University of Southampton
School of Physics and Astronomy

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Unified Theories of Flavour

Steve King,

1st September 2022

EISA
European Institute for Sciences and Their Applications

Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece


Aspen, Colorado in 1997

At Aspen, where we were collaborating on our first paper on “Strong Unification”

At Graham’s retirement fest in Oxford

P. Ramond, R.G. Roberts and G.G.Ross, Nucl. Phys. B406 (1993)

Stitching the Yukawa Quilt

Graham favoured the symmetric matrices

$$Y^u \propto \begin{pmatrix} 0 & \epsilon^3 & O(\epsilon^3) \\ . & \epsilon^2 & O(\epsilon^2) \\ . & . & 1 \end{pmatrix}, \quad Y^d \propto \begin{pmatrix} 0 & 1.5\bar{\epsilon}^3 & 0.4\bar{\epsilon}^3 \\ . & \bar{\epsilon}^2 & 1.3\bar{\epsilon}^2 \\ . & . & 1 \end{pmatrix}$$

"Hierarchical just like the UK"

$$\epsilon \approx 0.05, \quad \bar{\epsilon} \approx 0.15.$$

Note (1,1) texture zero and symmetric matrices leading to the successful GST relation

$$V_{us} = \sqrt{\frac{m_d}{m_s}} - \sqrt{\frac{m_u}{m_c}} e^{i\sigma}$$

"Chance to be correct"

S.F. King and G.G.Ross, Phys. Lett. B 574 (2003), [hep-ph/0307190]

SU(3) Family Symmetry and Pati-Salam Unification

Field	SU(3)	$SU(4)_{PS}$	$SU(2)_L$	$SU(2)_R$
ψ	$\mathbf{3}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
ψ^c	$\mathbf{3}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{2}$
θ	$\overline{\mathbf{3}}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
$\overline{\theta}$	$\mathbf{3}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{2}$
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
Σ	$\mathbf{1}$	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{3}$
ϕ_3	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}\oplus\mathbf{1}$
ϕ_{23}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

"Little Flavour Magnets"

$$
\begin{aligned}
P_{\rm Yuk} &\sim \frac{1}{M^2}\psi_i\phi_3^i\psi_j^c\phi_3^j H \\
&+ \frac{\Sigma}{M^3}\psi_i\phi_{23}^i\psi_j^c\phi_{23}^j H \\
&+ \frac{1}{M^5}\left((\epsilon^{ijk}\psi_i^c\overline{\phi_{23}}_j\overline{\phi_{3,k}})(\psi_l\phi_{23}^l) + (\epsilon^{ijk}\psi_i\overline{\phi_{23}}_j\overline{\phi_{3,k}})(\psi_l^c\phi_{23}^l)\right) H(\phi_{23}^m\overline{\phi}_{3,m}) \\
&+ \frac{1}{M^5}(\epsilon^{ijk}\psi_i^c\overline{\phi_{23}}_j\psi_k)H(\phi_{23}^l\overline{\phi}_{3,l})^2 + \frac{1}{M^5}(\epsilon^{ijk}\psi_i^c\overline{\phi_3}_j\psi_k)H(\phi_{23}^l\overline{\phi}_{23,l})(\phi_{23}^m\overline{\phi}_{3,m}) \\
&+ \frac{1}{M^4}\left(\psi_i\phi_{23}^i\psi_j^c\phi_3^j + \psi_i\phi_3^i\psi_j^c\phi_{23}^j\right) H.S \\
P_{\rm Maj} &\sim \frac{1}{M}\psi_i^c\theta^i\theta^j\psi_j^c \\
&+ \frac{1}{M^{11}}\psi_i^c\phi_{23}^i\psi_j^c\phi_{23}^j(\theta^k\overline{\phi_{23,k}})(\theta^l\overline{\phi_{3,l}})(\phi_3\overline{\phi_{23}})^3 \\
&+ \frac{1}{M^{13}}(\epsilon^{ijk}\psi_i^c\overline{\phi_{23,j}\phi_{3,k}})^2(\theta^k\overline{\phi_{23,k}})(\theta^l\overline{\phi_{3,l}})(\phi_3\overline{\phi_{23}})(\phi_{23}\overline{\phi_3})^2
\end{aligned}
$$

Plus shaping symmetries and extra fields

Alignment and Yukawa matrices

$$< \phi_3 >=< \overline{\phi_3} >= \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d \end{pmatrix} \qquad < \phi_{23} >= \begin{pmatrix} 0 \\ 1 \\ e^{i\theta} \end{pmatrix} b$$

$$\frac{a_3^u}{M^u} = \frac{a_3^d}{M^d} = \sqrt{\bar\epsilon}.$$

$$\epsilon \equiv \frac{b}{M^u}, \quad \bar\epsilon \equiv \frac{b}{M^d}$$

$$Y^u \approx \begin{pmatrix} 0 & \epsilon^3(g + \frac{h}{3} + \frac{h'}{3}) & \epsilon^3(g - \frac{h}{3})(1 + O(\bar\epsilon)) \\ \epsilon^3(g' - \frac{h}{3} - \frac{h'}{3}) & \epsilon^2(-\frac{2}{3}) & \epsilon^2(-\frac{2}{3}) + c'\epsilon^3\bar\epsilon^{-\frac{1}{2}} \\ \epsilon^3(g' + \frac{h}{3})(1 + O(\bar\epsilon)) & \epsilon^2(-\frac{2}{3}) + c\epsilon^3\bar\epsilon^{-\frac{1}{2}} & 1 + O(\bar\epsilon) \end{pmatrix} \bar\epsilon, \rightarrow Y^u \propto \begin{pmatrix} 0 & \epsilon^3 & O(\epsilon^3) \\ . & \epsilon^2 & O(\epsilon^2) \\ . & . & 1 \end{pmatrix}$$

$$Y^d \approx \begin{pmatrix} 0 & \bar\epsilon^3(g + h + h') & \bar\epsilon^3(g - h)(1 + O(\bar\epsilon)) \\ \bar\epsilon^3(g' - h - h') & \bar\epsilon^2 & \bar\epsilon^2 + c'\bar\epsilon^{\frac{5}{2}} \\ \bar\epsilon^3(g' + h)(1 + O(\bar\epsilon)) & \bar\epsilon^2 + c\bar\epsilon^{\frac{5}{2}} & 1 + O(\bar\epsilon) \end{pmatrix} \bar\epsilon, \rightarrow Y^d \propto \begin{pmatrix} 0 & 1.5\bar\epsilon^3 & 0.4\bar\epsilon^3 \\ . & \bar\epsilon^2 & 1.3\bar\epsilon^2 \\ . & . & 1 \end{pmatrix}$$

$$Y^e \approx \begin{pmatrix} 0 & \bar\epsilon^3(g + h + h') & \bar\epsilon^3(g - h)(1 + O(\bar\epsilon)) \\ \bar\epsilon^3(g' - h - h') & \bar\epsilon^2(3) & \bar\epsilon^2(3) + c'\bar\epsilon^{\frac{5}{2}} \\ \bar\epsilon^3(g' + h)(1 + O(\bar\epsilon)) & \bar\epsilon^2(3) + c\bar\epsilon^{\frac{5}{2}} & 1 + O(\bar\epsilon) \end{pmatrix} \bar\epsilon,$$

GJ for charged leptons

$$Y^\nu \approx \begin{pmatrix} 0 & \epsilon^3(g + \frac{h}{3} + \frac{h'}{3}) & \epsilon^3(g - \frac{h}{3})(1 + O(\bar\epsilon)) \\ \epsilon^3(g' - \frac{h}{3} - \frac{h'}{3}) & \epsilon^2(-\alpha) & \epsilon^2(-\alpha) + c'\epsilon^3\bar\epsilon^{-\frac{1}{2}} \\ \epsilon^3(g' + \frac{h}{3})(1 + O(\bar\epsilon)) & \epsilon^2(-\alpha) + c\epsilon^3\bar\epsilon^{-\frac{1}{2}} & 1 + O(\bar\epsilon) \end{pmatrix} \bar\epsilon.$$

Neutrinos c.f. up quarks

Neutrino mass and mixing

$$Y^\nu \approx \begin{pmatrix} 0 & \epsilon^3(g+\frac{h}{3}+\frac{h'}{3}) & \epsilon^3(g-\frac{h}{3})(1+O(\bar\epsilon)) \\ \epsilon^3(g'-\frac{h}{3}-\frac{h'}{3}) & \epsilon^2(-\alpha) & \epsilon^2(-\alpha)+c'\epsilon^3\bar\epsilon^{-\frac{1}{2}} \\ \epsilon^3(g'+\frac{h}{3})(1+O(\bar\epsilon)) & \epsilon^2(-\alpha)+c\epsilon^3\bar\epsilon^{-\frac{1}{2}} & 1+O(\bar\epsilon) \end{pmatrix}\bar\epsilon \;\rightarrow\; M_\nu^D \equiv \begin{pmatrix} 0 & a & a' \\ e & b & b' \\ f & c & c' \end{pmatrix}$$

$$M_{RR} \approx \begin{pmatrix} \epsilon^6\bar\epsilon^3 & 0 & 0 \\ 0 & \epsilon^6\bar\epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} M_3 \;\rightarrow\; M_\nu^M \sim \begin{pmatrix} M_1^M & 0 & 0 \\ 0 & M_2^M & 0 \\ 0 & 0 & M_3^M \end{pmatrix} \qquad M_1^M < M_2^M \ll M_3^M \approx \frac{\langle\theta\rangle^2}{M^\nu}$$

Hierarchical Diagonal RHNs

Type I seesaw $m_\nu = M_\nu^D (M_\nu^M)^{-1} (M_\nu^D)^T$

Dominant | **Sub-dominant** | **Decoupled**

$$m_\nu \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & e^2 & ef \\ 0 & ef & f^2 \end{pmatrix} \frac{1}{M_1^M} + \begin{pmatrix} a^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix} \frac{1}{M_2^M} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & c'^2 \end{pmatrix} \frac{1}{M_3^M}$$

SRHND

hep-ph/9806440,
hep-ph/9912492,
hep-ph/0204360

$$m_{\nu_3} \sim \frac{e^2+f^2}{M_{11}^M}, \quad \tan\theta_{23} \sim \frac{e}{f} \qquad m_{\nu_2} \sim \frac{a^2}{M_2^M s_{12}^2}, \quad \tan\theta_{12} \sim \frac{\sqrt{2}a}{b-c}, \quad \theta_{13} \lesssim \frac{m_{\nu_2}}{m_{\nu_3}} \qquad m_{\nu_1} \sim \frac{c'^2}{M_3^M}$$

Model predicted $\theta_{13} \sim \bar\epsilon \sim 0.15$ **way before it was measured**

How to test such models?

Two options:

1. Proton decay and Gravitational Waves

Fu, S.F.K., Marsili, Pascoli, Turner, Zhou 2209.XXXXXX (tomorrow!)

2. At the TeV scale with LHC and B physics

Mario F. Navarro and S.F.K. 2209.XXXXXX (tomorrow!)

We focus on second option here...

S.F. King, JHEP 11 (2021), [2106.03876]

Twin PS Theory of Flavour with a TeV scale Vector Leptoquark

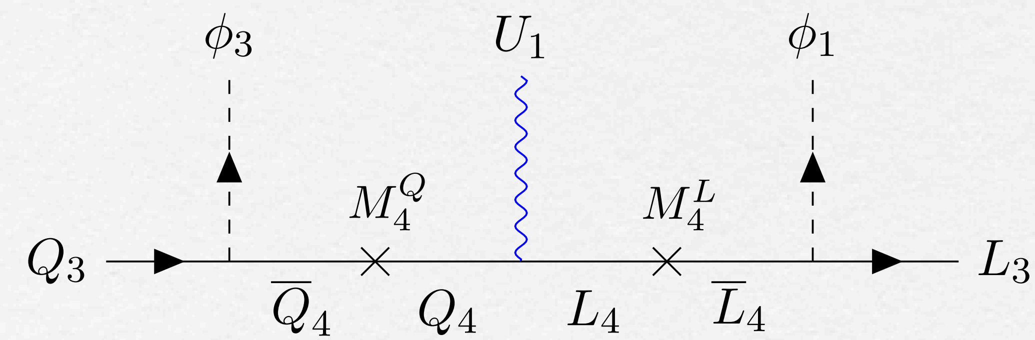
TeV

Field	$SU(4)^I_{PS}$	$SU(2)^I_L$	$SU(2)^I_R$	$SU(4)^{II}_{PS}$	$SU(2)^{II}_L$	$SU(2)^{II}_R$
$\psi_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
$\psi^c_{1,2,3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$
$\psi_{4,5,6}$	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi}_{4,5,6}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\psi^c_{4,5,6}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\overline{\psi^c}_{4,5,6}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
ϕ	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$
$\overline{\phi}, \overline{\phi'}$	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
H	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
$\overline{H}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	$\overline{\mathbf{4}}$	$\overline{\mathbf{2}}$	$\mathbf{1}$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

Plus shaping symmetries and extra fields

Motivated by B anomalies have SU(4)$^I_{PS}$ at TeV

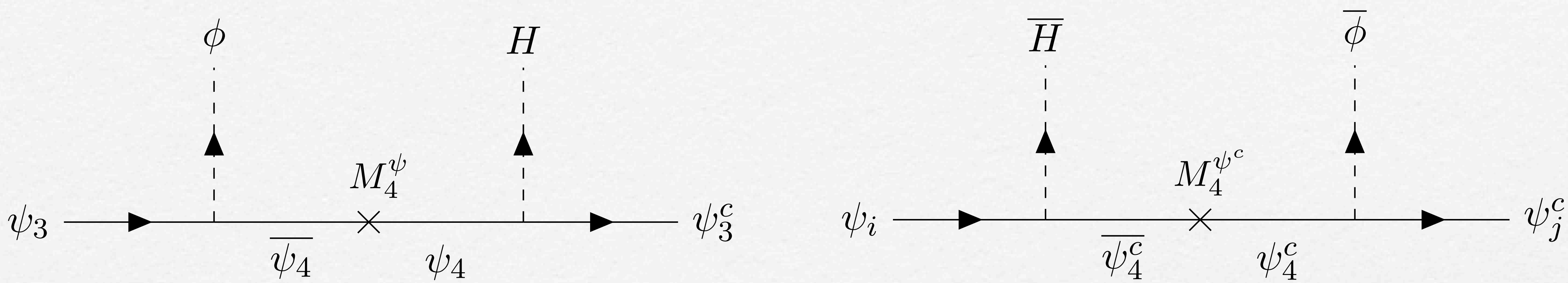
$$G^I_{422} \times G^{II}_{422} \xrightarrow{M_{\rm high}} G_{4321} \xrightarrow{M_{\rm low}} G_{321}$$



Chiral families 1,2,3 mix with vector-like families 4,5,6

This mixing generates VLQ couplings (above) and Yukawa matrices

Yukawa matrices



$$M_u \sim \begin{pmatrix} 0 & \bar{m}_u^0 & \bar{m}_u^0 \\ m_u^0 & m_c & m_c \\ m_u^0 & m_c & m_t \end{pmatrix}, \quad M_d \sim \begin{pmatrix} 0 & \bar{m}_d^0 & \bar{m}_d^0 \\ m_d^0 & m_s & m_s \\ m_d^0 & m_s & m_b \end{pmatrix}$$

$$M_\nu^D \sim \begin{pmatrix} 0 & \bar{m}_{\nu_e}^D & \bar{m}_{\nu_e}^D \\ m_{\nu_e}^D & m_{\nu_\mu}^D & m_{\nu_\mu}^D \\ m_{\nu_e}^D & m_{\nu_\mu}^D & m_{\nu_\tau}^D \end{pmatrix}, \quad M_e \sim \begin{pmatrix} 0 & \bar{m}_e^0 & \bar{m}_e^0 \\ m_e^0 & m_\mu & m_\mu \\ m_e^0 & m_\mu & m_\tau \end{pmatrix}$$

Looks familiar?

- Hierarchical
- Symmetric
- (1,1) zero
- Personal Higgs

Neutrino mass and mixing from SRHND

Mario F. Navarro and S.F.K. 2209.XXXXXX

B anomalies in a Twin PS ToF

$$G^{I}_{422} \times G^{II}_{422} \xrightarrow{M_{\rm high}} G_{4321} \xrightarrow{M_{\rm low}} G_{321}$$

TeV scale U_1, Z', g'

Observable		Experiment/constraint
$R_{K^{(*)}}$	δC_L^{μ}	$-0.40^{+0.08}_{-0.09}$ [25]
$R_{D^{(*)}}$	g_{V_L}	0.05 ± 0.02 [4]
$B_s - \bar{B}_s$	$\delta(\Delta M_s)$	$\lesssim 0.11$(see Section 2.4.2 and [27])
	$\mathcal{B}(\tau \to 3\mu)$	$< 2.1 \cdot 10^{-8}$ (90% CL) [40]
	$\mathcal{B}(\tau \to \mu\gamma)$	$< 5.0 \cdot 10^{-8}$ (90% CL) [41]
	$\mathcal{B}(B_s \to \tau^{\pm}\mu^{\mp})$	$< 3.4 \cdot 10^{-5}$ (90% CL) [42]
	$\mathcal{B}(B^+ \to K^+\tau^{\pm}\mu^{\mp})$	$< 2.8 \cdot 10^{-5}$ (90% CL) [43]
	$\mathcal{B}(\tau \to \mu\phi)$	$< 8.4 \cdot 10^{-8}$ (90% CL) [44]
	$\mathcal{B}(K_L \to \mu e)$	$< 4.7 \cdot 10^{-12}$ (90% CL) [45]
	$(g_\tau/g_{e,\mu})_{\ell+\pi+K}$	1.0003 ± 0.0014 [3]
	$\mathcal{B}(B_s \to \tau^+\tau^-)$	$< 5.2 \times 10^{-3}$ (90% CL) [46]
	$\mathcal{B}(B \to K\tau^+\tau^-)$	$< 2.25 \times 10^{-3}$ (90% CL) [47]
	$\mathcal{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)/\mathcal{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\rm SM}$	$< 3.5\,(3.2)$ (90% CL) [48, 49]

Focus on low energy 4321

L.Di Luzio, A.Greljo and M.Nardecchia, Phys. Rev. D 96 (2017) [1708.08450]

Key features of our analysis

- GIM-like (3 VLFs)
- PS unification
- Fermion masses (2nd, 3rd family)
- Fermiophobic construction

Input parameters

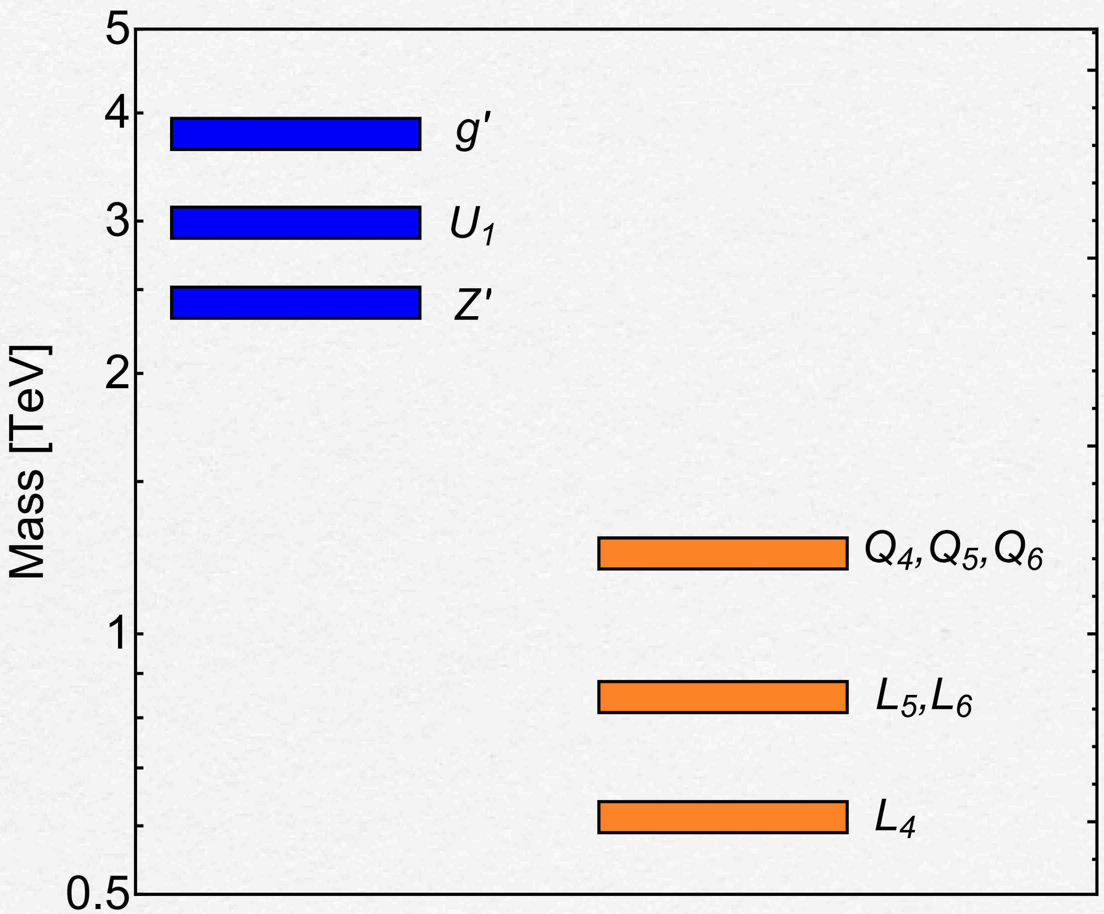
	ψ_1^c	ψ_2^c	ψ_3^c	ψ_4^c	ψ_5^c	ψ_6^c	$\overline{\psi_4}$	$\overline{\psi_5}$	$\overline{\psi_6}$
ψ_1	0	0	0	0	0	0	0	0	$x_{16}^{\psi}\phi$
ψ_2	0	0	0	$y_{24}^{\psi}\overline{H}$	$y_{25}^{\psi}\overline{H}$	0	0	$x_{25}^{\psi}\phi$	0
ψ_3	0	0	0	$y_{34}^{\psi}\overline{H}$	$y_{35}^{\psi}\overline{H}$	0	$x_{34}^{\psi}\phi$	$x_{35}^{\psi}\phi$	0
ψ_4	0	0	$y_{43}^{\psi}H$	0	0	0	$\bar{M}_{44}^{\psi}$	M_{45}^{ψ}	0
ψ_5	0	0	$y_{53}^{\psi}H$	0	0	0	M_{54}^{ψ}	$\bar{M}_{55}^{\psi}$	0
ψ_6	0	0	0	0	0	0	0	0	$\bar{M}_{66}^{\psi}$
$\overline{\psi_4^c}$	0	$x_{42}^{\psi^c}\overline{\phi'}$	$x_{43}^{\psi^c}\overline{\phi}$	$M_{44}^{q^c,e^c}$	$M_{45}^{\psi^c}$	0	0	0	0
$\overline{\psi_5^c}$	0	$x_{52}^{\psi^c}\overline{\phi'}$	$x_{53}^{\psi^c}\overline{\phi}$	$M_{54}^{\psi^c}$	$M_{44}^{q^c,e^c}$	0	0	0	0
$\overline{\psi_6^c}$	$x_{61}^{\psi^c}\overline{\phi}$	0	0	0	0	$M_{66}^{q^c,e^c}$	0	0	0

- Zeroes enforced by symmetries

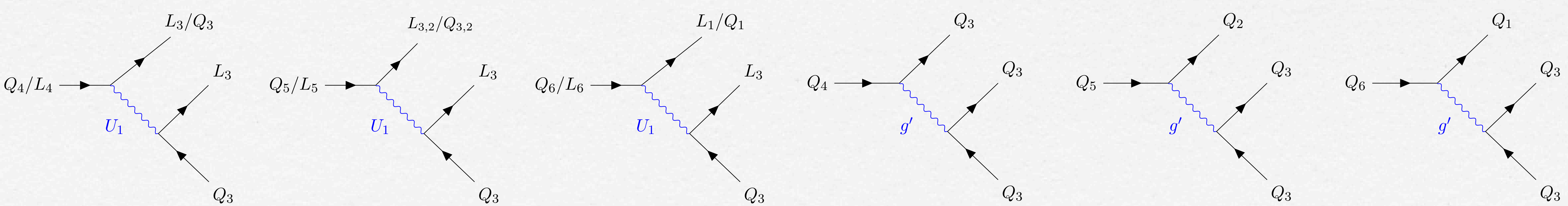
Benchmark and output

benchmark (BP)				Output			
g_4	3.5	λ_{15}^{44}	-0.5	s_{34}^Q	0.978	$M_{g'}$	3782.86 GeV
$g_{3,2,1}$	1, 0.65, 0.36	λ_{15}^{55}, λ_{15}^{66}	2.5, 0.8	s_{34}^L	0.977	$M_{Z'}$	2414.32 GeV
x_{34}^{ψ}	2	$x_{42}^{\psi^c}$	0.4	$s_{25}^Q = s_{16}^Q$	0.1986	s_{23}^u	0.042556
$x_{25}^{\psi} = x_{16}^{\psi}$	0.41	$x_{43}^{\psi^c}$	1	$s_{25}^L = s_{16}^Q$	0.1455	s_{23}^d	0.001497
M_{44}^{ψ}	320 GeV	$M_{44}^{\psi^c}$	5 TeV	$s_{\theta_{LQ}}$	0.7097	s_{23}^e	-0.111
M_{55}^{ψ}	780 GeV	$y_{53,43,34,24}^{\psi}$	-0.3, 1, 1, 1	$\widetilde{M}_4^Q$	1226.82 GeV	V_{cb}	0.04106
M_{66}^{ψ}	930 TeV	$\langle H_t \rangle$	177.2 GeV	$\widetilde{M}_5^Q$	1238.69 GeV	m_t	172.91 GeV
M_{45}^{ψ}	-700 GeV	$\langle H_c \rangle$	26.8 GeV	$\widetilde{M}_4^L$	614.038 GeV	m_c	1.270 GeV
M_{54}^{ψ}	50 GeV	$\langle H_b \rangle$	4.25 GeV	$\widetilde{M}_5^L$	845.263 GeV	m_b	4.180 GeV
$\langle \phi_3 \rangle$	0.6 TeV	$\langle H_s \rangle$	2.1 GeV	$\widetilde{M}_6^Q$	1235.73 GeV	m_s	0.0987 GeV
$\langle \phi_1 \rangle$	0.3 TeV	$\langle H_\tau \rangle$	1.75 GeV	$\widetilde{M}_6^L$	842.39 GeV	m_τ	1.7765 GeV
v_{15}	0.4 TeV	$\langle H_\mu \rangle$	4.5788 GeV	M_{U_1}	2986.99 GeV	m_μ	105.65 MeV

Benchmark Spectrum

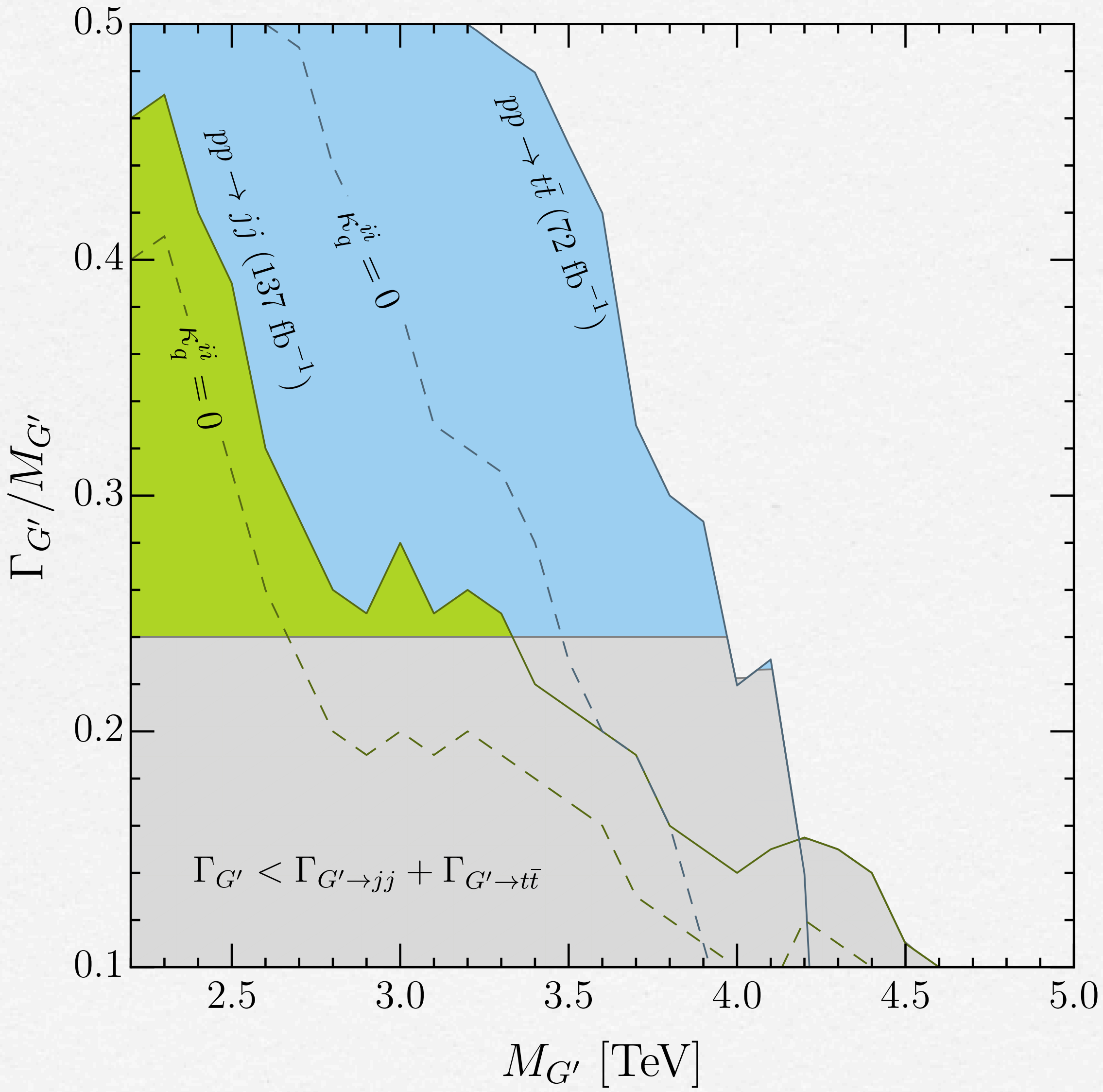


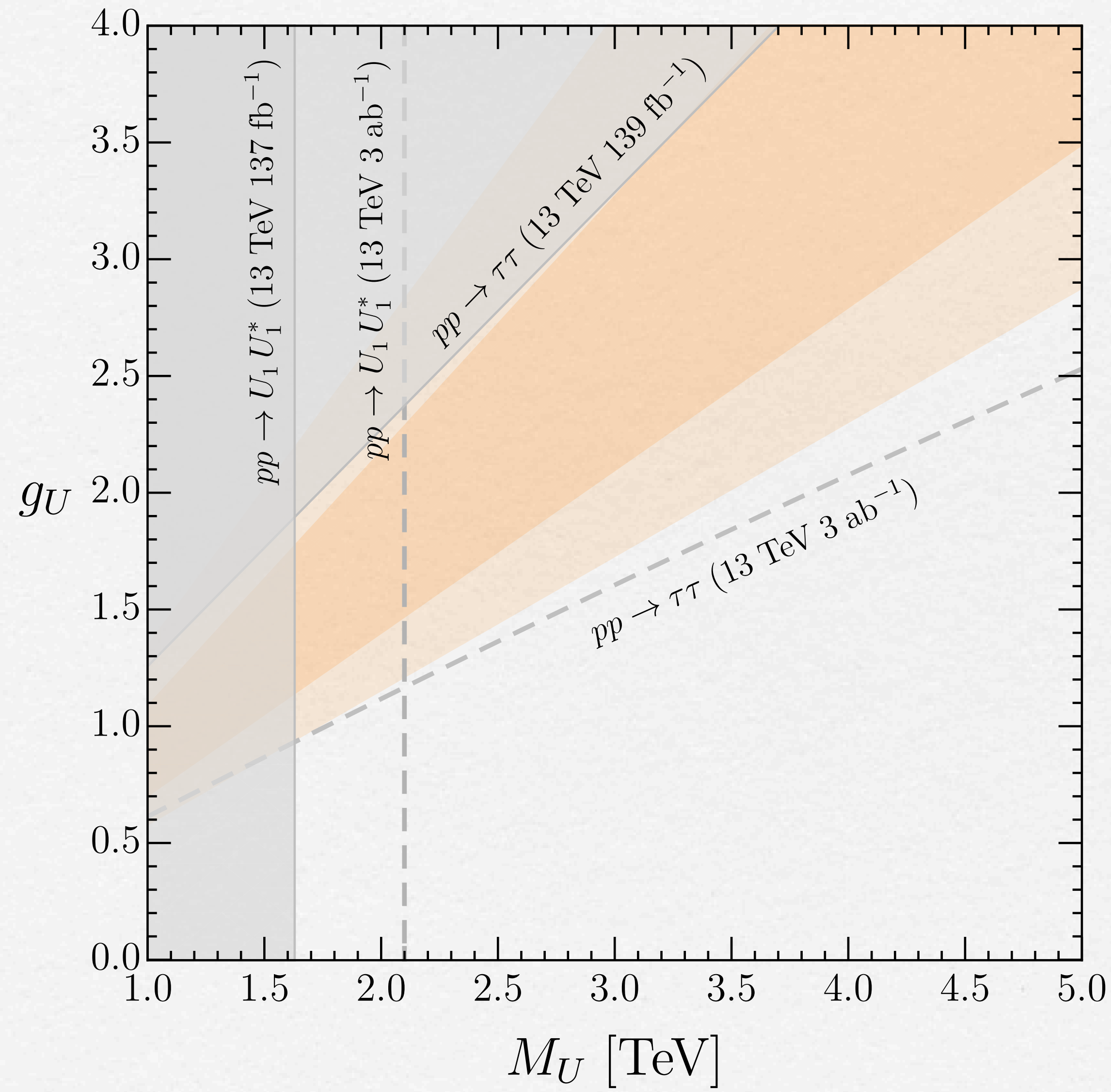
Particle	Decay mode	$\mathcal{B}$(BP)	Γ/M
U_1	$Q_3L_5 + Q_5L_3$	~ 0.47	0.32
	Q_3L_3	~ 0.22	
	Q_5L_5	~ 0.24	
	$Q_iL_a + Q_aL_i$	~ 0.07	
g'	Q_3Q_3	~ 0.3	0.5
	Q_5Q_5	~ 0.3	
	Q_6Q_6	~ 0.3	
	$Q_1Q_6+Q_2Q_5 + Q_3Q_4$	~ 0.1	
Z'	L_5L_5	~ 0.29	0.24
	L_6L_6	~ 0.29	
	L_3L_3	~ 0.27	
	$Q_3Q_3+Q_5Q_5 + Q_6Q_6$	~ 0.09	
	$L_1L_6 + L_2L_5 + L_3L_4$	~ 0.06	



C.Cornella, D.A.Faroughy, J.Fuentes-Martin, G.Isidori and M.Neubert, JHEP 08 (2021) [2103.16558]

LHC limits on g' and U_1





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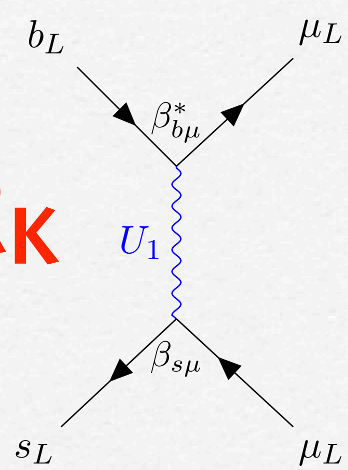
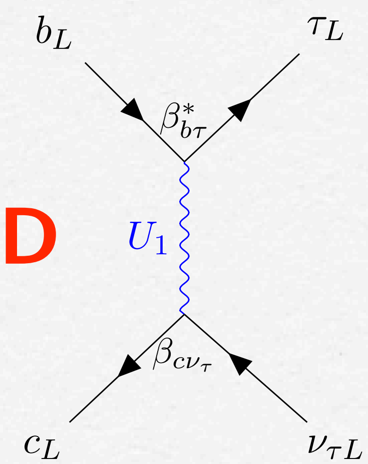
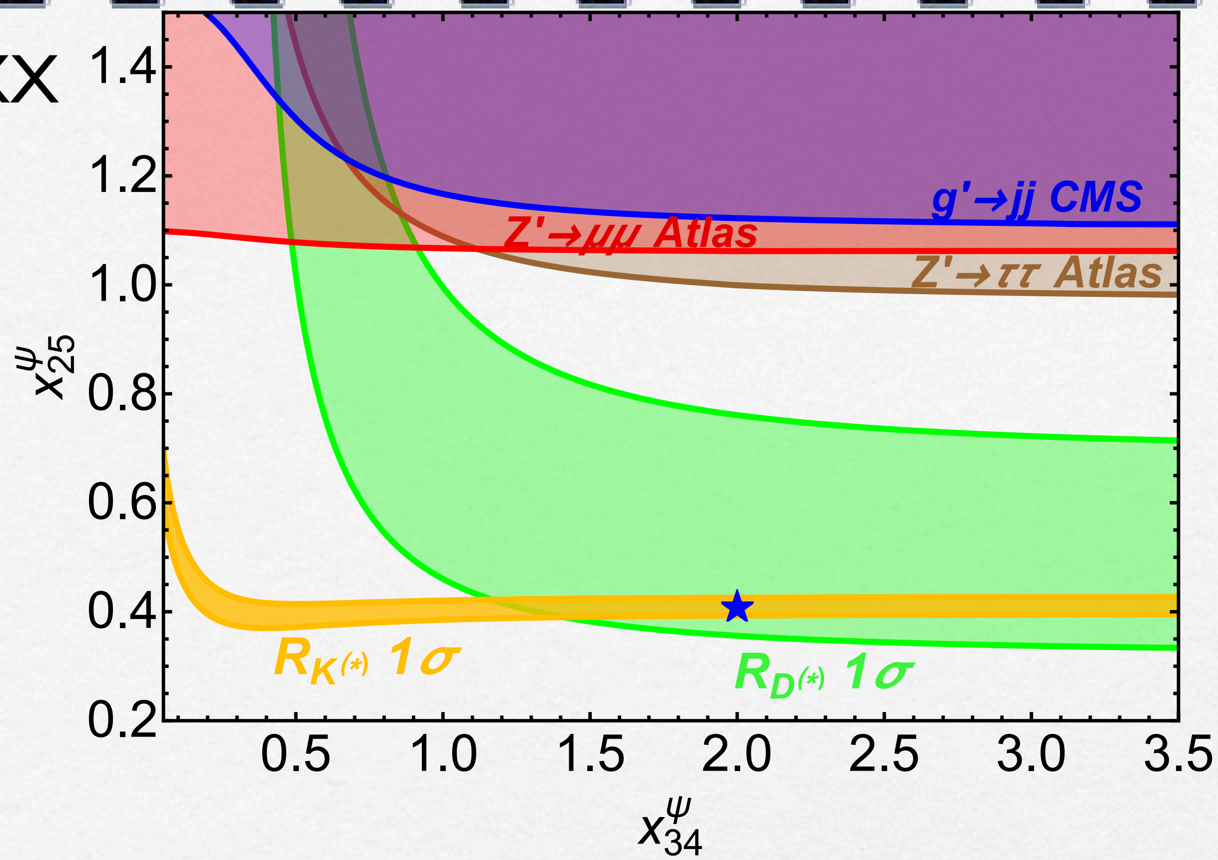
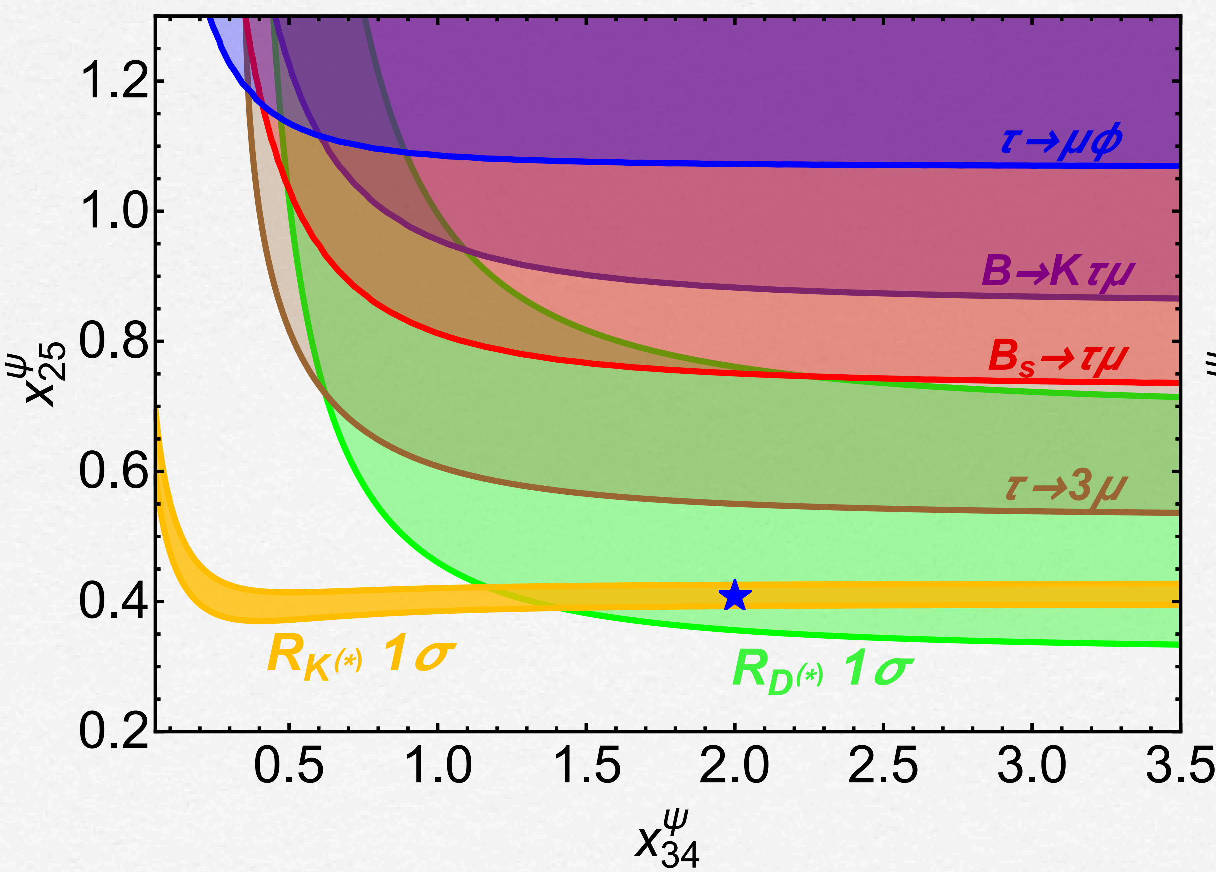
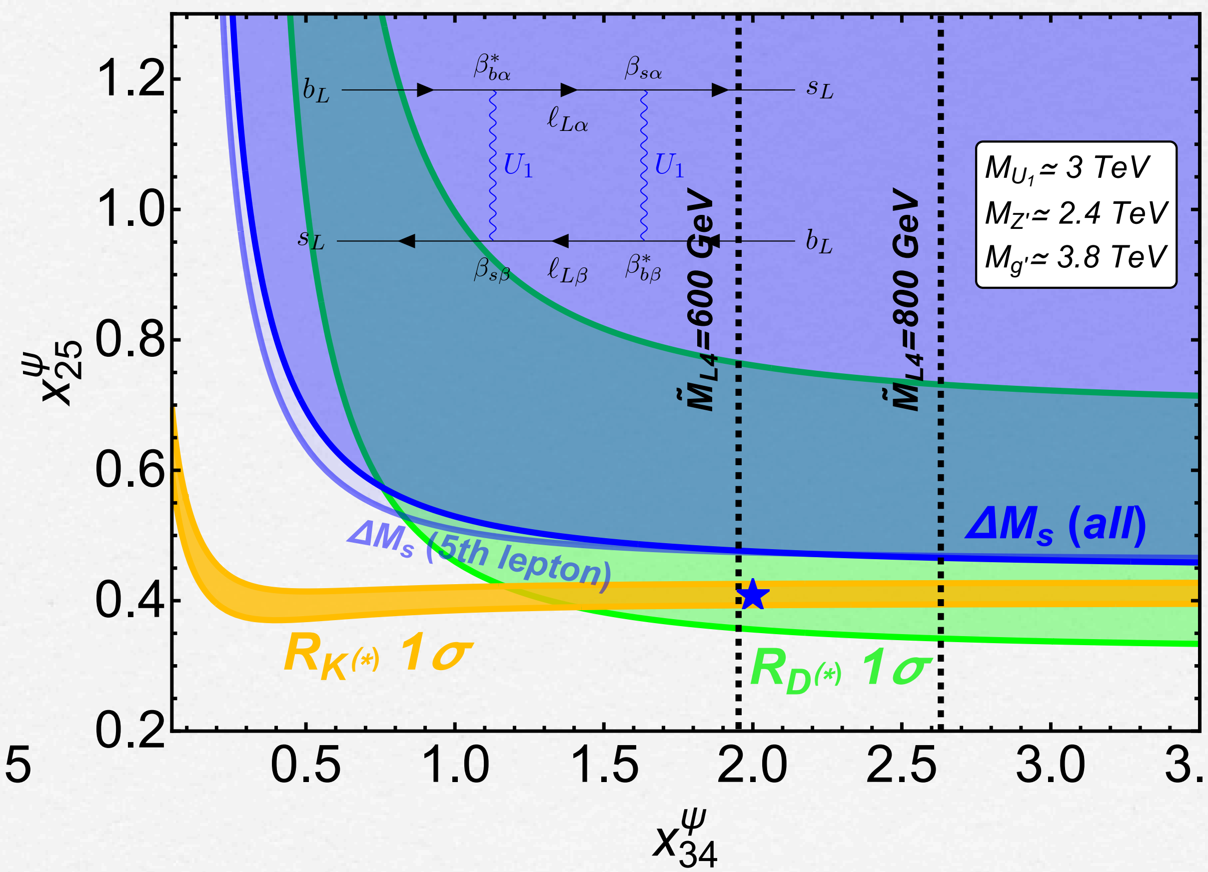
R_K, R_D anomalies

R_K 

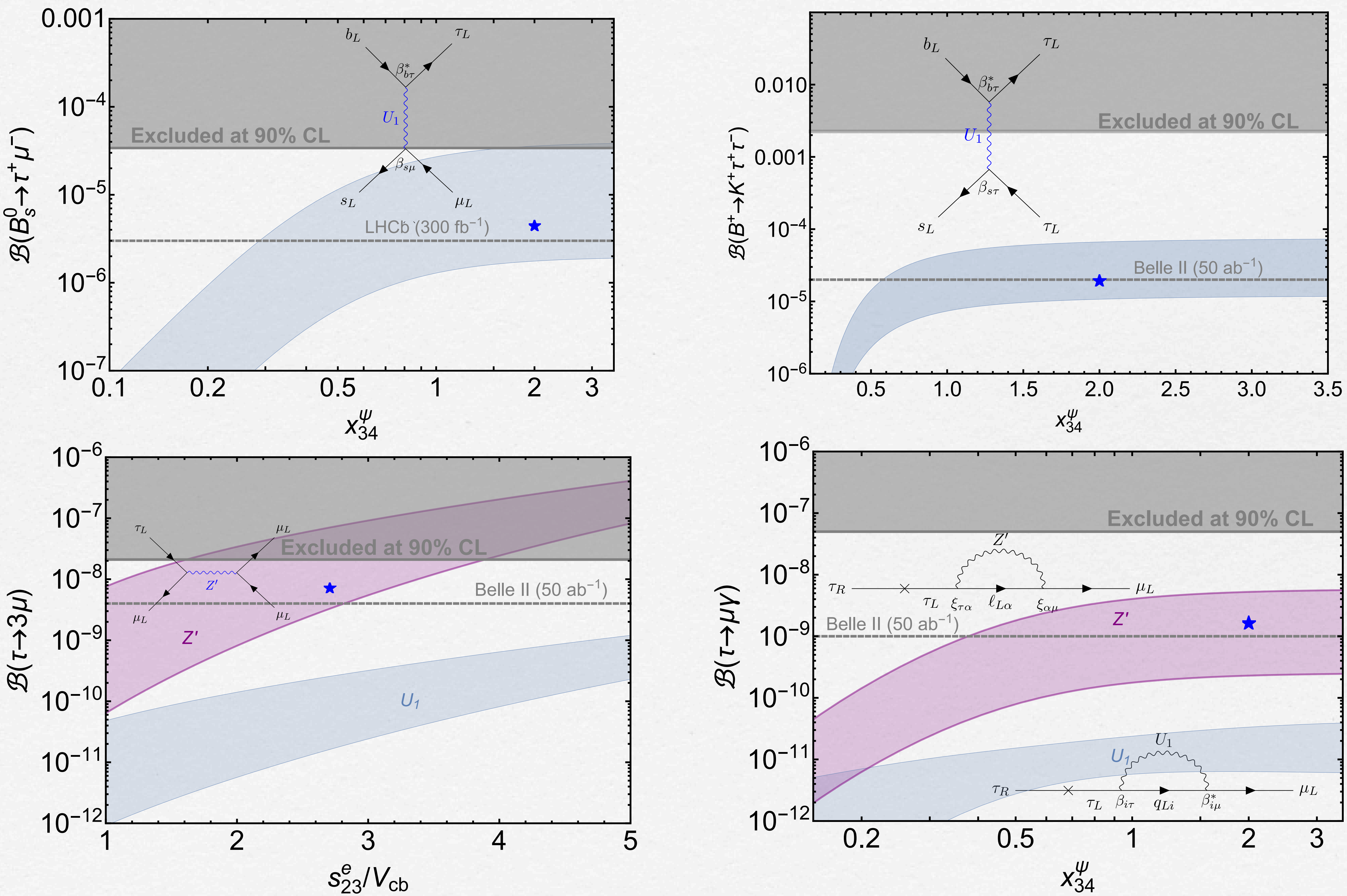
R_D 



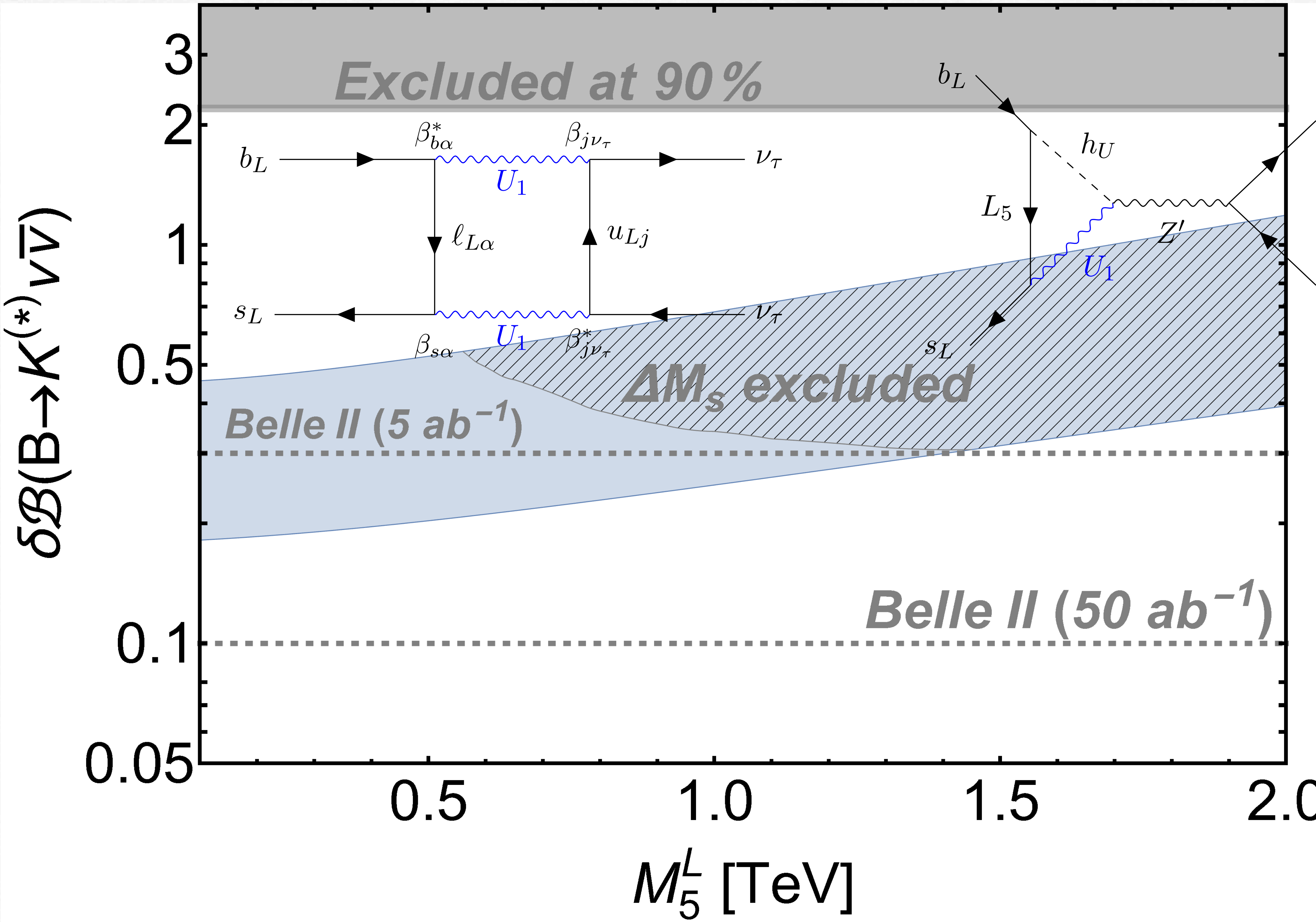




Predictions for LHCb and Belle II



Prediction for B->K nu nu at Belle II



Conclusion

- SU(3) x PS model still valid today, θ_{13} prediction confirmed
- Such high scale models difficult to test directly (PD, GWs ?)
- It is possible that Nature has given us a lucky break and provided us with a TeV scale PS symmetry
- $(PS)^2$ with TeV scale PS symmetry reproduces similar mass matrices to Graham's and explains R_K, R_D
- This allows the theory to be probed by experiments such as LHC, LHCb, Belle II, providing a testable theory of flavour

Standard Model

Yukawa matrices (basis dependent)

$$-\mathscr{L}_Y = (Y_u)_{ij}\, \overline{q_{iL}}\, \tilde{\phi}\, u_{iR} + (Y_d)_{ij}\, \overline{q_{iL}}\, \phi\, d_{iR} + (Y_\ell)_{ij}\, \overline{\ell_{iL}}\, \phi\, e_{iR} + \text{H.c.}$$

Mass matrices (basis dependent)

$$m_u \equiv \frac{v}{\sqrt{2}} Y_u\,, \qquad m_d \equiv \frac{v}{\sqrt{2}} Y_d\,, \qquad m_\ell \equiv \frac{v}{\sqrt{2}} Y_\ell\,.$$

Fermion masses and mixing (observables)

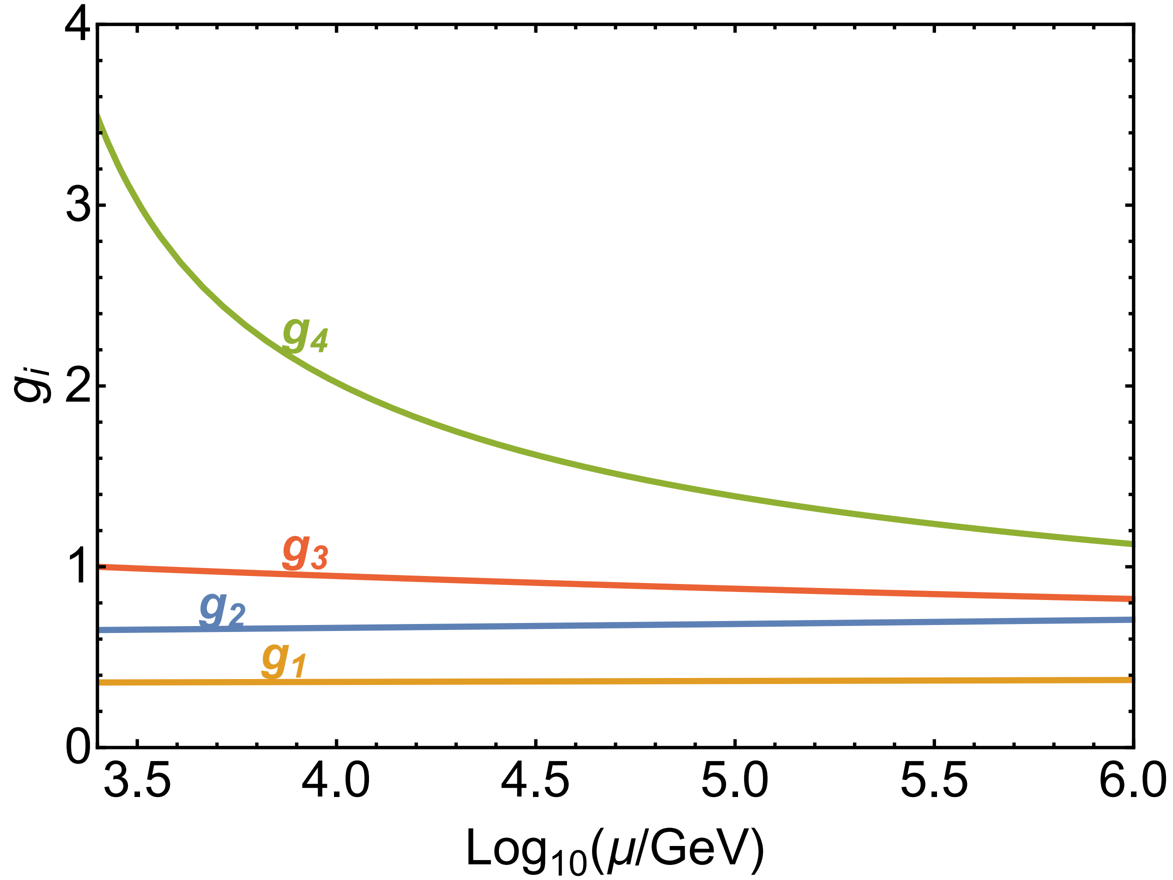
$$m_u \longrightarrow U_L^{u\dagger} m_u U_R^u = \text{diag}\,(m_u, m_c, m_t)\,, \qquad V \equiv U_L^{u\dagger} U_L^d\,.$$

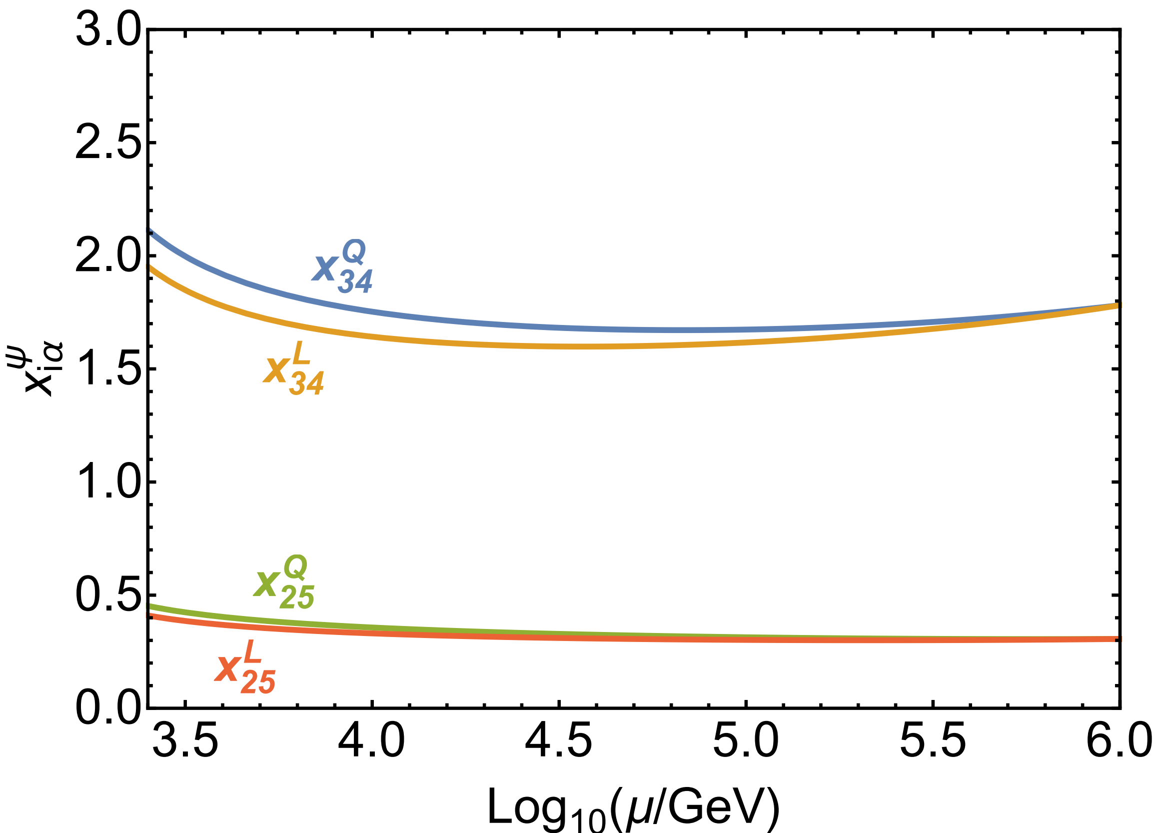
$$m_d \longrightarrow U_L^{d\dagger} m_d U_R^d = \text{diag}\,(m_d, m_s, m_b)\,,$$

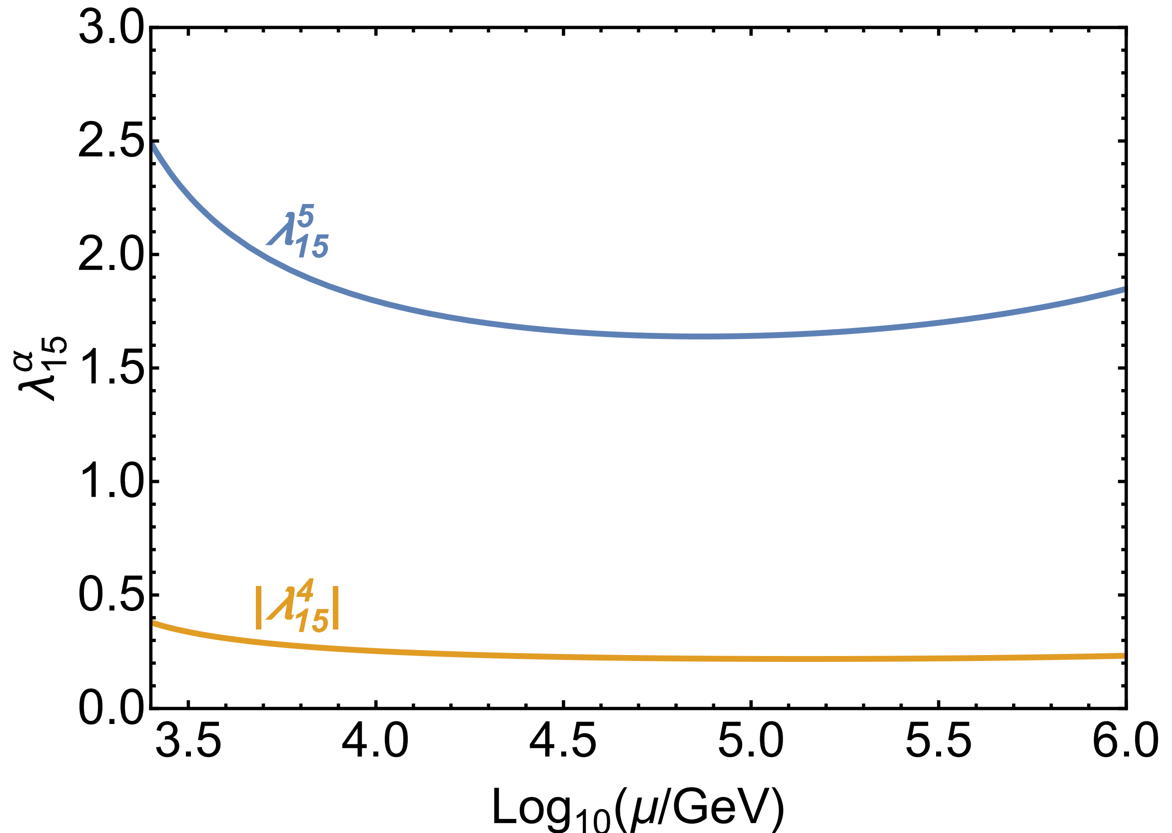
$$m_\ell \longrightarrow U_L^{e\dagger} m_\ell U_R^e = \text{diag}\,(m_\ell, m_\mu, m_\tau)\,.$$

(basis independent)

Perturbativity







LHC production