Flavor vs. Collider

Motoi Endo (KEK)

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Who am I?

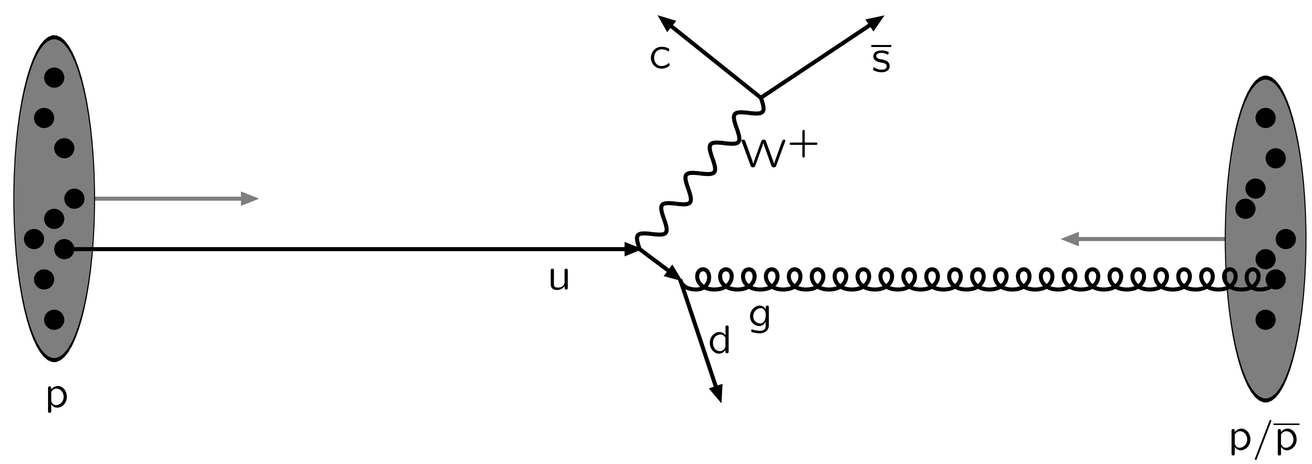
Professor at KEK
Theory center

Particle phenomenology
& particle cosmology
Recently, flavor physics

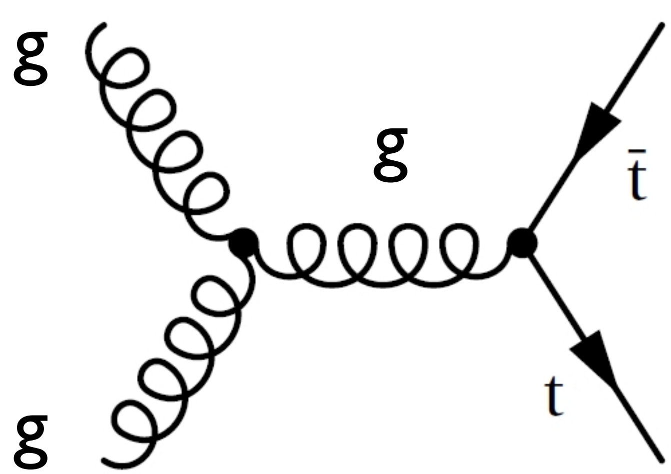
- 03/2005 PhD
  Tohoku university (Japan)
- 04/2005 postdoc
  ICRR (Japan)
- 09/2005 postdoc
  DESY Hamburg (Germany)
- 10/2008 postdoc
  CERN (Switzerland)
- 07/2009 Assist. Prof.
  Univ. of Tokyo (Japan)
- 03/2016 Assoc. Prof.
  KEK (Japan)

“Direct” search for new particles at *colliders*

LHC: proton-proton collision at center-of-energy of 7-14TeV



New particle productions e.g., via pp → χχ (cf. gg → t$\bar{t}$)

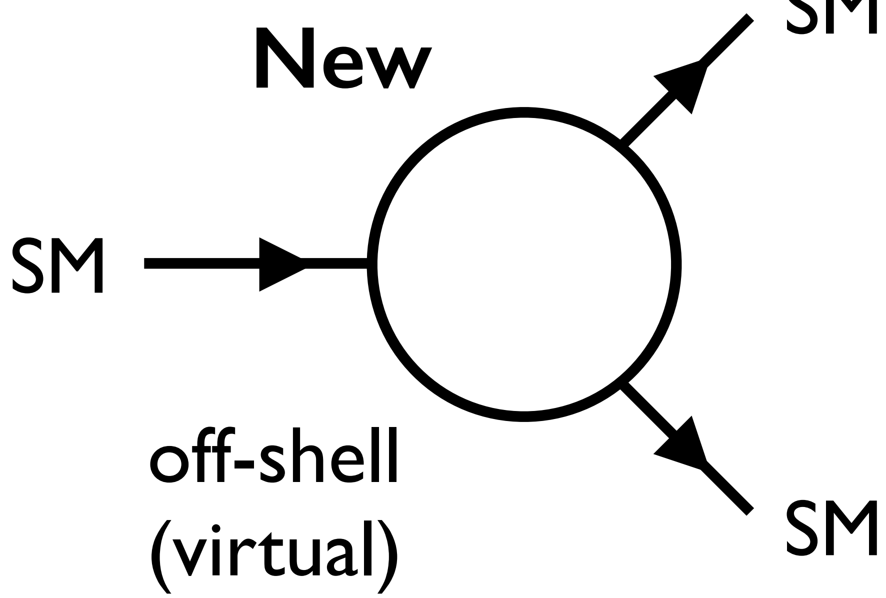


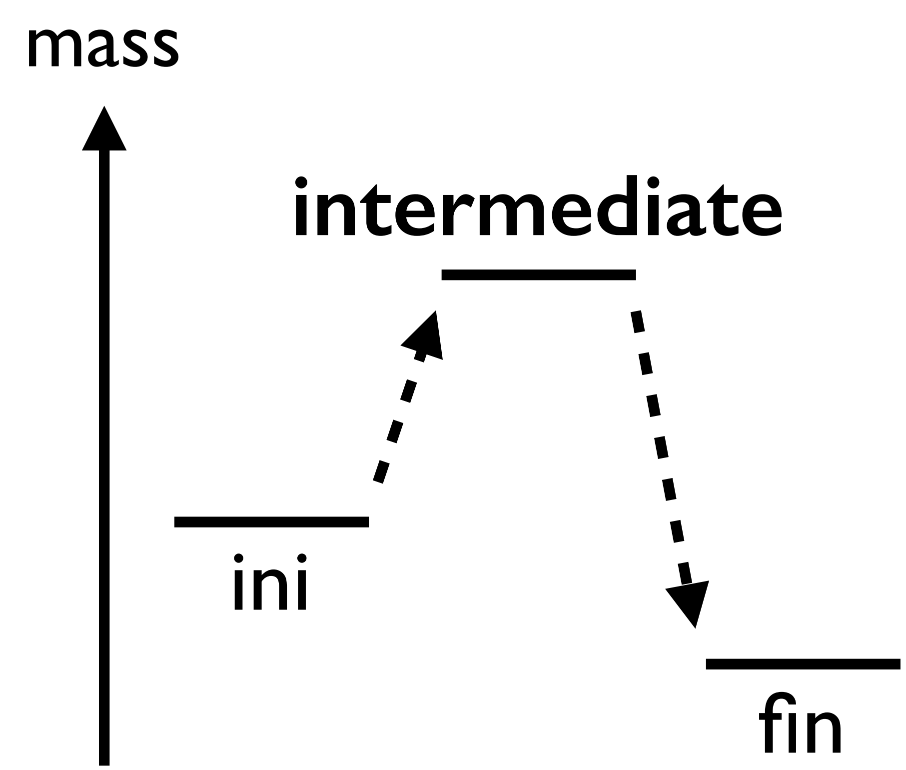
New heavy particles can be produced directly by collisions at high energy.

Sensitivity is limited by beam energy.

How to probe BSM in higher energy scale?

“Indirect” search at *flavor* experiments





Processes with initial and final states composed by SM particles.

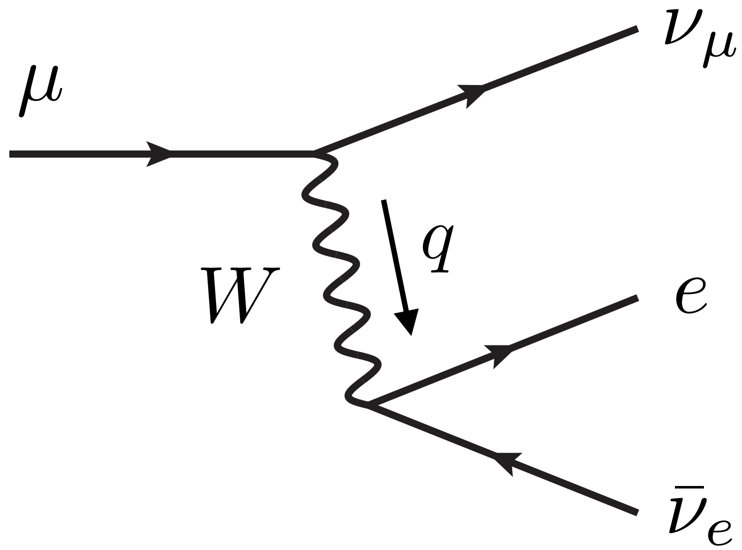
Heavy particles can appear indirectly, *i.e.*, through radiative corrections.

Quantum principle allows heavy new particles to contribute as intermediate (off-shell/virtual) states.

Example of decay induced by heavy particle

Muon decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

SM



$$\mathcal{A} \propto \frac{g^2}{q^2 - M_W^2} (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma_\mu P_L \nu_e)$$

$$\approx -\frac{g^2}{M_W^2} (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma_\mu P_L \nu_e)$$

Fermi coupling const. $\dfrac{G_F}{\sqrt{2}} = \dfrac{g^2}{8M_W^2}$

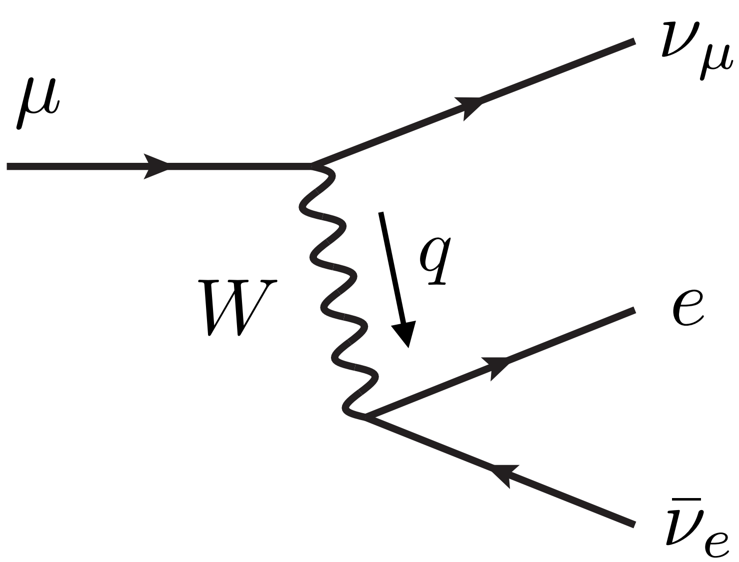
Muon decay proceeds via off-shell exchange of W-boson even though W boson is much heavier than muon.

Muon lifetime (inverse of total decay rate of muon) has been used to determine Fermi coupling constant.

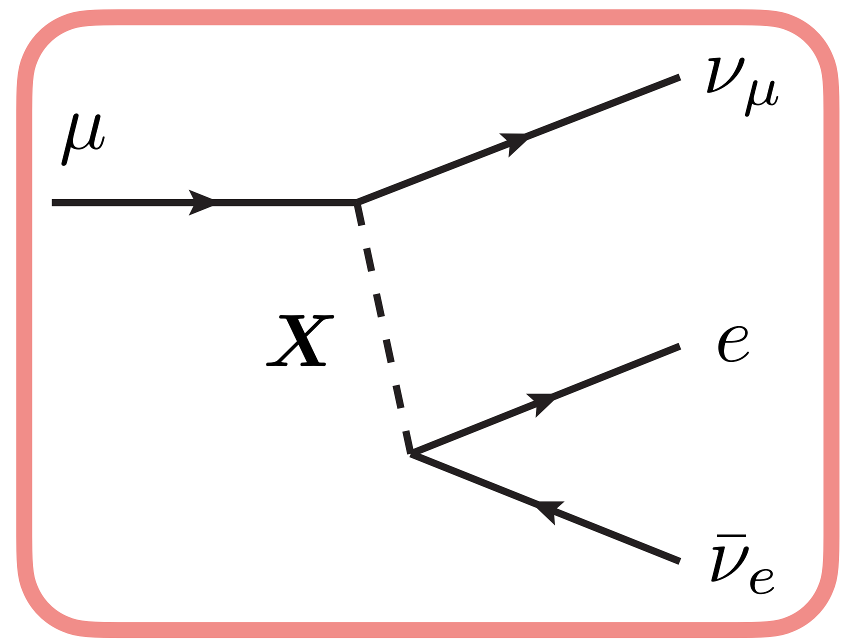
Correction from heavy new particle

Muon decay: $\boldsymbol{\mu^- \to e^- \bar{\nu}_e \nu_\mu}$

SM



Physics beyond SM (BSM)



$$G_F \to G_F^{\mathrm{SM}} + \boxed{\delta G_F}$$

Introduce new heavy particles (X) in off-shell states.

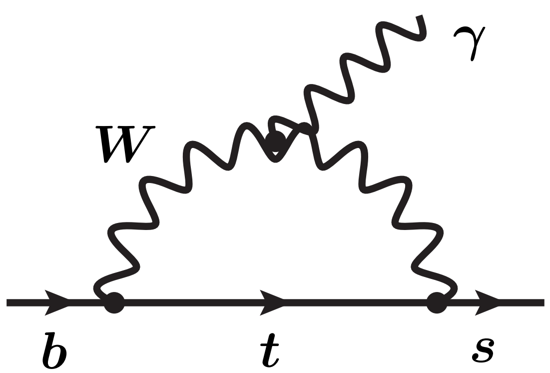
Such contributions are observed as deviations from SM predictions.

Sensitivity to BSM is determined by precision rather than beam energy.

Which process is sensitive to BSM?

Quark *flavor* violation

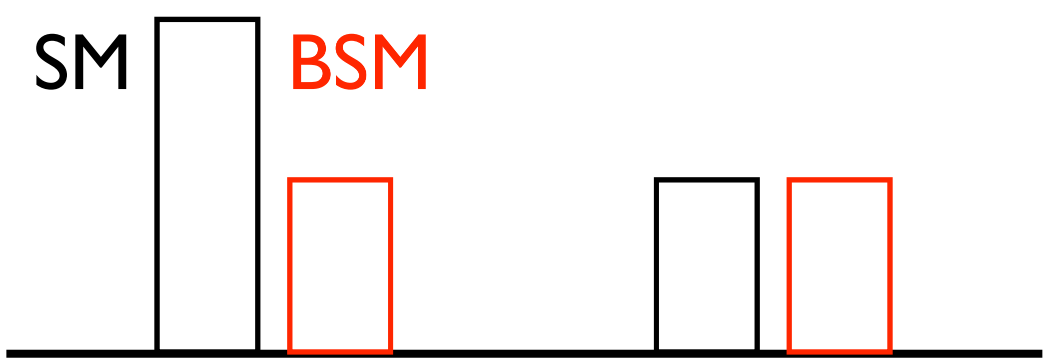
Processes where a quark changes its type = *flavor* (e.g., bottom to strange), violating the conservation of individual quark identity.



High sensitivity to (off-shell) contributions of new particles:

SM contributions are highly suppressed or forbidden at the tree level.

Exp - SM = BSM



Outline

- What is ‘collider’ & ‘flavor’? — Done
- Quark flavor violation
- Hint of physics beyond SM (BSM)

Lecture & Review

- How to test BSM contributions?
  - Test with collider observables
  - Test with flavor observables

Advanced

- Summary

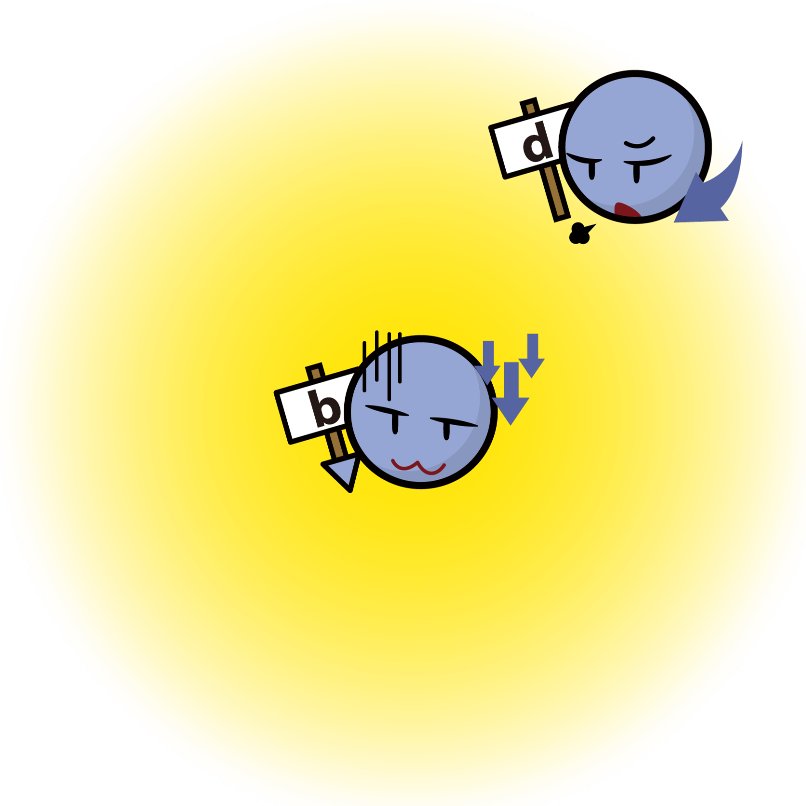
B meson

Quarks are not isolated (cf. confinement), but dressed by quarks and gluons.

B meson consists of b quark w/. light u,d quark ($m_b \gg m_{u,d}$).

$$B^0 : \ (\bar{b}d)$$

$$\bar{B}^0 : \ (b\bar{d})$$



Pseudo scalar

$$J^P = 0^-$$

b quark decays into lighter quarks by exchanging W boson in SM.

Many decay channels — Targets at Belle II, LHCb, future exp, e.g., Z factory

LHCb experiment

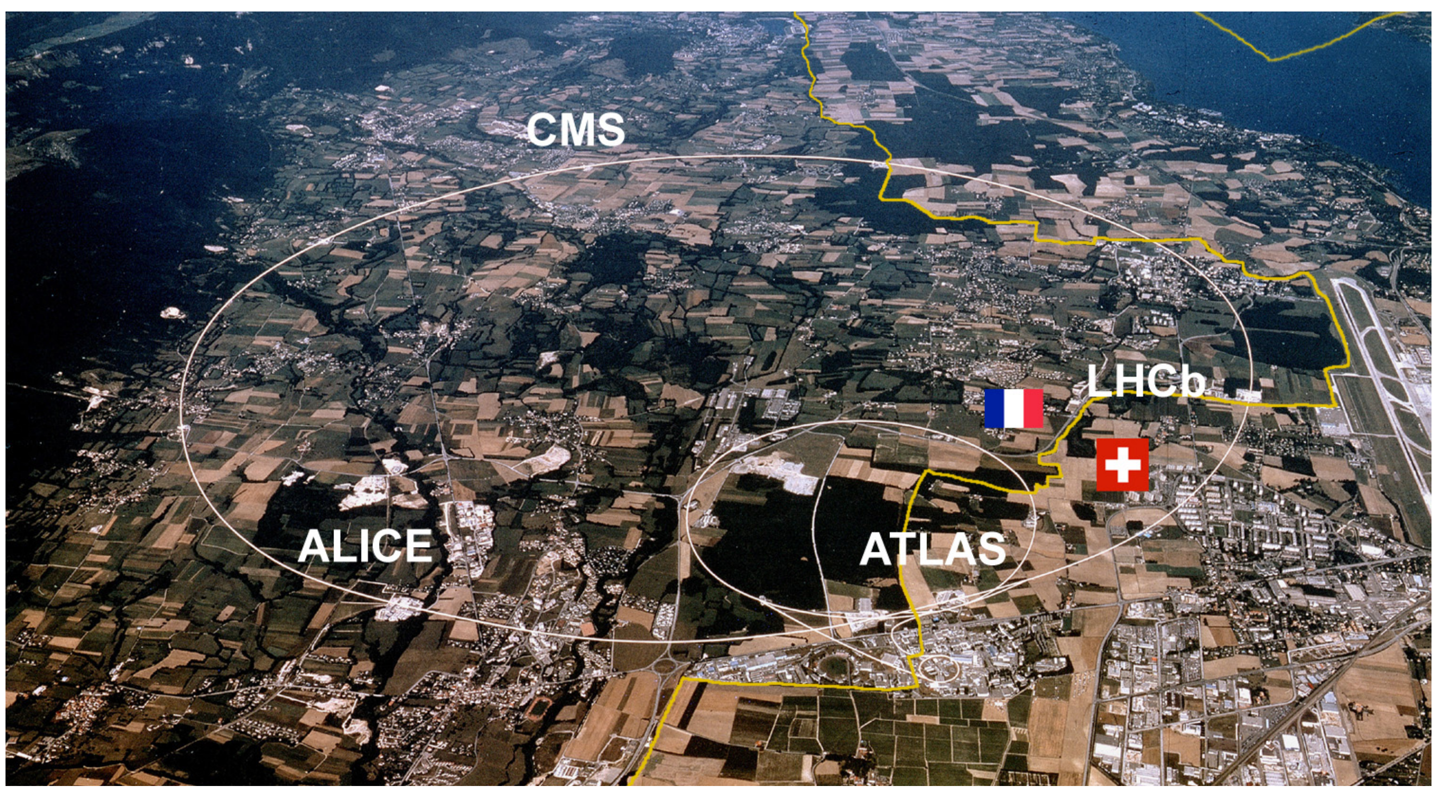
one of four LHC experiments, 2008-

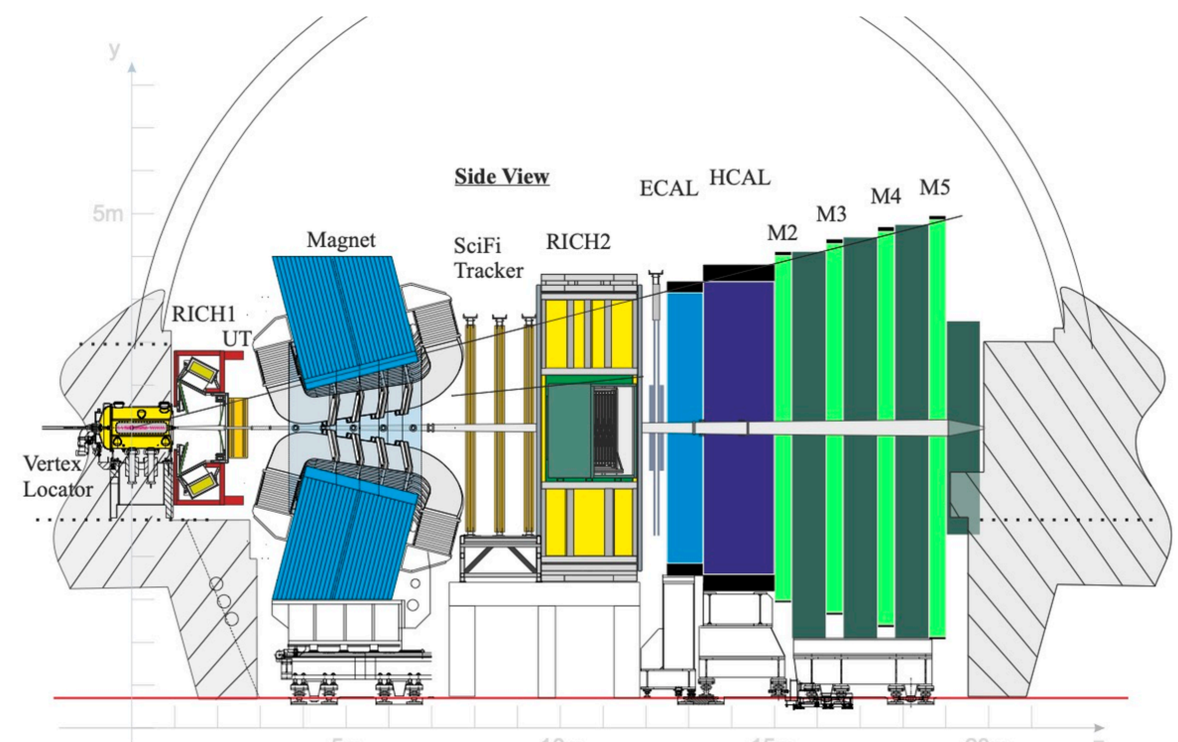
pp collision at $\sqrt{s}$=7-14TeV, producing b quarks in forward region.

Target integrated luminosity: 270-300fb^{-1} (~2041)

→ B^0: 3×10^{13}, $B^{\pm}$: 3×10^{13}. Moreover, B_s^0: 1×10^{13}, $B_c^{\pm}$: 1×10^{11}, Λ_b: 2×10^{13}

Hadron collider: huge statistics, but challenging to reconstruct events.





Belle II experiment

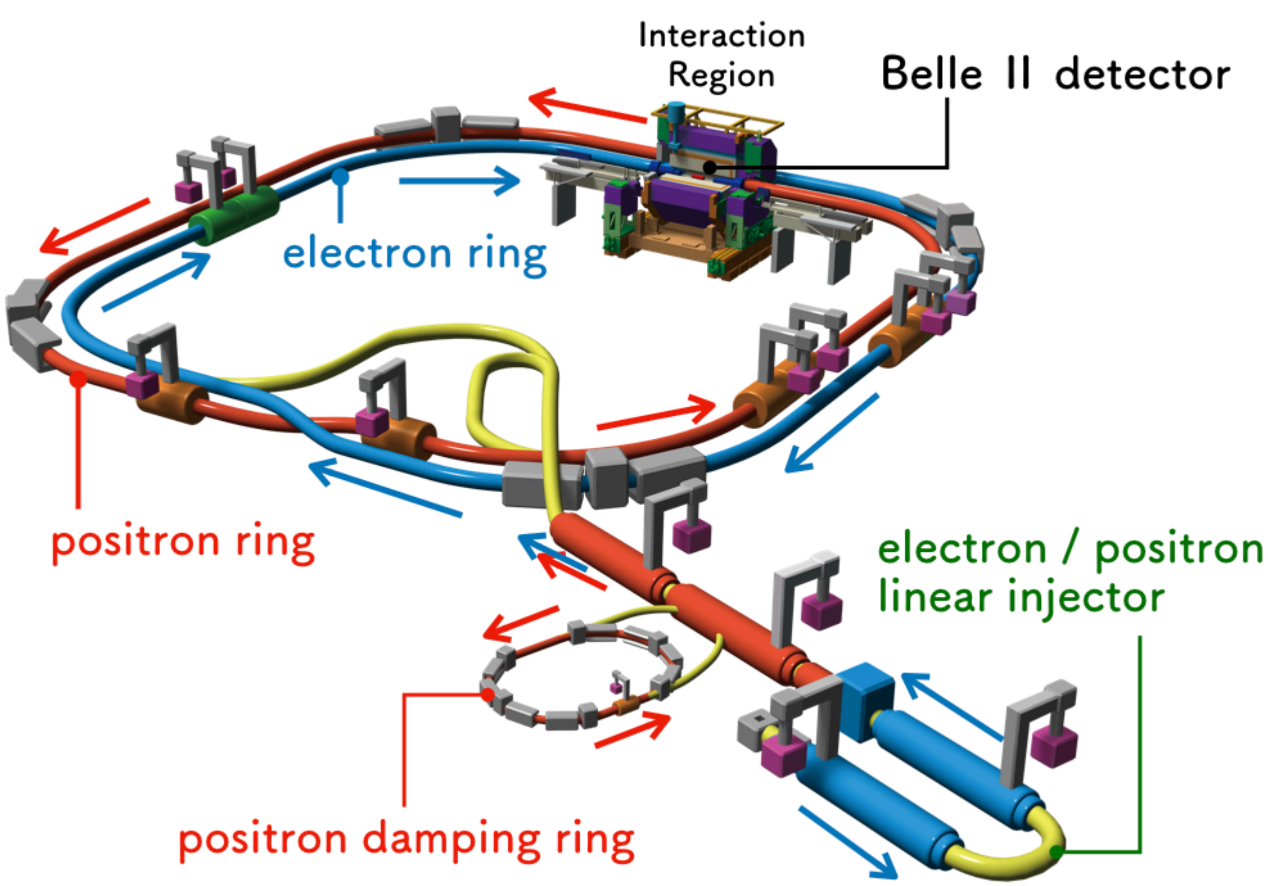
cf. Belle: 1999-2010, Belle II: 2018-

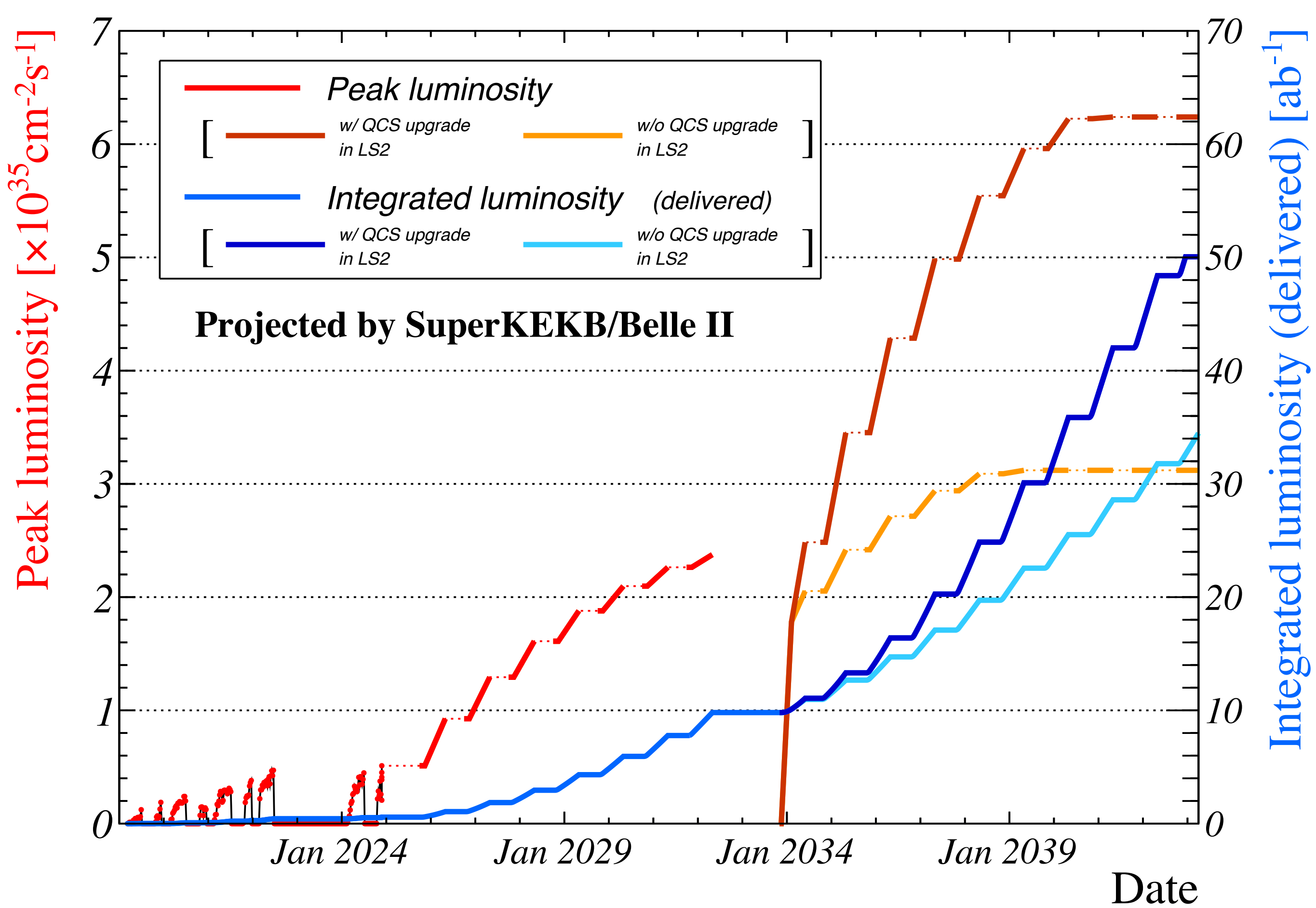
e- (7GeV) e+ (4GeV) → Υ(4S) → $B\bar{B}$ (also $D\bar{D}$, $\tau^+\tau^-$, …)

Target integrated luminosity: 50ab^{-1} (~2040s)

→ B^0: 5.4×10^{10}, $B^\pm$: 5.7×10^{10} (also B_s^0 via Υ(5S) production)

Lepton collider: clean environment allows us to reconstruct events.





Z factory project

e+e- collision at √s~90GeV (around Z-boson mass)

→ Experiment of Z-boson factory cf. Higgs factory

(i) proposals of future "Higgs Factories"

$\int L$ / ab^{-1} \ $\sqrt{s}$ / GeV	91	160	240-250	350-365	550	1000-3000	Beam Polarization
LCF	0.1	0.5*	3	0.4	8	8	(80%, 30%)
CEPC	100	6.9	21.6	1*			(0, 0)
FCC-ee	205	19.2	10.8	3.16			(0, 0)

(+ emerging Muon Colliders, μTristen, HELEN, HALHF, ReLiC, ALEGRO, XCC, etc)

LCF: Linear Collider Facility @ CERN; identical to scenarios proposed by LC Vision Team up to 550 GeV; representing ILC, CLIC, C³

Z factory project

e+e- collision at √s~90GeV (around Z-boson mass)

→ Experiment of Z-boson factory cf. Higgs factory

→ B-hadron factory cf. Br(Z→bb)=15.12%

Lepton collider: clean environment allows us to reconstruct events.

All B hadrons are produced.

"Tera-Z"=10^{12} Z

Particle	BESIII	Belle II (50 ab^{-1} on $\Upsilon(4S)$)	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	-	5.4×10^{10}	3×10^{13}	4.8×10^{11}
$B^\pm$	-	5.7×10^{10}	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	-	6.0×10^8 (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	-	1×10^{11}	7.2×10^8
Λ_b^0, $\bar{\Lambda}_b^0$	-	-	2×10^{13}	1×10^{11}

Ai et.al, Flavor Physics at CEPC: a General Perspective, 2412.19743

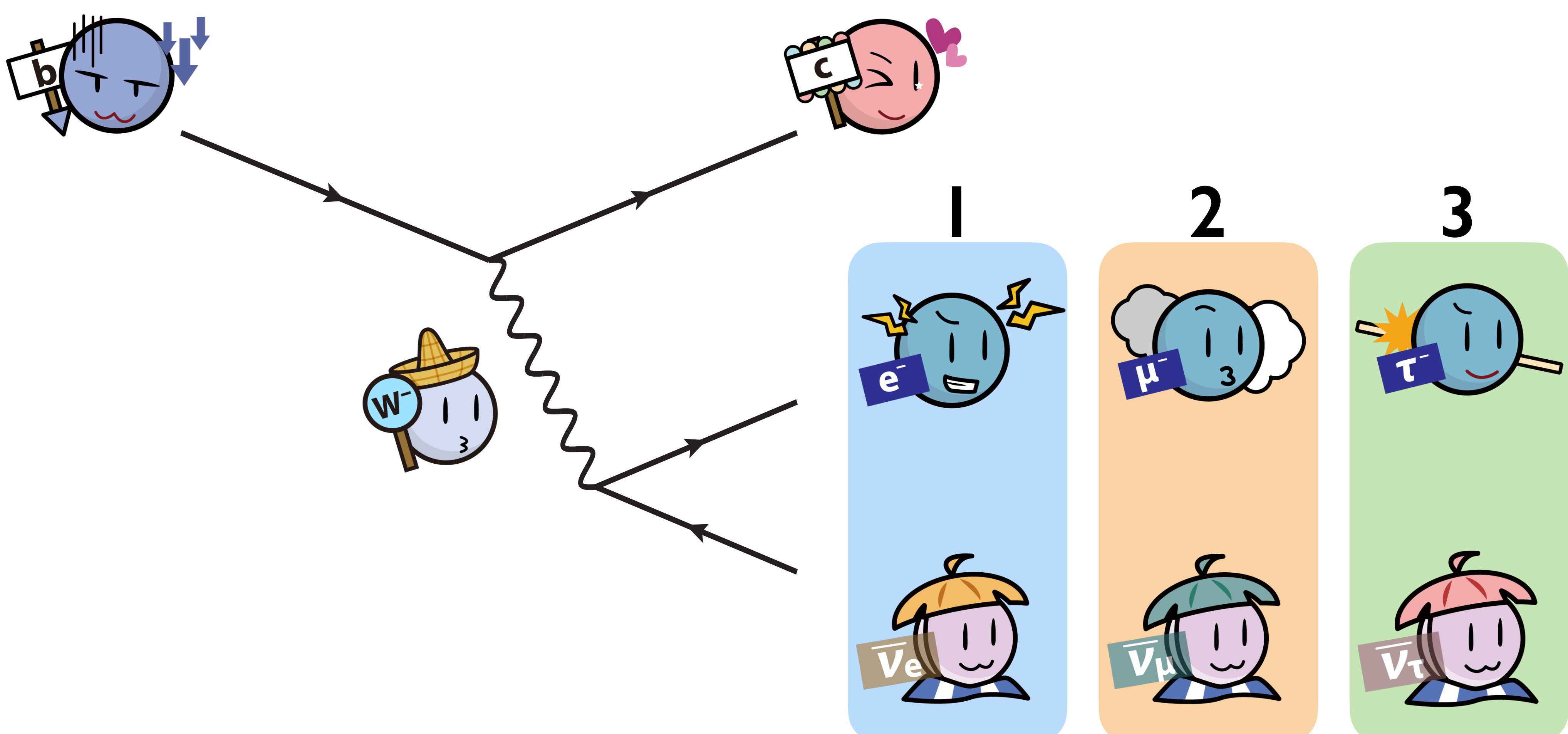
FCC-ee: ~5x"Tera-Z"

* LCF also proposes Giga-Z projects

Semileptonic decay of b quark

Electron, muon, and tau lepton have same gauge charges.
In SM, quark decay rates into leptons become same (but mass effects).

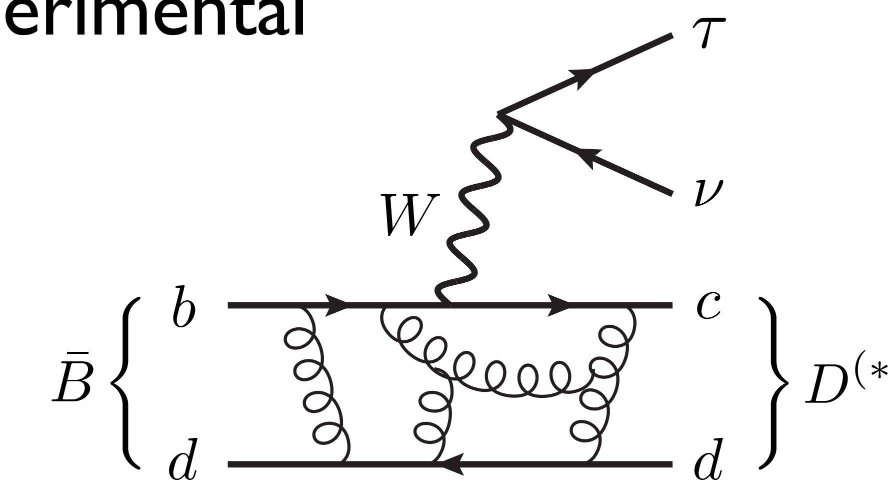
— lepton-flavor universality



$$B, D : J^P = 0^-$$
$$D^* : J^P = 1^-$$

Lepton-flavor universality violation

Making ratios benefits from cancellations of experimental and theoretical uncertainties (hadrons and V_{cb}).



$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\Gamma(B \to D^{(*)}\ell^-\bar{\nu}_\ell)} \qquad \ell = e,\ \mu$$

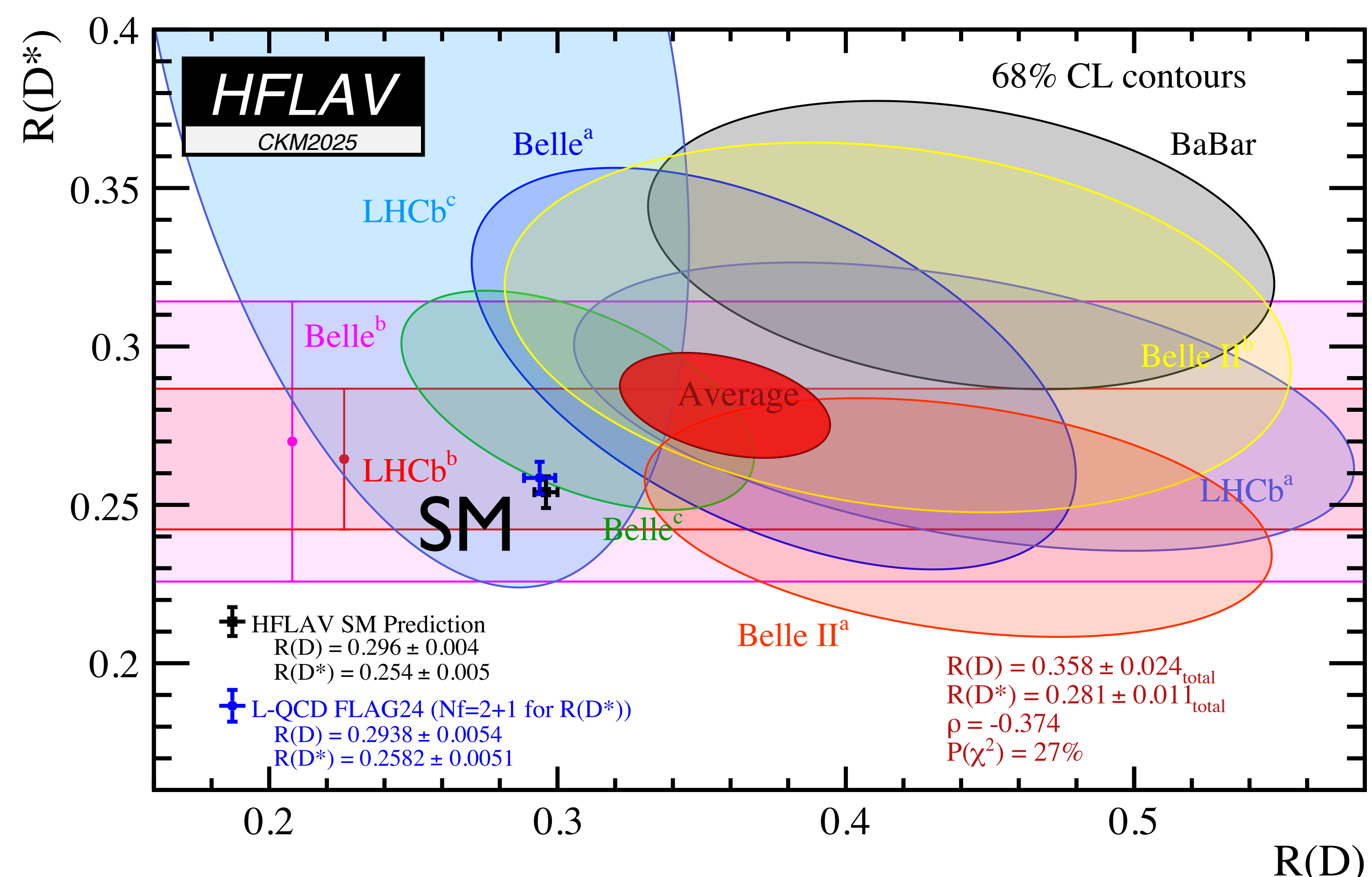
Current status:

3.8σ tension

from SM

BSM contributions to $B \to D^{(*)} l\nu$ are limited.

Imply BSM in $b \to c\tau\bar{\nu}$.



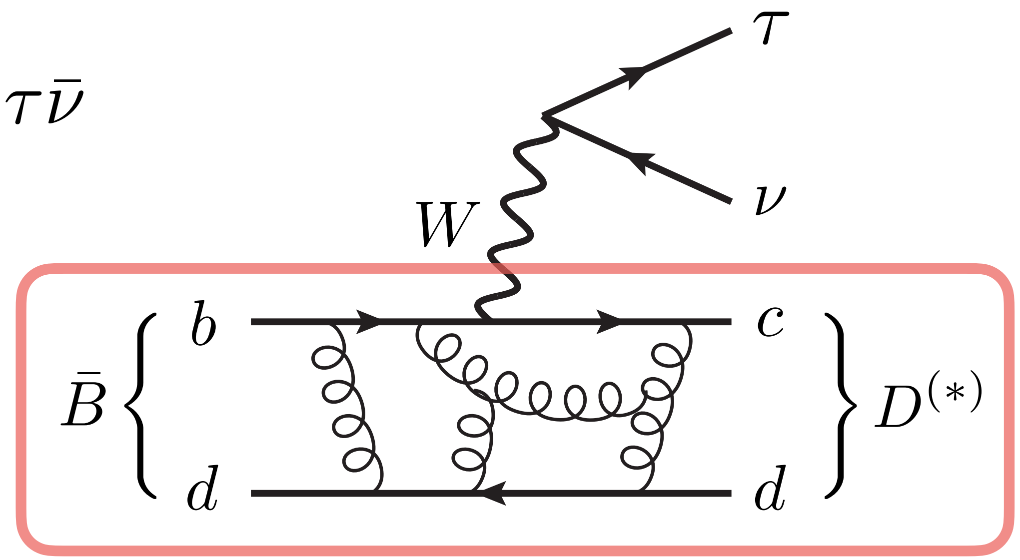
Heavy flavor averaging group

Theoretical prediction

In SM, b quark decay proceeds via W boson exchange.

b quark is not isolated, but is dressed by quark and gluons:

$$b \to c\tau\bar{\nu} \quad \Rightarrow \quad \bar{B} \to D\tau\bar{\nu},\ \bar{B} \to D^*\tau\bar{\nu}$$



Transition amplitude:

$$\mathcal{A} = -\frac{4G_F}{\sqrt{2}} V_{cb} \langle D^{(*)}\tau\bar{\nu}|(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_\tau)|\bar{B}\rangle$$

Introduce hadron matrix elements including form factors.

$$\langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle = f_+(q^2)(p_B + p_D)^\mu + f_-(q^2)(p_B - p_D)^\mu$$

$$\langle D|\bar{c}\gamma^\mu\gamma_5 b|\bar{B}\rangle = 0$$

Hadron matrix element parametrization

1. List all dynamical variables, e.g., momentum, polarization vector

$$p_B,\ p_D$$

2. Matrix elem. consists of all possible linear combinations of variables in '1' which match the Lorentz structures and symmetries (e.g., C, P, T)

$$\langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle :\ p_B^\mu,\, p_D^\mu \ \rightarrow\ (p_B+p_D)^\mu,\ (p_B-p_D)^\mu$$

$\langle D|\bar{c}\gamma^\mu\gamma_5 b|\bar{B}\rangle = 0$ because of Parity

Parity: odd odd odd

3. Form factors are Lorentz scalar ($q = p_B - p_D$)

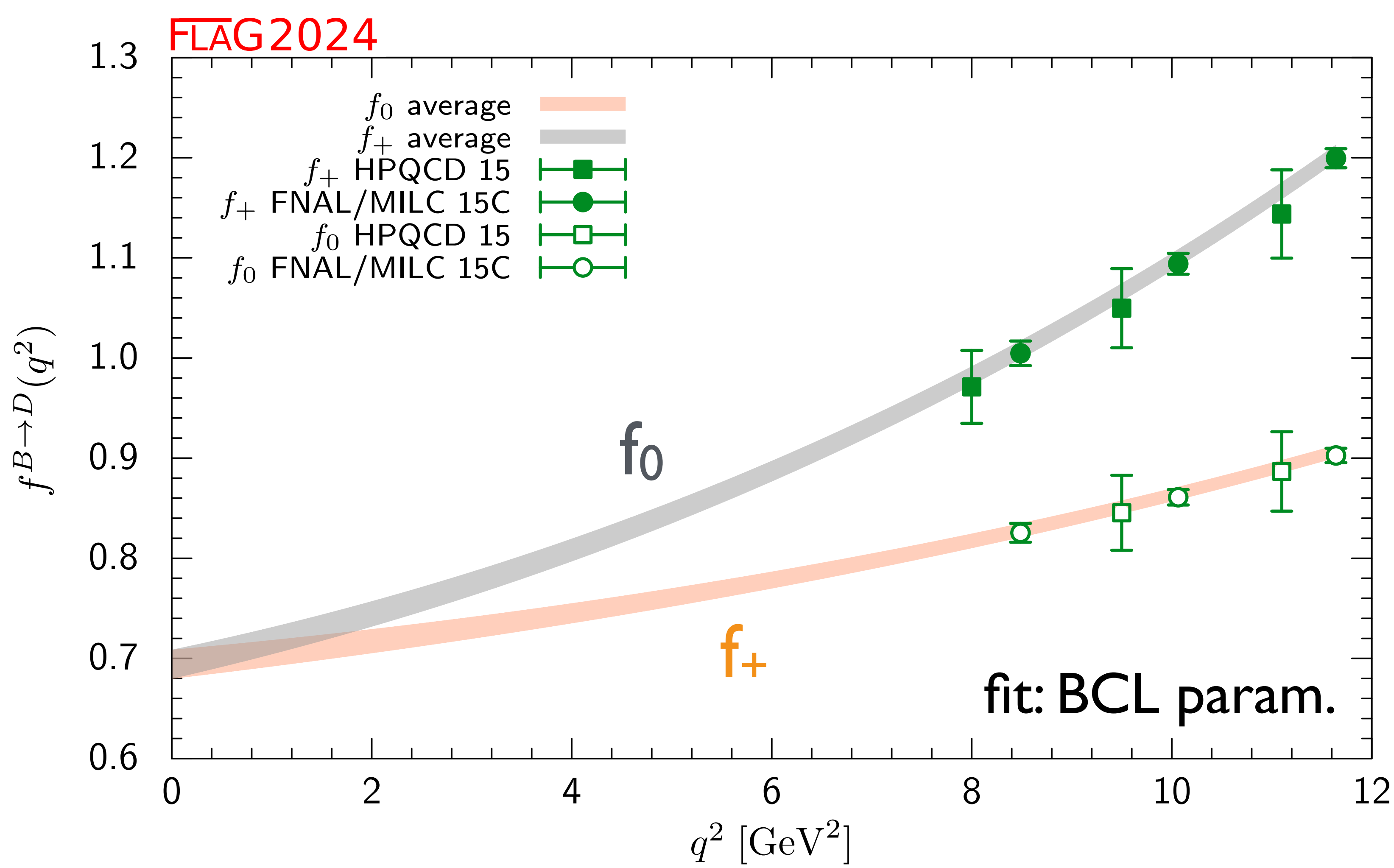
$$p_B^2 = m_B^2,\ p_D^2 = m_D^2,\ p_B\cdot p_D\,(\rightarrow q^2)$$

$$\rightarrow\ \langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle = f_+(q^2)(p_B+p_D)^\mu + f_-(q^2)(p_B-p_D)^\mu$$

4. Determine form factors by using lattice, experimental inputs, etc.
   → Literature search

Form factor from lattice

$$\langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle = f_+(q^2)(p_B+p_D)^\mu + f_-(q^2)q^\mu$$
$$= f_+(q^2)(p_B+p_D)^\mu + \left[f_0(q^2) - f_+(q^2)\right]\frac{m_B^2 - m_D^2}{q^2}q^\mu$$



$$q = p_B - p_D$$

Flavor Lattice Averaging Group

Form factor for BSM

Scalar operator: $q = p_B - p_D = p_b - p_c$

$$q_\mu \langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle = \langle D|\bar{c}(\not{p}_b - \not{p}_c)b|\bar{B}\rangle = (m_b - m_c)\langle D|\bar{c}b|\bar{B}\rangle$$

$$q_\mu \langle D|\bar{c}\gamma^\mu b|\bar{B}\rangle = q_\mu \left[f_+(q^2)(p_B + p_D)^\mu + \left[f_0(q^2) - f_+(q^2)\right] \frac{m_B^2 - m_D^2}{q^2} q^\mu \right]$$

$$= (m_B^2 - m_D^2) f_0(q^2)$$

$$\therefore \quad \boxed{\langle D|\bar{c}b|\bar{B}\rangle = \frac{m_B^2 - m_D^2}{m_b - m_c} f_0(q^2)}$$

Here, Dirac equation in momentum space representation: $\not{p}\psi = m\psi$

Also, $\langle D|\bar{c}\gamma_5 b|\bar{B}\rangle = 0$

Tensor operator: new form factor $f_T(q^2)$

$$\boxed{\langle D|\bar{c}\sigma^{\mu\nu} b|\bar{B}\rangle = -\frac{2i f_T(q^2)}{m_B + m_D} (p_B^\mu p_D^\nu - p_B^\nu p_D^\mu)}$$

Decay rate

Transition amplitude

$$
\begin{aligned}
\mathcal{A} &= -\frac{4G_F}{\sqrt{2}} V_{ub} \langle D\ell^+\bar{\nu}|(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)|\bar{B}\rangle \\
&= -\frac{4G_F}{\sqrt{2}} V_{ub} \langle D(k)|\bar{c}_L\gamma^\mu b_L|\bar{B}(p)\rangle\, \bar{u}(p_\tau)\gamma_\mu P_L v(p_\nu) \\
&= -\sqrt{2}G_F V_{ub} \langle D(k)|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle\, \bar{u}(p_\tau)\gamma_\mu P_L v(p_\nu) \qquad \leftarrow \; P_L = \frac{1-\gamma_5}{2} \\
&= -\sqrt{2}G_F V_{ub} \left[f_+(q^2)P^\mu + f_-(q^2)q^\mu\right]\, \bar{u}(p_\tau)\gamma_\mu P_L v(p_\nu) \\
&= -\sqrt{2}G_F V_{ub} f_+(q^2)\bar{u}(p_\nu)\not{P} P_L v(p_e) + \underbrace{(m_\tau \text{ term})}_{\text{ignore for simplicity}} \qquad \leftarrow \text{ EOM for leptons}
\end{aligned}
$$

$$
\begin{cases} P = p_B + p_D \\ q = p_B - p_D = p_\tau + p_\nu \end{cases}
$$

Spin-averaged/summed amplitude squared:

$$
\overline{\sum_{\text{spin}}}|\mathcal{M}|^2 = 2G_F^2|V_{ub}|^2 f_+(q^2)^2(\lambda_B - u^2)
$$

where $u = -2k(p_\tau - p_\nu),\ \lambda_B = \lambda(m_B^2, m_D^2, q^2)$

$$
[\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx]
$$

Decay rate

Integration of 3-body phase space (m_τ is neglected)

$$\frac{d\Gamma(\bar{B}\to D\tau\bar{\nu})}{dq^2} = \frac{1}{256\pi^3 m_B^3}\int_{-\lambda_B^{1/2}}^{+\lambda_B^{1/2}} du \overline{\sum_{\rm spin}}|\mathcal{M}|^2 = \frac{G_F^2|V_{ub}|^2}{192\pi^3 m_B^3} f_+(q^2)^2\lambda_B^{3/2}$$

Including m_τ (w/o derivation → Let's try!)

$$\frac{d\Gamma(\bar{B}\to D\tau\bar{\nu})}{dq^2} = \frac{G_F^2|V_{ub}|^2}{192\pi^3 m_B^3}\lambda_B^{1/2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \times\left[\left(1+\frac{m_\tau^2}{2q^2}\right)\lambda_B f_+(q^2)^2 + \frac{3m_\tau^2}{2q^2}(m_B^2-m_D^2)^2 f_0(q^2)^2\right]$$

$$m_\tau^2 < q^2 < (m_B - m_D)^2$$

* Instead of q^2, w is also used in literature:

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

Outline

- What is ‘collider’ & ‘flavor’? — Done
- Quark flavor violation
- Hint of physics beyond SM (BSM)

Lecture & Review

- How to test BSM contributions?
  - Test with collider observables
  - Test with flavor observables

Advanced

- Summary

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Lepton-flavor universality violation

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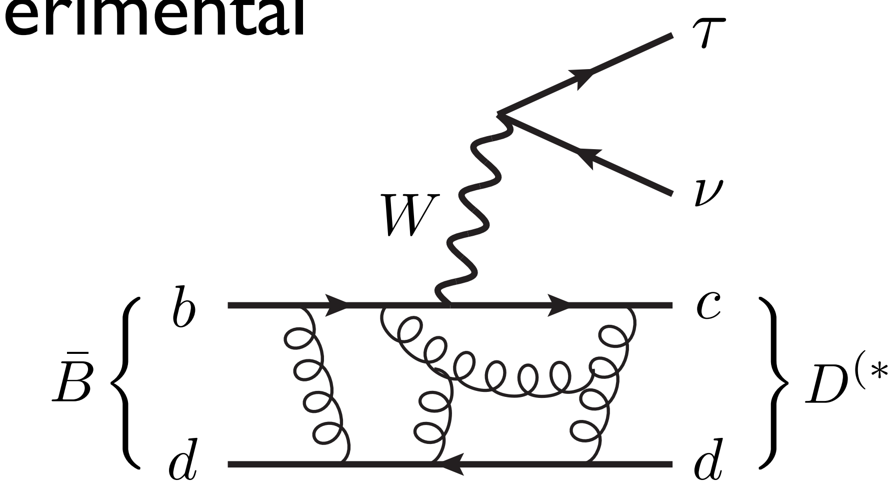

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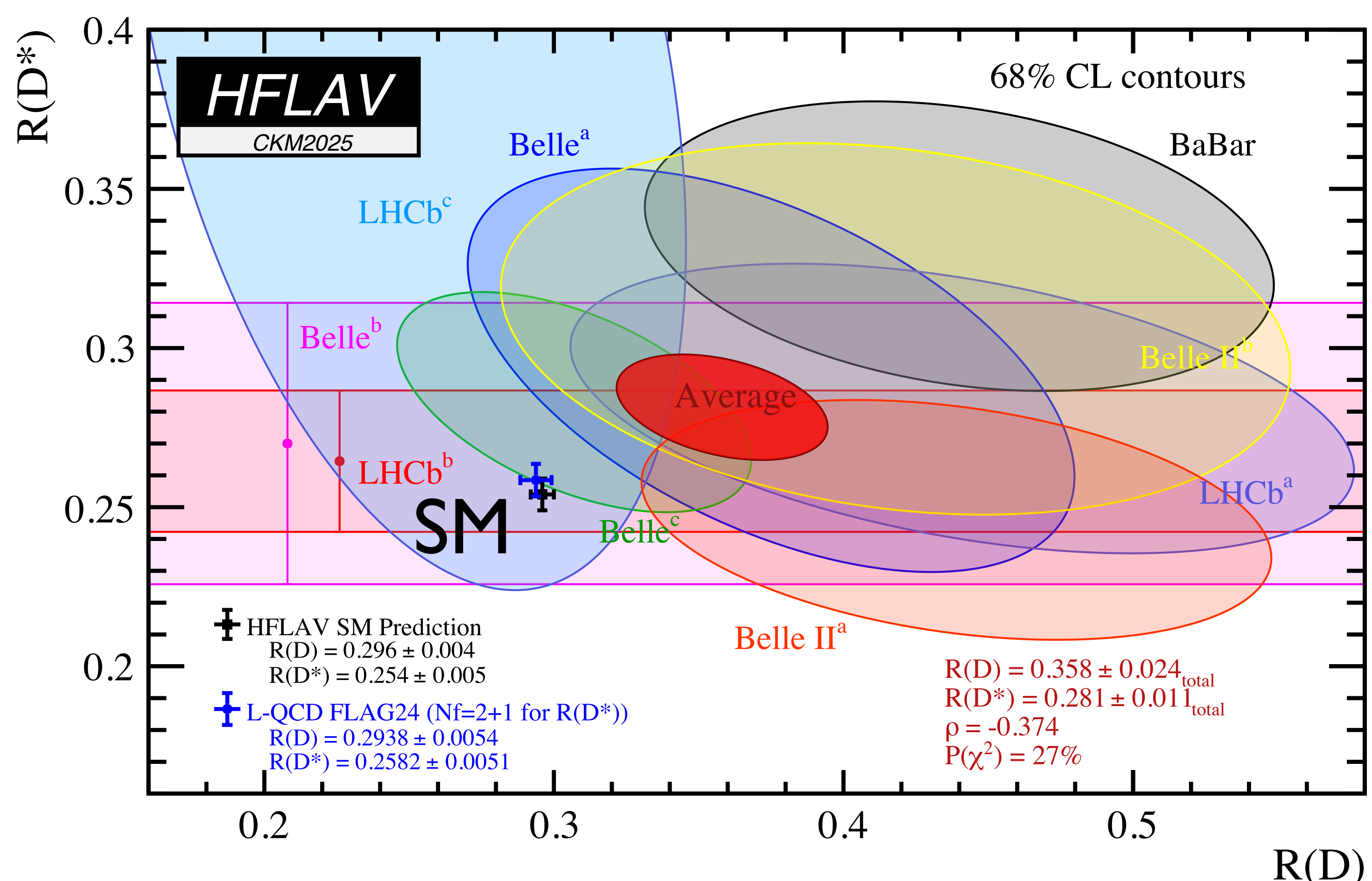


Heavy flavor averaging group

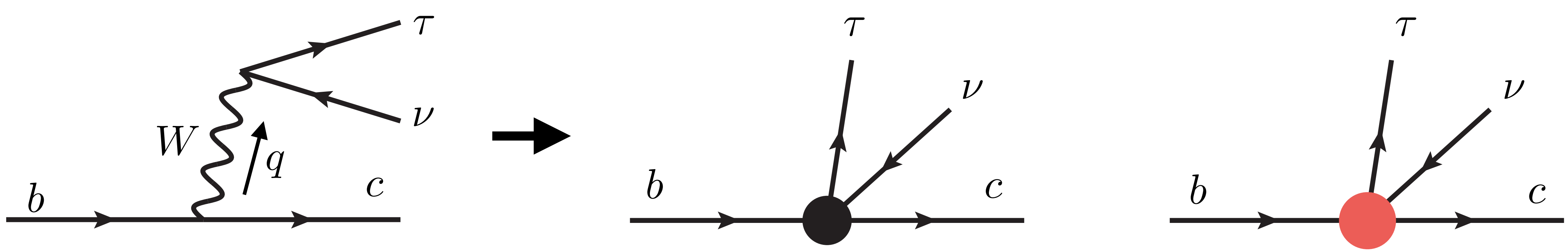
Physics beyond SM: low-energy effective theory

SM contribution is obtained by integrating out heavy W-boson propagation, leading to effective interaction (→ low-energy effective theory).

Similarly, by integrating out new heavy particles, BSM contributions are expressed by effective interactions.

Standard Model

New heavy particle



$$\frac{g^2}{q^2 - M_W^2}(\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) \approx \frac{-g^2}{M_W^2}(\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) \qquad \frac{1}{M^2}(\bar{c}\,\Gamma\, b)(\bar{\tau}\,\Gamma\,\nu)$$

W-boson

effective

effective

Physics beyond SM: low-energy effective theory

BSM contributes only to tau channel.

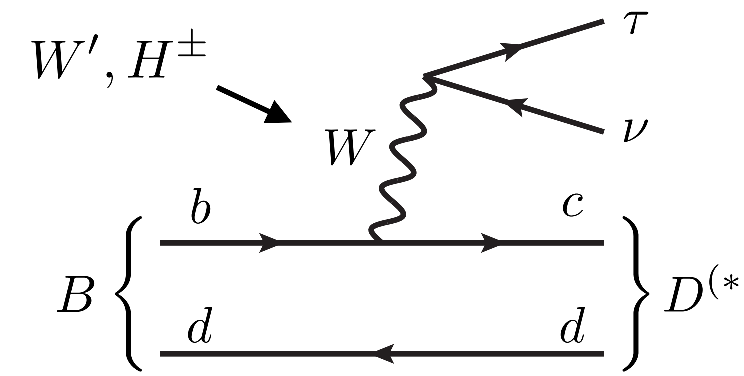
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\underbrace{1}_{\text{SM}} + C_{V_L}) O_{V_L} + C_{S_L} O_{S_L} + C_{S_R} O_{S_R} + C_T O_T \Big]$$

Fit to R_D and R_{D^*} results

	operator	Wilson coefficient	
V_L	$(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$	$C_{V_L} \approx 0.08$	BSM scale O(1)TeV
S_L	$(\bar{c} P_L b)(\bar{\tau} P_L \nu)$	$C_{S_L} \approx -0.57 \pm i\,0.86$	
S_R	$(\bar{c} P_R b)(\bar{\tau} P_L \nu)$	$C_{S_R} \approx 0.18$	
T	$(\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$	$C_T \approx 0.02 \pm i\,0.13$	

Constraints/correlations depend on UV models.

Iguro, Kitahara, Watanabe, PRD 110 (2024) 075005



BSM models in UV scale

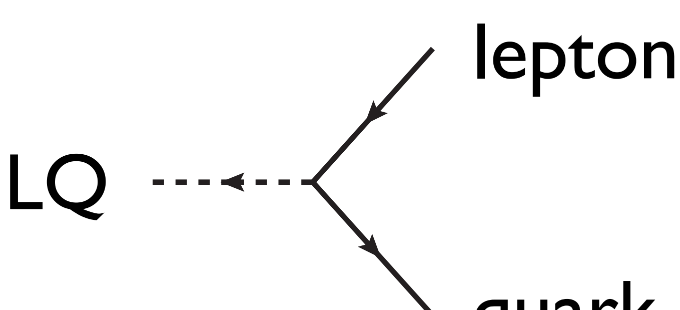
W' is ruled out by flavor constraints on Z' and colliders.

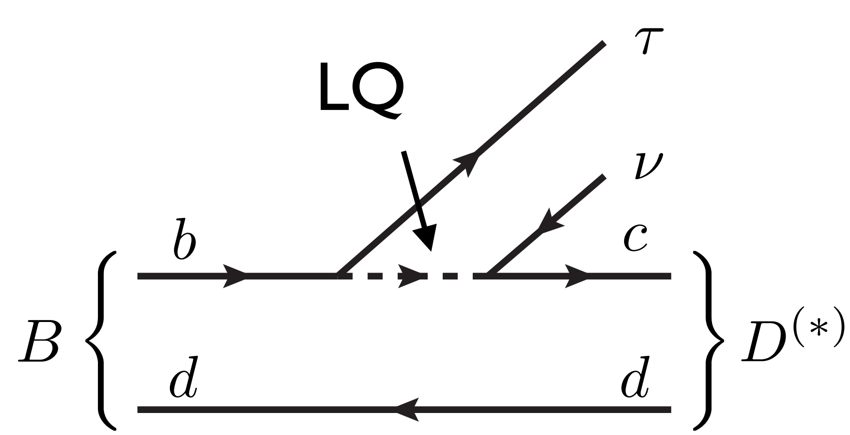
Charged Higgs boson in Type-II two-Higgs doublet model (2HDM) cannot explain R_D and R_{D^*} excesses simultaneously.

Two major scenarios: charged Higgs boson (non Type-II) & leptoquark.

Leptoquark (LQ): spin 0 or 1 boson, carry both lepton & baryon #, couple to lepton and quark simultaneously.

R_2, S_1, U_1 can explain both R_D, R_{D^*} excesses.





LQ charge

$(SU(3), SU(2), U(1))$	Spin	Symbol
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2
$(\mathbf{3}, \mathbf{2}, 1/6)$	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
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	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
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$

Fit to R_D and R_{D^*} in LQ models

LQ contribution after LQ decoupling: $C_i \sim \dfrac{g_{\rm LQ}^2}{M_{\rm LQ}^2}$

$$\mathrm{R}_{\boldsymbol{2}}: \ \boldsymbol{C_{S_L} = 4C_T}$$

$$\mathrm{S}_{\boldsymbol{1}}: \ \boldsymbol{C_{V_L}\,,\ C_{S_L} = -4C_T}$$

$$\mathrm{U}_{\boldsymbol{1}}: \ \boldsymbol{C_{S_R} = -2e^{i\phi}C_{V_L}} \quad \text{[UV: U(2)-flavored model]}$$

Include QCD corrections, and then, fit to R_D and R_{D^*} exp. data

$$\mathrm{R}_{\boldsymbol{2}}: \ \boldsymbol{C_{S_L} = 8.4\,C_T = -0.09 \pm i\,0.56}$$

$$\mathrm{S}_{\boldsymbol{1}}: \ \boldsymbol{C_{S_L} = -8.9\,C_T = 0.18 \ \ (C_{V_L} = 0)}$$

$$\mathrm{U}_{\boldsymbol{1}}: \ \boldsymbol{C_{V_L} = 0.08\,,\ \phi = 0.5\pi \ \ (C_{S_R} = -3.7e^{i\phi}C_{V_L})}$$

All are consistent with experimental constraints such as LHC.

Iguro, Kitahara, Watanabe, PRD 110 (2024) 075005

Outline

- What is ‘collider’ & ‘flavor’? — Done
- Quark flavor violation
- Hint of physics beyond SM (BSM)

Lecture & Review

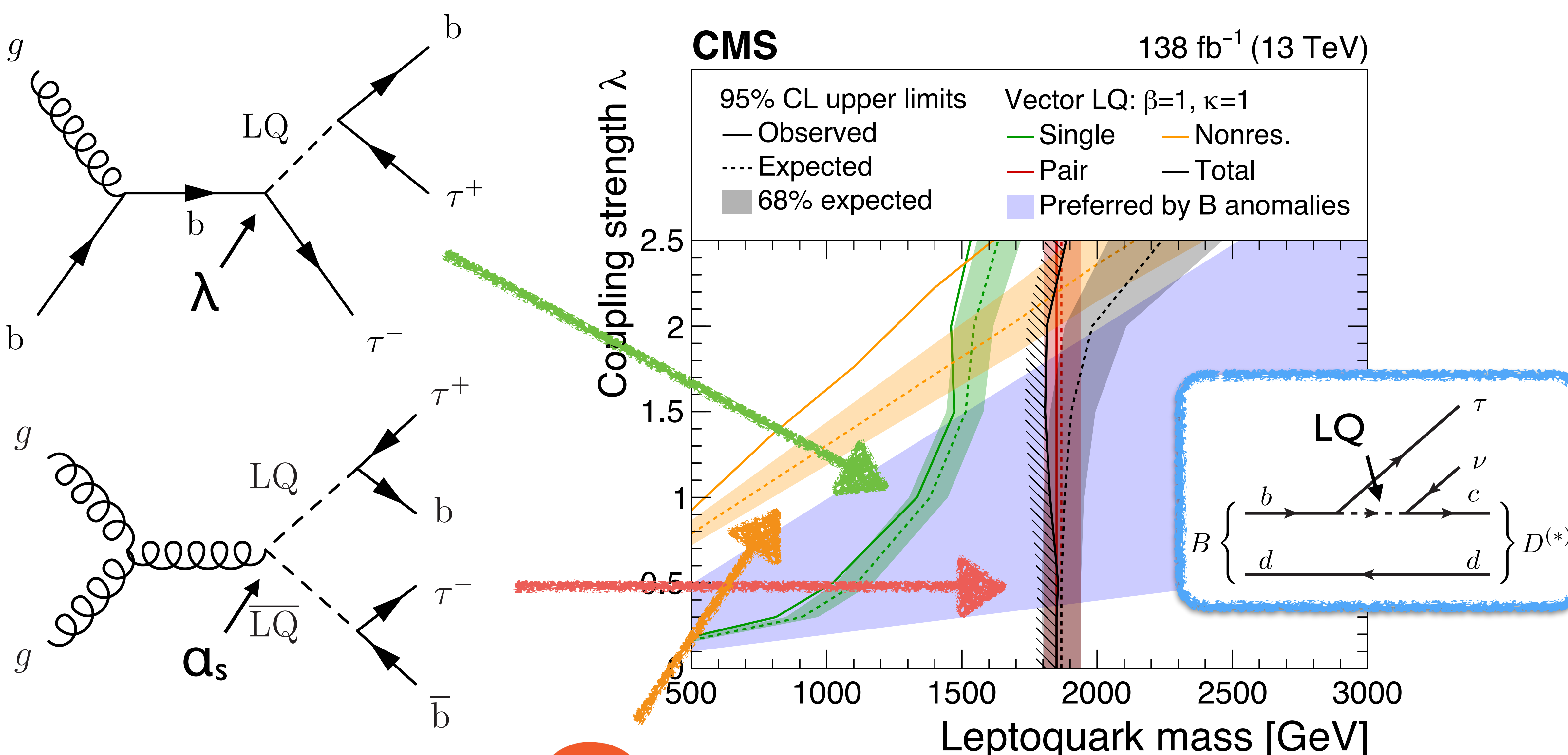
- How to test BSM contributions?
  - Test with collider observables
  - Test with flavor observables

Advanced

- Summary

Direct search for new particle at colliders

Direct (on-shell) productions of new particle → LQ mass >~1.8TeV



CMS collaboration, JHEP 05 (2024) 311

ATLAS collaboration, JHEP 10 (2025) 054

Indirect search at colliders

$b\bar{b} \to \tau^+\tau^-$ scattering via LQ exchange.

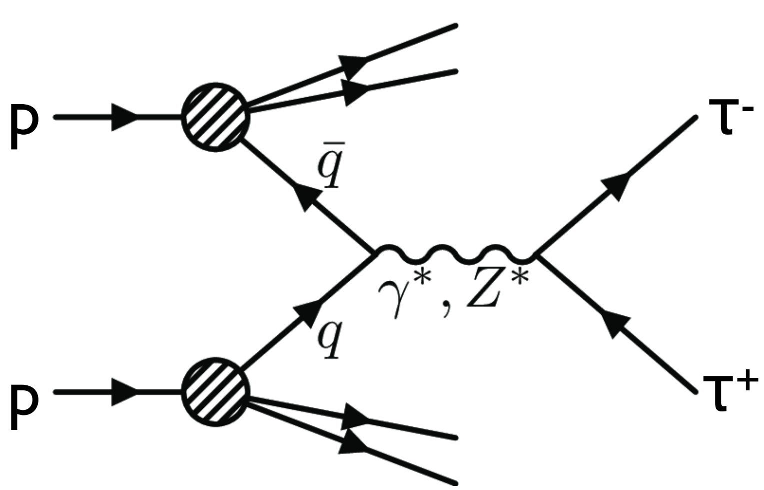
τ pair production in SM: γ, Z exchange

$\tau^+\tau^-$ invariant mass distribution

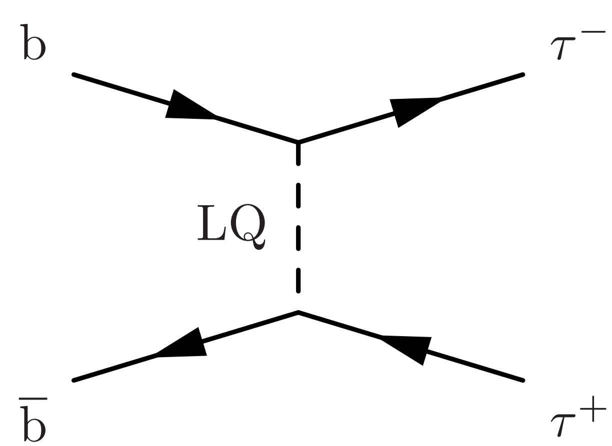
$$m_{\tau\tau}^2 \equiv (p_{\tau^+} + p_{\tau^-})^2$$

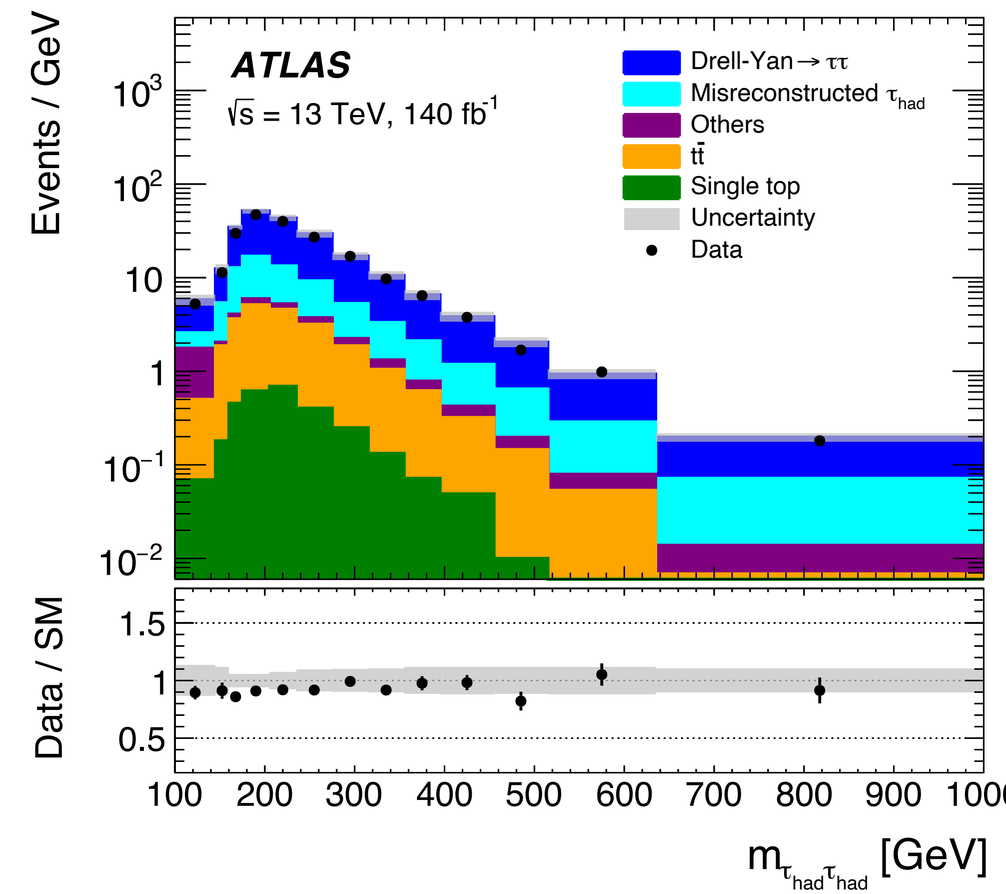
LQ predicts events w/. large $m_{\tau\tau}$ ↔ SM

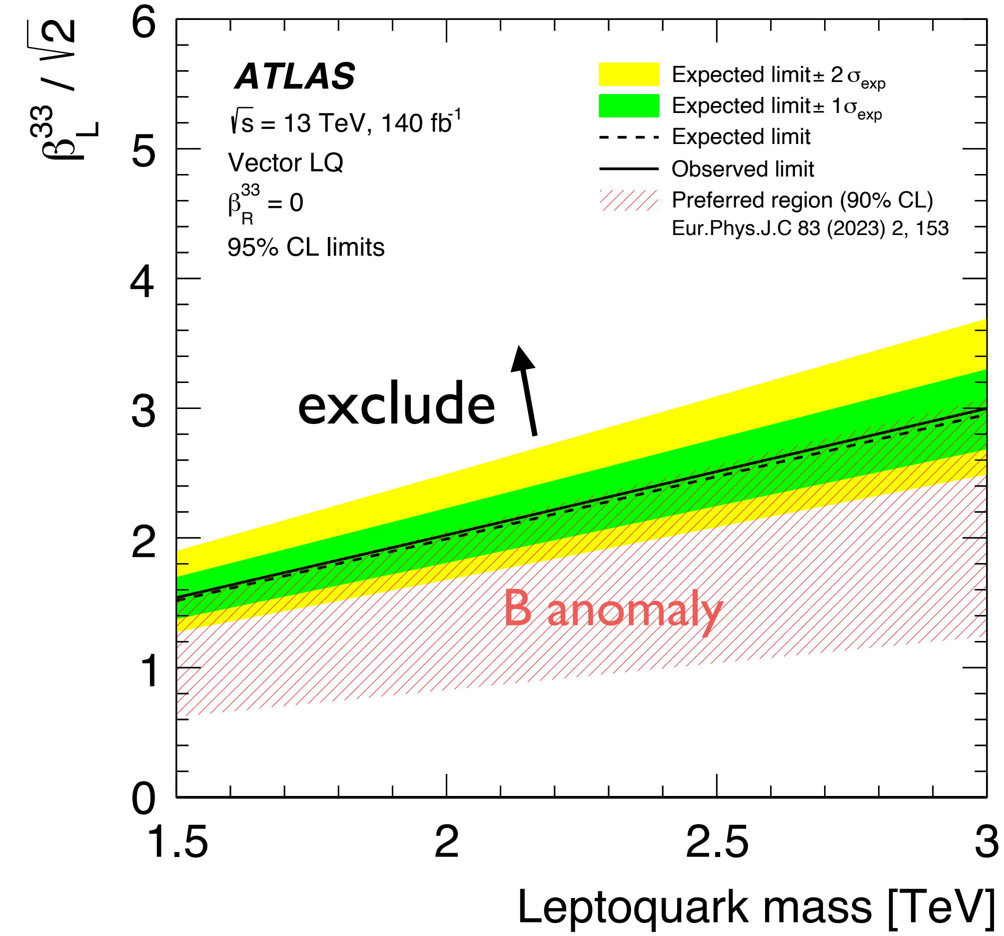
SM



LQ





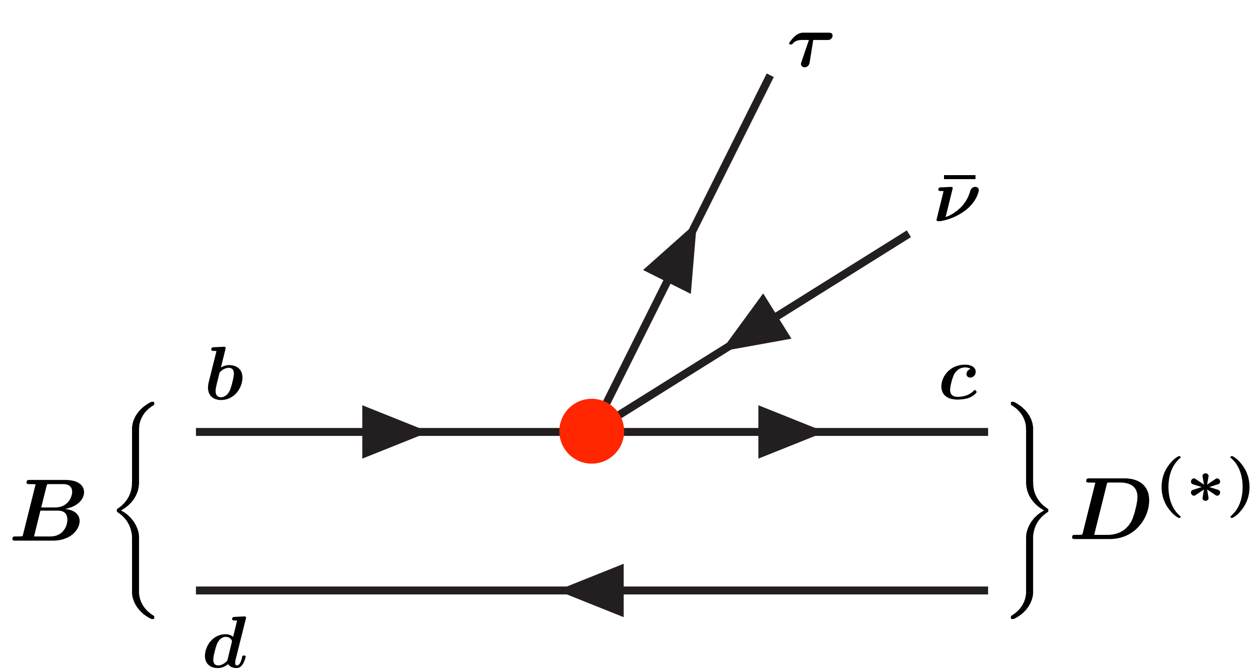


Crossing symmetry

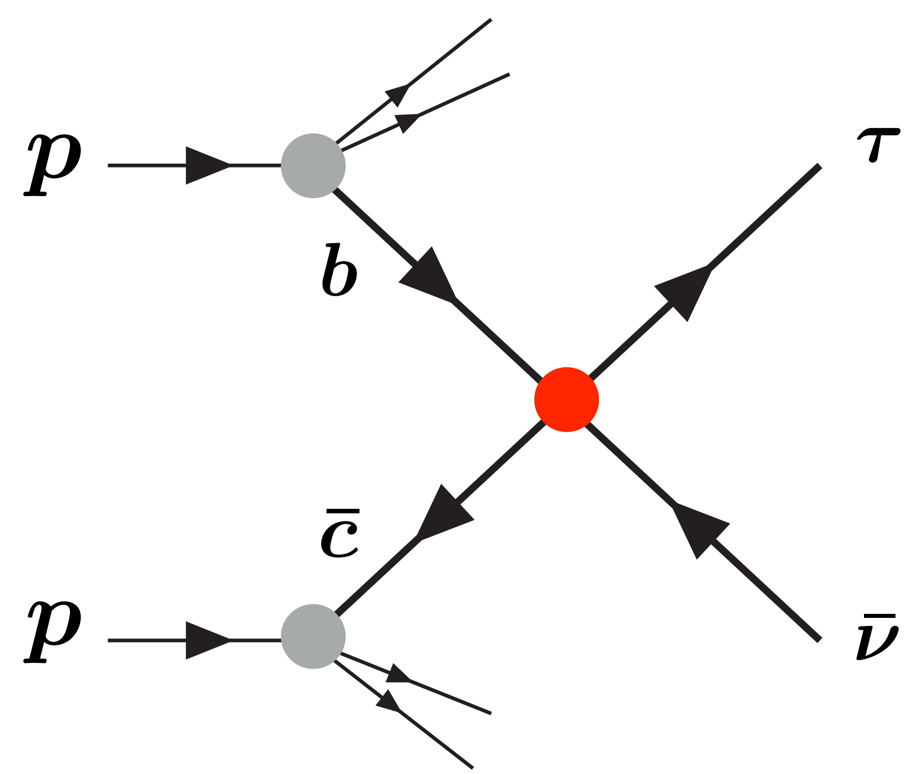
bb→ττ depends only on b-τ coupling of LQ.

Generally contributes to b$\bar{c}$→τ$\bar{\nu}$ scattering due to crossing sym.

B meson decay

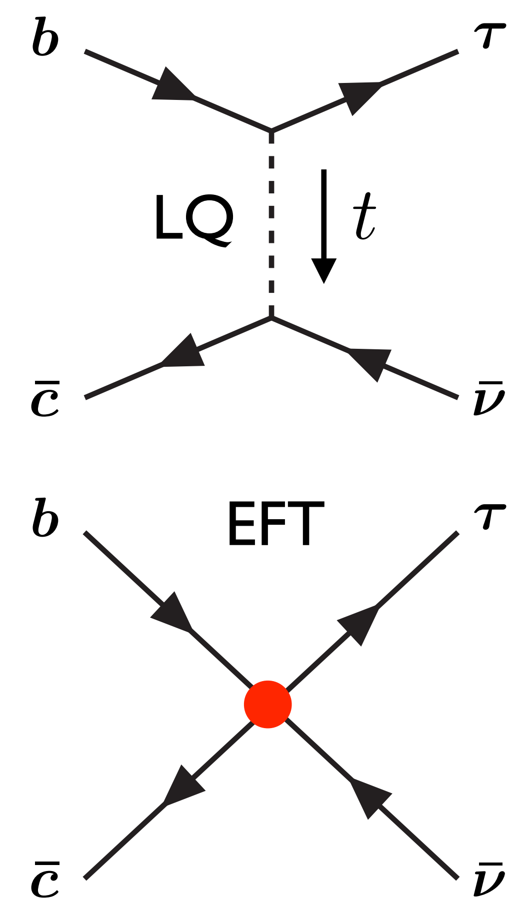


LHC



LHC search

ATLAS, PRD 100 (2019) 5, 052013
CMS, PLB 792 (2019) 107



Search for events with energetic ("hard") τ with large missing transverse energy ("MET").

In LQ models, effective interactions are generated by t-channel exchange of LQ.

LQ $\quad \mathcal{A} \propto \dfrac{1}{t - M_{\rm LQ}^2} \quad (t<0)$

EFT $\quad \rightarrow \dfrac{-1}{M_{\rm LQ}^2}$ if $|t| \ll M_{\rm LQ}^2$

Not always the case for $M_{\rm LQ}$~1TeV because S/B is large in the region with *hard* τ and *large* MET.

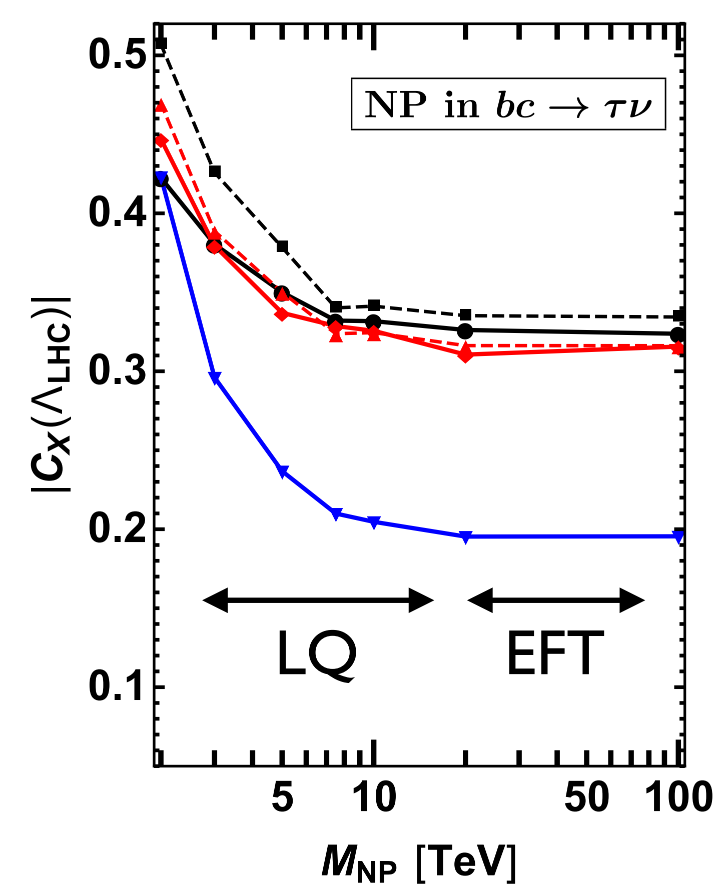


Fig. 95% upper limit on Wilson coefficient
Iguro, Takeuchi, Watanabe, EPJC 81 (2021) 5, 406

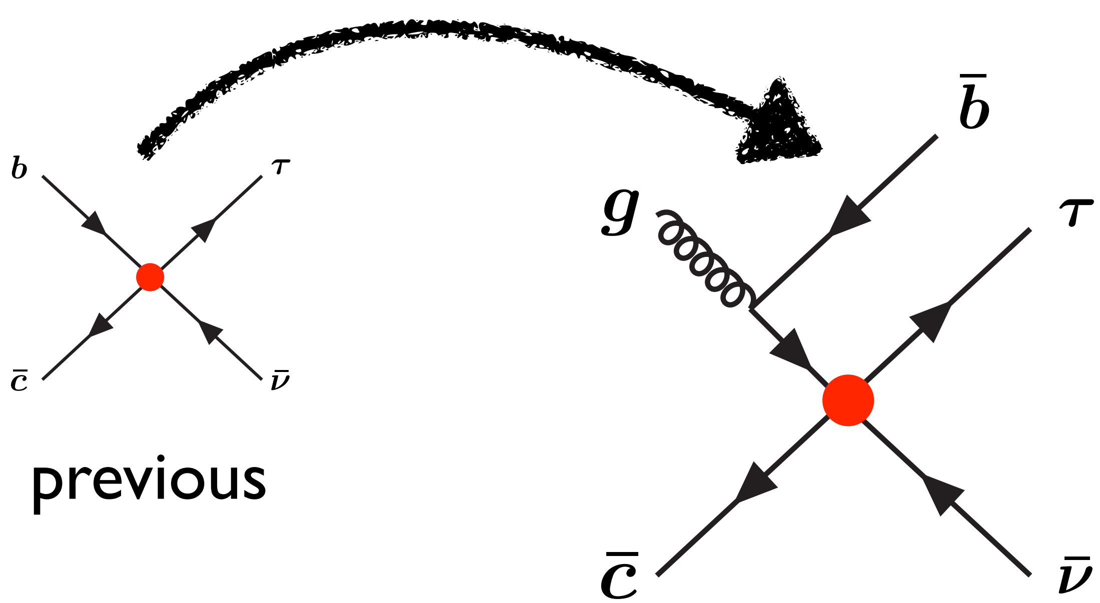
Additional b-jet in final state

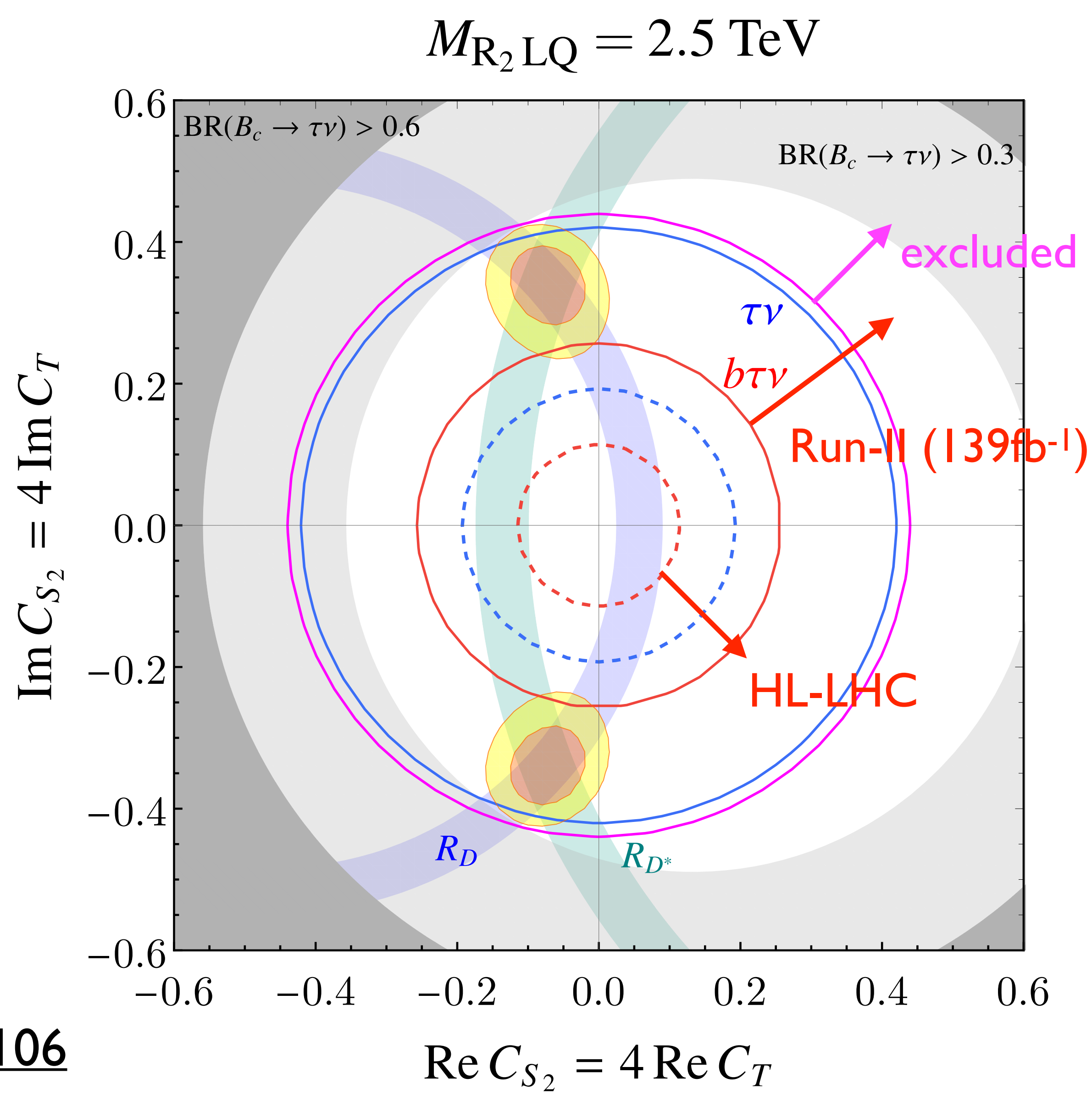
Assign b quark in the final state.

Advantage: parton distribution function & SM background events.
Disadvantage: three-body final state.

→ Better sensitivity to BSM.

Most of $R_{D(*)}$-favored parameter regions are accessible at HL-LHC.





Endo, Iguro, Kitahara, Takeuchi, Watanabe, JHEP 02 (2022) 106

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- What is ‘collider’ & ‘flavor’? — Done
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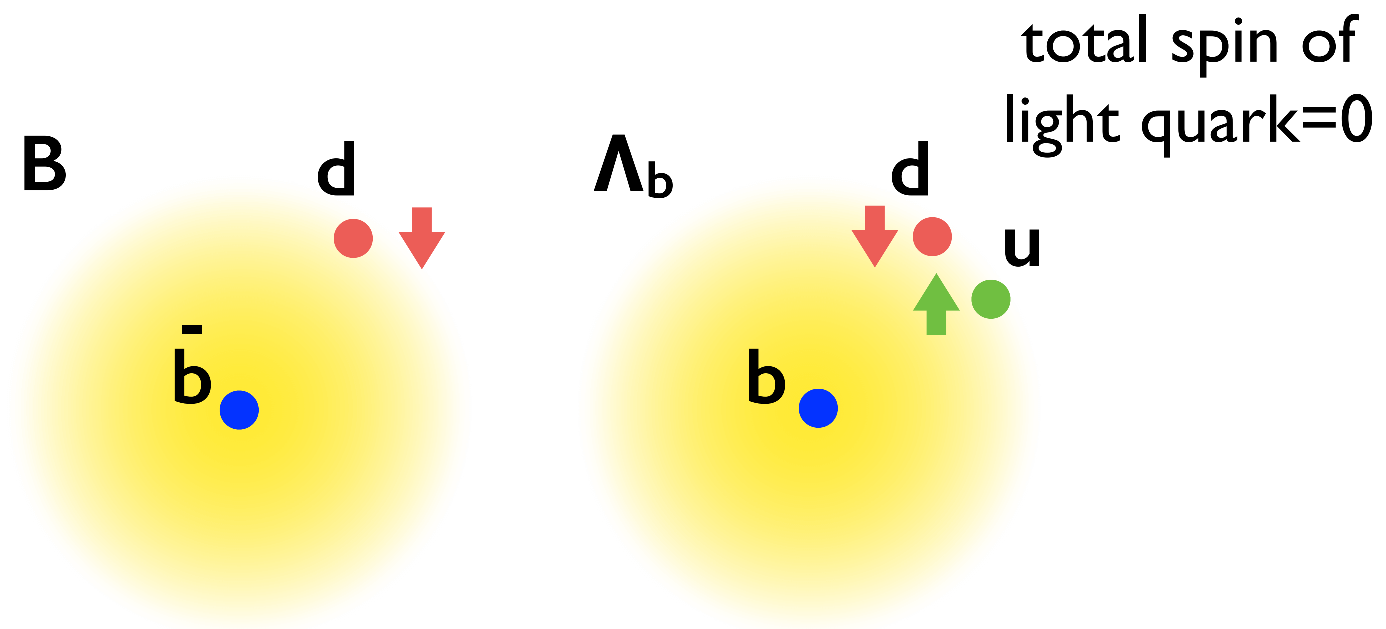
Q. How to test R_D and R_{D^*} excess?

Other decays proceed via $b \to c\tau\nu$. [cf., Λ_Q baryon made of (udQ)]

$$R_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu})}$$

$$\begin{cases} R_{\Lambda_c}^{\rm exp} = 0.285 \pm 0.073 \\ R_{\Lambda_c}^{\rm SM} = 0.324 \pm 0.004 \end{cases}$$



Consistent with SM prediction (↔ R_D, R_{D^*}).

BSM structure or shortcomings in experimental results/SM values?

LHCb: PRL 128 (2022) 19, 191803 + Bernlochnrer, Ligeti, Papucci, Robinson, PRD 107 (2023) 1,L011502
SM: Bernlochnrer, Ligeti, Robinson, Sutchliffe, PRL 121 (2018) 20,202001

$$R_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}$$
$$\ell = e,\ \mu$$

Sum rule for b→c semileptonic decays

BSM contribution

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1 + C_{V_L}) O_{V_L} + C_{S_L} O_{S_L} + C_{S_R} O_{S_R} + C_T O_T \Big]$$

For any C_X, sum rule is satisfied, ME, Iguro, Mishima, Watanabe, JHEP 05 (2025) 112

$$\boxed{\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\rm SM}} \approx \frac{1}{4}\frac{R_D}{R_D^{\rm SM}} + \frac{3}{4}\frac{R_{D^*}}{R_{D^*}^{\rm SM}}}$$

← exp (incl. BSM)

← SM

$\Lambda_b \to \Lambda_c \tau\nu$ $B \to D\tau\nu$ $B \to D^*\tau\nu$

- Test of R_D and R_{D^*} anomaly: If experimental results *violate* sum rule, there are potential problems in experimental results/SM values.
- Once $B \to D\tau\nu$ and $B \to D^*\tau\nu$ are measured precisely, $\Lambda_b \to \Lambda_c \tau\nu$ does not provide additional information about BSM.

* Proposed initially based on empirical observations, *i.e.*, without clarifying background.
cf. Blanke, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić, PRD 99 (2019) 7, 075006
Amano, Jido, Leupold, PRD 105 (2022) 5, L051504

Heavy quark limit and zero recoil limit

Hadron wave functions are factorized in the heavy quark limit ($m_{b,c} \to \infty$).

$$\mathcal{M}(H_b \to H_c \tau \bar{\nu}) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_X \mathcal{C}_X \langle H_c | \bar{c} \Gamma_X b | H_b \rangle \langle \tau \bar{\nu} | \bar{\tau} \Gamma_X \nu | 0 \rangle$$

Clebsch-Gordan

$$= \sum_{\text{spin}} \underline{\langle s_c, \lambda_c; J_{\ell_c}, \lambda | J_{H_c}, \lambda_{H_c} \rangle \langle s_b, \lambda_b; J_{\ell_b}, \lambda | J_{H_b}, \lambda_{H_b} \rangle}$$

$$\times \underline{M_{\lambda_c, \lambda_b}} \, \underline{\langle \phi_c(J_{\ell_c}, \lambda) | \phi_b(J_{\ell_b}, \lambda) \rangle}$$

heavy-quark transition light sector: form factor (Isgur-Wise ftn)

$$M_{\lambda_c, \lambda_b} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_X \mathcal{C}_X \, \bar{u}_c(\lambda_c) \Gamma_X u_b(\lambda_b) \, \langle \tau \bar{\nu} | \bar{\tau} \Gamma_X \nu | 0 \rangle$$

Form factor dependencies are reduced in the zero-recoil limit ($m_c \to m_b$).

Consequently, the following sum rule holds exactly in these limits:

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\text{SM}}} = \frac{1}{4} \frac{R_D}{R_D^{\text{SM}}} + \frac{3}{4} \frac{R_{D^*}}{R_{D^*}^{\text{SM}}}$$

note: $R_{H_c} = \dfrac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)} \quad \ell = e, \mu$

ME, Iguro, Mishima, Watanabe, PRD 113 (2026) 1, 014021

Sum rule with experimental results

Corrections arising from violating the limits are negligible.

Compared with experimental results:

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\rm SM}} \approx \frac{1}{4}\frac{R_D}{R_D^{\rm SM}} + \frac{3}{4}\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \longleftarrow \text{ exp in } R_D \text{ and } R_{D^*}$$

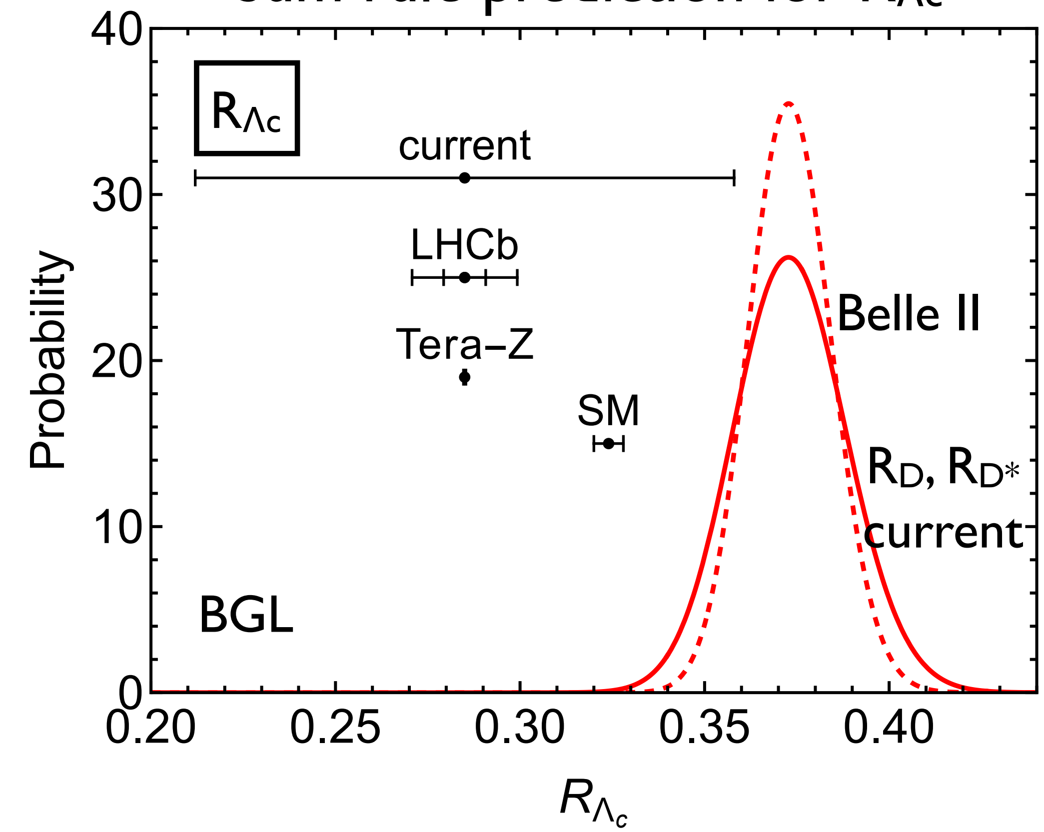
Conclusion:

Current experimental results satisfy the sum rule.

$R_{\Lambda c}$ prediction will become more precise by Belle II (→ form factor).

R_D and R_{D^*} excess can be tested by LHCb and Tera-Z.

Sum rule prediction for $R_{\Lambda c}$



ME, Iguro, Mishima, Watanabe, JHEP 01 (2026) 143

Summary

Flavor (and CP) violations are key probes for BSM at high energy scales.

Sensitivity to BSM can reach above ~1TeV.

We reviewed the semileptonic decays of B mesons.

Currently, potential BSM signals have been reported in $B \to D^{(*)}\tau\nu$.

We provided an overview of BSM interpretations.

Could be tested in the near future through interplay of flavor & collider.

Backup

Form factor for anti-quark

In the previous slides, $\langle D|\bar{c}\,\Gamma\, b|\bar{B}\rangle$ is $\langle D_d^+|\bar{c}\,\Gamma\, b|\bar{B}_d^0\rangle$ or $\langle \bar{D}_u^0|\bar{c}\,\Gamma\, b|B_u^-\rangle$, where the spectator quark is 'd' or 'u'.

Interchange of d↔u makes no difference because of isospin symmetry.

(→ isospin violation)

Sign depends on operators for quarks↔anti-quarks (→ next slide)

$$\langle D^-|\bar{b}\gamma^\mu c|B^0\rangle = -\langle D^+|\bar{c}\gamma^\mu b|\bar{B}^0\rangle$$

$$\langle D^-|\bar{b}c|B^0\rangle = \langle D^+|\bar{c}b|\bar{B}^0\rangle$$

$$\langle D^-|\bar{b}\sigma^{\mu\nu} c|B^0\rangle = -\langle D^+|\bar{c}\sigma^{\mu\nu} b|\bar{B}^0\rangle$$

for $CP|B(p)\rangle = -|\bar{B}(\tilde{p})\rangle,\ CP|D(p)\rangle = -|\bar{D}(\tilde{p})\rangle$ under CP transformation.

Four momentum: $p = (E, \vec{p}), \quad \tilde{p} = (E, -\vec{p})$

Form factor for anti-quark: derivation

CP transformation (see, e.g., QFT textbook by Peskin&Schroeder)

$$(CP)\,\bar{\psi}_1(p_1)\,\gamma^\mu\,\psi_2(p_2)\,(CP) = -(-)^\mu\,\bar{\psi}_2(\tilde{p}_2)\,\gamma^\mu\,\psi_1(\tilde{p}_1)$$

$$(CP)\,\bar{\psi}_1(p_1)\psi_2(p_2)\,(CP) = \bar{\psi}_2(\tilde{p}_2)\psi_1(\tilde{p}_1)$$

$$(CP)\,\bar{\psi}_1(p_1)\,\sigma^{\mu\nu}\,\psi_2(p_2)\,(CP) = -(-)^\mu(-)^\nu\,\bar{\psi}_2(\tilde{p}_2)\,\sigma^{\mu\nu}\,\psi_1(\tilde{p}_1)$$

$$[(-)^\mu = 1 \text{ for } \mu = 0 \text{ and } -1 \text{ for } \mu = 1,2,3]$$

Vector: $\langle D^-|\bar{b}\gamma^\mu c|B^0\rangle = \langle D^-|(CP)^2\bar{b}\gamma^\mu c(CP)^2|B^0\rangle \qquad \leftarrow (CP)^2 = 1$

$$= [-\langle D^+|]\cdot[-(-)^\mu\bar{c}\gamma^\mu b]\cdot[-|B^0\rangle]\Big|_{p\to\tilde{p}} \qquad \leftarrow (CP)|M(p)\rangle = -|\bar{M}(\tilde{p})\rangle$$

$$= -(-)^\mu\langle D^+|\bar{c}\gamma^\mu b|\bar{B}^0\rangle\Big|_{p\to\tilde{p}}$$

$$= -(-)^\mu\left[f_+(\tilde{q}^2)(\tilde{p}_B+\tilde{p}_D)^\mu + \left[f_0(\tilde{q}^2)-f_+(\tilde{q}^2)\right]\frac{m_B^2-m_D^2}{\tilde{q}^2}\tilde{q}^\mu\right]$$

$$\tilde{p}^\mu = (-)^\mu p^\mu$$
$$\tilde{q}^2 = q^2$$

$$= -\left[f_+(q^2)(p_B+p_D)^\mu + \left[f_0(q^2)-f_+(q^2)\right]\frac{m_B^2-m_D^2}{q^2}q^\mu\right]$$

$$= -\langle D^+|\bar{c}\gamma^\mu b|\bar{B}^0\rangle$$

$$(CP)\,\bar{\psi}_1(p_1)\,\gamma^\mu\,\psi_2(p_2)\,(CP) = -(-)^\mu\,\bar{\psi}_2(\tilde{p}_2)\,\gamma^\mu\,\psi_1(\tilde{p}_1)$$

Form factor for anti-quark: derivation

Scalar: CP transformation or apply equation of motion:

$$q_\mu \langle D^- | \bar{b}\gamma^\mu c | B^0 \rangle = \langle D^- | \bar{b}(\not{p}_b - \not{p}_c) c | B^0 \rangle = -(m_b - m_c)\langle D^- | \bar{b} c | B^0 \rangle$$

$$q_\mu \langle D^- | \bar{b}\gamma^\mu c | B^0 \rangle = q_\mu \left[-f_+(q^2)(p_B + p_D)^\mu - \left[f_0(q^2) - f_+(q^2) \right] \frac{m_B^2 - m_D^2}{q^2} q^\mu \right]$$

$$= -(m_B^2 - m_D^2) f_0(q^2)$$

$$\langle D^- | \bar{b}\gamma^\mu c | B^0 \rangle = -\langle D^+ | \bar{c}\gamma^\mu b | \bar{B}^0 \rangle$$

$$\therefore \quad \langle D^- | \bar{b} c | B^0 \rangle = \frac{m_B^2 - m_D^2}{m_b - m_c} f_0(q^2) = \langle D^+ | \bar{c} b | \bar{B}^0 \rangle$$

Dirac equation for *anti-quark* in momentum space repr.: $\not{p}\psi = -m\psi$

Tensor: CP transformation

$$\langle D^- | \bar{b}\sigma^{\mu\nu} c | B^0 \rangle = -\langle D^+ | \bar{c}\sigma^{\mu\nu} b | \bar{B}^0 \rangle$$

$$(CP)\, \bar{\psi}_1(p_1)\, \sigma^{\mu\nu}\, \psi_2(p_2)\, (CP) = -(-)^\mu (-)^\nu\, \bar{\psi}_2(\tilde{p}_2)\, \sigma^{\mu\nu}\, \psi_1(\tilde{p}_1)$$

cf. Relative sign between operators is independent of phase convention.