HIGH-ENERGY VS. FLAVOR EXPERIMENTS

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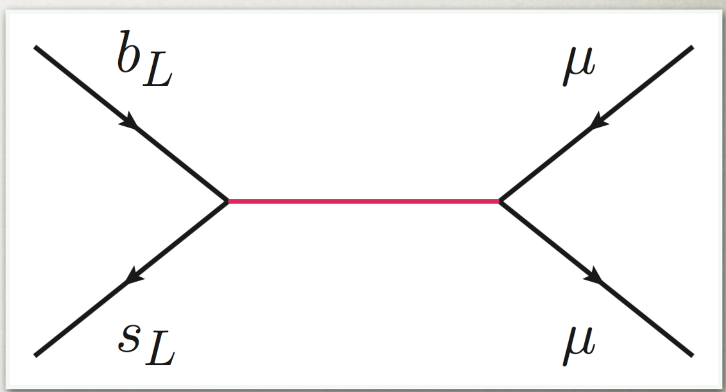
Hints for NP in Heavy Flavors, Nagoya, Nov 16 2018

HIGH ENERGY VS. FLAVOR EXPERIMENTS

- at low energies probe off-shell states

$$Br(i \to f) \propto \left(\frac{g_i g_f}{m^2}\right)^2$$



- at high energies on-shell production
  - s-channel

$$\sigma(i \to X) \times Br(X \to f) \propto \mathcal{L}_i(m) \left(\frac{g_i g_f}{m^2}\right)^2 \frac{1}{\Gamma_{\rm tot}}$$

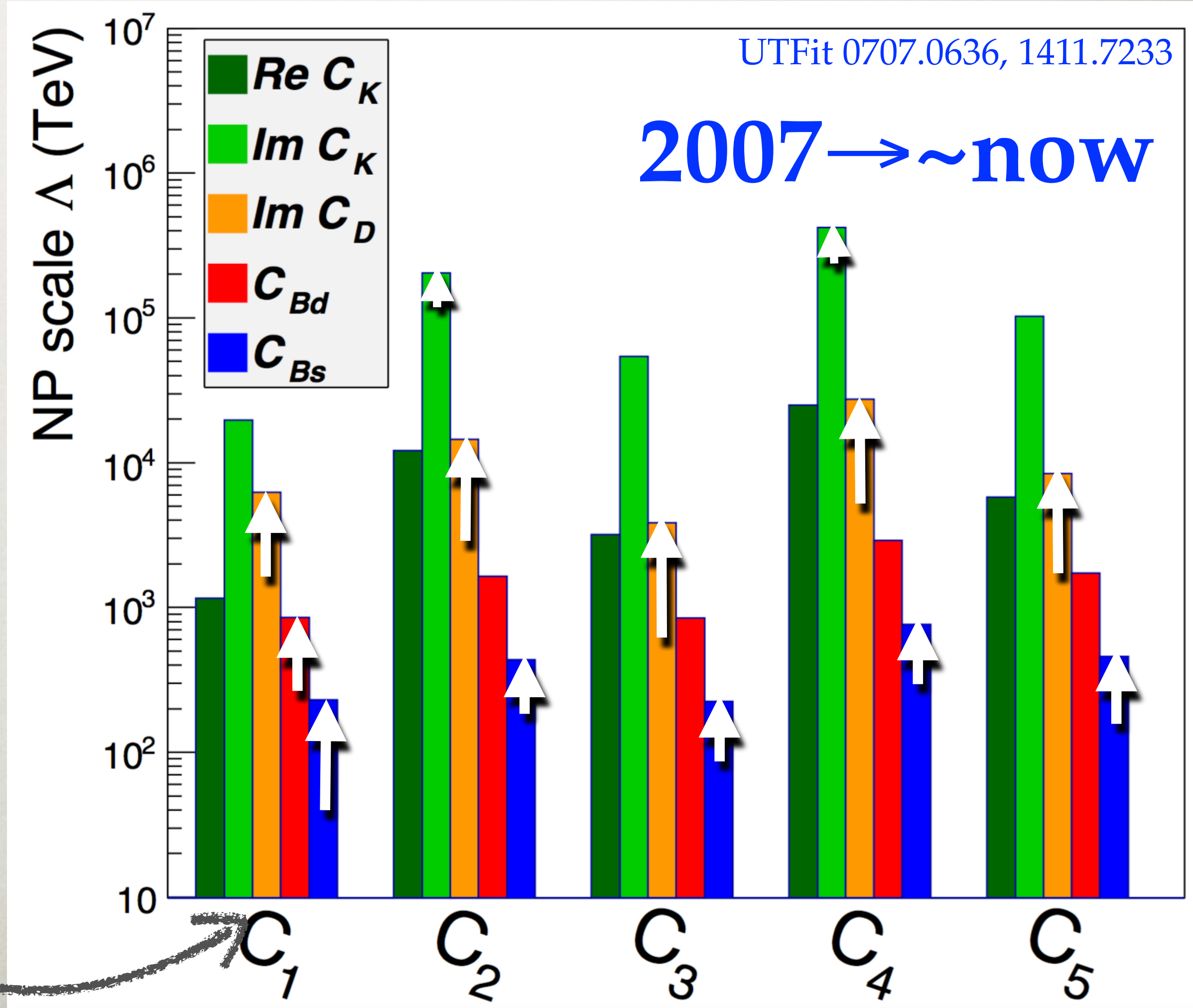
  - other options: *t*-channel, pair production, ...
- probe different combinations of couplings and masses*

*small print: at high eng. could also still be off shell, which couplings depend on which prod/decay channel, etc

HIGH ENERGY VS. FLAVOR EXPERIMENTS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- flavor experiments: may probe much higher scales
- an impressive progress on flavor bounds in last 10 years
  - in D, B_s mixing
  - also from ε_K



$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

OUTLINE

- $b \to s\mu\mu$ and $b \to c\tau\upsilon$ anomalies
- theories of flavor and (HE-)LHC
- Higgs and flavor
- electroweak baryogenesis and flavor

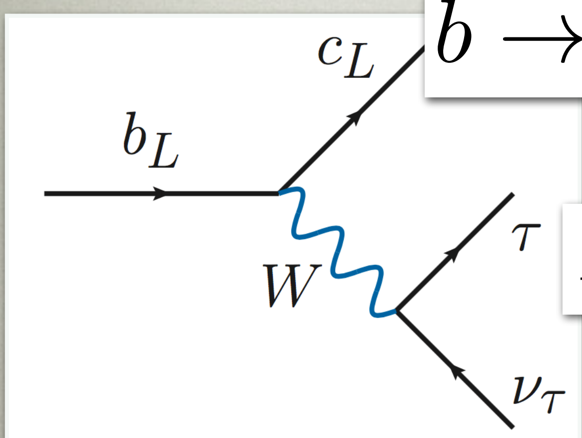
B anomalies vs. high energy

PRESENT EXPERIMENTAL SITUATION

- many different transitions measured
- two quark level transitions show ~4σ deviations from the SM*

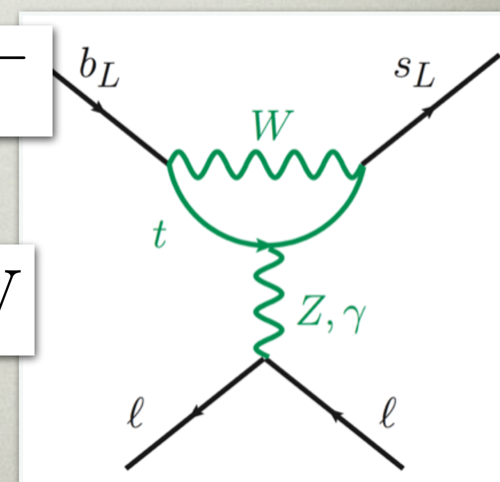
$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

$b \to c\tau\nu$



$\Lambda_{\rm NP} \sim 3$ TeV

$b \to s\mu^+\mu^-$

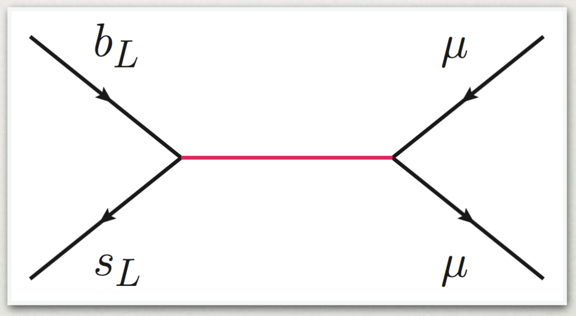


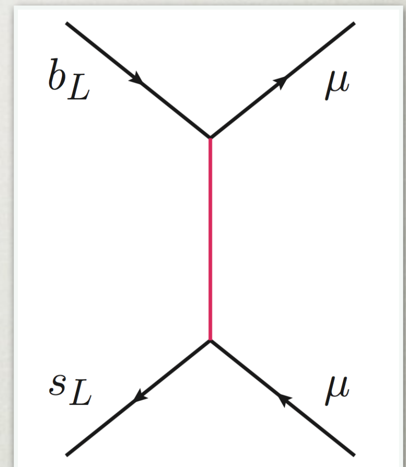
$\Lambda_{\rm NP} \sim 30$ TeV

* there are other interesting deviations, e.g., ~3σ deviation in ε'/ε, see, e.g., Buras et al, 1507.06345; RBC-UKQCD, 1502.00263

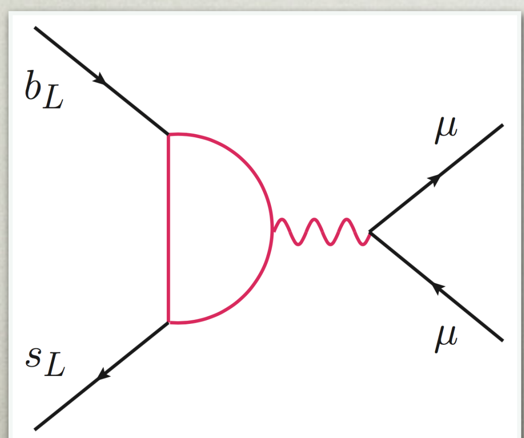
WHAT KIND OF NP?

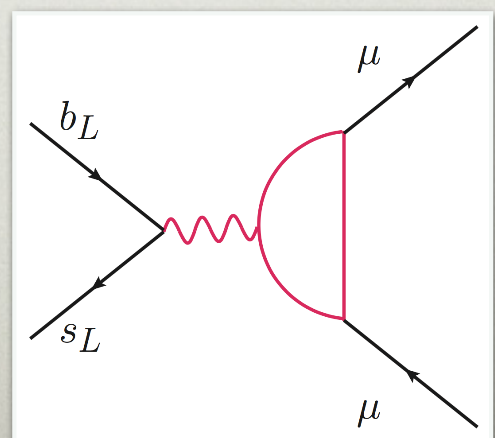
- only a finite number of viable single mediators
- ***b→sμμ***: two classes of models
  - tree level: Z', leptoquarks S_3, V_1, V_3
    - can be heavy, *10s* of TeV

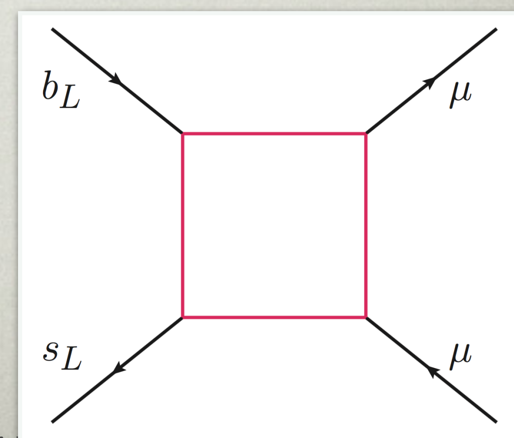




  - loop level: need to be light ≲TeV

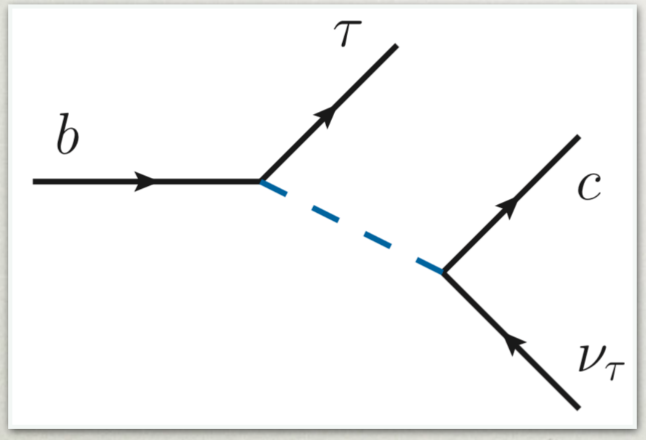


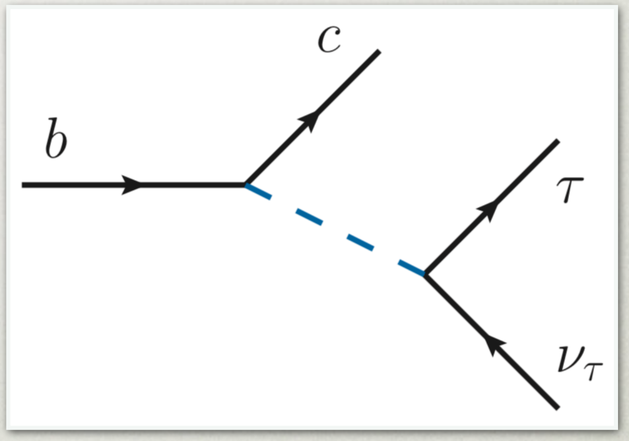




WHAT KIND OF NP?

- only a finite number of viable single mediators
- ***b→cτν***: needs to be tree level
  - has to be light, up to few TeV





- for both anomalies: coupling to quarks need to be present *(b,s* or *b,c)*
  - LHC searches should lead to relevant constraints

BOUNDS ON SIMPLIFIED MODELS

- all the four tree level mediators couple to LH quarks and leptons

Freytsis, Ligeti, Ruderman, 1506.08896

$$(g_q \bar{q}_L \boldsymbol{\tau} \gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau} \gamma^\mu \ell_L) W'_\mu$$

$$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i \tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$$

$$(\lambda \, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda} \, \bar{d}_R \gamma_\mu e_R) U^\mu$$

$$(\lambda \, \bar{q}_L^c i \tau_2 \ell_L + \tilde{\lambda} \, \bar{u}_R^c e_R) S$$

Faroughy, Greljo, Kamenik, 1609.07138

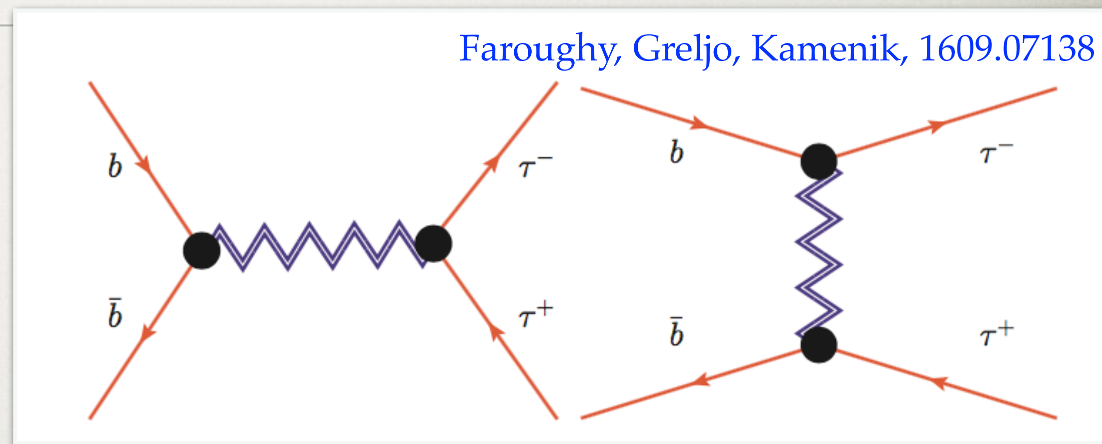
- the q_L flavor struct. that roughly minimizes constraints
  - only coupling to
  - then $b \to c \tau \nu$ is V_{cb} suppressed

$$Q_3 = \begin{pmatrix} V_{ub} u_L + V_{cb} c_L + V_{tb} t_L \\ b_L \end{pmatrix}$$

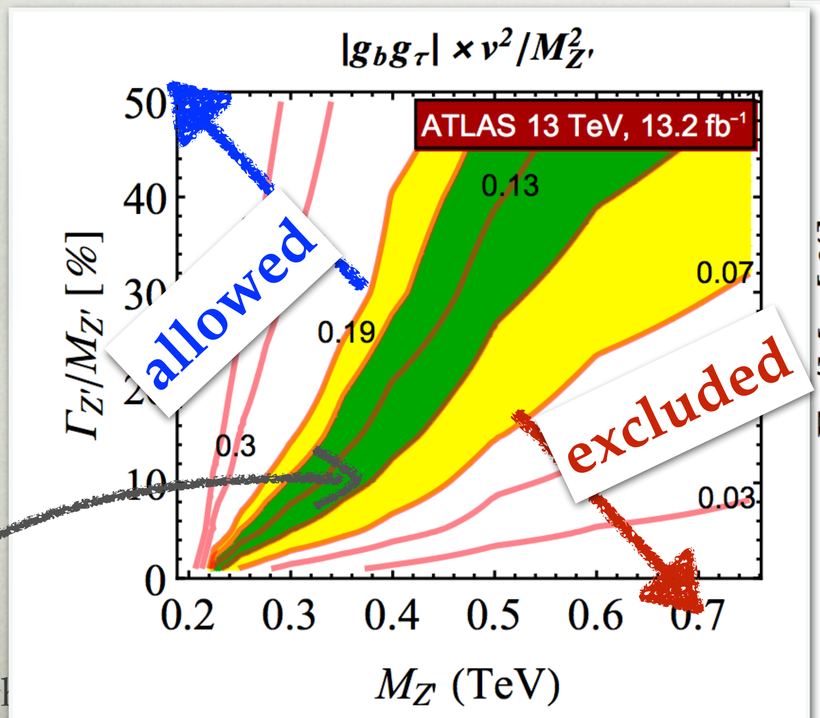
DIRECT SEARCHES IN $\tau\tau$

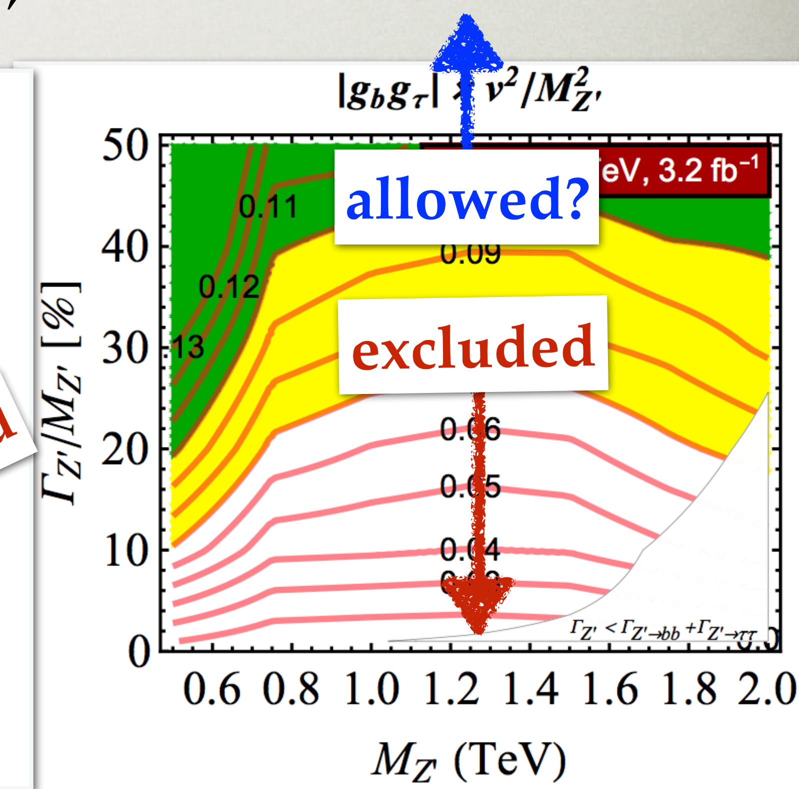
- $b\to c\tau\nu$ implies a $1/V_{cb}$ enhanced $b\bar{b}\to\tau^+\tau^-$
- severe bounds from LHC

Faroughy, Greljo, Kamenik, 1609.07138



- for instance for vector triplet: W', Z'





unitarity bound

$m_{W'} < 6.5\text{TeV}$

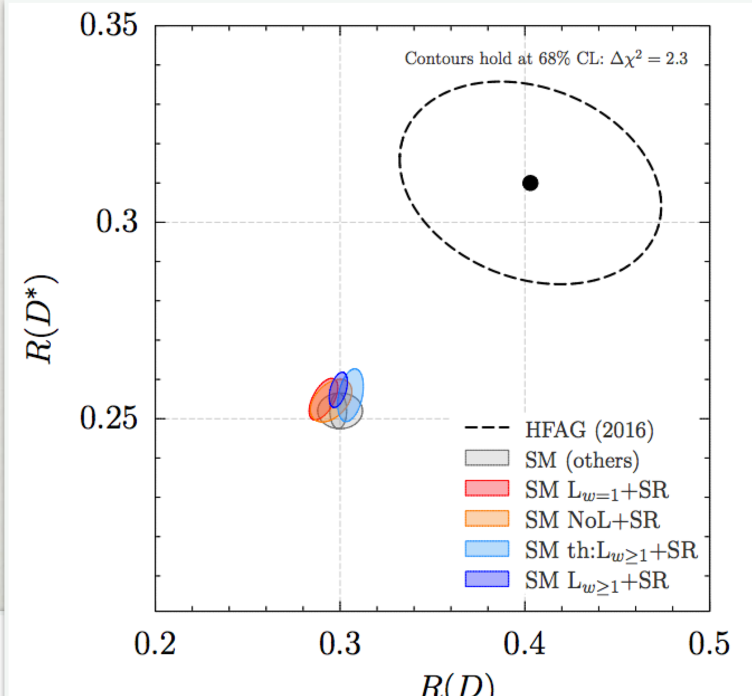
di Luzio, Nardecchia, 1706.01868

for $b\to c\tau\nu$ need:

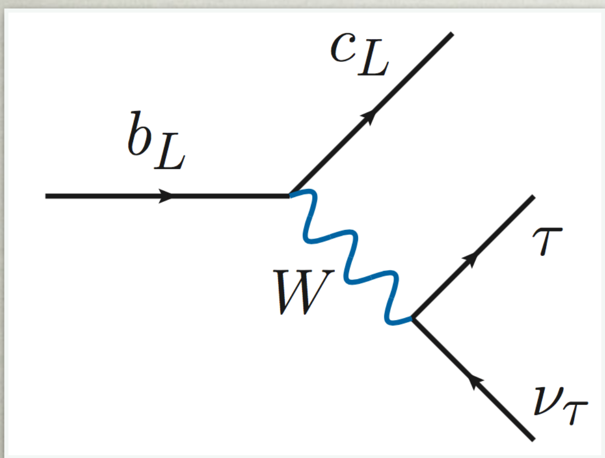
MODELS WITH RIGHT HANDED NEUTRINO

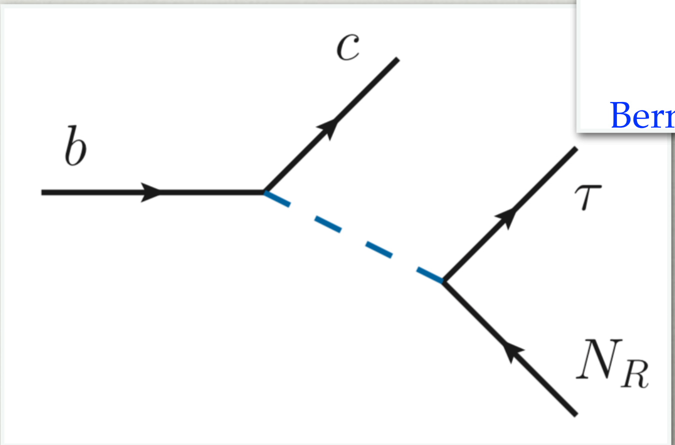
Robinson, Shakya, JZ, 1807.04753

- experimentally R_D, R_{D^*} above SM
  - no interf. between NP and SM
- N_R not part of a doublet
  - the constraints from charged leptons are absent



Bernlochner et al, 1703.05330





MODELS WITH RIGHT-HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

mediator	irrep	$\delta\mathcal{L}_{\rm int}$	WCs
W'_μ	$(1,1)_1$	$g'\big(c_q \bar u_R \gamma_\mu d_R + c_N \bar\ell_R \gamma_\mu N_R\big) W'^\mu$	$c_{\rm VR}$
~~Φ~~	~~$(1,2)_{1/2}$~~	~~$y_u \bar u_R Q_L \epsilon \Phi + y_d \bar d_R Q_L \Phi^\dagger + y_N \bar N_R L_L \epsilon \Phi$~~	
U_1^μ	$(3,1)_{2/3}$	$\big(\alpha_{LQ} \bar L_L \gamma_\mu Q_L + \alpha_{\ell d} \bar\ell_R \gamma_\mu d_R\big) U_1^{\mu\dagger} + \alpha_{uN} \big(\bar u_R \gamma_\mu N_R\big) U_1^\mu$	$c_{\rm SL}$, $c_{\rm VR}$
~~R_2~~	~~$(3,2)_{1/6}$~~	~~$\alpha_{Ld}(\bar L_L d_R)\epsilon \tilde R_2^\dagger + \alpha_{QN}(\bar Q_L N_R)$~~ [illegible]	
S_1	$(\bar 3,1)_{1/3}$	$z_u(\bar U_R^c \ell_R) S_1 + z_d(\bar d_R^c N_R) S_1 + z_Q(\bar Q_L^c \epsilon L_L) S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4 c_{\rm T}$

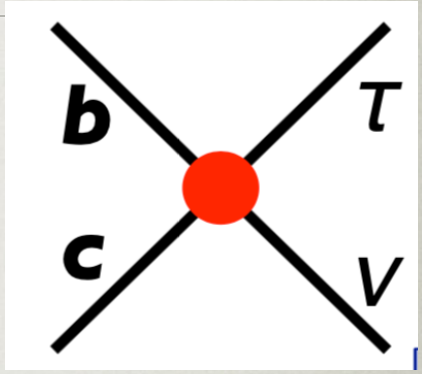
excluded from $B_c \to \tau\nu$

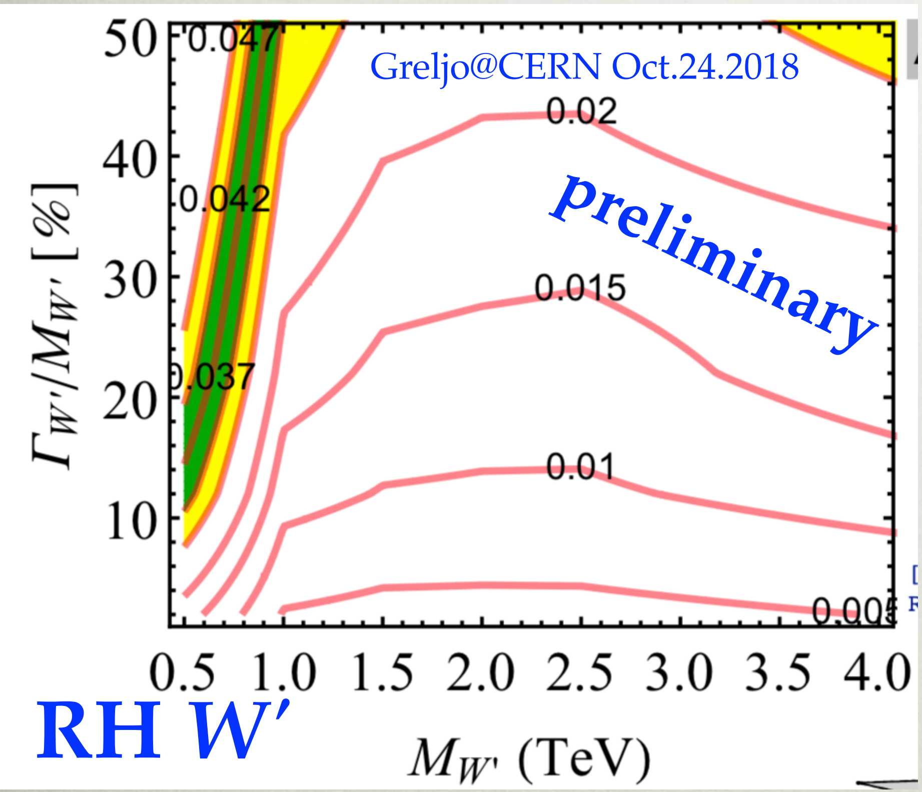
excluded from $B \to K\nu\nu$

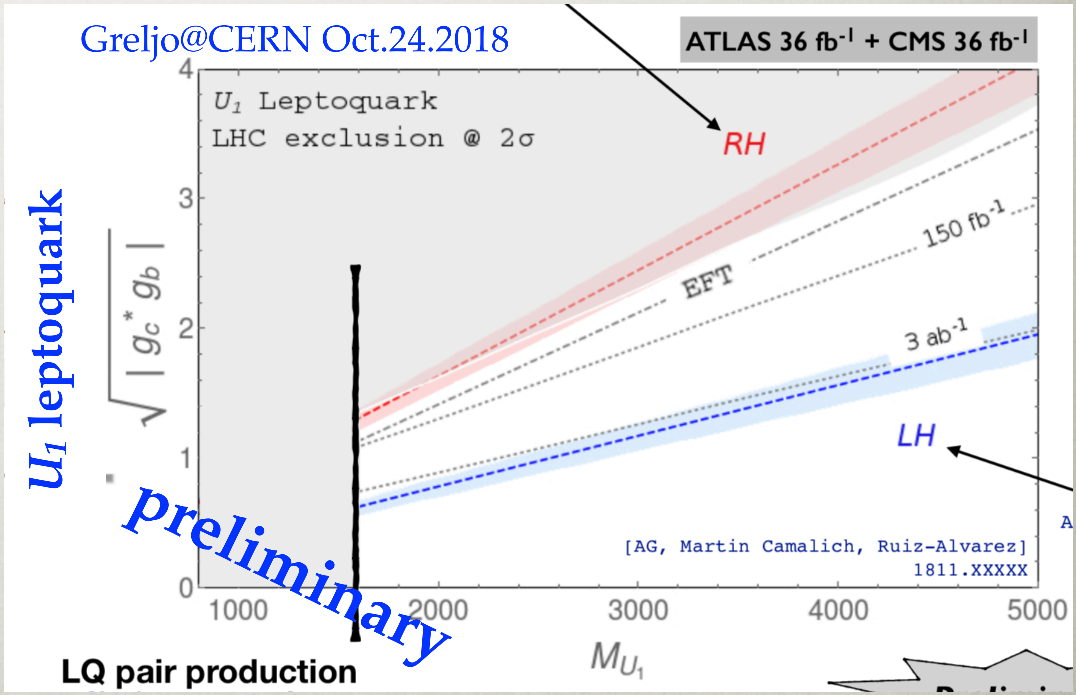
DIRECT SEARCHES IN $\tau\upsilon$

ATLAS, 1801.06992; CMS, 1807.11421

- $R_{D(*)}$ directly probed in $pp\to\tau\upsilon$



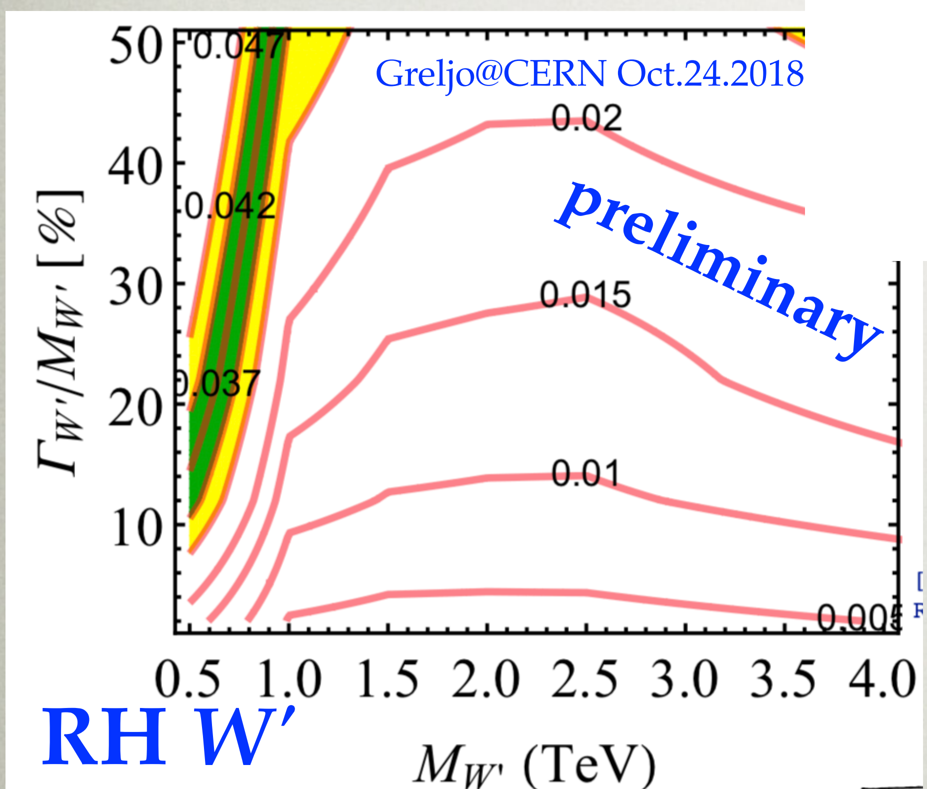


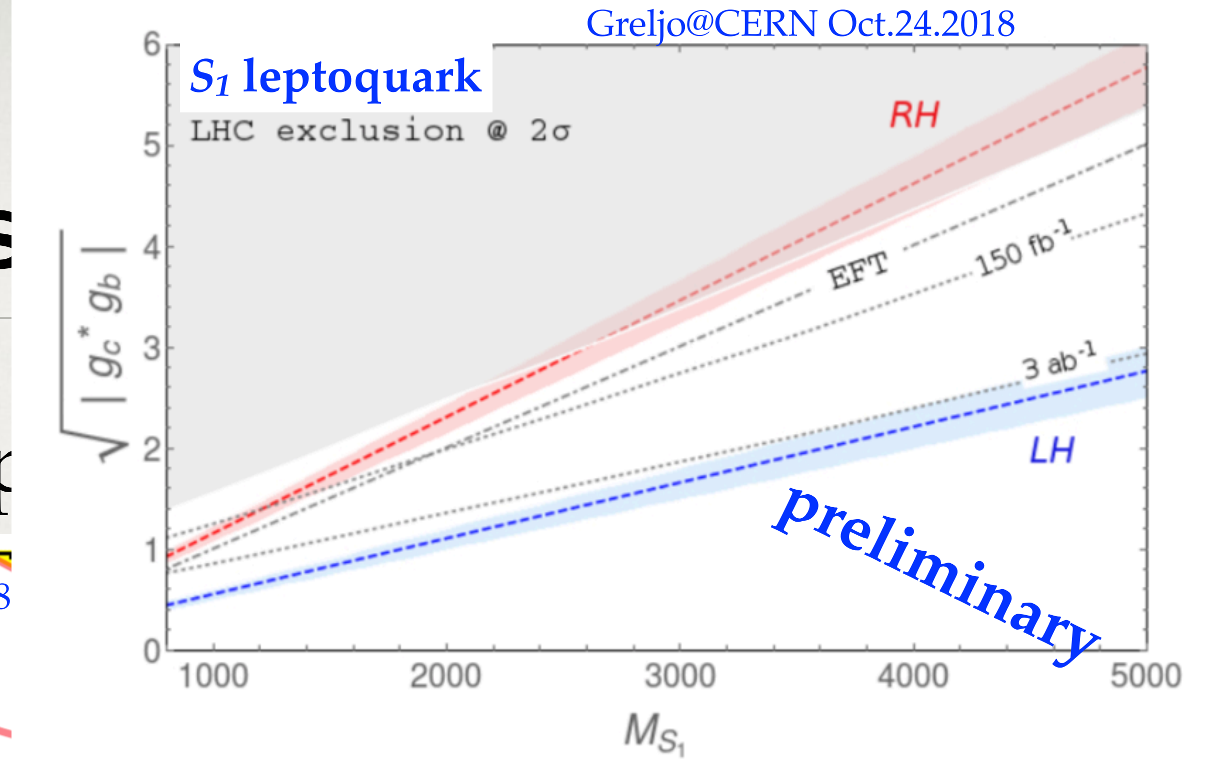


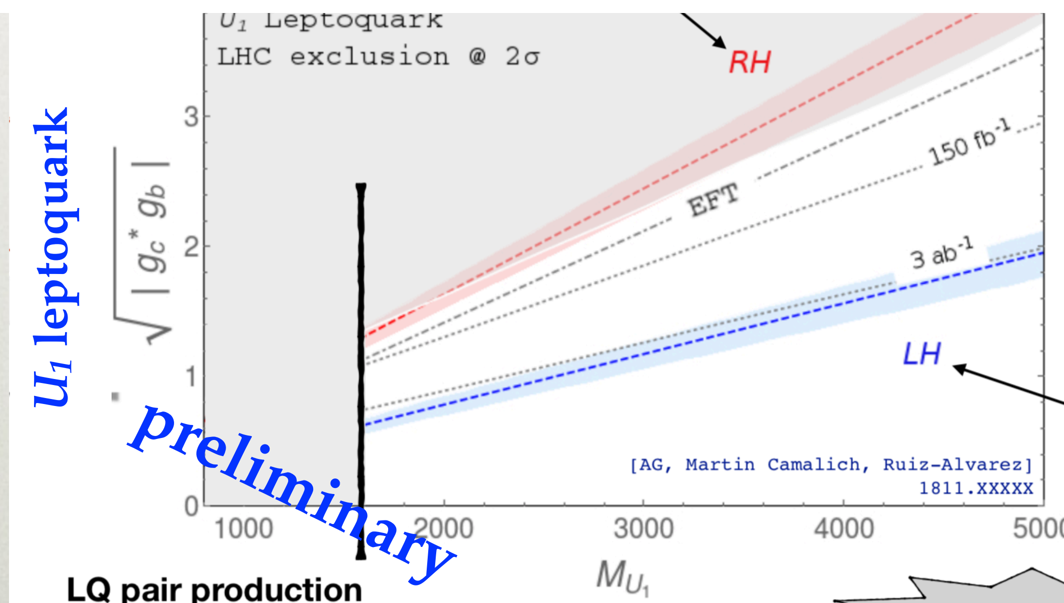
DIRECT S

ATLAS, 1801.06992; CMS, 1807.11421

- $R_{D(*)}$ directly p







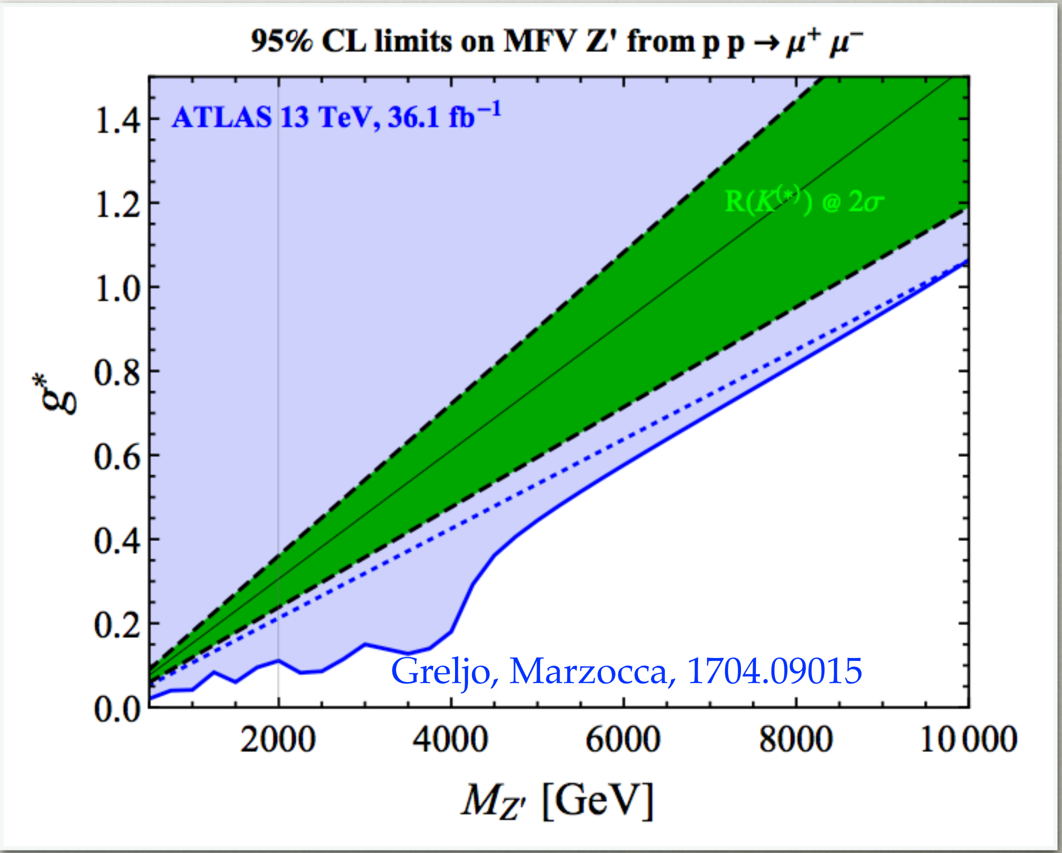
THE Z' MODELS FOR $b \to s\mu\mu$

- similarly the $b \to s\mu\mu$ get bounded by ATLAS, CMS from $pp \to Z' \to \mu\mu$
  - flavor structure important
  - e.g., for MFV ansatz

$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(1 + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

$$J_\mu = g_Q^{(1),ij}(\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl}(\bar{L}_k \gamma^\mu L_l)$$

Greljo, Marzocca, 1704.09015

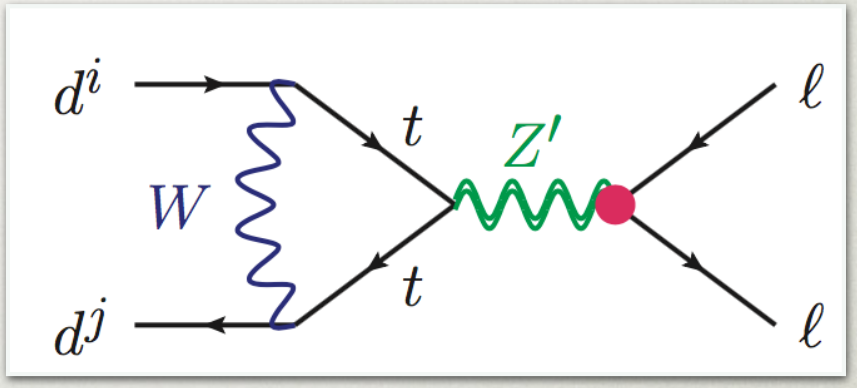


TOP-PHILIC Z'

Kamenik, Soreq, JZ, 1704.06005

- top-philic Z' avoids contraints from dimuon resonance searches
  - $b \to s$ due to SM W in the loop

$$c^{(3,1)}_{Q_{ij}L_{22}} \sim \left(\not{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$



- automatic $(\bar{s}b)_{V\text{-}A}$ chiral structure
  - MFV structure: all FV due to CKM
    - there is a correlated signal in $K \to \pi\nu\nu$

cf. NA62 reach: 10% of the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \simeq (8.4 \pm 1.0) \times 10^{-11} \times \frac{1}{3} \sum_\ell \left| 1 + 0.11(C_9^{\ell,\mathrm{NP}} - C_{10}^{\ell,\mathrm{NP}}) \right|^2$$

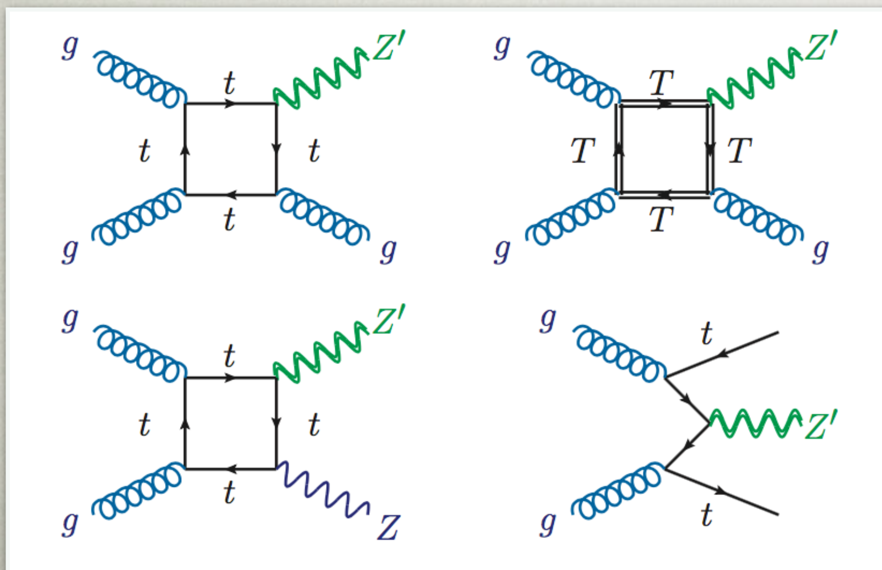
SM value

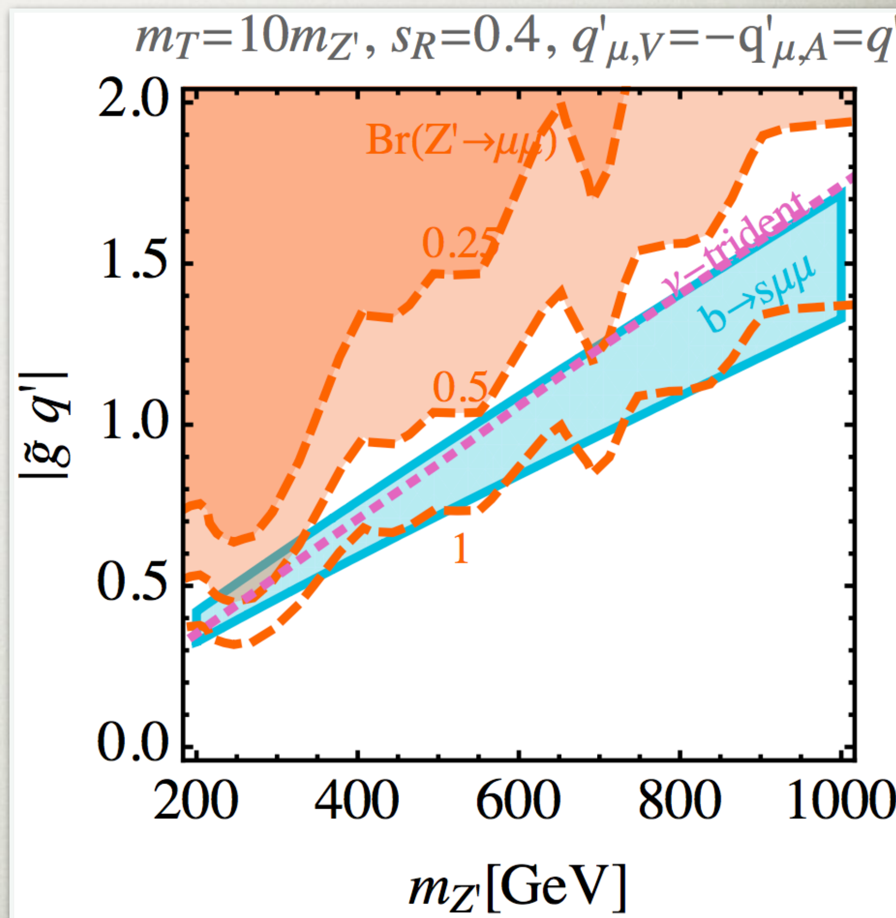
see also Bordone, Buttazzo, Isidori, Monnard, 1705.10729

Kamenik, Soreq, JZ, 1704.06005
Camargo-Molina, Celis, Faroughy, 1805.04917

DIRECT SEARCHES

- contraints from dimuon searches: loop production or assoc. $t\bar{t}$
- depends on $Br(Z'\to\mu\mu)$
  - below $\bar{t}t$ threshold:
    - coupling to μ_L $\Rightarrow Br(Z'\to\mu\mu)=0.5$
    - coupling to $\mu_L,\tau_L \Rightarrow Br(Z'\to\mu\mu)=0.25$
- interesting possible searches at LHC
  - $pp\to\bar{t}t(Z'\to\mu\mu), \bar{t}t(Z'\to\tau\tau), \bar{t}t(Z'\to\bar{t}t)$





FLAVOR MODELS AND (HE-)LHC

MODELS OF FLAVOR

- SM flavor puzzle: the origin of hierarchies between SM fermion masses?
- several solutions
  - extra dimensional RS models
  - Frogatt-Nielsen models
  - partial compositness
  - clockwork flavor model

Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

- in all cases important constraints from flavor observables
- some predict states at ~TeV

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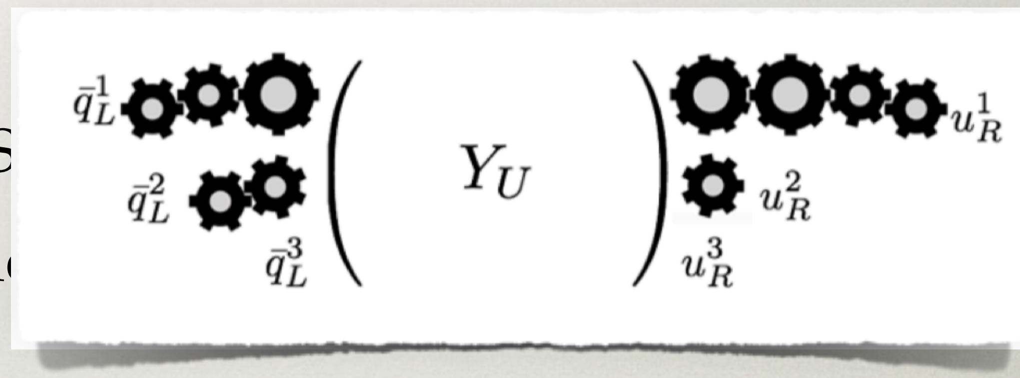


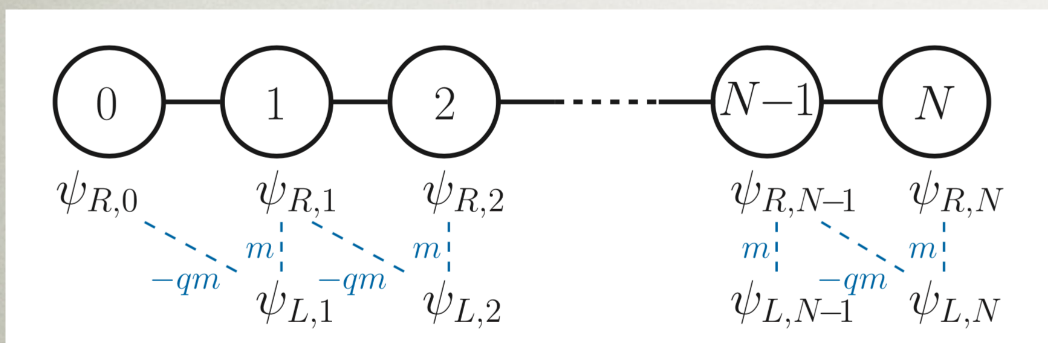
Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

CLOCKWORK FLAVOR

- the hierarchy from clockworking

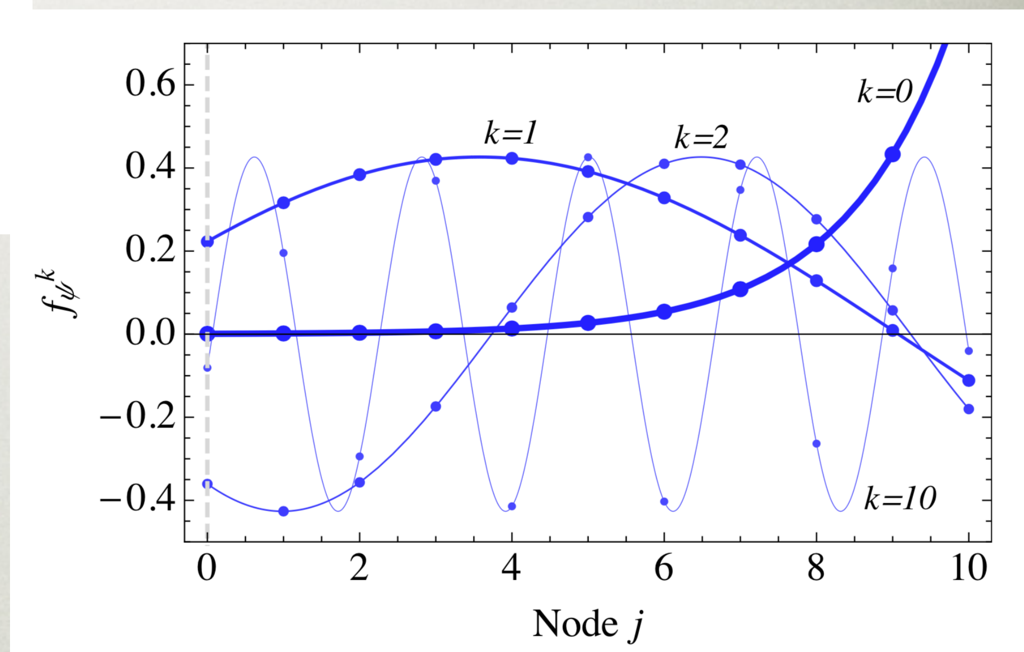
Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

  - chiral fermion coupled to a chain of vector-like fermions



- zero mode overlap with 0-th node exponentially suppressed

$$f_\psi \sim 1/q^N$$



- if Higgs on *0*-th node → hierarchical masses

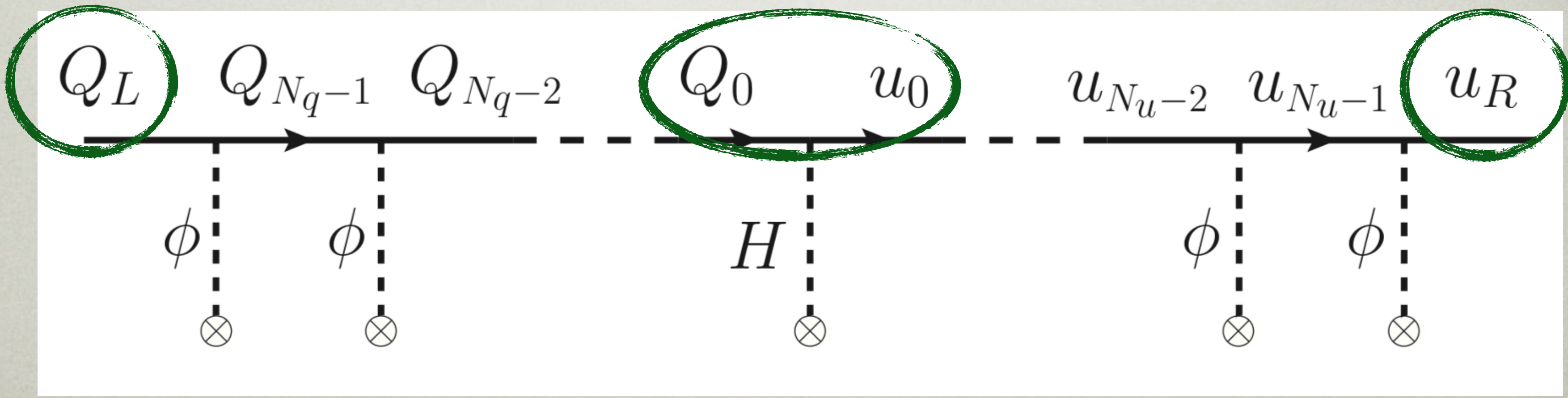
CW vs FN

- clockwork flavor very reminiscent of Froggatt-Nielsen
- if clockwork from horizontal *U(1)*
  - in FN: $\lambda=\langle\phi\rangle/m\sim 0.2$
  - in CW: $\lambda=m/\langle\phi\rangle\sim 0.2$

Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

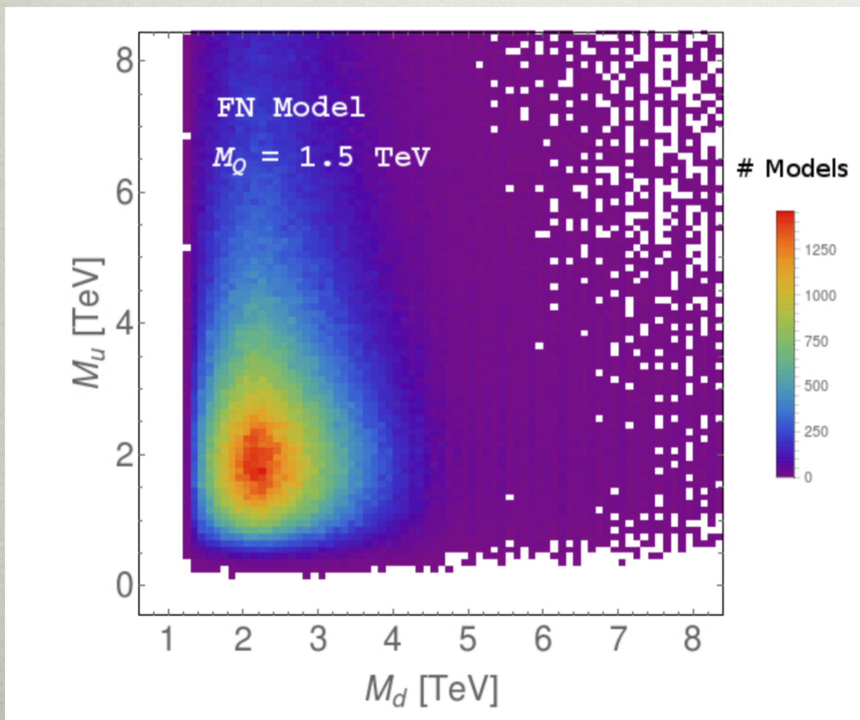
CW: vectorlike — chiral — vectorlike

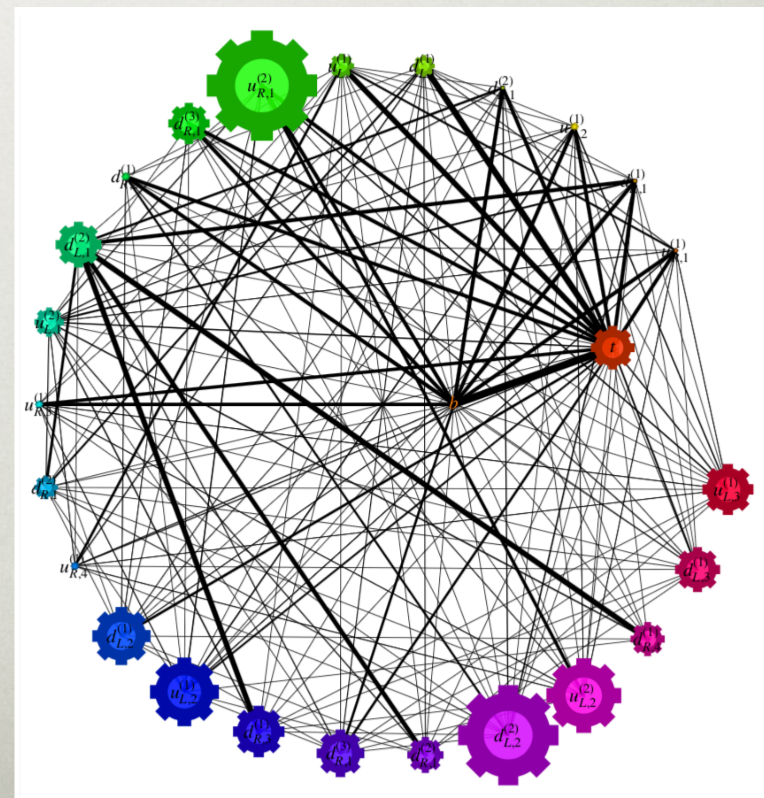
FN: chiral — vector-like — chiral



CW gears

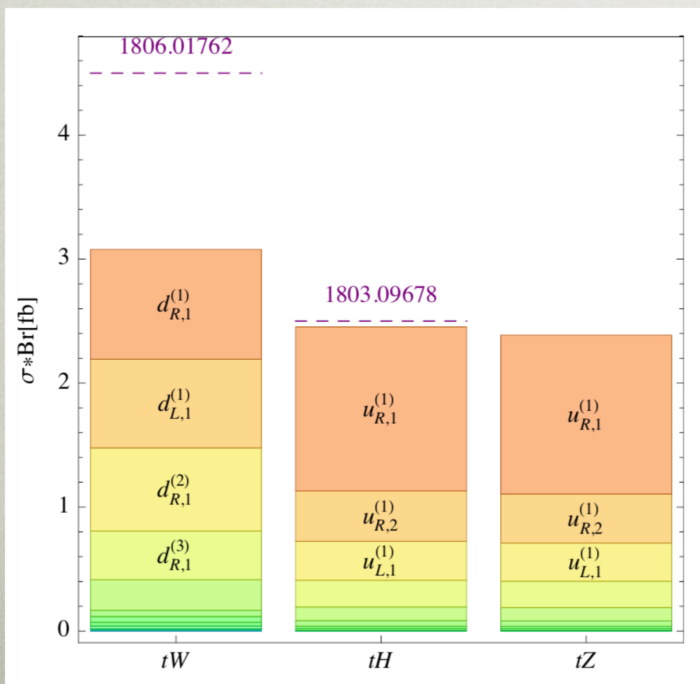
- minimal field content: just vector-like fermion "gears"
    - CW protection against FCNCs from overlap suppressions
- the bounds from flavor require them to be above few TeV
- have relatively complex decay chains

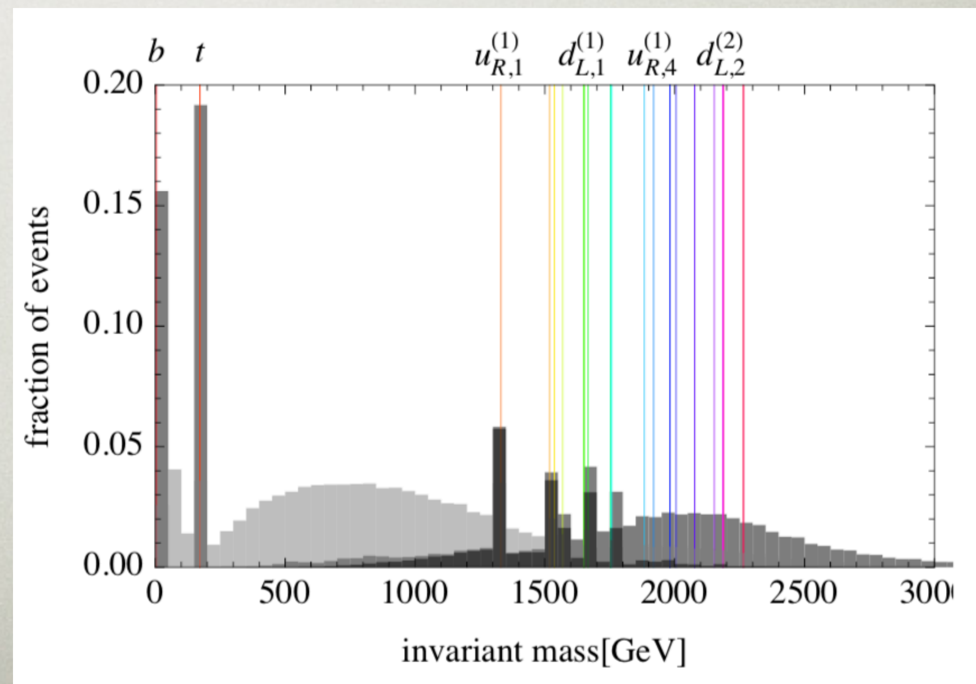




HOW TO SEARCH FOR GEARS?

- from low energy observables
  Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792
  - B_s, B_d, D, K mixing; rare meson decays $b \to sll$, $b \to s\nu\bar{\nu}$ and $s \to d\nu\bar{\nu}$
- from on-shell production at LHC
  - pair production with tW+X, tH+X, tZ+X decays
  - vector-like searches: several lightest gears contribute
  - modified hemisphere clustering could reveal individual gears





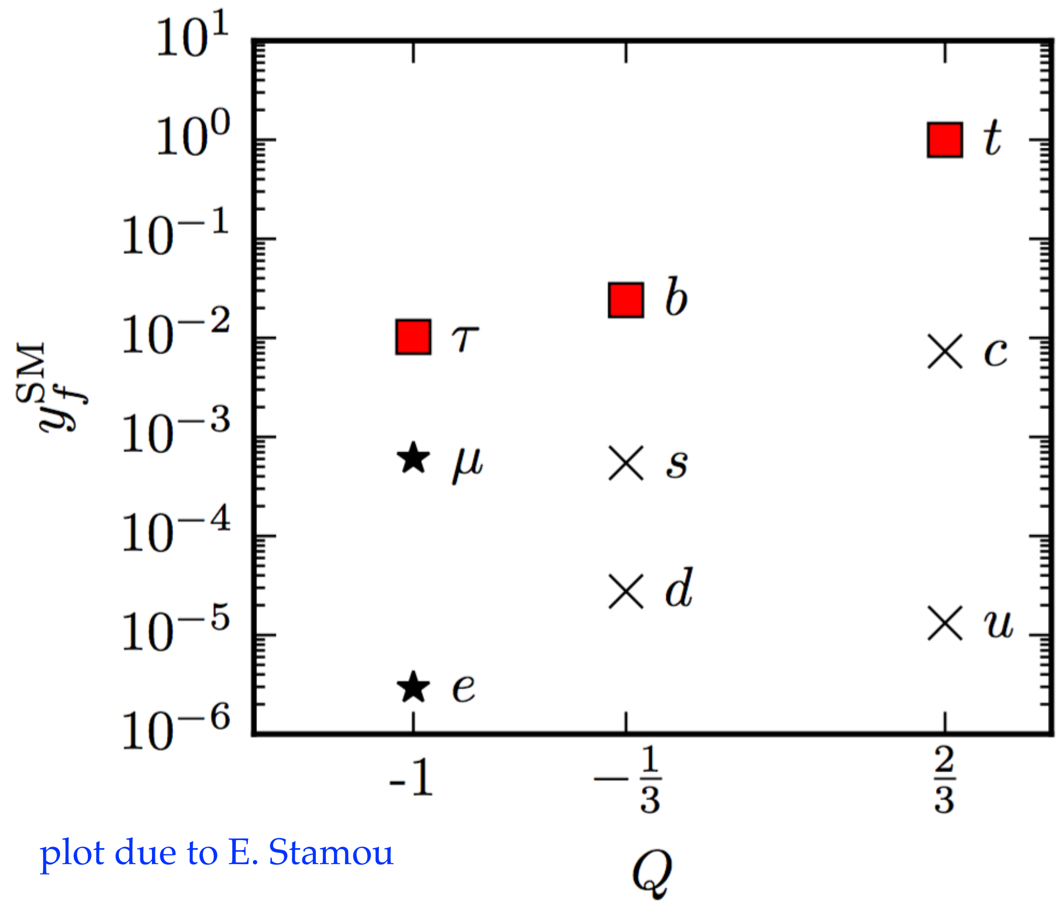
HIGGS AND FLAVOR

HIGGS - A NEW PROBE OF FLAVOR

- in the SM all flavor structure due to the Higgs Yukawa couplings

$$y_f = \sqrt{2} m_f / v$$

- implies Higgs has very hierarchical couplings to fermions
- how well have we tested this?



plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

    $$y_{ii}/m_i = \sqrt{2}/v$$

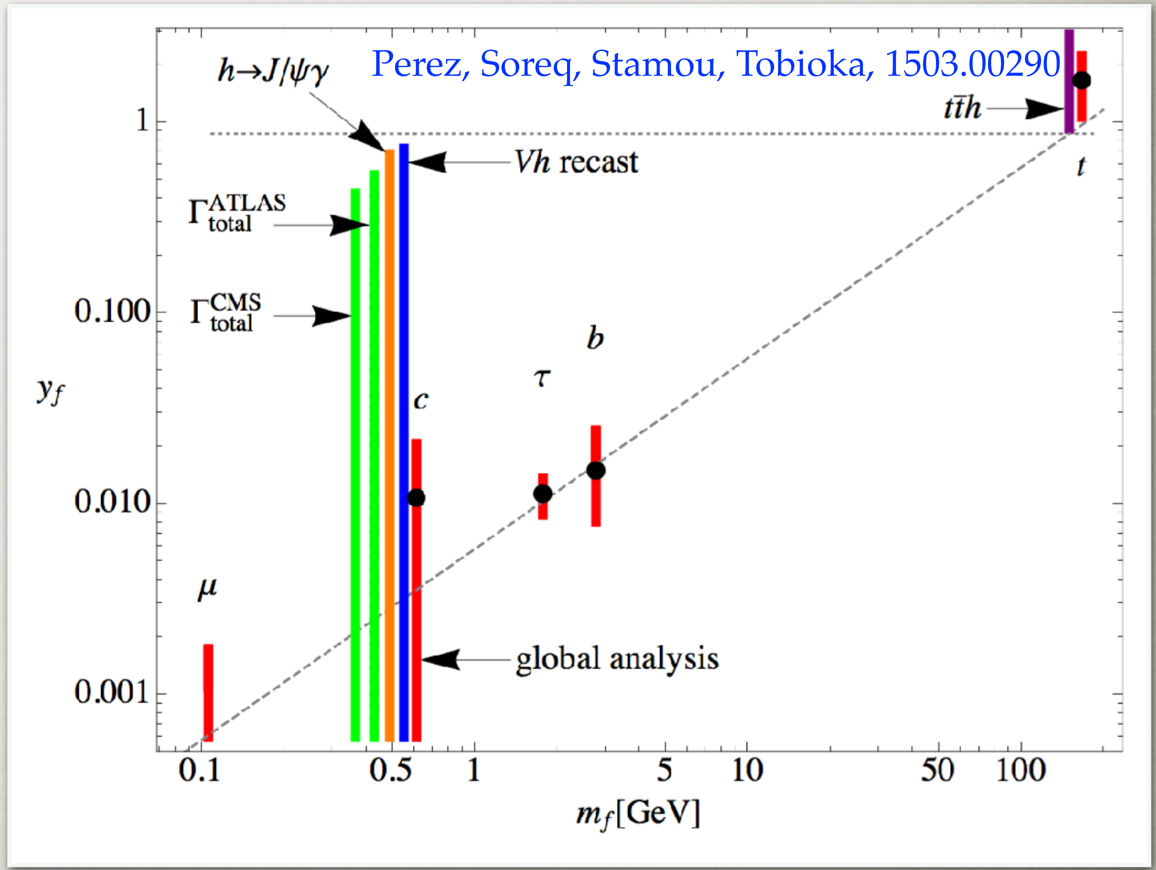
  - diagonality (flavor violation)

    $$y_{ij} = 0, \quad i \neq j$$

  - reality (CP violation)

    $$\mathrm{Im}(y_{ij}) = 0$$

$$y_f^{\rm SM} = \sqrt{2} m_f/v$$



HIERARCHICAL COUPLINGS?

- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - yes, but for quarks with some assumptions

$$\frac{Y^{\rm exp}_{e(\mu)}}{Y^{\rm exp}_{\tau}} < 0.22(0.10), \qquad \frac{Y^{\rm exp}_{u(c)}}{Y^{\rm exp}_{t}} \lesssim 0.04, \qquad \frac{Y^{\rm exp}_{d(s)}}{Y^{\rm exp}_{t}} < 0.7(6)$$

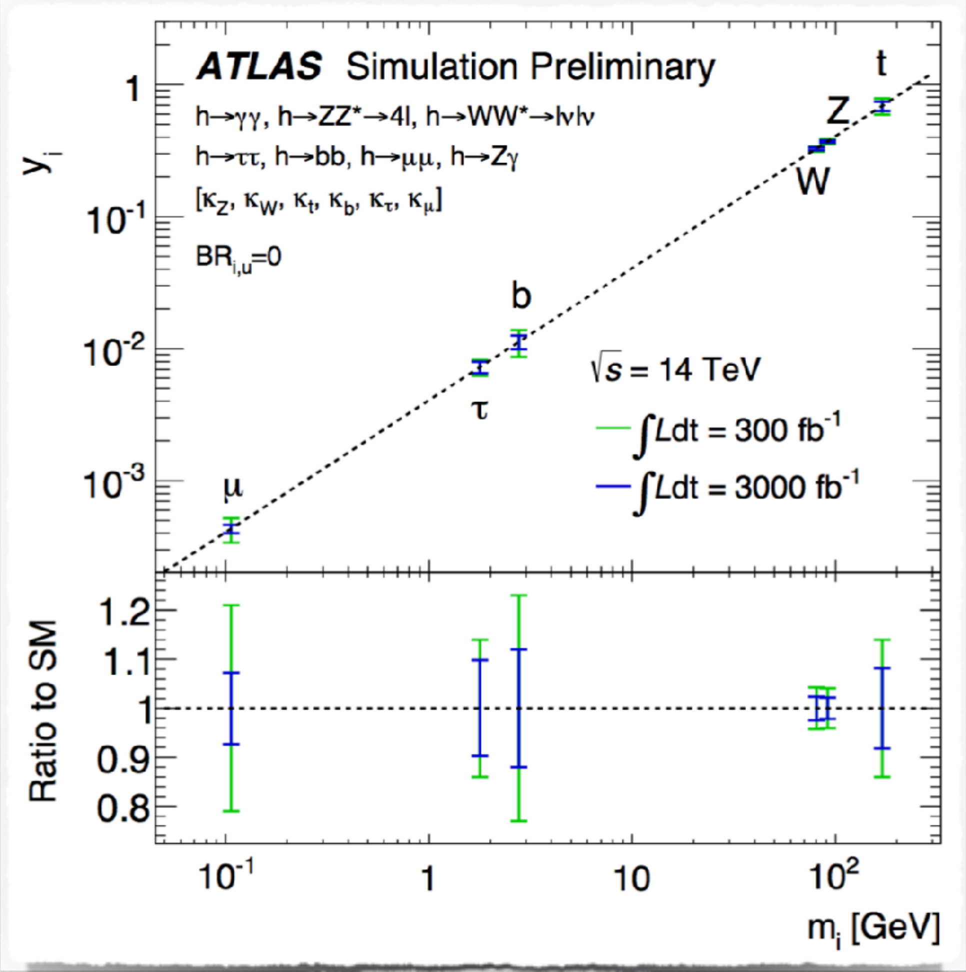
direct measurements

global fit

p_T distrib.

MUON YUKAWA

- the SM Higgs muon Yukawa accessible at high-luminosity LHC
- the only one among the first two generations of fermions
- could significantly deviate from the SM
  - could even be zero



FLAVOR VIOLATING COUPLINGS

- in the SM Higgs couplings flavor diagonal
  - discovering flavor violating couplings means New Physics
- for $h\to\tau\mu$, $h\to\tau e$ the best probe is LHC
- for $h\to\mu e$ the best probe are indirect searches

FLAVOR VIOLATING COUPLINGS

- accessible directly for charged lepton final states
  - from $h \to \tau\mu$, $h \to \tau e$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

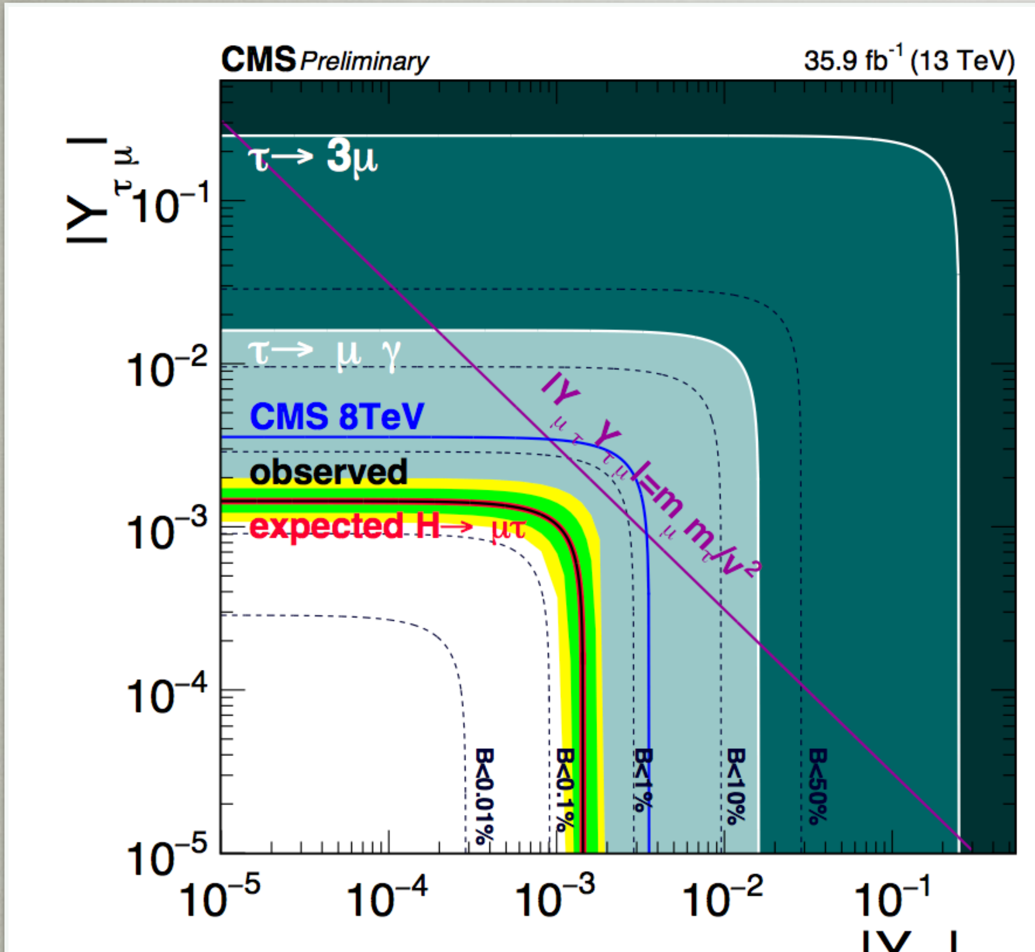
for $\hat{\lambda}_{ij} = 1$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

IOLATING

LINGS



CMS-HIG-17-001-pas

for charged lepton

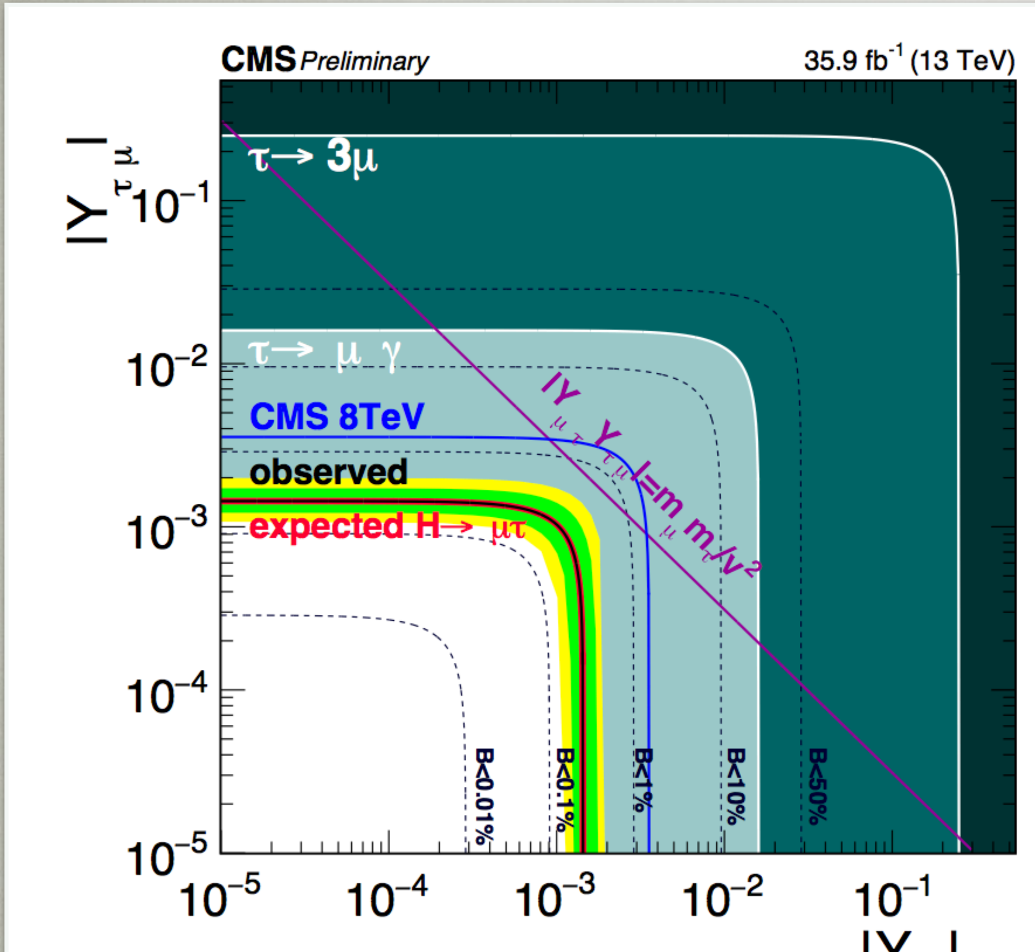
- from $h \to \tau\mu$, $h \to \tau e$

for $\hat{\lambda}_{ij} = 1$

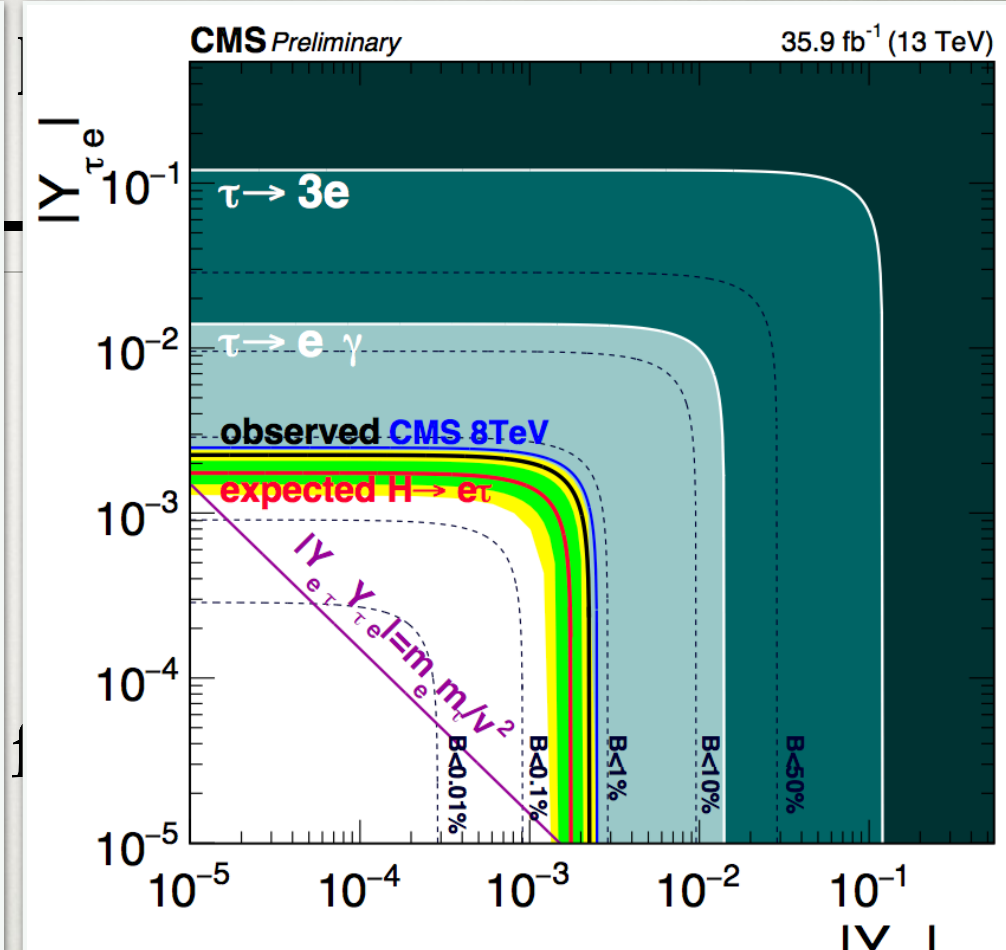
$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$



CMS-HIG-17-001-pas



CMS-HIG-17-001-pas

- from $h \to \tau\mu$, $h \to \tau e$

for $\hat{\lambda}_{ij} = 1$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

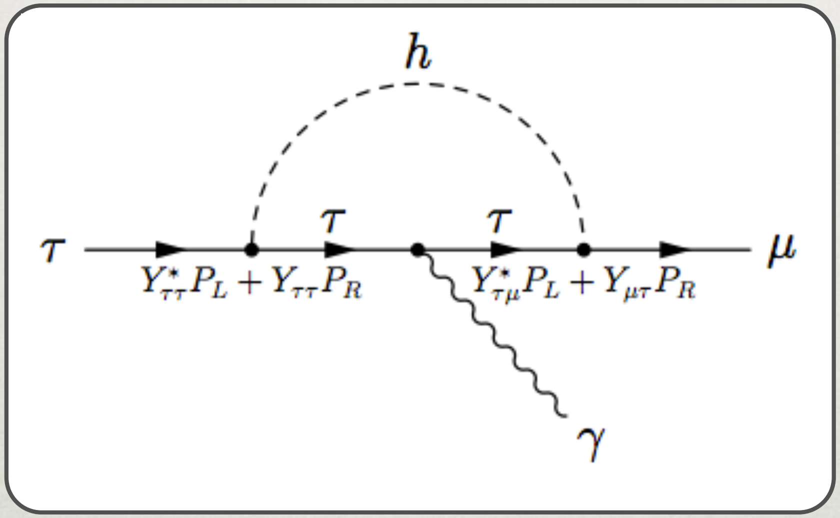
$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

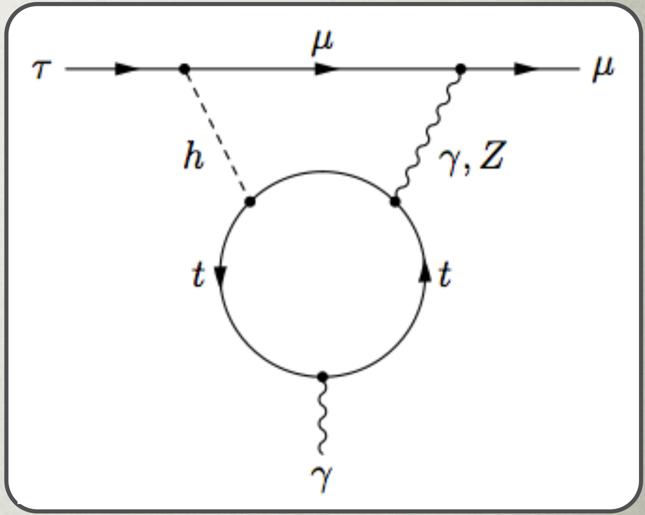
INDIRECT BOUNDS ON $h\to\tau\mu$

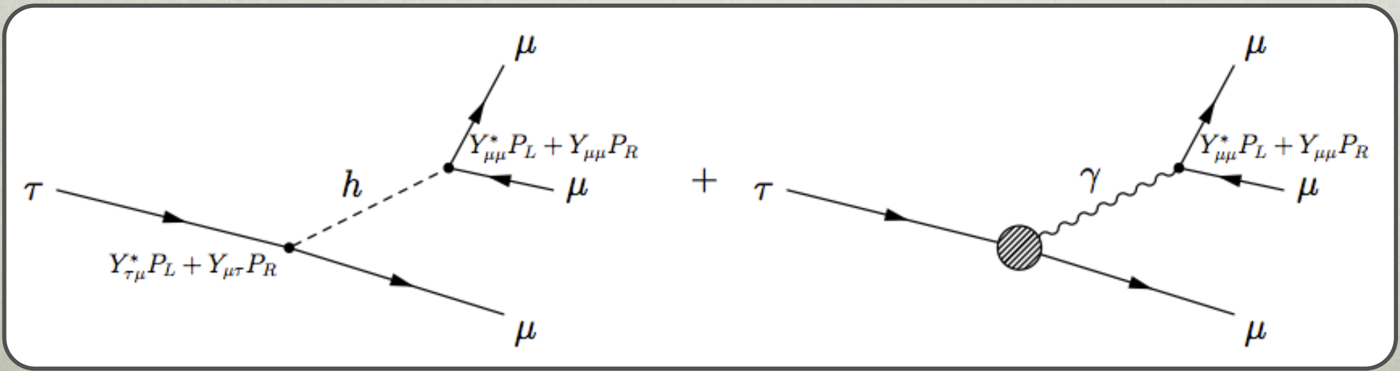
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- also indirect bounds from charged lepton FCNC transitions
  - $\tau\to\mu\gamma$
  - $\tau\to 3\mu$



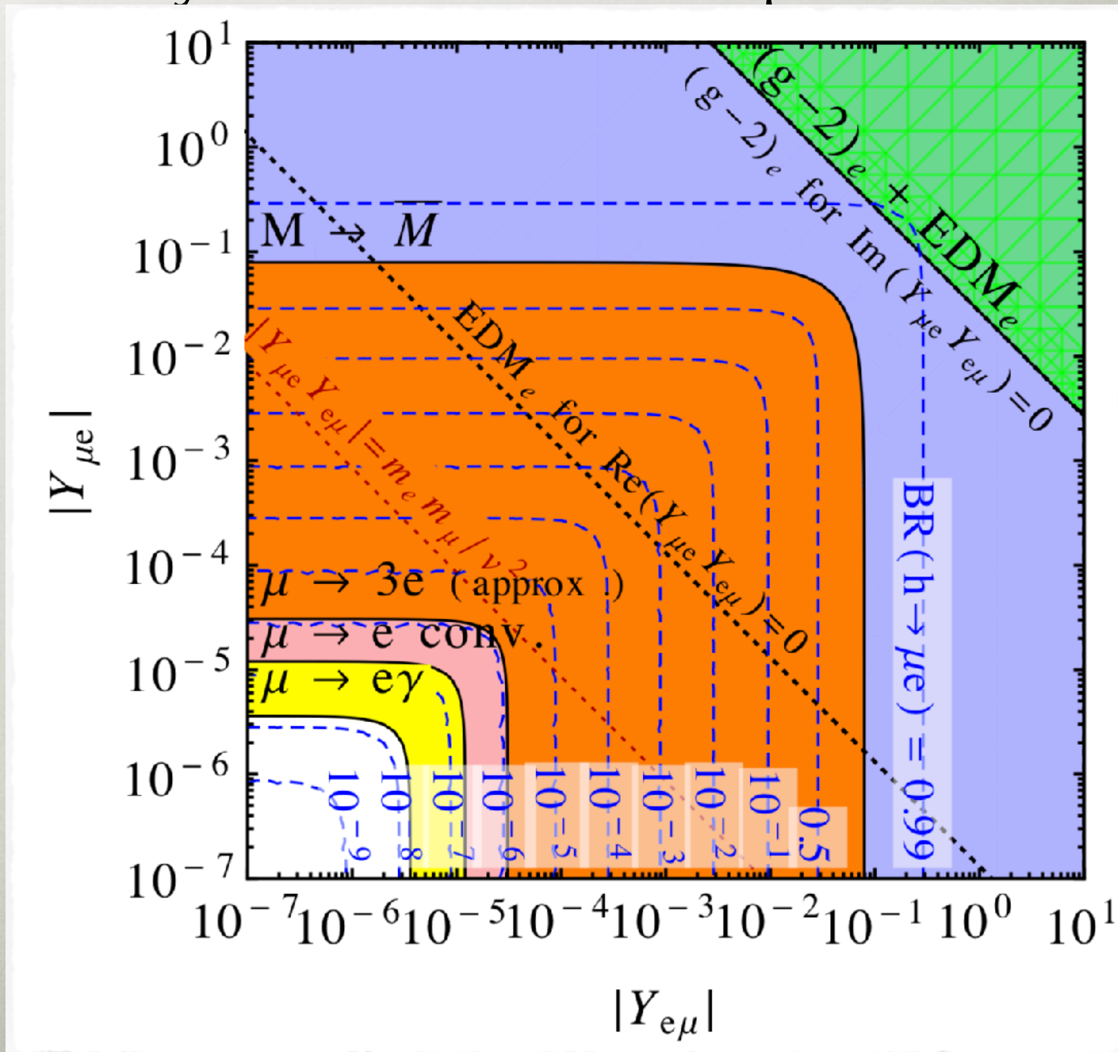




INDIRECT BOUNDS ON $h \to e\mu$

Harnik, Kopp, JZ, 1209.1397

- indirect bounds especially severe for $h \to e\mu$
- $Br(h \to e\mu) < 10^{-8}$ required to surpass the bound from $Br(\mu \to e\gamma)$
- caveat: could be cancellations in the loop

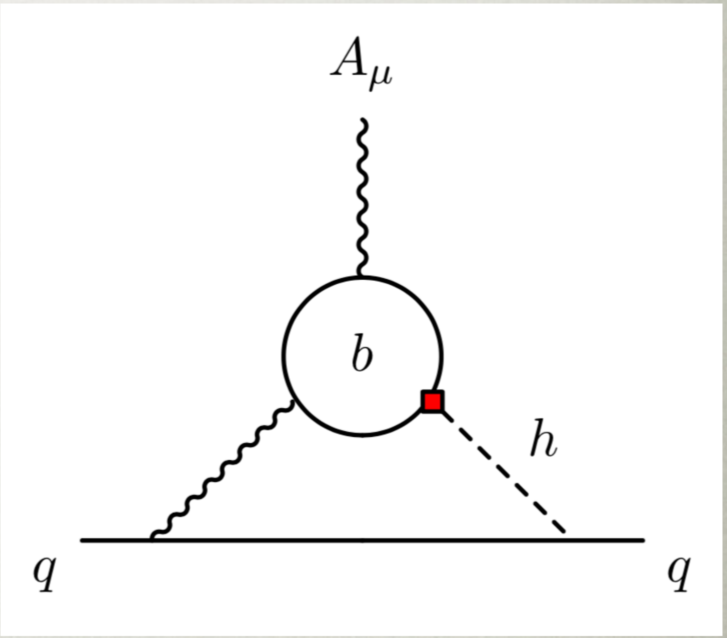


BOUNDS FROM EDMS

- stringent constraints from EDMs Brod, Haisch, JZ, 1310.1385
- recently NLL resummation for bottom and charm for hadronic EDMs Brod, Stamou, 1810.12303
- most stringent bounds from electron EDM

$$|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$$

ACME collaboration, Nature 562 (2018) 355–360



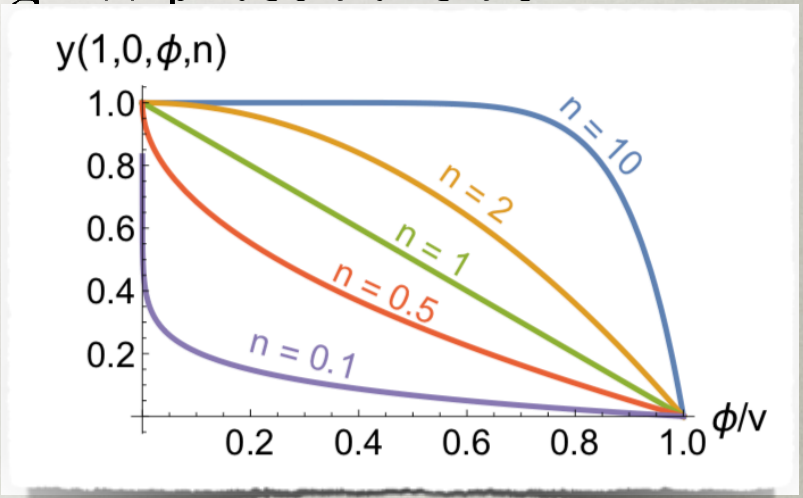
$$\tilde{\kappa}_t < 1.2 \times 10^{-3} \qquad \tilde{\kappa}_b < 0.4 \qquad \tilde{\kappa}_c < 1 \qquad \tilde{\kappa}_\tau < 0.30$$

FLAVOR AND ELECTROWEAK BARYOGENESIS

BARYOGENESIS AND VARYING YUKAWAS

review: Servant, 1807.11507

- in models of flavor Yukawas have dynamical origin
- viable EWBG if Yukawas change during EW phase transition
  - strong 1st order phase transition
  - large Yukawas at early times, thus enhanced sources of CPV



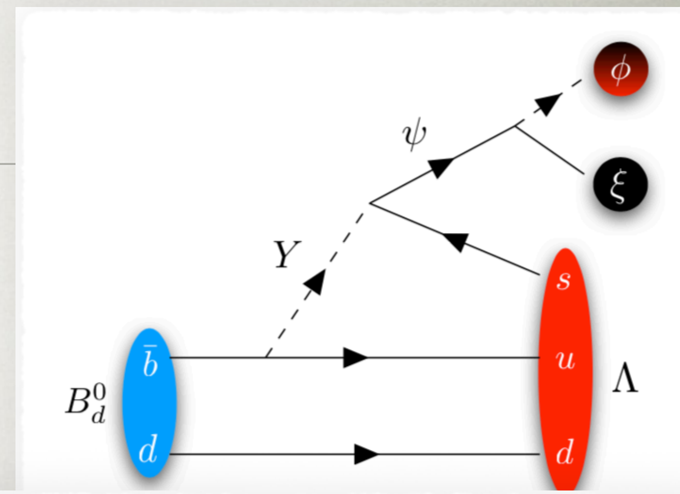
- models: two flavon FN, RS with Goldberger-Wise, composite Higgs
- searches at LHC: searches for flavons, radion/dilaton, other states part of complete models
- searches at Belle II: all the classic flavor observables - B mixing, etc,
  - sometimes model dep. modes, e.g. decay to axiflavon, a: $B\to Ka, D\to\pi a$, etc

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

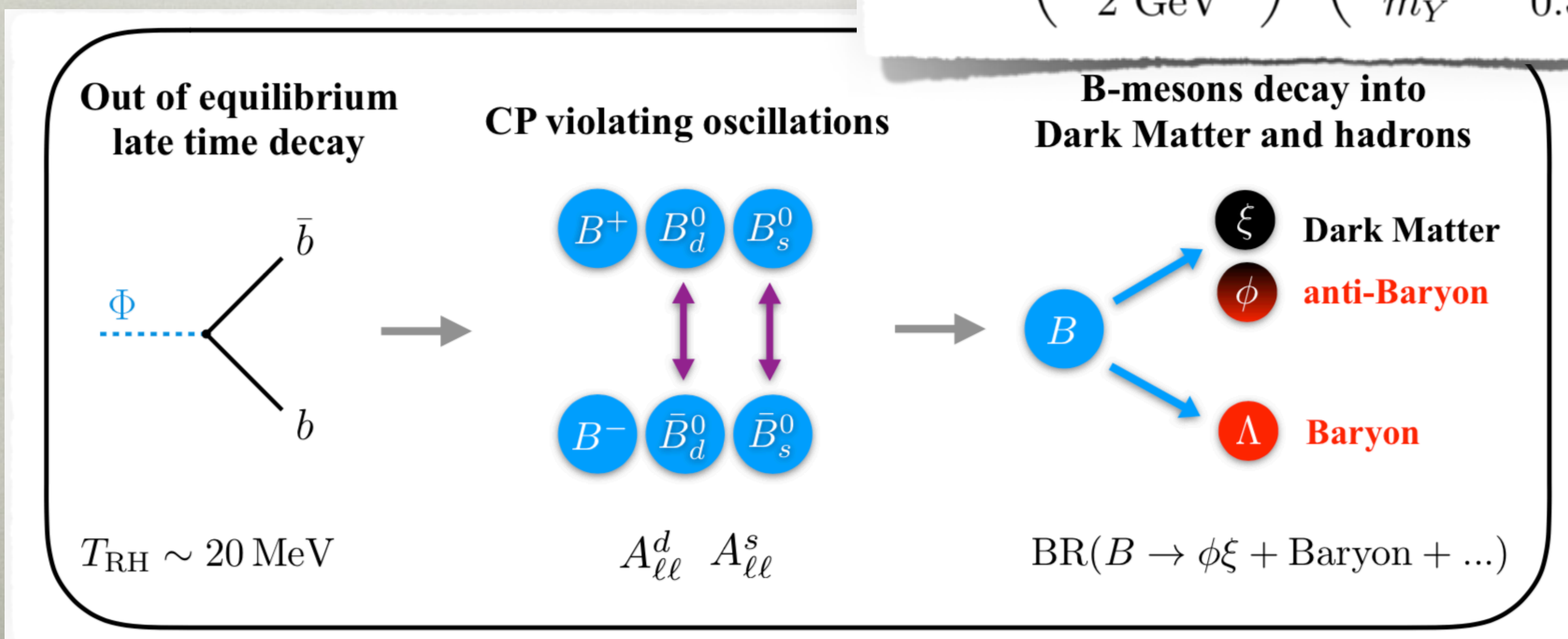
BARYOGENESIS FROM B MIXING

Elor, Escudero, Nelson, 1810.00880

- viable baryogenesis with only SM CPV
- dark particle ψ carries baryon number
  - search at Belle for $B \to$baryon+MET
- needs a colored mediator, Y, search for it at ATLAS, CMS



$$\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4 .$$

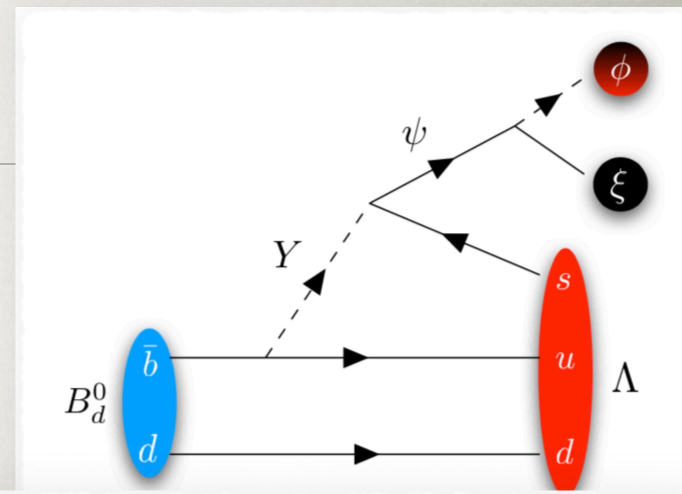


Elor

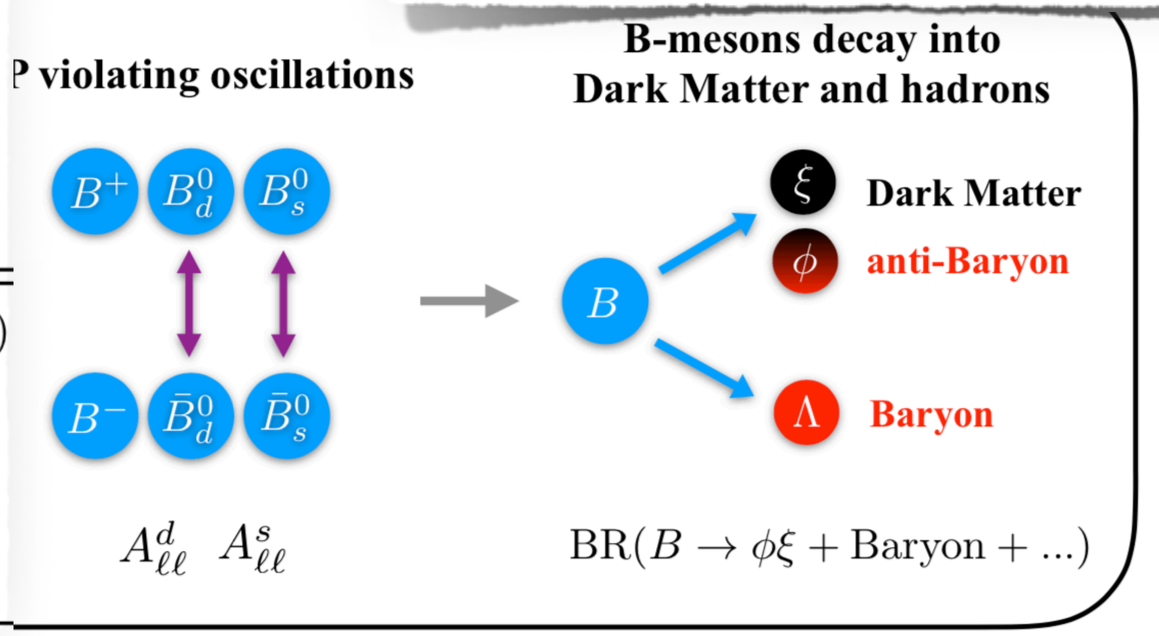
Initial State	Final state
B_d	$\psi + \Lambda\,(usd)$
B_s	$\psi + \Xi^0\,(uss)$
B^+	$\psi + \Sigma^+\,(uus)$
Λ_b	$\bar{\psi} + K^0$
B_d	$\psi + n\,(udd)$
B_s	$\psi + \Lambda\,(uds)$
B^+	$\psi + p\,(duu)$
Λ_b	$\bar{\psi} + \pi^0$
B_d	$\psi + \Xi_c^0\,(csd)$
B_s	$\psi + \Omega_c\,(css)$
B^+	$\psi + \Xi_c^+\,(csu)$
Λ_b	$\bar{\psi} + D^- + K^+$
B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
B_s	$\psi + \Xi_c^0\,(cds)$
B^+	$\psi + \Lambda_c\,(dcu)$
Λ_b	$\bar{\psi} + \overline{D}^0$

OGENESIS FROM B MIXING

- nesis with only SM CPV
- carries baryon number
- e for $B\to$baryon+MET
- mediator, Y,
- ATLAS, CMS



$$\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) \simeq$$
$$10^{-3}\left(\frac{m_B - m_\psi}{2\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_Y}\frac{\sqrt{y_{ub}y_{\psi s}}}{0.53}\right)^4 .$$



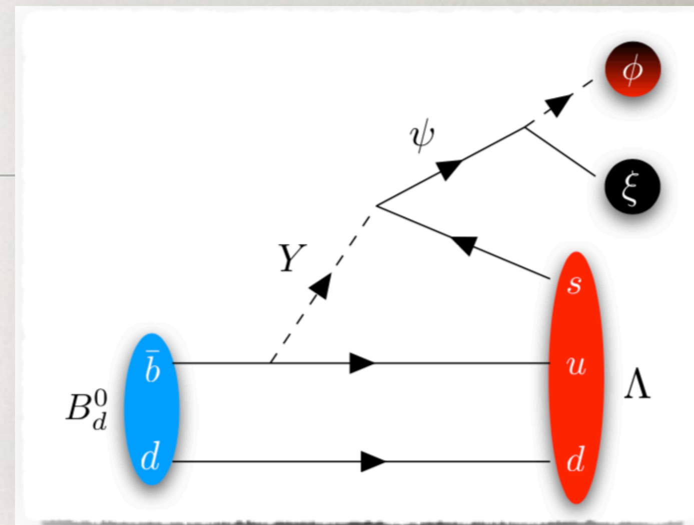
CONCLUSIONS

- nontrivial constraints on $b \to c\tau\upsilon$ and $b \to s\mu\mu$ anomalies from high p_T measurements
- many other interesting interplays
  - a sample: clockwork flavor, Higgs and flavor, baryogenesis and flavor

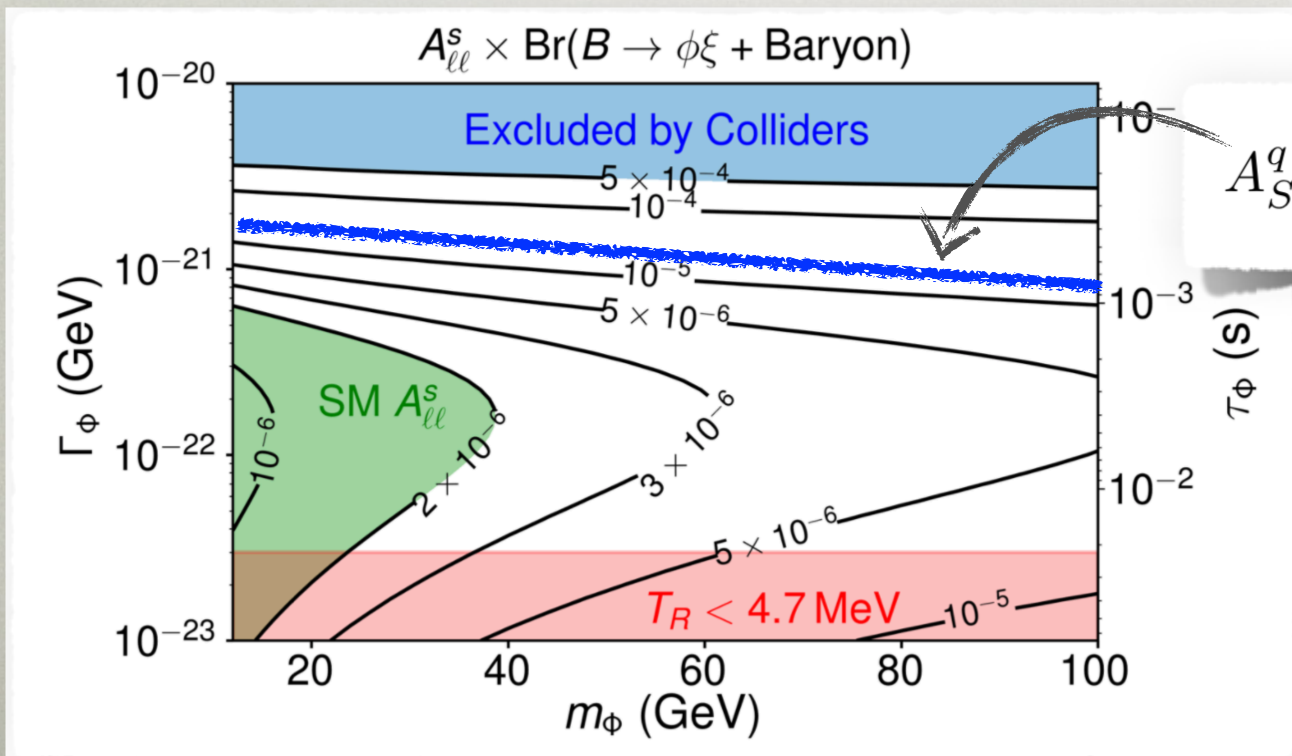
BACKUP SLIDES

BARYOGENESIS FROM B MIXING

Elor, Escudero, Nelson, 1810.00880



- viable baryogenesis with only SM CPV
- dark particle ψ carries baryon number
  - search at Belle for $B \rightarrow$ baryon +MET
- needs a colored mediator, Y, search for it at ATLAS, CMS



$$A^q_{SL} = \mathrm{Im}\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right)$$

MODELS WITH SM NEUTRINO

Freytsis, Ligeti, Ruderman, 1506.08896

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad \mathcal{O}_{V_L}\langle$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$\rangle(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda \bar{u}_R \ell_L + \tilde{\lambda} \bar{q}_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda} \bar{q}^c_L \gamma_\mu e_R)V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad \frac{1}{2}\mathcal{O}_{V_L}\langle$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda \bar{q}^c_L i\tau_2 \boldsymbol{\tau}\ell_L \boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$\rangle(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda} \bar{u}^c_R e_R)S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

2 color singlet mediators

6 leptoquark mediators

DIRECT SEARCHES IN $\tau\tau$

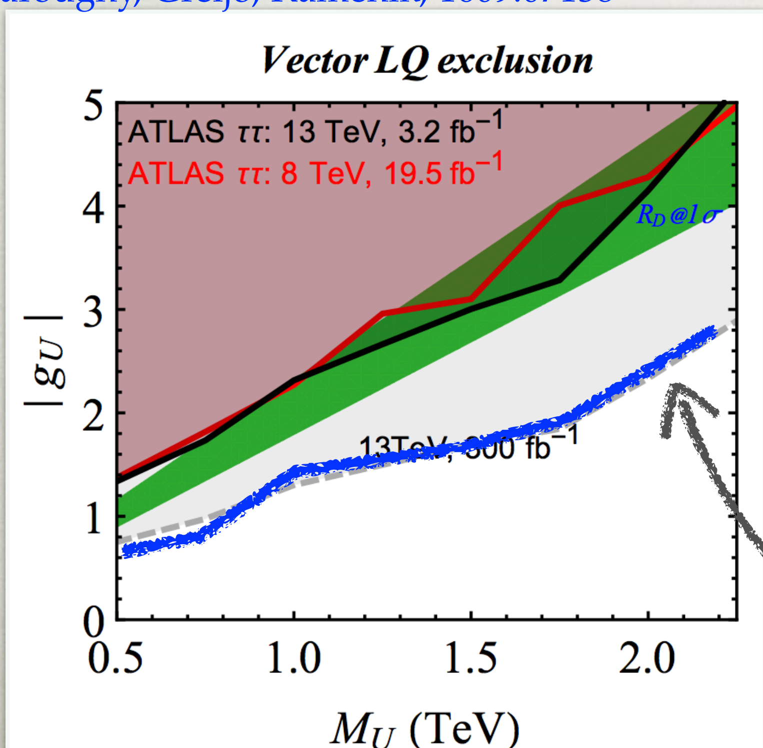
- vector leptoquark: U_μ

g_U

$$(\lambda \bar{q}_L^3 \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R) U^\mu$$

  - bounds depend somewhat on flavor structure assumed

Faroughy, Greljo, Kamenik, 1609.07138



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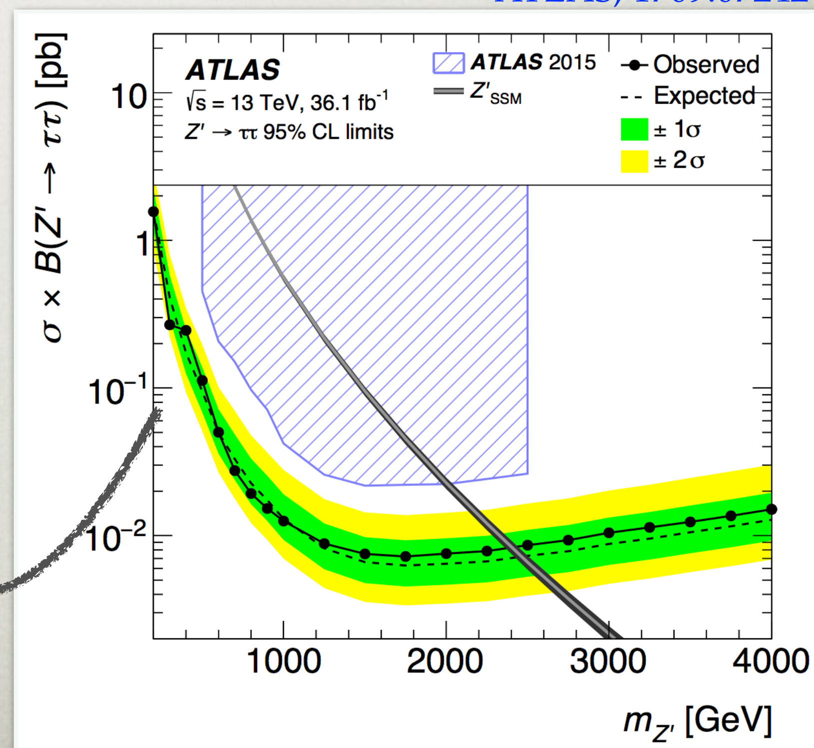
ATLAS, 1709.07242



DIRECT SEARCHES IN $\tau\tau$

- vector leptoquark: U_μ
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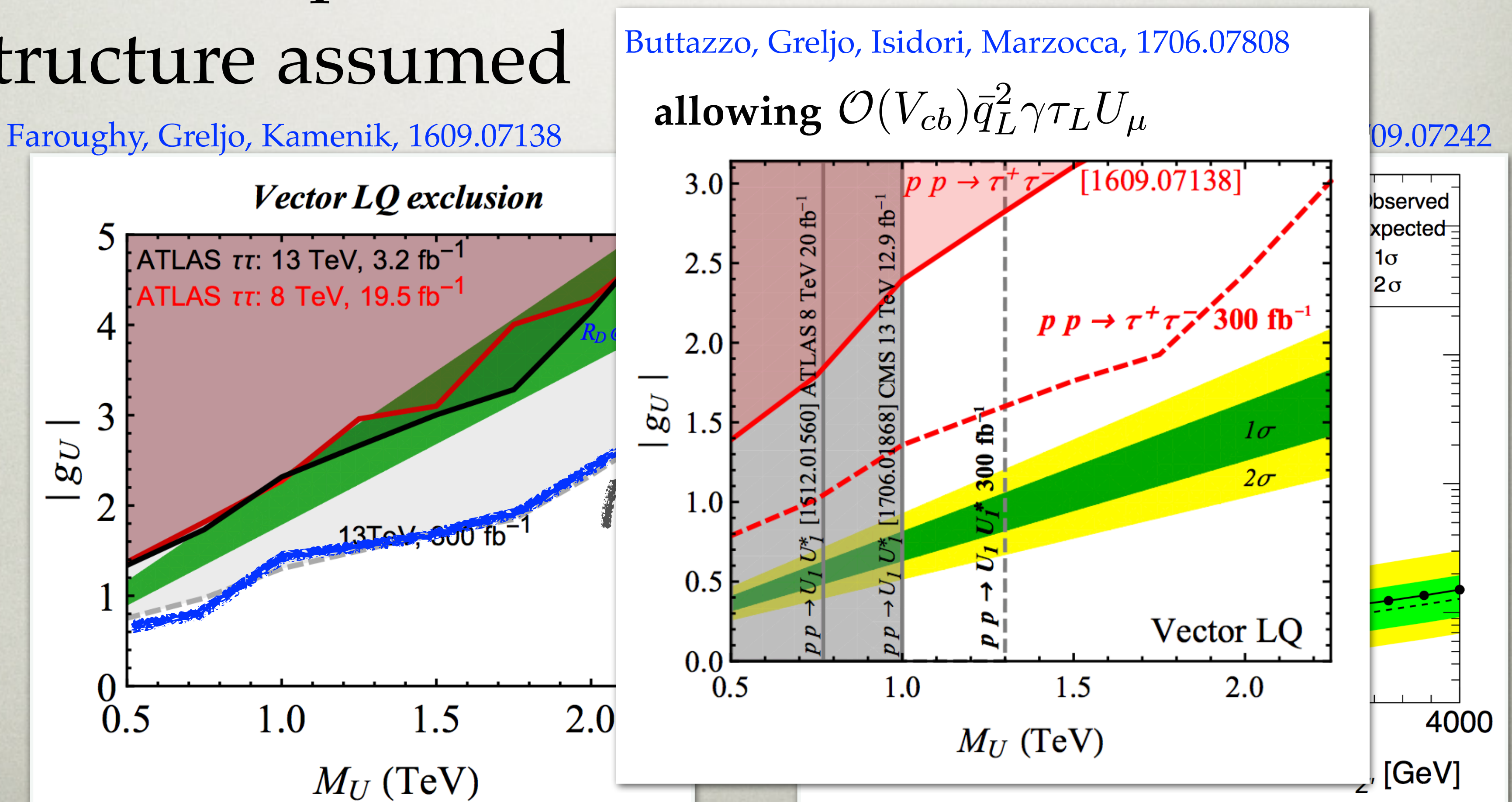
gu

$$(\lambda \bar{q}_L^3 \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R) U^\mu$$



LEPTOQUARK FOR BOTH $b \to c\tau\nu$ AND $b \to s\mu\mu$

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

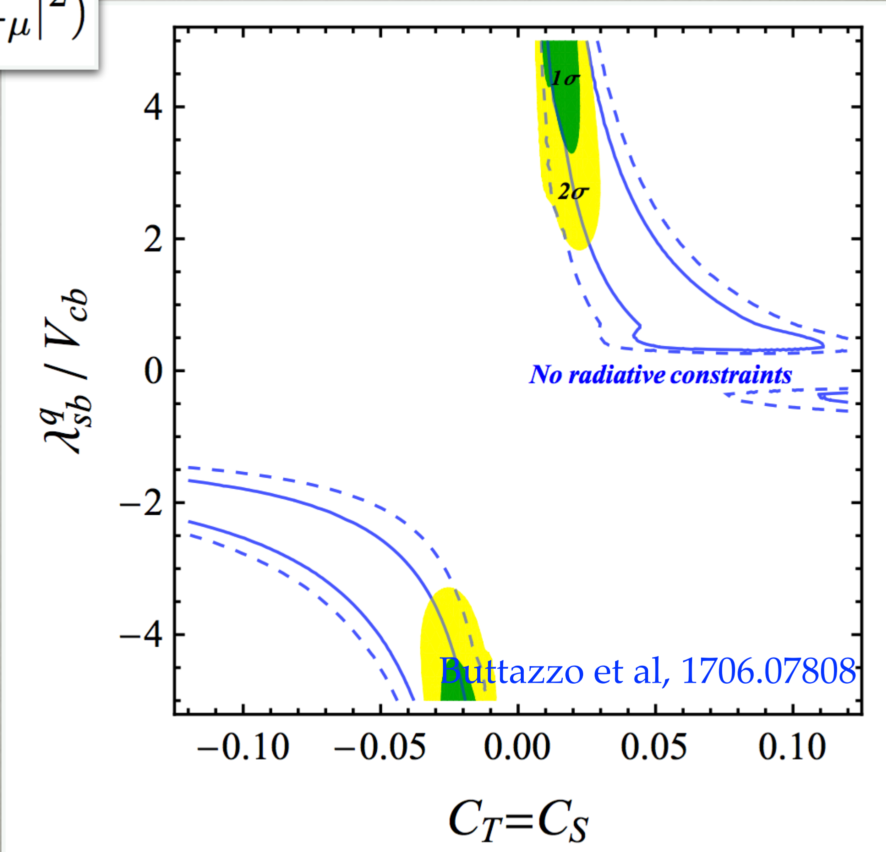
- in EFT possible to explain all anomalies

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\;(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\;(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

$$\lambda^q_{sb} = \mathcal{O}(|V_{cb}|)\;,\quad \lambda^\ell_{\tau\mu} = \mathcal{O}(|V_{\tau\mu}|)\;,\quad \lambda^\ell_{\mu\mu} = \mathcal{O}(|V_{\tau\mu}|^2)$$

  - with MFV-like flavor structure
  - predicts *Br(b→sττ)~O(100)x SM*
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu \equiv (\mathbf{3},\mathbf{1},2/3)$$



LEPTOQUARK FOR BOTH $b\to c\tau\upsilon$ AND $b\to s\mu\mu$

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

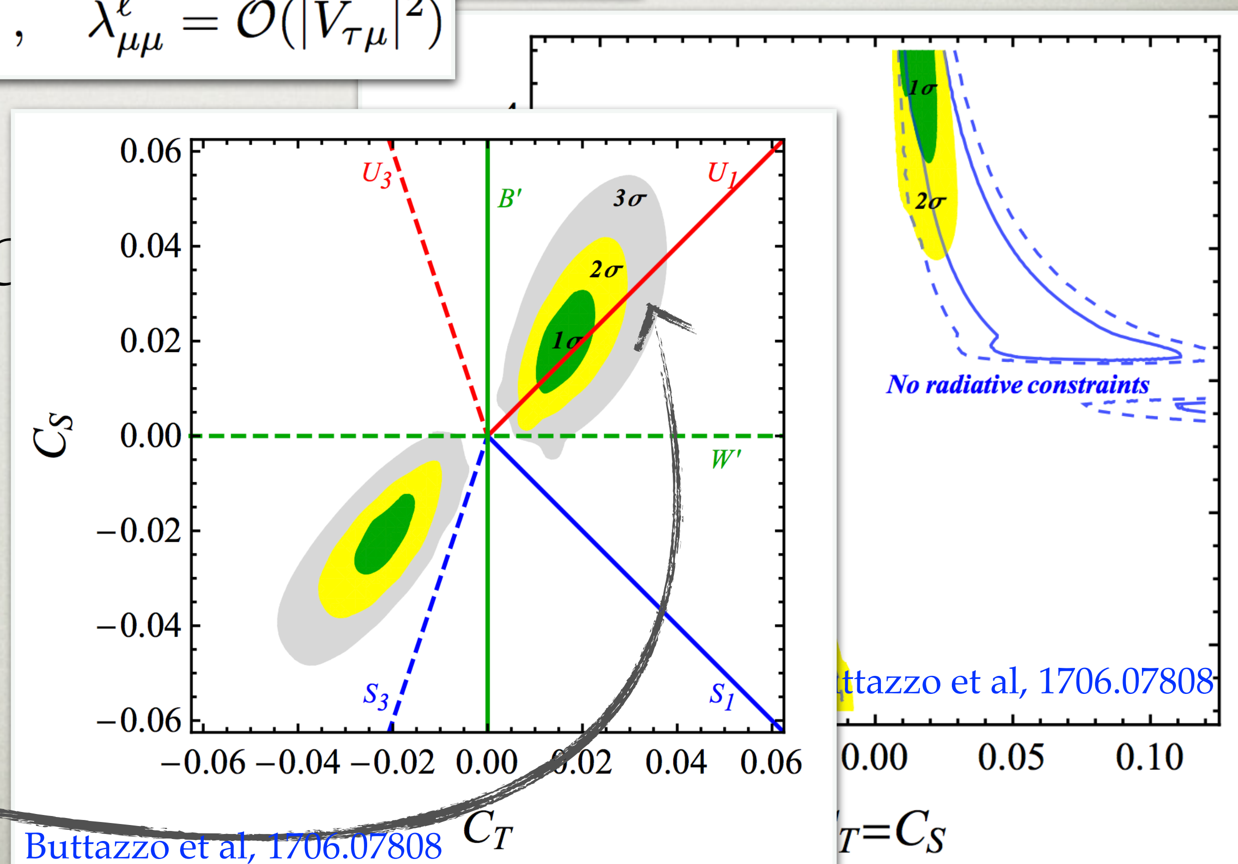
- in EFT possible to explain all anomalies

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

$$\lambda^q_{sb}=\mathcal{O}(|V_{cb}|)\ ,\quad \lambda^\ell_{\tau\mu}=\mathcal{O}(|V_{\tau\mu}|)\ ,\quad \lambda^\ell_{\mu\mu}=\mathcal{O}(|V_{\tau\mu}|^2)$$

  - with MFV-like flavor
  - predicts $Br(b\to s\tau\tau)\sim C$
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu\equiv(\mathbf{3},\mathbf{1},2/3)$$



Buttazzo et al, 1706.07808

LEPTOQUARK FOR BOTH

$b \to c\tau\upsilon$ AN

Buttazzo, Greljo, Isidori, Marzocca, 1706.07808

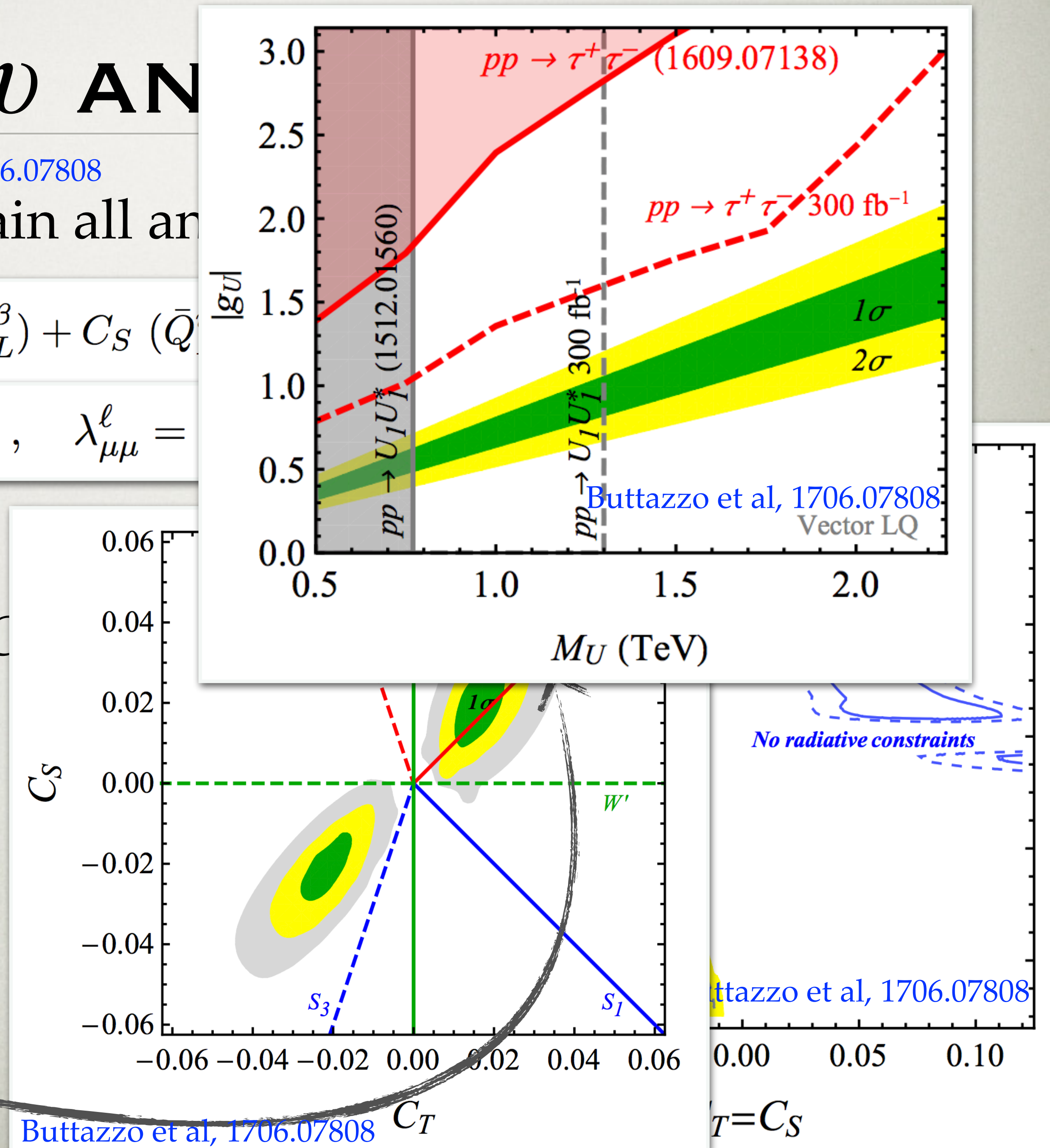
- in EFT possible to explain all an

$$\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}\right.$$

$$\lambda^q_{sb} = \mathcal{O}(|V_{cb}|)\ ,\quad \lambda^\ell_{\tau\mu} = \mathcal{O}(|V_{\tau\mu}|)\ ,\quad \lambda^\ell_{\mu\mu} =$$

  - with MFV-like flavor
  - predicts $Br(b \to s\tau\tau) \sim C$
- if NP contribs. dominated by one field
  - only one option: vector leptoquark

$$U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$$



MODELS WITH RIGHT-HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

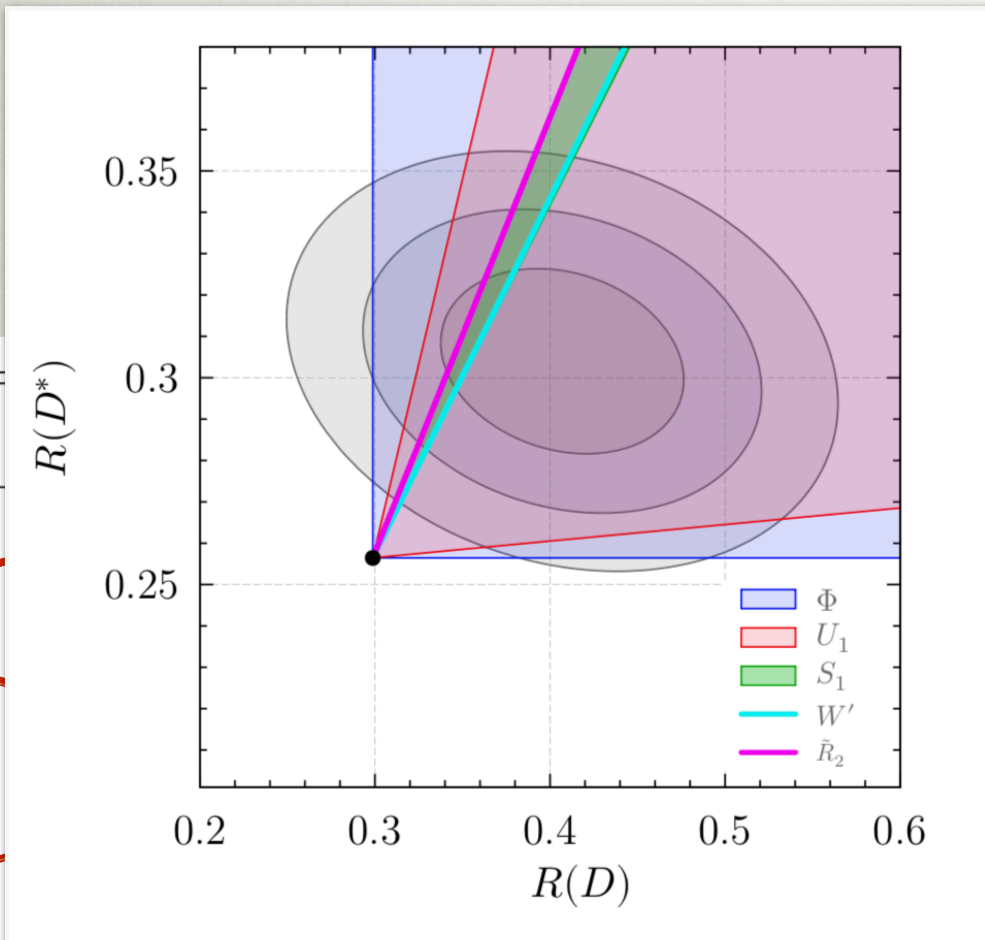
mediator	irrep	$\delta\mathcal{L}_{\text{int}}$	WCs
W'_μ	$(1,1)_1$	$g'\left(c_q \bar{u}_R \gamma_\mu d_R + c_N \bar{\ell}_R \gamma_\mu N_R\right) W'^\mu$	c_{VR}
Φ	$(1,2)_{1/2}$	$y_u \bar{u}_R Q_L \epsilon \Phi + y_d \bar{d}_R Q_L \Phi^\dagger + y_N \bar{N}_R L_L \epsilon \Phi$	c_{SL}, c_{SR}
U_1^μ	$(3,1)_{2/3}$	$\left(\alpha_{LQ} \bar{L}_L \gamma_\mu Q_L + \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R\right) U_1^{\mu\dagger} + \alpha_{uN}\left(\bar{u}_R \gamma_\mu N_R\right) U_1^\mu$	c_{SL}, c_{VR}
$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}\left(\bar{L}_L d_R\right) \epsilon \tilde{R}_2^\dagger + \alpha_{QN}\left(\bar{Q}_L N_R\right) \tilde{R}_2$	$c_{\text{SR}} = 4c_{\text{T}}$
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c \ell_R) S_1 + z_d(\bar{d}_R^c N_R) S_1 + z_Q(\bar{Q}_L^c \epsilon L_L) S_1$	c_{VR}, $c_{\text{SR}} = -4c_{\text{T}}$

2 color singlet mediators

3 leptoquark mediators

MODELS WITH RIGHT- UTRINO

Robinson, Shakya, JZ, 1807.04753



		$\delta\mathcal{L}_{\rm int}$	WCs
		$+ c_N \bar{\ell}_R \gamma_\mu N_R) W'^\mu$	$c_{\rm VR}$
		$+ y_d \bar{d}_R Q_L \Phi^\dagger +$ $\bar{N}_R L_L \epsilon \Phi$	$c_{\rm SL}, c_{\rm SR}$
		$+ \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R) U_1^{\mu\dagger} +$ $_R \gamma_\mu N_R) U_1^\mu$	$c_{\rm SL}, c_{\rm VR}$
$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}(\bar{L}_L d_R)\epsilon \tilde{R}_2^\dagger + \alpha_{QN}(\bar{Q}_L N_R)\tilde{R}_2$	$c_{\rm SR} = 4c_{\rm T}$
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c \ell_R)S_1 + z_d(\bar{d}_R^c N_R)S_1 +$ $z_Q(\bar{Q}_L^c \epsilon L_L)S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4c_{\rm T}$

2 color singlet mediators

3 leptoquark mediators

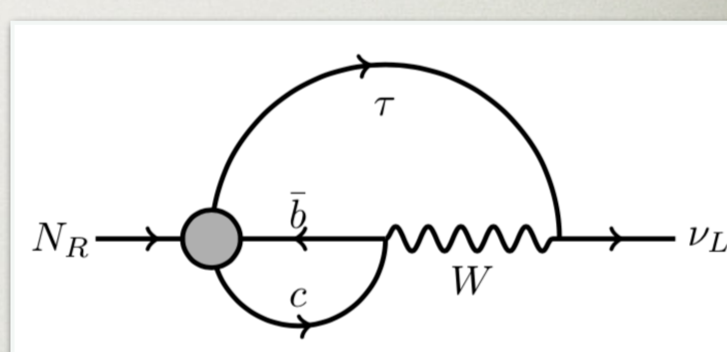
MODELS WITH RIGHT-HANDED NEUTRINO

Robinson, Shakya, JZ, 1807.04753

mediator	irrep	$\delta\mathcal{L}_{\rm int}$	WCs
W'_μ	$(1,1)_1$	$g'\big(c_q\bar{u}_R\gamma_\mu d_R + c_N\bar{\ell}_R\gamma_\mu N_R\big)W'^\mu$	$c_{\rm VR}$
~~Φ~~	~~$(1,2)_{1/2}$~~	~~$y_u\bar{u}_R Q_L\epsilon\Phi + y_d\bar{d}_R Q_L\Phi^\dagger + y_N\bar{N}_R L_L\epsilon\Phi$~~	**excluded from $B_c\to\tau\nu$**
U_1^μ	$(3,1)_{2/3}$	$\big(\alpha_{LQ}\bar{L}_L\gamma_\mu Q_L + \alpha_{\ell d}\bar{\ell}_R\gamma_\mu d_R\big)U_1^{\mu\dagger} + \alpha_{uN}\big(\bar{u}_R\gamma_\mu N_R\big)U_1^\mu$	$c_{\rm SL}$, $c_{\rm VR}$
~~R_2~~	~~$(3,2)_{1/6}$~~	~~$\alpha_{Ld}(\bar{L}_L d_R)\epsilon\tilde{R}_2^\dagger + \alpha_{QN}(\bar{Q}_L N_R)$~~	**excluded from $B\to K\nu\nu$**
S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c\ell_R)S_1 + z_d(\bar{d}_R^c N_R)S_1 + z_Q(\bar{Q}_L^c\epsilon L_L)S_1$	$c_{\rm VR}$, $c_{\rm SR} = -4c_{\rm T}$

MODELS WITH RIGHT-HANDED NEUTRINO

- left with three simplified models: W', U_1, S_1
- couplings of U_1, S_1 further constrained
  - potentially too large contribs. to neutrino masses at 2 loops



- net result: all three match predominantly onto EFT operator

$$\mathcal{O}_{\rm VR} = \left(\bar{c}_R \gamma^\mu b_R\right)\left(\bar{\tau}_R \gamma_\mu N_R\right),$$

'3221' gauge model

- straightforward to UV complete W' model
- '3221' gauge model: $SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$
  - $SU(2)_V \times U(1)' \to U(1)_Y$ breaking, e.g., via $SU(2)_V$ doublet, H_V
  - extra vector-like fermions

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	$U(1)'$
Extra vector-like fermions				
$Q'^i_{L,R}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	1/6
$L'^i_{L,R}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	-1/2

  - large mixing with b_R, c_R, τ_R, ν_R ($\lambda v_V/M \gg 1$)

RIGHT-HANDED NEUTRINO

- the N_R in $b \to c\tau N_R$ is Majorana, mostly from L_R'
- for single generation neutrino mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & 0 & 0 \\ \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & \mu & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 \\ 0 & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 & M_L \\ 0 & 0 & M_L & 0 \end{pmatrix}$$

$$(\nu_L', \nu_R'^c, N_L', N_R'^c)$$

- for $v_{EW} = 0$, SM neutrino ν_L' decouples
- for $\mu = 0$ a massless Majorana neutrino is the state

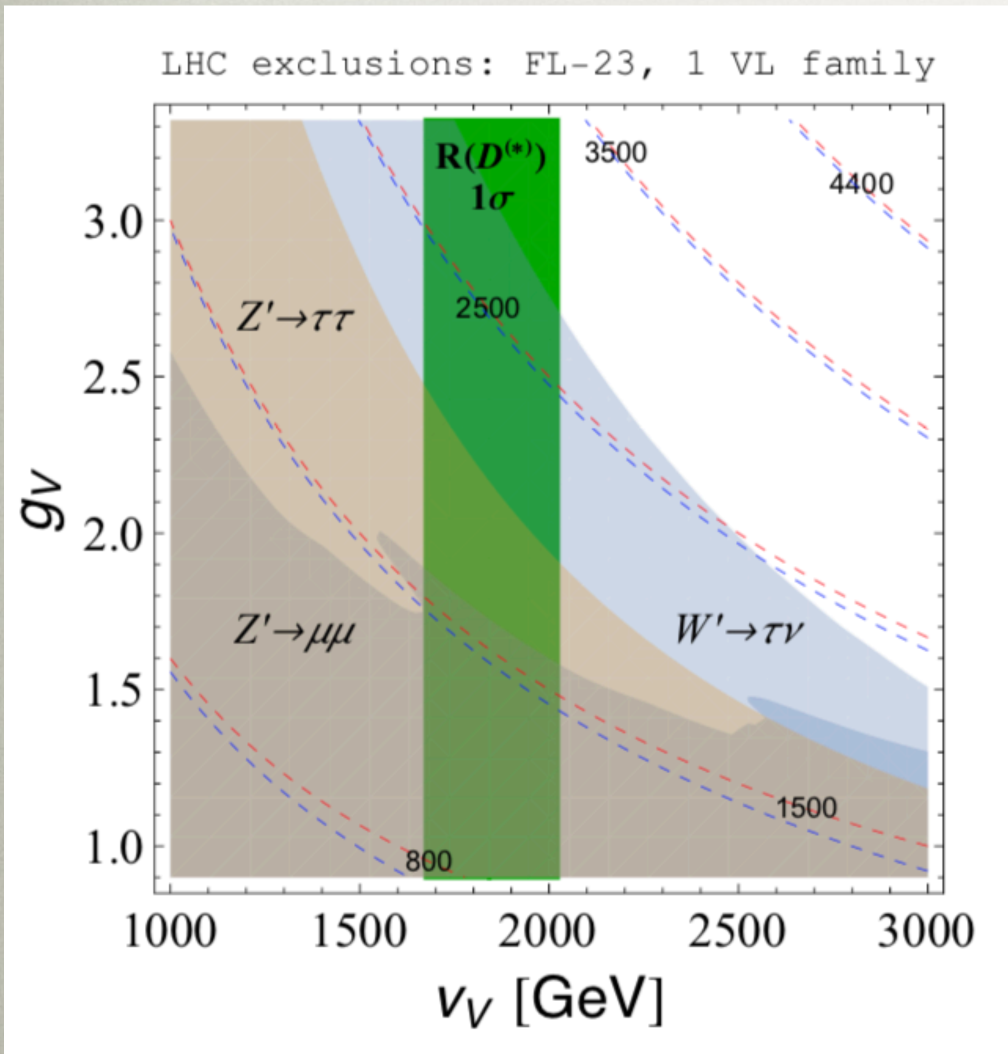
$$N_R^c = \cos\theta_N \nu_R'^c - \sin\theta_N N_R'^c \qquad \tan\theta_N = (\lambda_\nu v_V)/(\sqrt{2}M_L)$$

  - for $\lambda_\nu v_V \gg M_L$ the massless RH neutrino has a large admixture of N_R'

LHC constraints

- assume minimal flavor structure needed for the anomaly
  - large couplings to b,c,τ
- LHC constraints from $pp \to W' \to \tau N_R$, $pp \to Z' \to \tau\tau$ searches
- if only the SM channels open $Br(W' \to \tau N_R) : Br(W' \to cb) \simeq 1{:}3$
- reduced, if vector-like fermions light enough

LHC constraints



vor structure needed for

b,c,τ

m $pp \to W' \to \tau N_R$, $pp \to$

nels open $Br(W' \to \tau N_R)$:

- reduced, if vector-like fermions light enough

LHC constraints