^c \cdot U'$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_{U'} U' \cdot U'^c + cc$
DV	$Q'(3,2)_{-\frac{5}{6}}, Q'^c(\bar{3},2)_{\frac{5}{6}}$ $D''(3,3)_{-\frac{4}{3}}, D''^c(\bar{3},3)_{\frac{4}{3}}$	$Y_{Q'd^c} H^T \epsilon Q' d^c + Y_{Q'D''^c} H^\dagger \sigma Q' \cdot D''^c + Y_{Q'^c D''} H^T \epsilon \sigma Q'^c \cdot D''$ $+ M_{Q'} Q'^T \epsilon Q'^c + M_{D''} D'' \cdot D''^c + cc$
UV	$Q''(3,2)_{\frac{7}{6}}, Q''^c(\bar{3},2)_{-\frac{7}{6}}$ $U''(3,3)_{\frac{5}{3}}, U''^c(\bar{3},3)_{-\frac{5}{3}}$	$Y_{Q''u^c} H^\dagger Q'' u^c + Y_{Q''U''^c} H^T \epsilon \sigma Q'' \cdot U''^c + Y_{Q''^c U''} H^\dagger \sigma Q''^c \cdot U''$ $+ M_{Q''} Q''^T \epsilon Q''^c + M_{U''} U'' \cdot U''^c + cc$

Connect the size of the NP Yukawa couplings to Hbb deviation.

Integrating out heavy quarks:

$$\begin{aligned} & Q(3, 2)_{\frac{1}{6}}, \quad Q^c(\bar{3}, 2)_{-\frac{1}{6}} \\ & D(3, 1)_{-\frac{1}{3}}, \quad D^c(\bar{3}, 1)_{\frac{1}{3}} \end{aligned}$$

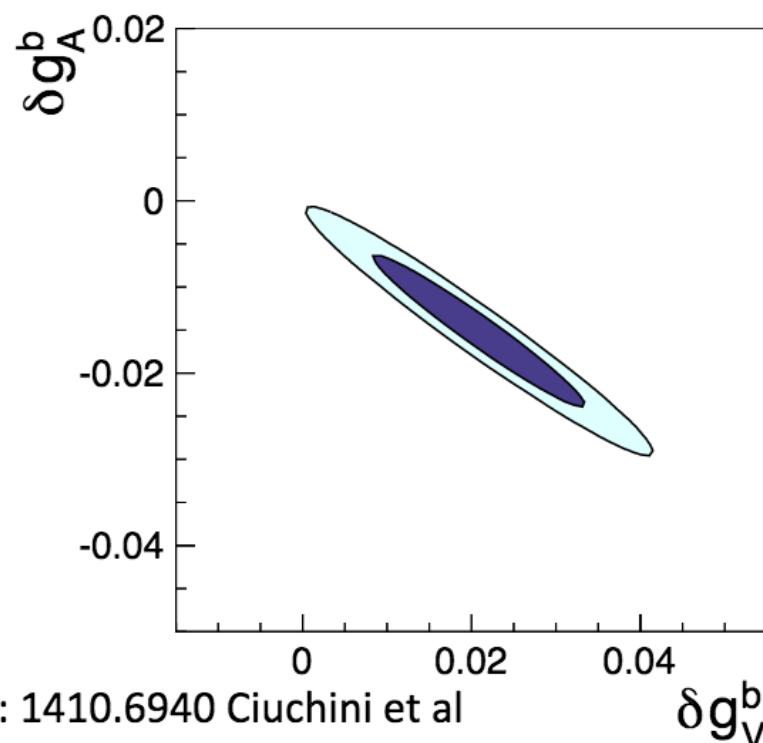
$$\delta r_b \approx -2\delta g_{Ab} + \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_b} \sqrt{|\delta g_{Vb}^2 - \delta g_{Ab}^2|} e^{i\phi}$$

Connect the size of the NP Yukawa couplings to Hbb deviation.

Integrating out heavy quarks:

$$\begin{aligned} & Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ & D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}} \end{aligned}$$

$$\delta r_b \approx -2\delta g_{Ab} + \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_b} \sqrt{|\delta g_{Vb}^2 - \delta g_{Ab}^2|} e^{i\phi}$$



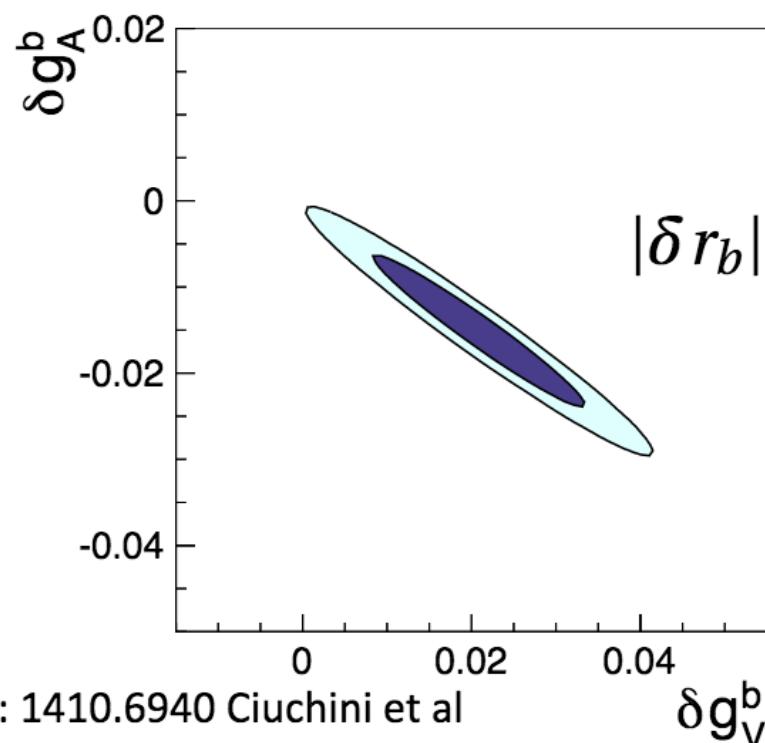
EWPT: 1410.6940 Ciuchini et al

Connect the size of the NP Yukawa couplings to Hbb deviation.

Integrating out heavy quarks:

$$\begin{aligned} & Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ & D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}} \end{aligned}$$

$$\delta r_b \approx -2\delta g_{Ab} + \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_b} \sqrt{|\delta g_{Vb}^2 - \delta g_{Ab}^2|} e^{i\phi}$$



$$|\delta r_b| \approx 0.1|Y_{Q^c D}| \left(\sqrt{|\delta g_{Vb}^2 - \delta g_{Ab}^2|} / 10^{-3} \right)$$

Connect the size of the NP Yukawa couplings to Hbb deviation.

Integrating out heavy quarks:

$$\boxed{Q(3,2)_{\frac{1}{6}}, \quad Q^c(\bar{3},2)_{-\frac{1}{6}} \\ D(3,1)_{-\frac{1}{3}}, \quad D^c(\bar{3},1)_{\frac{1}{3}}}$$

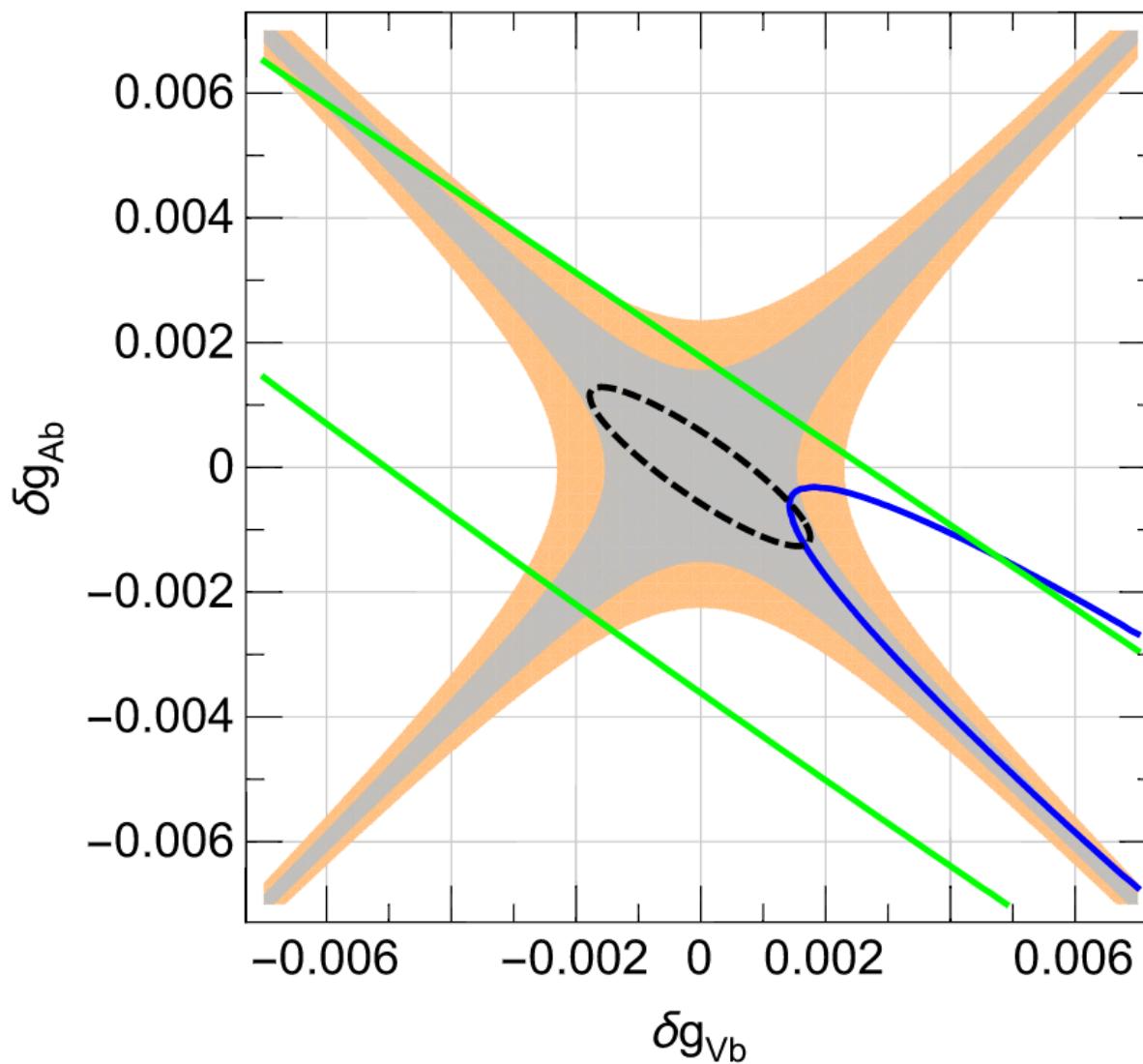
$$\delta r_b \approx -2\delta g_{Ab} + \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_b} \sqrt{|\delta g_{Vb}^2 - \delta g_{Ab}^2|} e^{i\phi}$$

One complex phase $\phi = \arg \left(\frac{Y_{Q^c D} Y_{qD^c} Y_{Qd^c} M_Q M_D}{|\mathcal{M}| |\mathcal{M}_{2 \times 2}|} \right)$

$\phi \neq 0 \rightarrow$ CPV in Hbb; imaginary part adds in quadrature in $\Gamma(h \rightarrow b\bar{b})$,
smaller effect in μ_b

Hbb deviation > 20% \rightarrow Zbb deviation > 10^{-3}

Otherwise – very large Yukawa... unstable



$$\Lambda_{UV} \sim 10 M_1$$

$$\Lambda_{UV} \sim 100 M_1$$

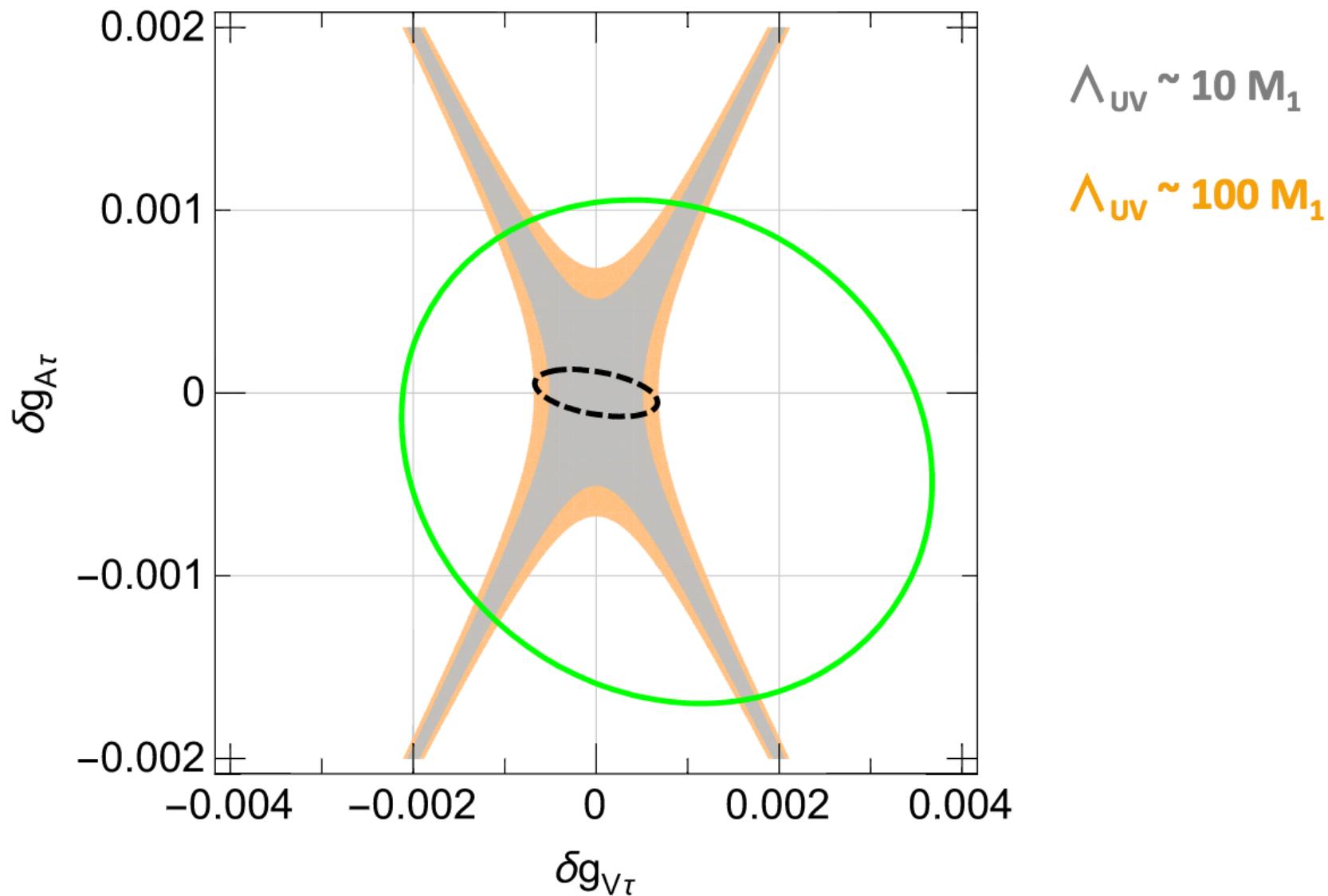
Hbb deviation > 20% → Zbb deviation > 10⁻³

Applies to all of the representations

DI, DIV $\delta r_d \approx -2\delta g_{Ad} + \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_d} \sqrt{|\delta g_{Vd}^2 - \delta g_{Ad}^2|} e^{i\phi}$

DII, DIII $\delta r_d \approx -2\delta g_{Vd} - \frac{2|Y_{Q^c D}|v}{\sqrt{2}m_d} \sqrt{|\delta g_{Vd}^2 - \delta g_{Ad}^2|} e^{i\phi}$

$H\pi\pi$ deviation > 20% $\rightarrow Z\pi\pi$ deviation > 10^{-3}



$\Lambda_{UV} \sim 10 M_1$

$\Lambda_{UV} \sim 100 M_1$

Hπ

$$\boxed{\begin{array}{ll} L(1,2)_{-\frac{1}{2}}, & L^c(1,2)_{\frac{1}{2}} \\ E(1,1)_{-1}, & E^c(1,1)_1 \end{array}}$$

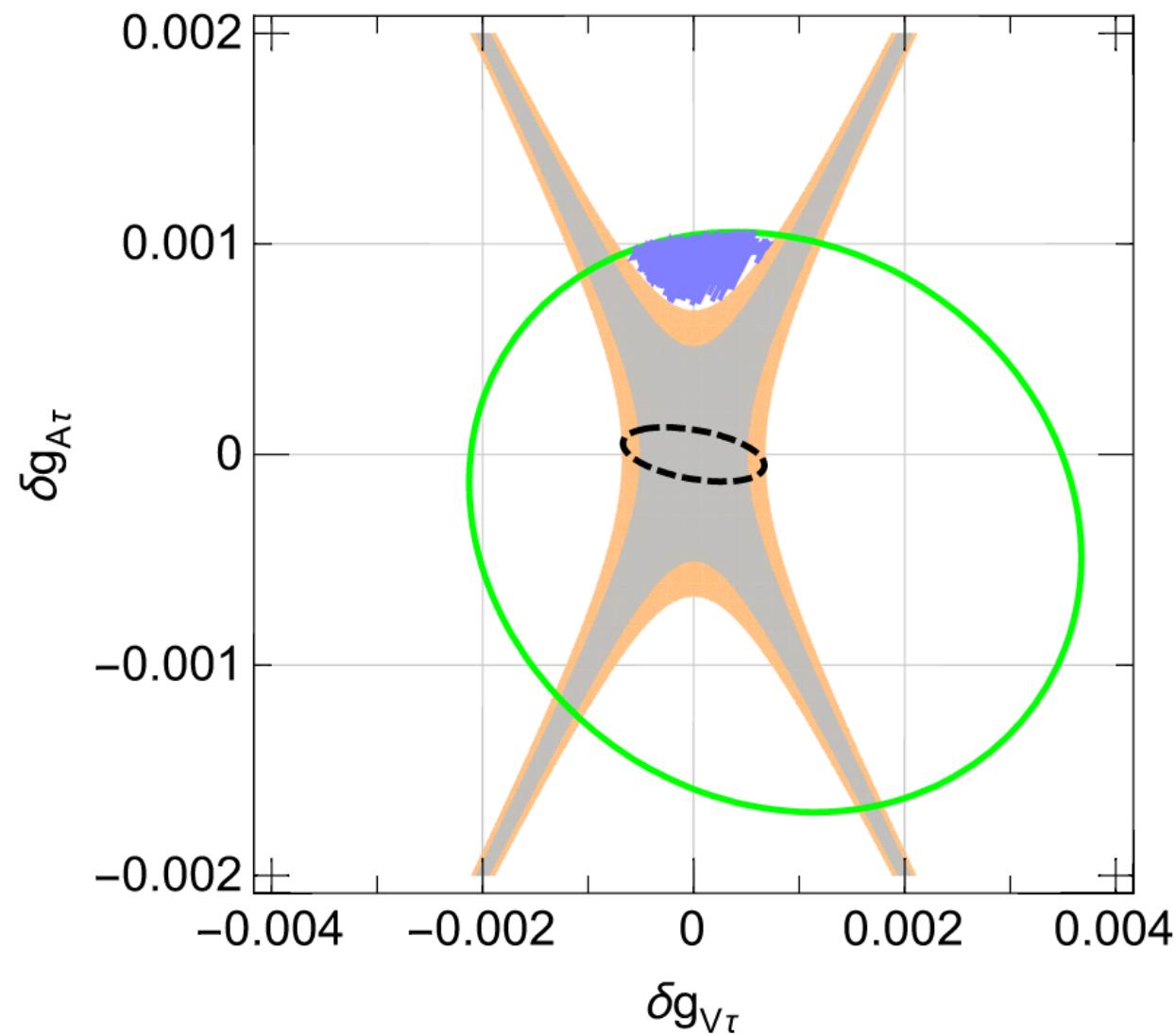
$$\delta r_\tau \approx -2\delta g_{A\tau} + \frac{2|Y_{L^c E}|v}{\sqrt{2}m_\tau} \sqrt{|\delta g_{V\tau}^2 - \delta g_{A\tau}^2|} e^{i\phi}$$

Obtained by integrating out heavy states;
 But applies down to $M \sim 100$ GeV: really, expansion is in $\delta g_{A,V}$

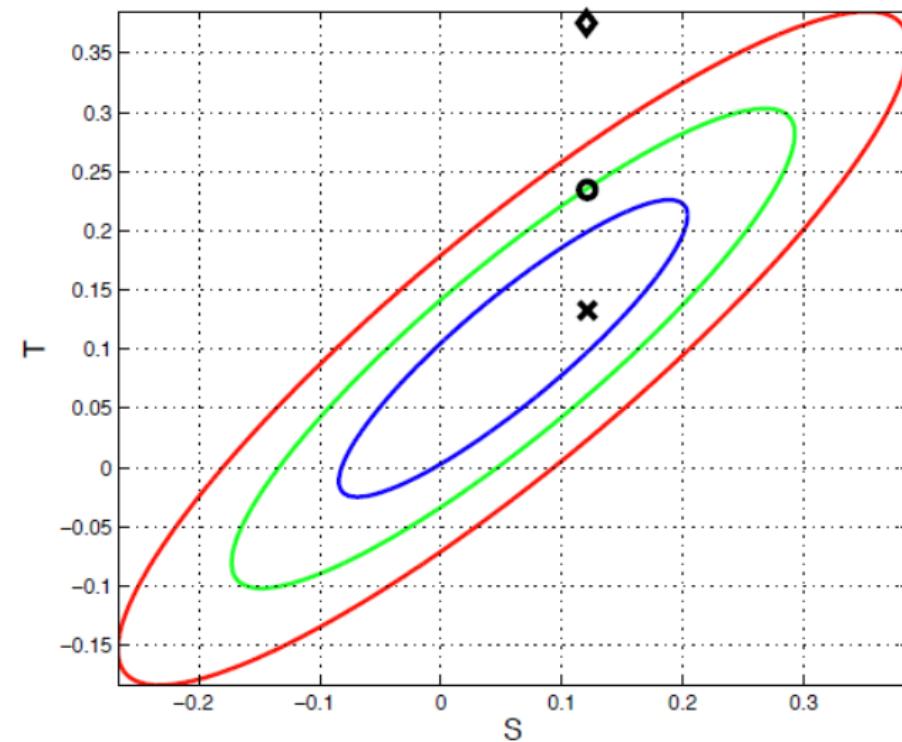
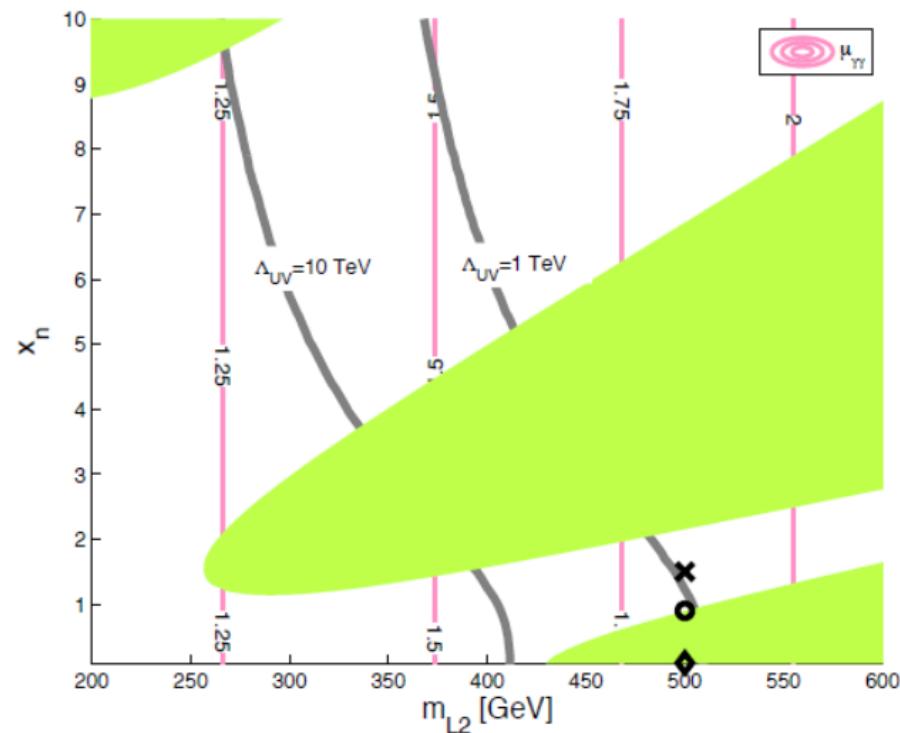
Verify explicitly by scanning over parameters:

$$\begin{aligned} -\mathcal{L} &= (l^- L^- E^-) \mathcal{M} \begin{pmatrix} e^{c+} \\ E^{c+} \\ L^{c+} \end{pmatrix}, \quad \mathcal{M} = VDU, \\ V &= e^{i\theta_v \Lambda_7} e^{i\gamma_v \Lambda_3} e^{i\beta_v \Lambda_2} e^{i\phi \Lambda_3}, \quad U = e^{i\beta_u \Lambda_2} e^{i\gamma_u \Lambda_3} e^{i\theta_u \Lambda_7} \end{aligned}$$

$$D = \text{diag}(m_\tau, M_1, M_2)$$



Tuning (with more fermions) to evade EWPTs



Of course, need light charged fermions to pull the effect in the first place

→ Irreducible electroweak production at LHC

As we saw, mass of lightest charged state is important to set the stability constraint.
Detectability model-dependent.

To make lightest charged state decay, need to add matter/couplings to SM fermions

