# Study of exclusive $c \to s e \nu_e$ transitions


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**In collaboration with D. Becirevic, F. Jaffredo & O. Sumensari, in preparation**

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# Introduction

Indirect searches for New Physics

$$\mathcal{O}^{\rm exp} = \mathcal{O}^{\rm SM}\left(1 + \delta_{\rm NP}\right)$$

Very precise measurement

Highly accurate theoretical prediction

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For example in $B \to D^* \ell \nu$

$c \to s \ell \nu$ represents a good testing ground:
BESIII + best environment for lattice QCD

# Introduction

## CKM Unitarity

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Global fits:

UTFit Collaboration, arXiv:2212.03894

$$|V_{cs}|^{\text{UTFit}} = 0.97345(20)$$

CKMfitter Group, arXiv:2405.08046

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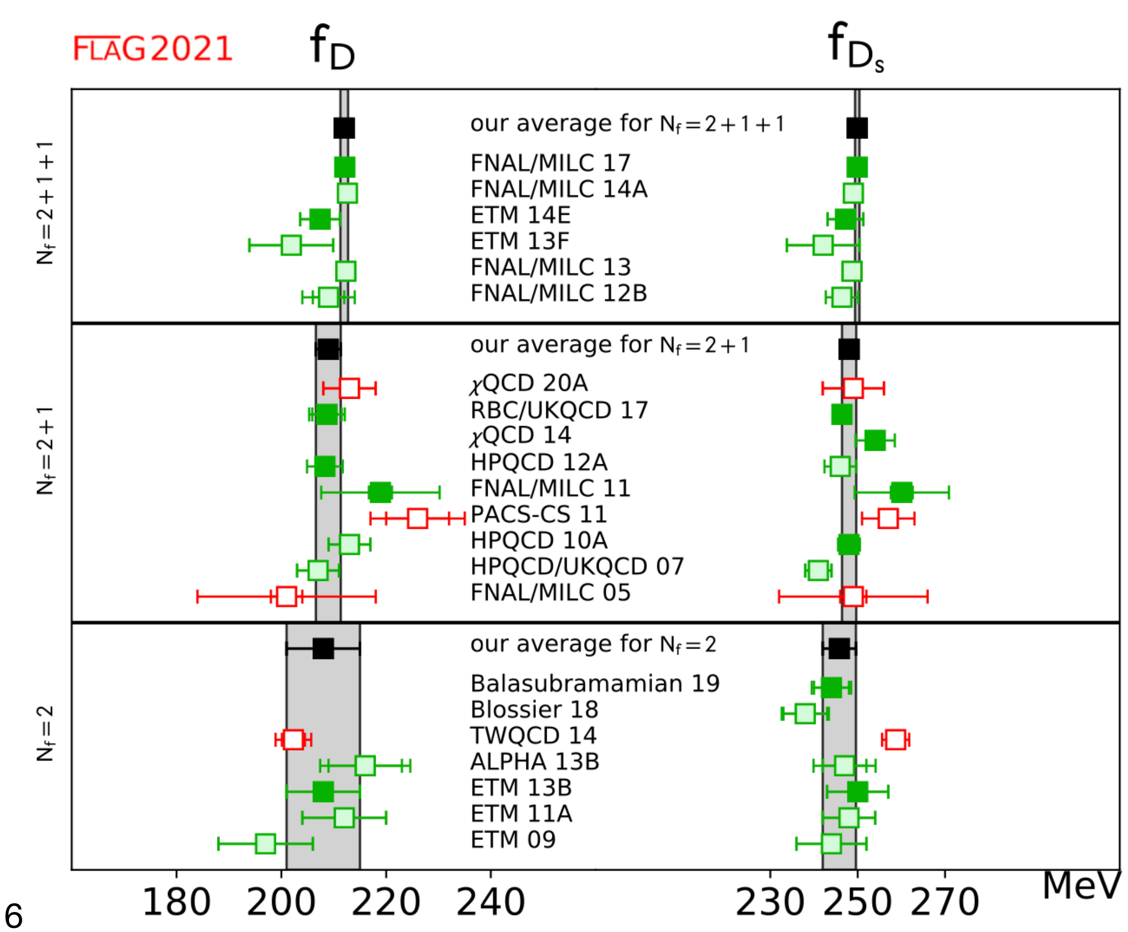
Leptonic modes:

$$\mathscr{B}\left(D_s \to \mu(\tau)\nu\right) \propto f_{D_s}^2 |V_{cs}|^2$$

$$\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s\rangle = ik_\mu f_{D_s}$$

Only input from lattice QCD

FLAG Collaboration, arXiv:2111.09849



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$$f_{D_s} = 249.9(0.5)\ \text{MeV}$$

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BESIII Collaboration, arXiv:2407.11727

$$\mathscr{B}\left(D_s \to \mu\nu\right) = \left(0.55 \pm 0.03\right)\%$$

$$\mathscr{B}\left(D_s \to \tau\nu\right) = \left(5.60 \pm 0.25\right)\%$$

$$|V_{cs}| = 0.997 \pm 0.018$$

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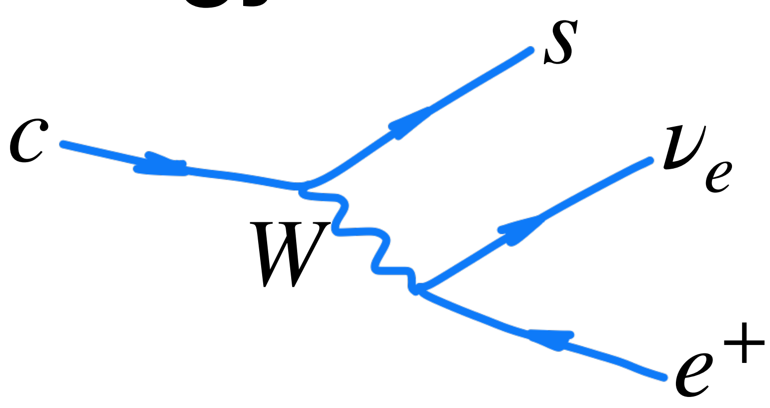
# New Physics in $c \to s e \nu_e$

## Low-energy EFT




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

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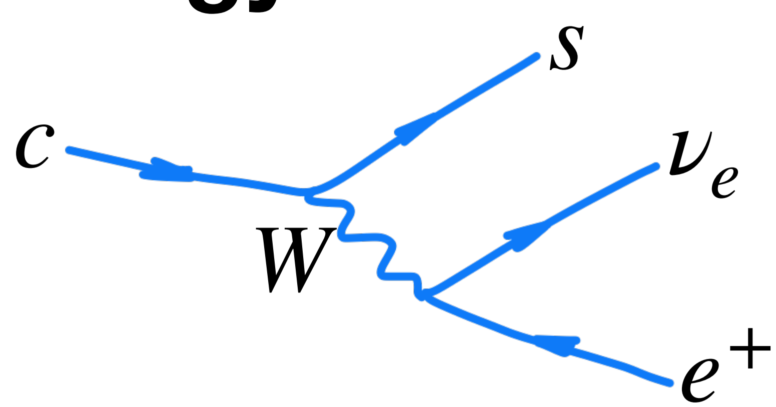


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Basis of **operators** with well defined **parity** transformations **under QCD**

$$\mathcal{O}_{V(A)} = (\bar{c}\gamma_\mu(\gamma_5)s) \left(\bar{\ell}_L \gamma^\mu \nu_L\right)$$

$$g^{\ell}_{S(P)} = g^{\ell}_{S_R} \pm g^{\ell}_{S_L} \qquad g^{\ell}_{V(A)} = g^{\ell}_{V_R} \pm g^{\ell}_{V_L} \qquad g^{\ell}_{T} = g^{\ell}_{T}$$

# New Physics in $c \to s e \nu_e$

## Low-energy data

$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{cs} \Big[ \left(1 + g^{\ell}_{V_L}\right) \left(\bar{c}_L \gamma_\mu s_L\right) \left(\bar{\ell}_L \gamma^\mu \nu_L\right) + g^{\ell}_{V_R} \left(\bar{c}_R \gamma_\mu s_R\right) \left(\bar{\ell}_L \gamma^\mu \nu_L\right)$$
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### Meson decays

$D_s \to e\nu$

$$\mathcal{B}\left(D_s \to e\nu_e\right) < 8.3 \times 10^{-5}$$

Belle Collaboration, arXiv:1307.6240

$D_s \to \phi e\nu$

$$\mathcal{B}\left(D_s \to \phi e\nu_e\right) = (2.39 \pm 0.16) \times 10^{-2}$$

PDG Collaboration, 2020

$D \to K e\nu$

$$\mathcal{B}\left(D^0 \to K^- e\nu_e\right) = (3.509 \pm 0.016) \times 10^{-2}$$
$$\mathcal{B}\left(D^+ \to K^0 e\nu_e\right) = (8.86 \pm 0.09) \times 10^{-2}$$

BESIII Collaboration, arXiv:2408.09087

Info on binned distribution

See also
C. Bolognani *et al*., arXiv:2407.06145

### Baryon decays

$\Lambda_c \to \left(\Lambda \to p\pi\right) e\nu$

BESIII Collaboration, arXiv:2207.14149

Derived angular distribution from "experimental" FF

# Charmed hadron decays

## (Semi-) leptonic meson decays

CKM unitarity

Leptonic:

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

Experimental measurement

Lattice QCD

$$\langle 0 | \bar{s} \gamma_\mu \gamma_5 c | D_s \rangle = i k_\mu f_{D_s}$$

New physics?

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Semileptonic: **Pseudoscalar** in final state $D \to K e \nu_e$

In the SM

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = \tau_D G_F^2 |V_{cs}|^2 \frac{\lambda^{3/2}(m_D^2, m_K^2, q^2)}{192\pi^3 m_D^3} f_+^2$$

$$\langle K | \bar{c}\gamma_\mu s | D \rangle \propto f_+, f_0$$

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$$\langle K|\bar{c}\gamma_\mu s|D\rangle \propto f_+, f_0$$

In the presence of NP

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} \propto f_+\,,\ f_0\,,\ f_T$$

$$\langle K|\bar{c}\sigma_{\mu\nu} s|D\rangle \propto f_T$$

# Charmed hadron decays

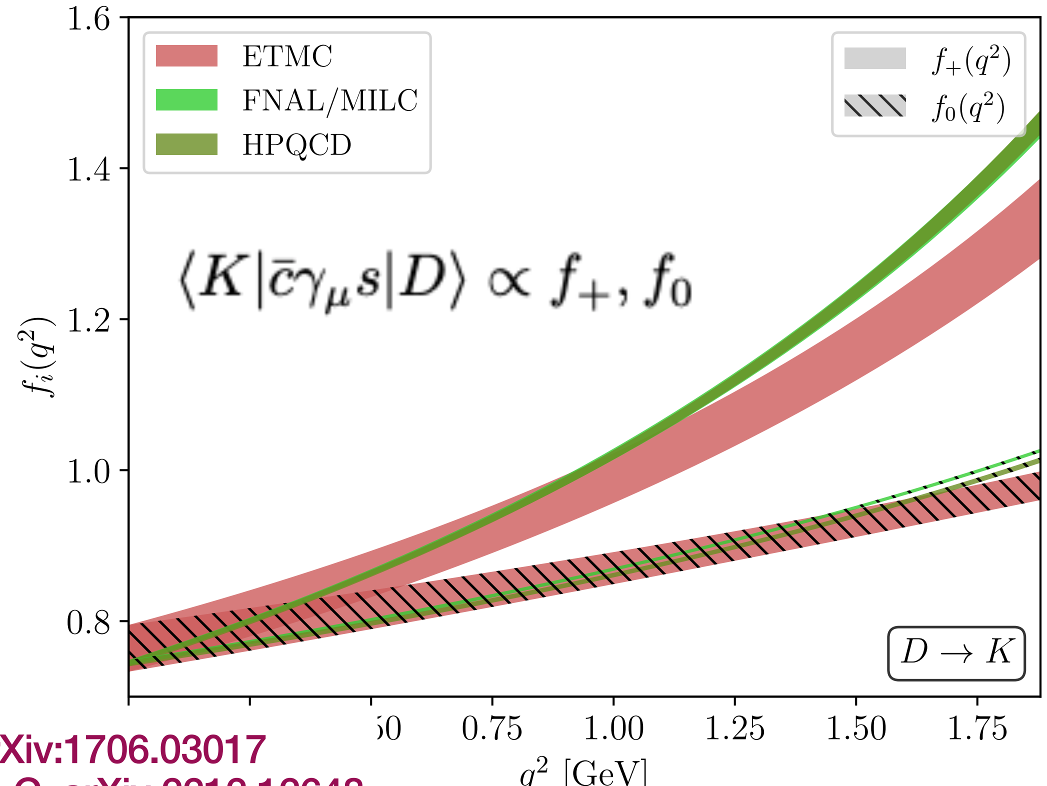
## (Semi-) leptonic meson decays

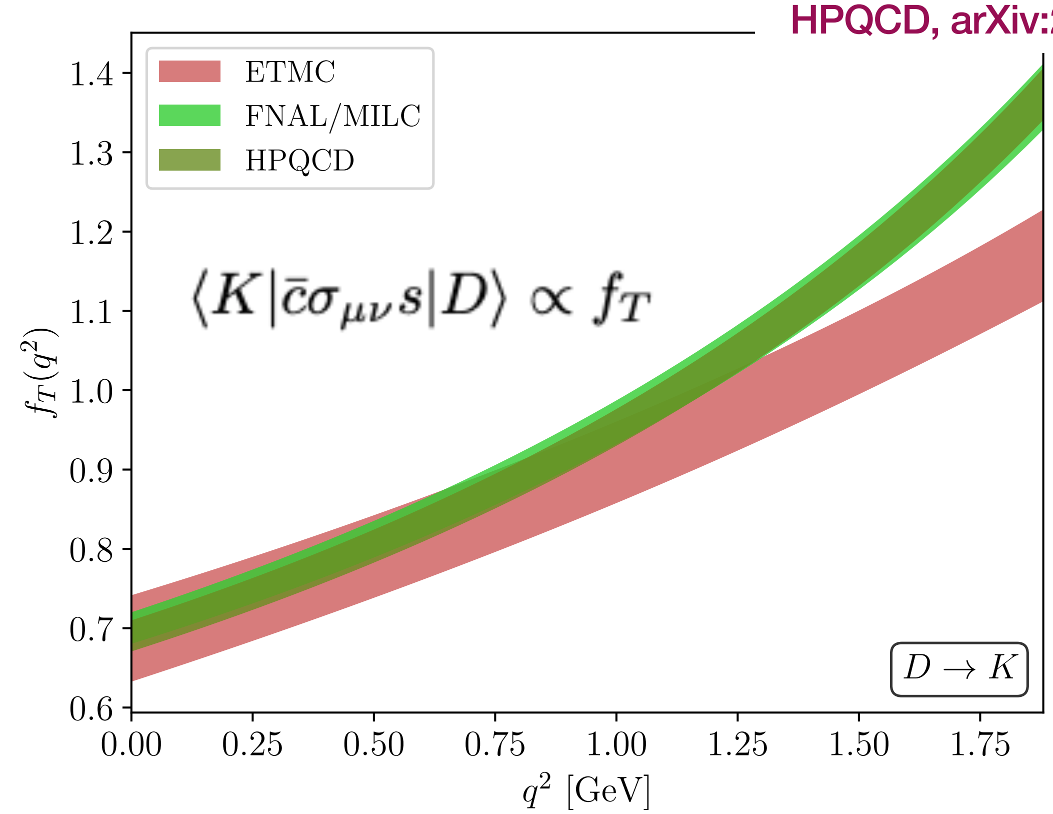
Leptonic:

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

Semileptonic: **Pseudoscalar** in final state $D \to K e \nu_e$

ETMC, arXiv:1803.04807
FNAL/MILC, arXiv:2212.12648
HPQCD, arXiv:2207.12468

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# Charmed hadron decays

## (Semi-) leptonic meson decays

Leptonic:

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

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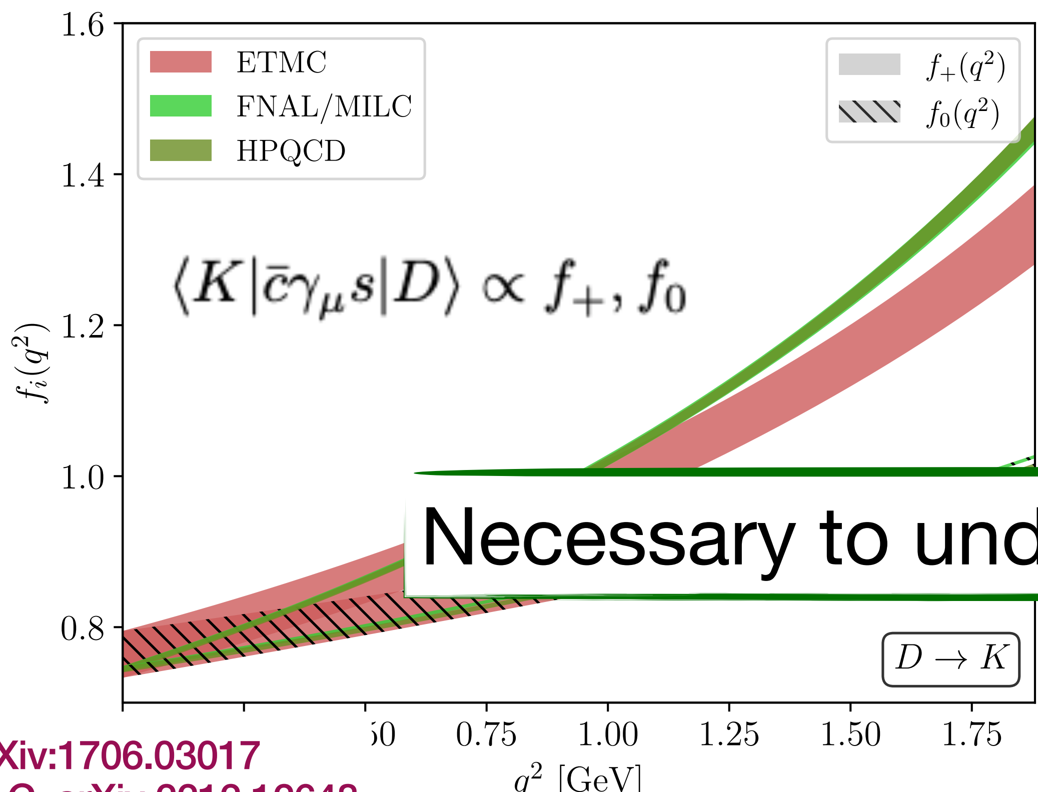


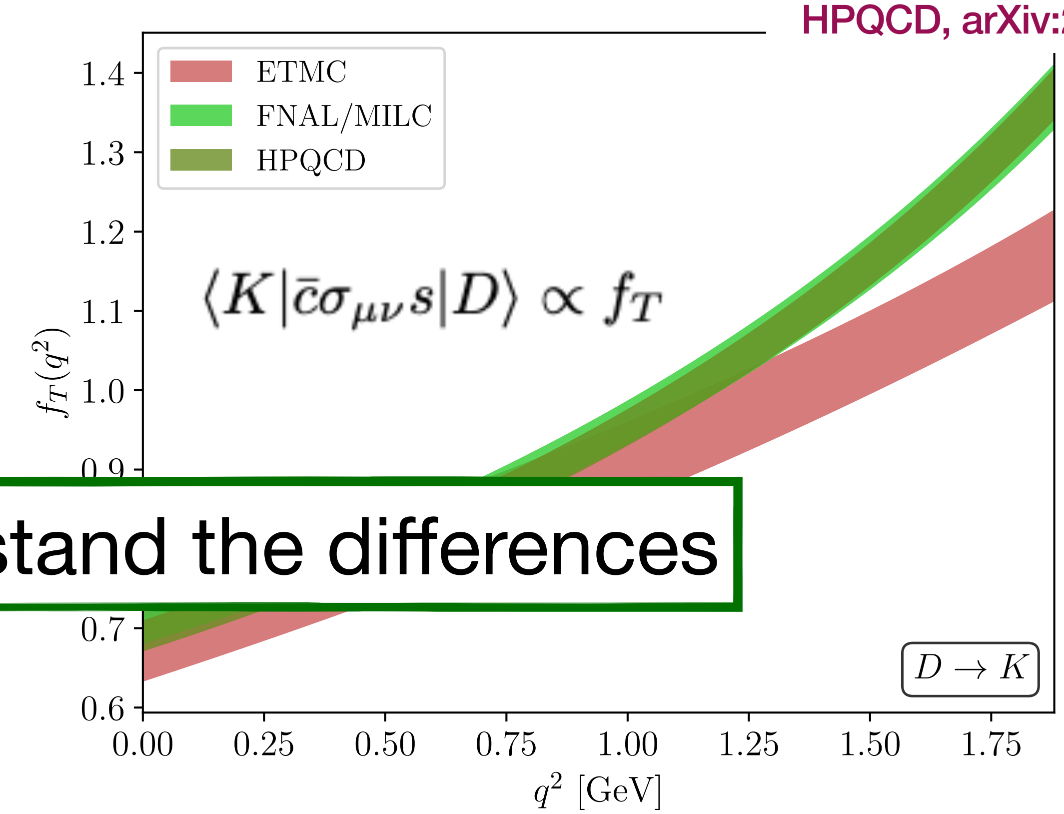


Necessary to understand the differences

ETMC, arXiv:1706.03017
FNAL/MILC, arXiv:2212.12648
HPQCD, arXiv:2204.09883

# Charmed hadron decays

## (Semi-) leptonic meson decays

Leptonic:

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

Semileptonic: **Vector** in final state $D_s \to \phi e \nu_e$

Already in the **SM**, many **more FF** are necessary

$$\langle \phi | V_\mu | D_s \rangle \propto V$$

$$\langle \phi | A_\mu | D_s \rangle \propto A_1\,, A_2\,, A_0$$

Relevant for NP

$$\langle \phi | T_{\mu\nu} | D_s \rangle \propto T_1\,, T_2\,, T_3$$

# Charmed hadron decays

## (Semi-) leptonic meson decays

Leptonic:

$$\mathcal{B}\left(D_s \to \ell\nu_\ell\right) = \tau_{D_s} \frac{G_F^2|V_c}{8}$$

Semileptonic:

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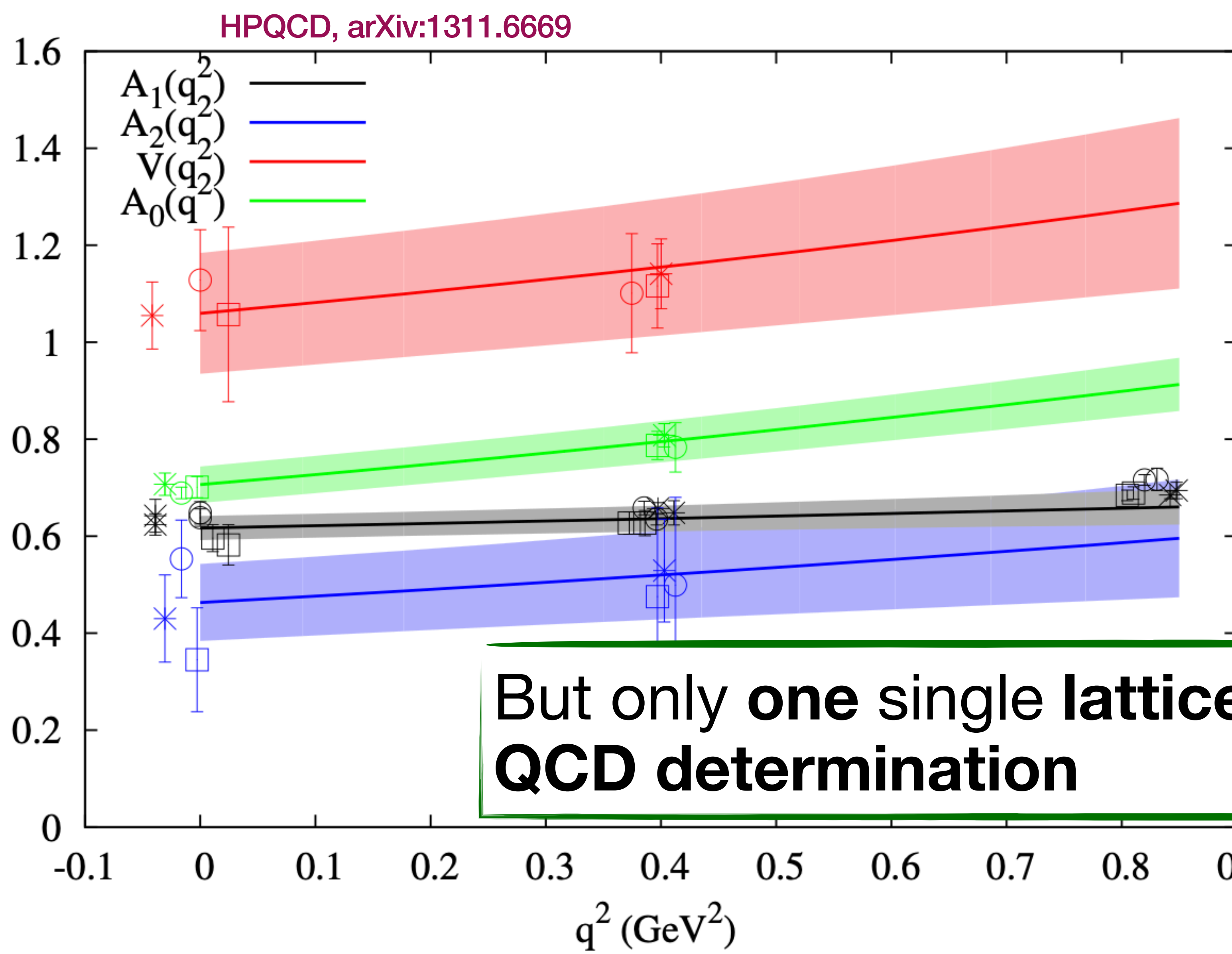


But only **one** single **lattice QCD determination**

# Charmed hadron decays

## Semileptonic baryon decays

$\Lambda_c \to \Lambda e \nu_e$

$\langle \Lambda | V_\mu | \Lambda_c \rangle \propto f_\perp\,, f_+\,, f_0$ $\quad$ $\langle \Lambda | A_\mu | \Lambda_c \rangle \propto g_\perp\,, g_+\,, g_0$ $\quad$ $\langle \Lambda | T_{\mu\nu} | \Lambda_c \rangle \propto h_\perp\,, h_+\,, h_0\,, \tilde{h}_\perp\,, \tilde{h}_+$

S. Meinel, arXiv:1611.09696

Only lattice QCD determination

# Charmed hadron decays

## Semileptonic 3-body decays

$\Lambda_c \to \Lambda e \nu_e$

$\langle \Lambda | V_\mu | \Lambda_c \rangle \propto f_\perp \,, f_+ \,, f_0$ $\qquad$ $\langle \Lambda | A_\mu | \Lambda_c \rangle \propto g_\perp \,, g_+ \,, g_0$ $\qquad$ $\langle \Lambda | T_{\mu\nu} | \Lambda_c \rangle \propto h_\perp \,, h_+ \,, h_0 \,, \tilde{h}_\perp \,, \tilde{h}_+$

S. Meinel, arXiv:1611.09696

Only lattice QCD determination

Any **3-body decay** can be written as

$$\frac{\mathrm{d}^2\mathcal{B}^{\lambda_\ell}}{\mathrm{d}q^2 \mathrm{d}\cos\theta} = a^{\lambda_\ell}(q^2) + b^{\lambda_\ell}(q^2)\cos\theta + c^{\lambda_\ell}(q^2)\cos^2\theta$$

One could measure up to 3 observables to fully describe the decay distribution

# Charmed hadron decays

## Semileptonic 3-body decays

$\Lambda_c \to \Lambda e \nu_e$

$\langle \Lambda | V_\mu | \Lambda_c \rangle \propto f_\perp, f_+, f_0$ $\langle \Lambda | A_\mu | \Lambda_c \rangle \propto g_\perp, g_+, g_0$ $\langle \Lambda | T_{\mu\nu} | \Lambda_c \rangle \propto h_\perp, h_+, h_0, \tilde{h}_\perp, \tilde{h}_+$

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For $D_{(s)}$ **decays** we **only** have measured $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$

Instead, the **full decay rate** distribution for the $\Lambda_c$ has been **measured**

# $\Lambda_c \to (\Lambda \to p\pi)\, e\nu_e$

## 4-body decay rate

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

BESIII measured full decay rate

BESIII Collaboration, arXiv:2207.14149
BESIII Collaboration, arXiv:2306.02624

The experimental collaboration provides only the **fitted FF assuming SM**

# $\Lambda_c \to (\Lambda \to p\pi)\, e\nu_e$

## 4-body decay rate

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$D_4$ and $E_4 \to 0$

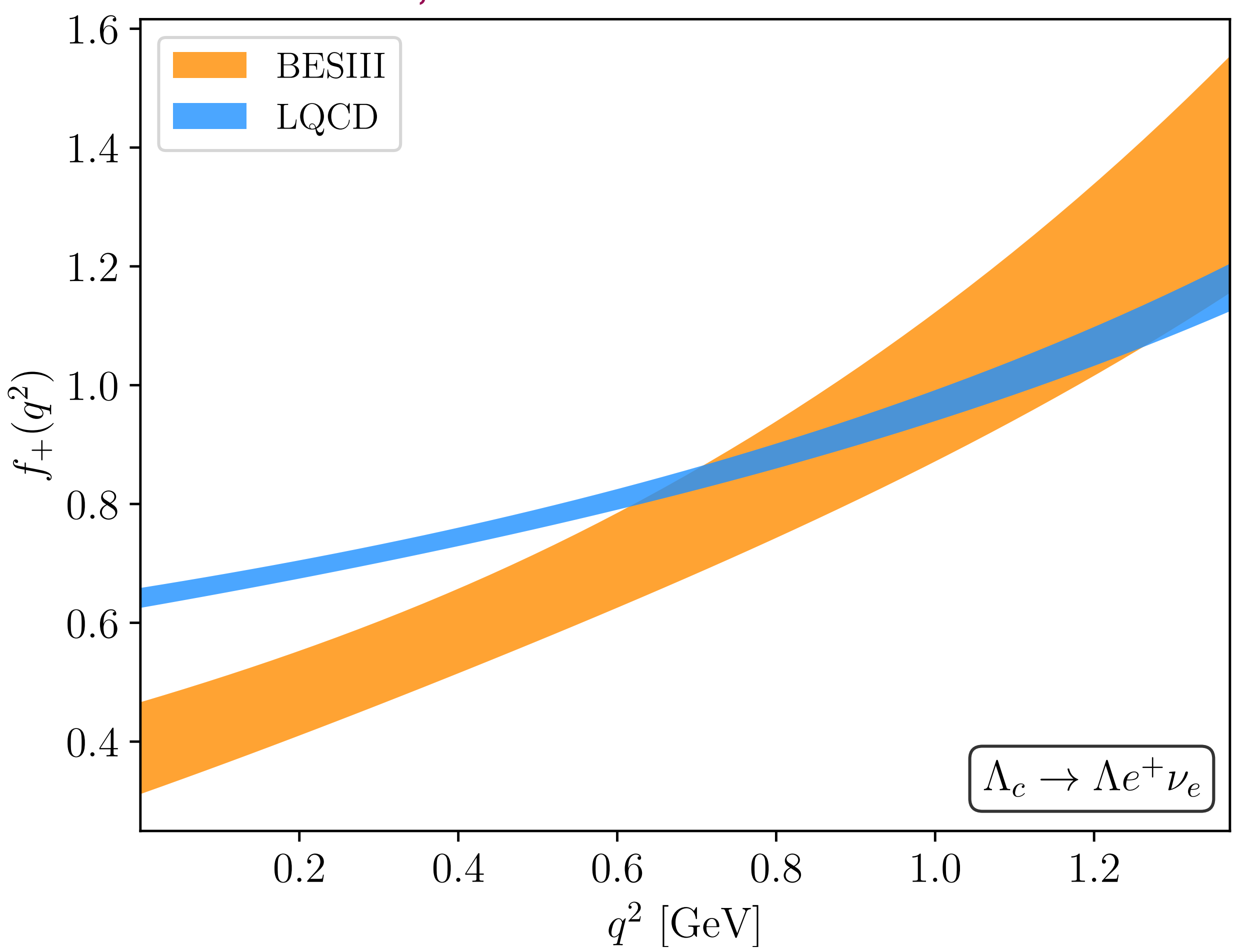
Crucial to provide the full distribution of events and their correlations

# $\Lambda_c \to (\Lambda \to p\pi)\, e\nu_e$

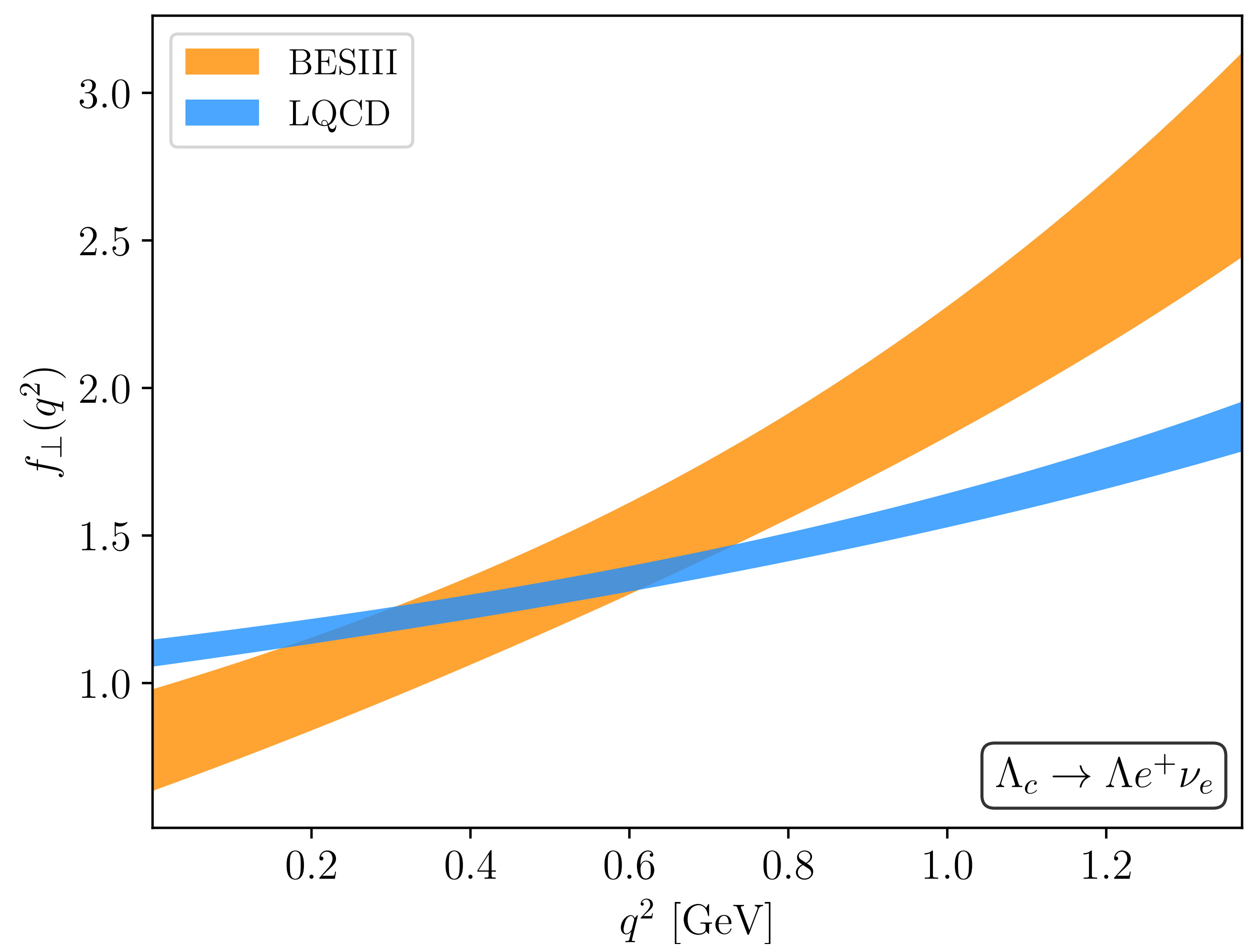
# Extracted form factors

$\langle \Lambda | V_\mu | \Lambda_c \rangle \propto f_\perp\,, f_+\,, f_0$ $\qquad$ $\langle \Lambda | A_\mu | \Lambda_c \rangle \propto g_\perp\,, g_+\,, g_0$

S. Meinel, arXiv:1611.09696
BESIII Collaboration, arXiv:2207.14149




D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation



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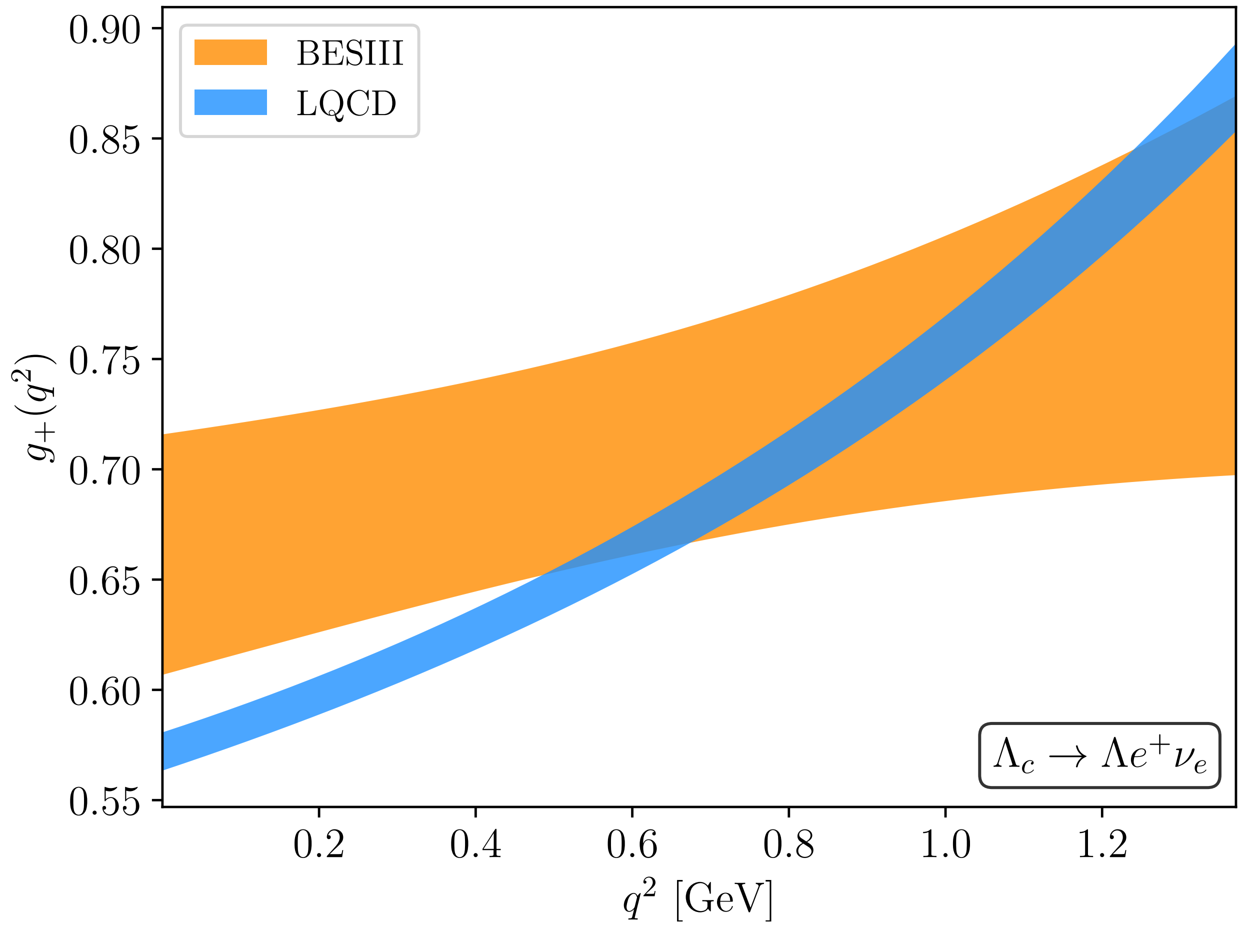


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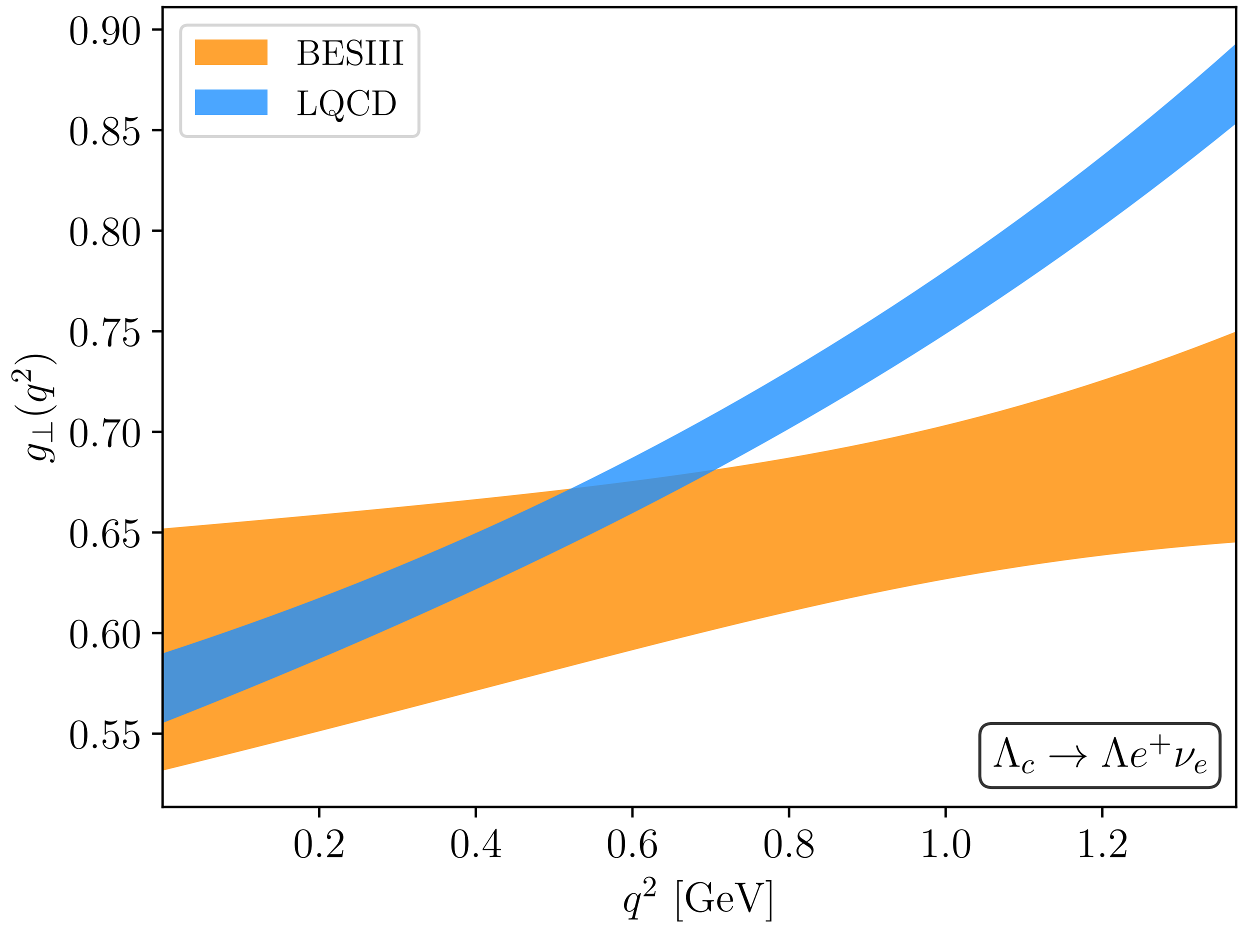

# $\Lambda_c \to \Lambda e \nu_e$

# Comparison of different observables

$$\frac{\mathrm{d}^2\mathcal{B}^{\lambda_\ell}}{\mathrm{d}q^2\mathrm{d}\cos\theta} = a^{\lambda_\ell}(q^2) + b^{\lambda_\ell}(q^2)\cos\theta + c^{\lambda_\ell}(q^2)\cos^2\theta$$

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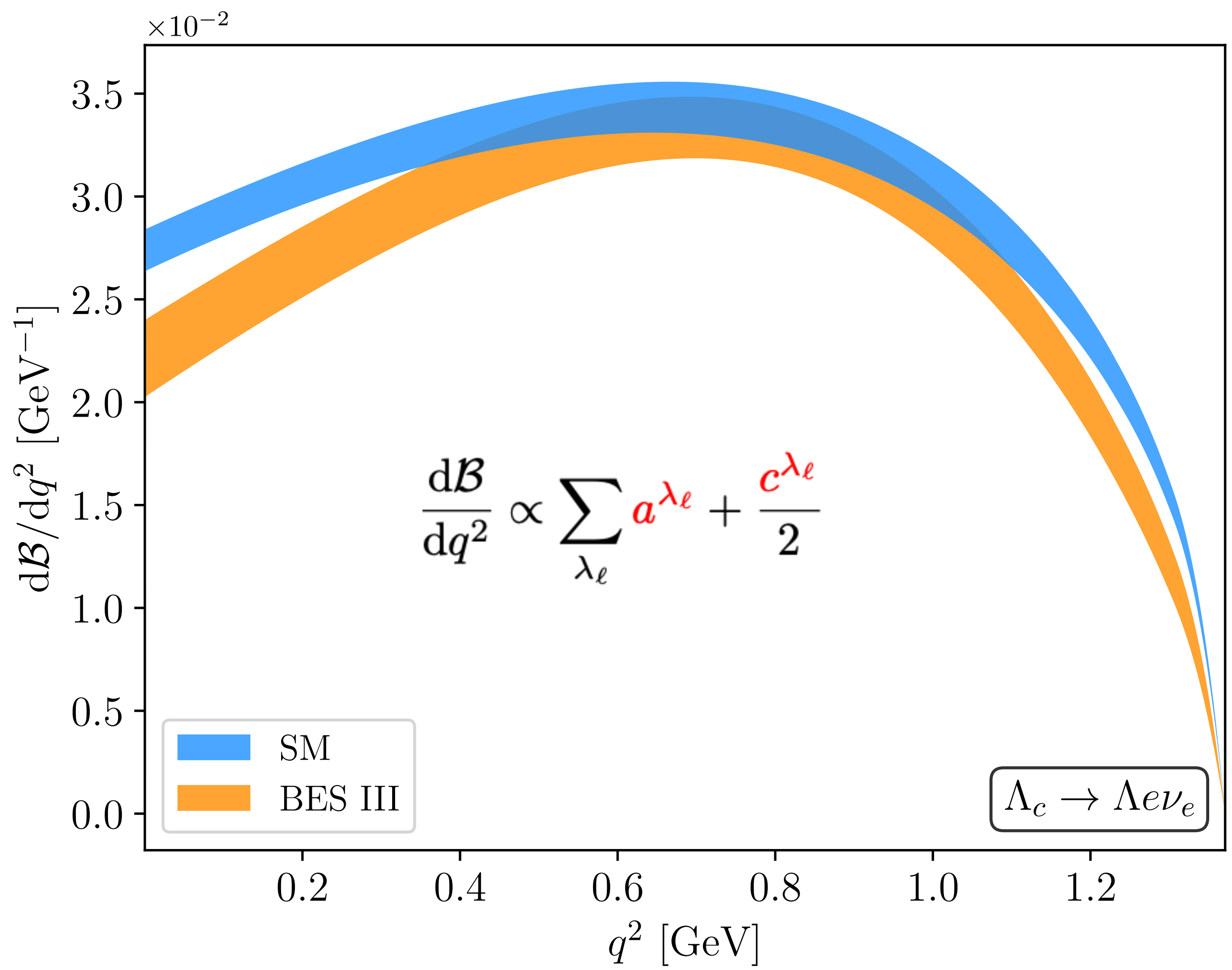
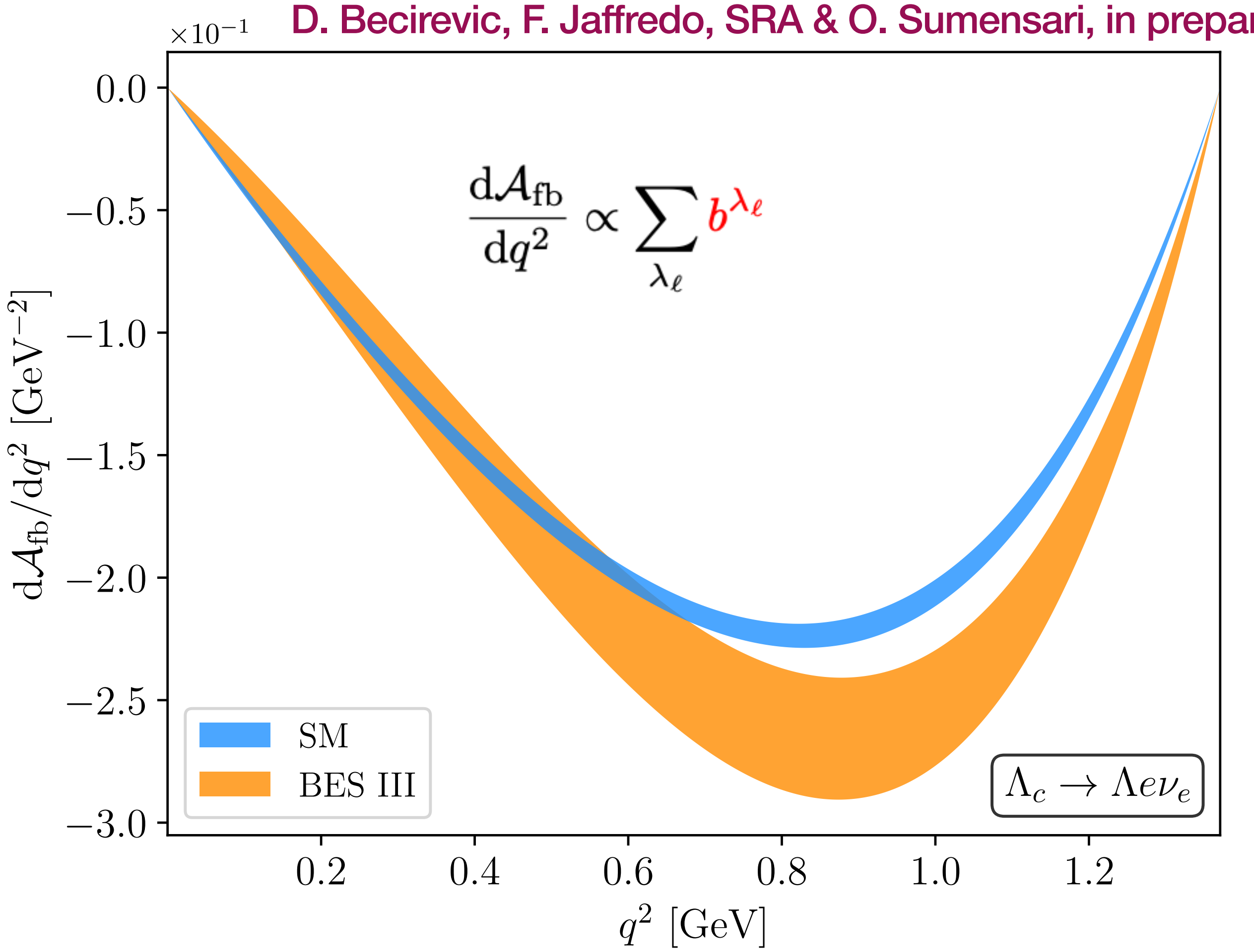


# $\Lambda_c \to (\Lambda \to p\pi)\, e\nu_e$

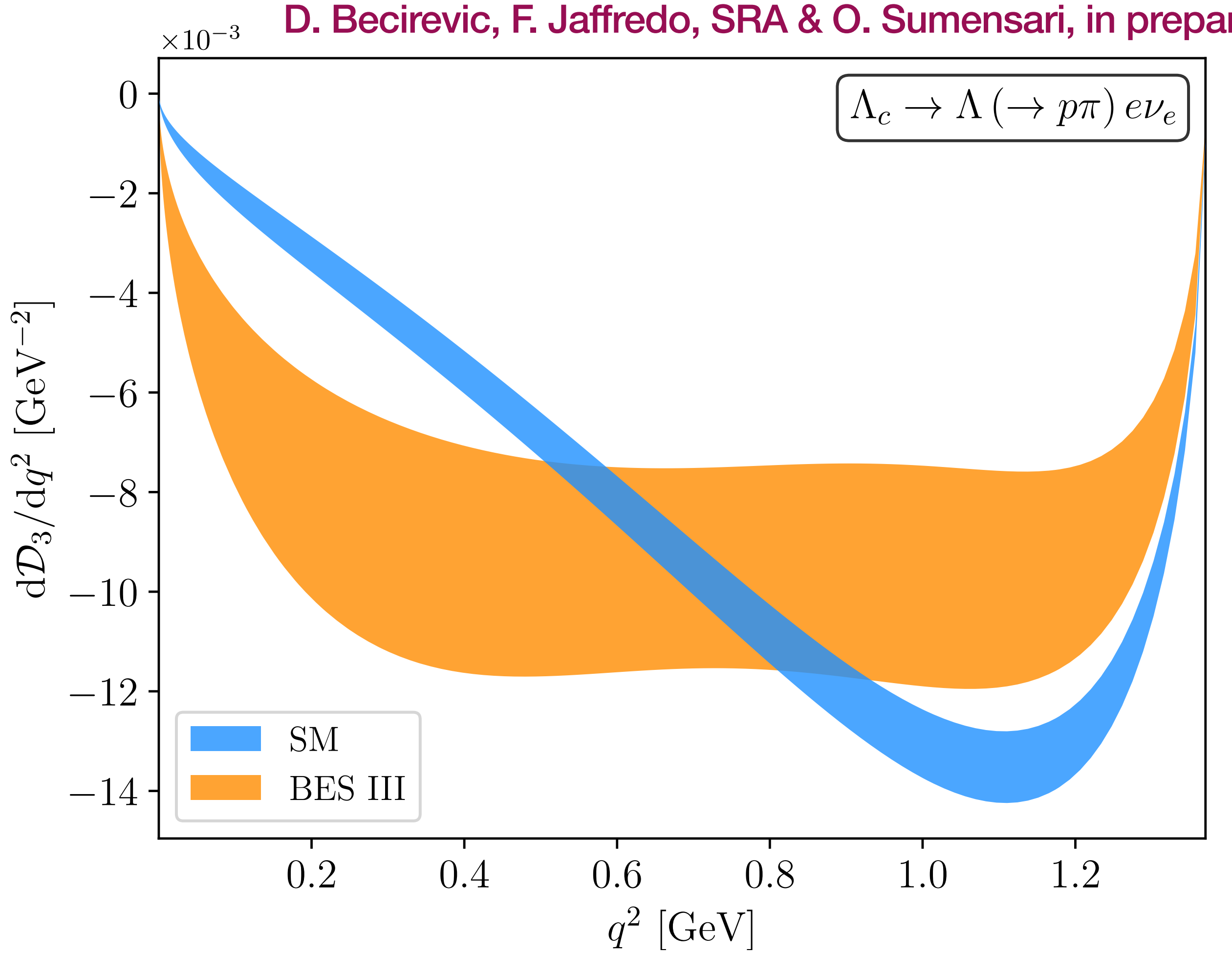
## Comparison of different observables

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

S. Meinel, arXiv:1611.09696
BESIII Collaboration, arXiv:2207.14149

Not accessible in 3-body decay rate

D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation




**Integrated quantities** are **consistent** with the **SM**

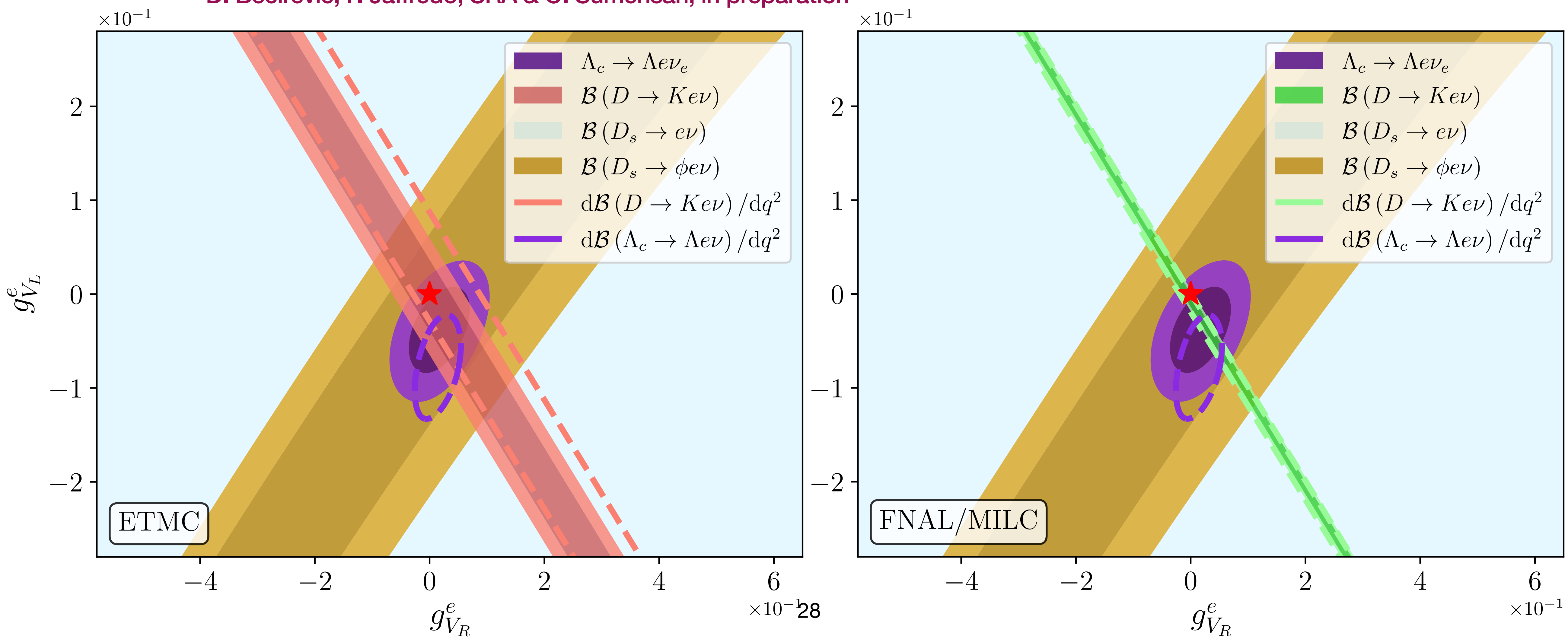
# New Physics in $c \to s e \nu_e$

## Low-energy data

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

Include vector couplings

D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation



# New Physics in $c \to s e \nu_e$

## Low-energy data

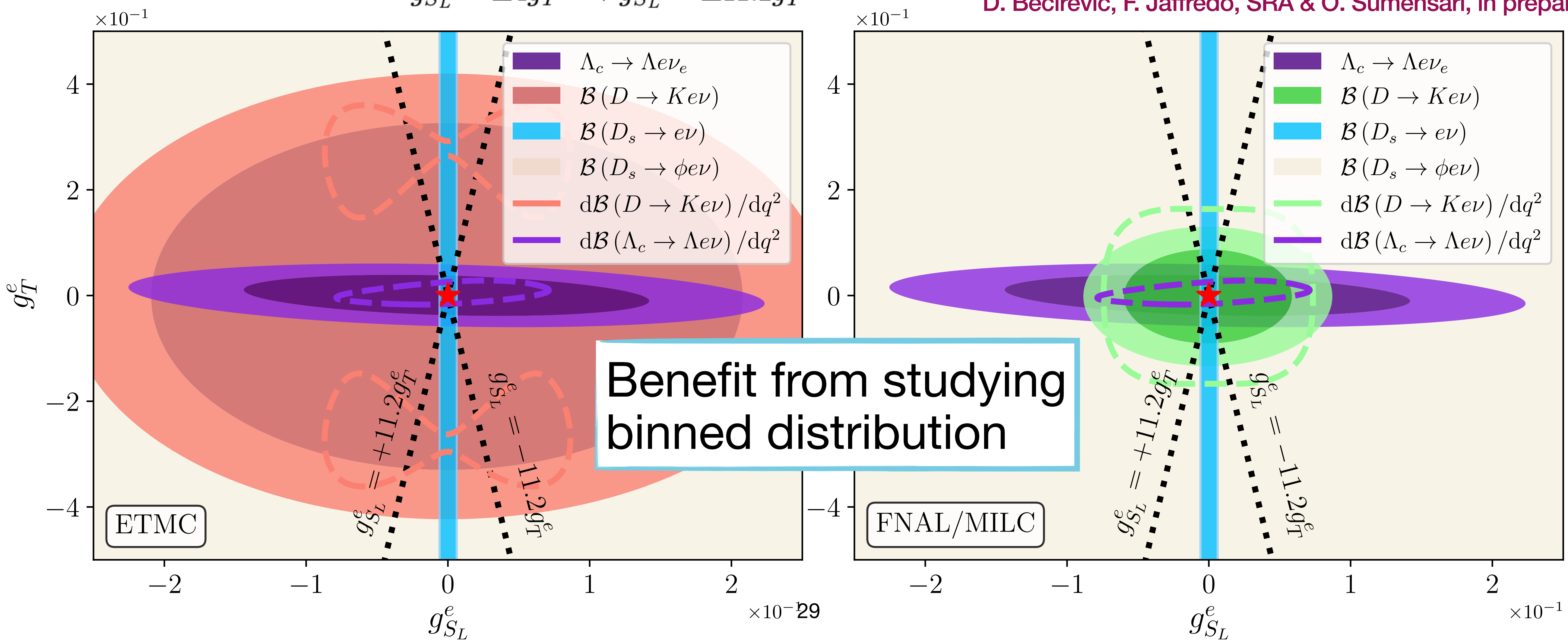
$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{cs} \Big[ \big(1 + g_{V_L}^{\ell}\big) \left(\bar{c}_L \gamma_\mu s_L\right) \left(\bar{\ell}_L \gamma^\mu \nu_L\right) + g_{V_R}^{\ell} \left(\bar{c}_R \gamma_\mu s_R\right) \left(\bar{\ell}_L \gamma^\mu \nu_L\right) + g_{S_L}^{\ell} \left(\bar{c}_R s_L\right)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

Motivated by $S_1$ or $R_2$ leptoquarks

$\Lambda_{\rm NP} \to 2\,\text{GeV}$

$g_{S_L} = \pm 4 g_T \longrightarrow g_{S_L} \simeq \pm 11.2 g_T$

D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation



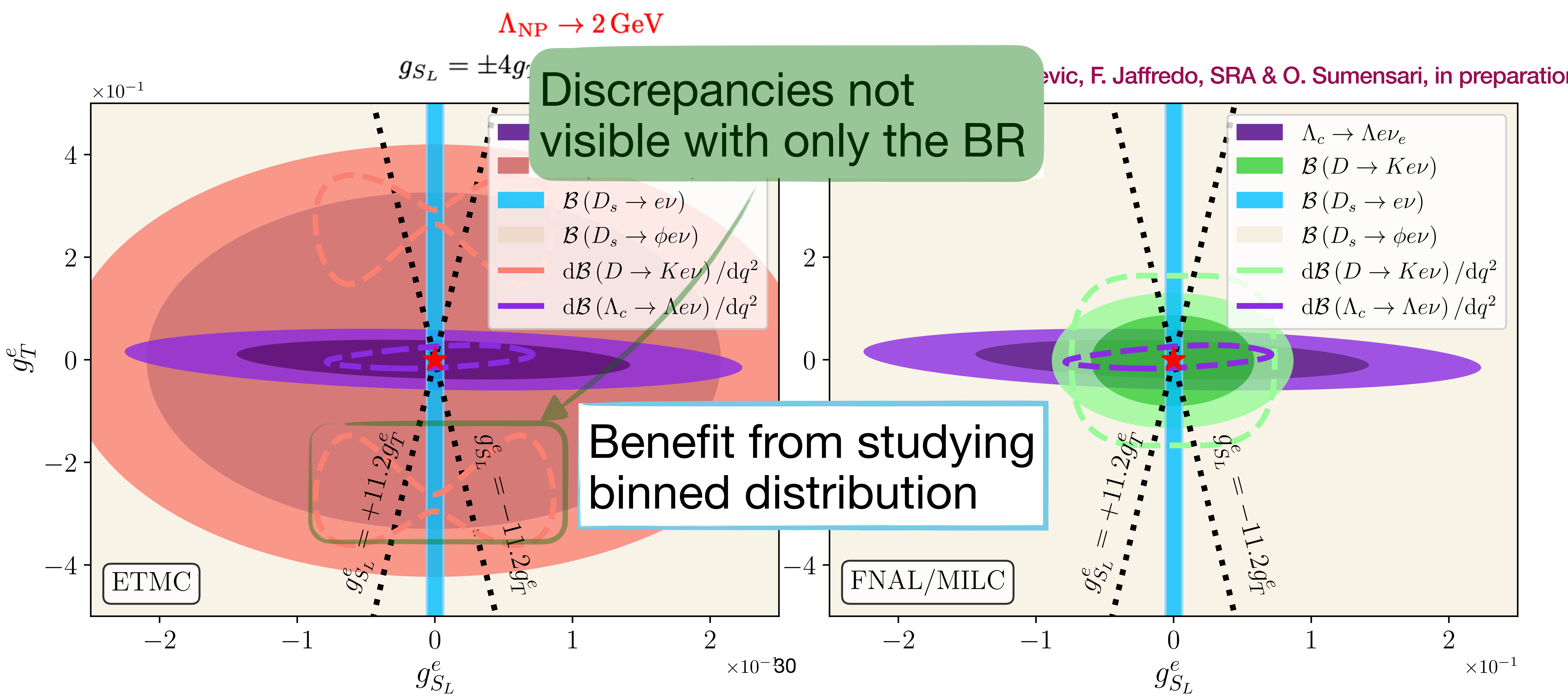

Benefit from studying binned distribution

# New Physics in $c \to s e \nu_e$

## Low-energy data

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

Motivated by $S_1$ or $R_2$ leptoquarks



# New Physics in $c \to s e \nu_e$

## High-$p_T$ tails @ LHC

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

$$g^{\ell}_{V_L} = \frac{v^2}{\Lambda^2_{\rm NP}} \mathcal{C}^{(3)}_{lq}\,, \quad g^{\ell}_{S_L} = \frac{v^2}{2\Lambda^2_{\rm NP} V_{cs}} \mathcal{C}^{(1)}_{lequ}\,, \quad g^{\ell}_{S_R} = \frac{v^2}{2\Lambda^2_{\rm NP}} \mathcal{C}_{ledq}\,, \quad g^{\ell}_{T} = \frac{v^2}{2\Lambda^2_{\rm NP} V_{cs}} \mathcal{C}^{(3)}_{lequ}$$

Drell-Yan processes at colliders

HighPT

J. Fuentes-Martín *et al.*, arXiv:2003.12421
L. Allwicher *et al.*, arXiv:2207.10714
L. Allwicher *et* al., arXiv:2207.10756

$$\sigma\left(pp \to \ell\nu\right) \propto \int f_{\bar{s}} f_c \hat{\sigma}\left(\bar{s}c \to \ell\nu\right) + \left(s \leftrightarrow c\right)$$

# New Physics in $c \to s e \nu_e$

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Drell-Yan processes at colliders

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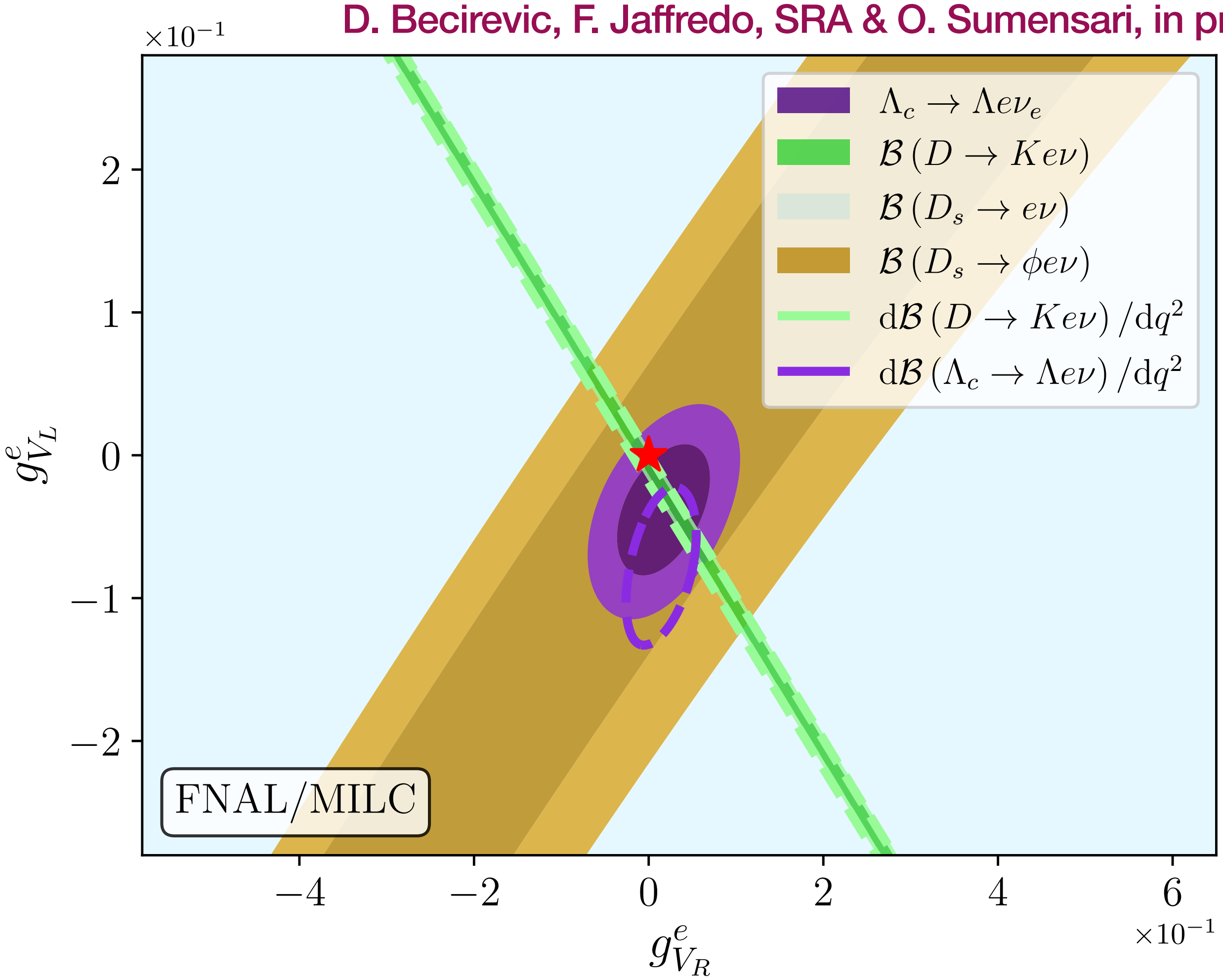
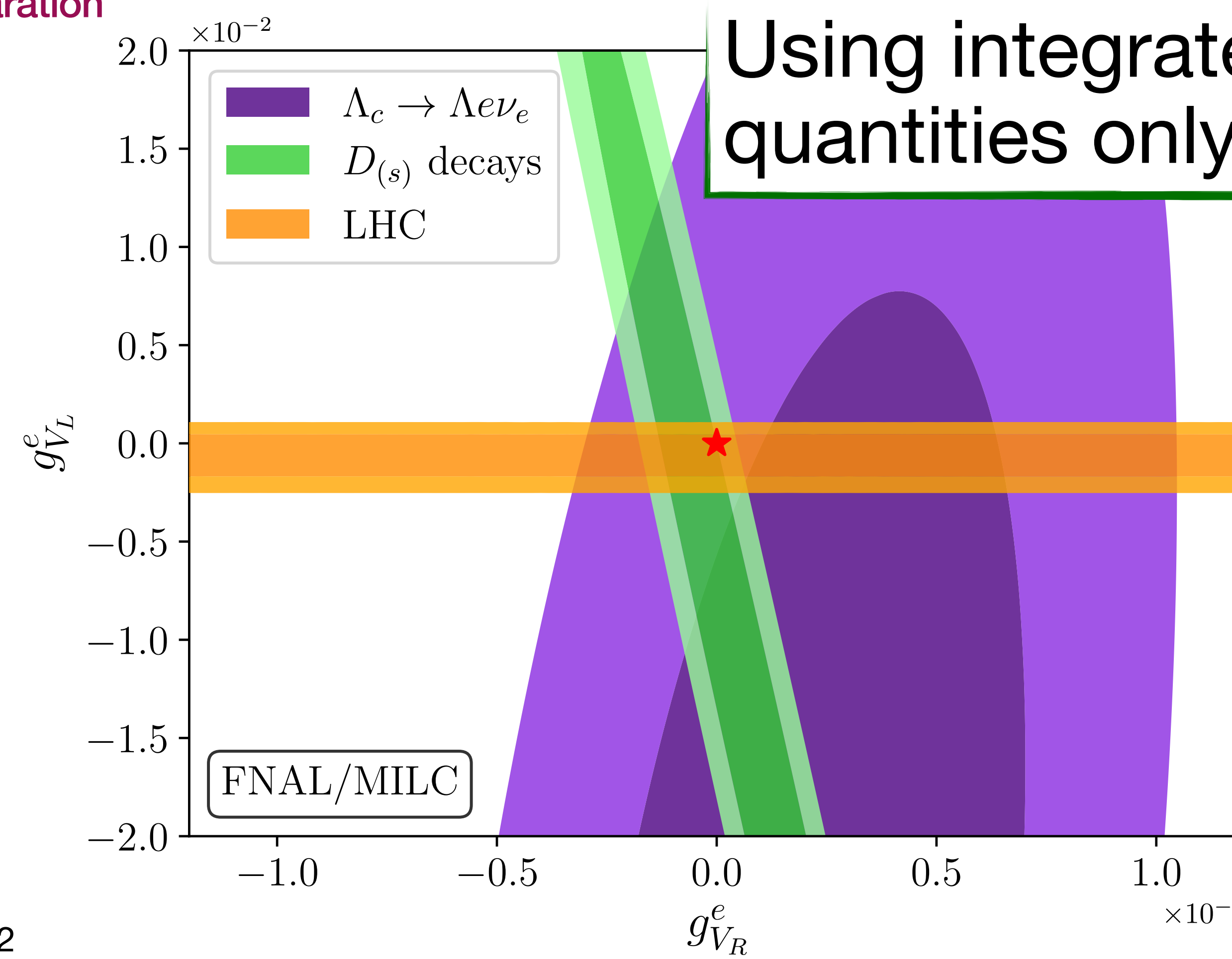
D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation




Using integrated quantities only

# New Physics in $c \to s e \nu_e$

## High-$p_T$ tails @ LHC

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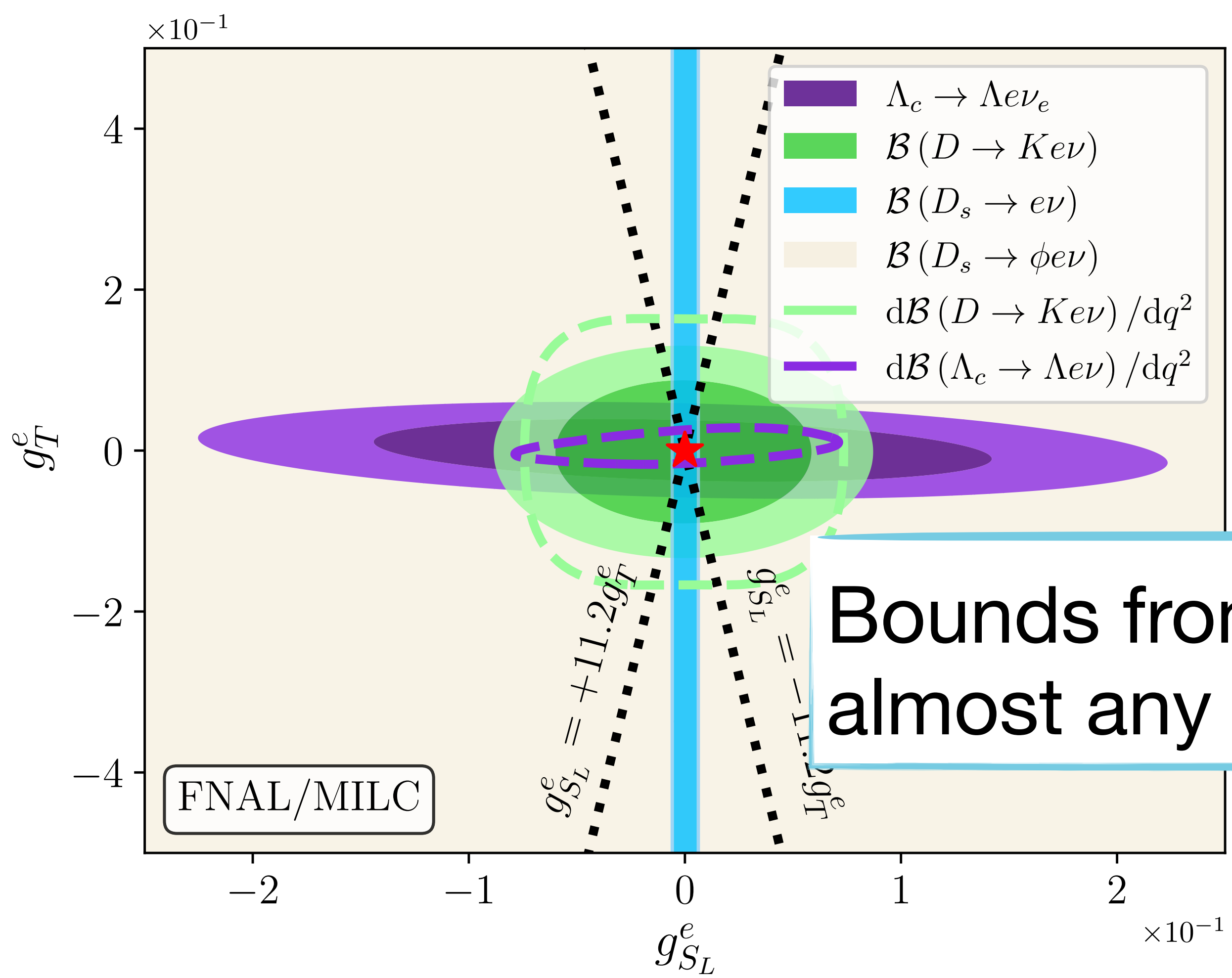
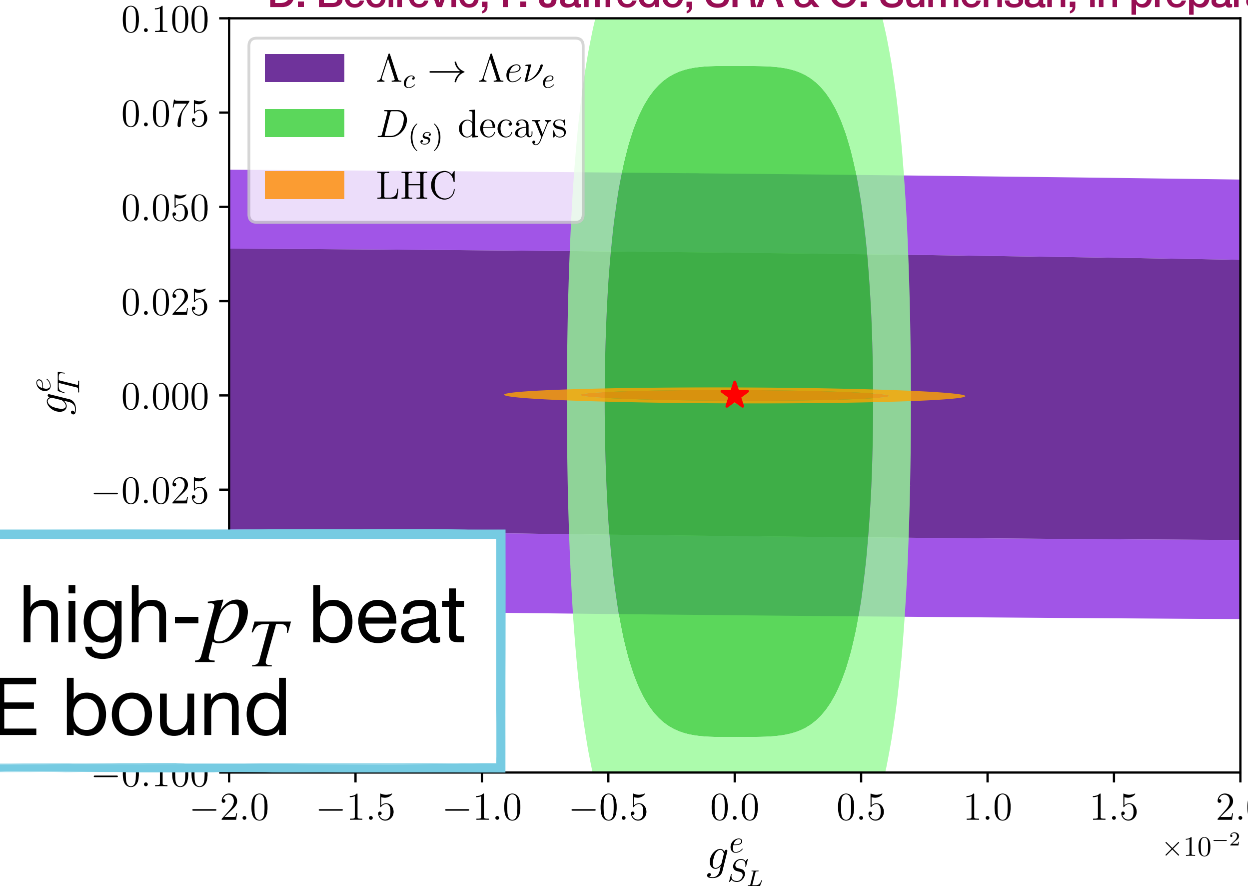



D. Becirevic, F. Jaffredo, SRA & O. Sumensari, in preparation




Bounds from high-$p_T$ beat almost any LE bound

# Conclusions

- **Indirect tests of NP** need very **high precision** from both **experiment** and **theory**
- **Lattice QCD** results for relevant **semileptonic decays** is **not** completely **satisfactory**
- The **full $q^2$-distributions of angular observables** would be **very useful**

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- The **full $q^2$-distributions of angular observables** would be **very useful**
- **High-$p_T$ tails** of Drell-Yan processes highly **constrain any NP** in **semileptonic $c \to s$ transitions**
- If there is **no NP** in $c \to s\ell\nu$, we can then use all this data to **test lattice QCD**

Important to understand **theory** inputs in **channels** more sensitive to NP, like $B \to D^*\ell\nu$

# Back up slides

# Back up slides

## BESIII

They study a plethora of decays

$$e^+e^- \to \psi(c\bar{c}) \to D\bar{D}$$

$$e^+e^- \to D_s^{*+}\bar{D}_s^{*-}, \Lambda_c^+\bar{\Lambda}_c^-$$

$D_s \to \ell\nu$
BESIII Collaboration, arXiv:2407.11727

$D \to K\ell\nu$
BESIII Collaboration, arXiv:2408.09087

$D_s \to \phi\ell\nu$
BESIII Collaboration, arXiv:2307.03024

$\Lambda_c \to \Lambda\ell\nu$
BESIII Collaboration, arXiv:2207.14149

BESIII Collaboration, arXiv:2306.02624

Measured the $q^2$-dependence of the branching fractions

# Back up slides

## Comparison of branching fractions