On exclusive b→ c $\ell\nu$ decay modes

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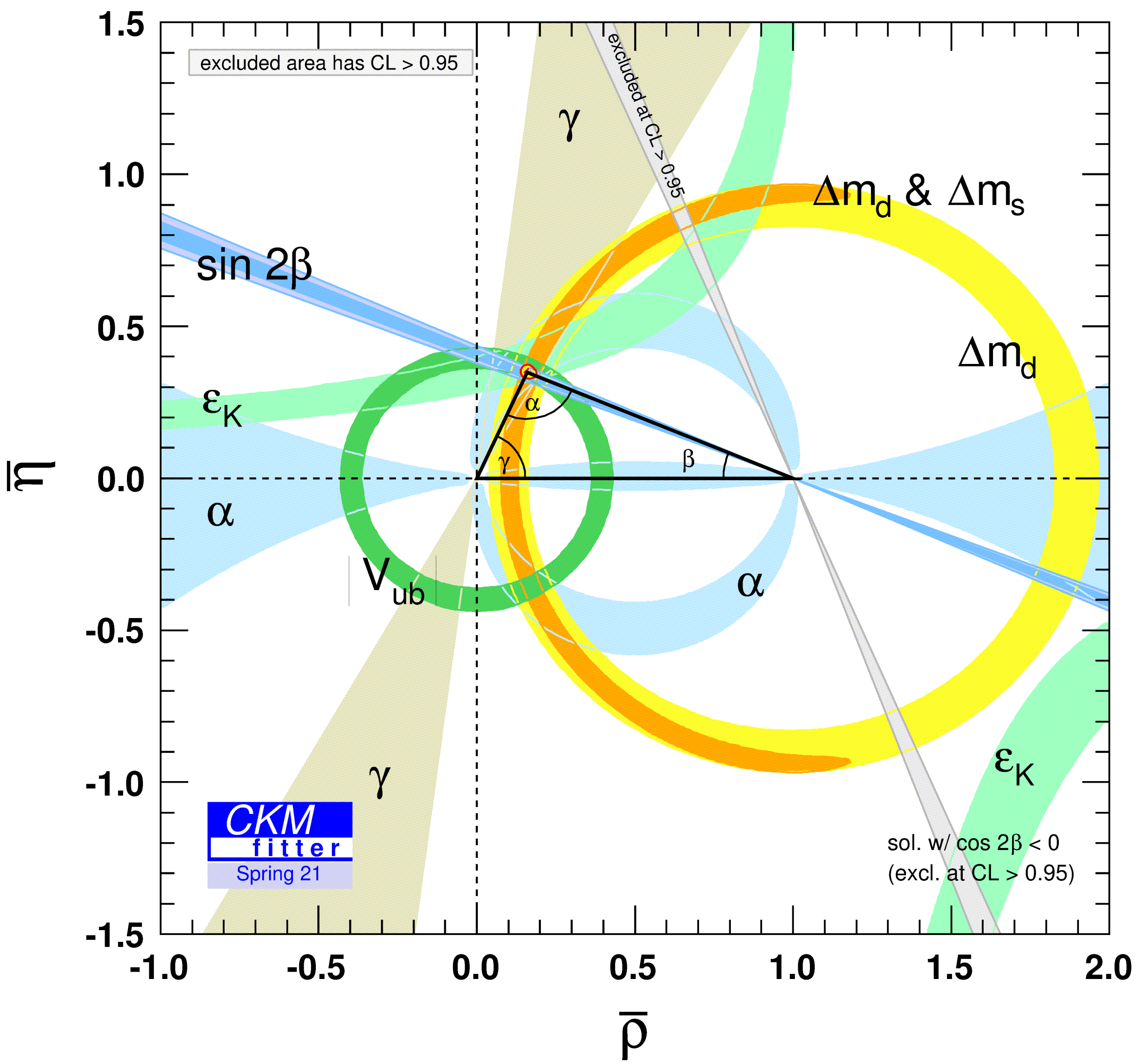
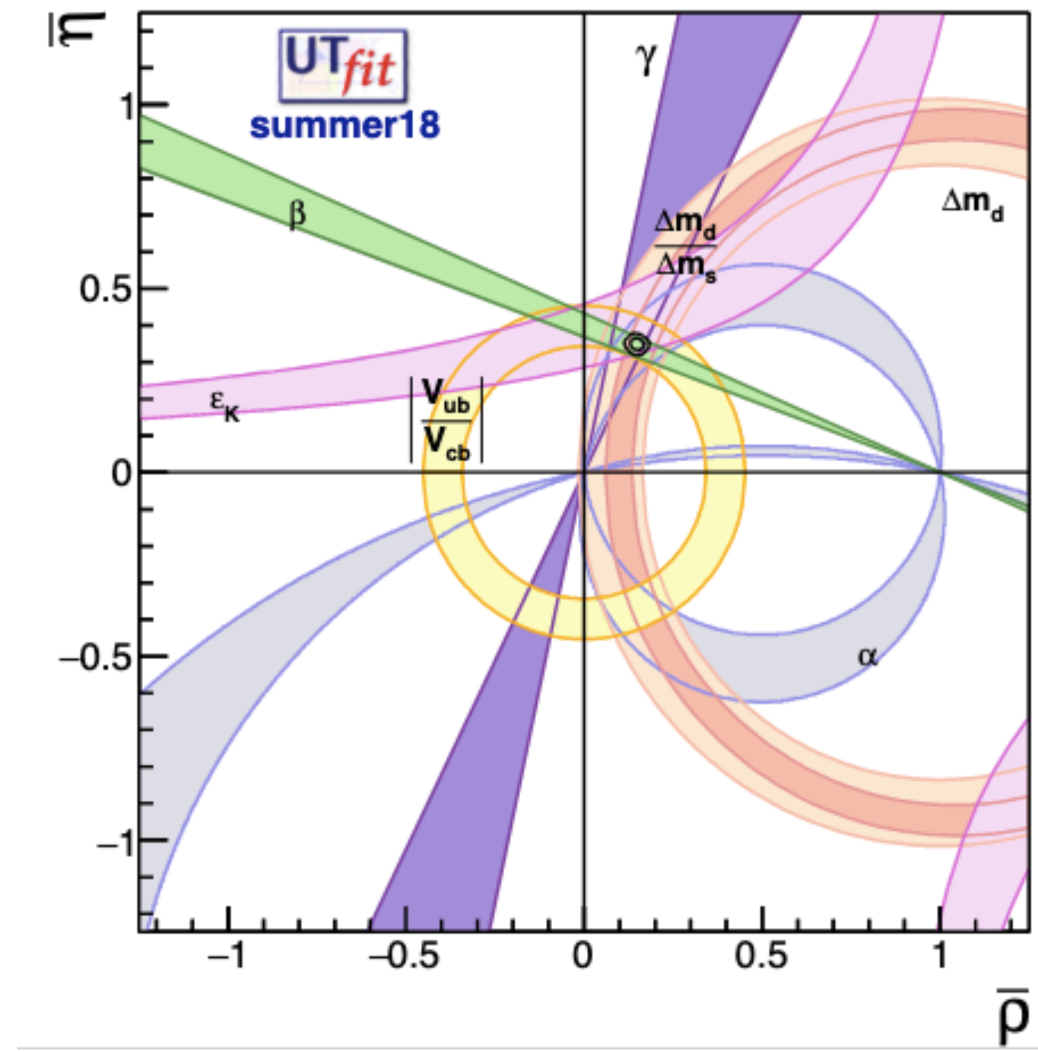
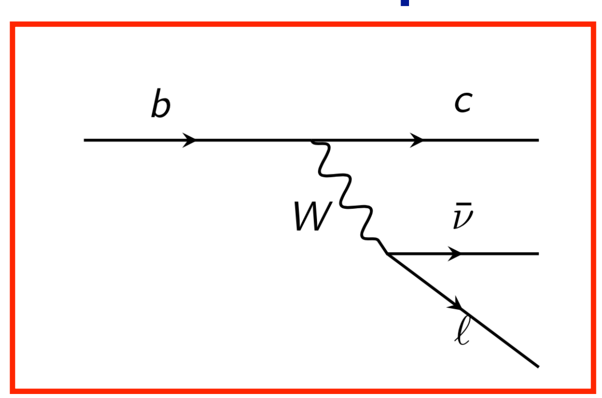
based on works with F. Jaffredo, A. Le Yaouanc, and O. Sumensari

CKM-ology



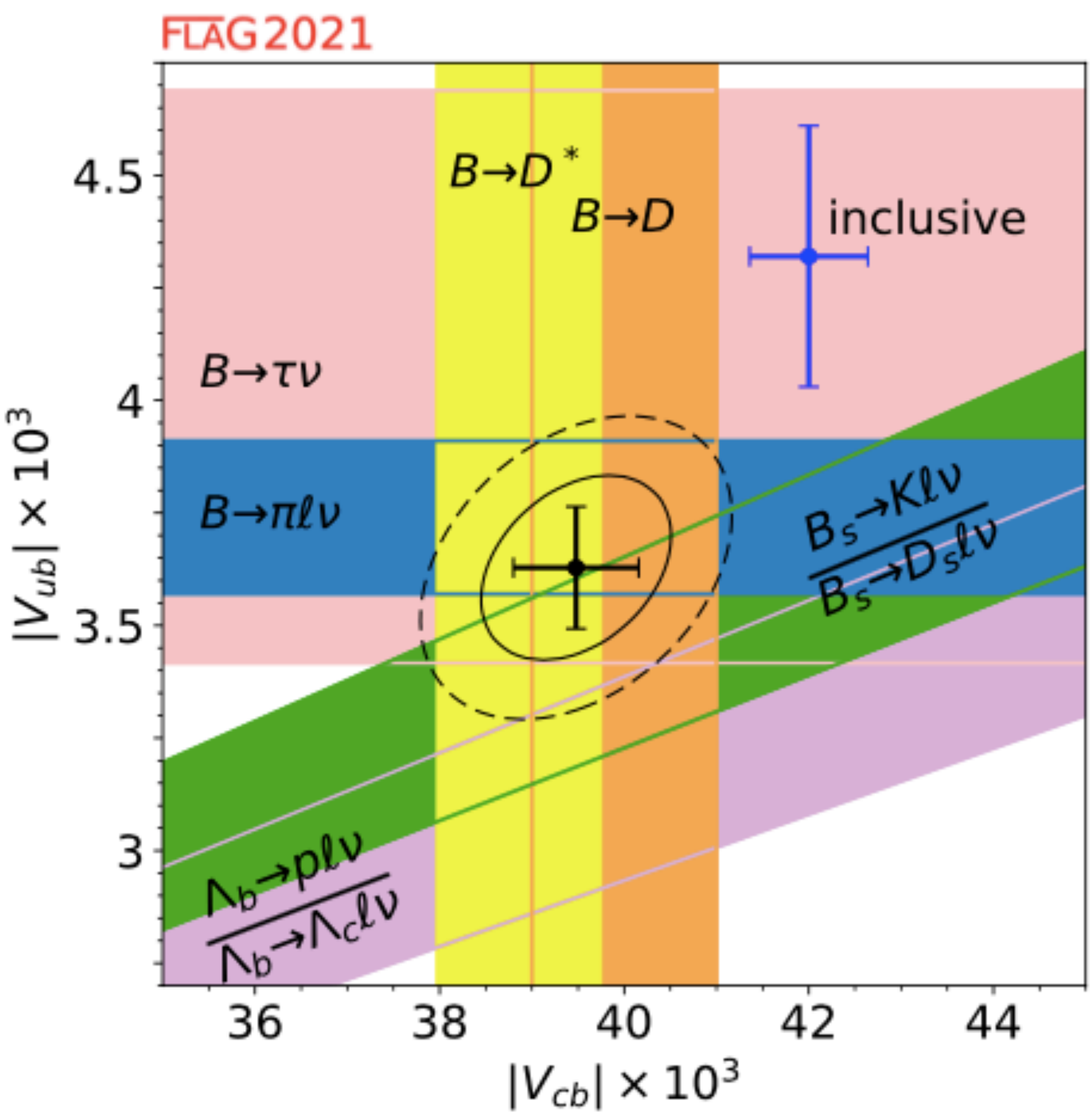


✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?
Is V_{ud} well controlled? V_{us} keeps coming back (EM)…



CKM-ology - Small flavor 'anomaly'

- ✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?



- ✘ Belle II (excl + incl), LHCb (excl)

- ✘ QCD on very fine lattices
  B → D and B → D* at *w*=*1*
- ✘ Nowadays probed *non-zero recoil*

2111.09849

CKM-ology - Small flavor 'anomaly'

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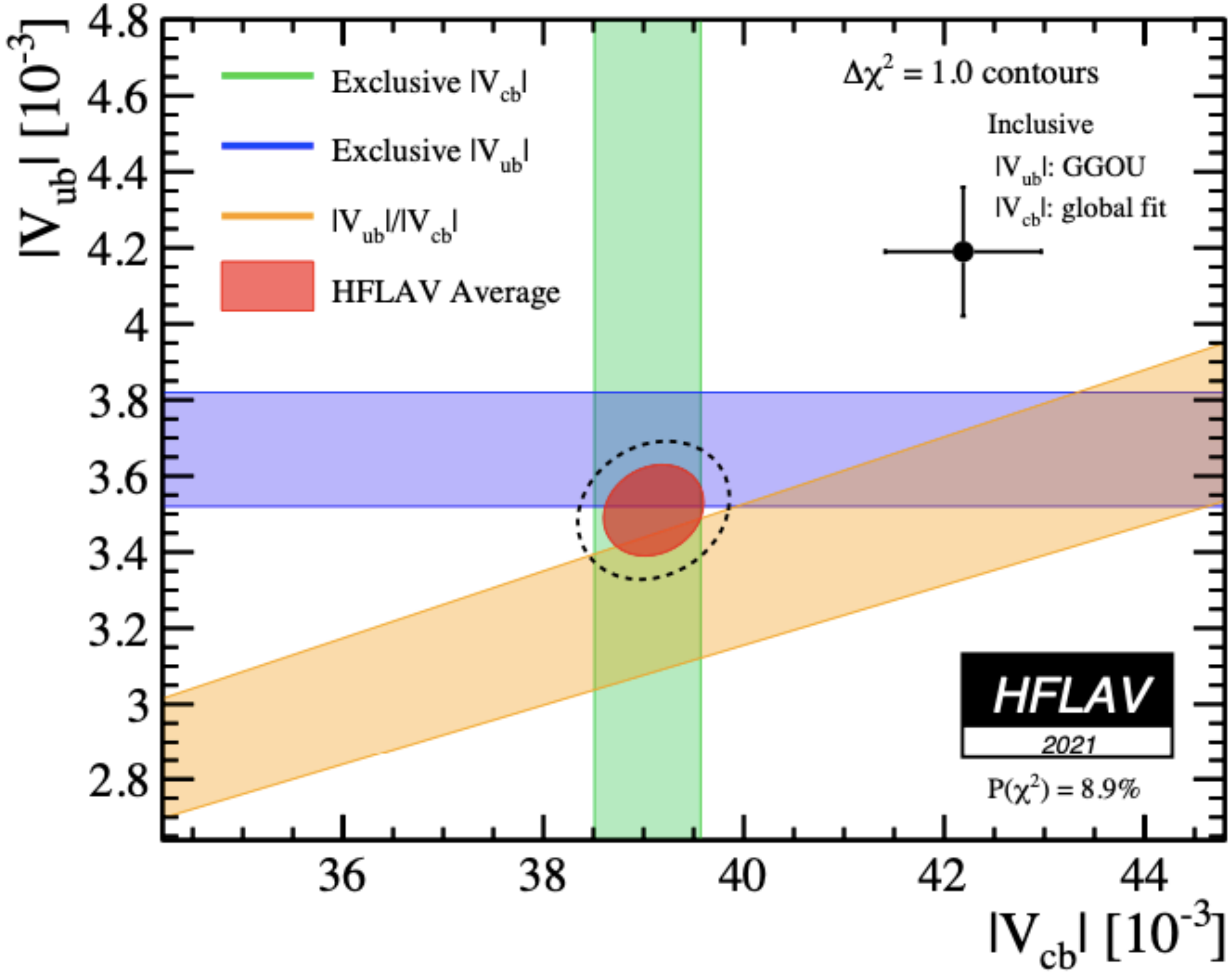


- Lattice, best way to go $B \to D$ at various small *w*, but for w accessible from LQCD, a huge phase space suppression
- Experimentally appealing $B \to D^*$ (also *Luke theorem)*

2206.07501

HQE

$$\hat{h}_V = 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c\big[\hat{L}_2^{(c)} - \hat{L}_5^{(c)}\big] + \varepsilon_b\big[\hat{L}_1^{(b)} - \hat{L}_4^{(b)}\big] + \varepsilon_c\varepsilon_b \hat{M}_9$$
$$\hat{h}_{A_1} = 1 + \hat{\alpha}_s C_{A_1} + \varepsilon_c\left(\hat{L}_2^{(c)} - \hat{L}_5^{(c)}\frac{w-1}{w+1}\right) + \varepsilon_b\left(\hat{L}_1^{(b)} - \hat{L}_4^{(b)}\frac{w-1}{w+1}\right) + \varepsilon_c\varepsilon_b \hat{M}_9$$
$$\hat{h}_{A_2} = \hat{\alpha}_s C_{A_2} + \varepsilon_c\big[\hat{L}_3^{(c)} + \hat{L}_6^{(c)}\big] - \varepsilon_c\varepsilon_b \hat{M}_{10}$$
$$\hat{h}_{A_3} = 1 + \hat{\alpha}_s (C_{A_1} + C_{A_3}) + \varepsilon_c\big[\hat{L}_2^{(c)} - \hat{L}_3^{(c)} + \hat{L}_6^{(c)} - \hat{L}_5^{(c)}\big] + \varepsilon_b\big[\hat{L}_1^{(b)} - \hat{L}_4^{(b)}\big] + \varepsilon_c\varepsilon_b\big[\hat{M}_9 + \hat{M}_{10}\big]$$

2206.11281

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

- tricky part - shapes… $\hat{h}(w) = h(w)/\xi(w)$
  - $h_{A_1}(w) = 1 - \rho^2(w-1) + \frac{c}{2}(w-1)^2 + \ldots$
  - $h_{A_1}(w) = \left(\frac{2}{w+1}\right)^{2\rho^2}$ $\quad c = \rho^2\left(\rho^2 + \frac{1}{2}\right)$
  - $h_{A_1}(w) = 1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3$ $\quad z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$

$$c = \frac{3}{32}\rho^2\left(23\rho^2 - 5\right)$$

CLN or BGL or…

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

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

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

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

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

$$R_1(w) = \underline{R_1(1)} - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = \underline{R_2(1)} + 0.11(w-1) - 0.06(w-1)^2$$

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

CLN 9712417

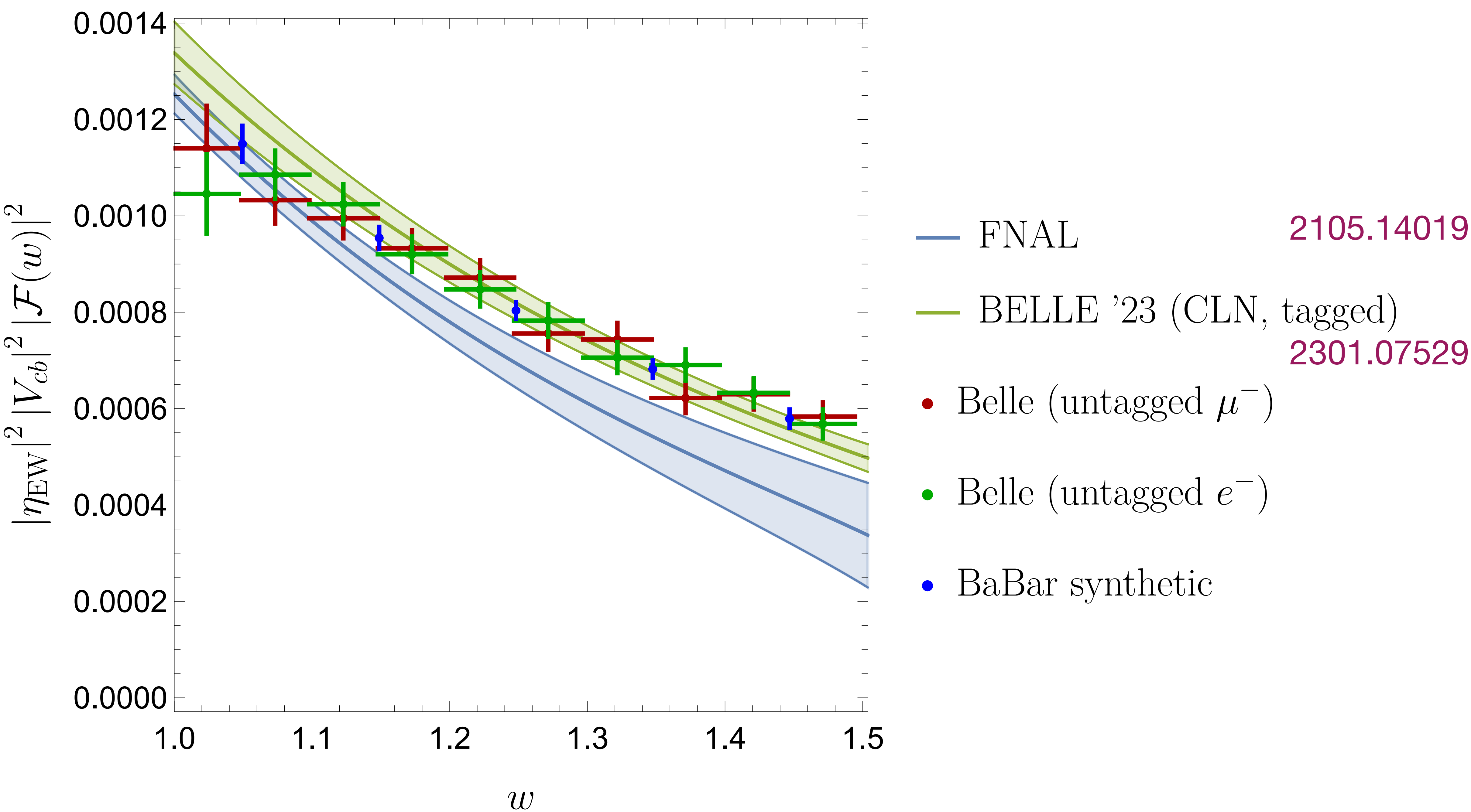
BGL 9705252

these should be fit too and not fixed as in CLS

✘ 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…

We still do not have a control over hadronic uncertainties with

$$\frac{d\mathcal{B}(B \to D^*\ell\bar{\nu})}{dq^2} = \frac{1}{2m_B m_{D^*}} \frac{d\mathcal{B}(B \to D^*\ell\bar{\nu})}{dw} \propto |V_{cb}|^2 |\mathcal{F}(w)|^2$$



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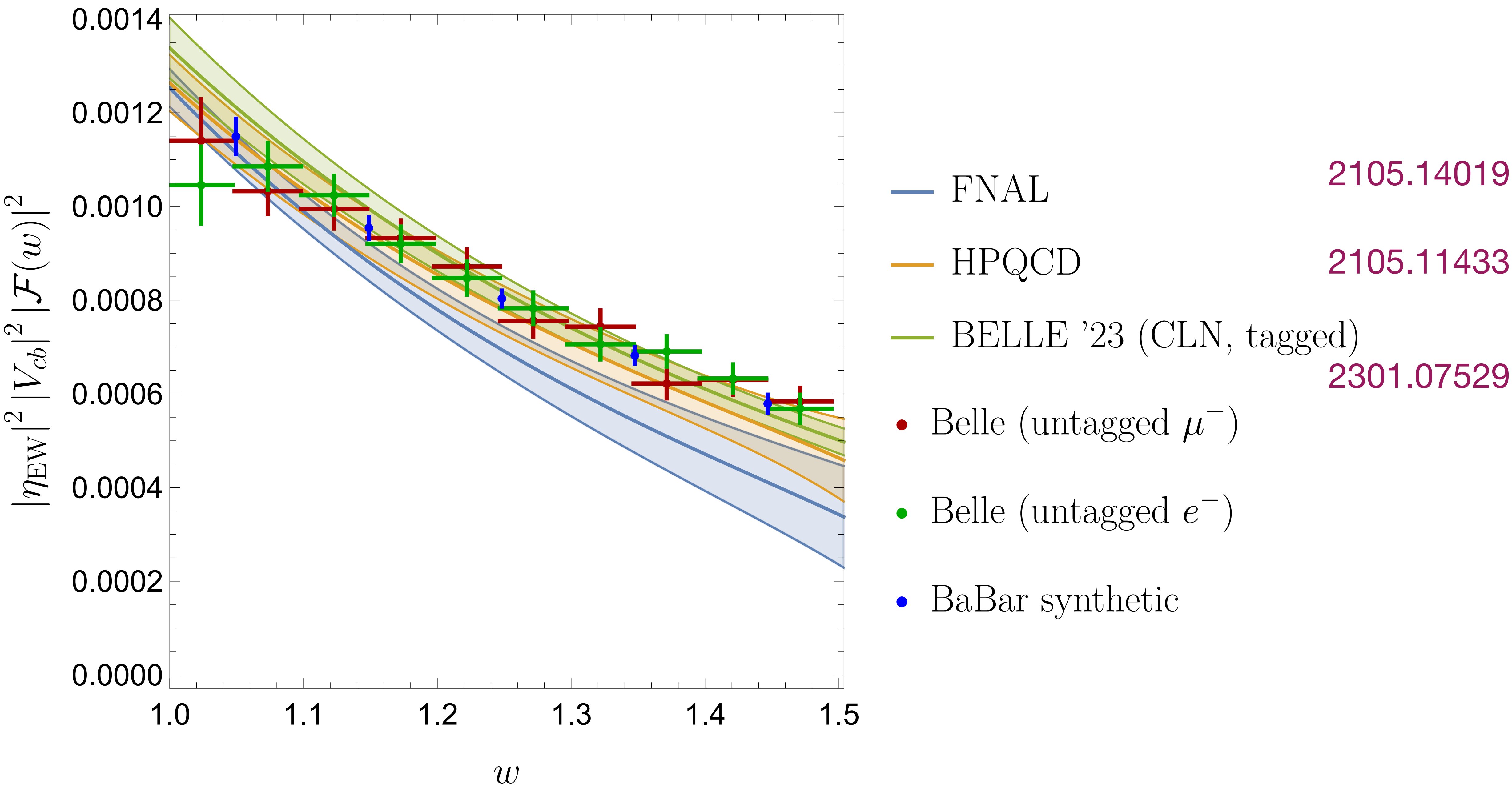

- Assuming with HPQCD that $\mathcal{F}(w)^{B_s \to D_s^*} = \mathcal{F}(w)^{B \to D^*}$

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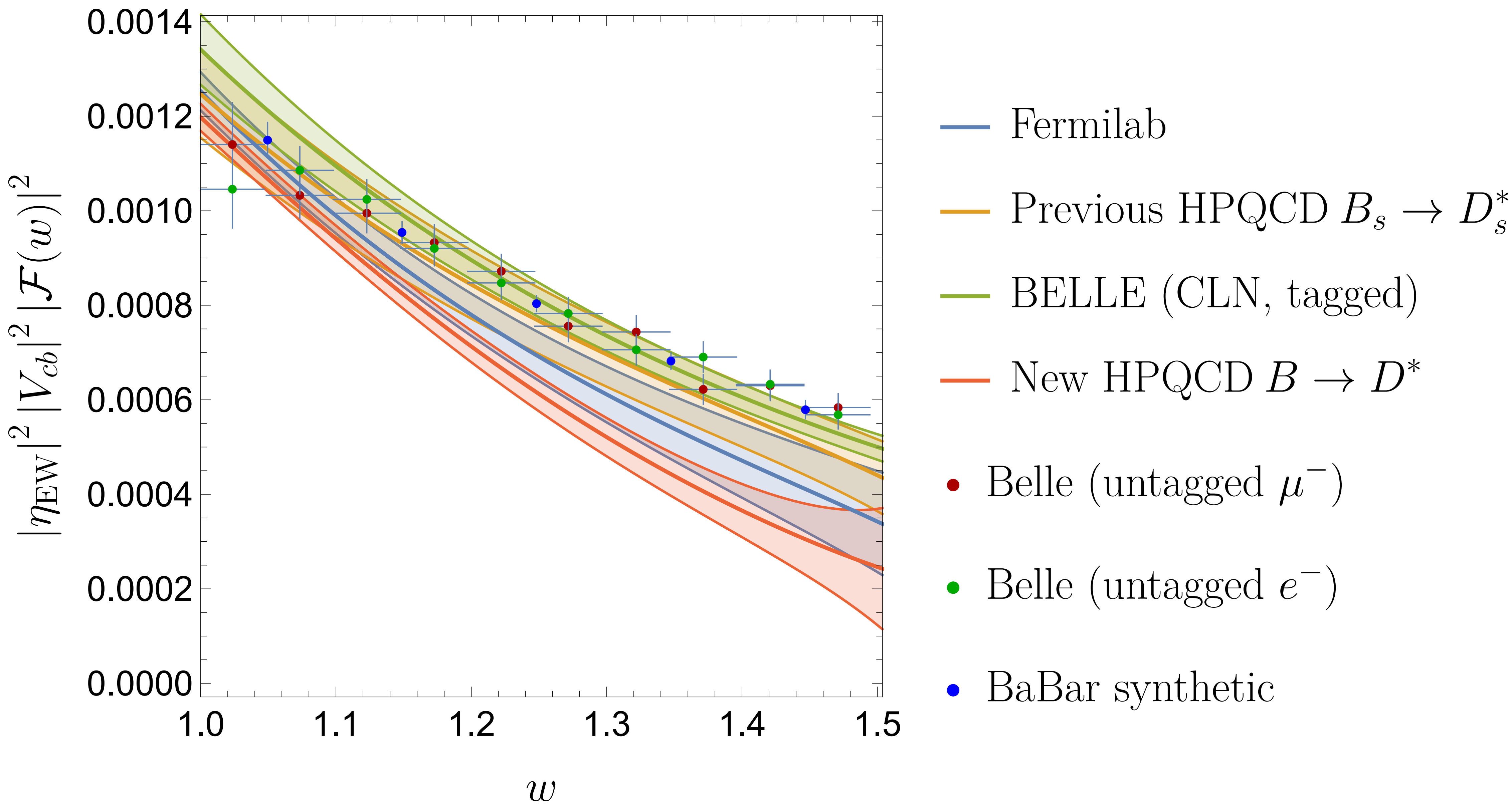
$$\frac{d\mathcal{B}(B \to D^* \ell \bar{\nu})}{dq^2} = \frac{1}{2m_B m_{D^*}} \frac{d\mathcal{B}(B \to D^* \ell \bar{\nu})}{dw} \propto |V_{cb}|^2 |\mathcal{F}(w)|^2$$



2105.14019

2105.11433

2301.07529

2304.03137

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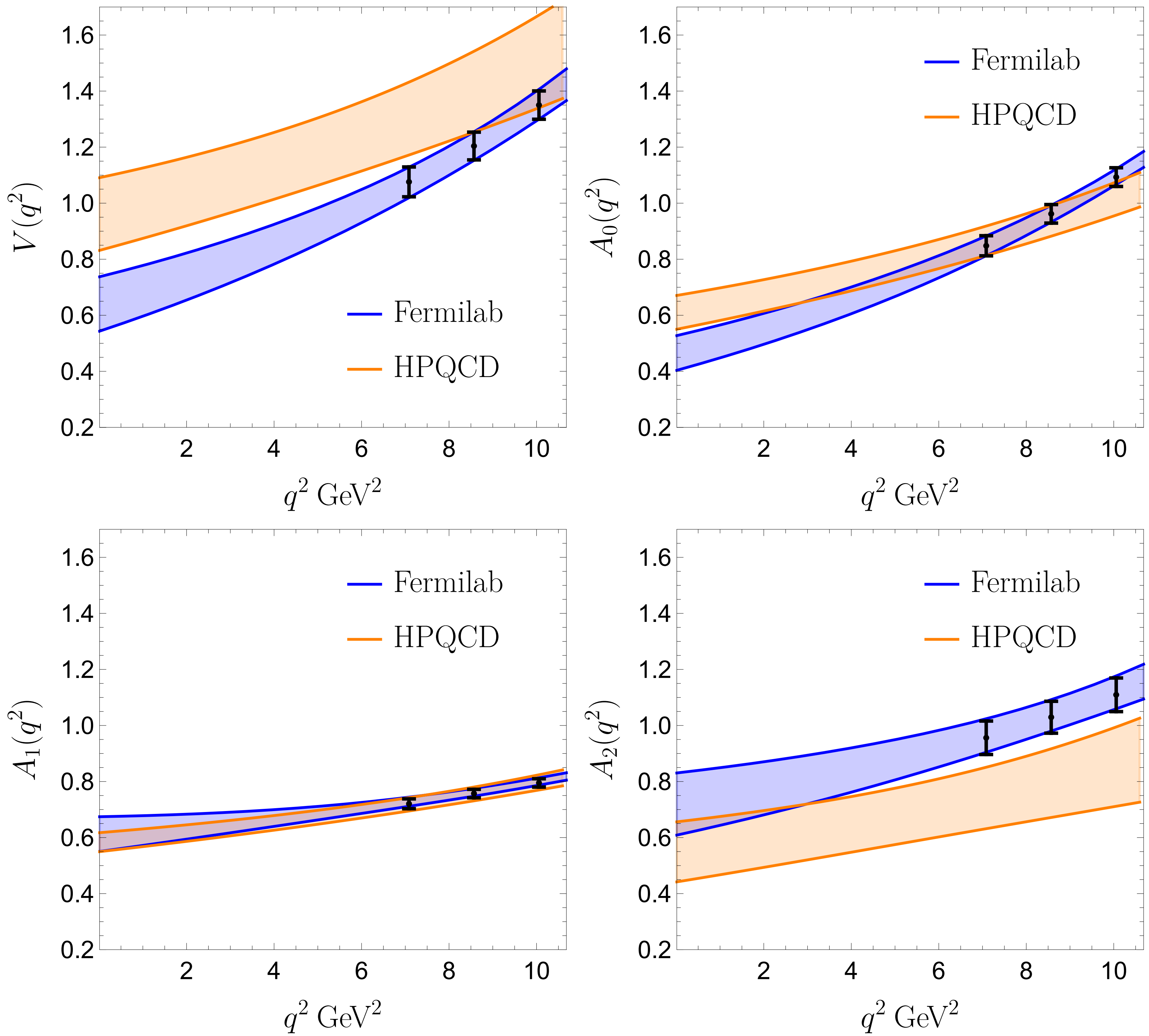
$B \to D^* \ell \bar{\nu}$



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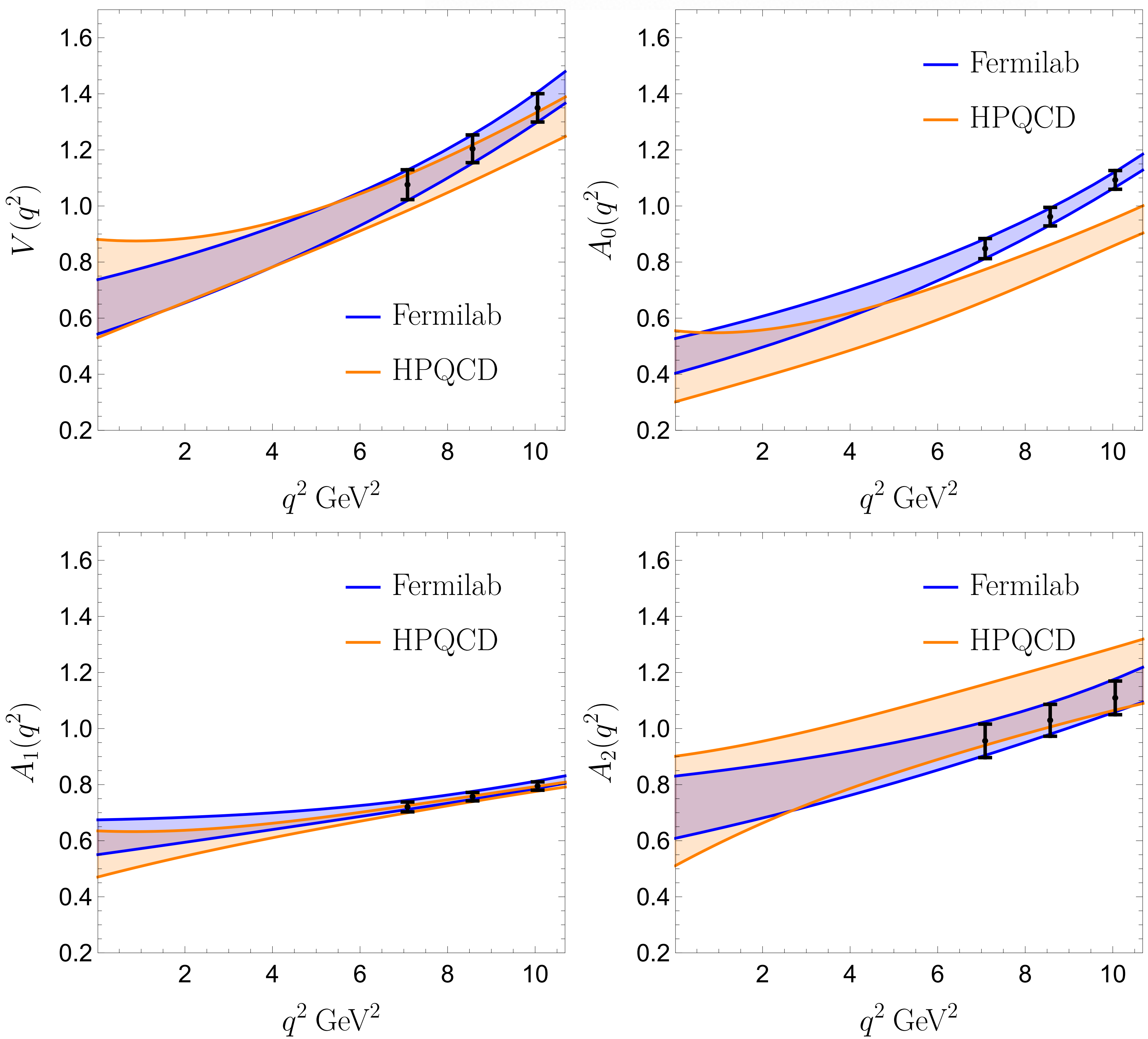

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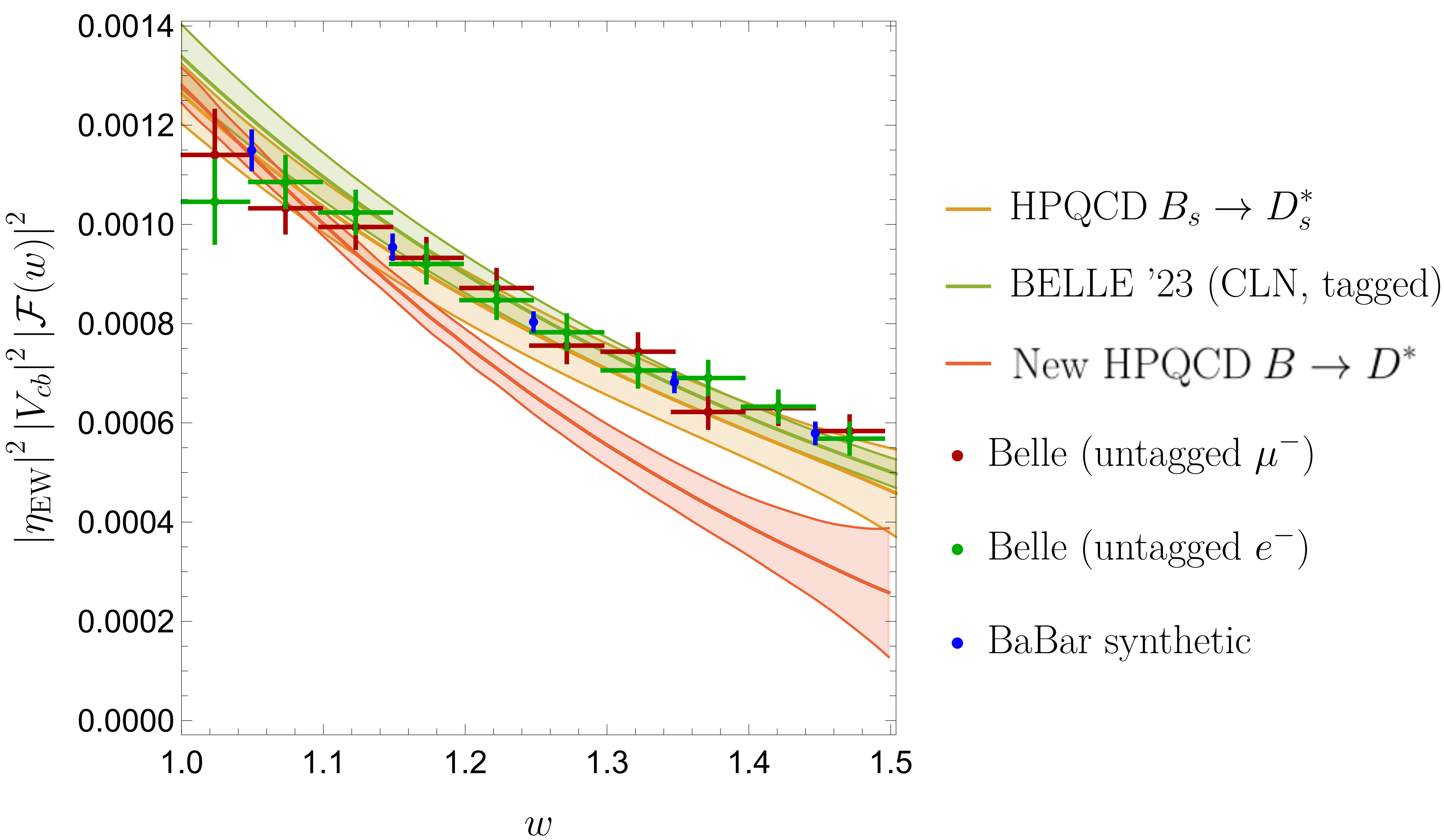
New HPQCD

- ✘ One more lattice spacing
- ✘ Chiral extrapolation

New HPQCD results suggest spectator light quark mass dependence

How can we understand that?

$$\frac{d\mathcal{B}(B \to D^* \ell \bar{\nu})}{dq^2} = \frac{1}{2 m_B m_{D^*}} \frac{d\mathcal{B}(B \to D^* \ell \bar{\nu})}{dw} \propto |V_{cb}|^2 |\mathcal{F}(w)|^2$$



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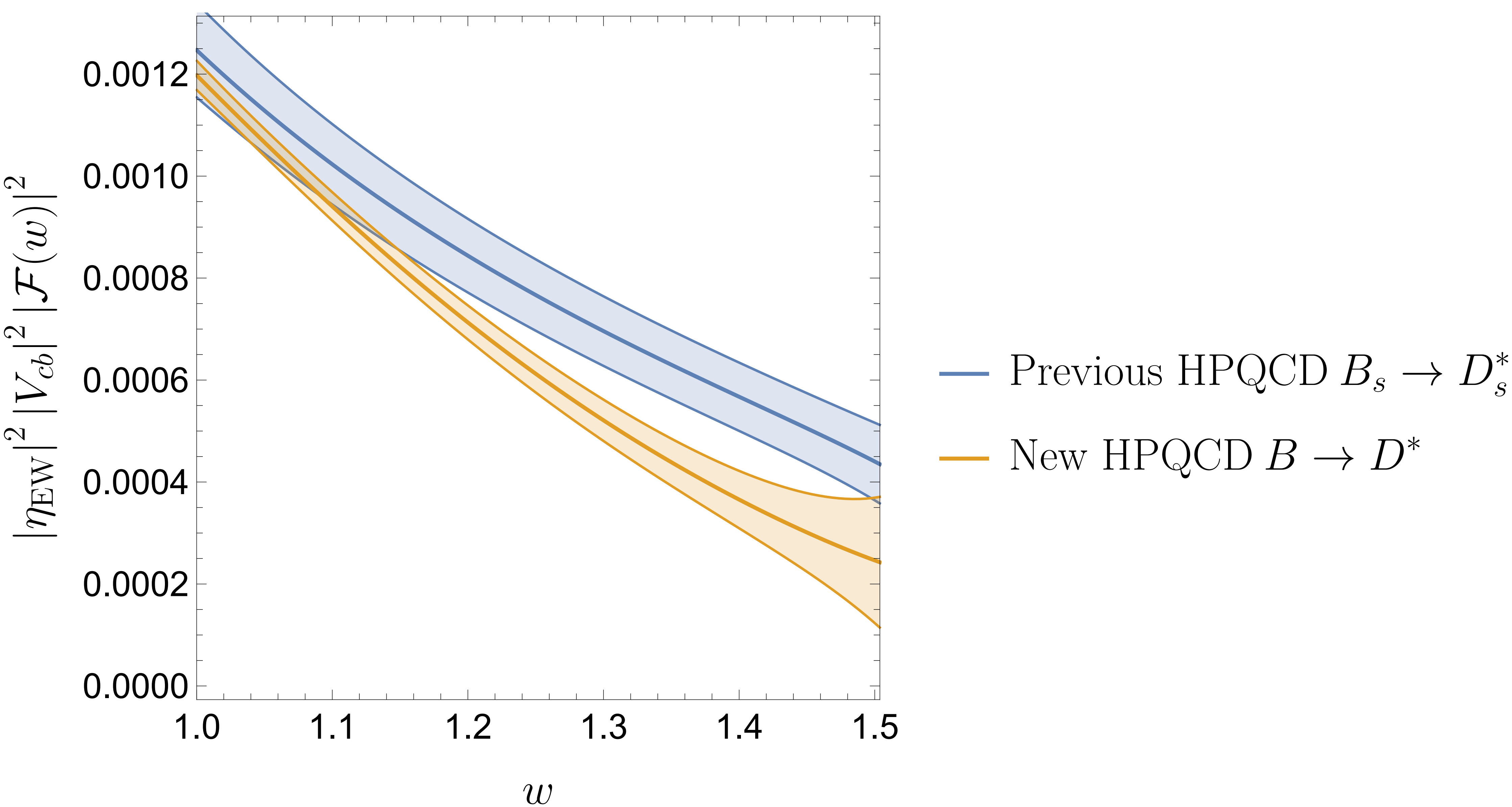
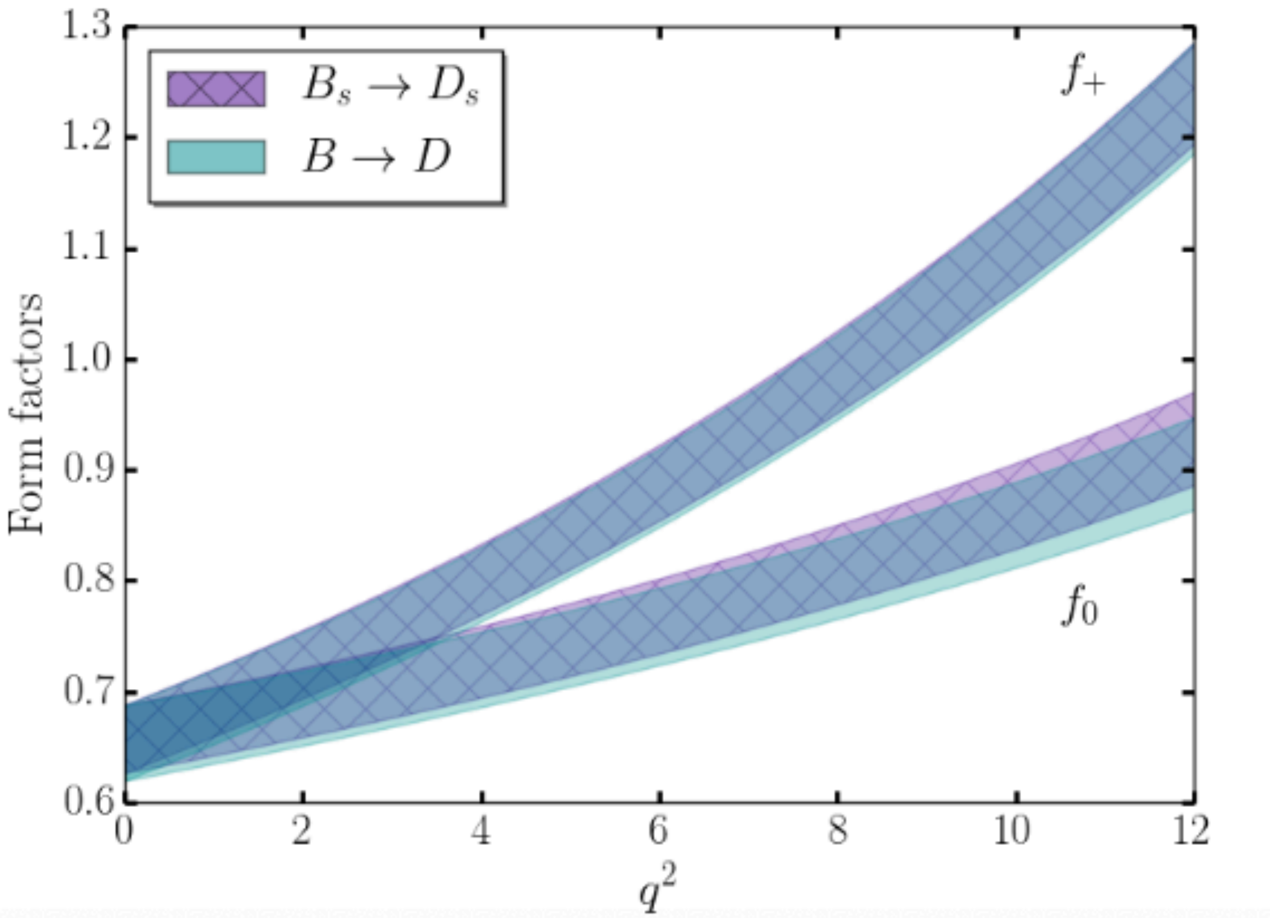
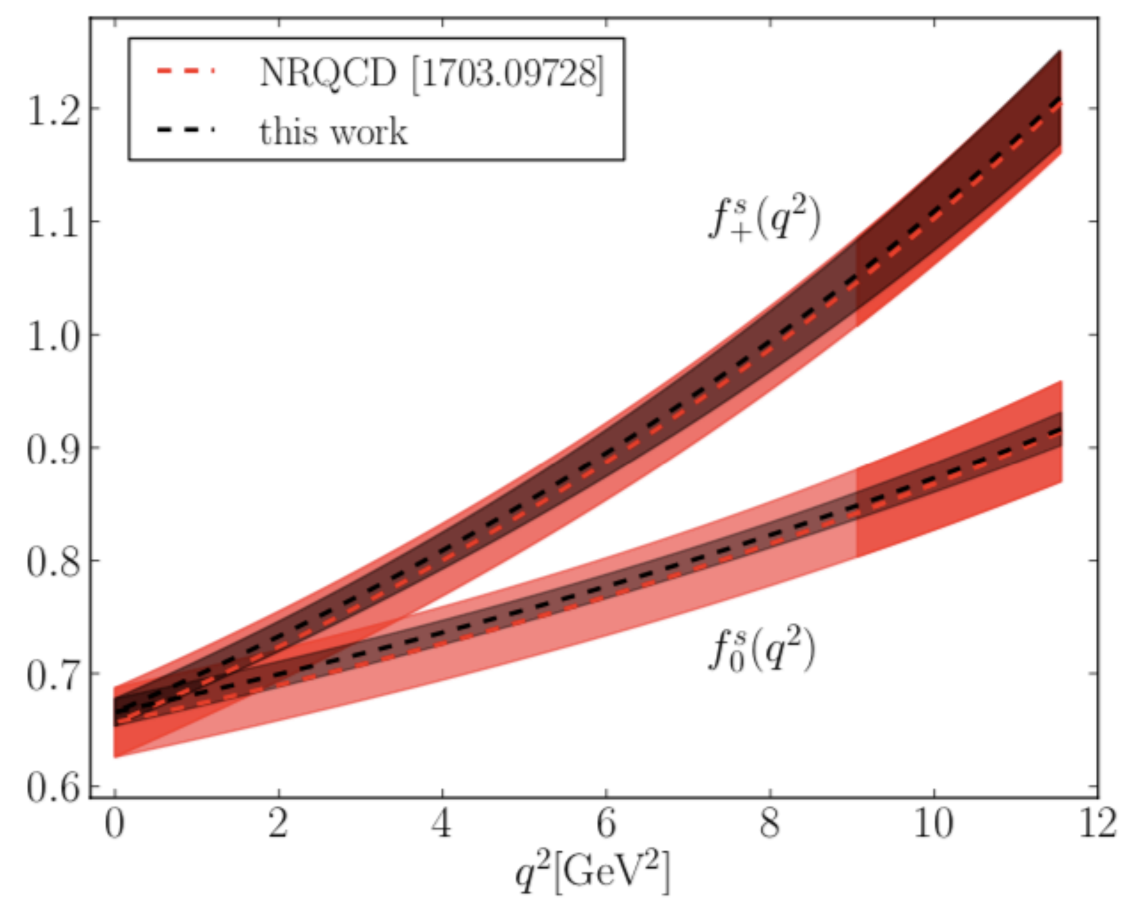


Light spectator quark mass dependence?





$B \to D^* \ell \bar{\nu}$

Do we understand well B → D at w=1?*

$\mathcal{F}(1) = 0.906(4)(12) \qquad (N_\mathrm{f} = 2+1)$ 1403.0635

$\mathcal{F}(1) = 0.895(10)(24) \qquad (N_\mathrm{f} = 2+1+1)$ 1711.1103

- The value of $\mathcal{F}(1)$ seems to be too large when comparing the exclusive and inclusive semileptonics at $w = 1$.
- As if all the other $B \to D(n)$ semileptonic modes were tiny or negligible - "oversaturation". 1206.2296
- Since $|V_{cb}|\mathcal{F}(1)$ comes from fit with exp. data, a lower $\mathcal{F}(1)$ would lead to larger $|V_{cb}|$.
- Necessary to double check with $B \to D\ell\nu$.
- Lattice results for $\mathcal{F}(1)$ with different regularization would be highly welcome.

Side remark: Never ending problem $|V_{cb}|$

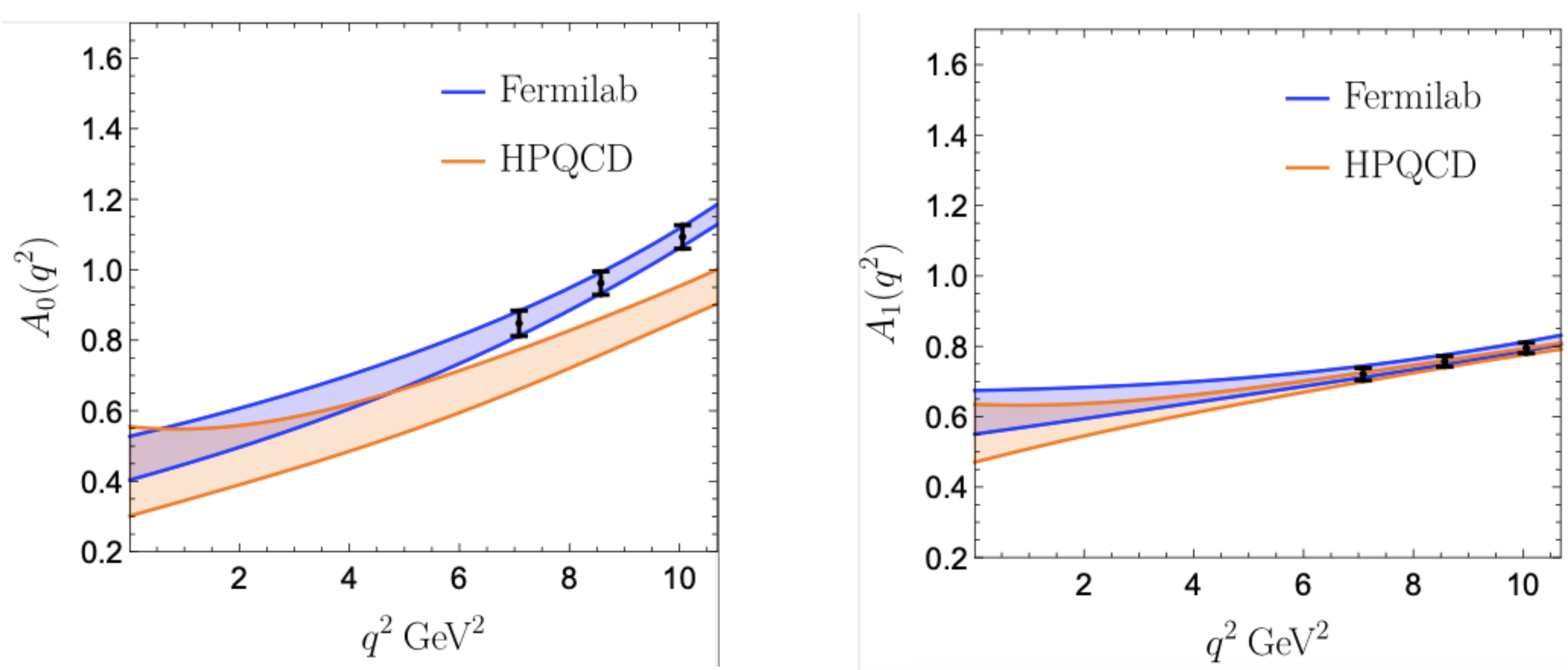
There is no canonical way/parametrization that would lead to reliable $|V_{cb}|$.

Never forget that we need dynamical QCD information! Changing variables ain't gonna do it!
At least TRY various options - and cross check!

Eg1. Can we measure the slowly varying scalar helicity amplitude? (!)

Eg2. Try this!

$$\lim_{m_\ell \to 0} \left. \frac{d\mathcal{B}(B \to D^* \ell \bar{\nu})}{dq^2} \right|_{q^2=0} = \tau_B \frac{G_F^2 m_B^3 |V_{cb}|^2}{192\pi^3} \left(1 - \frac{m_{D^*}^2}{m_B^2}\right)^3 |A_0(0)|^2$$



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Side remark: Never ending problem $|V_{cb}|$

$$\lim_{m_\ell \to 0} \frac{d\mathcal{B}(B \to D^*\ell\bar{\nu})}{dq^2}\Bigg|_{q^2=0} = \tau_B \frac{G_F^2 m_B^3 |V_{cb}|^2}{192\pi^3}\left(1 - \frac{m_{D^*}^2}{m_B^2}\right)^3 |A_0(0)|^2$$

- $A_0(0) = 0.47(6)^{\rm FNAL}, \cancel{0.61(6)^{\rm HPQCD}}\ 0.44(12)^{\rm HPQCD-23}, 0.78(23)^{\text{"LCSR"}}$ 0809.0222
- Use HFLAV results with e.g. CLN: $R_2(1) = 0.853(17) \Rightarrow R_2(w_{\max})$ 2206.07501

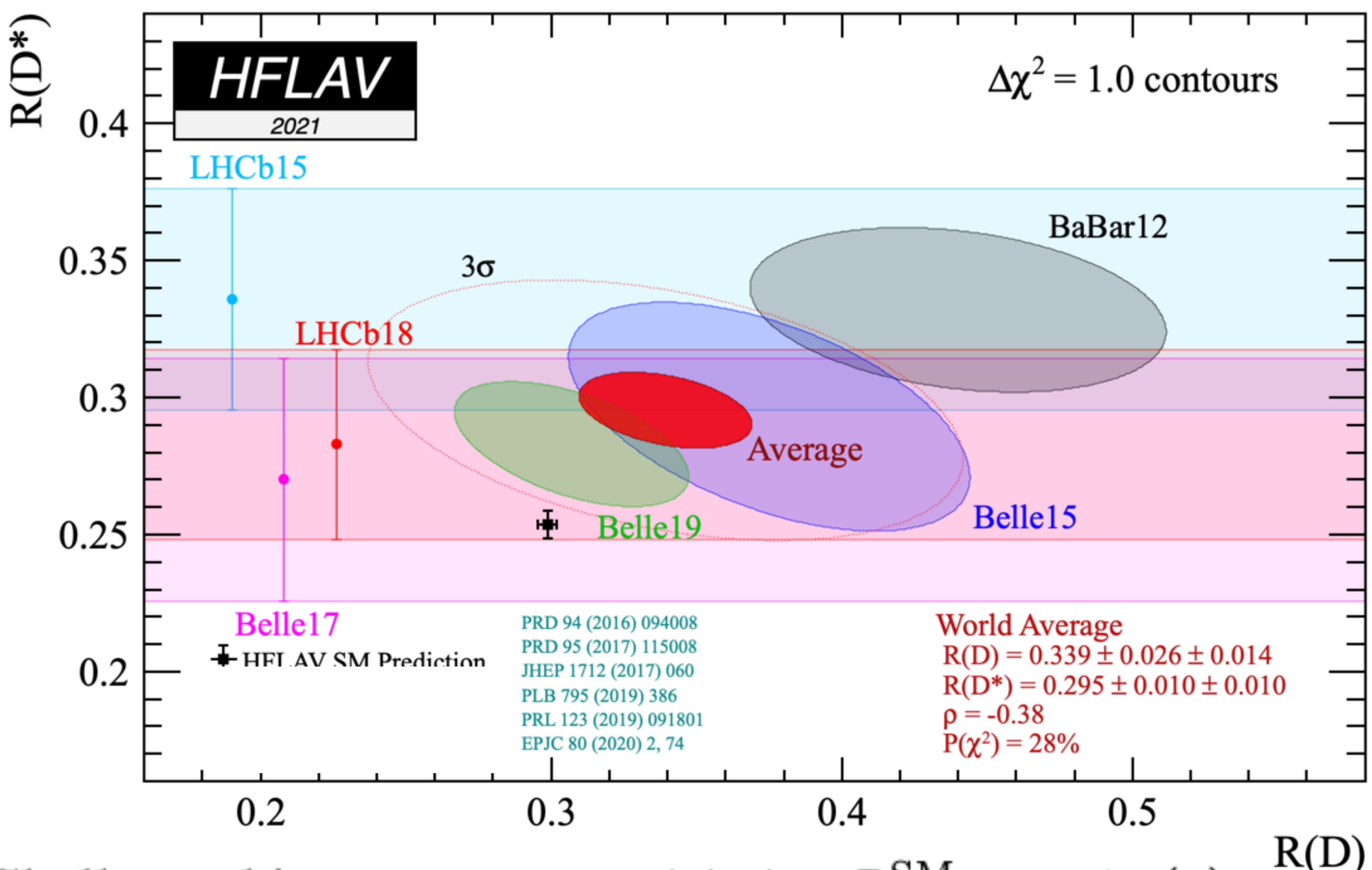
$$\frac{A_0(0)}{A_1(0)}\Bigg|_{\rm HFLAV}^{\rm CLN} = 1.087(14) \ \to \ A_0(0) = 0.66(7)^{\rm FNAL}, 0.63(8)^{\rm HPQCD}, 0.79(22)^{\text{"LCSR"}}$$

- Use measured $\mathcal{B}(B \to D\pi^\pm)$ and $\mathcal{B}(B \to D^*\pi^\pm)$ to either check whether or not $a_1^{D\pi} = a_1^{D^*\pi}$ or to extract $A_0(m_\pi^2)/f_0(m_\pi^2)$ More in the paper to come.

Hint of LFUV ['scare' or 'joy'] possibility to study NP effects

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

$$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3\ \text{TeV}$$



LHCb

- $B_c \to J/\psi\, \ell\bar{\nu}$

$$R^{\rm exp}_{J/\psi} > R^{\rm SM}_{J/\psi}$$

- $\Lambda_b \to \Lambda_c\, \ell\bar{\nu}$

$$R^{\rm exp}_{\Lambda_c} \approx R^{\rm SM}_{\Lambda_c}$$

NEW and can be improved... a lot

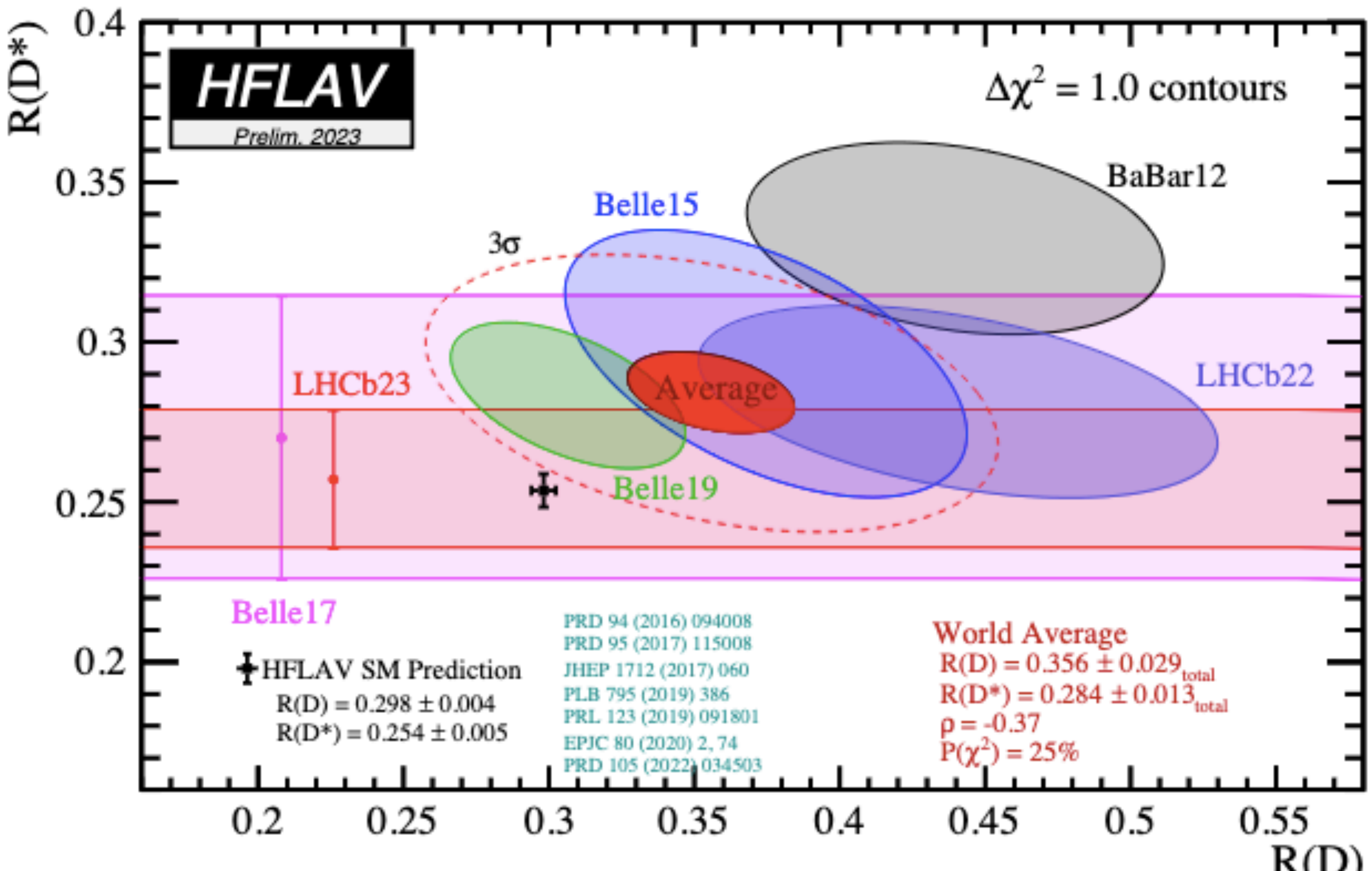
2201.03497

Challenged in 2109.15248 claiming $R^{\rm SM}_{D^*} = 0.275(8)$

Hint of LFUV ['scare' or 'joy'] possibility to study NP effects

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

2302.02886



LHCb

- $B_c \to J/\psi\, \ell\bar{\nu}$

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- $\Lambda_b \to \Lambda_c\, \ell\bar{\nu}$

$$R^{\rm exp}_{\Lambda_c} \approx R^{\rm SM}_{\Lambda_c}$$

NEW and can be improved... a lot

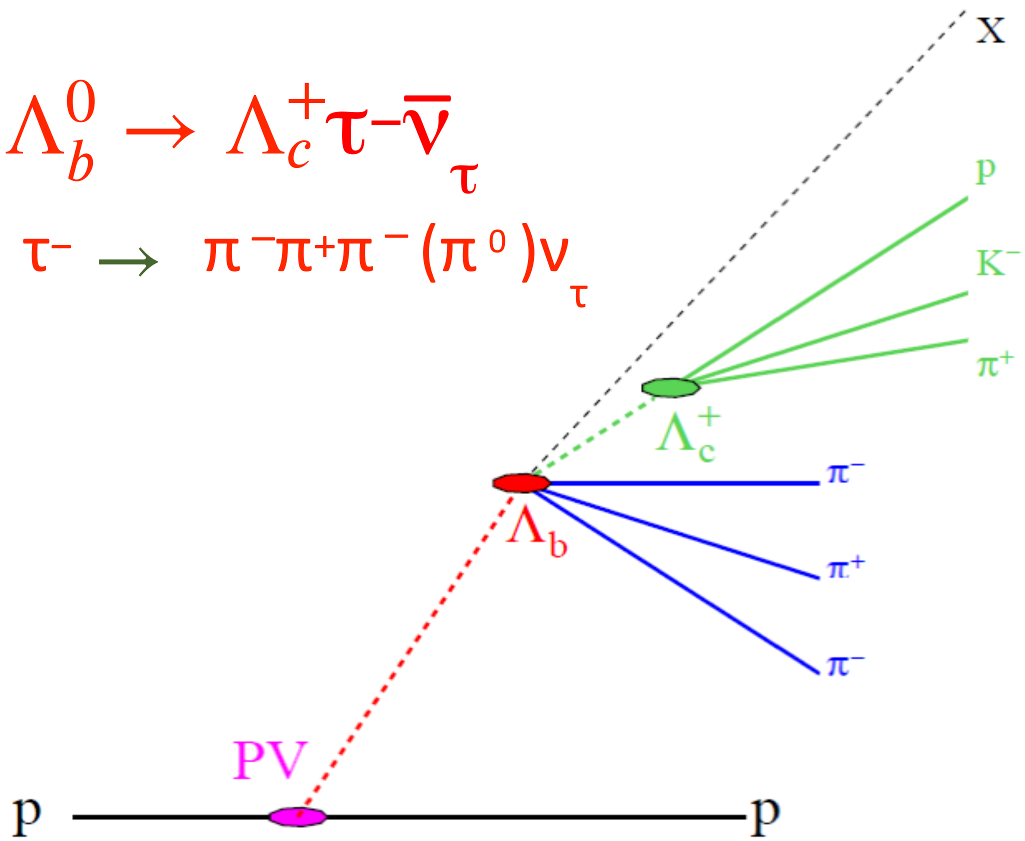
2201.03497

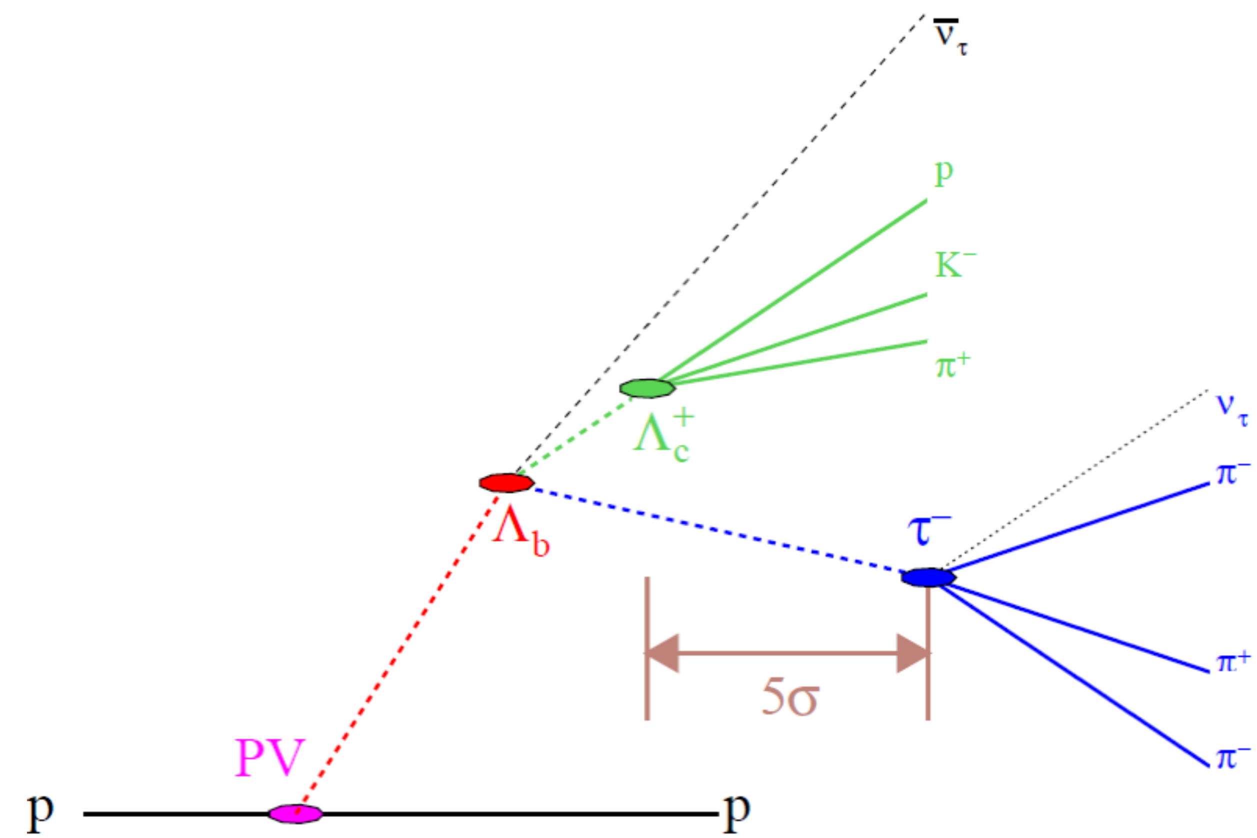
A comment on R_{Λ_c}

2201.03497

$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

$\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

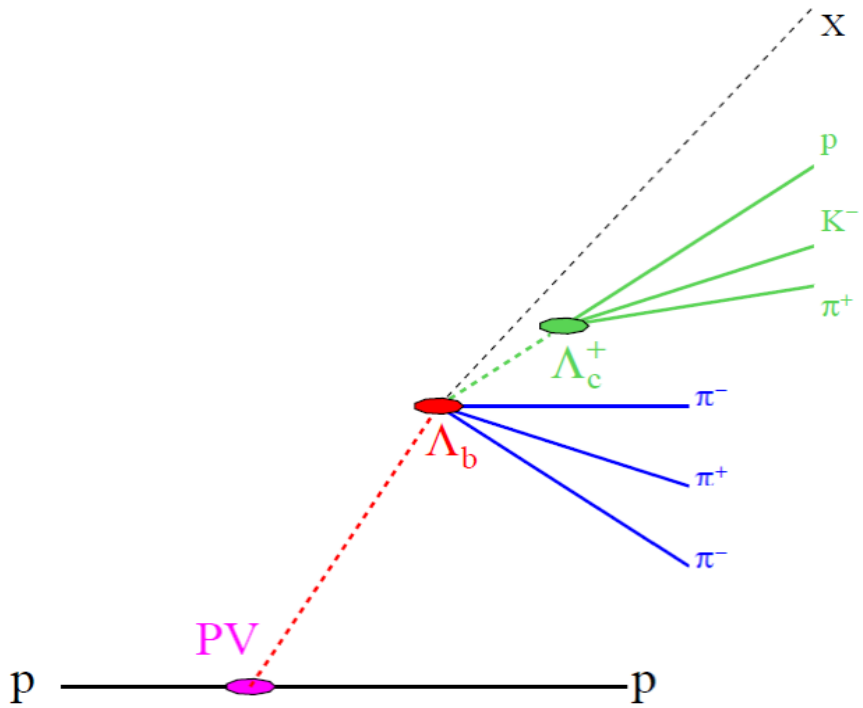


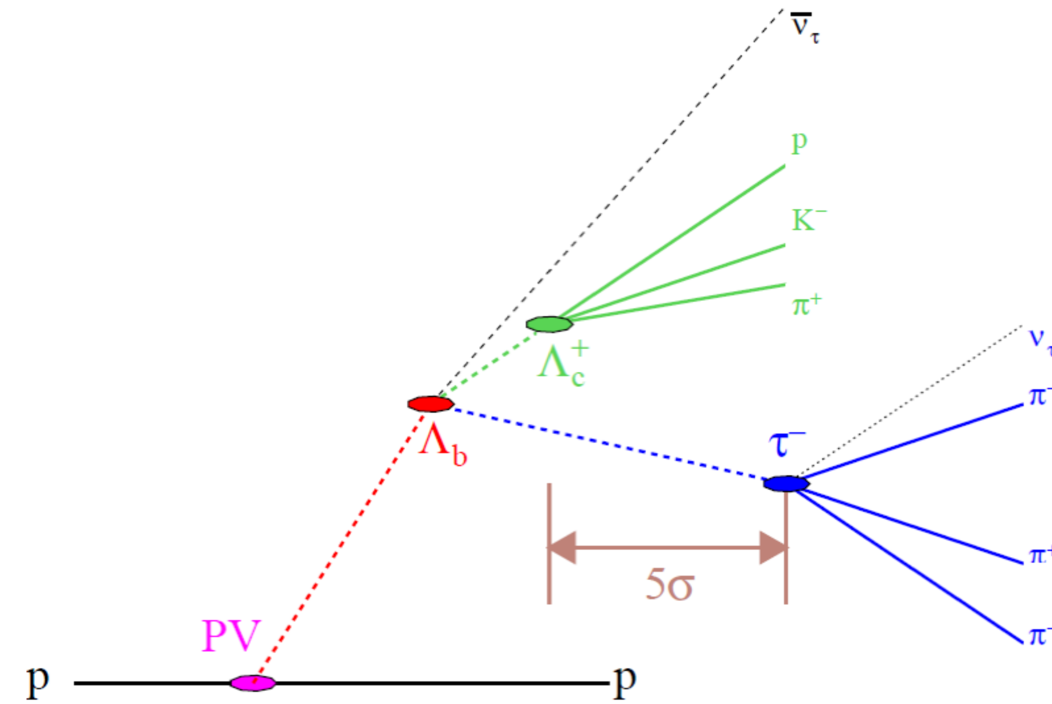


$$K_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)} = 2.46(27)(40)$$

2201.03497

A comment on R_{Λ_c}





$$K_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)} = 2.46(27)(40)$$

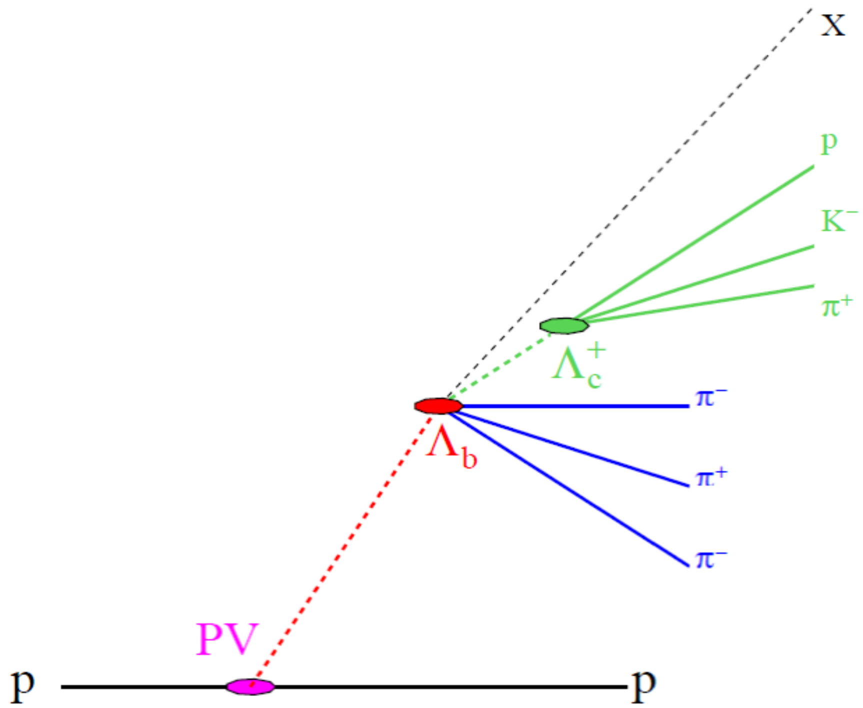
20%

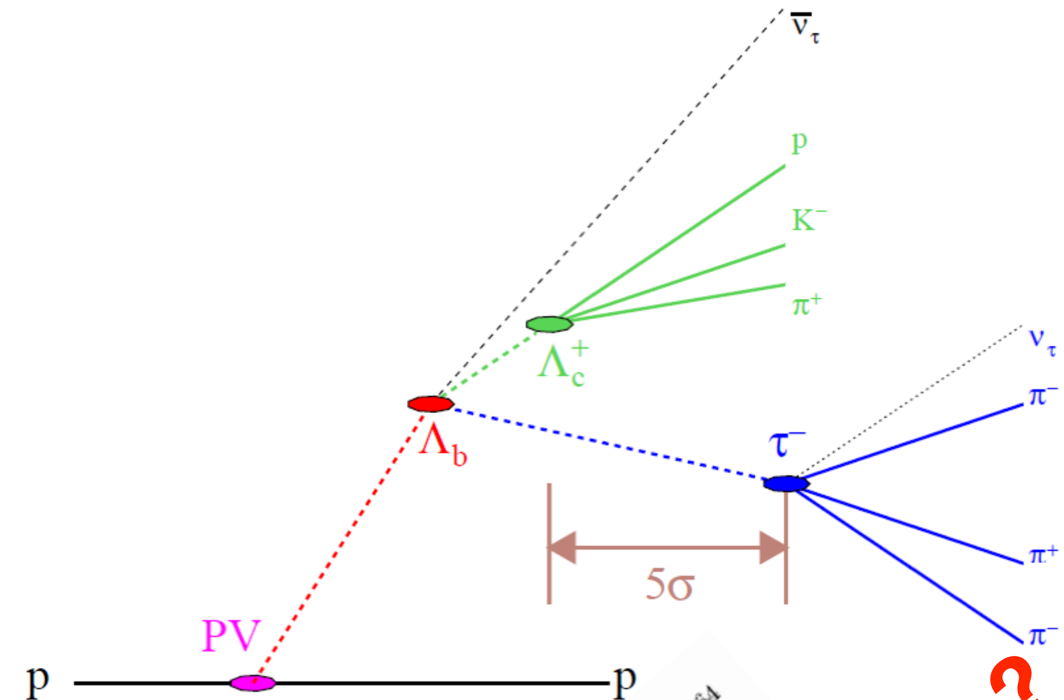
$\Gamma(\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-)/\Gamma_{\text{total}}$ Γ_{35}/Γ

VALUE (10^{-3}) 14%	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
7.6 ± 1.1	**OUR FIT** Error includes scale factor of 1.1.				
$14.8^{+3.8}_{-3.1} \pm 1.1$		[1] AALTONEN	2012A	CDF	$p\bar{p}$ at 1.96 TeV

• • We do not use the following data for averages, fits, limits, etc. • •

A comment on R_{Λ_c}





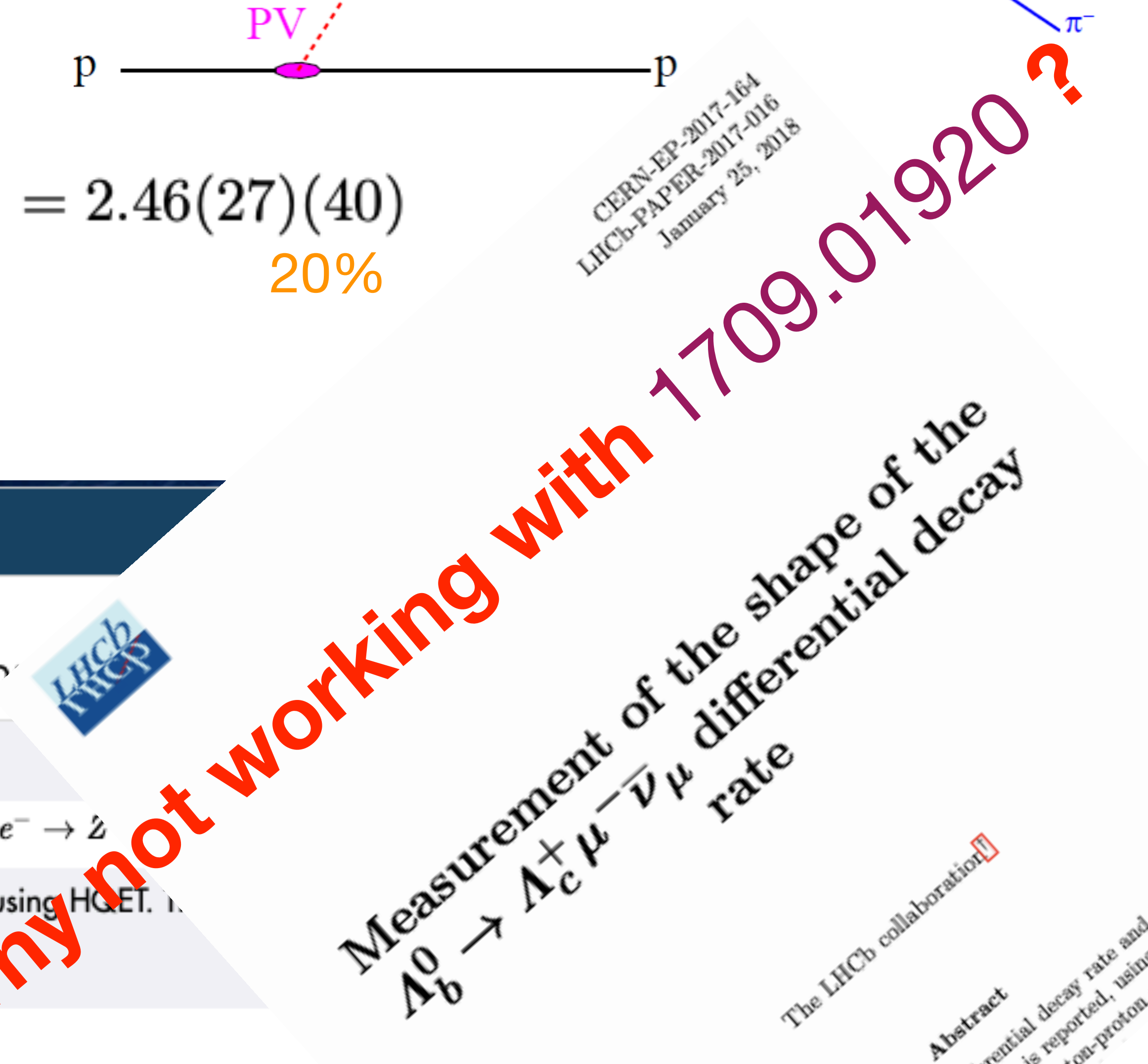
$$K_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)} = 2.46(27)(40)$$

20%

$\Gamma(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)/\Gamma_{\text{total}}$

VALUE 22%	DOCUMENT ID		TECN	CO
$\mathbf{0.062^{+0.014}_{-0.013}}$ OUR FIT				
$0.050\ ^{+0.011}_{-0.008}\ ^{+0.016}_{-0.012}$	[1] ABDALLAH	2004A	DLPH	$e^+ e^- \to Z$

[1] Derived from a combined likelihood and event rate fit to the distribution of the Isgur-Wise variable and using HQET. T... form factor is measured to be $\rho^2 = 2.03 \pm 0.46\ ^{+0.72}_{-1.00}$.



Why not working with 1709.01920 ?

EFT - exclusive $b \to c\ell\nu$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{eff}} = -2\sqrt{2} G_F V_{cb} \Big[& (1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L) \\
& + g_{S_R} (\bar{c}_L b_R)(\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \Big] + \mathrm{h.c.}
\end{aligned}
$$

EFT - exclusive $b \to c\ell\nu$

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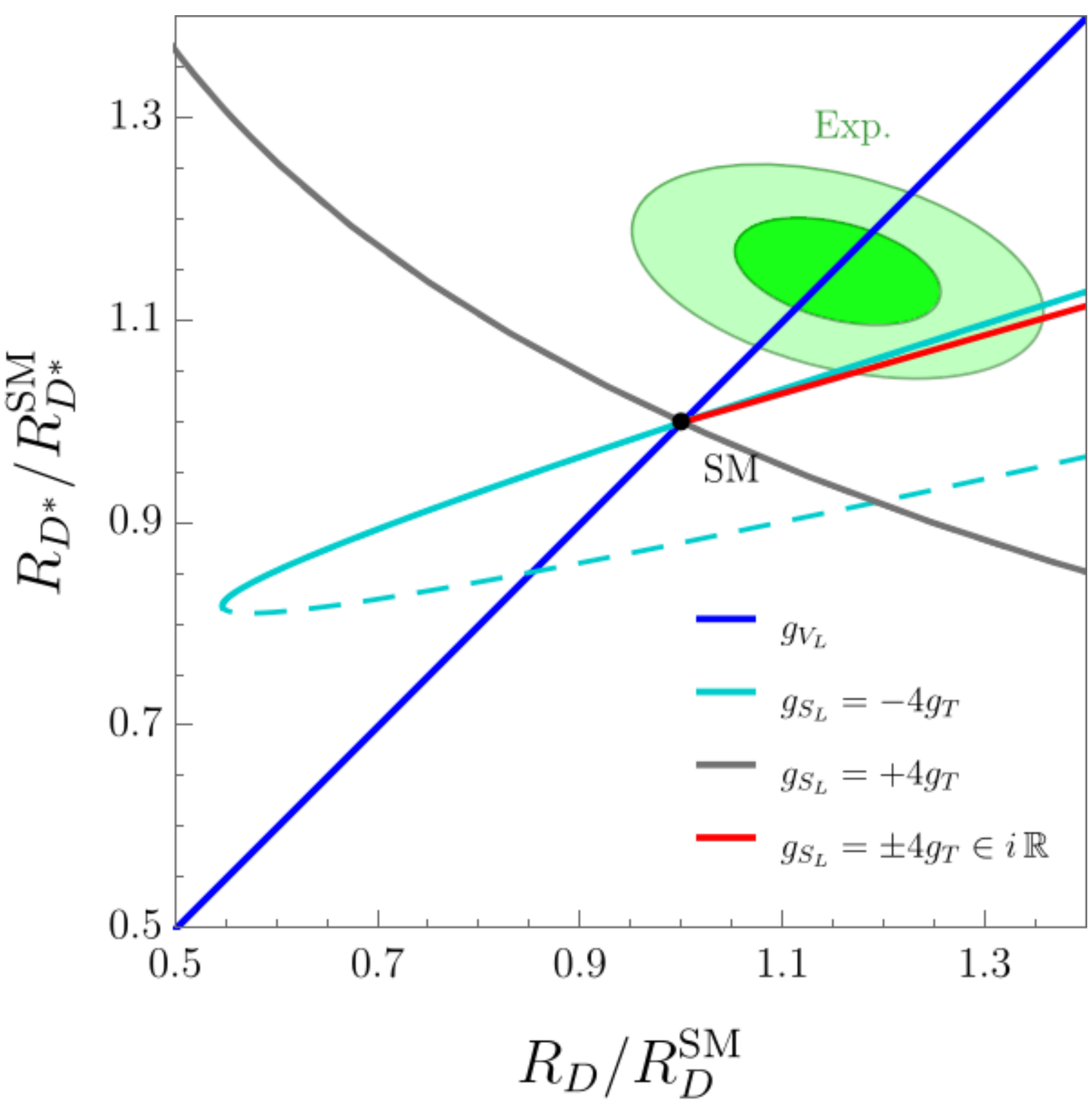
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$



2103.12504

EFT - exclusive $b \to c\ell\nu$

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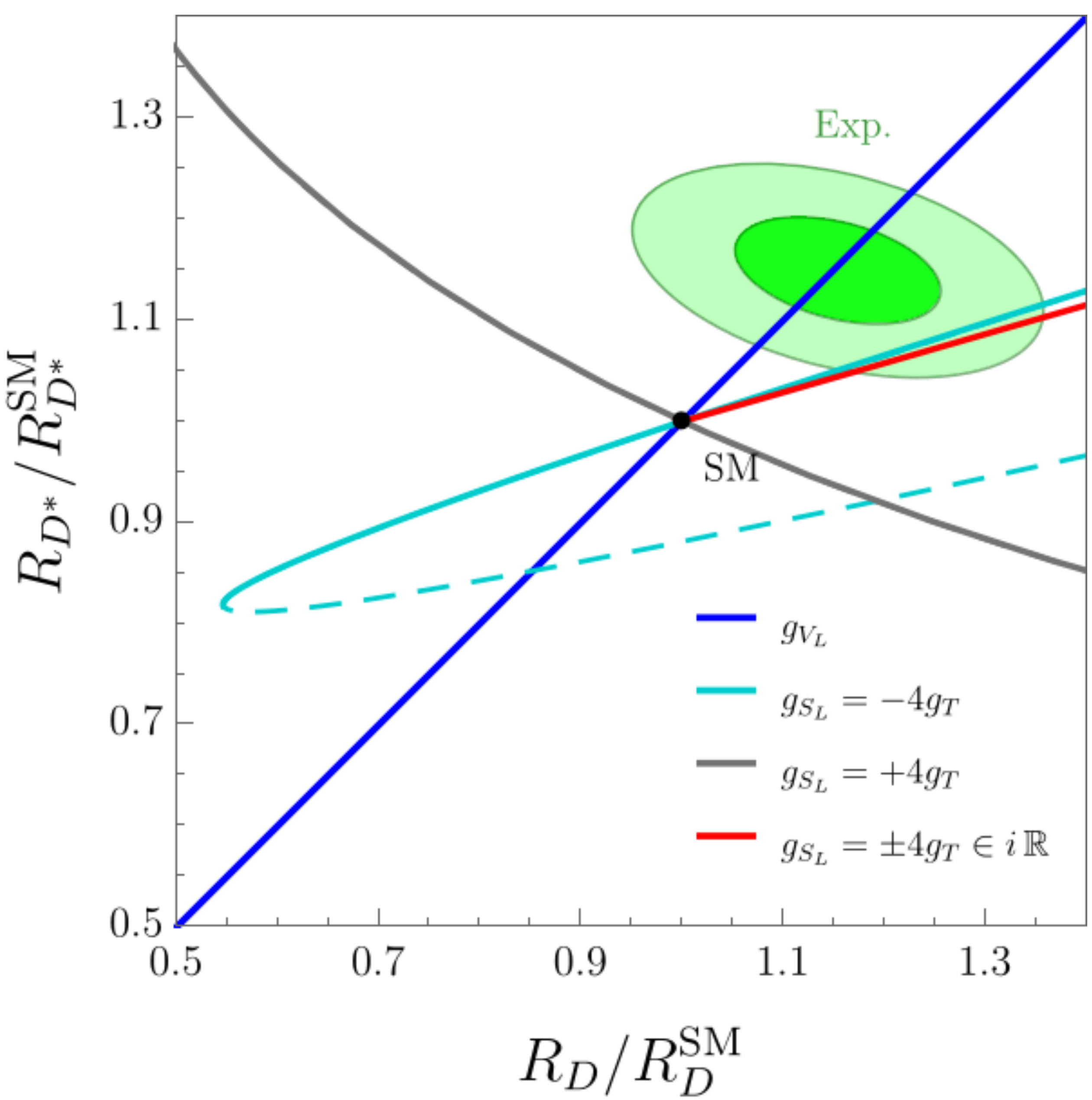
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$



Need better data and more observables to discriminate among various possibilities.

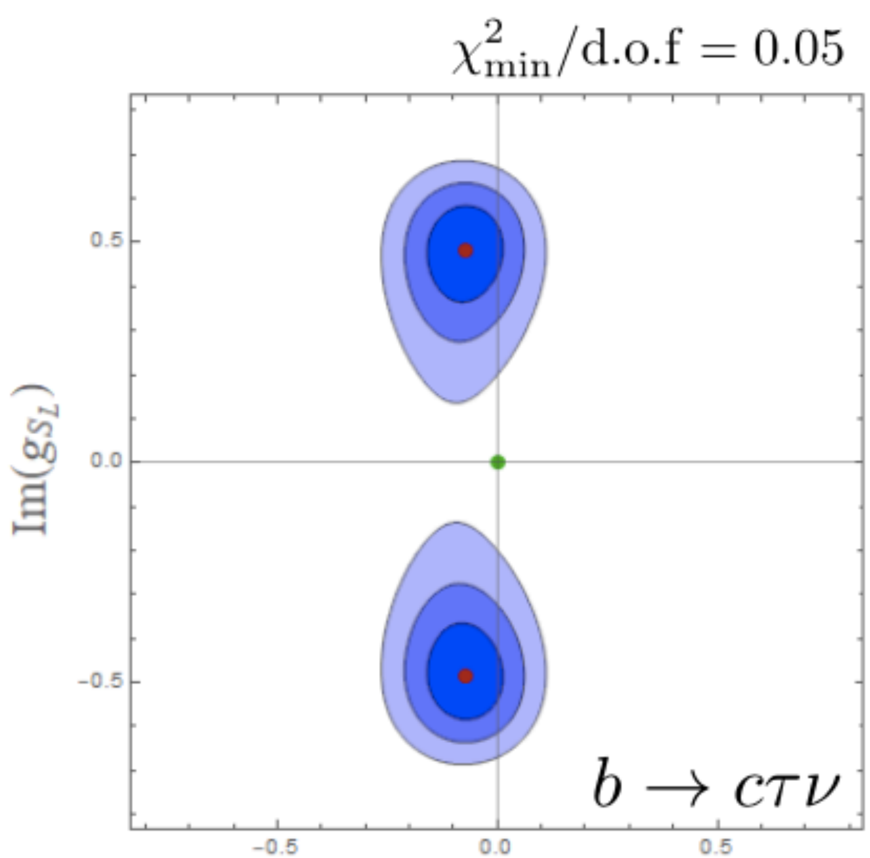
Dream goal is to confidently & simultaneously determine all NP cplgs from fit with the data.

Angular distributions can help!

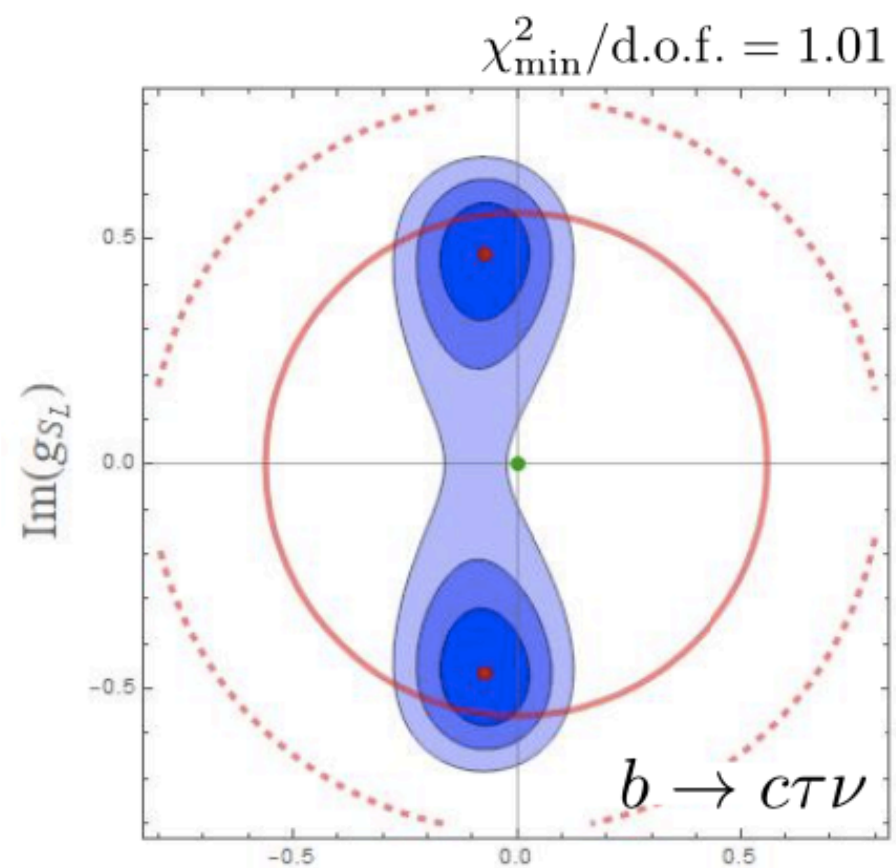
vast literature…

Impact of R_{Λ_c}

Wilson Coefficient	$R(D)$ and $R(D^*)$	$R(\Lambda_c)$	Combined	$\chi^2_{\rm min}/{\rm d.o.f}$
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	$0.7 \to 1.0$



$g_{S_L} = +4g_T$



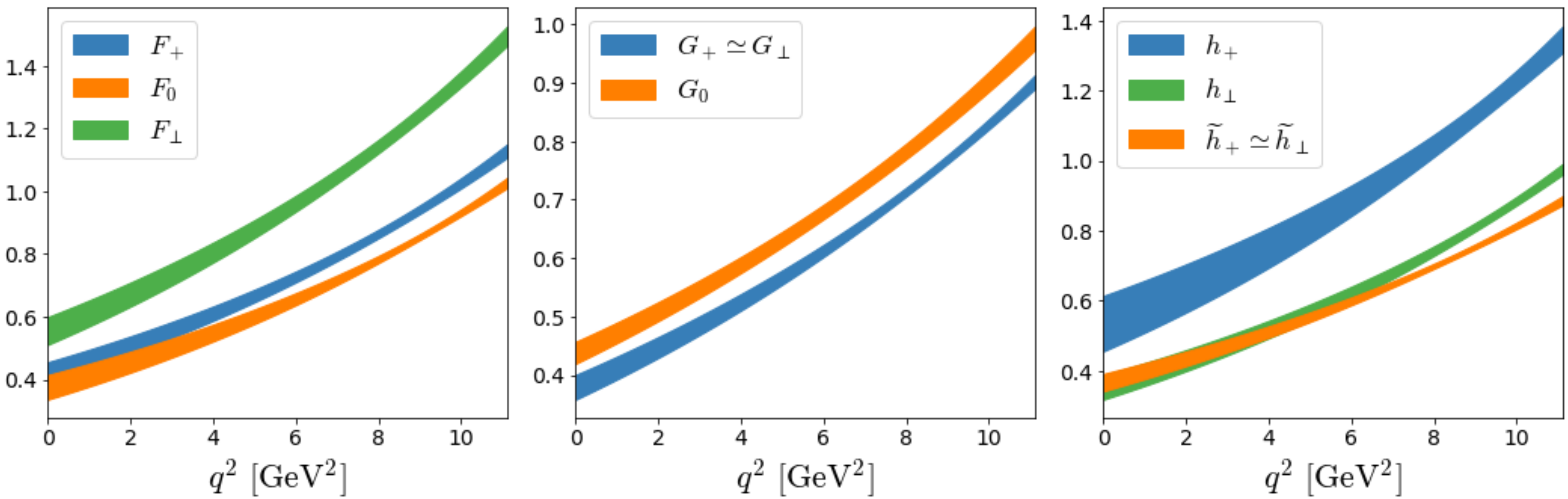
$g_{S_L} = +4g_T$

We still do not have a full/good control over hadronic uncertainties

Mode	$B \to D\ell\bar{\nu}$	$B \to D^*\ell\bar{\nu}$	$\Lambda_b \to \Lambda_c\ell\bar{\nu}$
$\langle V_\mu \rangle$	**2** ✓	**1** ✓	**3** ✓
$\langle A_\mu \rangle$		**3** ✓	**3** ✓
$\langle T_{\mu\nu} \rangle$	**1** ×	**3** ✔	**4** ✓
	1503.07237 1505.03925	2105.14019 2304.03137	1503.01421 1702.02243

$\Lambda_b \to \Lambda_c \ell \bar{\nu}$

$\langle \Lambda_c | \bar{c}\gamma_\mu b | \Lambda_b \rangle$ $\langle \Lambda_c | \bar{c}\gamma_\mu \gamma_5 b | \Lambda_b \rangle$ $\langle \Lambda_c | \bar{c}\sigma_{\mu\nu} b | \Lambda_b \rangle$



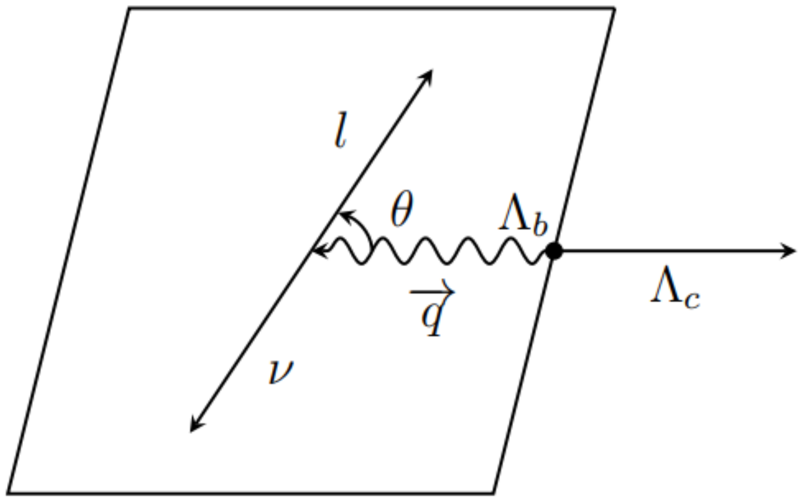
1503.01421

1702.02243

Keep in mind: Less than a half of available q^2's computed on the lattice. Otherwise "z-parametrization".

Angular observables can help disentangling among various NP scenarios

Many works with mesons: $\mathbf{B} \to \mathbf{D}\ell\bar{\nu}$ $\mathbf{B} \to \mathbf{D}^*\ell\bar{\nu}$



Let us now play with baryons:

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

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

Each $a_{\lambda_c}^{\lambda_l}(q^2)$, $b_{\lambda_c}^{\lambda_l}(q^2)$, $c_{\lambda_c}^{\lambda_l}(q^2)$ is a function of kinematics, form factors and the NP couplings g_{V_L}, g_{S_L}, g_{S_R}, g_T.

12-2=10 observables

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

1907.12554 1908.02328 1909.10769 1702.02243 1502.04864 2209.13409

Three powerful observables:

- $$\mathcal{A}_{\rm fb}(q^2) = \frac{1}{\Gamma}\left[\int_0^1 - \int_{-1}^0\right]\frac{d\Gamma}{d\cos\theta}\, d\cos\theta$$

- $$\mathcal{A}_{\pi/3}(q^2) = \frac{1}{\Gamma}\left[\int_0^{\pi/3} + \int_{2\pi/3}^{\pi} - \int_{\pi/3}^{2\pi/3}\right]\frac{d\Gamma}{d\cos\theta}\sin\theta\, d\theta$$

- $$\mathcal{A}_{\lambda}(q^2) = \frac{1}{\Gamma}\left[\frac{d\Gamma^+}{dq^2} - \frac{d\Gamma^-}{dq^2}\right]$$

Examples:

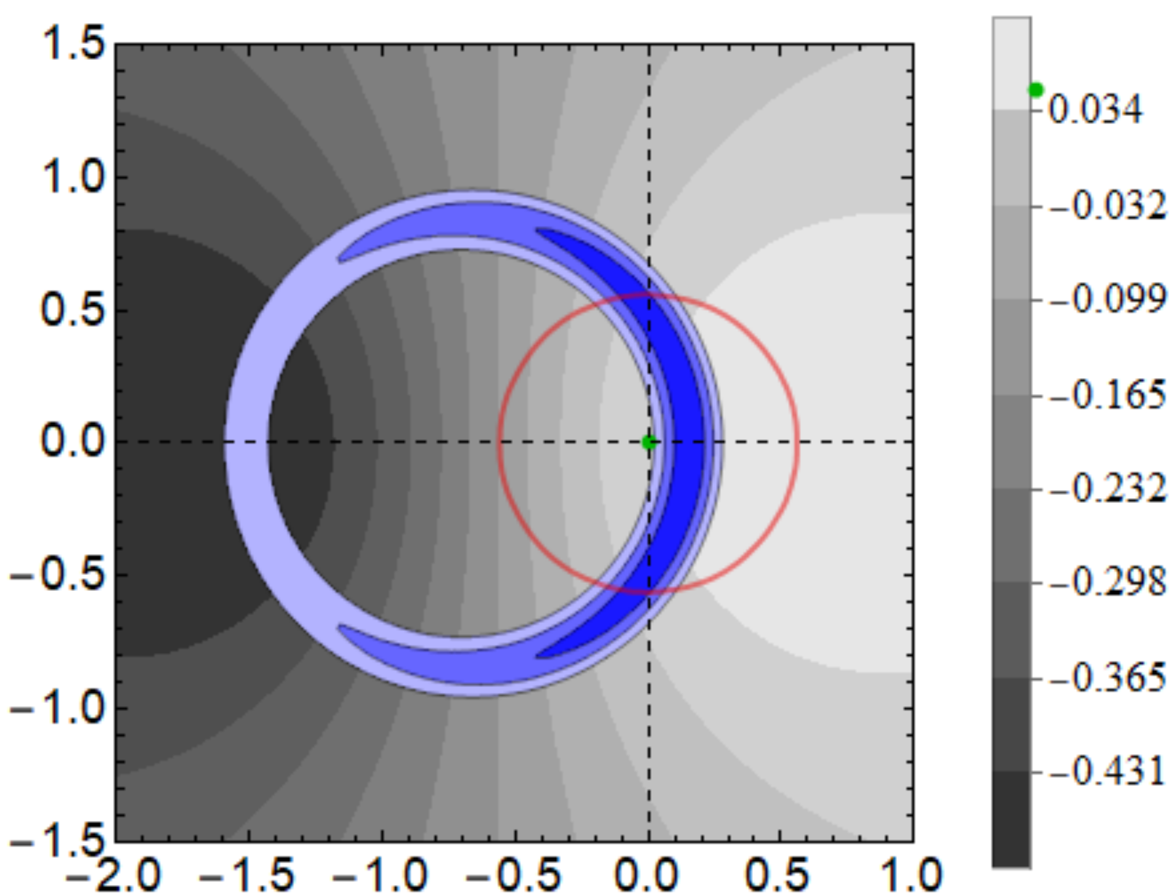
$U_1 : g_{V_L}$ $\quad R_2 : g_{S_L} = 4\, g_T$ $\quad S_1 : g_{S_L} = -4\, g_T$

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

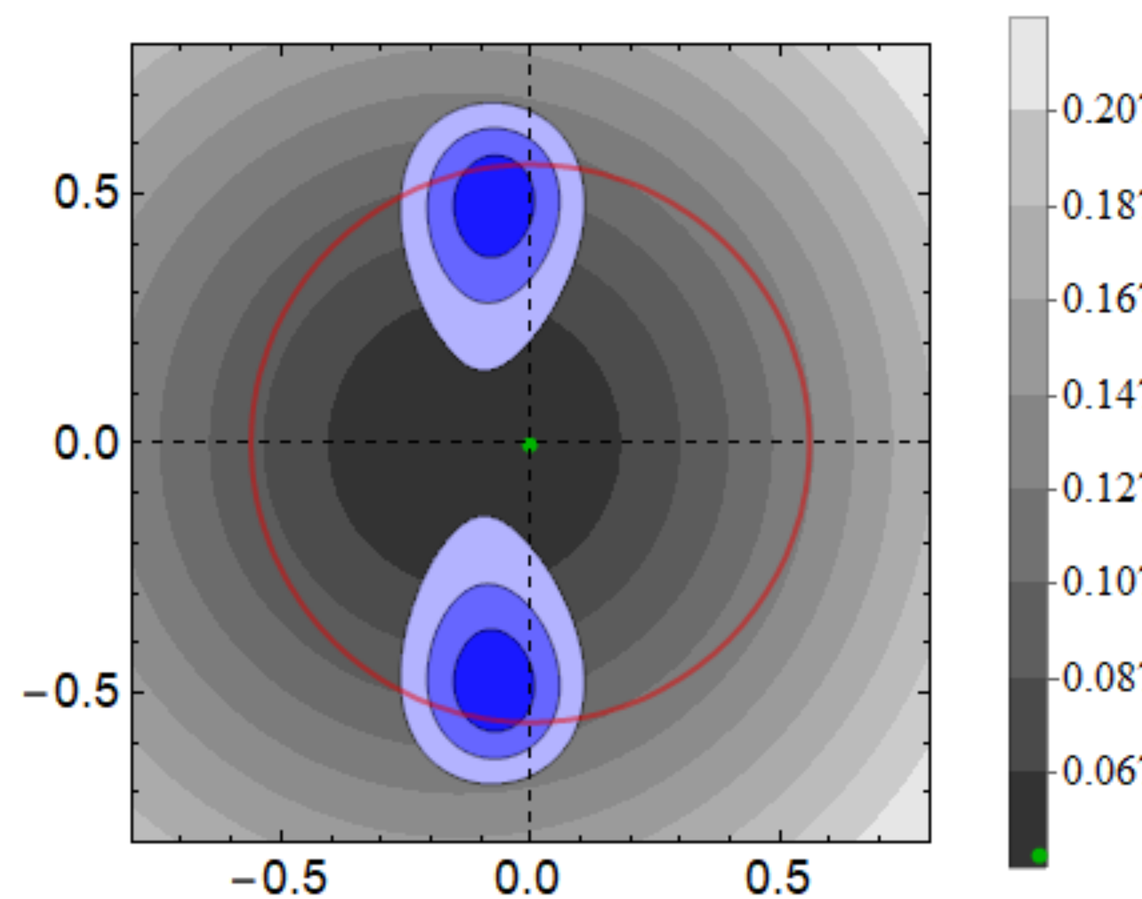
2209.13409

(At least) Three powerful observables:

$$\langle \mathcal{A}_{\rm fb}^{\tau} \rangle$$



S_1



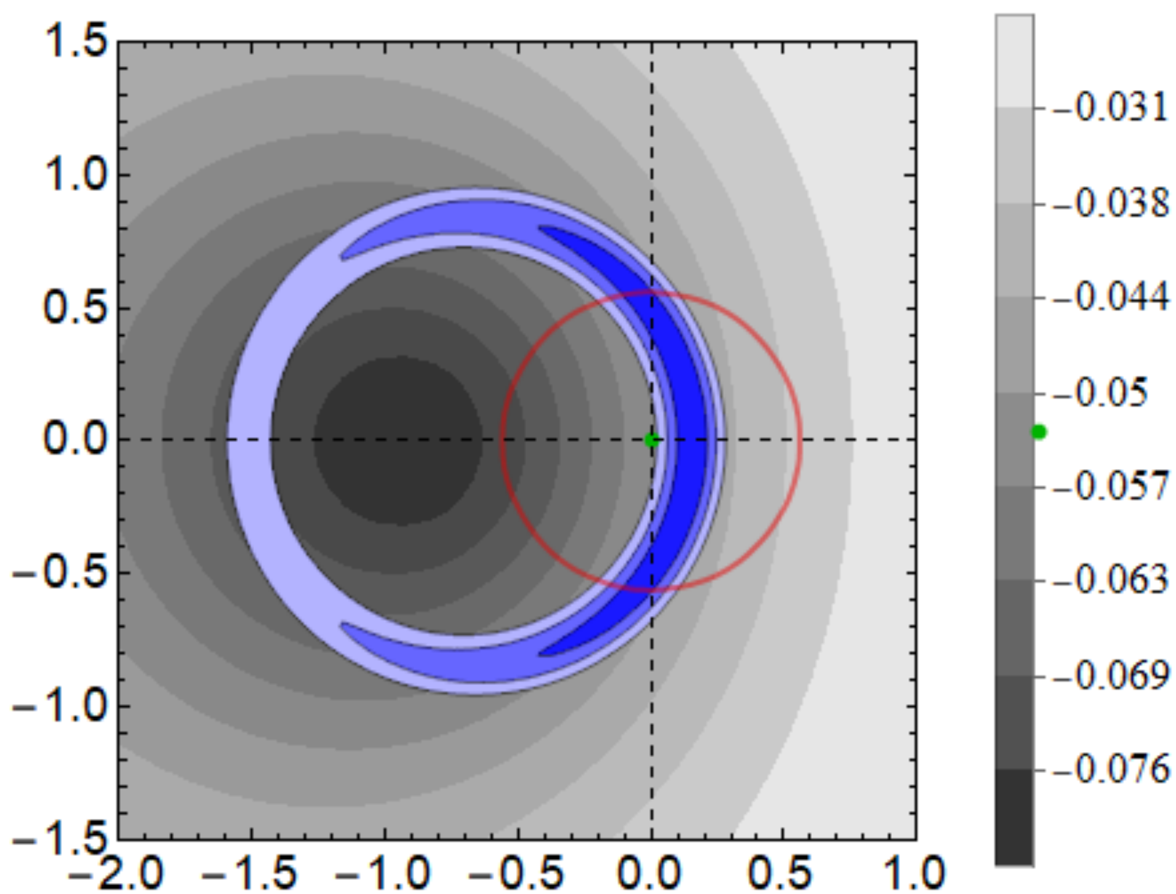
R_2

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

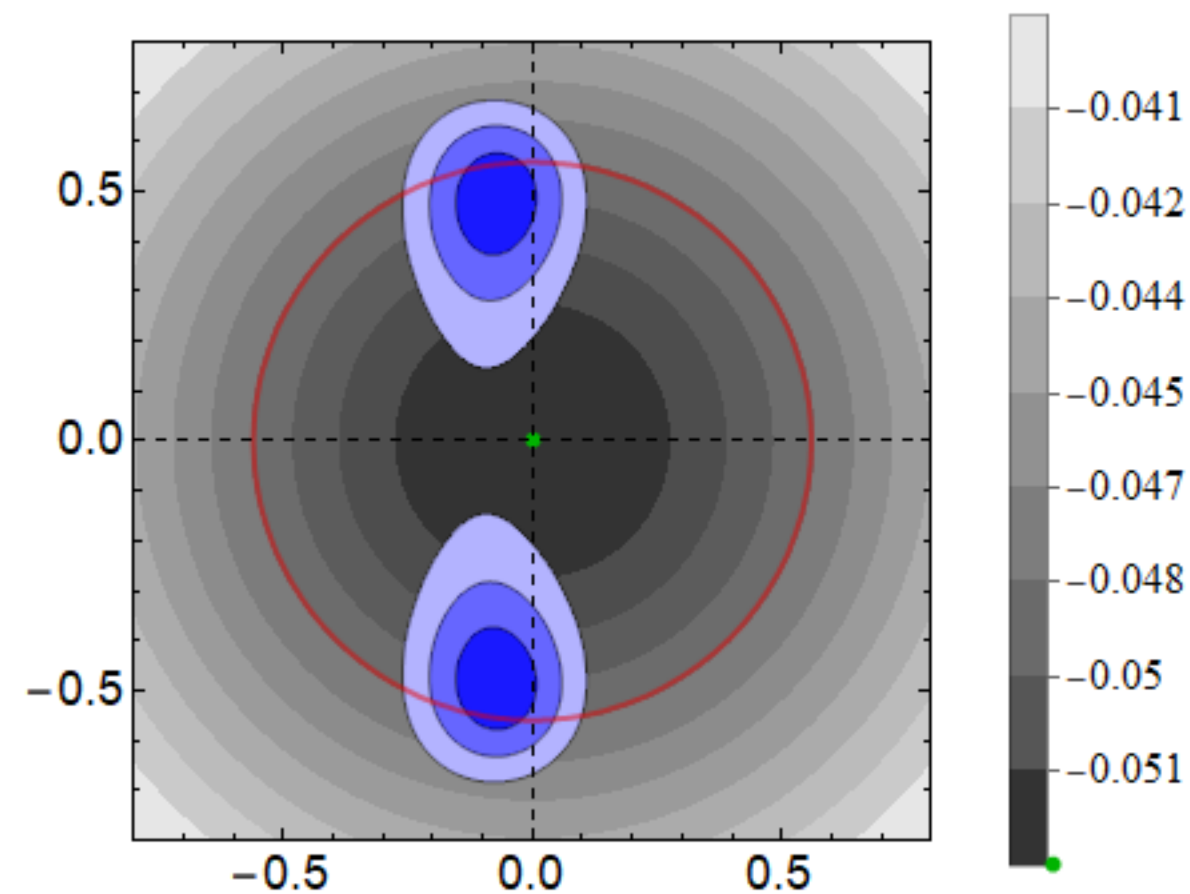
2209.13409

Three powerful observables:

$\langle \mathcal{A}^{\tau}_{\pi/3} \rangle$:



S_1



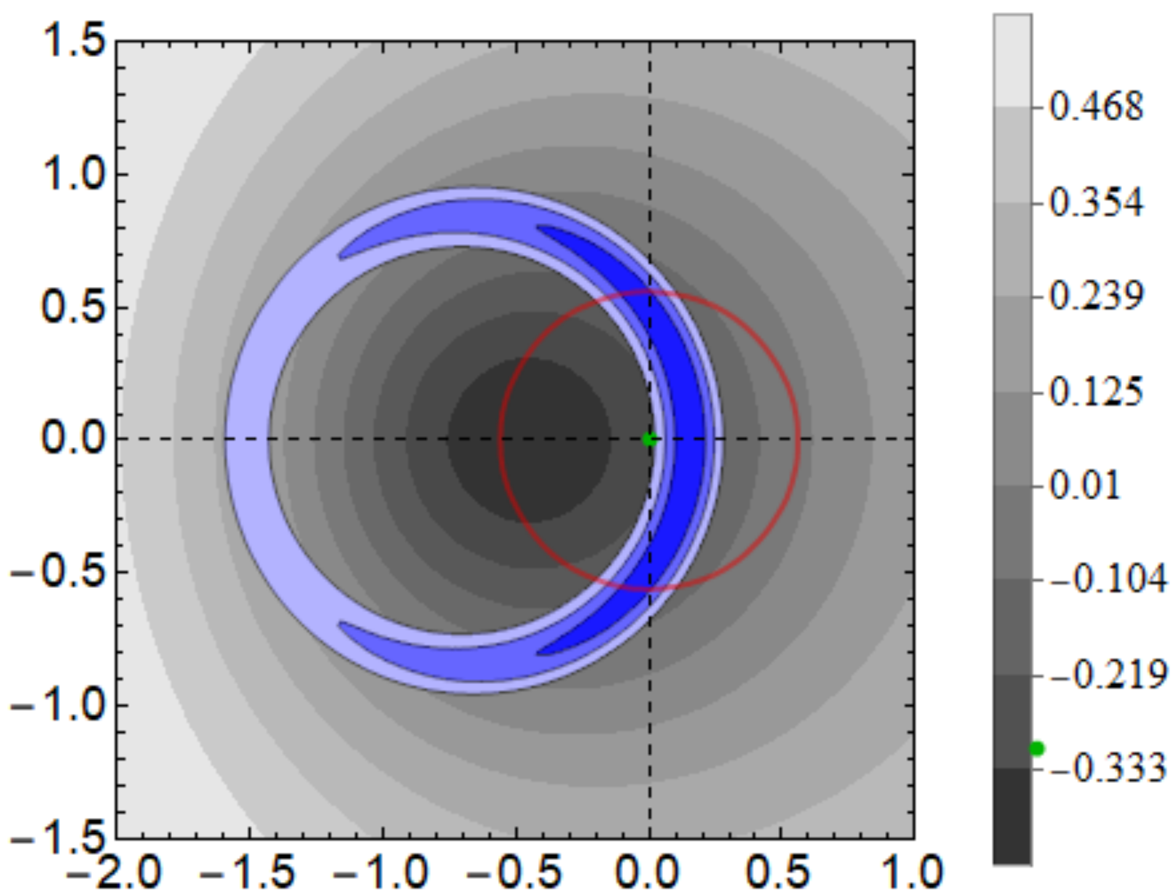
R_2

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

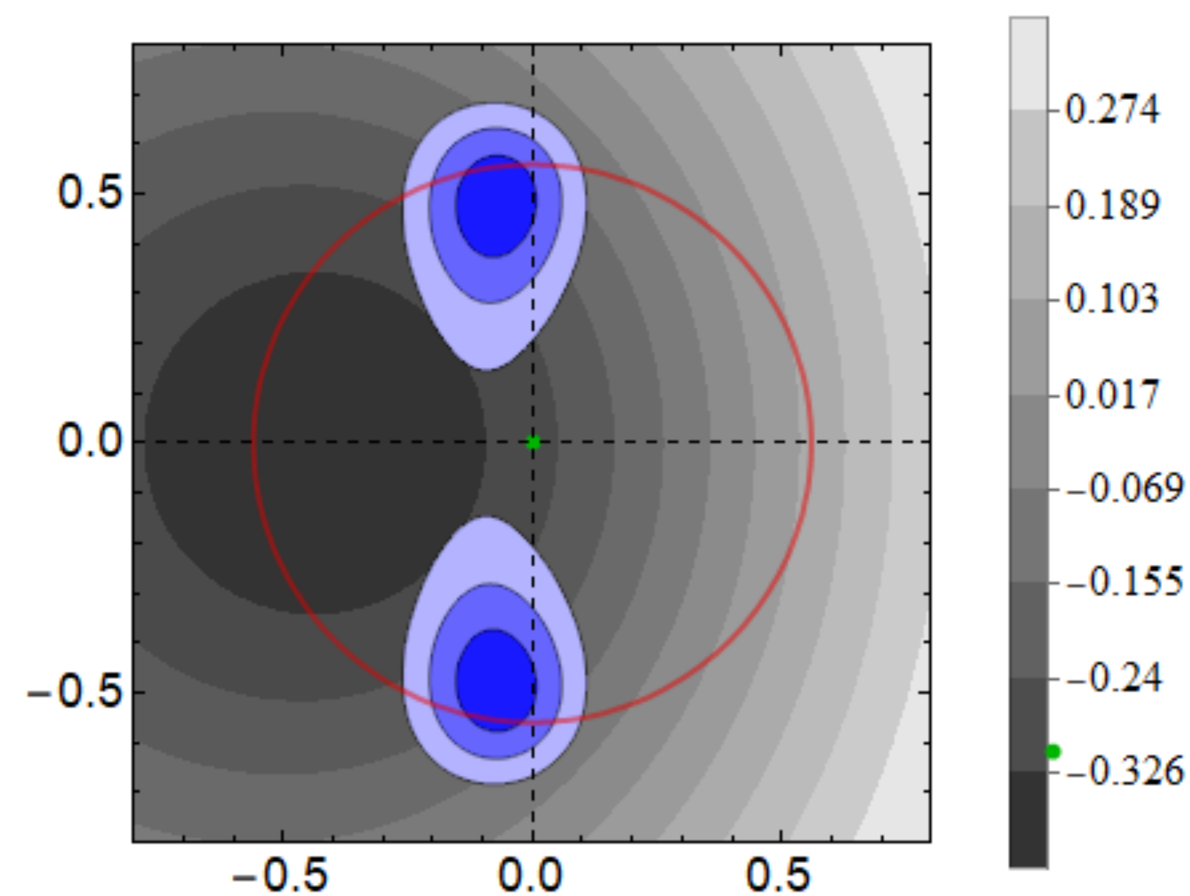
2209.13409

Three powerful observables:

$$\langle \mathcal{A}_\lambda^\tau \rangle$$



S_1



R_2

$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$

2209.13409

NB: $\mathcal{B}(\Lambda_c \to \Lambda\pi) = 1.30(7)\%$ or $\mathcal{B}(\Lambda_c \to pK_S) = 1.59(8)\%$

Many more angular observables and checking on Im[g_X] ≠ 0

...

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

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

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

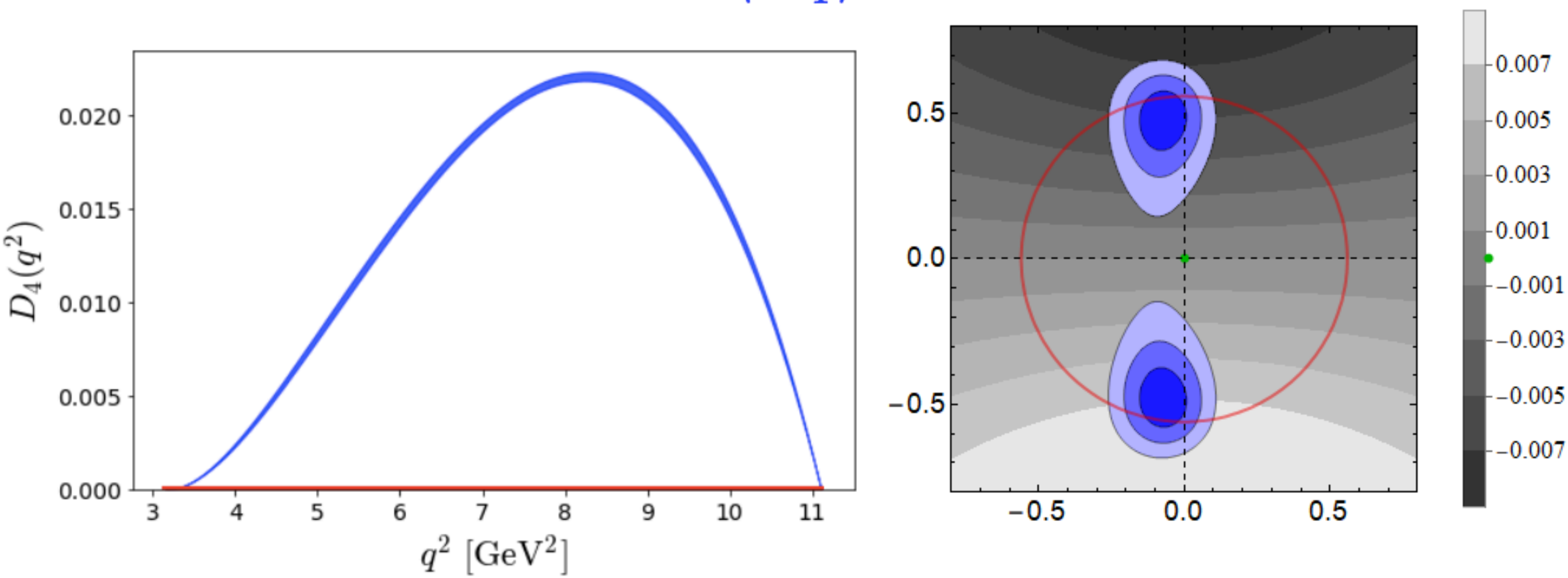
2209.13409

$\Lambda_b \longrightarrow \Lambda_c(\rightarrow \Lambda\pi)\ell\nu$

NB: $\mathcal{B}(\Lambda_c \to \Lambda\pi) = 1.30(7)\%$ or $\mathcal{B}(\Lambda_c \to pK_S) = 1.59(8)\%$

Many more angular observables and checking on Im[g_X] ≠ 0

$\langle D_4^\tau \rangle$



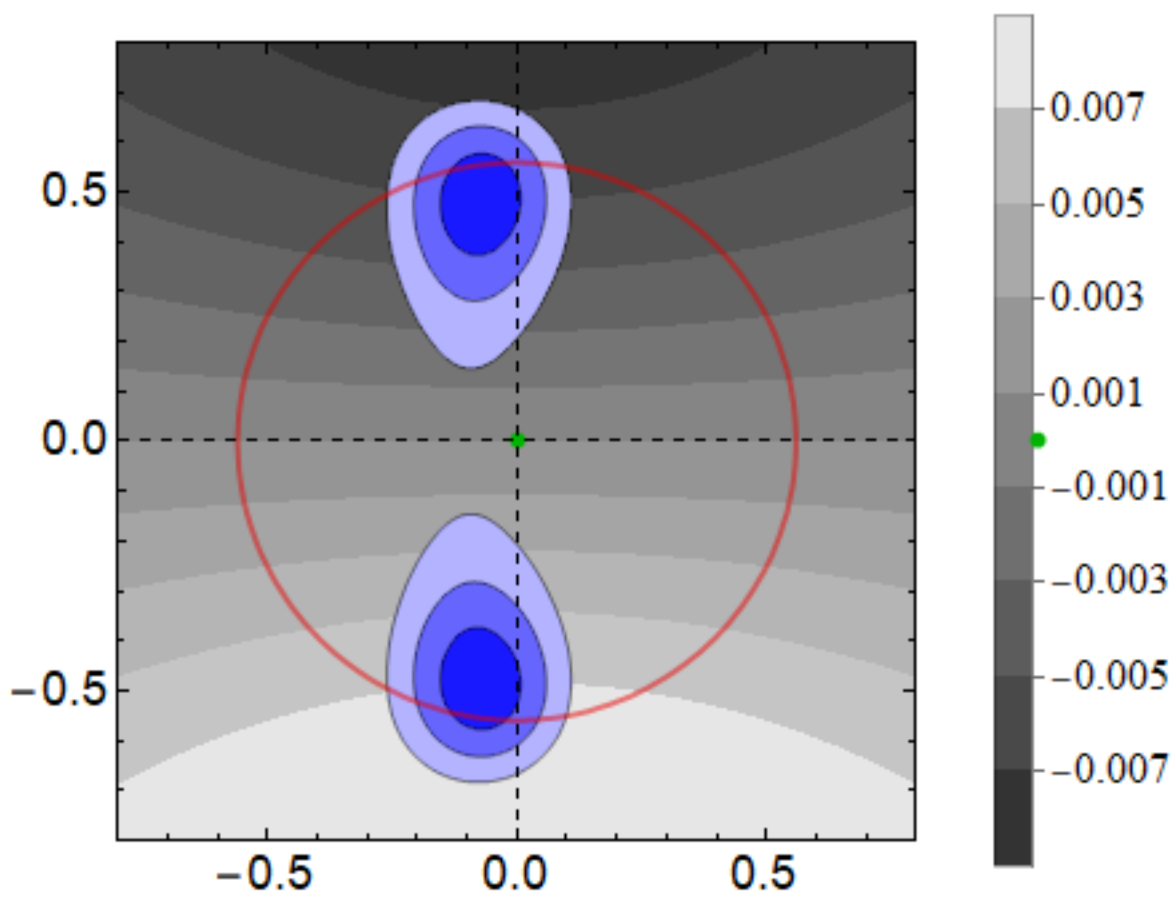
R_2

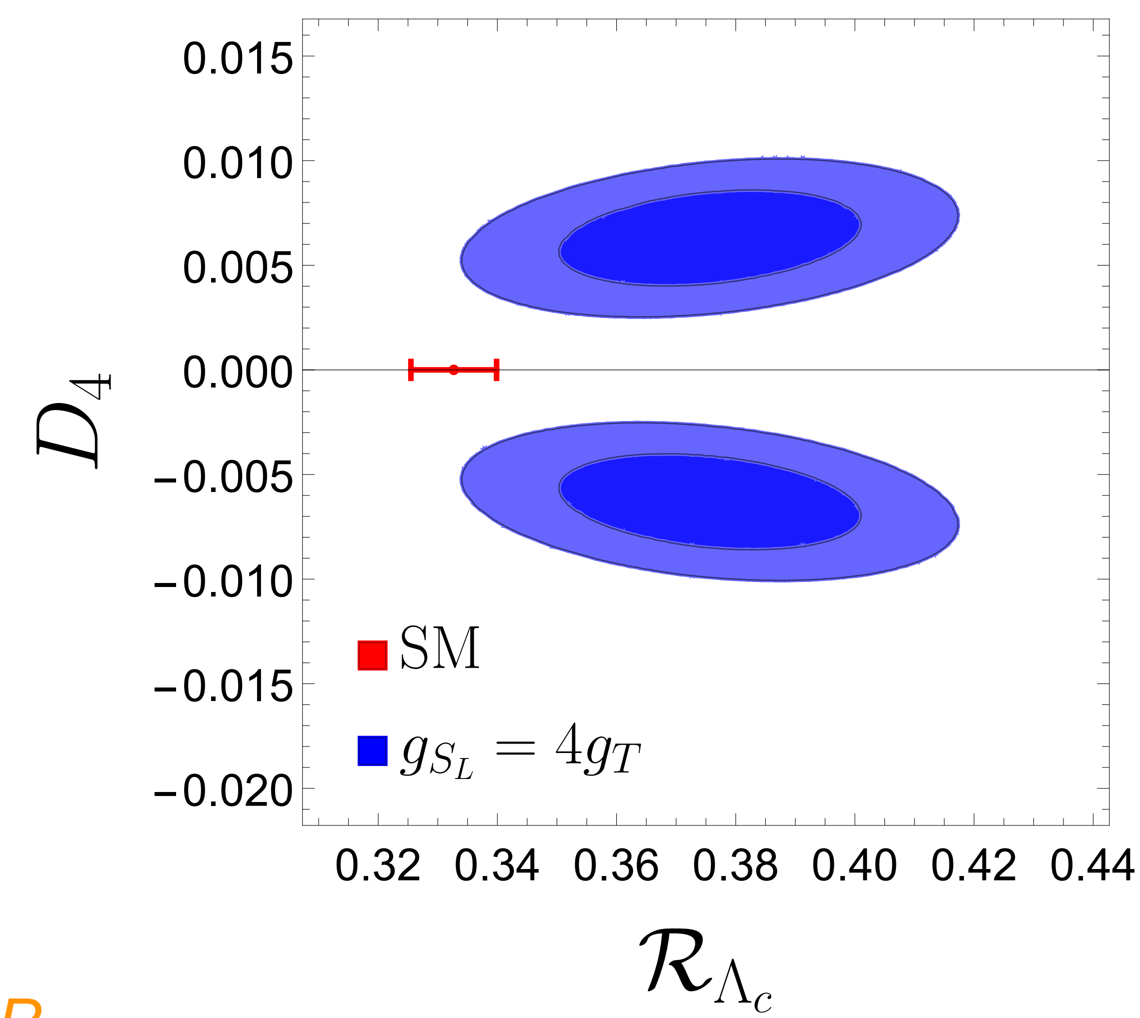
2209.13409

$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$

Many more angular observables and checking on Im[g_X] ≠ 0

$\langle D_4^\tau \rangle$

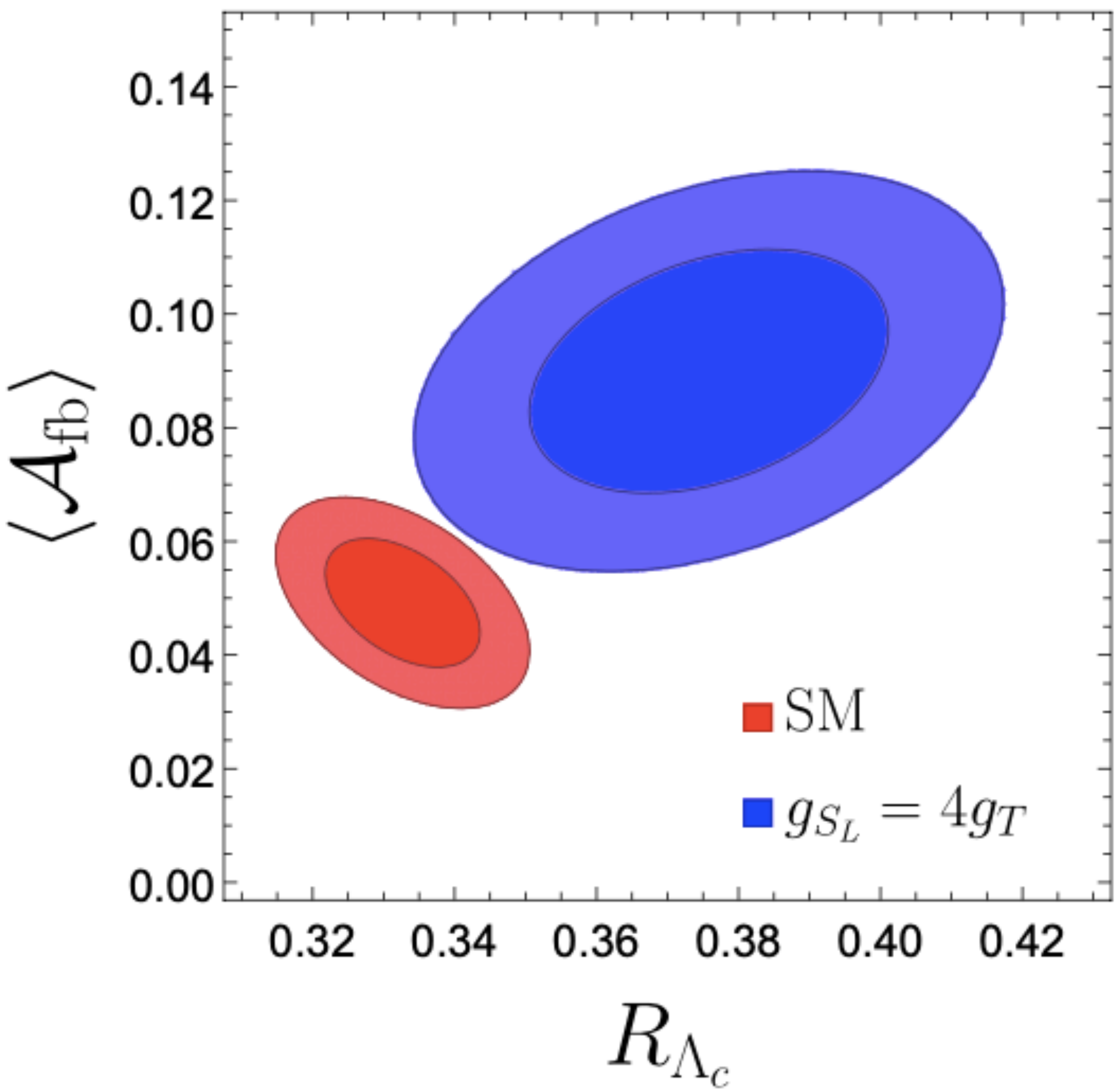


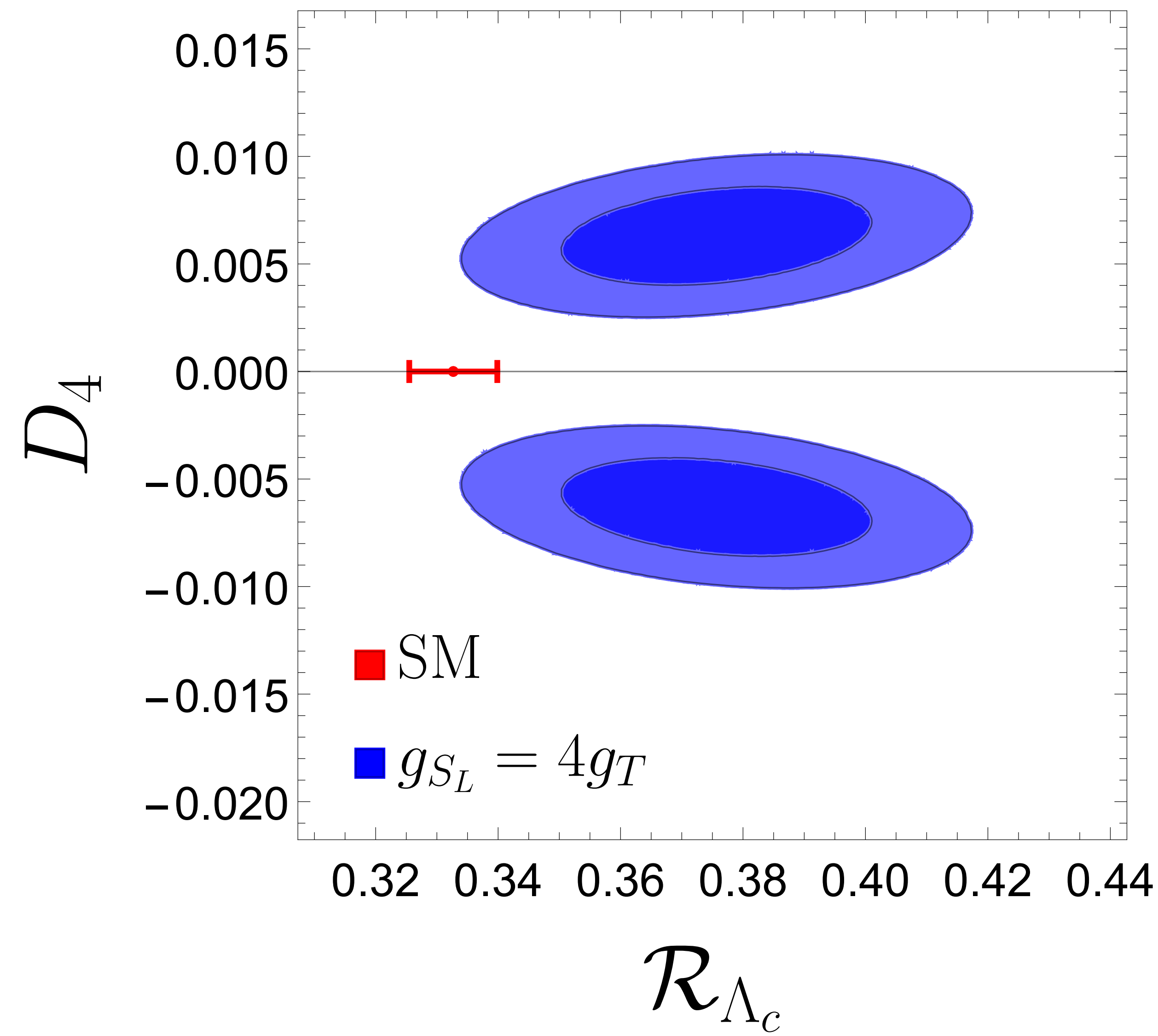


R_2

2209.13409

$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$



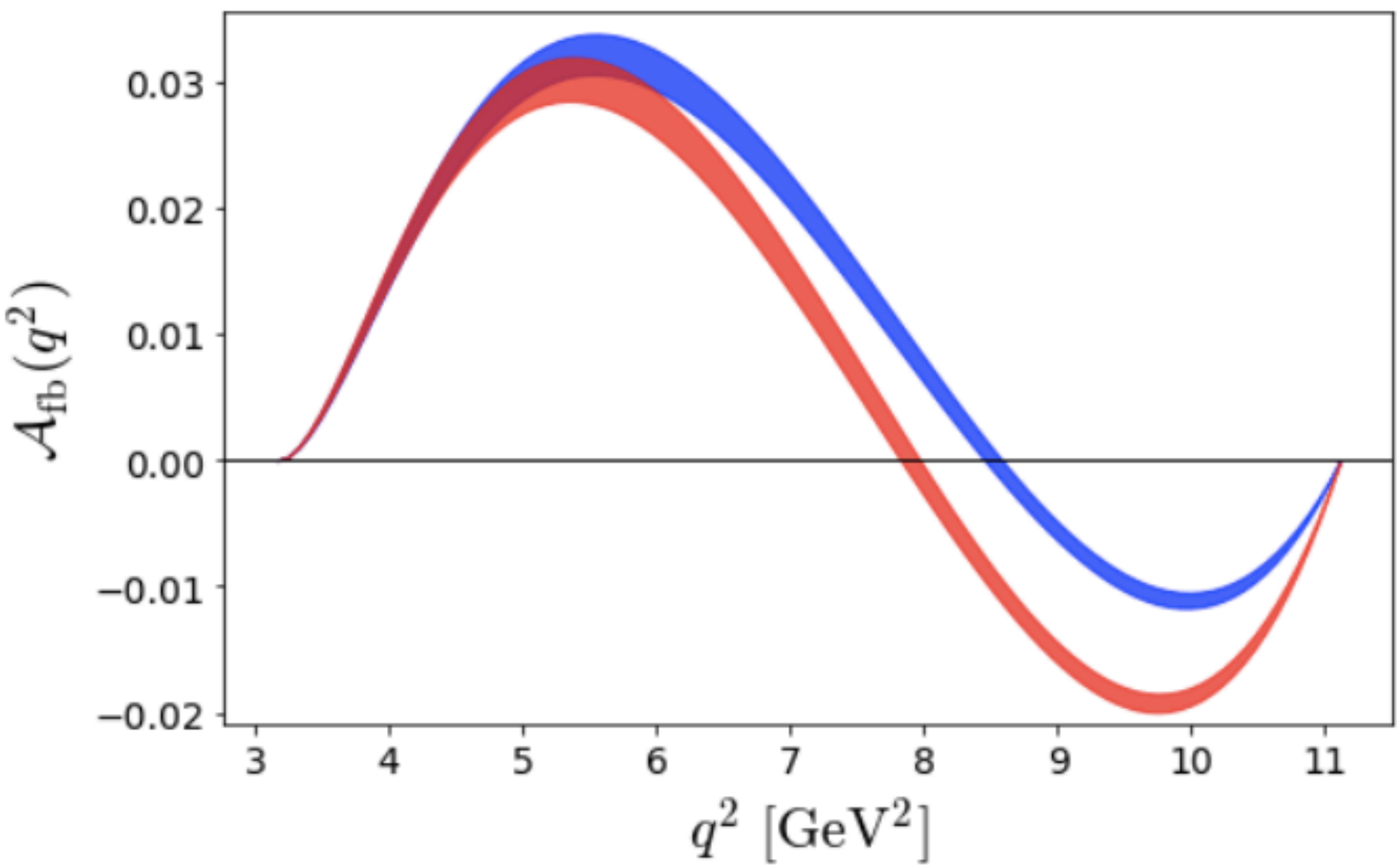


R_2

2209.13409

$$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$$

And there is also this…



R_2

CONCLUDING REMARKS

- Hadronic uncertainties are with us and one should always keep in mind that nonperturbative QCD is not solved.
- Results from various models and SR suffer from systematics that is next-to-impossible to estimate.
- LQCD is the only good way to go but the situation is unsatisfactory for a reliable fit with data to extract $|V_{cb}|$ and/or NP parameters.
- Exclusive V_{cb} should be checked on in several possible ways. [Sanity check and can be helpful for testing other ideas - e.g. factorization.]
- R_D and R_{D^*} are too few observables to understand the source of LFUV. Too many NP solutions exist and could be filtered by angular $B \to D^{(*)} \tau \nu$ and $\Lambda_b \to \Lambda_c \tau \nu$ observables. Should revisit $B \to D^{(*)} \ell \nu$ too.
- All of the $\Lambda_b \to \Lambda_c \ell \nu$ form factors are known from LQCD in SM and BSM. LHCb showed it is possible to measure $\mathcal{B}(\Lambda_b \to \Lambda_c \tau \nu)$. A partial angular is doable.
- There are 18 observables that can be extracted from $\Lambda_b \to \Lambda_c (\to \Lambda \pi) \tau \nu$. Even a small subset would be very helpful to discriminate among various scenarios.
- There are observables allowing to check whether or not there is a nonzero NP phase!