New Physics thru Flavor

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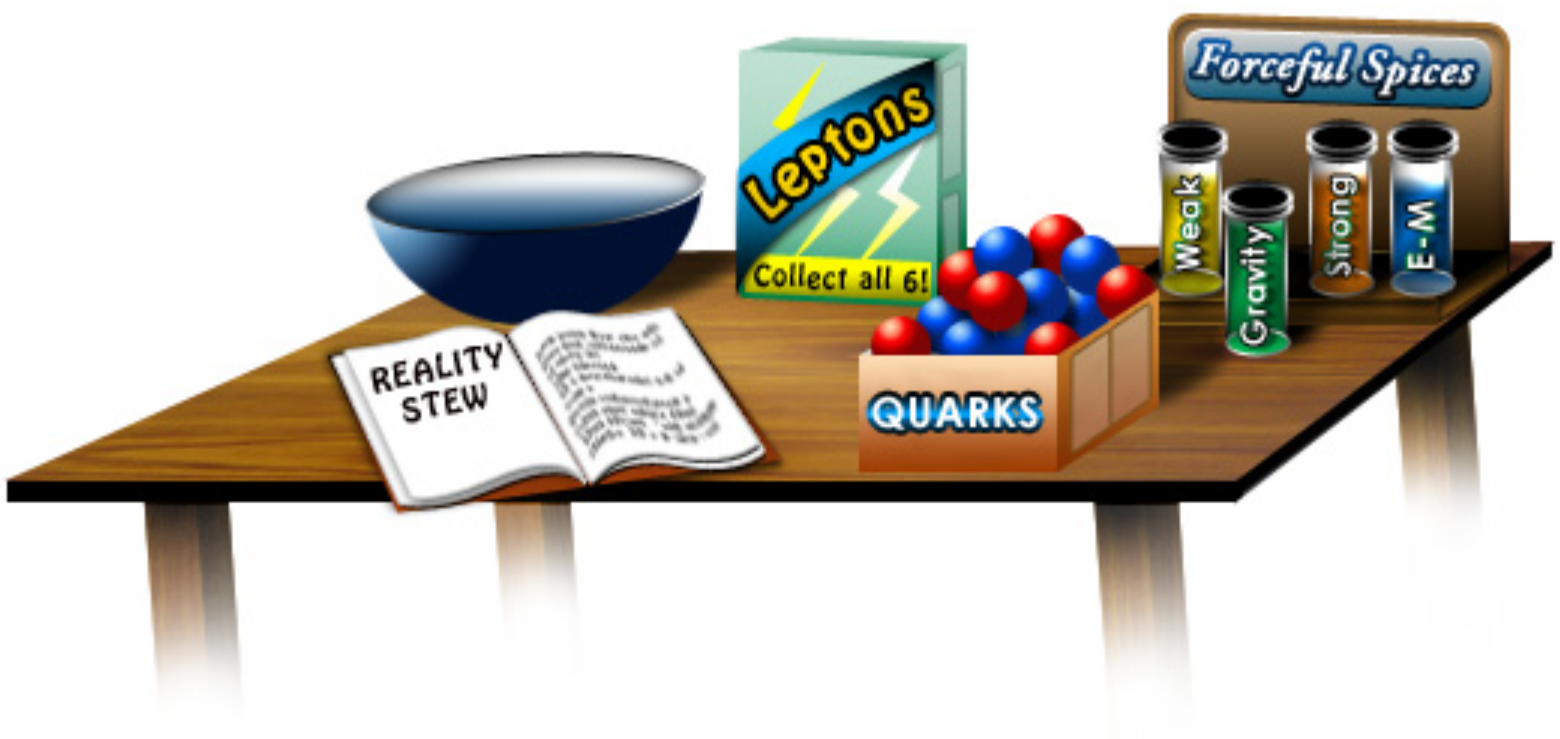

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Standard…

- ✘ P and C broken by weak int. but CP is a symmetry (1 gen)
- ✘ Going from the gauge to mass basis

$$\mathcal{L}_Y^{\rm SM} = -Y_d^{ij}\overline{Q}_L^i \phi D_R^j - Y_u^{ij}\overline{Q}_L^i \widetilde{\phi} U_R^j + \text{h.c.}$$

$$\mathcal{L}_Y^{\rm SM} = -\left(1+\frac{h}{v}\right)\left[m_d \bar{d}d + m_u \bar{u}u + m_e \bar{e}e\right]$$

- ✘ With 3 gen cannot simultaneously diagonalize *u* and *d* ⇒ mixing : CKM matrix

- ✘ V_{CKM} unitary ⇒ 3 real parameters + 1 phase (CPV!)

$$\lambda \qquad A \qquad \rho \qquad \eta$$

CKM-ology

$$\lambda \qquad A \qquad \rho \qquad \eta$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = \sin\theta_C \approx 0.224 \qquad A \simeq 0.82 \qquad \sqrt{\rho^2+\eta^2} \approx 0.45$$

- ✘ One way to go: Fix CKM entries through tree level processes
  → overconstrain by loop-induced processes
  → look for BSM physics through FCNC
- ✘ V_{CKM} unitary ⇒ 3 real parameters + 1 phase (CPV!)

Extracting parameters

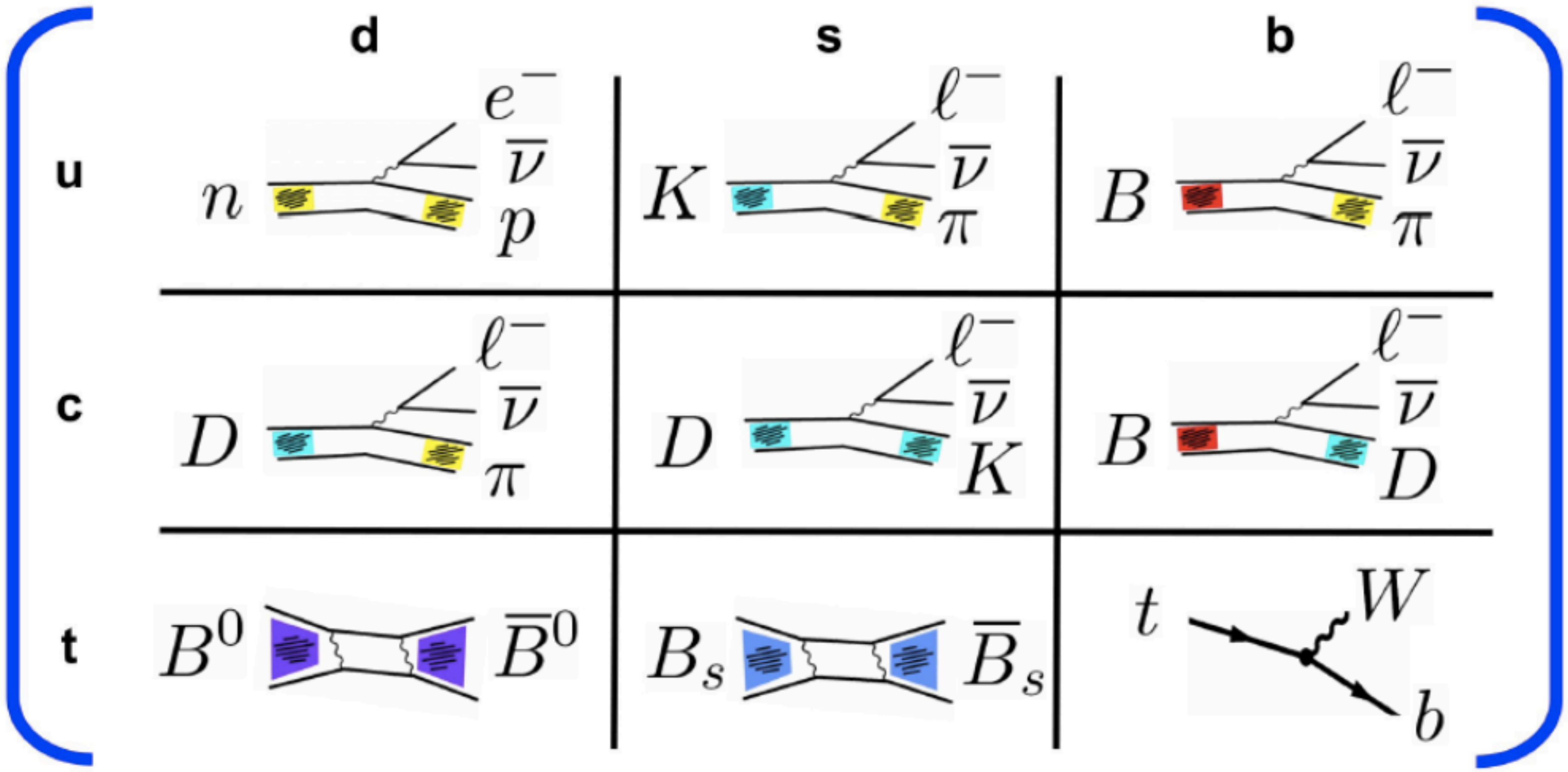
Decay rate = Kinematics CKM coupling Hadronic quantities

Experiments:
NA62, KOTO
BESIII, LHCb
LHC,Belle-II

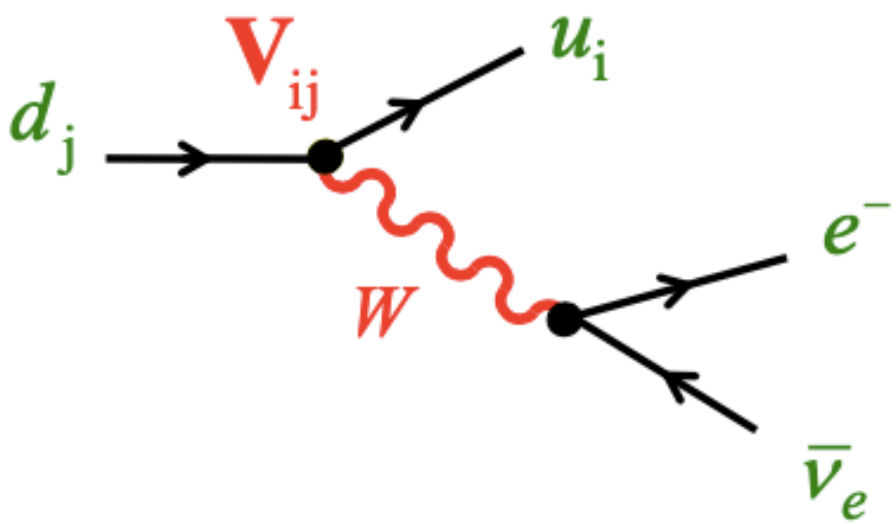
Nonperturbative QCD
Lattice QCD
Models such as LCSR

CKM

V =



FCC



$$\Gamma(d_j \to u_i\, e^- \,\bar{\nu}_e) \propto \left|\mathbf{V}_{ij}\right|^2$$

$$\langle P'(k')|\bar{u}_i \gamma^\mu d_j|P(k)\rangle = C_{PP'}\left\{(k+k')^\mu f_+(q^2) + (k-k')^\mu f_-(q^2)\right\}$$

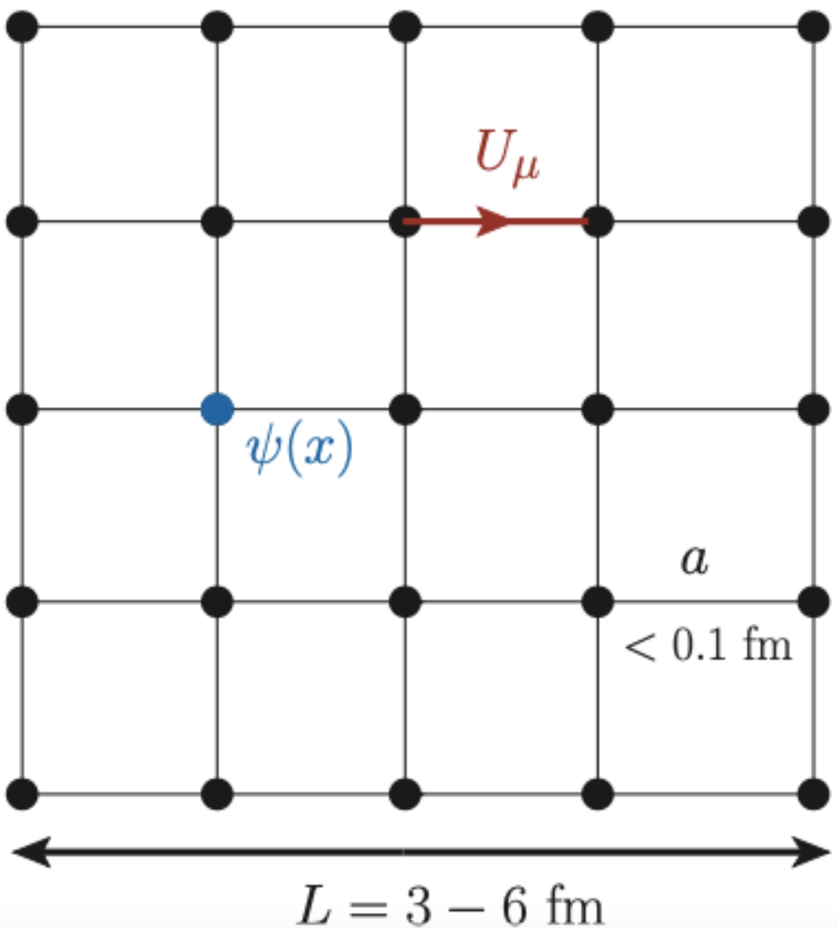
$$\Gamma(P \to P' l \nu) = \frac{G_F^2 M_P^5}{192\pi^3} |\mathbf{V_{ij}}|^2 C_{PP'}^2 \, |f_+(0)|^2 \,\mathbf{I}\, (1+\delta_{RC})$$

$$\mathbf{I} \approx \int_0^{(M_P-M_{P'})^2} \frac{dq^2}{M_P^8} \lambda^{3/2}(q^2, M_P^2, M_{P'}^2) \left|\frac{f_+(q^2)}{f_+(0)}\right|^2$$

- Get q^2 distribution from experiment
- Measure Γ
- Extract $|V_{ij}|\, f_+(0)$
- $f_+(0)$ from LQCD
- Symmetries help too

[Intermezzo: Lattice QCD]

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + \sum_{f=1}^{N_f} \overline{\psi}_f(x)\left(i\not{D} - m_f\right)\psi_f(x) \qquad \not{D} = \gamma^\mu\left[\partial_\mu - igA_\mu(x)\right]$$



- Break-up spacetime into a 4D grid : lattice spacing a, spatial extent L, time extent T
- Lattice spacing : natural UV regulator for the theory

  1) Rotational/translational Lorentz symmetries are broken

  2) Gauge symmetry is preserved

Quark fields $\psi(x), \overline{\psi}(x)$ on each site

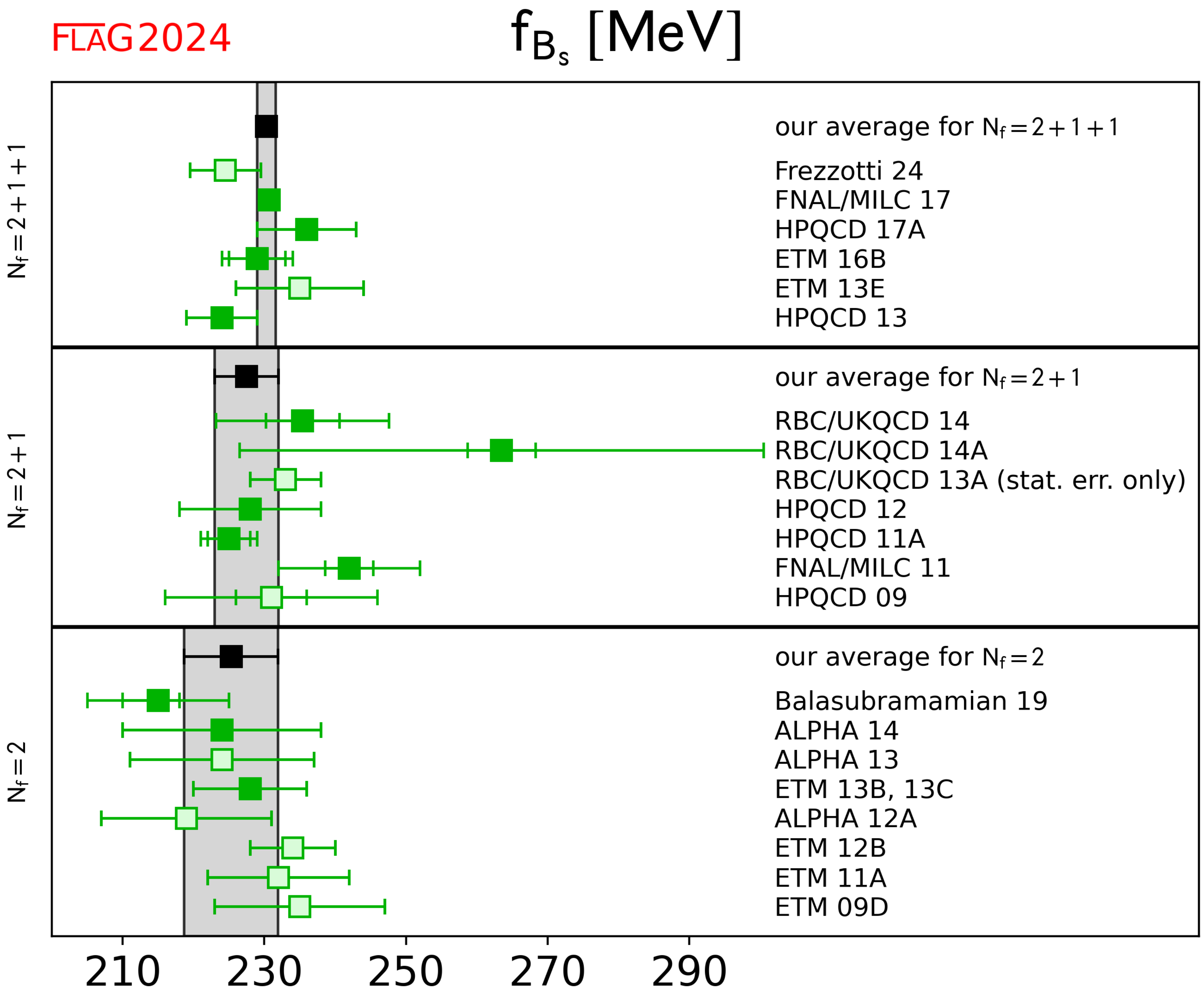
- $\psi^a_\alpha(x)$: $\alpha =$ Dirac index
  $a =$ color index

$\Rightarrow 3 \times 4 = 12$ complex numbers per site

Glue field $U_\mu(x)$ on links : parallel transporter

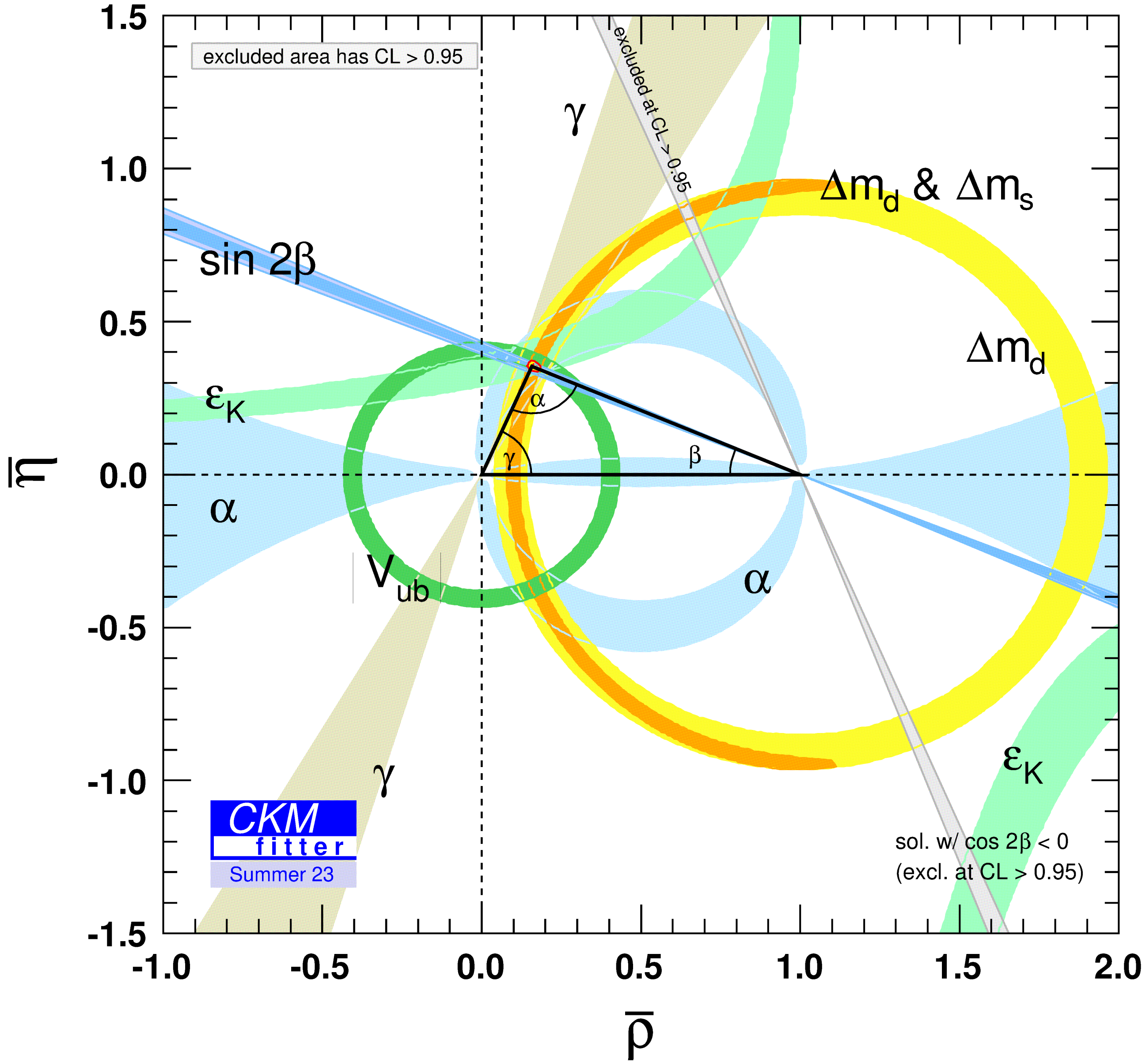
$$U_\mu(x) = \mathcal{P}e^{ig\int_x^{x+a\hat{\mu}} A_\nu(y)\mathrm{d}y^\nu} \in \mathrm{SU}(3)$$

$$\langle 0|\bar{s}\gamma_\mu\gamma_5 b|B_s(p)\rangle = i f_{B_s} p_\mu$$

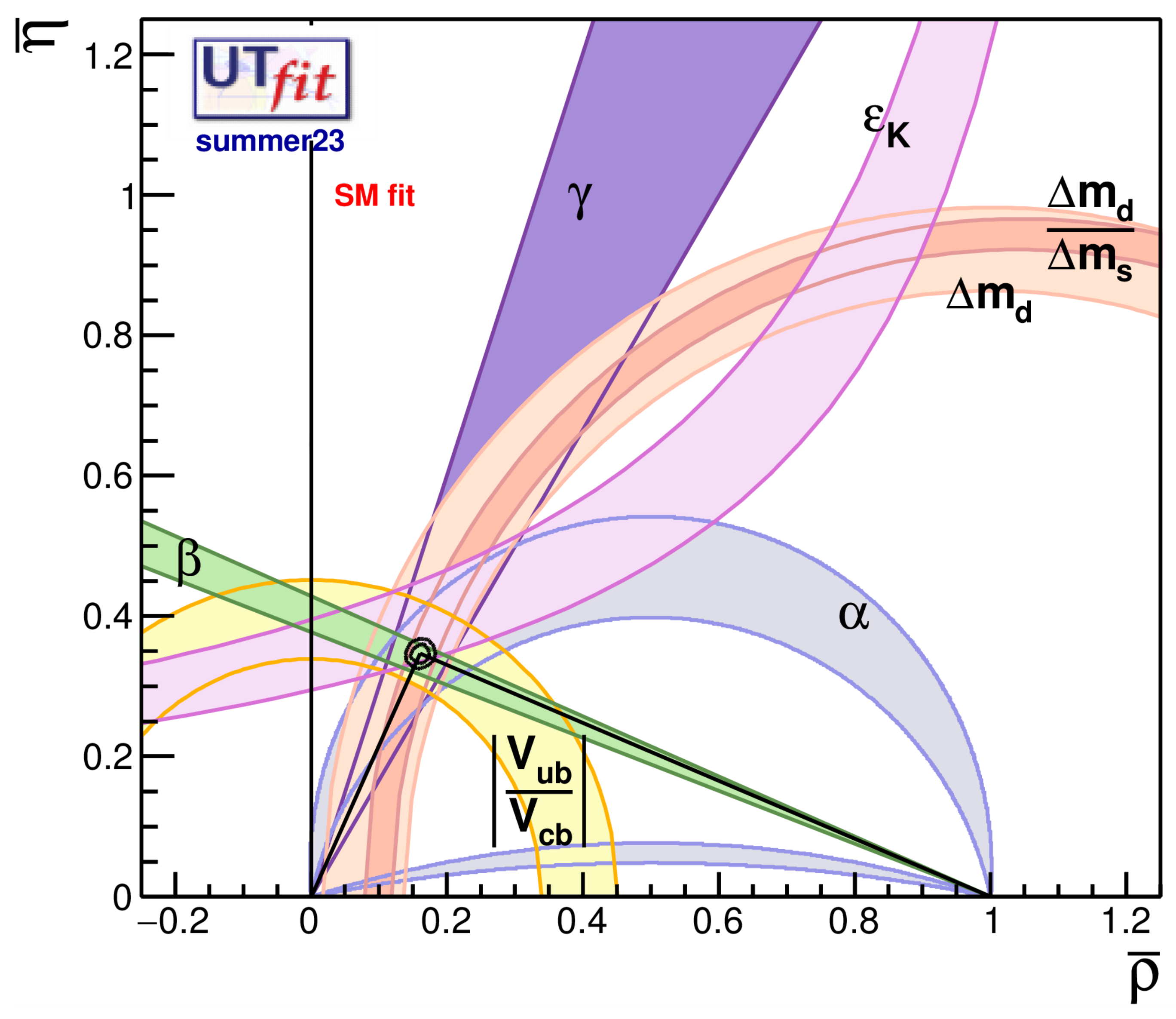


- For some quantities per-mill accuracy
- Not everything can be computed on the lattice with a pheno required precision
- FLAG averages… cf. http://flag.unibe.ch

UTA

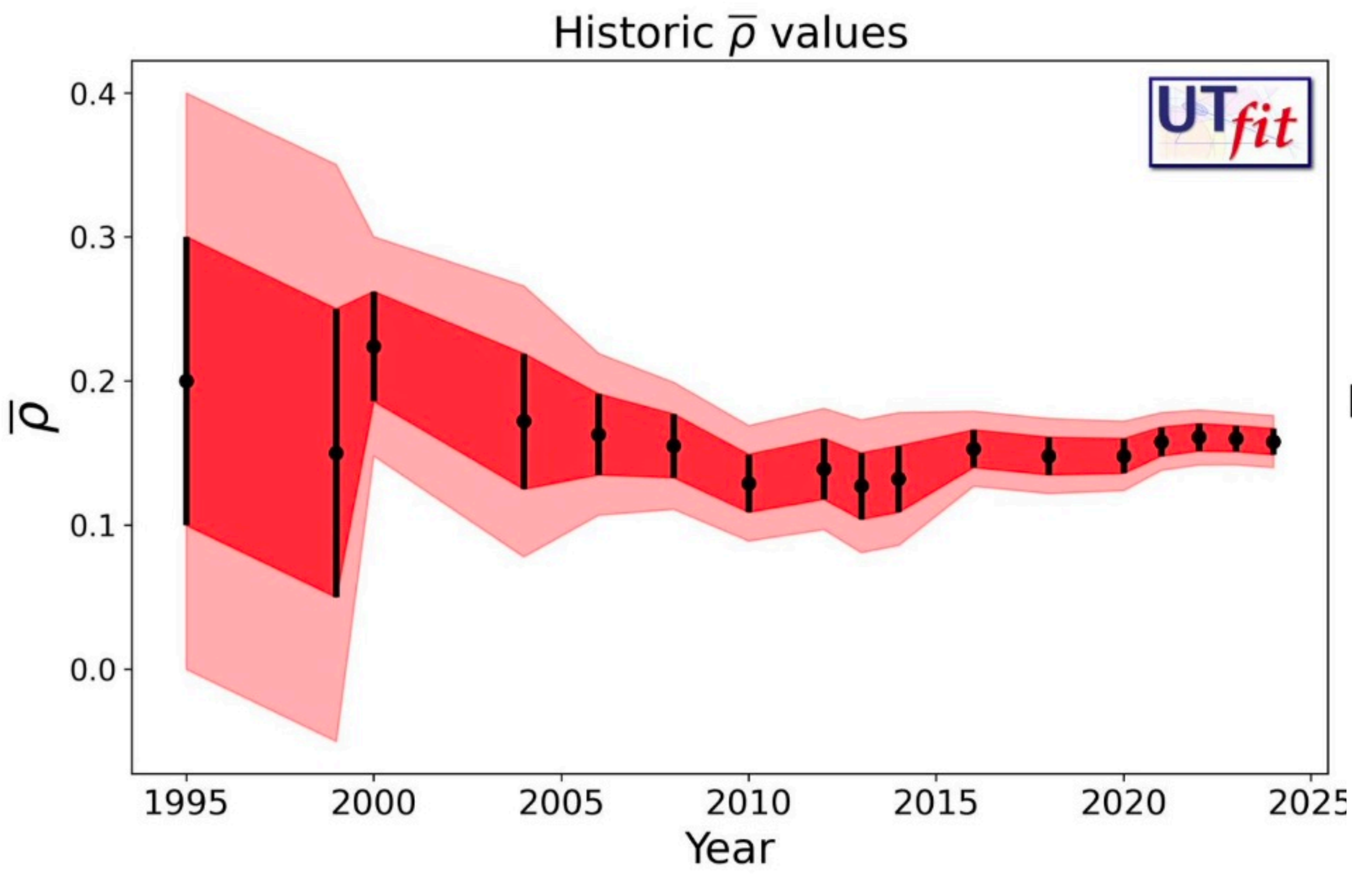


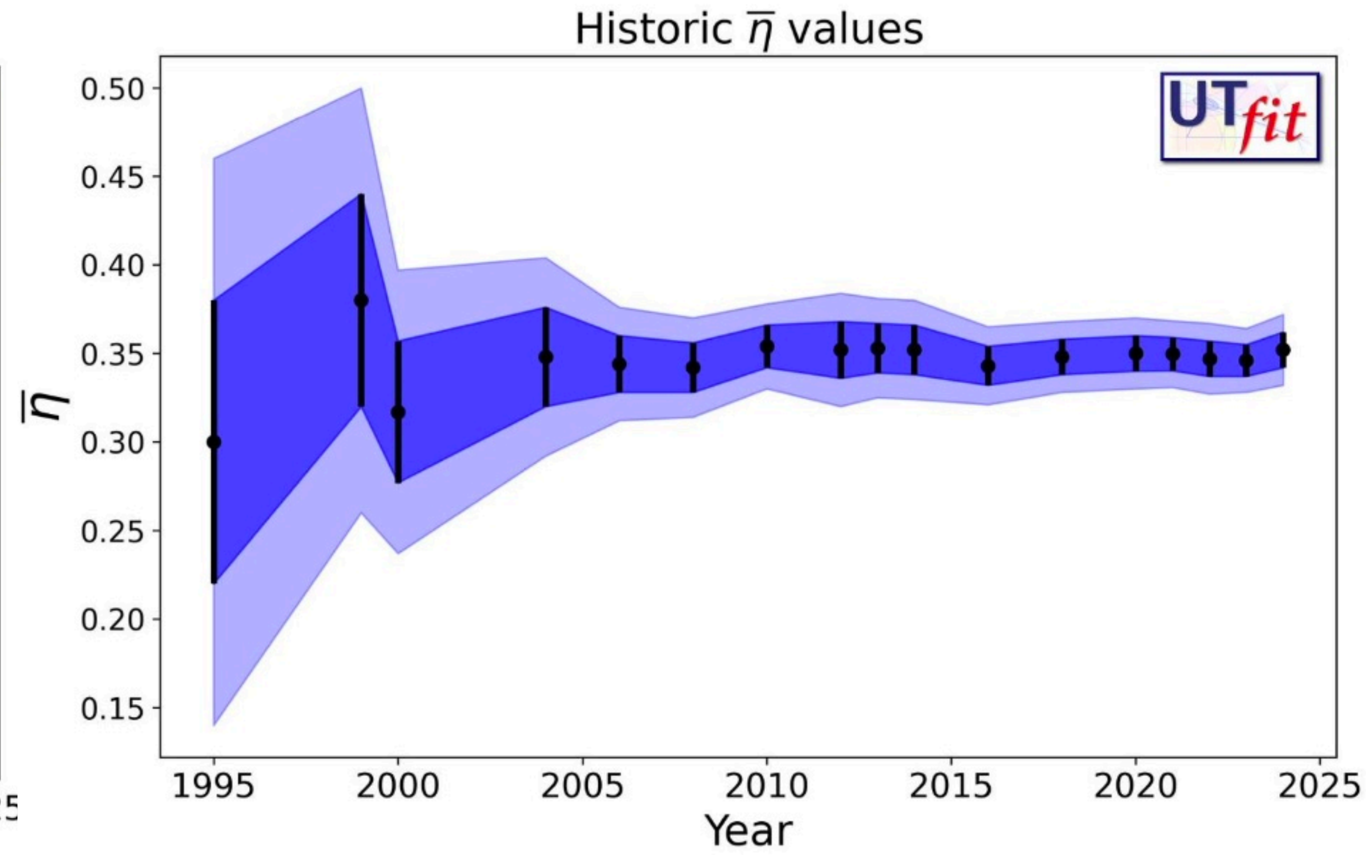
http://ckmfitter.in2p3.fr



http://www.utfit.org

CP violation

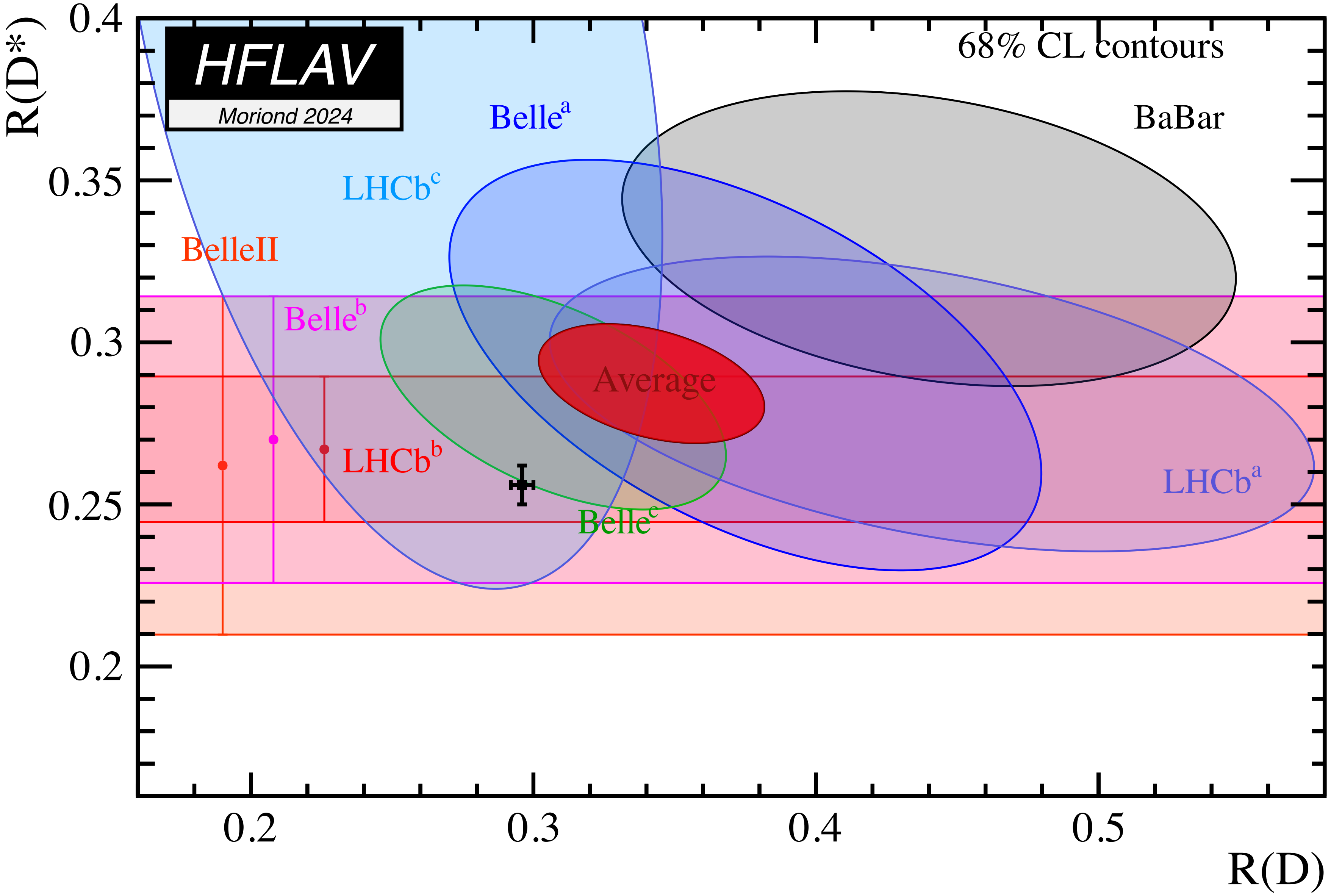




Reaching out to BSM

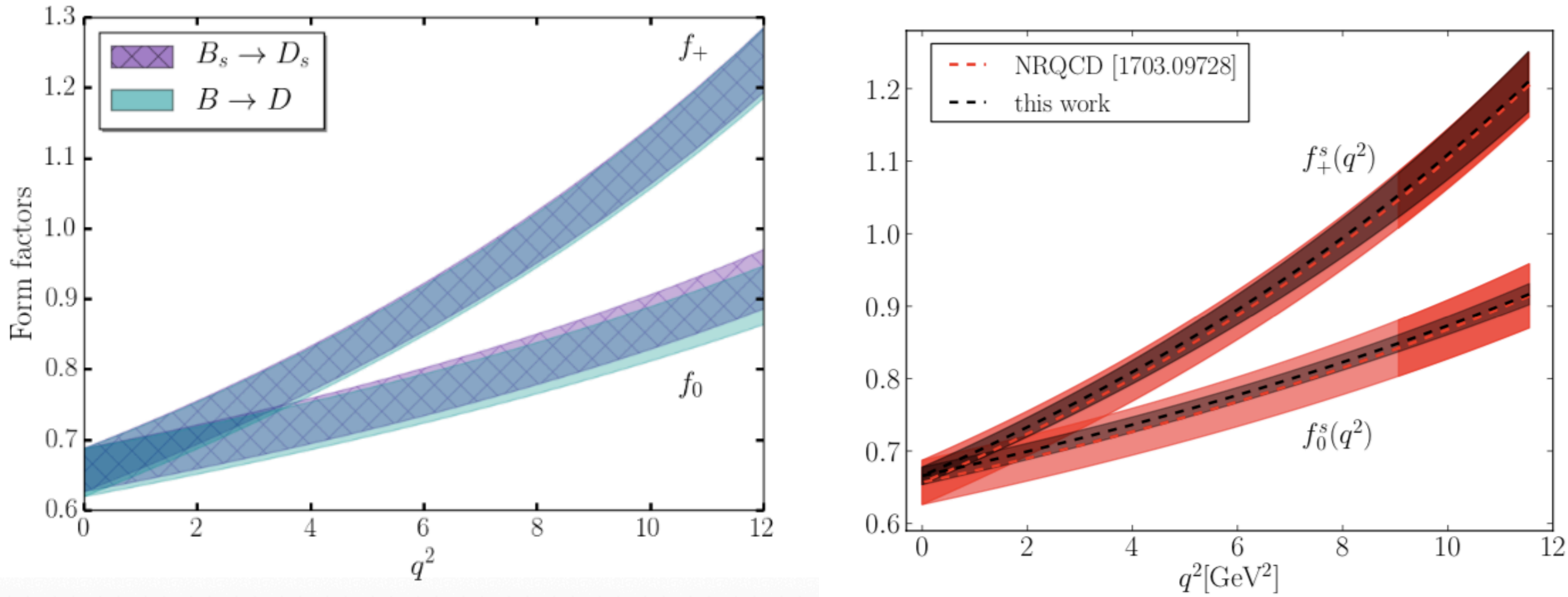
LFUV

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$



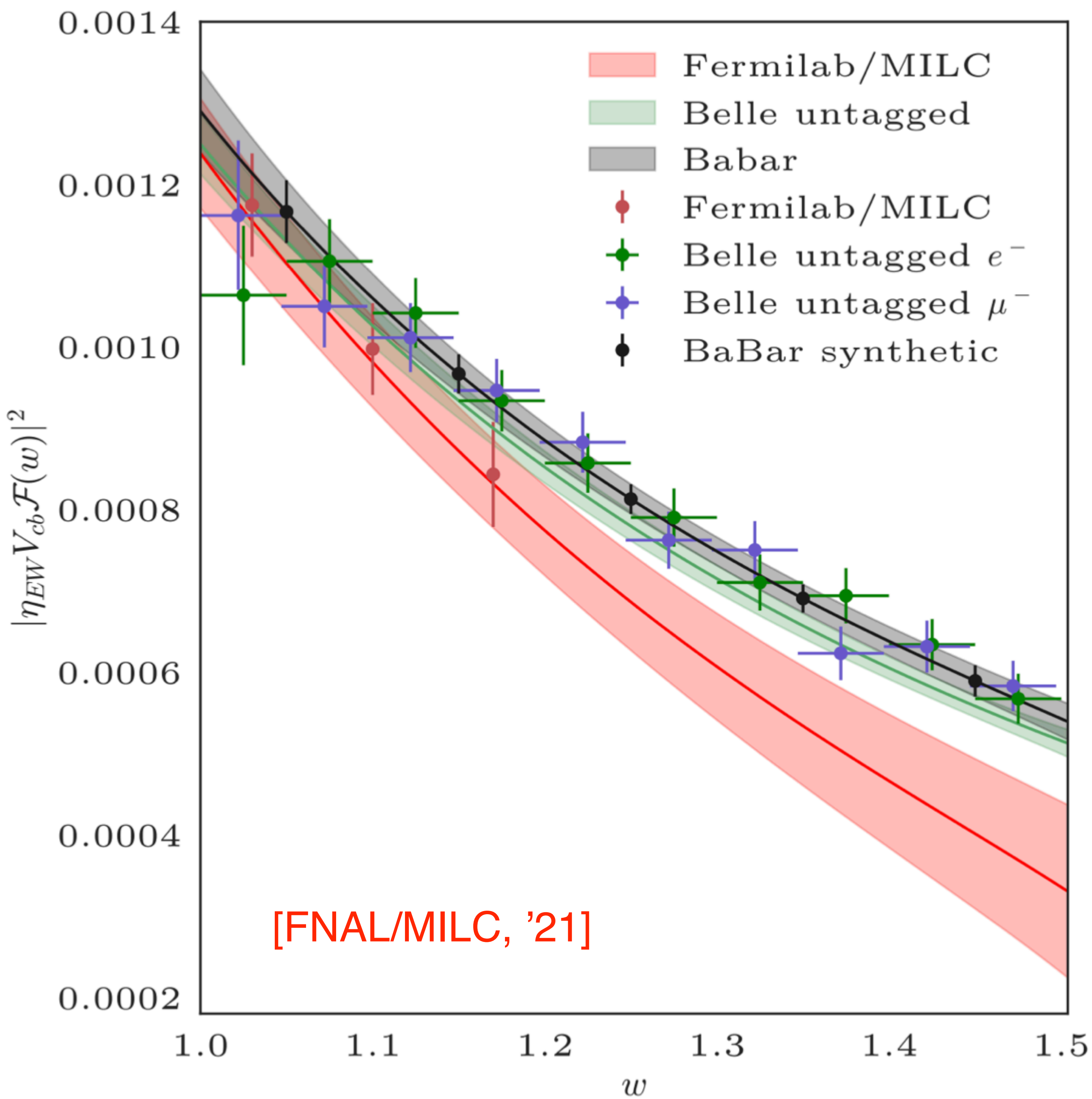
- LHCb also studied $B_c \to J/\psi\ell\nu$ $R^{\mathrm{LHCb}}_{J/\psi} > R^{\mathrm{exp}}_{J/\psi}$
- LHCb again $\Lambda_b \to \Lambda_c\ell\nu$ $R^{\mathrm{LHCb}}_{\Lambda_c} > R^{\mathrm{exp}}_{\Lambda_c}$
- LQCD good for R_D, problems with R_{D^*}
- Assuming NP couples only to τ we can use exp-ly determined form factors

$$\langle D|\bar{c}\gamma_\mu b|B\rangle \propto f_+(q^2), f_0(q^2)$$

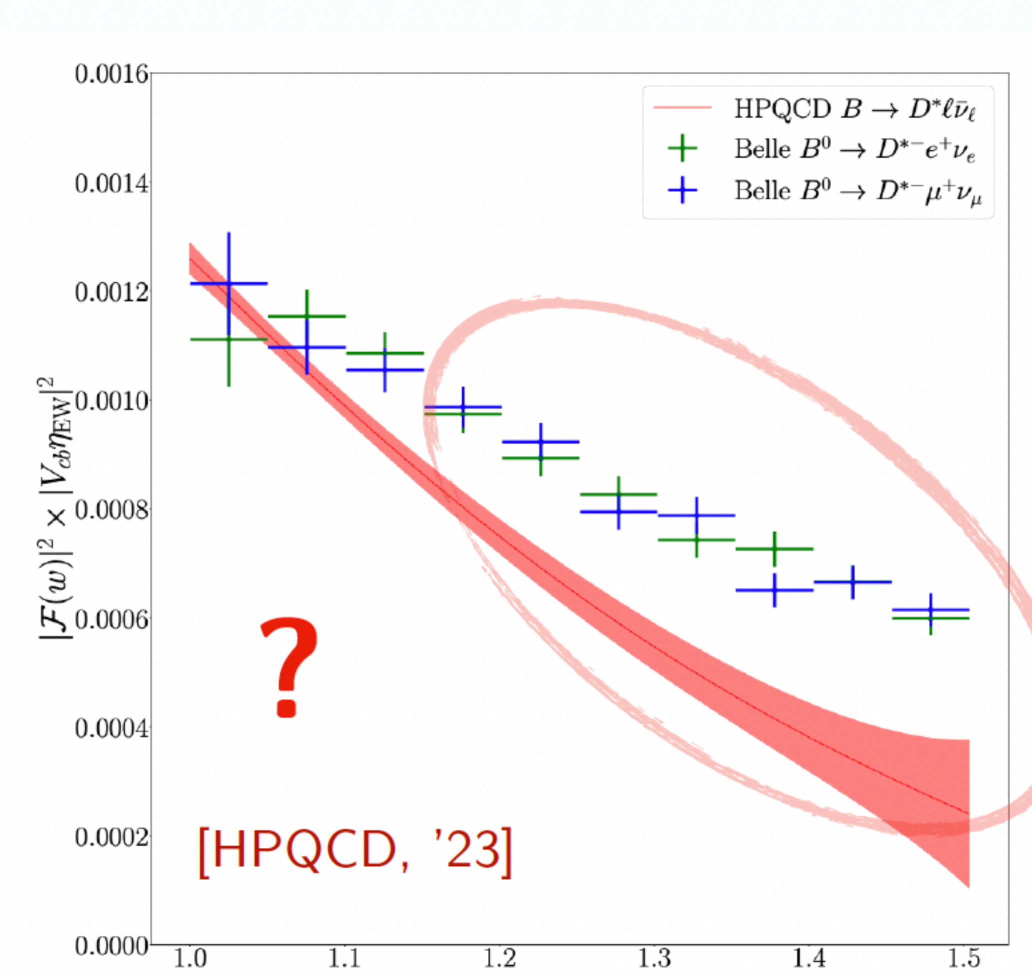


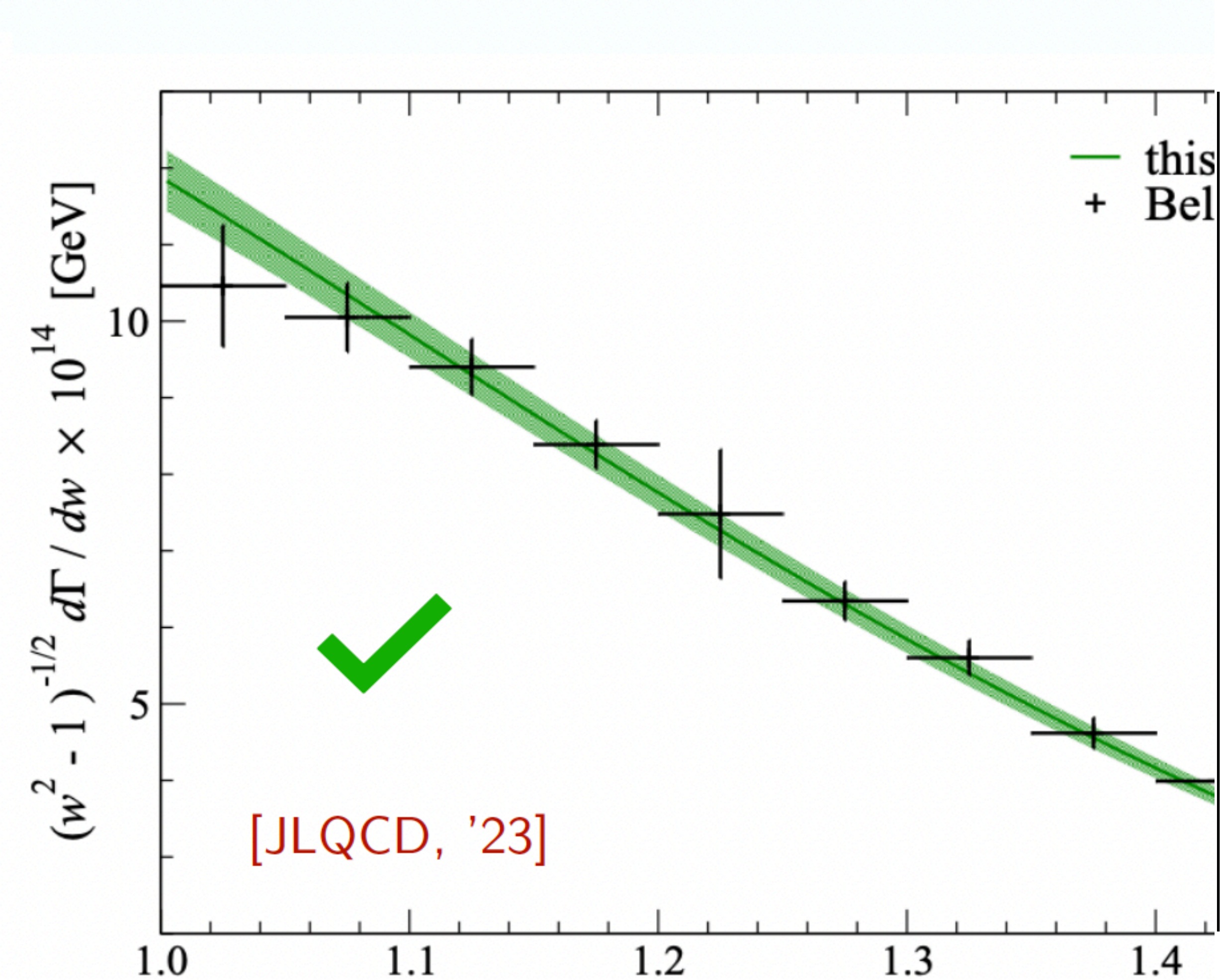
- ★ 2 lattice results agree in the continuum limit
- ★ Going from high to low q^2s facilitated by constraint $f_0(0)=f_+(0)$
- ★ Only one (staggered) lattice regularization/discretization of QCD

$$\langle D^* | \bar{c}\gamma_\mu(1-\gamma_5)b|B\rangle \propto V(q^2), A_{1,2,0}(q^2) \propto \mathcal{F}(w) \ldots$$



$$\langle D^*|\bar{c}\gamma_\mu(1-\gamma_5)b|B\rangle \propto V(q^2), A_{1,2,0}(q^2) \propto \mathcal{F}(w)\ldots$$





★ Two different discretisation procedure - different results in continuum

★ V_{cb} extraction - problem (sic!)

★ *We can use exp info on angular distribution and convert them to FFs... which is what we do...* cf. 2404.16772

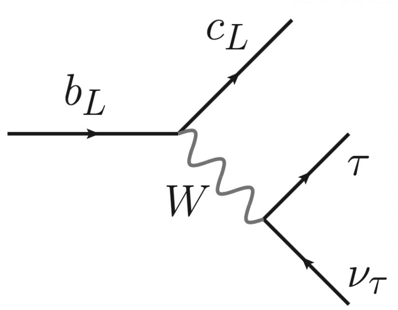
Scalar Leptoquarks in $R_{D^{(*)}}$

Can any scalar leptoquark, with a minimalistic set of Yukawa couplings pass R_D and R_{D^*} test ?

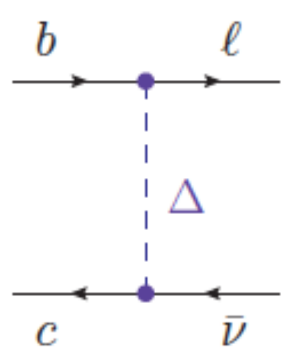
$$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+\underline{g_{V_L}})(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) + \underline{g_{V_R}}(\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{\tau L})$$

$$+\underline{g_{S_L}}(\bar{c}_R b_L)(\bar{\tau}_R\nu_{\tau L}) + \underline{g_T}(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_{\tau L}) +$$

$$+\underline{\tilde{g}_{S_R}}(\bar{c}_L b_R)(\bar{\tau}_L N_R) + \underline{\tilde{g}_T}(\bar{c}_L\sigma^{\mu\nu}b_R)(\bar{\tau}_L\sigma_{\mu\nu}N_R)\Big] + \text{h.c.}$$



SM



LQs

LQ →($SU(3)_c$, $SU(2)_L$, $U(1)_Y$)

Previously [2103.12504] OK

$$U_1 = (3,1,2/3) : g_V$$
$$R_2 = (3,2,7/6) : g_{S_L} = 4g_T$$
$$S_1 = (\bar{3},1,1/3) : g_{S_L} = -4g_T, g_V$$

R_2 =(3,2,7/6)

$\tilde{R}_2$ = (3,2,1/6)

S_1= (3,1,1/3)

cf. 2404.16772

$R_2 = (3, 2, 7/6)$

Minimal model: couplings to the third generation leptons only

$$\mathcal{L}_{R_2} = y_R^{b\tau} V_{jb}^* (\overline{u}_j P_R \tau) R_2^{5/3} + y_R^{b\tau} (\overline{b} P_R \tau) R_2^{2/3} - y_L^{c\tau} (\overline{c} P_L \tau) R_2^{5/3} + y_L^{c\tau} (\overline{c} P_L \nu_\tau) R_2^{2/3} + \text{h.c.}$$

running $m_{R2} \to m_b$

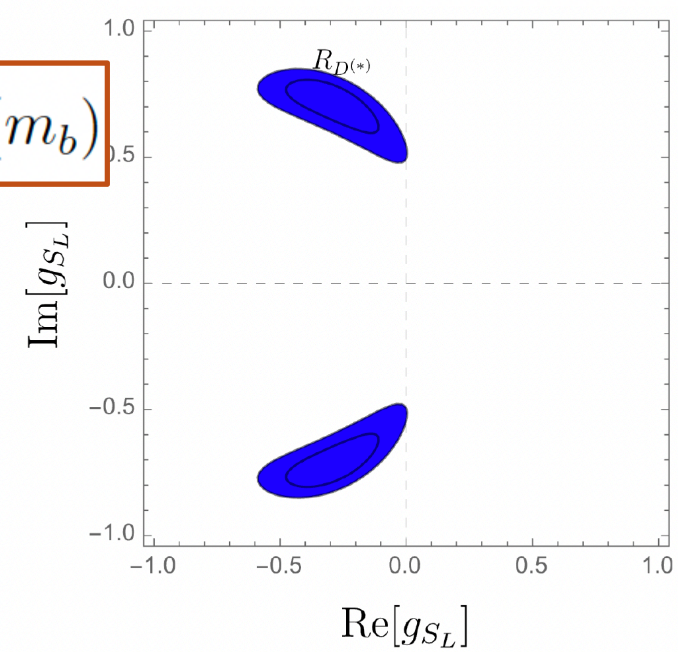
$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

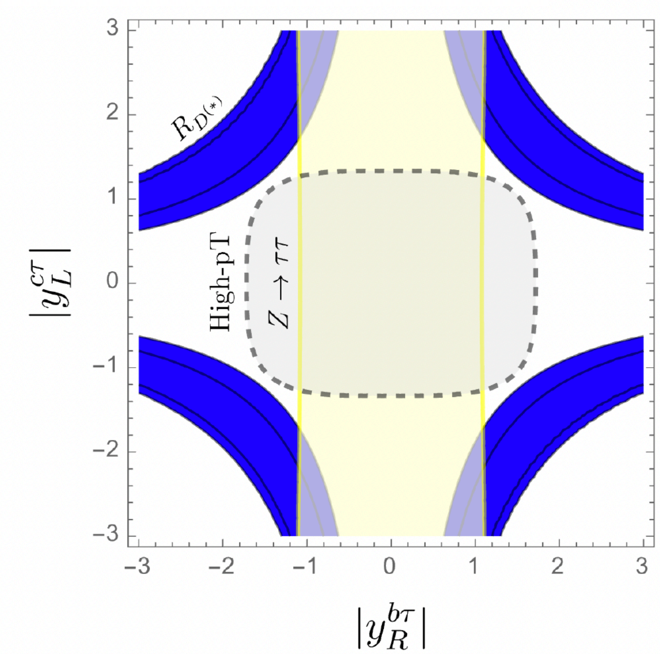
$$g_{S_L}(m_{R_2}) = 4 g_T(m_{R_2})$$

$$g_{S_L}(m_b) = 8.8 \times g_T(m_b)$$

One Yukawa should be complex

$$g_{S_L}(m_b) = 0.60 \times \frac{1}{2} |y_R^{b\tau} y_L^{c\tau}| e^{i\varphi} \, .$$





Constraint from high p_T tail helps and (almost) kills the scenario.

R_2 is (almost) out of game

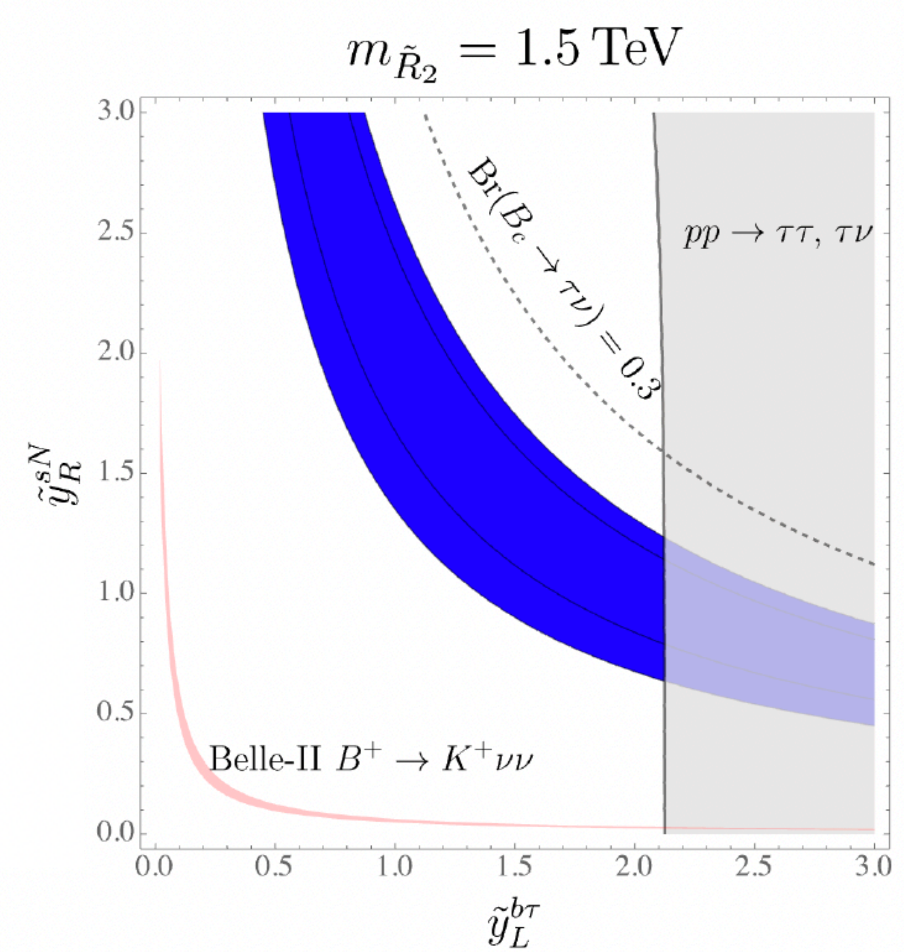
$\widetilde{R}_2 = (3, 2, 1/6)$

- It can couple to non-SM right-handed neutrino N_R

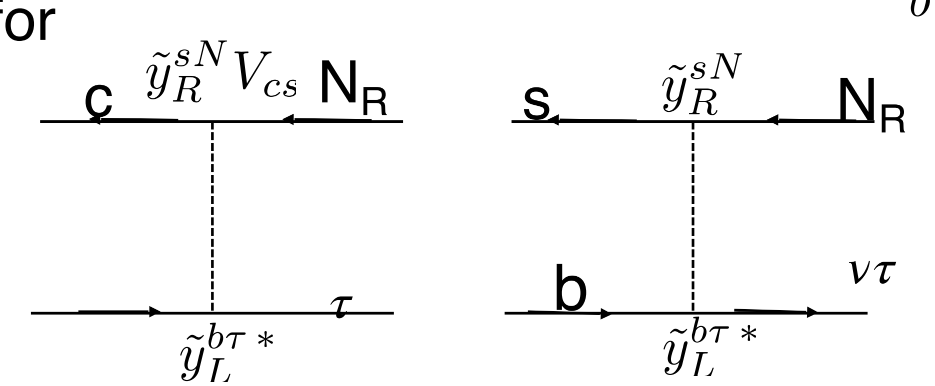
$$\mathcal{L} = -\,\tilde{y}_L^{b\tau}(\bar{b}P_L\tau)\widetilde{R}_2^{2/3} + \tilde{y}_L^{b\tau}(\bar{b}P_L\nu)\widetilde{R}_2^{-1/3} + \\ + \tilde{y}_R^{sN}(\bar{s}P_R N_R)\widetilde{R}_2^{-1/3} + \tilde{y}_R^{sN}V_{js}(\bar{u}_j P_R N_R)\widetilde{R}_2^{2/3} + \text{h.c.}$$

$$\tilde{y}_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_L^{b\tau} \end{pmatrix}, \qquad \tilde{y}_R = \begin{pmatrix} 0 \\ \tilde{y}_R^{sN} \\ 0 \end{pmatrix},$$

$$\mathcal{B} \propto |\mathcal{A}_{\rm SM} + \mathcal{A}_{\rm NP}^{\nu_L}|^2 + |\mathcal{A}_{\rm NP}^{N_R}|^2$$



However, there is the tree diagram for $b \to s\nu\bar{N}_R$



Huge effect to $B \to K\nu\nu$
cf. 2401.17440

$\tilde{R}_2$ is out of game!

S_1= (3,1,1/3)

Weak singlet S_1 - electric charge 1/3.
Interaction with quark/lepton both being weak doublets, or weak singlets

$$\mathcal{L}_{S_1} = y_L^{b\tau}\, V_{ib}^*(\overline{u_i^C} P_L\, \tau)\, S_1 - y_L^{b\tau}\, (\overline{b^C} P_L\, \nu_\tau)\, S_1 + y_R^{c\tau}\, (\overline{c^C} P_R \tau)\, S_1 + \text{h.c.}$$

Minimal setting

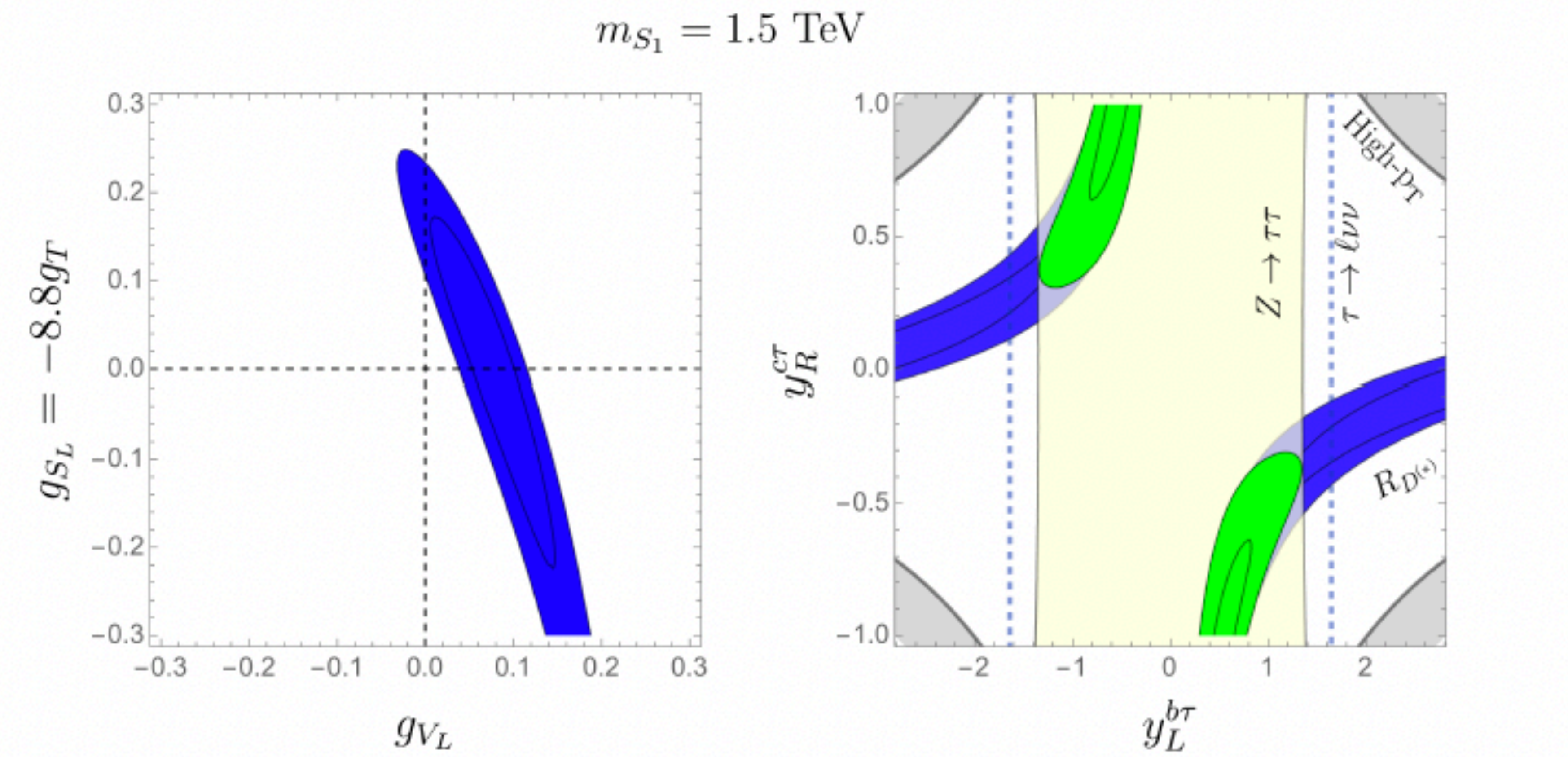
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_R^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},$$

$$g_{V_L} = \frac{v^2}{4V_{cb}} \frac{V_{cb}\,|y_L^{b\tau}|^2}{m_{S_1}^2}$$

$$g_{S_L}(m_{S_1}) = -\frac{v^2}{4V_{cb}} \frac{y_L^{b\tau} y_R^{c\tau\,*}}{m_{S_1}^2}$$

$$g_{S_L}(m_b) = -8.8 \times g_T(m_b)$$

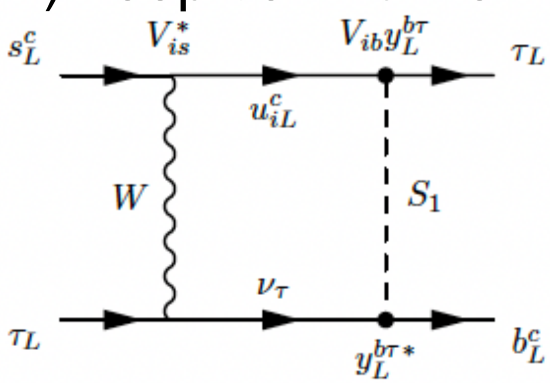
cf. 2404.16772



Consequences

1) $$\frac{\mathcal{B}(B_c \to \tau\nu)^{S_1}}{\mathcal{B}(B_c \to \tau\nu)^{\rm SM}} \in [1.13, 1.48]\,, \qquad \mathcal{B}(B_c \to \tau\nu)^{\rm SM} = (2.24 \pm 0.07)\% \times \left(\frac{V_{cb}}{0.0417}\right)^2$$

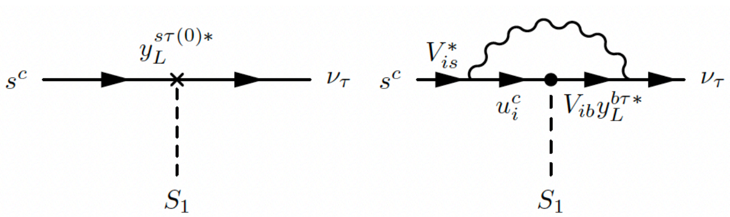
2) Loop contribution to b → sττ or b → sν_τ ν_τ



$$\frac{\mathcal{B}(B_s \to \tau\tau)^{S_1}}{\mathcal{B}(B_s \to \tau\tau)^{\rm SM}} \in [0.73, 0.98]\,, \qquad \frac{\mathcal{B}(B \to K\tau\tau)^{S_1}}{\mathcal{B}(B \to K\tau\tau)^{\rm SM}} \in [0.73, 0.98]$$

3) b → sν_τ ν_τ

$$C_L^{S_1} = (-9.3 + 0.4\, i) \times 10^{-2}\, |y_L^{b\tau}|^2$$



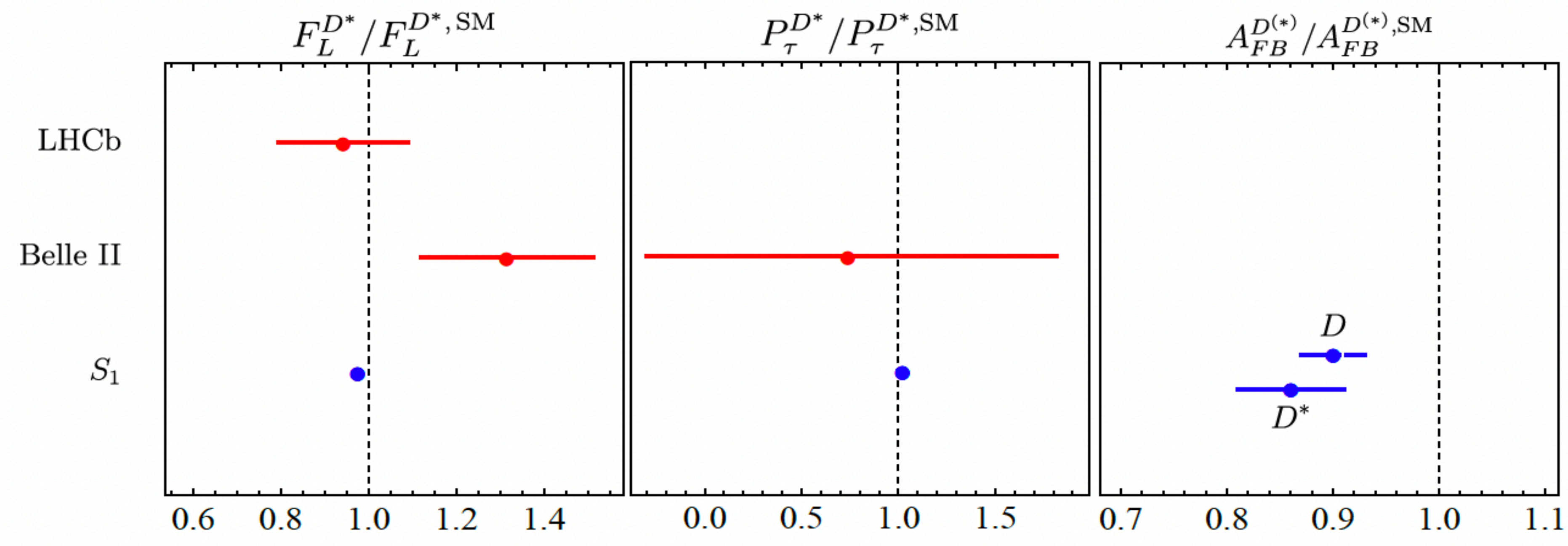
(imaginary part comes from the fermions being on the mass shell in the loops)

$$\frac{\mathcal{B}(B \to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\rm SM}} = \left|1 + \frac{\delta C_L^{S_1}}{3\, C_L^{\rm SM}}\right|^2 \in [1.001, 1.02] \quad (@2\sigma)$$

only 3 % enhancement over the SM

4) $V_{ub} |y_L^{b\tau}|^2$ $\left\{ \begin{array}{l} \mathcal{B}(B^- \to \tau\nu) \\ \mathcal{B}(B \to \pi\tau\nu) \end{array} \right\}$

5) for B →D(*) angular observables

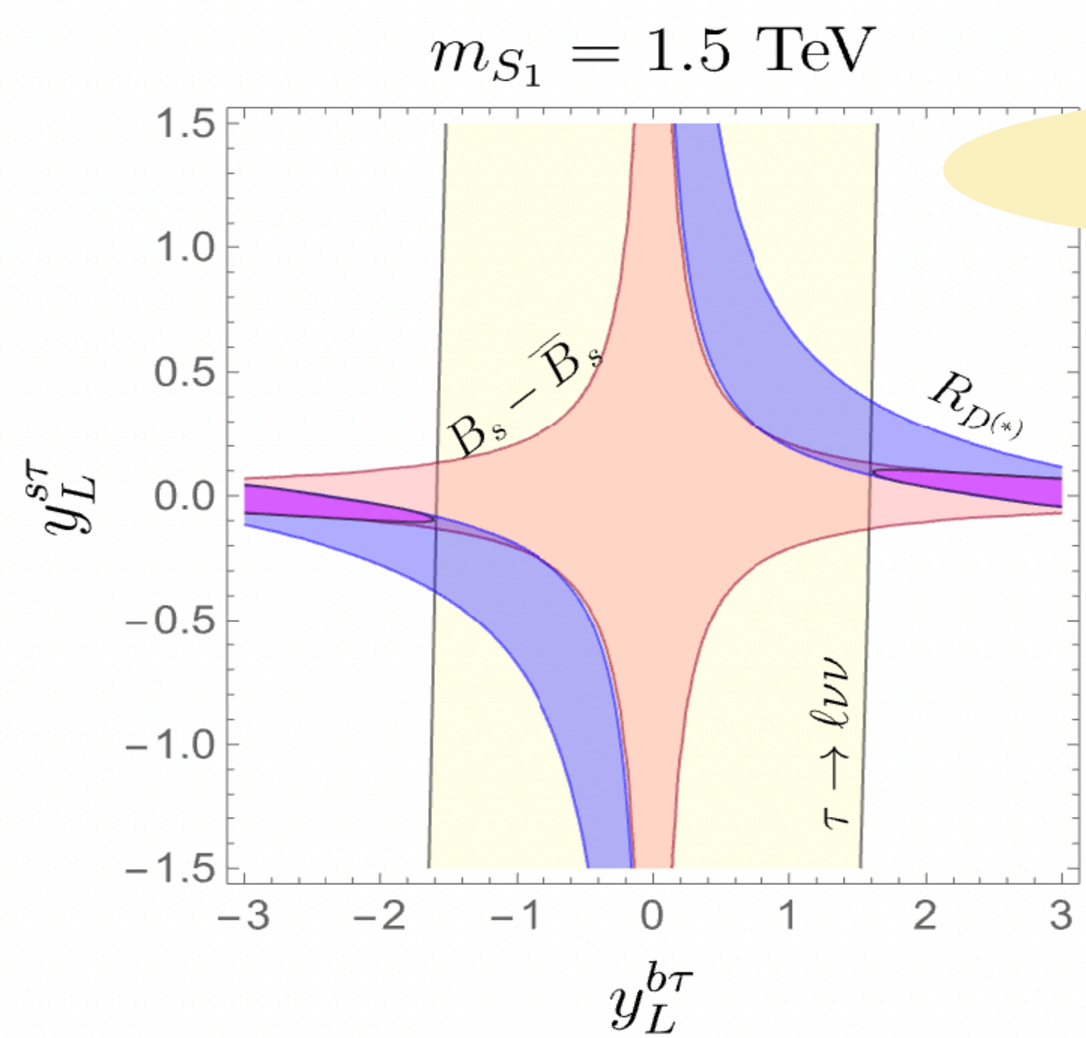


S$_1$ with V-A couplings only

$$g_{V_L} = -\frac{v^2}{m_{S_1}^2}\frac{V_{cs}}{V_{cb}} y_L^{s\tau} y_L^{b\tau}$$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{s\tau} \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = 0$$

No right-handed fermions ($y_R{}^{c\tau} = 0$)



S$_1$ (V-A) cannot survive!

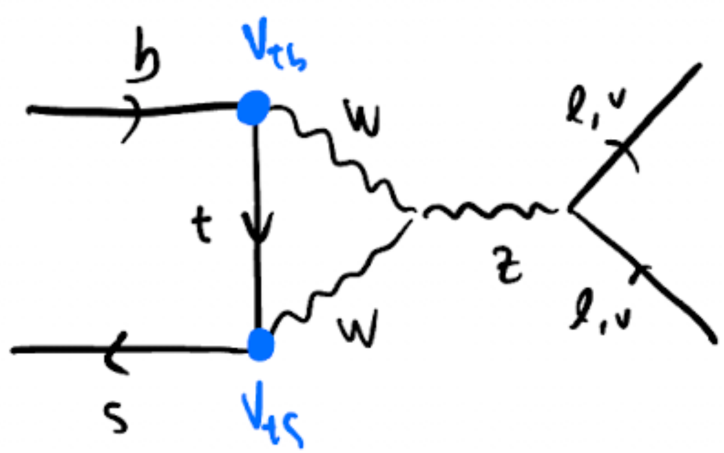
Search for physics BSM

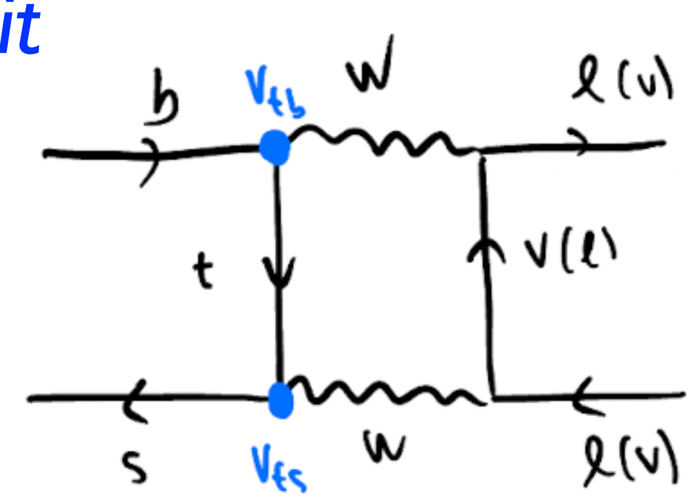
Decay rate = Kinematics CKM coupling Wilson coeff.s Hadronic quantities

Experiments

From UTA
CKMfitter, UTfit

NP QCD



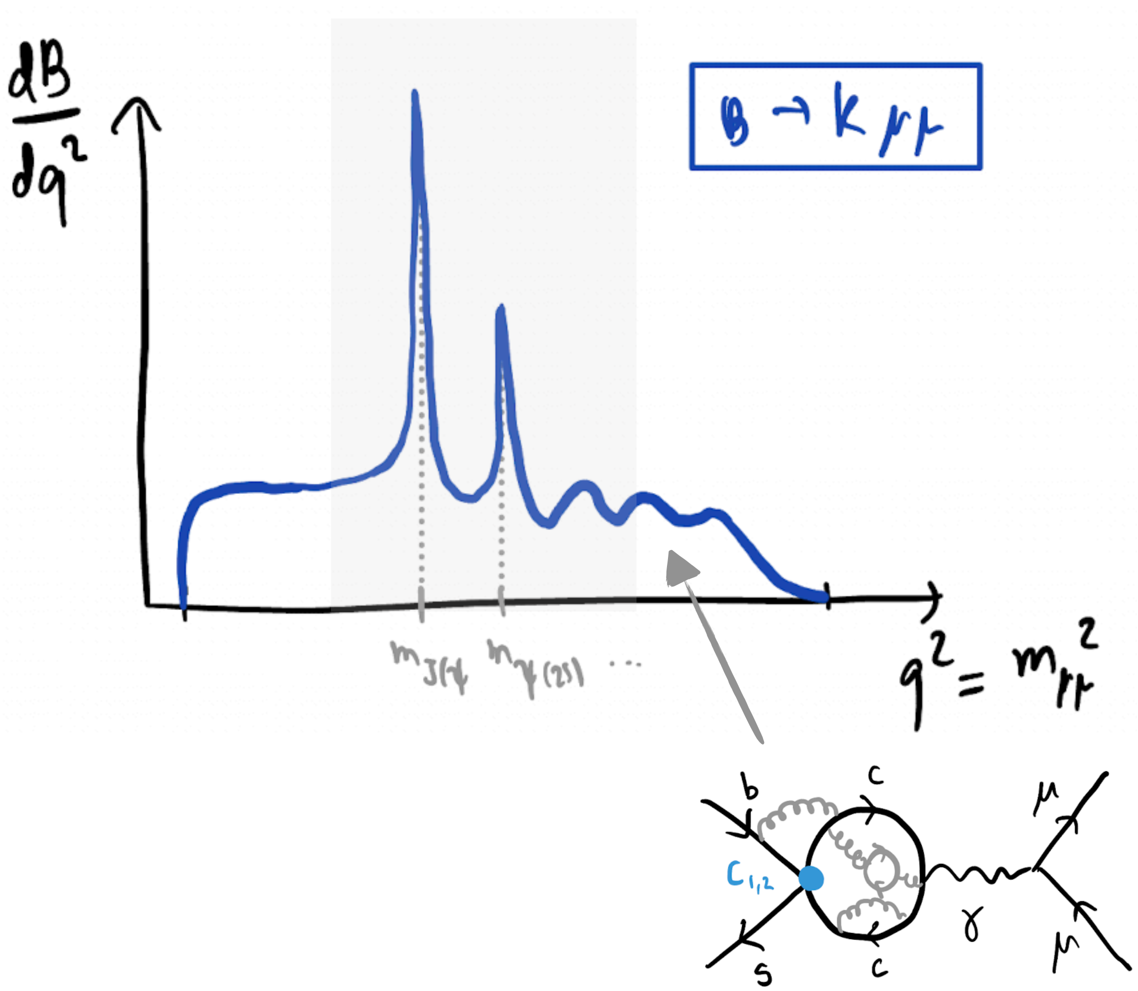


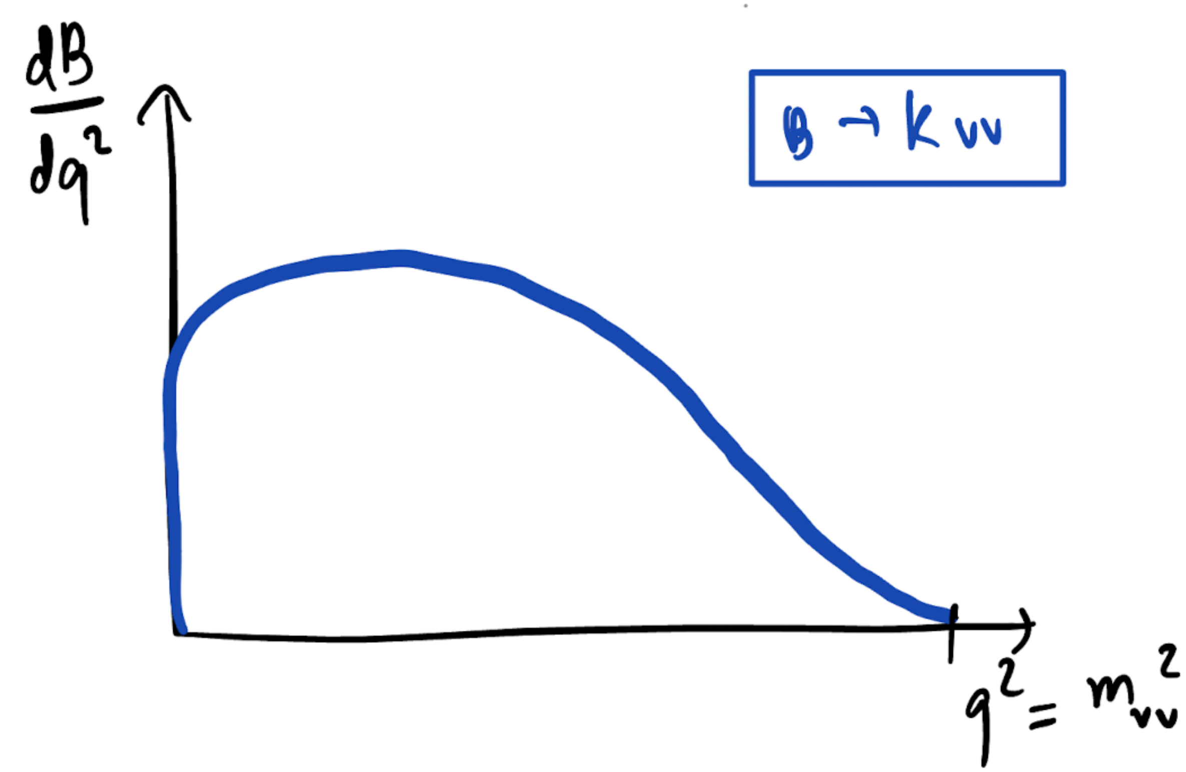
- $B \to K^{(*)}\ell\ell$:

  - *Sensitive to new physics effects.* ✓
  - *Experimentally clean (especially for $\ell = \mu$)* ✓
  - *Many observables (angular distribution).* ✓
  - *Theoretically challenging (non-factorizable contributions…)* ✗

- $B \to K^{(*)}\nu\bar{\nu}$:

  - *Sensitive to new physics effects.* ✓
  - *Exp. more challenging (missing energy).* ✓
  - *Fewer observables.* ✓
  - ***Theoretically cleaner!*** ✓
  - ***Sensitive to operators with τ-leptons.*** ✓





Courtesy of O. Sumensari

$B \to K\nu\bar{\nu}$ in the SM

- **Effective Hamiltonian** within the SM:

$$\mathcal{L}_{\text{eff}}^{\text{b}\to\text{s}\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\text{em}}}{2\pi}\sum_i C_L^{\text{SM}}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Li}) + \text{h.c.}\,,$$

$\lambda_t = V_{tb}V_{ts}^*$

- **Short-distance** contributions known to **good precision**:

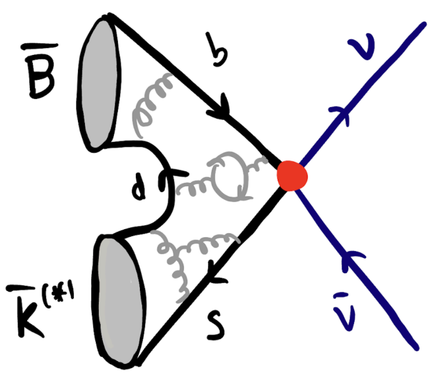
$$C_L^{\text{SM}} = -X_t/\sin^2\theta_W$$
$$= -6.32(7)$$

Including NLO QCD and two-loop EW contributions:

$$X_t = 1.462(17)(2)$$

Two main sources of uncertainties:

i) Hadronic matrix-element:



Known Lorentz factors

$$\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle = \sum_a K_a^\mu\,\mathcal{F}_a(q^2)$$

Form-factors (e.g., LQCD)

ii) CKM matrix:

From CKM unitarity:

$$|V_{tb}V_{ts}^*| = |V_{cb}|(1+\mathcal{O}(\lambda^2))$$

Which value to take (incl. vs. excl.)?

Courtesy of O. Sumensari

Form-factors: $B \to K\nu\bar{\nu}$

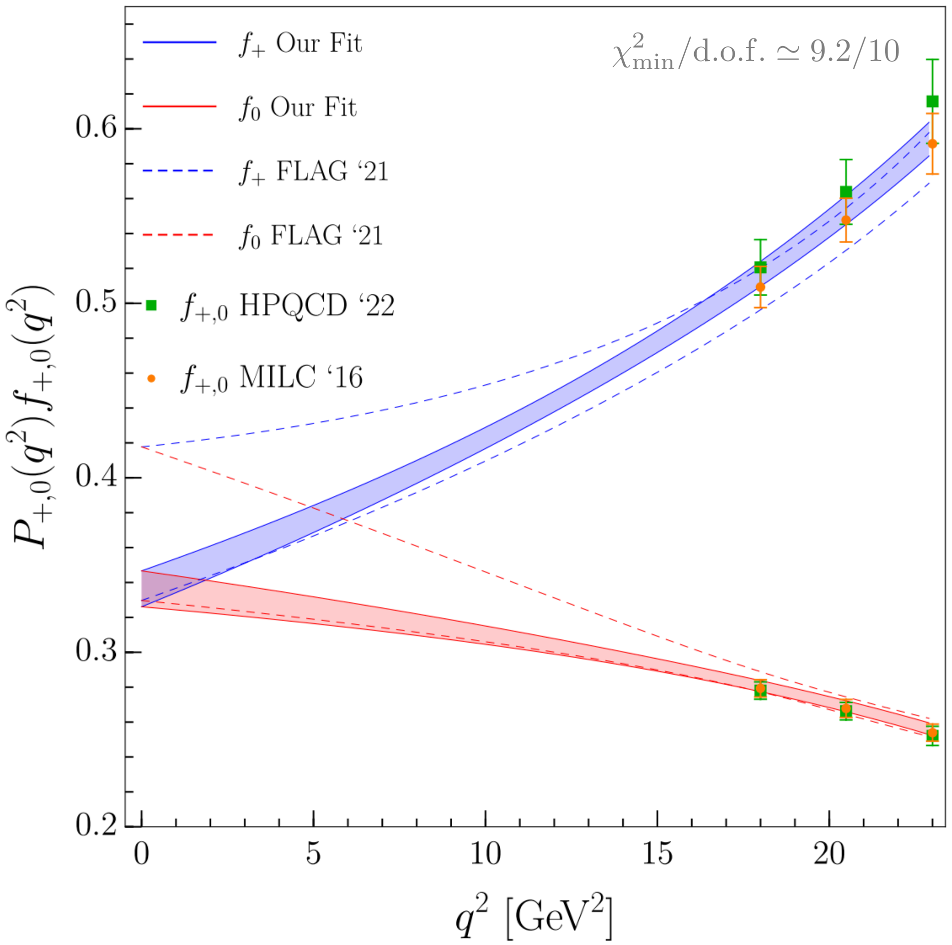
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\rm max}$) for all form-factors:

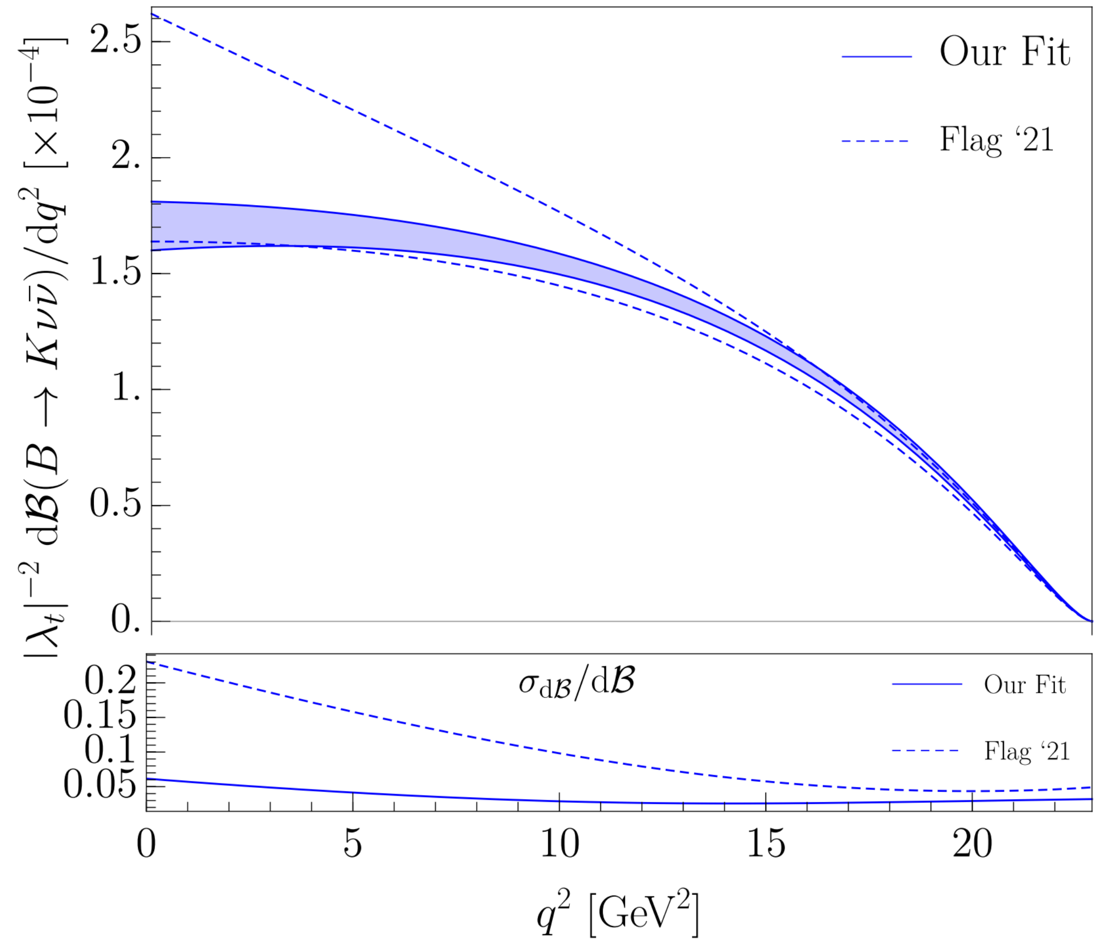
$$\langle K(k)|\bar{s}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

with $f_+(0) = f_0(0)$.

Only form-factor needed for $B \to K\nu\bar{\nu}$!

- We update the FLAG average by combining [HPQCD '22] results with [FNAL/MILC '16]:





Pole factor:
$P_i(q^2) = 1 - q^2/M_i^2$

cf. 2301.06990

[NEW] Belle-II results

[2311.14647]

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\text{exp}} = \left[2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right] \times 10^{-5}$$

$\approx 3\sigma$ above the SM prediction

$$\mathcal{B}(B^\pm \to K^\pm\nu\bar{\nu})^{\text{SM}} = 4.4(3) \times 10^{-6}$$

$$R^{\nu\nu\,(\text{exp})}_{K^+} = 5.4 \pm 1.5$$

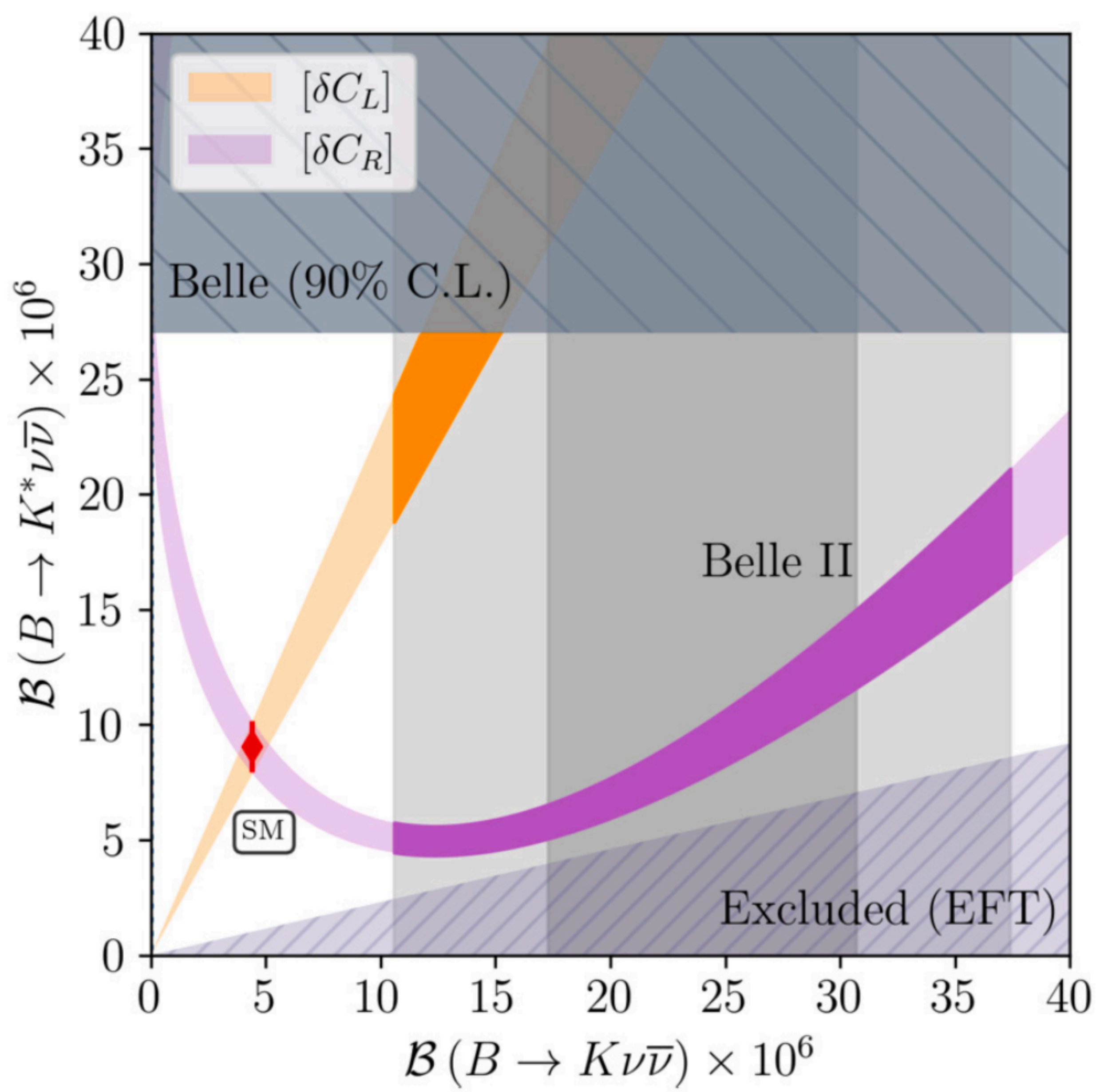
Use EFT to see how we can accommodate this result.

EFT for $b \to s\nu\bar{\nu}$

- Low-energy EFT:

$$\mathcal{L}_{\rm eff}^{\rm b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi}\sum_{ij}\left[C_L^{\nu_i\nu_j}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj}) + C_R^{\nu_i\nu_j}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})\right] + \text{h.c.}\,,$$

- Complementarity of $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$:



cf. 2309.02246

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2)\times U(1)_Y$:

$b \to s\ell\ell$ | $b \to s\nu\bar{\nu}$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\bar{L}_i\gamma^\mu L_j)(\bar{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{L}_i\gamma^\mu\tau^I L_j)(\bar{Q}_k\tau^I\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ld}]_{ijkl} = (\bar{L}_i\gamma^\mu L_j)(\bar{d}_k\gamma_\mu d_l)$$
$$[\mathcal{O}_{eq}]_{ijkl} = (\bar{e}_i\gamma^\mu e_j)(\bar{Q}_k\gamma_\mu Q_l)$$
$$[\mathcal{O}_{ed}]_{ijkl} = (\bar{e}_i\gamma^\mu e_j)(\bar{d}_k\gamma_\mu d_l)$$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\bar{L}_i\gamma^\mu L_j)(\bar{Q}_k\gamma_\mu Q_l) = (\bar{\ell}_{Li}\gamma^\mu\ell_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) + (\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) + \ldots$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{L}_i\gamma^\mu\tau^I L_j)(\bar{Q}_k\gamma_\mu\tau^I Q_l) = (\bar{\ell}_{Li}\gamma^\mu\ell_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) - (\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) + \ldots$$

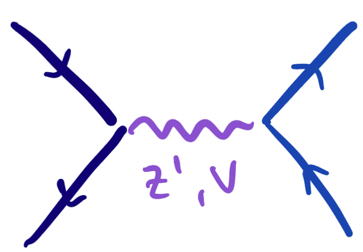
$$[\mathcal{O}_{ld}]_{ijkl} = (\bar{L}_i\gamma^\mu L_j)(\bar{d}_k\gamma_\mu d_l) = (\bar{\ell}_{Li}\gamma^\mu\ell_{Lj})(\bar{d}_{Rk}\gamma_\mu d_{Rl}) + (\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})(\bar{d}_{Rk}\gamma_\mu d_{Rl})$$

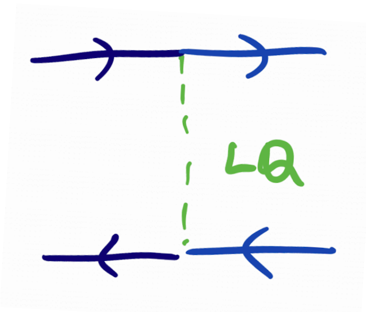
- Correlations for concrete mediators:

- $Z' \sim (\mathbf{1},\mathbf{1},0)$:	$\mathcal{C}_{lq}^{(1)} \neq 0\,, \quad \mathcal{C}_{lq}^{(3)} = 0$
- $V \sim (\mathbf{1},\ \mathbf{3},\ 0)$	$\mathcal{C}_{lq}^{(1)} = 0\,, \quad \mathcal{C}_{lq}^{(3)} \neq 0$
- $U_1 \sim (\mathbf{3},\mathbf{1},2/3)$	$\mathcal{C}_{lq}^{(1)} = \mathcal{C}_{lq}^{(3)}$
- $S_3 \sim (\bar{\mathbf{3}},\mathbf{3},1/3)$	$\mathcal{C}_{lq}^{(1)} = 3\,\mathcal{C}_{lq}^{(3)}$

…

$(SU(3)_c,\ SU(2)_L,\ U(1)_Y)$





$$\frac{\mathcal{C}}{\Lambda^2} \simeq (5\ \mathrm{TeV})^{-2}$$

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2)\times U(1)_Y$:

$b \to s\ell\ell$ $\qquad$ $b \to s\nu\bar{\nu}$

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$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{L}_i\gamma^\mu\tau^I L_j)(\bar{Q}_k\gamma_\mu\tau^I Q_l) = (\bar{\ell}_{Li}\gamma^\mu\ell_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) - (\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})(\bar{d}_{Lk}\gamma_\mu d_{Ll}) + \dots$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\bar{L}_i\gamma^\mu L_j)(\bar{d}_k\gamma_\mu d_l) = (\bar{\ell}_{Li}\gamma^\mu\ell_{Lj})(\bar{d}_{Rk}\gamma_\mu d_{Rl}) + (\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})(\bar{d}_{Rk}\gamma_\mu d_{Rl})$$

Which flavor?

I) *Couplings to muons* are *tightly constrained* by $\mathcal{B}(B_s \to \mu\mu)$. ✗

II) *LFV couplings* are *constrained* by searches for $\mathcal{B}(B_s \to \ell_i\ell_j)$ and $\mathcal{B}(B \to K^{(*)}\ell_i\ell_j)$. ✗

III) The **only viable option** is coupling to τ's *(due to weak exp. limits on $b \to s\tau\tau$).* ✓

⇒ **Predictions:**

$$\frac{\mathcal{B}(B_s\to\tau\tau)}{\mathcal{B}(B_s\to\tau\tau)^{\rm SM}} \simeq \frac{\mathcal{B}(B\to K^{(*)}\tau\tau)}{\mathcal{B}(B\to K^{(*)}\tau\tau)^{\rm SM}} \simeq 10$$

experimentally challenging

Other way to go is through neutrinos, cf. 2404.17440

Can we figure out a scenario which would simultaneously accommodate $R_{D^{(*)}}$ and $R_K^{\nu\nu}$?

- Let us introduce a RH neutrino(s) and study RR operators

$$\mathcal{L}_{\rm eff} \supset \mathcal{L}^{b\to c\tau N_R} + \mathcal{L}^{b\to sN_R N_R}$$
$$= -\sqrt{2}G_F C_{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R N_R) - \sqrt{2}G_F \widetilde{C}_{RR}(\bar{s}\gamma_\mu P_R b)(\bar{N}_R\gamma^\mu P_R N_R) + \text{h.c.}$$

- No interference with SM.

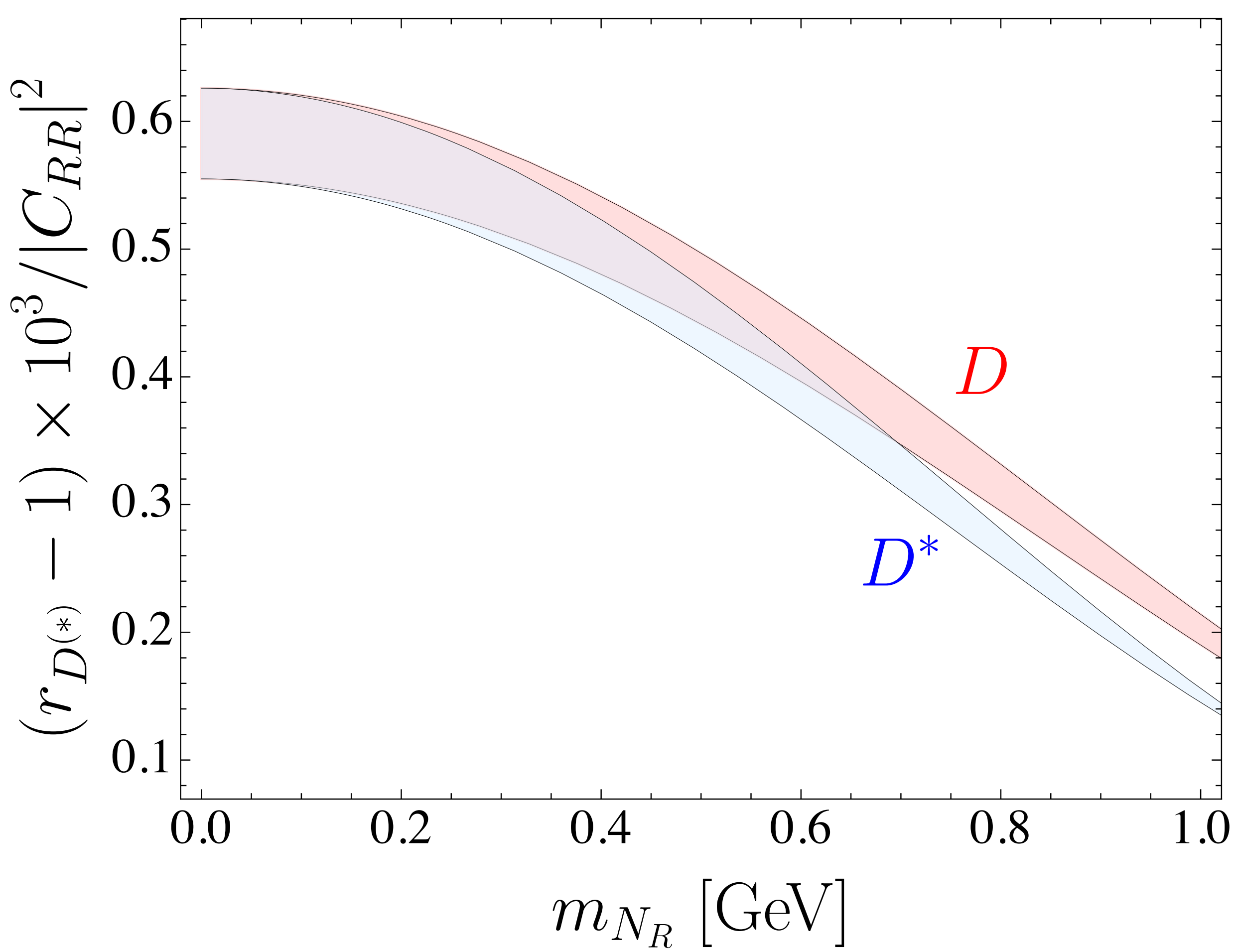
$$\mathcal{B}(B\to D^{(*)}\tau\text{`inv'}) = \mathcal{B}(B\to D^{(*)}\tau\nu)^{\rm SM} + \mathcal{B}(B\to D^{(*)}\tau N_R)$$
$$\mathcal{B}(B\to K^{(*)}\text{`inv'}) = \mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM} + \mathcal{B}(B\to K^{(*)}N_R N_R)$$

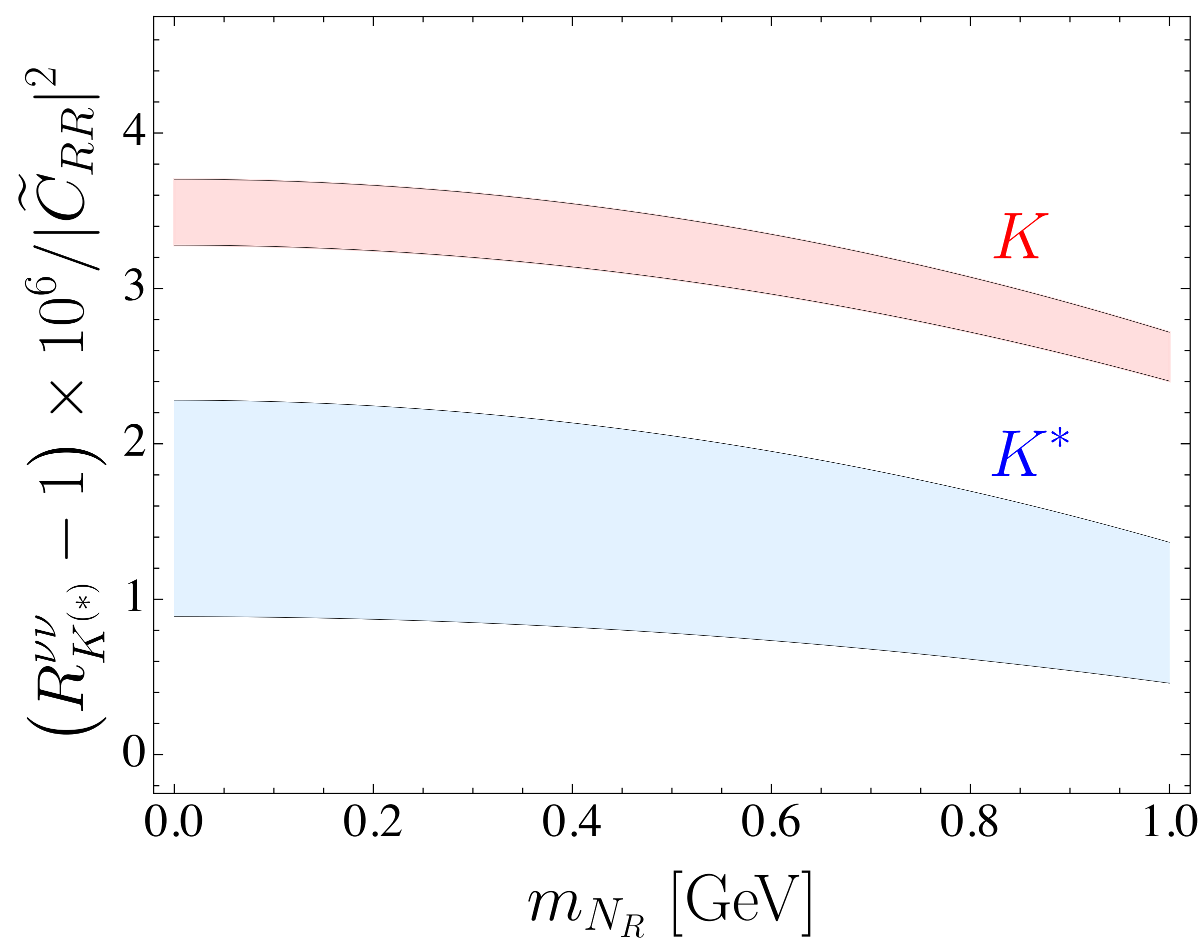
cf. 2410.23257

- Let us introduce a RH neutrino(s) and study RR operators

$$\mathcal{L}_{\text{eff}} \supset \mathcal{L}^{b\to c\tau N_R} + \mathcal{L}^{b\to sN_RN_R}$$
$$= -\sqrt{2}G_F\, C_{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R N_R) - \sqrt{2}G_F \widetilde{C}_{RR}(\bar{s}\gamma_\mu P_R b)(\bar{N}_R\gamma^\mu P_R N_R) + \text{h.c.}$$

- No interference with SM
- N_R can be massless or massive





- Scenario for both...

$$\mathcal{L}_{\rm eff} \supset \mathcal{L}^{b\to c\tau N_R} + \mathcal{L}^{b\to s N_R N_R}$$

$$= -\sqrt{2}G_F\, C_{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R N_R) - \sqrt{2}G_F \widetilde{C}_{RR}(\bar{s}\gamma_\mu P_R b)(\bar{N}_R\gamma^\mu P_R N_R) + \text{h.c.}$$

- Predictions

$m_{N_R} = 0\,\text{GeV}$ | $m_{N_R} = 0.6\,\text{GeV}$ | $m_{N_R} = 1\,\text{GeV}$

Quantity	SM	Case 1.	Case 2.	Case 3.
$\lvert C_{RR}\rvert \times 10^2$	–	1.6(2)	2.0(2)	3.1(4)
$A_{\rm fb}^{D}$	0.360(0)	0.360(0)	0.341(4)	0.329(4)
$A_{\rm fb}^{D^*}$	$-0.06(1)$	$-0.06(1)$	$-0.06(1)$	$-0.06(1)$
P_τ^{D}	0.325(3)	0.25(2)	0.26(2)	0.28(1)
$P_\tau^{D^*}$	$-0.51(2)$	$-0.39(4)$	$-0.41(3)$	$-0.43(3)$
$F_L^{D^*}$	0.46(1)	0.46(1)	0.46(1)	0.45(1)
R_{B_c}	1	1.17(10)	1.29(13)	1.63(31)
$R_{J/\psi}$	0.258(4)	0.296(10)	0.292(10)	0.277(7)

Quantity	SM	Case 1.	Case 2.	Case 3.
$\lvert\widetilde{C}_{RR}\rvert \times 10^3$	–	1.1(2)	1.2(2)	1.3(2)
$R_{K^*}^{\text{'inv'}}$	1	5.3 ± 1.5	5.2 ± 1.4	4.9 ± 1.3
$F_L^{K^*}$	0.48(7)	0.47(7)	0.47(7)	0.47(7)
$\mathcal{B}(B_s \to \text{'inv'})$	0	0	$(9 \pm 3) \times 10^{-7}$	$(3 \pm 1) \times 10^{-6}$
$R_{D_s}^{\text{'inv'}}$	1	5.3 ± 1.4	5.4 ± 1.4	5.5 ± 1.4

Concrete Model (S_1)

$$\mathcal{L}_{\text{eff}} \supset \mathcal{L}^{b\to c\tau N_R} + \mathcal{L}^{b\to s N_R N_R}$$

$$= -\sqrt{2}G_F C_{RR}(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_R N_R) - \sqrt{2}G_F \widetilde{C}_{RR}(\bar{s}\gamma_\mu P_R b)(\bar{N}_R\gamma^\mu P_R N_R) + \text{h.c.}$$

- Scalar LQ

$$\mathcal{L} \supset y^R_{c\tau}\,\overline{c^c}P_R\tau\,S_1 + y^R_{sN}\,\overline{s^c}P_R N_R\,S_1 + y^R_{bN}\,\overline{b^c}P_R N_R\,S_1 + \text{h.c.}$$

$$C_{RR} = -\frac{v^2}{4m_{S_1}^2}y^{R*}_{c\tau}y^R_{bN}$$

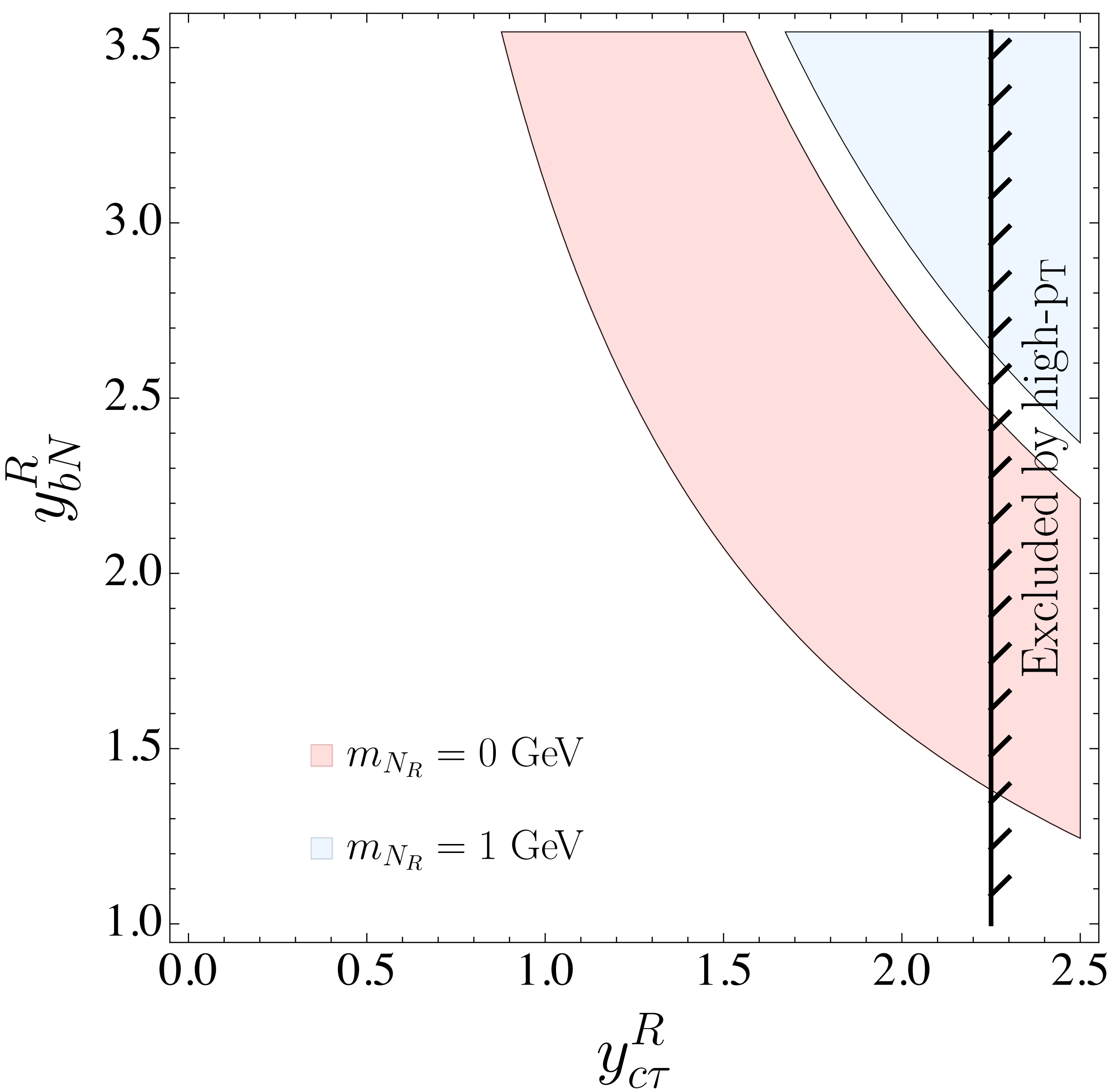
$$\widetilde{C}_{RR} = -\frac{v^2}{2m_{S_1}^2}y^{R*}_{sN}y^R_{bN}$$

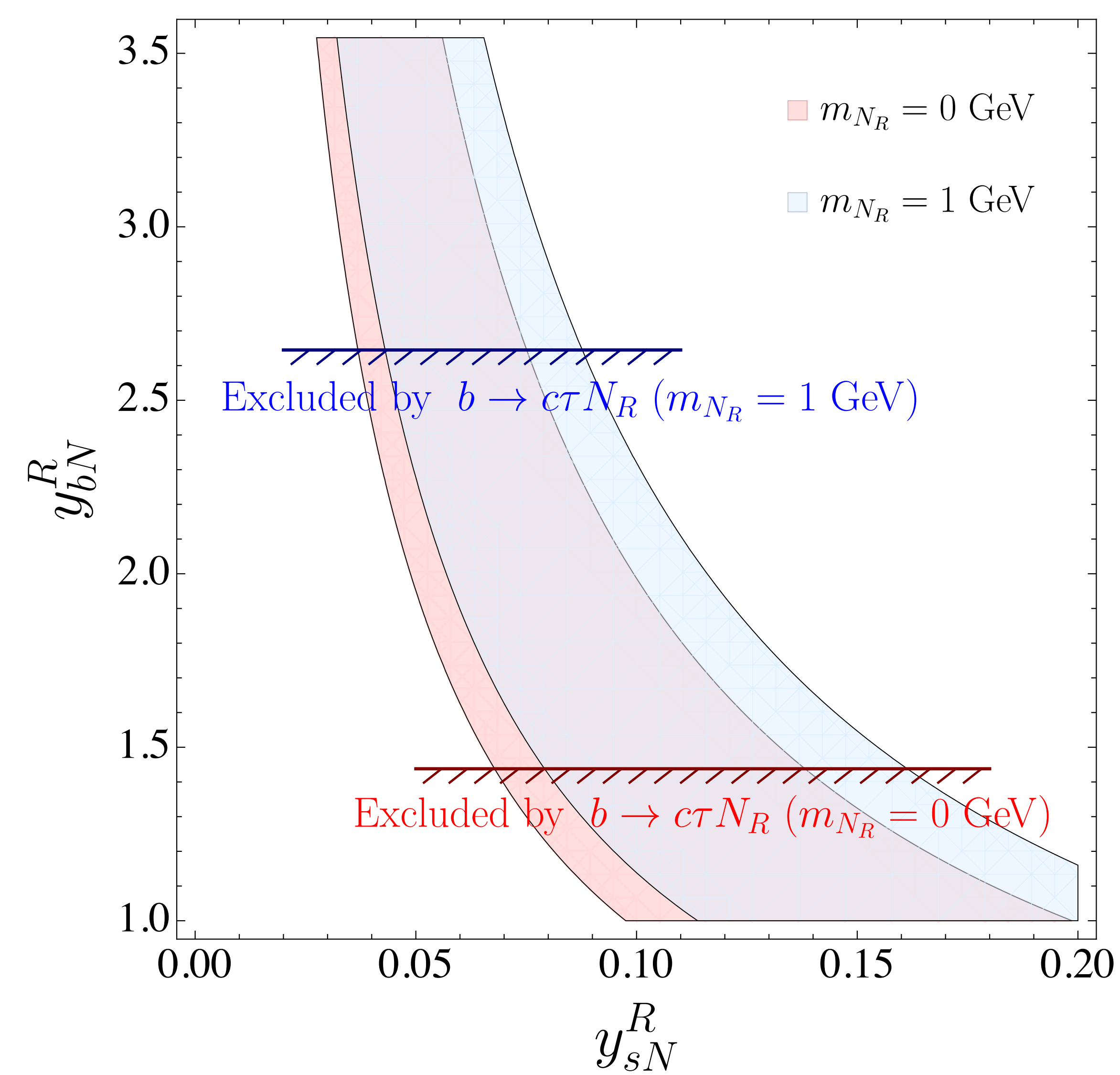
cf. 2410.23257

Concrete Model (S_1)

$$\mathcal{L} \supset y^R_{c\tau}\, \overline{c^c} P_R \tau\, S_1 + y^R_{sN}\, \overline{s^c} P_R N_R\, S_1 + y^R_{bN}\, \overline{b^c} P_R N_R\, S_1 + \text{h.c.}$$

$$C_{RR} = -\frac{v^2}{4m^2_{S_1}} y^{R*}_{c\tau} y^R_{bN} \qquad \widetilde{C}_{RR} = -\frac{v^2}{2m^2_{S_1}} y^{R*}_{sN} y^R_{bN}$$





Concrete Model (S_1)

$$\mathcal{L} \supset y^R_{c\tau}\,\overline{c^c} P_R \tau\, S_1 + y^R_{sN}\,\overline{s^c} P_R N_R\, S_1 + y^R_{bN}\,\overline{b^c} P_R N_R\, S_1 + \text{h.c.}$$

$$\Delta m_{B_s} = \left(1 + \frac{C_{S_1}}{C_{SM}}\right) \Delta m^{\text{SM}}_{B_s}$$

$$C_{S_1} = \frac{\left|y^{R\,*}_{sN}\, y^R_{bN}\right|^2}{256\pi^2\lambda_t^2}\frac{v^2}{m^2_{S_1}} = \frac{\left|\widetilde{C}_{RR}\right|^2}{64\pi^2\lambda_t^2}\frac{m^2_{S1}}{v^2}$$

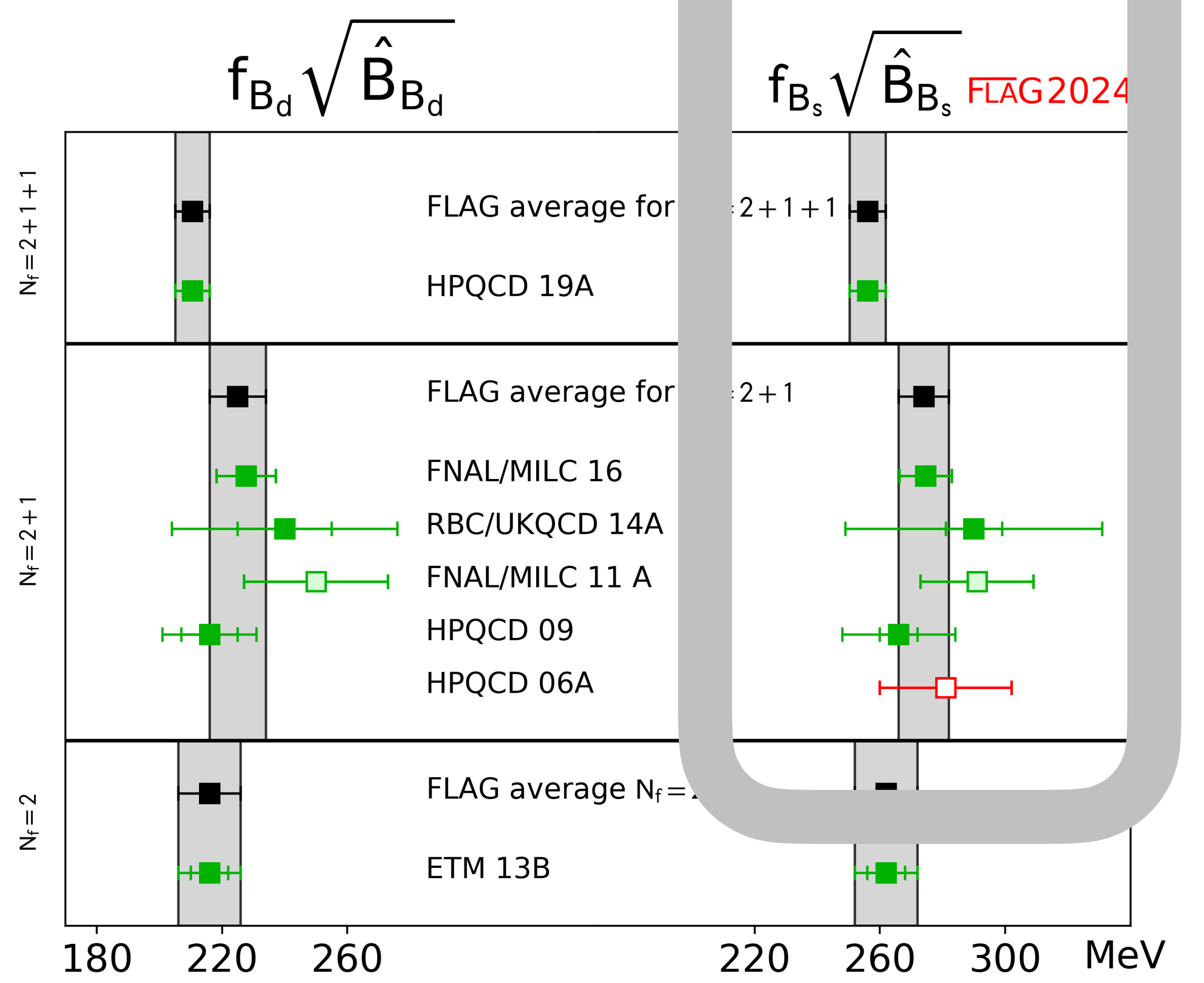
$$\widetilde{C}_{RR} = -\frac{v^2}{2m^2_{S_1}} y^{R*}_{sN} y^R_{bN}$$

Concrete Model (S_1)

$$\mathcal{L} \supset y^R_{c\tau}\,\overline{c^c} P_R \tau\, S_1 + y^R_{sN}\,\overline{s^c} P_R N_R\, S_1 + y^R_{bN}\,\overline{b^c} P_R N_R\, S_1 + \text{h.c.}$$

$$\Delta m_{B_s} = \left(1 + \frac{C_{S_1}}{C_{SM}}\right) \Delta m^{\rm SM}_{B_s}$$

$$\Delta m^{\rm exp}_{B_s} = 17.765(6)\,\text{ps}^{-1}$$



CONCLUDING REMARK