Exclusive b→ c $\ell\nu$ modes as windows to New Physics

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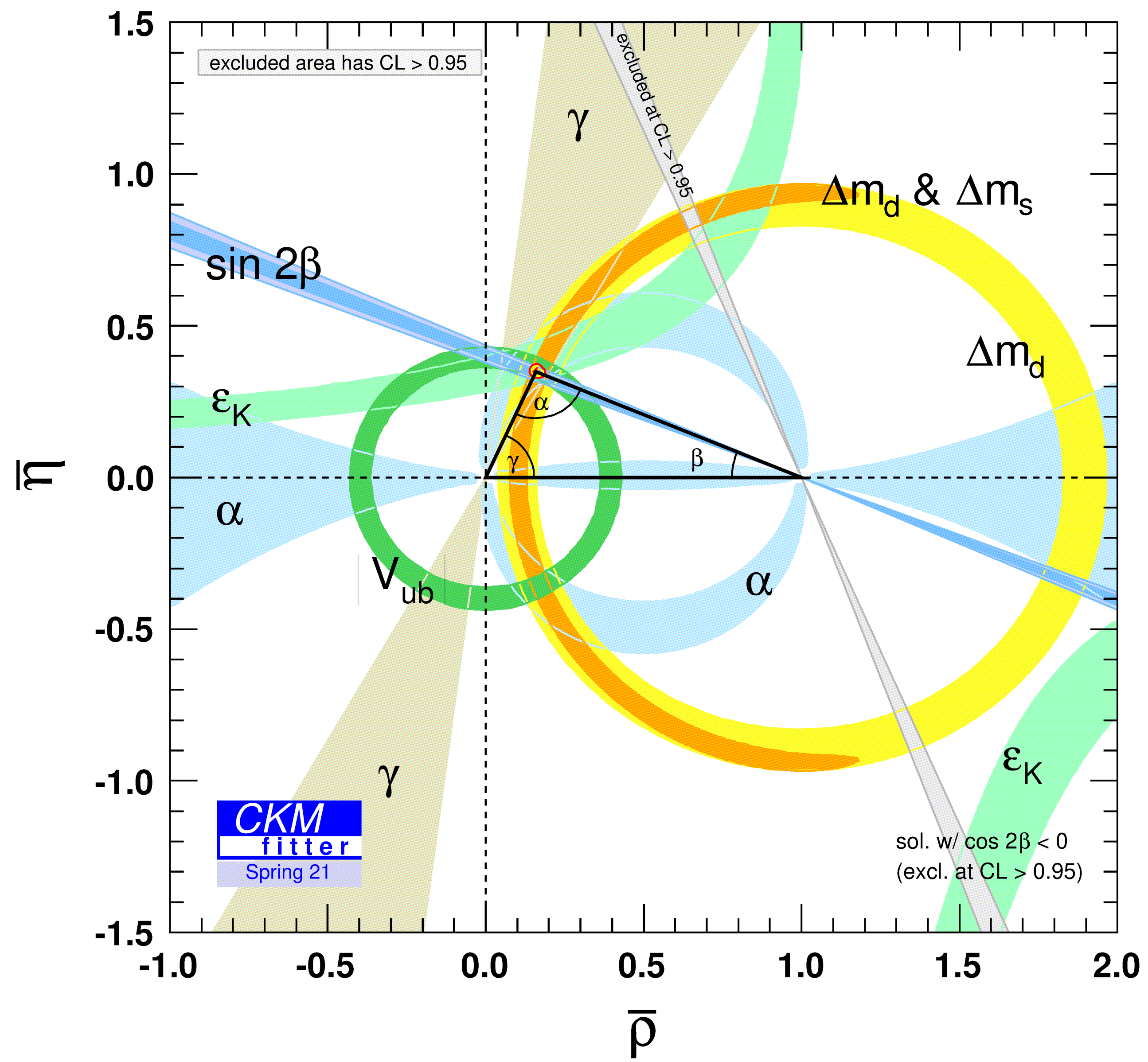
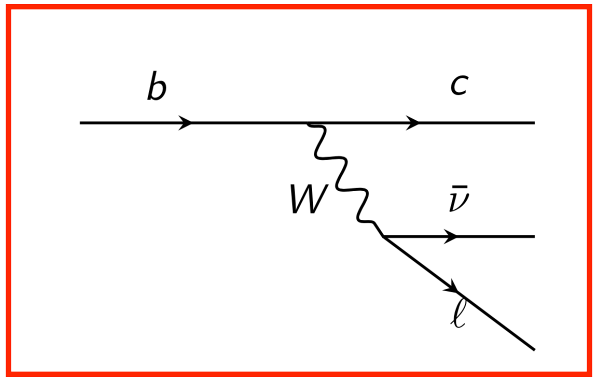
based on works with F. Jaffredo, A. Le Yaouanc, and O. Sumensari

CKM-ology

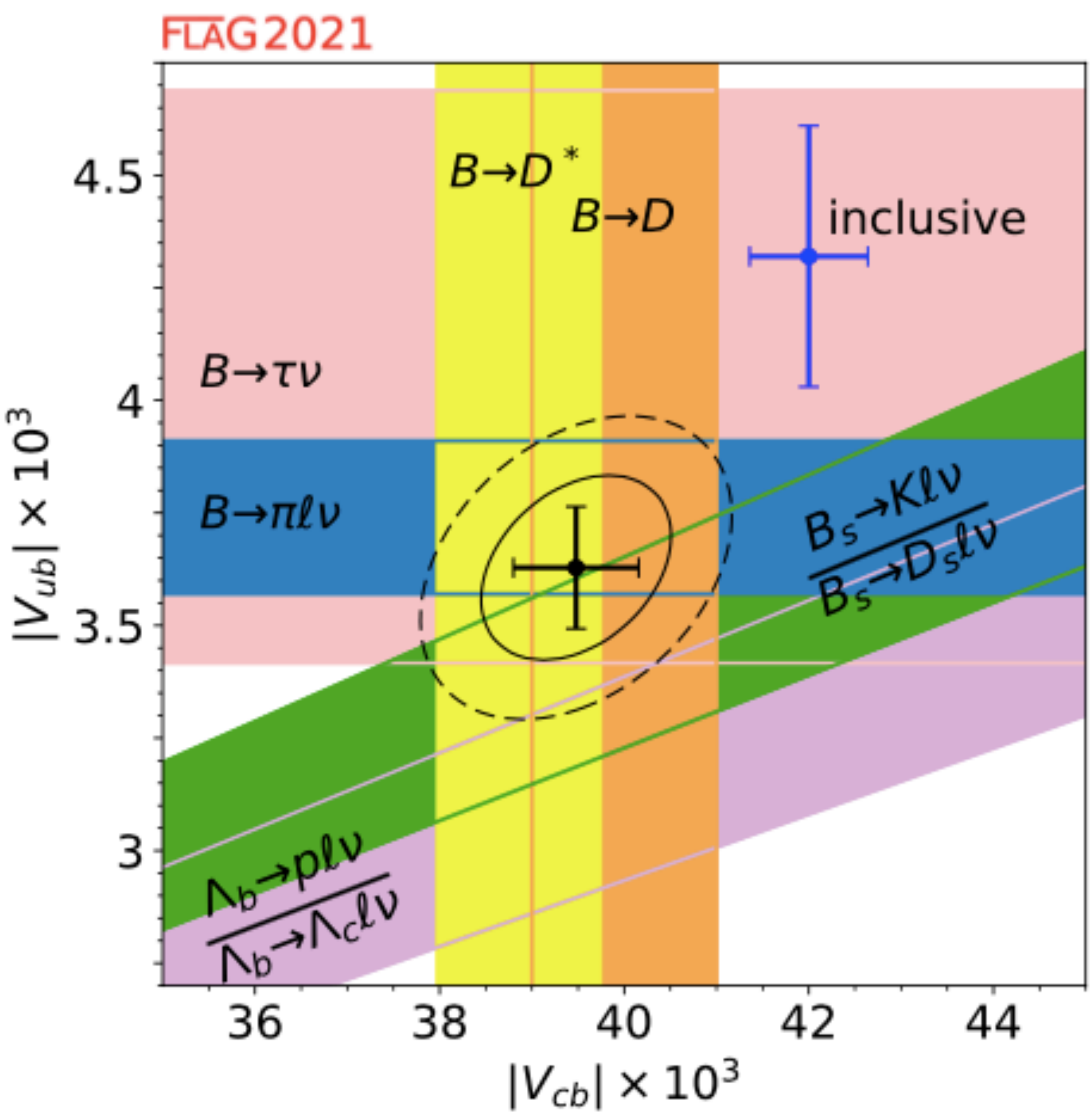


- ✘ Still open: inclusive v exclusive V_{ub} and V_{cb}? Is V_{ud} well controlled? V_{us} keeps coming back (EM)…



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*
- ✘ *New:* B → D* at *non-zero recoil*

2111.09849

CKM-ology - Small flavor 'anomaly'

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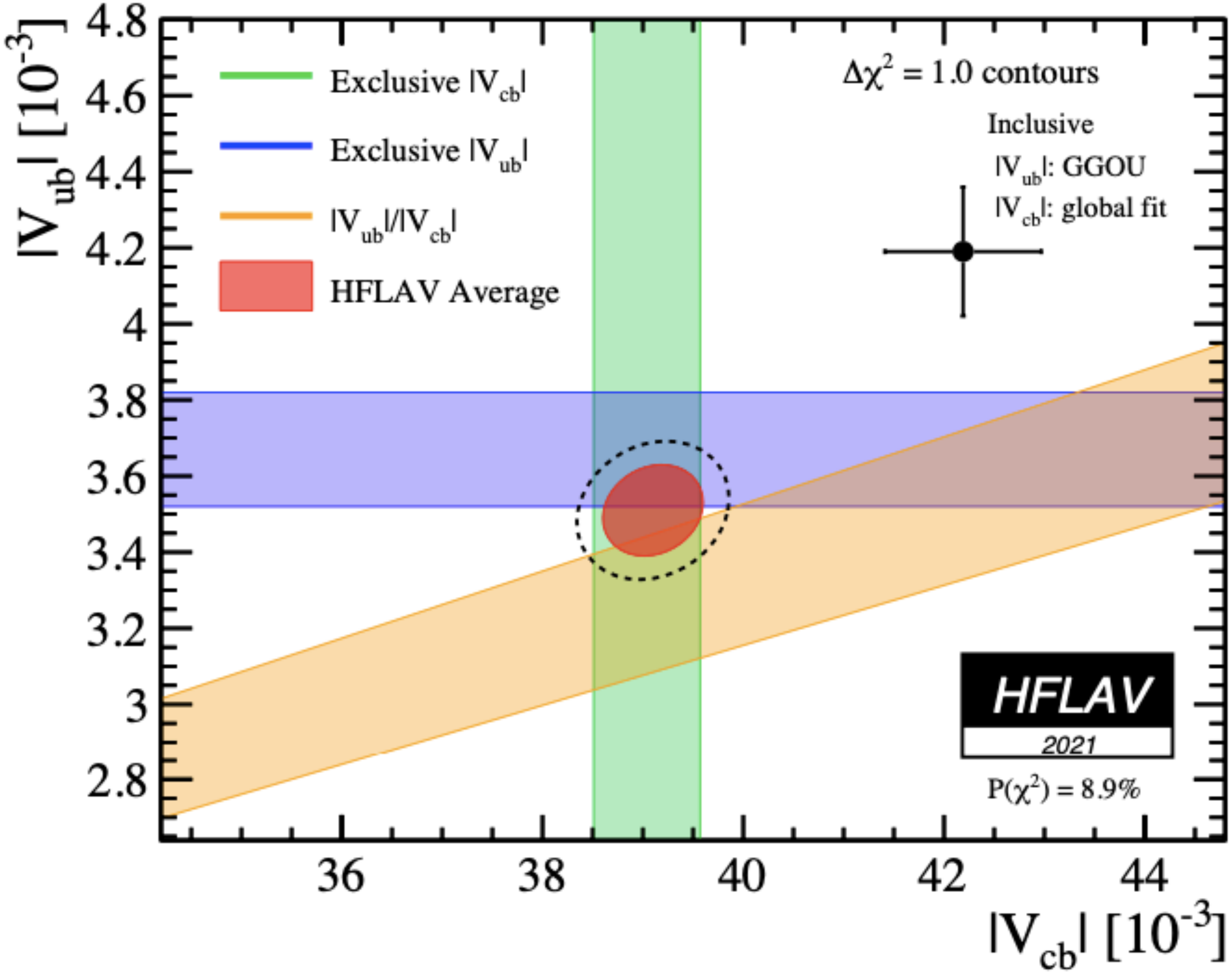
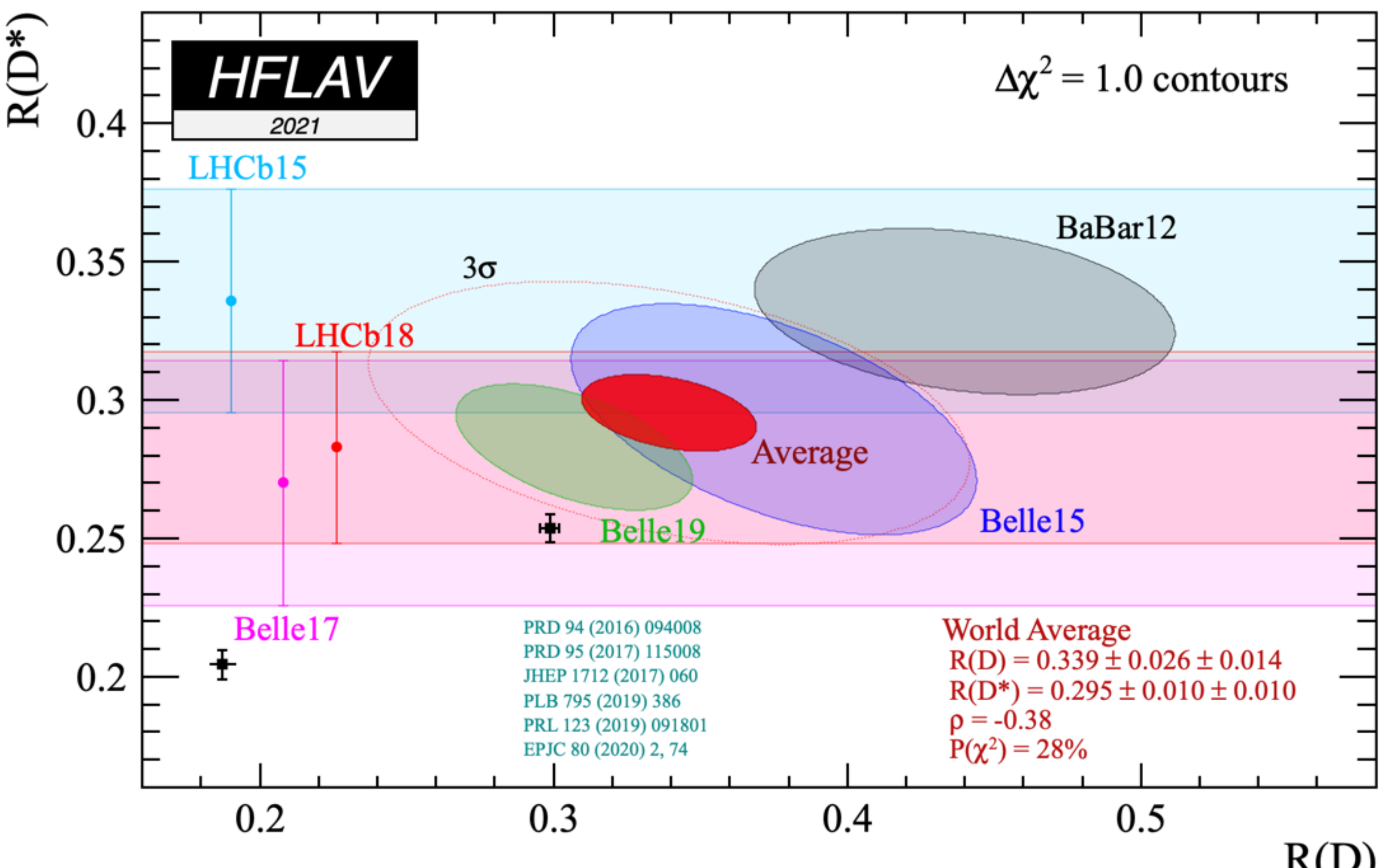


2206.07501

LFUV ['scare'] needs to study NP effects

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

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



LHCb

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

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

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

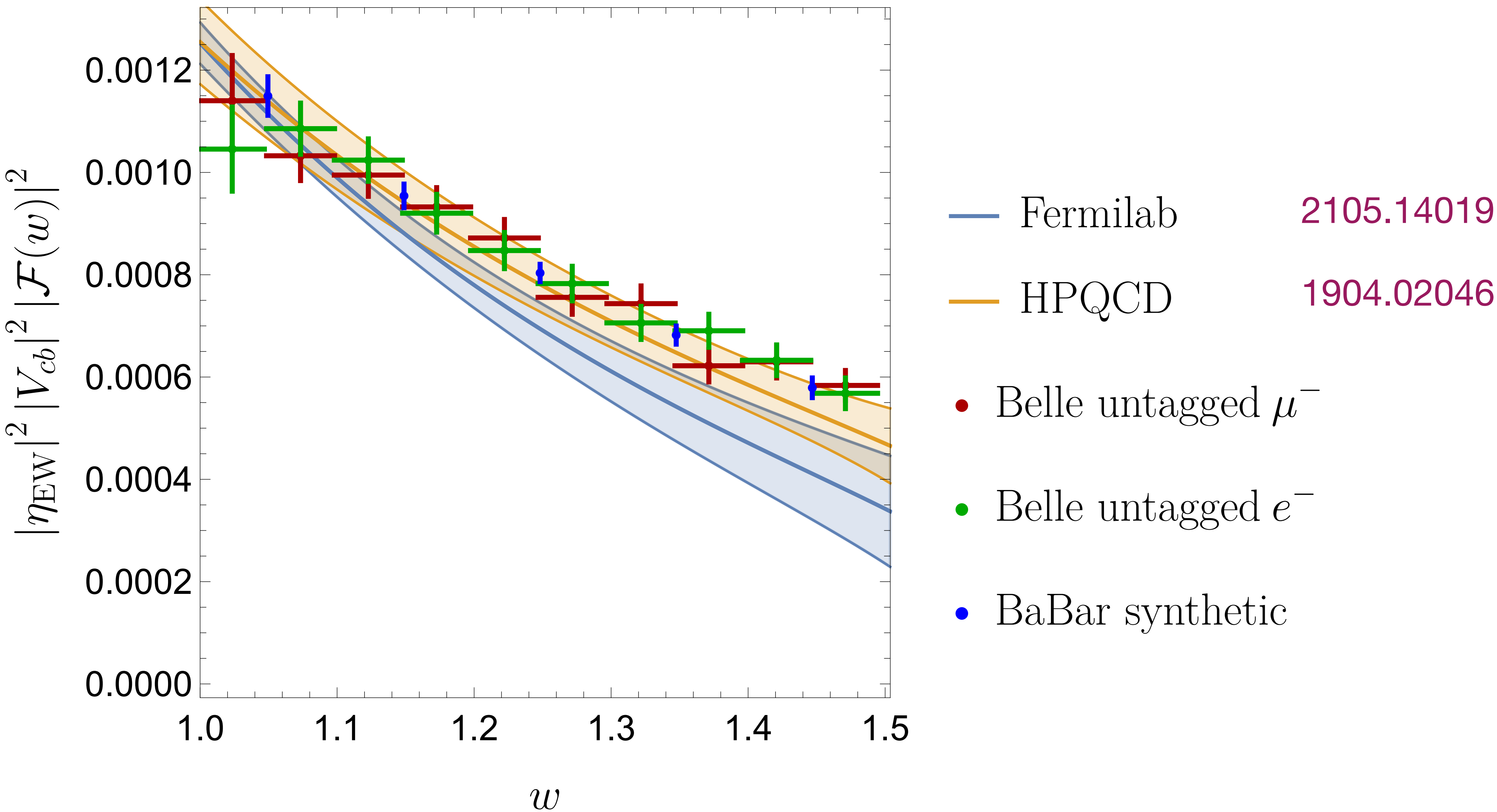
$$R^{\rm exp}_{\Lambda_c} \approx R^{\rm SM}_{\Lambda_c}$$

NEW and can be improved... a lot

2201.03497

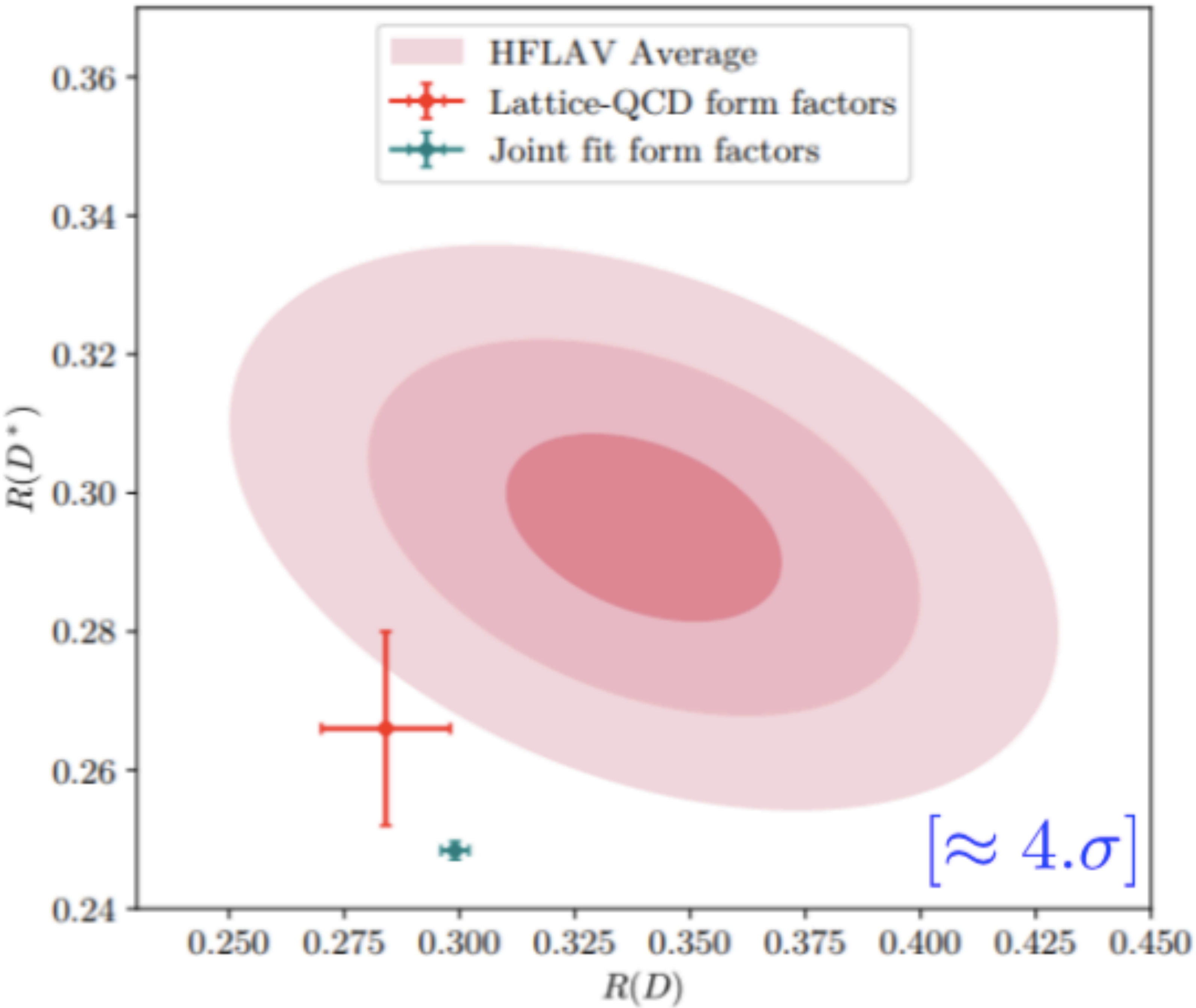
We still do not have a control over hadronic uncertainties

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



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

Warning!



2105.14019

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

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

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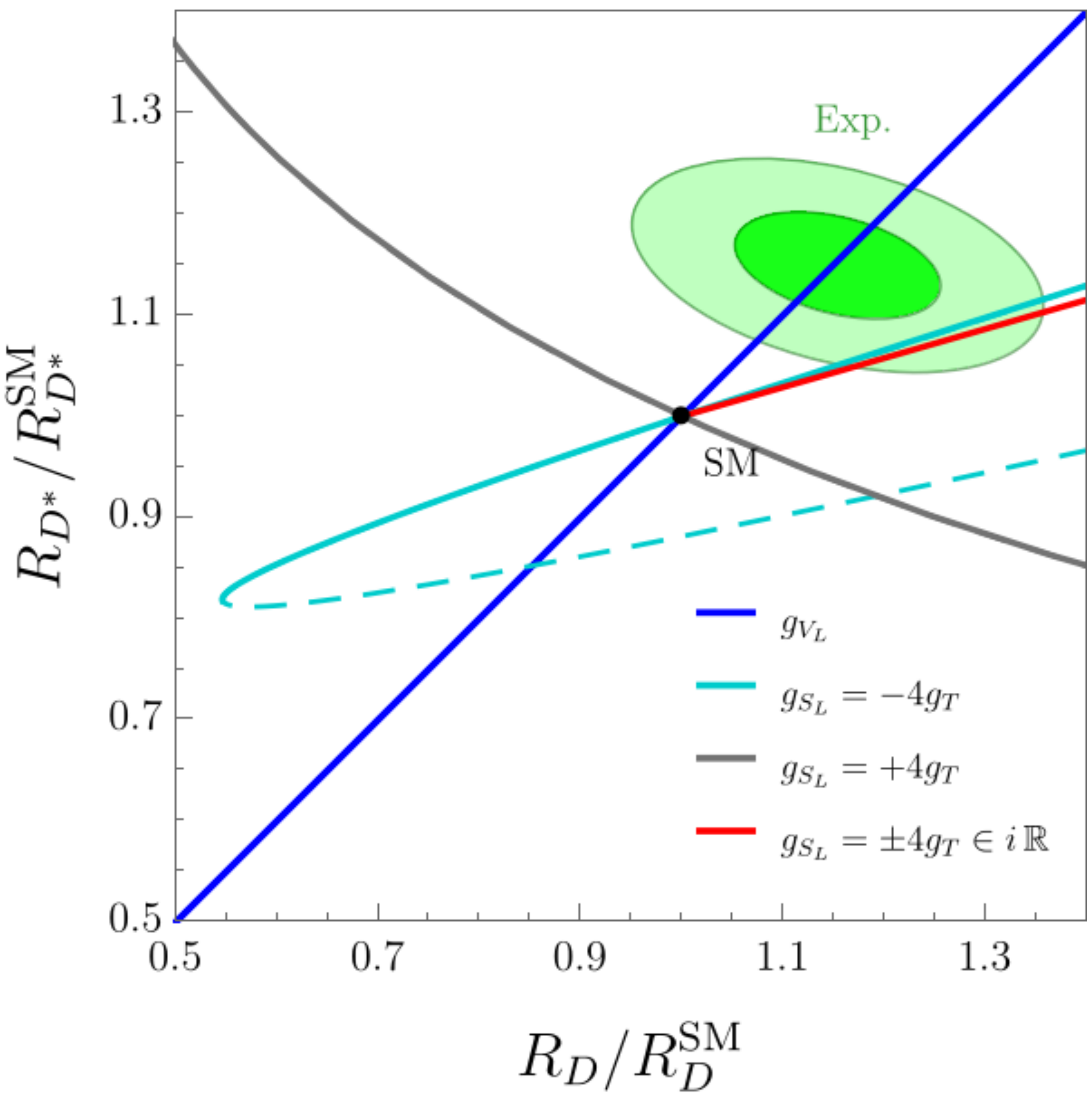

2103.12504

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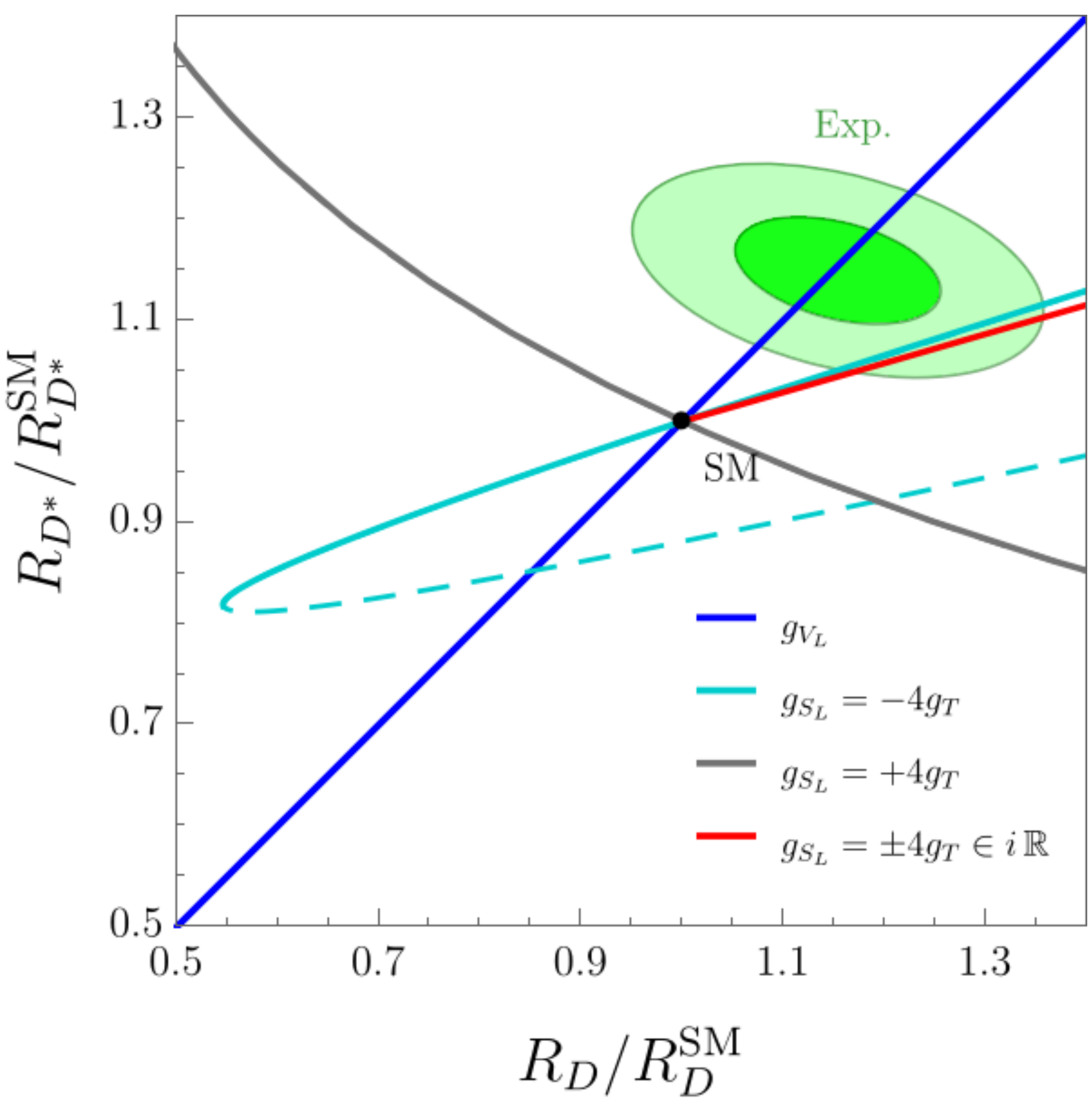


Need better data and more observables to discriminate among various possibilities.

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

Angular distributions can help!

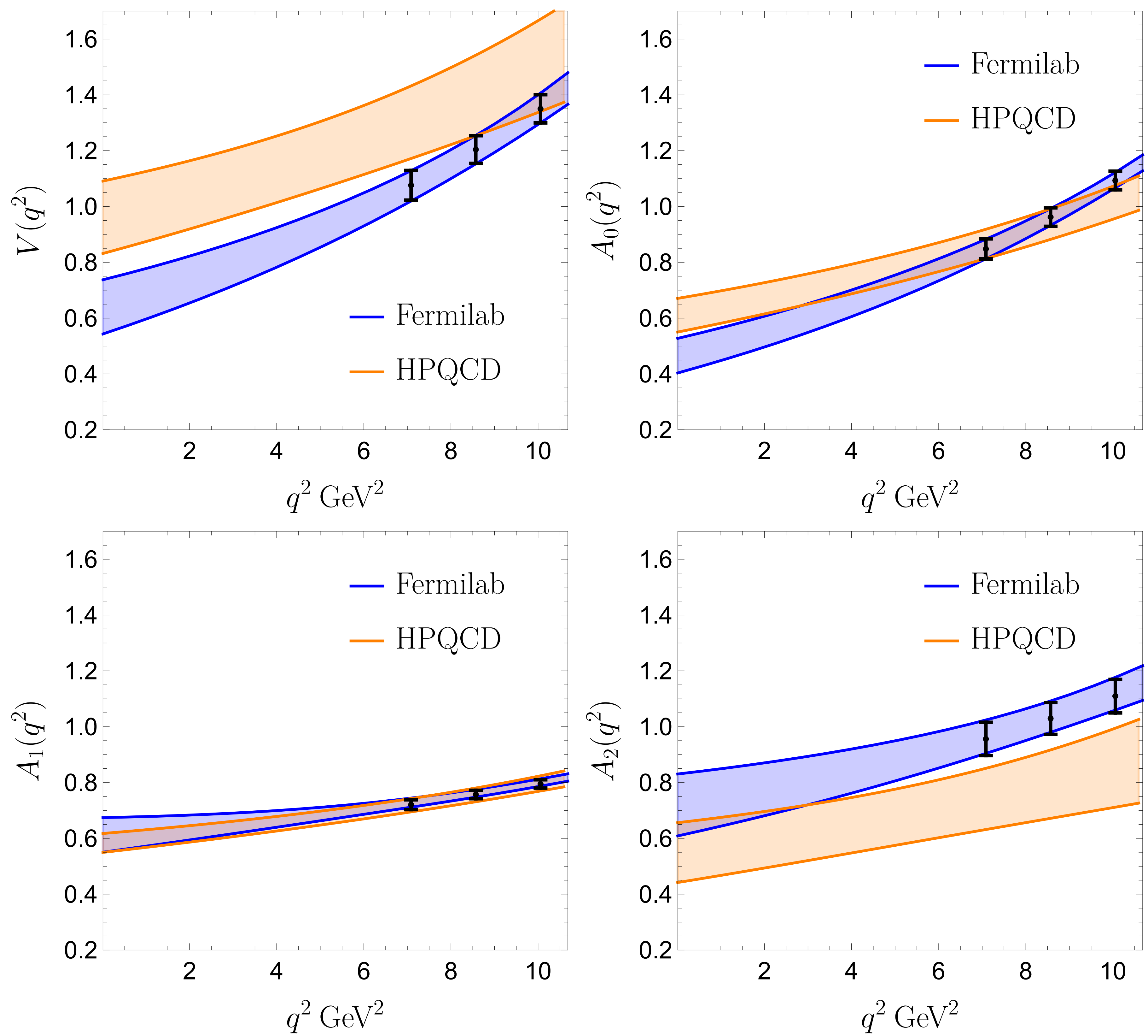
vast literature…

We still do not have a full 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	1904.02046	1503.01421
1505.03925	2105.14019	1702.02243

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



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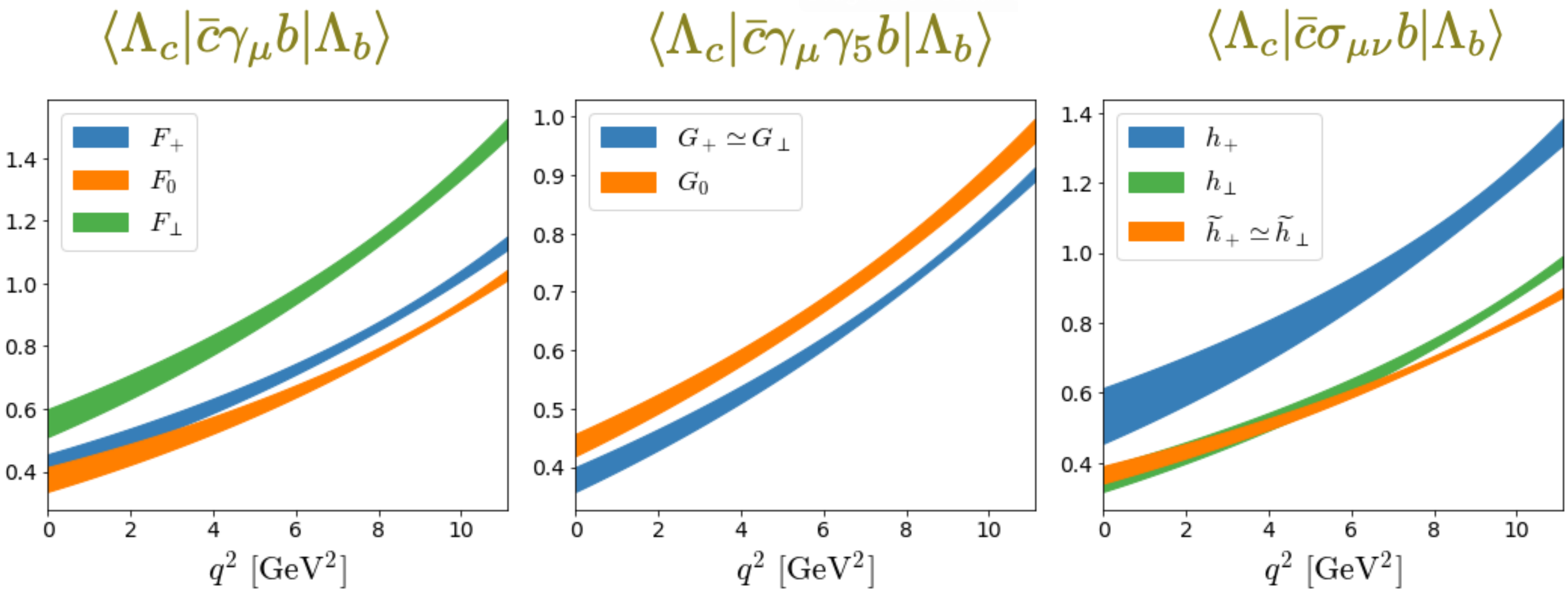
$\Lambda_b \to \Lambda_c \ell \bar{\nu}$



1503.01421

1702.02243

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

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

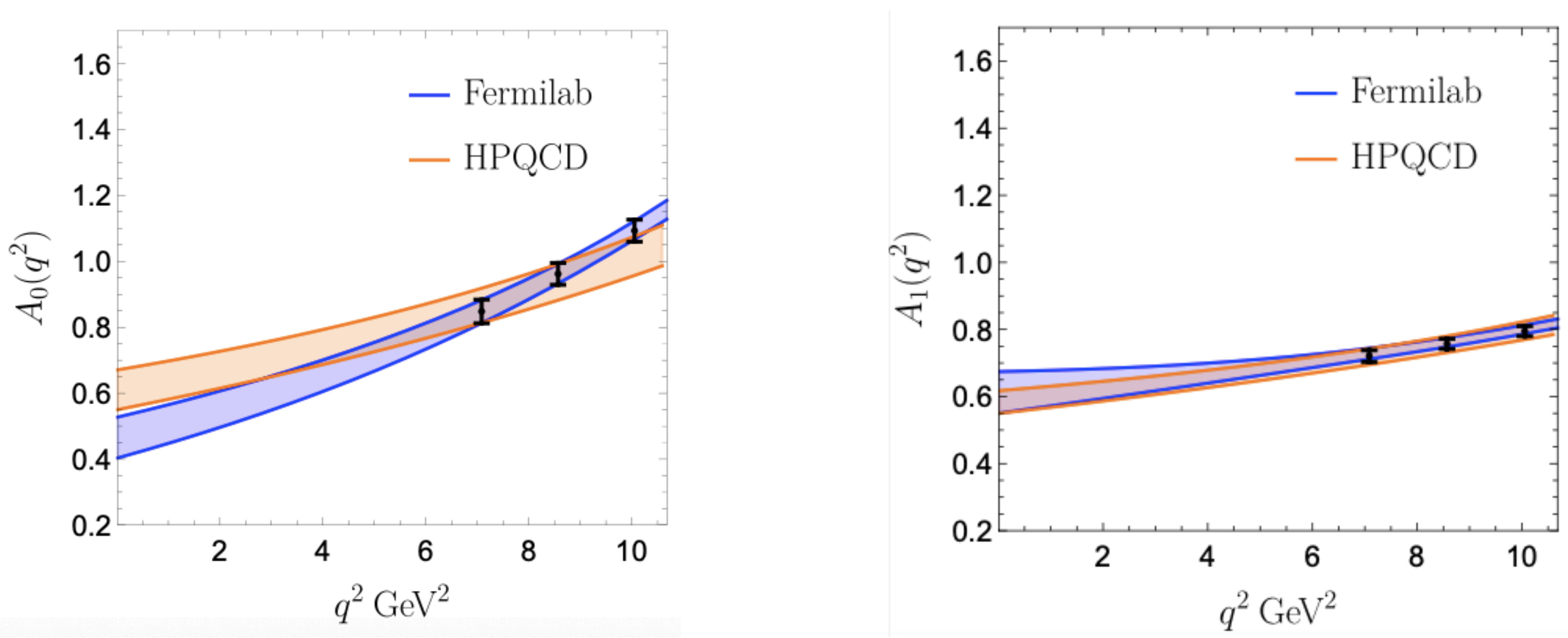
There is no canonical way/parametrization to extract $|V_{cb}|$.

Never forget that we need dynamical QCD information!
Try various options - to at least cross check!

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

Eg2. Try this:

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



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

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

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

$$\frac{A_0(0)}{A_1(0)}\bigg|_{\rm HFLAV}^{\rm CLN} = 1.087(14) \to \quad A_0(0) = 0.64(4)^{\rm FNAL}, 0.66(7)^{\rm HPQCD}, 0.79(22)^{\rm ``LCSR"}$$

- 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.

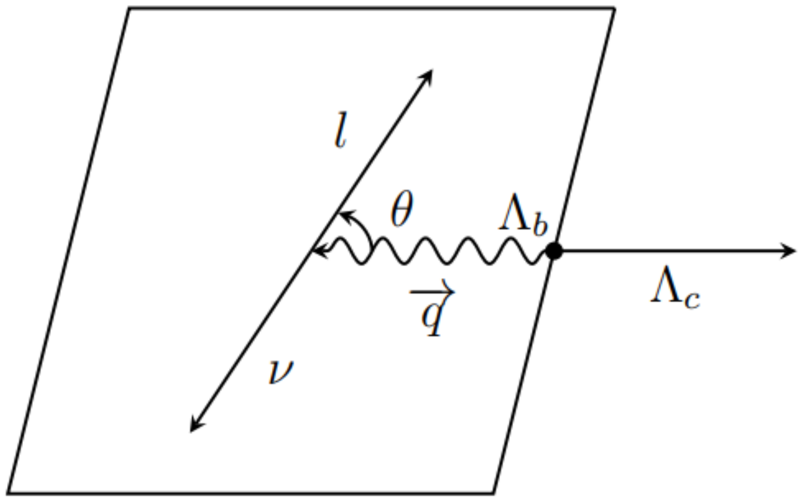
1904.02046

2105.14019

0809.0222

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:

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

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

12-2=10 observables

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.

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

1907.12554 1908.02328 1909.10769 1702.02243 1502.04864

Three powerful observables:

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

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

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

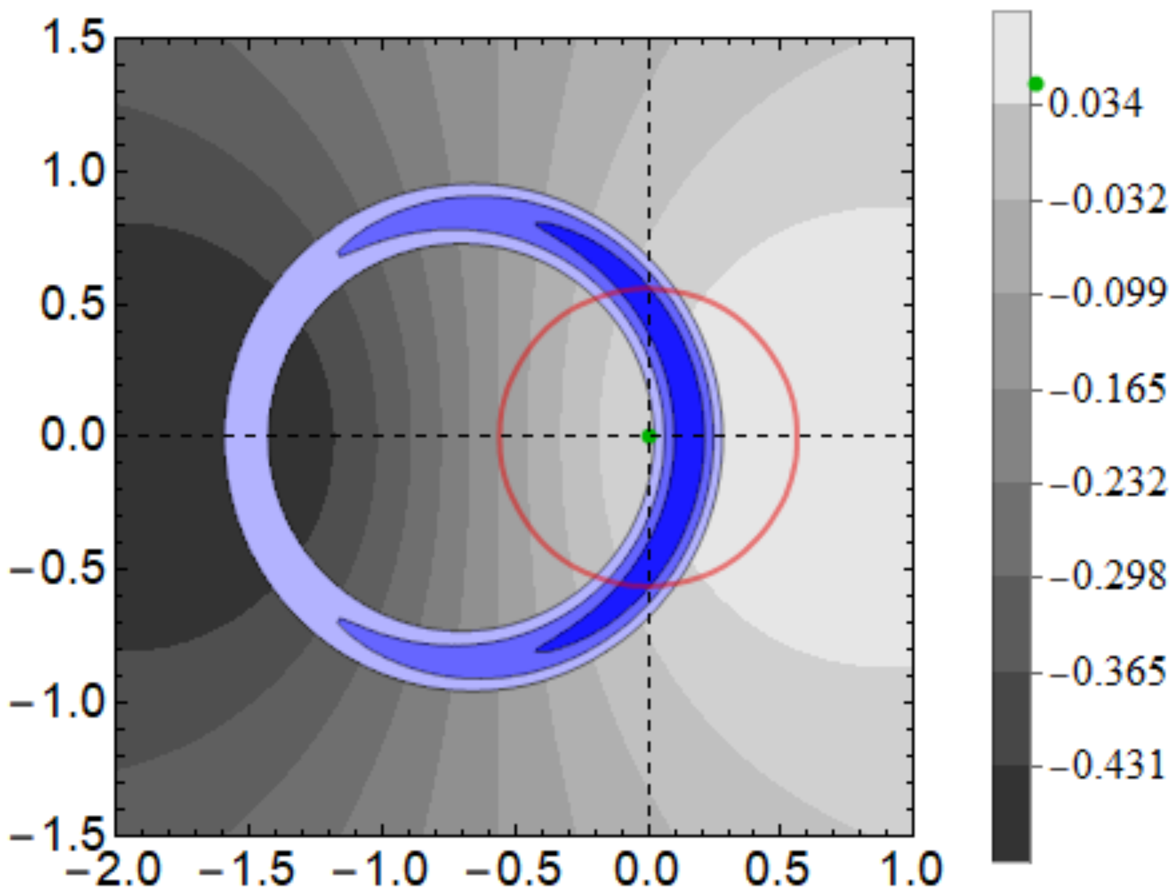
Examples:

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

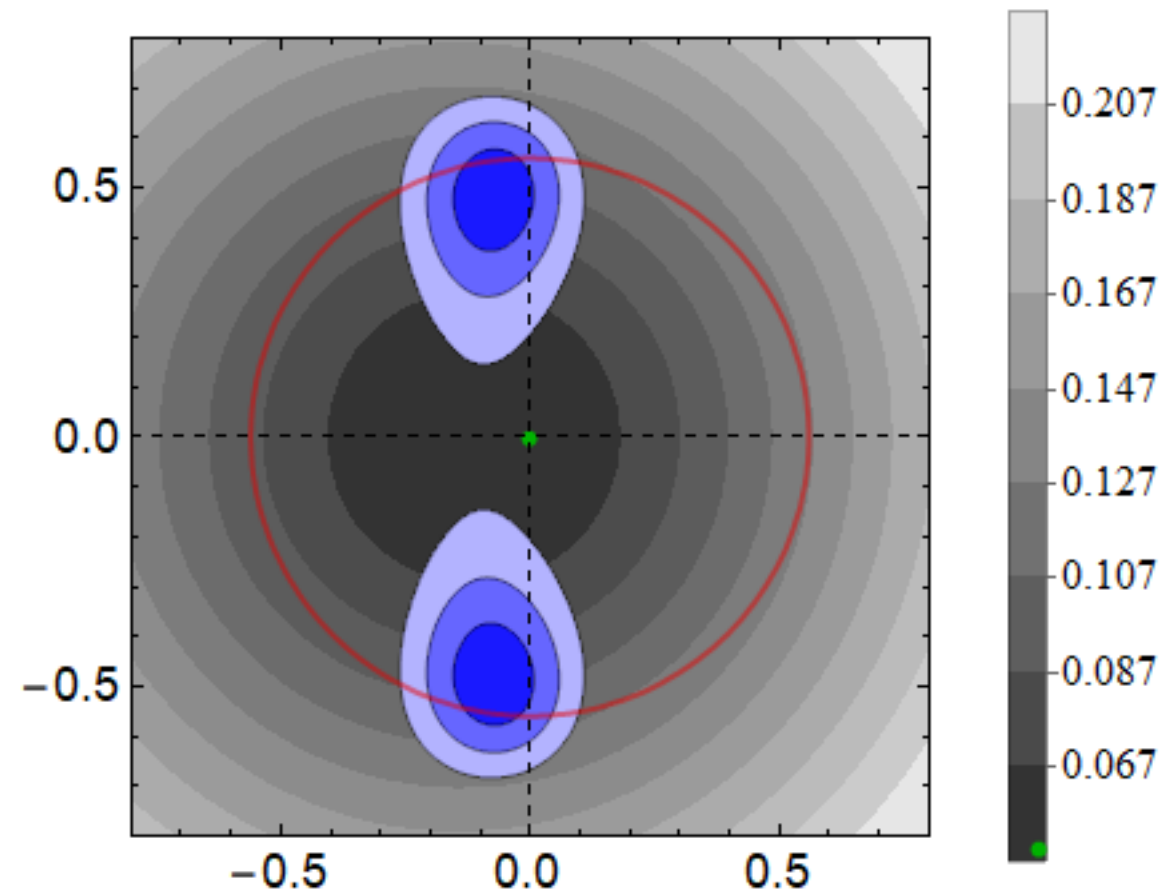
Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

Three powerful observables:

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



S_1

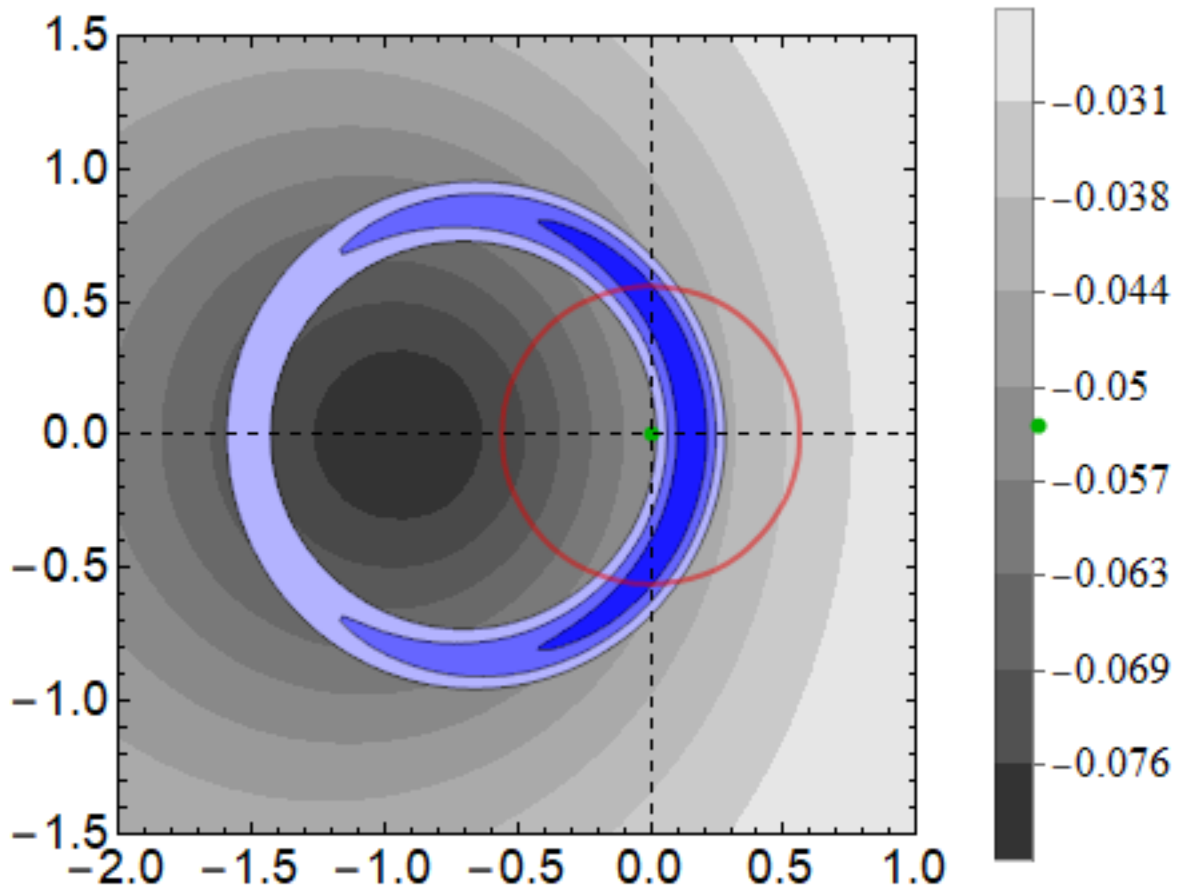


R_2

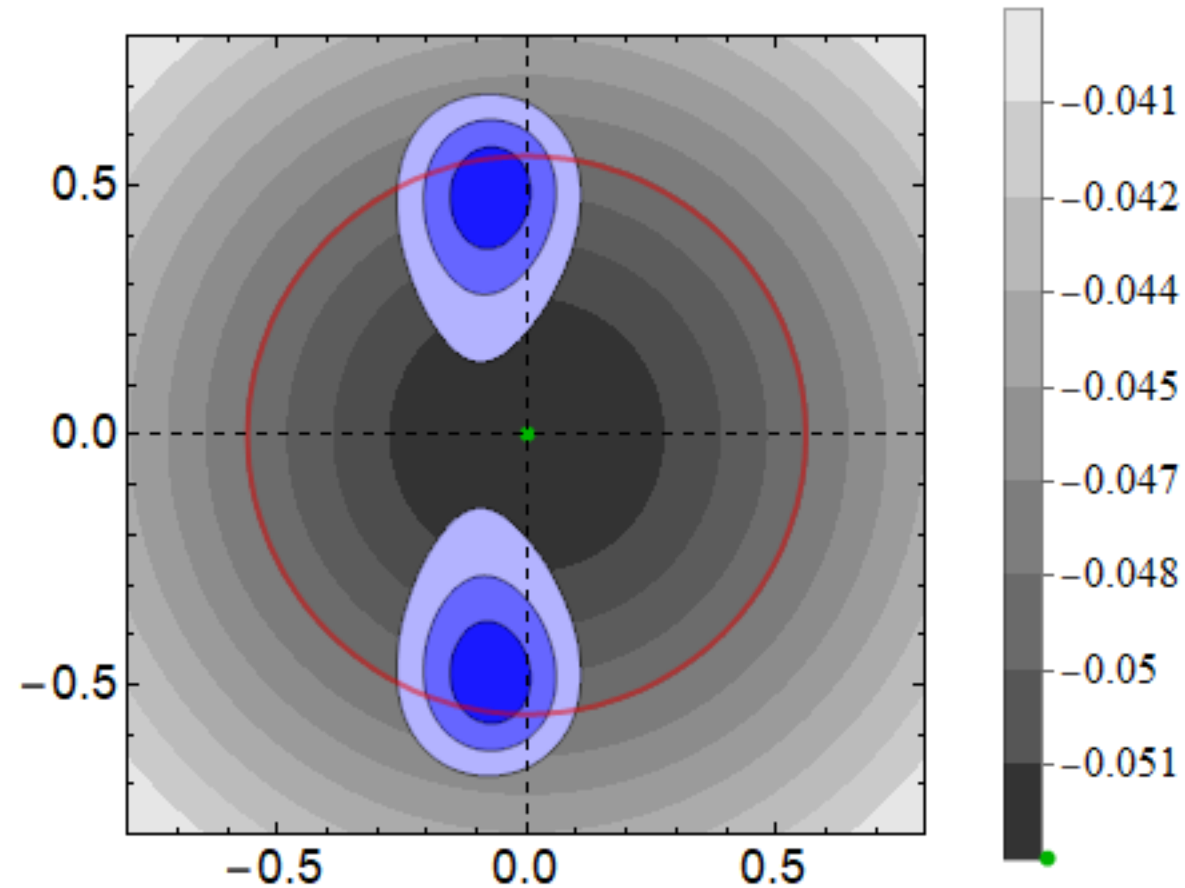
Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

Three powerful observables:

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



S_1

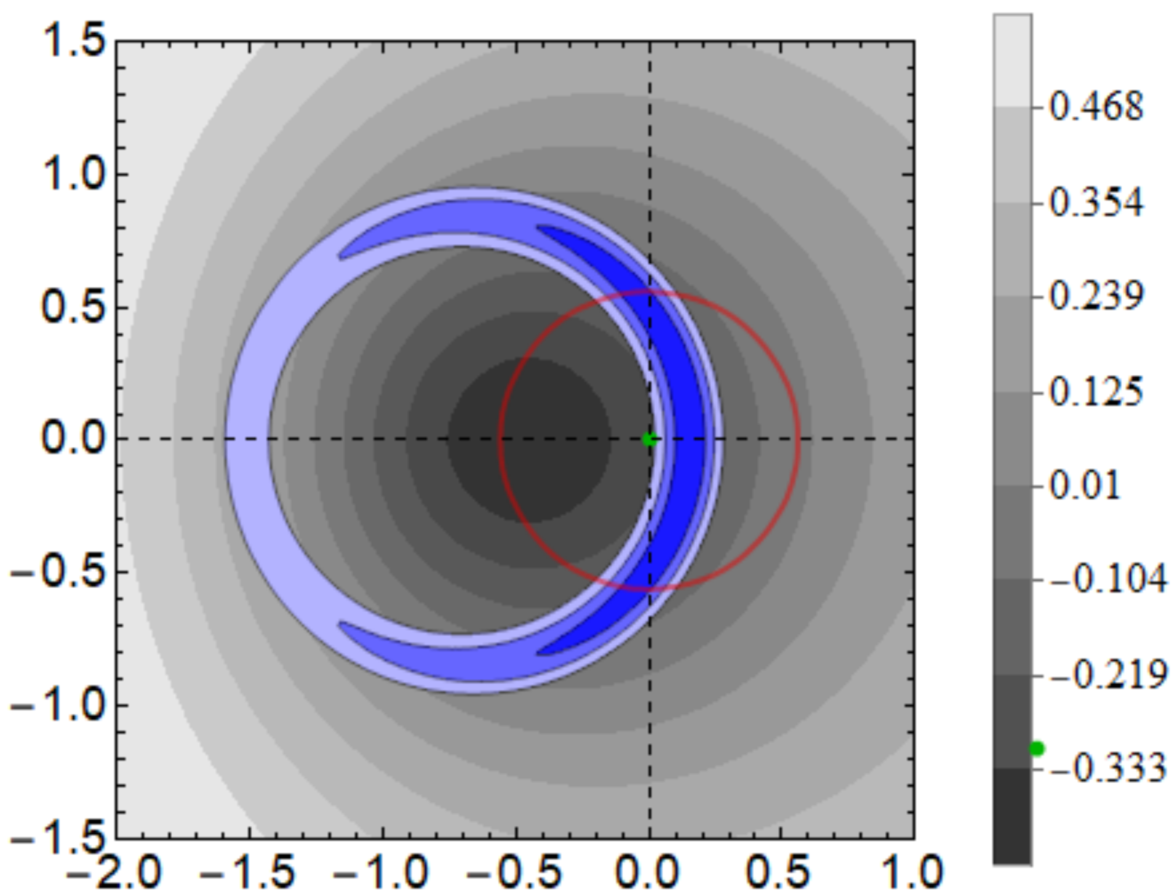


R_2

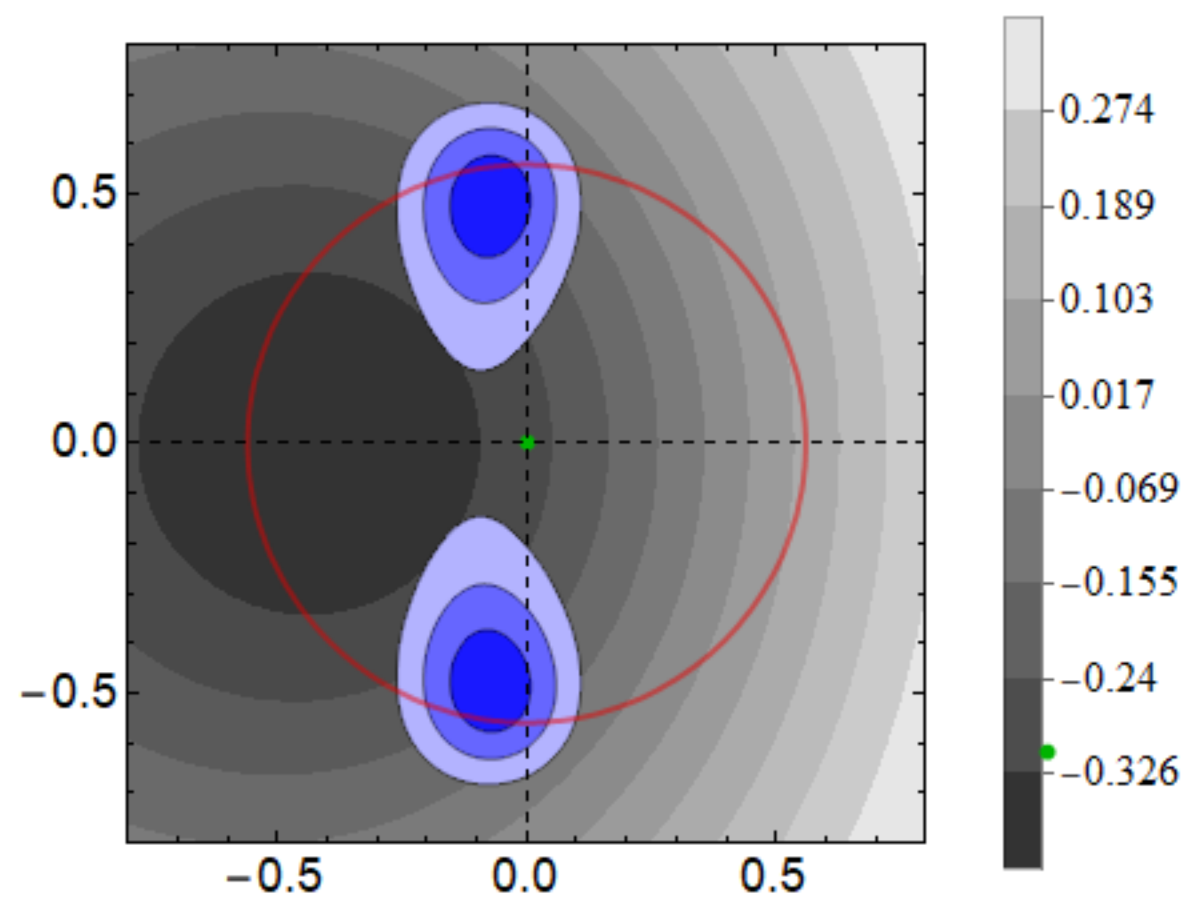
Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

Three powerful observables:

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



S_1



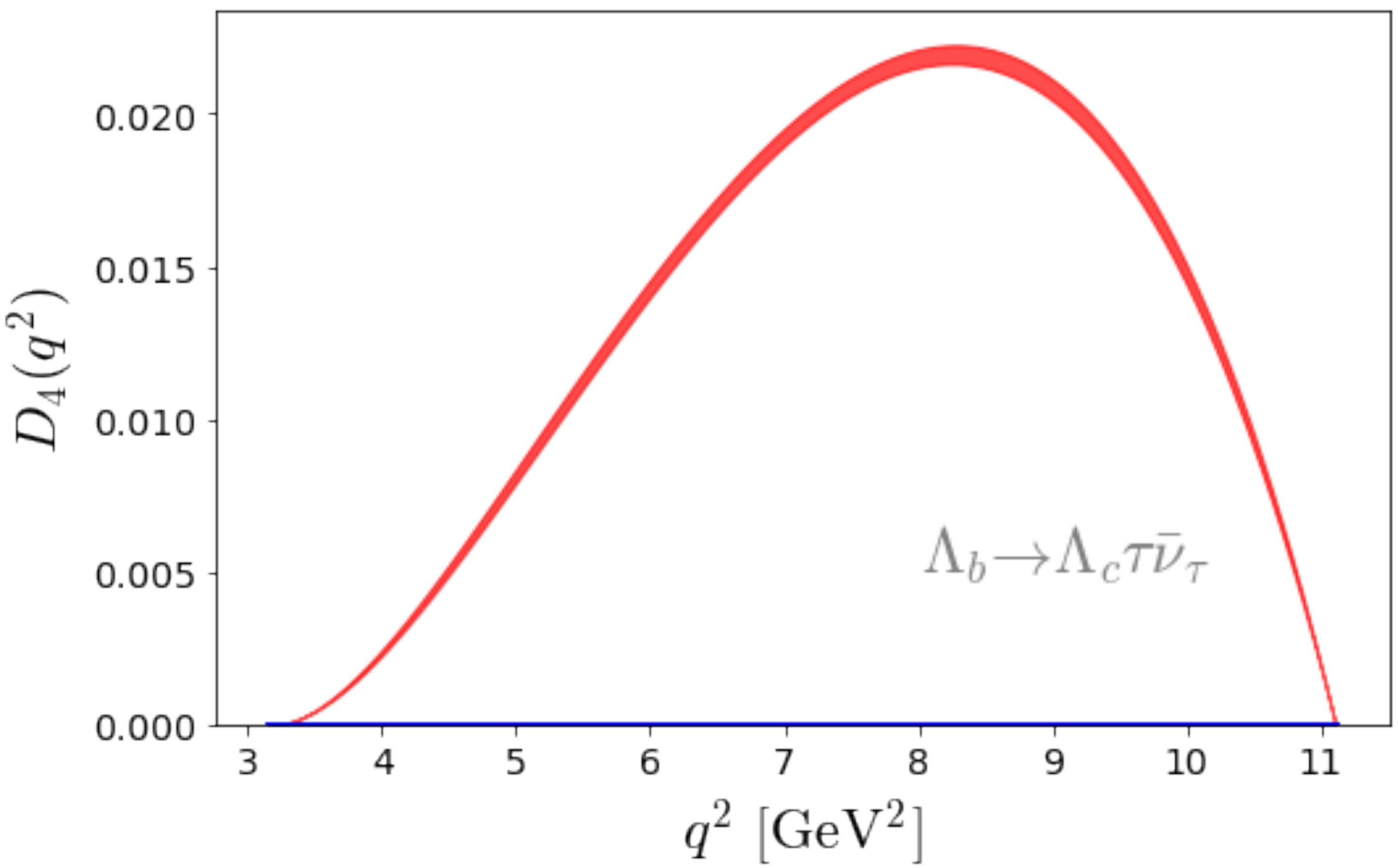
R_2

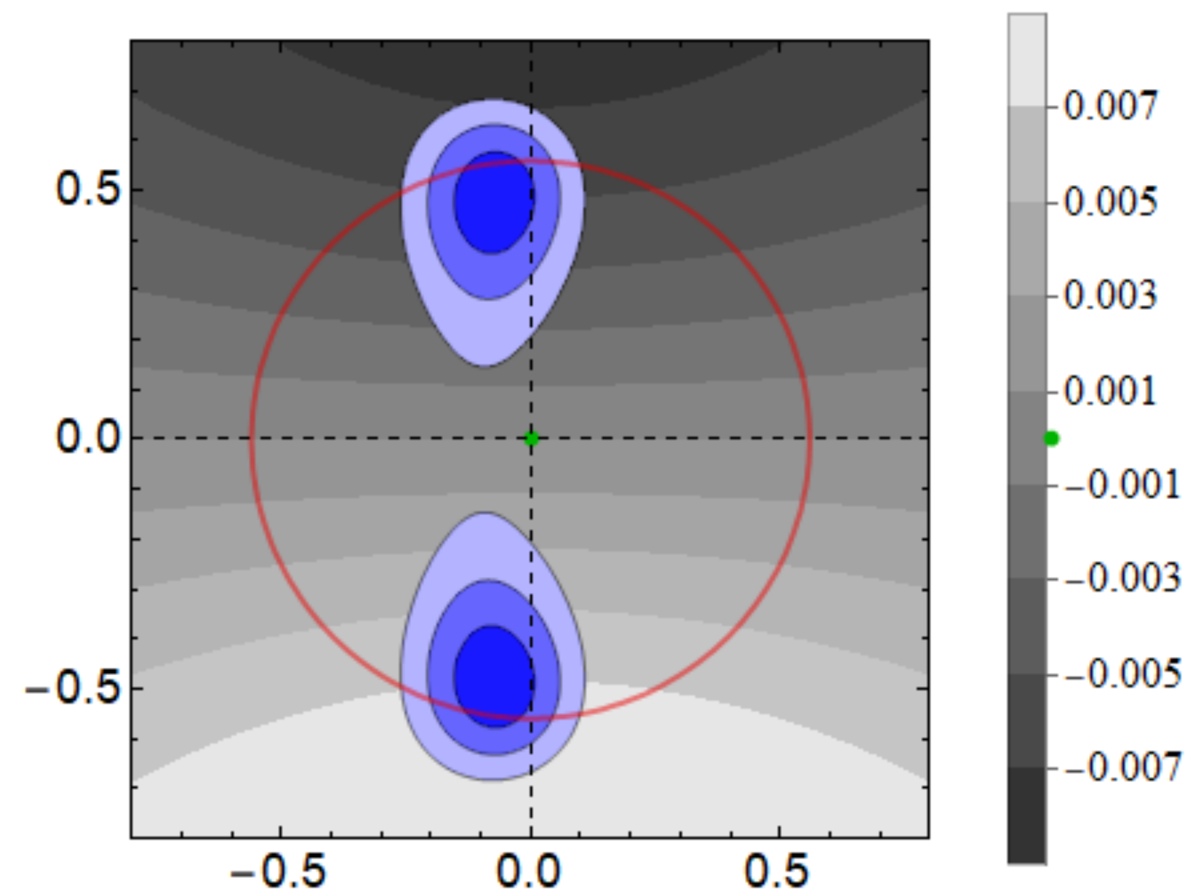
$\Lambda_b \longrightarrow \Lambda_c(\rightarrow \Lambda\pi)\ell\nu$

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

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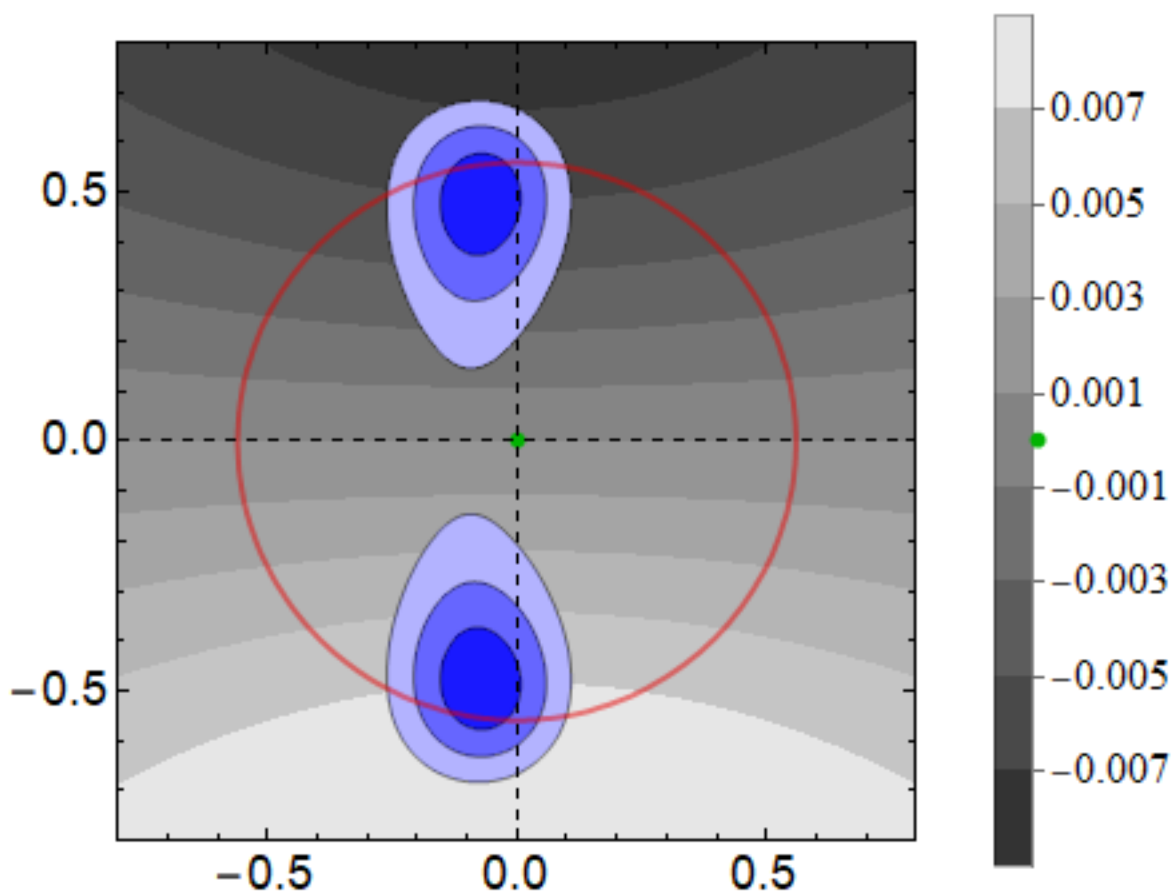
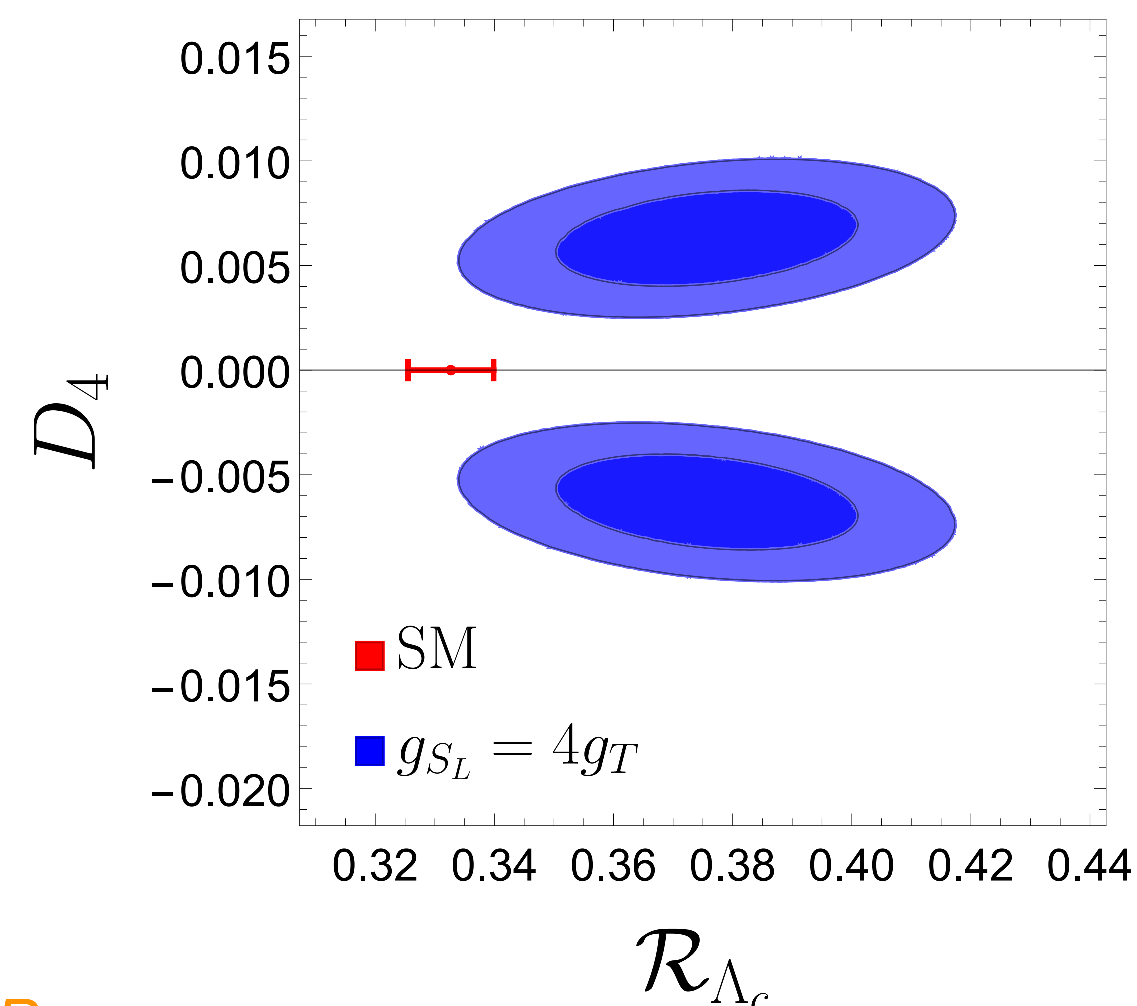
Many more angular observables and checking on Im[g_X] ≠ 0

$\langle D_4^\tau \rangle$





R_2

CONCLUDING REMARKS

- Hadronic uncertainties are with us and one should always keep in mind that nonperturbative QCD is <u>not</u> solved.
- Results from various models and SR suffer from systematics that is often next-to-impossible to estimate [reliably].
- LQCD is the only good way to go but the situation is still unsatisfactory for a reliable fit with data to extract $|V_{cb}|$ and NP parameters.
- Exclusive V_{cb} should be checked on in several possible ways. Sanity check that can be helpful for testing other ideas.
- 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.
- All of the $\Lambda_b \to \Lambda_c \ell \nu$ form factors are known from LQCD in SM and BSM. LHCb showed it possible to measure $B(\Lambda_b \to \Lambda_c \tau\nu)$. Can we hope to see an [partial] angular analysis?
- There are 38 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!