Maximizing the impact of New Physics in the $b \to c\tau\nu$ anomalies

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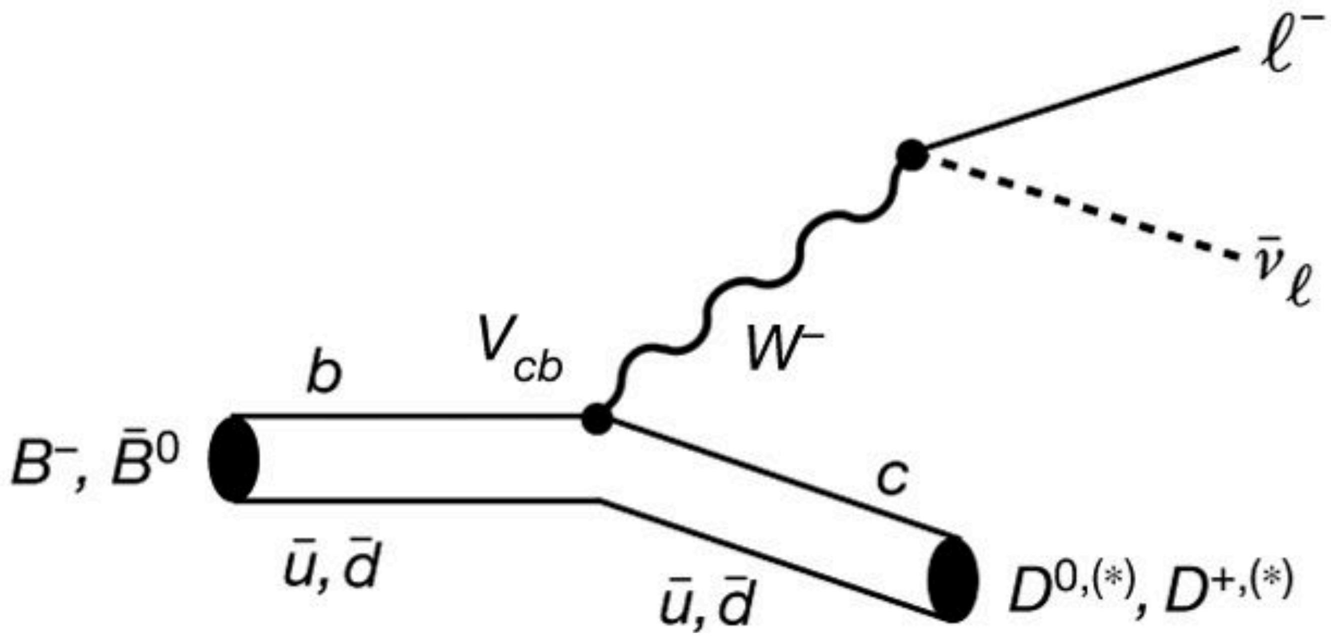
Asadi & DS 1905.03311
Asadi, Nakai & DS 1905.xxxxx

The RD/RD* anomalies



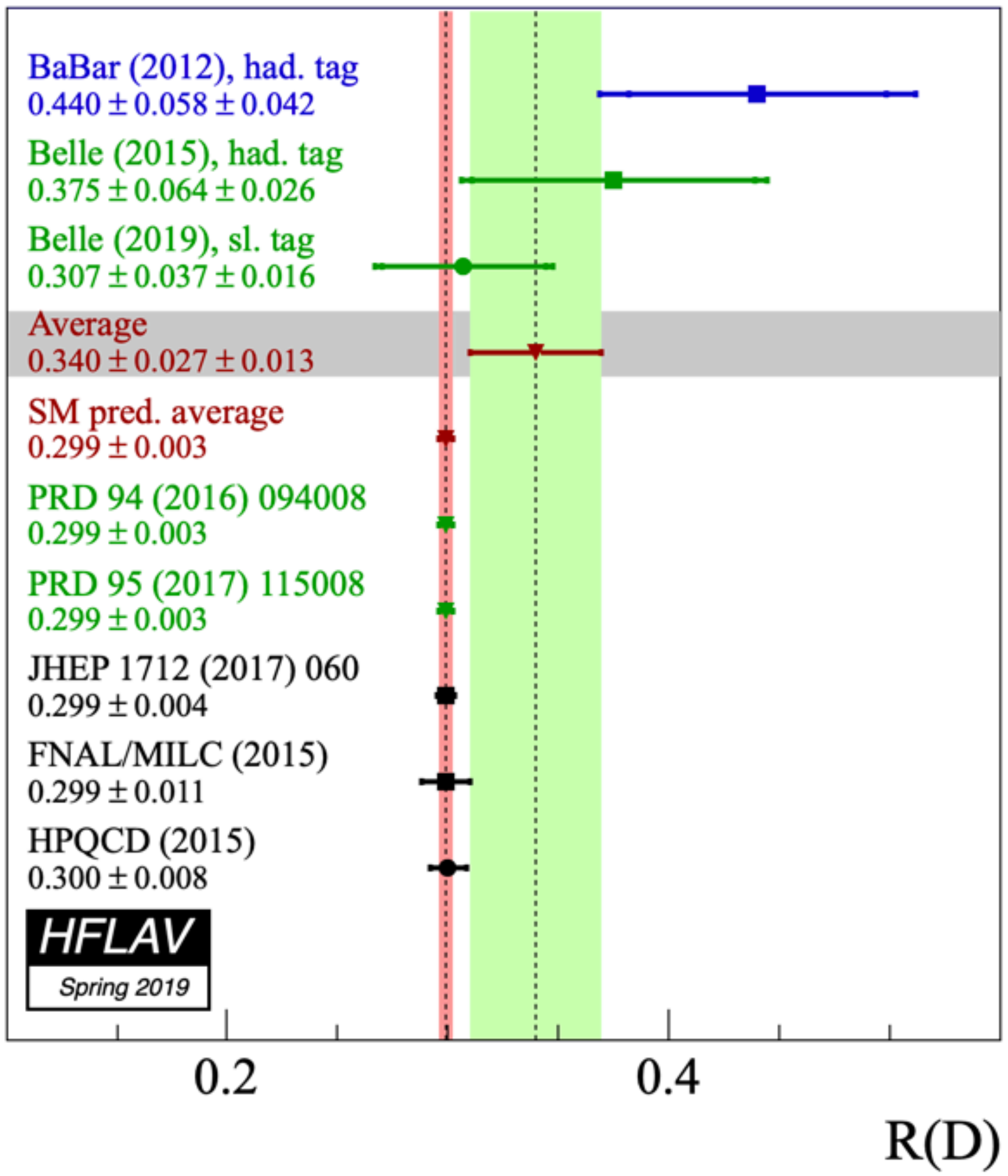
$J^{CP}(D) = 0^-$

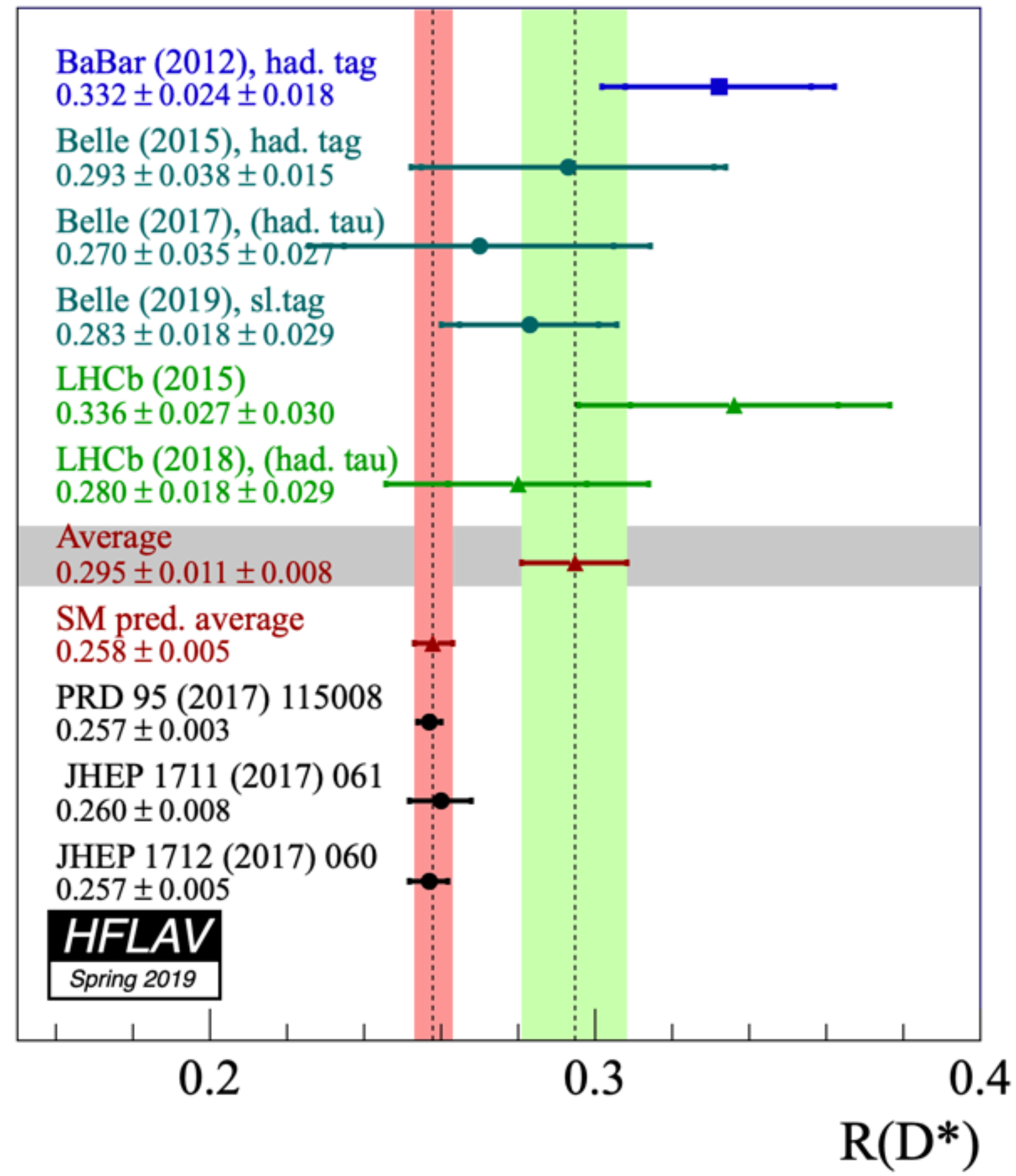
$J^{CP}(D^*) = 1^-$

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}l\bar{\nu})} \qquad (l = e, \mu)$$

Ratio is theoretically clean, probe of lepton flavor universality

The RD/RD* anomalies

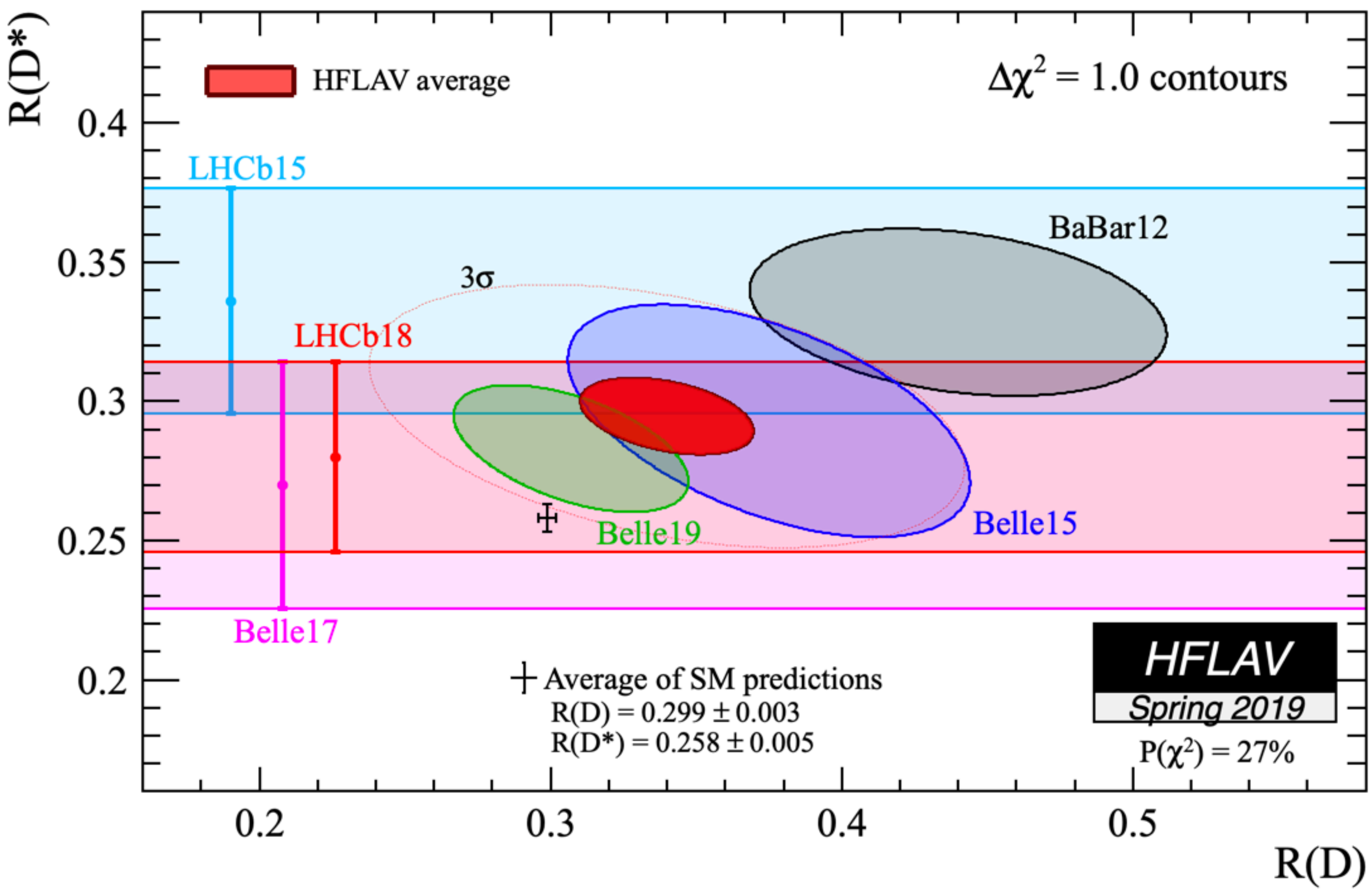




Multiple channels, three experiments: consistently high

See T. Kitahara's talk on Monday for more details

The RD/RD* anomalies



Combined significance: 3.1σ (was 3.8σ before Moriond '19)

See T. Kitahara's talk on Monday for more details

Implications of the anomaly

Dim 6 effective Hamiltonian for b→cτν transitions:

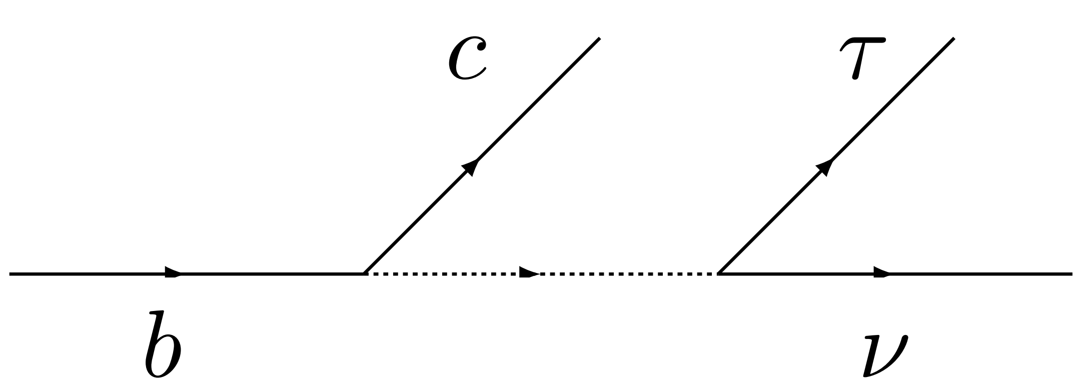
$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left(\mathcal{O}^V_{LL} + \sum_{\substack{X=S,V,T \\ M,N=L,R}} C^X_{MN} \mathcal{O}^X_{MN} \right)$$

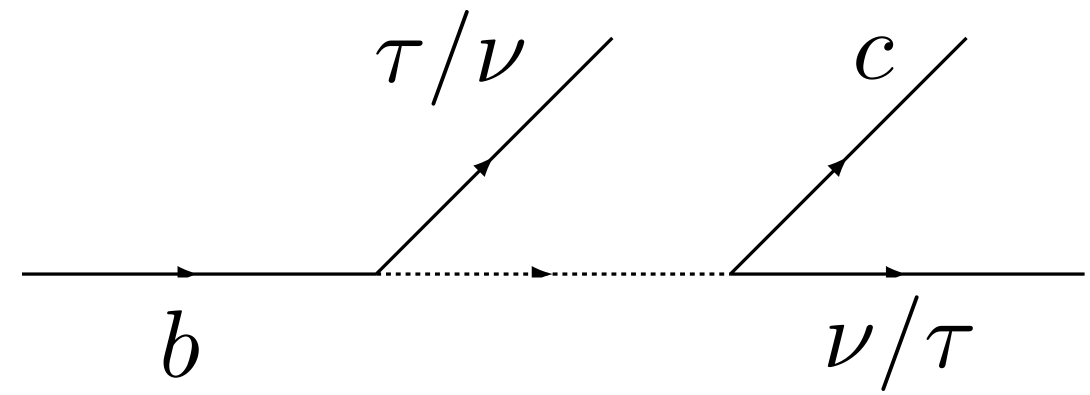
$$\begin{aligned} \mathcal{O}^S_{MN} &\equiv (\bar{c} P_M b)(\bar{\tau} P_N \nu) \\ \mathcal{O}^V_{MN} &\equiv (\bar{c} \gamma^\mu P_M b)(\bar{\tau} \gamma_\mu P_N \nu) \\ \mathcal{O}^T_{MN} &\equiv (\bar{c} \sigma^{\mu\nu} P_M b)(\bar{\tau} \sigma_{\mu\nu} P_N \nu) \end{aligned}$$

5 SM Wilson operators: $\mathcal{O}^V_{LL},\ \mathcal{O}^V_{RL},\ \mathcal{O}^S_{LL},\ \mathcal{O}^S_{RL},\ \mathcal{O}^T_{LL}$

- Only LH neutrinos
- $\mathcal{O}^T_{RL} = 0$

Implications of the anomaly



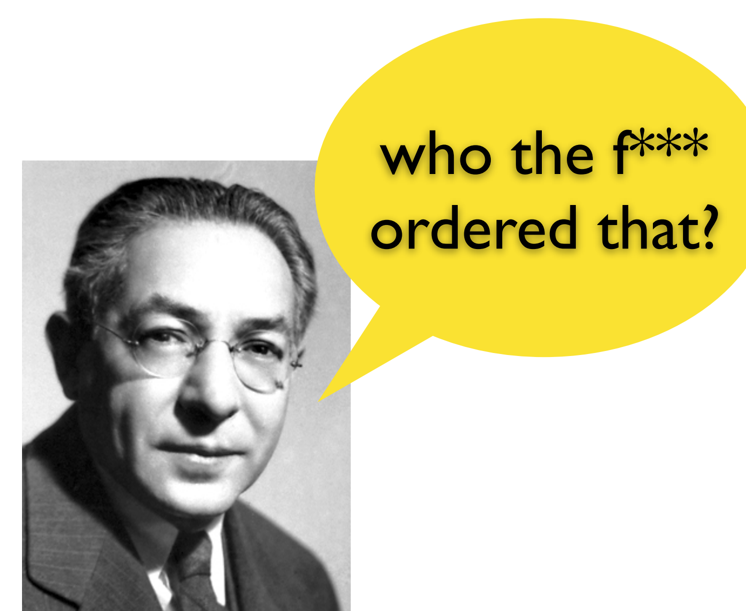


$$\frac{V_{cb}}{m_W^2} \sim \frac{1}{\Lambda_{NP}^2}$$

Need:

- Light mediator $\Lambda_{NP} \lesssim 1 \text{ TeV}$
- Large couplings
- Tree-level

Possibilities: charged Higgs, W' or leptoquark



Implications of the anomaly

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- *Charged Higgs:* contributes to $B_c \to \tau\nu$. Indirect bounds from total width ($Br(B_c \to \tau\nu) \lesssim 30\%$) and LEP search for $B_u \to \tau\nu$ ($Br(B_c \to \tau\nu) \lesssim 10\%$) rule out these explanations of the anomaly.
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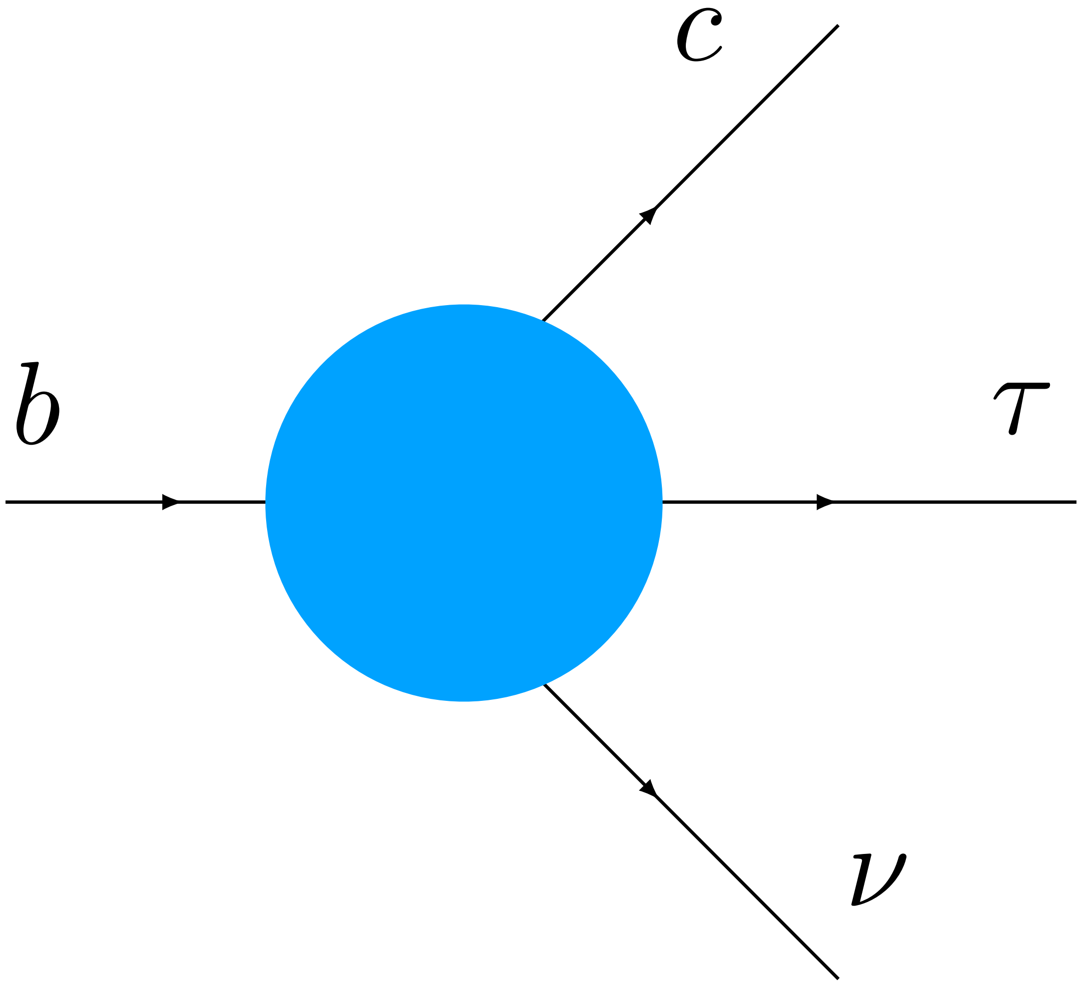
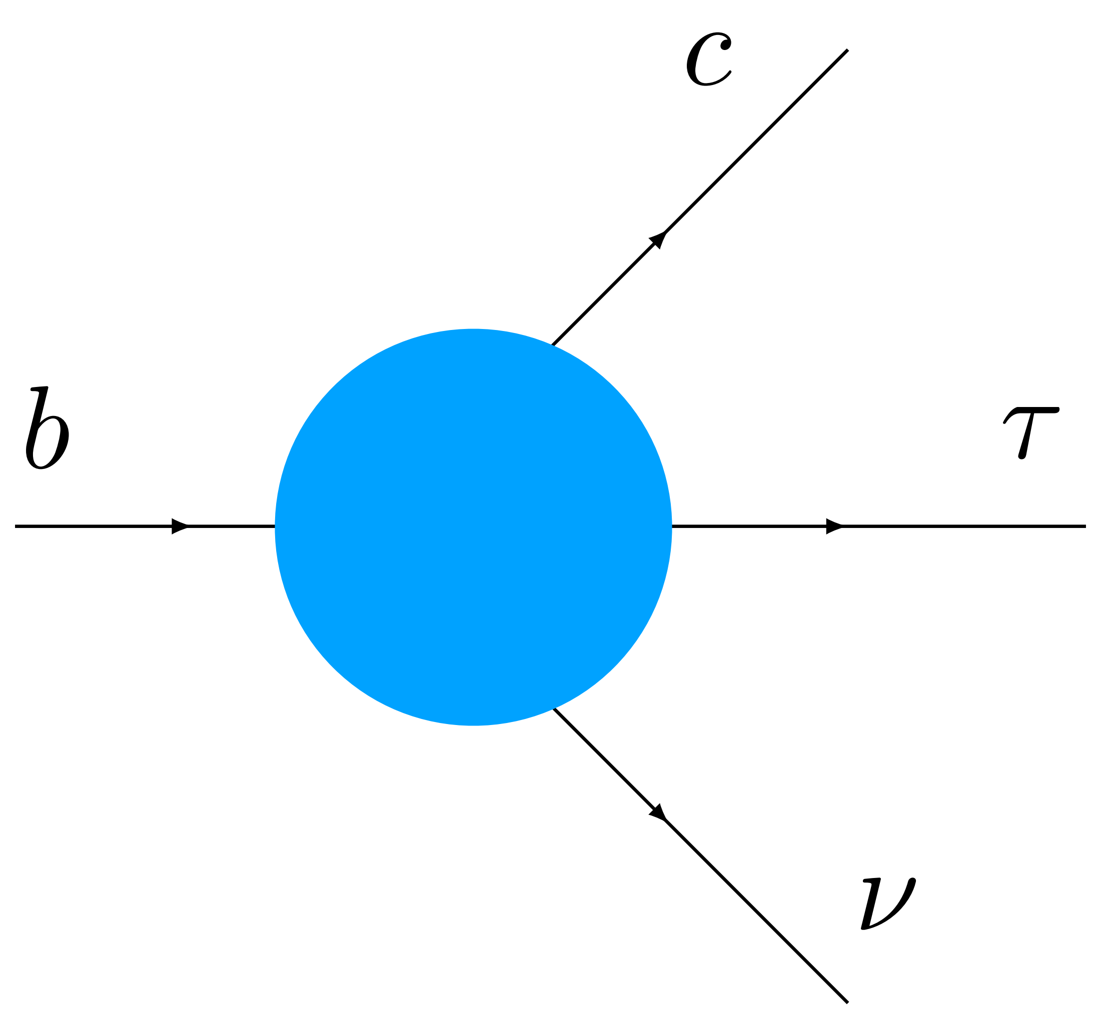
- *W primes*: Strong constraints from $Z' \to \tau\tau$ searches rule out these models (Faroughy et al 1609.07138, Crivellin et al 1703.09226)

- *Leptoquarks*: Strong LHC constraints from pair production, DY, and mono-tau, but much parameter space remains
(many people….see e.g. Schmaltz & Zhong 1810.10017; Greljo et al 1811.07920)

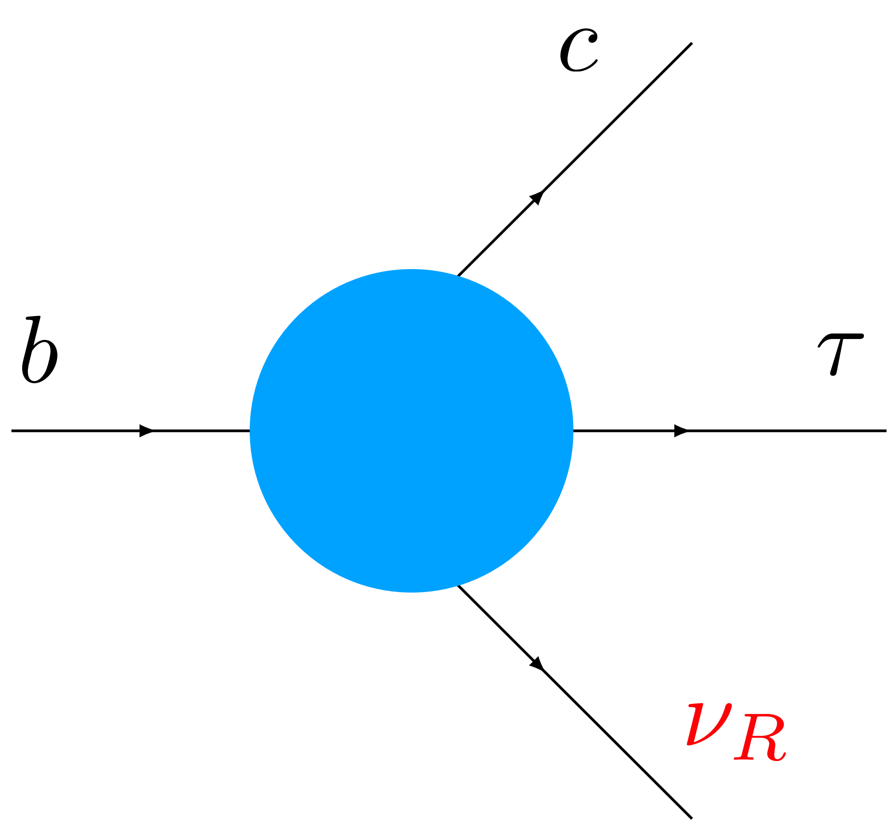


ARE WE SURE THAT THESE ARE SM NEUTRINOS?



ARE WE SURE THAT THESE ARE SM NEUTRINOS?

➡ Could be a light, weakly-interacting BSM particle instead?



Allowing for RH neutrinos opens up new avenues for model building and phenomenology (Asadi, Buckley & DS 1804.04135, 1810.06597)

He & Valencia 1211.0348
Dutta et al 1307.6653
Cline 1512.02210
Becirevic et al 1608.08501
Bardhan et al 1610.03038
Dutta & Bhol 1611.00231

Iguro & Omura 1802.01732
Greljo et al 1804.04642
Abdullah et al 1805.01869
Robinson et al 1807.04753

Azatov et al 1807.10745
Heeck et al 1808.07492
Carena et al 1809.01107
Iguro et al 1810.05843

Summary of models

Mediator	Operator Combination	Viability
Colorless Scalars	$\mathcal{O}^S_{XL}$	✗ $(Br\,(B_c \to \tau\nu))$
W'^{μ} (LH fermions)	$\mathcal{O}^V_{LL}$	✗ (collider bounds)
S_1 LQ $(\bar{3}, 1, 1/3)$ (LH fermions)	$\mathcal{O}^S_{LL} - x\mathcal{O}^T_{LL}$, $\mathcal{O}^V_{LL}$	✓
U_1^{μ} LQ $(3, 1, 2/3)$ (LH fermions)	$\mathcal{O}^S_{RL}$, $\mathcal{O}^V_{LL}$	✓
R_2 LQ $(3, 2, 7/6)$	$\mathcal{O}^S_{LL} + x\mathcal{O}^T_{LL}$	✓
S_3 LQ $(\bar{3}, 3, 1/3)$	$\mathcal{O}^V_{LL}$	✗ $(b \to s\nu\nu)$
U_3^{μ} LQ $(3, 3, 2/3)$	$\mathcal{O}^V_{LL}$	✗ $(b \to s\nu\nu)$
V_2^{μ} LQ $(\bar{3}, 2, 5/6)$	$\mathcal{O}^S_{RL}$	✗ $(R_{D^{(*)}}$ value)
Colorless Scalars	$\mathcal{O}^S_{XR}$	✗ $(Br\,(B_c \to \tau\nu))$
W'^{μ} (RH fermions)	$\mathcal{O}^V_{RR}$	✓
$\tilde{R}_2$ LQ $(3, 2, 1/6)$	$\mathcal{O}^S_{RR} + x\mathcal{O}^T_{RR}$	✗ $(b \to s\nu\nu)$
S_1 LQ $(\bar{3}, 1, 1/3)$ (RH fermions)	$\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{RR} - x\mathcal{O}^T_{RR}$	✓
U_1^{μ} LQ $(3, 1, 2/3)$ (RH fermions)	$\mathcal{O}^S_{LR}$, $\mathcal{O}^V_{RR}$	✓

(from Asadi, Buckley & DS 1810.06597)

Beyond RD/RD*

Several more observables that are sensitive to NP in $b \to c\tau\nu$ transitions have been measured recently.

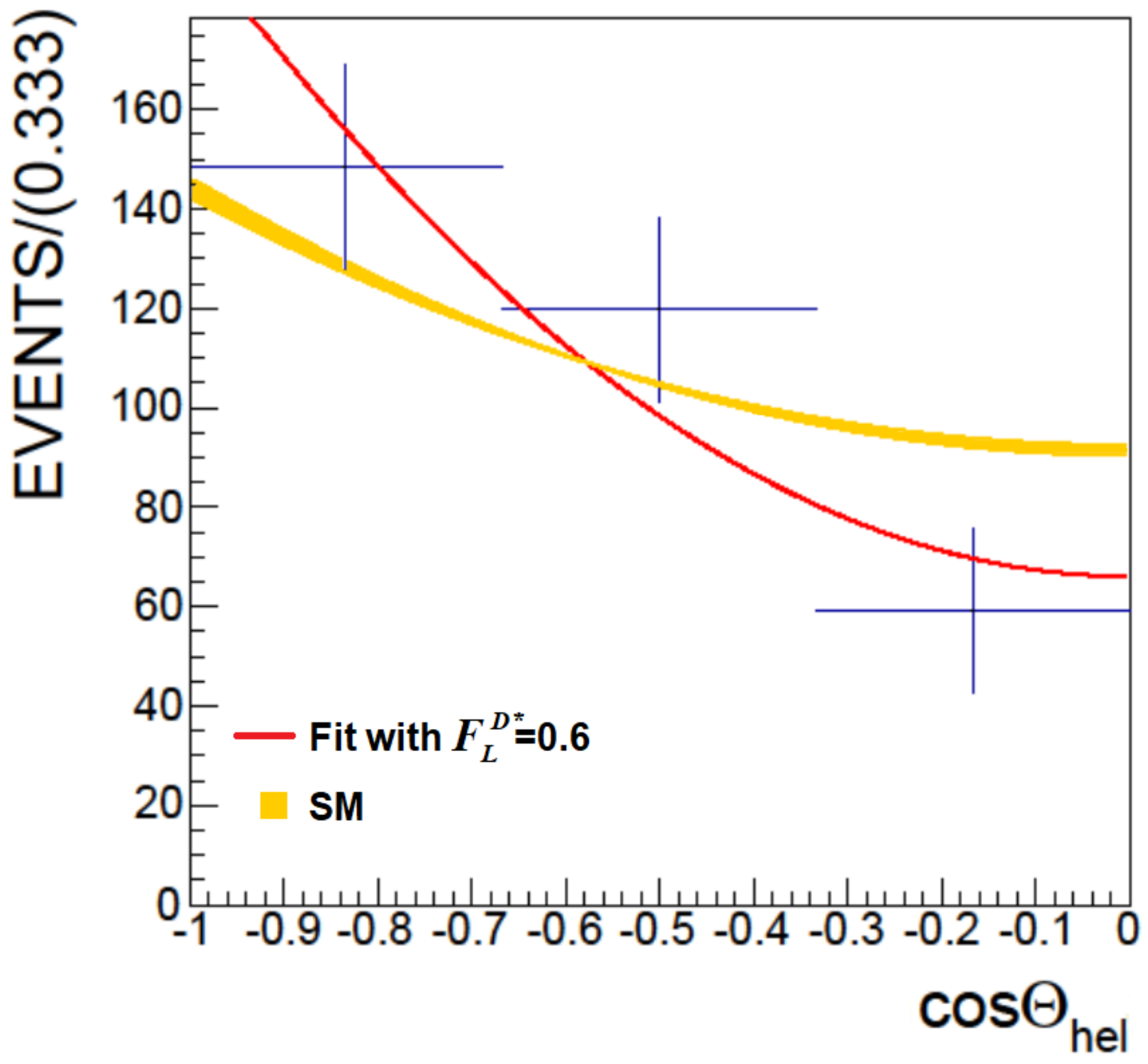
These have the potential to help distinguish between different models and motivate new model-building directions.

Today's talk:

Recent measurements of FLD* and R(J/psi)

Belle measurement of FLD*

(1903.03102)



$$F_{D^*}^L = \frac{\Gamma(\bar{B} \to D_L^* \tau\nu)}{\Gamma(\bar{B} \to D_L^* \tau\nu) + \Gamma(\bar{B} \to D_T^* \tau\nu)}.$$

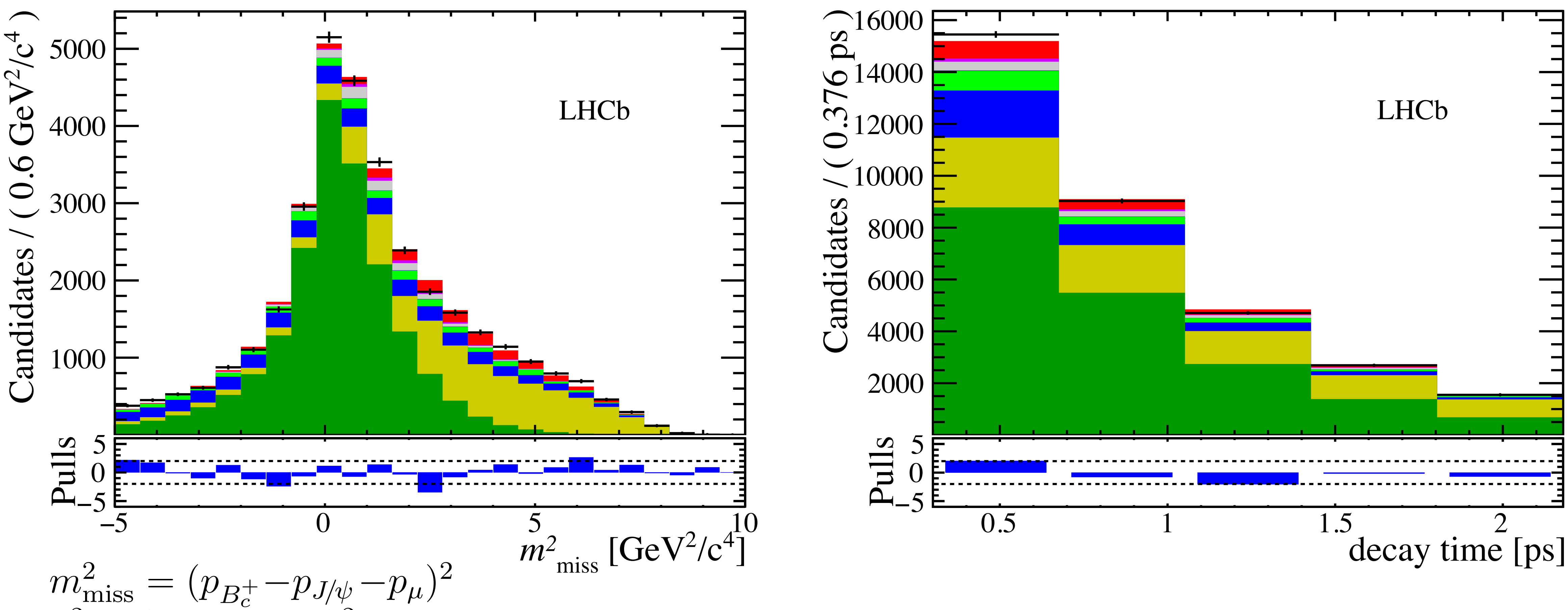
$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$$

$$(F_L^{D^*})_{\text{SM}} = 0.457 \pm 0.010$$

We report the first measurement of the D^* polarization in semitauonic decay $B^0 \to D^{*-}\tau^+\nu_\tau$. The result is based on a data sample of 772×10^6 $B\bar{B}$ pairs collected with the Belle detector. The fraction of D^{*-} longitudinal polarization, measured assuming SM dynamics, is found to be $F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$, and agrees within 1.6 (1.8) standard deviations with the SM predicted values $(F_L^{D^*})_{\text{SM}} = 0.457 \pm 0.010$ [21] (0.441 ± 0.006 [20]).

LHCb measurement of R(J/psi)

(1711.05623)



$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst}).$$

$$R_{J/\psi}{}^{SM} \in (0.2, 0.39)$$

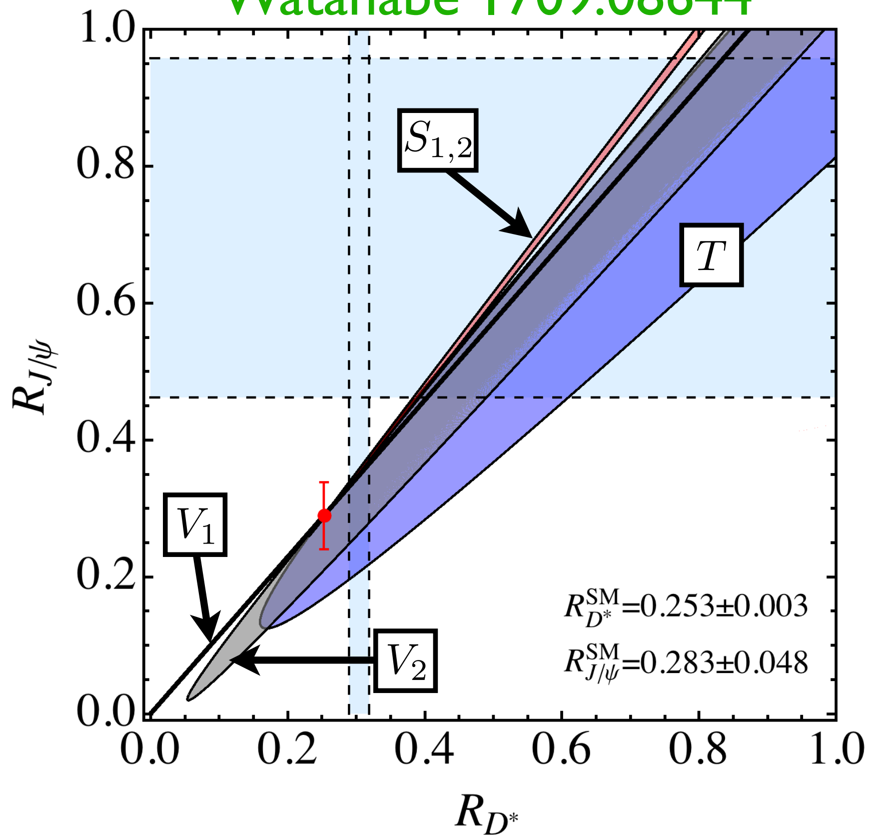
Status of models

Leljak et al 1901.08368

	SM	V_L	S_L	S_R	$S_L = 4T_L$	$(V_L, S_L = -4T_L)$	(S_R, S_L)	(V_L, S_R)	Re,Im$[S_L = 4T_L]$
R_{η_c}	0.32	$0.39^{0.42}_{0.36}$	$0.44^{0.55}_{0.33}$	$0.49^{0.59}_{0.40}$	$0.26^{0.34}_{0.20}$	0.42	0.45	0.44	0.43
$R_{J/\psi}$	0.23	$0.29^{0.31}_{0.26}$	$0.24^{0.24}_{0.23}$	$0.23^{0.22}_{0.23}$	$0.25^{0.26}_{0.23}$	0.29	0.22	0.27	0.26

Table 4: The values of R_{η_c} and $R_{J/\psi}$ in the presence of different NP scenarios. The subscript and the superscript are the values for the 2σ range of the NP couplings.

Watanabe 1709.08644



Iguro et al 1811.08899

	$F_L^{D^*}$
R_2 LQ	[0.43, 0.44]
S_1 LQ	[0.42, 0.48]
U_1 LQ	[0.43, 0.47]
SM	0.46(4)
data	0.60(9)
Belle II	0.04

(see also Tran et al 1801.06927,
Blanke et al 1811.09603)

Maximizing FLD* and R(J/psi)

The measured values of FLD* and R(J/psi) are too high even for NP models!

So far just single mediators, single and pairs of Wilson coefficients studied…

Question: fix R_D, R_{D*} and $Br(B_c \to \tau\nu)$.

How large can we make FLD* and R(J/psi)?

(Asadi & DS, 1905.03311)

Numerical formulas for the observables

$$R_{D^*} F^L_{D^*} = 0.116 \left(|C^V_{-L}|^2 + 0.08|C^S_{-L}|^2 + 7.02|C^T_{LL}|^2 + \mathrm{Re}\left[(C^V_{-L})(0.24(C^S_{-L})^* - 4.37(C^T_{LL})^*) \right] \right),$$

$$R_{J/\psi} = 0.289 \left(0.98|C^V_{-L}|^2 + 0.02|C^V_{+L}|^2 + 0.05|C^S_{-L}|^2 + 10.67|C^T_{LL}|^2 \right.$$
$$\left. + \ \mathrm{Re}\left[C^V_{-L}(0.14(C^S_{-L})^* - 5.15(C^T_{LL})^*) \right] + 0.24\mathrm{Re}\left[C^V_{+L}(C^T_{LL})^* \right] \right),$$

$$R_D = 0.299 \left(|C^V_{+L}|^2 + 1.02|C^S_{+L}|^2 + 0.9|C^T_{LL}|^2 + \mathrm{Re}\left[(C^V_{+L})(1.49(C^S_{+L})^* + 1.14(C^T_{LL})^*) \right] \right),$$

$$R_{D^*} = 0.257 \left(0.95|C^V_{-L}|^2 + 0.05|C^V_{+L}|^2 + 0.04|C^S_{-L}|^2 + 16.07|C^T_{LL}|^2 \right.$$
$$\left. + \ \mathrm{Re}\left[C^V_{-L}(+0.11(C^S_{-L})^* - 5.89(C^T_{LL})^*) \right] + 0.77\mathrm{Re}\left[C^V_{+L}(C^T_{LL})^* \right] \right),$$

$$Br(B_c \to \tau\nu) = 0.023 \left(|C^V_{-L} + 4.33 C^S_{-L}|^2 \right),$$

$$C^S_{\pm L} \equiv C^S_{RL} \pm C^S_{LL} \qquad C^V_{\pm L} \equiv C^V_{LL} \pm C^V_{RL}$$

A nontrivial optimization problem. 10 real dimensional space.

A maximum exists

All the observables are real, symmetric, positive-semidefinite quadratic forms

$$\mathcal{O} = z_5^\dagger M_{\mathcal{O}} z_5 = x_5^T M_{\mathcal{O}} x_5 + y_5^T M_{\mathcal{O}} y_5$$

$$z_5 = x_5 + i y_5 = (C^V_{-L}, C^V_{+L}, C^S_{-L}, C^S_{+L}, C^T_{LL})$$

A global maximum exists: null vectors for RD and RD* are orthogonal

$$C^S_{-L},\ C^V_{-L} \qquad C^S_{+L}$$

After imposing RD, RD* constraints, left with compact space.
Any function on a compact space must have a maximum somewhere.

Maximum occurs for real WCs

Idea: use method of Lagrange multipliers

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$$\tilde{\mathcal{O}} = \mathcal{O} - \lambda_1(R_D - R_D^{(0)}) - \lambda_2(R_{D^*} - R_{D^*}^{(0)}) - \lambda_3(\mathrm{Br}(B_c \to \tau\nu) - \mathrm{Br}(B_c \to \tau\nu)^{(0)})$$

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→ one constraint on $\lambda_{1,2,3}$

Maximum occurs for real WCs

Idea: use method of Lagrange multipliers

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cannot tune to get more than one null eigenvector

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→ one constraint on $\lambda_{1,2,3}$

cannot tune to get more than one null eigenvector

→ $x_5,\ y_5$ must be parallel

can set $y_5 = 0$ with overall rephasing

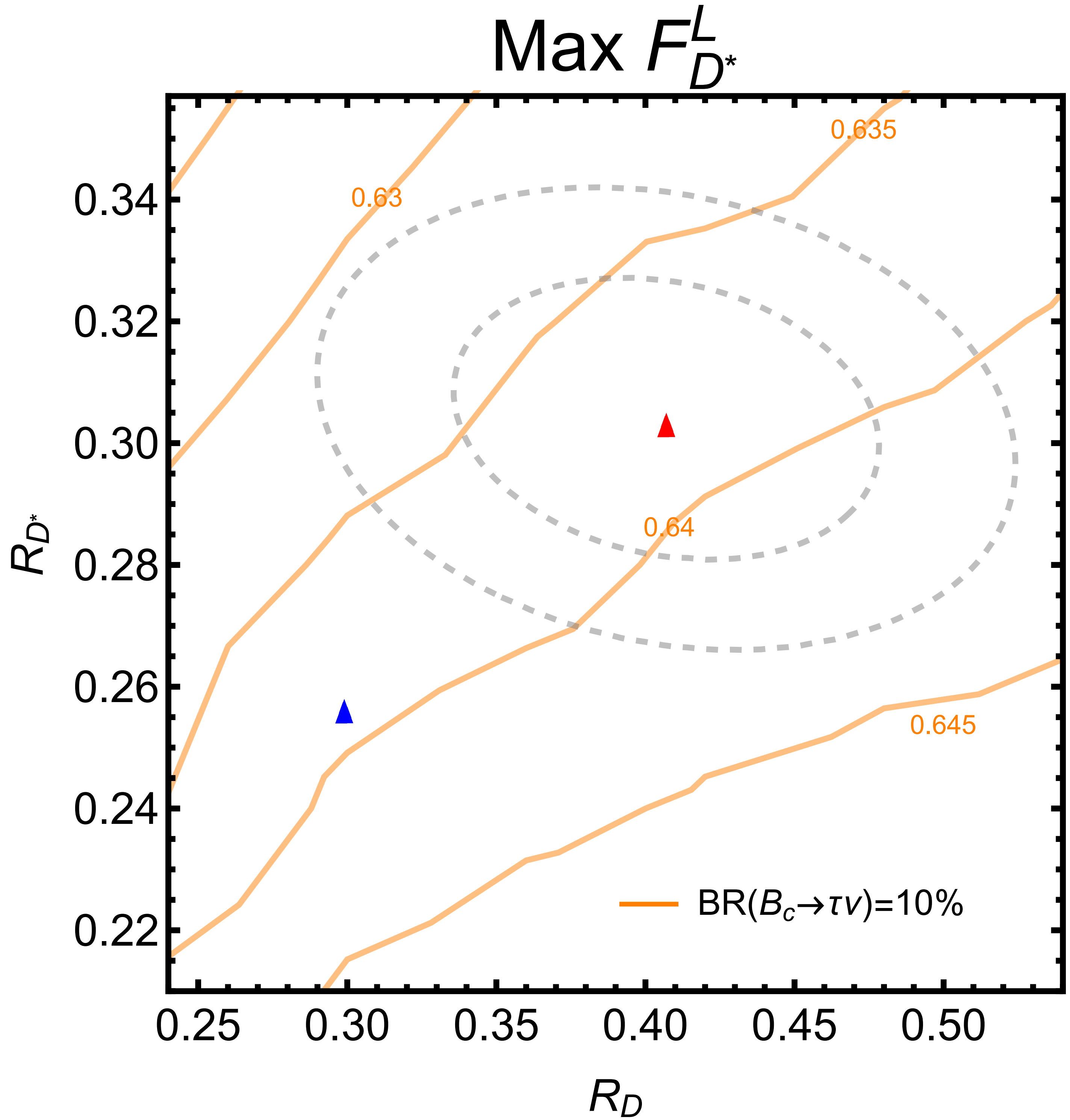
Maximizing FLD* and R(J/psi)

Can extend this argument to show that including RH neutrinos doesn't affect the global maximum.

Reduce parameter space from 10 or 20 -> 5. Solve three constraints: 5->2.

Can numerically maximize and explicitly verify with a plot.

Results

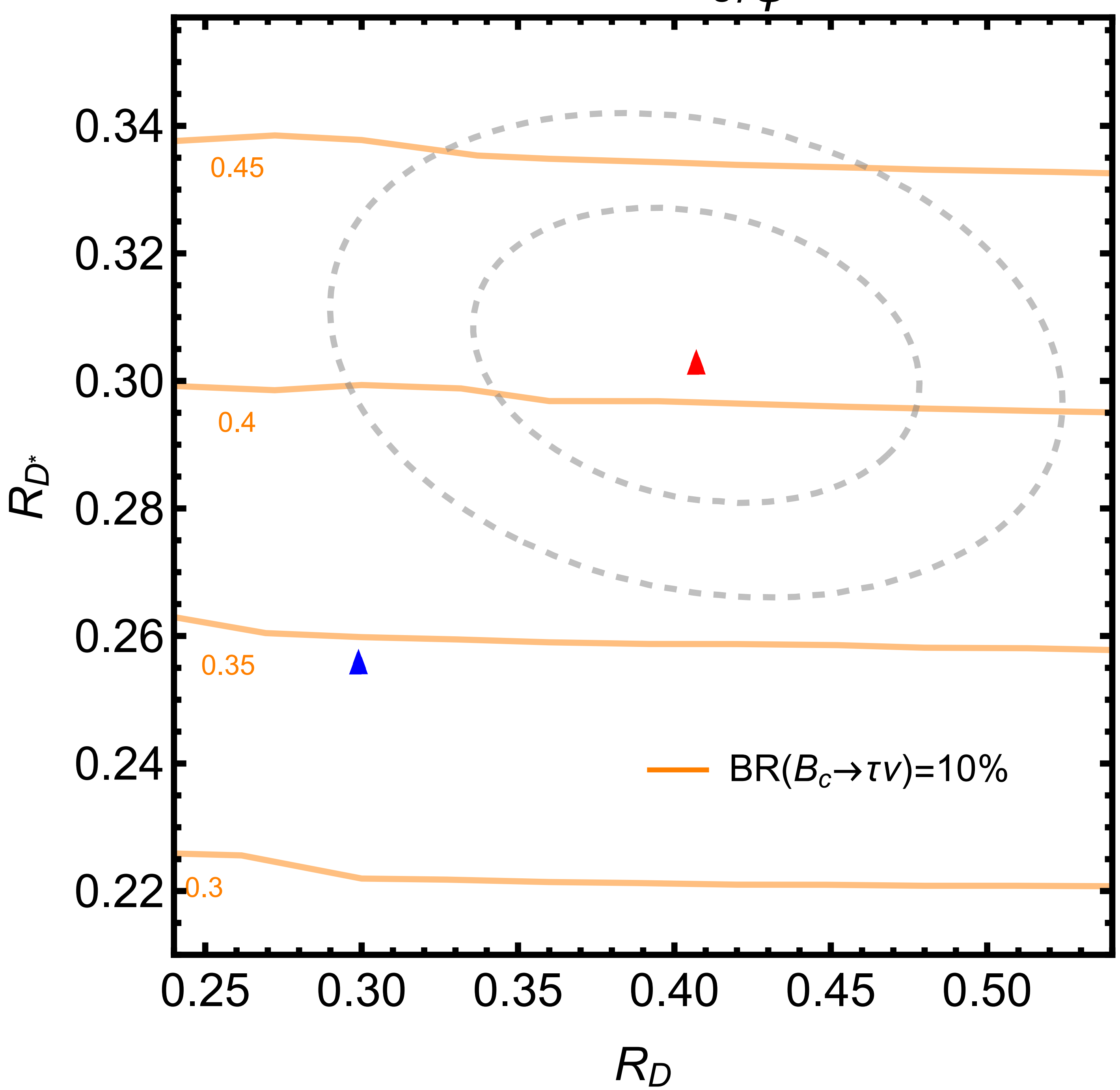


$$F^L_{D^*} = 0.60 \pm 0.08 \pm 0.035$$

Central value of FLD* measurement can be attained.

Results

Max $R_{J/\psi}$



$$R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18.$$

However, central value of R(J/psi) measurement cannot be attained

Results

max FLD*

C^S_{RL}	C^S_{LL}	C^V_{LL}	C^V_{RL}	C^T_{LL}	R_D	R_{D^*}	$F^L_{D^*}$	$R_{J/\psi}$	$Br(B_c \to \tau\nu)$
-0.669	-0.884	0.097	2.029	-0.329	0.407	0.304	0.620	0.406	0.023
-0.791	-0.739	0.118	1.977	-0.302	0.407	0.304	0.638	0.410	0.1
-0.972	-0.555	0.142	1.948	-0.298	0.407	0.304	0.662	0.412	0.3

max R(J/psi)

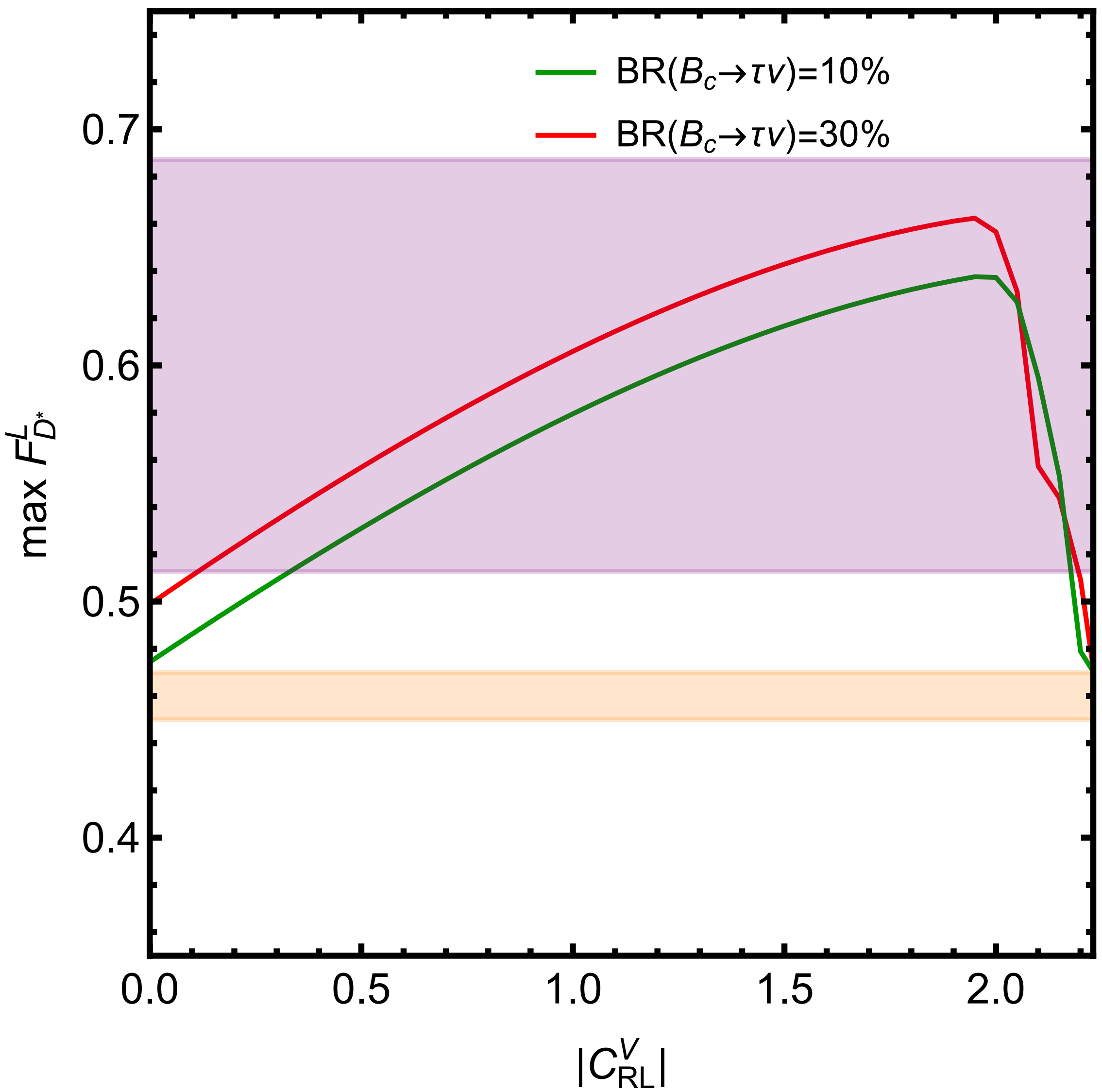
C^S_{RL}	C^S_{LL}	C^V_{LL}	C^V_{RL}	C^T_{LL}	R_D	R_{D^*}	$F^L_{D^*}$	$R_{J/\psi}$	$Br(B_c \to \tau\nu)$
-0.659	-0.857	0.109	1.967	-0.286	0.407	0.304	0.620	0.409	0.023
-0.787	-0.726	0.124	1.948	-0.282	0.407	0.304	0.637	0.410	0.1
-0.967	-0.542	0.147	1.919	-0.277	0.407	0.304	0.660	0.413	0.3

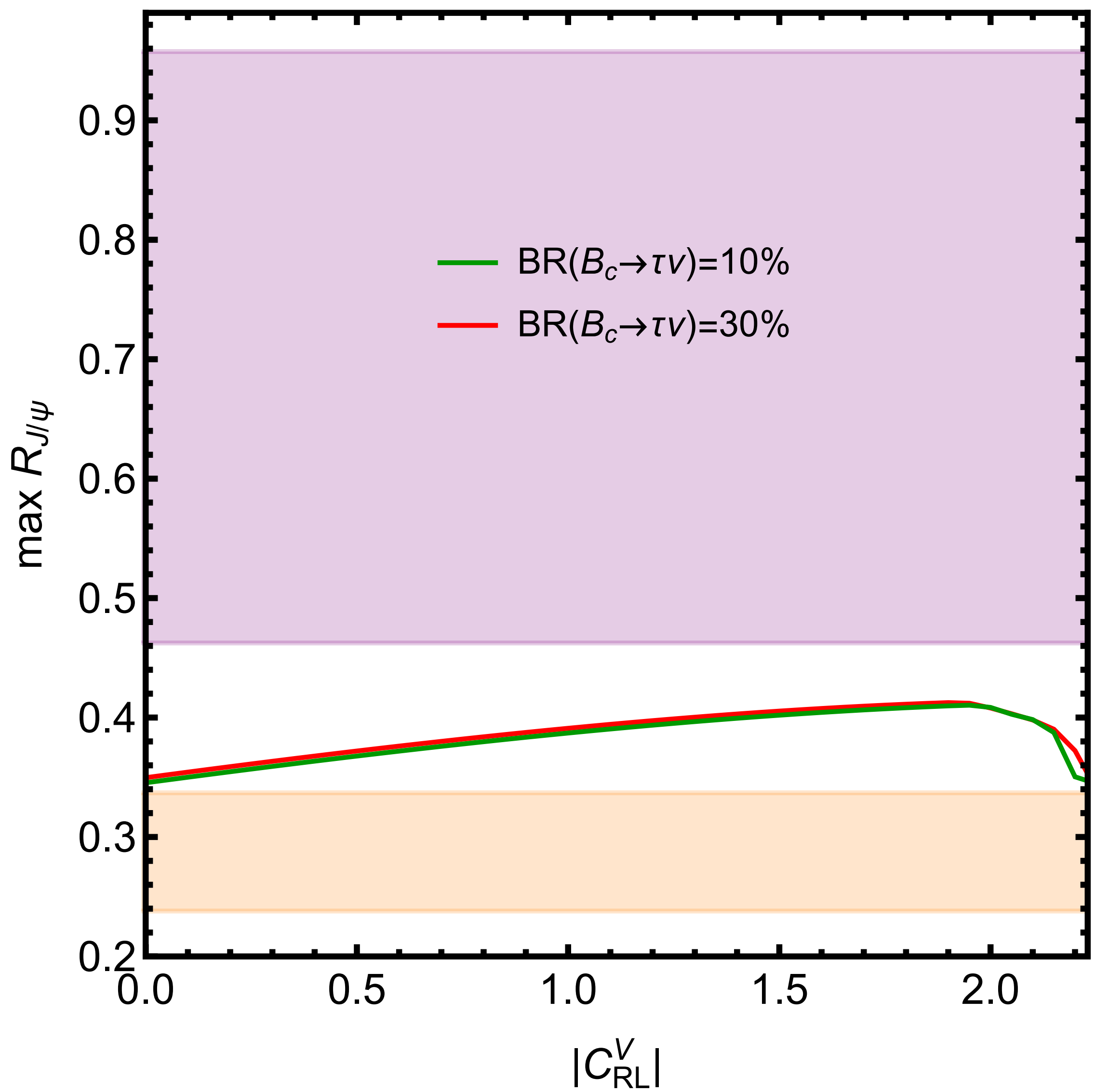
Points are uncannily similar…needs to be further understood…

Both require large CVRL!

See recent work of Murgui et al who reached similar conclusions via global fits 1904.09311

Results





Maximum with fixed CVRL

Arguments against $\mathcal{O}_{RL}^{V}$

$$\mathcal{O}_{RL}^{V} = (\bar{c}\gamma^{\mu} P_R b)(\bar{\tau}\gamma_{\mu} P_L \nu)$$

forbidden by both $SU(2)_L$ and $U(1)_Y$

$$(\bar{c}_R \gamma^{\mu} b_R)(\bar{L}_3 \gamma_{\mu} \tau^a L_i) H^A \tau^a H^B \epsilon_{AB}$$

dimension 8 operator

$$(\bar{c}_R \gamma^{\mu} b_R) H^A D_{\mu} H^B \epsilon_{AB}$$

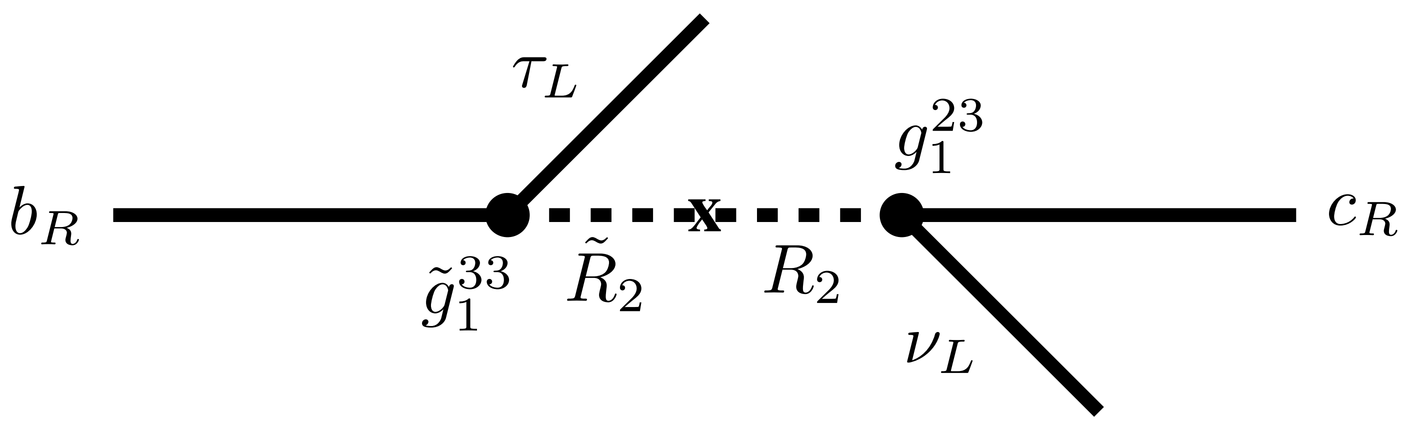
dimension 6 operator
but flavor universal

"No go theorem"

A loophole?

Key idea: use two leptoquarks that mix through Higgs vev

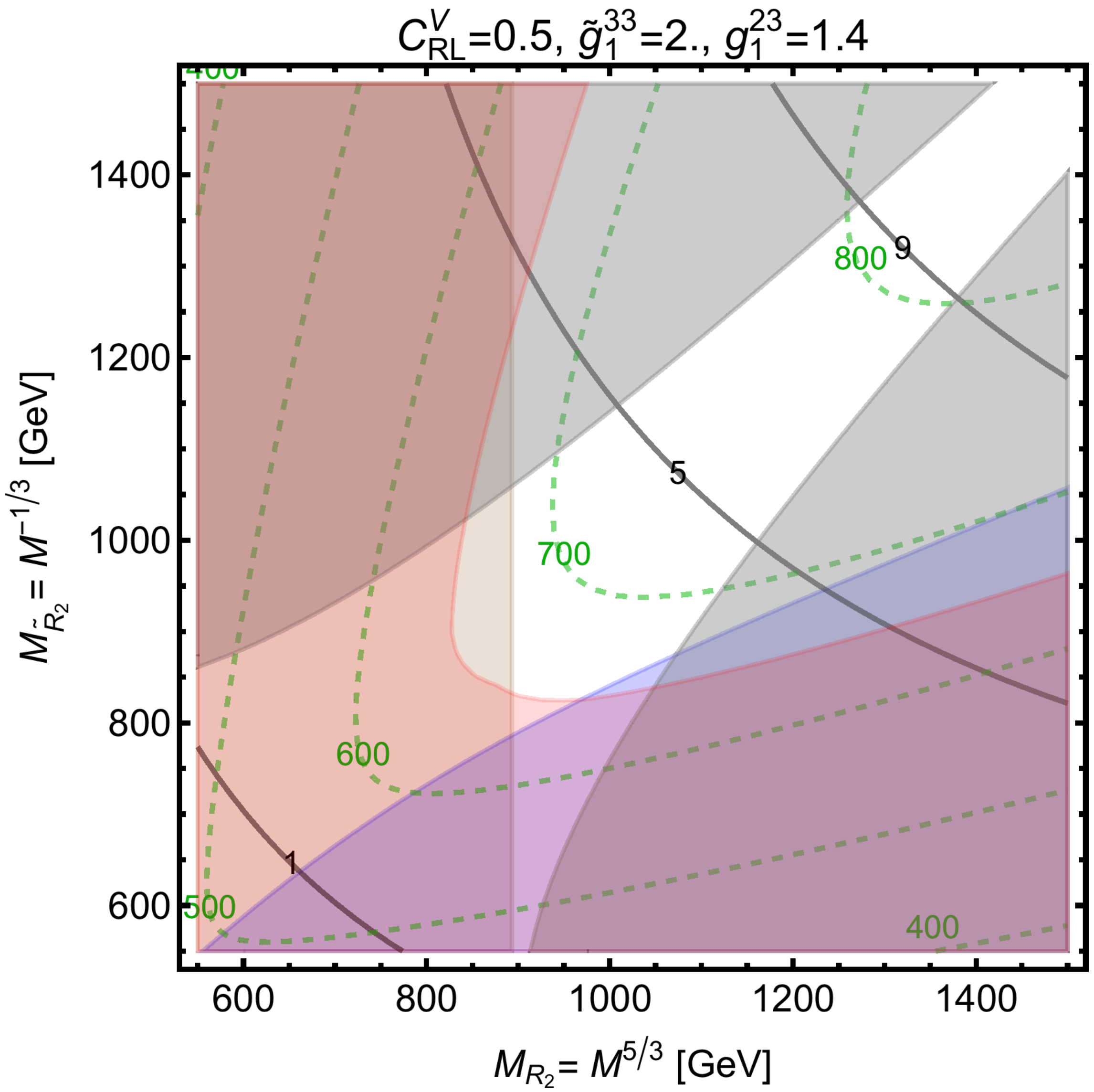
Asadi, Nakai & DS
1905.xxxxx



$$R_2 = \begin{pmatrix} {R_2}^{5/3} \\ {R_2}^{2/3} \end{pmatrix}, \qquad \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{2/3} \\ \tilde{R}_2^{-1/3} \end{pmatrix} \qquad M^2_{2/3} = \begin{pmatrix} M^2_{R_2} - \lambda_R v^2 & \lambda_R v^2 \\ \lambda_R v^2 & M^2_{\tilde{R}_2} - \lambda_R v^2 \end{pmatrix}$$

$$C^V_{RL} \sim \frac{\lambda_R v^4}{M^4}$$

Can try to overcome dim 8 suppression with light leptoquarks
and large quartic coupling



stringent bounds from $\tau^+\tau^-$, direct leptoquark searches, SUSY searches

but some viable parameter space still remains!

Conclusions

The central measured values of FLD* and R(J/psi) are both higher than their SM predictions. They are also higher than the predictions from any known NP model.

We developed a semi-analytical method to maximize FLD* and R(J/psi) in the full space of dimension 6 WCs, subject to RD/RD* constraints.

- Using our method, we showed that FLD* is achievable in the space of WCs but R(J/psi) is not.
- Requires large CVRL WC — "no go theorem" can be evaded with a novel leptoquark model
- Our method is generalizable and can be applied to essentially any $b \to c\tau\nu$ observable.

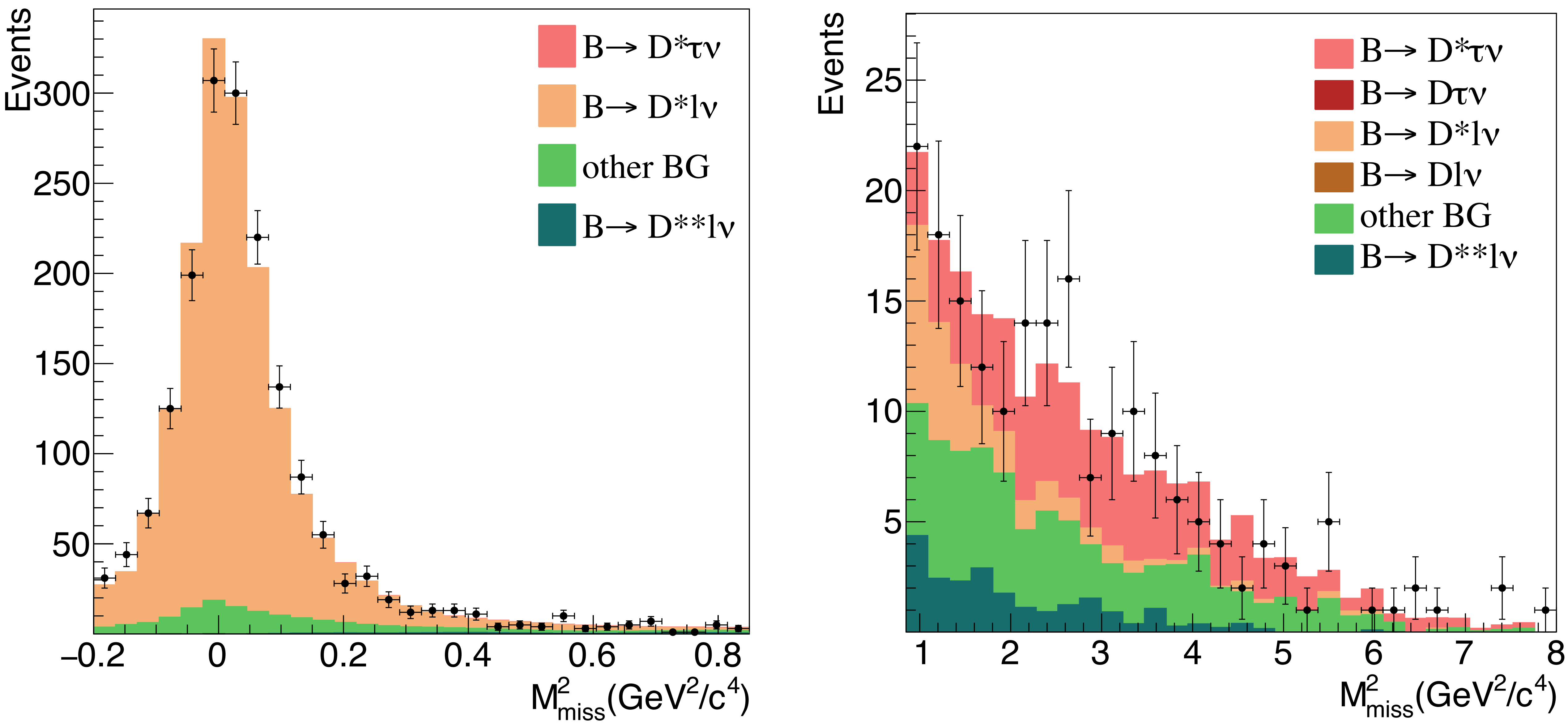
Experimental error bars are still large — very likely a fluctuation.

Upcoming measurements by LHCb and Belle II could prove to be interesting. Meanwhile we have new ideas for model building to explore.

Stay tuned!

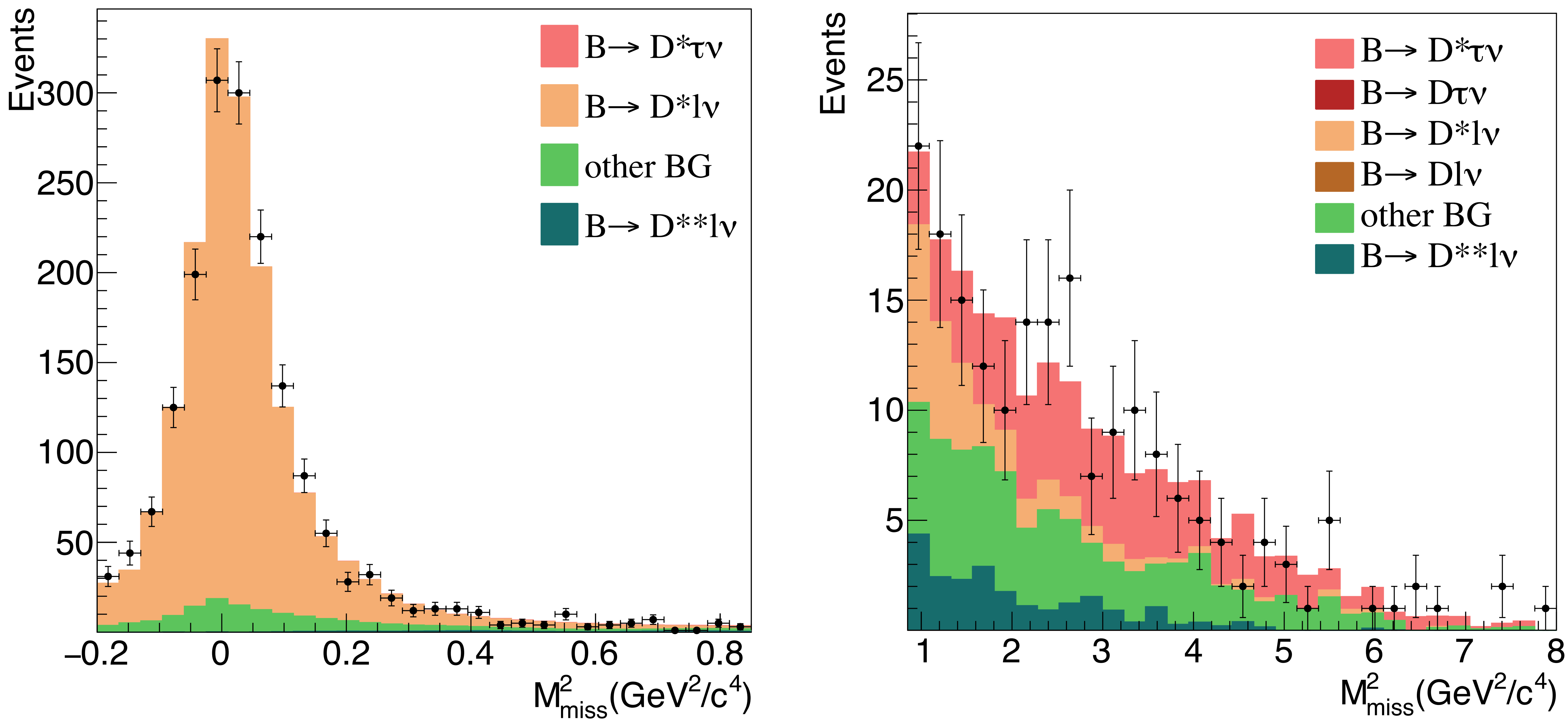
Thanks for your attention!

Belle 1507.03233



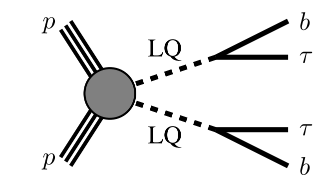
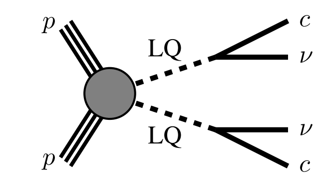
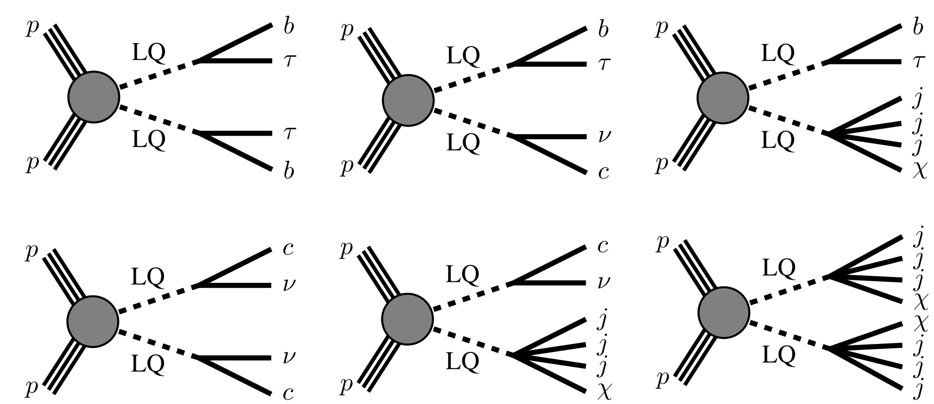
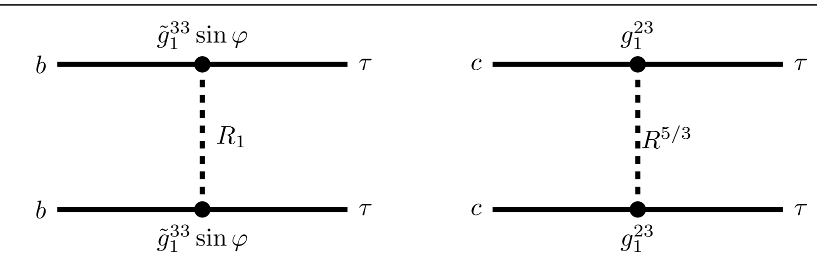
ARE WE SURE THAT THESE ARE SM NEUTRINOS?

Belle 1507.03233



ARE WE SURE THAT THESE ARE SM NEUTRINOS?

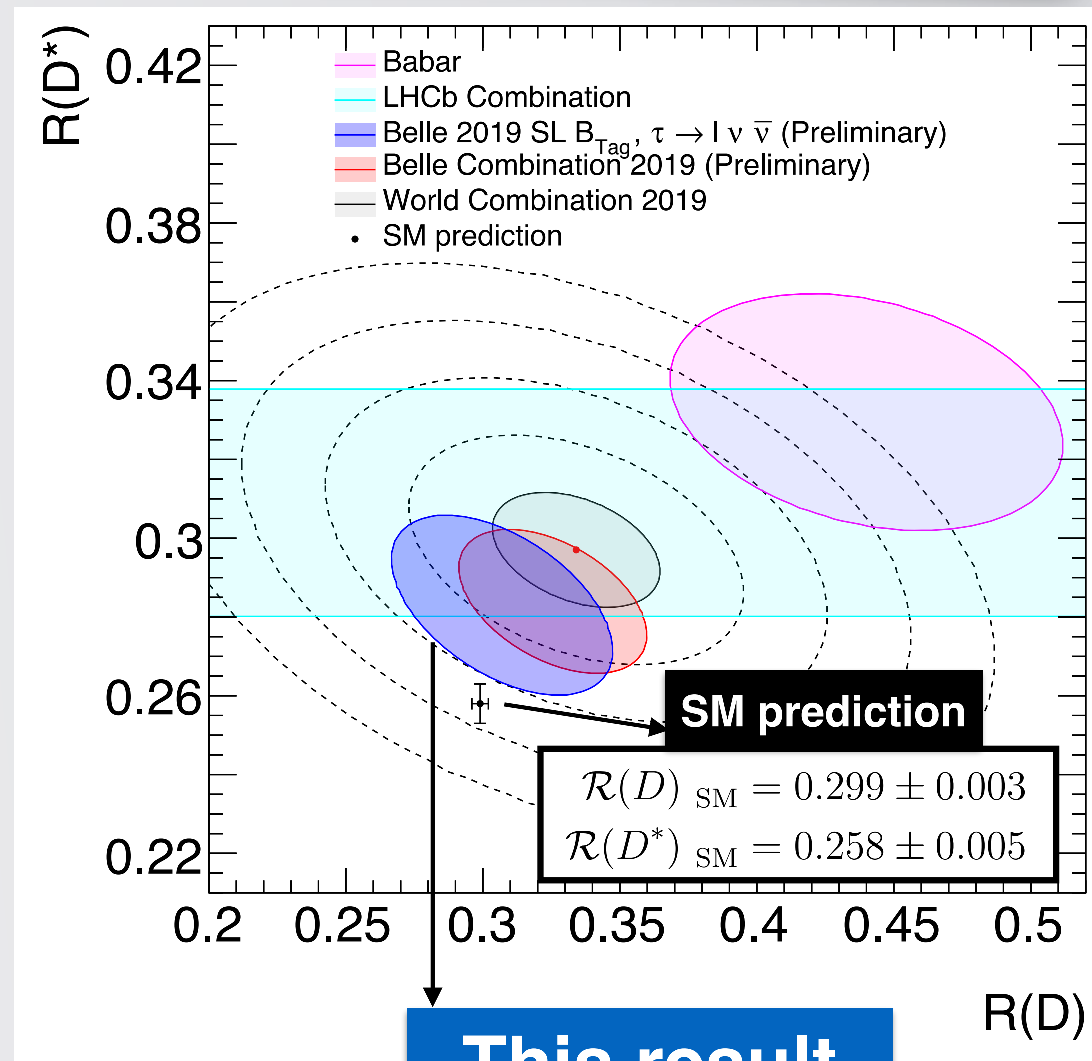
➡ Could be a light, weakly-interacting BSM particle instead?

Description	Experiment+Luminosity	*reducible* vs. *irreducible*	Reference	Diagrams
Direct LQ search for $b\tau$ final state	CMS-35.9 fb^{-1}	*reducible*	[48]	
Direct LQ search for $c\nu$ final state	ATLAS-36.1 fb^{-1}	*reducible*	[45]	
generic SUSY search with MET	CMS-35.9 fb^{-1}	*reducible*	[51–54]	
Interference with the SM DY	ATLAS-36.1 fb^{-1}	*irreducible*	[46] (based on [63])	

Moriond 2019 update from Belle [paper is out: 1904.08794]

Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**

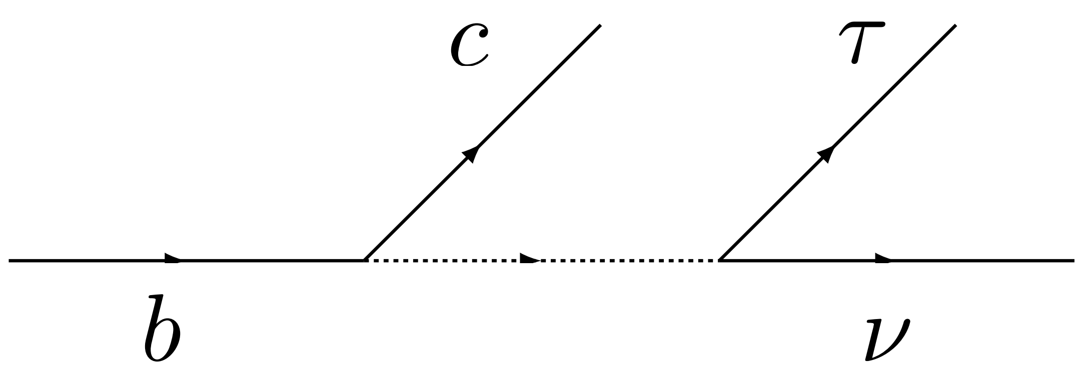


This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

These latest results not included in today's talk…

Problems with charged Higgs



Contributes to $B_c \to \tau\nu$

BR currently not measured. LHCb prospects are not good…

Upper bound from SM predictions for other final states decay widths, compared to measured total width
(Alonso, Grinstein & Camalich 1611.06676.)

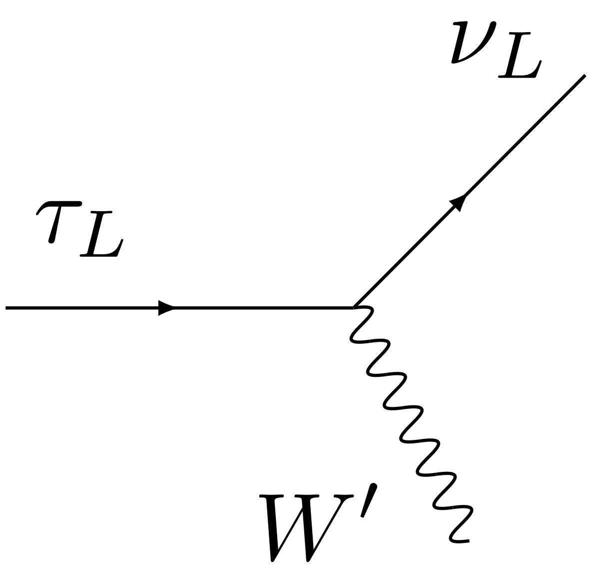
$$\mathrm{Br}(B_c \to \tau\nu) \lesssim 30\%$$

Upper bound based on LEP search for $B_u \to \tau\nu$
(Akeroyd & Chen 1708.04072)

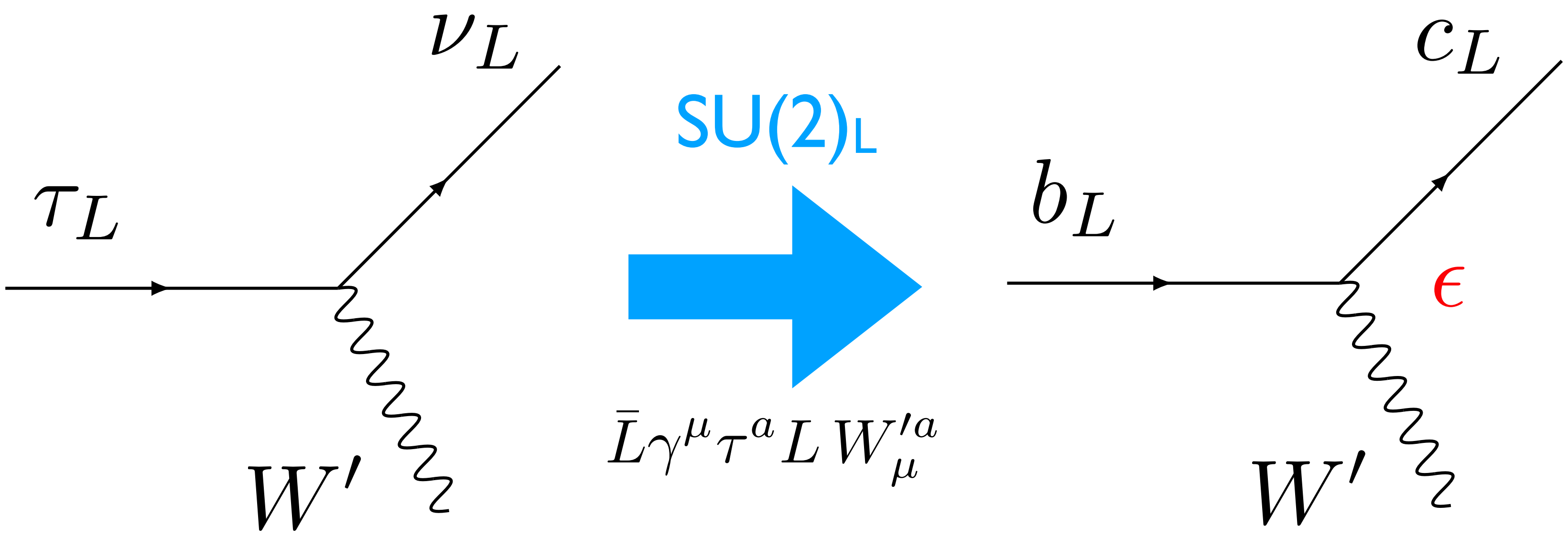
$$\mathrm{Br}(B_c \to \tau\nu) \lesssim 10\%$$

Rules out charged Higgs explanations of RD/RD* anomaly!

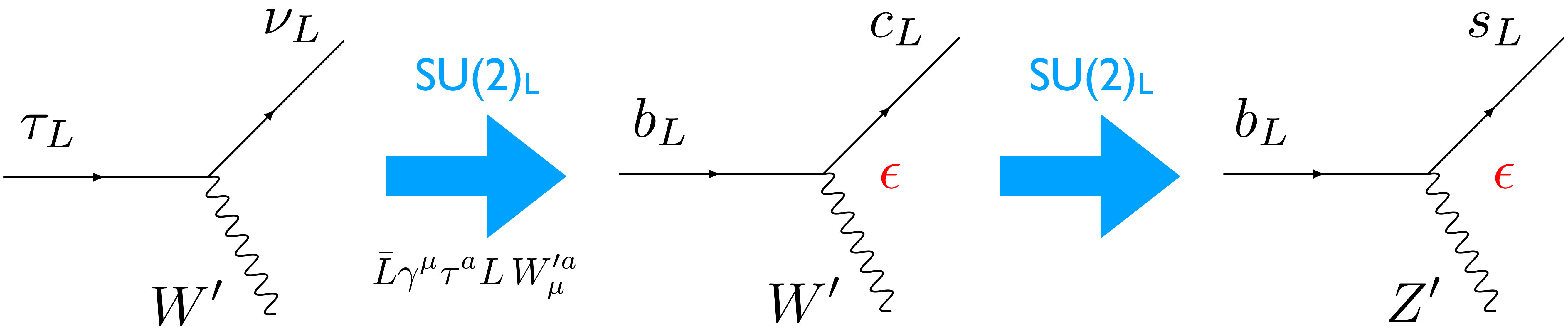
Problems with W'



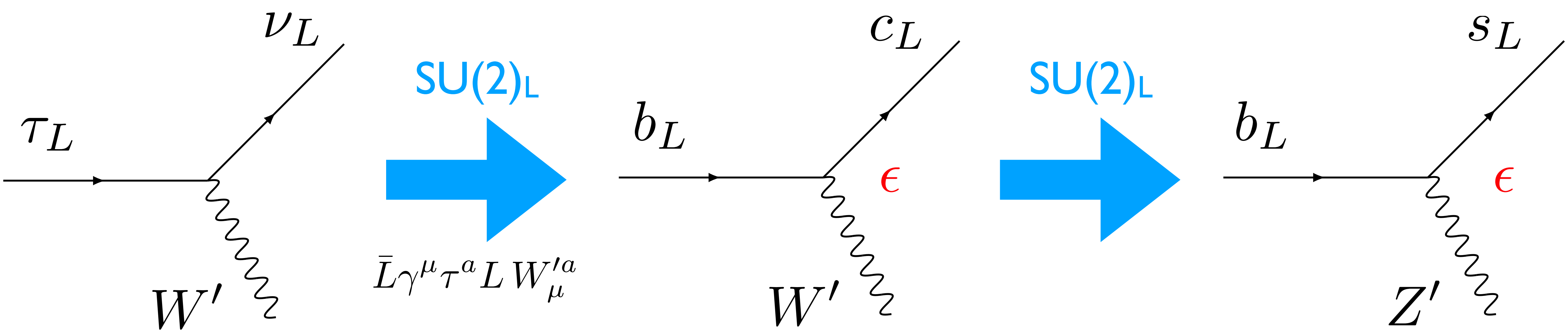
Problems with W'



Problems with W'

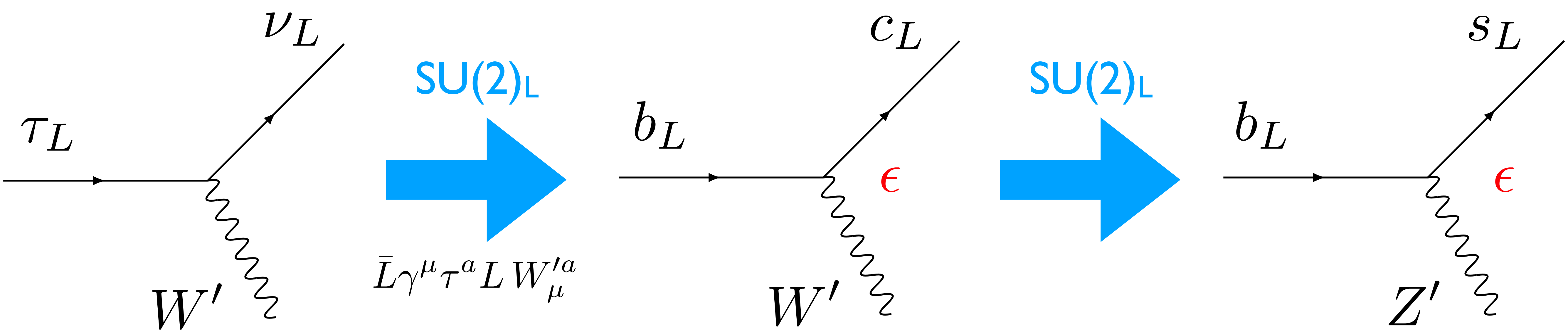


Problems with W'



Tree-level FCNCs!

Problems with W'

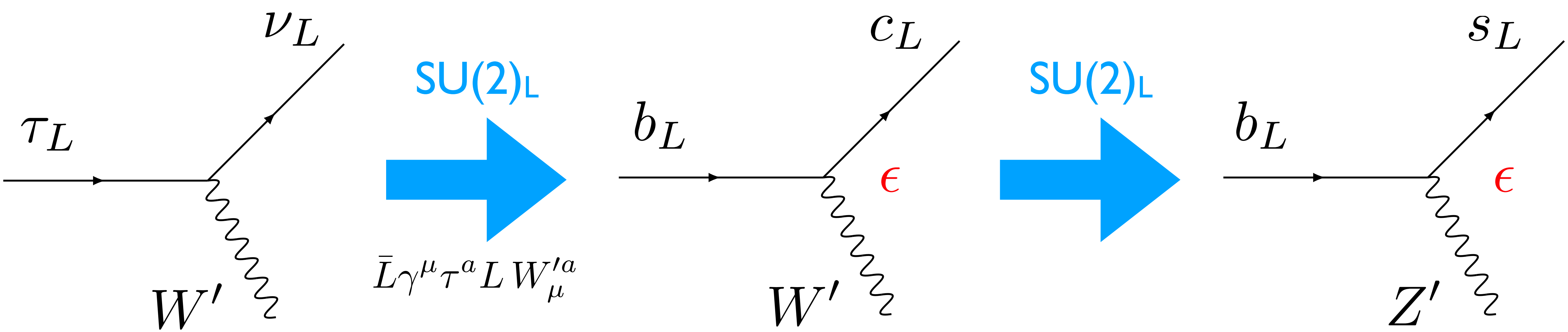


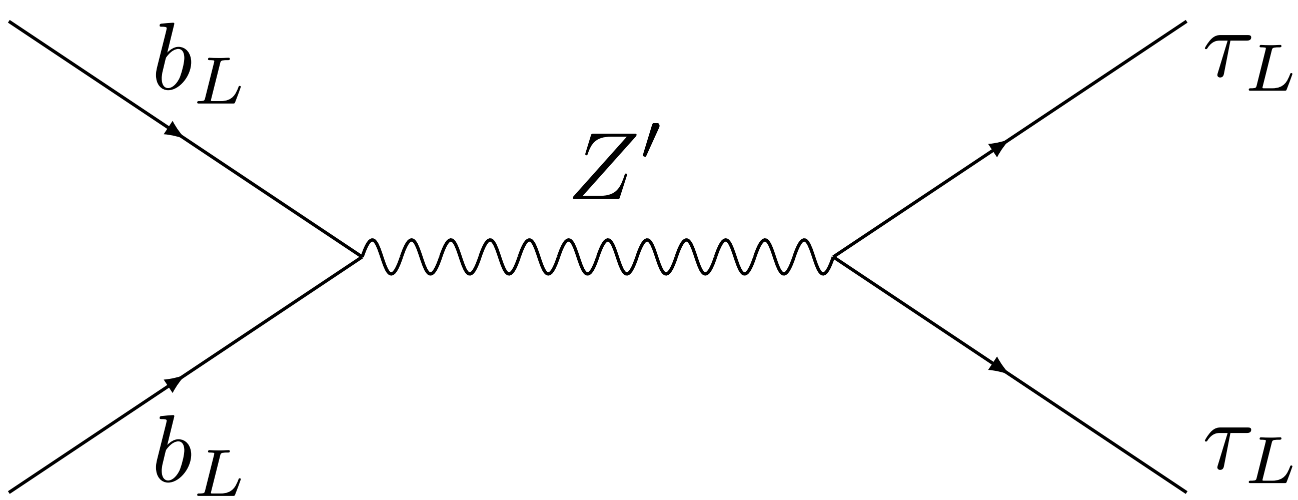
Tree-level FCNCs!

Need 3rd generation dominance

$\epsilon \sim V_{cb}$

Problems with W'





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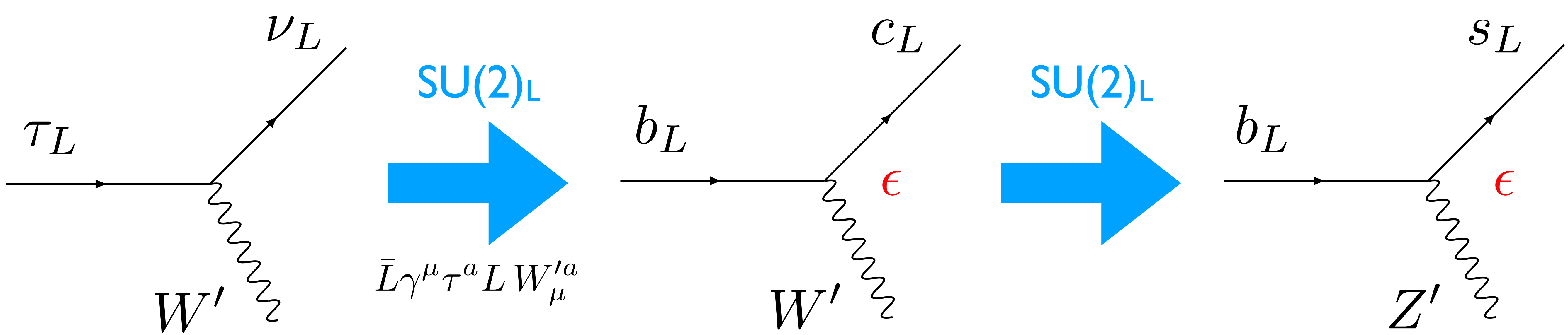
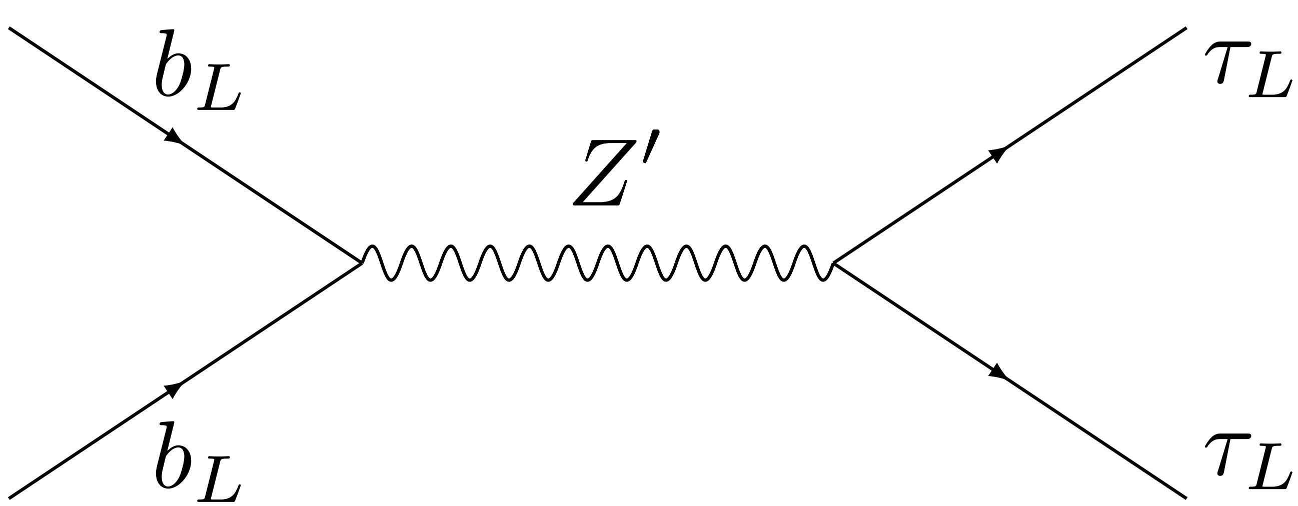




Tree-level FCNCs!

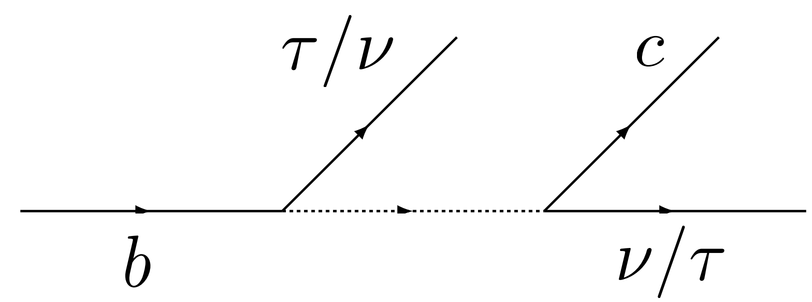
Need 3rd generation dominance

$\epsilon \sim V_{cb}$

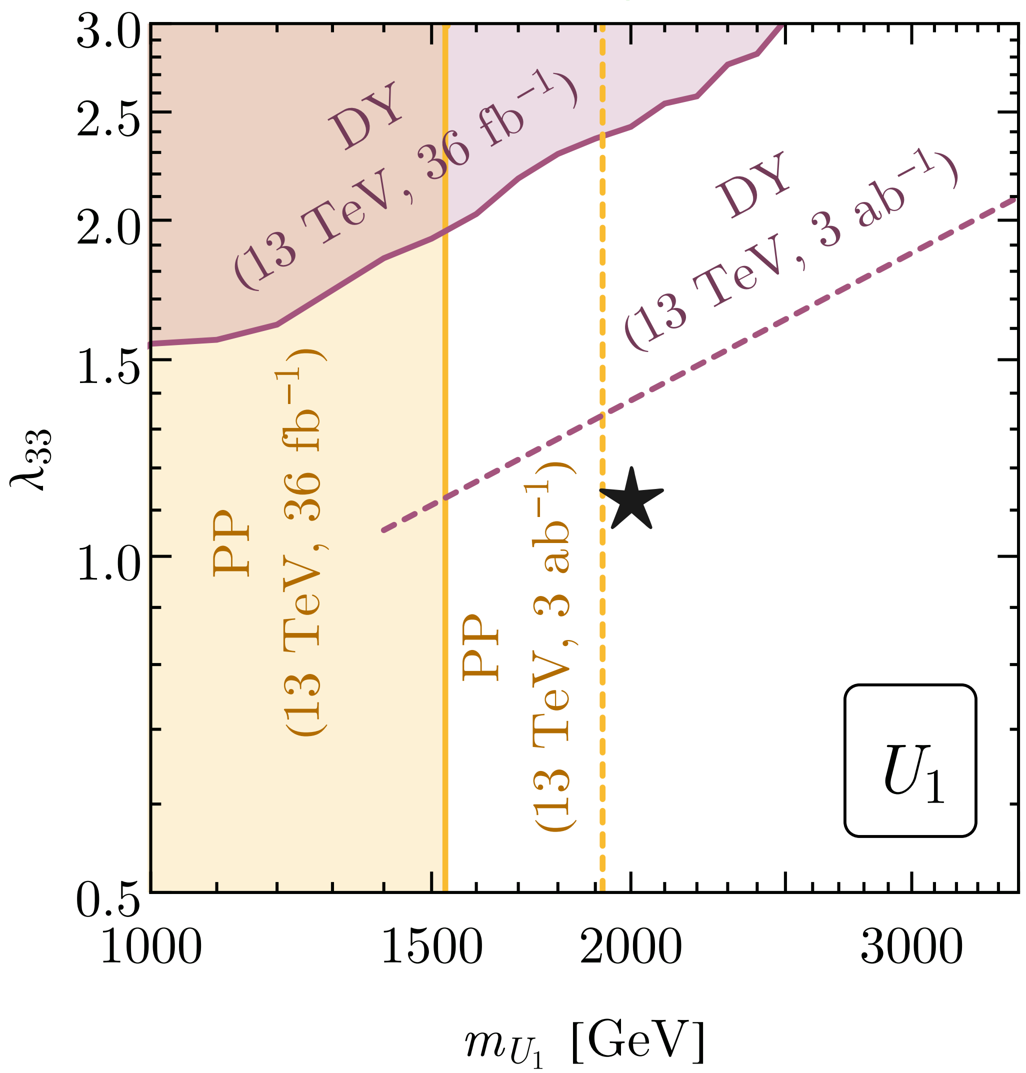
Strong constraints from Z'→ττ resonance searches rule out these models!

Faroughy et al 1609.07138, Crivellin et al 1703.09226

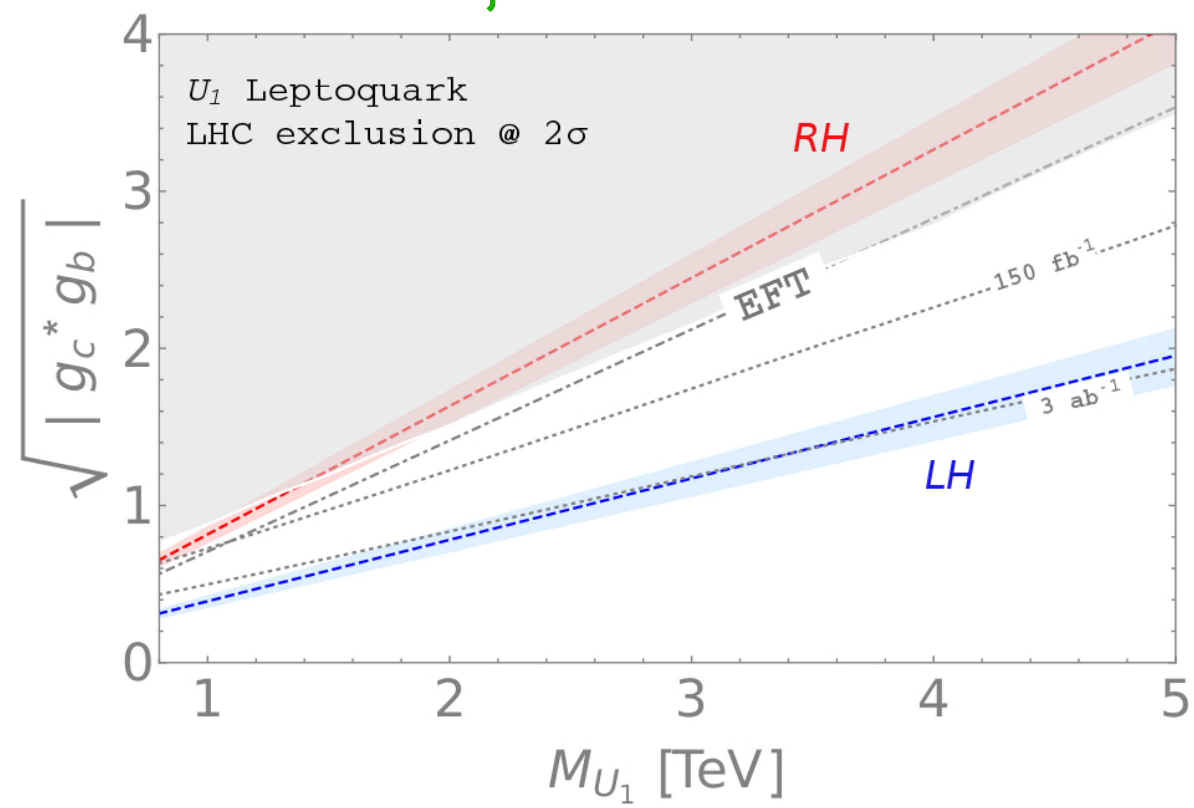
Leptoquarks



Schmaltz & Zhong 1810.10017



Greljo et al 1811.07920



Strong LHC constraints from pair production, DY, and mono-tau, but much parameter space remains