Can we look for New Physics through c→ s $\ell\nu$ modes?

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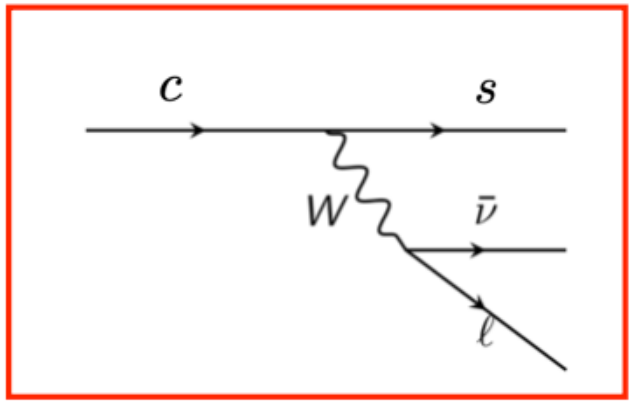
based on the work with F. Jaffredo, O. Sumensari, and S. Rosauro-Alcaraz

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

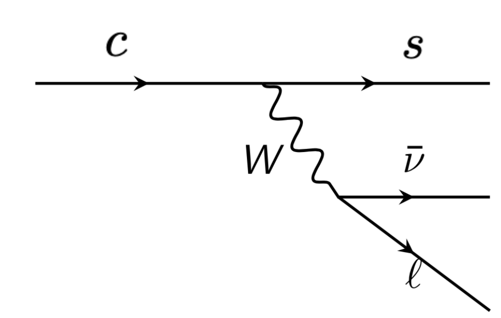
- ✗ Nonperturbative QCD stands on the way.
  LQCD tremendous progress but $B \to D^* \ell \nu$ still problematic (3pt fns)

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



cf. also Bolognani et al 2407.06145

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

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

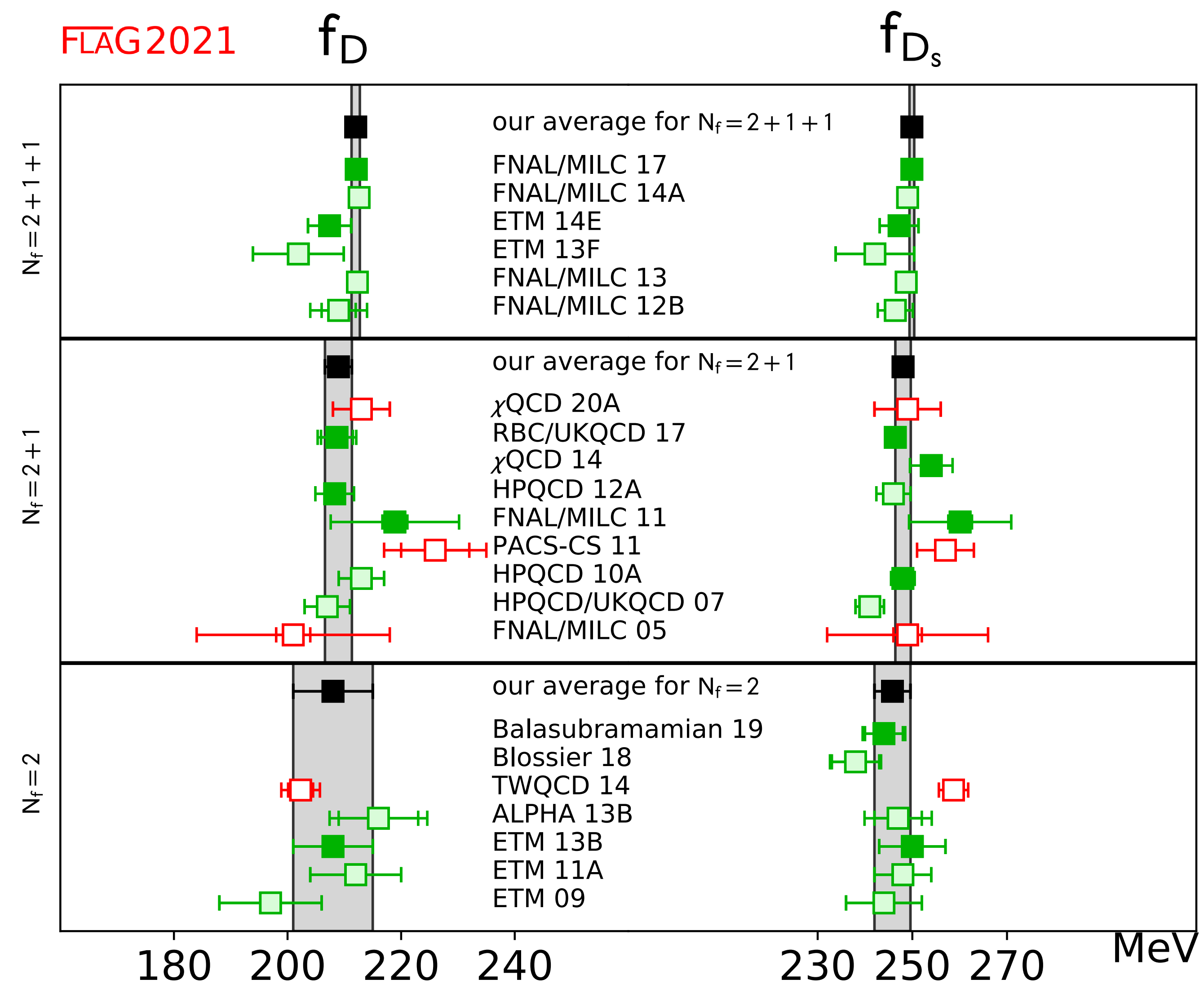
BESIII, 2303.12600 BESIII, 2303.12468

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, 2111.09849

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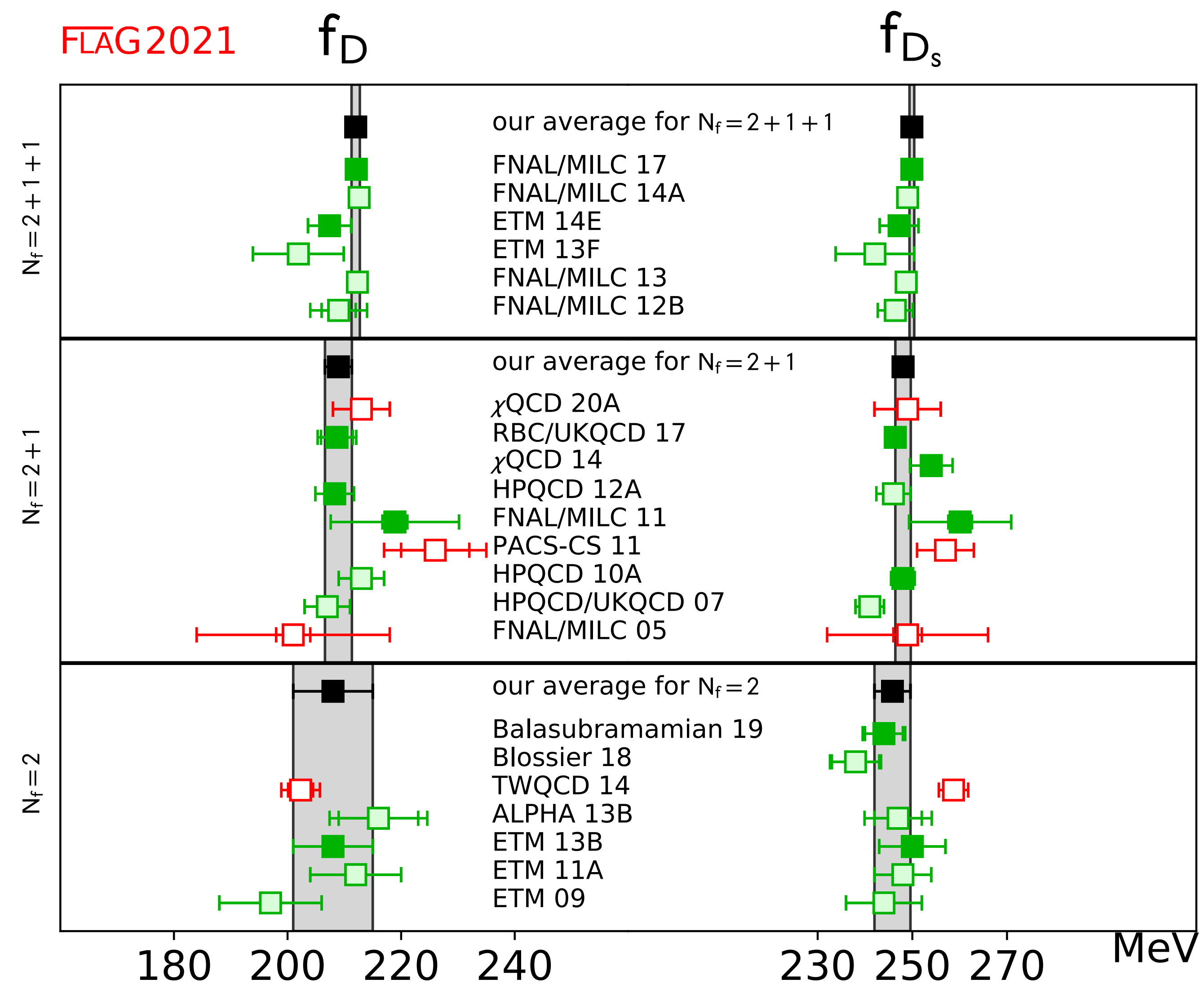


$$|V_{cs}|^{\mu} = 0.967(13)$$

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

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

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

Cannot match the UT precision unless using detailed semileptonics

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

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

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

$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{cs} \Big[\left(1 + g^\ell_{V_L}\right) (\bar{s}_L \gamma_\mu c_L) \left(\bar{\ell}_L \gamma^\mu \nu_L\right) + g^\ell_{V_R} (\bar{s}_R \gamma_\mu c_R) \left(\bar{\ell}_L \gamma^\mu \nu_L\right)$$

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

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:

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

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

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

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

- Pseudoscalar in the final state - easier for lattices

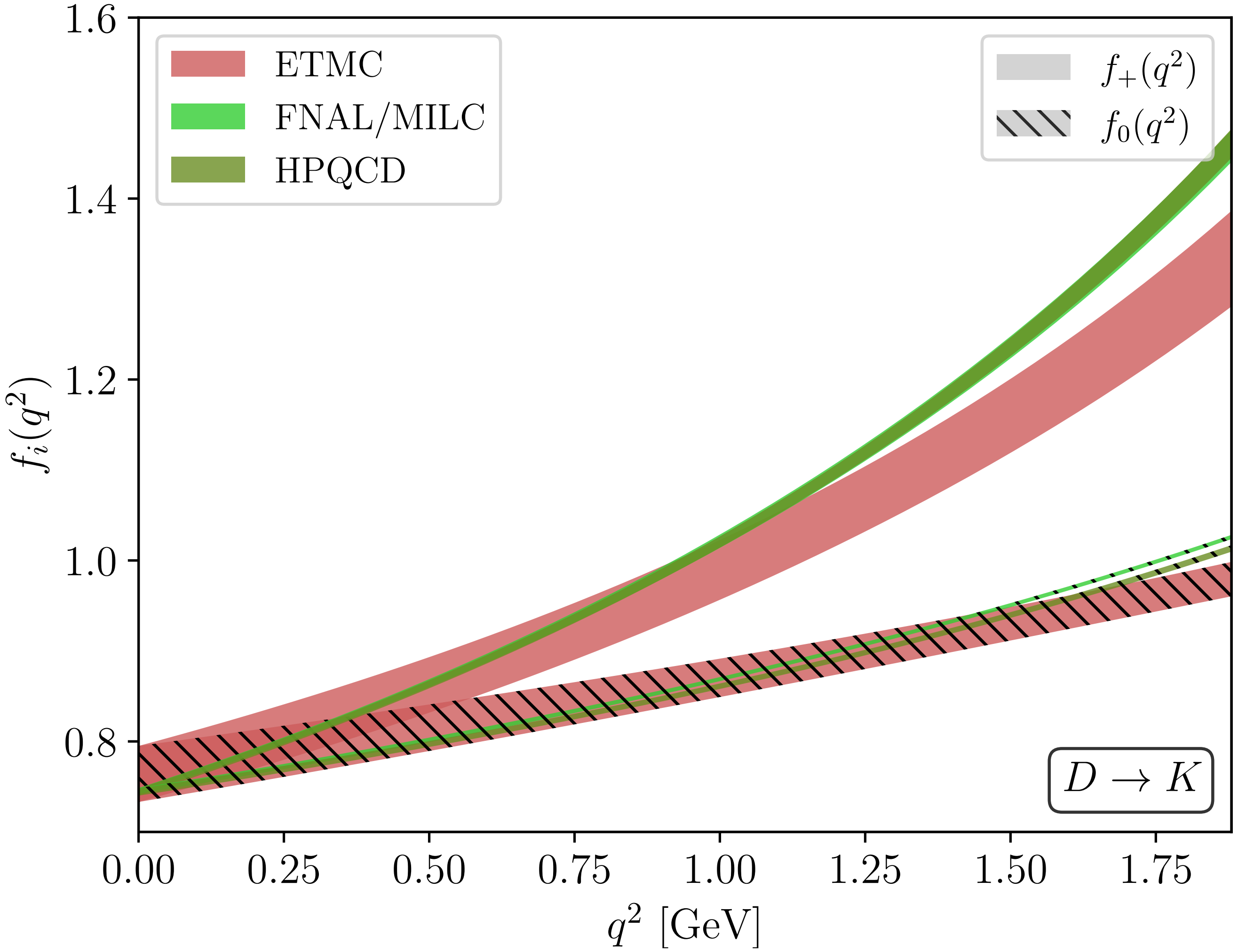
- We focus on the electron modes [more precise]
  LFUV tests (μ/e) successful so far (cf. PDG)

or recent BESIII 2306.02624 v 2207.14149

Semileptonics - mesons (LQCD)

✘ **Mesons:**

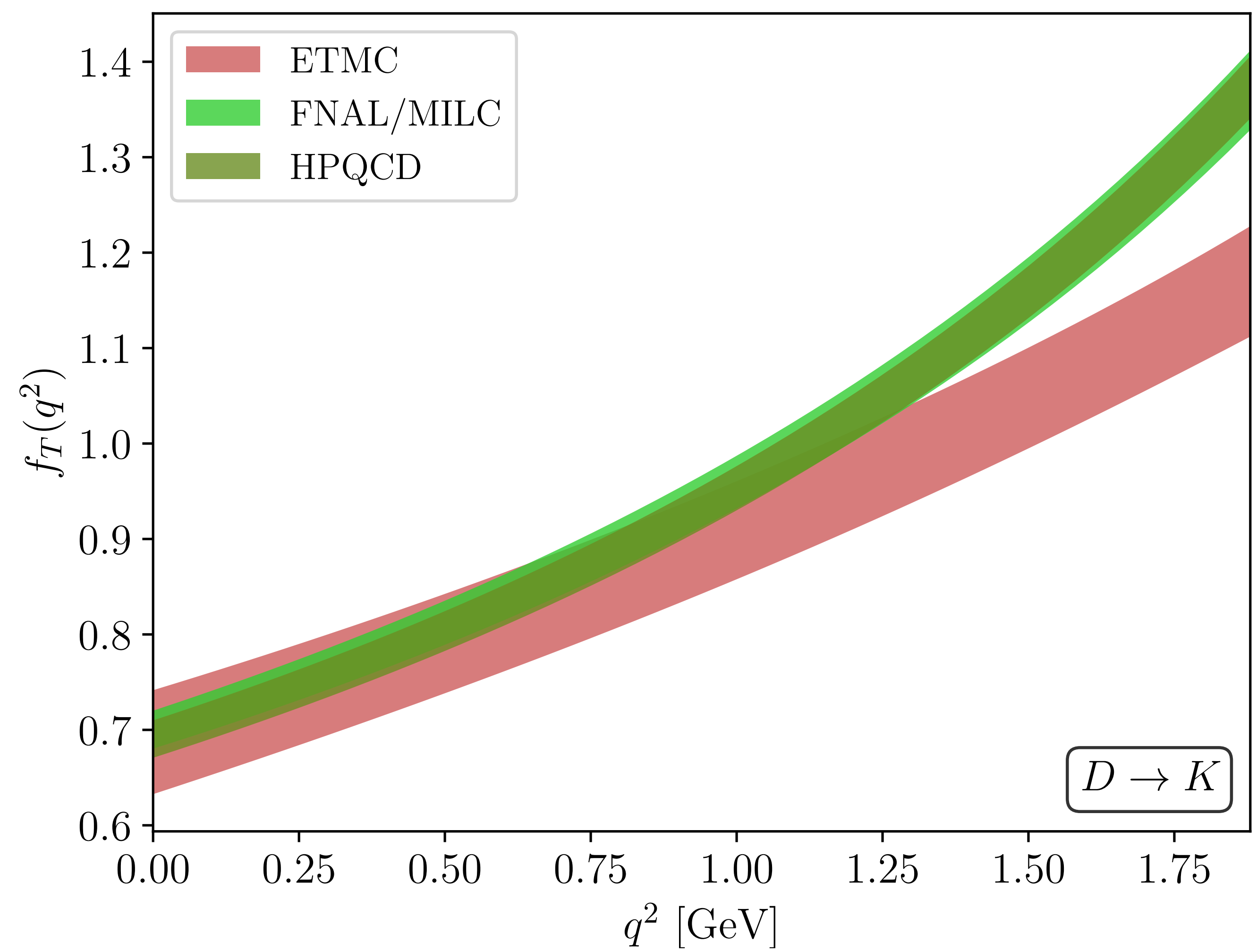
$D \to K\ell\nu$: $\langle K(k)|\bar{c}\gamma_\mu s|D(p)\rangle \propto f_+(q^2), f_0(q^2)$ $\langle K(k)|\bar{c}\gamma_\mu\gamma_5 s|D(p)\rangle = 0$ $\langle K(k)|\bar{c}\sigma_{\mu\nu} s|D(p)\rangle \propto f_T(q^2)$



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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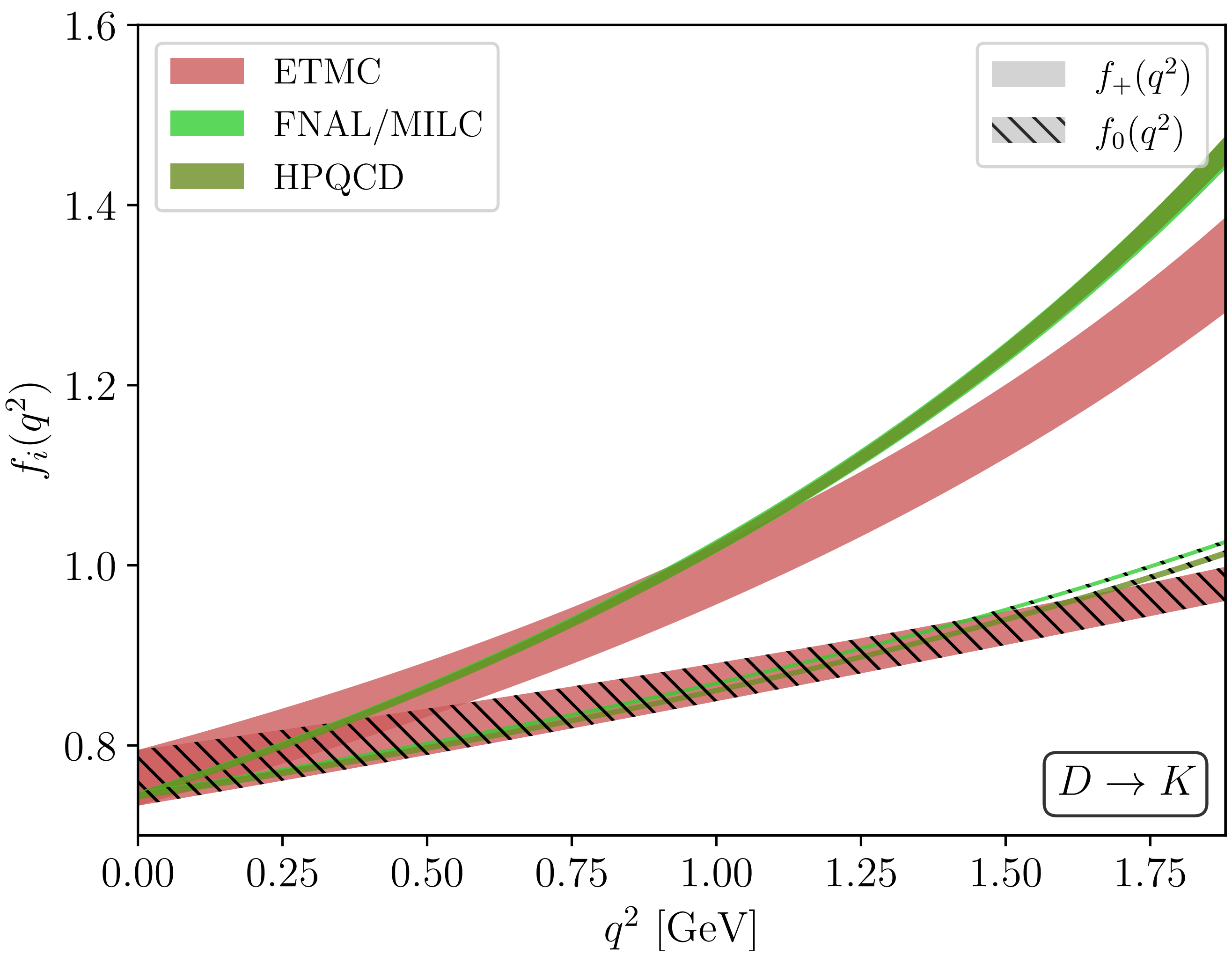
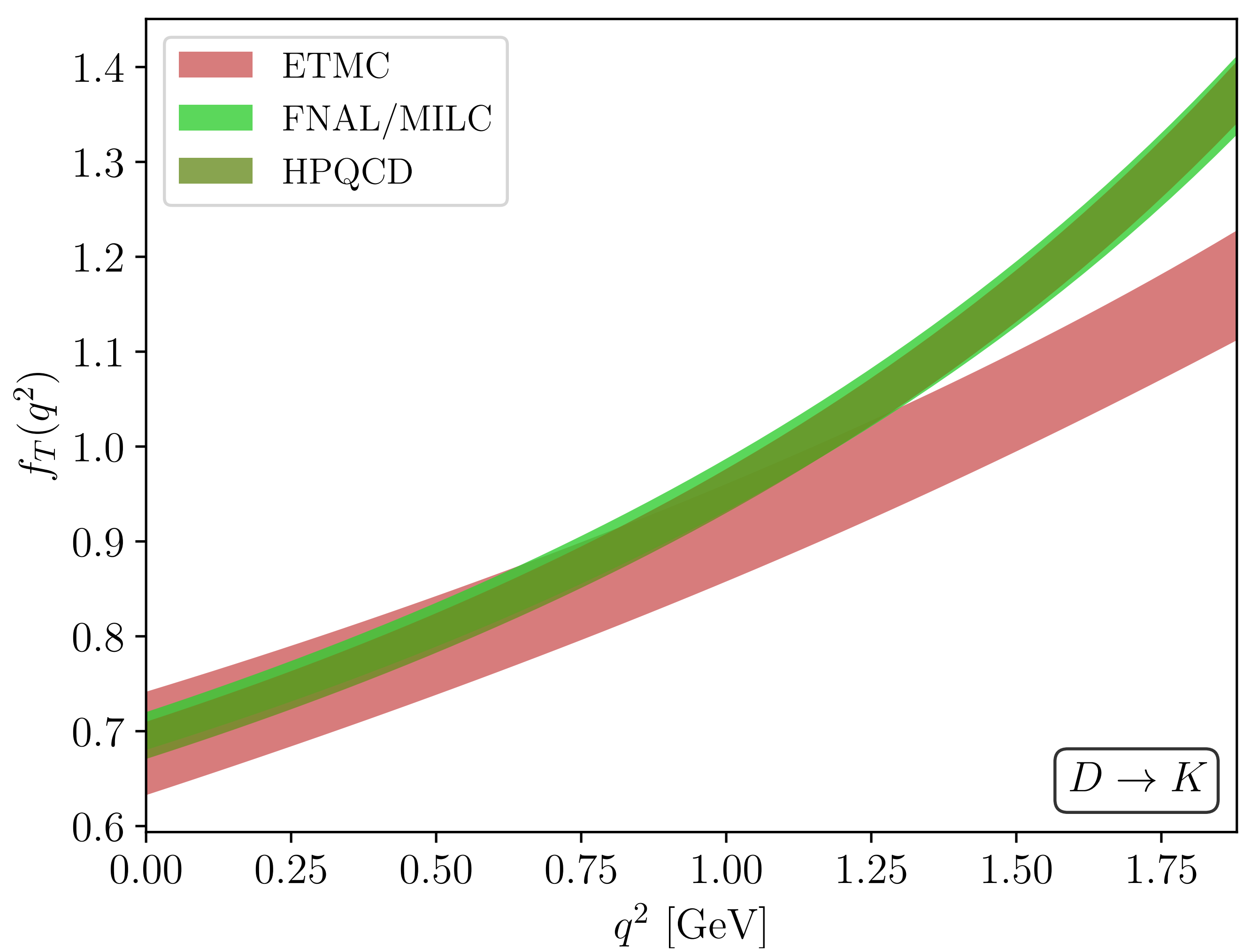




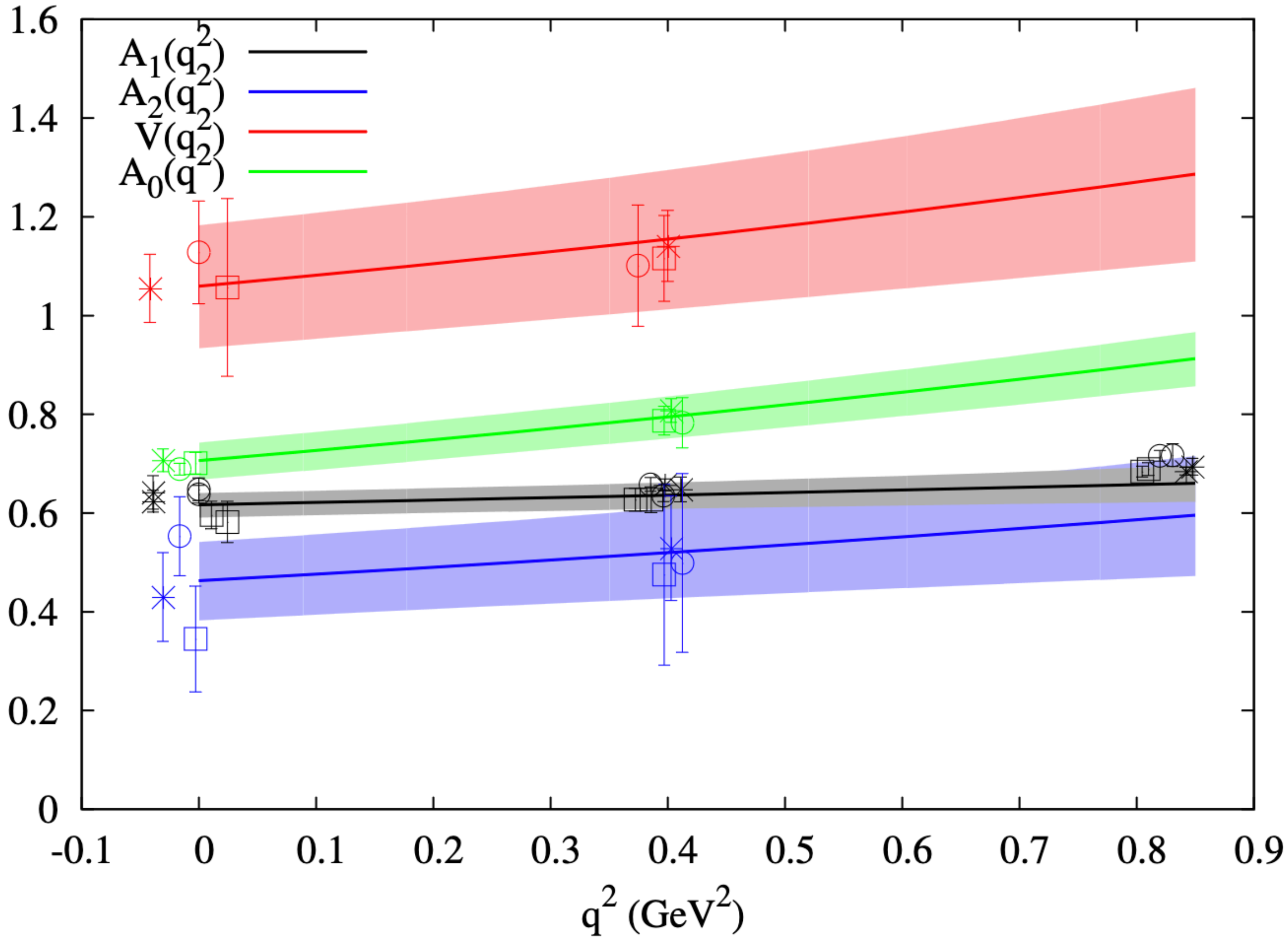
More work needed to understand the differences (lattice artefacts)

Semileptonics - mesons (LQCD)

- **Mesons:**

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

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



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

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

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

A detailed lattice study: Meinel 1611.09696

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

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

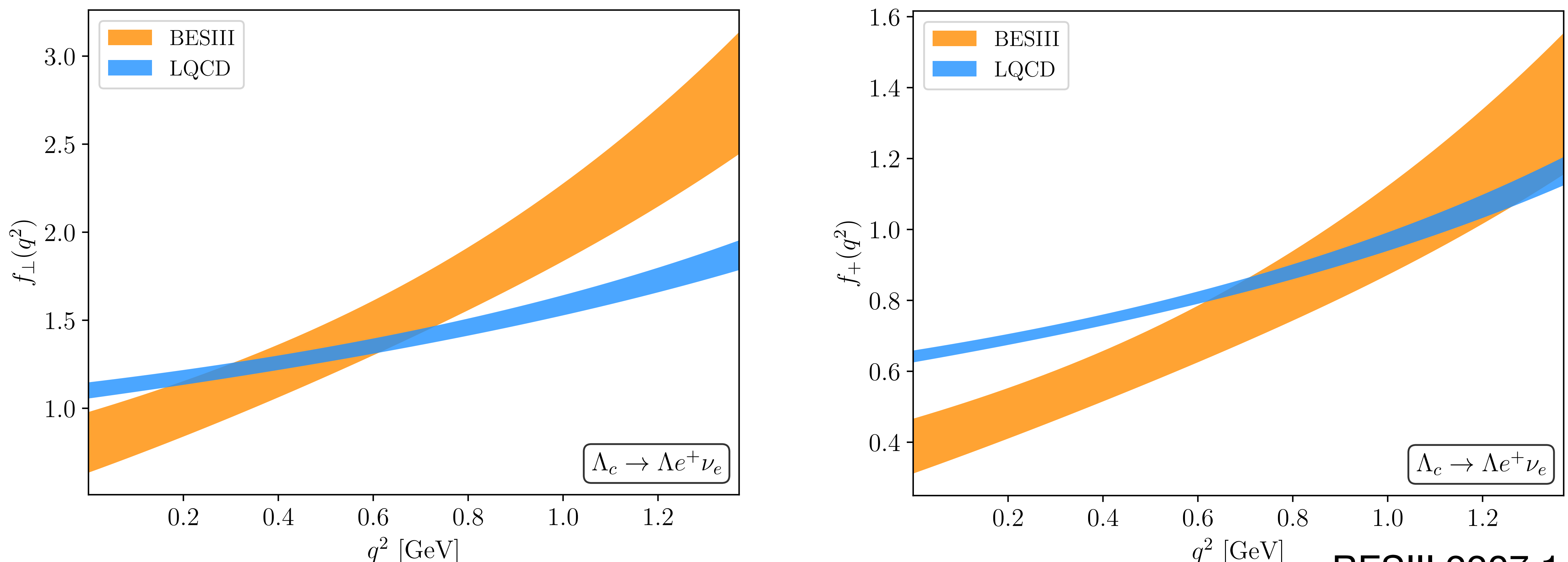
Invert the angular coefficients [exp] to extract the FF and compare to LQCD

BESIII 2207.14149

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

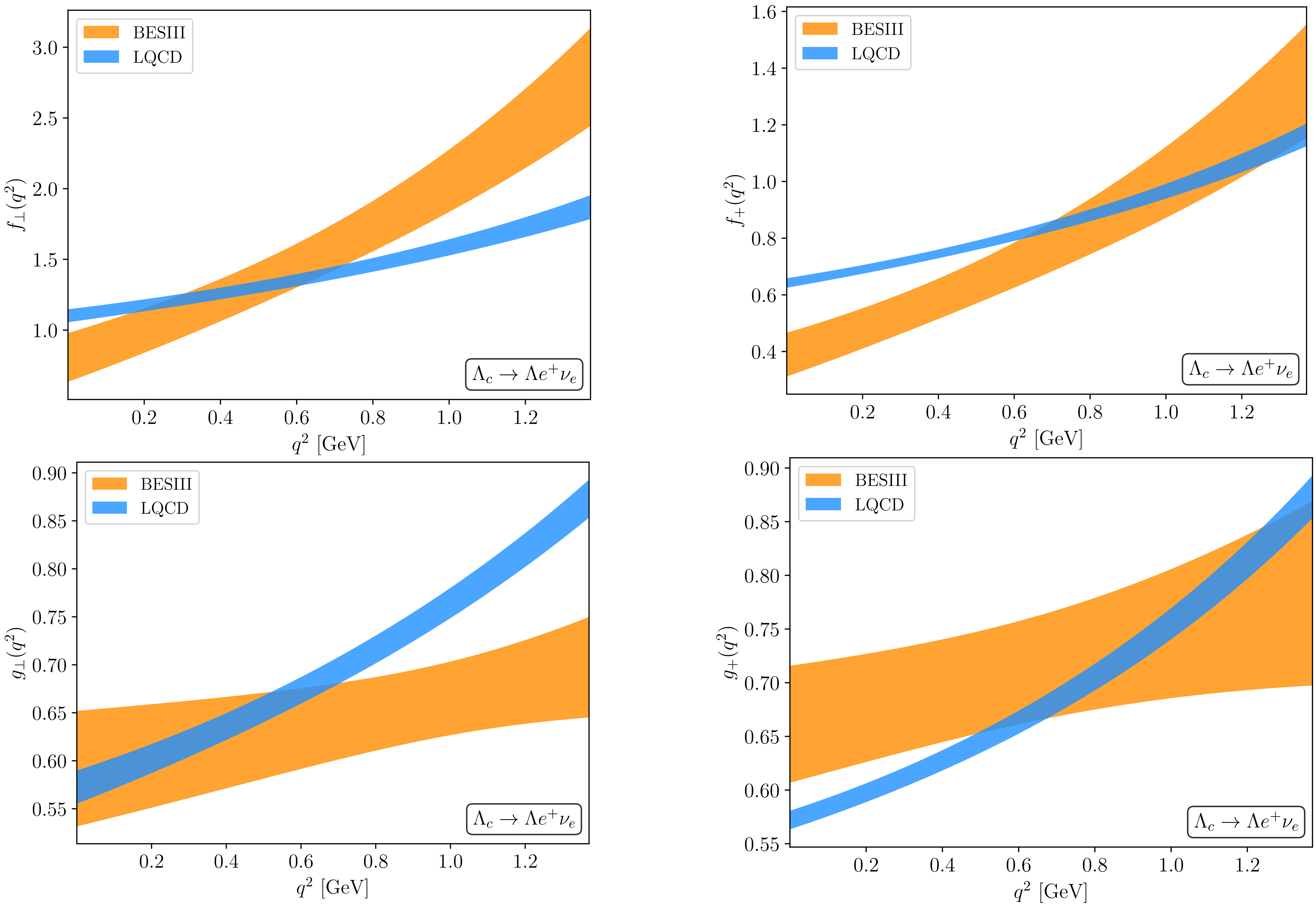
$$\frac{d^4\Gamma^{\lambda_\ell}}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} = A_1^{\lambda_\ell} + A_2^{\lambda_\ell}\cos\theta_\Lambda + \left(B_1^{\lambda_\ell} + B_2^{\lambda_\ell}\cos\theta_\Lambda\right)\cos\theta + \left(C_1^{\lambda_\ell} + C_2^{\lambda_\ell}\cos\theta_\Lambda\right)\cos^2\theta$$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

Invert the angular coefficients to extract the FF and compare to LQCD



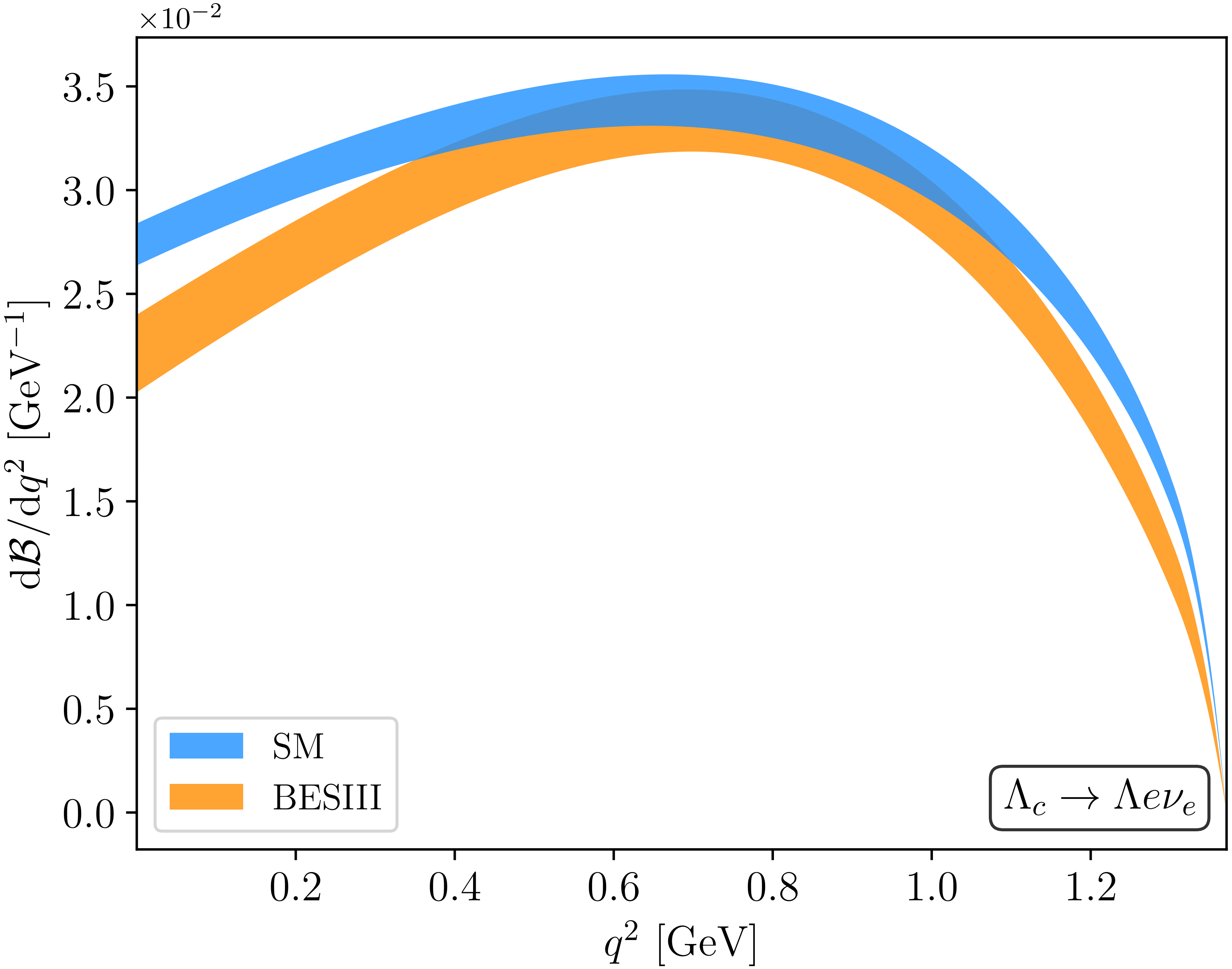
BESIII 2207.14149
Meinel 1611.09696

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



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

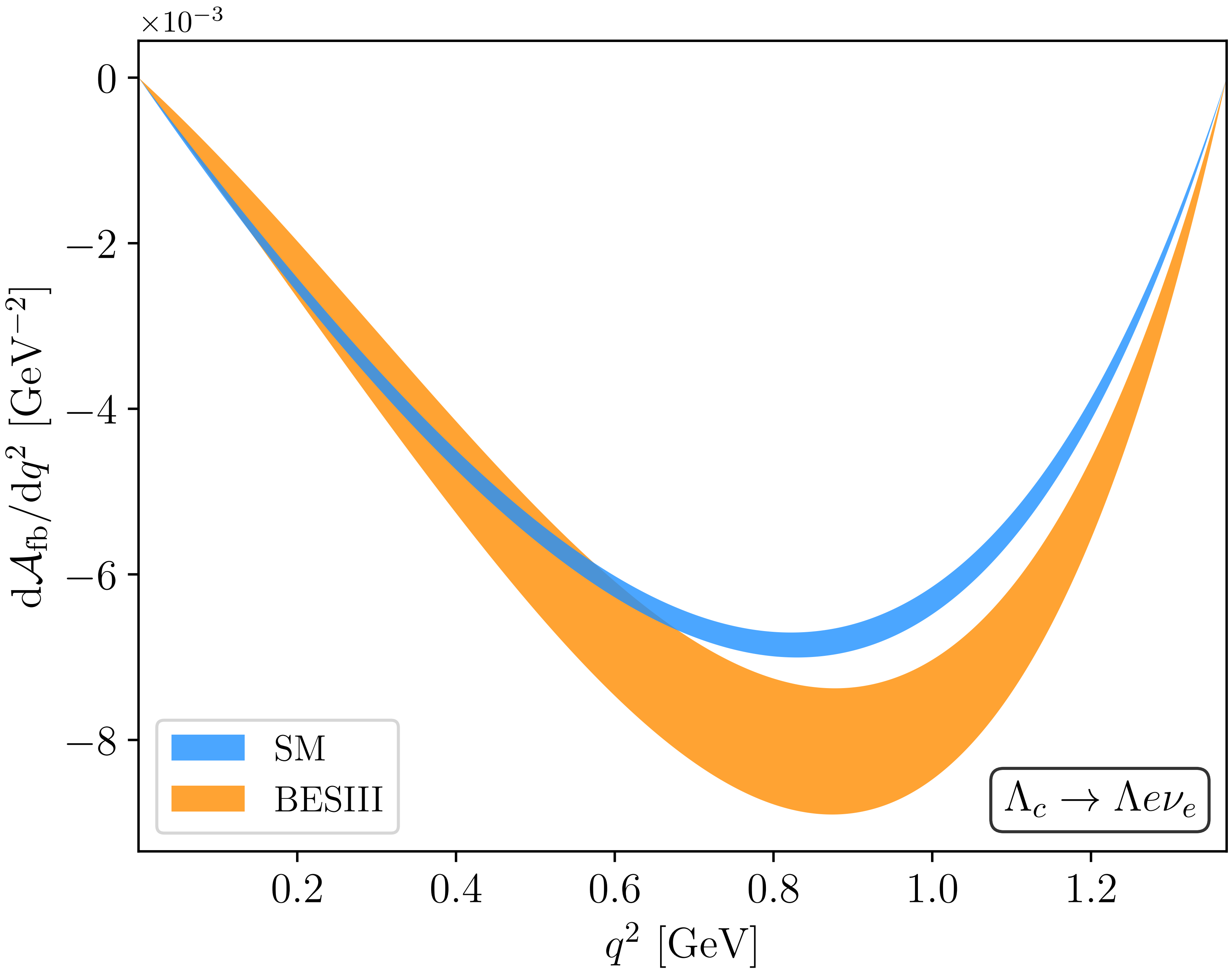
$$\frac{\mathrm{d}\mathcal{B}(q^2)}{\mathrm{d}q^2} = 2\tau_{\Lambda_c} \sum_{\lambda,\lambda_\ell} \left[a_\lambda^{\lambda_\ell}(q^2) + \frac{c_\lambda^{\lambda_\ell}(q^2)}{3} \right]$$



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

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

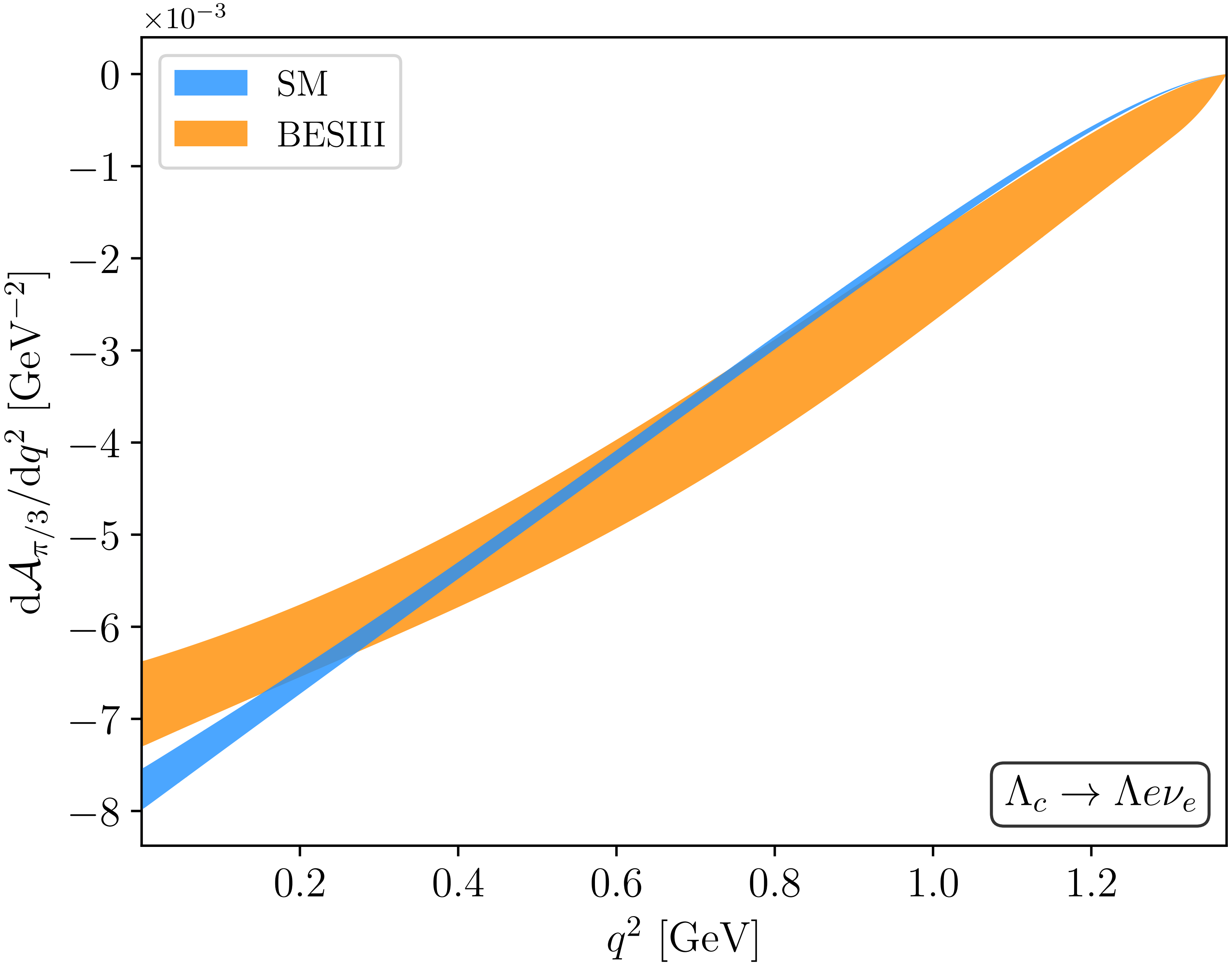
$$\frac{\mathrm{d}A_{\mathrm{fb}}(q^2)}{\mathrm{d}q^2} \propto \sum_{\lambda,\lambda_\ell} b_\lambda^{\lambda_\ell}(q^2)$$



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

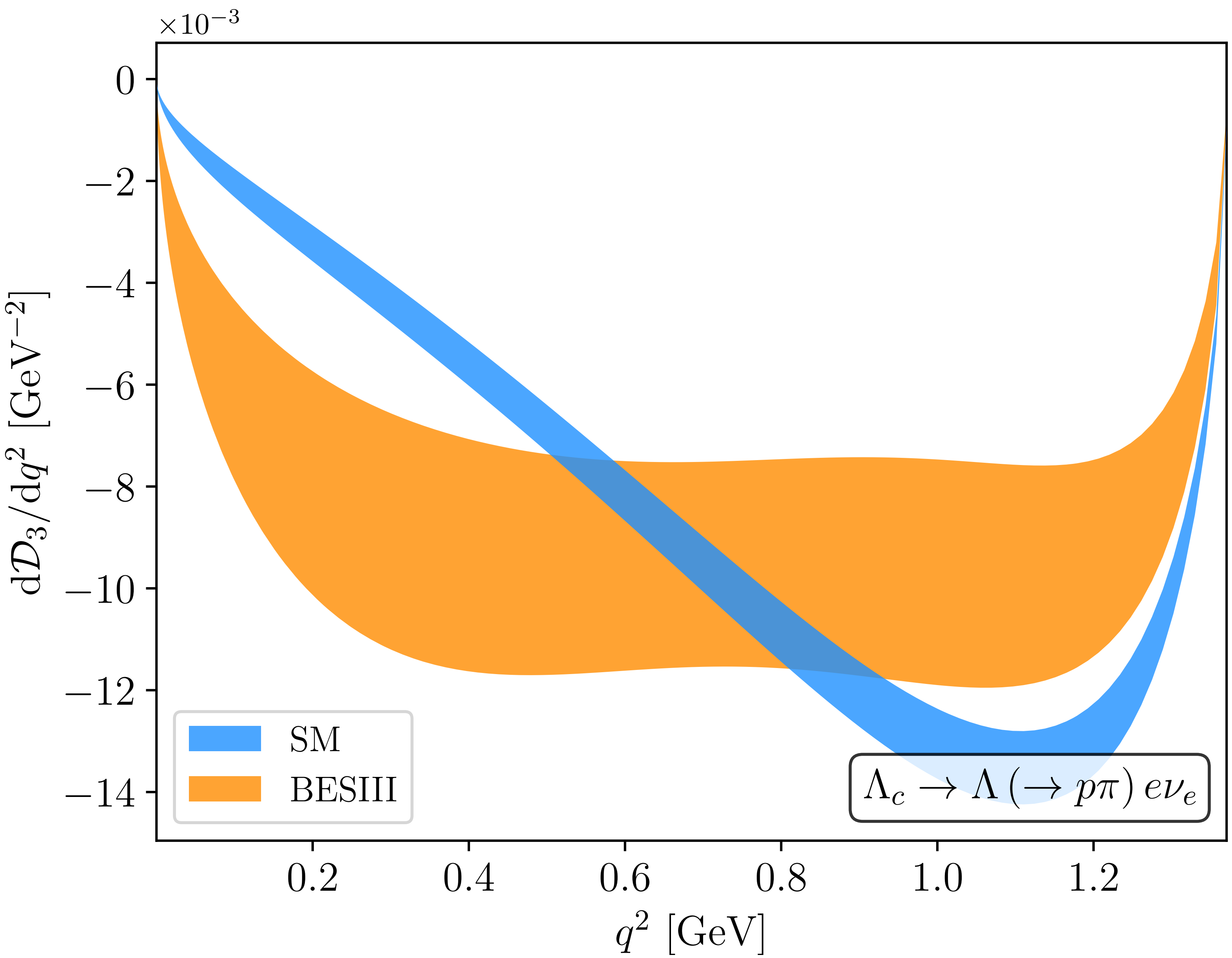
In terms of $\Lambda_c \to \Lambda e \nu$ observables

$$\frac{\mathrm{d}A_{\pi/3}(q^2)}{\mathrm{d}q^2} \propto \sum_{\lambda,\lambda_\ell} c_\lambda^{\lambda_\ell}(q^2)$$



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

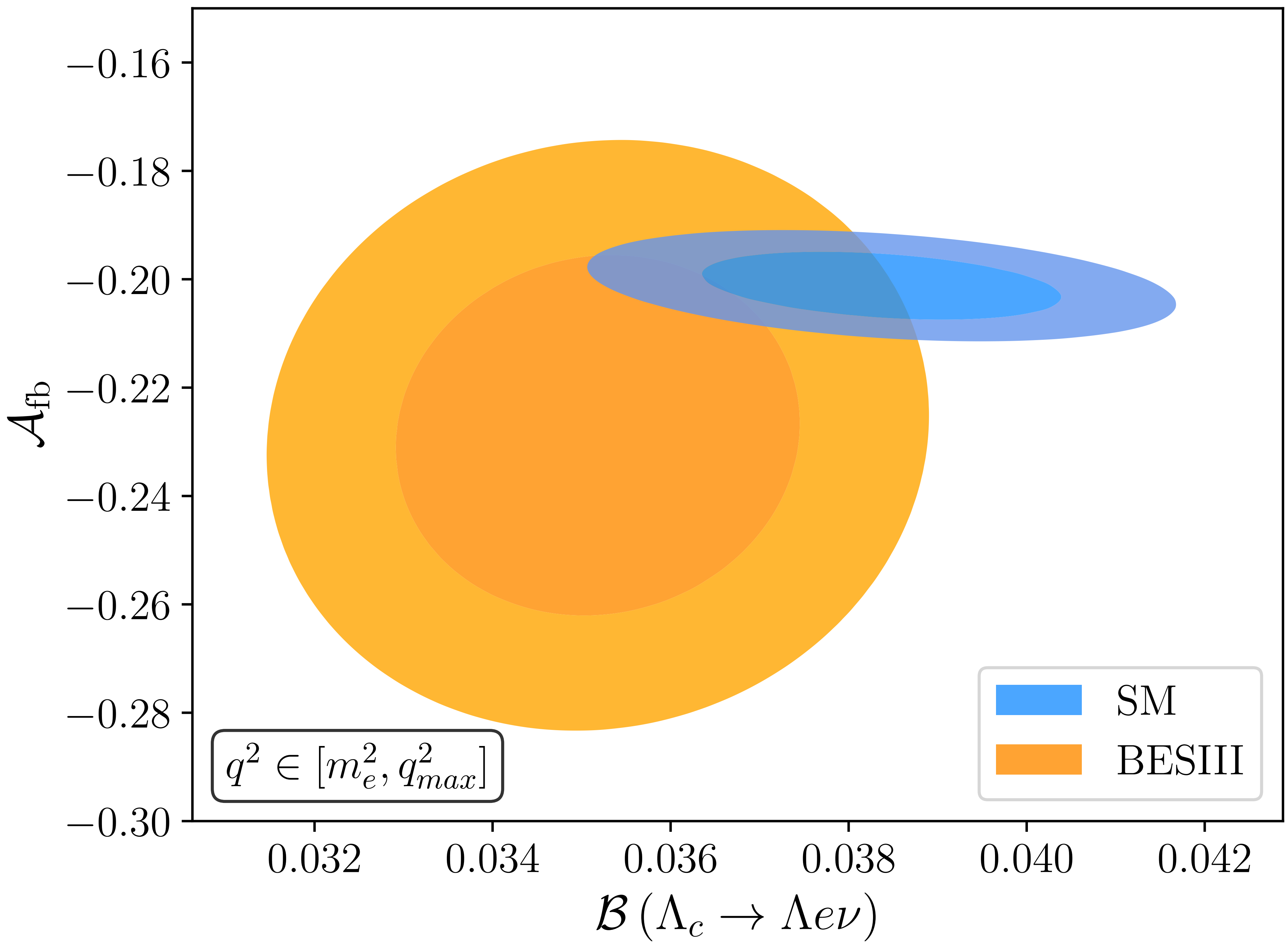
In terms of $\Lambda_c \to \Lambda(\to p\pi)\, e\nu$ observables



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]

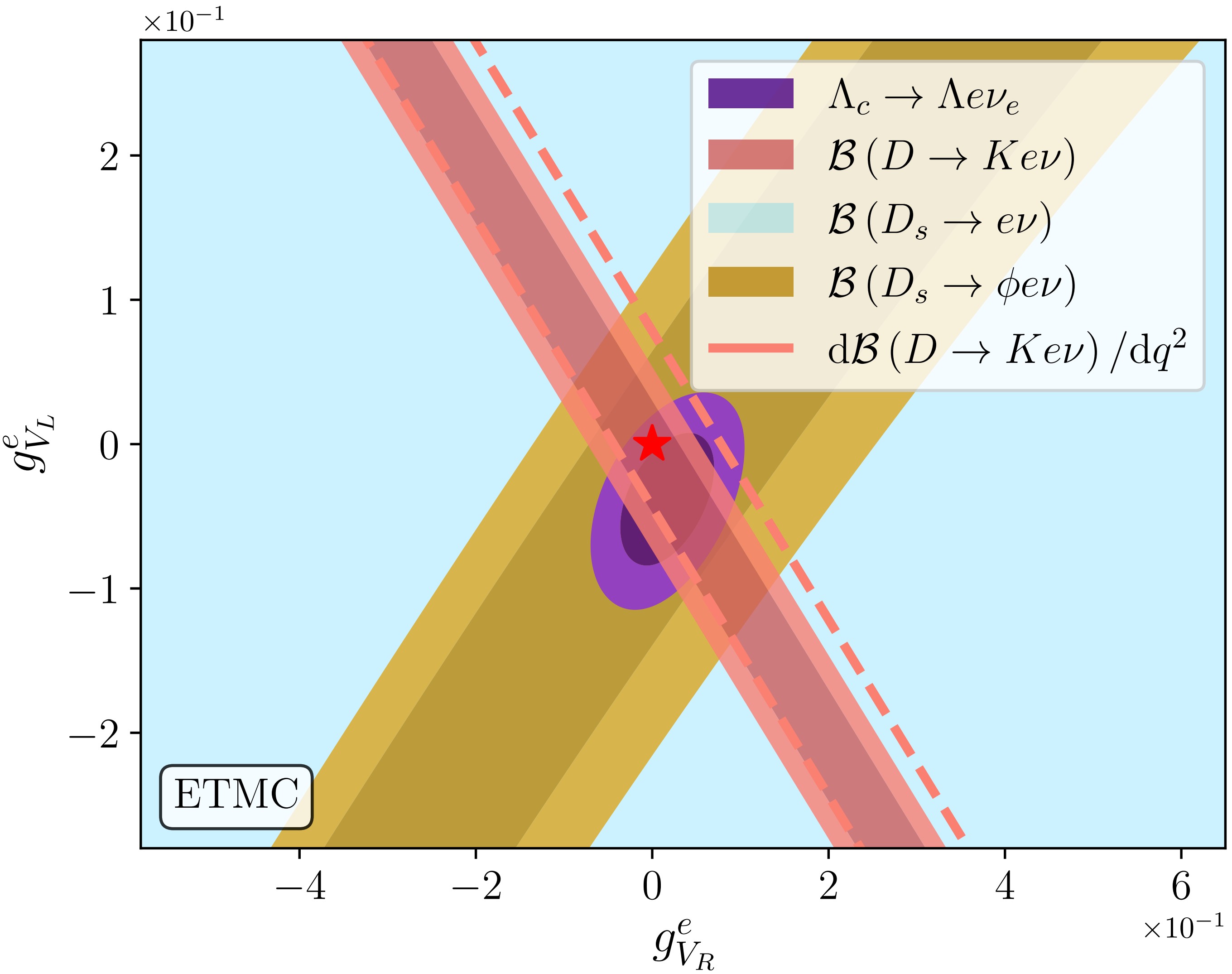
Integrated characteristics quite consistent with SM…

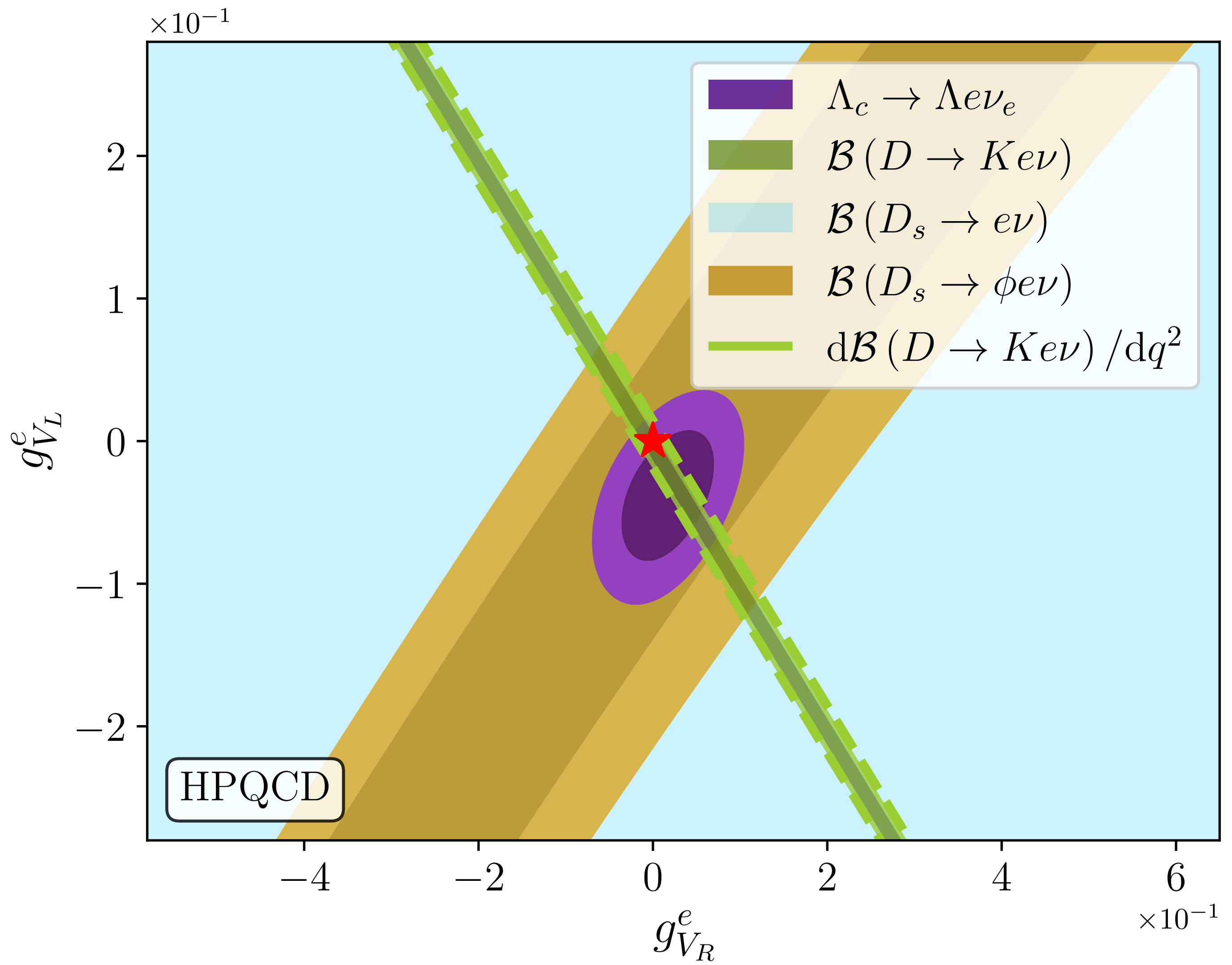
One interesting case…



Try and feed in NP contributions

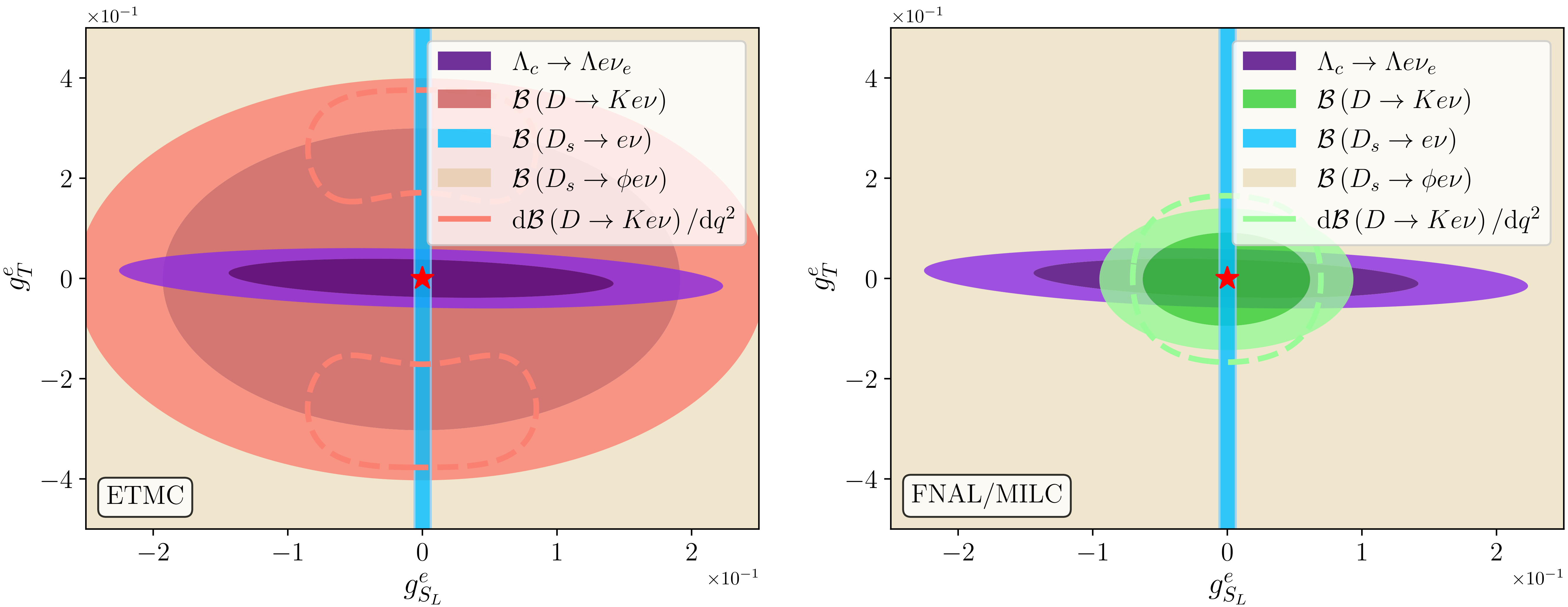
Include mesons too (where info on binned distribution is available)…





Checking on 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

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

LHC window to high-p_T tails of…

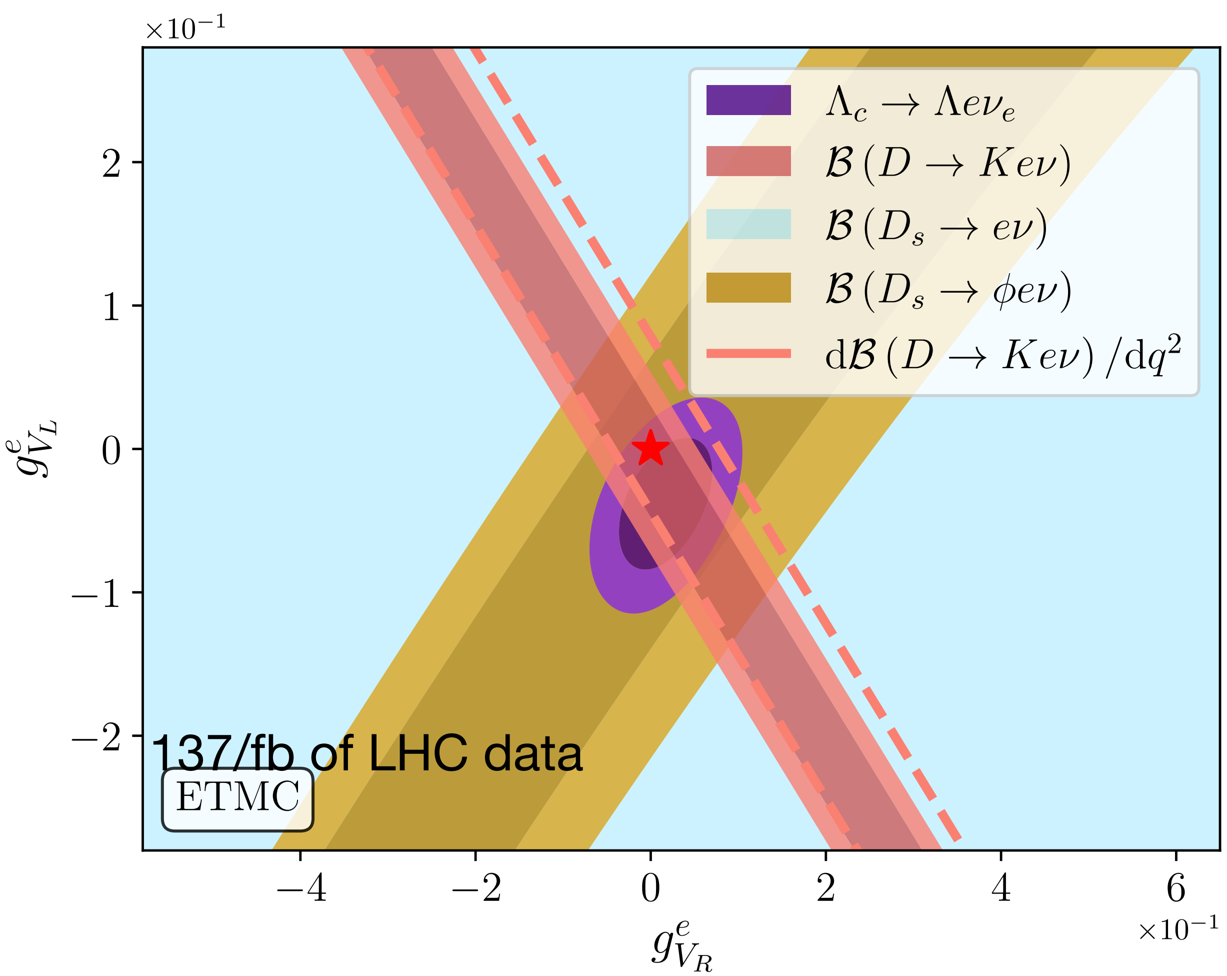
$$\sigma(pp \to \ell\nu) = \int_0^1 x_1 x_2 f_{\bar{s}}(x_1,\mu) f_c(x_2,\mu)\, \hat{\sigma}(\bar{s}c \to \ell\nu) + (\bar{s} \leftrightarrow c)$$

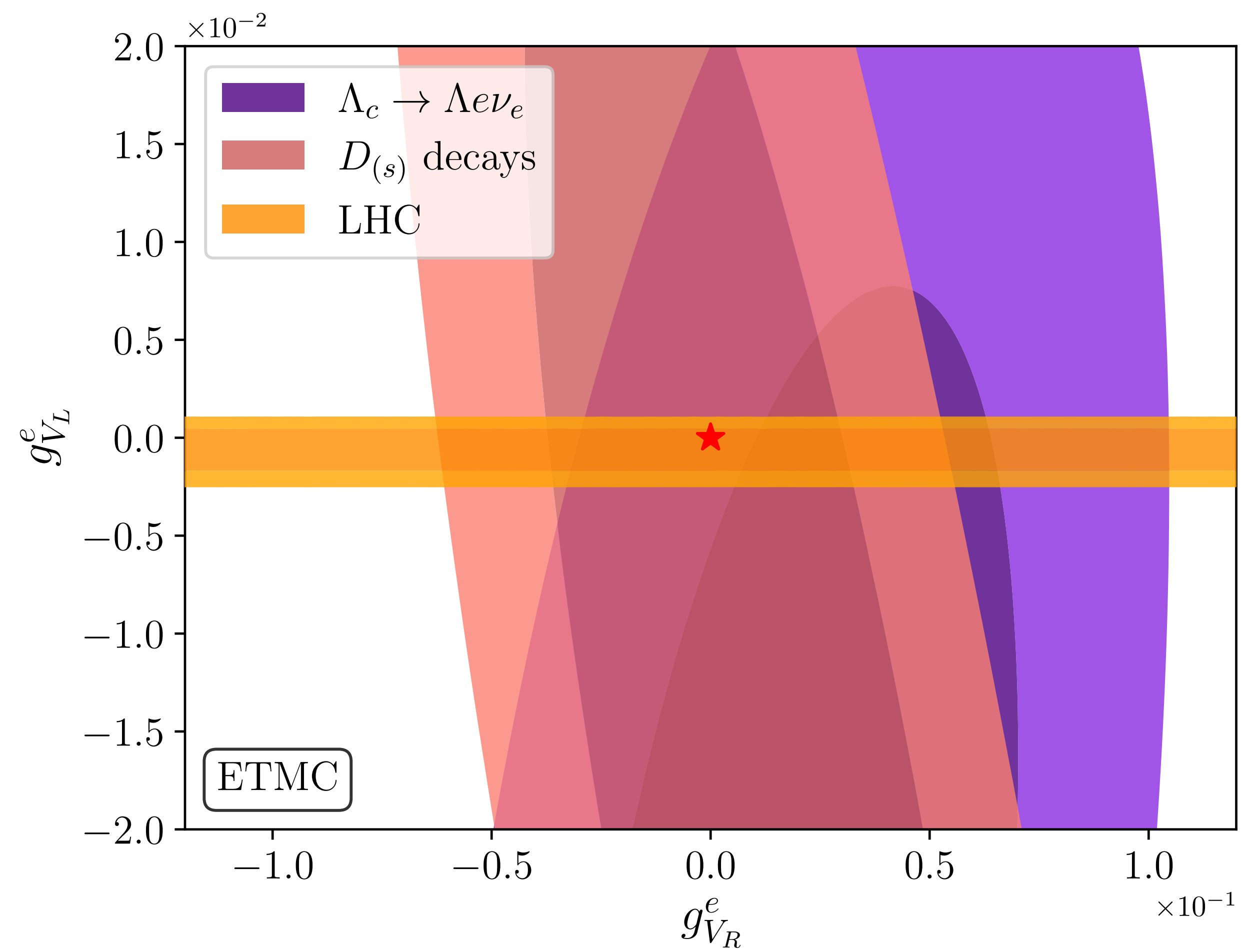
So stringent for ℓ=e that reconsidering K-factor becomes indispensable

Camalich et al 2003.12421, Allwicher et al 2207.10714

137/fb of LHC data

HighPT





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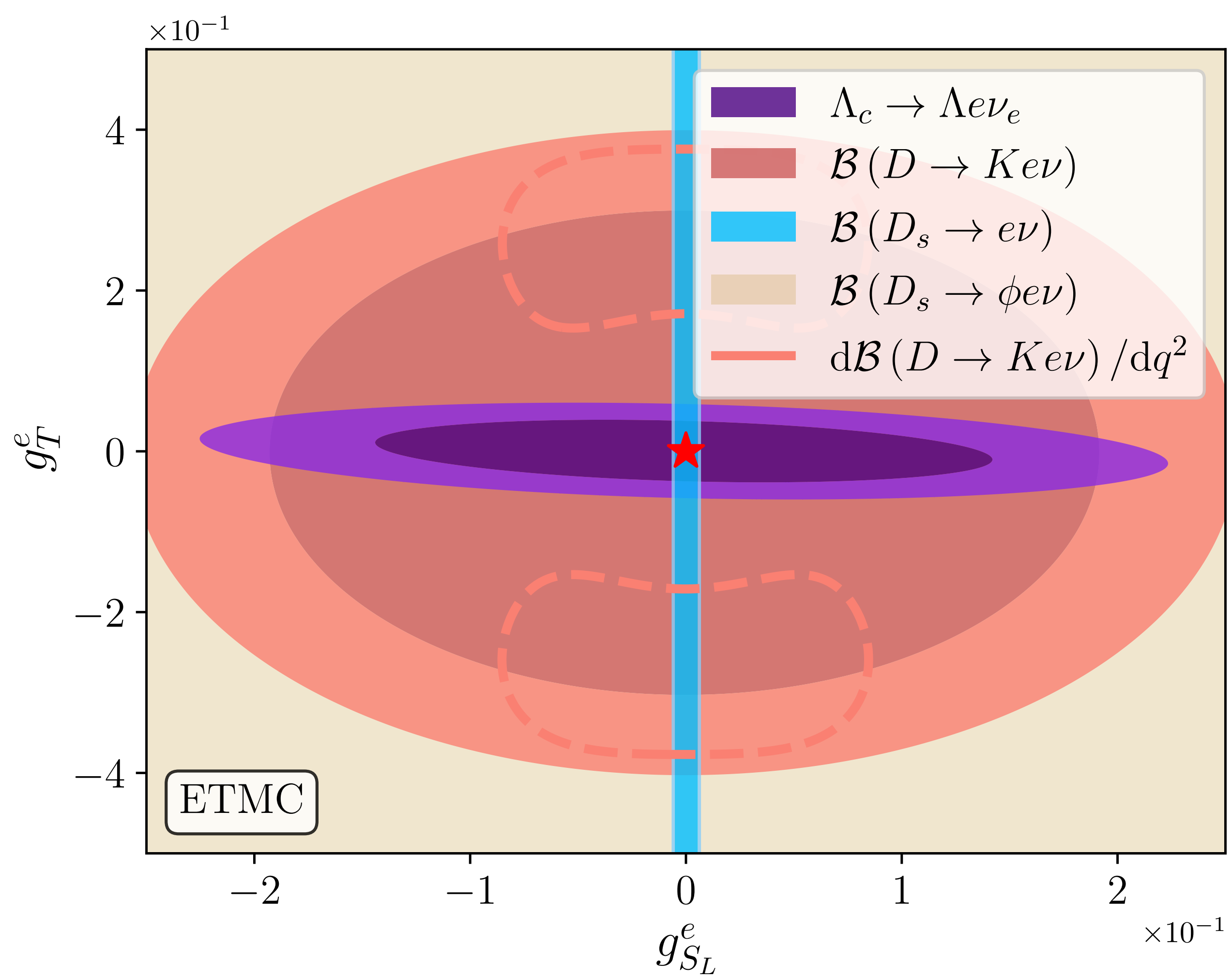

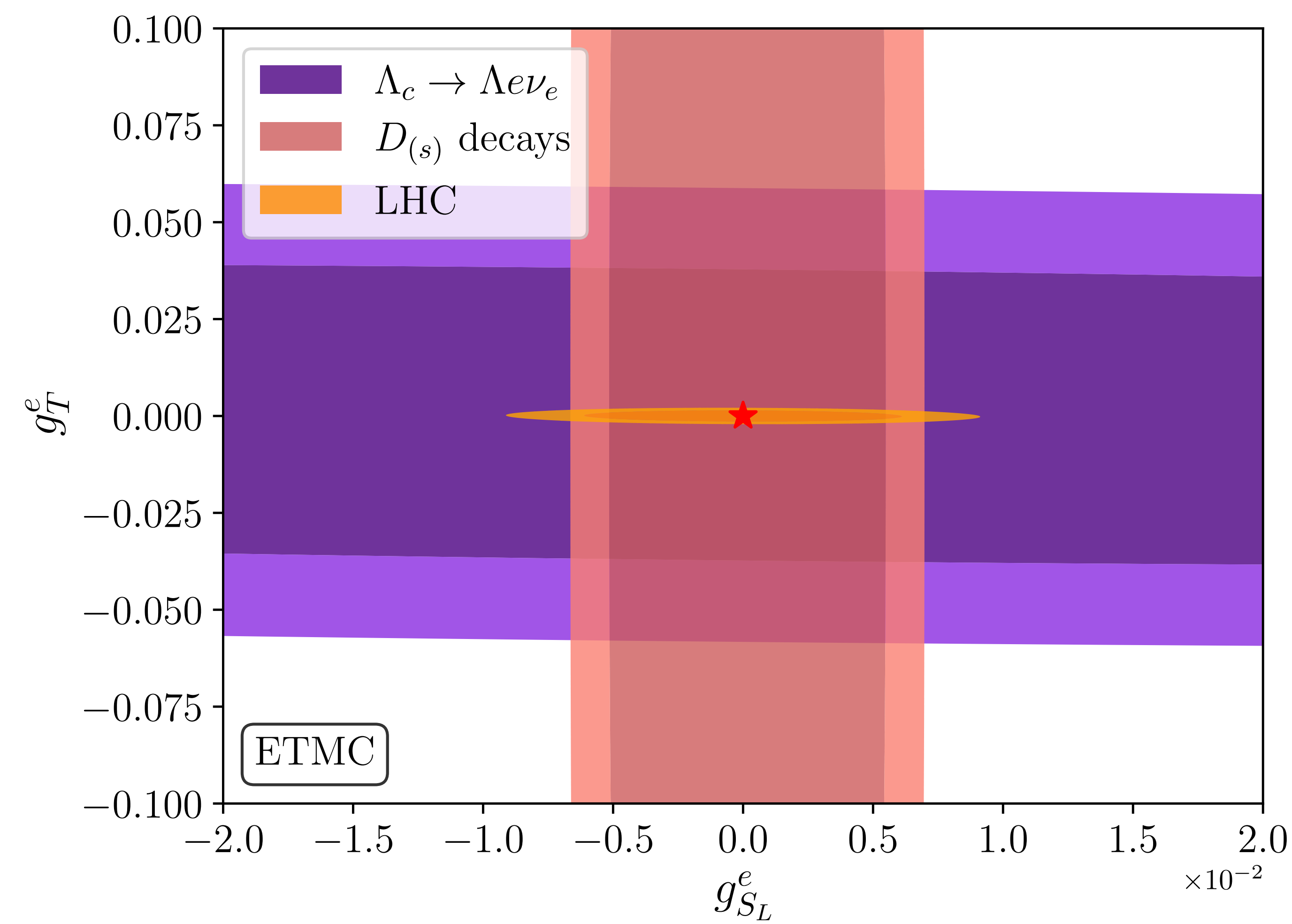

Concluding Remarks

- 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

- Both mesons at rest
- Continuum limit taken
- Treatment of artefacts at fixed lat spacing could be a source of disagreement