Nonstandard interaction between leptons and heavy quarks

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BSM (=‘non-standard’) interactions

higher dimensional (dim>4) operators, e.g., four-Fermi interactions

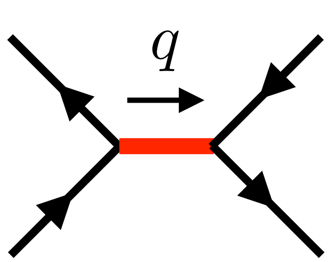
$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$

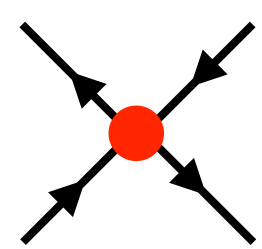
$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$

Generated by integrating-out new (heavy) particles

Today, we consider interactions between quarks and leptons.



$$\frac{1}{q^2-M^2} \xrightarrow[q^2 \ll M^2]{\text{integrate-out}}$$



$$\frac{1}{-M^2}$$

NSI's induce rich phenomena

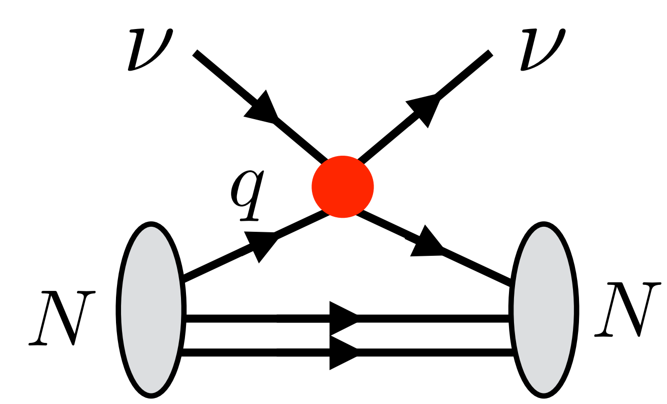
Example: $(Q_{\ell q}^{(1)})_{ijkl} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$

l = charged or neutral leptons
q = up- or down-type quarks
i,j,k,l = generation

Flavor-Conserving (FC) light (up, down) quarks

Ex. exotic neutrino-nucleaon scattering

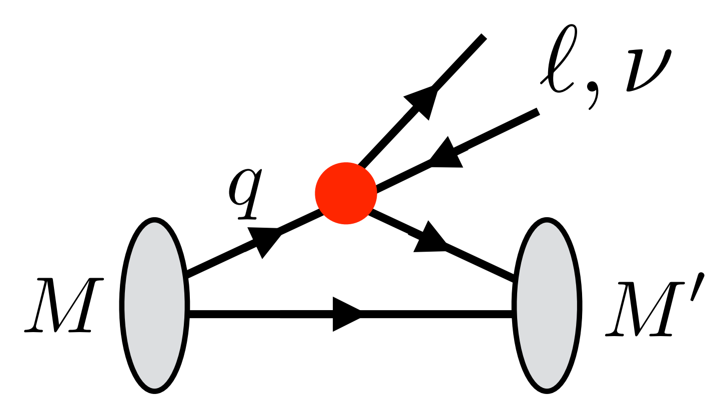
→ "neutrino nonstandard interaction"



Flavor-violating quarks or FC heavy quarks

Quark flavor violation (rare meson decays)

→ Today's topics



Today's topics

Several hints of BSM in rare B decays

- Quark flavor-violating interaction

  Ref. ME, Iguro, Kitahara, Takeuchi, Watanabe, JHEP 02(2022)106

- Quark flavor-conserving interaction

  Ref. ME, Mishima, Ueda, JHEP 05(2021)050

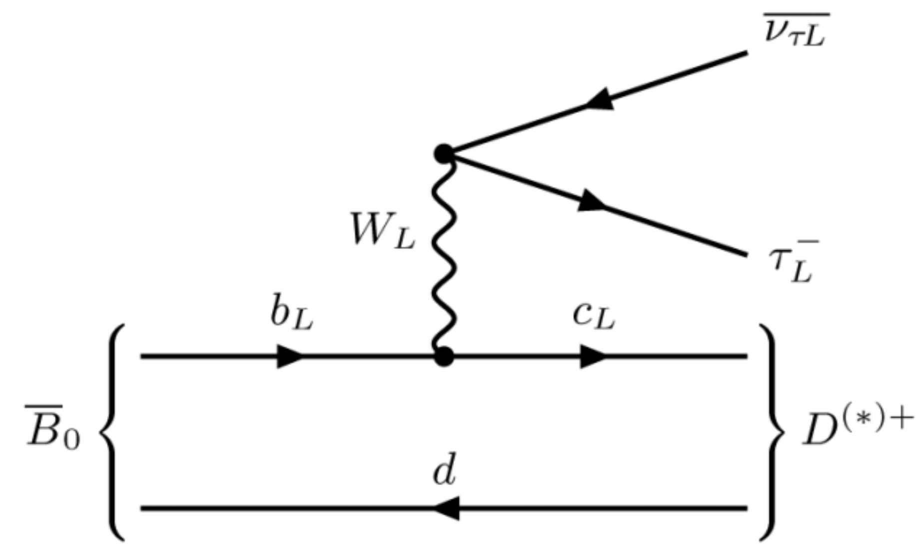
- Summary

Quark-flavor violating nonstandard interaction

Ref. ME, Iguro, Kitahara, Takeuchi, Watanabe, JHEP 02(2022)106

Hints of BSM in B meson decays

Charged-current anomaly: $b \to c\ell^- \bar{\nu}_\ell$



$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}$$

Theoretical progresses in SM prediction

Form factor: $1/m_c^2$ correction, include all exp data

[Bordone et al.,'19; Iguro, Watanabe,'20]

Discrepancy between exp and SM

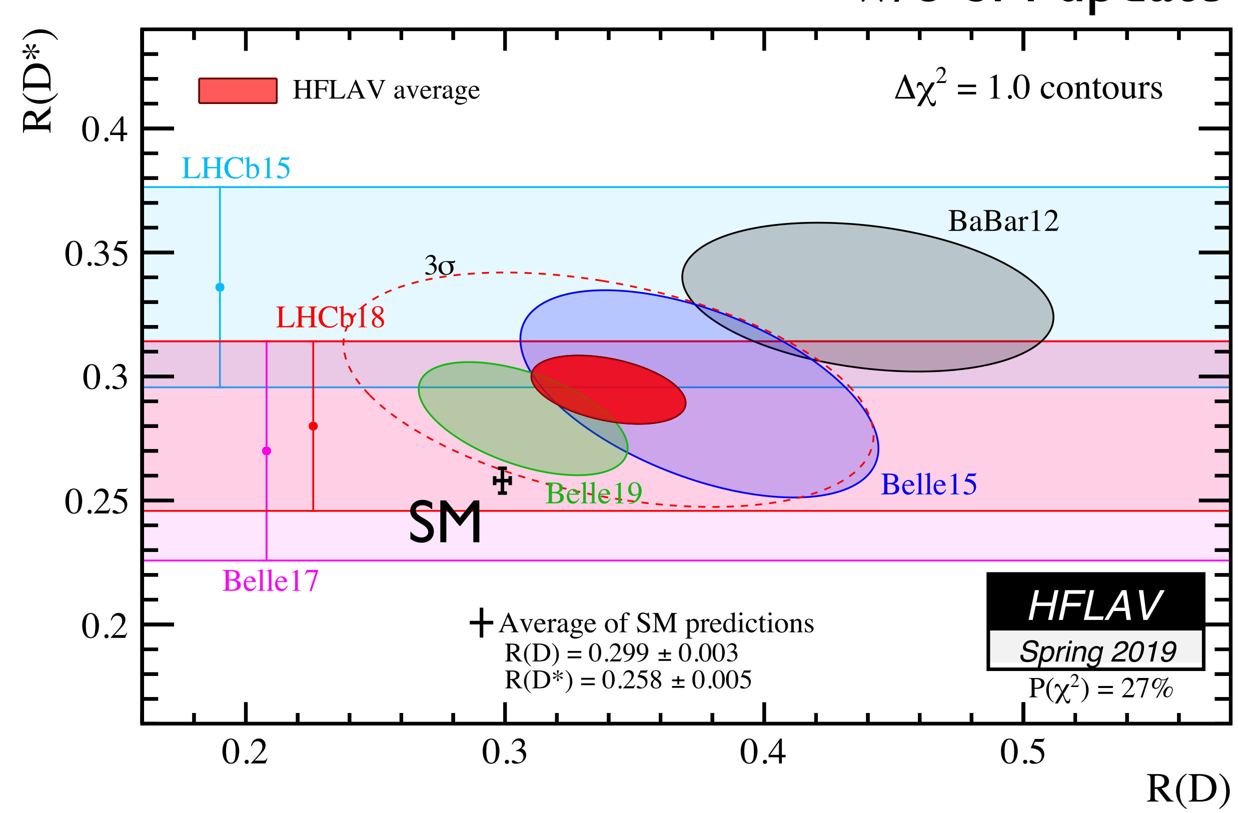
2019 R(D): 1.4σ, R(D*): 2.5σ

⇒ **2022 R(D): 1.7σ, R(D*): 3.4σ**

Combined significance is **4.2σ**

… hints of BSM, i.e., NSI

w/o SM update



Effective field theory

Charged-current anomaly: $b \to c\ell^- \bar{\nu}_\ell$

Relevant effective Hamiltonian (below EWSB scale)

$$\mathcal{H}_{\rm eff} = 2\sqrt{2}G_F V_{cb}\Big[(1+C_{V_1})(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_{V_2}(\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$+ C_{S_1}(\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau) + C_{S_2}(\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$
$$+ C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau)\Big] + \text{h.c.}\,,$$

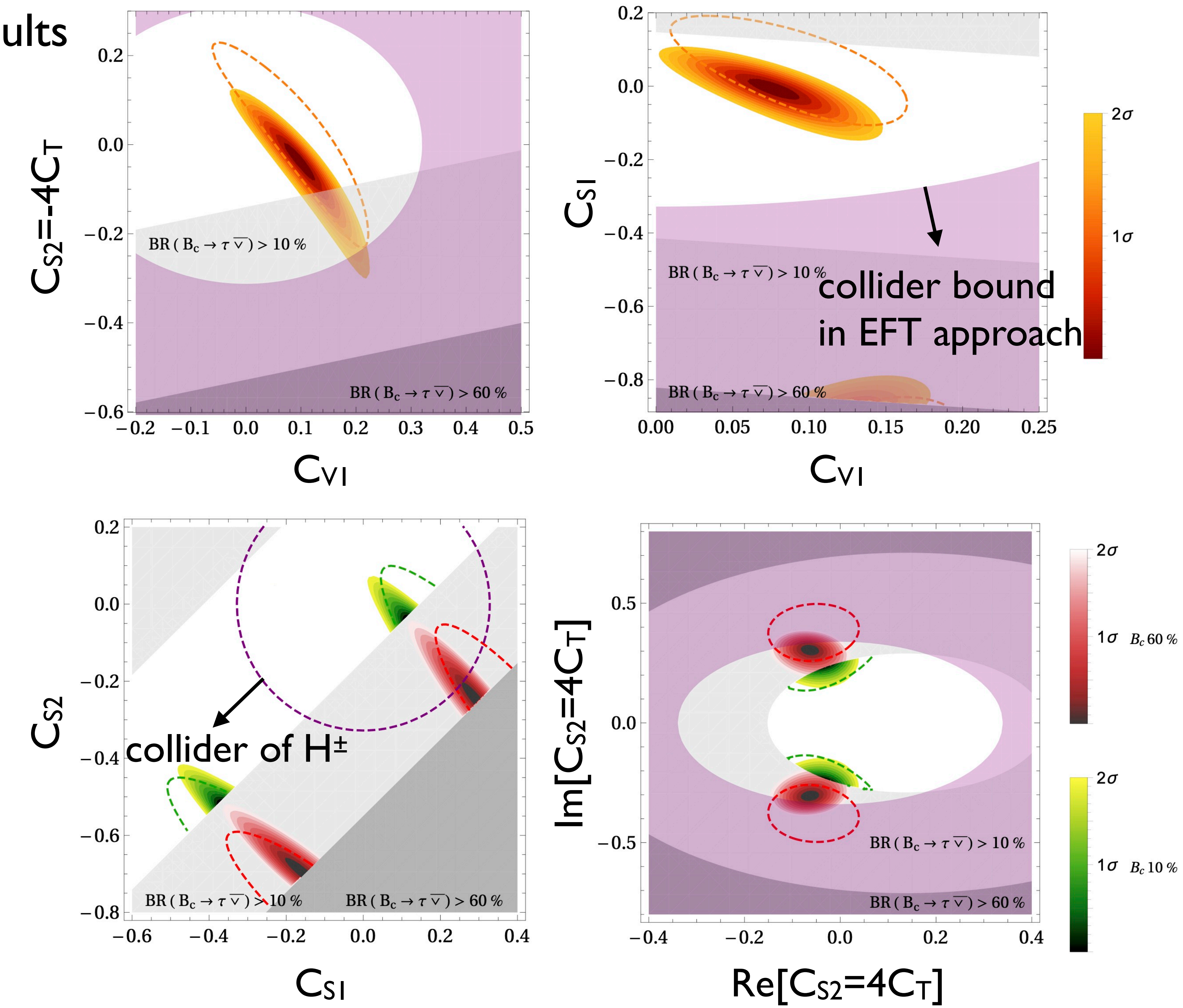
Operators are normalized by ~$G_F V_{cb}$ → dim[C_i]=0

LFUV $(O_{V2})_{cb\tau\nu}$ arises from dim-8 in SMEFT → ~v^2/Λ^2 in most BSM

Universal set, $(O_{V2})_{cb\tau\nu}$ = $(O_{V2})_{cb\mu\nu}$ = $(O_{V2})_{cbe\nu}$, is generated by $i(\tilde{H}^\dagger D_\mu H)(\overline{u}_p \gamma^\mu d_r)$ by exchanging Z boson at tree-level (after taking Higgs VEV)

BSM energy scale is typically O(1-10)TeV

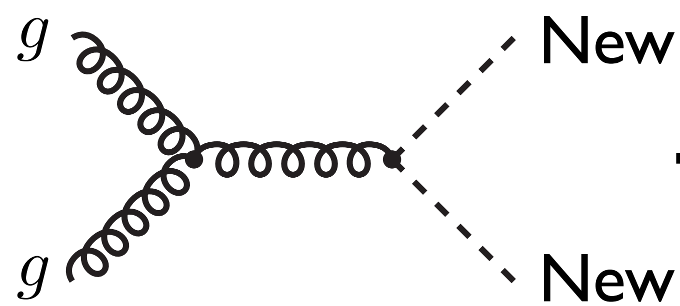
2D fit results



[Blanke,Crivellin,Kitahara,Moscati,Nierste,Nisandzic'19]

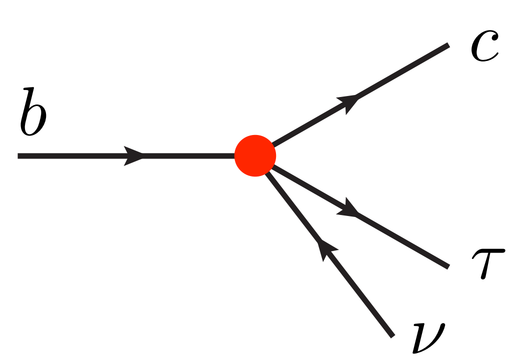
Search for new particle (effects) at LHC

Direct production



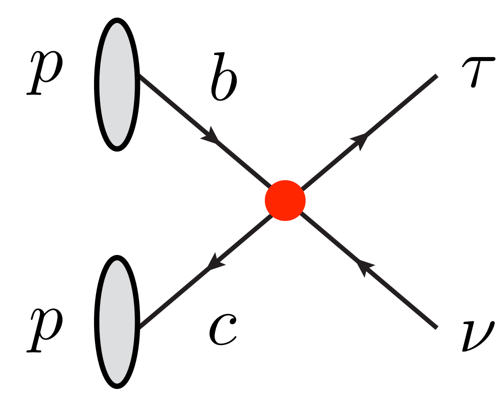
→ sensitivity is limited by collision energy

Indirect search



$b \to c\tau\bar{\nu}$

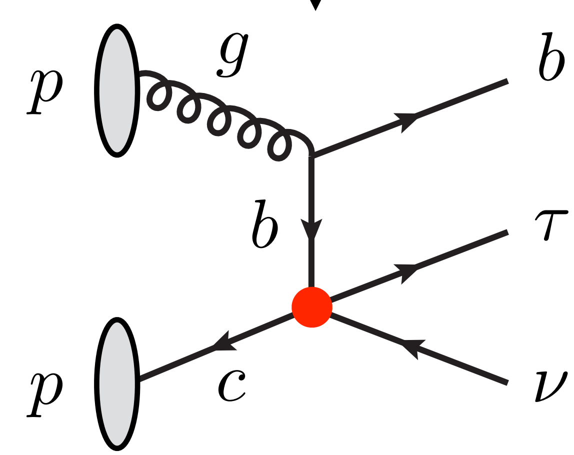
→



$pp \to \tau\bar{\nu}$

ATLAS, CMS

↓



New study on pp→τν + b-jet

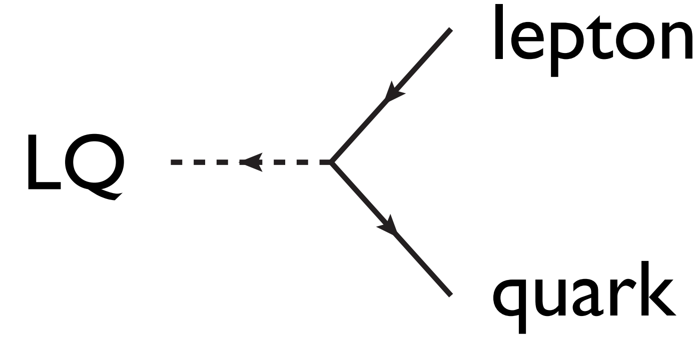
Compared to pp→τν:

- Sig. suppressed by 3-body final state
- Much smaller SM background

Benchmark model: leptoquark

Leptoquark is a spin 0 or 1 particle carrying both lepton and baryon #

Couple to lepton and quark:

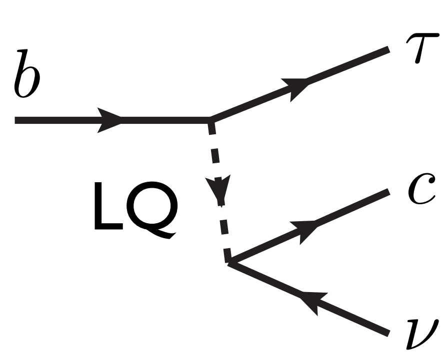


Introduced in models unifying quarks and leptons, e.g., Pati-Salam model

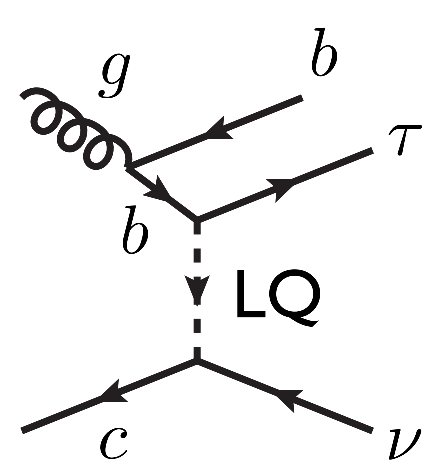
Mass >~1TeV by LHC direct searches

R(D), R(D*) are explained by R_2, S_1, U_1

R(D), R(D*)



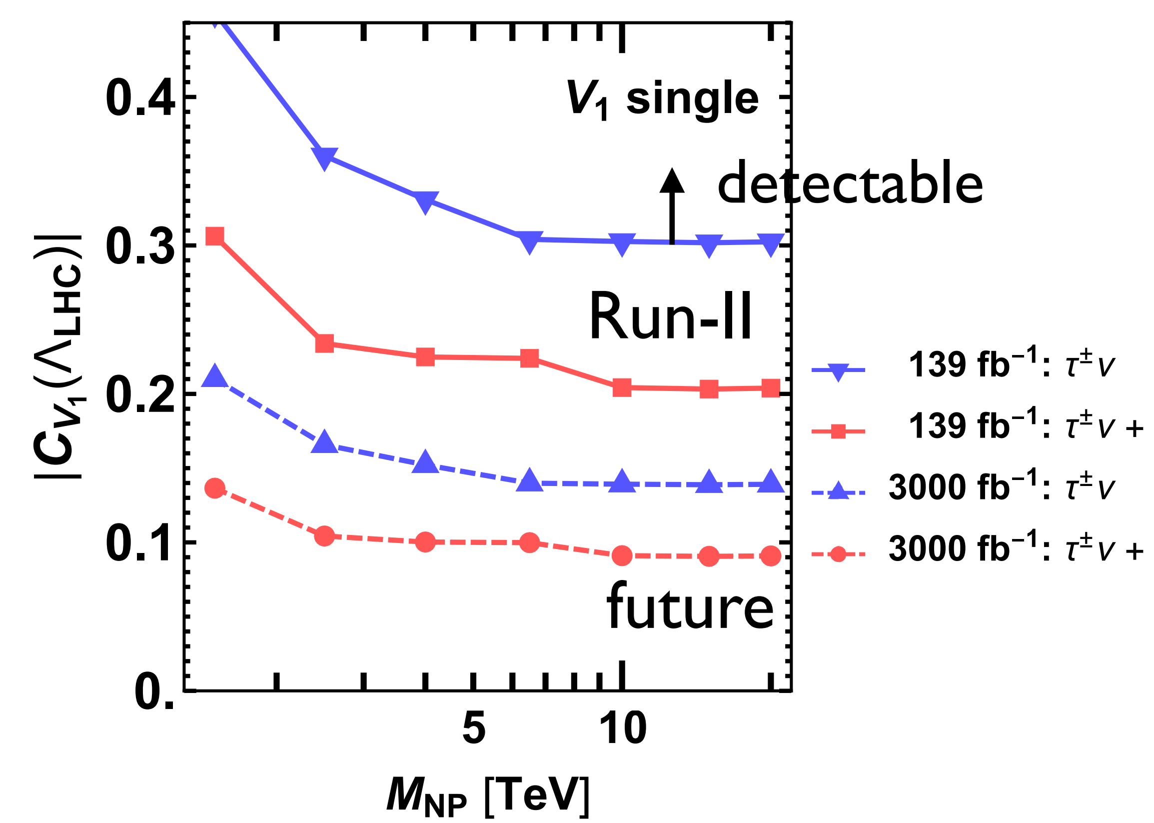
LHC



$(SU(3), SU(2), U(1))$	Spin	Symbol	dim-6
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$C_{S2}=4C_T$
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	C_{V1}, $C_{S2}=-4C_T$
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	C_{V1}, C_{S1}
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	

Result: U$_1$ (vector) LQ

Sensitivity is improved by τν+b analysis versus traditional τν search.

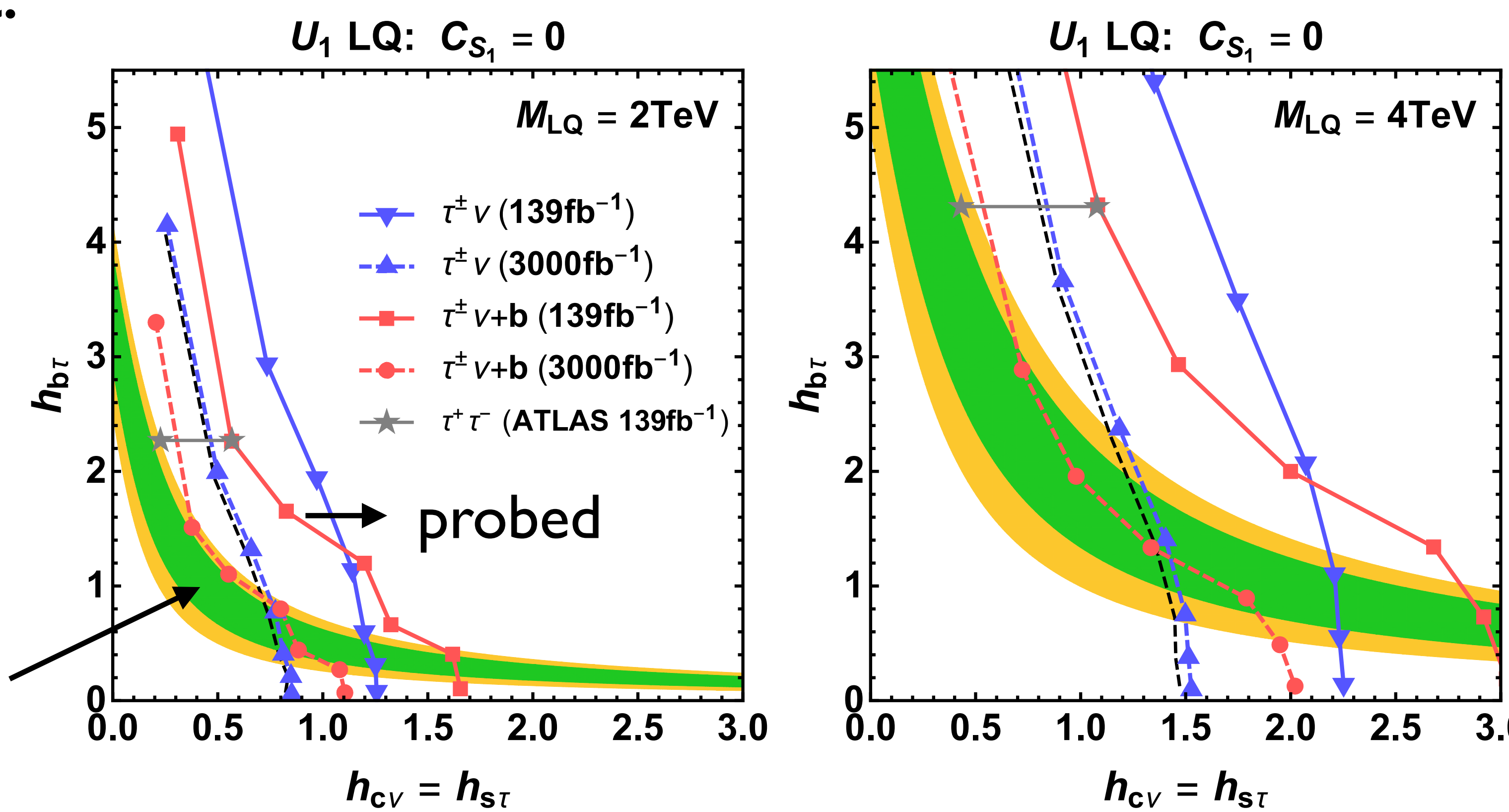


Sensitivity depends on LQ mass, i.e., EFT approx. is not always valid.

Because of SU(2) symmetry, LQ-s-τ int. is predicted due to LQ-c-ν int.

$$\bar{Q}_L \gamma^\mu L_L U_{1,\mu}$$

For U$_1$, large LQ-c-ν coupling region can be probed.



R(D), R(D*)

Result: R_2 and S_1 LQ

Flavor constraint must be taken into account.

R_2 model predicts $C_{S2}=4C_T$

Constraint from $B(B_c\to\tau\nu)$ [large uncert.]

All region can be probed by $\tau\nu$+b channel if the current (Run-II) data are analyzed.

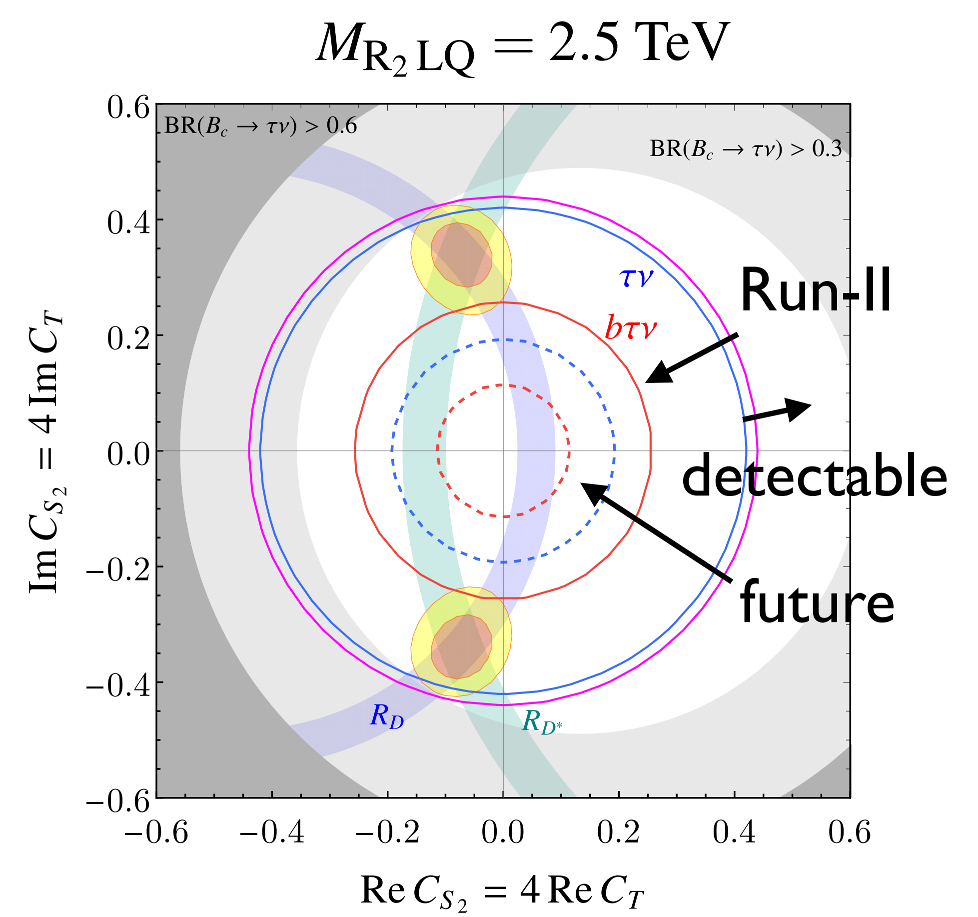
S_1 model predicts (C_{V1}, $C_{S2}=-4C_T$)

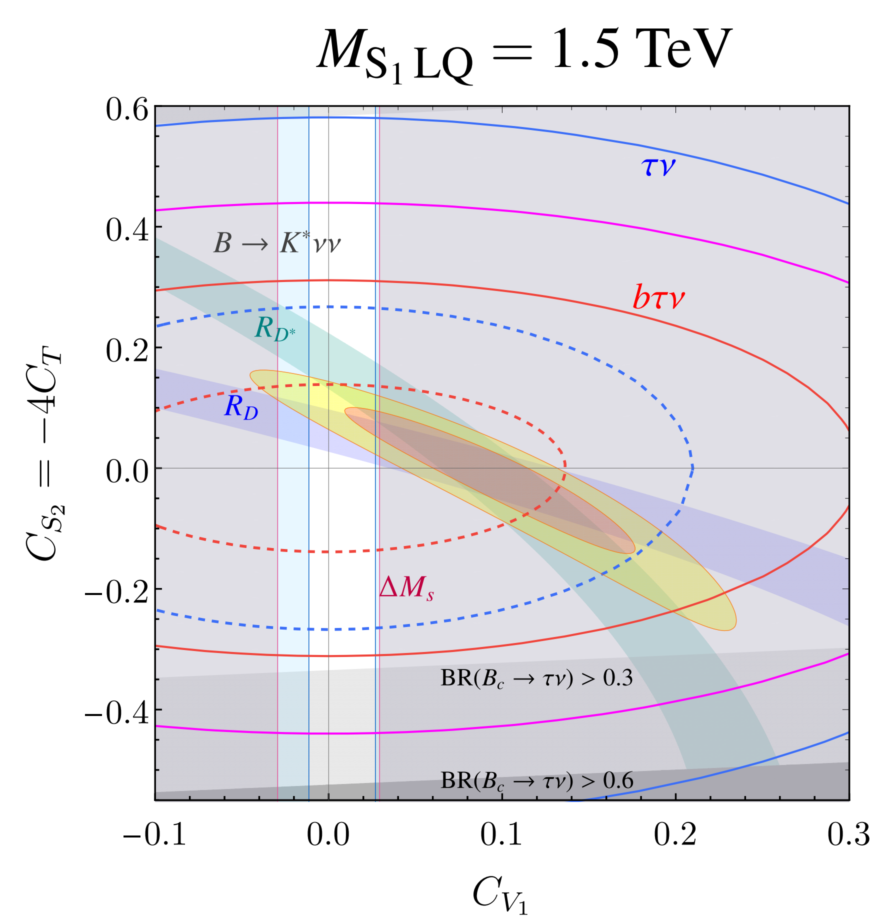
Robust constraint from ΔM_s, $B\to K^*\nu\nu$

Most R(D*) region can be probed in future.

pp→τν+b channel is powerful to probe BSM responsible for R(D), R(D*)

cf. Blanke et.al. applied to charged Higgs model.





Quark-flavor conserving nonstandard interaction

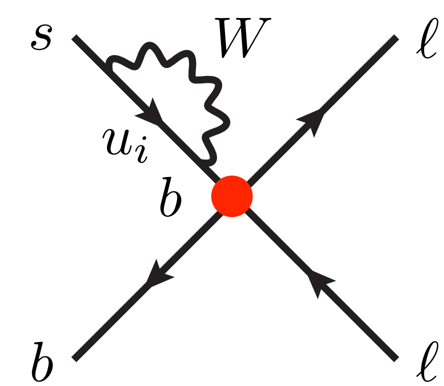
contribution to quark flavor violations

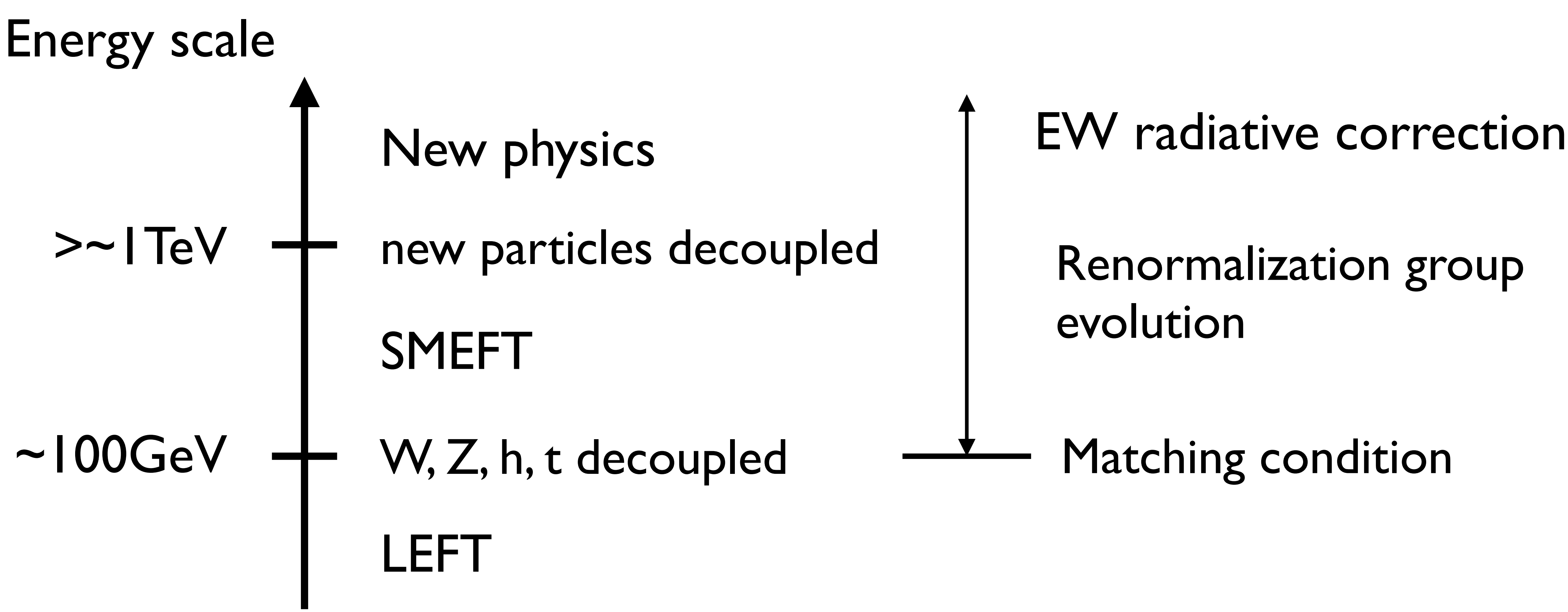
Ref. ME, Mishima, Ueda, JHEP 05(2021)050

Why flavor-<u>conserving</u> int. induce flavor <u>violations</u>?

In general, CKM matrix in W boson loop triggers flavor violations.

Ex. (bbll) operator → (bsll) operator





Traditional study

Renormalization group evolution (especially of Yukawa matrix)

[e.g., Coy,Frigerio,Mescia,Sumensari'20]

→ Need finite terms (EW threshold corrections) for low-scale BSM.

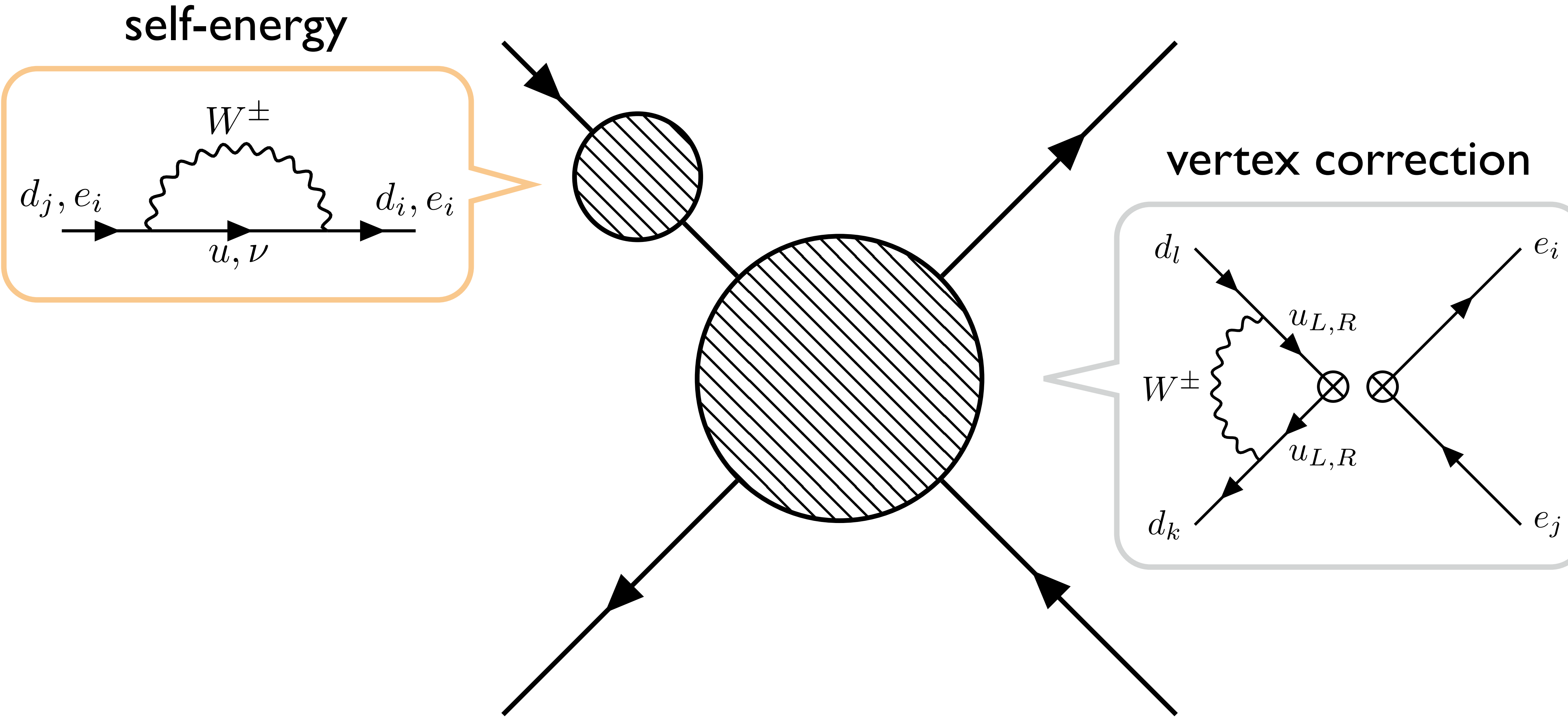
Approximation of quark (&lepton) mass → 0 in calculating matching cond.

Quark (&lepton) mass (m) ≪ BSM scale (M)

Valid when the amplitudes are expanded by m/M (→0)

→ Can we apply this approximation *at the begging of* calculation?

EW radiative corrections



Self-energy correction

On-shell condition of fermion propagator (with flavor-changing corrections)

$$S_{ij}(\not{p}) = \frac{\not{p}+m_i}{p^2-m_i}\delta_{ij} + \frac{\not{p}+m_i}{p^2-m_i}(-\Sigma_{ij})\frac{\not{p}+m_j}{p^2-m_j} + \cdots$$

→ simple pole only at $p^2=m_i^2$

(m_i: fermion mass)

↑ Radiative correction

$$\Sigma_{ij}(p) = \not{p}[P_L\Sigma_{ij}^L(p^2) + P_R\Sigma_{ij}^R(p^2)] + P_L\Sigma_{ij}^{DL}(p^2) + P_R\Sigma_{ij}^{DR}(p^2)$$

Fermion wave function (i≠j)

$$f_{L,R,i}^{(0)} = (Z_{ij}^{L,R})^{1/2} f_{L,R,j} = \left(\delta_{ij} + \frac{1}{2}\delta Z_{ij}^{L,R}\right) f_{L,R,j}$$

$$\delta Z_{ij}^L = \frac{2}{m_j^2 - m_i^2}\left[m_j^2\Sigma_{ij}^L(m_j^2) + m_i m_j \Sigma_{ij}^R(m_j^2) + m_i\Sigma_{ij}^{DL}(m_j^2) + m_j\Sigma_{ij}^{DR}(m_j^2)\right]$$ etc.

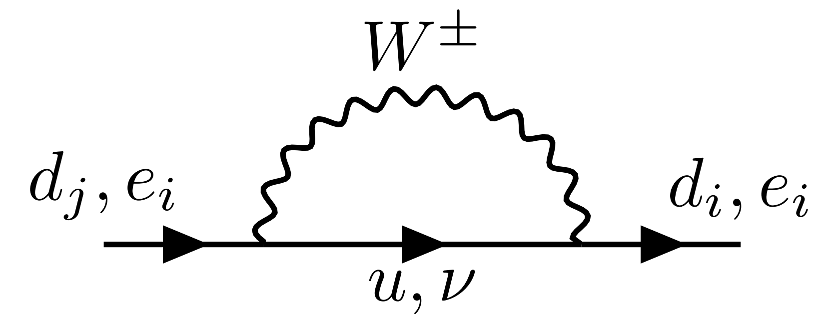
c.f. analogous to diagonalization of mass matrix

Because fermion masses appear in denominator, m→0 approx. in advance is not valid for calculating flavor-changing self-energy corrections.

Self-energy correction

EW 1-loop correction ($m_i \ll m_j$ for i<j)

$$\frac{1}{2}\delta Z^L_{ij} = \frac{\alpha \lambda^{ij}_{m'}}{\pi s^2_W}\left[K_{ij}(x_{m'},\mu) - \Xi_1(x_{m'}) - \frac{1}{2}\Xi_0(\mu)\right],$$
$$\frac{1}{2}\delta \overline{Z}^L_{ij} = \frac{\alpha \lambda^{ij}_{m'}}{\pi s^2_W}\left[\overline{K}_{ij}(x_{m'},\mu) - \Xi_1(x_{m'}) - \frac{1}{2}\Xi_0(\mu)\right],$$
$$\frac{1}{2}\delta Z^R_{ij} = 0, \quad \frac{1}{2}\delta \overline{Z}^R_{ij} = 0,$$



summed over m'

$$\lambda^{ij}_{m'} = V^*_{m'i}V_{m'j},\ x_i = m^2_{ui}/M^2_W$$

Left-handed quarks receive EW corrections.

Result depends on flavor (i,j) structure.

$$K_{ij}(x,\mu) = \begin{cases} K_0(x,\mu), & (i=j) \\ K_1(x,\mu), & (i<j) \\ K_2(x,\mu), & (i>j) \end{cases} \qquad \overline{K}_{ij}(x,\mu) = \begin{cases} K_0(x,\mu), & (i=j) \\ K_2(x,\mu), & (i<j) \\ K_1(x,\mu), & (i>j) \end{cases}$$

$K_{0,1,2}$: loop functions, $\Xi_{0,1}$: gauge-dependent functions (R_ξ gauge)

→ Apply to explicit decay process

Hints of BSM in B meson decays

Neutral-current anomaly: $b \to s\mu^+\mu^-$

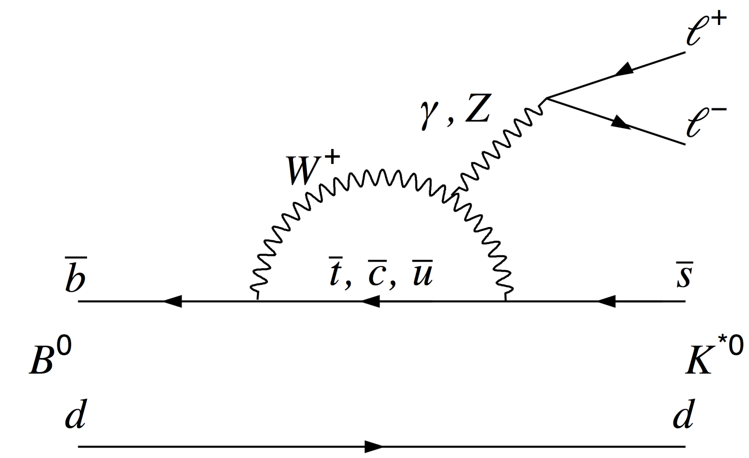
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

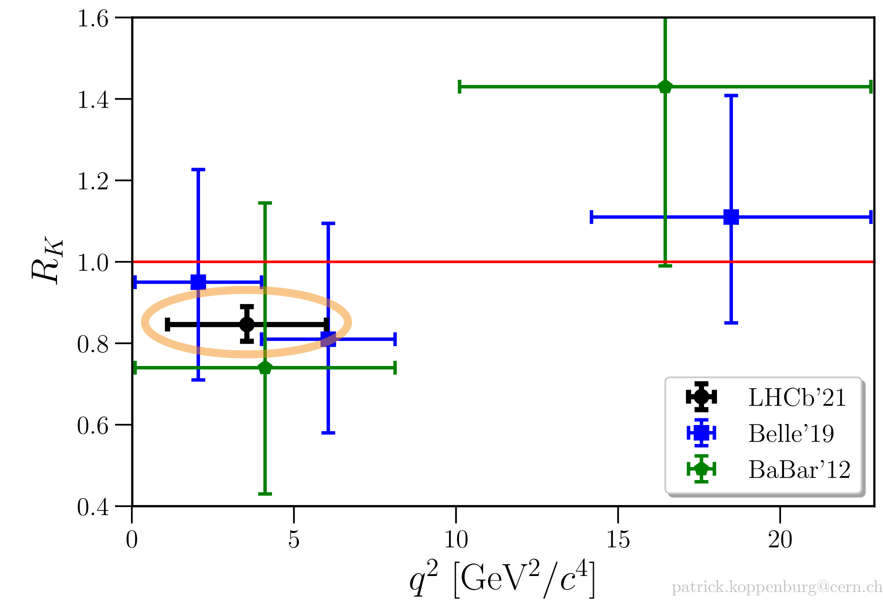
New LHCb ('20) result of R(K) confirms deviation between exp and SM.

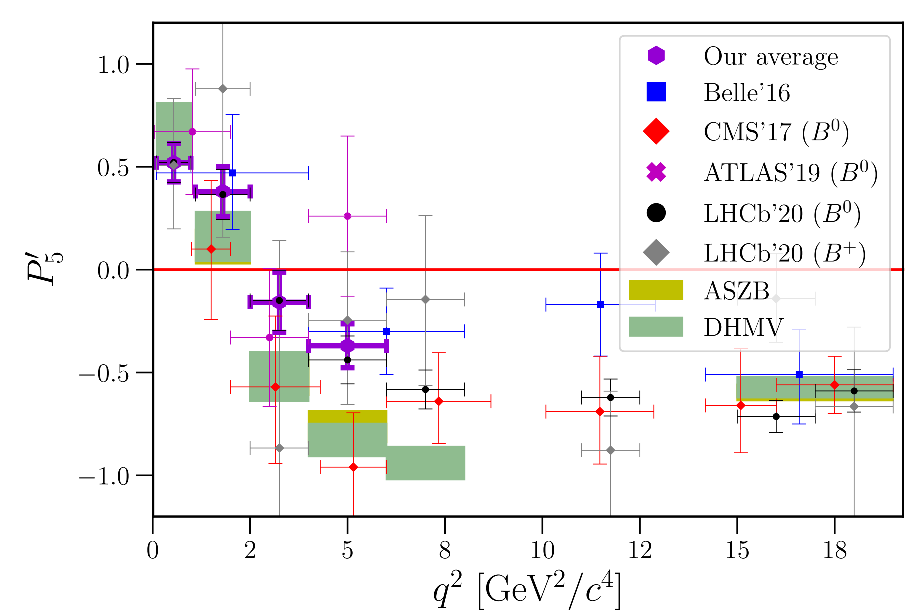
Significance: 3.1σ in R(K), ~2σ deviations in R(K*)

Angular distribution (P₅') of B→K*μμ also shows strong tension with SM (>3σ), though potentially large hadronic uncertainty exists.

→ hints of BSM, i.e., NSI







Effective field theory

Relevant effective Hamiltonian (below EWSB scale)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\left[C_9 Q_9 + C_{10} Q_{10}\right],$$

$$(Q_9)_{ijkl} = \frac{e^2}{16\pi^2}(\bar{d}_i \gamma_\mu P_L d_j)(\bar{e}_k \gamma^\mu e_l),$$

$$(Q_{10})_{ijkl} = \frac{e^2}{16\pi^2}(\bar{d}_i \gamma_\mu P_L d_j)(\bar{e}_k \gamma^\mu \gamma_5 e_l),$$

ACDMN	Complete fit: 246 observables		
1D Hyp.	Best fit	$\mathrm{Pull}_{\rm SM}$ (σ)	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	$-1.06^{+0.15}_{-0.14}$	7.0	39.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	$-0.44^{+0.07}_{-0.08}$	6.2	22.8 %

[Capdevila,Descotes-Genon,Matias,Novoa-Brunet'19]

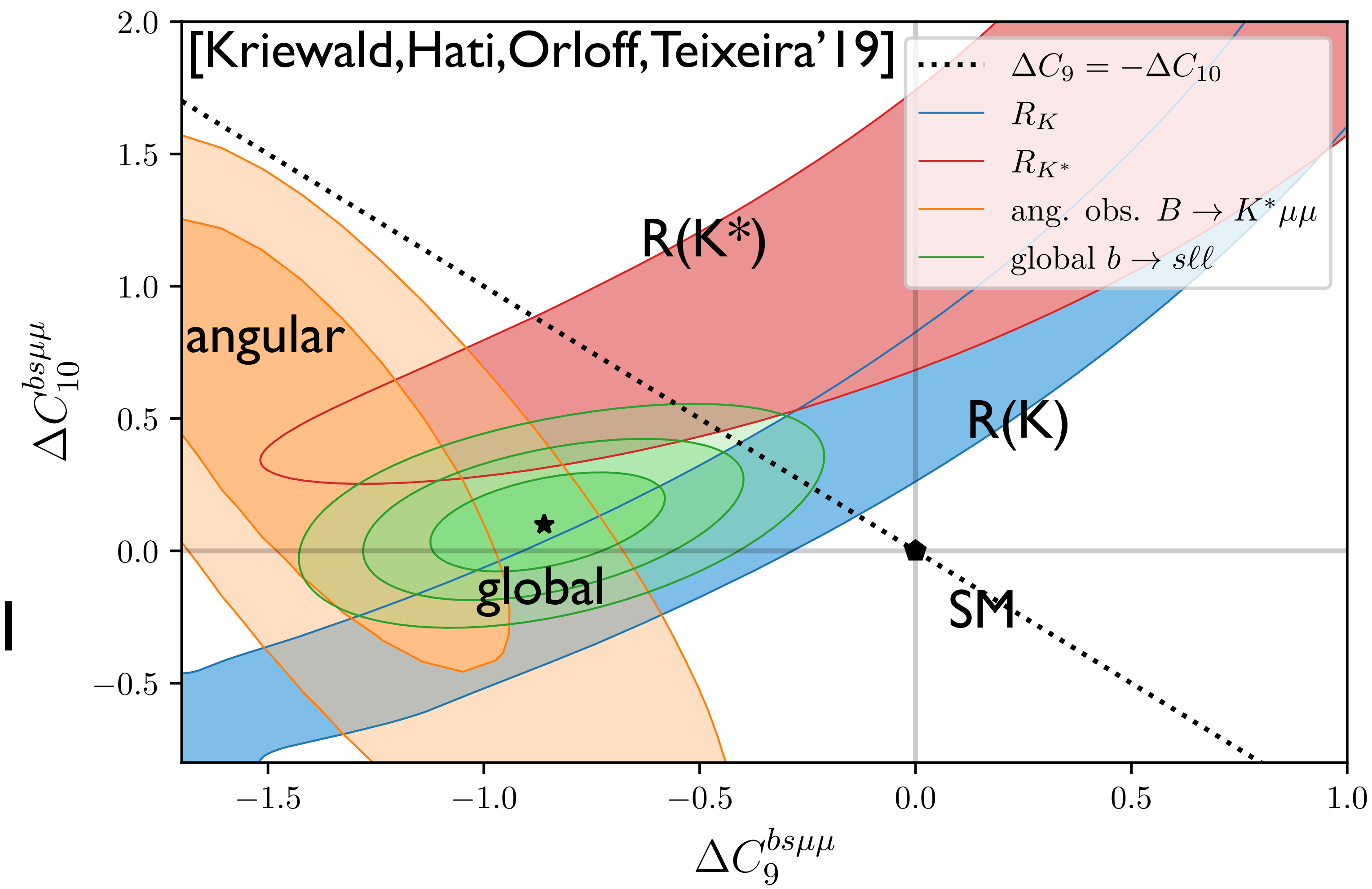
SM prediction

C_9(SM)=4.1, C_{10}(SM)=-4.3

BSM scale

Λ(tree) ~ O(10)TeV

Λ(loop) ~ O(1)TeV ← FC NSI

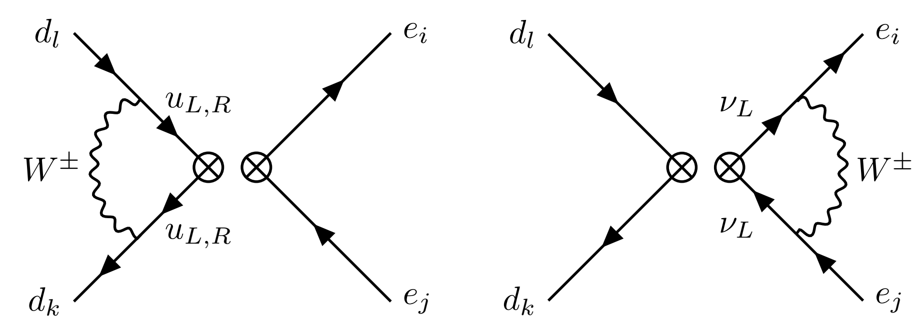


Flavor-conserving interaction induces flavor violation

$$(C_{\ell q}^{(1)}) \qquad\qquad (C_{9,10})$$

$$(\bar{\ell}_{L,2}\gamma_\rho \ell_{L,2})(\bar{q}_{L,3}\gamma^\rho q_{L,3}) \xrightarrow{\text{EW loop}} (\bar{b}_L \gamma_\mu s_L) \times (\bar{\mu}\gamma^\mu \mu), (\bar{\mu}\gamma^\mu\gamma_5 \mu)$$

Including vertex correction



$$
\begin{aligned}
(C_9)^{\rm EW}_{ijkl} &= -(C_{10})^{\rm EW}_{ijkl} \\
&= \frac{v^2}{s_W^2}\lambda^{ii'}_{m'}\lambda^{j'j}_{n'}\,(C^{(1)}_{\ell q})_{kli'j'} \times
\begin{cases}
I_2(x_{m'}, x_{n'}, \mu), & (i'=i, j'=j) \\
\left[J_2(x_{m'}, x_{n'}) + K_1(x_{m'}, \mu)\right], & (i'<i, j'=j) \\
\left[J_2(x_{m'}, x_{n'}) + K_2(x_{m'}, \mu)\right], & (i'>i, j'=j) \\
\left[J_2(x_{m'}, x_{n'}) + K_1(x_{n'}, \mu)\right], & (i'=i, j'<j) \\
\left[J_2(x_{m'}, x_{n'}) + K_2(x_{n'}, \mu)\right], & (i'=i, j'>j) \\
J_2(x_{m'}, x_{n'}). & (i'\neq i, j'\neq j)
\end{cases}
\end{aligned}
$$

$$I_2(x,y,\mu) = J_2(x,y) + K_0(x,\mu) + K_0(y,\mu),$$

Depend on flavor (i,j) structure through self-energy corrections

Flavor-conserving interaction induces flavor violation

ACDMN	Complete fit: 246 observables		
1D Hyp.	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$ (σ)	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$-1.06^{+0.15}_{-0.14}$	7.0	39.5 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$-0.44^{+0.07}_{-0.08}$	6.2	22.8 %

$$\longrightarrow \quad c_{\ell q}^{(1)} = -1.9^{+0.3}_{-0.4} \ \ @ \ \mu = M_W \quad \text{for } (C_{\ell q}^{(1)})_{2233} = \frac{c_{\ell q}^{(1)}}{(1\,\mathrm{TeV})^2}$$

Imply BSM scale ~TeV (Note: RG evolutions have not been included)

Flavor violations are induced from flavor-conserving interactions.

Pay attention to treatment of quark masses.

Neutral-current B anomaly implies BSM in ~TeV scale.

Summary

We considered NSI between leptons and quarks, particularly quark flavor-violating (FV) and flavor-conserving (FC) interactions.

In light of charged-current B anomaly ($b \to c\tau\nu$), $pp \to \tau\nu$ + b-jet search is powerful to probe FV interactions at LHC.

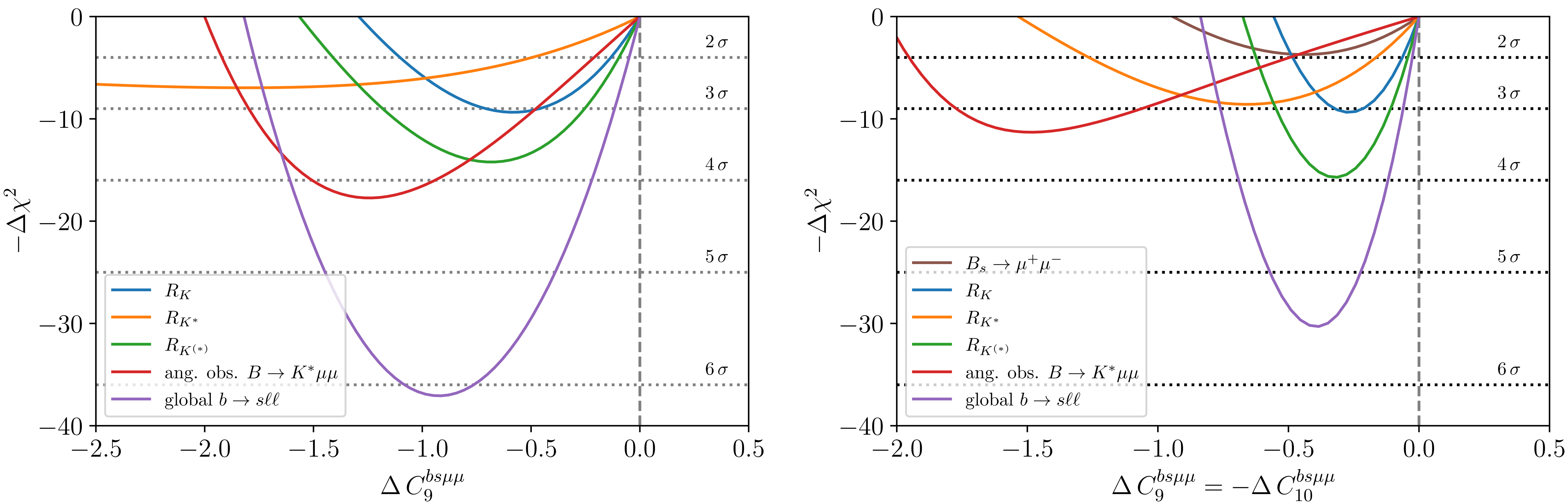
FC interactions can induce quark-flavor violations.

In the analysis, we have to pay attention to the quark masses.

In light of neutral-current B anomaly ($b \to s\mu\mu$), BSM w/ FC interactions are implied to exist in ~TeV scale, which could be a target of LHC.

The NSI between leptons and quarks are expected to be probed in future.

Backup slide



0
−10
−20
−30
−40
$-\Delta\chi^2$
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
$\Delta\, C_9^{bs\mu\mu}$
2 σ
3 σ
4 σ
5 σ
6 σ
R_K
R_{K^*}
$R_{K^{(*)}}$
ang. obs. $B \to K^* \mu\mu$
global $b \to s\ell\ell$
0
−10
−20
−30
−40
$-\Delta\chi^2$
−2.0
−1.5
−1.0
−0.5
0.0
0.5
$\Delta\, C_9^{bs\mu\mu} = -\Delta\, C_{10}^{bs\mu\mu}$
2 σ
3 σ
4 σ
5 σ
6 σ
$B_s \to \mu^+\mu^-$
R_K
R_{K^*}
$R_{K^{(*)}}$
ang. obs. $B \to K^* \mu\mu$
global $b \to s\ell\ell$

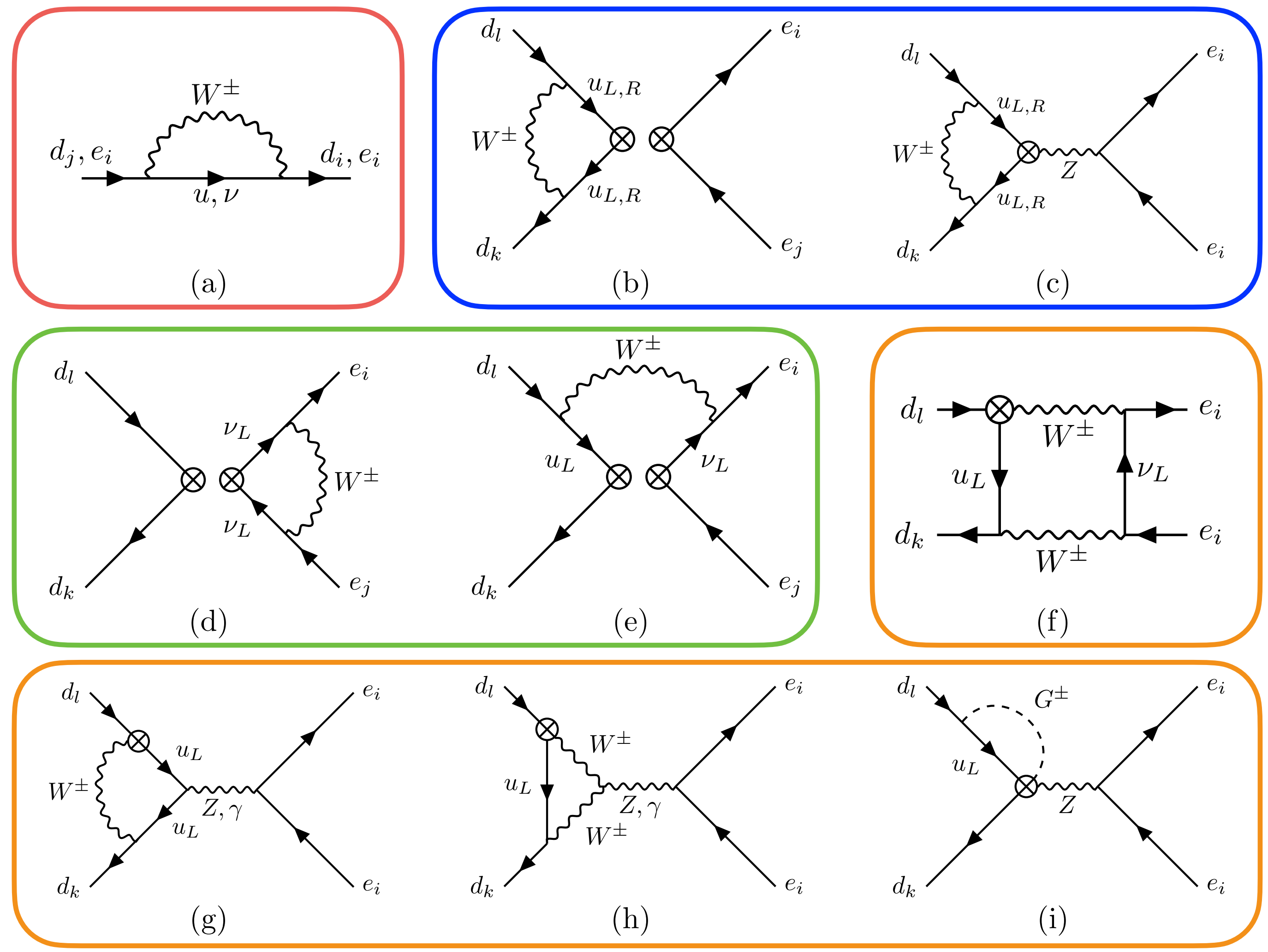
EW radiative corrections

b→sll

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
$\mathcal{O}_{eu}$		✓							
$\mathcal{O}_{\ell u}$		✓							
$\mathcal{O}_{qe}$	✓	✓							
$\mathcal{O}_{\ell q}^{(1)}$	✓	✓							
$\mathcal{O}_{\ell q}^{(3)}$	✓	✓		✓	✓				
$\mathcal{O}_{Hu}$			✓						
$\mathcal{O}_{Hq}^{(1)}$	✓		✓						
$\mathcal{O}_{Hq}^{(3)}$	✓		✓			✓	✓	✓	✓

self-energy

EW corrections to quarks



EW corrections to leptons
(necessary for gauge inv.)

corrections to $O_{Hu,q}$