Looking for New Physics through b→ $s\nu\nu$, b→ $c\ell\nu$ and c→ $s\ell\nu$

Damir Bečirević

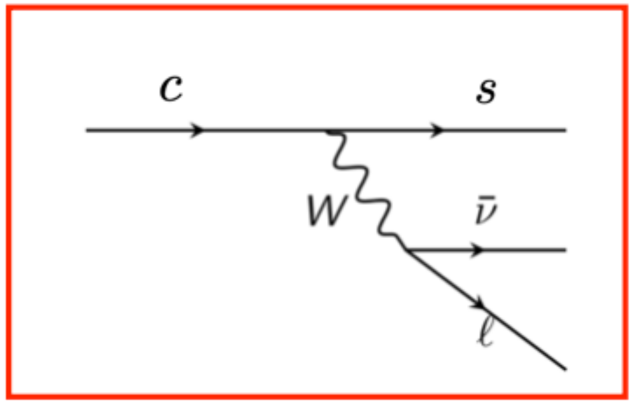
Pôle Théorie, IJCLab
CNRS et Université Paris-Saclay

Intro

- ✘ Common strategy: Measure weak interactions processes to high precision and compare exp to robust/accurate theoretical predictions in order to either fix CKM or to extract couplings to BSM physics

- ✘ Nonperturbative QCD stands on the way.
  LQCD tremendous progress but $B \to D^*\ell\nu$ still problematic (3pt fns)

- ✘ $c \to s\ell\nu$ good testing ground [excellent results from BESIII + best environment for LQCD]



cf. also Bolognani et al 2407.06145

Extracting parameters

Decay rate = Kinematics CKM/NP coupling Hadronic quantities

Experiments:

NA62, KOTO
BESIII, LHCb
LHC,Belle-II

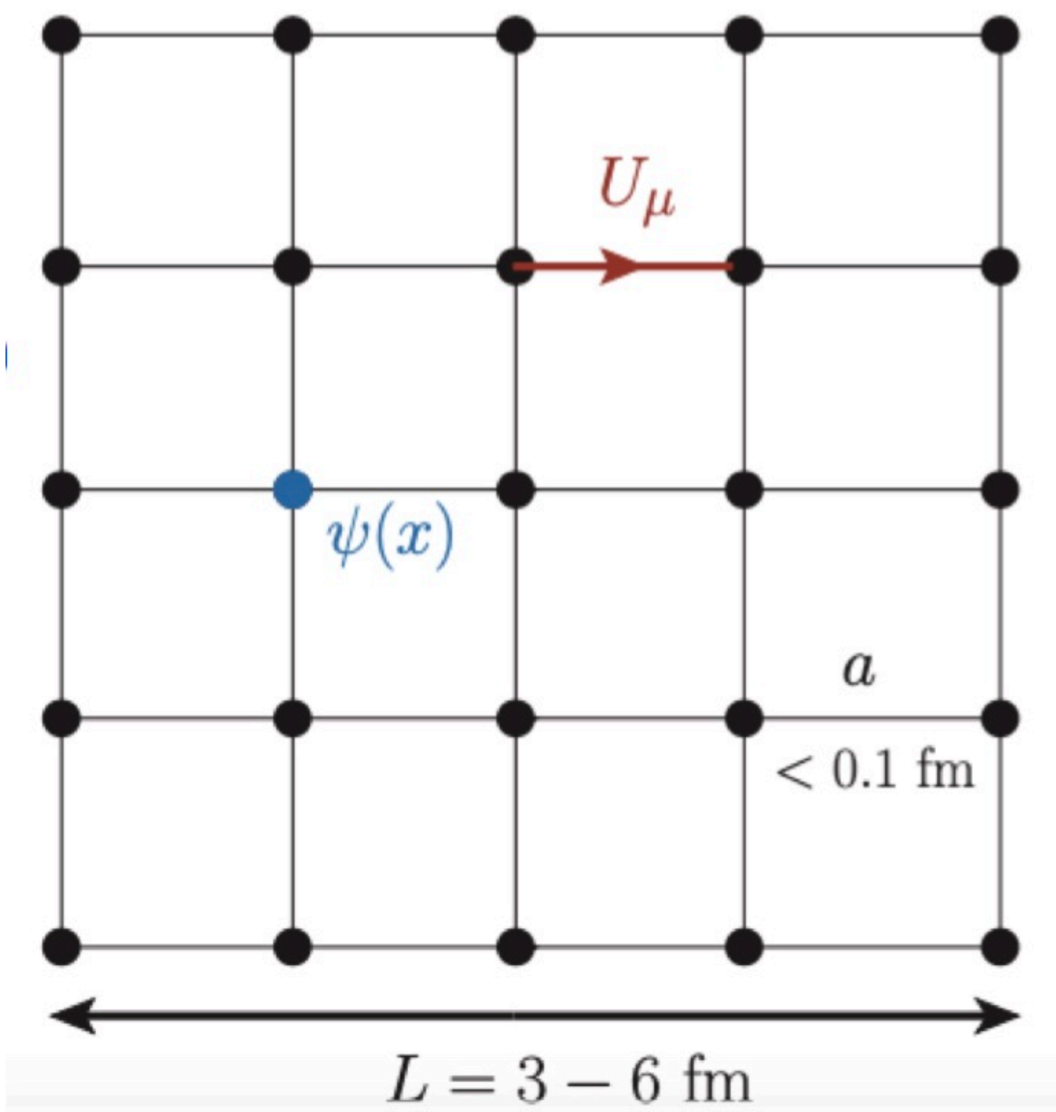
Nonperturbative QCD

Lattice QCD or
Models, QCDSR, LCSR…

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)

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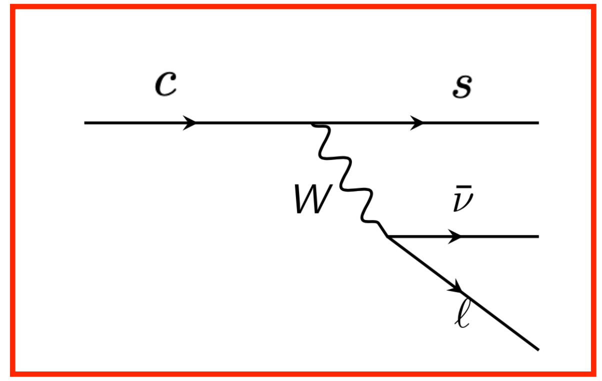
- ✘ Regularized QCD - path integral GF ⇔ MC methods (stat. errors)
- ✘ Systematics (finite spacing, volume etc) are difficult but can be and are handled
- ✘ Ab initio means NO additional parameter is introduced apart from those in the original Lagrangian (coupling and quark masses)
- ✘ Not everything 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!

CKM Unitarity - V_{cs}



- From the global fits:

$$|V_{cs}|^{\text{UTFit}} = 0.9735(2) \qquad\qquad |V_{cs}|^{\text{CKMfitter}} = 0.9735(1)$$

- Possible checks thanks to charm factory at BESIII
- Leptonic modes are the best suited: QCD ‘simple’ for lattices
- Recent updates (BESIII - 2023):

$$\mathcal{B}(D_s \to \mu\nu) = 5.29(14) \times 10^{-3}$$

BESIII, 2307.14585

$$\mathcal{B}(D_s \to \tau\nu) = 5.44(21)\%\Big|_{\tau\to\pi\nu}, \quad 5.34(19)\%\Big|_{\tau\to\mu\nu\nu}$$

BESIII, 2303.12600

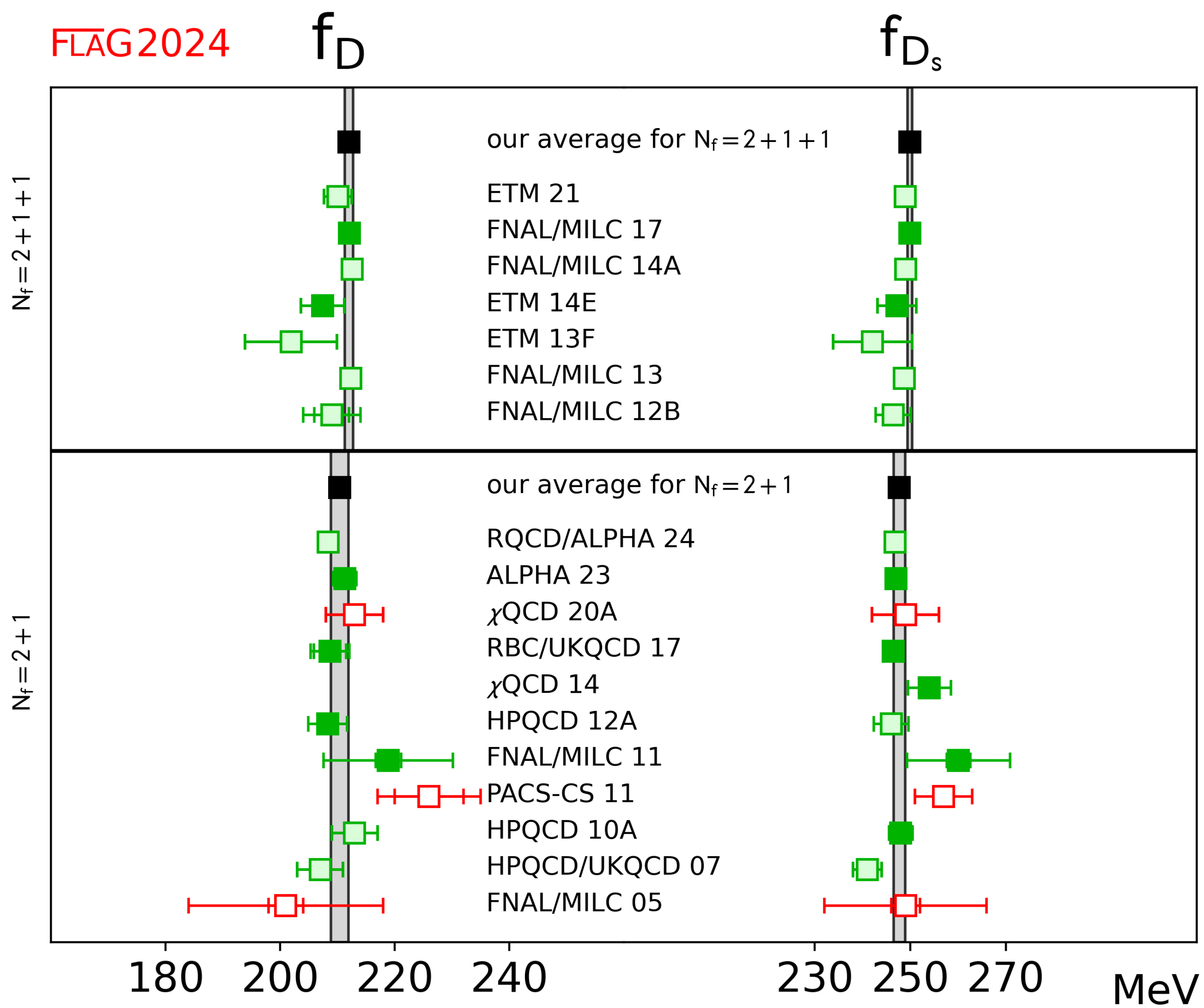
BESIII, 2303.12468

Checking on V_{cs}

- From the global fits:

$$|V_{cs}|^{\text{UTFit}} = 0.9735(2) \qquad |V_{cs}|^{\text{CKMfitter}} = 0.9735(1)$$

- Hadronic matrix element $\langle 0|\bar{c}\gamma_\mu\gamma_5 s|D_s(p)\rangle = i f_{D_s} p_\mu$



$$f_{D_s} = 249.9(5)\ \text{MeV}$$

0.2%!

FLAG rev, 2411.04268

Checking on V_{cs}

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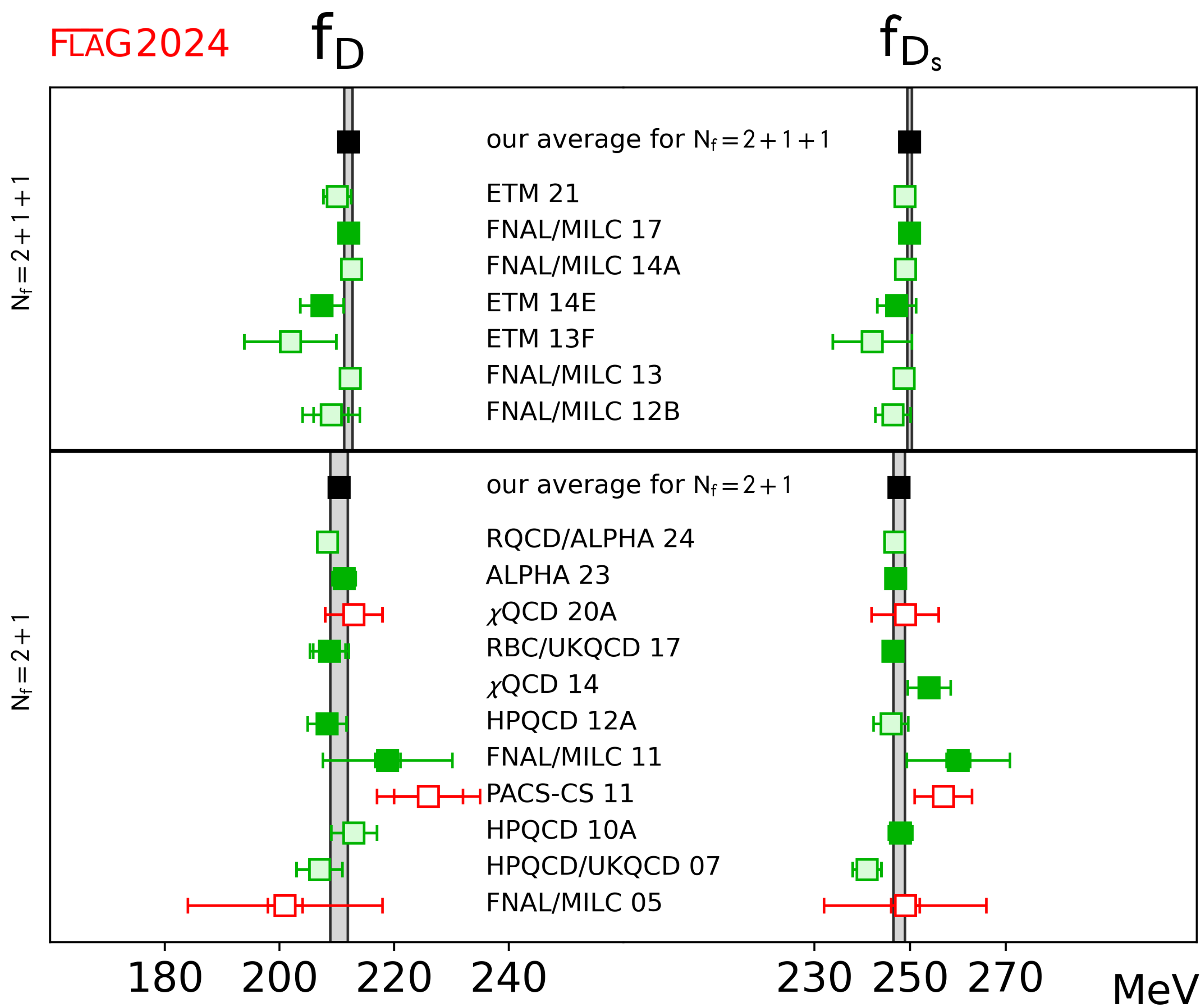

$$|V_{cs}|^{\mu} = 0.967(13)$$

$$|V_{cs}|^{\tau_1} = 0.993(20)$$

$$|V_{cs}|^{\tau_2} = 0.984(20)$$

Watch out - soft photons!
cf. Frezzotti et al 2306.05904

Cannot match the UT precision unless using detailed semileptonics

EFT $c \to s\, \ell\nu$

$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{cs} \Big[\left(1 + g^{\ell}_{V_L}\right) (\bar{s}_L \gamma_\mu c_L) \left(\bar{\ell}_L \gamma^\mu \nu_L\right) + g^{\ell}_{V_R} (\bar{s}_R \gamma_\mu c_R) \left(\bar{\ell}_L \gamma^\mu \nu_L\right)$$
$$+ g^{\ell}_{S_L} (\bar{s}_R c_L) \left(\bar{\ell}_R \nu_L\right) + g^{\ell}_{S_R} (\bar{s}_L c_R) \left(\bar{\ell}_R \nu_L\right) + g^{\ell}_T (\bar{s}_R \sigma_{\mu\nu} c_L) \left(\bar{\ell}_R \sigma^{\mu\nu} \nu_L\right) \Big] + \text{h.c.}$$

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$$+ g^\ell_{S_L} (\bar{s}_R c_L) \left(\bar{\ell}_R \nu_L\right) + g^\ell_{S_R} (\bar{s}_L c_R) \left(\bar{\ell}_R \nu_L\right) + g^\ell_T (\bar{s}_R \sigma_{\mu\nu} c_L) \left(\bar{\ell}_R \sigma^{\mu\nu} \nu_L\right) \Big] + \text{h.c.}$$

V-A | V+A | S-P | S+P | T

$$g^\ell_{S(P)} = g^\ell_{S_R} \pm g^\ell_{S_L} \qquad g^\ell_{V(A)} = g^\ell_{V_R} \pm g^\ell_{V_L} \qquad g^\ell_T = g^\ell_T$$

$$\mathcal{B}\,(D_s \to \ell\nu) = \tau_{D_s} \frac{G_F^2 |V_{cs}|^2 f_{D_s}{}^2 M_{D_s} m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2 \left| 1 - g^\ell_A + g^\ell_P \frac{M_{D_s}^2}{m_\ell (m_c + m_s)} \right|^2$$

exp | CKMU | LQCD | ??

Semileptonics - mesons

- ✘ Mesons:

$D \to K\ell\nu$: $\langle K(k)|\bar{c}\gamma_\mu s|D(p)\rangle \propto f_+(q^2), f_0(q^2)$ $\langle K(k)|\bar{c}\gamma_\mu\gamma_5 s|D(p)\rangle = 0$ $\langle K(k)|\bar{c}\sigma_{\mu\nu} s|D(p)\rangle \propto f_T(q^2)$

$D \to K^*\ell\nu$: $\langle K^*(k)|V_\mu|D(p)\rangle \propto V(q^2)$ $\langle K^*(k)|A_\mu|D(p)\rangle \propto A_1(q^2), A_2(q^2), A_0(q^2)$

$\langle K^*(k)|T_{\mu\nu}|D(p)\rangle \propto T_1(q^2), T_2(q^2), T_3(q^2)$

and similarly for $D_s \to \phi\ell\nu$

- ✘ Pseudoscalar in the final state - easier for lattices

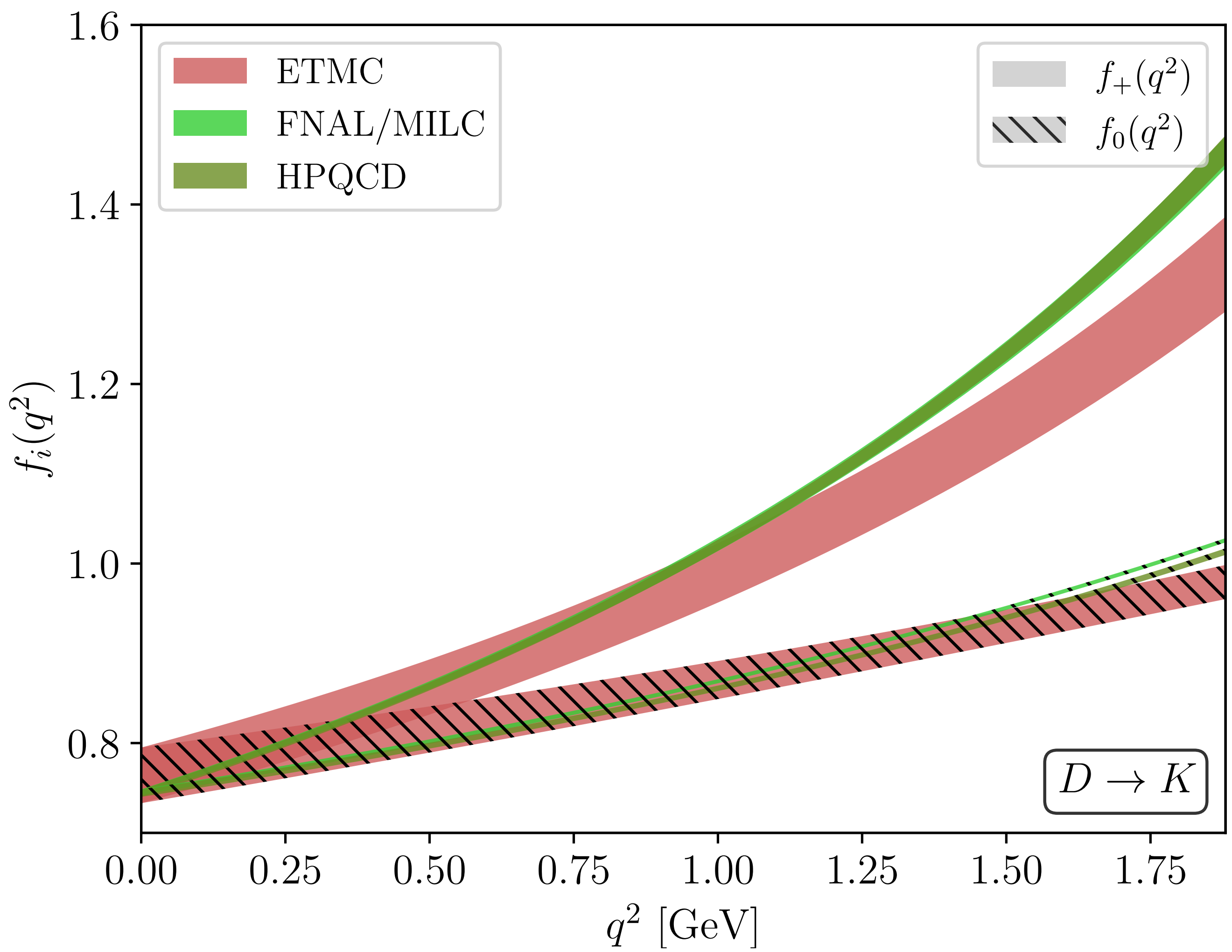
- ✘ We focus on the electron modes [more precise]
  LFUV tests (μ/e) successful so far (cf. PDG)

or recent BESIII 2306.02624 v 2207.14149

Semileptonics - mesons (LQCD)

- **Mesons:**

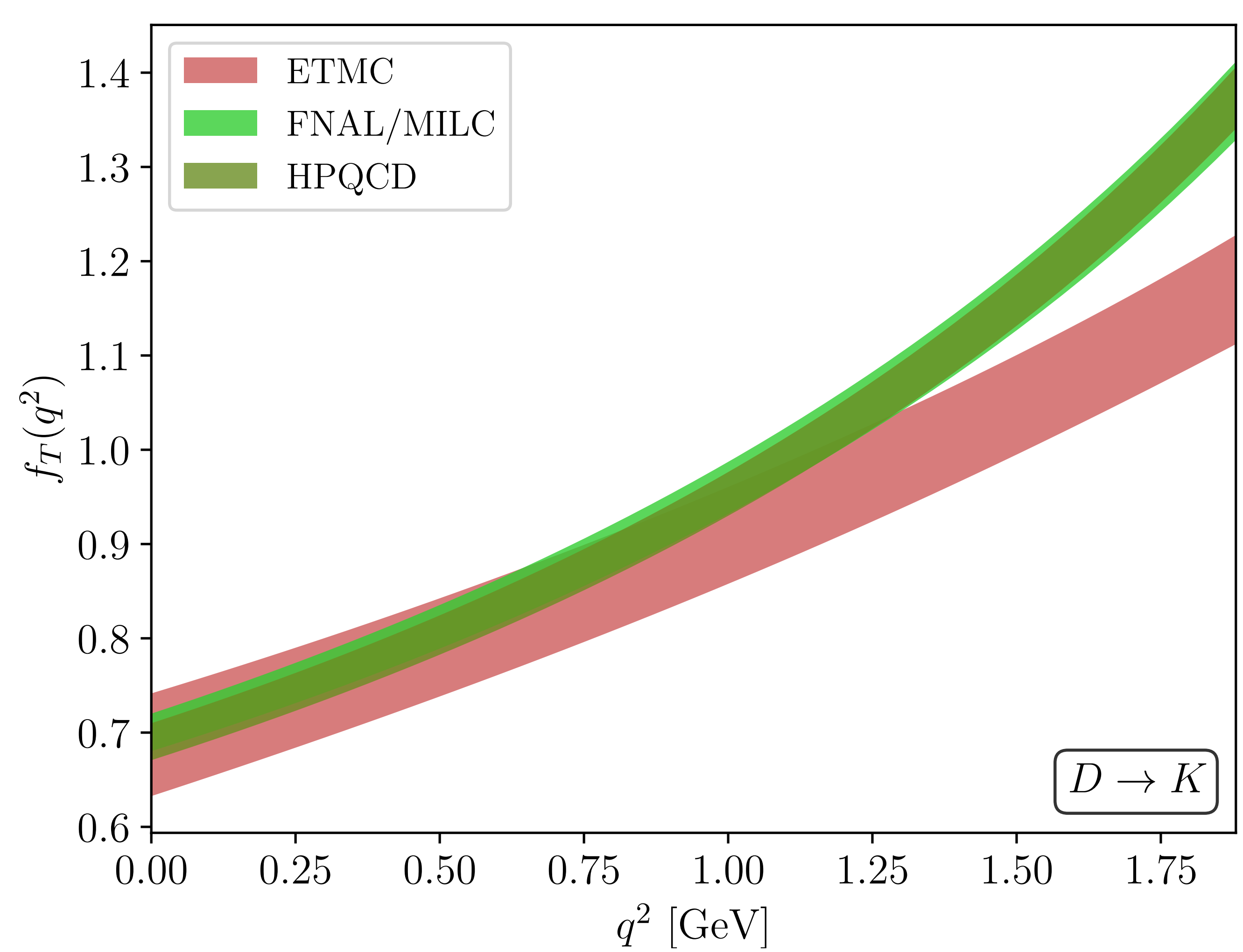
$D \to K\ell\nu$: $\langle K(k)|\bar{c}\gamma_\mu s|D(p)\rangle \propto f_+(q^2), f_0(q^2)$ $\langle K(k)|\bar{c}\gamma_\mu\gamma_5 s|D(p)\rangle = 0$ $\langle K(k)|\bar{c}\sigma_{\mu\nu}s|D(p)\rangle \propto f_T(q^2)$



ETMC, 1706.03017

FNAL/MILC, 2212.12648

HPQCD, 2204.09883



ETMC, 1803.04807

FNAL/MILC, 2212.12648

HPQCD, 2207.12468

Semileptonics - mesons (LQCD)

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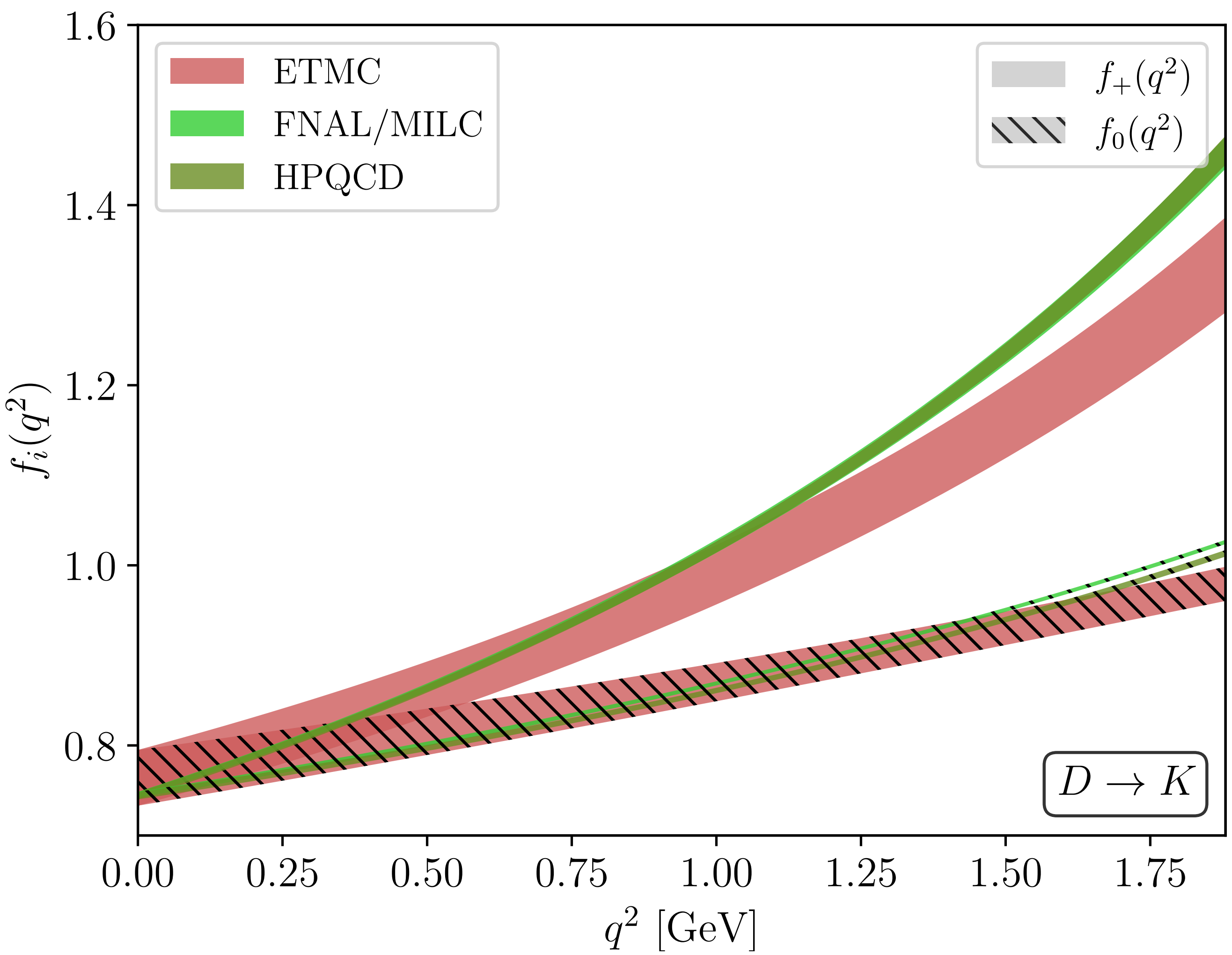
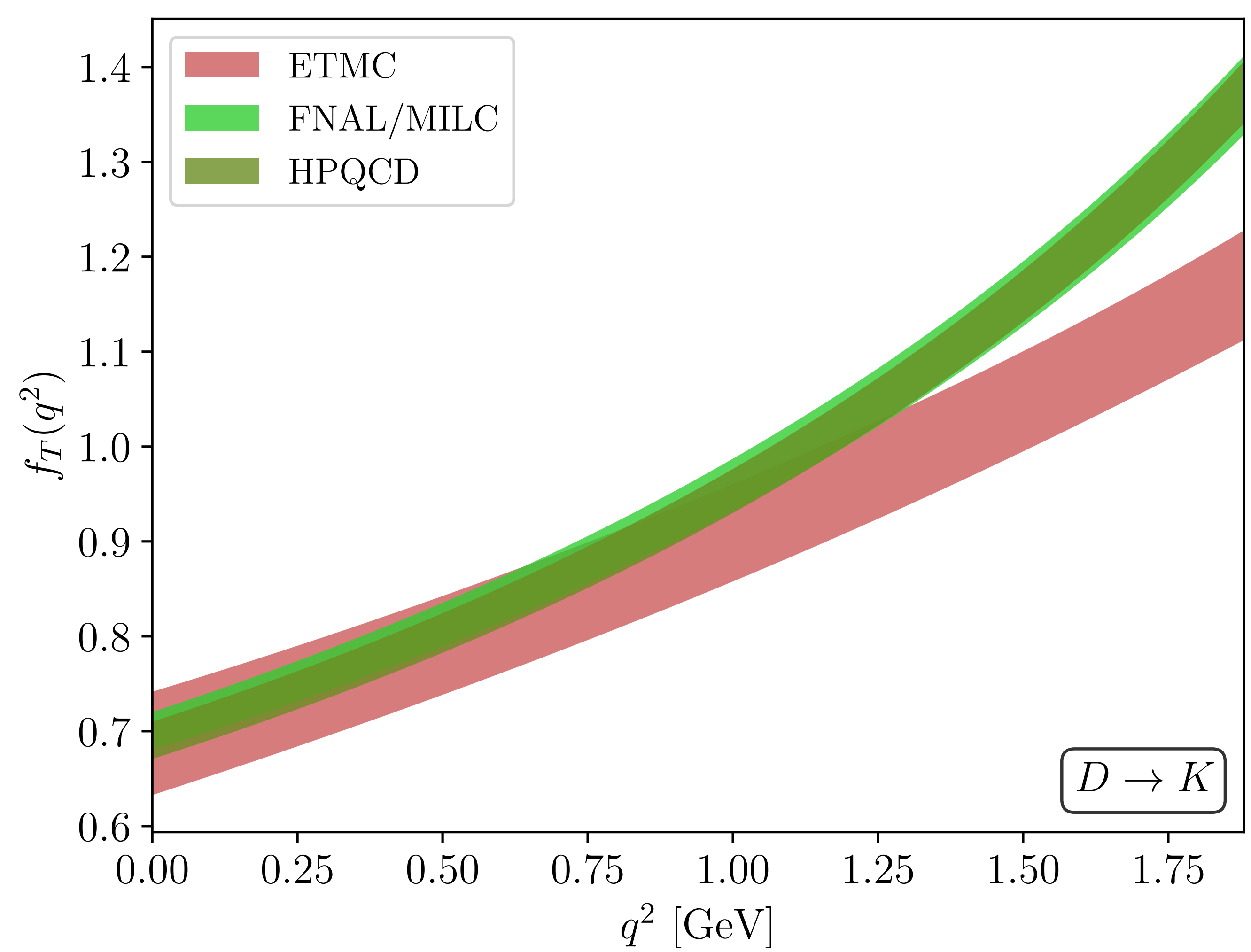




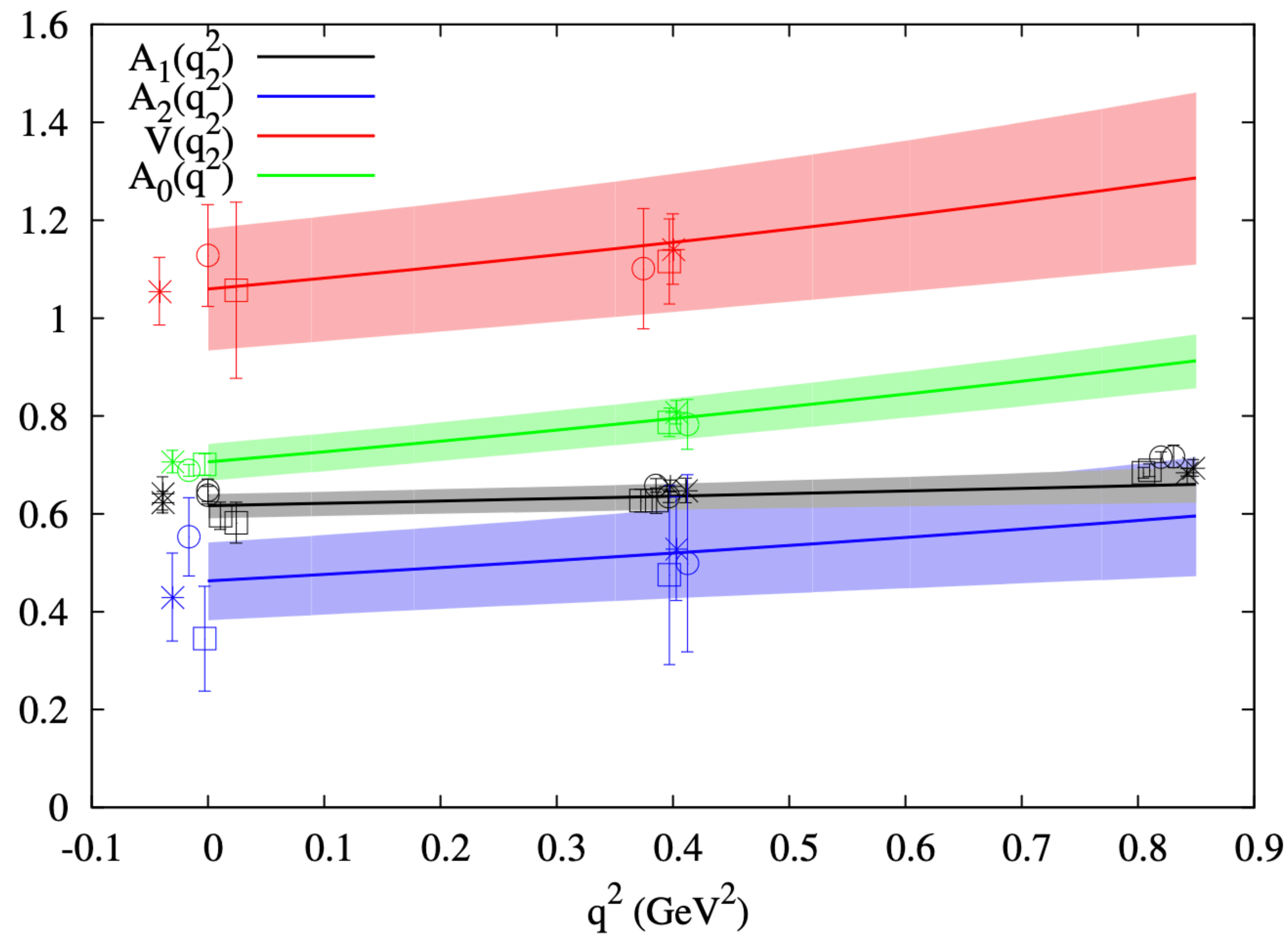
More work needed to understand the differences (lattice artefacts)

Semileptonics - mesons (LQCD)

- **Mesons:**

$D_s \to \phi \ell \nu: \quad \langle \phi(k)|V_\mu|D_s(p)\rangle \propto V(q^2) \quad \langle \phi(k)|A_\mu|D_s(p)\rangle \propto A_1(q^2), A_2(q^2), A_0(q^2)$

$\langle \phi(k)|T_{\mu\nu}|D_s(p)\rangle \propto T_1(q^2), T_2(q^2), T_3(q^2)$



Only one LQCD computation

- Only 2 kinematical situations
- This mode can be very useful!

BESIII, 2307.03024

HPQCD, 1311.6669

Semileptonics - experiment (ang. distr.)

$$\frac{d^2\Gamma_\lambda^{\lambda_\ell}}{dq^2 d\cos\theta} = a_\lambda^{\lambda_\ell}(q^2) + b_\lambda^{\lambda_\ell}(q^2)\cos\theta + c_\lambda^{\lambda_\ell}(q^2)\cos^2\theta$$

Functions of kinematic variables, q^2-dependent form factors and NP couplings

- 3 observables even for PS meson in the final state (can this be done exply?)
- using secondary decay of V meson in the final state (bunch of observables)
- baryons very useful too

$$\Lambda_c \to \Lambda \ell \nu : \quad \langle \Lambda(k)|V_\mu|\Lambda_c(p)\rangle \propto f_\perp(q^2), f_+(q^2), f_0(q^2) \quad \langle \Lambda(k)|A_\mu|\Lambda_c(p)\rangle \propto g_\perp(q^2), g_+(q^2), g_0(q^2)$$

$$\langle \Lambda(k)|T_{\mu\nu}|\Lambda_c(p)\rangle \propto h_\perp(q^2), h_+(q^2), h_0(q^2), \widetilde{h}_\perp(q^2), \widetilde{h}_+(q^2)$$

A detailed lattice study: Meinel 1611.09696

BESIII $\Lambda_c \to \Lambda(\to p\pi)\, e\nu$

$$\frac{d^4\Gamma^{\lambda_\ell}}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} = A_1^{\lambda_\ell} + A_2^{\lambda_\ell}\cos\theta_\Lambda + \left(B_1^{\lambda_\ell} + B_2^{\lambda_\ell}\cos\theta_\Lambda\right)\cos\theta + \left(C_1^{\lambda_\ell} + C_2^{\lambda_\ell}\cos\theta_\Lambda\right)\cos^2\theta$$
$$+ \left(D_3^{\lambda_\ell}\sin\theta_\Lambda\cos\phi + \underline{D_4^{\lambda_\ell}}\sin\theta_\Lambda\sin\phi\right)\sin\theta + \frac{1}{2}\left(E_3^{\lambda_\ell}\sin\theta_\Lambda\cos\phi + \underline{E_4^{\lambda_\ell}}\sin\theta_\Lambda\sin\phi\right)\sin 2\theta$$

Invert the angular coefficients [exp] to extract the FF and compare to LQCD

BESIII 2207.14149

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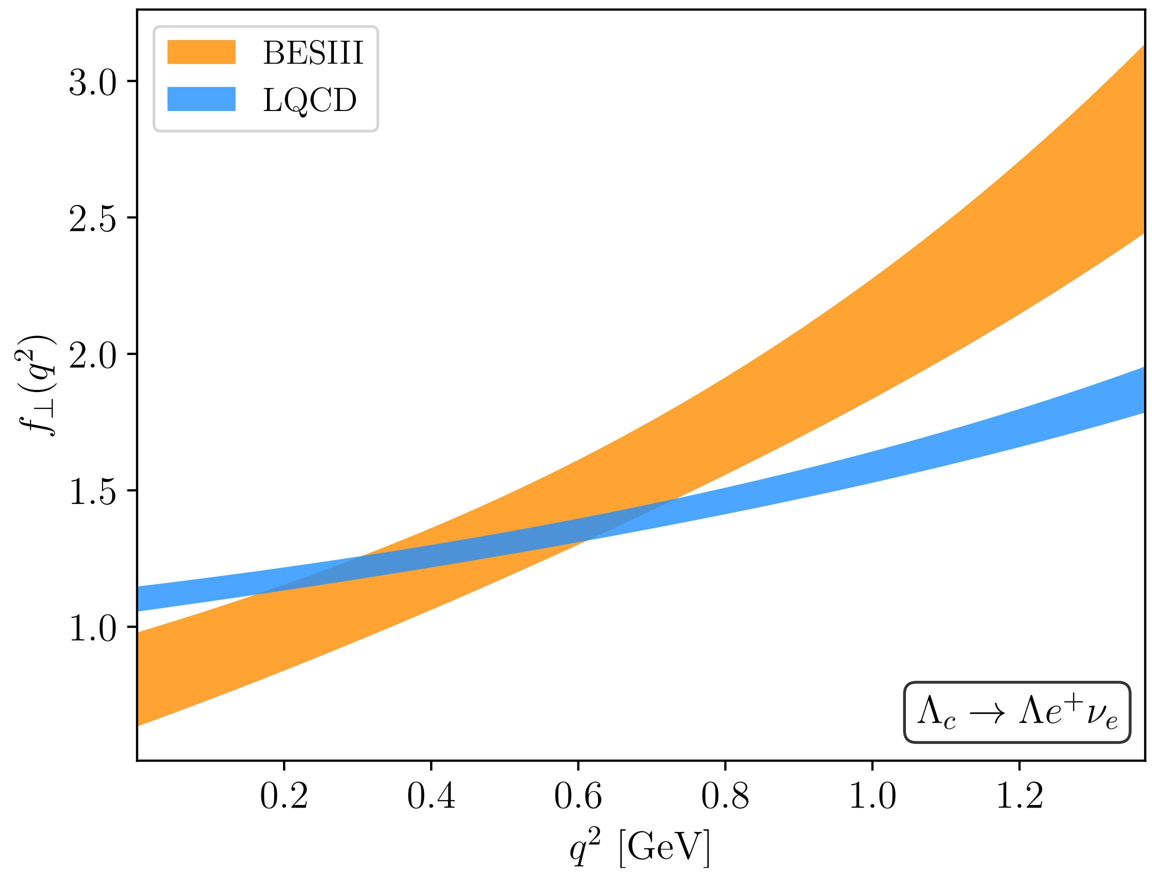
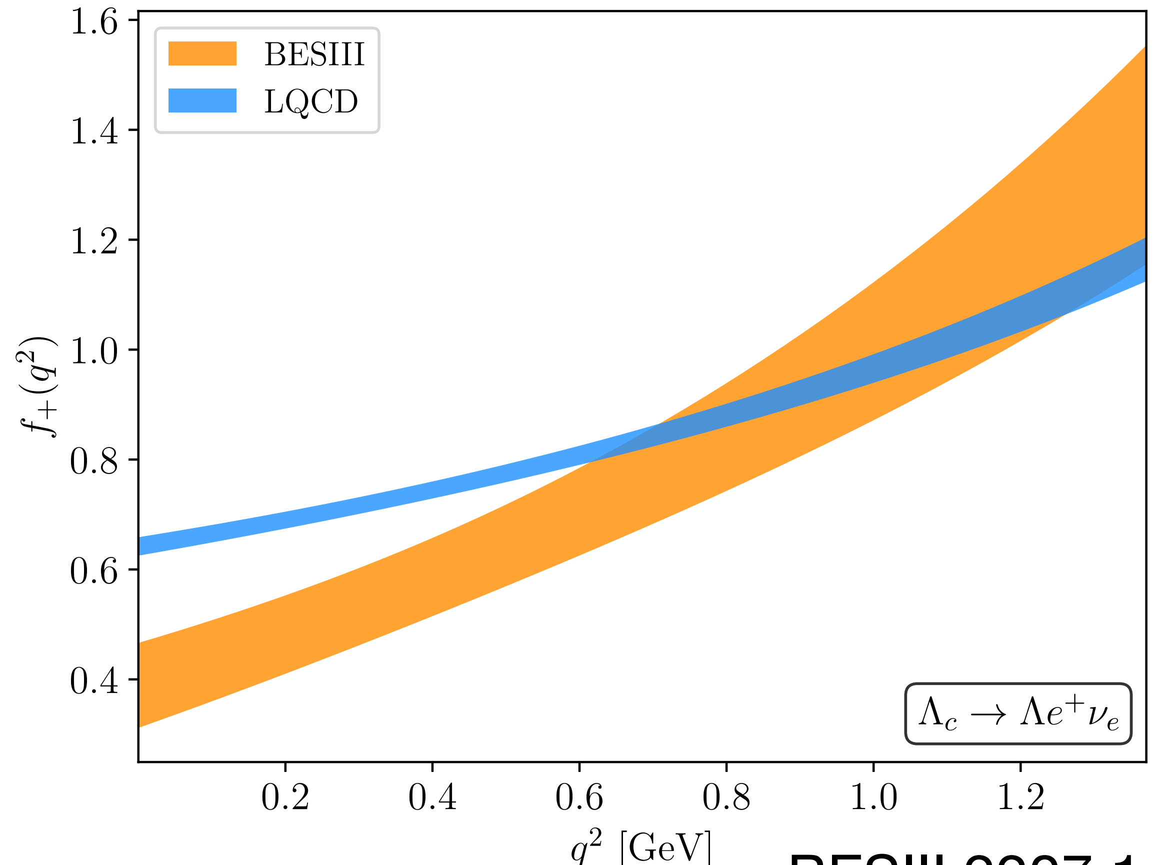
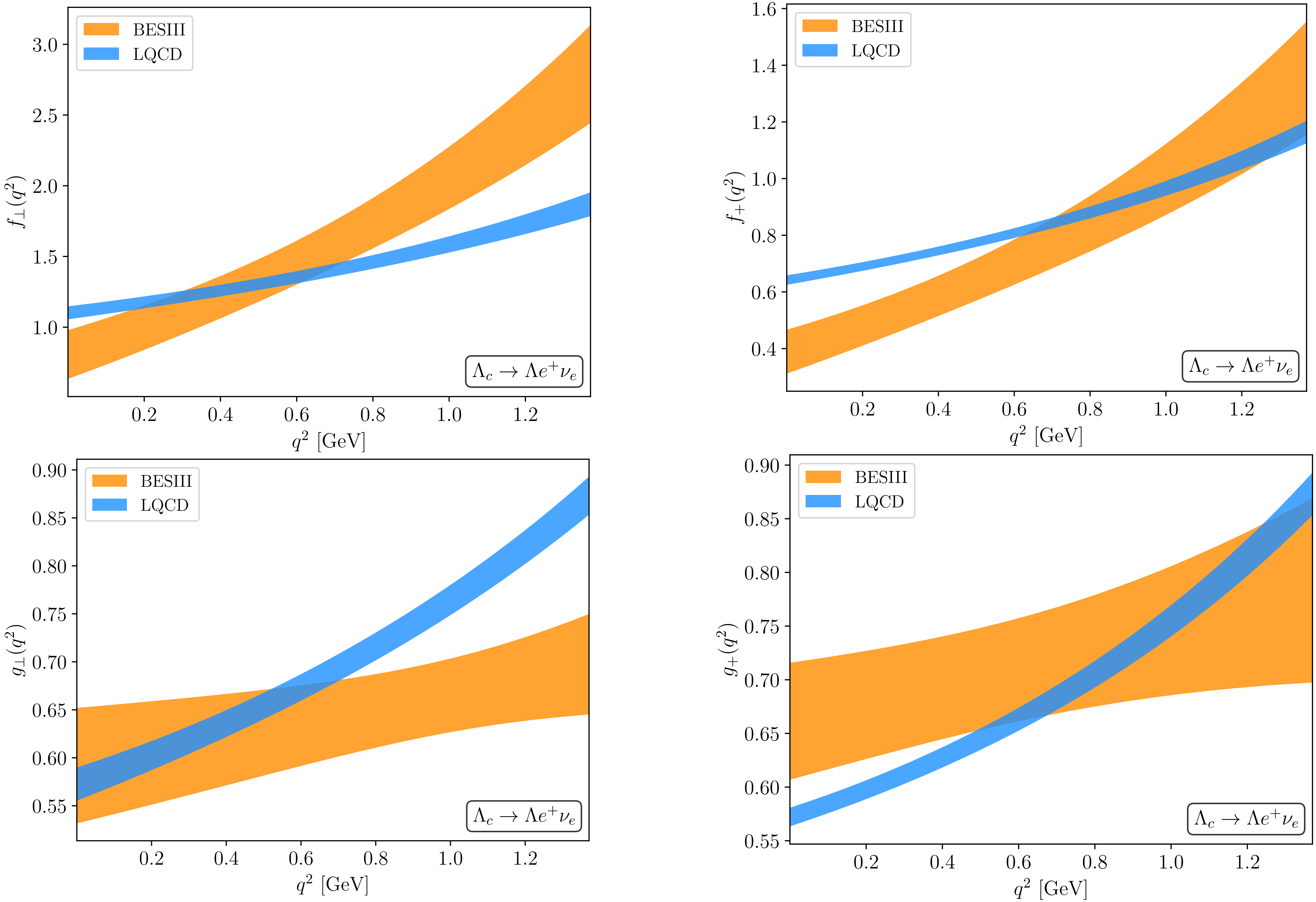




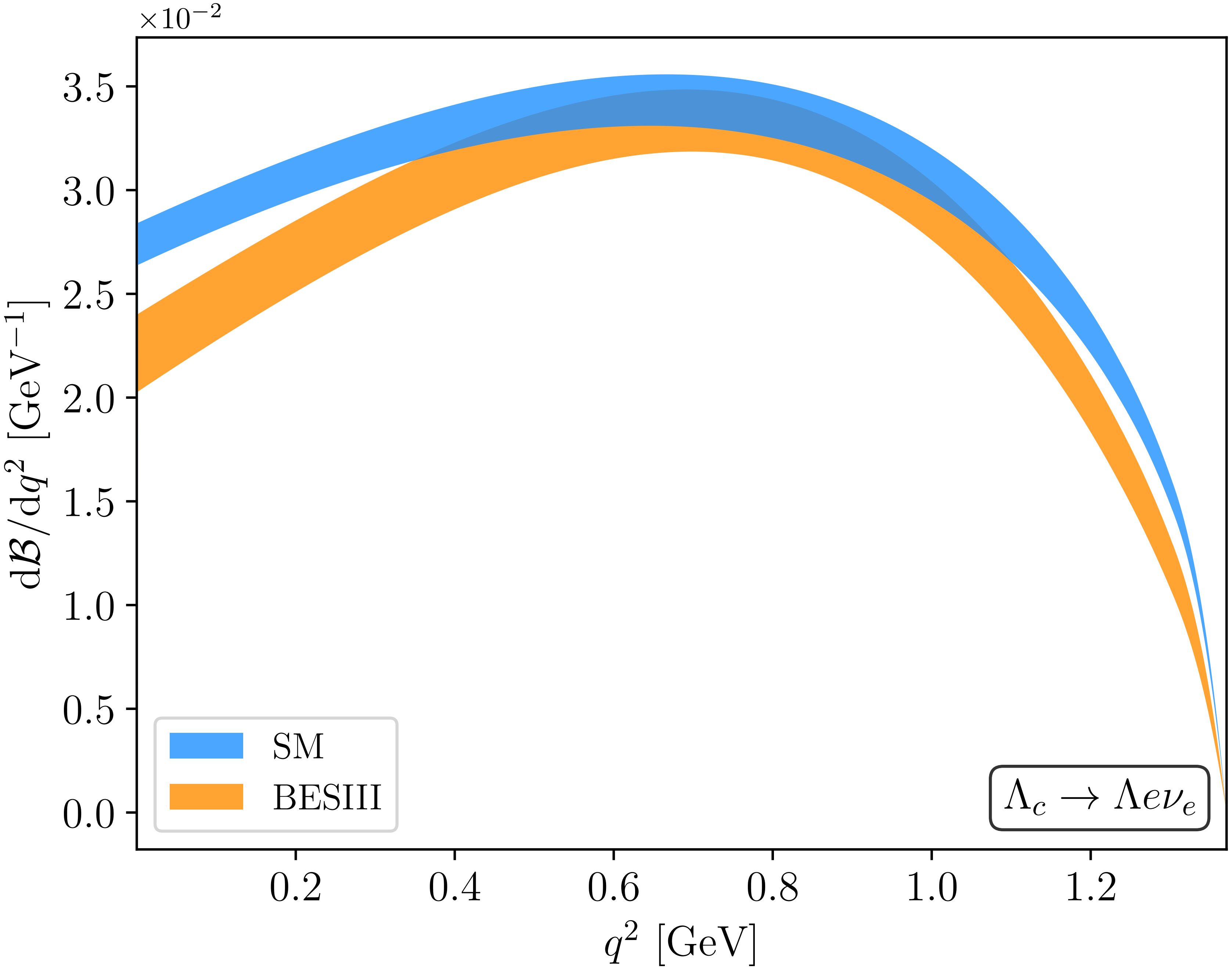
BESIII 2207.14149
Meinel 1611.09696

BESIII $\Lambda_c \to \Lambda(\to p\pi)\, e\nu$



In terms of $\Lambda_c \to \Lambda(\to p\pi)\, e\nu$ observables

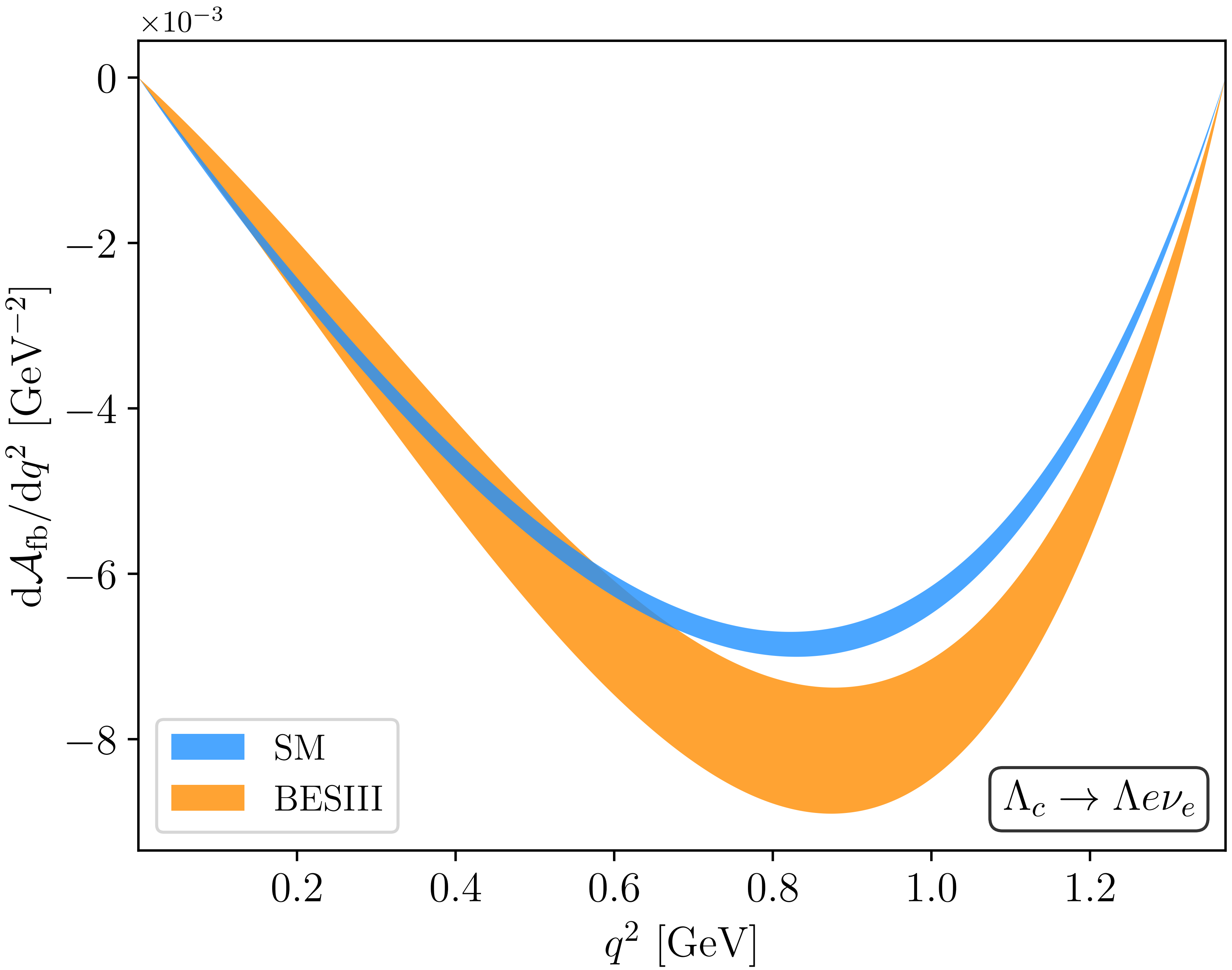
$$\frac{\mathrm{d}\mathcal{B}(q^2)}{\mathrm{d}q^2} = 2\tau_{\Lambda_c} \sum_{\lambda,\lambda_\ell} \left[a_\lambda^{\lambda_\ell}(q^2) + \frac{c_\lambda^{\lambda_\ell}(q^2)}{3} \right]$$



$$\frac{\mathrm{d}^2\Gamma_\lambda^{\lambda_\ell}}{\mathrm{d}q^2\mathrm{d}\cos\theta} = a_\lambda^{\lambda_\ell}(q^2) + b_\lambda^{\lambda_\ell}(q^2)\cos\theta + c_\lambda^{\lambda_\ell}(q^2)\cos^2\theta$$

In terms of $\Lambda_c \to \Lambda(\to p\pi)\, e\nu$ observables

$$\frac{\mathrm{d}A_{\rm fb}(q^2)}{\mathrm{d}q^2} \propto \sum_{\lambda,\lambda_\ell} b_\lambda^{\lambda_\ell}(q^2)$$



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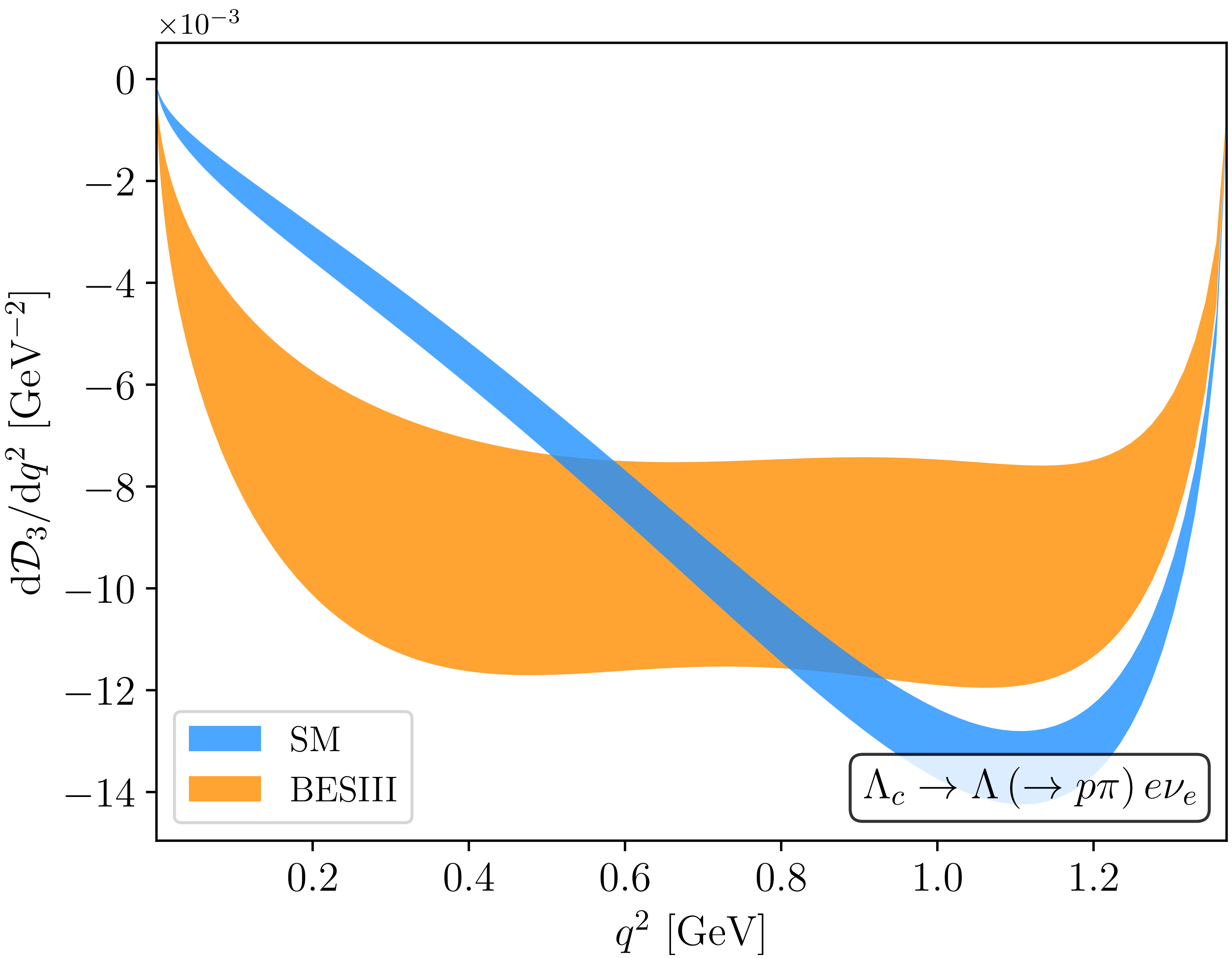
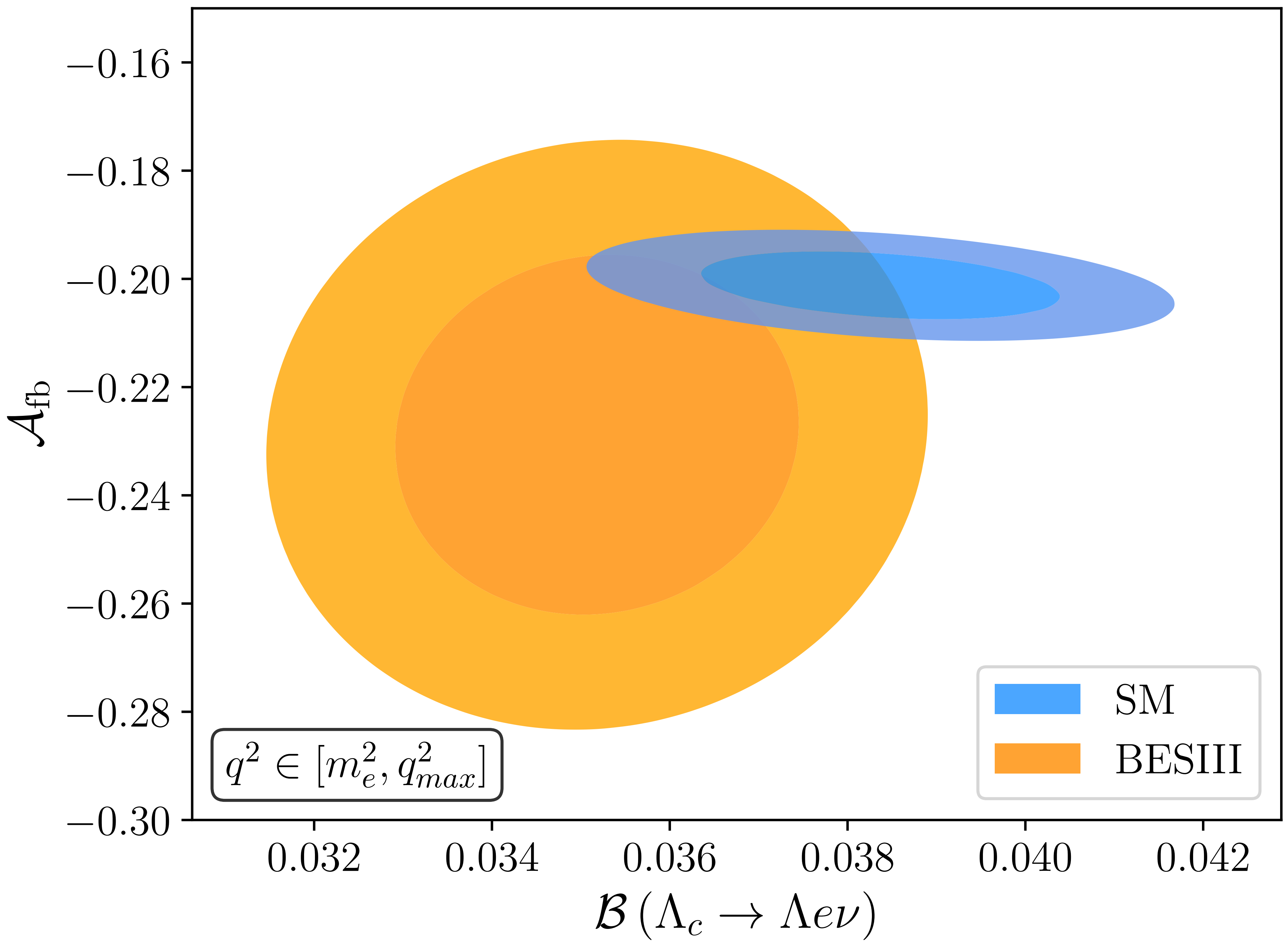


NB: No info on q^2-binned data! Only on the same [correlated] parameters of the FF parametrization used in the LQCD paper [1611.09696]

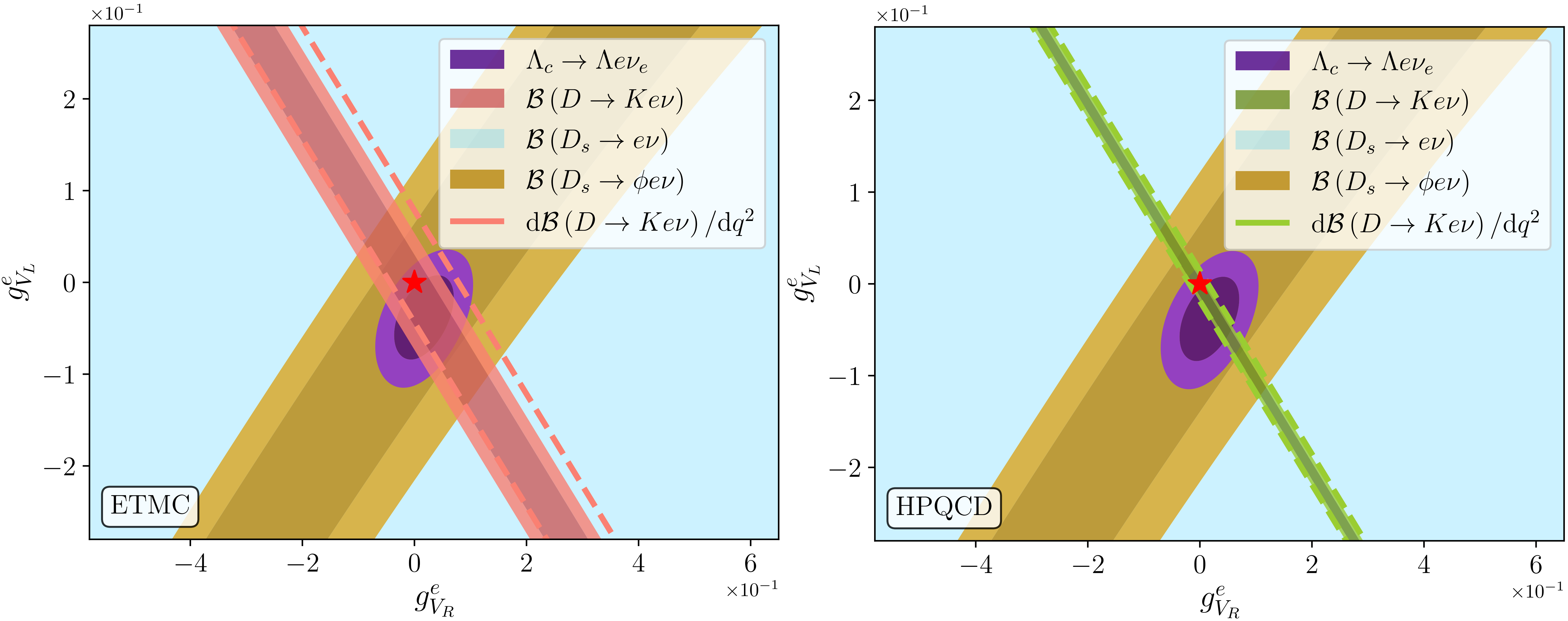
Integrated characteristics quite consistent with SM…

One interesting case…



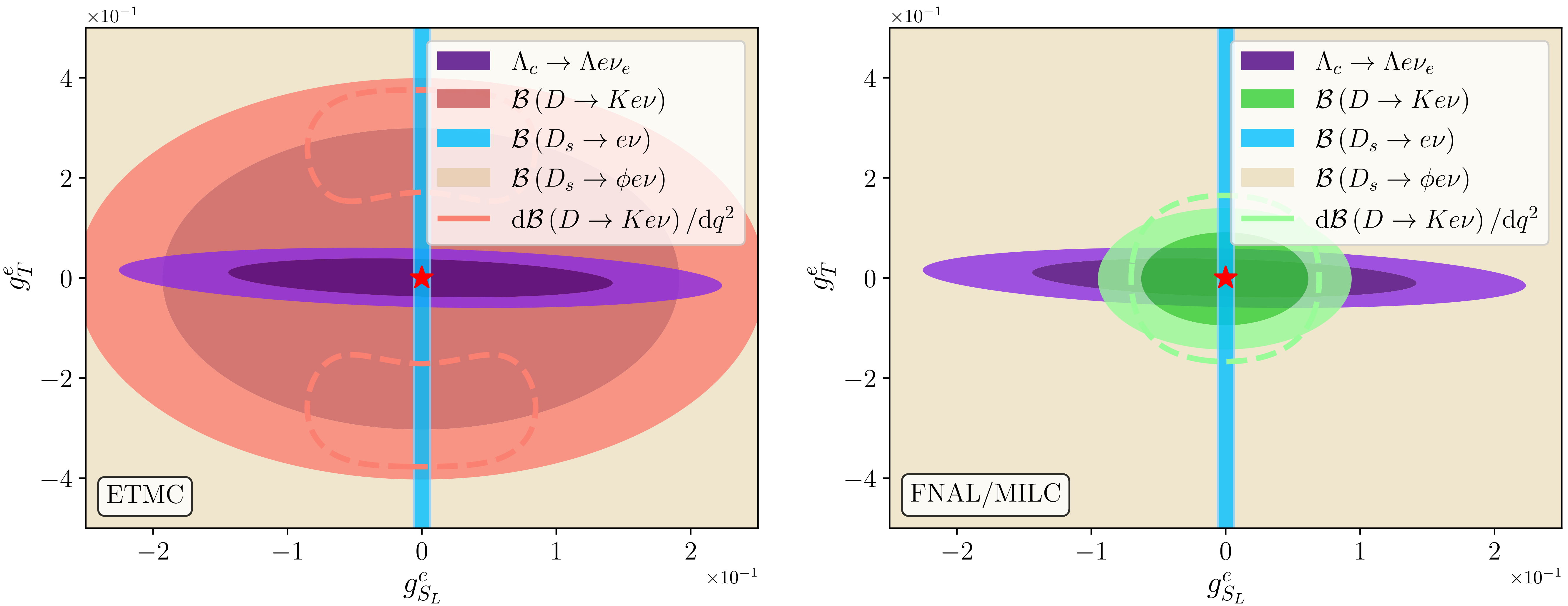
Try and feed in NP contributions

Include mesons too (where info on binned distribution is available)…



Checking on the presence of coupling to RH current

Try and feed in NP contributions



Notice the benefit of the binned distribution in $D \to K\, e\, \nu$ $\langle dB/dq^2 \rangle$

In the scenarios with S_1 or R_2 SLQ

$$g_{S_L} = \pm 4\, g_T \xrightarrow{\Lambda_{\rm NP} \to 2\ \rm GeV} g_{S_L} \simeq \pm 11.2\, g_T$$

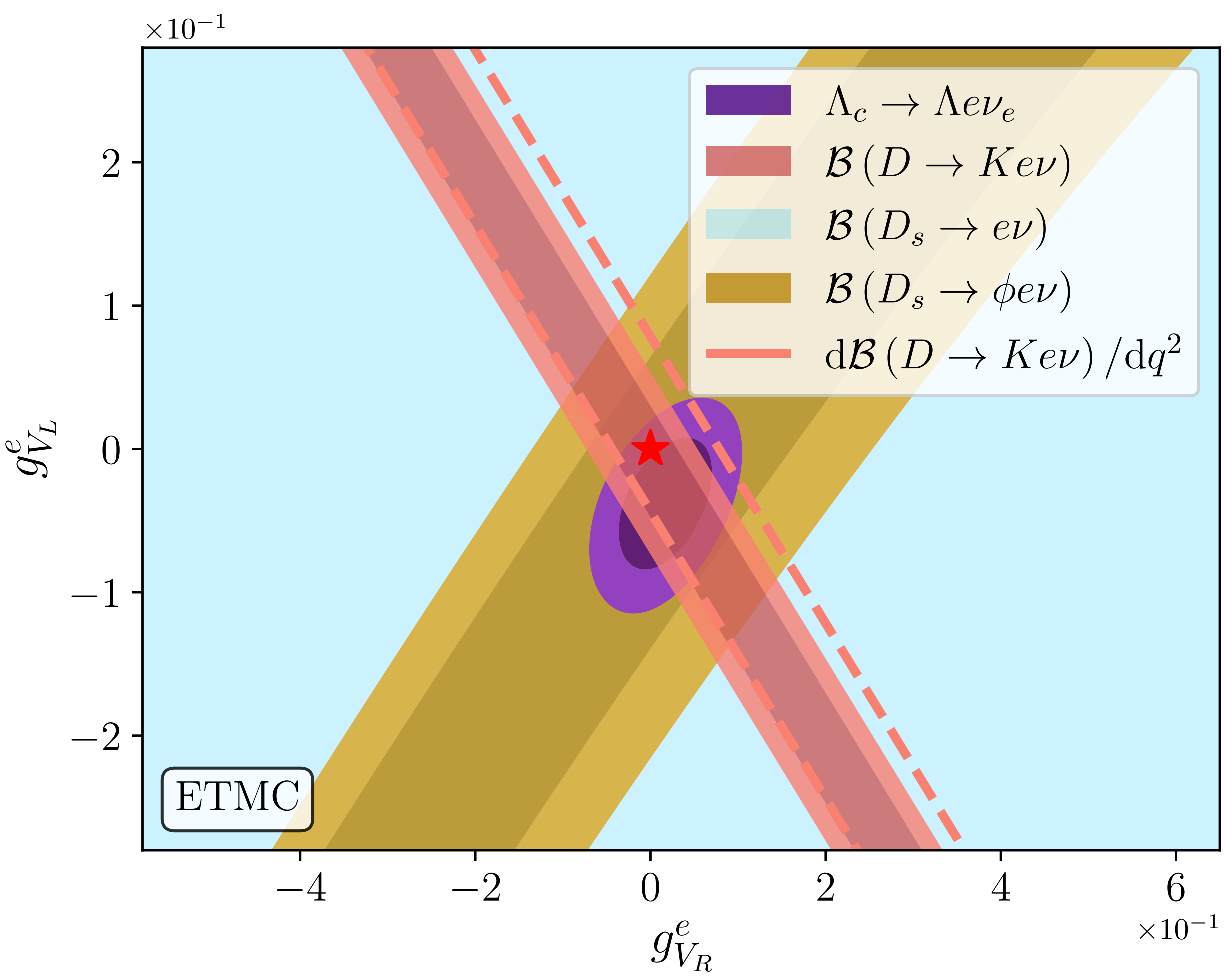
LHC window to high-p_T tails of…

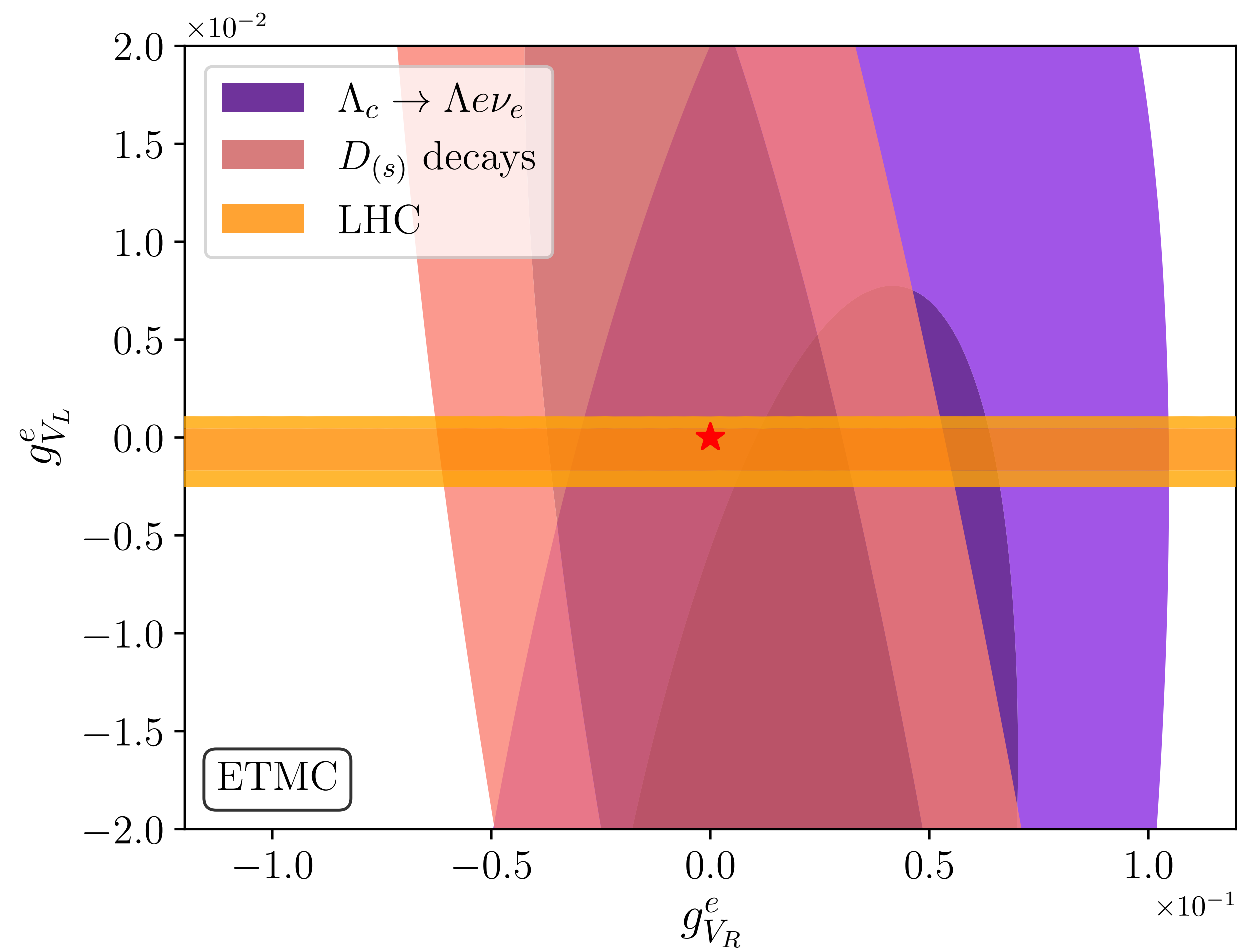
$$\sigma(pp \to \ell\nu) = \int_0^1 dx_1\, dx_2\, f_{\bar{s}}(x_1,\mu) f_c(x_2,\mu) \hat{\sigma}(\bar{s}c \to \ell\nu) + (\bar{s} \leftrightarrow c)$$

So stringent for ℓ=e that reconsidering K-factor becomes indispensable

Camalich et al 2003.12421, Allwicher et al 2207.10714

137/fb of LHC data HighPT





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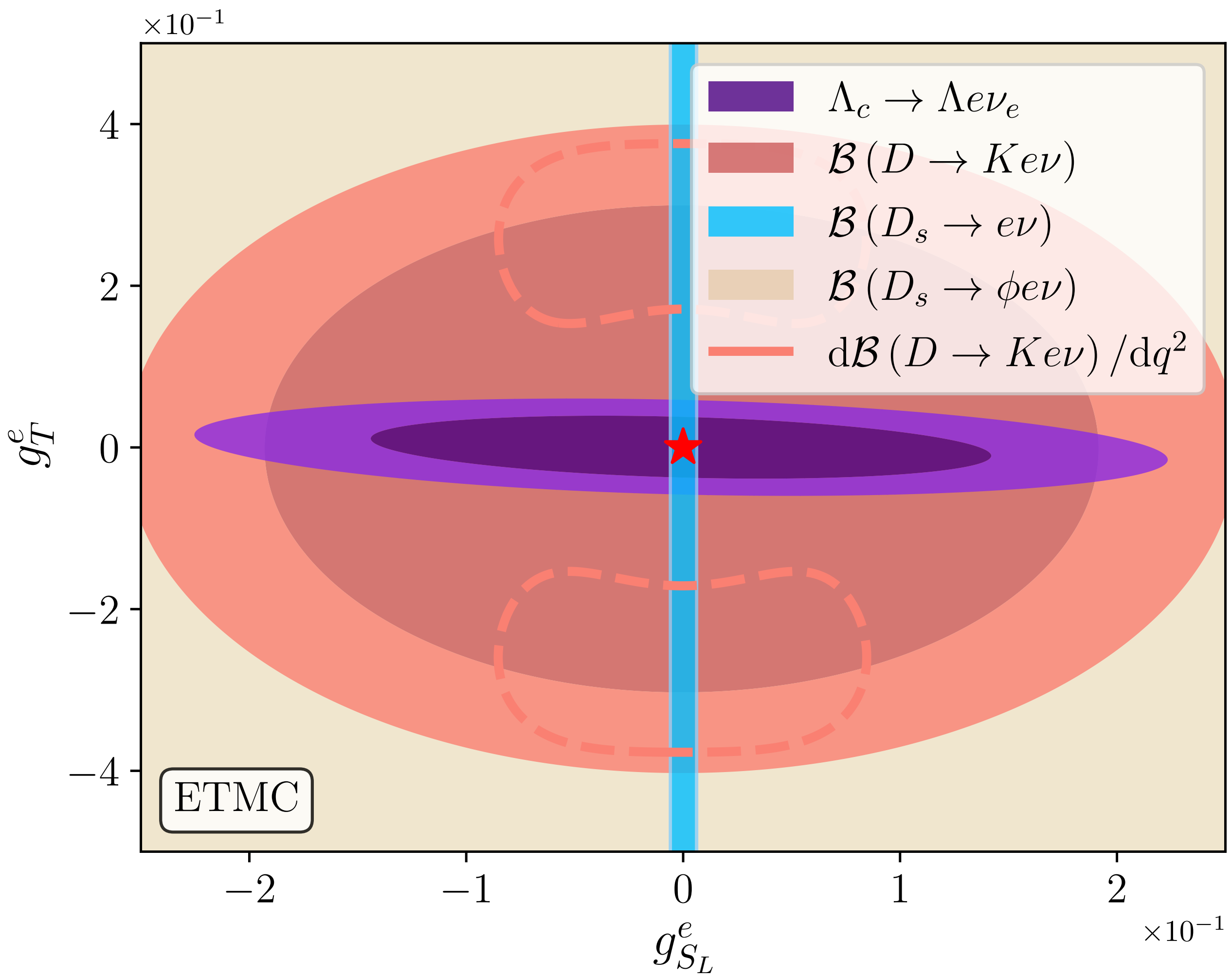
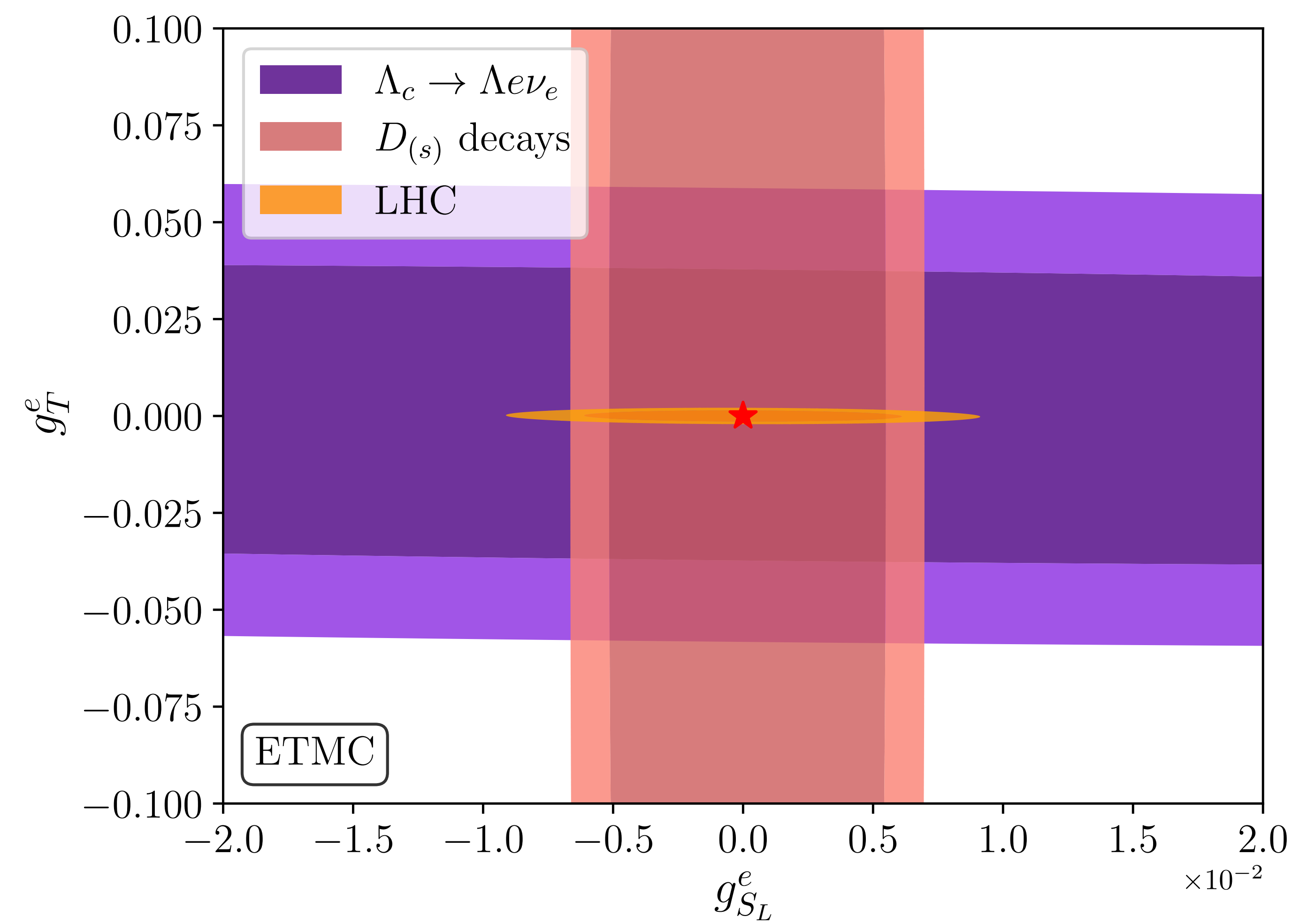




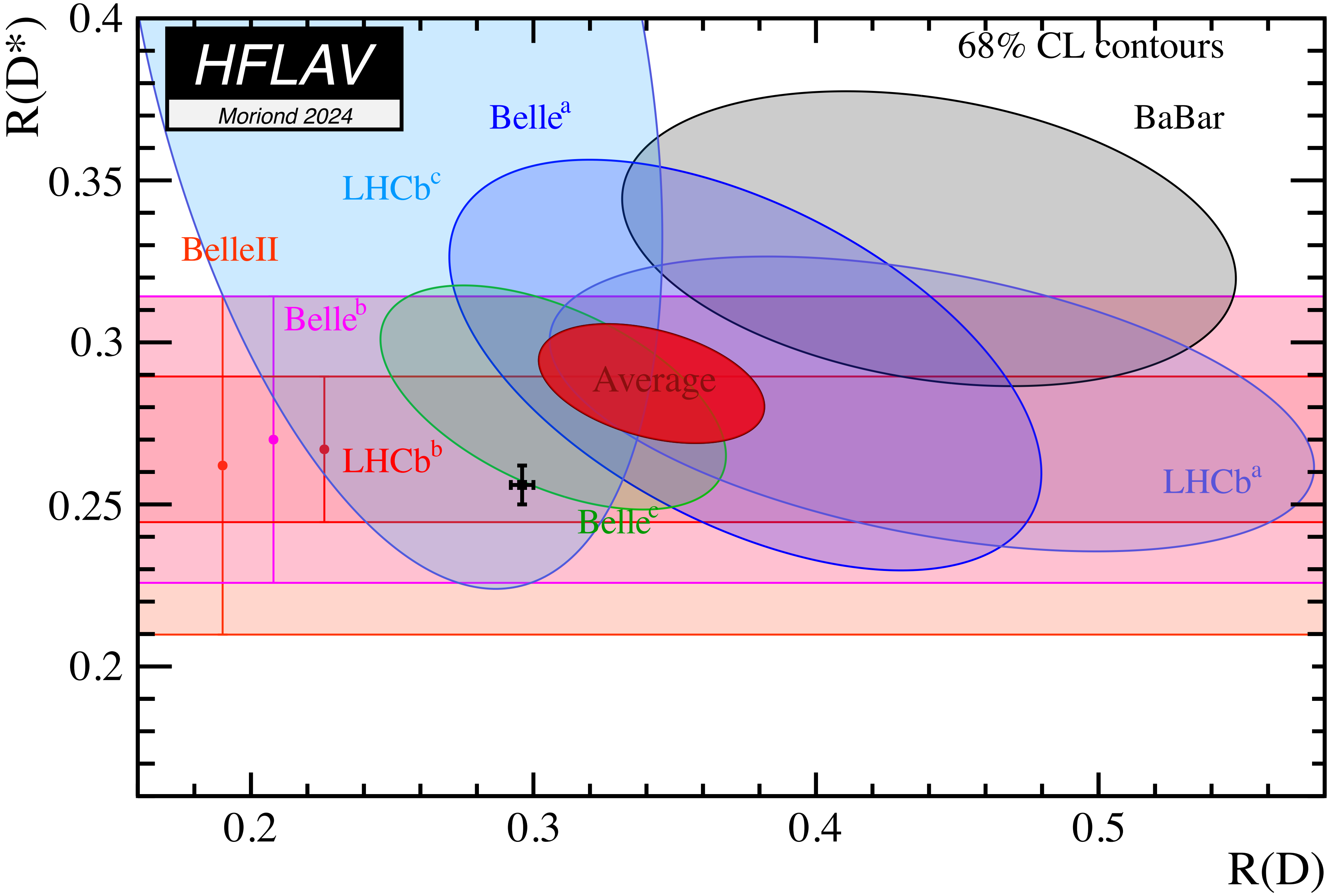
Concluding remarks 1

- Testing the strategy to extract NP couplings from low energy data
- LQCD control over the SL meson form factors is not fully satisfactory
- Another LQCD estimates of $D_s \to \phi\, \ell\nu$ and $\Lambda_c \to \Lambda\, \ell\nu$ form factors needed
- Exp info on the q^2-binned distributions of angular observables would be very welcome too
- LHC info on high-p_T tails of DY lead to very stringent constraints on NP couplings

  K-factor should be scrutinized but even if $K \simeq 2$, there is very little room for NP in channels with e or μ in the final state
- If there are no NP contributions to $c \to s\, e\nu$ or they are indeed tiny, this is becoming a LQCD laboratory: form factor normalizations and shapes
- That could be an important 1st step to solving the $B \to D^* \ell\, \nu$ form factor [LQCD] ambiguity/problem/discrepancy

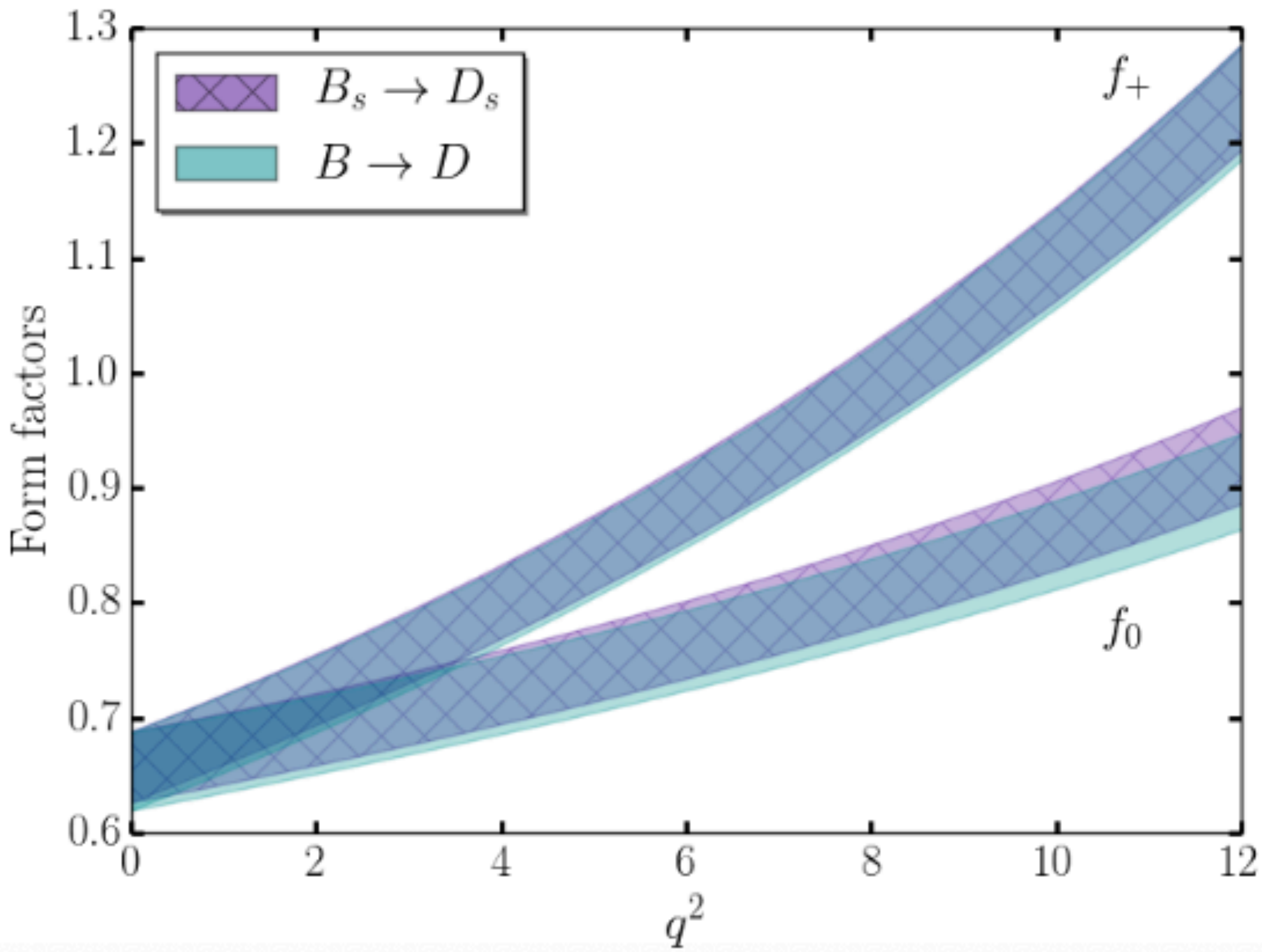
LFUV

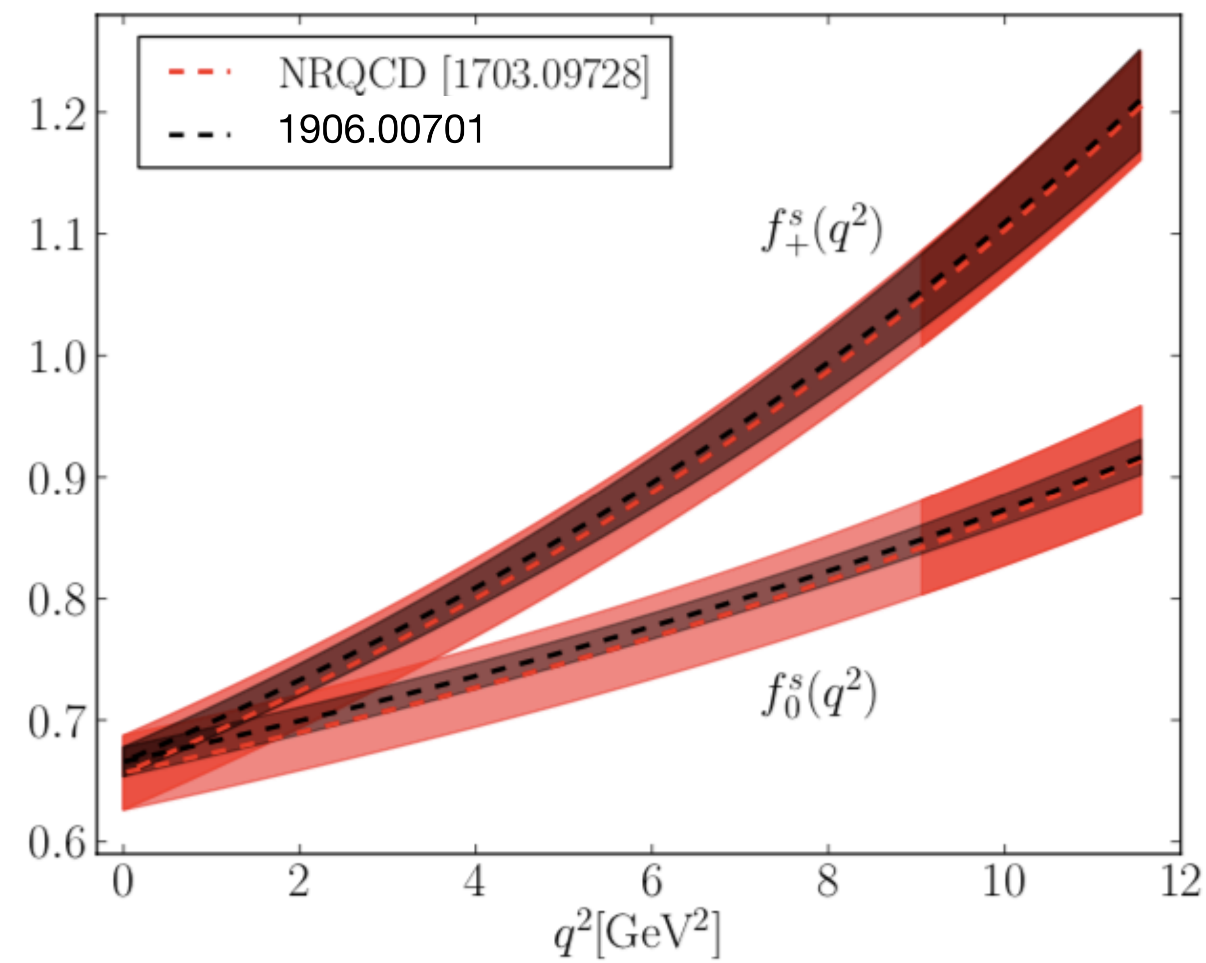
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$



- 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

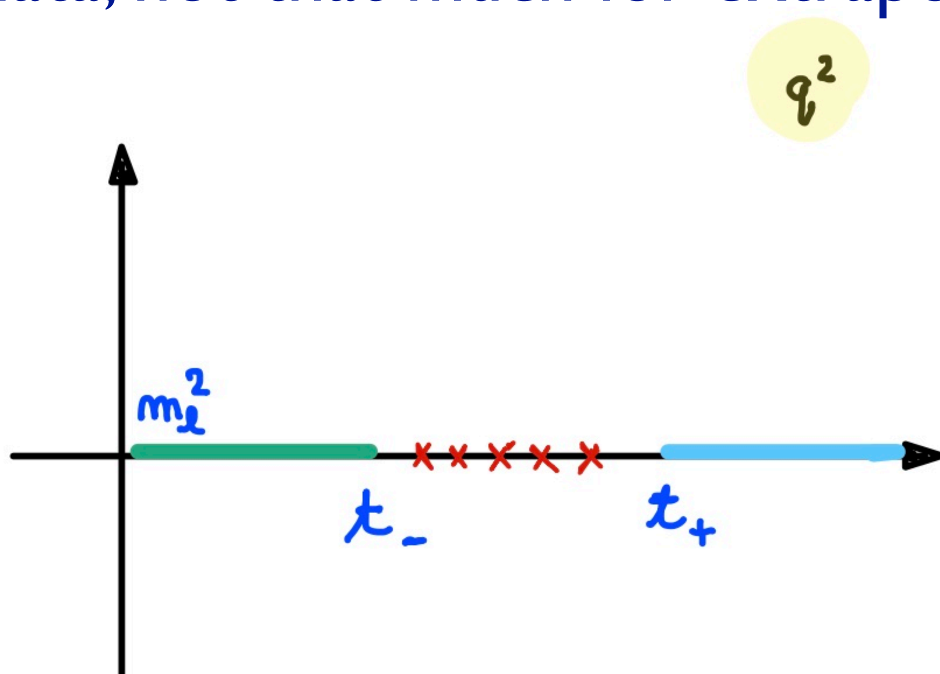
Intermezzo: on the shapes of FFs

Slightly heavy/messy a story (esp. for vector meson in the final state):

1. Matrix elements in terms of form factors $\quad q^2 = m_B^2 + m_{D^*}^2 - 2m_B m_{D^*}\, w$

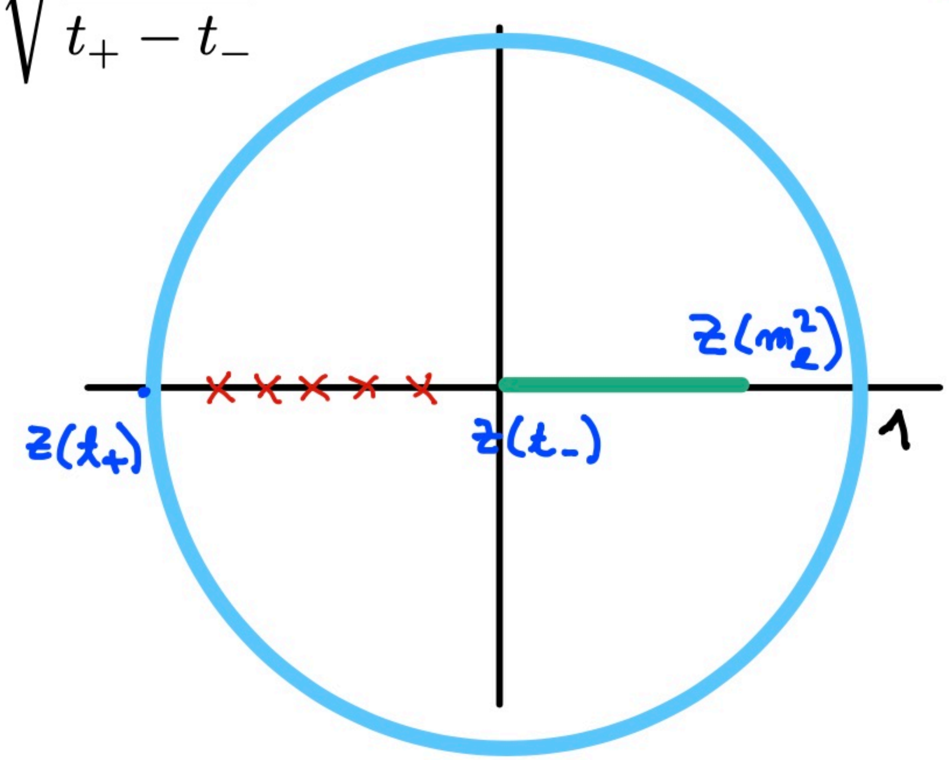
   $V(q^2), A_{1,2,0}(q^2)$ or $f(q^2), g(q^2), F_1(q^2), F_2(q^2)$ or $h_V(w), h_{A1,A2,A3}(w)$

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, not that much for extrapolation, cf. 4.



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

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



Intermezzo: on the shapes of FFs

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

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

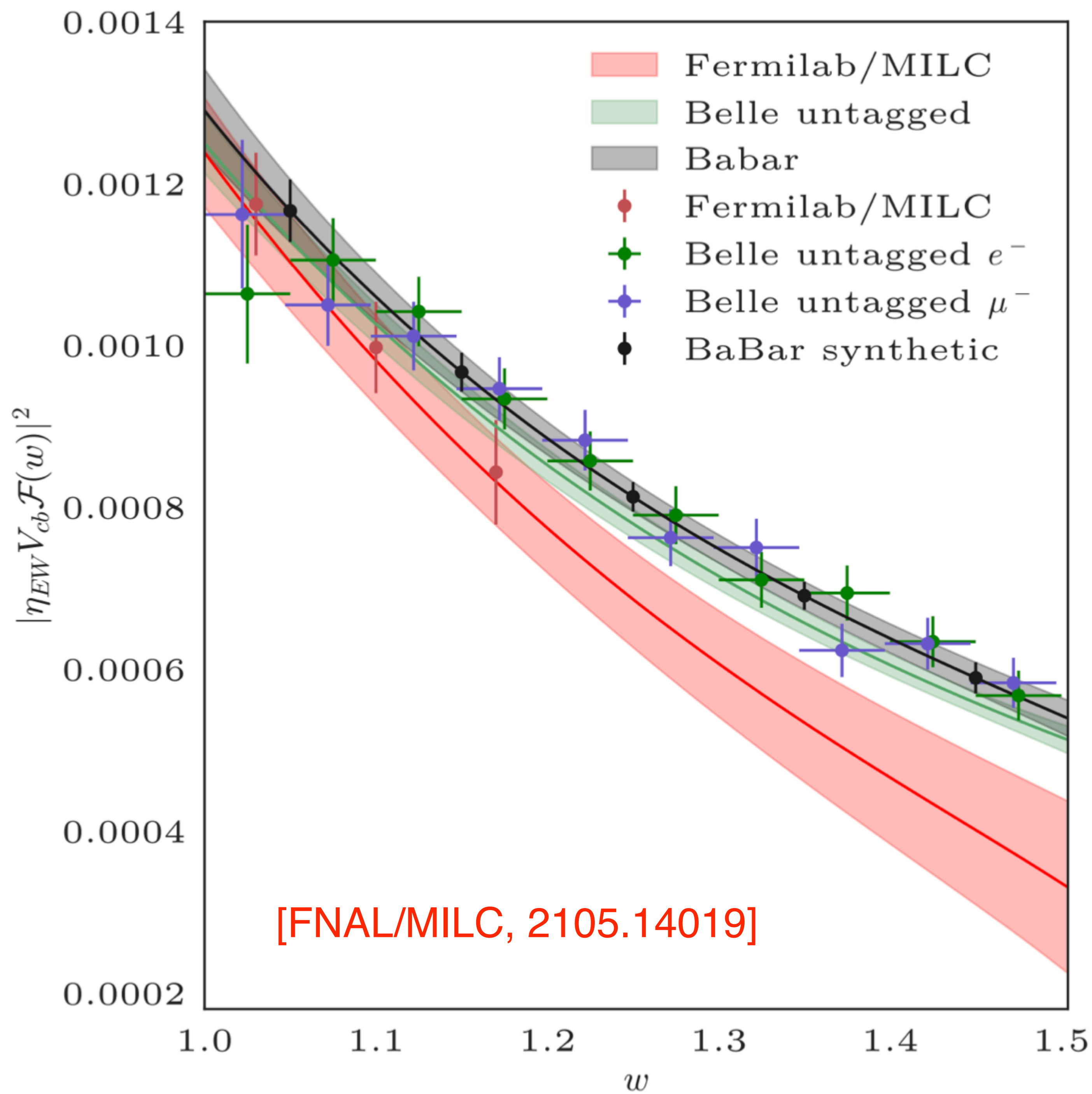
$$P(z(q^2)) = \prod_{i=1}^{n_{\text{poles}}} \frac{z(q^2) - z(m_i^2)}{1 - z(q^2) z(m_i^2)}$$

4. Need to model nonetheless b/c P(z) sent poles onto the circle (branch cuts not controlled anyway!) and the physical info is `lost'. In heavy-to-light the pole is explicitly factored out and then z-expansion applied (BCL).

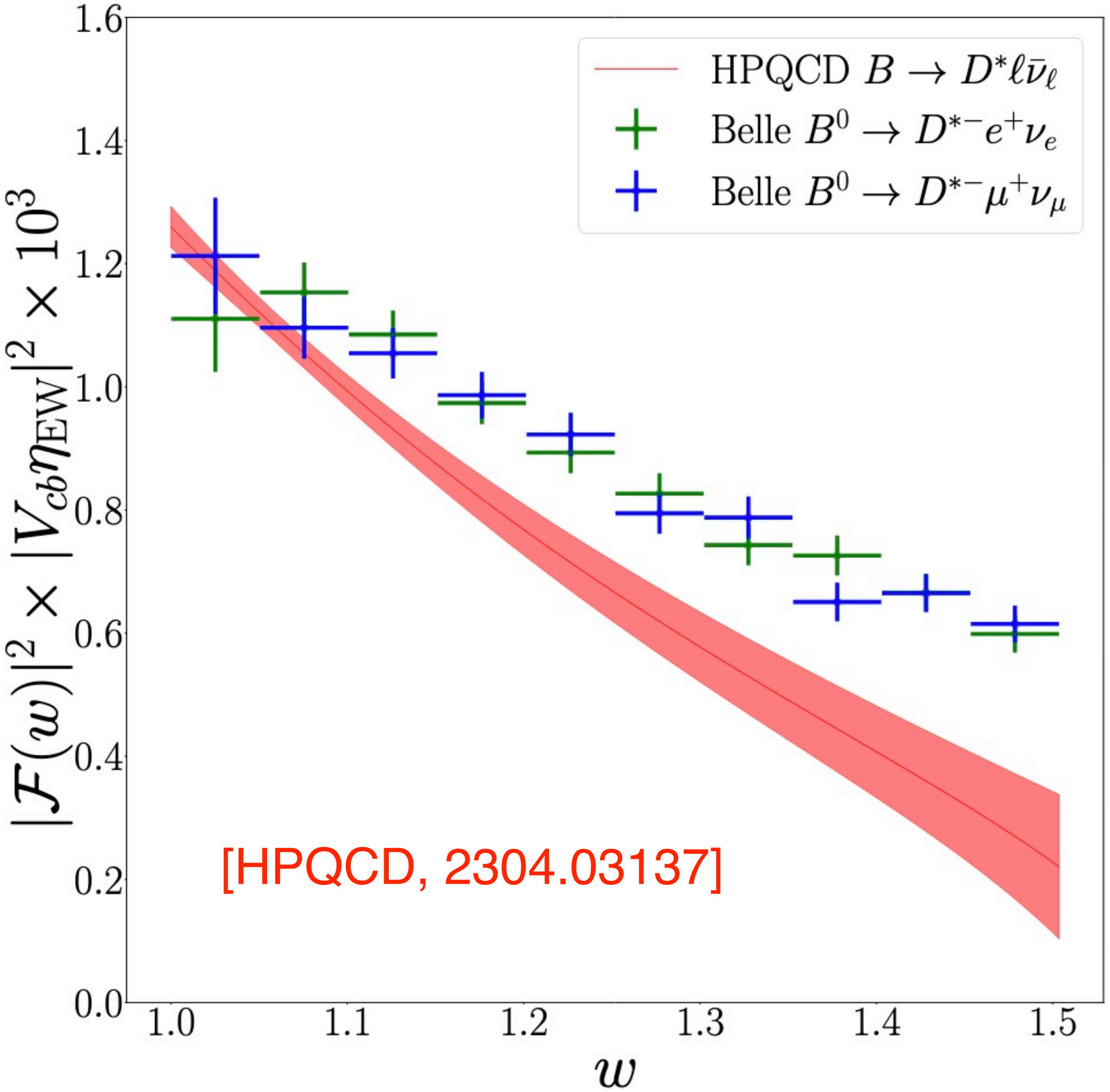
$$\mathcal{F}(q^2) = \frac{1}{1 - q^2/m_{\text{pole}}^2} \sum_{n=0}^{N} \widetilde{a}_n \; z(q^2)^n$$

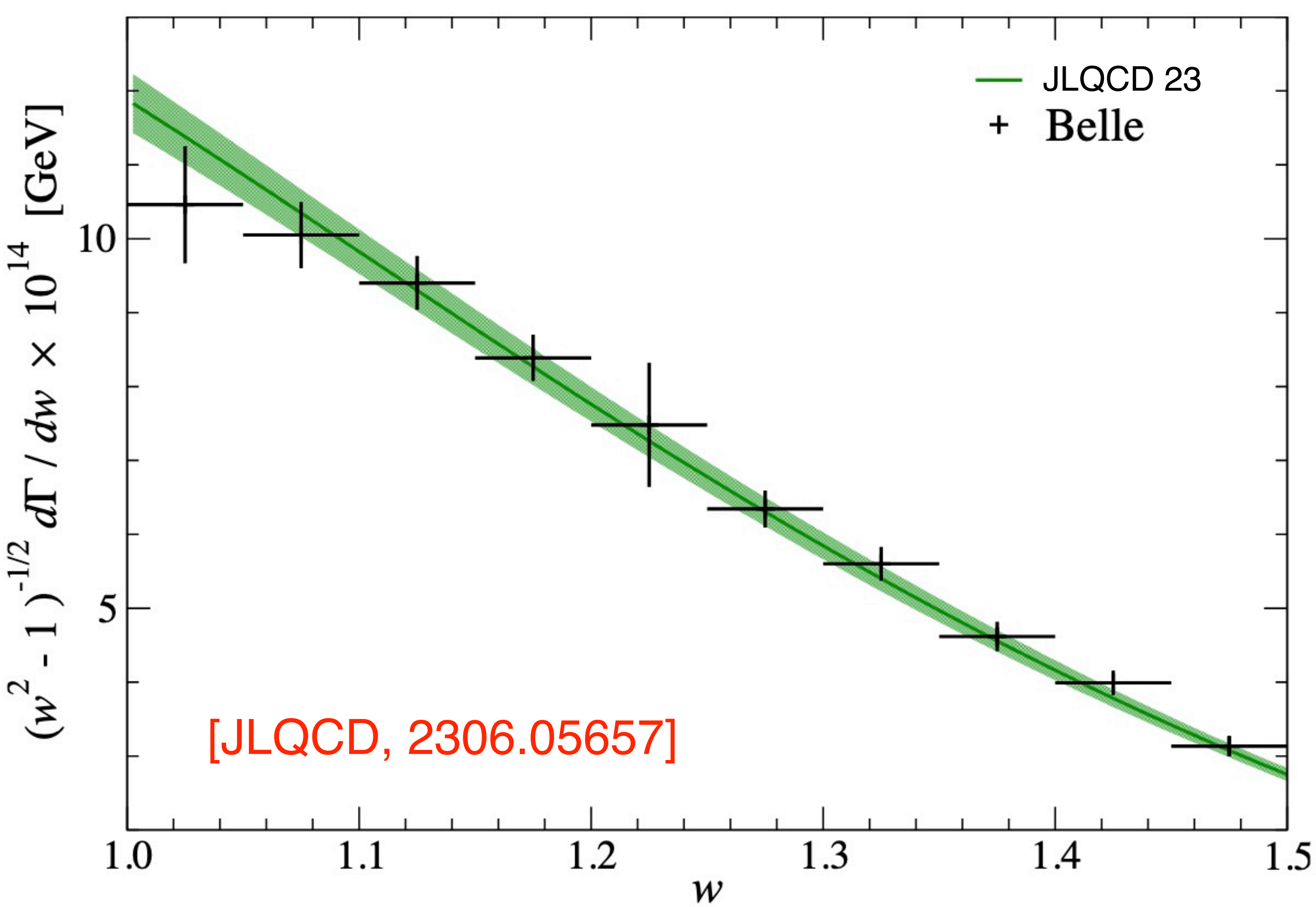
5. One might as well expanded in q^2/Λ^2, or model differently… sigh!

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

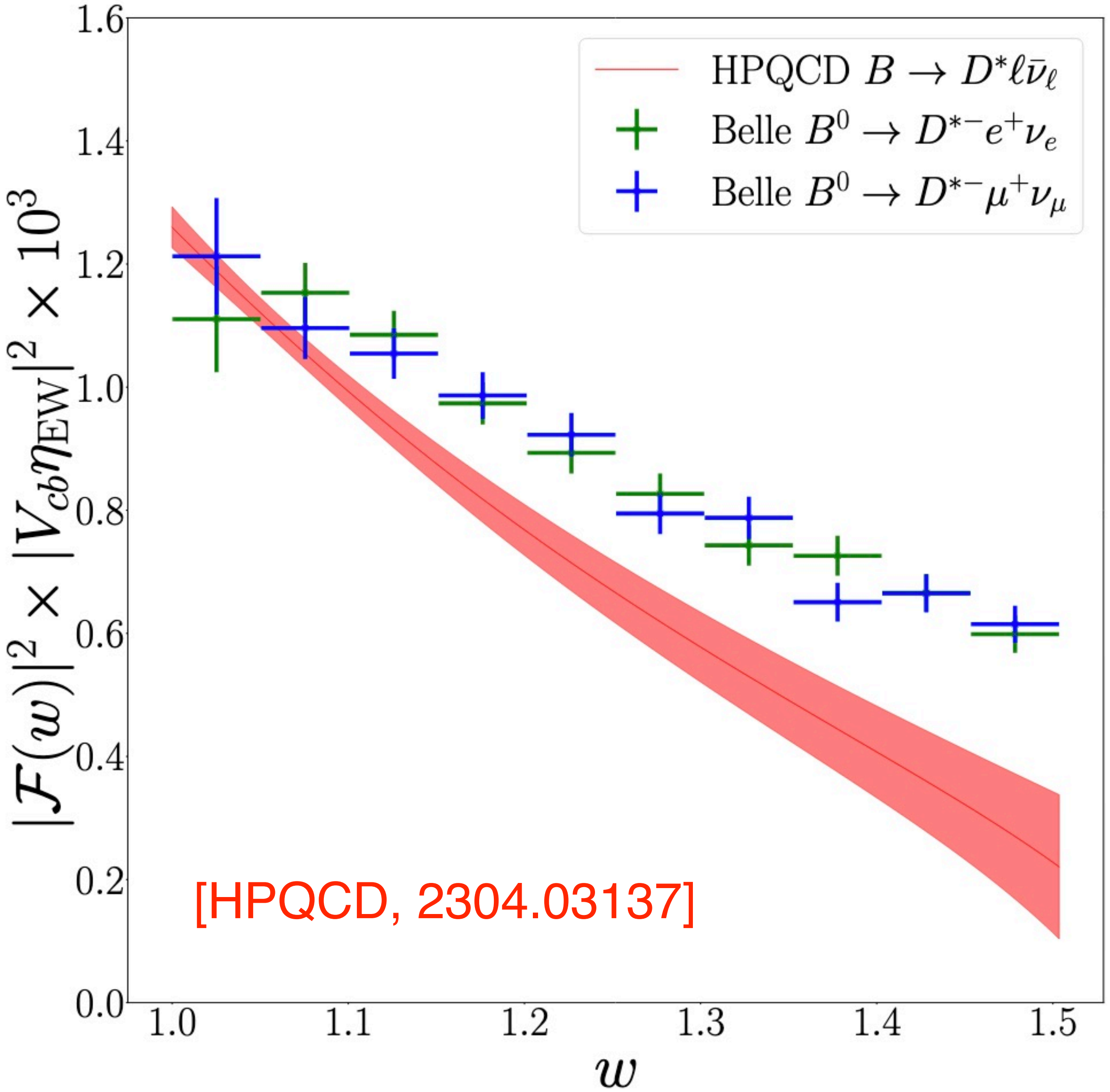


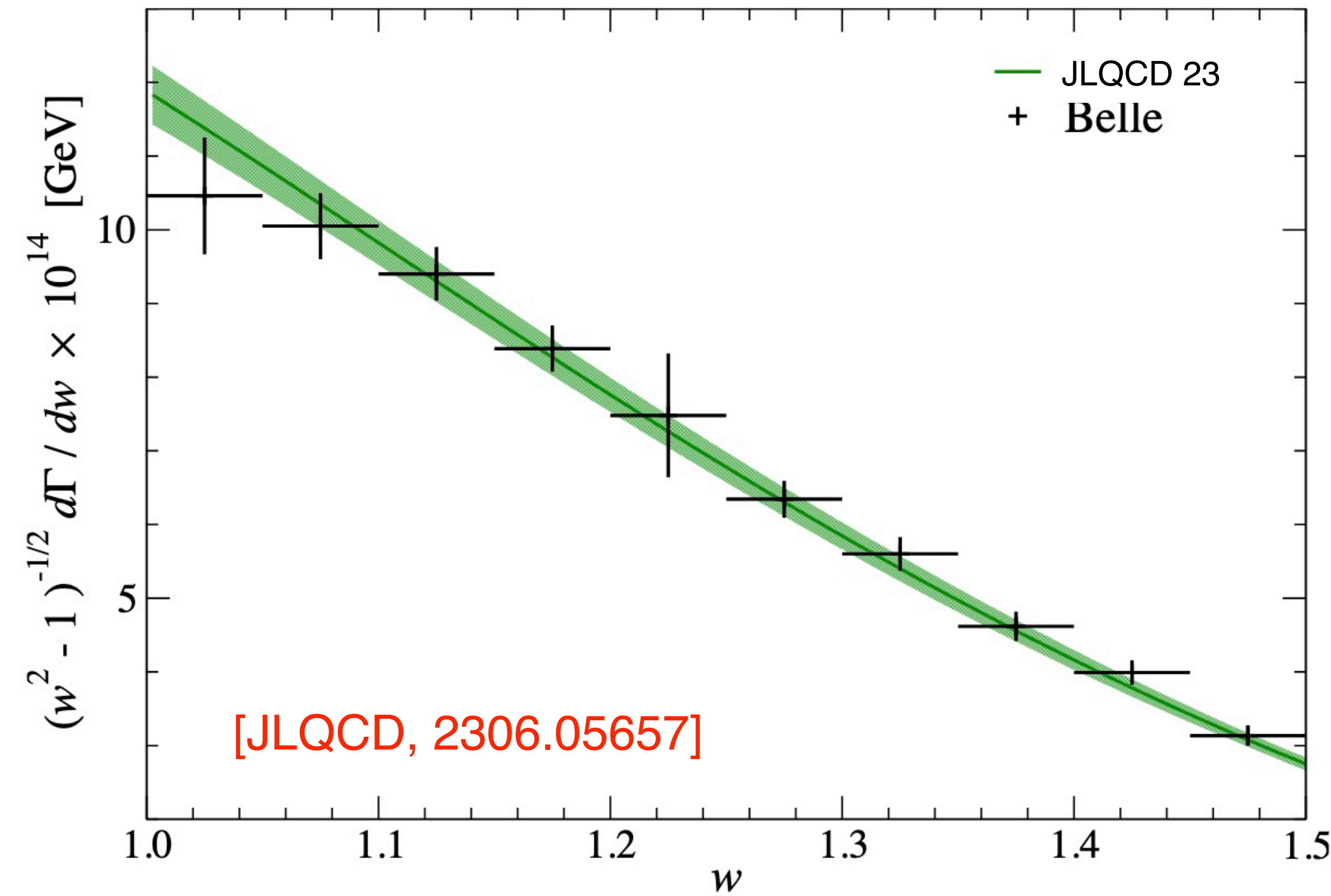
$$\langle D^*|\bar{c}\gamma_\mu(1-\gamma_5)b|B\rangle \propto V(q^2), A_{1,2,0}(q^2) \propto \mathcal{F}(w)\ldots$$





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





★ Two different discretisation procedure - different results in continuum
★ V_{cb} extraction - (not a) problem
★ *We can use exp info on angular distribution and convert them to FFs... which is what we do...* cf. 2404.16772

CLN or BGL or…

$$\frac{d\Gamma(\overline{B} \to D^* \ell^- \overline{\nu}_\ell)}{dw} = \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2 \chi(w) \eta_{EW}^2 \mathcal{F}^2(w) |V_{cb}|^2$$

$$\chi(w)\mathcal{F}^2(w) = h_{A_1}^2(w)\sqrt{w^2-1}(w+1)^2 \left\{ 2\left[\frac{1-2wr+r^2}{(1-r)^2}\right]\left[1 + R_1^2(w)\frac{w-1}{w+1}\right] + \left[1 + (1 - R_2(w))\frac{w-1}{1-r}\right]^2 \right\}$$

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

$r = m_{D^*}/m_B$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right]$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

CLN 9712417

BGL 9705252

these should be fit too and not fixed as in CLN

✘ Exp data fit very well with CLN, but eventually [with ever better precision] BGL should be the ultimate choice, if you decide to follow this route…

SM and if NP affects only decays to $\tau\nu$...

a. Use HFLAV results [2206.07501]

$$\rho^2 = 1.121(24), \quad R_1(1) = 1.269(26), \quad R_2(1) = 0.853(17)$$

b. With $R_0(w) = \left[1 - \frac{q^2}{(m_B + m_{D^*})^2}\right] \frac{A_0(q^2)}{A_1(q^2)}$, and $\frac{A_0(0)}{A_1(0)} = \frac{1}{2m_{D^*}}\left[m_B + m_{D^*} - (m_B - m_{D^*})\frac{A_2(0)}{A_1(0)}\right]$

we have $R_0(w_{\rm max}) = \frac{m_B + m_{D^*}}{2m_{D^*}} - \frac{m_B - m_{D^*}}{2m_{D^*}} R_2(w_{\rm max}) = 1.087(14)$;

and from LQCD we only take $R_0(1) = \frac{4m_B m_{D^*}}{(m_B + m_{D^*})^2} \frac{A_0(q^2_{\rm max})}{A_1(q^2_{\rm max})} = 1.087(26)$

$$\Longrightarrow \quad \boxed{R_0(w) = 1.09 - 0.16(w-1)}$$

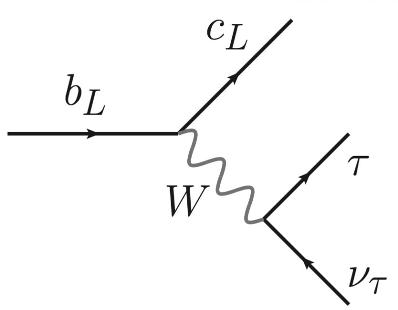
c. We get:

$$R_{D^*}^{\rm SM} = 0.247(2) \quad < \quad R_{D^*}^{\rm exp} = 0.285(12)$$

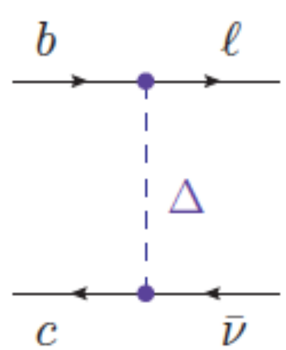
Scalar Leptoquarks in $R_{D(*)}$

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

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

Weak singlet S_1 - electric charge 1/3.

Interaction with quark/lepton both being weak doublets, or weak singlets

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

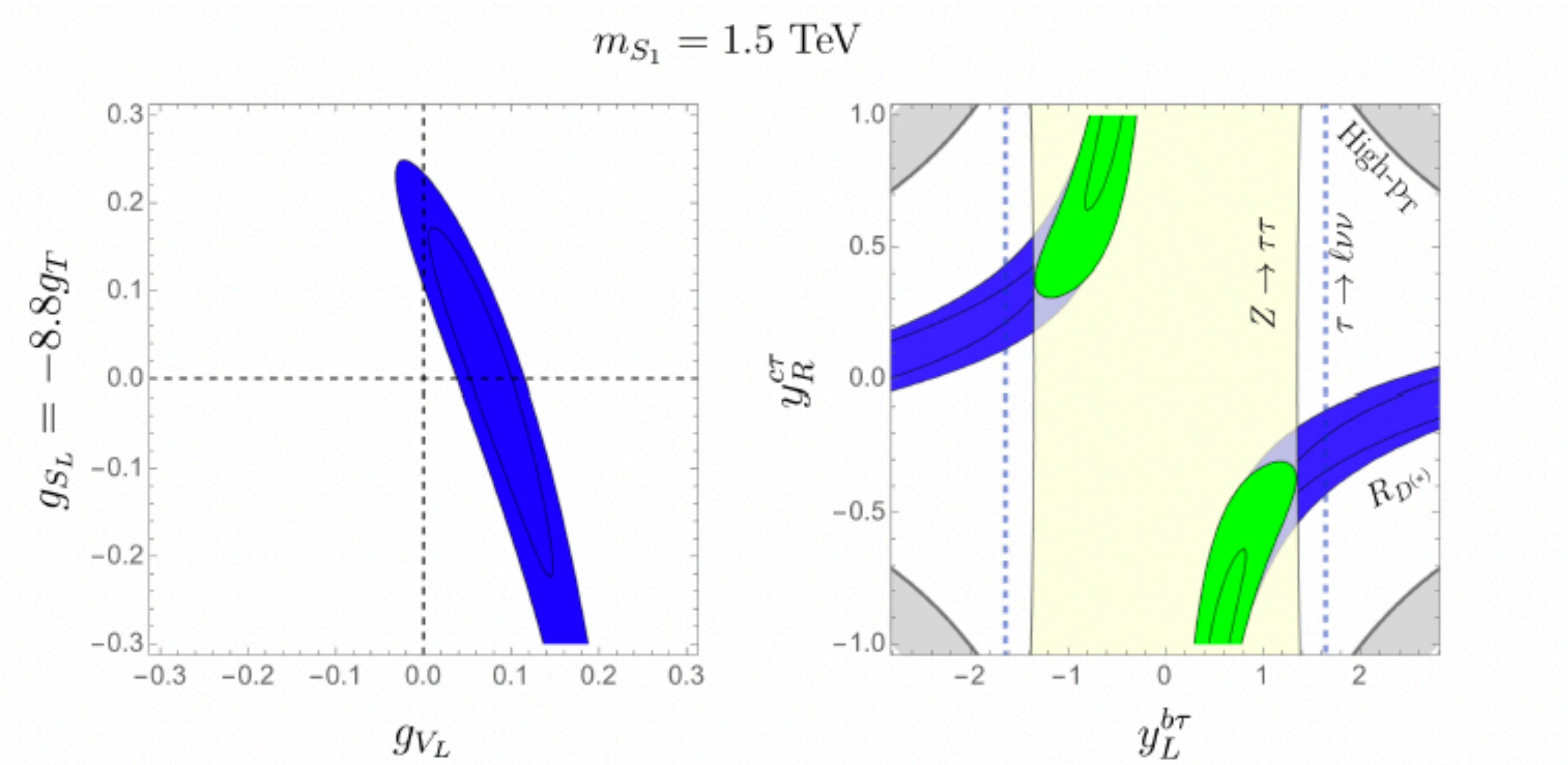
Minimal setting

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

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

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

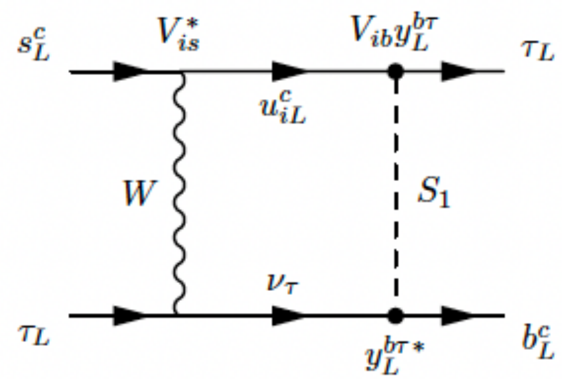
$$g_{S_L}(m_b) = -8.8 \times g_T(m_b)$$



cf. 2404.16772

And then what?

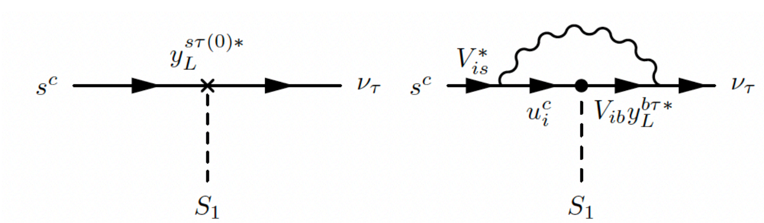
- $$\frac{\mathcal{B}(B_c \to \tau\nu)^{S_1}}{\mathcal{B}(B_c \to \tau\nu)^{\rm SM}} \in [1.13, 1.48]\,, \qquad \mathcal{B}(B_c \to \tau\nu)^{\rm SM} = (2.24 \pm 0.07)\% \times \left(\frac{V_{cb}}{0.0417}\right)^2$$
- Contribution to $b \to s\tau\tau$ or $b \to s\nu_\tau\nu_\tau$



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

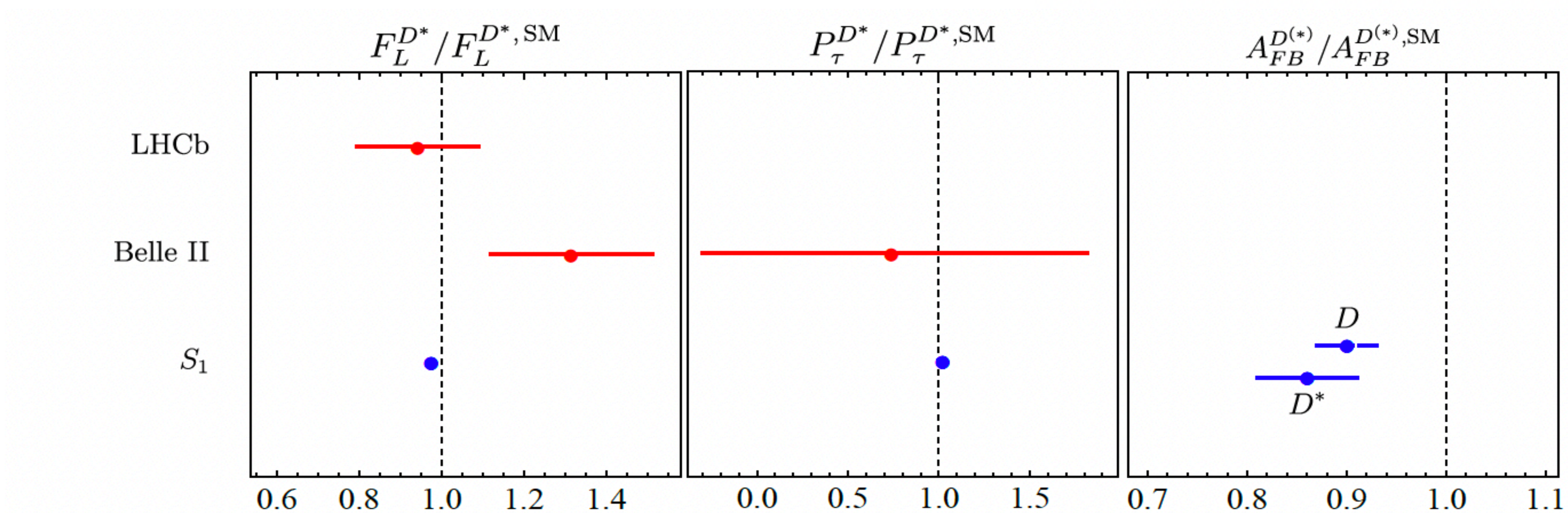
- $b \to s\nu_\tau\nu_\tau$

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



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

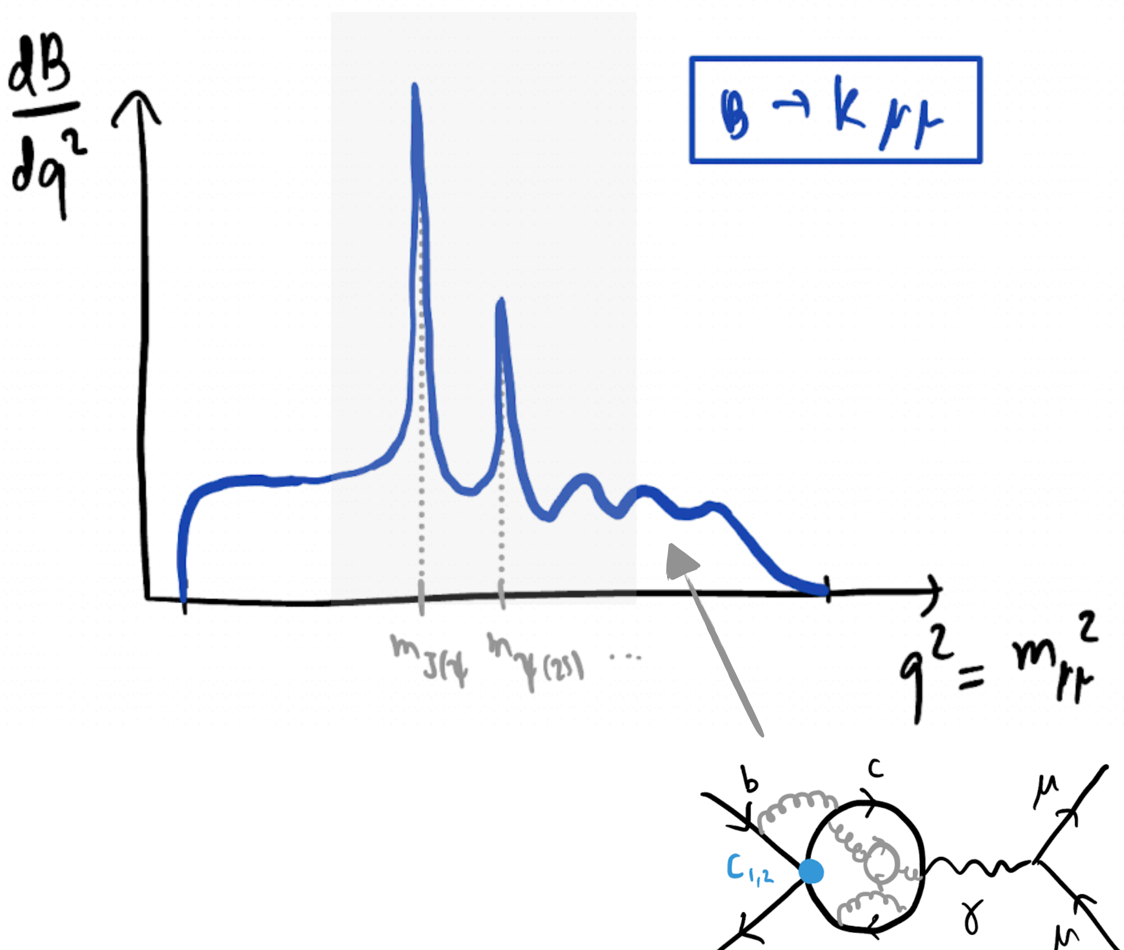
$$\frac{\mathcal{B}(B \to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\rm SM}} = \left|1 + \frac{\delta C_L^{S_1}}{3\, C_L^{\rm SM}}\right|^2 \in [1.001, 1.02] \quad (@2\sigma)$$

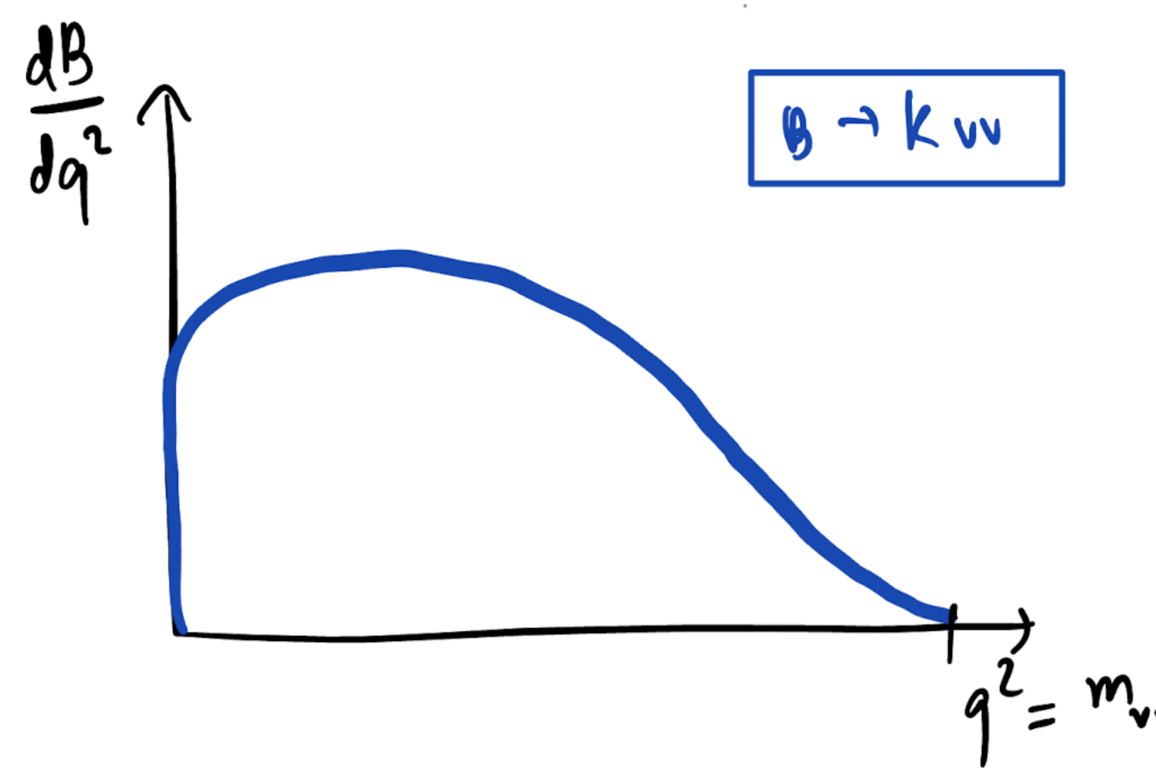
- 

$B \to K\nu\bar{\nu}$ is (not) better…

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

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

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

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

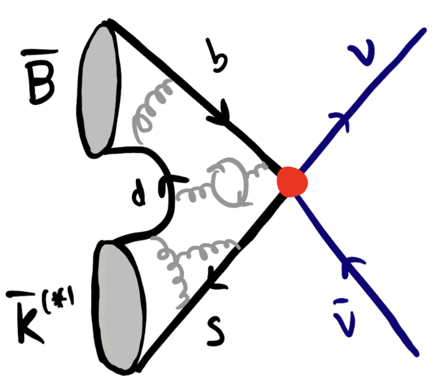
$$C_L^{\text{SM}} = -X_t/\sin^2\theta_W$$
$$= -6.32(7)$$

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: $B \to K\nu\bar{\nu}$

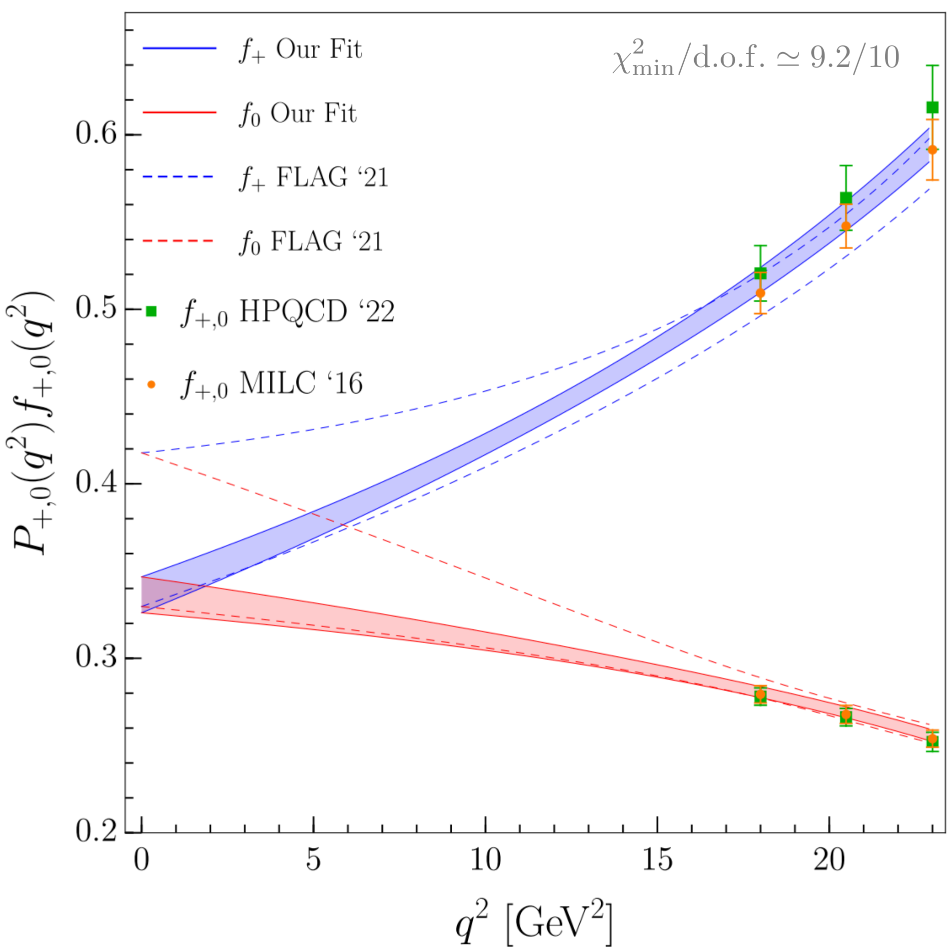
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\text{max}}$) for all form-factors:

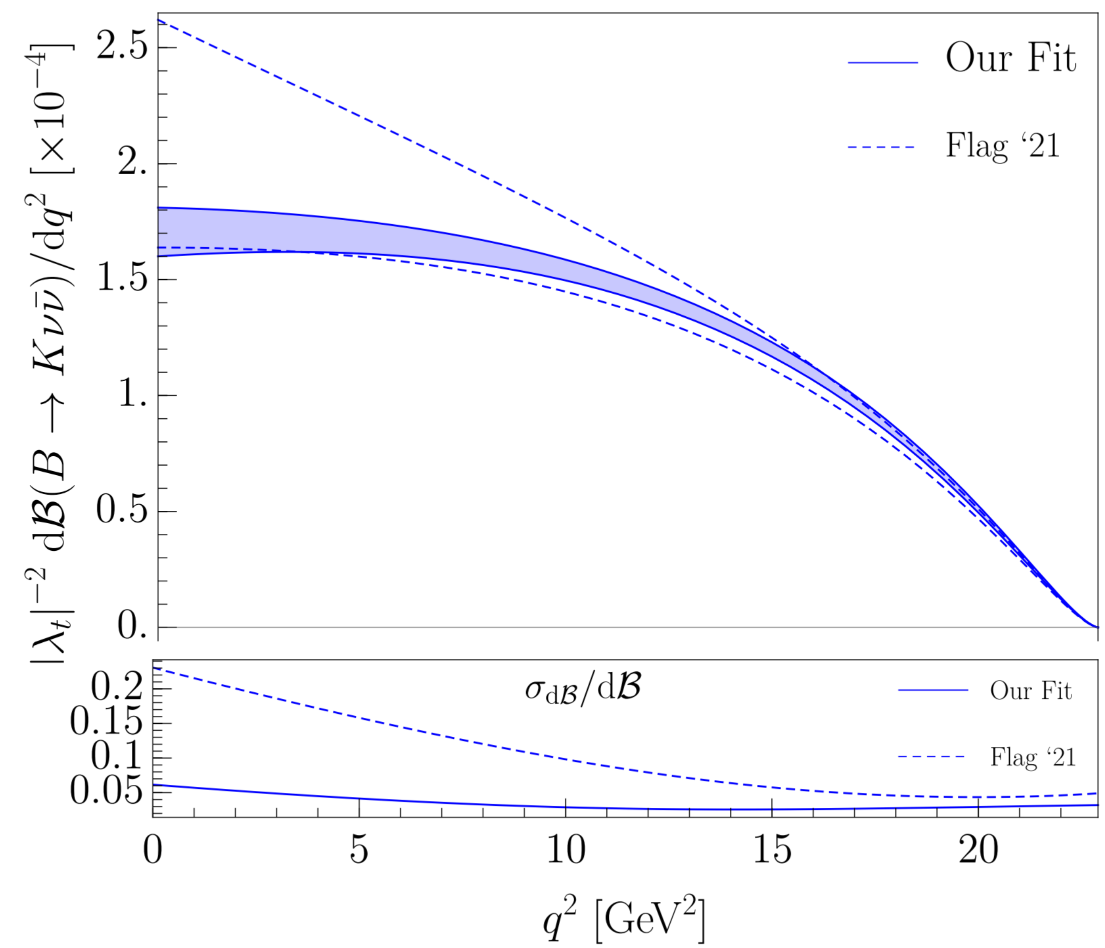
$$\langle K(k)|\bar{s}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

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

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

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

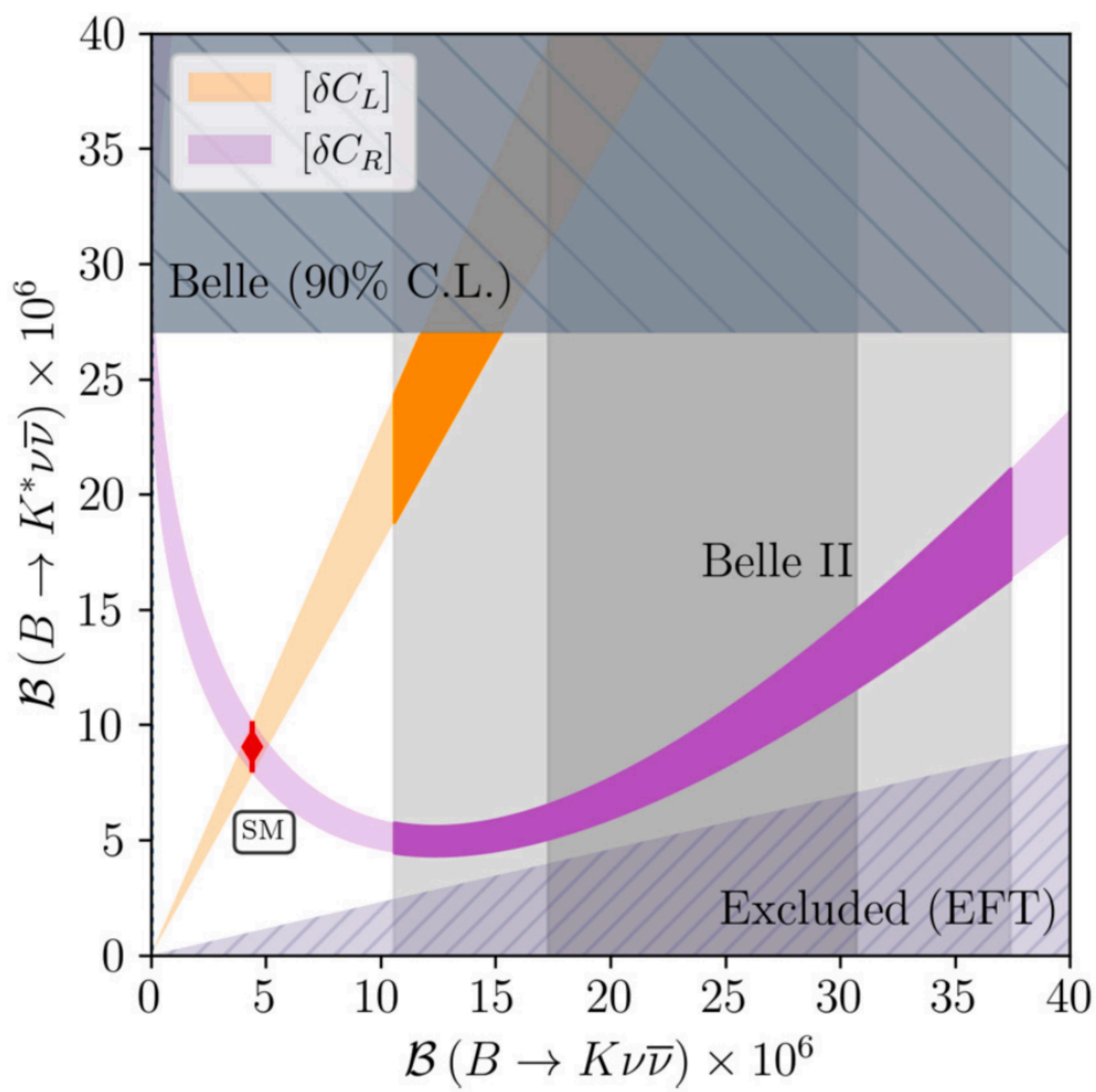
Use EFT to see how we can accommodate this result.

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

- Low-energy EFT:

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

- 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 $SU(2) \times U(1)_Y$:

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

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

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

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

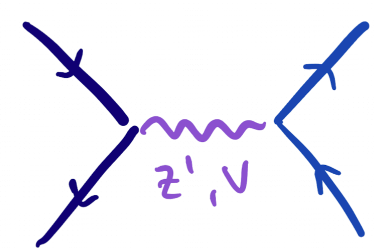
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l) = (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl}) + (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl})$$

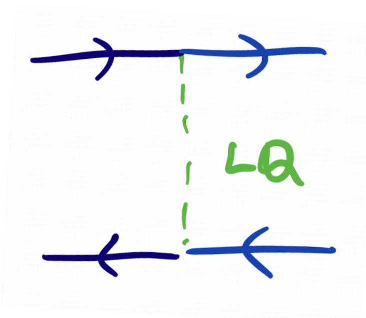
- Correlations for concrete mediators:

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

…

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





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

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

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

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

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

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

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

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

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

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

- No interference with SM.

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

cf. 2410.23257

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

$$\mathcal{L}_{\rm eff} \supset \mathcal{L}^{b\to c\tau N_R} + \mathcal{L}^{b\to sN_RN_R}$$
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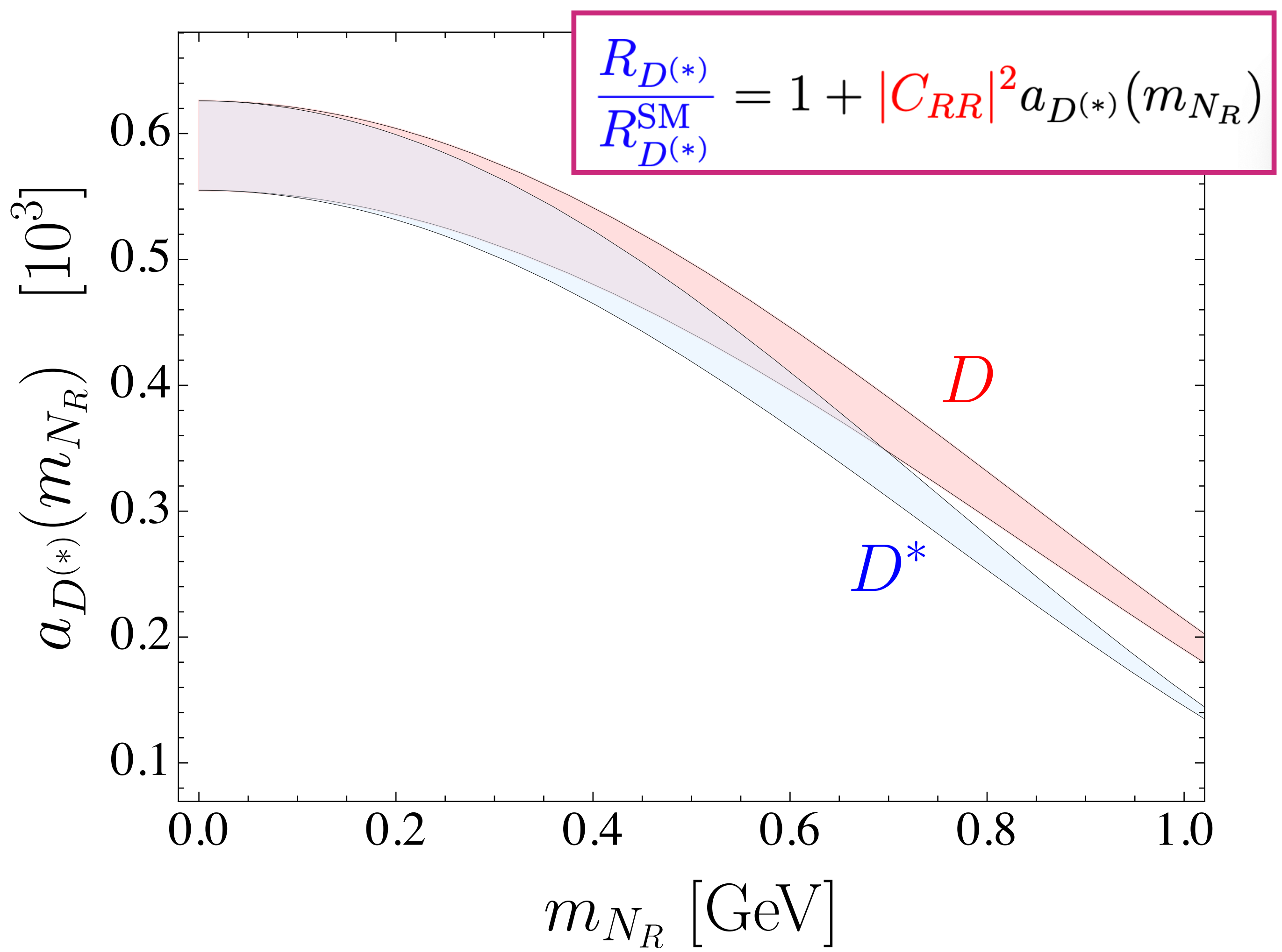
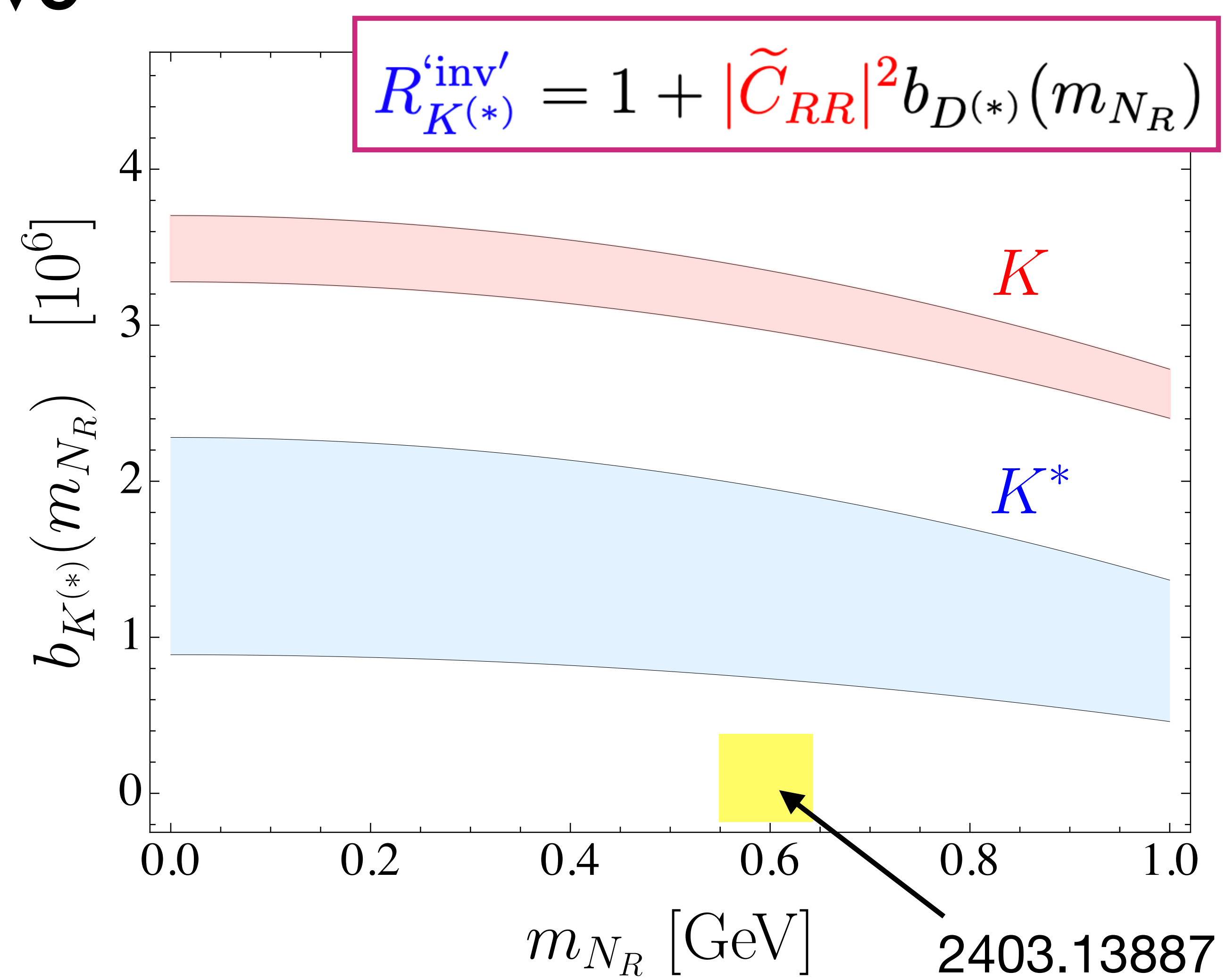
- No interference with SM
- N_R can be massless or massive





- 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_{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_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)

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

- 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)

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

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

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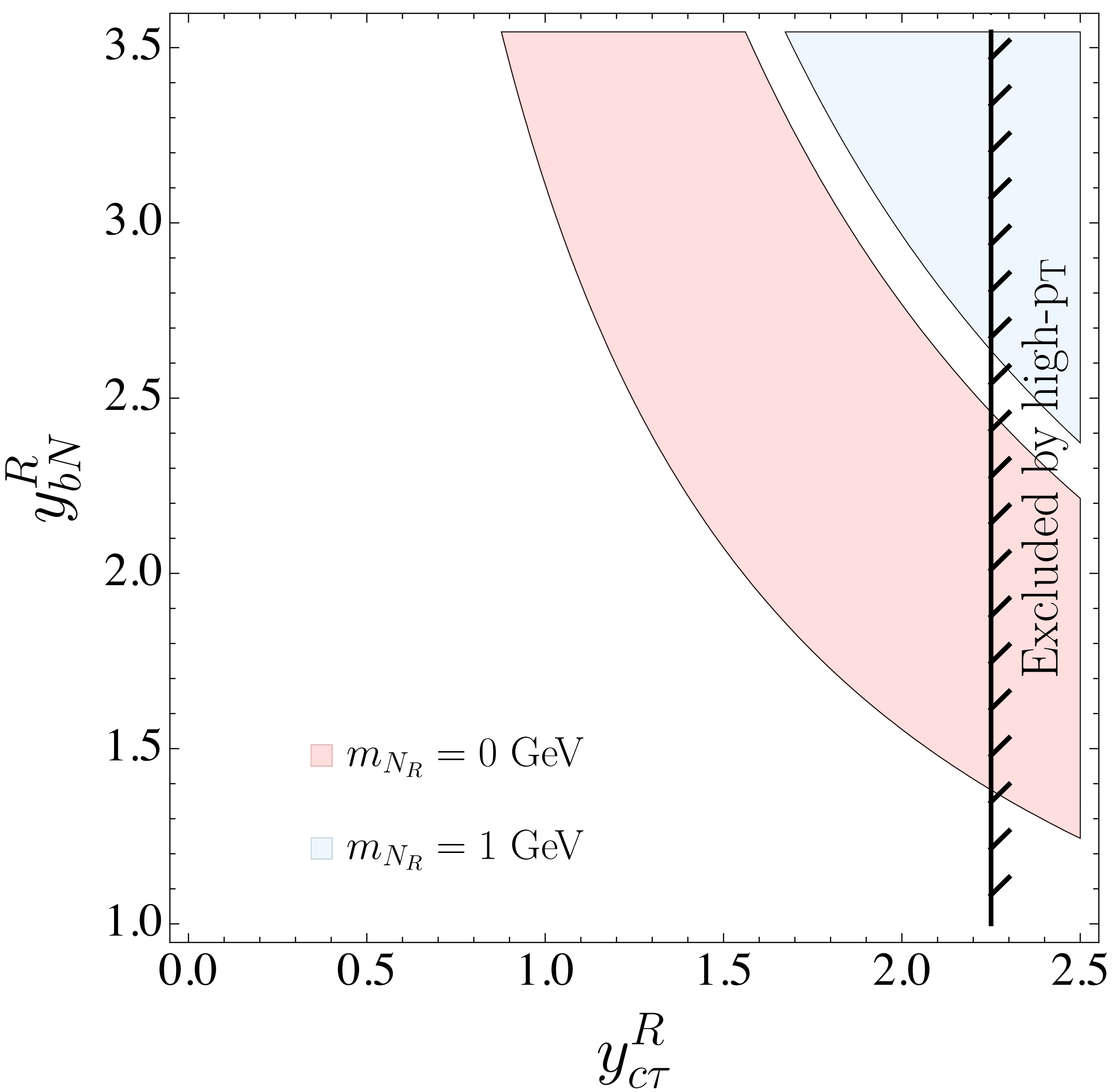
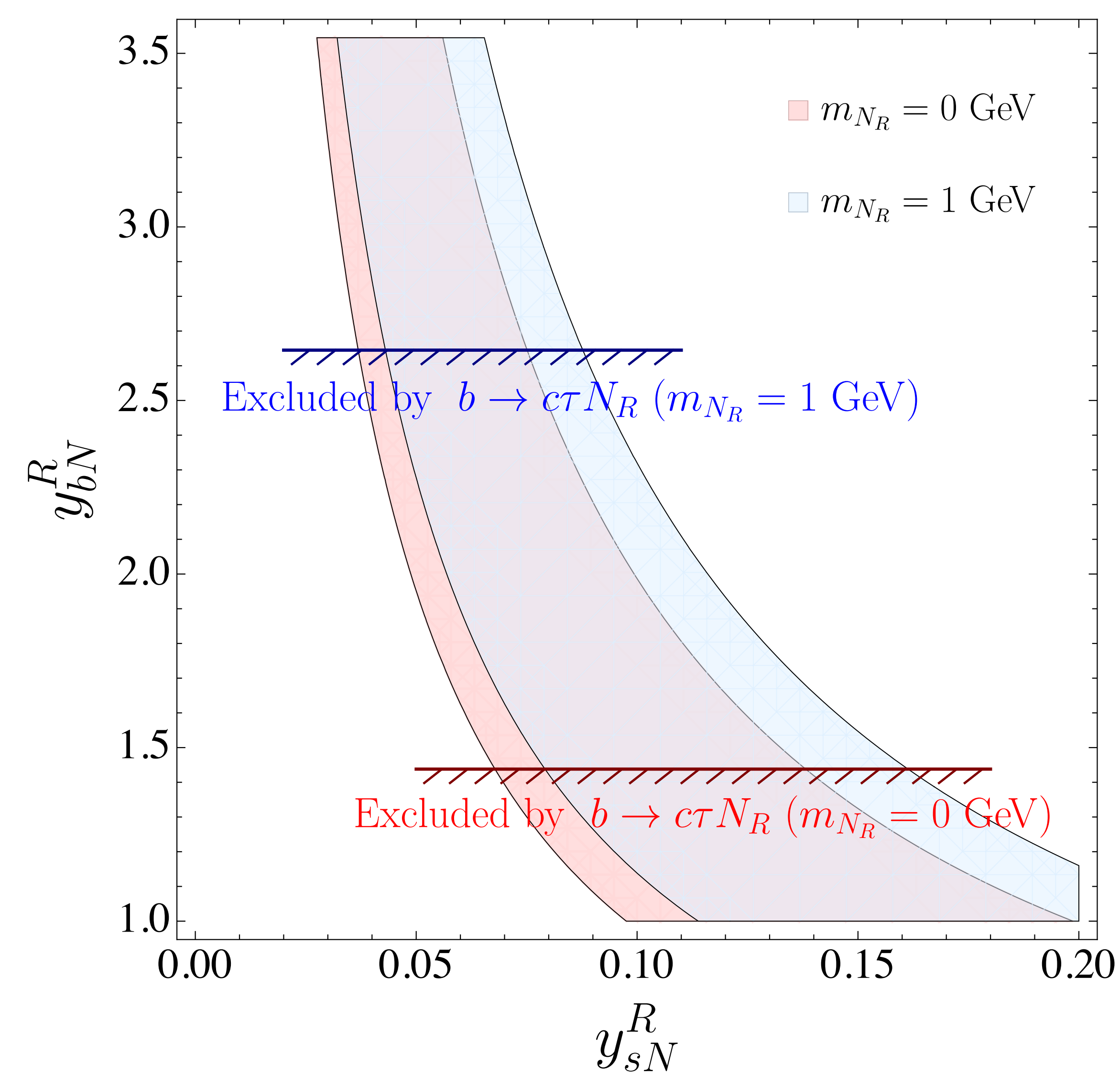




Concrete Model (S_1)

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

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

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

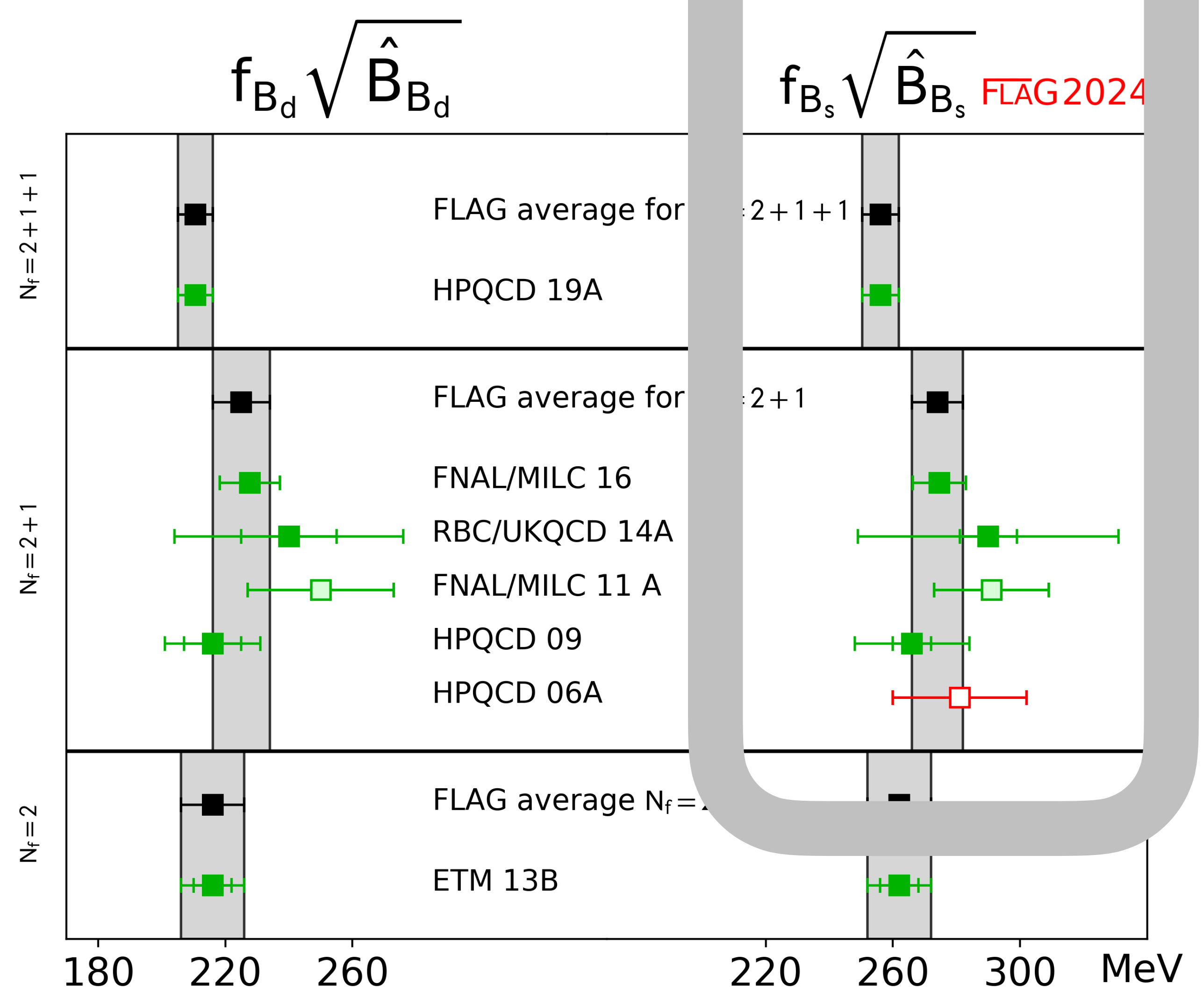
$$\widetilde{C}_{RR} = -\frac{v^2}{2m^2_{S_1}} y^{R*}_{sN} y^R_{bN}$$

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 Remarks 2

- Hadronic uncertainties are a major obstacle to interpreting the potential deviations between the measured and predicted (in SM) quantities.
- In scenarios with NP affecting only decays to 3rd generation leptons we can combine the experimental info on angular distribution with minimal lattice input and find 3σ difference between the SM value and the exp WA of R_{D^*}.

  Can we have the partial decay widths i.e. binned R_D and/or R_{D^*}?
- 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.
- If one wants to accommodate both $R_{D^{(*)}}$ and R_K^{inv} we find that 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.

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 [Martinelli et al. '21]

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

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

- Alternative strategy: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$ [Buras, Venturini. '21, '22]

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

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

[HPQCD '19]

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

[FLAG '21]

There is **no a clear answer** to this **ambiguity** so far.

Courtesy of O. Sumensari