Istituto Nazionale di Fisica Nucleare

Constraining Flavor from the semileptonic decays of baryons.

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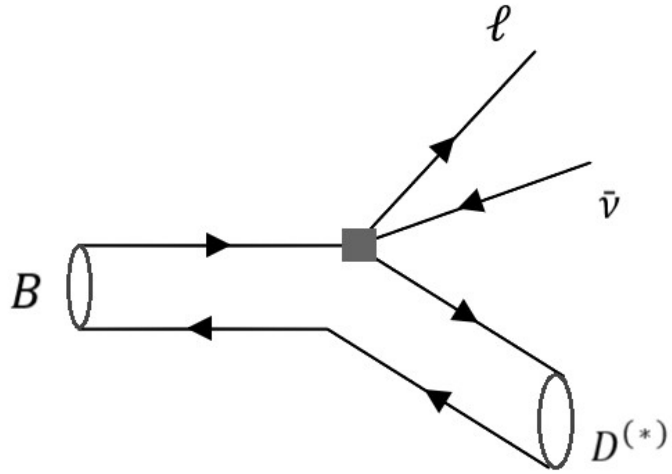
[2209.13409], [240x.xxxxx]

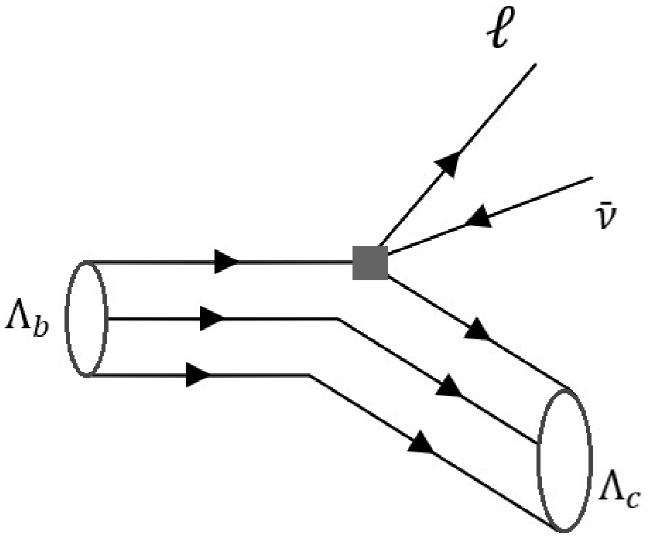
Motivations

- Low-energy flavor physics is mostly probed using mesons.
- Remaining hints of LFUV in $b \to c\ell\nu$.

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

- NP observables should not depend on the spectator(s).





Computing baryon observables

- Low energy observable, $m_{\Lambda_b} = 5.6\,\mathrm{GeV}$.
- Assuming NP at a scale $\Lambda \sim \mathcal{O}(1\,\mathrm{TeV})$, can be computed using a weak EFT.

Charged Lagrangian

$$\mathcal{L}_{\mathrm{NP}} = -\frac{4G_F V_{ij}}{\sqrt{2}} \sum_X g_X \mathcal{O}_X + \mathrm{h.c.}$$

$$X \in V_L, V_R, S_R, S_L, T$$

Neutral Lagrangian :

$$\mathcal{L}_{\mathrm{NP}} = -\frac{4G_F V_{ti} V_{tj}^*}{\sqrt{2}} \sum_X \left(\delta C_X \mathcal{O}_X + \delta C'_X \mathcal{O}'_X\right) + \mathrm{h.c.}$$

$$X \in 9, 10, S, P, 9', 10', S', P', \ldots$$

$$\mathcal{O}_X = (\bar{q}_i \Gamma q_j)(\bar{\ell}_\alpha \Gamma \ell_\beta) \quad \text{with} \quad \Gamma \in P_{L/R}, \gamma^\mu P_{L/R}, \sigma^{\mu\nu} P_L$$

- Process that can be studied :

$$\begin{aligned} b \to c :&\quad \Lambda_b \to \Lambda_c \ell \nu \\ &\quad \Lambda_b \to \Lambda_c^* \ell \nu \\ c \to s :&\quad \Lambda_c \to \Lambda \ell \nu \\ s \to u :&\quad \Lambda \to p \ell \nu \end{aligned}$$

$$\begin{aligned} b \to s :&\quad \Lambda_b \to \Lambda \ell \ell' \\ b \to u :&\quad \Lambda_b \to n \ell \ell' \end{aligned}$$

Example for b→c

$$\mathcal{L}_{NP} = -\frac{4G_F V_{cb}}{\sqrt{2}} \Big[g_{V_L} (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + g_{V_R} (\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

$$+ g_{S_L} (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) + g_{S_R} (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) + g_T (\bar{c}\sigma_{\mu\nu} P_L b)(\bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau) \Big] + h.c.$$

- 5 Wilson Coefficents.
- Leptonic part of the amplitude can be computed exactly.
- The quark part of the amplitude has to be parameterized in term of Hadronic Form Factors.

$$\langle \Lambda_c | \bar{c} b | \Lambda_b \rangle = F_0(q^2) \frac{M_{\Lambda_b} - M_{\Lambda_c}}{m_b - m_c} \overline{u}_{\Lambda_c} u_{\Lambda_b}$$

$$\langle \Lambda_c | \bar{c}\gamma_5 b | \Lambda_b \rangle = G_0(q^2) \frac{M_{\Lambda_b} + M_{\Lambda_c}}{m_b + m_c} \overline{u}_{\Lambda_c} \gamma_5 u_{\Lambda_b}$$

$$\vdots$$

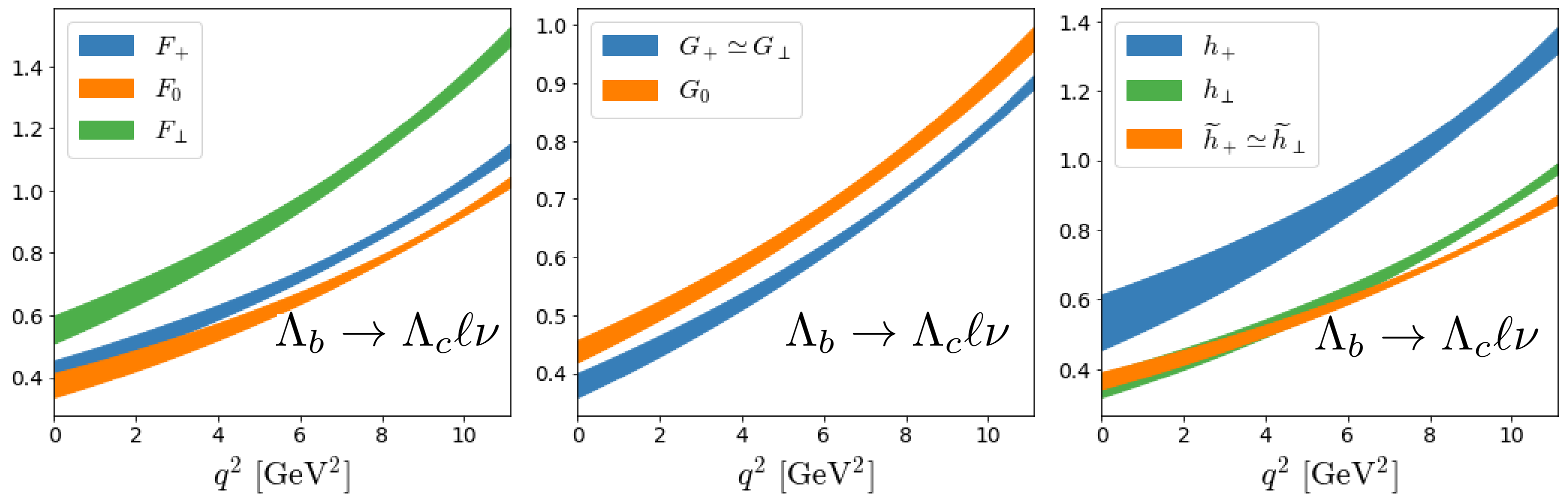
Computing baryon observables

- From quark to hadrons : Form Factors parameterization:

$$\langle \Lambda_c | \Gamma | \Lambda_b \rangle \propto \underbrace{F_0, F_+, F_\perp}_{\text{Vector}}, \underbrace{G_0, G_+, G_\perp}_{\text{Axial}}, \underbrace{h_+, h_\perp, \widetilde{h}_+, \widetilde{h}_\perp}_{\text{Tensor}}$$

- Obtained from LQCD

$\Lambda_b \to \Lambda_c \ell \nu$ [Detmold, Lehner, Meinel `15] [Datta, Kamali, Meinel, Rashed `17]
$\Lambda_b \to \Lambda \ell_1 \ell_2$ [Detmold, Meinel `16]
$\Lambda_c \to \Lambda \ell \nu$ [Meinel `17] (Missing tensor form factors)
$\Lambda_b \to \Lambda_c^* \ell \nu$ [Meinel, Rendon `21] (Only for high-q^2)



3-body decay

- Similar to the meson case,

$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = \frac{\sqrt{\lambda_{\Lambda_b \Lambda_c}(q^2)}}{1024\pi^3 M_{\Lambda_b}^3}\left(1 - \frac{m_l^2}{q^2}\right)\sum_{\lambda_l \lambda_b \lambda_c}\left|\mathcal{M}_{\lambda_c}^{(3)\lambda_b \lambda_l}\right|^2 .$$

- But with approx. twice the number of d.o.f:

$$\frac{\mathrm{d}^2\Gamma(B \to D^{(*)}\ell^{\lambda_l}\nu)}{\mathrm{d}q^2 \mathrm{d}\cos\theta} = a^{\lambda_l}(q^2) + b^{\lambda_l}(q^2)\cos\theta + c^{\lambda_l}(q^2)\cos^2\theta$$

$\rightarrow$ 4 observables

$$\frac{\mathrm{d}^2\Gamma(\Lambda_b \to \Lambda_c^{\lambda_c}\ell^{\lambda_l}\nu)}{\mathrm{d}q^2 \mathrm{d}\cos\theta} = a_{\lambda_c}^{\lambda_l}(q^2) + b_{\lambda_c}^{\lambda_l}(q^2)\cos\theta + c_{\lambda_c}^{\lambda_l}(q^2)\cos^2\theta$$

$\rightarrow$ 10 observables

$$\Gamma_{\text{tot}} \propto \int \mathrm{d}q^2 \left(a + \frac{c}{3}\right)$$

First LHCb measurement

For B-physics, only one is currently measured: $\mathcal{B}(\Lambda_b \to \Lambda_c \tau \nu)$ by LHCb.

$$\mathcal{R}(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c \mu \nu)}$$

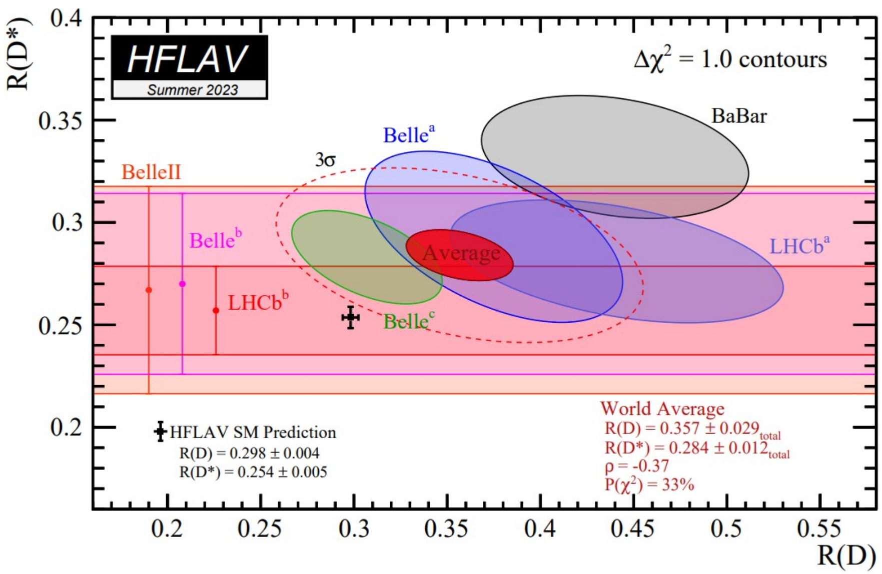
$$\mathcal{R}(\Lambda_c)_{|\text{LHCb}} = 0.242 \pm 0.076$$
$$\mathcal{R}(\Lambda_c)_{|\text{SM}} = 0.333 \pm 0.013$$

[LHCb 2201.03497]

→ Compatible with SM
→ Opposite trend.

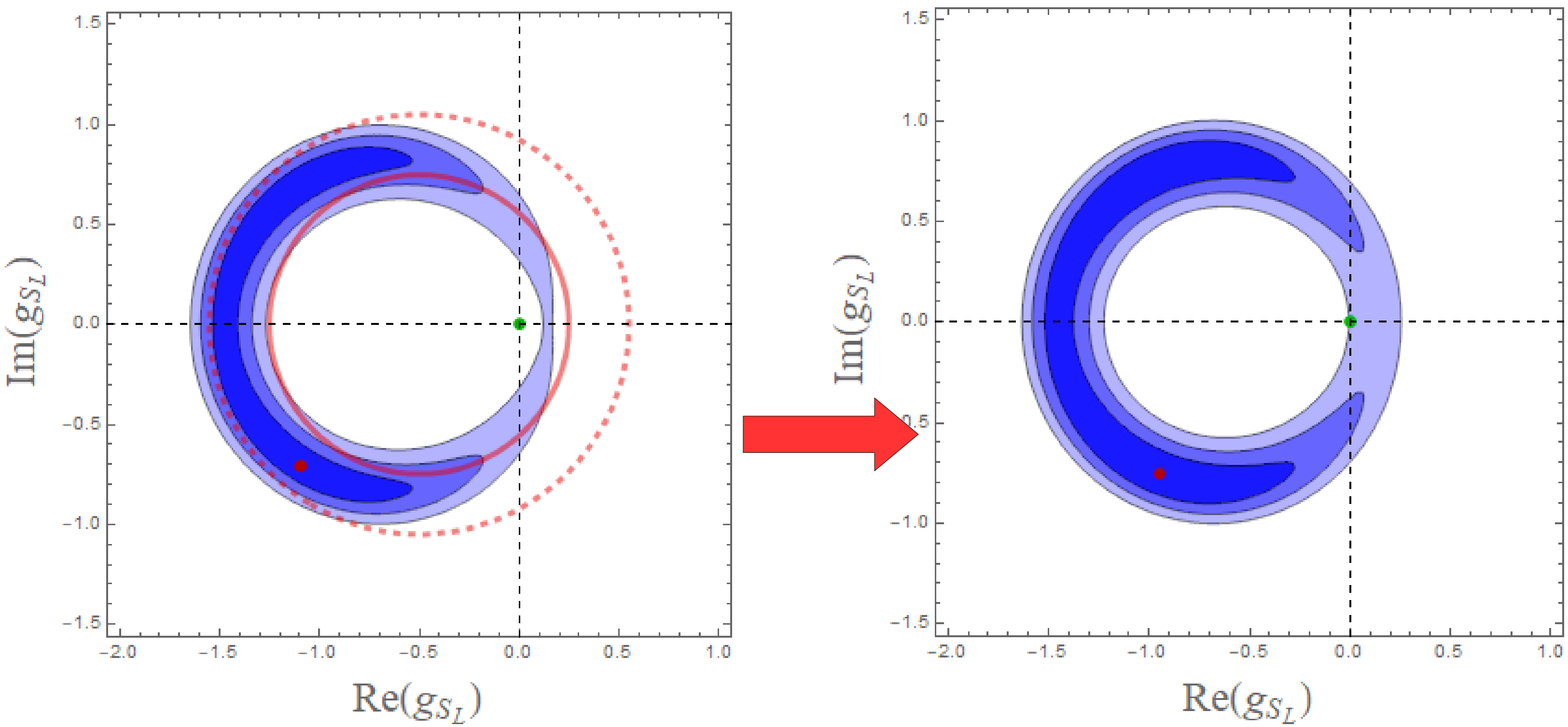
- While $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are 2.0σ and 2.2σ above SM prediction.

But with uncertainties 5× smaller.



How does it change the flavor $b \to c \tau \nu$ fit ?

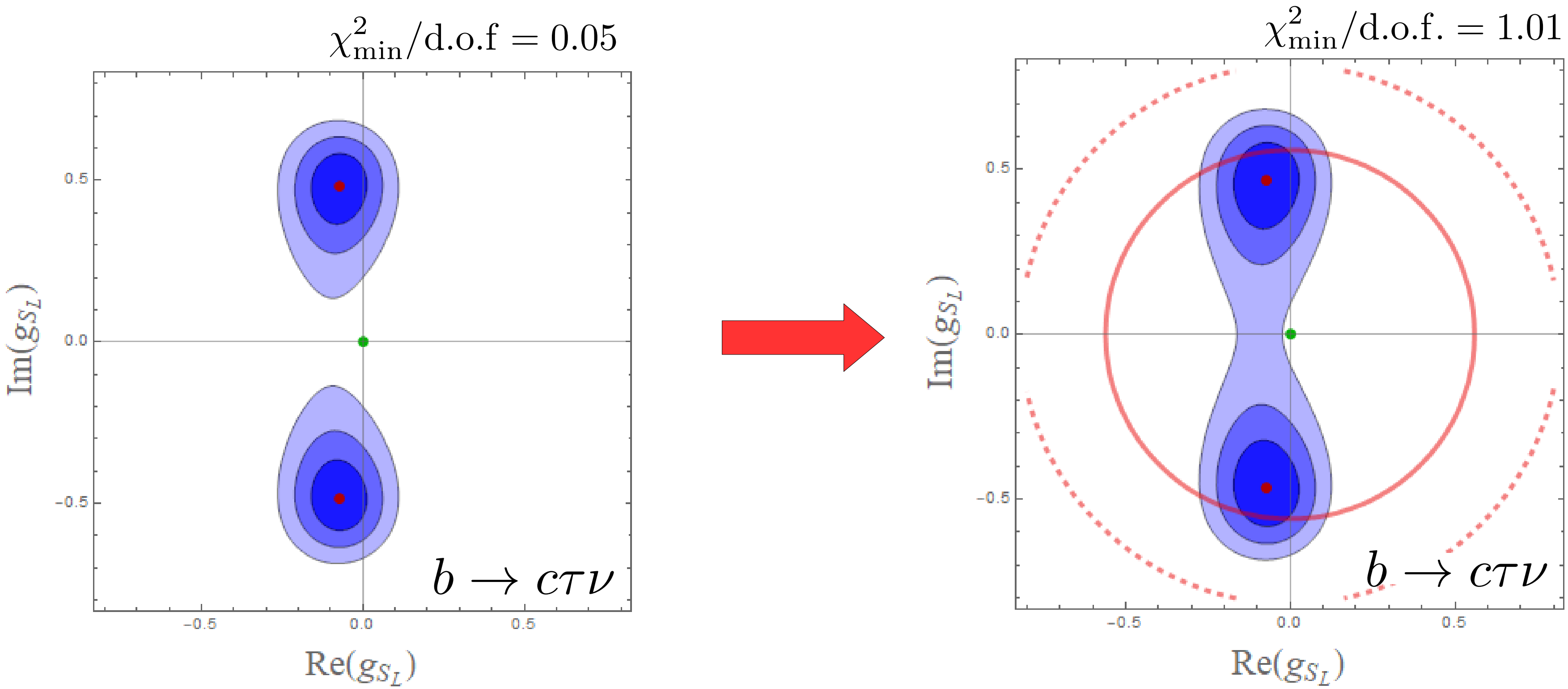
Too soon to change the fit



Wilson Coefficient	$R(D)$ and $R(D^*)$	$R(\Lambda_c)$	Combined	$\chi^2_{\rm min}$/d.o.f
g_{V_L}	0.084 ± 0.029	-0.15 ± 0.14	0.077 ± 0.035	$0.06 \to 1.3$
g_{S_L}	-1.47 ± 0.08	-0.53 ± 0.54	-1.45 ± 0.11	$0.5 \to 2.1$
g_T	-0.027 ± 0.011	0.13 ± 0.14	-0.026 ± 0.013	$1.2 \to 1.7$
$g_{S_L} = +4g_T \in i\mathbb{R}$	$\pm 0.49 \pm 0.10$	0.0 ± 0.39	$\pm 0.47 \pm 0.13$	$0.9 \to 1.6$
$g_{S_L} = -4g_T$	0.16 ± 0.06	0.0 ± 0.39	0.15 ± 0.07	$0.7 \to 1.0$

Too soon to change the fit

- Allowed regions for the Wilson coefficients remain practically the same.
- The χ^2_{min} increases significantly.



$g_{S_L} = +4 g_T$ $g_{S_L} = +4 g_T$

Adding the secondary decay

$$B \to D^* (\to D\pi)\, \tau\nu$$

$$\Lambda_b \to \Lambda_c (\to \Lambda\pi)\, \tau\nu$$

[Gutsche, Ivanov, Körner, Lyubovitskij, Santorelli, Habyl `15]
[Böer, Kokulu, Toelstede, van Dyk `19]
[Datta, Kamali, Meinel, Rashed `17]
[Penalva, Hernandez, Nieves, `19]
[Mu, Li, Zou, Zhu `19]

Can be computed using 2 physical parameters: $\Gamma(\Lambda_c \to \Lambda\pi)$ and

$$\alpha = \frac{\langle \Lambda^+ \pi | \Lambda_c^+ \rangle^2 - \langle \Lambda^- \pi | \Lambda_c^- \rangle^2}{\langle \Lambda^+ \pi | \Lambda_c^+ \rangle^2 + \langle \Lambda^- \pi | \Lambda_c^- \rangle^2}.$$

	Observed primary Branching Fraction	Observed secondary Branching Fraction	Asymmetry α
$\Lambda_b \to \Lambda(\to p\pi)\ell\ell$	$\sim 10^{-6}$	$(63.9 \pm 0.05)\%$	0.732 ± 0.014
$\Lambda_c \to \Lambda(\to p\pi)\ell\nu$	$(1.30 \pm 0.07)\%$	$(63.9 \pm 0.05)\%$	0.732 ± 0.014
$\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu$	$(1.50 \pm 0.38)\%$	$(1.30 \pm 0.07)\%$	-0.84 ± 0.09
$\Lambda_b \to \Lambda_c(\to pK_S)\tau\nu$	$(1.50 \pm 0.38)\%$	$(1.59 \pm 0.08)\%$	0.2 ± 0.5

For comparison, LHCb used $\mathcal{B}(\Lambda_c \to pK^-\pi^+) = (6.28 \pm 0.32)\%.$

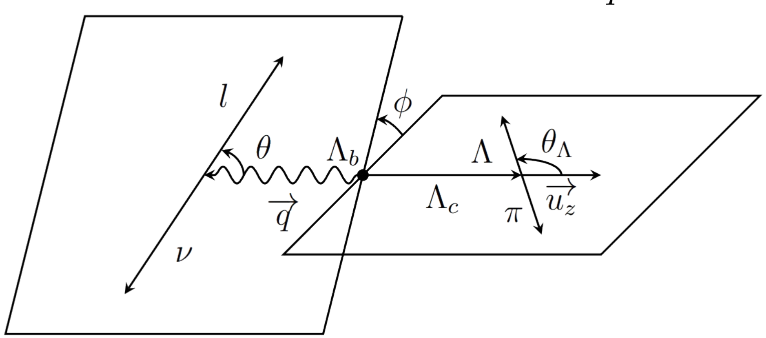
Some observables

- 38 observables in total.
- Some combinations can be measured by event counting:

$$\Gamma_{\rm tot} \propto A_1 + C_1/3$$

$$A^{\ell}_{\rm fb} \propto B_1$$ Lepton Forward-Backard Asymmetry

$$A^{\Lambda}_{\rm fb} \propto A_2 + C_2/3$$ Baryon Forward-Backard Asymmetry



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

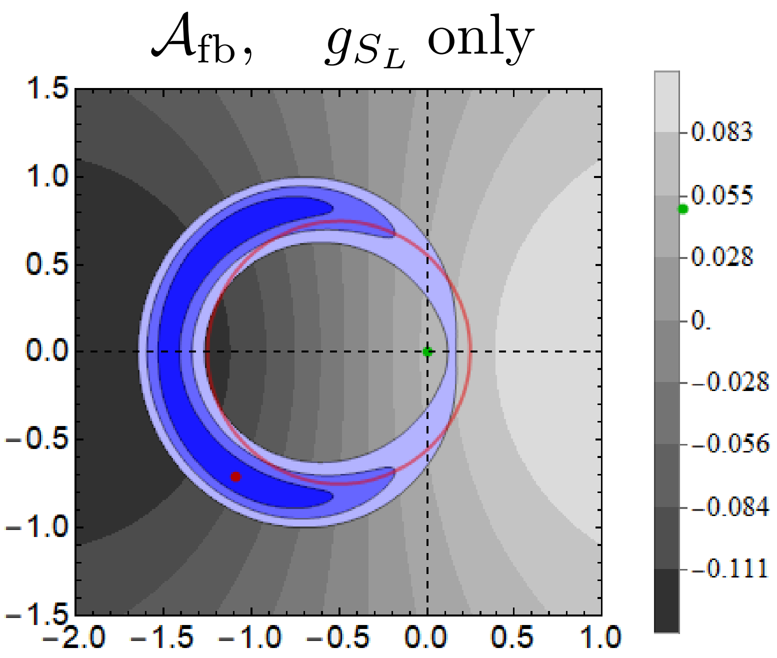
$\mathcal{A}_{\rm fb}$ Baryon

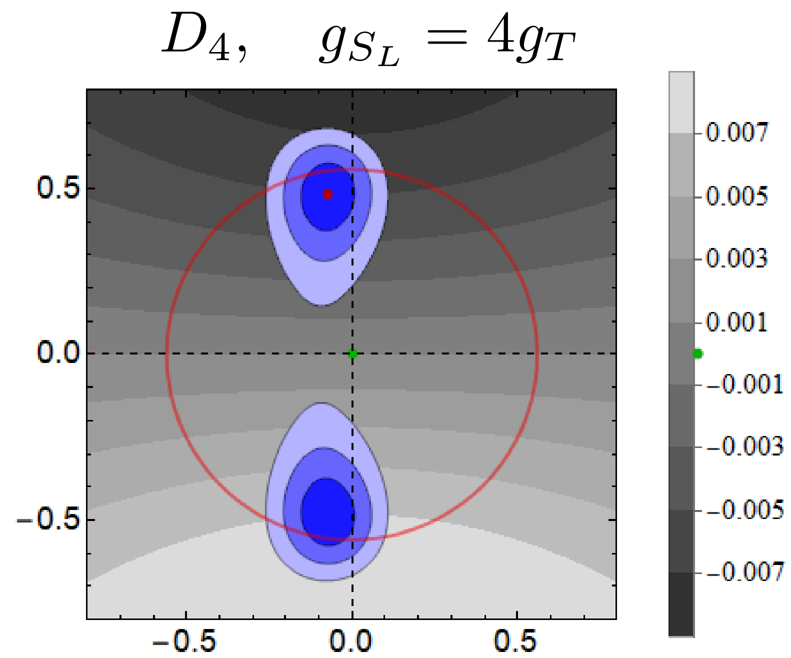
$\mathcal{A}_{\rm fb}$ Lepton

CP-Violating

- g_{V_L} only affects the total Branching Fraction → Distribution is SM-like.
- D_4 and E_4 are sensitive to imaginary part of Wilson Coefficients.
  → CP-violating phase

Some observables





$\mathcal{A}_{\rm fb}$ can easily flip sign.

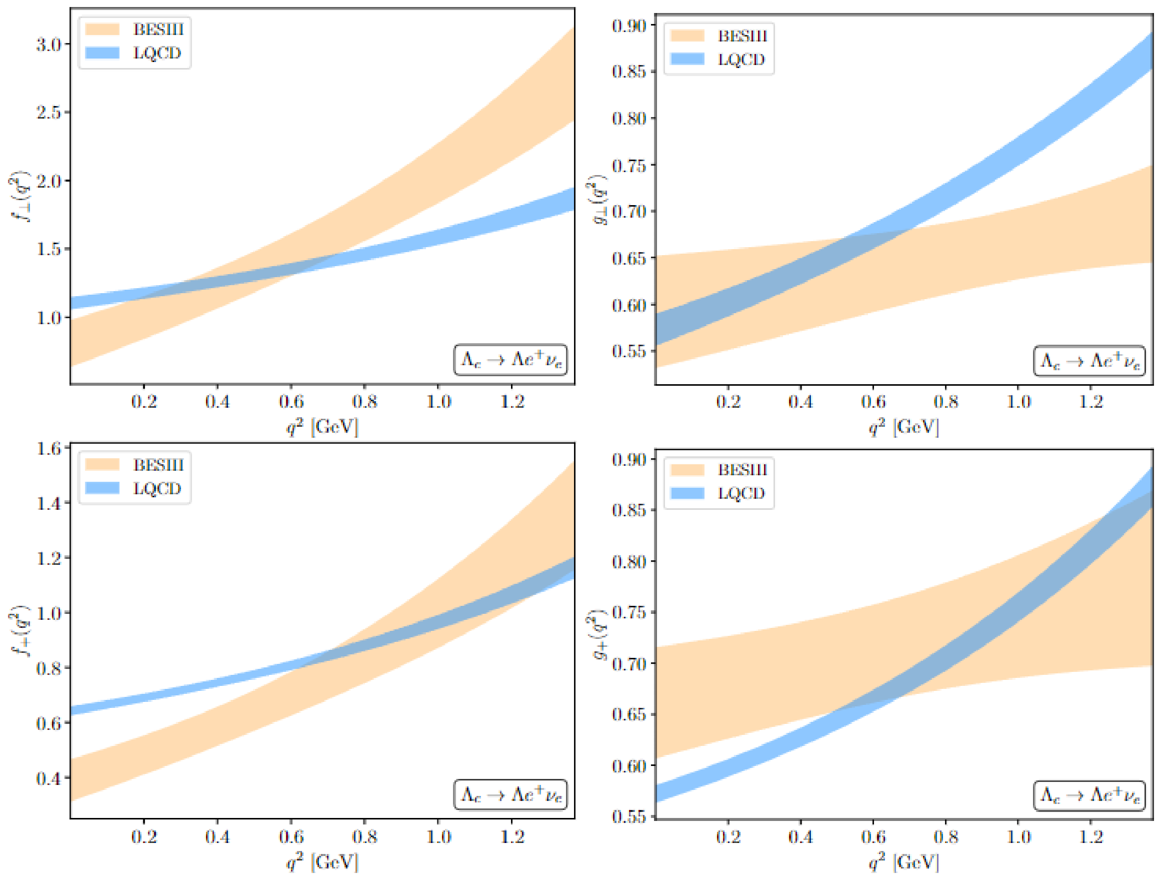
D_4 is exactly 0 in the SM.

D_4 is sensitive to the CP-phase.

- Angular observables can help discriminate among various scenarios, even if branching fraction are compatible with SM.

BESIII angular analysis

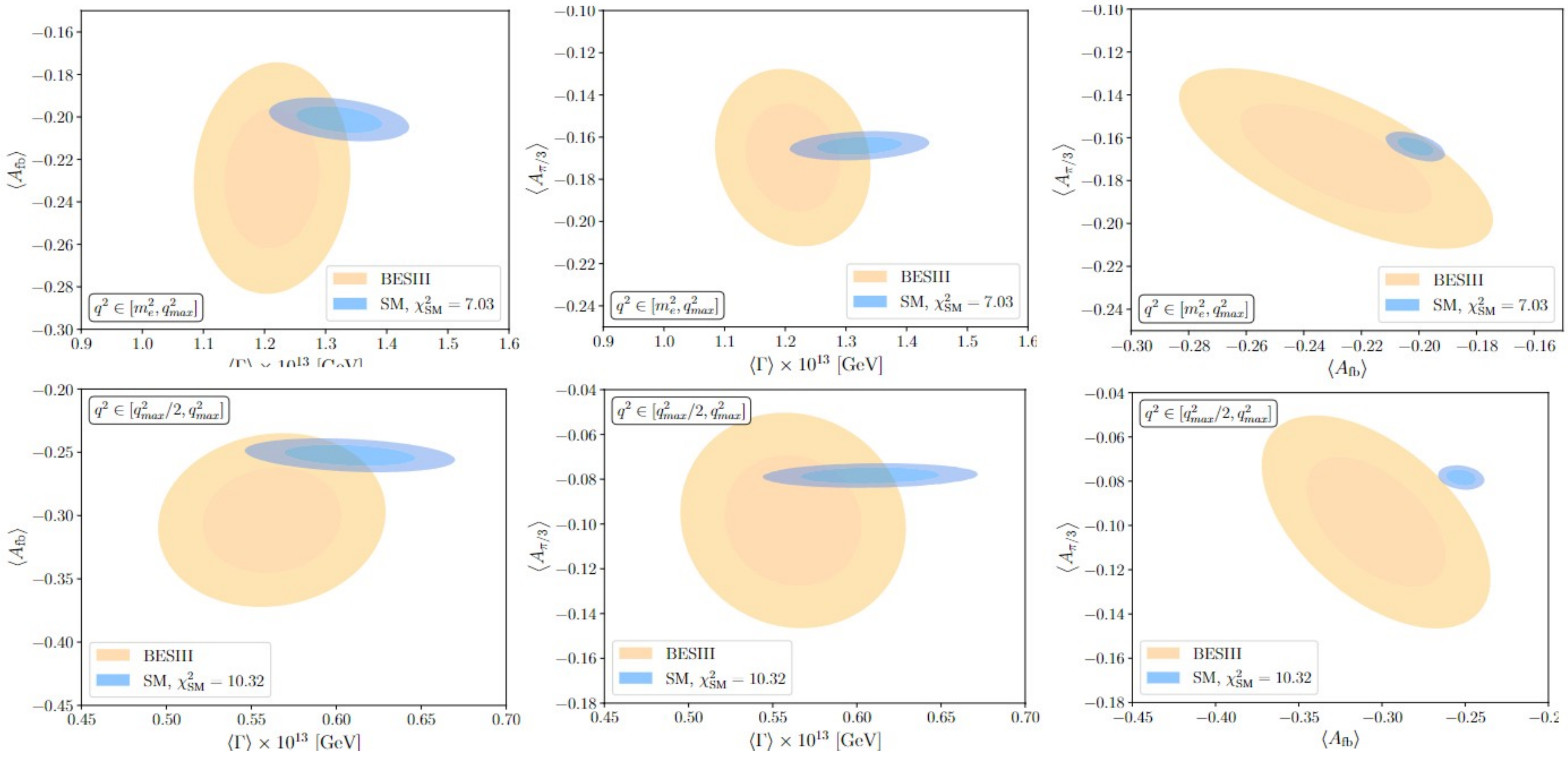
- Last year, BESIII published the first angular analysis of $\Lambda_c \to \Lambda e \nu$.
- However, they assumed no NP, and used it to extract experimental FFs.
- They found a bad agreement, even though the total branching fraction is SM-like.



[Meinel `17]
[BESIII `23]

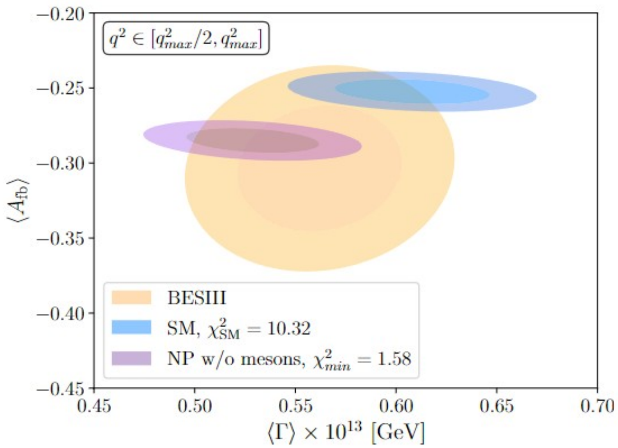
BESIII angular analysis

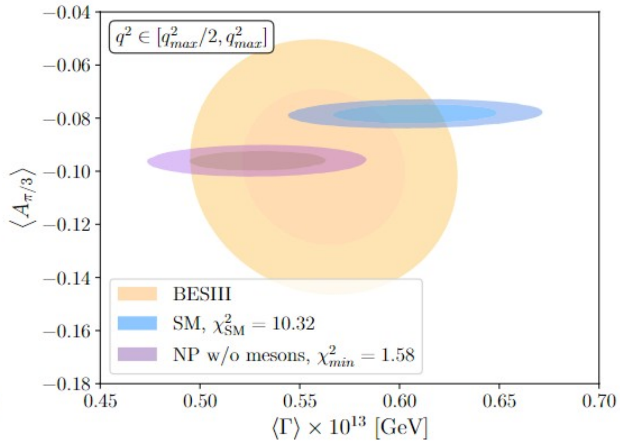
- The discrepancy cannot be seen on the branching fraction alone, only with the angular distribution (at high-q²).

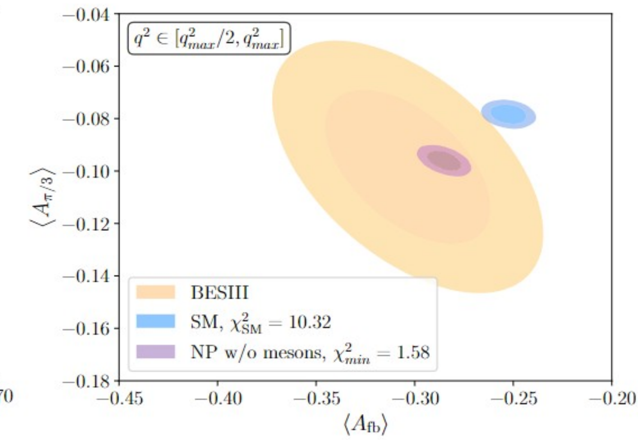


BESIII angular analysis

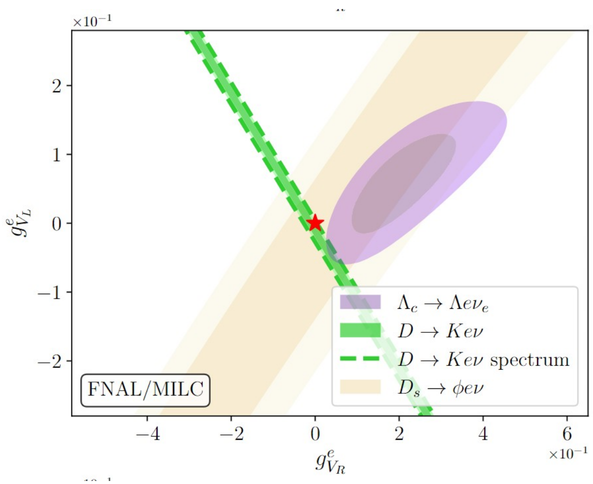
- It is possible to improve the fit significantly by adding NP.
- $g^e_{V_R} = 0.19,\ g^e_{V_L} = 0.056\ :$

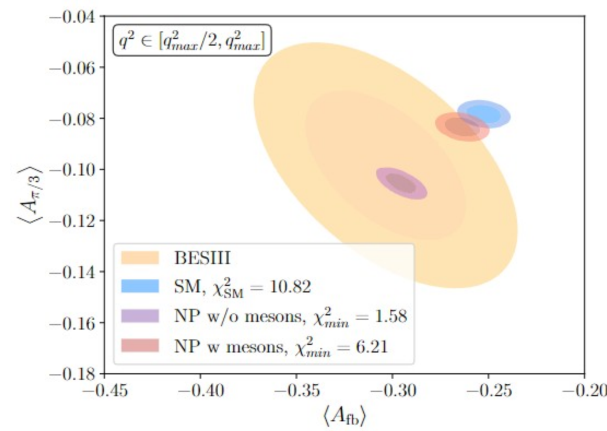






- Does not really agree with meson decay:





LFV case

- Every cross-section expressed in terms of “magic numbers”.

$$\mathcal{B}(\Lambda_b \to \Lambda \ell_i^- \ell_j^+) \times 10^9 = a_9\,|C_9 + C_{9'}|^2 + a_{10}\,|C_{10} + C_{10'}|^2 + a_S\,|C_S + C_{S'}|^2 + a_P\,|C_P + C_{P'}|^2$$
$$+\, b_9\,|C_9 - C_{9'}|^2 + b_{10}|C_{10} - C_{10'}|^2 + b_S\,|C_S - C_{S'}|^2 + b_P|C_P - C_{P'}|^2$$
$$+\, c_{9S}\,\mathrm{Re}[(C_9 + C_{9'})(C_S + C_{S'})^*] + c_{10P}\,\mathrm{Re}[(C_{10} + C_{10'})(C_P + C_{P'})^*]\,,$$

- If $m_{\ell_i} \ll m_{\ell_j}$:

$$\mathrm{a}_9 \simeq a_{10}\,, \quad b_9 \simeq b_{10}\,, \quad c_{9S} \simeq -c_{10P}\,, \quad a_S \simeq a_P\,, \quad b_S \simeq b_P\,,$$

$\longrightarrow$ Lepton mass hierarchy makes the LH/RH “scalar only” or “vector only” scenarios proportional to a single magic number.

Process hierarchy

- We can directly compare the magic numbers:

- $C^{(\prime)}_{S,P} \neq 0,\ C^{(\prime)}_{9,10} = 0\ :$

$$\mathcal{B}(B_s \to \ell_i \ell_j) > \mathcal{B}(B \to K \ell_i \ell_j) > \mathcal{B}(\Lambda_b \to \Lambda \ell_i \ell_j) > \mathcal{B}(B \to K^* \ell_i \ell_j)\,.$$

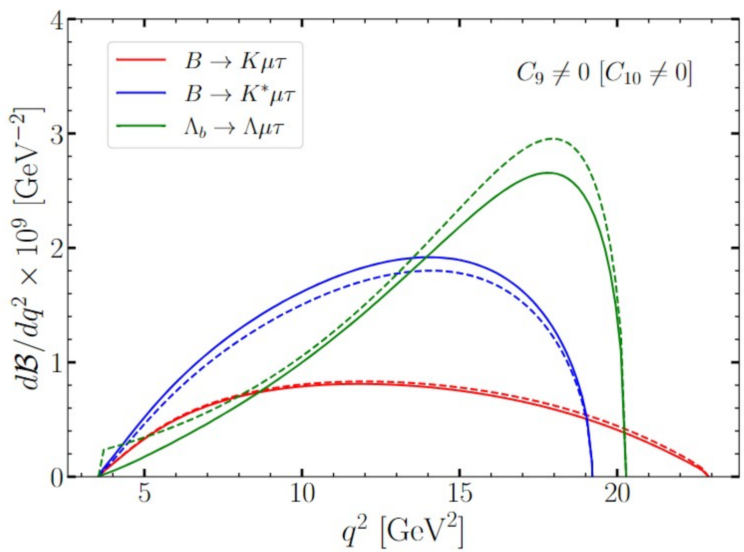
0.097   0.631   0.823

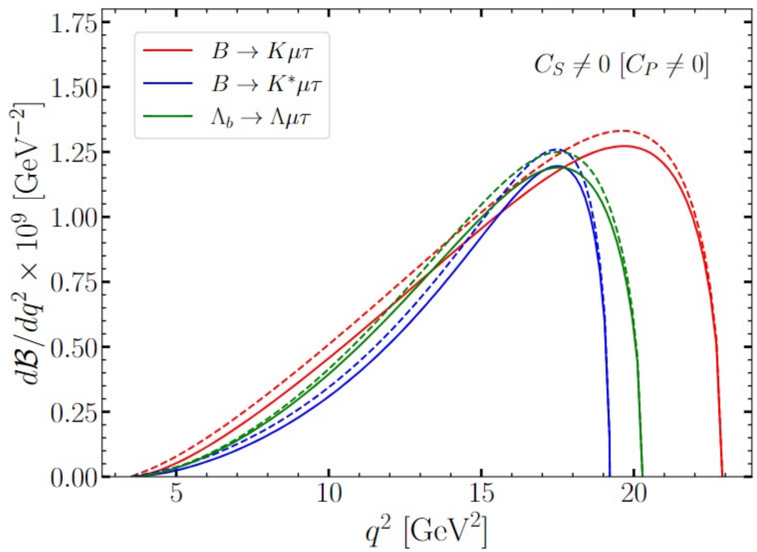
- $C^{(\prime)}_{9,10} \neq 0,\ C^{(\prime)}_{S,P} = 0\ :$

$$\mathcal{B}(B_s \to \ell_i \ell_j) < \mathcal{B}(B \to K \ell_1 \ell_2) < \mathcal{B}(\Lambda_b \to \Lambda \ell_i \ell_j) < \mathcal{B}(B \to K^* \ell_i \ell_j)\,.$$

0.93   0.58   0.94

Indirect constraints





Decay	Exp. Limit	Decay	Exp. Limit	Decay	Exp. Limit
$B^0 \to e\mu$	1.0×10^{-9}	$B^0 \to e\tau$	1.6×10^{-5}	$B^0 \to \mu\tau$	1.2×10^{-5}
$B^+ \to \pi^+ e\mu$	1.7×10^{-7}	$B^+ \to \pi^+ e\tau$	7.5×10^{-5}	$B^+ \to \pi^+ \mu\tau$	7.2×10^{-5}
$B_s \to e\mu$	6.0×10^{-9}	$B_s \to e\tau$	1.4×10^{-3}	$B_s \to \mu\tau$	3.4×10^{-5}
$B^+ \to K^+ e\mu$	1.3×10^{-8}	$B^+ \to K^+ e\tau$	3.1×10^{-5}	$B^+ \to K^+ \mu\tau$	3.1×10^{-5}
$B^0 \to K^{*0} e\mu$	1.3×10^{-8}	$B^0 \to K^{*0} e\tau$	–	$B^0 \to K^{*0} \mu\tau$	1.8×10^{-5}

[LHCb, Belle]

Concrete scenarios: LFV Higgs

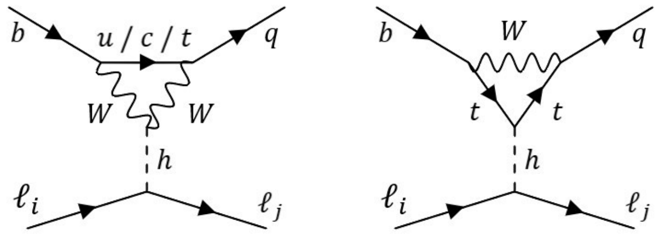
- NP coupling to lepton can be described by the d=6 operator:

$$\mathcal{L}_{\text{eff}}^{(6)} \supset \frac{c_{eH}^{ij}}{\Lambda^2} \left(H^\dagger H\right)\left(\overline{L}_i H e_{Rj}\right) + \text{h.c.}\,.$$

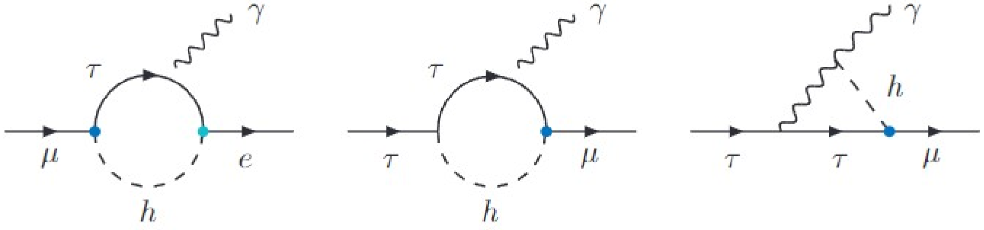
- After EWSB+diagonalization:

$$\mathcal{L}_{\text{Yuk}} \supset -y_\ell^{ij}\, h\, \bar{\ell}_{Li} \ell_{Rj} + \text{h.c.}, \qquad \text{with} \qquad y_\ell^{ij} = \delta_{ij} \frac{\sqrt{2} m_{\ell_i}}{v} + \frac{3v^2}{2\sqrt{2}\Lambda^2} c_{eH}^{ij}\,.$$

- Contributes to $b \to q \ell_i \ell_j$ via Higgs-penguins:



- Strong constraints from $\ell_i \to \ell_j \gamma$:



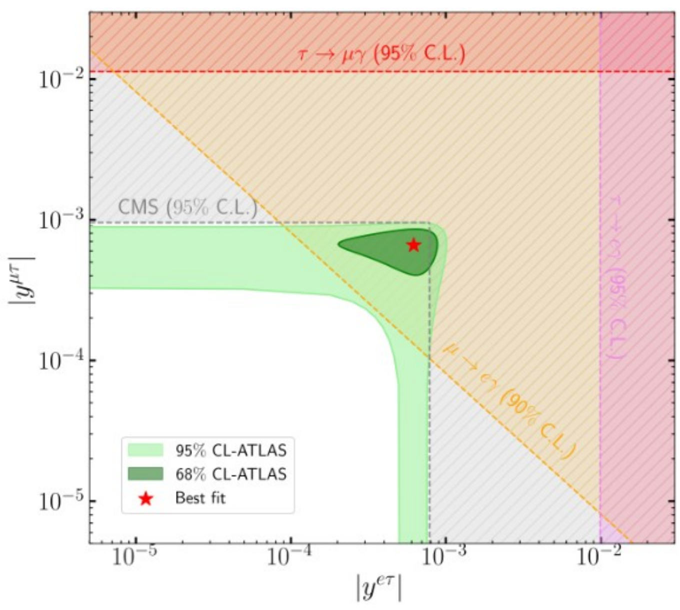
Small detour: LFV Higgs

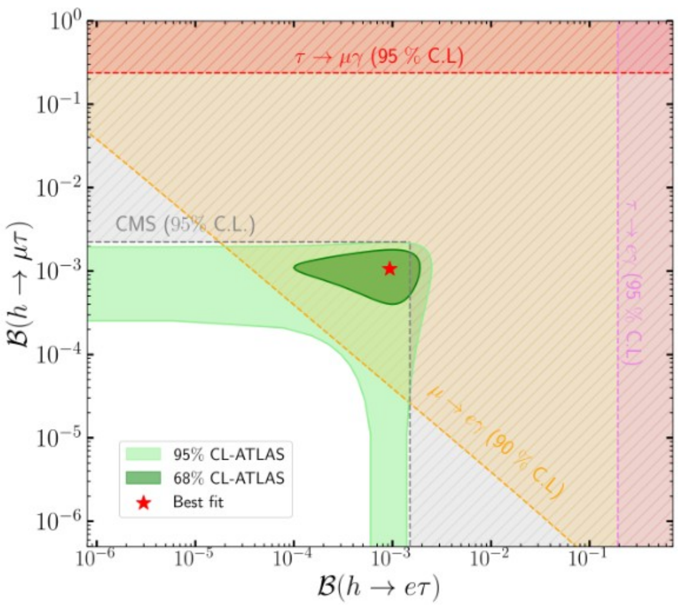
- Assuming $y_\ell^{\mu e}$ to be small, and considering the current constraints:

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$
$$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\gamma) < 4.2 \times 10^{-8}$$

$\rightarrow$ We find the relation:

$$\mathcal{B}(\mu \to e\gamma) \approx 3.7 \times 10^{-13} \left[\frac{\mathcal{B}(h \to e\tau)}{10^{-4}}\right] \left[\frac{\mathcal{B}(h \to \mu\tau)}{10^{-4}}\right].$$





Concrete scenarios: LFV Higgs

- From this plot, we find an upper limit on $y_\ell^{e\tau}$ and $y_\ell^{\mu\tau}$.
- Using the matching:

$$C_{S(P)}^{(q)\,ij} = -\frac{y_\ell^{ij} \pm y_\ell^{ji\,*}}{2}\frac{m_b}{v}\frac{1}{16\pi\alpha_{\rm em}} \times \left[\frac{6x_t}{x_h} - \frac{2x_t^3}{(1-x_t)^3}\log x_t + \frac{4x_t^2}{(1-x_t)^3}\log x_t - \frac{x_t^2}{(1-x_t)^2} + \frac{3x_t}{(1-x_t)^2}\right],$$

→ Loop and b-suppressed

- We find:

$$\mathcal{B}(\Lambda_b \to \Lambda e\tau) < 8\times 10^{-15}\,,$$
$$\mathcal{B}(\Lambda_b \to \Lambda \mu\tau) < 6\times 10^{-15}\,.$$

→ Cannot be seen by experiment

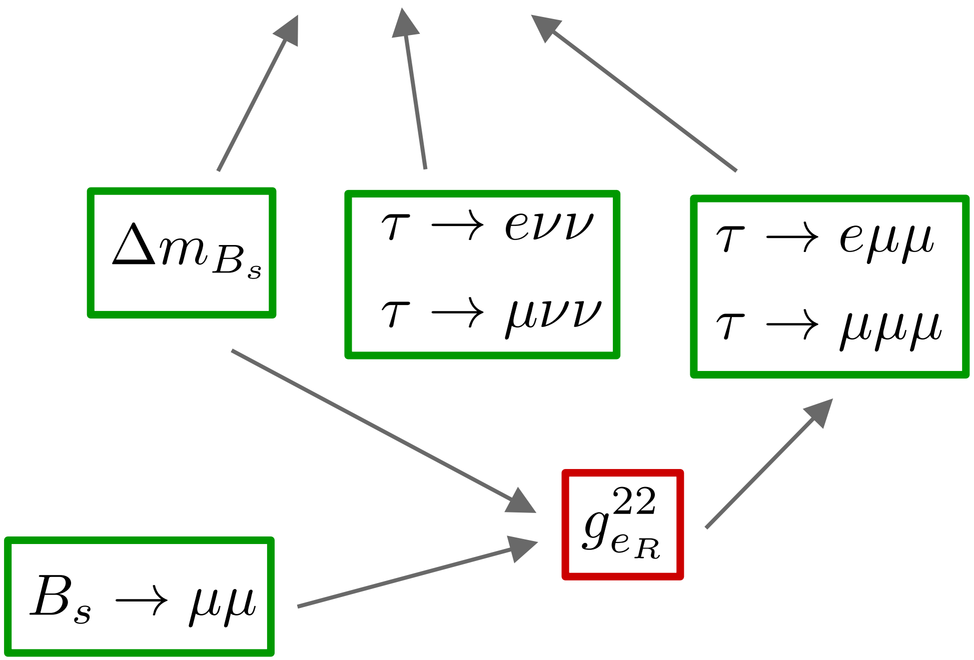
Concrete scenarios: LFV Z'

- SM extended with a $Z' \sim (\mathbf{1},\mathbf{1},0)$.

$$\mathcal{L}_{Z'} \supset \sum_{\psi} g_{\psi}^{ij}\, \bar{\psi}_i \gamma^{\mu} \psi_j \, Z'^{\mu} \,,$$

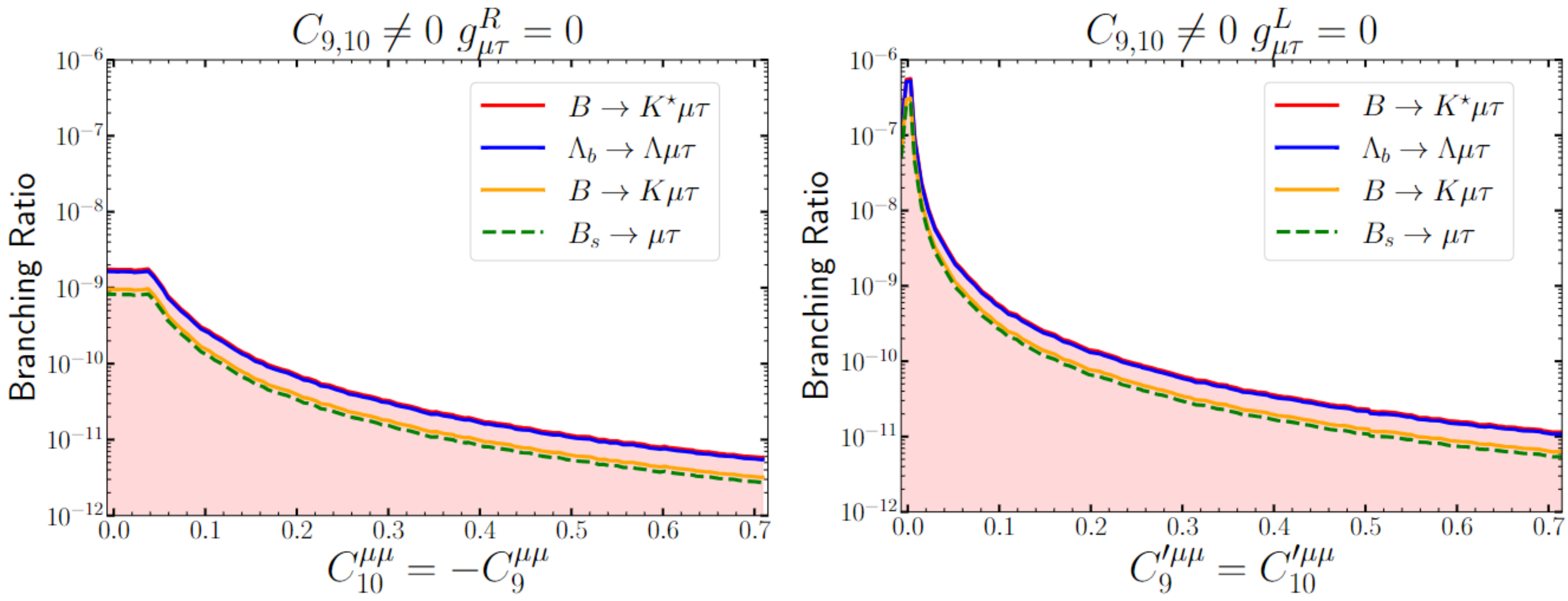
- EFT matching

$$C_{9/10}^{s\,ij} = \mp \frac{v^2}{m_{Z'}^2} \frac{\pi}{\alpha_{\rm em} V_{tb} V_{ts}^*} g_Q^{23} (g_L^{ij} \pm g_{e_R}^{ij}) \qquad C_{9'/10'}^{s\,ij} = \mp \frac{v^2}{m_{Z'}^2} \frac{\pi}{\alpha_{\rm em} V_{tb} V_{ts}^*} g_{d_R}^{23} (g_L^{ij} \pm g_{e_R}^{ij}) \,,$$



Concrete scenarios: LFV Z'

- Putting all the constraints together :



→ can be as large as 10^{-6} !

Conclusion

- $\Lambda_b \to \Lambda_c \ell \nu$ can provide another test of LFUV.
- Hadronic uncertainties are under control thanks to LQCD.
- Measurements of $\mathcal{R}(\Lambda_c)$ by LHCb in 2022, do not change the global picture.
- Angular distribution offer the possibility of measuring many observables, sensitive to every combination of WC.
- BESIII analysis of $\Lambda_c \to \Lambda e \nu$ favors right-handed vector NP, but contradicts other meson measurements.
- LFV decays of hadrons and mesons are actively being searched.
- Their hierarchy gives a large clue about the structure of NP.
- Explicit models: LFV Z' can still produce experimentally accessible LFV decays, LFV H cannot.

Thank you !