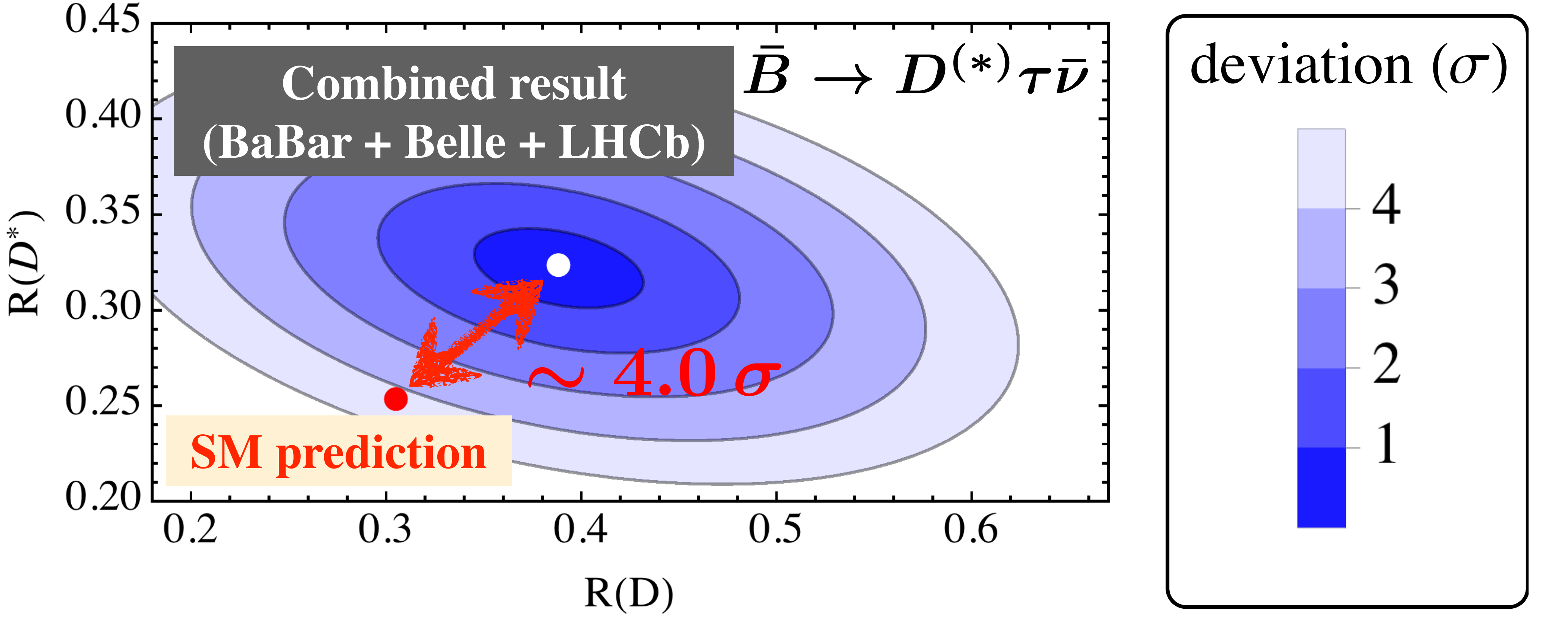
Mini-workshop on $\bar{B} \to D^{(*)}\tau\bar{\nu}$

March 27, 2017

Three ways of probing NP in $\bar{B} \to D^{(*)}\tau\bar{\nu}$

Ryoutaro Watanabe (U. Montréal)

based on
arXiv:1412.3761, 1603.05248, 1609.09078



How can we probe NP in this process?

Three possible ways

[1] measuring distributions

[2] detecting collider signals

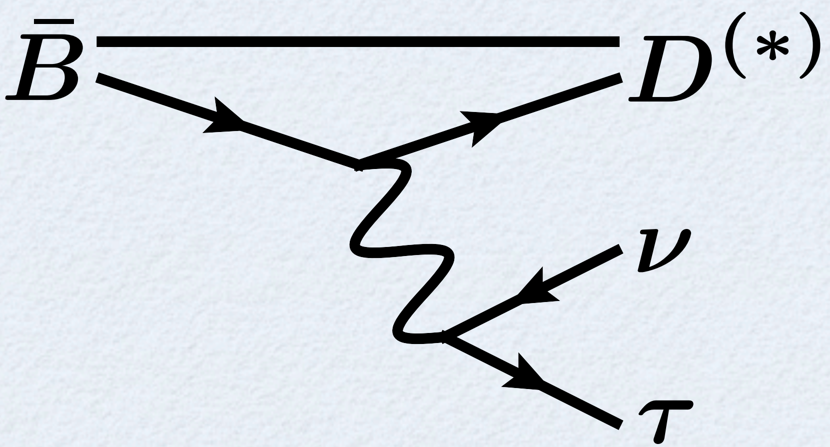
[3] looking at correlations with other processes

[1]
Distributions

arXiv:1412.3761

Usage :

Distinguish NP type by looking at difference in shape of q^2 distribution



$$q^2 = (p_B - p_{D^{(*)}})^2$$

[Distributions]

Possible NP scenario :

$$\mathcal{L}_{\mathrm{eff}}^{\mathrm{NP}} \equiv -2\sqrt{2} G_F V_{cb}\, C_{\mathrm{NP}} \mathcal{O}_{\mathrm{NP}}$$

- **Vector** **(W' vector, Vector Leptoquark)**

$$\mathcal{O}_{V_1} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu) \quad / \quad \mathcal{O}_{V_2} = (\bar{c}\gamma^{\mu} P_R b)(\bar{\tau}\gamma_{\mu} P_L \nu)$$

- **Scalar** **(Charged Higgs, Scalar Leptoquark)**

$$\mathcal{O}_{S_1} = (\bar{c}\, P_R b)(\bar{\tau} P_L \nu) \quad / \quad \mathcal{O}_{S_2} = (\bar{c}\, P_L b)(\bar{\tau} P_L \nu)$$

- **Tensor**

$$\mathcal{O}_{T} = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$$

- **"LQ specific" combination**

$$C_{\mathrm{LQ}_1} \equiv C_{S_2} = +4 C_T \quad / \quad C_{\mathrm{LQ}_2} \equiv C_{S_2} = -4 C_T$$

[Distributions]

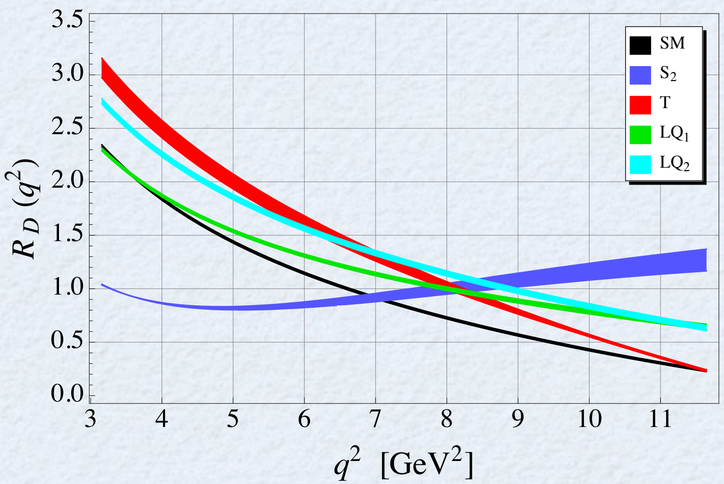
TEST

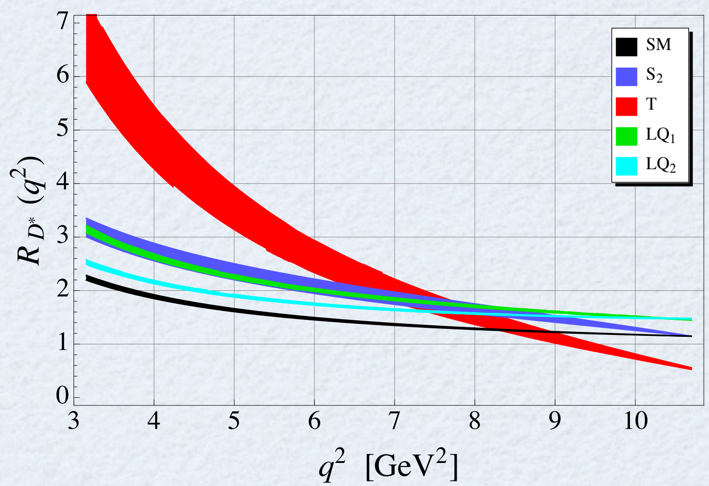
- **Assumption :** **The current deviations in $R_{D^{(*)}}$ remain in future**
- **Question :** **"When" can we probe NP at Belle2 experiment ?**
- **Approach :**

Evaluate required Belle2 luminosity
so that NP can be distinguished with 95%CL

(Image)

Distributions for the case that C_{NP} = best fitted to the current results of $R_{D^{(*)}}$





[Distributions]

TEST

- **Result :**

$\mathcal{L}$ [fb^{-1}]		model						
		SM	V_1	V_2	S_2	T	LQ$_1$	LQ$_2$
"data"	V_1	1170 (270)		10^6 (–)	500 (–)	900 (–)	4140 (–)	2860 (1390)
	V_2	1140 (270)	10^6 (–)		510 (–)	910 (–)	4210 (–)	3370 (1960)
	S_2	560 (290)	560 (13750)	540 (36450)		380 (–)	1310 (35720)	730 (4720)
	T	600 (270)	680 (–)	700 (–)	320 (–)		620 (–)	550 (1980)
	LQ$_1$	1010 (270)	4820 (–)	4650 (–)	1510 (–)	800 (–)		5920 (1940)
	LQ$_2$	1020 (250)	3420 (1320)	3990 (1820)	1040 (20560)	650 (4110)	5930 (1860)	

for q^2 distribution

(for $R_{D^{(*)}}$)

[Distributions]

TEST

- **Result :**

$\mathcal{L}$ [fb^{-1}]		model						
		SM	V_1	V_2	S_2	T	LQ_1	LQ_2
"data"	V_1	1170 (270)		10^6 (–)	500 (–)	900 (–)	4140 (–)	2860 (1390)

for q^2 distribution (upper values)

(for $R_{D^{(*)}}$) (values in parentheses)

How to see the table : ex) "data" = V1

If q^2 data looks like that for V1 prediction,

we can distinguish [the data] with [S2 model]

when Belle2 accumulates 500fb^-1 data

[Distributions]

TEST

- **Result :**

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		SM	V_1	V_2	S_2	T	LQ$_1$	LQ$_2$
"data"	V_1	1170 (270)		10^6 (–)	500 (–)	900 (–)	4140 (–)	2860 (1390)

← **for q^2 distribution**

← **(for $R_{D^{(*)}}$)**

How to see the table : ex) "data" = V1

If q^2 data looks like that for V1 prediction,
we can distinguish [the data] with [S2 model]
when Belle2 accumulates 500fb^-1 data

- **Found :**

Measuring q^2 distribution with ~5ab^-1

can identify NP type for almost all cases

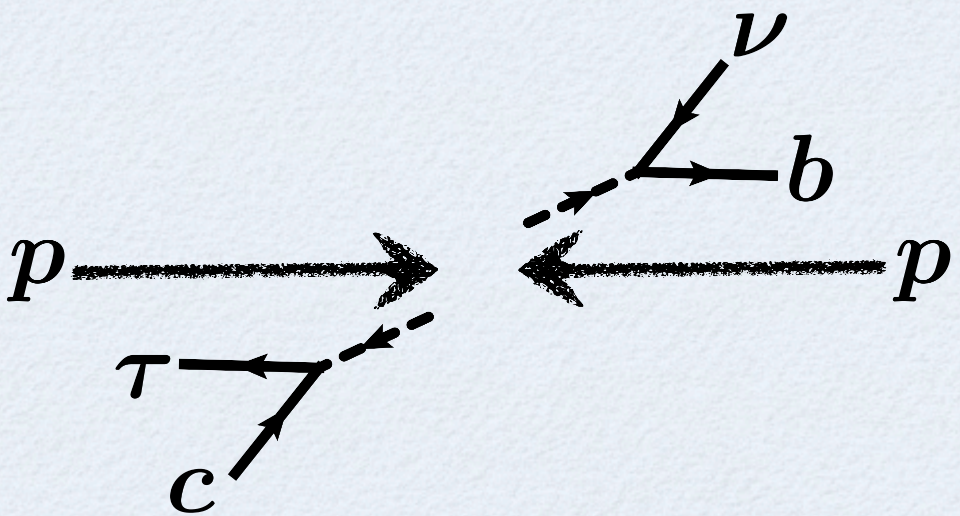
[2]

Collider signal

arXiv: 1603.05248

Usage :

Directly detect NP signal at LHC,
consistent with the $R_{D^{(*)}}$ anomaly



Model dependent

Scalar LQ

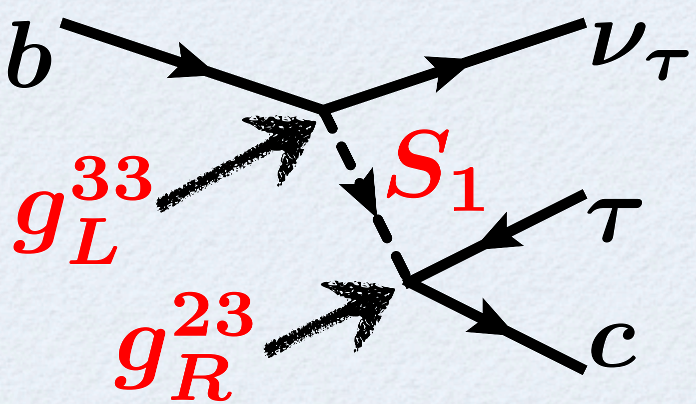
[Collider signal]

Scalar Leptoquark

- **Lagrangian**

$$\mathcal{L}_{\rm LQ} = \left(g_L^{ij}\, \overline{Q}_L^{c,i} (i\sigma_2) L_L^j + g_R^{ij}\, \overline{u}_R^{c,i} \ell_R^j \right) S_1$$

- $\bar{B} \to D^{(*)} \tau \bar{\nu}$



Minimum setup to address the anomaly :

$$\frac{g_L^{33} g_R^{23*}}{M_{S_1}^2} \simeq -0.5\, C_{\rm SM}$$

$$\left(C_{\rm SM} = 2\sqrt{2} G_F V_{cb} \right)$$

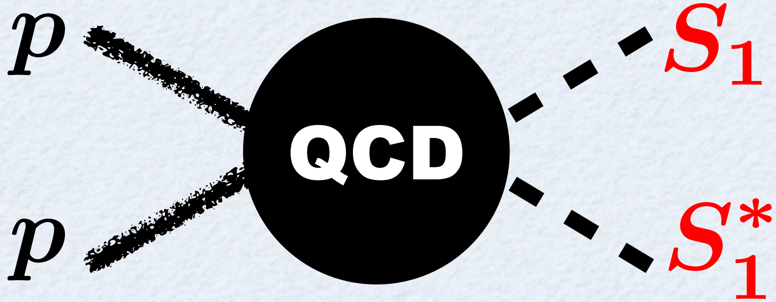
- **Decay process**

g_L^{33} : $S_1 \to b\nu_\tau,\, t\tau$ $\qquad$ g_R^{23} : $S_1 \to c\tau$

[Collider signal]

LQ production at the LHC

- **Pair production due to QCD**



$\sigma \sim 10\,\mathrm{fb}$

(for $M_{S_1} = 1\,\mathrm{TeV}$)

(independent of $g_{L,R}$)

- **Possible signal pattern**

$$pp \to S_1 S_1^* \to \begin{cases} (t\tau)(t\tau) \\ (b\nu)(b\nu) \\ (c\tau)(c\tau) \\ \vdots \end{cases}$$

Detailed cut analyses for these two signals are available

[Collider signal]

Detailed cut analyses

$(b\nu)(b\nu)$

SUSY sbottom search can be applied

[ATLAS-COM-PHYS-2014-555]

Just follow the same analyses for the case of

$$M_{\tilde{\chi}_1^0} = 0$$

$(c\tau)(c\tau)$

LQ search by $(b\tau)(b\tau)$ can be referred

[CMS, arXiv:1408.0806]

c-jet tagging rate has to be implemented

"ideal" [arXiv:1505.06689]

$\epsilon_{c\to c} = 50\%, \quad \epsilon_{b\to c} = 20\%, \quad \epsilon_{\mathrm{light}\to c} = 0.5\%$

"robust" [arXiv:1501.01325]

$\epsilon_{c\to c} = 19\%, \quad \epsilon_{b\to c} = 13\%, \quad \epsilon_{\mathrm{light}\to c} = 0.5\%$

"another" [ATLAS-PHYS-2015-001]

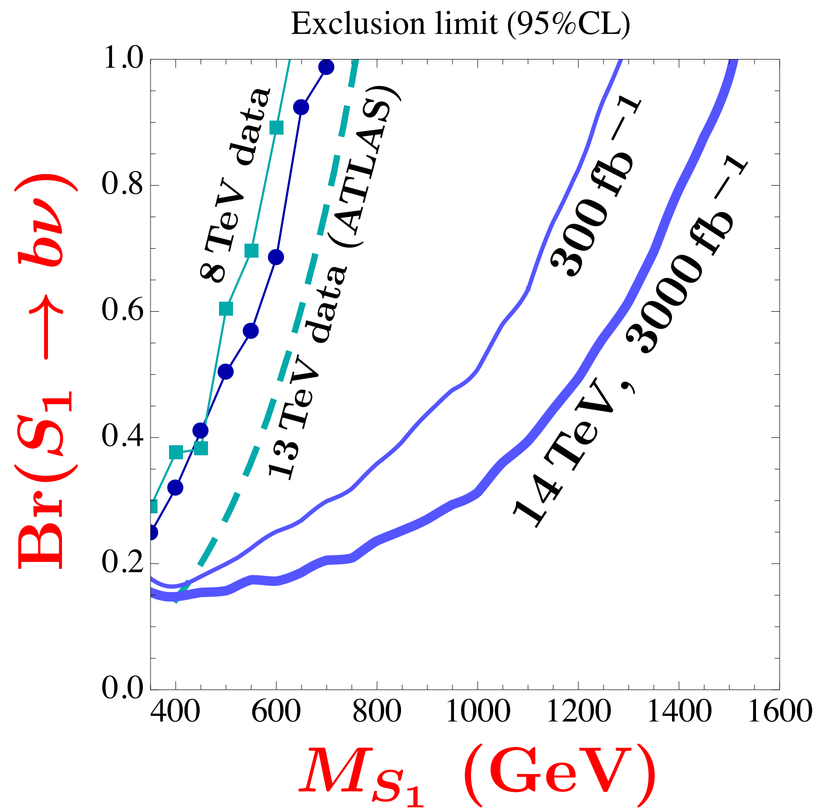
$\epsilon_{c\to c} = 40\%, \quad \epsilon_{b\to c} = 25\%, \quad \epsilon_{\mathrm{light}\to c} = 10\%$

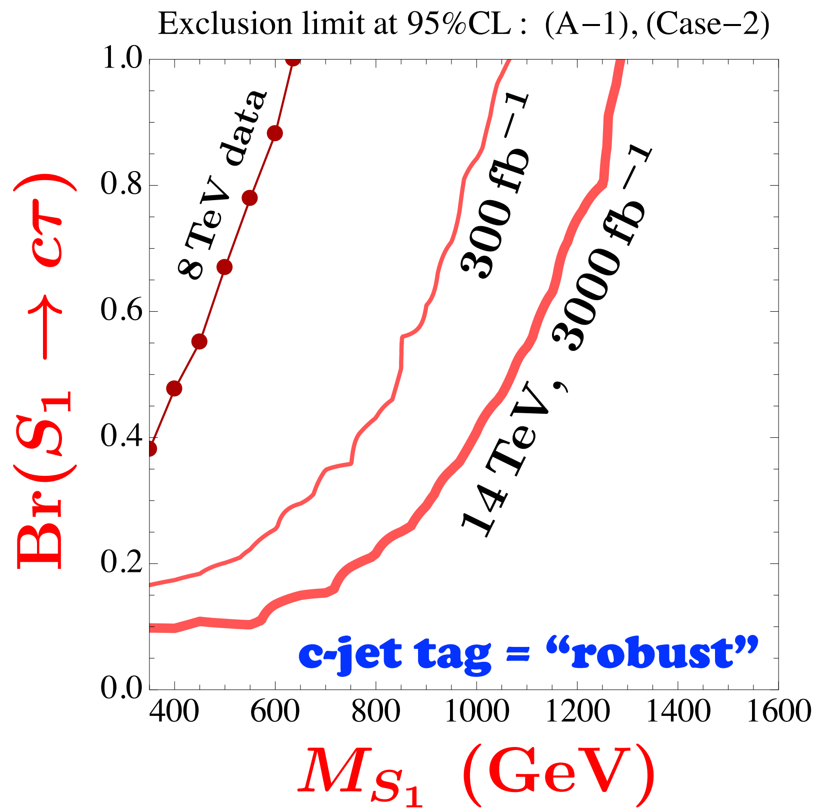
[Collider signal]

Detailed cut analyses

$(b\nu)(b\nu)$

$(c\tau)(c\tau)$



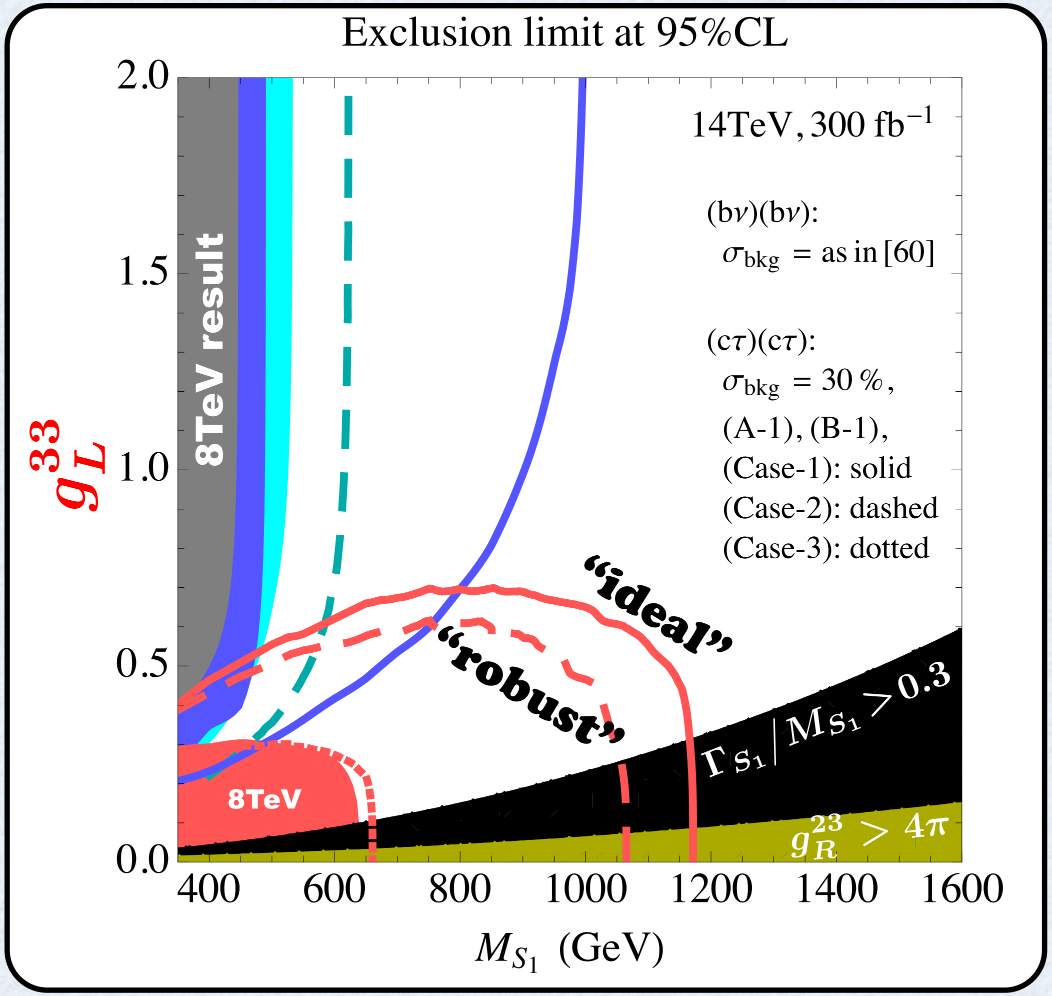


How can we confirm the $R_{D^{(*)}}$ anomaly ?

[Collider signal]

Collider limit with respect to the B anomaly

- **Condition :** $g_R^{23*} \simeq -0.5\, C_{\rm SM} M_{S_1}^2 / g_L^{33}$



Blue : $pp \to S_1 S_1^* \to (b\nu)(\bar{b}\bar{\nu})$

Red : $pp \to S_1 S_1^* \to (c\tau)(\bar{c}\bar{\tau})$

✔ **c-jet tagging is significant to search S1 leptoquark motivated by R(D(*))**

✔ **Improvement of c-tagging is still significant**

$\lesssim 800\,\mathrm{GeV}$ **Scalar-LQ (explaining the anomaly) can be probed at the LHC**

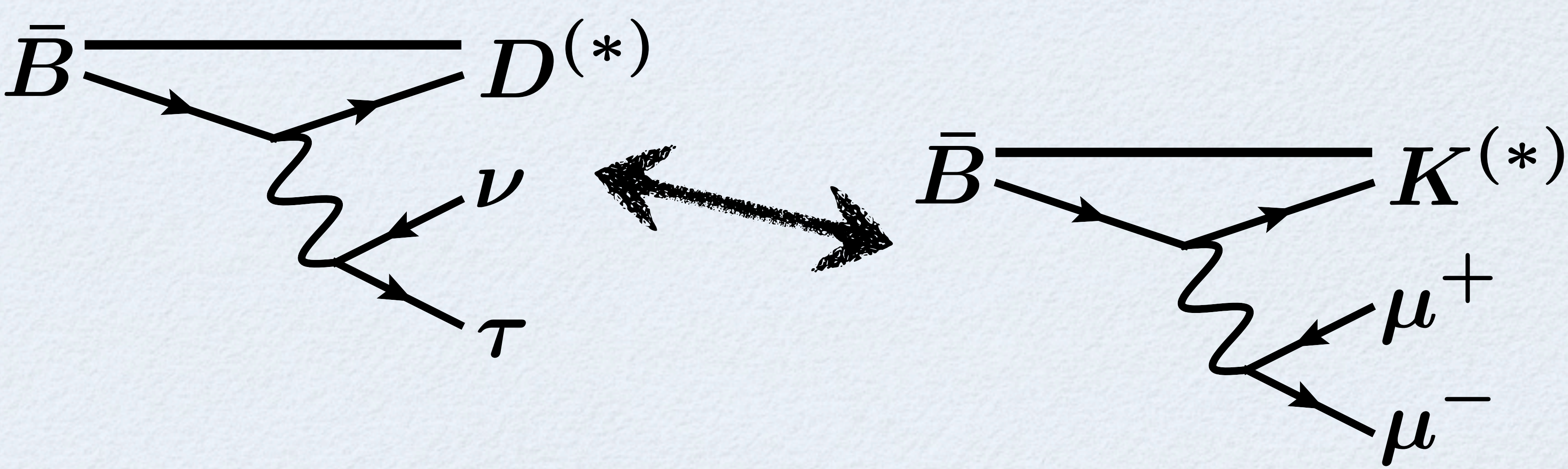
[3]

Correlation

arXiv: 1609.09078

Usage :

Identify NP model by looking at correlations with other processes



[Correlation with others]

Deviations from SM in $b \to s\mu^+\mu^-$

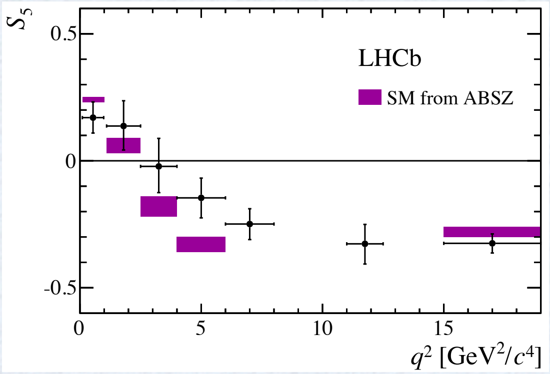
Observable 1. $R_K = \Gamma(\bar{B} \to K\mu^+\mu^-) \Big/ \Gamma(\bar{B} \to Ke^+e^-)$

$$\text{SM}: \quad 1 \pm \mathcal{O}(0.01)$$

$$\text{LHCb}: \quad 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

$\sim 2.6\,\sigma$ **1406.6482 (LHCb)**

Observable 2. **Angular analyses of** $\bar{B} \to K^*\ell^+\ell^-$



Including all,

$\sim 4.0\,\sigma$

1308.1707 (LHCb)
1512.04442 (LHCb)
1604.04042 (Belle)

Observable 3. **Angular analyses of** $\bar{B}_s \to \phi\,\ell^+\ell^-$

$\sim 3.5\,\sigma$

1305.2168 (LHCb)
1506.08777 (LHCb)

[Correlation with others]

Viable explanation to address the two anomalies

$$\mathcal{L}_{\rm NP} = \frac{g_q g_\ell}{\Lambda_{\rm NP}^2} \left[\bar{Q}_L^3 \gamma_\mu (\sigma^I) Q_L^3\right] \left[\bar{L}_L^3 \gamma^\mu (\sigma^I) L_L^3\right]$$

Third generation LH fermions: $Q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \quad L_L^3 = \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$

2-3 mixings are realized at mass eigenstate:

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\rm gauge} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\rm mass}$$

$$\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}_{\rm gauge} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \\ 0 & -\sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}_{\rm mass}$$

[Correlation with others]

Mixing structure correlates the processes

$$\mathcal{L}^{\rm eff} \supset -\frac{g_q g_\ell}{m_{V'}^2} \sin\theta_D \cos\theta_D \sin^2\theta_L \, (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$+2V_{cs}\frac{g_q g_\ell}{m_{V'}^2} \sin\theta_D \cos\theta_D \cos^2\theta_L \, (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L)$$

$$+\cdots$$

[Correlation with others]

Mixing structure correlates the processes

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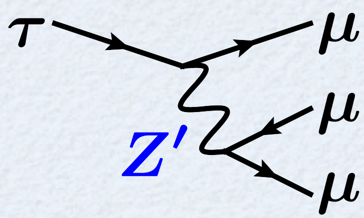
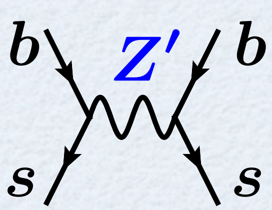
$$+\cdots$$

Significant constraints



$\tau \to 3\mu$ **[PDG 2016]**

Upper limit of Br : $\mathrm{Br} < 2.1\times 10^{-8}$ (90%CL)

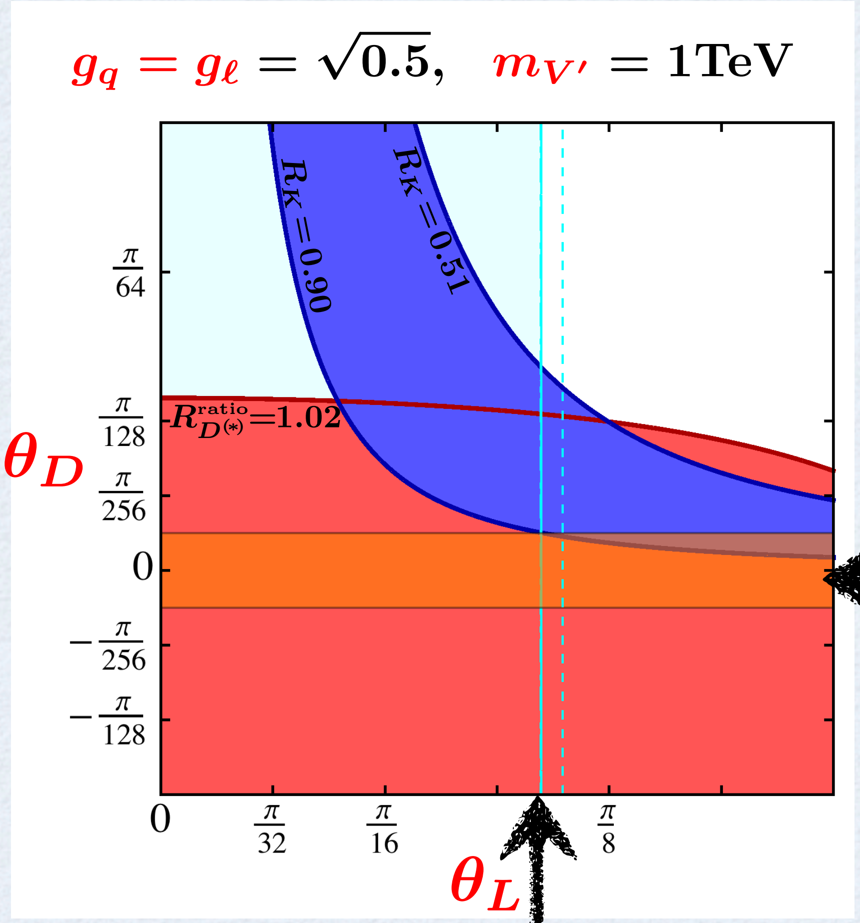


B_s-$\bar{B}_s$ mixing **[PDG 2016]**

Mass difference of Bs : $\Delta M_s = (17.76 \pm 0.02)\,\mathrm{ps}^{-1}$

[Correlation with others]

Constraints = Prediction



$\tau \to 3\mu$

$\pm 3\sigma$ allowed for the $R_{D^{(*)}}$ anomaly

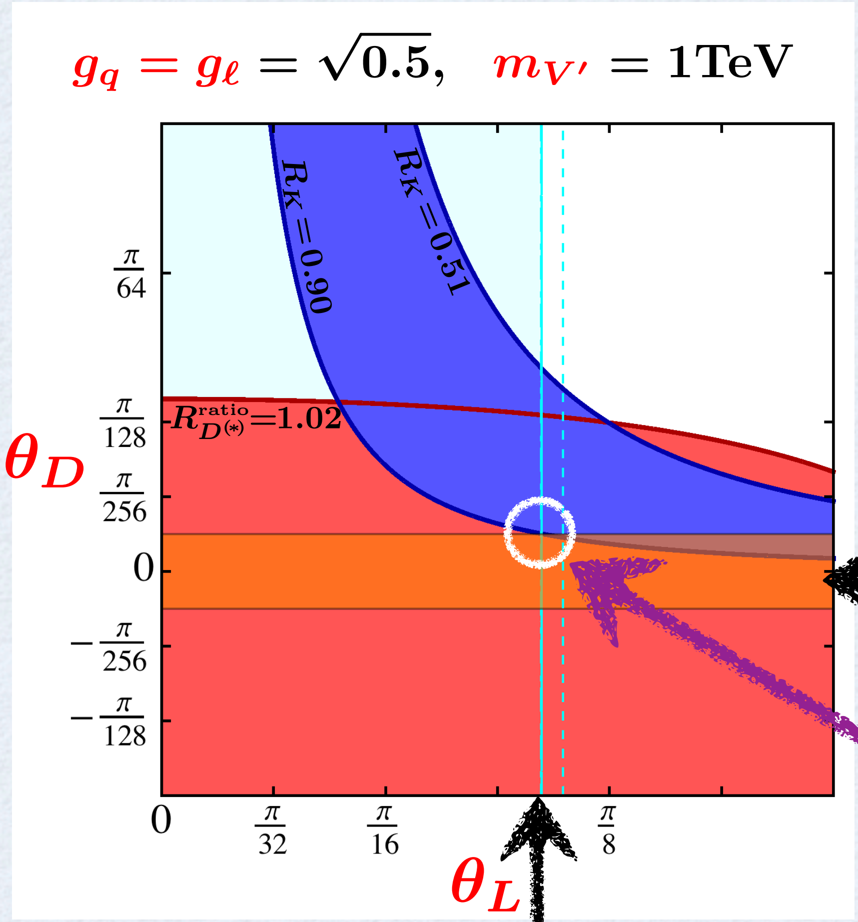
$\pm 3\sigma$ for the $b \to s\mu\mu$ anomaly

B_s-$\bar{B}_s$ mixing

See also Alakabha's talk

[Correlation with others]

Constraints = Prediction



$\pm 3\sigma$ allowed for the $R_{D^{(*)}}$ anomaly

$\pm 3\sigma$ for the $b \to s\mu\mu$ anomaly

B_s-$\bar{B}_s$ mixing

$\tau \to 3\mu$

Barely viable!

= pretty much predictive

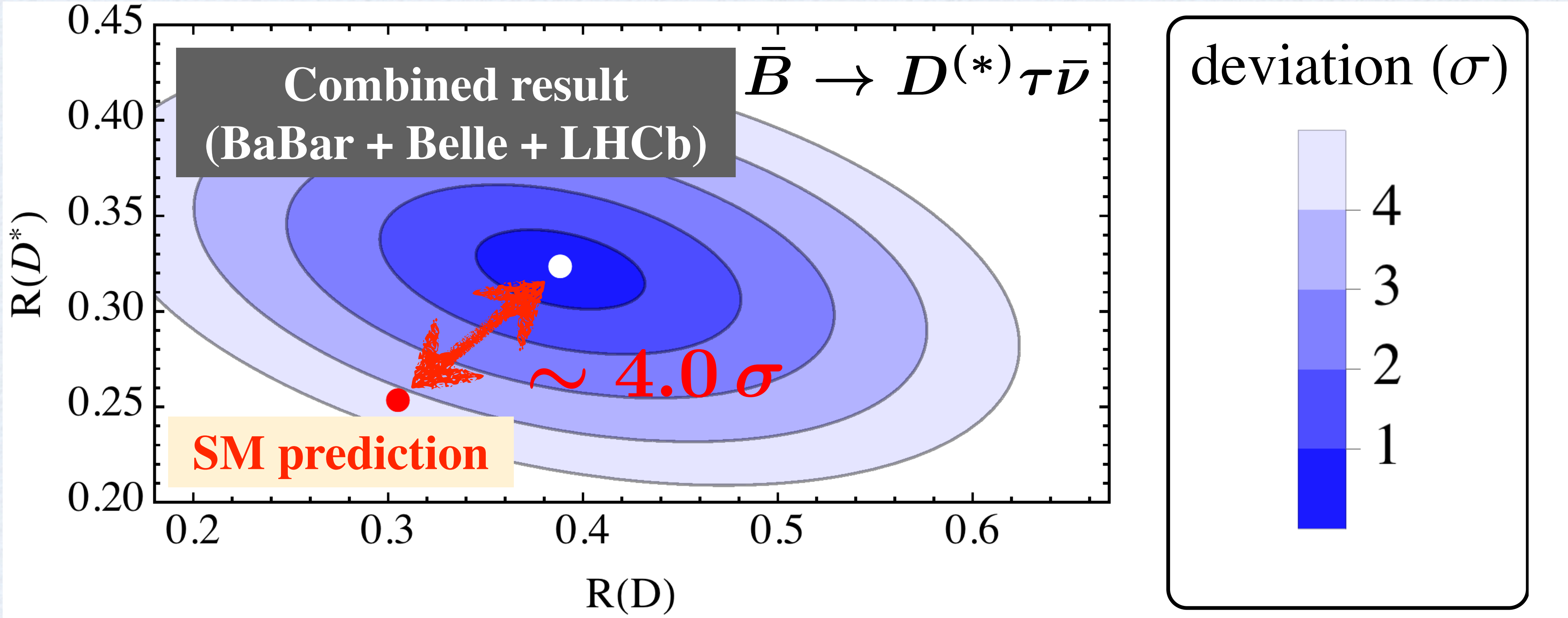
$R_K \simeq 0.9 \quad (\text{ex. } R_K^{\text{SM}} = 1)$

$R_{D^{(*)}} \simeq R_{D^{(*)}}^{\text{SM}}$

$\tau \to 3\mu :$ just below limit

See also Alakabha's talk

Summary



How can we probe NP in this process?

Three possible ways

- **[1] measuring distributions**
- **[2] detecting collider signals**
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[1]

Distributions

arXiv:1412.3761

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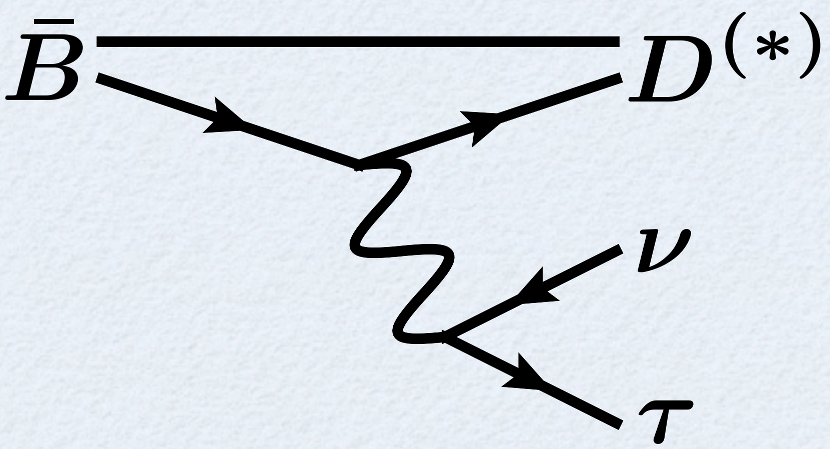

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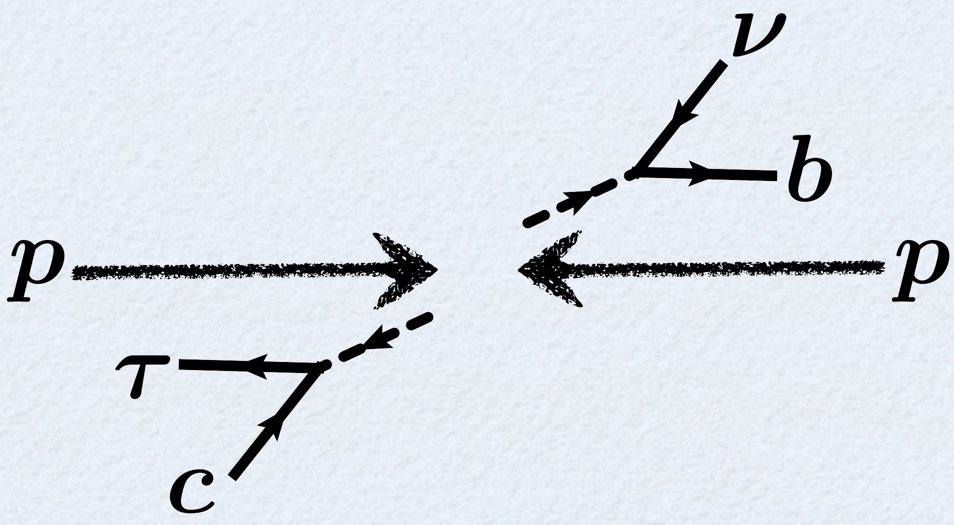

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