# B (and D) decays…

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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

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

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

- ✘ With 3 gen's 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!)
- ✘ Why 3 gen's? Why hierarchical pattern of masses and CKM mixings?

# Extracting parameters

Decay rate = Kinematics CKM coupling Hadronic quantities

***Experiments:***

*NA62, KOTO*

*BESIII, LHCb*

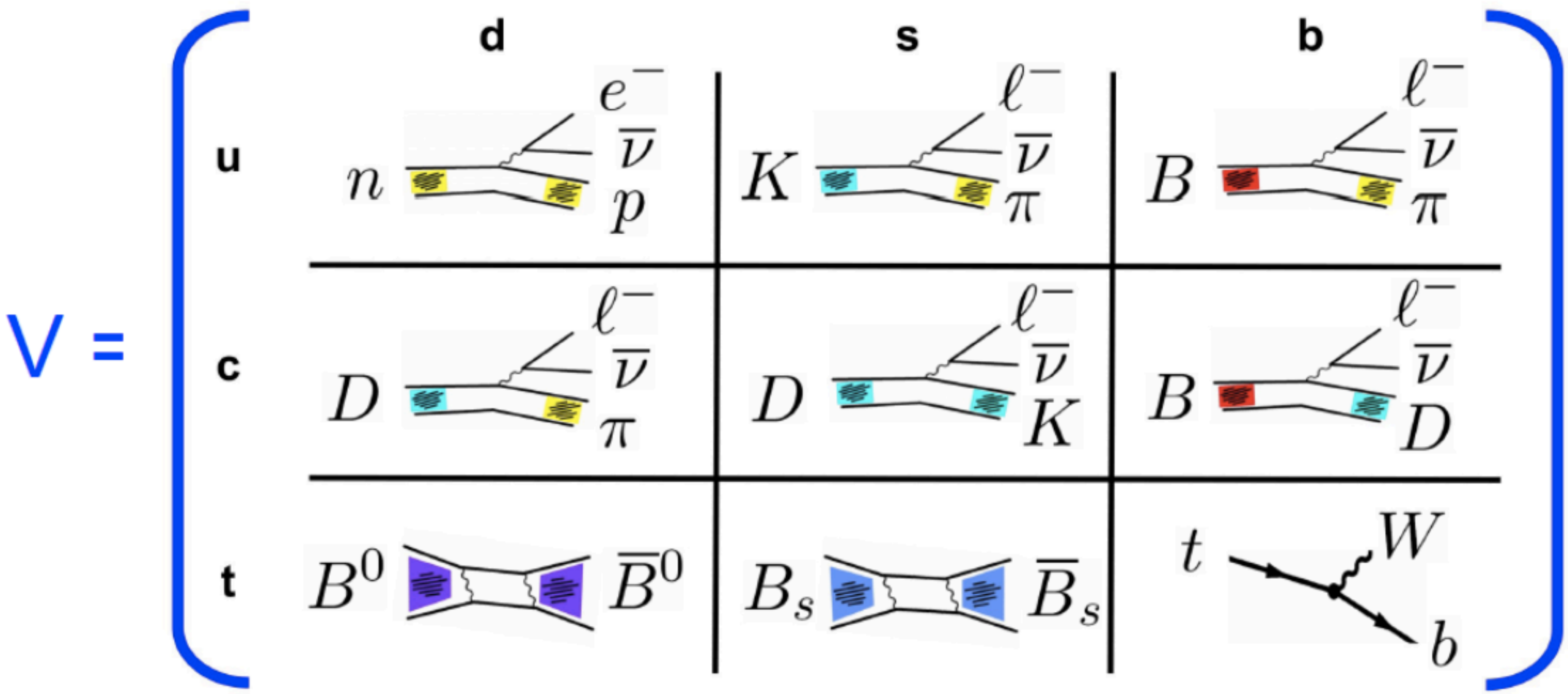
*LHC,Belle-II*

***Nonperturbative QCD***

*Lattice QCD*

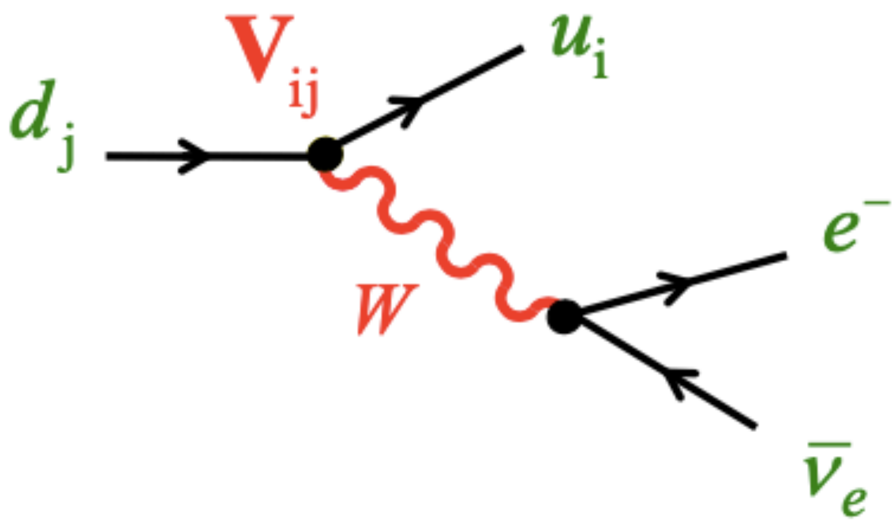
*Models such as LCSR*

# CKM




Reconstruction through semileptonics except for the last row…

# FCC




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

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

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

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

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

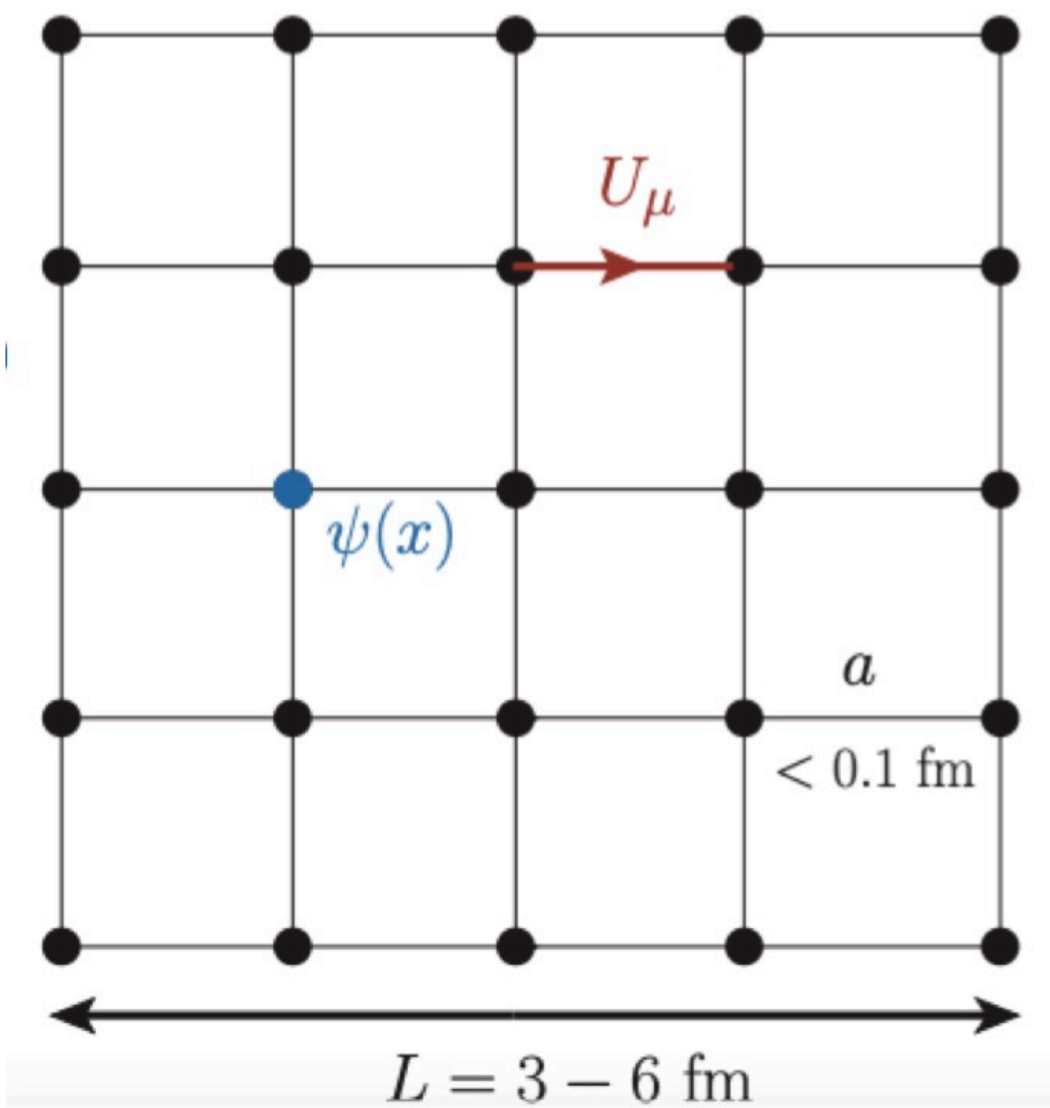
$\chi$S: Ademollo-Gatto theorem $f_+(0) = 1 + \mathcal{O}((m_s-m_u)^2)$ for $K \to \pi$ — *$\chi$PT*

HQS: Luke theorem for A1(w=1) = 1 + $\mathcal{O}(1/m_b^2)$ for $B \to D^*$ — *HQE*

# Only one slide on LQCD

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

$$\not{D} = \gamma^\mu\left[\partial_\mu - igA_\mu(x)\right]$$




- Regularized QCD - path integral GF ⇔ MC methods (stat. errors)
- Systematics (finite spacing, volume etc) are difficult but can be and are handled
- Ab initio means NO additional parameter is introduced apart from those in the original Lagrangian (coupling and quark masses)

# Only one slide on LQCD

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

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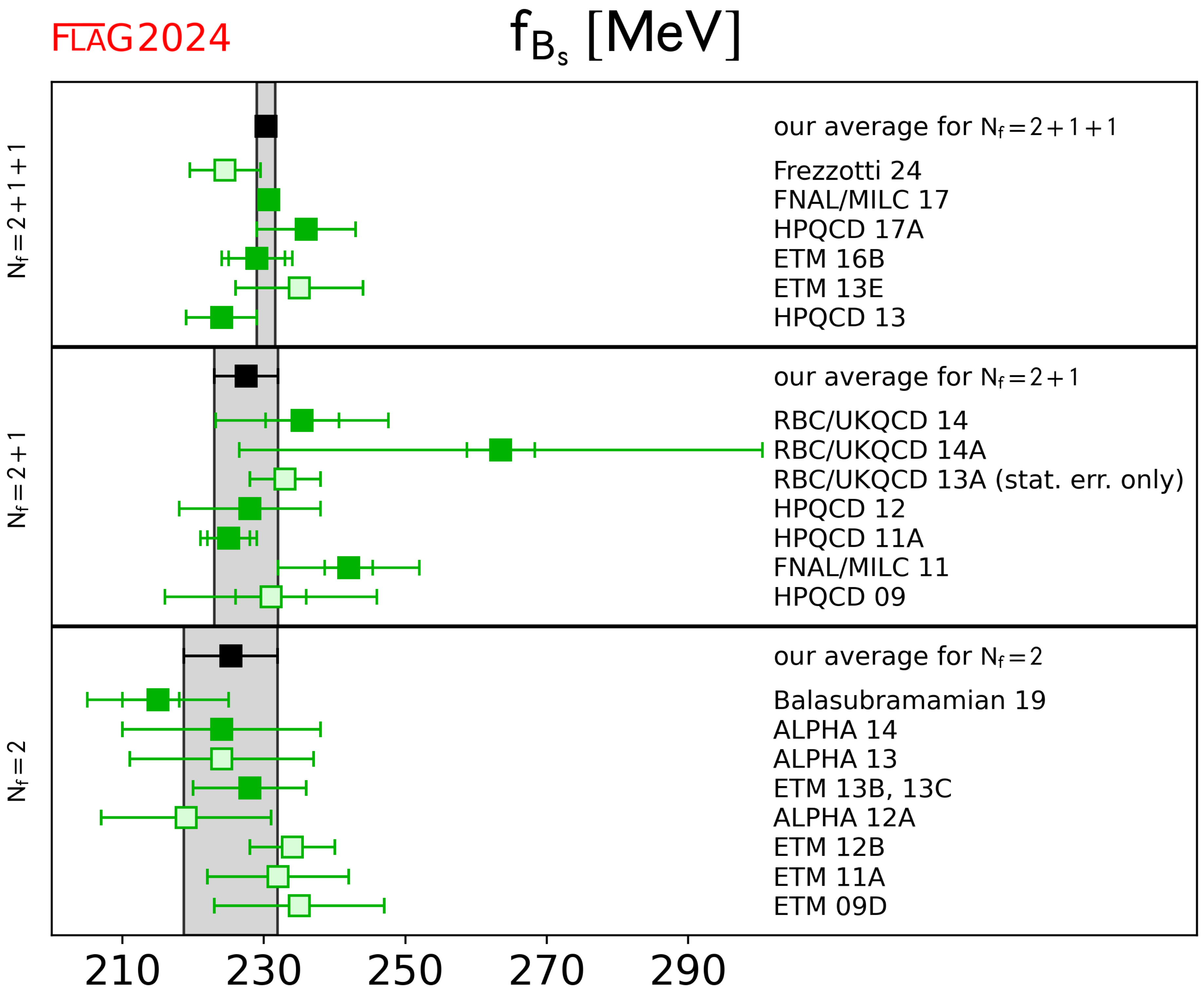
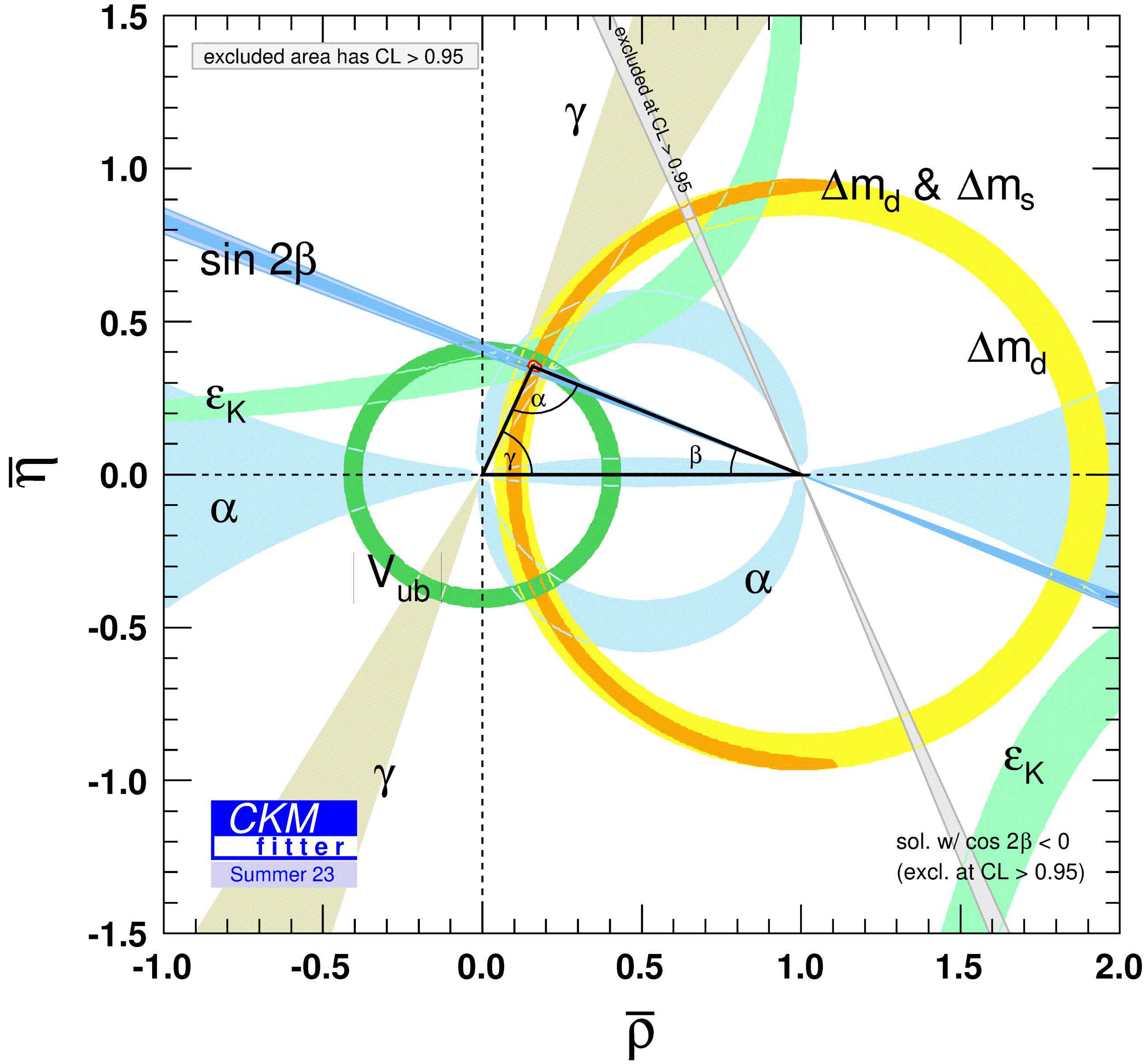
- ✘ Regularized QCD - path integral GF ⇔ MC methods (stat. errors)
- ✘ Systematics (finite spacing, volume etc) are difficult but can be and are handled
- ✘ Ab initio means NO additional parameter is introduced apart from those in the original Lagrangian (coupling and quark masses)
- ✘ Not everything can be computed precisely on the lattice [if requiring high precision it becomes increasingly difficult].
- ✘ Numerical answers.
- ✘ Need analytic approaches to interpret or learn from LQCD results!

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

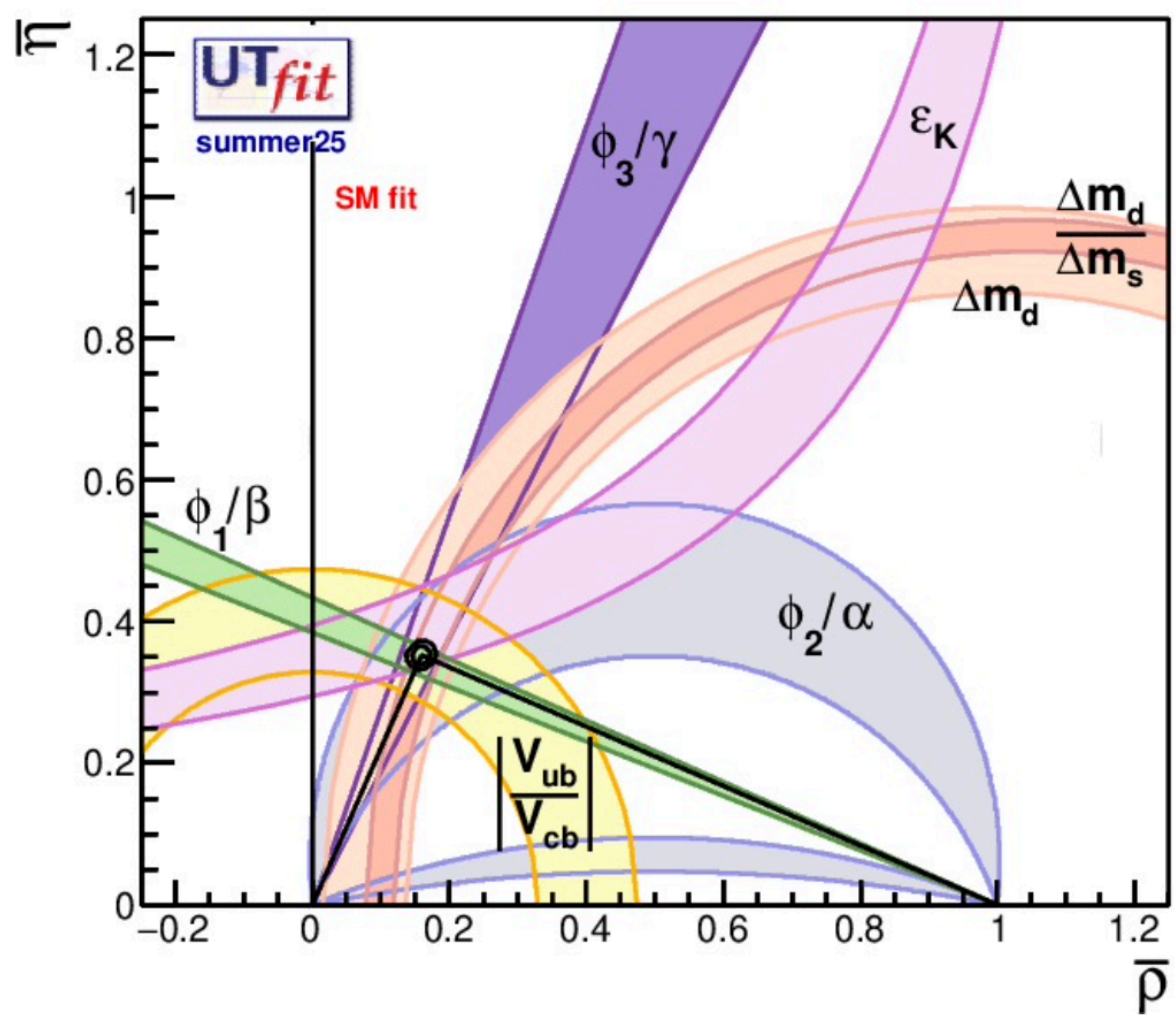



- ✦ For some quantities per-mill accuracy
- ✦ Not everything can be computed on the lattice with a pheno required precision
- ✦ FLAG averages… cf. http://flag.unibe.ch

# UTA



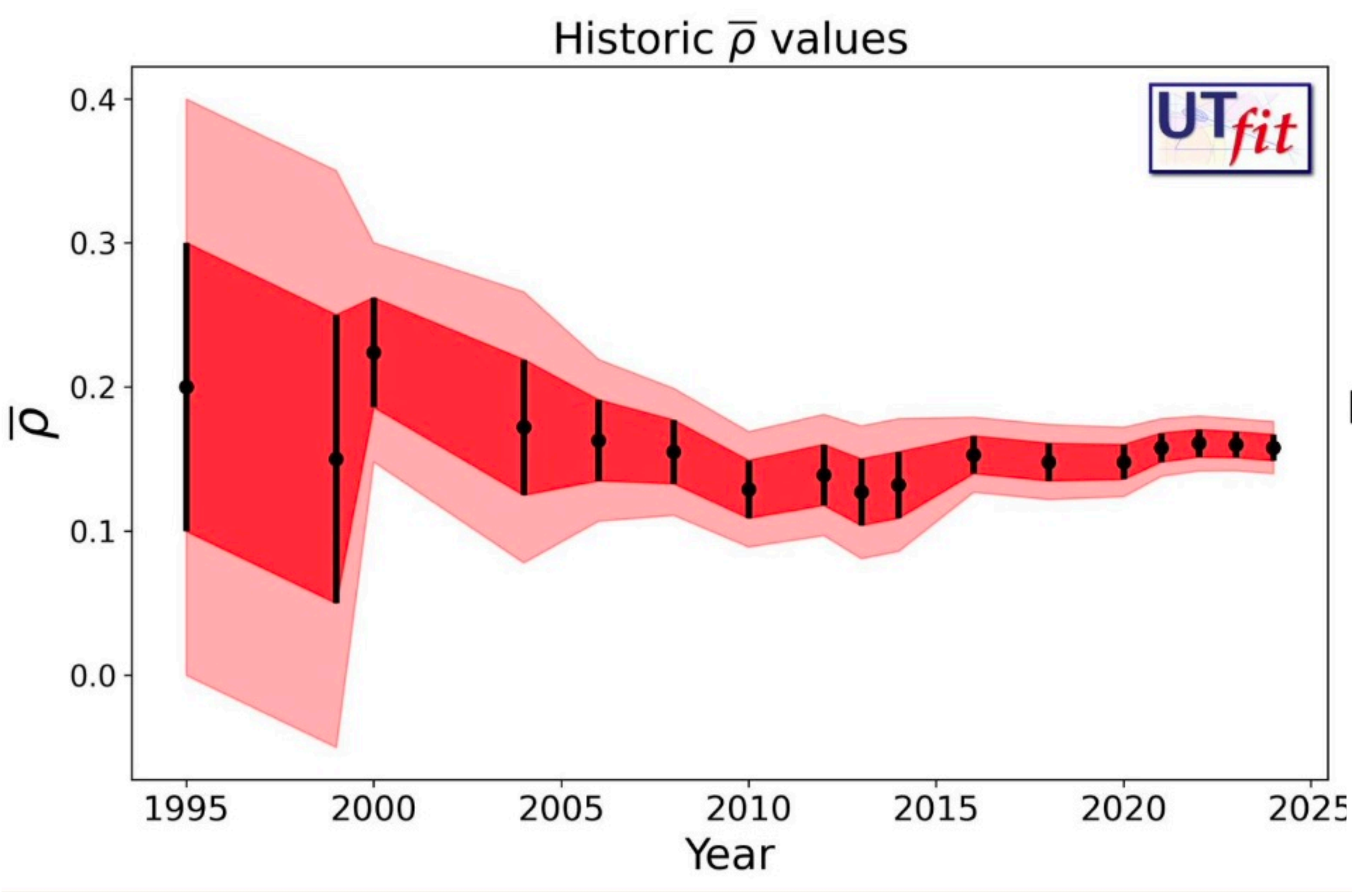

http://ckmfitter.in2p3.fr

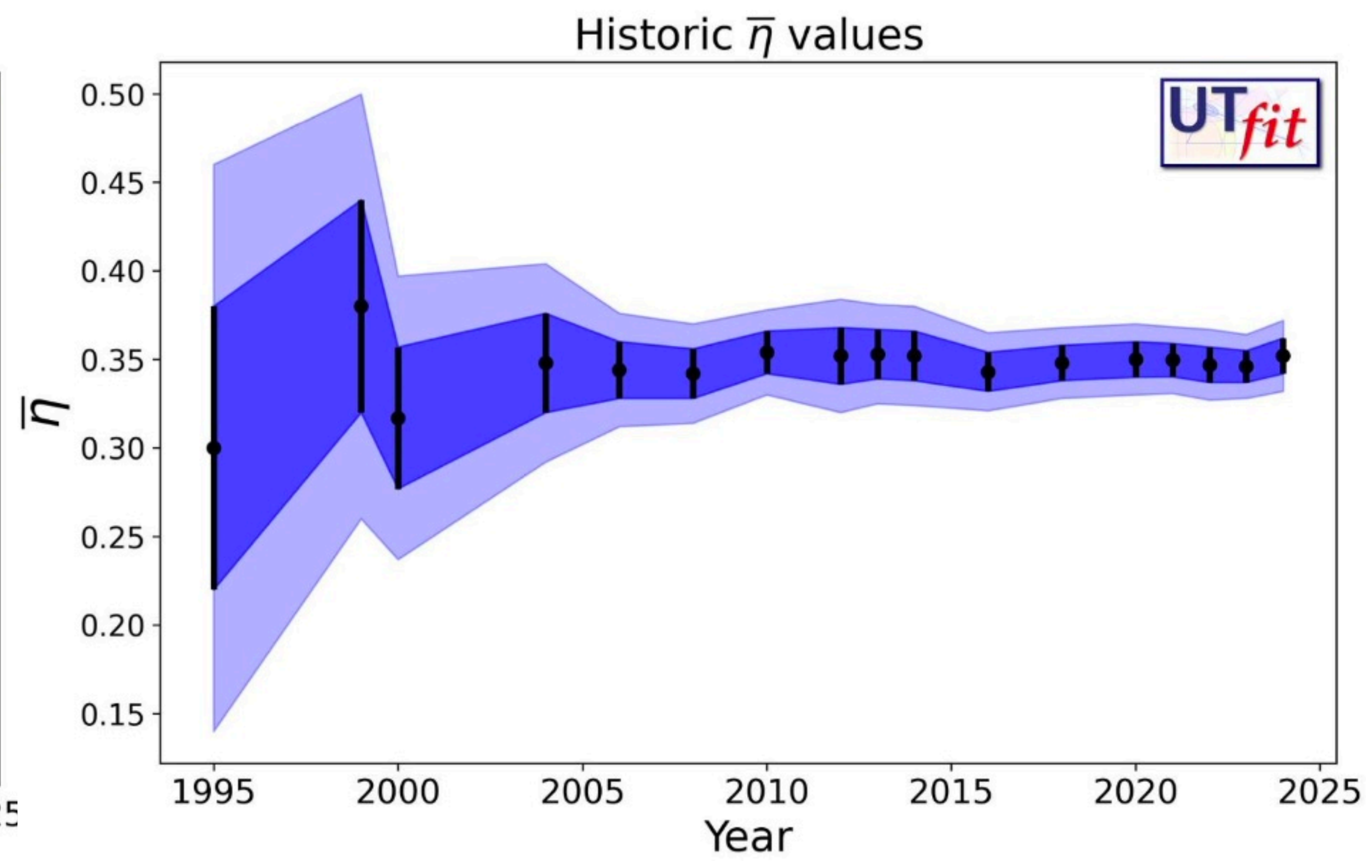



http://www.utfit.org

Importantly: triangles made of tree- and loop-processes coincide to a % level

# CP violation



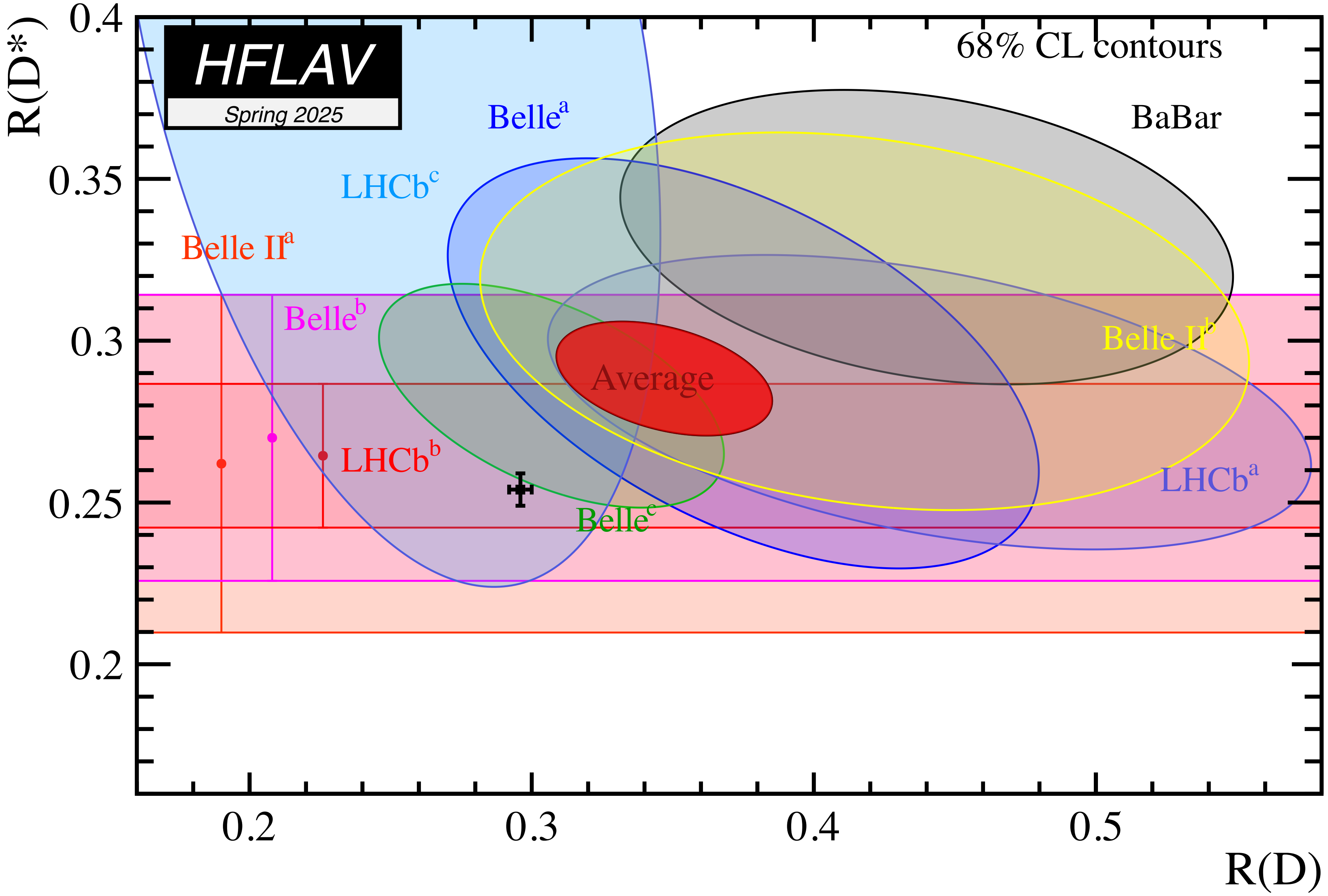




Direct CPV is observed in many places/experiments but it is a small effect [small to trigger BAU]. Is there a BSM CPV phase?

# Path to BSM and/or understanding NP-QCD

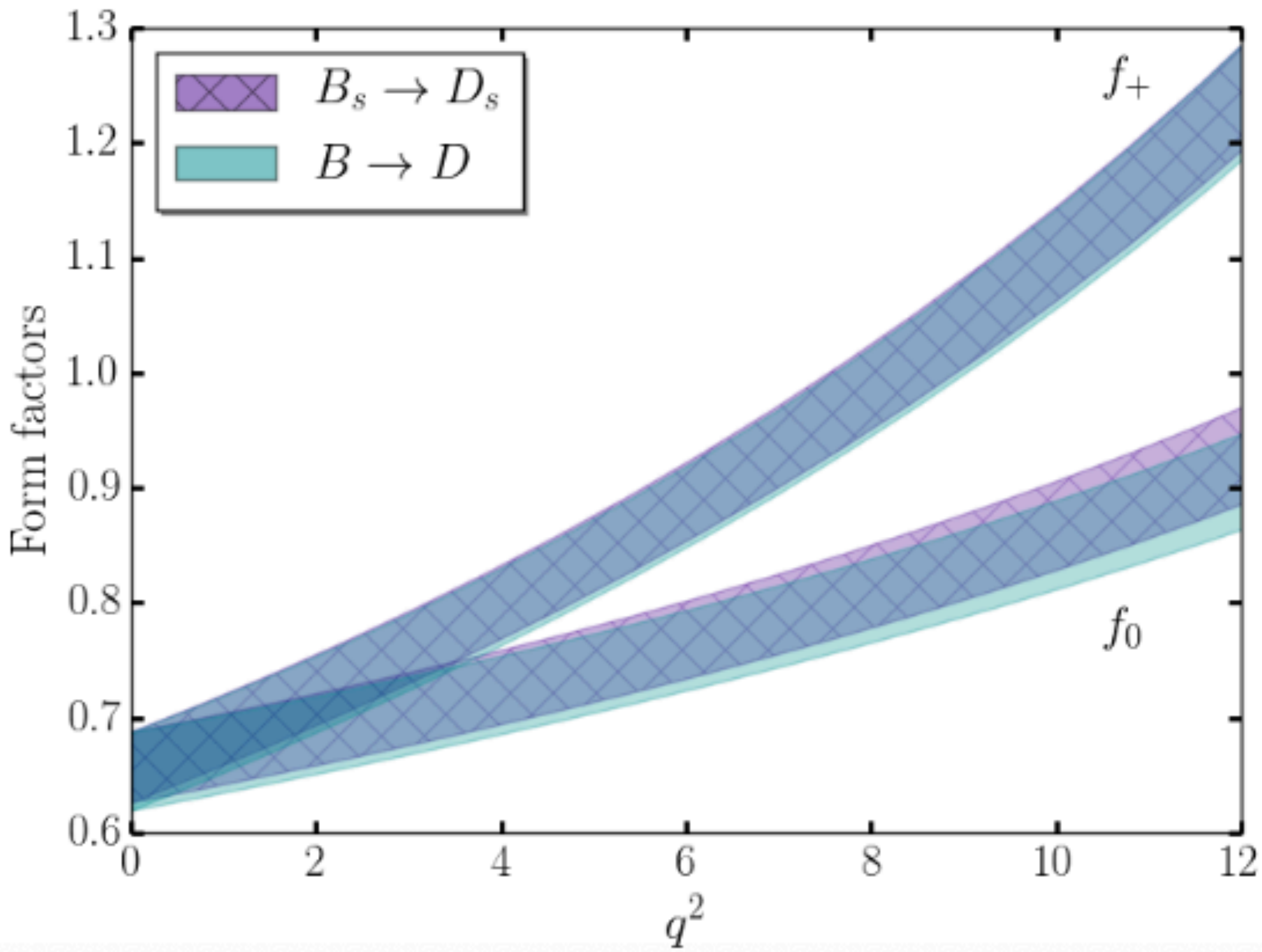
# LFUV

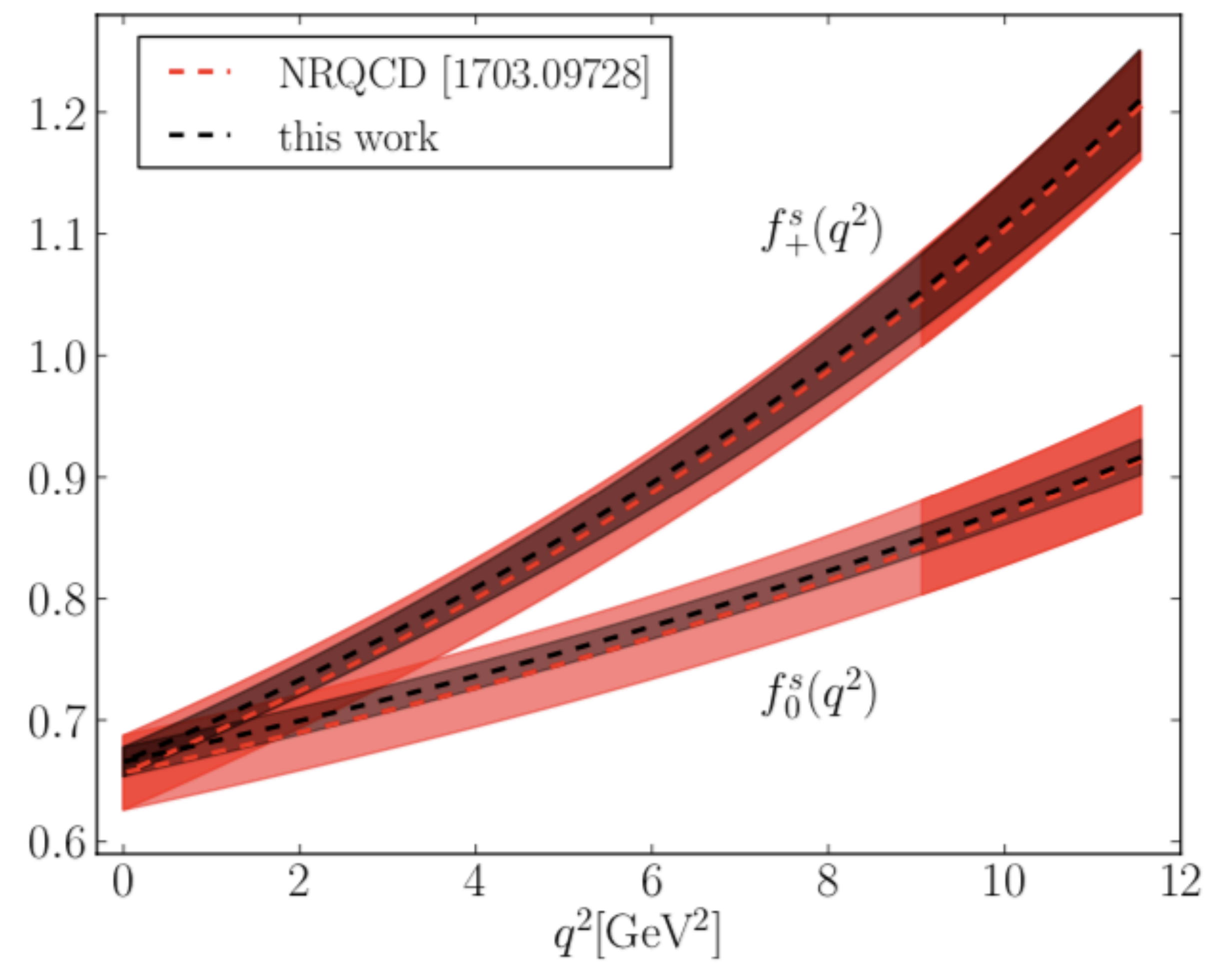
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$




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

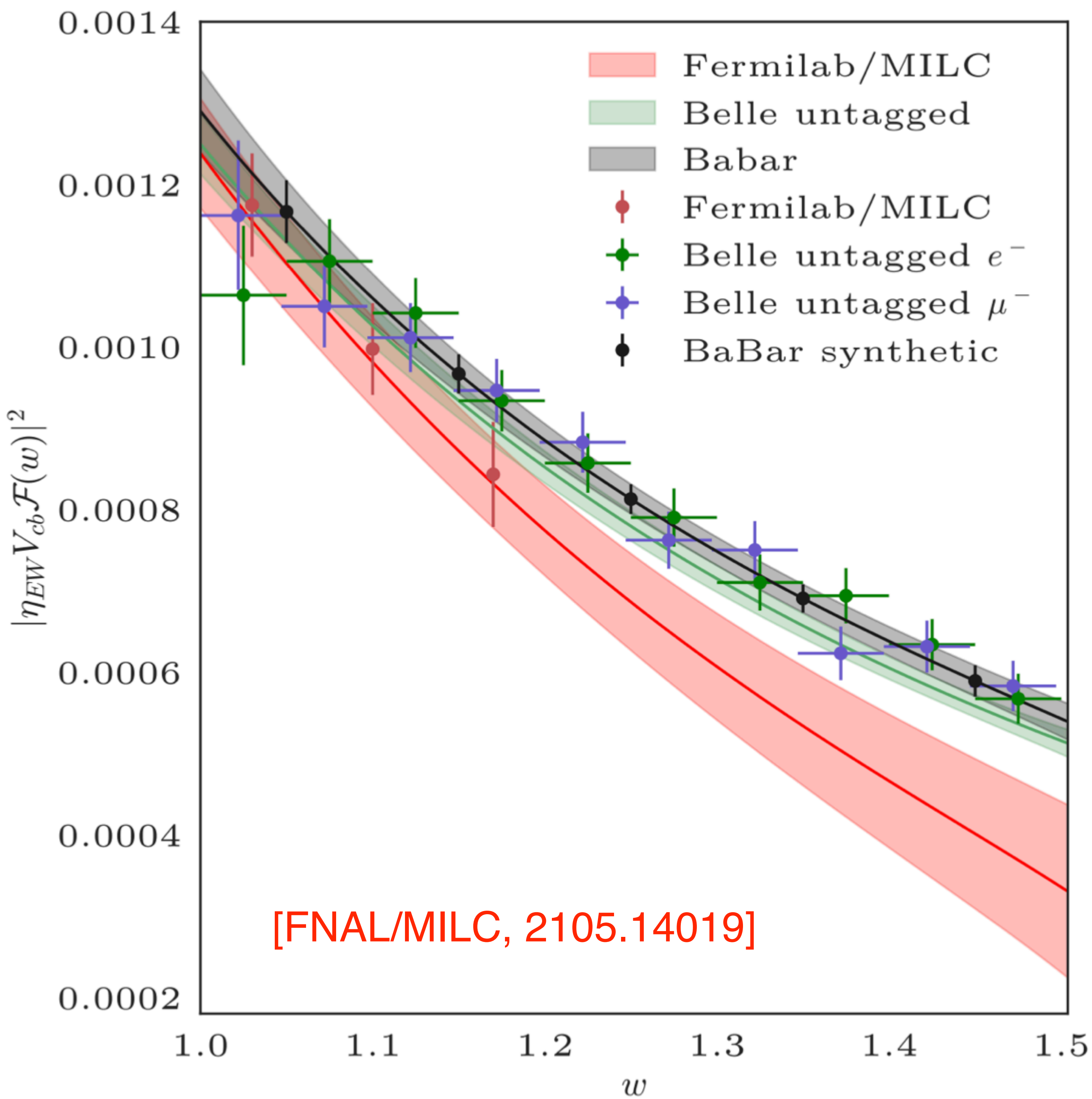
$$\langle D|\bar{c}\gamma_\mu b|B\rangle \propto f_+(q^2), f_0(q^2)$$




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

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



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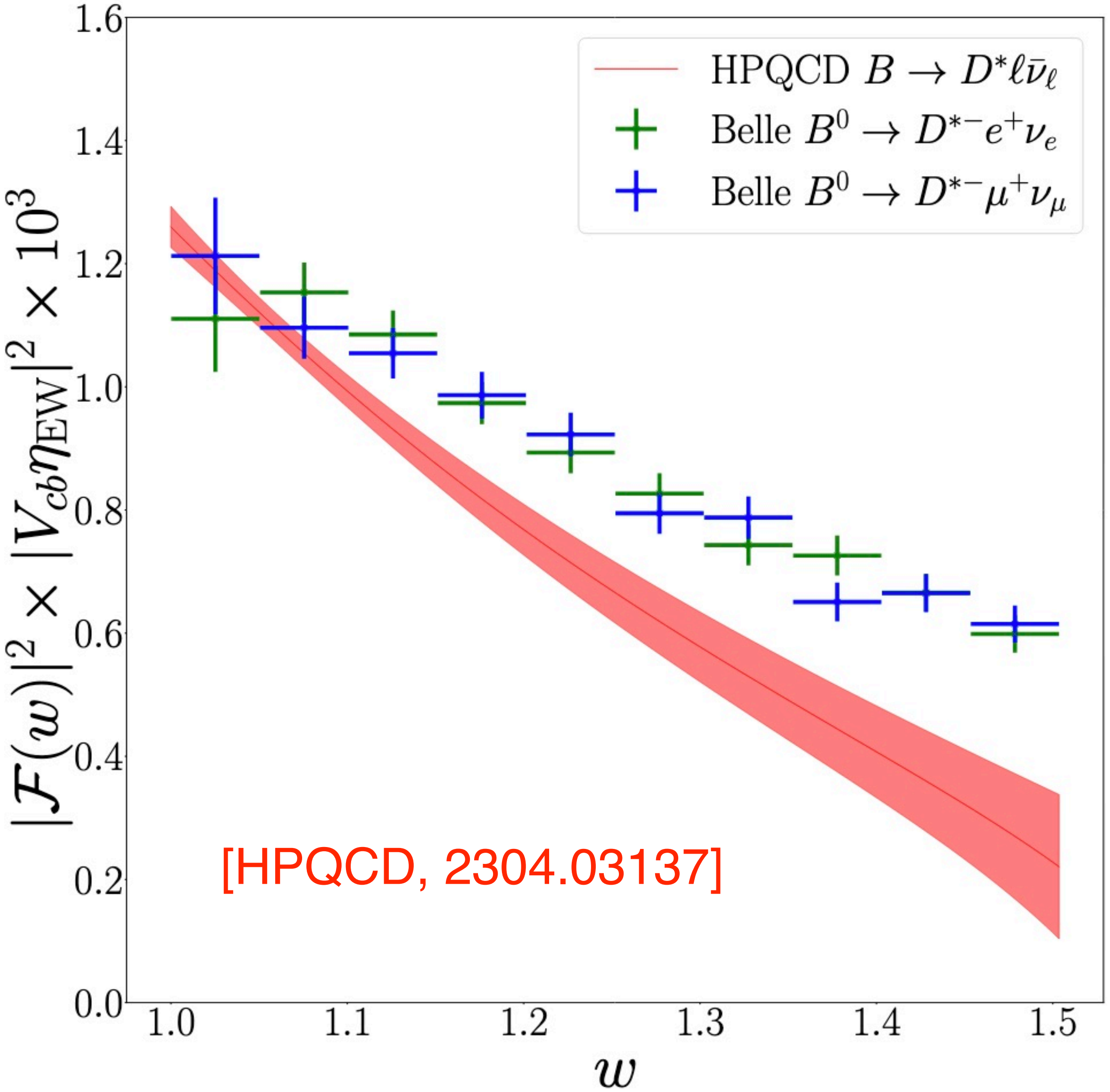
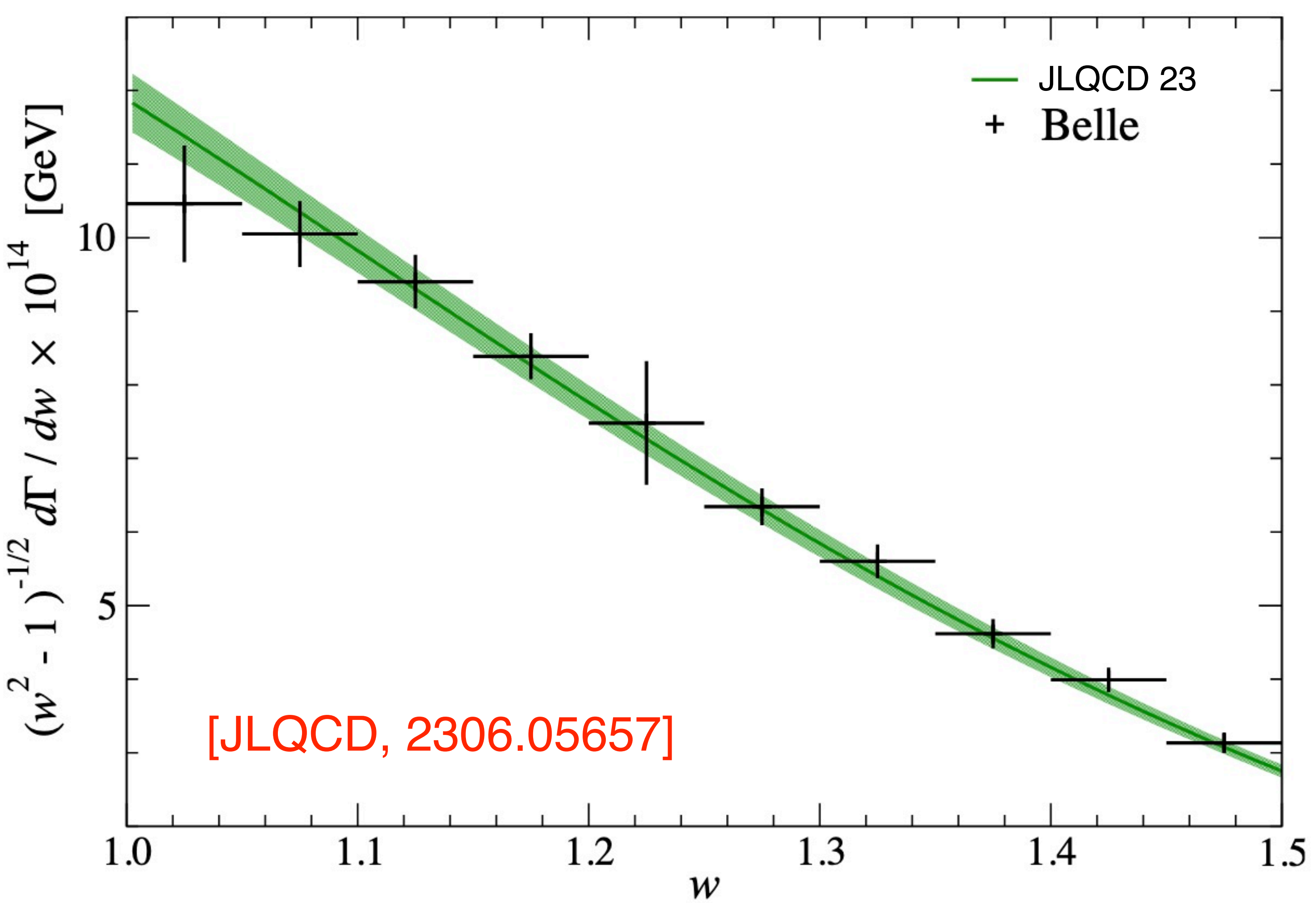


$$\langle D^*|\bar{c}\gamma_\mu(1-\gamma_5)b|B\rangle \propto V(q^2), A_{1,2,0}(q^2) \propto \mathcal{F}(w)\ldots$$

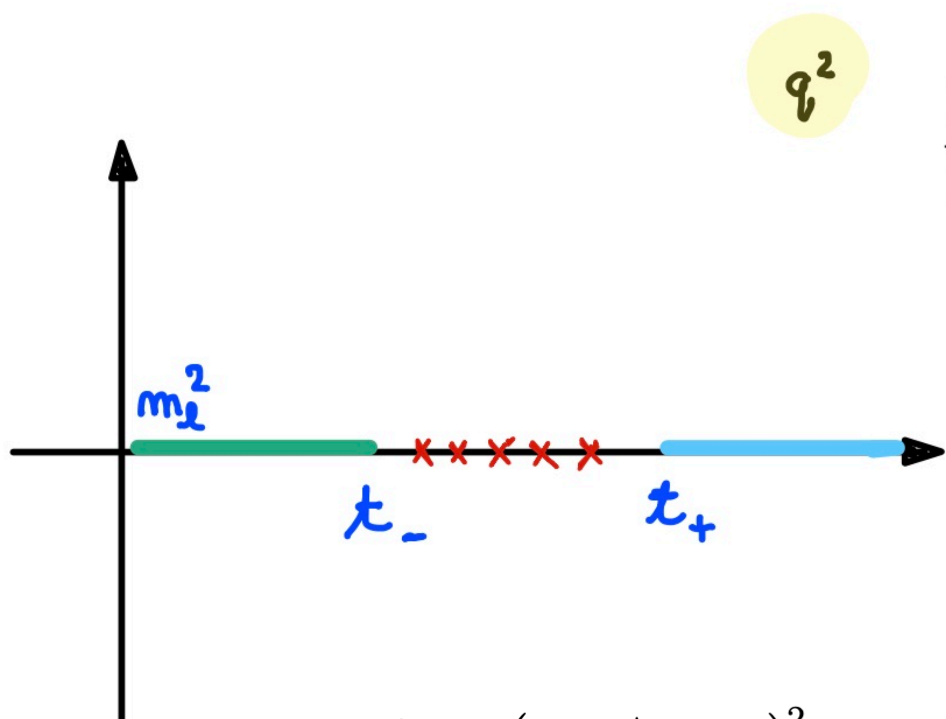
Messy [and slightly boring a] story:

$$q^2 = m_B^2 + m_{D^*}^2 - 2m_B m_{D^*}\, w$$

1. Matrix elements in terms of form factors

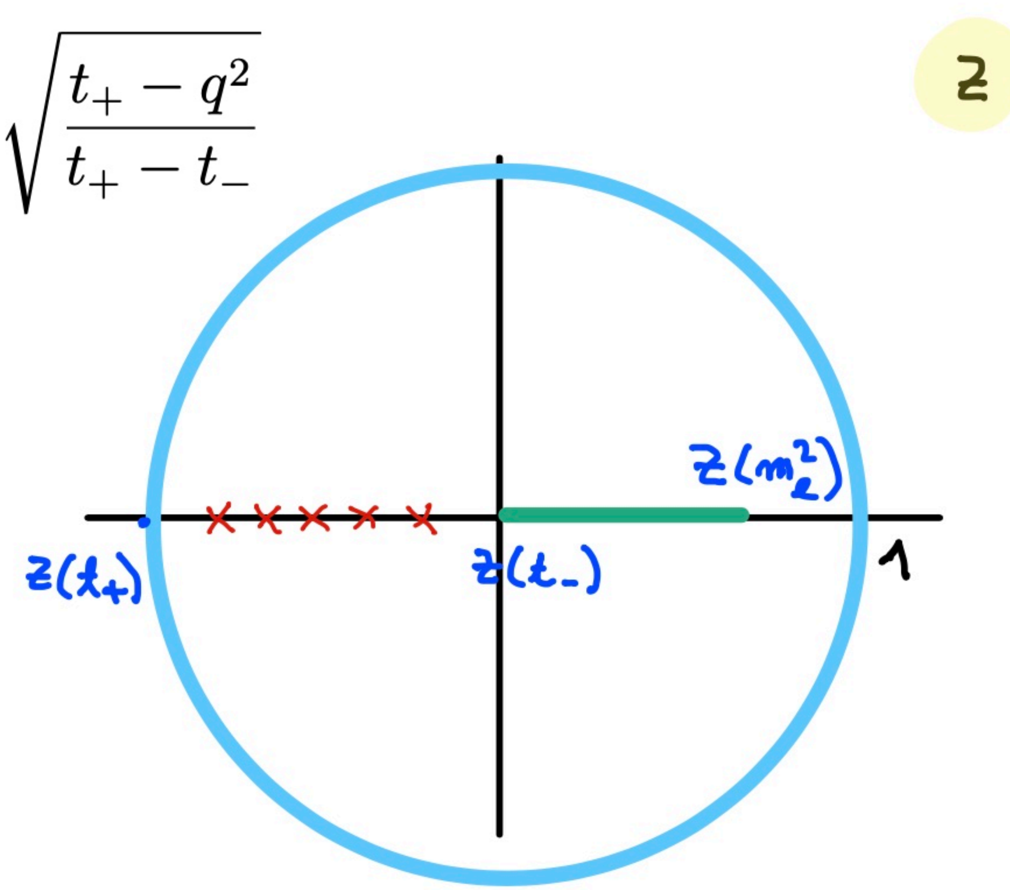
   $V(q^2), A_{1,2,0}(q^2)$ or $f(q^2), g(q^2), F_1(q^2), F_2(q^2)$ or $h_V(w), h_{A1,A2,A3}(w)$

2. Instead of $q^2$ one may use conformal mapping onto the disc $|z(q^2)| \leq 1$, and expand form factors in powers of z, with analiticity/unitarity (dispersion relations) helping to tame the error due to truncation of the series. Good for interpolation of the data, <u>not</u> for extrapolation, cf. 4.




$$t_\pm = (m_B \pm m_{D^*})^2$$

$$\frac{1+z}{1-z} = \sqrt{\frac{t_+ - q^2}{t_+ - t_-}}$$



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

$$\mathcal{F}(q^2) = \frac{1}{P(z(q^2))\phi_{\mathcal{F}}(z(q^2))}\sum_{n=0}^{N} a_n \; z(q^2)^n$$

$$P(z(q^2)) = \prod_{i=1}^{n_{\mathrm{poles}}} \frac{z(q^2)-z(m_i^2)}{1-z(q^2)z(m_i^2)}$$

Fixed by the data
exp or LQCD
[QCD dynamical info!]

4. Need to model nonetheless: P(z) cancel poles (branch cuts not controlled anyway!) but the physical info is `**lost**' (SIC!). To save the day, in heavy-to-light modes explicitly factor out the first pole and then z-expansion applied (BCL).

$$\mathcal{F}(q^2) = \frac{1}{1-q^2/m_{\mathrm{pole}}^2}\sum_{n=0}^{N} \widetilde{a}_n \; z(q^2)^n$$

5. You might have as well expanded in $q^2/t_+$, or model differently in a physically more intuitive/instructive way…

# Remark…

a. This is used abundantly for all the semileptonic decays and going from basis to basis, from $q^2$ to $z$ is not changing anything unless a new NP-QCD info is provided. Extrapolating the parameters of z-expansion is not justified. Lattice results are obtained at large $q^2$'s!

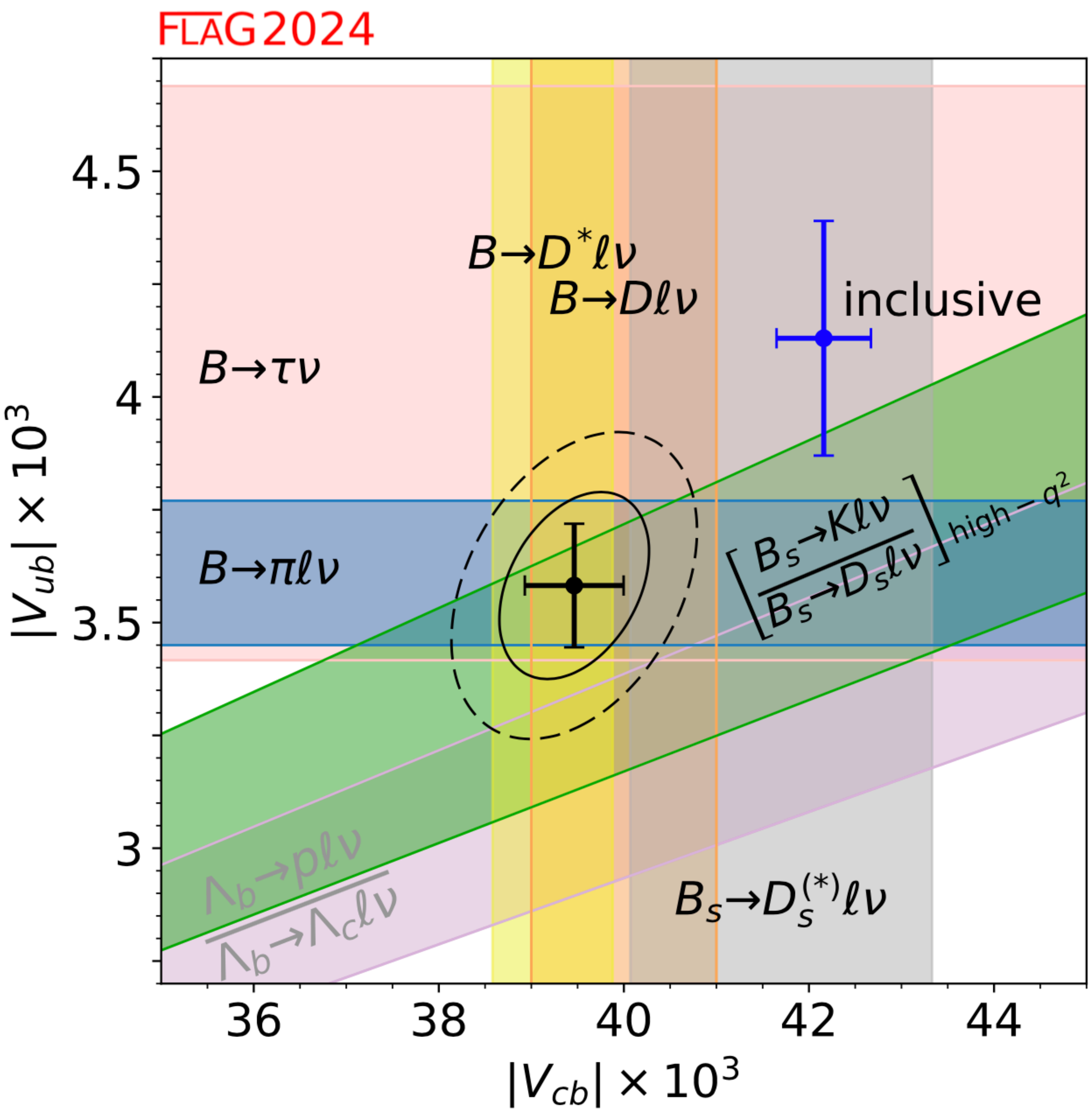
b. <u>Semileptonics New Age</u>: use solely LQCD results with physical quark masses and provide the results in a limited range of $q^2$'s ($z$'s or $w$'s). Compare theory with experiment for the relevant partial branching fractions. [*Otherwise, it all becomes way too political and only >10 years later we dare to open the cupboard… packed with skeletons.*]

c. Use analytic approaches to understand the LC distribution amplitudes, low energy (LE) constants, various LE sum rules, evaluate higher $1/m_{b,c}$ corrections… and perhaps tackle the details of confinement and of SChSB

NB: charm sector can be viewed as a LE QCD laboratory!

# CKM-ology - Small flavor 'anomaly'

- ✘ Inclusive v exclusive $V_{ub}$ and $V_{cb}$

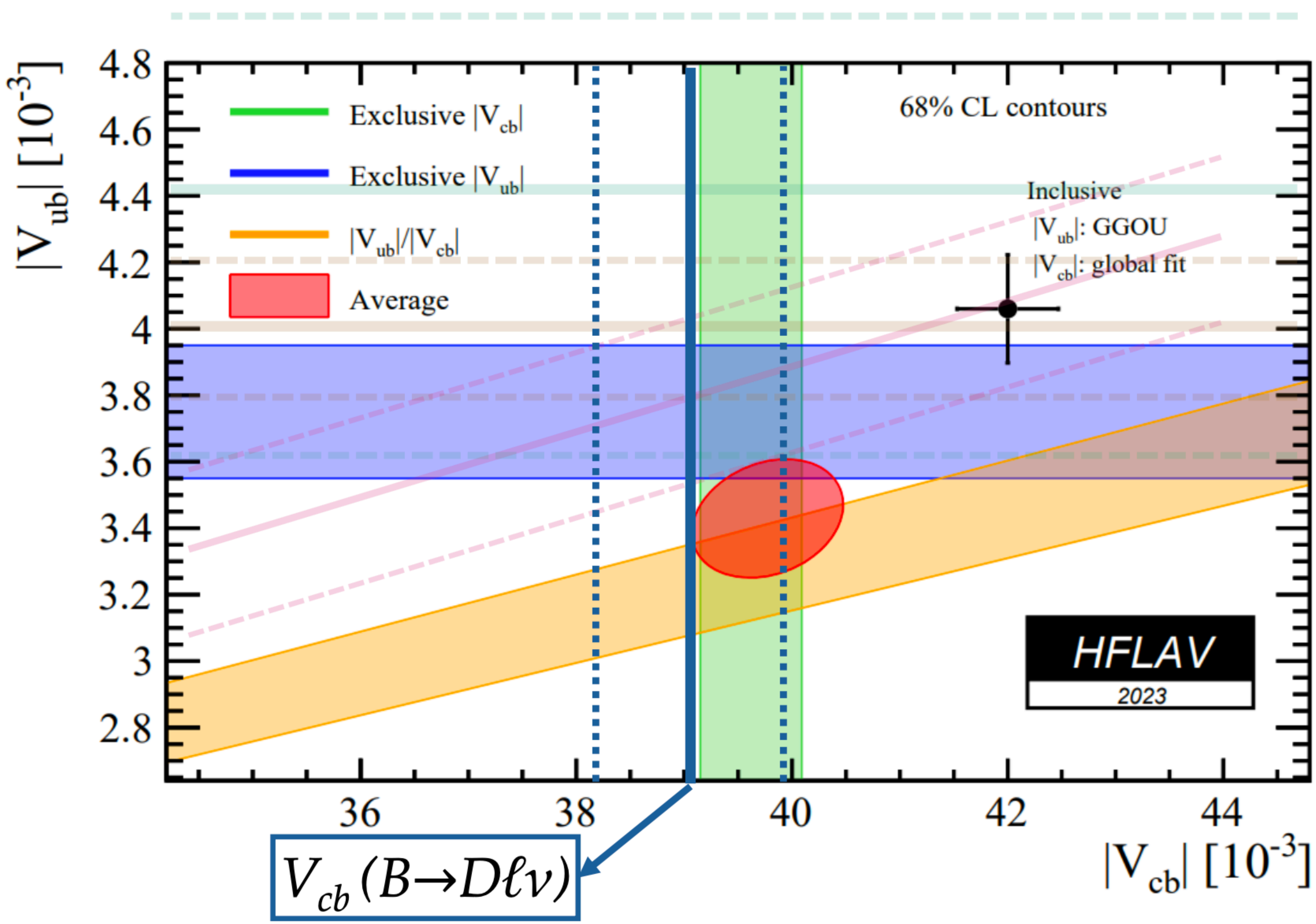



- ✘ Belle II (excl + incl), LHCb (excl)
- ✘ LQCD… situation unclear for exclusives but new developments to tackle inclusives

cf. updates at http://flag.unibe.ch

# CKM-ology - Small flavor 'anomaly'

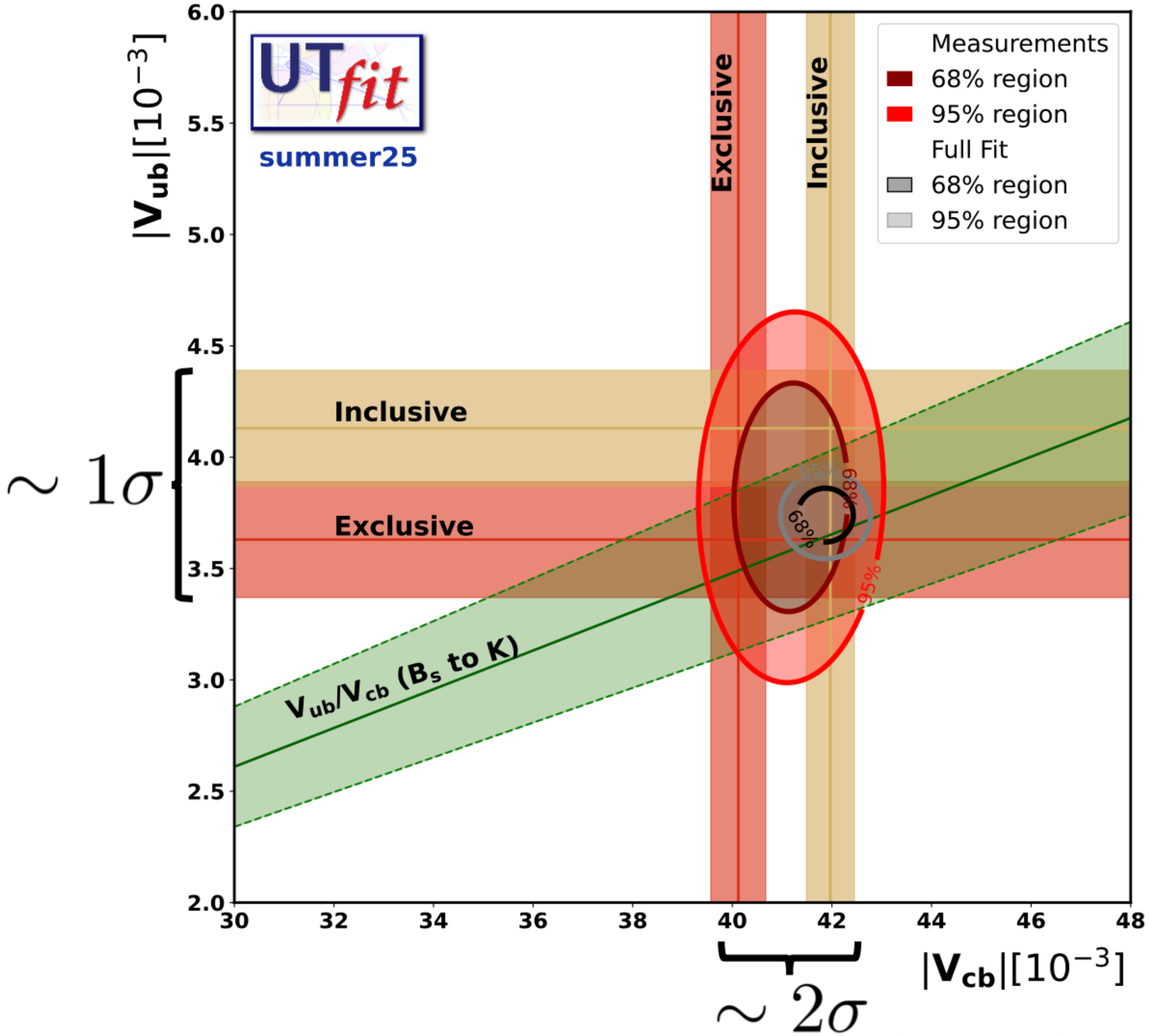
- Last month we learned…




- Belle II @EPS-HEP 2025: discrepancy is still there but picture is blurred

# CKM-ology - Small flavor 'anomaly'

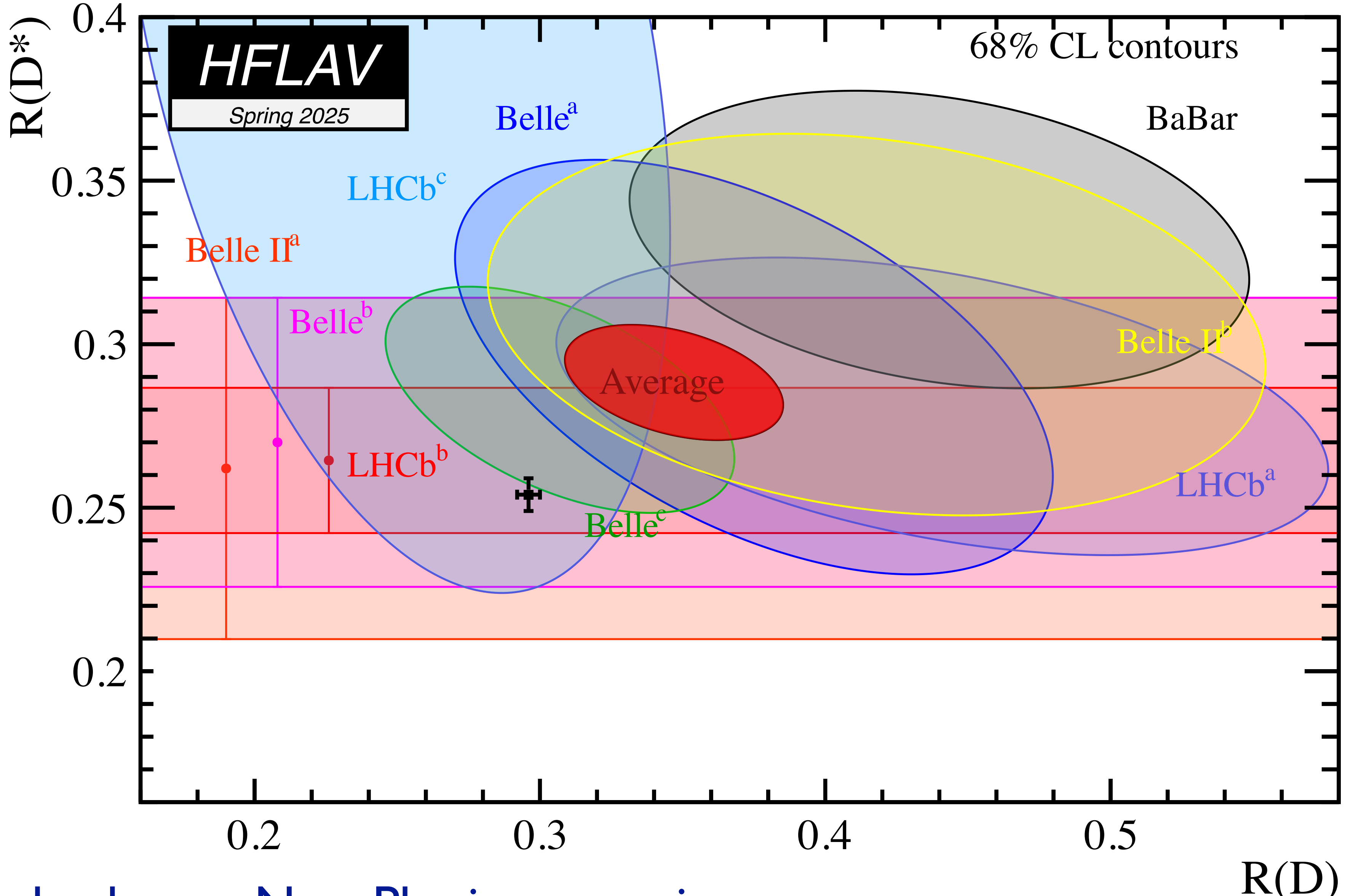
- ✘ Last month we also learned…




- ✘ UTfit @EPS-HEP 2025

Do we really understand Vub? Less symmetries, huge phase space…

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



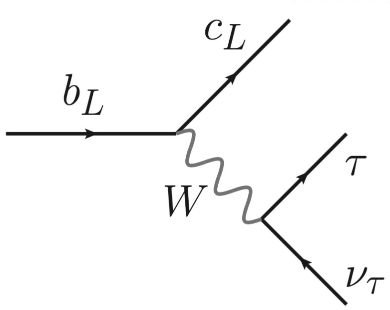

Use $R_D$ ($R_{D^*}$) to check on a New Physics scenario.

Before the death of $R_K$ ($R_{K^*}$)-anomaly/discrepancy, leptoquark scenarios were the only ones capable to accommodate both anomalies [$R_K$ ($R_{K^*}$) < 1, and $R_D$ ($R_{D^*}$)$^{\text{exp}}$ > $R_D$ ($R_{D^*}$)$^{\text{SM}}$]. Now it is all reset, even though we learned a lot in the process…

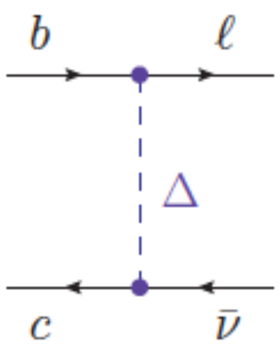
# Scalar Leptoquarks in $R_{D^{(*)}}$

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

Previously

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

$R_2$ =(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)

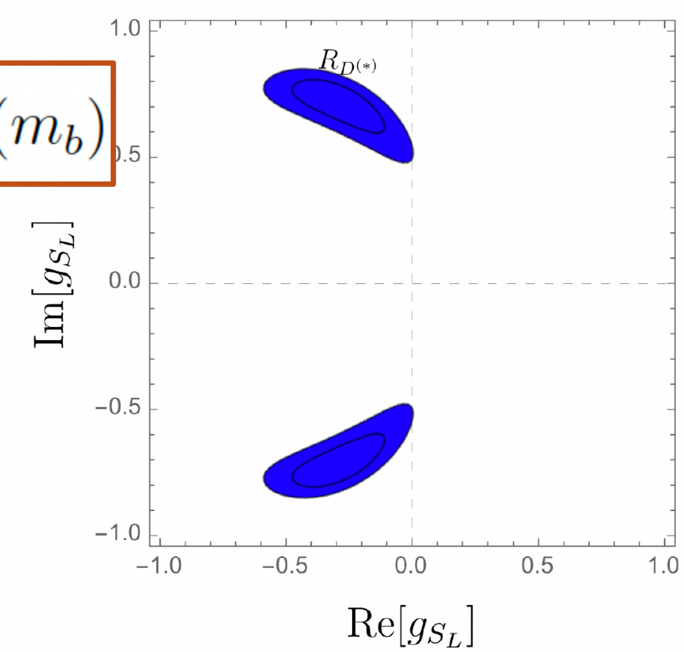
Minimal model: couplings to the third generation leptons only

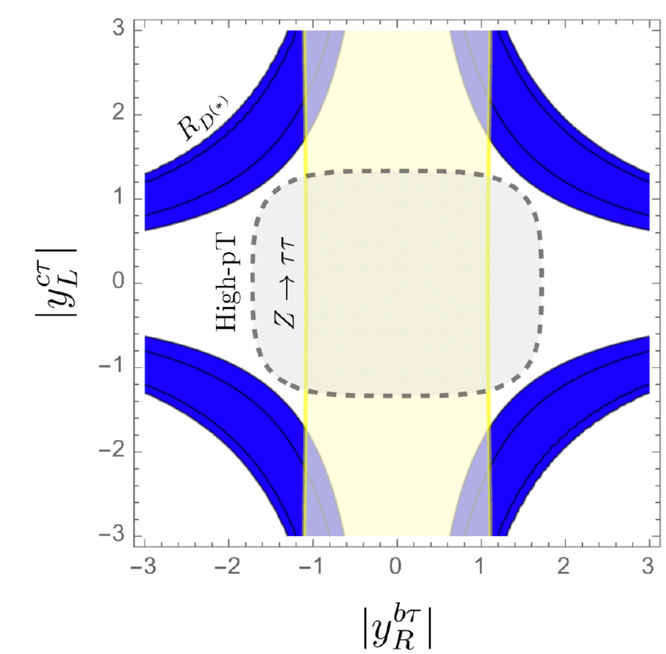
$$\mathcal{L}_{R_2} = y_R^{b\tau} V_{jb}^* (\overline{u}_j P_R \tau) R_2^{5/3} + y_R^{b\tau} (\overline{b} P_R \tau) R_2^{2/3} - y_L^{c\tau} (\overline{c} P_L \tau) R_2^{5/3} + y_L^{c\tau} (\overline{c} P_L \nu_\tau) R_2^{2/3} + \text{h.c.}$$

running $m_{R_2} \to m_b$

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

$$g_{S_L}(m_{R_2}) = 4 g_T(m_{R_2}) \qquad \boxed{g_{S_L}(m_b) = 8.8 \times g_T(m_b)}$$




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

# $S_1 = (3,1,1/3)$

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

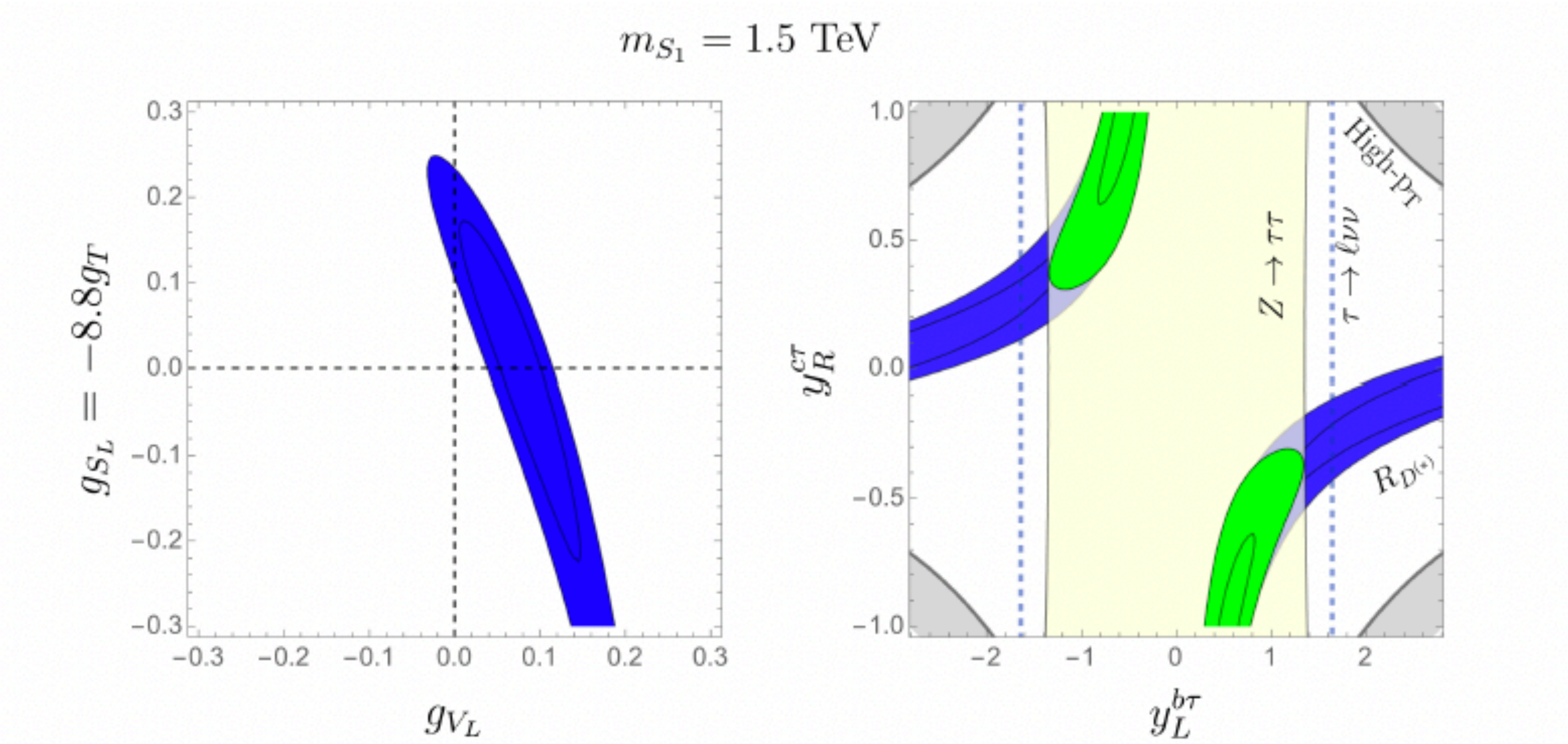
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_R^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},$$

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

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

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

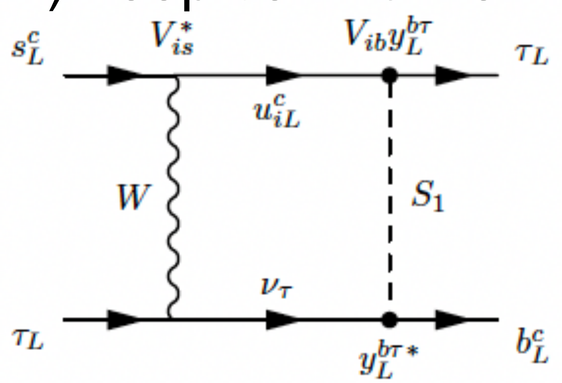
cf. 2404.16772



# Consequences

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

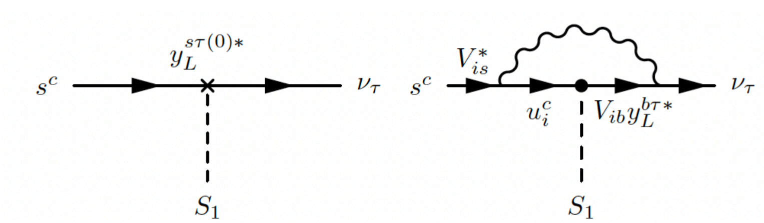
2) Loop contribution to b $\rightarrow$ s$\tau\tau$ or b $\rightarrow$ s$\nu_\tau\nu_\tau$




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

3) b $\rightarrow$ s$\nu_\tau\nu_\tau$

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



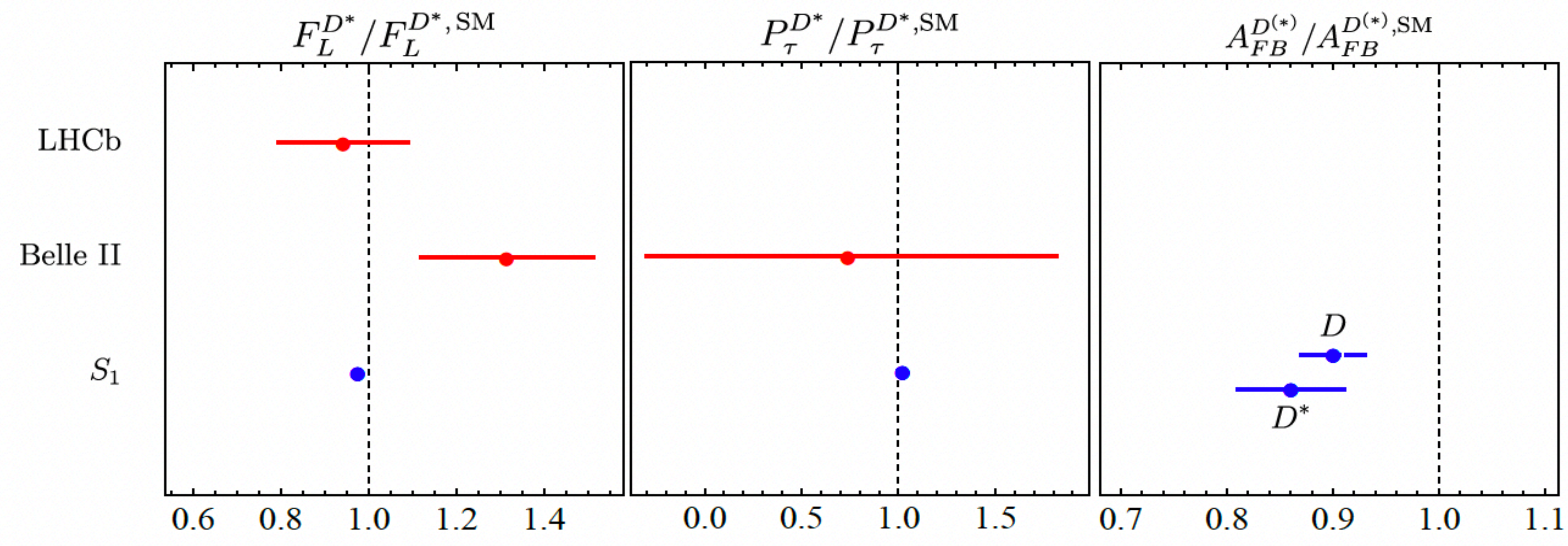

(imaginary part comes from the fermions being on the mass shell in the loops)

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

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

only 3 % enhancement over the SM

5) for B →D(*) angular observables

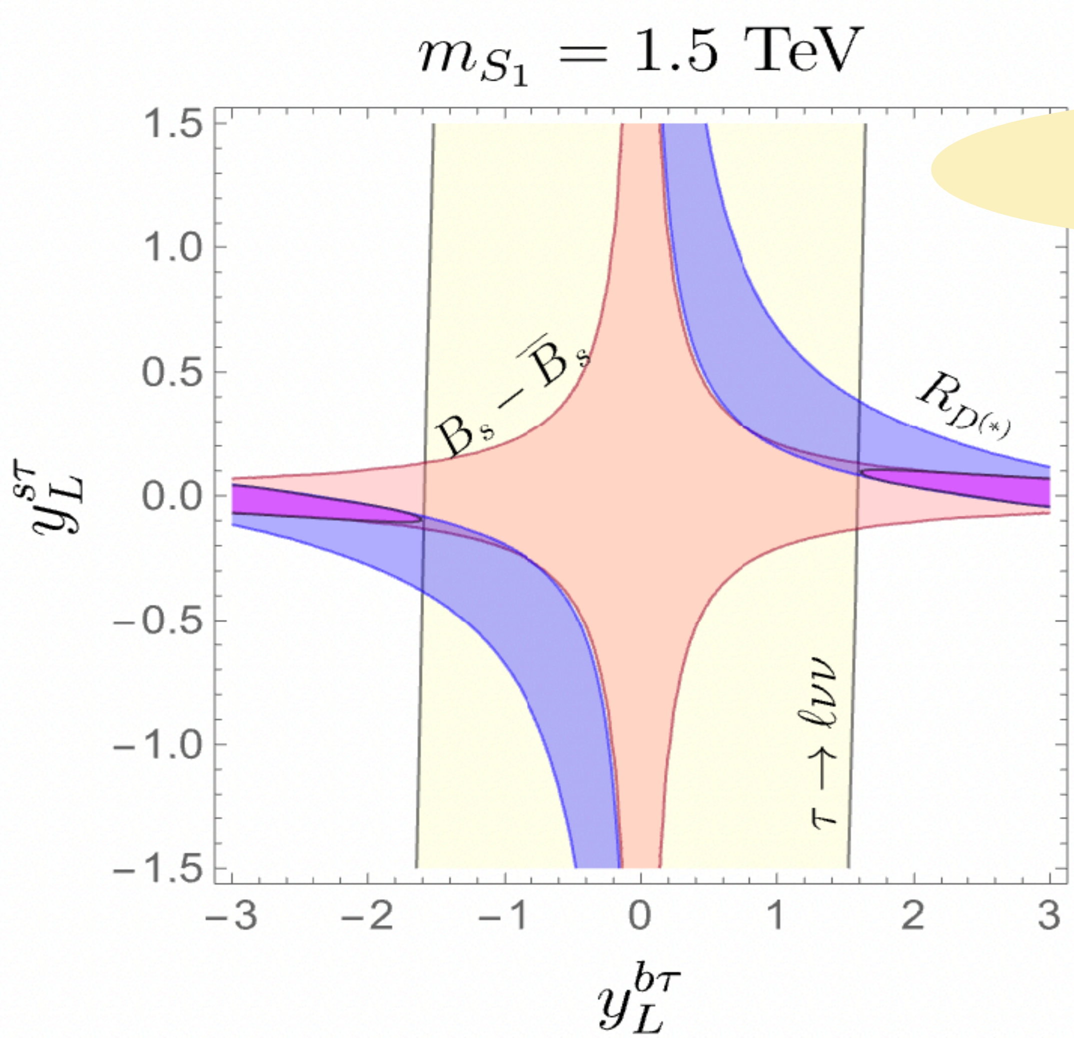



S$_1$ with *V-A* couplings only

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

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

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




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

# *En vogue*: A heavy neutral lepton $N_R$ solution

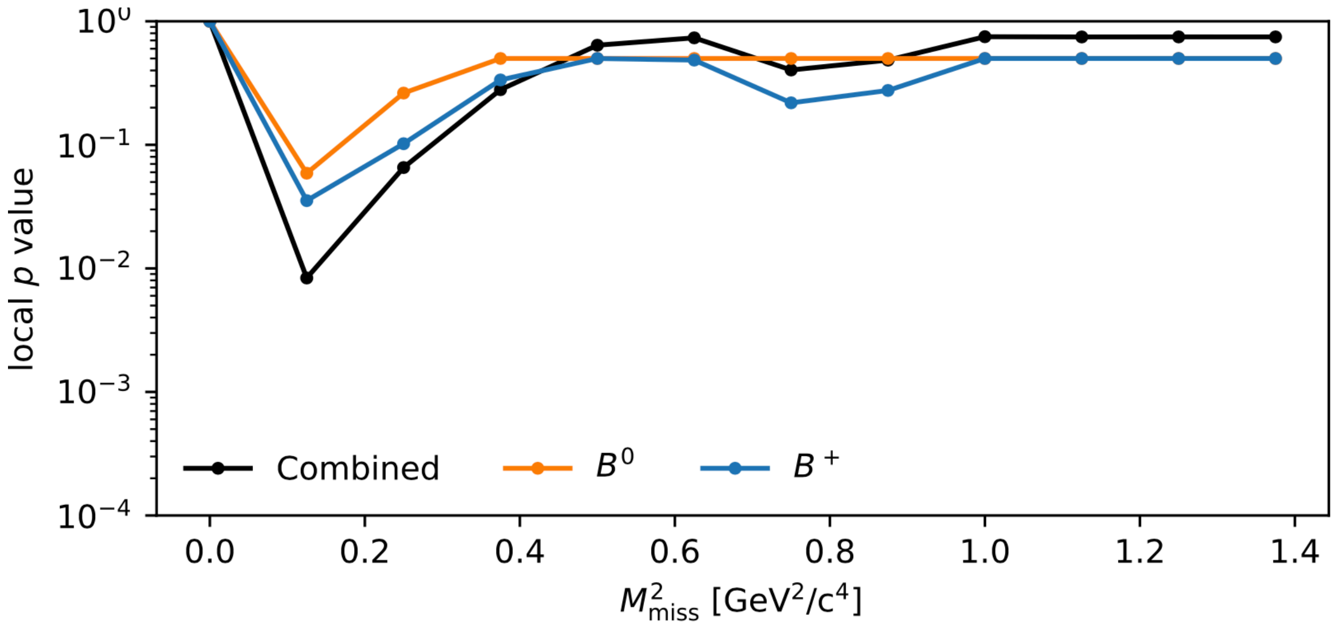
$$\mathcal{H}_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[ (\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_{\ell,L}) + \underline{g^N_{V_R}} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_R \gamma^\mu N_R) + \underline{g^N_{S_L}} (\bar{c}_R b_L)(\bar{\ell}_L N_R)$$

$$+ \underline{g^N_{S_R}} (\bar{c}_L b_R)(\bar{\ell}_L N_R) + \underline{g^N_T} (\bar{c}_L \sigma_{\mu\nu} b_R)(\bar{\ell}_L \sigma^{\mu\nu} N_R) + \mathrm{h.c.} \Big]$$

Using the full set of observables obtained from the angular analyses of both $B \to D^* \mu N$ and $B \to D^* e N$ by Belle-II:

➡ Hint of $m_N \simeq 350$ MeV

➡ Not stat. significant though, i.e. no preference for any heavy $N_R$ model over SM




cf. 2410.11945

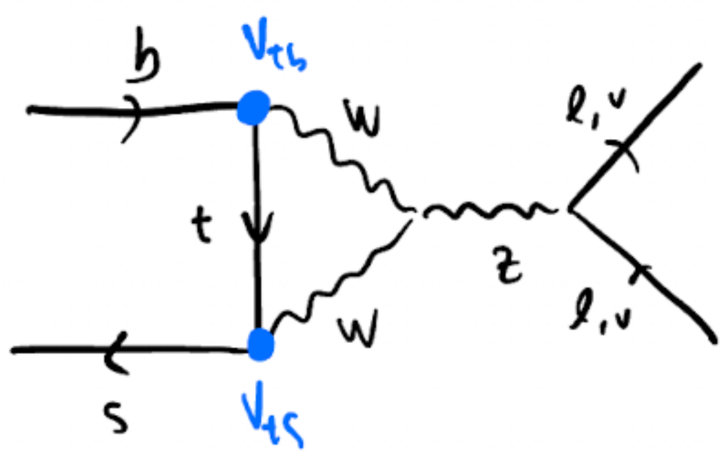
# Search for physics BSM

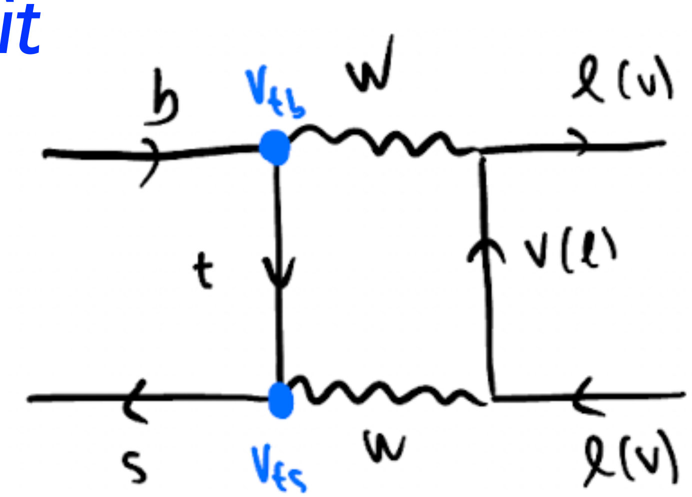
Decay rate = Kinematics CKM coupling Wilson coeff.s Hadronic quantities

***Experiments*** 

***From UTA***
*CKMfitter, UTfit*

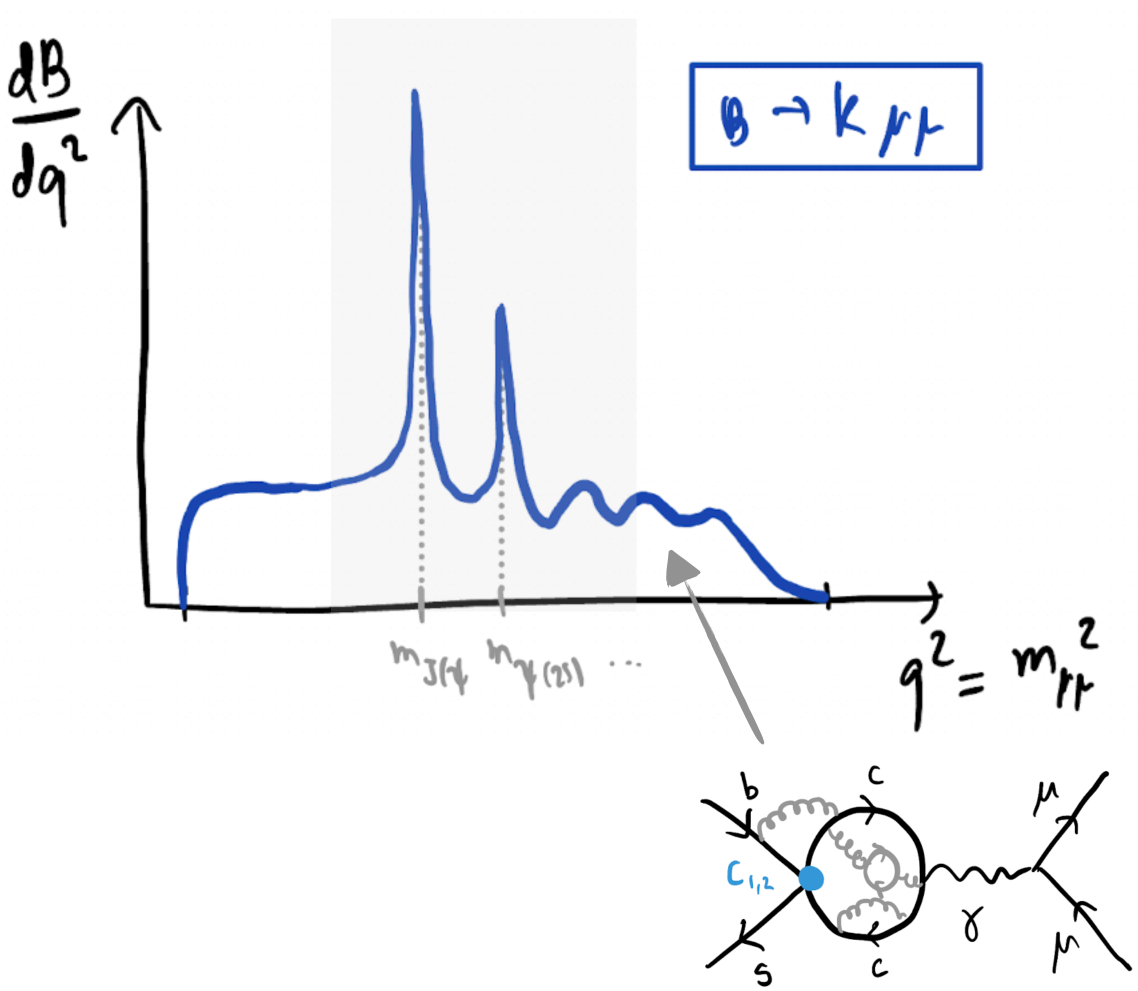
***NP QCD***



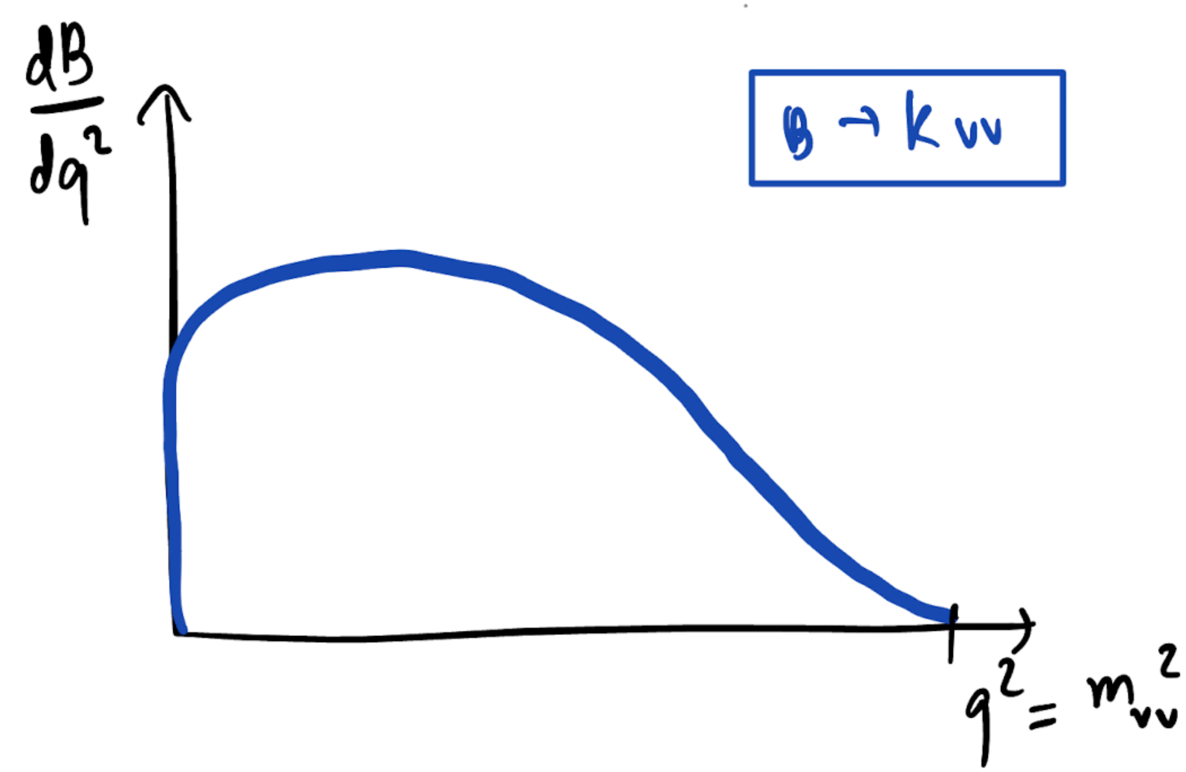
- $B \to K^{(*)}\ell\ell$ :

- 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 $\tau$-leptons.**



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

- **Effective Hamiltonian** within the SM:

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

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

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

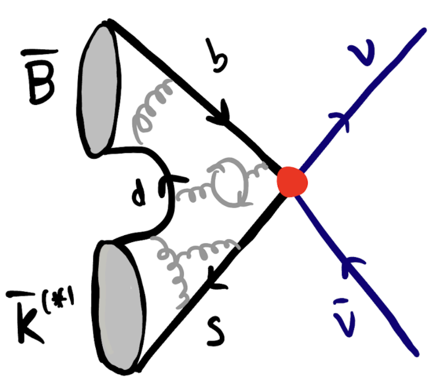
$$C_L^{\rm SM} = -X_t/\sin^2\theta_W$$
$$= -6.32(7)$$

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.)?

# Belle-II result

[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

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

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

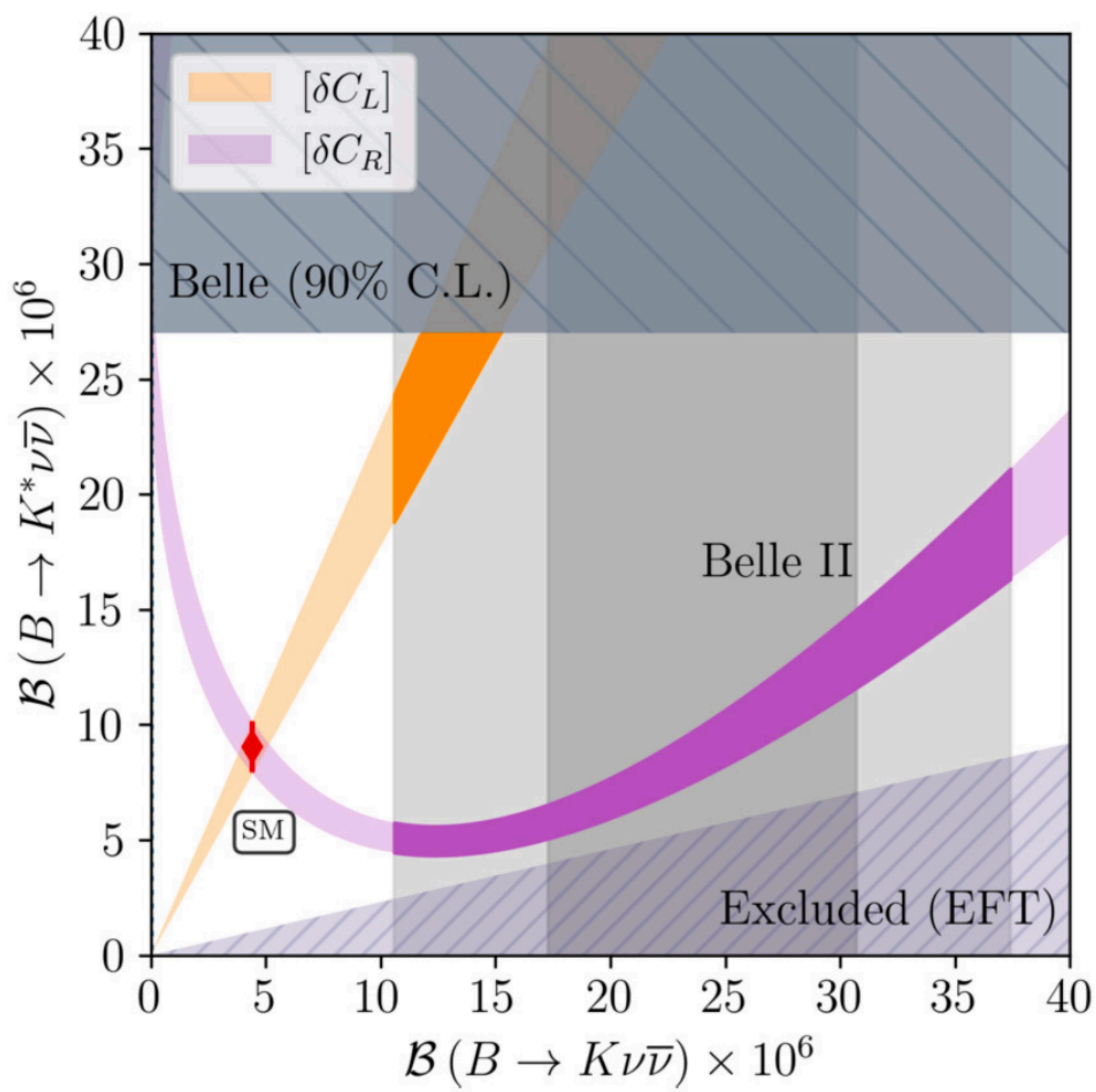
Use EFT to see how we can accommodate this result.

# 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 $b \to s\ell\ell$)

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

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

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

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

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

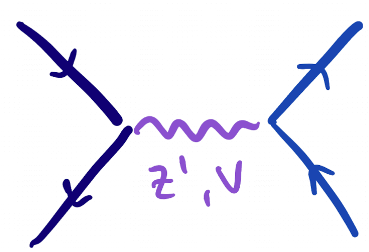
$$\begin{aligned}[\mathcal{O}_{ld}]_{ijkl} &= (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l) \\ &= (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl}) + (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl})\end{aligned}$$

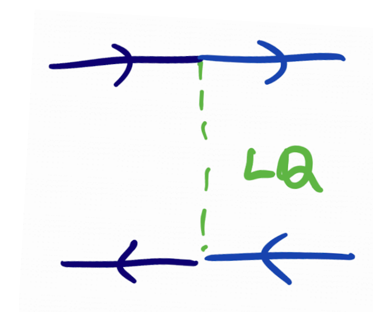
- Correlations for concrete mediators:

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

$\ldots$

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




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

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

- $\psi^4$ 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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$$\begin{aligned}[\mathcal{O}_{lq}^{(3)}]_{ijkl} &= (\overline{L}_i\gamma^\mu \tau^I L_j)(\overline{Q}_k\gamma_\mu \tau^I Q_l)\\ &= (\overline{\ell}_{Li}\gamma^\mu \ell_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) - (\overline{\nu}_{Li}\gamma^\mu \nu_{Lj})(\overline{d}_{Lk}\gamma_\mu d_{Ll}) + \ldots\end{aligned}$$

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

## Which flavor?

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

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

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

$\Rightarrow$ **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 ways to go is through neutrinos, cf. 2404.17440, relating to $K \to \pi\nu\nu$ 2410.21444, call for ALPs 2504.00383, other light mediator 2505.11499, flavour violation 2404.06533, other new particles 2404.06533, and many more.

Figuring out a scenario that could simultaneously accommodate $R_{D^{(*)}}$ and $R_K^{\nu\nu}$?

- 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.

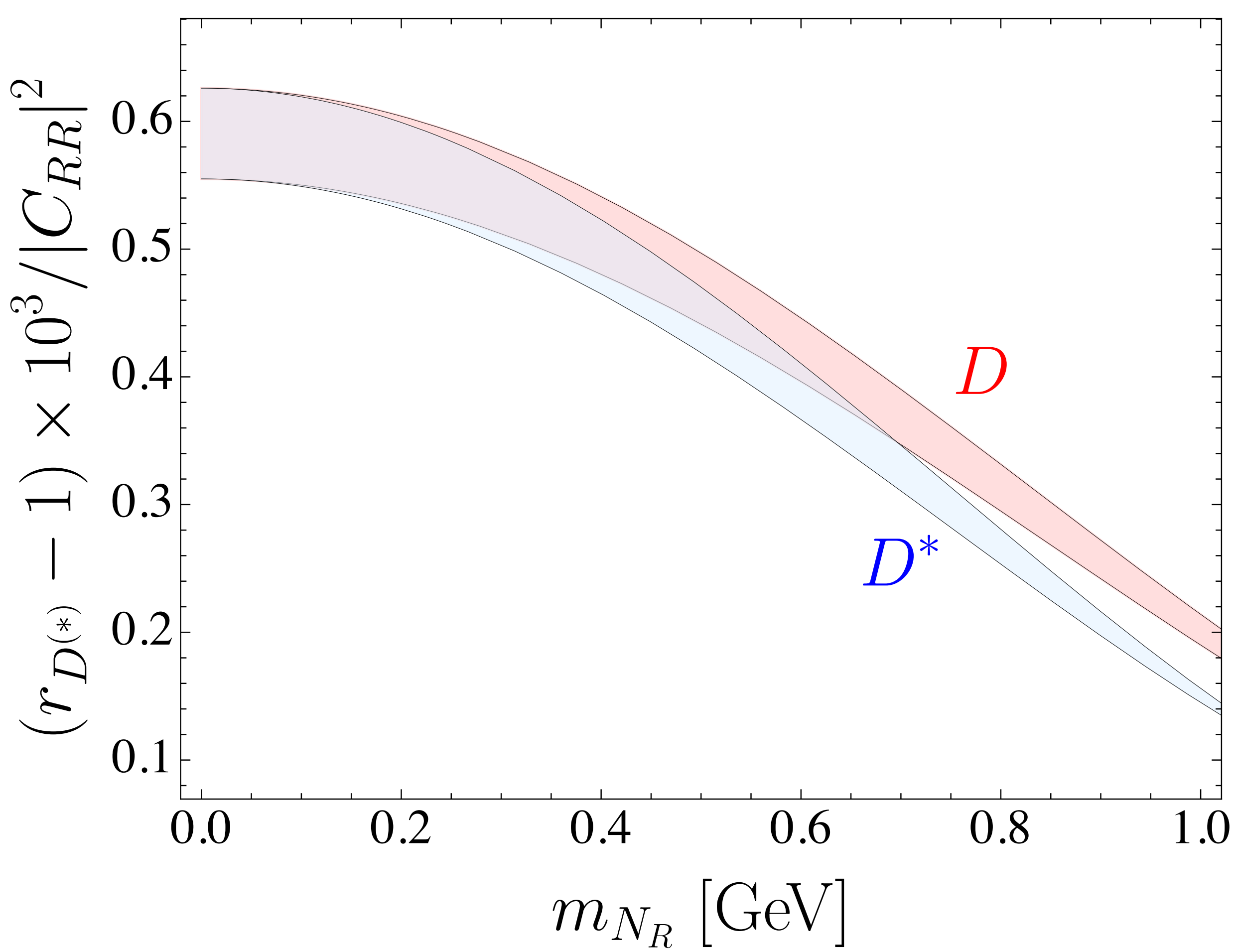
$$\mathcal{B}(B \to D^{(*)}\tau\text{‘inv’}) = \mathcal{B}(B \to D^{(*)}\tau\nu)^{\text{SM}} + \mathcal{B}(B \to D^{(*)}\tau N_R)$$
$$\mathcal{B}(B \to K^{(*)}\text{‘inv’}) = \mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\text{SM}} + \mathcal{B}(B \to K^{(*)}N_R N_R)$$

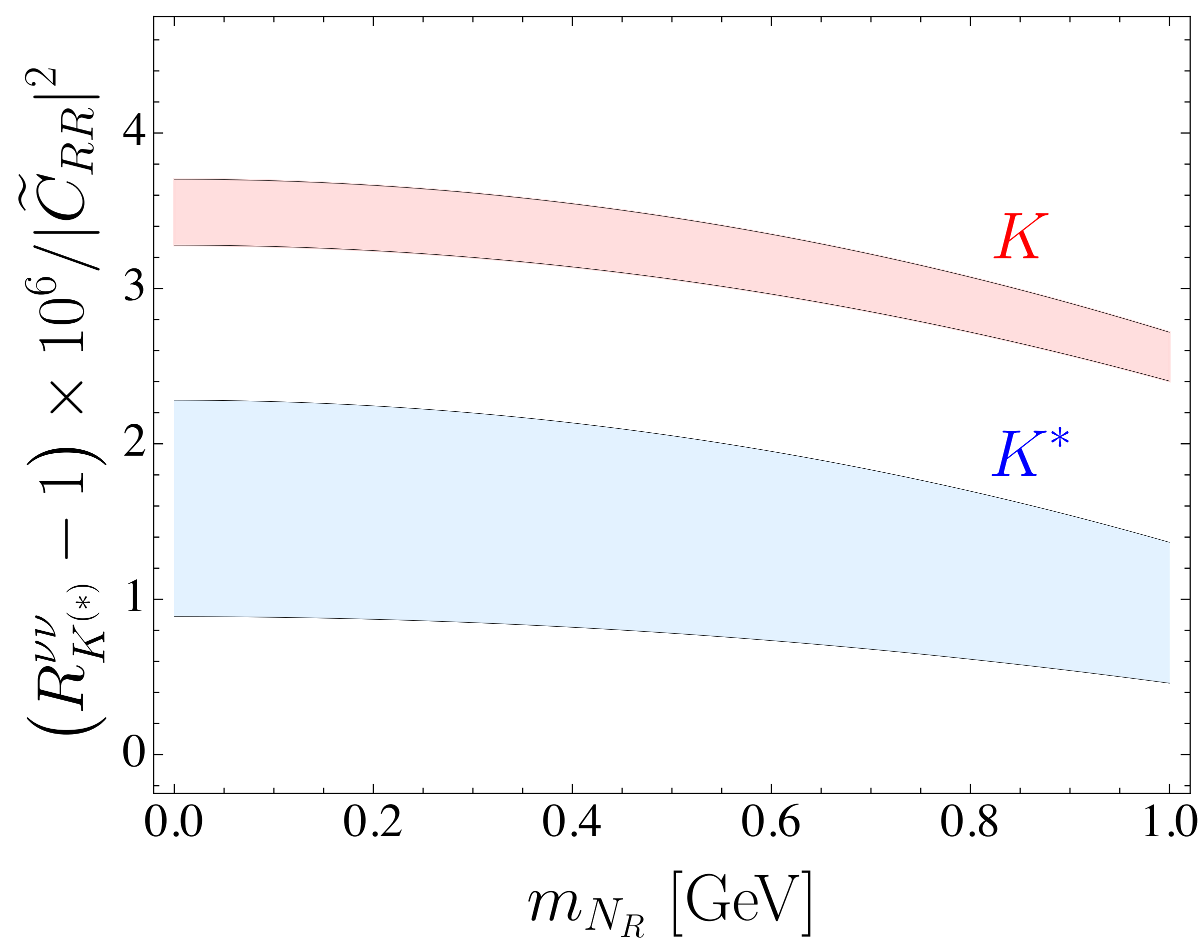
cf. 2410.23257

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

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

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



- Scenario for both...

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

- 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) |
| $A_{\text{fb}}^{D}$ | 0.360(0) | 0.360(0) | 0.341(4) | 0.329(4) |
| $A_{\text{fb}}^{D^*}$ | −0.06(1) | −0.06(1) | −0.06(1) | −0.06(1) |
| $P_\tau^{D}$ | 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 | $5.3 \pm 1.5$ | $5.2 \pm 1.4$ | $4.9 \pm 1.3$ |
| $F_L^{K^*}$ | 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 | $5.3 \pm 1.4$ | $5.4 \pm 1.4$ | $5.5 \pm 1.4$ |

# Concrete Model ($S_1$)

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

- Scalar LQ

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

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

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

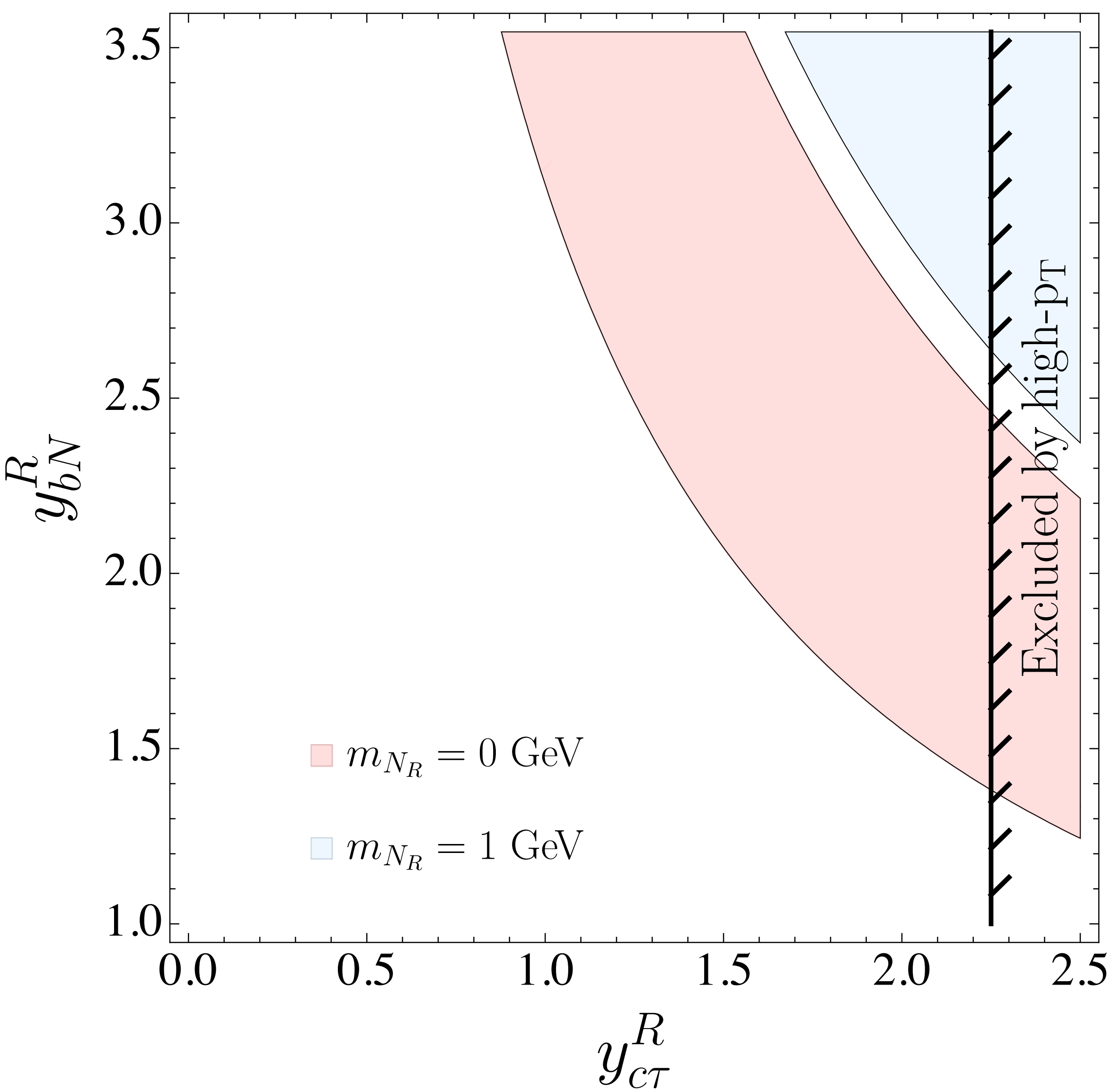
cf. 2410.23257

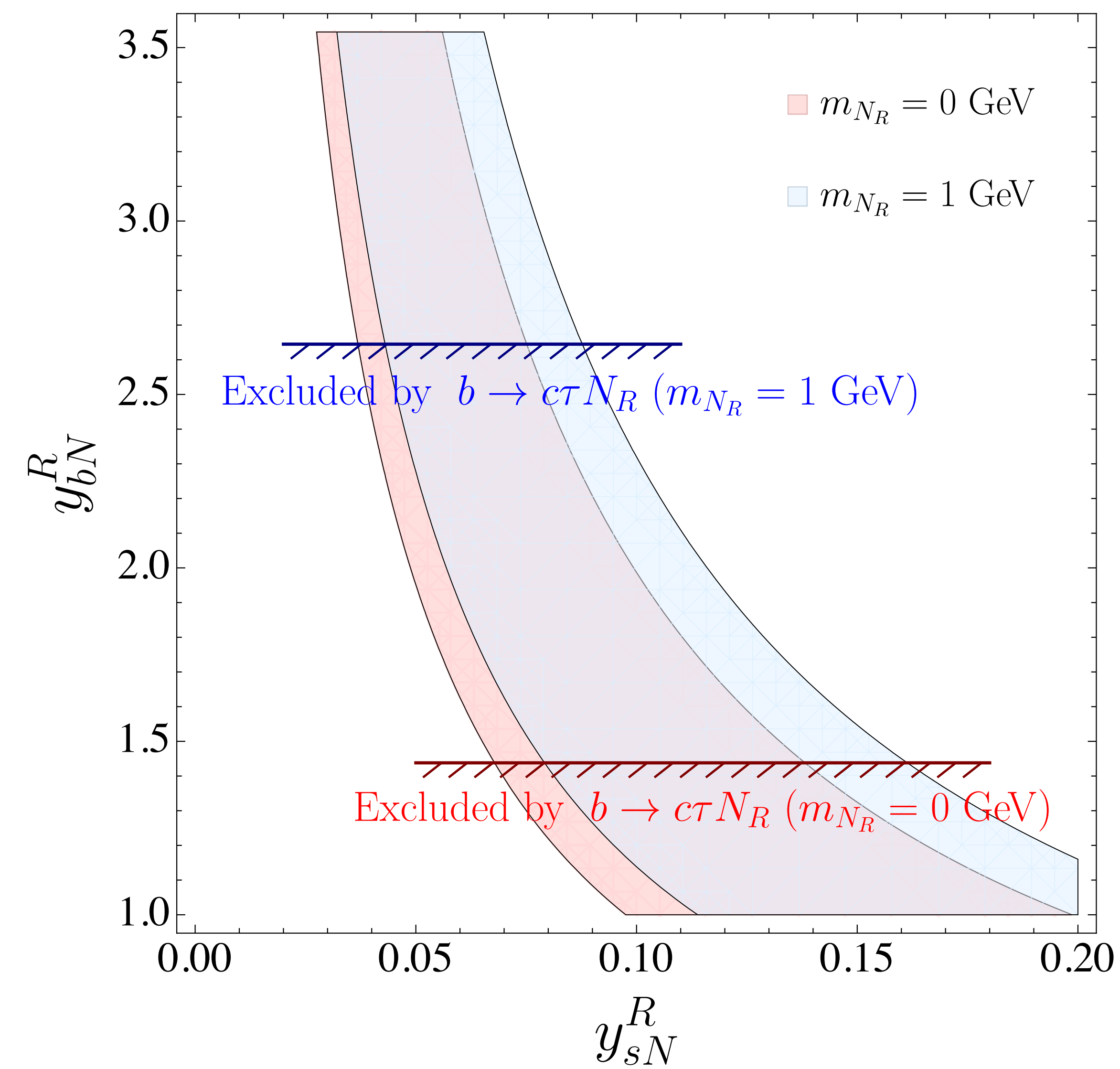
# Concrete Model ($S_1$)

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

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

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



# Concrete Model ($S_1$)

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

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

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

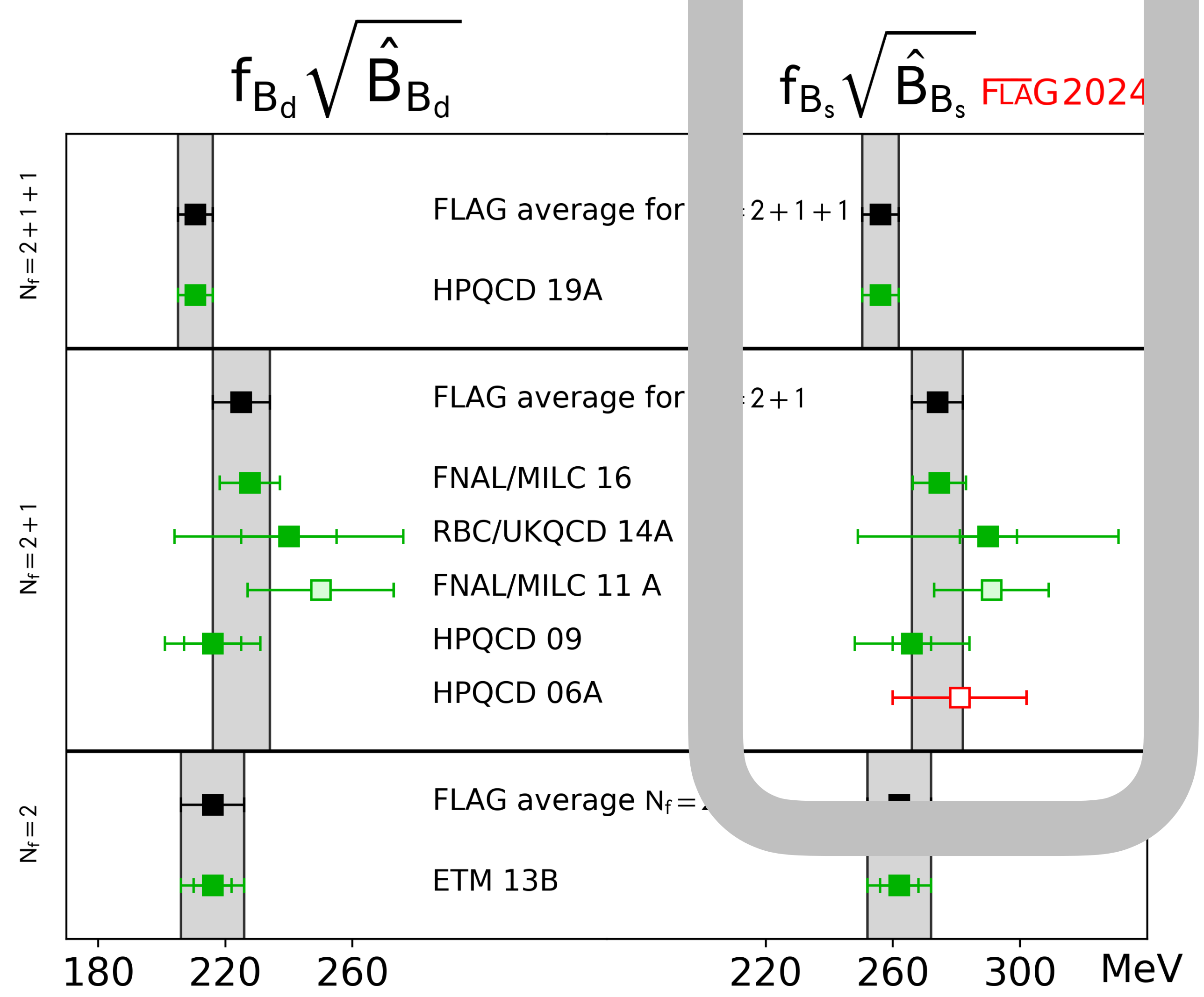
$$\widetilde{C}_{RR} = -\frac{v^2}{2m^2_{S_1}} y^{R*}_{sN} y^R_{bN}$$

# Concrete Model ($S_1$)

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

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

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



# Which CKM value?

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

- Using available $b \to c\ell\bar{\nu}$ data:

$$|\lambda_t| \times 10^3 = \begin{cases} 41.4 \pm 0.8\,, & (B \to X_c l\bar{\nu}) \\ 39.3 \pm 1.0\,, & (B \to D l\bar{\nu}) \\ 37.8 \pm 0.7\,, & (B \to D^* l\bar{\nu}) \end{cases}$$

[HFLAV, '22]
[FLAG, '21]
[HFLAV, '22]

… to be compared to CKM global fits:

cf. also 2409.10492

$$|\lambda_t|_{\mathrm{UTfit}} = (41.4 \pm 0.5) \times 10^{-2}$$

$$|\lambda_t|_{\mathrm{CKMfitter}} = (40.5 \pm 0.3) \times 10^{-2}$$

- Alternative strategy: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$

$$|\lambda_t| \times 10^3 = \begin{cases} 41.9 \pm 1.0\,, & (N_f = 2+1+1) \\ 39.2 \pm 1.1\,, & (N_f = 2+1) \end{cases}$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 256 \pm 6\ \mathrm{MeV} \qquad (N_f = 2+1+1)$$

[HPQCD '19]

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 274 \pm 8\ \mathrm{MeV} \qquad (N_f = 2+1)$$

[FLAG '24]

There is **no clear answer** to this **ambiguity.**

# Novelty in b→s $\ell\ell$: $B_s \to \mu\mu\gamma$

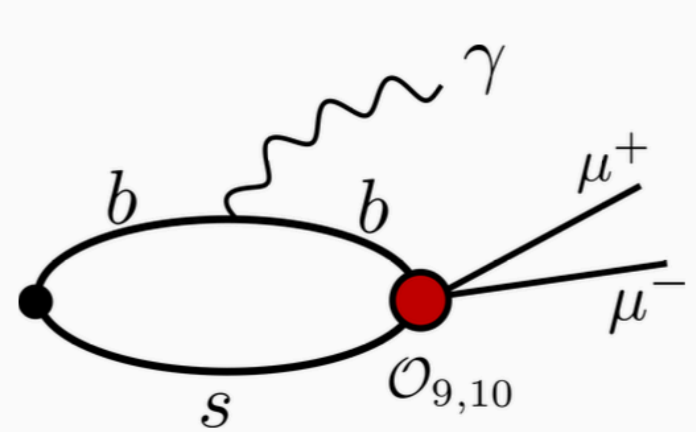
$$\boxed{\mathcal{H}_{\text{eff}}^{b\to s} = 2\sqrt{2}G_F V_{tb}V_{ts}^* \left[\sum_{i=1,2} C_i(\mu)\mathcal{O}_i^c + \sum_{i=3}^{6} C_i(\mu)\mathcal{O}_i + \frac{\alpha_{\text{em}}}{4\pi}\sum_{i=7}^{10} C_i(\mu)\mathcal{O}_i\right]}$$

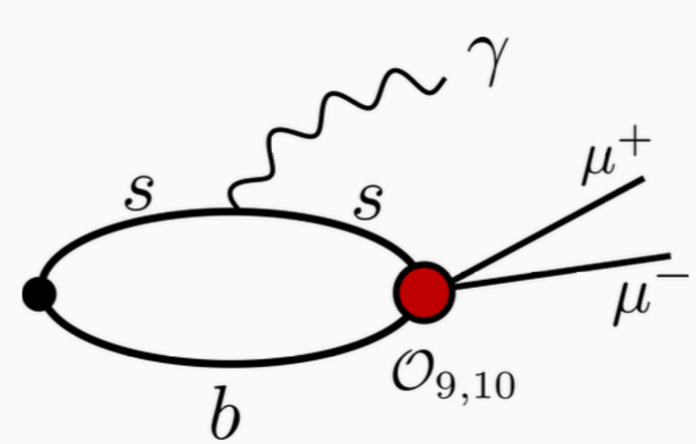
$$\mathcal{O}_7 = -\frac{m_b}{e}\bar{s}\sigma^{\mu\nu}F_{\mu\nu}P_R b \qquad \mathcal{O}_9 = \left(\bar{s}\gamma^\mu P_L b\right)(\bar{\mu}\gamma_\mu\mu) \qquad \mathcal{O}_{10} = \left(\bar{s}\gamma^\mu P_L b\right)(\bar{\mu}\gamma_\mu\gamma^5\mu)$$

- ✘ $B_s \to \mu\mu\gamma$ computed on the lattice in 2402.03262

$$H_9^{\mu\nu}(p,k) = H_{10}^{\mu\nu}(p,k) = i\int d^4y\; e^{iky}\;\hat{\mathrm{T}}\langle 0|\left[\bar{s}\gamma^\nu P_L b\right](0)J_{\text{em}}^\mu(y)|\bar{B}_s(\boldsymbol{p})\rangle$$

$$= -i\left[g^{\mu\nu}(k\cdot q) - q^\mu k^\nu\right]\frac{F_A}{2m_{B_s}} + \varepsilon^{\mu\nu\rho\sigma}k_\rho q_\sigma\frac{F_V}{2m_{B_s}}$$



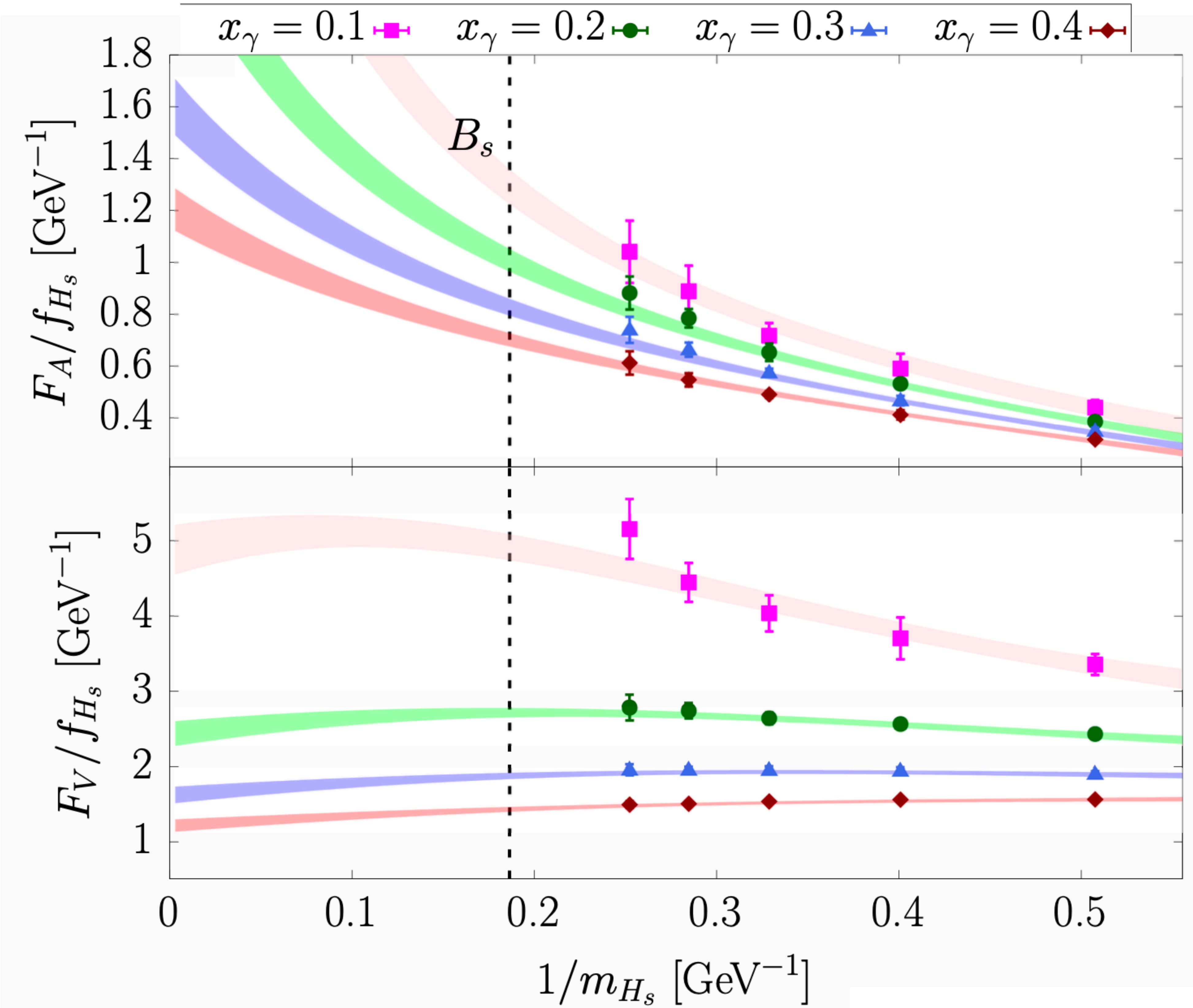




$$F_{V,A} \equiv F_{V,A}(x_\gamma)$$

$$x_\gamma = \frac{2E_\gamma}{m_{B_s}}$$

# $Bs \to \mu\mu\gamma$ :

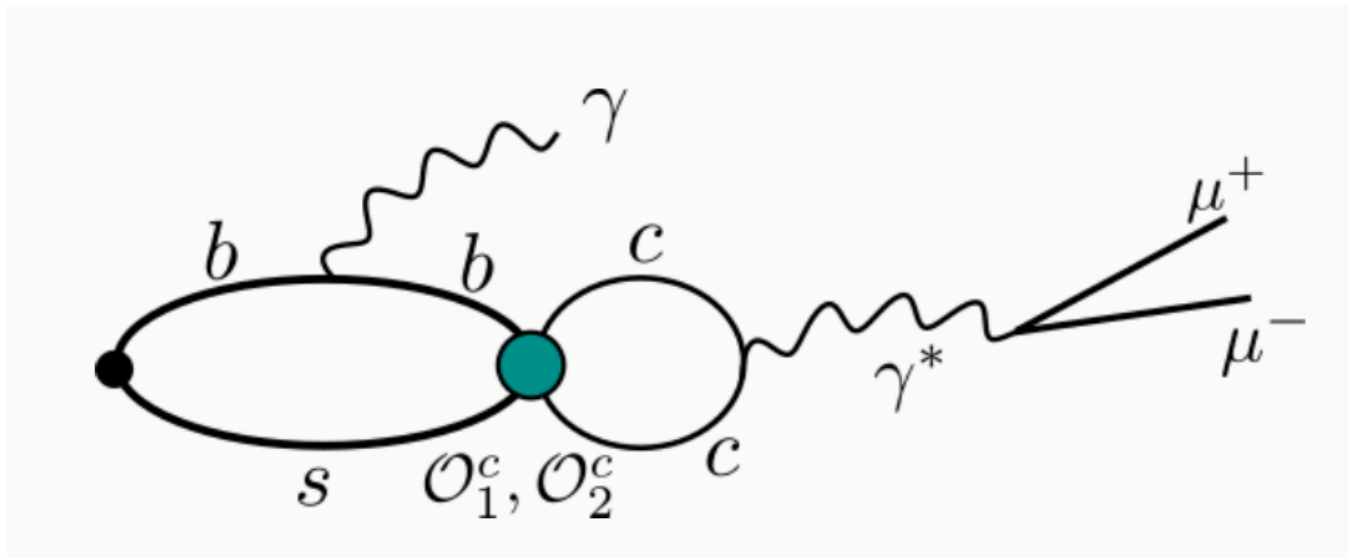
$$\int \mathrm{d}t_y\, \mathrm{d}^3y\, \mathrm{d}^3x\, e^{E_\gamma t_y}\, e^{-i\boldsymbol{k}\boldsymbol{y}}\, \hat{\mathrm{T}}\langle 0|\underbrace{J_V^\nu}_{\bar{s}\gamma^\nu b}(t,0) J^\mu_{\mathrm{em}}(t_y,\boldsymbol{y})\phi^\dagger_{B_s}(0,\boldsymbol{x})|0\rangle$$




$0.1 \leq x_\gamma \leq 0.4 \implies 4.16\ \mathrm{GeV} \leq \sqrt{q^2} \leq 5.1\ \mathrm{GeV}$

# $Bs \to \mu\mu\gamma$ : Key part not computed

$$H^{\mu\nu}_{i=1,2}(p,k) = \frac{(4\pi)^2}{q^2} \int d^4y\, d^4x\, e^{iky} e^{iqx}\, \hat{\mathrm{T}} \langle 0 | J^\mu_{\rm em}(y) J^\nu_{\rm em}(x) \mathcal{O}_i(0) | \bar{B}_s(p) \rangle$$




- ✘ Contributes to the dominant $C_9$ : Use QHD and perturbation theory (not enough due to charmonium resonances)
- ✘ Add BW known resonances, not enough: need fudge factors (sic!)
- ✘ Include charm rescattering through dispersion relation and 1-gluon exchange.
- ✘ In $B \to K^{(*)}\ell\ell$ one models $B \to D^{(*)}\ Ds^{(*)} \to K^{(*)}\ \gamma^{(*)}$ by adding triangle diagrams cf. 2212.10516, 2405.17551…
- ✘ Exp. still much larger than predicted (what about the tetraquarks?)

# Charm laboratory…

- For $D_s \to \ell\nu\gamma$

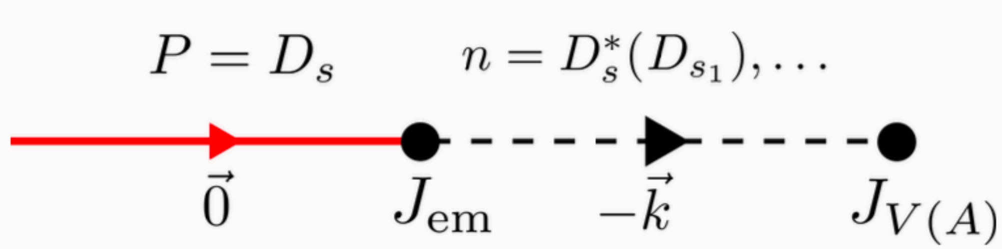
$$H_W^{\mu\nu}(\mathbf{k},\mathbf{p}) = i\int d^4y e^{iky}\langle 0|\mathcal{T}\left\{J_W^{\nu}(0)J_{\rm em}^{\mu}(y)\right\}|D_s(\mathbf{p})\rangle$$

$$= \frac{f_{D_s}}{p\cdot k}p^\mu p^\nu + i\frac{F_V}{m_{D_s}}\varepsilon^{\mu\nu\alpha\beta}p_\alpha k_\beta + \left[\frac{F_A}{m_{D_s}} + \frac{f_{D_s}}{p\cdot k}\right](p\cdot k)g^{\mu\nu} - p^\mu k^\nu) + \cancel{H_\perp^{\mu\nu}(\mathbf{k},\mathbf{p})}$$

- Insert the full set of states

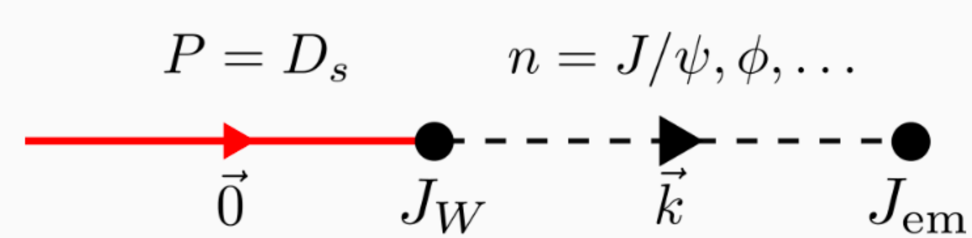
1st T.O. $t_y < 0$

$$H_{W,1}^{\mu\nu}(\boldsymbol{k},\mathbf{0}) = \sum_n \frac{B_W^{\mu\nu;n}(\boldsymbol{k})}{E_n(-\boldsymbol{k}) + E_\gamma - m_P - i\epsilon}$$




2nd T.O. $t_y > 0$

$$H_{W,2}^{\mu\nu}(\boldsymbol{k},\mathbf{0}) = \sum_n \frac{A_W^{\mu\nu;n}(\boldsymbol{k})}{E_n(\boldsymbol{k}) - E_\gamma - i\epsilon}$$




- Legit for a real photon as $E\gamma = |\boldsymbol{k}|$ and there is always a positive mass gap i.e. no problem for analytic continuation from Minkowski to Euclidean time

# Charm laboratory…

- If $E\gamma \neq |\boldsymbol{k}|$

$$H_W^{\mu\nu}(E_\gamma,\mathbf{k}) = i\int_{-\infty}^{0} dt\,\langle 0|J_W^\nu(0)e^{i(\mathcal{H}+E_\gamma-m_{D_s})t}J_{\rm em}^\mu(0,\mathbf{k})|D_s(\mathbf{p})\rangle + i\int_0^\infty dt\,\langle 0|J_{\rm em}^\mu(0,\mathbf{k})\underline{e^{-i(\mathcal{H}-E_\gamma)t}}J_W^\nu(0)|D_s(\mathbf{p})\rangle$$

- For a $J^P=1^-$ hadronic states lighter than $E\gamma$, no possible to analytically continue. Focus on the second term:

$$C_E(t) = \langle 0|J_{\rm em}(-it)J_W(0)|D_s\rangle$$

$$C(t) = \langle 0|J_{\rm em}(t)J_W(0)|D_s\rangle \qquad H(E) = i\int_0^\infty dt\, e^{iEt}C(t)$$

$$\rho(E') = \langle 0|J_{\rm em}(0)\delta(\mathcal{H}-E')J_W(0)|D_s\rangle$$

- Hadronic amplitude

$$H(E) = \lim_{\varepsilon\to 0}\int_{E^*}^\infty dE'\rho(E')\int_0^\infty dt e^{-i(E'-E-i\varepsilon)t} = \lim_{\varepsilon\to 0}\int_{E^*}^\infty dE'\,\frac{\rho(E')}{E'-E-i\varepsilon}$$

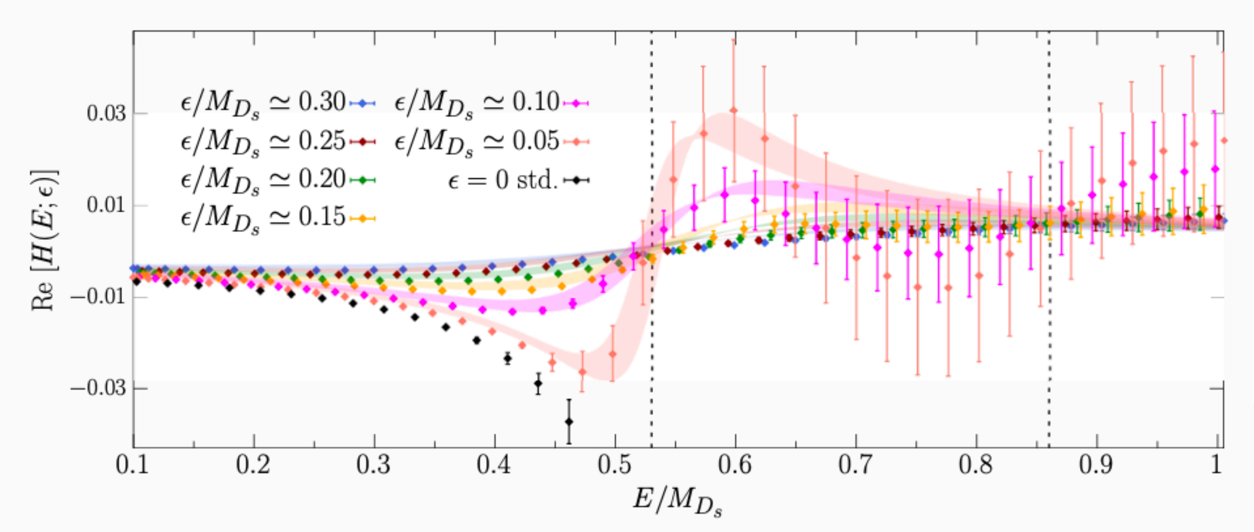
For E>E* we cannot set $\varepsilon=0$ prior to integration

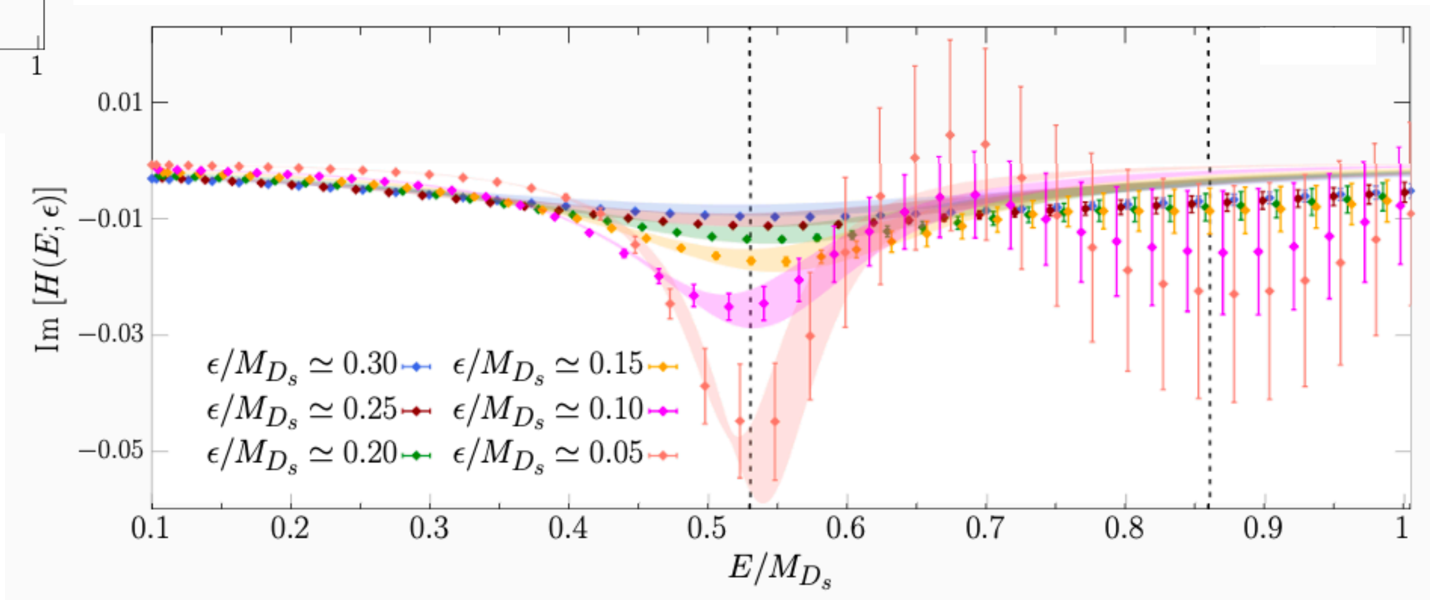
# HLT

- ✘ Promote $\varepsilon$ to a small (smearing) parameter [1903.06476]:

$$H(E;\varepsilon) = \int_{E^*}^{\infty} dE' \, \frac{\rho(E')}{E' - E - i\varepsilon} \int_{-\infty}^{\infty} dE' \, \frac{1}{\pi} \frac{\varepsilon}{(E'-E)^2 + \varepsilon^2} H(E')$$

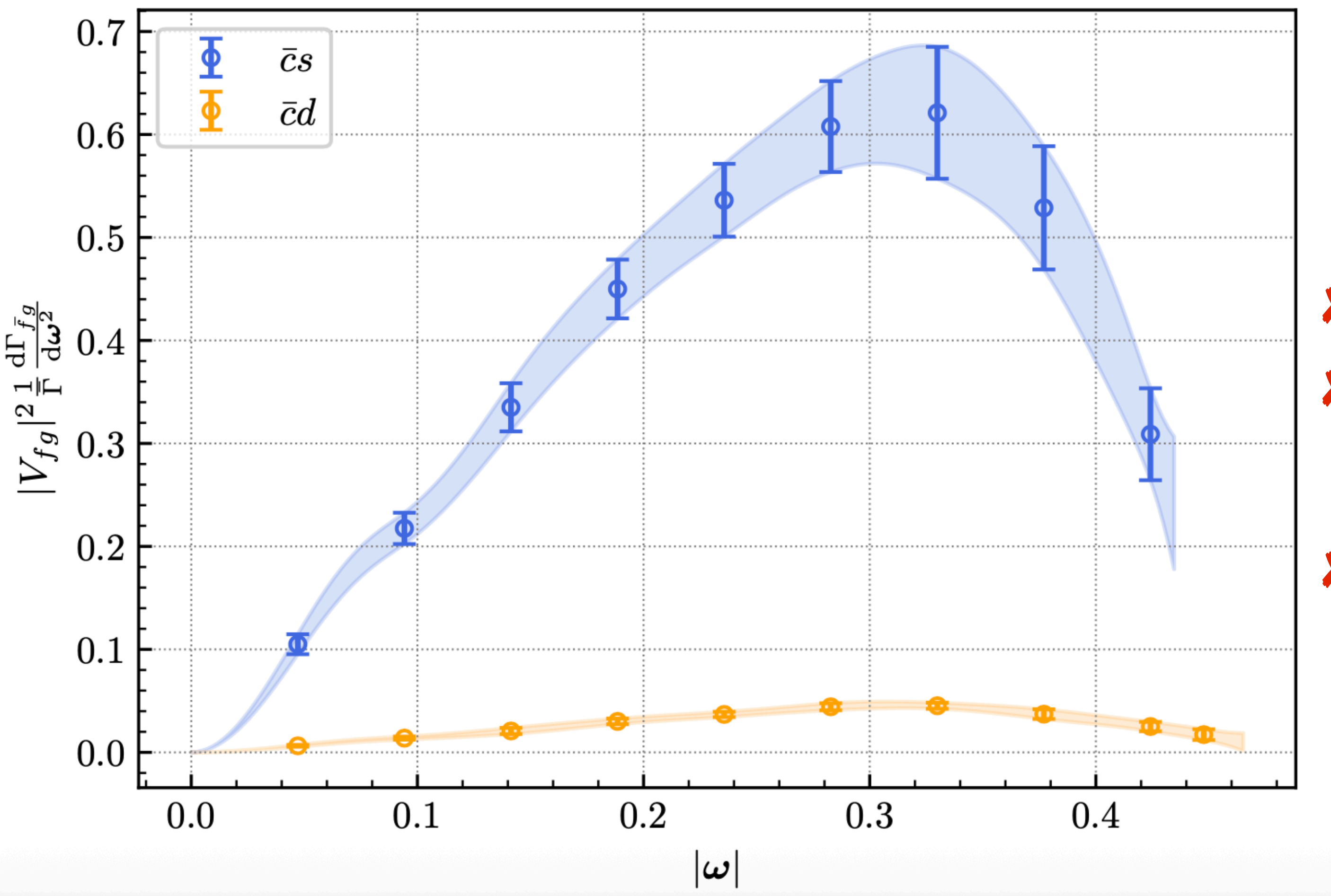
- ✘ There is a scaling regime in which *$\Delta(E)$ =$H(E;\varepsilon)$ - $H(E) \simeq \mathcal{O}(\varepsilon)$*



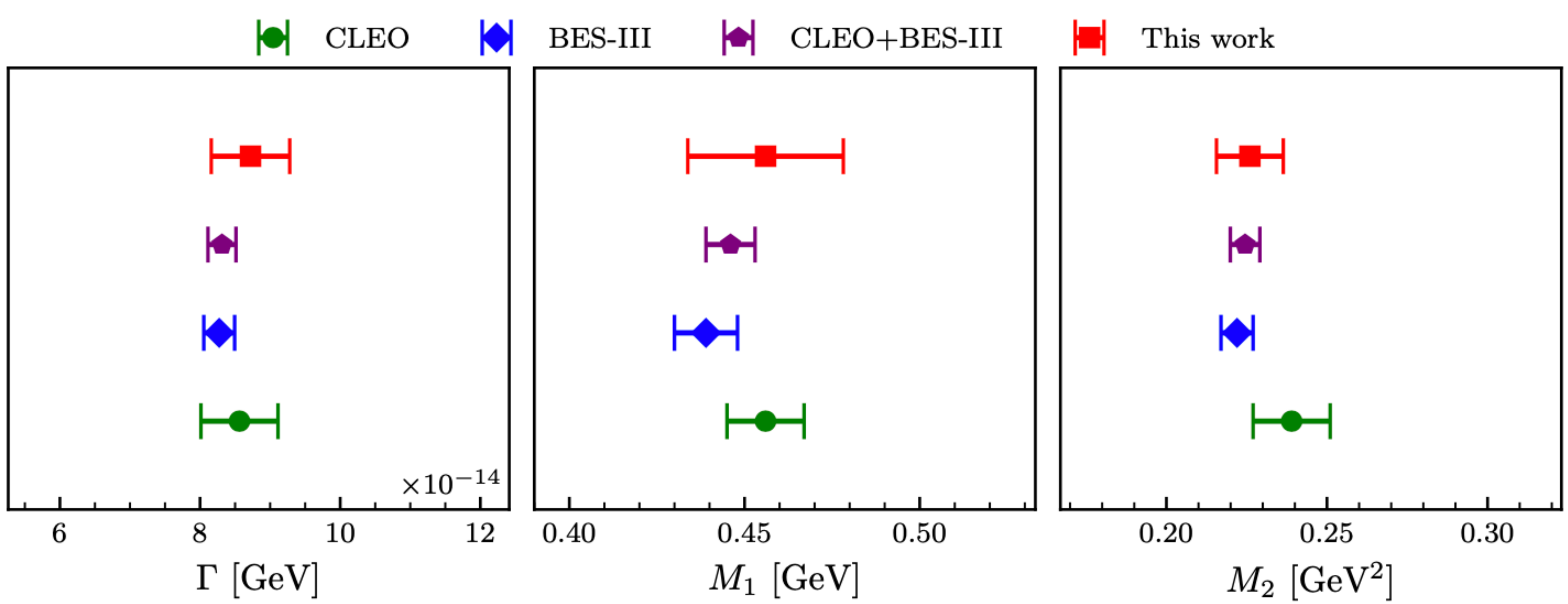



# *Tested on the inclusive Ds → X ℓ ν*

2504.06063,2504.06064



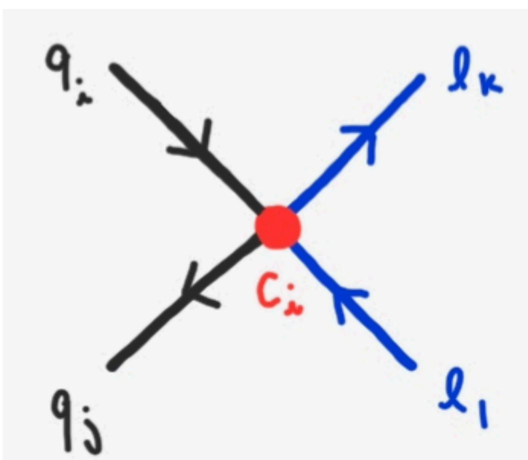

- ✘ Remarkable agreement with exp!
- ✘ Inclusive B → X ℓ ν around the corner (several groups working)
- ✘ Attempts to compute charm loops contributions to $C_9$ [$B \to K^{(*)}\ell\ell$ ]

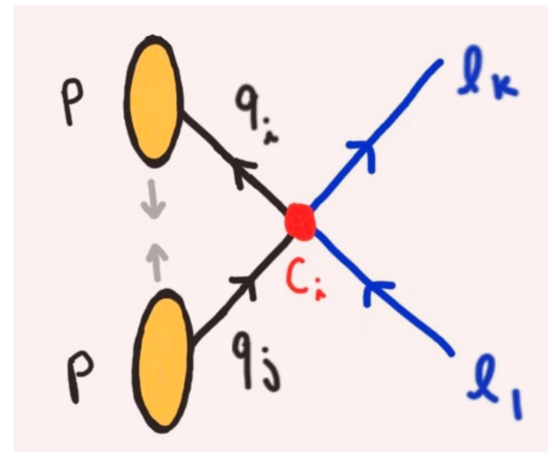


# Concluding Remarks 2

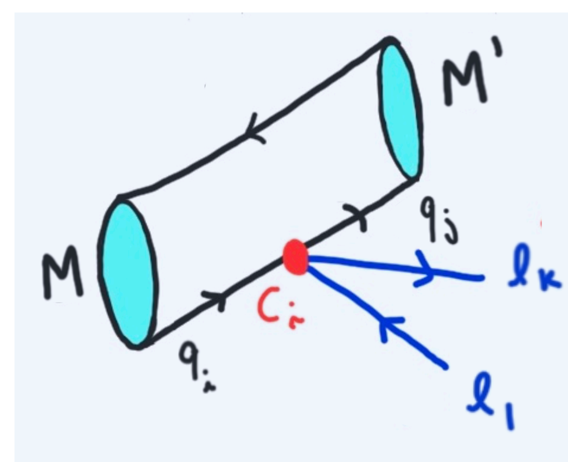
- Experiments are driving B-physics: Belle-II and LHC
- Charm experiments highly important: laboratory for testing ideas/methods
- Hadronic uncertainties are a major obstacle to interpreting the potential deviations between the measured and predicted (in SM) quantities. Very significant improvement on the LQCD side…
- High $p_T$ tails studied at LHC very helpful in constraining NP scenarios
- Interpreting $R_D$ and $R_{D^*}$ in terms of NP with a minimal SLQ setup is possible by using S1, and to a lesser extent R2. Alternatively, couple to a heavy RH neutrino.
- If one wants to accommodate both $R_{D^{(*)}}$ and $R_K^{inv}$ the RR-operators with an additional RH neutral lepton could do the job. A concrete model of such a scenario is again S1 which can be tested either via $R_{K^*}^{inv}$ or through $B_s$-mixing for which the LQCD estimate of the HME is needed.

# [Intermezzo] Probing flavor at the LHC




$pp \to \ell_k \ell_l$



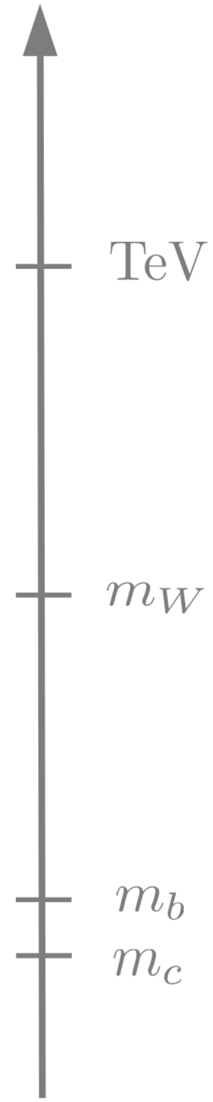

$M \to \ell_k \ell_l$

$\ell_k \to \ell_l M$

$M \to M' \ell_k \ell_l$

$\ldots$

**Flavorful New Physics?**




**High-$p_T$ searches** (CMS and ATLAS) **can probe** the **same four-fermion operators** constrained by **flavor-physics experiments** (NA62, KOTO, BES-III, LHCb, Belle-II...).


Many works on EFTs and Drell-Yan: Cirigliano et al. ’12, ’18], [de Blas et al. ’13], [Farina et al. ’16], [Dawson et al. ’18, ’21], [Greljo et al. ’18], [Shepherd et al. ’18], [Fuentes-Martín et al. ’20], [Marzocca et al. ’20], [Endo et al. ’21], [Boughezal et al. ’21], [Angelescu et al. ’20], [Allwicher et al. ’23]…