Pati–Salam and lepton universality in B decays

Julian Heeck

Moriond - EW Session - 3/22/2019

based on JHEP 1812 (2018) 103 with **Daniele Teresi**

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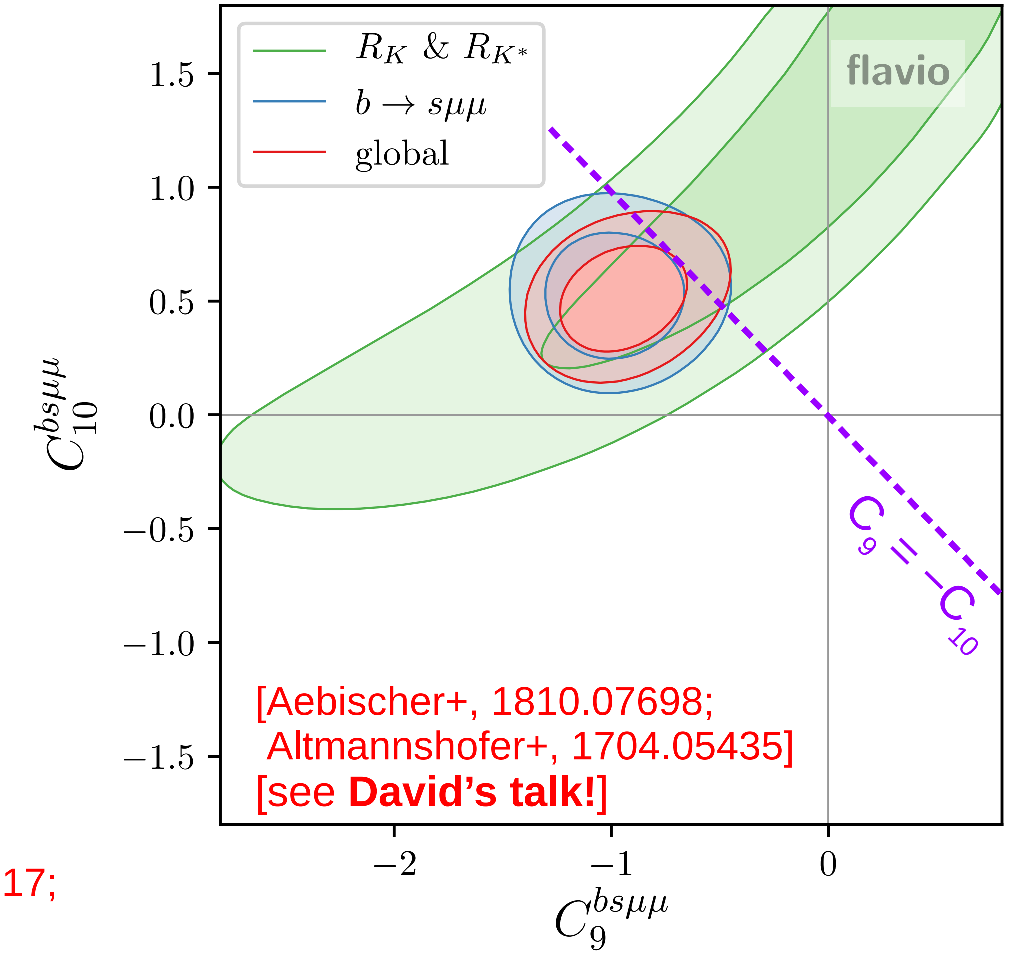
$$R_{K^{(*)}} \equiv \frac{\Gamma(B\to K^{(*)}\mu\mu)}{\Gamma(B\to K^{(*)}ee)}$$



[Aebischer+, 1810.07698;
Altmannshofer+, 1704.05435]
[see **David's talk!**]

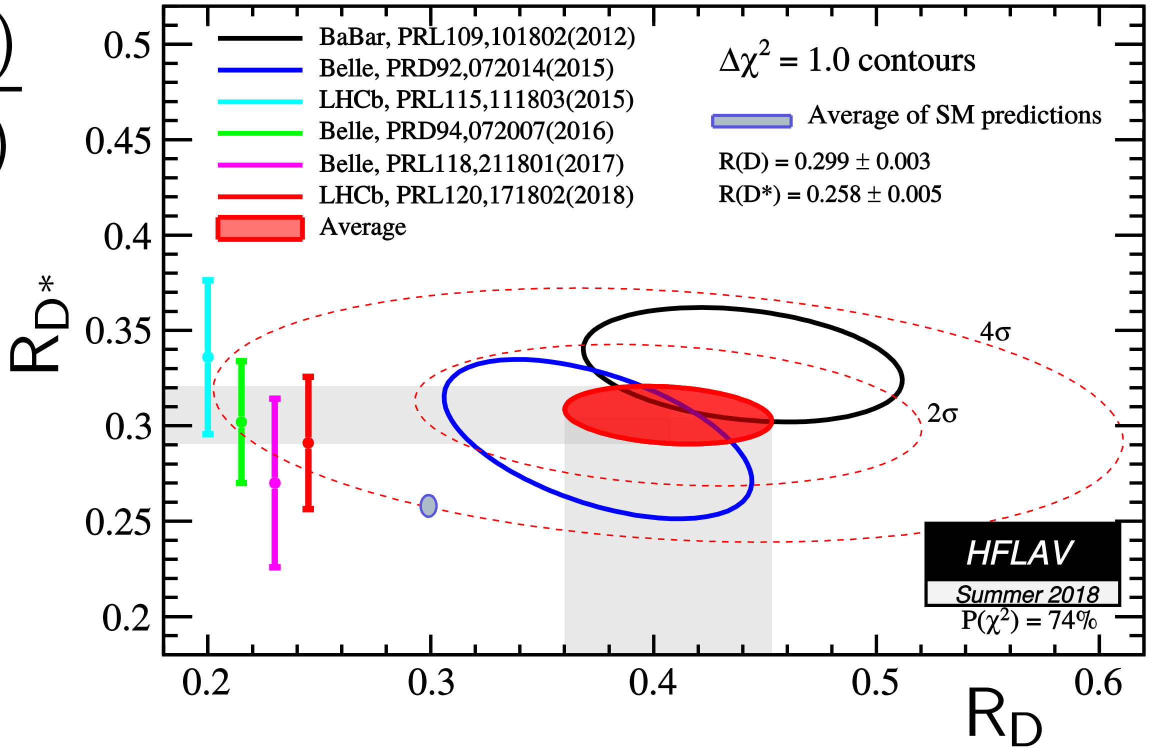
- Neutral current,

  loop-level SM.
- LHCb anomaly.
- Good operator ($C_9 = -C_{10}$)

  $$\frac{1}{(31\,\text{TeV})^2}\,\bar{s}\gamma_\alpha P_L b\,\overline{\mu}\gamma^\alpha P_L \mu\,.$$

  [Capdevila+, '17; Altmannshofer+, '17; Geng+, '17; Ciuchini+, '17; D'Amico+, '17;...]
- Tree-level UV: Z' or leptoquark. [arxiv.org/list/hep-ph/]
- High NP scale = heavy new boson = easy to have.
- Also look for B_s–$\bar{B}_s$ and di-muons at LHC.

$$R_{D^{(*)}} \equiv \frac{\Gamma(\overline{B}\to D^{(*)}\tau\nu)}{\Gamma(\overline{B}\to D^{(*)}\ell\nu)}$$



- Charged current, *tree-level* SM.
- LHCb, BaBar, Belle.
- Good operator

$$\frac{1}{(2.4\,\mathrm{TeV})^2}\,\bar{c}\gamma_\alpha P_L b\,\bar{\tau}\gamma^\alpha P_L \nu\,.$$

[HFLAV; Bernlochner+, ‘17; Di Luzio+, ‘17;...]

- ~~H^+~~, W’ or leptoquark.
- Low scale, many constraints: $B\to K\nu\nu$, $B_c\to\tau\nu$.

[Li+, 1605.09308; Alonso+, 1611.06676]

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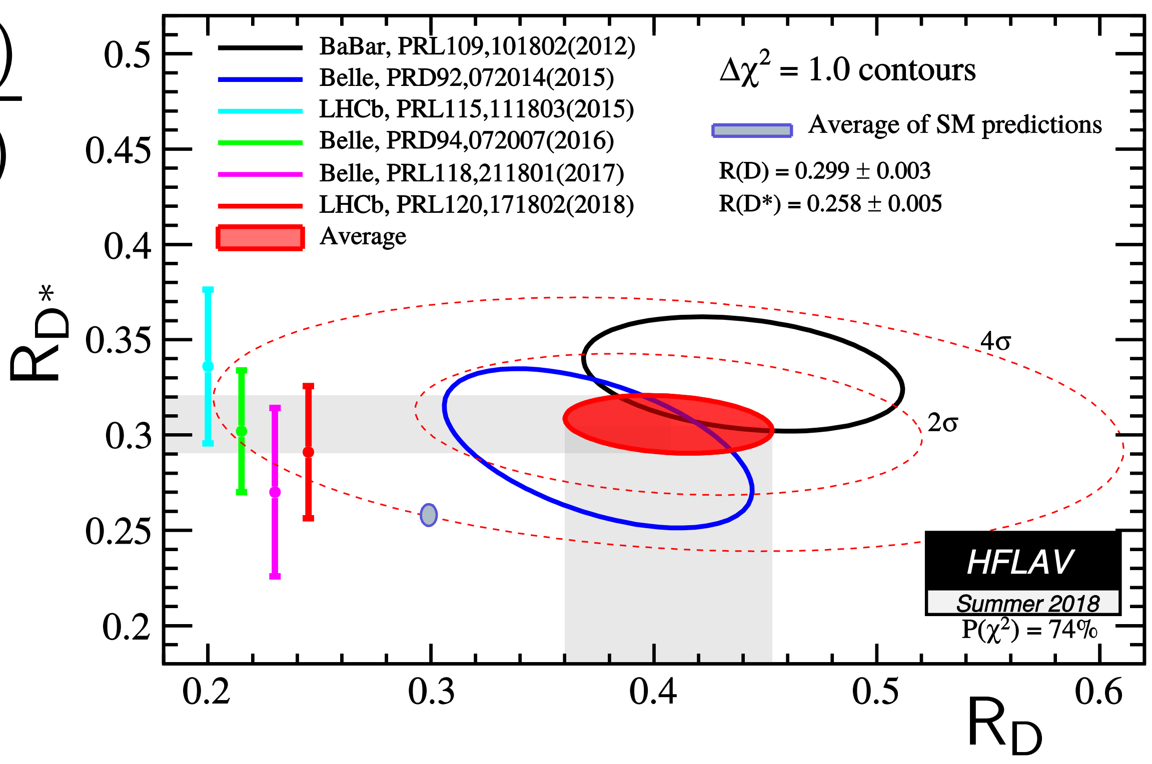

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$$\frac{1}{(2.4\,\mathrm{TeV})^2}\,\bar{c}\gamma_\alpha P_L b\,\bar{\tau}\gamma^\alpha P_L \nu$$

[HFLAV; Bernlochner+, ‘17; Di Luzio+, ‘17;...]

or right-handed neutrino!

[He, Valencia, ‘12/’17; Greljo+, ‘18; Asadi+, ‘18; Robinson+, ’18; Bečirević+, ‘16; Azatov+, ‘18]

- ~~H^+~~, W’ or leptoquark.
- Low scale, many constraints: B → Kνν, B_c → τν.
- Light (< 100 MeV) sterile neutrino? Evades B → Kνν.

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Leptoquarks?

- Bosons that couple to quarks & leptons, e.g.

$$\mathrm{L} = \mathrm{y}_{\mathrm{ij}}\mathrm{Q}_{\mathrm{i}}\mathrm{S}_3\mathrm{L}_{\mathrm{j}} + \mathrm{z}_{\mathrm{ij}}\mathrm{Q}_{\mathrm{i}}\mathrm{S}_3\mathrm{Q}_{\mathrm{j}} + \mathrm{h.c.}$$

- Leads to proton decay! Impose $U(1)_B$ or $U(1)_{e,\mu,\tau}$?
  [Barr, Freire '90; **JH**, Hambye, PRL 2018]
- For B anomalies:
  S_1, S_3, R_2, U_1, U_3 . [see **Andrei's talk!**]
- Too *ad hoc*? Leptoquarks part of GUTs as multiplet partners!

LQ	SM rep	spin	p decay
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, +1/3)$	0	yes
$\bar{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	0	yes
$\tilde{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, +4/3)$	0	yes
S_3	$(\overline{\mathbf{3}}, \mathbf{3}, +1/3)$	0	yes
R_2	$(\mathbf{3}, \mathbf{2}, +7/6)$	0	no
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, +1/6)$	0	yes
U_1	$(\mathbf{3}, \mathbf{1}, +2/3)$	1	no
$\bar{U}_1$	$(\mathbf{3}, \mathbf{1}, -1/3)$	1	no
$\tilde{U}_1$	$(\mathbf{3}, \mathbf{1}, +5/3)$	1	no
U_3	$(\mathbf{3}, \mathbf{3}, +2/3)$	1	no
V_2	$(\overline{\mathbf{3}}, \mathbf{2}, +5/6)$	1	yes
$\tilde{V}_2$	$(\overline{\mathbf{3}}, \mathbf{2}, -1/6)$	1	yes

[Review: Doršner+, '16]

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Leptoquarks?

- Bosons that couple to quarks & leptons, e.g.

$$L = y_{ij} Q_i S_3 L_j + z_{ij} Q_i S_3 Q_j + \text{h.c.}$$

- Leads to proton decay! Impose $U(1)_B$ or $U(1)_{e,\mu,\tau}$?
  [Barr, Freire ‘90; **JH**, Hambye, PRL 2018]

- For B anomalies:

  S_1, S_3, R_2, U_1, U_3 . [see **Andrei’s talk!**]

- Too *ad hoc*? Leptoquarks part of GUTs as multiplet partners!

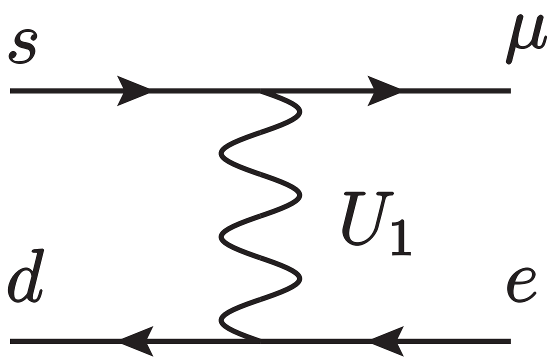
LQ	SM rep	$R_{K^{(*)}}$	$R_{D^{(*)}}$
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, +1/3)$	(✓)	✓
$\bar{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$		
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, +4/3)$		
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, +1/3)$	✓	
R_2	$(\mathbf{3}, \mathbf{2}, +7/6)$	✓	or ✓
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, +1/6)$		
U_1	$(\mathbf{3}, \mathbf{1}, +2/3)$	✓	✓
$\bar{U}_1$	$(\mathbf{3}, \mathbf{1}, -1/3)$		
$\tilde{U}_1$	$(\mathbf{3}, \mathbf{1}, +5/3)$		
U_3	$(\mathbf{3}, \mathbf{3}, +2/3)$	✓	
V_2	$(\bar{\mathbf{3}}, \mathbf{2}, +5/6)$		
$\tilde{V}_2$	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$		

[Angelescu+, 1808.08179]

Pati-Salam $\boxed{\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R}$

[Pati, Salam, '74]

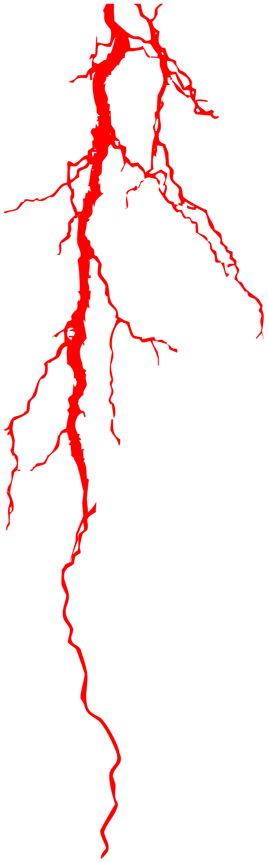
- Fermions: $\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}) \to Q_L \oplus L_L\,,$
  $\Psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2}) \to u_R \oplus d_R \oplus \ell_R \oplus N_R\,.$
- $\mathrm{SU}(4)_C \to \mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L}$ generates massive U_1.
- $K_L \to \mu e$ sets bound $\boxed{m_{U_1} \gtrsim 1000\ \mathrm{TeV}.}$



[Valencia, Willenbrock, '94; Smirnov, '07/'18]

- Need extra work to lower U_1 and get LFUV.

[Calibbi+, '17; Di Luzio+, '17; Blanke, Crivellin, '18; Bordone+, '18]



How about **scalar** leptoquarks?

Pati-Salam $\mathsf{SU}(4)_\mathsf{C} \times \mathsf{SU}(2)_\mathsf{L} \times \mathsf{SU}(2)_\mathsf{R} \to \mathrm{SM}$

- Breaking (and N_R mass!) via scalars

type-I seesaw

$$\Delta_R \sim (\overline{\mathbf{10}}, \mathbf{1}, \mathbf{3}) \supset S_1 \oplus \tilde{S}_1 \oplus \bar{S}_1 \oplus \delta_1\,,$$

$$\Delta_L \sim (\overline{\mathbf{10}}, \mathbf{3}, \mathbf{1}) \supset S_3 \oplus \delta_3\,.$$

type-II seesaw

$$\boxed{\mathcal{L} = \overline{\Psi}^c_L y^L \Delta_L \Psi_L + \overline{\Psi}^c_R y^R \Delta_R \Psi_R + \text{h.c.}}$$

no proton decay!

- Parity $X_L \leftrightarrow X_R$ requires Δ_L and sets $y_L = y_R$.
- Only one (symmetric) coupling matrix!

PS relates couplings of different LQs & to neutrinos!

[**JH**, Teresi, 1808.07492]

Type-II seesaw ↔ $R_{K^{(*)}}$

- $$\overline{\Psi}_L^c y^L \Delta_L \Psi_L \supset \underbrace{\left(\overline{Q}_L^c y^L L_L S_3\right)}_{R_{K^{(*)}}} + \frac{1}{\sqrt{2}} \underbrace{\left(\overline{L}_L^c y^L L_L \delta_3\right)}_{\text{type-II seesaw}}$$

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- $M_\nu \simeq -\sqrt{2}\langle\delta_3\rangle V_L^* y^L V_L^\dagger \quad \overset{*}{\Rightarrow} \quad y^L \propto \begin{pmatrix} 0.05 & 0.06 & -0.10 \\ 0.06 & \boxed{1} & \boxed{0.74} \\ -0.10 & 0.74 & 0.97 \end{pmatrix}$

- $m_{S_3} \sim 30\,\text{TeV}$ can give R(K)!

$*)$ normal ordering , $m_1 = 0\,, \delta_{\mathrm{CP}} = \alpha = \beta = 0\,.$

[**JH**, Teresi, 1808.07492]

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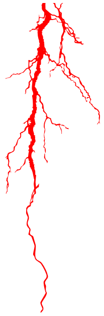
- $m_{S_3} \sim 30\,\text{TeV}$ can give R(K)!
- μ → e conversion too large, use CP phases to suppress.



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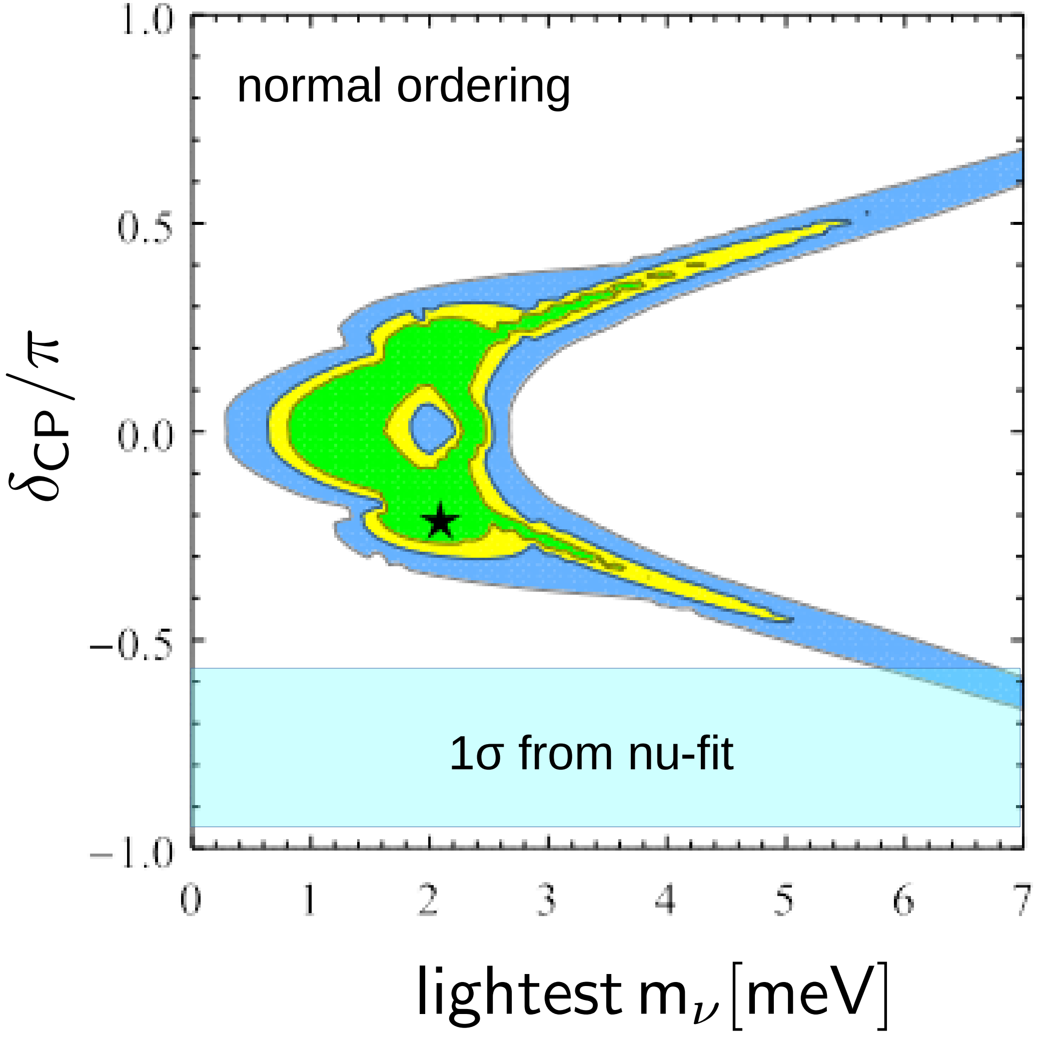
[**JH**, Teresi, 1808.07492]

$R_{K^{(*)}}$ & type-II seesaw

- R(K) and μ→e fix neutrino parameters!
- Fixing $\langle\delta_3\rangle = 50\,\text{meV}$:

parameter	best fit
M_{S_3}	11.4 TeV
m_{ν_1}	2.1 meV
δ_{CP}	-0.2π
α	0.55π
β	0.95π
χ^2	2.45



Should show up in next-gen μ→e!

[**JH**, Teresi, 1808.07492]

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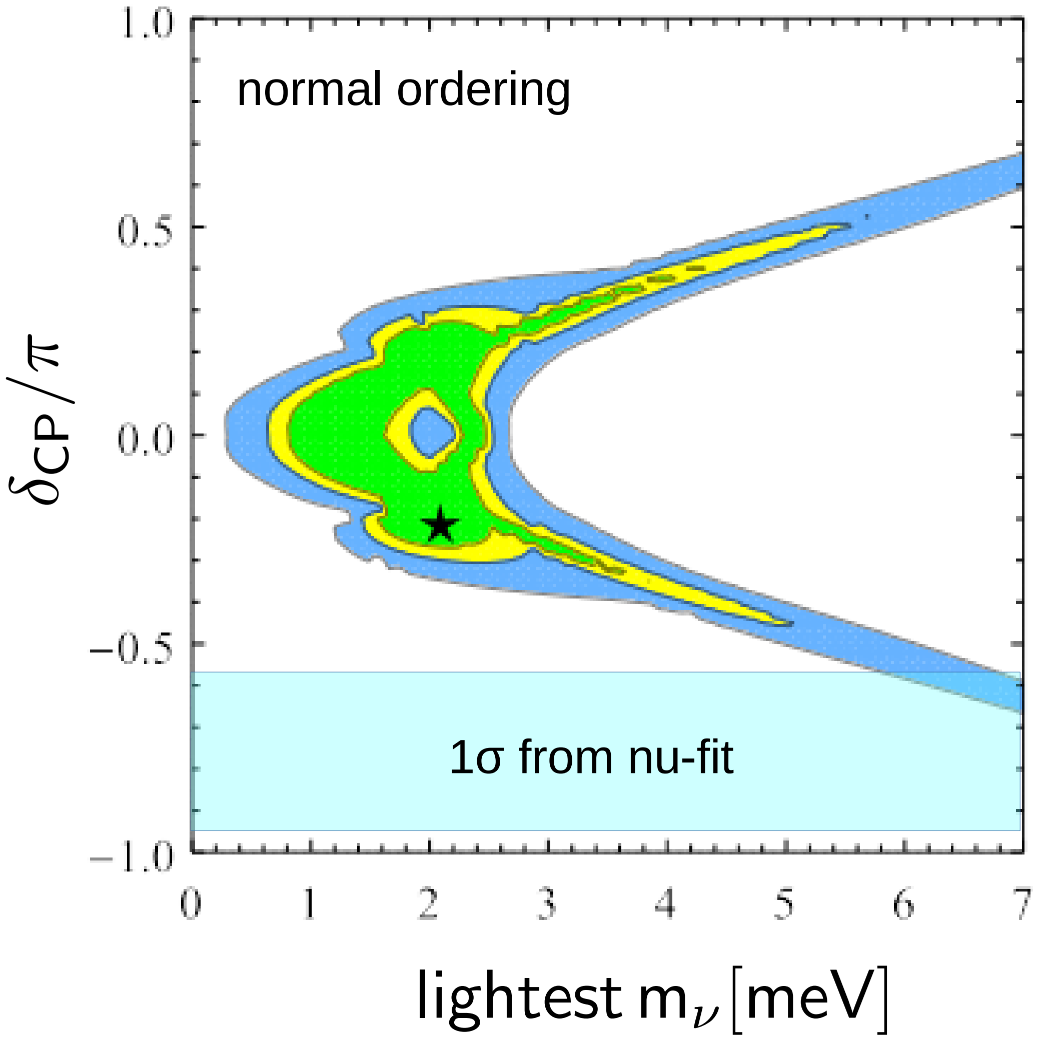

Non-trivial, only works for type-II seesaw with normal ordering!

What about $R_{D^{(*)}}$?

- Difficult, our S_1 LQs couple to N_R, not ν_L.
- Could use the R_2 LQs from the EWSB, but too flexible.
- Forget neutrino connection and assume one light N_R.
- S_3 gives R(K), S_1 gives R(D), same coupling matrix

$$y^L = y^R \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{23} & y_{33} \end{pmatrix} .$$

- Fixing $M_{S_1} = 1\,\text{TeV}$:

parameter	best fit
M_{S_3}	$6.5\,\text{TeV}$
y_{22}	0.034
y_{23}	1.17
χ^2	2.4

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$$y^L = y^R \simeq \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & \boxed{y_{22} \quad y_{23}} & \\ 0 & \boxed{y_{23}} & \cancel{y_{33}} \end{array}\right) \text{R(K)}$$

R(D)

- Fixing $M_{S_1} = 1\,\text{TeV}$:

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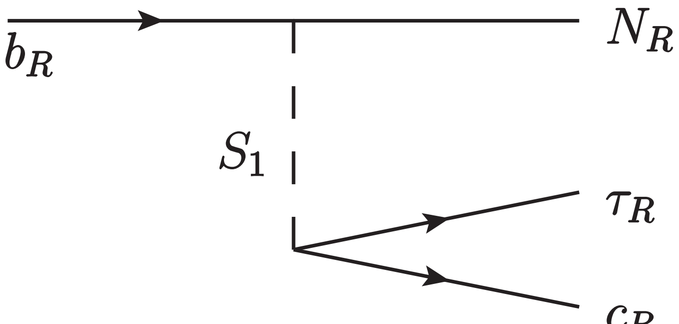
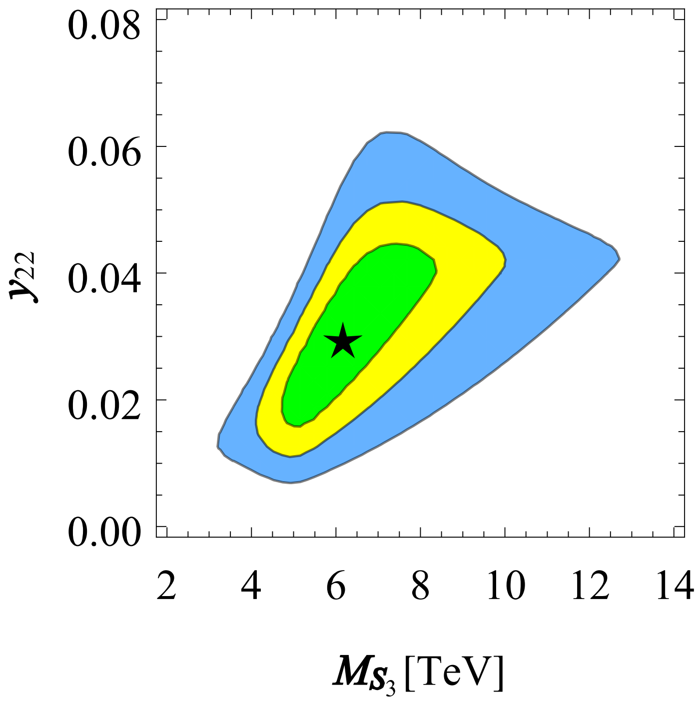
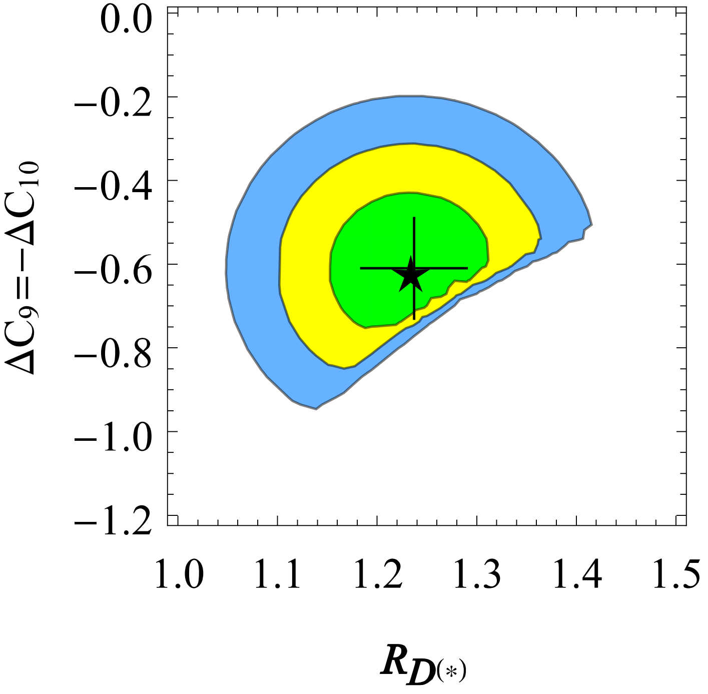






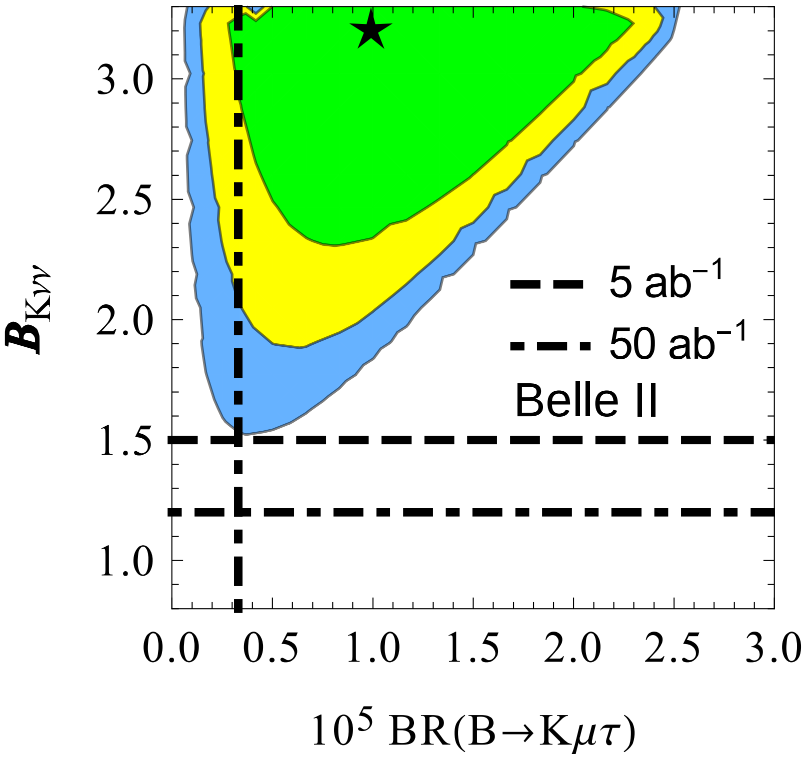
- S_1 testable in Belle-II:

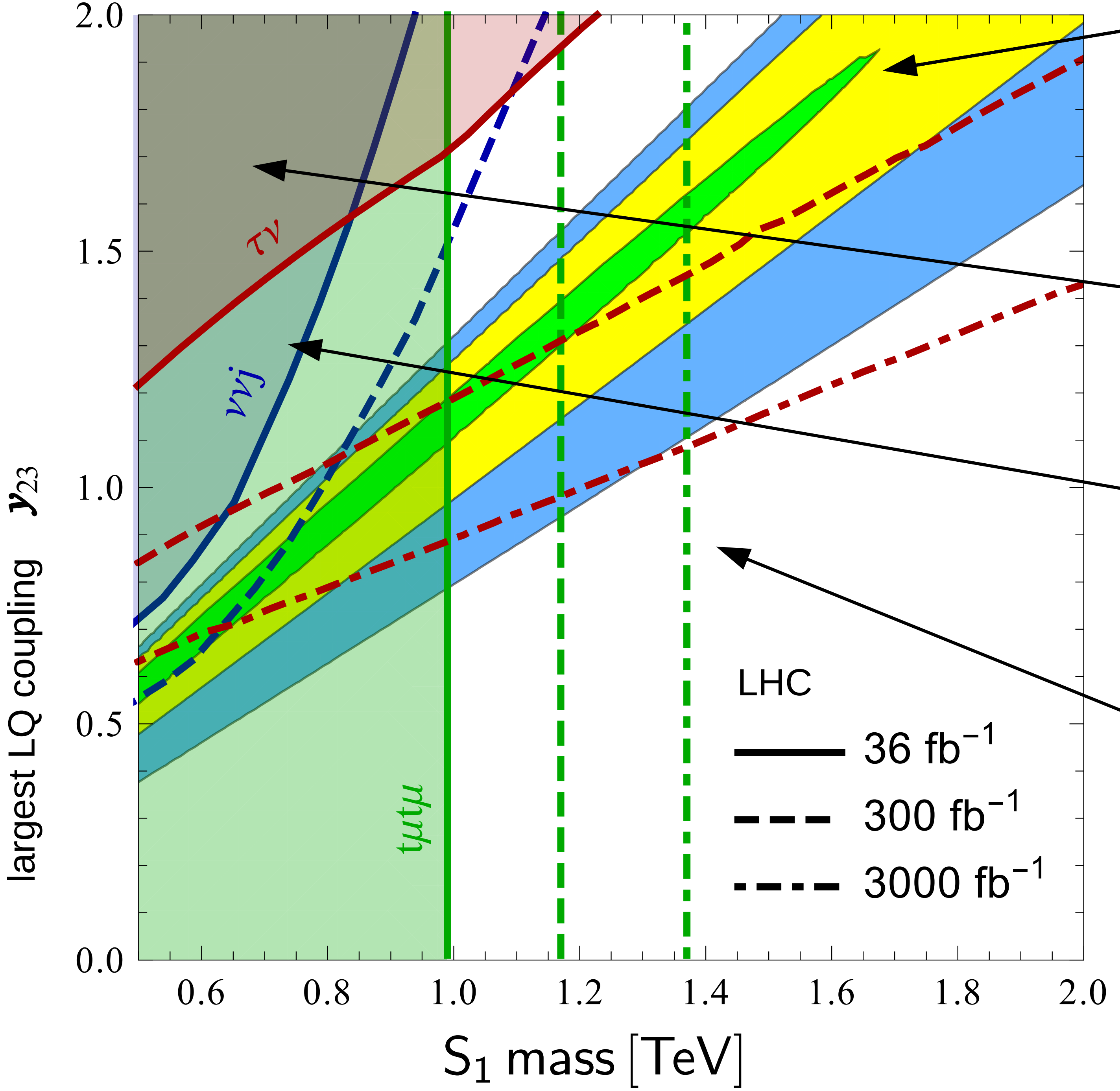
  $B \to K\nu\nu$ & $B \to K\mu\tau$

  and at the LHC:

  $pp \to \tau\nu, \nu\nu j, t\mu t\mu$.

- $\nu = N_R$ here.





R(K) & R(D)

pp → τν

[ATLAS, 1801.06992]

pp → ννj

[Azatov+, 1807.10745]

pp → S_1S_1
→ tμtμ

[CMS-PAS-B2G-16-027]

Conclusions

- Lepton non-universality in B decays very intriguing.
- New physics in the form of Z’, W’ or leptoquarks!
- LQ explanation fits surprisingly nicely into Pati-Salam:
  - Required for symmetry breaking & seesaw.
  - Automatically chiral & no proton decay.
  - Pati-Salam relates couplings of LQs and seesaw.
  - Parity relates S_3 and S_1 couplings.
- Testable: $\mathrm{pp} \to \tau\nu, \nu\nu\mathrm{j}, \mathrm{t}\mu\mathrm{t}\mu\,,$

$$\mathrm{BR}(\mathrm{S}_1 \to \mathrm{t}\mu) \simeq \mathrm{BR}(\mathrm{S}_1 \to \mathrm{c}\tau) \simeq \mathrm{BR}(\mathrm{S}_1 \to \mathrm{b}\,\mathrm{inv}).$$

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Backup

[**JH**, Teresi, 1808.07492]

Fermion masses

- $(\bar{\mathbf{4}}, \mathbf{2}, \mathbf{1}) \otimes (\mathbf{4}, \mathbf{1}, \mathbf{2}) = (\mathbf{1}, \mathbf{2}, \mathbf{2}) \oplus (\mathbf{15}, \mathbf{2}, \mathbf{2})$
- Just complex $(\mathbf{1}, \mathbf{2}, \mathbf{2})$: $\boxed{\mathsf{m_d} = \mathsf{m}_\ell \,, \quad \mathsf{m_u} = \mathsf{m}_\mathsf{N}^\text{Dirac}}$ [Volkas, '95]
- Diagonalization:

$$\mathsf{u}_\mathsf{L,R} \to \mathsf{V}^\dagger_\mathsf{L,R} \mathsf{u}_\mathsf{L,R} \,, \quad \nu_\mathsf{L} \to \mathsf{V}^\dagger_\mathsf{L} \nu_\mathsf{L} \,, \quad \mathsf{N}_\mathsf{R} \to \mathsf{V}^\dagger_\mathsf{R} \mathsf{N}_\mathsf{R}$$

with parity relation $\mathsf{V_R} \simeq \mathsf{V_L}$. [Maiezza+, '10]

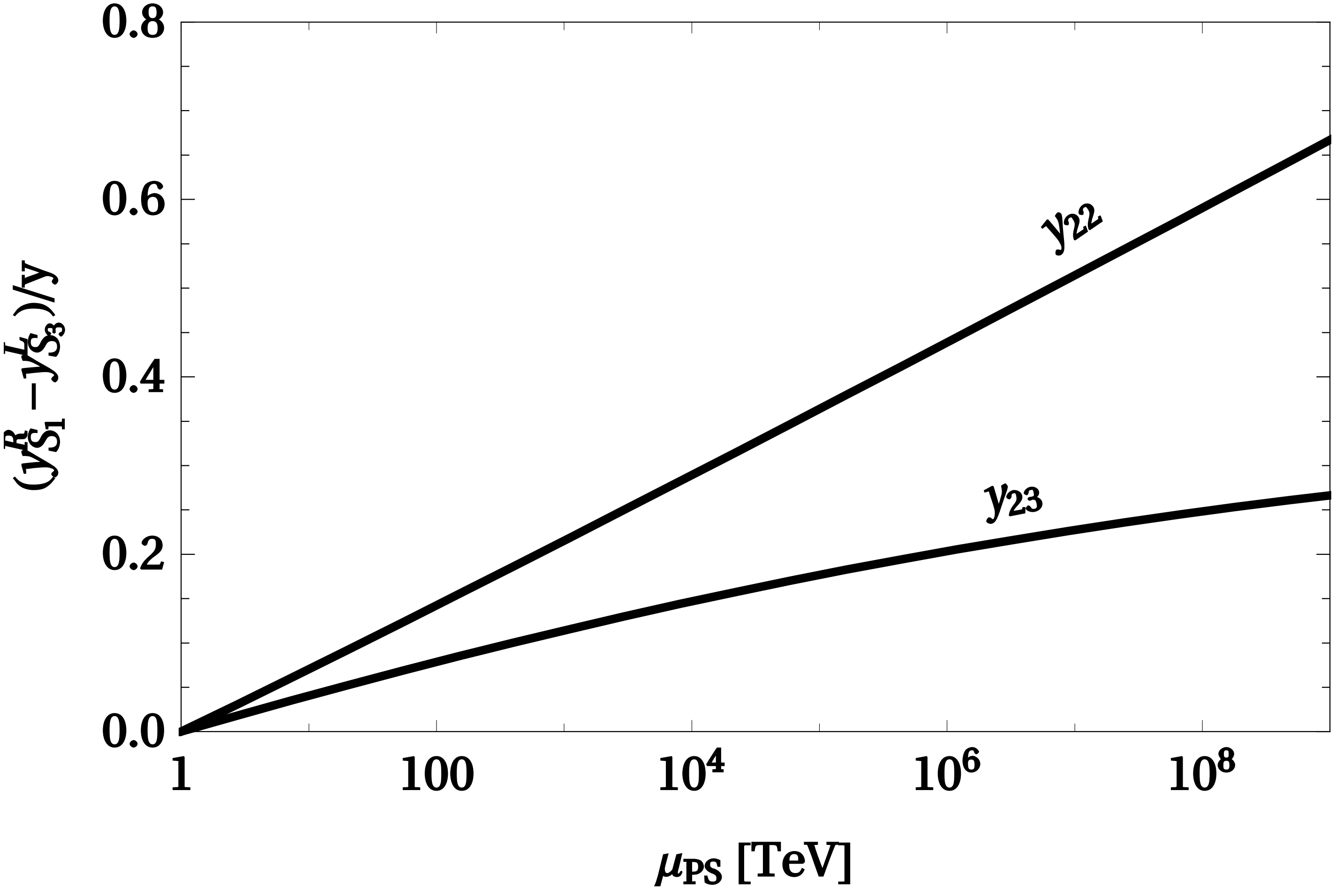
- Adding $\underbrace{(\mathbf{15}, \mathbf{2}, \mathbf{2})}$ gives freedom (4HDM) and R_2 LQs.

$$(\mathbf{1},\mathbf{2})_{\frac{1}{2}} \oplus (\mathbf{1},\mathbf{2})_{-\frac{1}{2}} \oplus (\mathbf{3},\mathbf{2})_{\frac{1}{6}} \oplus (\bar{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}} \oplus (\mathbf{3},\mathbf{2})_{\frac{7}{6}} \oplus (\bar{\mathbf{3}},\mathbf{2})_{-\frac{7}{6}} \oplus (\mathbf{8},\mathbf{2})_{\frac{1}{2}} \oplus (\mathbf{8},\mathbf{2})_{-\frac{1}{2}}$$

[**JH**, Teresi, 1808.07492]

RGEs

- The Pati-Salam relations $y = y^T$ and $y_L = y_R$ are broken!
- RGEs depend strongly on all other particle masses.
- Heavy N_R:



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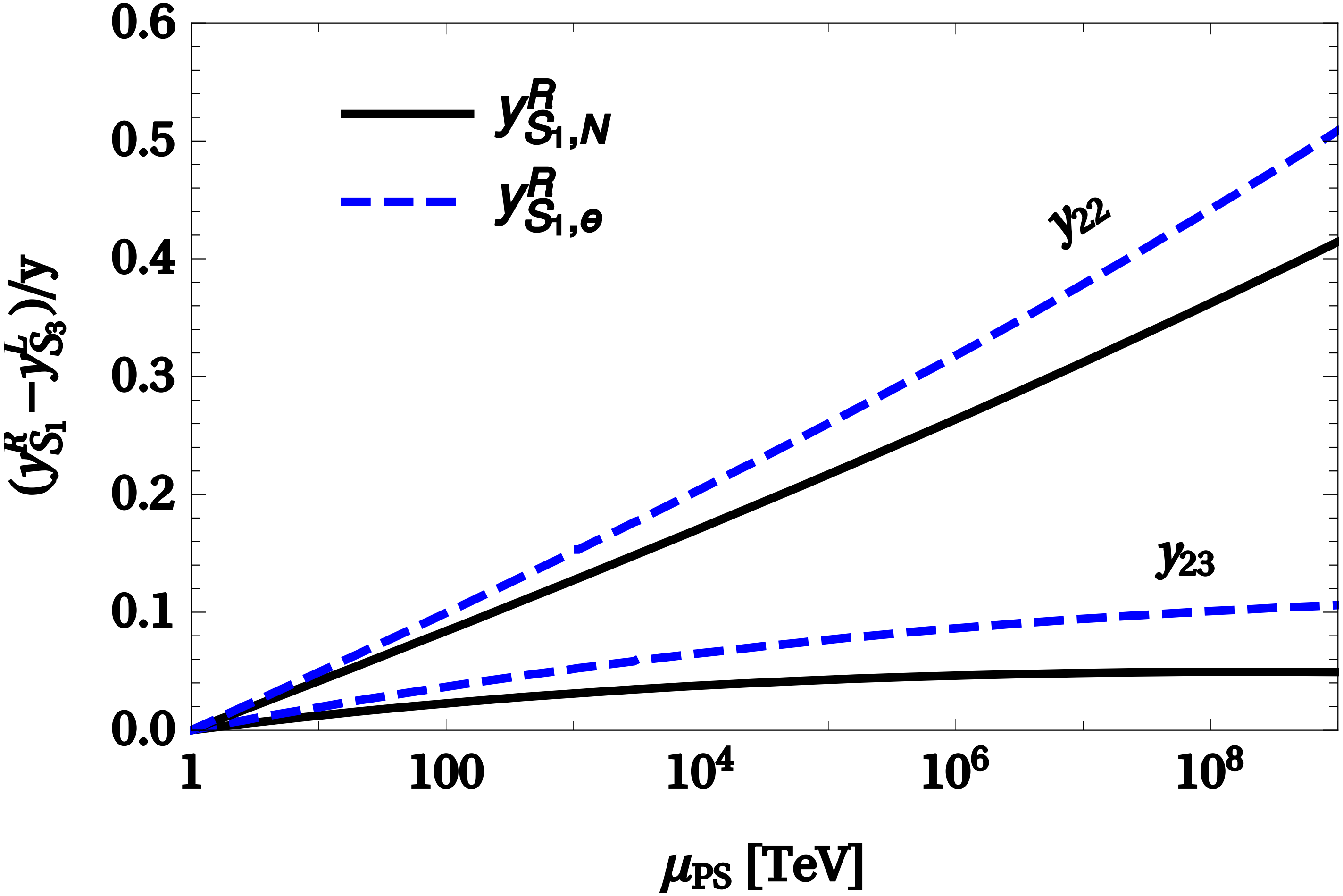

[**JH**, Teresi, 1808.07492]

Unification

- Parity requires $g_L = g_R$ at the PS scale. Possible?
- RGEs depend strongly on all other particle masses.
- Lowest order: $\frac{3}{5}\,\alpha_L^{-1}(\mu_{\rm PS}) = \alpha_1^{-1}(\mu_{\rm PS}) - \frac{2}{5}\alpha_C^{-1}(\mu_{\rm PS})$

$\Rightarrow \mu_{\rm PS} \sim 5 \times 10^{13}\,\mathrm{GeV}$.

- More light states change this.