University of Southampton
School of Physics and Astronomy

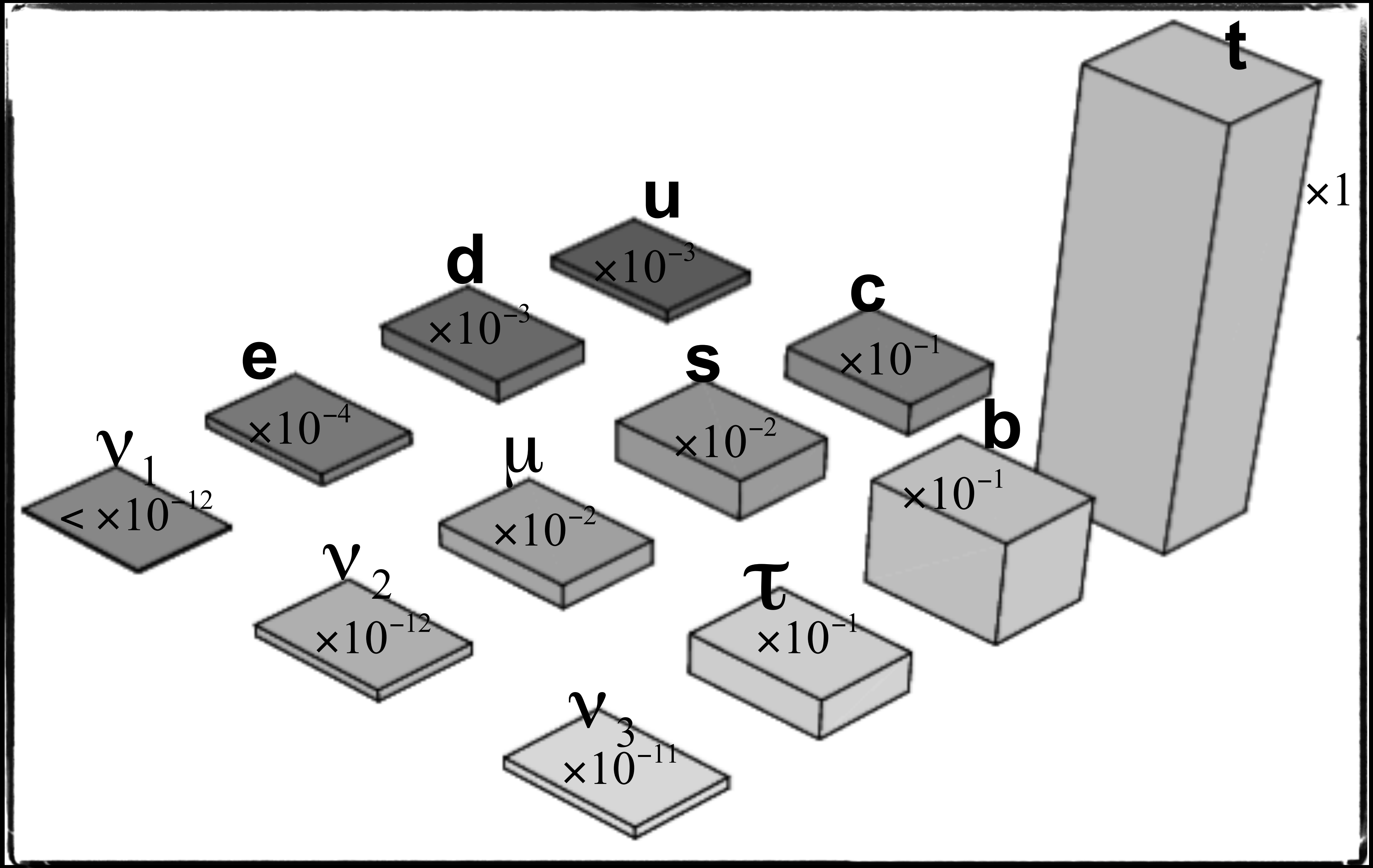
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Twin Pati-Salam Theory of Flavour with a TeV scale vector leptoquark

Based on [arXiv:2106.03876 [hep-ph]]

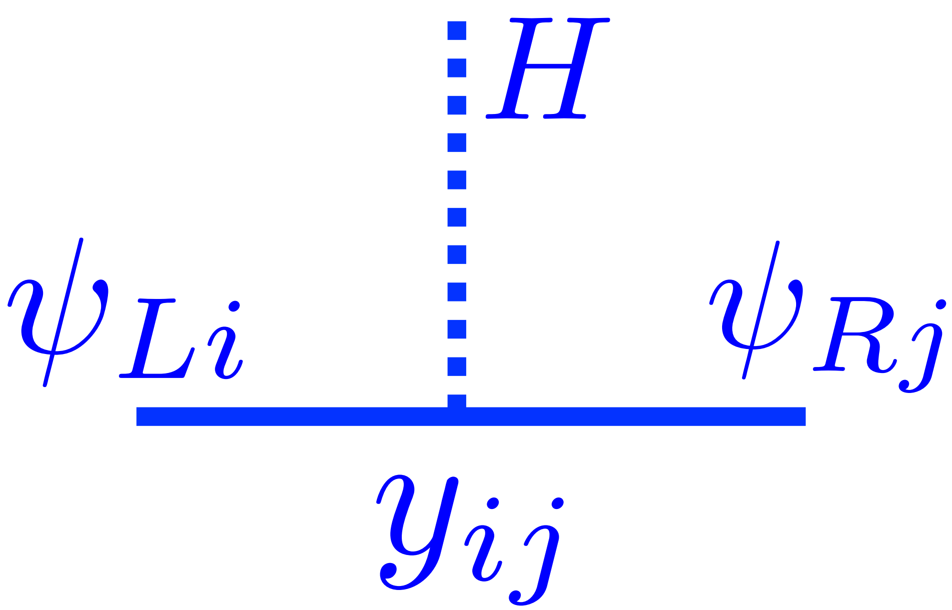
Steve King, 2nd September 2021

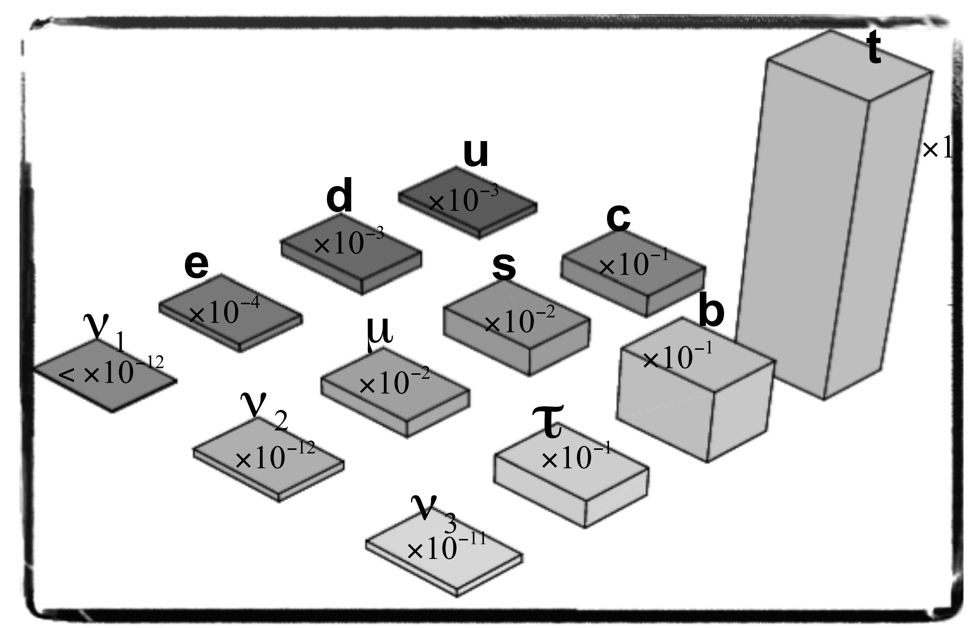
Flavour Problem



SM Yukawa couplings

$$y_{ij} H \overline{\psi}_{Li} \psi_{Rj}$$





Other flavour problems related to Lepton Flavour Universality (LFU)…

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Science & Environment

Machine finds tantalising hints of new physics

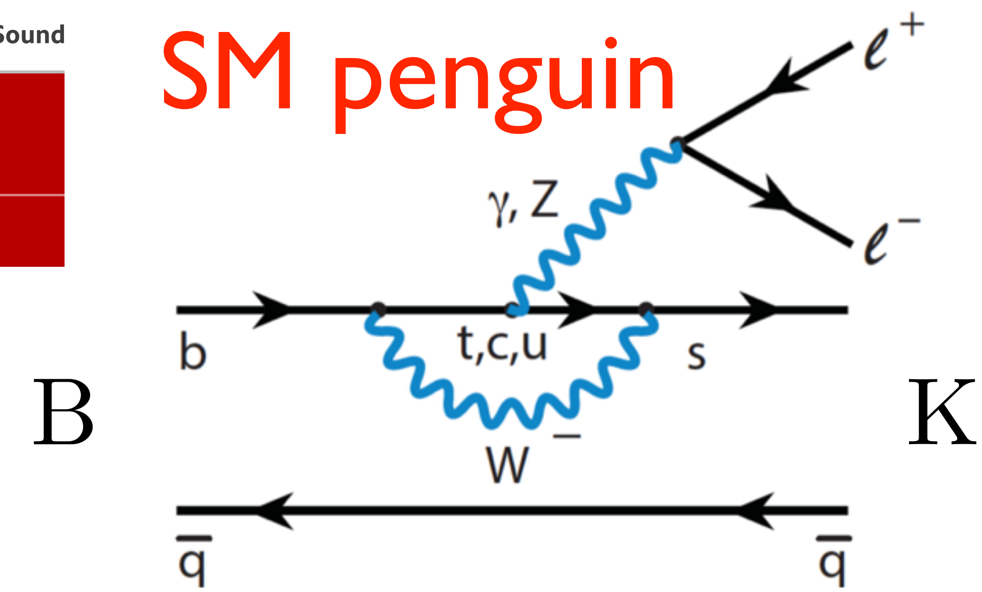
By Pallab Ghosh
Science correspondent

23 March

$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

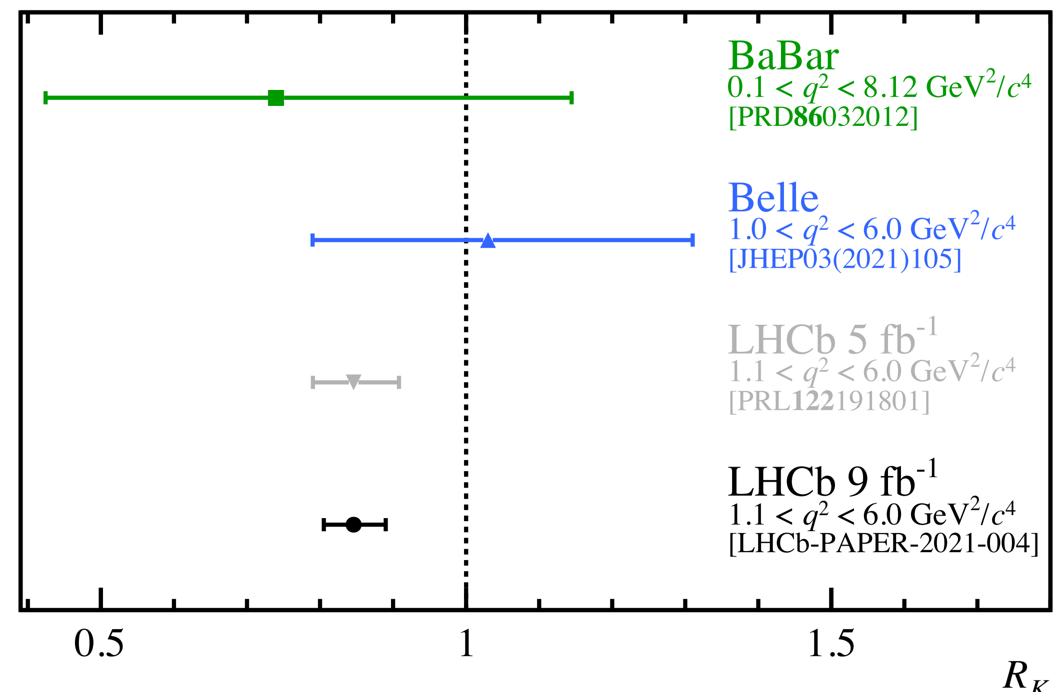
Physicists have uncovered a potential flaw in a theory that explains how the building blocks of the Universe behave.

SM penguin



$$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)} \overset{\mathrm{SM}}{\cong} 1$$

Actually use double ratio - see Monica talk



$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

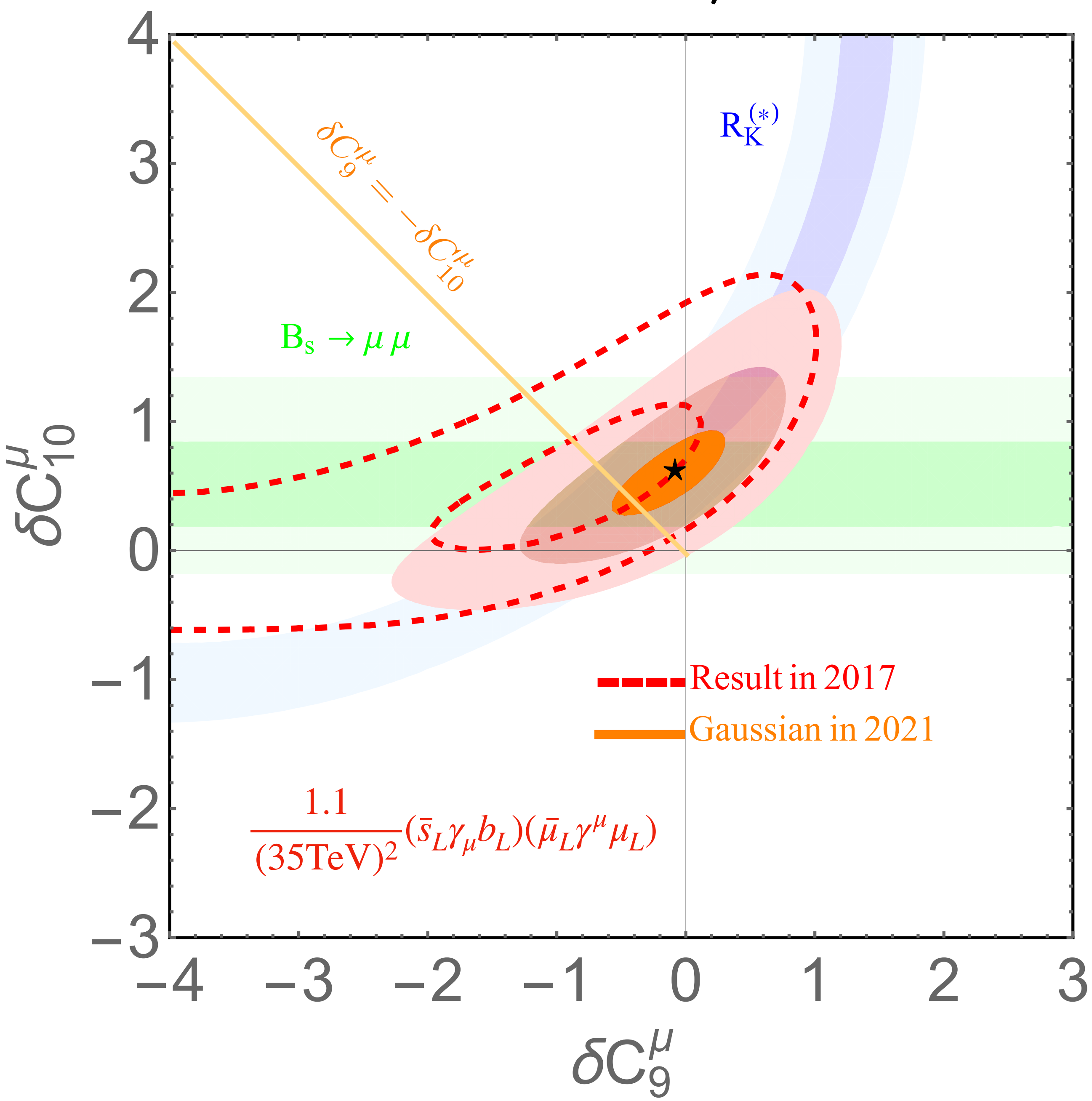
3.1σ departure from LFU!

R.Aaij et al. [LHCb], [arXiv:2103.11769]

Possible operators for R_K, R_{K^*}

$$\mathcal{L}^{\rm NP}_{b\to s\mu\mu} \supset \frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\left(\delta C^\mu_9 O^\mu_9 + \delta C^\mu_{10} O^\mu_{10}\right) + \text{h.c.}$$

L.S.Geng, B.Grinstein, S.Jager, S.Y.Li, J.M.Camalich and R.X.Shi, 2103.12738

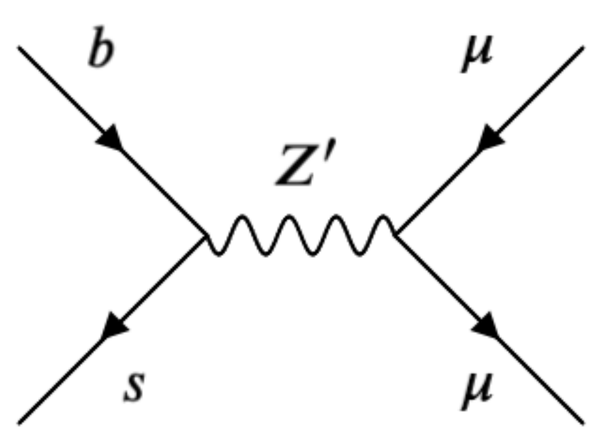


$$O^\mu_9 = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu)\,,$$

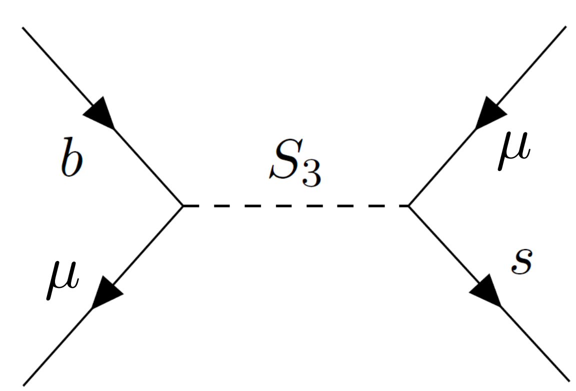
$$O^\mu_{10} = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma_5\mu)\,.$$

LH muons

$$\text{Re}\,(\delta C^\mu_9) \;=\; -\text{Re}\,(\delta C^\mu_{10})$$



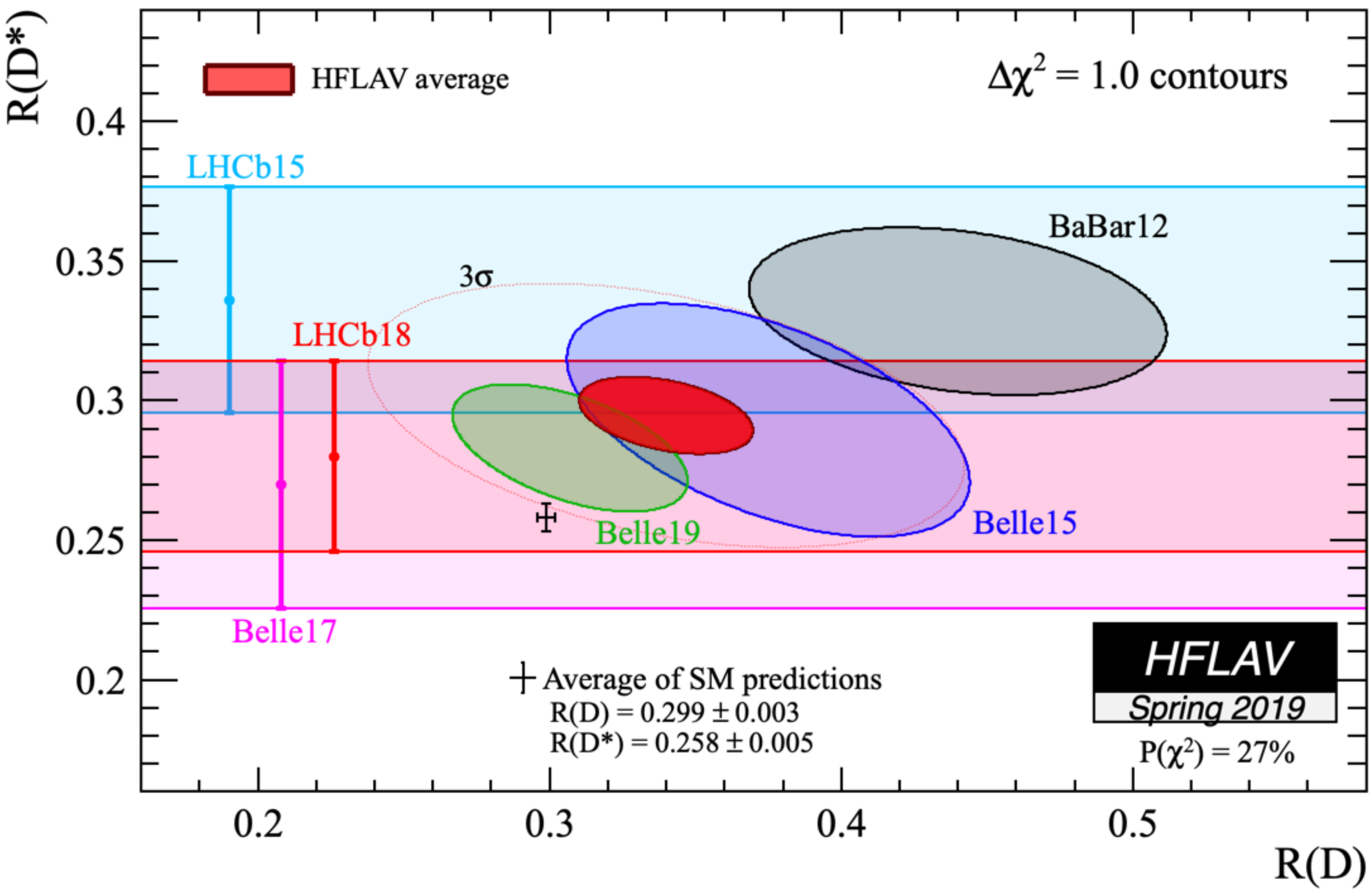
Z’



Leptoquark

b→cτν Measurements R_D, R_{D^*}

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu \Big/ B \to D^{(*)}\ell\nu$$



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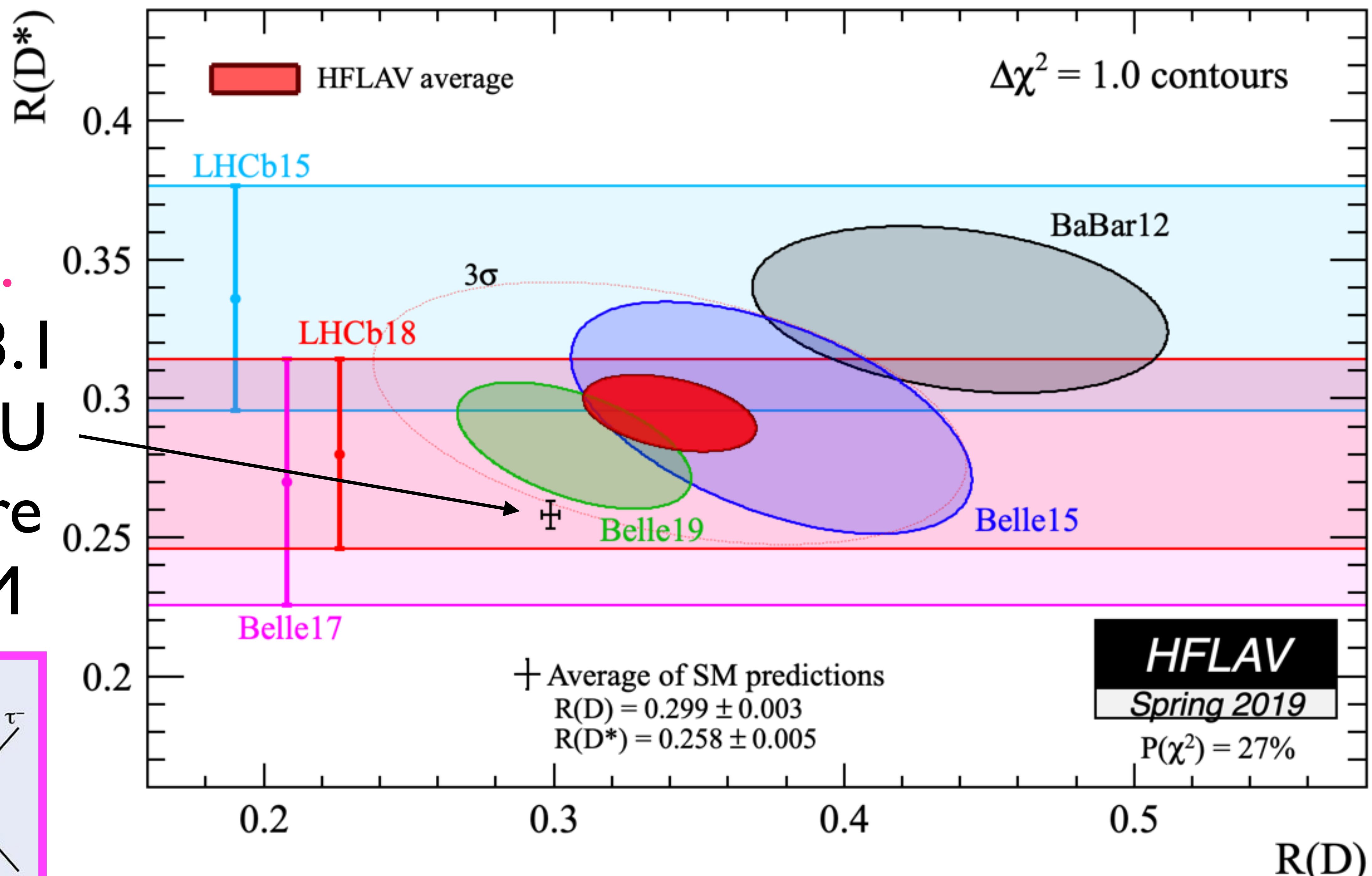
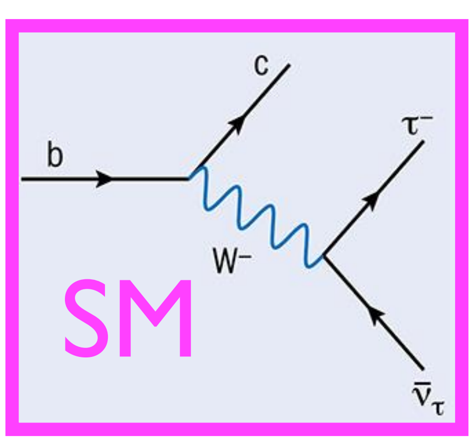


Not BBC News…

But still 3.1 sigma LFU departure from SM



Possible operators for R_D, R_{D^*}

$$O_V^L = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)(\bar{\tau}P_L\nu_\tau)$$

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \qquad O_S^L = (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau)$$

SM ⟵ New physics ⟶

$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} = 2\sqrt{2}G_F V_{cb}\left[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]$$

Possible operators for R_D, R_{D^*}

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau)$$

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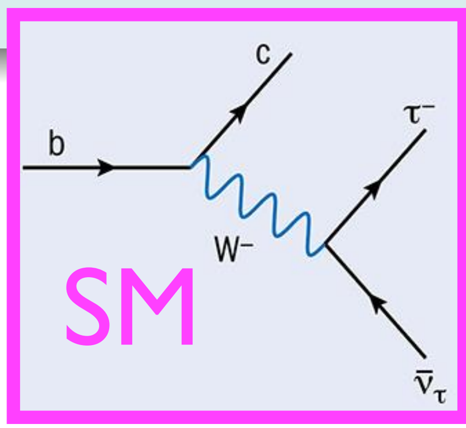

W W' Charged Higgs

Possible operators for R_D, R_{D^*}

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau)$$

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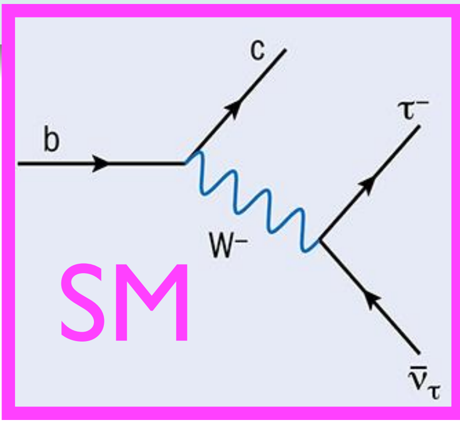
SM ⟵ New physics ⟶

$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} = 2\sqrt{2}G_F V_{cb}\left[(1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]$$



W W' Charged Higgs

Leptoquarks can contribute to all

Leptoquark scalar S1=(3,1,1/3)

Leptoquark scalar S2=(3,2,7/6)

Leptoquark scalar S3=(3,3,1/3)

Leptoquark vector U1=(3,1,2/3)

Leptoquark vector U3=(3,3,2/3)

Possible operators for R_D, R_{D^*}

$$O_V^L = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$

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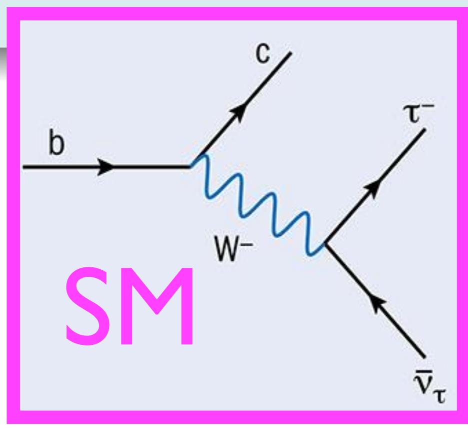
SM ← New physics →

$$\mathcal{H}_{\rm eff}^{\rm NP} = 2\sqrt{2}G_F V_{cb}\left[(1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]$$



W W' Charged Higgs

Leptoquarks can contribute to all

Leptoquark scalar S1=(3,1,1/3)

Leptoquark scalar S2=(3,2,7/6)

Leptoquark scalar S3=(3,3,1/3)

U_1 can explain both R_K and R_D → Leptoquark vector U1=(3,1,2/3)

Leptoquark vector U3=(3,3,2/3)

D.Buttazzo, A.Greljo, G.Isidori and D.Marzocca, JHEP11(2017)044 [arXiv:1706.07808].

Vector Leptoquark U_1

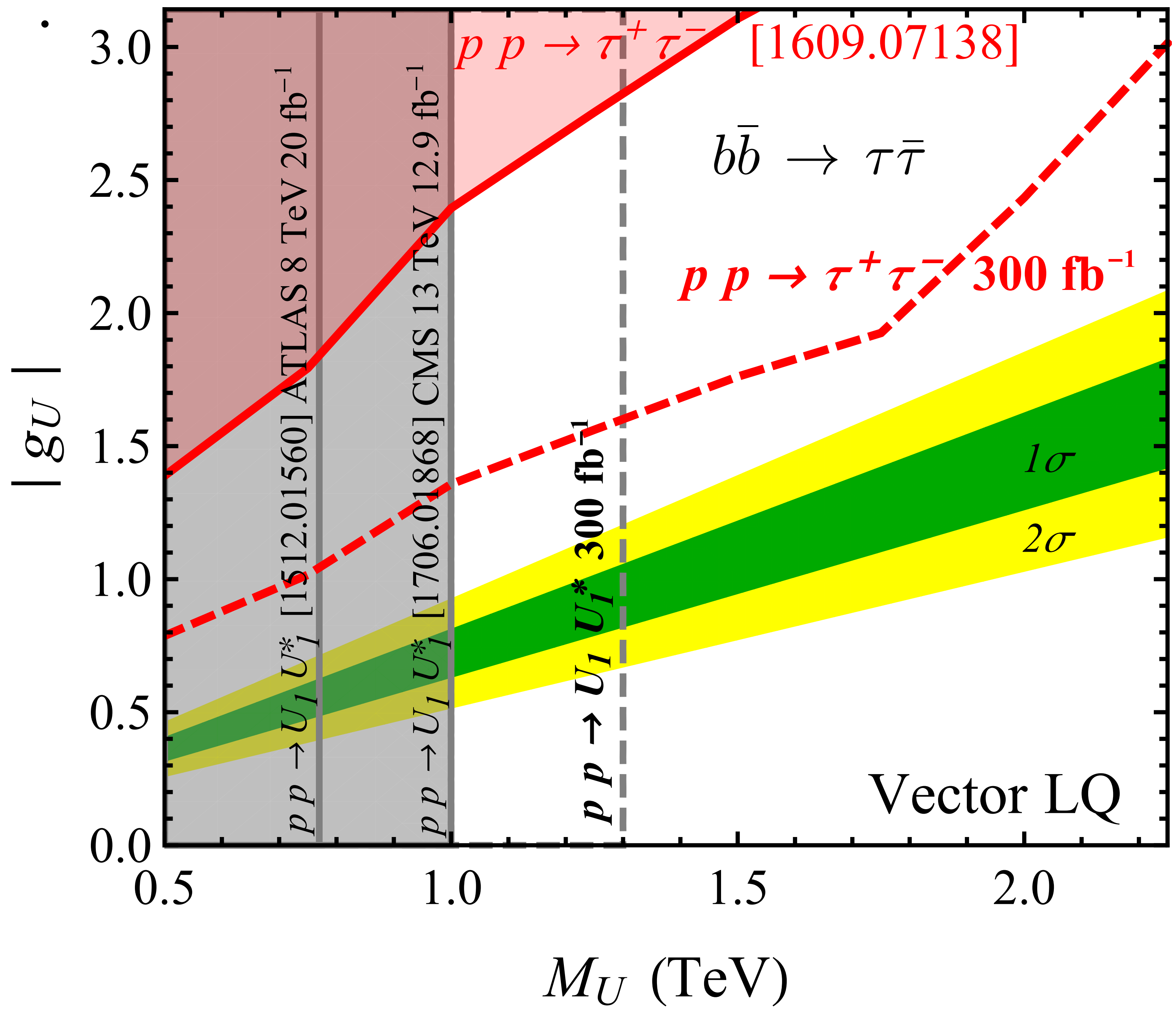
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})$$

$$J_U^\mu \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha\ .$$

LHC bound

$M_U \gtrsim 1$ TeV

$g_U \lesssim 2.5$



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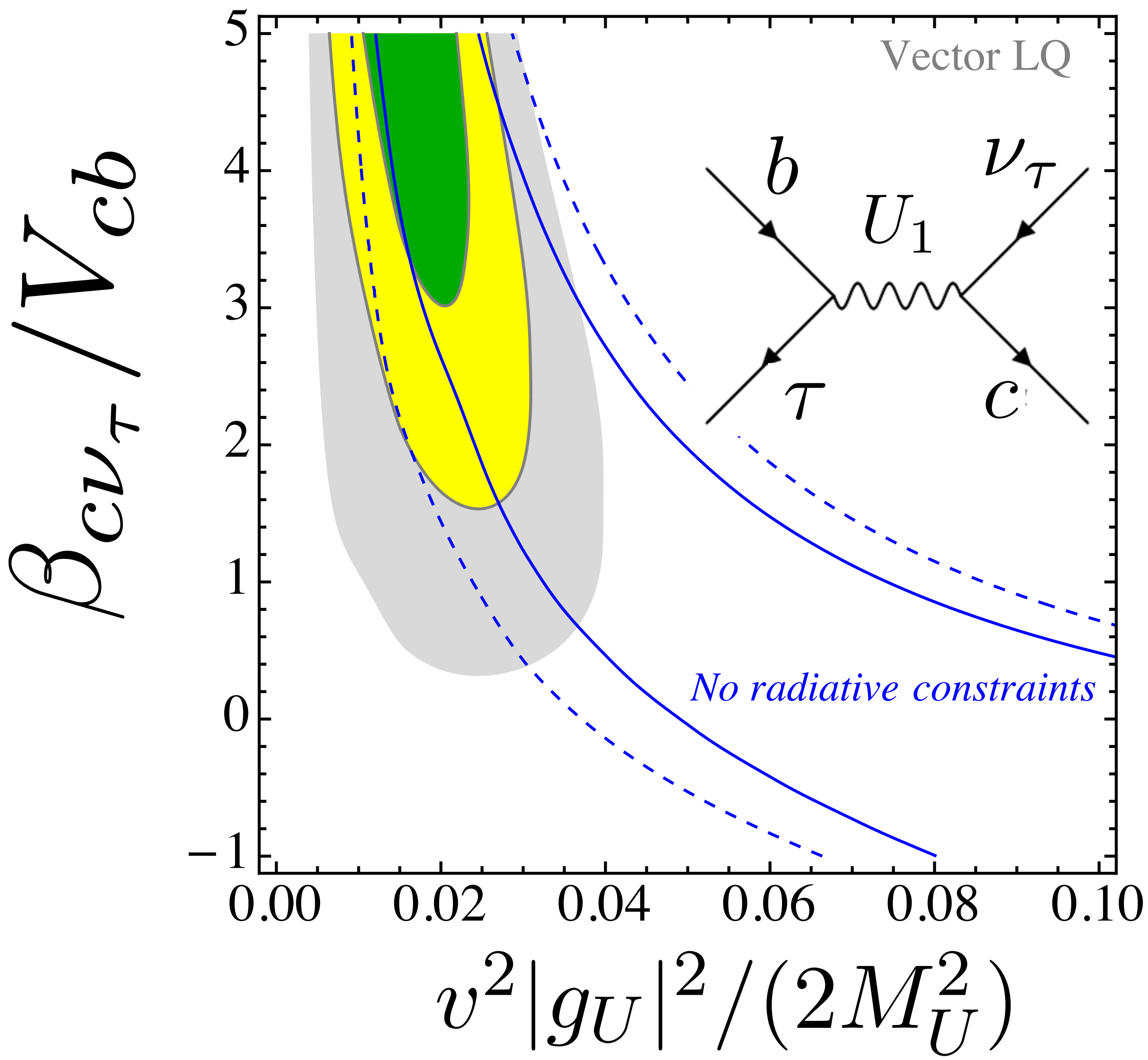
Vector Leptoquark U_1

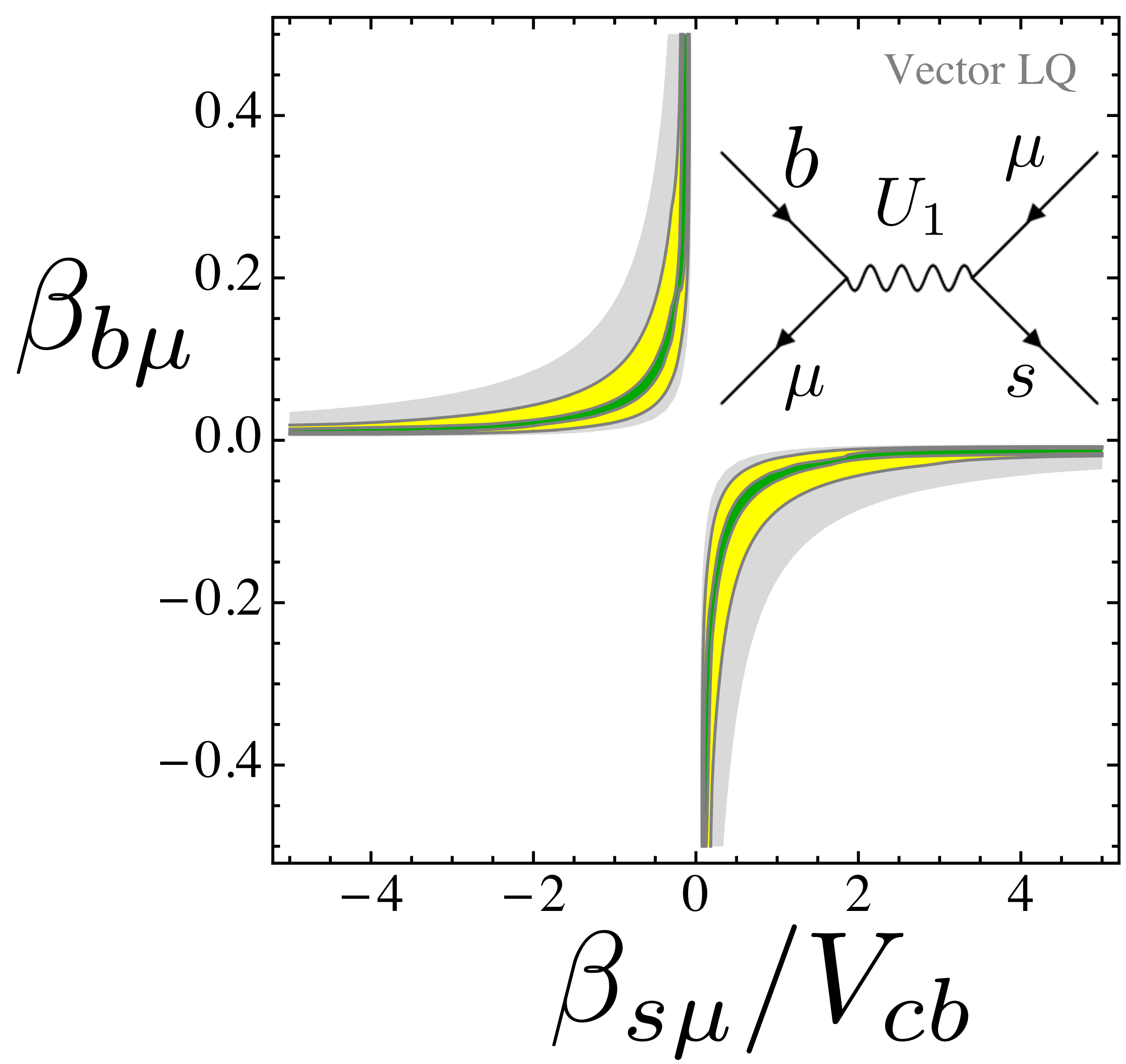
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})$$

$$J_U^\mu \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha\ .$$

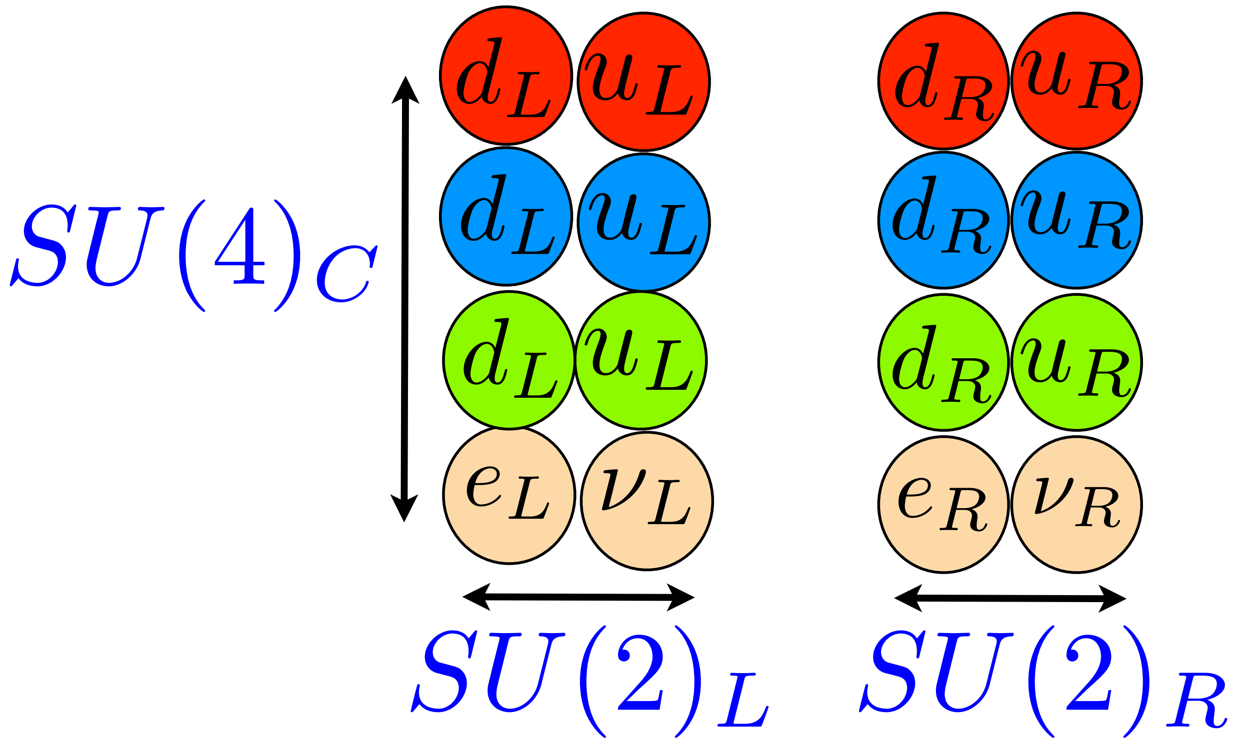
Fit to R_D



Fit to R_K

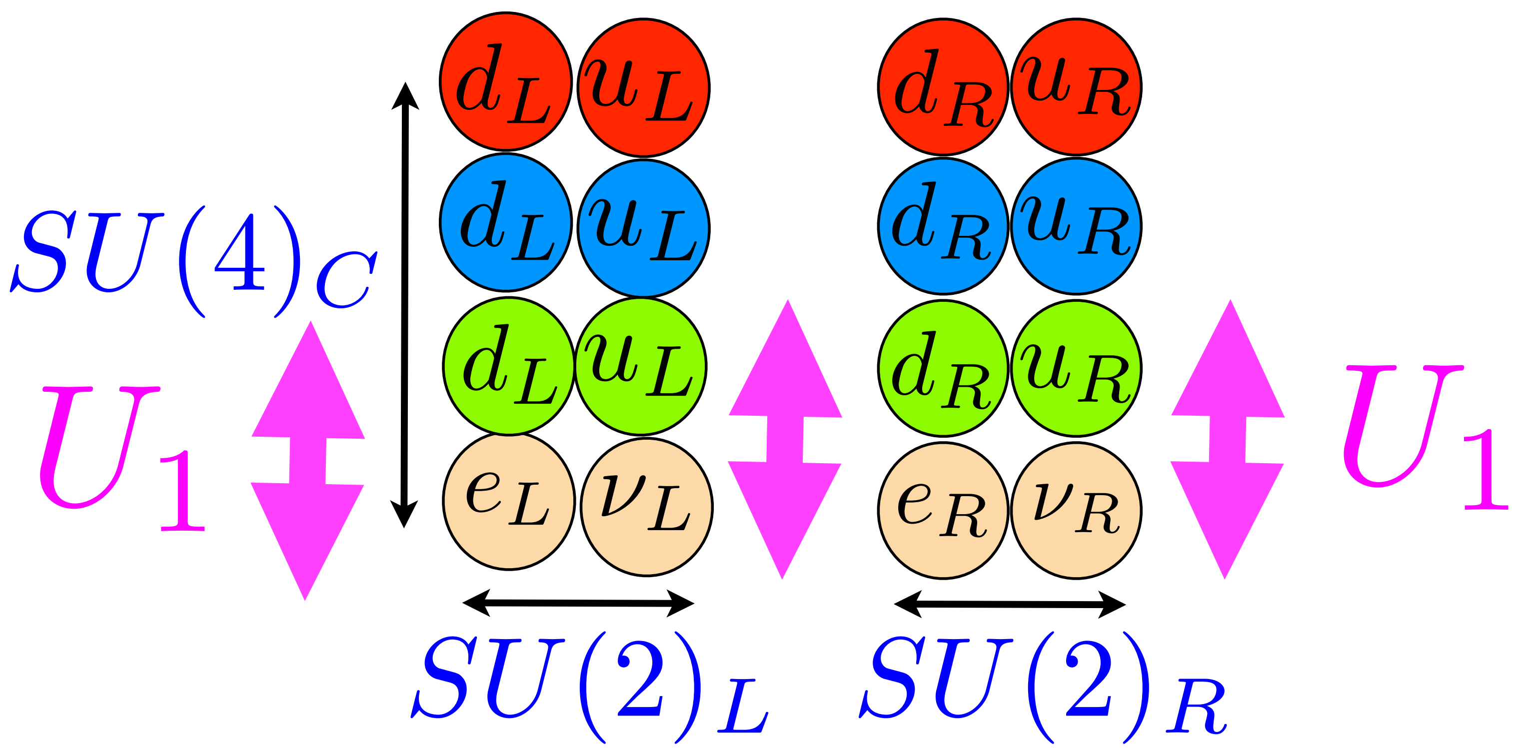


Vector Leptoquark U_1 from Pati-Salam



Quark-lepton unification
"leptons are fourth colour"

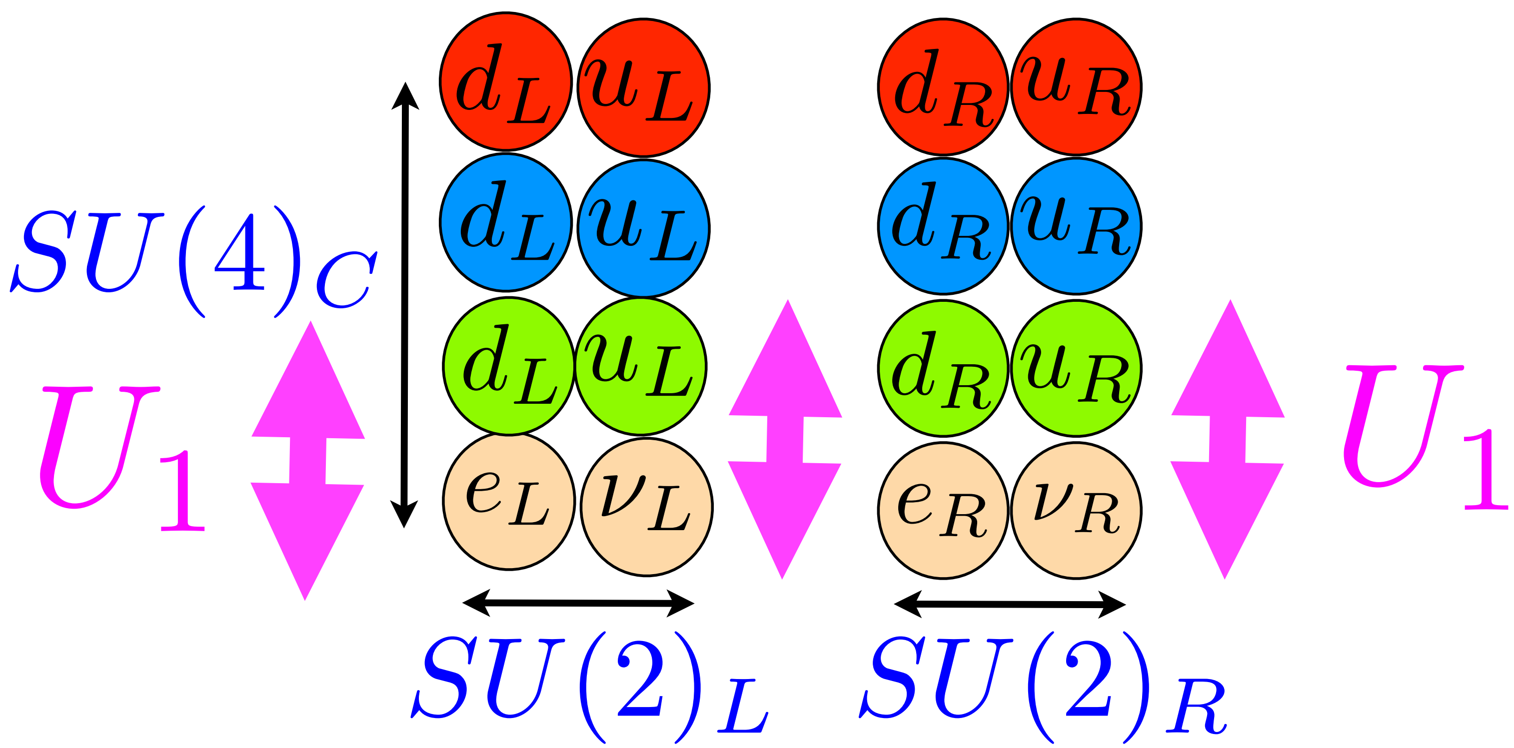
Vector Leptoquark U_1 from Pati-Salam



Quark-lepton unification "leptons are fourth colour"

U_1 can explain both R_K and R_D for 1 TeV mass

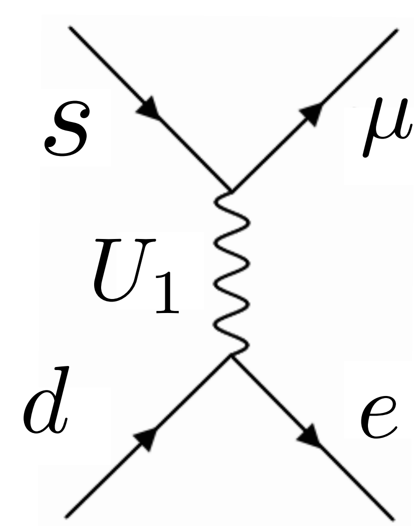
Vector Leptoquark U₁ from Pati-Salam



Quark-lepton unification
"leptons are fourth colour"

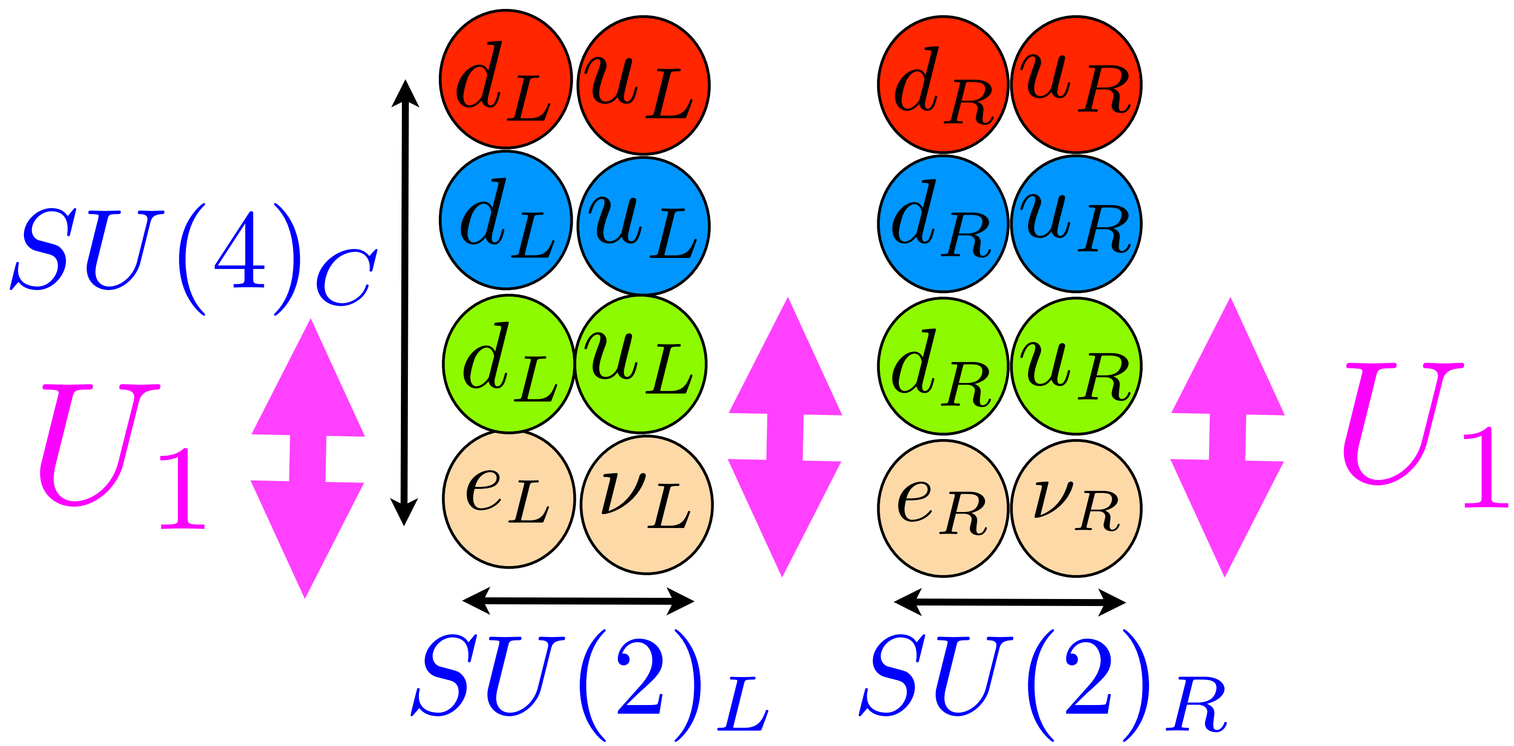
U₁ can explain both R_K and R_D for 1 TeV mass

But TeV mass not allowed due to $K_L \to \mu e$



$$M_{U_1} \gtrsim 1 \text{ PeV}$$

Vector Leptoquark U_1 from Pati-Salam

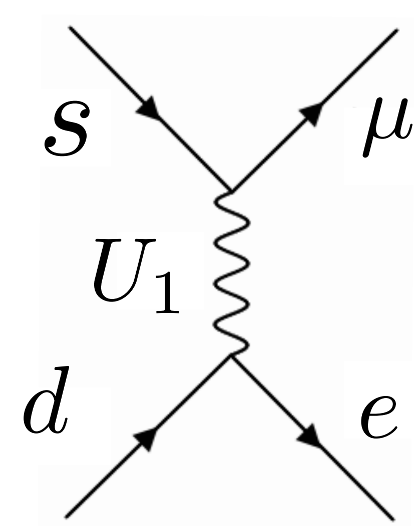


Quark-lepton unification
"leptons are fourth colour"

U_1 can explain both R_K and R_D for 1 TeV mass

But TeV mass not allowed due to $K_L \to \mu e$

Difficult to reconcile in a UV complete PS model



$M_{U_1} \gtrsim 1 \text{ PeV}$

Possible UV completions

- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + Vector-like fermions

  L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450
- $SU(4)\times U(2)_L\times SU(2)_R$ + Vector-like fermions

  L. Calibbi, AC, T. Li, arXiv:1709.00692
- $SU(4)\times SU(4)\times SU(4)$

  M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv:1712.01368
- $SU(4)\times SU(2)_L\times SU(2)_R$ including scalar LQs and light right-handed neutrinos

  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times SU(2)_L\times SU(2)_R$ in RS background

  M. Blanke, AC, arXiv:1801.07256

Possible UV completions

Andreas Crivellin

- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + Vector-like fermions

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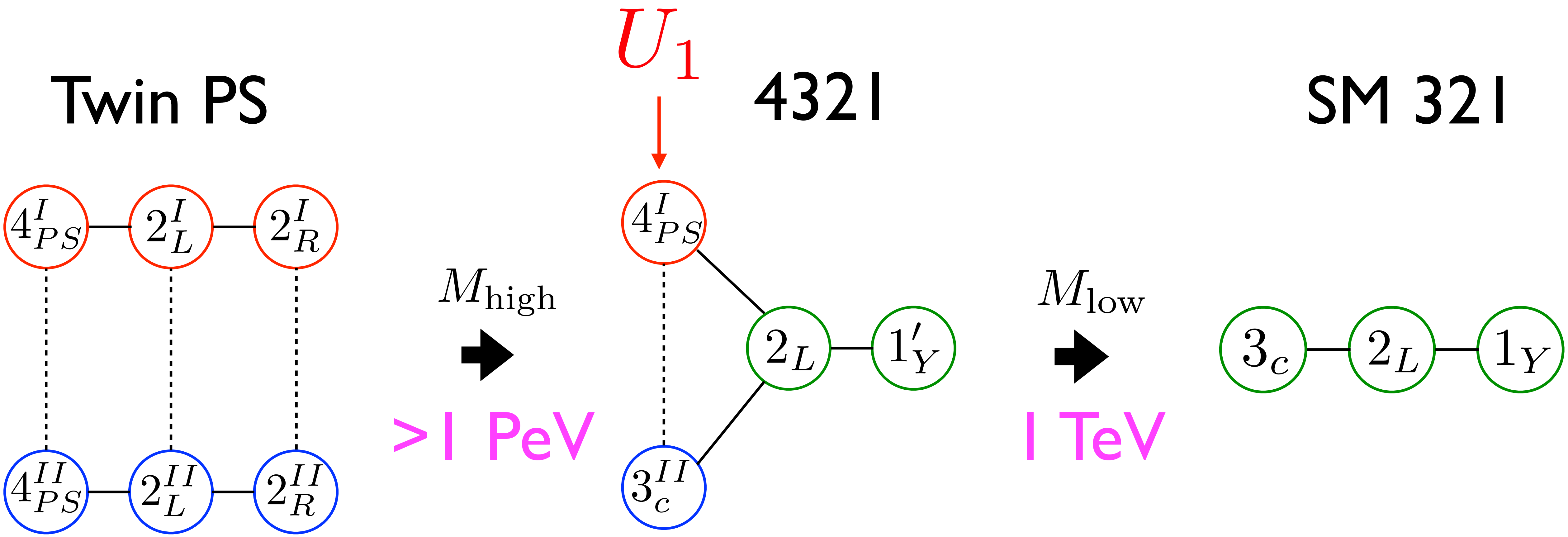
None of them attempt to explain the origin of quark and lepton masses

S.F.King, [arXiv:2106.03876]

Twin Pati-Salam

Each circle represents a gauge group



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Twin Pati-Salam

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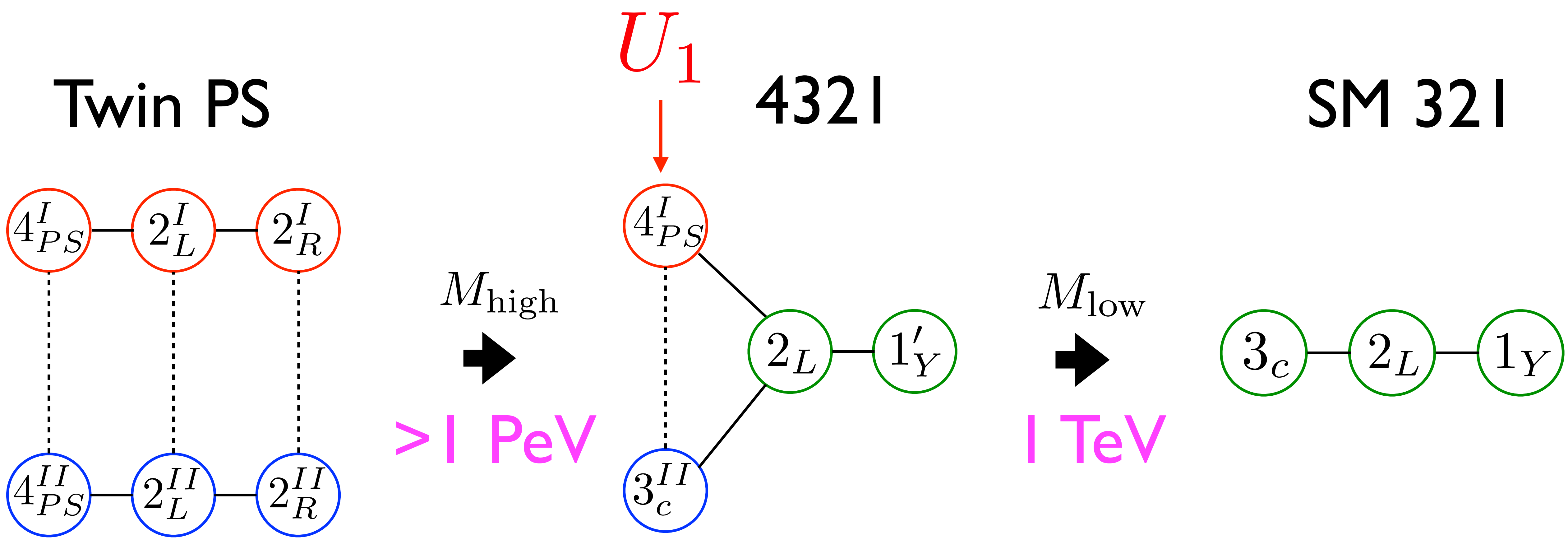


An attempt to explain the origin of fermion masses as well as RK and RD simultaneously

(N.B. Due to time limitations we ignore first family and neutrino masses in this talk - see paper for full model)

Field	$SU(4)^{I}_{PS}$	$SU(2)^{I}_{L}$	$SU(2)^{I}_{R}$	$SU(4)^{II}_{PS}$	$SU(2)^{II}_{L}$	$SU(2)^{II}_{R}$
$\psi_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
$\psi^{c}_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$

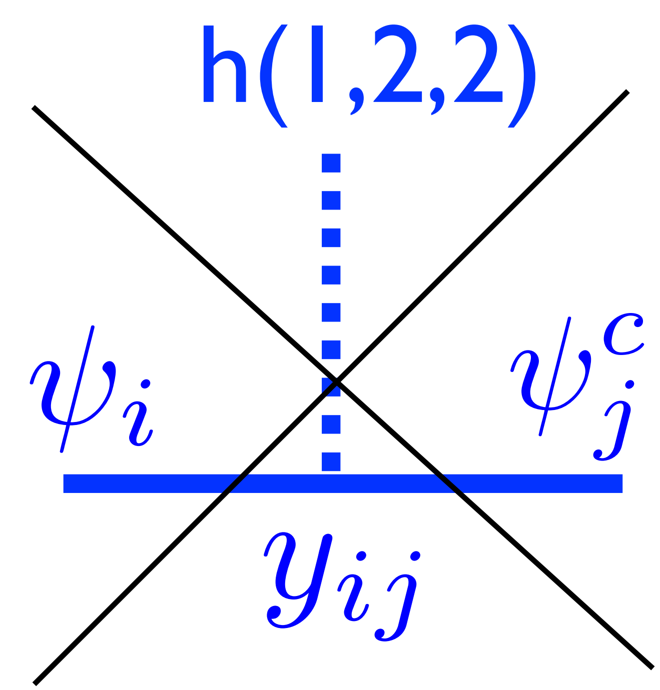
3 chiral families under second group do not couple to U_1

Field	$SU(4)^I_{PS}$	$SU(2)^I_L$	$SU(2)^I_R$	$SU(4)^{II}_{PS}$	$SU(2)^{II}_L$	$SU(2)^{II}_R$
$\psi_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
$\psi^c_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$
ψ_4	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi_4}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
ψ^c_4	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi^c_4}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

4th vector-like family under first group couple to U_1

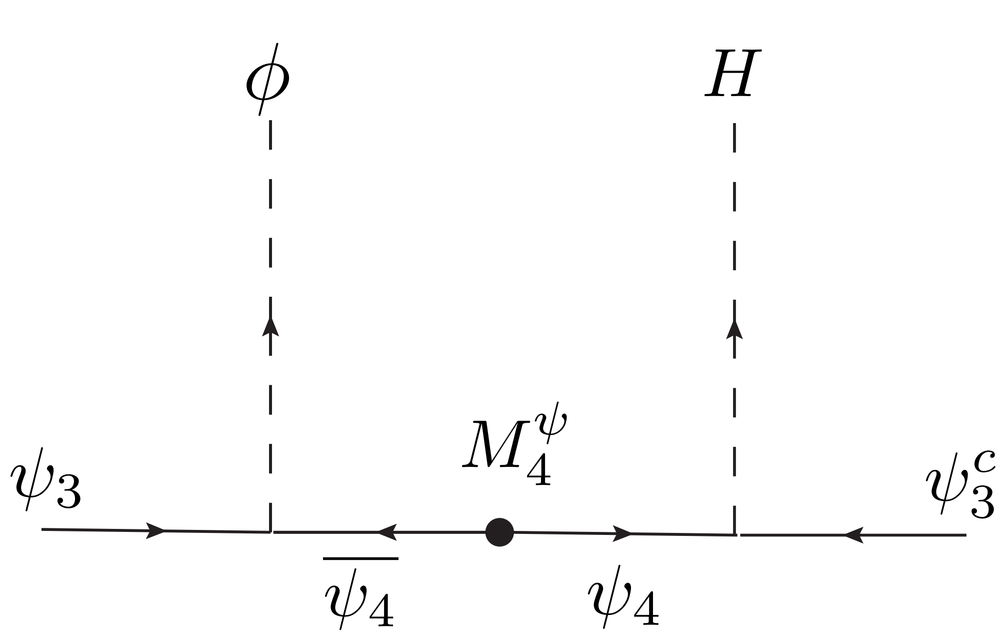
Field	$SU(4)^I_{PS}$	$SU(2)^I_L$	$SU(2)^I_R$	$SU(4)^{II}_{PS}$	$SU(2)^{II}_L$	$SU(2)^{II}_R$
$\psi_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
$\psi^c_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$
ψ_4	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi_4}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
ψ^c_4	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi^c_4}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
ϕ	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$
$\overline{\phi}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
H	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
$\overline{H}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$

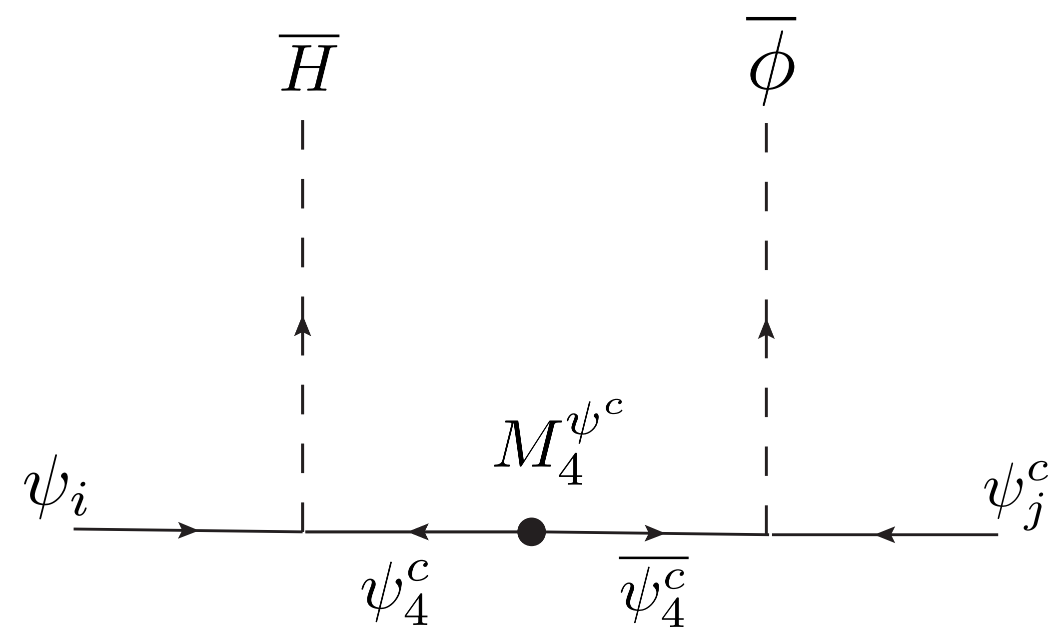
- Higgs transform under both groups and generate the mixing
- No Higgs h(1,2,2) under second group so no Yukawa coupling



Fermion Masses

Generated by mixing with vector-like family



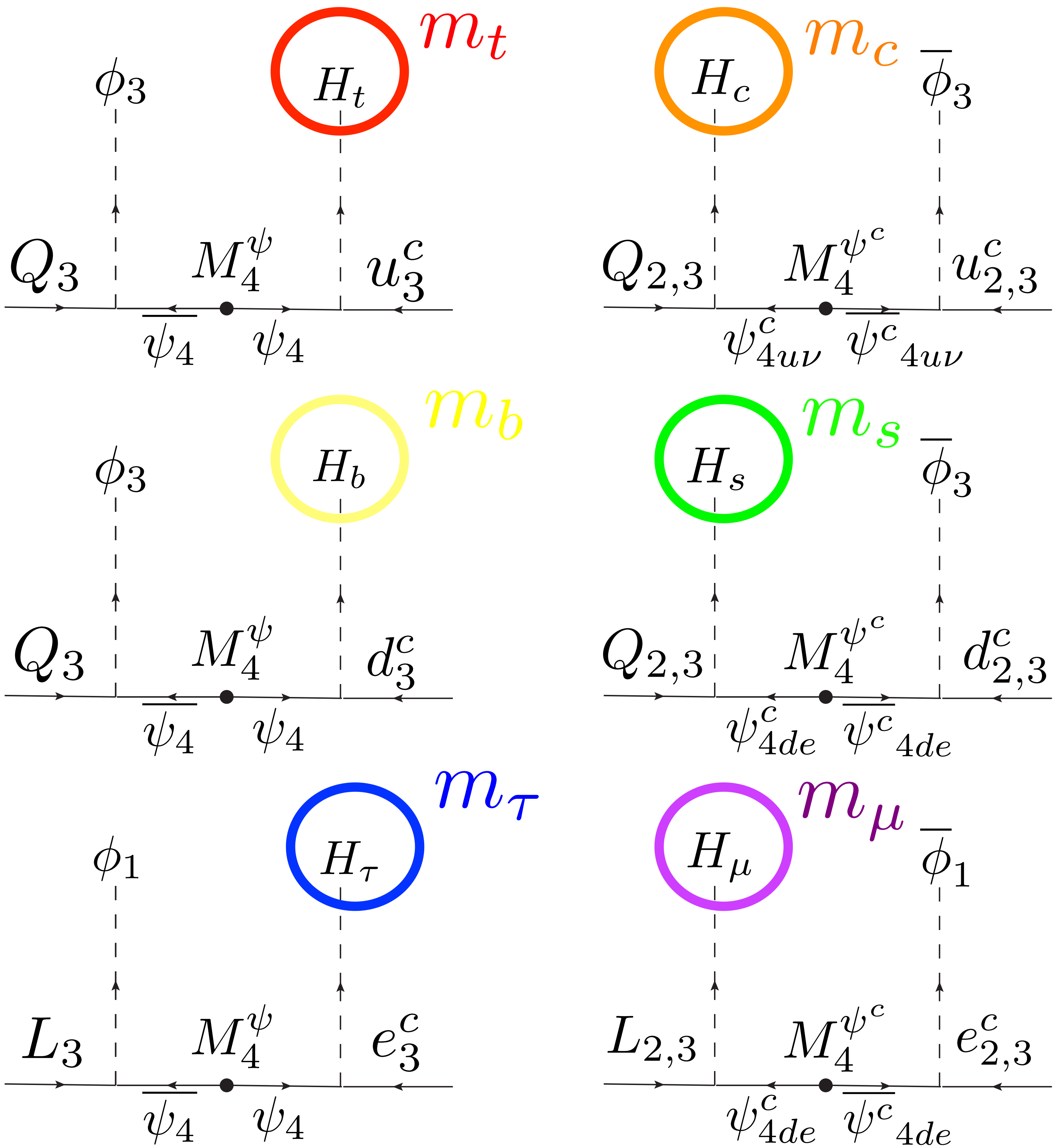


~ 1 $\qquad\qquad\qquad\qquad$ $\ll 1$

$$\mathcal{L}^{Yuk}_{4eff} = \begin{pmatrix} & \psi_1^c & \psi_2^c & \psi_3^c \\ \hline \psi_1| & 0 & 0 & 0 \\ \psi_2| & 0 & 0 & 0 \\ \psi_3| & 0 & 0 & x^{\psi}_{34} y^{\psi}_{43} \end{pmatrix} \frac{\phi}{M_4^{\psi}} H + \begin{pmatrix} & \psi_1^c & \psi_2^c & \psi_3^c \\ \hline \psi_1| & 0 & 0 & 0 \\ \psi_2| & 0 & y^{\psi}_{24} x^{\psi^c}_{42} & y^{\psi}_{24} x^{\psi^c}_{43} \\ \psi_3| & 0 & y^{\psi}_{34} x^{\psi^c}_{42} & y^{\psi}_{34} x^{\psi^c}_{43} \end{pmatrix} \frac{\overline{\phi}}{M_4^{\psi^c}} \overline{H}$$

3rd family $\qquad\qquad$ 23 block

Under 4321 have a personal Higgs for each mass



$$M_u \sim \begin{pmatrix} 0 & & \\ & m_c & m_c \\ & m_c & m_t \end{pmatrix}$$

$$M_d \sim \begin{pmatrix} 0 & & \\ & m_s & m_s \\ & m_s & m_b \end{pmatrix}$$

$$M_e \sim \begin{pmatrix} 0 & & \\ & m_\mu & m_\mu \\ & m_\mu & m_\tau \end{pmatrix}$$

4321 phenomenology

$$\frac{g_4}{\sqrt{2}} \left(\bar{Q}_{L4}\gamma^{\mu}L_{L4} + \text{H.c.}\right) U_{1\mu}$$

Vector Leptoquark

4321 phenomenology

no couplings to chiral quarks and leptons

$$\frac{g_4}{\sqrt{2}}\left(\bar{Q}_{L4}\gamma^{\mu}L_{L4} + \text{H.c.}\right)U_{1\mu}$$

Vector Leptoquark

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Vector Leptoquark

$$+\frac{g_4 g_s}{g_3}\left(\bar{Q}_{L4}\gamma^\mu T^a Q_{L4} - \frac{g_3^2}{g_4^2}\,\bar{Q}_{Li}\gamma^\mu T^a Q_{Li}\right) g'^{a}_\mu$$

coloron

Z'

$$+\frac{\sqrt{3}\,g_4 g_Y}{\sqrt{2}\,g_1}\left(\frac{1}{6}\bar{Q}_{L4}\gamma^\mu Q_{L4} - \frac{1}{2}\bar{L}_{L4}\gamma^\mu L_{L4} - \frac{g_1^2}{9g_4^2}\,\bar{Q}_{Li}\gamma^\mu Q_{Li} + \frac{g_1^2}{3g_4^2}\,\bar{L}_{Li}\gamma^\mu L_{Li}\right) Z'_\mu$$

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suppressed couplings to chiral quarks and leptons

4321 phenomenology

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suppressed couplings to chiral quarks and leptons

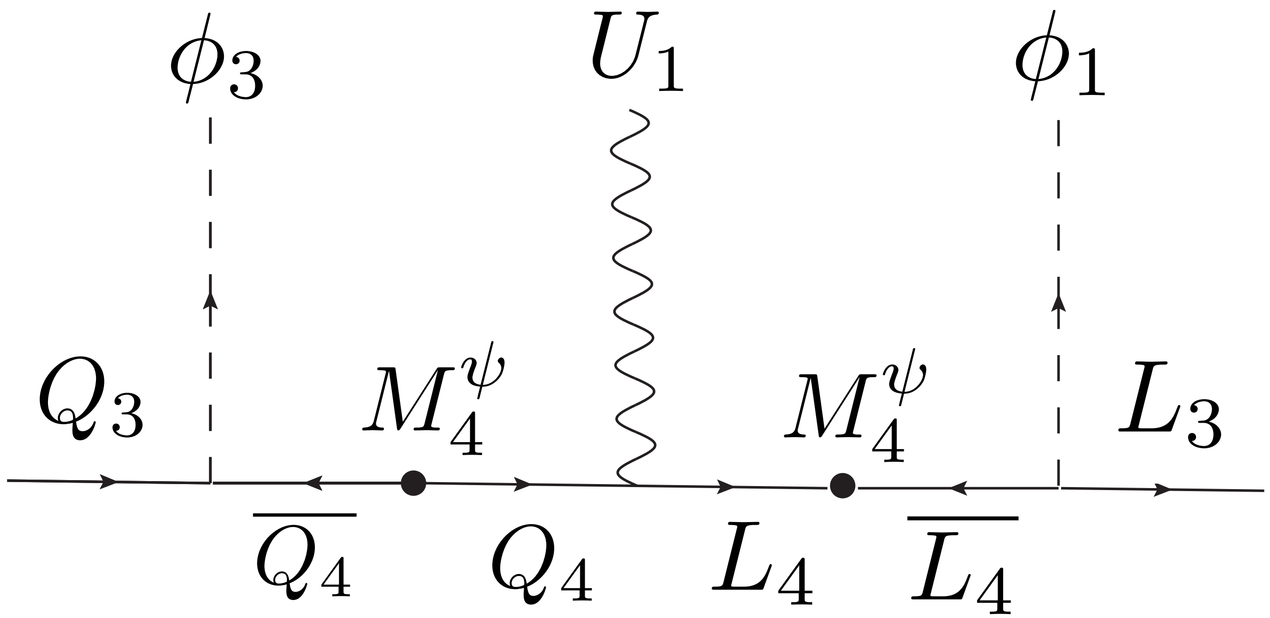
Typical Benchmark

TeV masses

$$g_4 \approx 3,\ g_3 \approx g_s \approx 1,\ g_1 \approx g_Y \approx 0.36,$$

$$M_{Z'} \approx 1.4\ \text{TeV}, \quad M_{U_1} \approx 1.6\ \text{TeV}, \ M_{g'} \approx 2.0\ \text{TeV}$$

Effective Vector Leptoquark U1 couplings



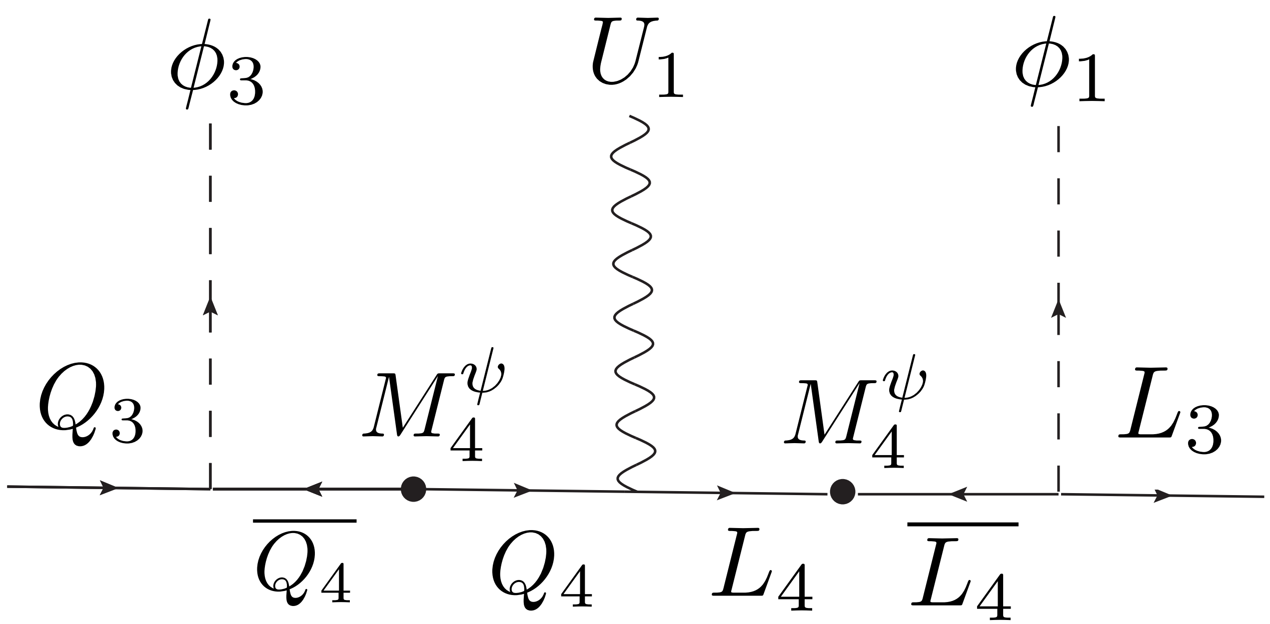
Mixing generates couplings to chiral quarks and leptons

Third family only

$$\frac{g_4}{\sqrt{2}} \frac{x_{34}^\psi \langle \phi_1 \rangle}{M_4^\psi} \frac{x_{34}^\psi \langle \phi_3 \rangle}{M_4^\psi} \bar{Q}_{L3} \gamma^\mu L_{L3} U_{1\mu} \quad \equiv g_U \bar{Q}_{L3} \gamma^\mu L_{L3} U_{1\mu}$$

After diagonalising mass matrices $\rightarrow g_U \beta_{i\alpha} \bar{Q}_{Li} \gamma^\mu L_{L\alpha} U_{1\mu}$

Effective Vector Leptoquark U₁ couplings



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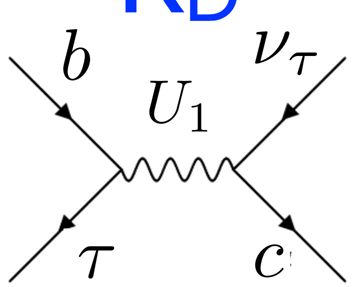
R_D

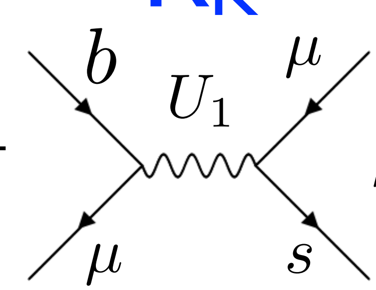
$\beta_{b\tau} \sim 1$



$\beta_{c\nu_\tau} \sim \frac{m_c}{m_t}$

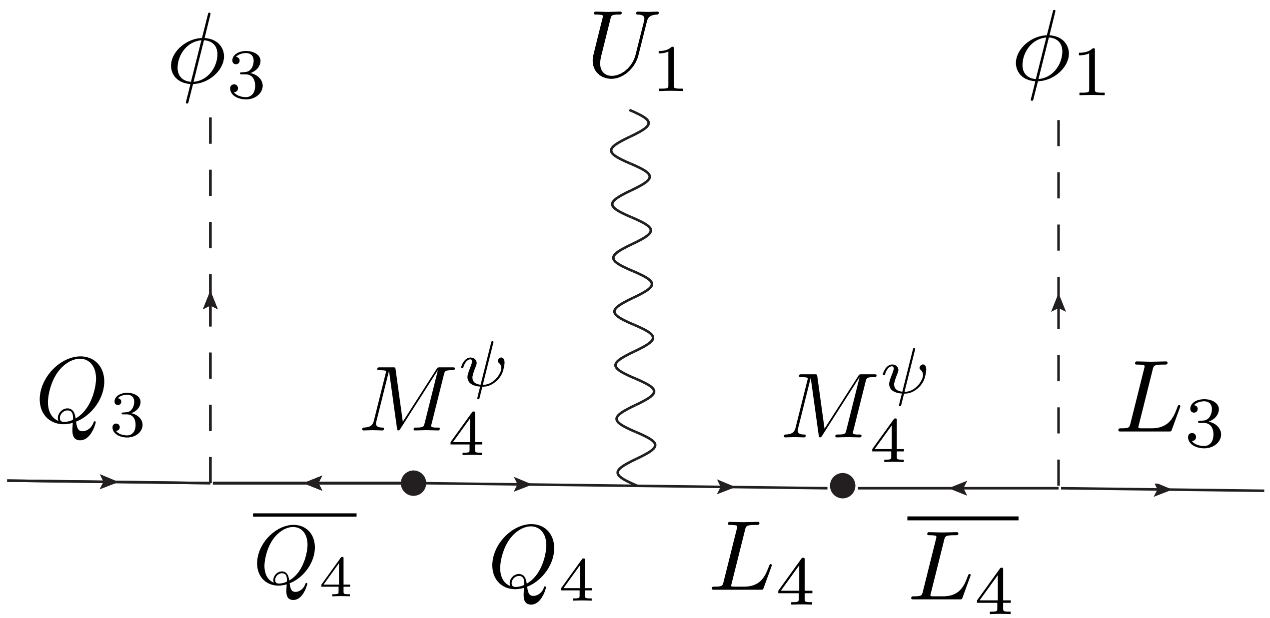
R_K

$\beta_{b\mu} \sim \frac{m_\mu}{m_\tau}$



$\beta_{s\mu} \sim \frac{m_\mu}{m_\tau} \frac{m_s}{m_b}$

Effective Vector Leptoquark U₁ couplings



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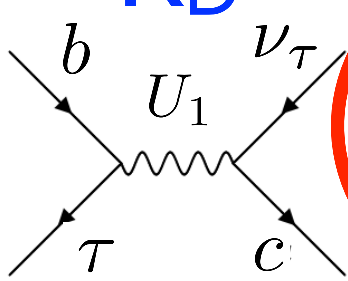
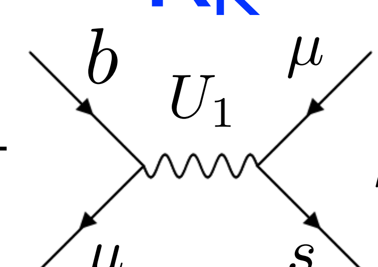


~ 0.007

$\beta_{c\nu_\tau} \sim \frac{m_c}{m_t}$

R_K

$\beta_{b\mu} \sim \frac{m_\mu}{m_\tau}$



$\beta_{s\mu} \sim \frac{m_\mu}{m_\tau} \frac{m_s}{m_b}$

Too small c.f. R_D best fit value $\beta_{c\nu_\tau} \sim 4V_{cb} \sim 0.16$

Conclusion

- Fermion mass and mixing is a great mystery of SM, which may be related to recent B physics anomalies
- R_K and R_D anomalies may be simultaneously explained by TeV scale vector leptoquark U_1 from Pati-Salam
- Pati-Salam usually broken above PeV to avoid FCNCs so this requires non-trivial UV completion
- The twin PS model yields a TeV scale vector leptoquark **and** explains fermion masses (usually not addressed)
- But the predicted mass matrices do not yield large enough couplings to explain R_D given the current data