Inclusive Semileptonic Heavy Baryon Decays:

New Results and Perspectives

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Anomalies 2021

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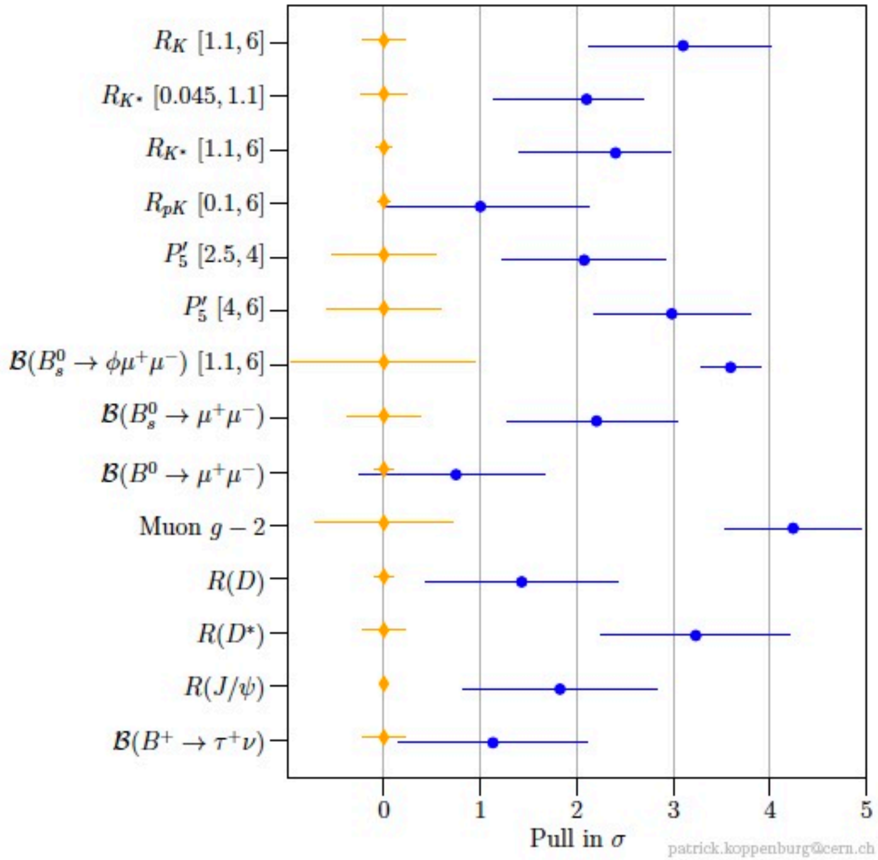
Fulvia De Fazio, Francesco Loparco, PC

Inclusive Semileptonic Λ_b Decays in the Standard Model and Beyond

JHEP 11 (2020) 032 , arXiv:2006.13759

Emerging anomalies in the flavour sector



Emerging anomalies in the flavour sector

New Physics revealed in low-energy experiments through

1) deviations of SM allowed processes with respect to the predictions
   - tree level processes $R(D^{(*)})$ & co
   - loop-induced processes $R(K^{(*)})$, P'_5, …
   - V_{cb}, V_{ub}, ε'/ε, $(g-2)_\mu$…

2) observations of processes forbidden (or heavily suppressed) in SM
   - LFV processes $\tau \to 3\mu$, $\mu \to e\gamma$ …

- collected hints of LFU violation ⇢ relations between 1) and 2)

- coherent pattern of deviations seems to be emerging
  the solution of old problems could be related to the other tensions
  example: $|V_{cb}|_{incl}$ vs $|V_{cb}|_{excl}$ might be related to the observed anomalies in $b \to c$ semileptonic modes

F. De Fazio, PC PRD 95 (17) 011701

what about $|V_{ub}|_{incl}$ vs $|V_{ub}|_{excl}$?

SM extension

- BSM at a high scale $\Lambda >> M_W$
- BSM gauge group G $\supset SU(3)_C \times SU(2)_L \times U(1)_Y$

$\Longrightarrow$ SM effective theory at the scale M_W

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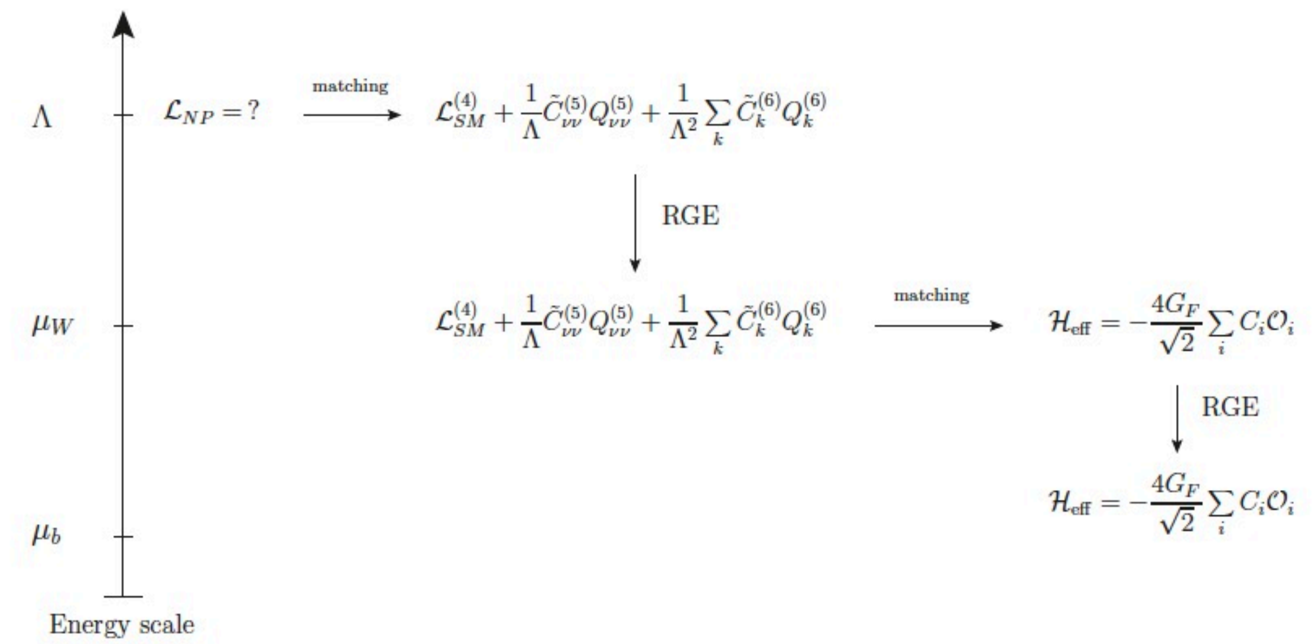

credits for the picture:
Aebischer Crivellin Fael Greub JHEP05 (2016) 037

- coefficients in the low-energy H_{eff} related to the high-scale ones
- coefficients in different processes related
- basis of effective operators, ordered by dimension, made of SM fields

Buchmuller and Wyler, NPB 268 (1986) 621
Grzadkowski et al., JHEP 10 (2010) 085

SM extension

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Weinberg opertor: ν mass

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} C_{\nu\nu}^{(5)} Q_{\nu\nu}^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

NP

$$\mathcal{L}^{kin} + \mathcal{L}^{gauge} + \mathcal{L}^{Higgs} + \mathcal{L}^{Yukawa}$$

accidental symmetries

- violates accidental symmetries
- source of CP violation in SM
- fermion masses

Semileptonic b decays

exclusive $b \to c,u$ modes

- hadronic uncertainties
- $b \to c$ form factor parametrization BGL vs CLN proposed to reconcile $|V_{cb}|_{incl}$ and $|V_{cb}|_{excl}$

- what about $|V_{ub}|$?

inclusive $b \to c,u$ modes: theoretically clean

- systematic expansion in $1/m_Q$ and α_s
- role of the shape function
- identification of the observables

Semileptonic b decays

extension of the SM effective Hamiltonian with D=6 operators and LH neutrinos

U=c,u

$$
\begin{aligned}
H_{\rm eff}^{b\to U\ell\nu} = \frac{G_F}{\sqrt{2}}V_{Ub}\,\Big[\; & (1+\epsilon_V^\ell)\left(\bar U\gamma_\mu(1-\gamma_5)b\right)\left(\bar\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right) \\
& + \epsilon_S^\ell\,(\bar U b)\left(\bar\ell(1-\gamma_5)\nu_\ell\right) + \epsilon_P^\ell\,\left(\bar U\gamma_5 b\right)\left(\bar\ell(1-\gamma_5)\nu_\ell\right) \\
& + \epsilon_T^\ell\,\left(\bar U\sigma_{\mu\nu}(1-\gamma_5)b\right)\left(\bar\ell\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell\right) \\
& + \epsilon_R^\ell\left(\bar U\gamma_\mu(1+\gamma_5)b\right)\left(\bar\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right)\Big] + h.c.\ .
\end{aligned}
$$

Buchmuller and Wyler, NPB 268 (1986) 621
Grzadkowski et al., JHEP 10 (2010) 085

Semileptonic b decays

extension of the SM effective Hamiltonian with D=6 operators and LH neutrinos

U=c,u

SM

$$H_{\rm eff}^{b\to U\ell\nu} = \frac{G_F}{\sqrt{2}} V_{Ub} \Big[(1+\epsilon_V^\ell)\,(\bar{U}\gamma_\mu(1-\gamma_5)b)\,(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell) + \epsilon_S^\ell\,(\bar{U}b)\,(\bar{\ell}(1-\gamma_5)\nu_\ell) + \epsilon_P^\ell\,(\bar{U}\gamma_5 b)\,(\bar{\ell}(1-\gamma_5)\nu_\ell) + \epsilon_T^\ell\,(\bar{U}\sigma_{\mu\nu}(1-\gamma_5)b)\,(\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell) + \epsilon_R^\ell\,(\bar{U}\gamma_\mu(1+\gamma_5)b)\,(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell) \Big] + h.c. \,.$$

complex
lepton flavour - dependent
couplings

Buchmuller and Wyler, NPB 268 (1986) 621
Grzadkowski et al., JHEP 10 (2010) 085

Beauty baryon inclusive decays

- Inclusive modes: optical theorem
  heavy quark expansion (HQE)

J. Chay, H. Georgi and B. Grinstein, PLB 247 (1990) 399
I.I.Y. Bigi, M.A. Shifman, N.G. Uraltsev and A.I. Vainshtein, PRL 71 (1993) 496

- Observables as a double expansion in powers of $1/m_Q$ and α_s/π
  $b \to u$: F. De Fazio, M. Neubert, hep-ph/9905351

- Clean correlations between meson (B, B_s) and baryon (Λ_b, Ξ_b, Ω_b) observables

Inclusive decay width

$$H_{\rm eff}^{b\to U\ell\nu} = \frac{G_F}{\sqrt{2}} V_{Ub} \sum_{i=1}^{5} C_i^\ell \, J_M^{(i)} \, L^{(i)M} + h.c.$$

$$C_1^\ell = (1+\epsilon_V^\ell)$$

$$C_{2,3,4,5}^\ell = \epsilon_{S,P,T,R}^\ell$$

hadronic currents

leptonic currents

SM: $\epsilon_{V,S,P,T,R}^\ell = 0$

$$J_\mu^{(1)} = \overline{U}\gamma_\mu(1-\gamma_5)b$$

$$L^{\mu(1)} = \overline{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell$$

$$d\Gamma = d\Sigma \frac{G_F^2 |V_{Ub}|^2}{4m_H} \sum_{i,j} C_i^* C_j (W^{ij})_{MN} (L^{ij})^{MN}$$

hadronic tensor

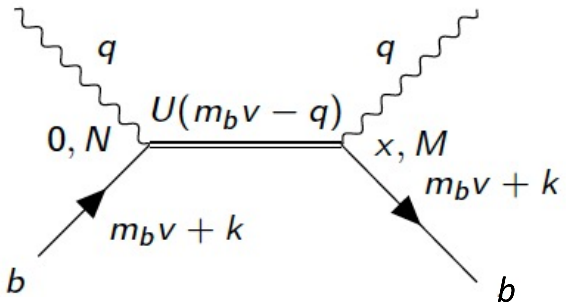
leptonic tensor

$$(W^{ij})_{MN} = \frac{1}{\pi} \mathrm{Im}(T^{ij})_{MN}$$

$$(T^{ij})_{MN} = i \int d^4x \, e^{i(m_b v - q)\cdot x} \langle H_b(v,s)| T[\hat{J}_M^{(i)\dagger}(x) \, \hat{J}_N^{(j)}(0)] |H_b(v,s)\rangle$$

$$= \langle H_b(v,s)| \bar{b}_v(0) \Gamma_M^{(i)\dagger} S_U(p_X) \Gamma_N^{(j)} b_v(0) |H_b(v,s)\rangle$$

intermediate U quark propagator



Inclusive decay width

heavy quark expansion

$$S_U(p_X) = S_U^{(0)} - S_U^{(0)}(i\not{D})S_U^{(0)} + S_U^{(0)}(i\not{D})S_U^{(0)}(i\not{D})S_U^{(0)} + \dots$$

$$\frac{1}{m_b \not{v} - \not{q} - m_U}$$

$$\begin{aligned}
\frac{1}{\pi}\mathrm{Im}(T^{ij})_{MN} = \; & \frac{1}{\pi}\mathrm{Im}\frac{1}{\Delta_0}\langle H_b(v,s)|\bar{b}_v[\Gamma_M^{(i)\dagger}\mathcal{P}\Gamma_N^{(j)}]b_v|H_b(v,s)\rangle \\
& - \frac{1}{\pi}\mathrm{Im}\frac{1}{\Delta_0^2}\langle H_b(v,s)|\bar{b}_v[\Gamma_M^{(i)\dagger}\mathcal{P}\gamma^{\mu_1}\mathcal{P}\Gamma_N^{(j)}](iD_{\mu_1})b_v|H_b(v,s)\rangle \\
& + \frac{1}{\pi}\mathrm{Im}\frac{1}{\Delta_0^3}\langle H_b(v,s)|\bar{b}_v[\Gamma_M^{(i)\dagger}\mathcal{P}\gamma^{\mu_1}\mathcal{P}\gamma^{\mu_2}\mathcal{P}\Gamma_N^{(j)}](iD_{\mu_1})(iD_{\mu_2})b_v|H_b(v,s)\rangle \\
& - \frac{1}{\pi}\mathrm{Im}\frac{1}{\Delta_0^4}\langle H_b(v,s)|\bar{b}_v[\Gamma_M^{(i)\dagger}\mathcal{P}\gamma^{\mu_1}\mathcal{P}\gamma^{\mu_2}\mathcal{P}\gamma^{\mu_3}\mathcal{P}\Gamma_N^{(j)}](iD_{\mu_1})(iD_{\mu_2})(iD_{\mu_3})b_v|H_b(v,s)\rangle \, .
\end{aligned}$$

$$\left\{ \begin{aligned} \Delta_0 &= p_U^2 - m_U^2 \\ p_U &= m_b v - q \end{aligned} \right.$$

HQE

hadronic matrix elements of operators with increasing number of derivatives

$$\mathcal{M}_{\mu_1\dots\mu_n} = \langle H_b(v,s)|(\bar{b}_v)_a(iD_{\mu_1})\dots(iD_{\mu_n})(b_v)_b|H_b(v,s)\rangle$$

non perturbative low-energy parameters

Inclusive decay width

$$\mathcal{O}\left(\frac{1}{m_b^n}\right) \dots \begin{cases} \mathcal{O}\left(\frac{1}{m_b^3}\right) \begin{cases} \mathcal{O}\left(\frac{1}{m_b^2}\right) \begin{cases} -2\, M_H\, \hat{\mu}_\pi^2 = \langle H_b | \overline{b}_v\, iD^\mu\, iD_\mu\, b_v | H_b \rangle \\ 2\, M_H\, \hat{\mu}_G^2 = \langle H_b | \overline{b}_v\, (-i\sigma_{\mu\nu})\, iD^\mu\, iD^\nu\, b_v | H_b \rangle \end{cases} \\ 2\, M_H\, \hat{\rho}_D^3 = \langle H_b | \overline{b}_v\, iD^\mu\, (iv \cdot D)\, iD_\mu\, b_v | H_b \rangle \\ 2\, M_H\, \hat{\rho}_{LS}^3 = \langle H_b | \overline{b}_v\, (-i\sigma_{\mu\nu})\, iD^\mu\, (iv \cdot D)\, iD^\nu\, b_v | H_b \rangle \end{cases} \\ \dots \end{cases}$$

Inclusive decay width

$$\mathcal{O}\left(\frac{1}{m_b^n}\right) \ldots \begin{cases} \mathcal{O}\left(\frac{1}{m_b^3}\right) \begin{cases} \mathcal{O}\left(\frac{1}{m_b^2}\right) \begin{cases} -2\,M_H\,\hat{\mu}_\pi^2 = \langle H_b|\overline{b}_v\; iD^\mu\; iD_\mu\; b_v|H_b\rangle \\ 2\,M_H\,\hat{\mu}_G^2 = \langle H_b|\overline{b}_v\,(-i\sigma_{\mu\nu})\; iD^\mu\; iD^\nu\; b_v|H_b\rangle \end{cases} \\ 2\,M_H\,\hat{\rho}_D^3 = \langle H_b|\overline{b}_v\; iD^\mu\,(iv\cdot D)\; iD_\mu\; b_v|H_b\rangle \\ 2\,M_H\,\hat{\rho}_{LS}^3 = \langle H_b|\overline{b}_v\,(-i\sigma_{\mu\nu})\; iD^\mu\,(iv\cdot D)\; iD^\nu\; b_v|H_b\rangle \end{cases} \\ \ldots \end{cases}$$

$\hat{\mu}_\pi^2$ matrix element of the kinetic energy operator

different for different hadrons (B vs Λ_b)

$$\mu_\pi^2(B) - \mu_\pi^2(\Lambda_b) = \frac{2m_b m_c}{m_b - m_c}\left[(m_{\Lambda_b} - m_{\Lambda_c}) - (\overline{m}_B - \overline{m}_D)\right]\left(1 + \mathcal{O}(1/m_{b,c}^2)\right)$$

$$\hat{\mu}_\pi^2(\Lambda_b) = (0.50 \pm 0.1)\,\mathrm{GeV}^2$$

Dominguez Nardulli Paver PC PRD54 (96) 4622

Inclusive decay width

$$
\mathcal{O}\left(\frac{1}{m_b^n}\right)\ldots
\begin{cases}
\mathcal{O}\left(\frac{1}{m_b^3}\right)
\begin{cases}
\mathcal{O}\left(\frac{1}{m_b^2}\right)
\begin{cases}
-2\, M_H\, \hat{\mu}_\pi^2 = \langle H_b | \bar{b}_v\, iD^\mu\, iD_\mu\, b_v | H_b \rangle \\
2\, M_H\, \hat{\mu}_G^2 = \langle H_b | \bar{b}_v\, (-i\sigma_{\mu\nu})\, iD^\mu\, iD^\nu\, b_v | H_b \rangle
\end{cases} \\
2\, M_H\, \hat{\rho}_D^3 = \langle H_b | \bar{b}_v\, iD^\mu\, (iv \cdot D)\, iD_\mu\, b_v | H_b \rangle \\
2\, M_H\, \hat{\rho}_{LS}^3 = \langle H_b | \bar{b}_v\, (-i\sigma_{\mu\nu})\, iD^\mu\, (iv \cdot D)\, iD^\nu\, b_v | H_b \rangle
\end{cases} \\
\ldots
\end{cases}
$$

$\hat{\mu}_G^2$ matrix element of the chromomagnetic operator

depends on the spin of the hadron - determined from the mass spectrum

$$\hat{\mu}_G^2(\Lambda_b) = 0$$

Inclusive decay width

$$\mathcal{O}\left(\frac{1}{m_b^n}\right)\dots\begin{cases}\mathcal{O}\left(\frac{1}{m_b^3}\right)\begin{cases}\mathcal{O}\left(\frac{1}{m_b^2}\right)\begin{cases}-2\,M_H\,\hat{\mu}_\pi^2 = \langle H_b|\overline{b}_v\; iD^\mu\; iD_\mu\; b_v|H_b\rangle \\ 2\,M_H\,\hat{\mu}_G^2 = \langle H_b|\overline{b}_v\;(-i\sigma_{\mu\nu})\; iD^\mu\; iD^\nu\; b_v|H_b\rangle\end{cases} \\ 2\,M_H\,\hat{\rho}_D^3 = \langle H_b|\overline{b}_v\; iD^\mu\;(iv\cdot D)\; iD_\mu\; b_v|H_b\rangle \\ 2\,M_H\,\hat{\rho}_{LS}^3 = \langle H_b|\overline{b}_v\;(-i\sigma_{\mu\nu})\; iD^\mu\;(iv\cdot D)\; iD^\nu\; b_v|H_b\rangle\end{cases} \\ \dots\end{cases}$$

$\hat{\rho}_D^3$ Darwin term $\quad \rho_D^3(\Lambda_b) \simeq \rho_D^3(B) \quad \rho_D^3(\Lambda_b) = (0.17 \pm 0.08)\,\mathrm{GeV}^3$

$\hat{\rho}_{LS}^3$ spin-orbit term $\quad \hat{\rho}_{LS}^3(\Lambda_b) = 0$

computation

$$\mathcal{M}_{\mu_1 \ldots \mu_n} = \langle H_b(v,s)|(\bar{b}_v)_a(iD_{\mu_1})\ldots(iD_{\mu_n})(b_v)_b|H_b(v,s)\rangle$$

general parametrization including dependence on the spin up to $O(1/m_b^3)$
B mesons: B.M. Dassinger, T. Mannel and S. Turczyk, JHEP 03 (2007) 087

new terms depending on the spin for polarized baryon

$O(1/m_b^2)$: A.V. Manohar and M.B. Wise, PRD 49 (1994) 1310
S. Balk, J.G. Korner and D. Pirjol, EPJC 1 (1998) 221

Results

$$\mathcal{M}^{\rho\sigma\lambda} = M_H \left[\left(\frac{\hat{\rho}_D^3}{3} \Pi^{\rho\lambda} v^\sigma \mathrm{P}_+ + \frac{\hat{\rho}_{LS}^3}{6} v^\sigma i\,\epsilon^{\rho\lambda\alpha\beta} v_\alpha \mathrm{S}_\beta \right) - \left(\frac{\hat{\rho}_D^3}{3} \Pi^{\rho\lambda} v^\sigma s^\mu \mathrm{S}_\mu - \frac{\hat{\rho}_{LS}^3}{2} v^\sigma i\,\epsilon^{\rho\lambda\alpha\beta} v_\alpha s_\beta \mathrm{P}_+ \right) \right]$$

$$\begin{aligned}\mathcal{M}^{\rho\sigma} = M_H \Bigg[\Bigg(& \frac{\hat{\mu}_\pi^2}{3} \Pi^{\rho\sigma} \mathrm{P}_+ + \frac{\hat{\mu}_G^2}{6} i\,\epsilon^{\rho\sigma\alpha\beta} v_\alpha \mathrm{S}_\beta + \\ & + \frac{\hat{\rho}_D^3 + \hat{\rho}_{LS}^3}{24 m_b} \Big(4 \left(i\,\epsilon^{\rho\sigma\alpha\beta} v_\alpha \mathrm{S}_\beta - v^\rho v^\sigma \slashed{v}\right) + \\ & \quad + v^\rho \left(2\gamma^\sigma + \slashed{v}\gamma^\sigma - \gamma^\sigma \slashed{v}\right) + v^\sigma \left(2\gamma^\rho + \slashed{v}\gamma^\rho - \gamma^\rho \slashed{v}\right)\Big)\Bigg) + \\ & + \Bigg(-\frac{\hat{\mu}_\pi^2}{3} \Pi^{\rho\sigma} \mathrm{P}_+ \slashed{s}\gamma_5 + \frac{\hat{\mu}_G^2}{2} i\,\epsilon^{\rho\sigma\alpha\beta} v_\alpha s_\beta \mathrm{P}_+ + \\ & + \frac{\hat{\rho}_D^3}{12 m_b} \Big(6\,i\,\epsilon^{\rho\sigma\alpha\beta} v_\alpha s_\beta + i \left(v^\rho \epsilon^{\sigma\mu\alpha\beta} - v^\sigma \epsilon^{\rho\mu\alpha\beta}\right) v_\alpha s_\beta \gamma_\mu + \\ & \quad + s^\rho v^\sigma \slashed{v}\gamma_5 + v^\rho s^\sigma \left(2\gamma_5 + \slashed{v}\gamma_5\right) + \left(2 v^\rho v^\sigma \slashed{v} - v^\rho \gamma^\sigma - v^\sigma \gamma^\rho\right) \slashed{s}\gamma_5\Big) + \\ & + \frac{\hat{\rho}_{LS}^3}{8 m_b} \Big(4\,i\,\epsilon^{\rho\sigma\alpha\beta} v_\alpha s_\beta + i \left(v^\rho \epsilon^{\sigma\mu\alpha\beta} - v^\sigma \epsilon^{\rho\mu\alpha\beta}\right) v_\alpha s_\beta \gamma_\mu + \\ & \quad + \left(s^\rho v^\sigma + v^\rho s^\sigma\right)\gamma_5 + \left(2 v^\rho v^\sigma \slashed{v} - v^\rho \gamma^\sigma - v^\sigma \gamma^\rho\right) \slashed{s}\gamma_5\Big)\Bigg)\Bigg]\end{aligned}$$

F. De Fazio, F. Loparco, PC JHEP 11 (2020) 032

Results

$$\mathcal{M}^\rho = M_H \Bigg[\Bigg(\frac{\hat\mu_\pi^2 - \hat\mu_G^2}{12 m_b} \left(v^\rho (3 + 5\,\slashed{v}) - 2\,\gamma^\rho\right) - \frac{\hat\rho_D^3 + \hat\rho_{LS}^3}{12 m_b^2} \left(4\,v^\rho\,\slashed{v} - \gamma^\rho\right) \Bigg) +$$

$$+ \Bigg(- \frac{\hat\mu_\pi^2}{12 m_b} \left(\left(v^\rho (3 + 5\,\slashed{v}) - 2\,\gamma^\rho\right) \slashed{s}\,\gamma_5 + 4\,s^\rho\,\mathrm{P}_+\,\gamma_5 \right) +$$

$$+ \frac{\hat\mu_G^2}{4 m_b} \left(\left(v^\rho (1 + 2\,\slashed{v}) - \gamma^\rho\right) \slashed{s}\,\gamma_5 + s^\rho\,\gamma_5 \right) +$$

$$+ \frac{\hat\rho_D^3}{12 m_b^2} \left(\left(v^\rho (1 + 4\,\slashed{v}) - 2\,\gamma^\rho\right) \slashed{s}\,\gamma_5 + s^\rho (2 - \slashed{v})\,\gamma_5 \right) +$$

$$+ \frac{\hat\rho_{LS}^3}{8 m_b^2} \left(\left(3\,v^\rho\,\slashed{v} - \gamma^\rho\right) \slashed{s}\,\gamma_5 + s^\rho\,\gamma_5 \right) \Bigg) \Bigg]$$

$$\mathcal{M} = M_H \left[\left(\mathrm{P}_+ - \frac{\hat\mu_\pi^2 - \hat\mu_G^2}{4 m_b^2} \right) + \left(\mathrm{P}_+ + \frac{\hat\mu_\pi^2}{24 m_b^2} (7 + 5\,\slashed{v}) - \frac{\hat\mu_G^2}{8 m_b^2} (3 + \slashed{v}) - \frac{\hat\rho_D^3}{6 m_b^3}\,\mathrm{P}_- \right) \slashed{s}\,\gamma_5 \right]$$

F. De Fazio, F. Loparco, PC JHEP 11 (2020) 032

Fully differential decay width

$$\frac{d^4\Gamma}{dE_\ell\, dq^2\, dq_0\, d\cos\theta_P}$$

- E_ℓ: lepton energy, with $p_\ell = (E_\ell, \boldsymbol{p}_\ell)$;
- q^2: dilepton invariant mass, with $q = (q_0, \boldsymbol{q})$;
- θ_P: angle between the hadron spin $\boldsymbol{s}$ and the lepton 3-momentum $\boldsymbol{p}_\ell$, i.e. $\cos\theta_P = \frac{\boldsymbol{s}\cdot\boldsymbol{p}_\ell}{|\boldsymbol{s}||\boldsymbol{p}_\ell|}$.

computed with all BSM operators

$$\Gamma(H_b \to X_U\, \ell^-\, \bar{\nu}_\ell) = \Gamma_0 \sum_{i,j} g_i^*\, g_j \left[\mathcal{C}_0^{(i,j)} + \frac{\hat{\mu}_\pi^2}{m_b^2}\,\mathcal{C}_{\hat{\mu}_\pi^2}^{(i,j)} + \frac{\hat{\mu}_G^2}{m_b^2}\,\mathcal{C}_{\hat{\mu}_G^2}^{(i,j)} + \frac{\hat{\rho}_D^3}{m_b^3}\,\mathcal{C}_{\hat{\rho}_D^3}^{(i,j)} + \frac{\hat{\rho}_{LS}^3}{m_b^3}\,\mathcal{C}_{\hat{\rho}_{LS}^3}^{(i,j)}\right]$$

$$\Gamma_0 = \frac{G_F^2 |V_{Ub}|^2 m_b^5}{192\pi^3}$$

incorporate the effects of NP through the ε couplings

expression at $O(1/m_b^3)$ including all NP operators and for non vanishing lepton mass

F. De Fazio, F. Loparco, PC JHEP 11 (2020) 032

Fully differential decay width

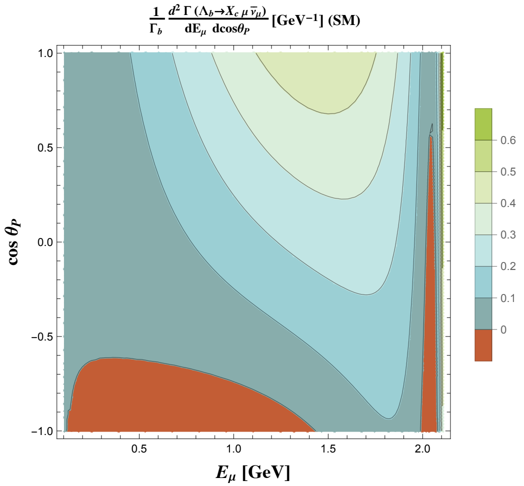
Perturbative QCD corrections in SM:

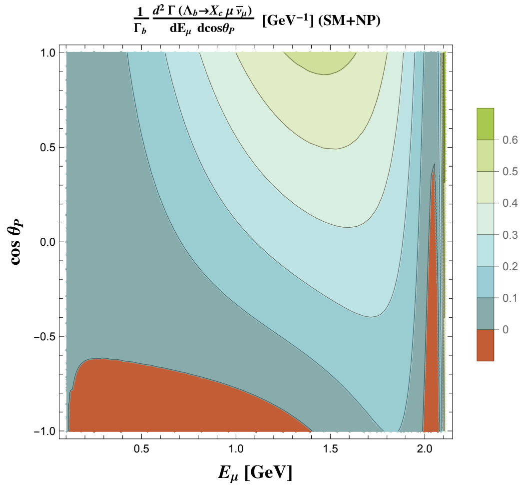
$O((\alpha_s/\pi)^3)$ for the the partonic width — Fael, Schonwald, Steinhauser, 2011.13654, 2005.06487, 2011.11655

$O(\alpha_s/\pi)$ for Γ_n: — Alberti Gambino Nandi 1311.7381
Mannel Pivovarov Rosenthal 1405.5072
Mannel Pivovarov 1907.09187
Capdevilla Gambino Nandi 2102.03343

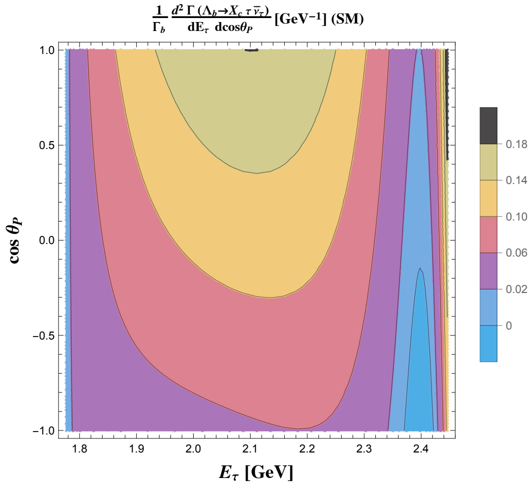
Results

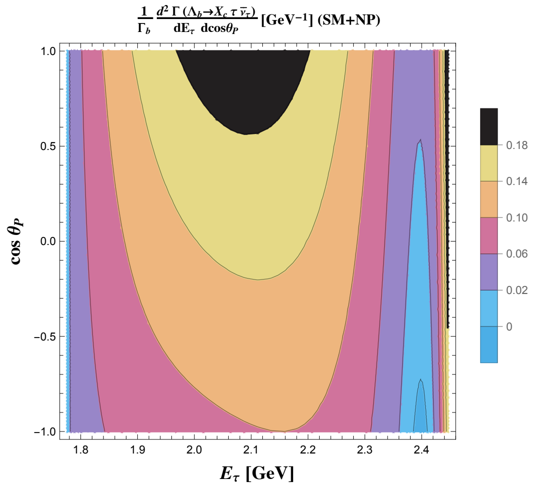
$\Lambda_b \to X_c\, l\, \nu_l$





$\Lambda_b \to X_c\, \tau\, \nu_\tau$

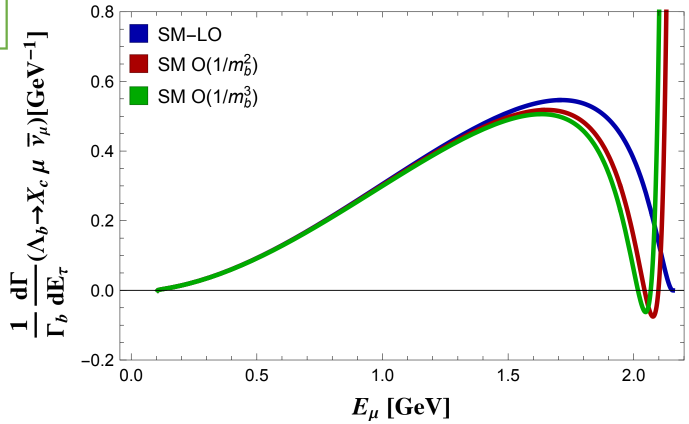


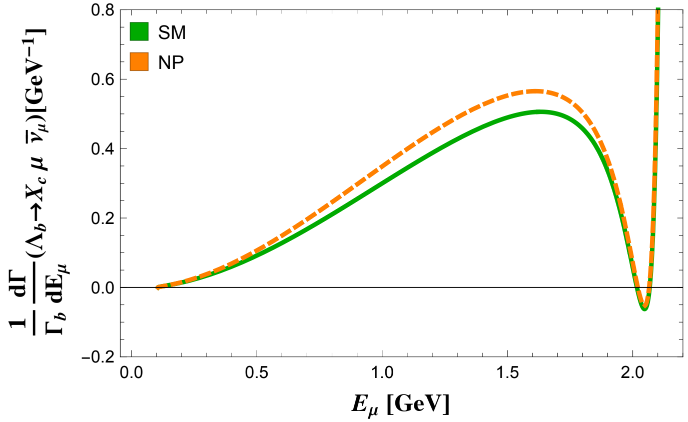


NP benchmark points: $b \to u$ F. De Fazio, F. Loparco, PC, PRD 100 (19) 075037
$b \to c$ F. De Fazio, PC, JHEP 06 (18) 082, R.X. Shi, L.S. Geng, B. Grinstein, S. Jager, J.M. Camalich JHEP 12 (19) 065

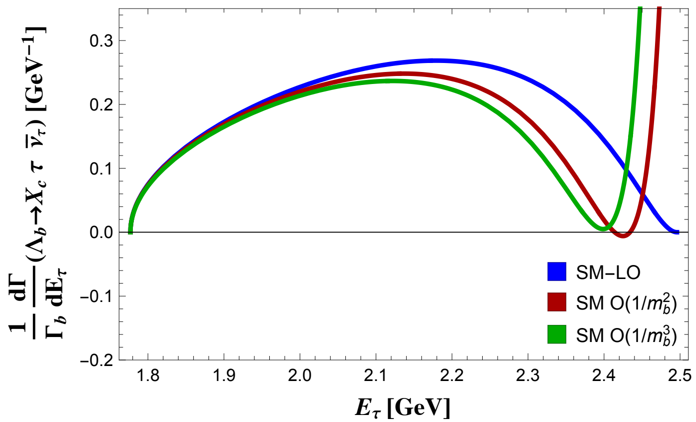
Results

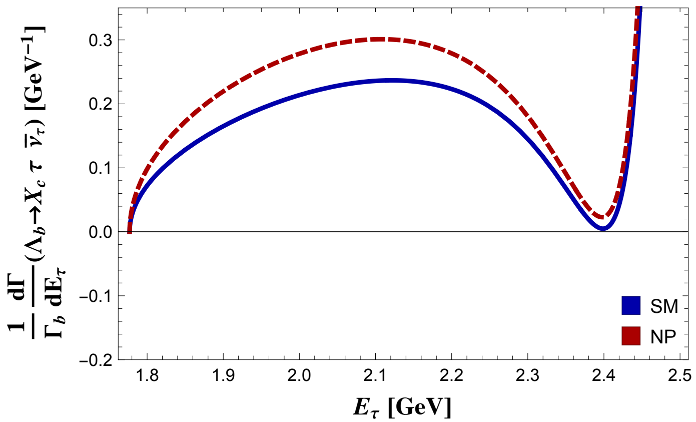
$\Lambda_b \to X_c\, l\, \nu_l$





$\Lambda_b \to X_c\, \tau\, \nu_\tau$

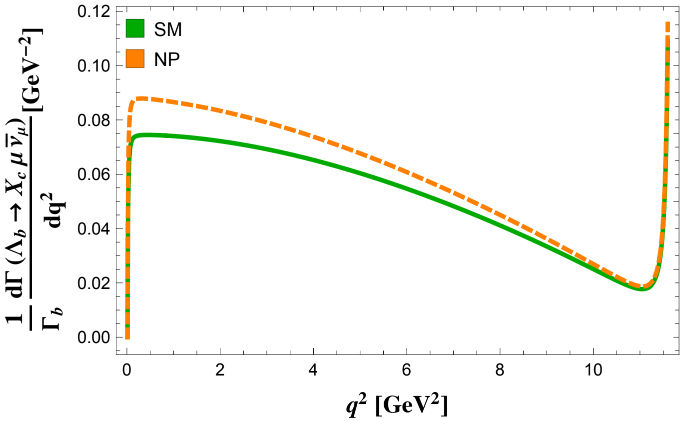




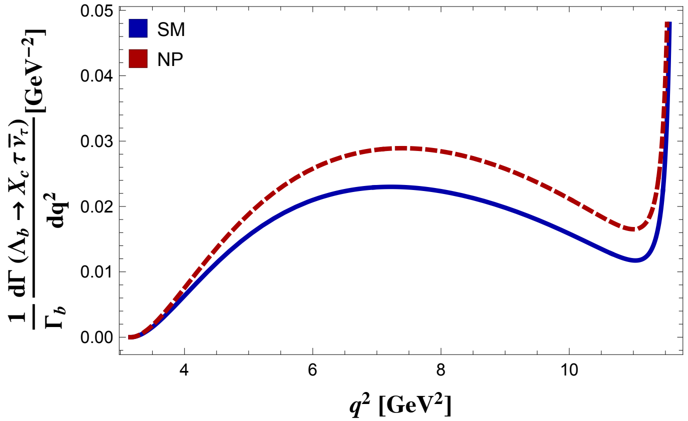
NP benchmark points: $b \to u$ F. De Fazio, F. Loparco, PC, PRD 100 (19) 075037
$b \to c$ F. De Fazio, PC, JHEP 06 (18) 082, R.X. Shi, L.S. Geng, B. Grinstein, S. Jager, J.M. Camalich JHEP 12 (19) 065

Results

$\Lambda_b \to X_c\, l\, \nu_l$



$\Lambda_b \to X_c\, \tau\, \nu_\tau$



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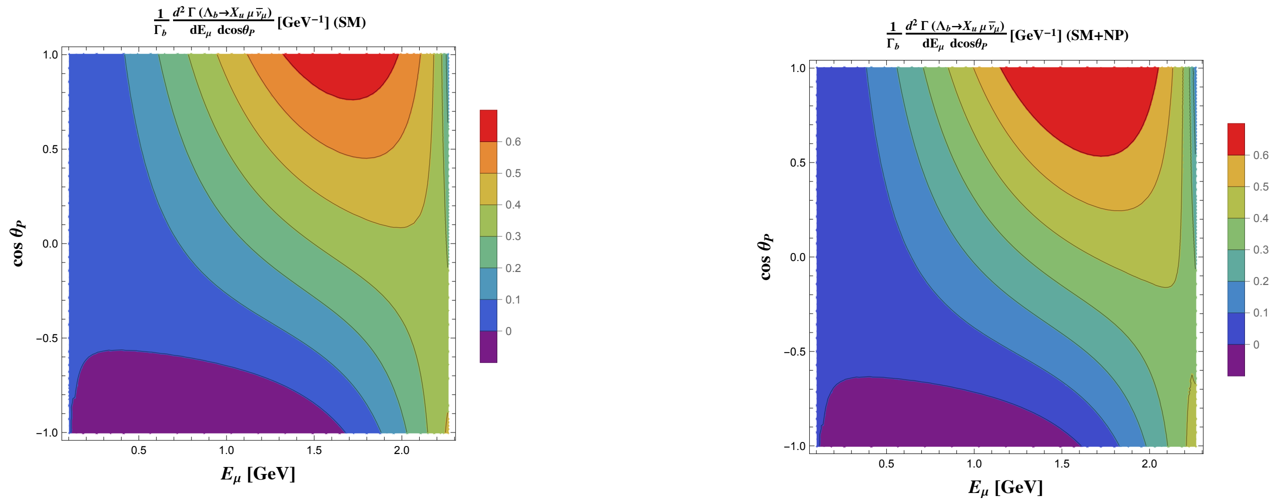
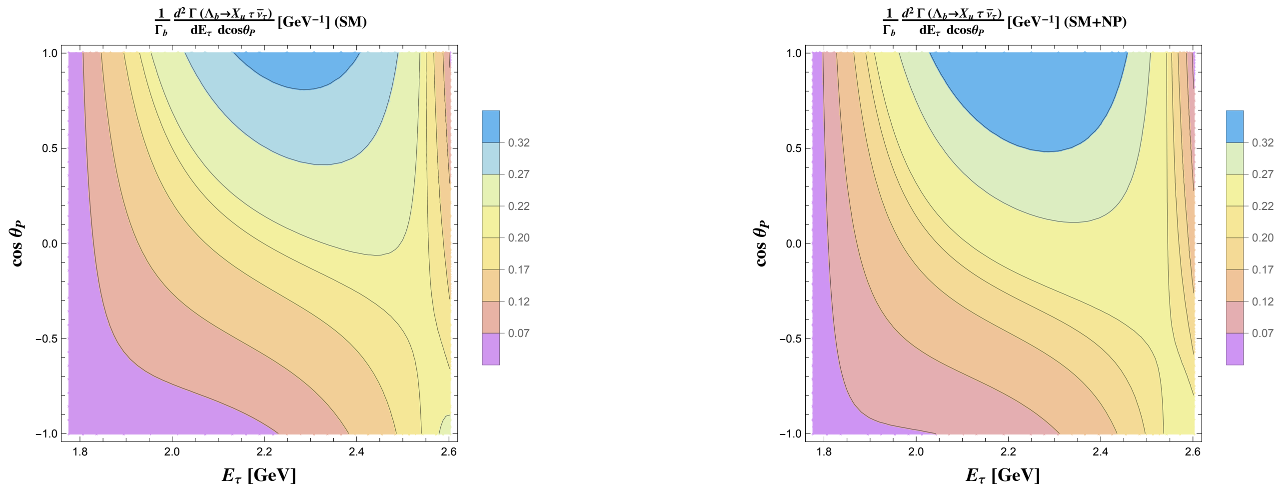


$\Lambda_b \to X_u\, \tau\, \nu_\tau$



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$b \to c$ F. De Fazio, PC, JHEP 06 (18) 082, R.X. Shi, L.S. Geng, B. Grinstein, S. Jager, J.M. Camalich JHEP 12 (19) 065

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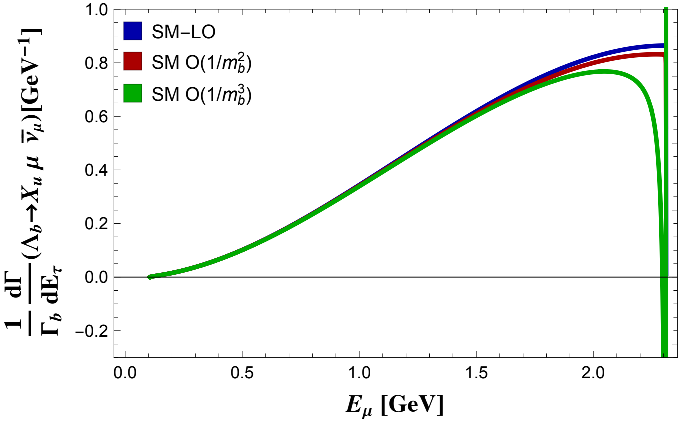
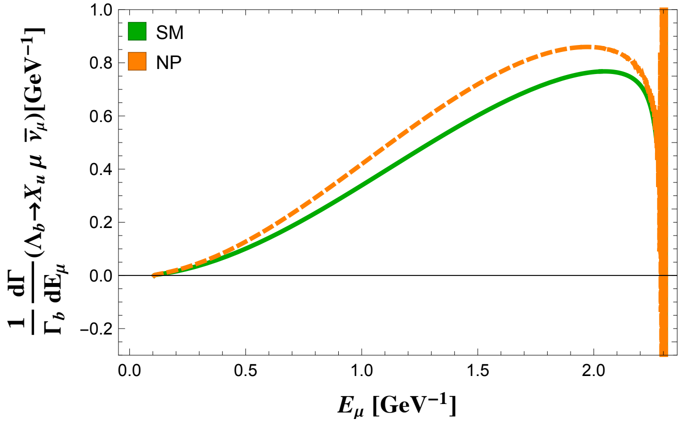
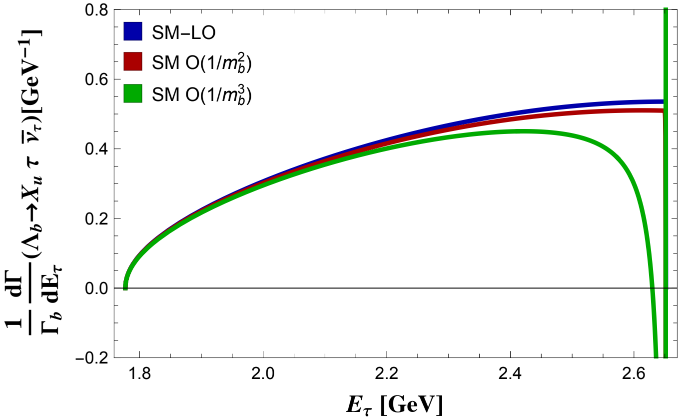
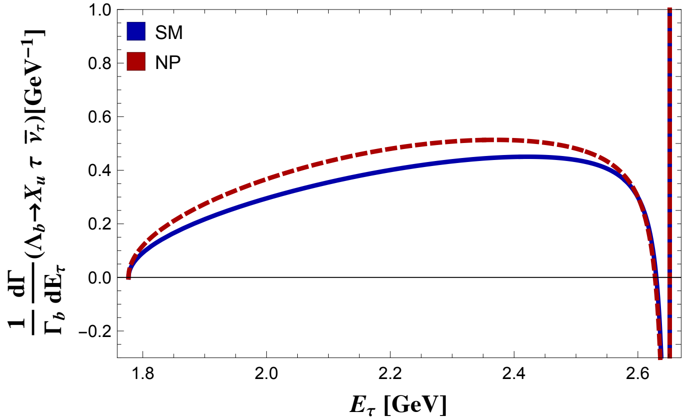




$\Lambda_b \to X_u\, \tau\, \nu_\tau$





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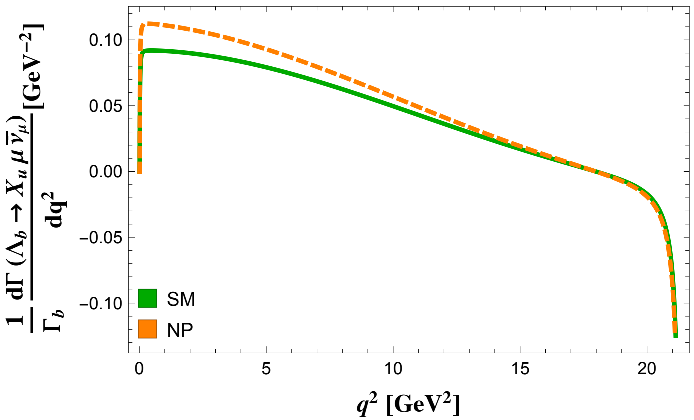
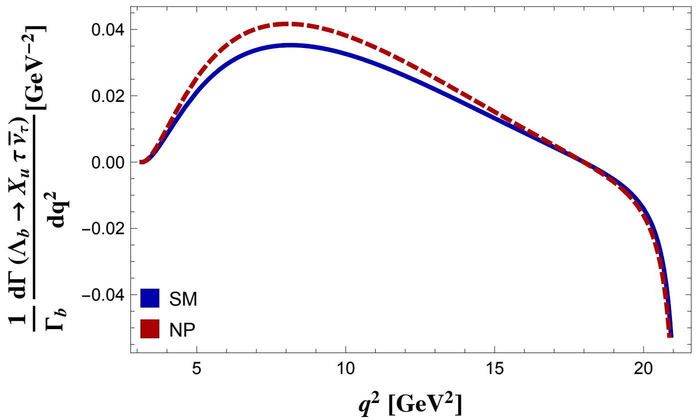
Results

$\Lambda_b \to X_u \, l \, \nu_l$



$\Lambda_b \to X_u \, \tau \, \nu_\tau$



NP benchmark points: b → u F. De Fazio, F. Loparco, PC, PRD 100 (19) 075037
b → c F. De Fazio, PC, JHEP 06 (18) 082, R.X. Shi, L.S. Geng, B. Grinstein, S. Jager, J.M. Camalich JHEP 12 (19) 065

Results

observables sensitive to Λ_b polarization and to BSM contributions
longitudinal polarization expected for Λ_b from b quark produced in top or Z^0 decays

$$\frac{d\Gamma(\Lambda_b \to X_U \ell \bar{\nu}_\ell)}{d\cos\theta_P} = A_\ell^U + B_\ell^U \cos\theta_P$$

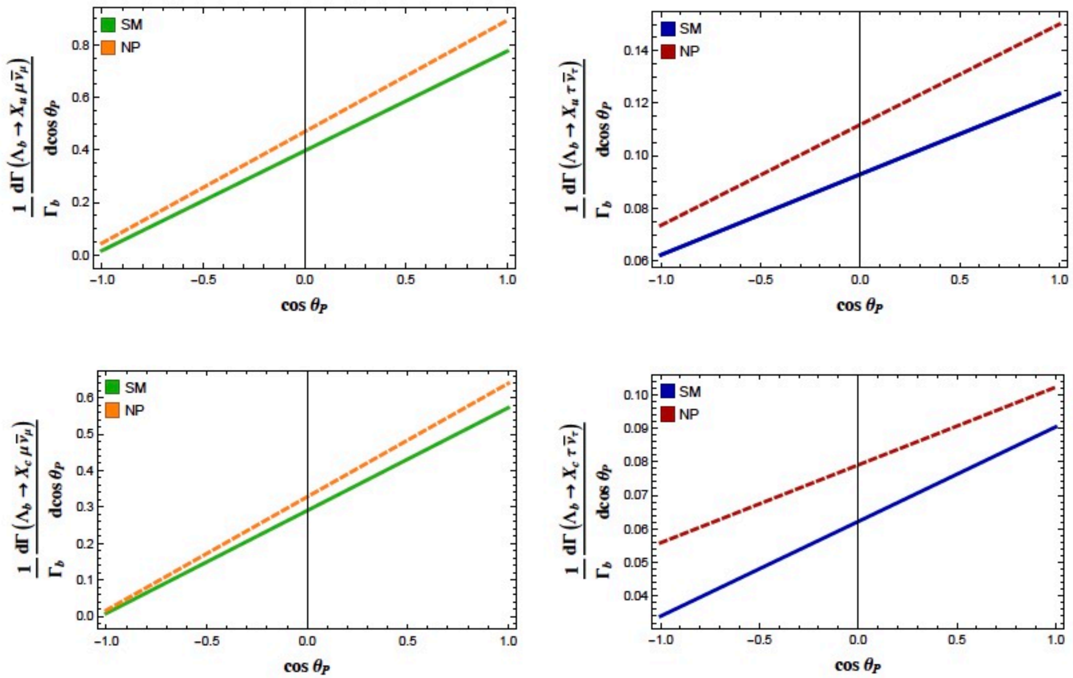
angle between ℓ direction and Λ_b spin

$$R_{\Lambda_b}(X_U) = \frac{A_\tau^U}{A_\mu^U}$$

analogous to R(D(*))
does not require considering polarization

$$R_S^U = \frac{B_\tau^U}{B_\mu^U}$$

slope ratios for $\ell=\tau$ and $\ell=\mu$



Results

Identification of observables sensitive to Λ_b polarization and to BSM effects
(Longitudinal polarization expected for Λ_b resulting from b quark produced in top or Z^0 decays)

$$\frac{d\Gamma(\Lambda_b \to X_U \ell \bar{\nu}_\ell)}{d\cos\theta_P} = A_\ell^U + B_\ell^U \cos\theta_P$$

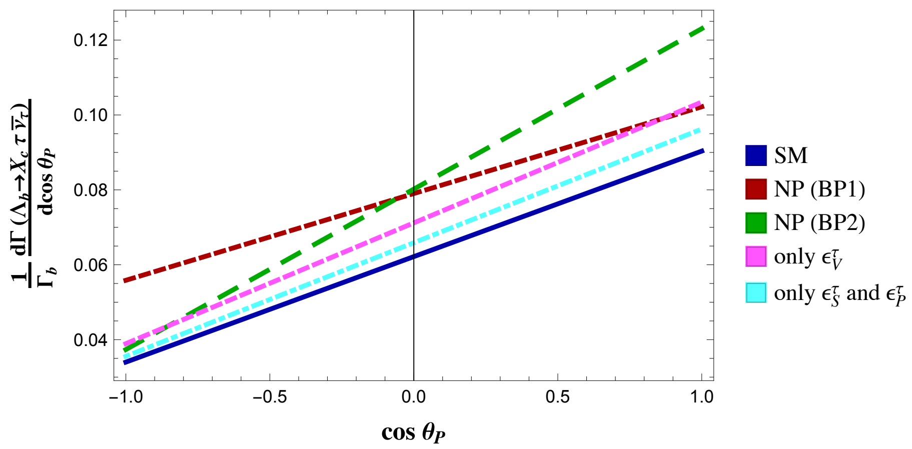
angle between ℓ^- direction and Λ_b spin

$$R_{\Lambda_b}(X_U) = \frac{A_\tau^U}{A_\mu^U}$$

analogous to $R(D^{(*)})$ does not require considering polarization

$$R_S^U = \frac{B_\tau^U}{B_\mu^U}$$

slope ratios for $\ell=\tau$ and $\ell=\mu$



Results

observables sensitive to Λ_b polarization and to BSM contributions
longitudinal polarization expected for Λ_b from b quark produced in top or Z^0 decays

P. Colangelo, F. Loparco, FDF
JHEP 11 (2020) 032

$$\frac{d\Gamma(\Lambda_b \to X_U \ell \bar{\nu}_\ell)}{d\cos\theta_P} = A_\ell^U + B_\ell^U \cos\theta_P$$

angle between ℓ direction and Λ_b spin

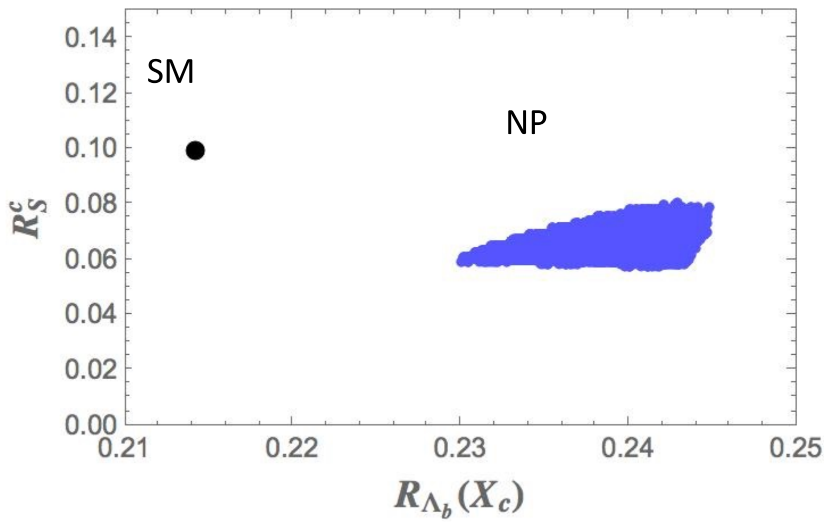
$$R_{\Lambda_b}(X_U) = \frac{A_\tau^U}{A_\mu^U}$$

analogous to $R(D^{(*)})$

$$R_S^U = \frac{B_\tau^U}{B_\mu^U}$$

slope ratios for $\ell=\tau$ and $\ell=\mu$

$$R_{\Lambda_b}(X_u)^{SM} = 0.234$$
$$R_{\Lambda_b}(X_c)^{SM} = 0.214$$



- New clean observable but difficult to measure at LHC
- accessible using polarized Λ_b from Z decays at a lepton collider (FCC-e or muon)

Possible connection with the $|V_{cb}|$ puzzle

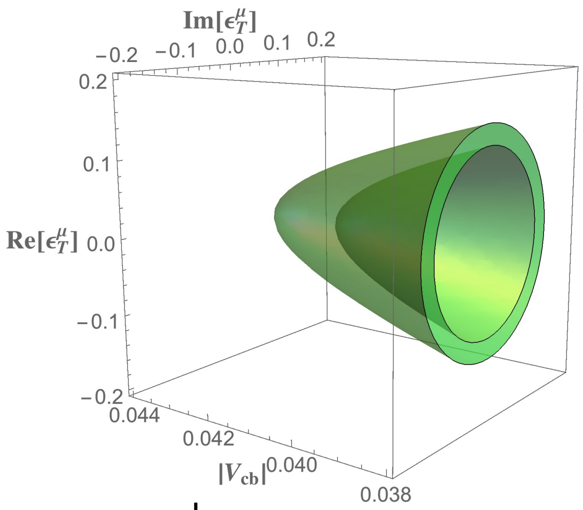
Include the tensor operator in $b \to c\, \ell \nu_\ell$ Hamiltonian with lepton-flavour dependent coupling

$B \to X_c\, \ell \nu_\ell$

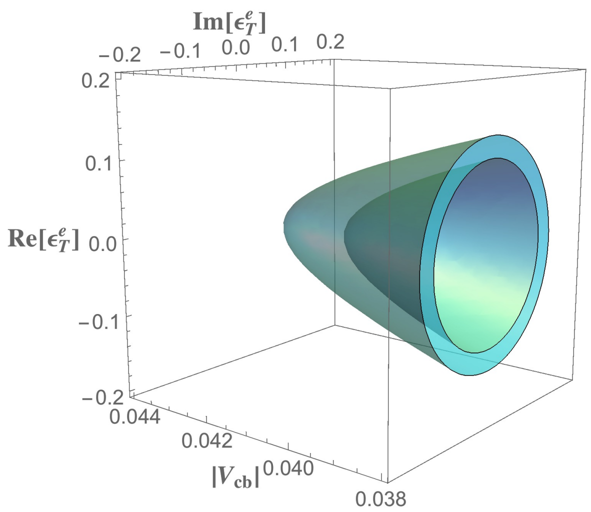
$$\Gamma = \Gamma_{SM} + |\varepsilon_T|^2\, \Gamma_{NP} + \mathrm{Re}(\varepsilon_T)\, \Gamma_{INT}$$

parameter space $\left(\mathrm{Re}(\varepsilon_T^\ell),\ \mathrm{Im}(\varepsilon_T^\ell),\ |V_{cb}|\right)$

input (PDG) $B(B^+ \to X_c e^+ \nu_e) = (10.8 \pm 0.4) \times 10^{-2}$



μ mode



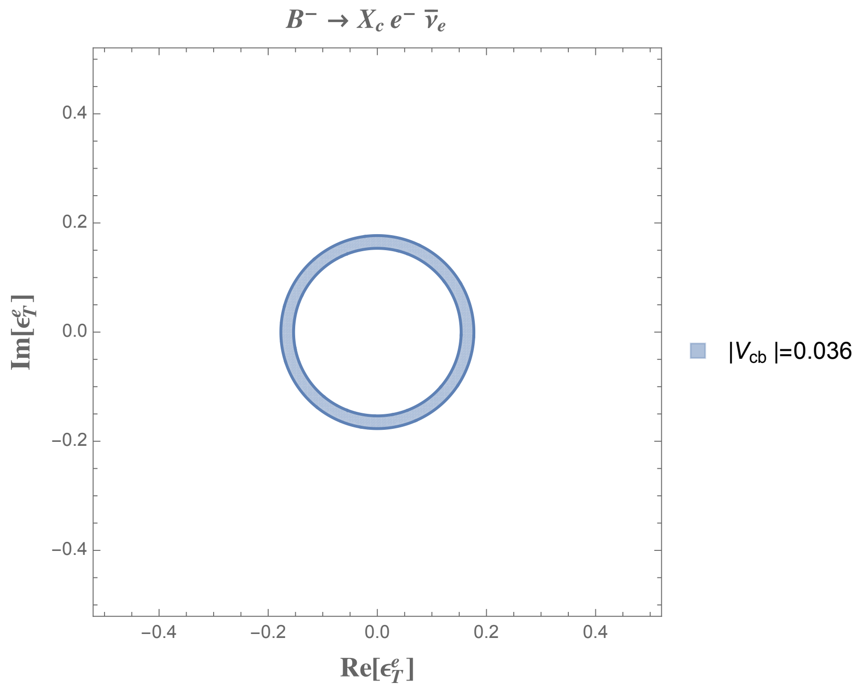
e mode

De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

$B \to X_c \, \ell \nu_\ell$
allowed regions in parameter space

allowed ε_T^ℓ correlated to $|V_{cb}|$

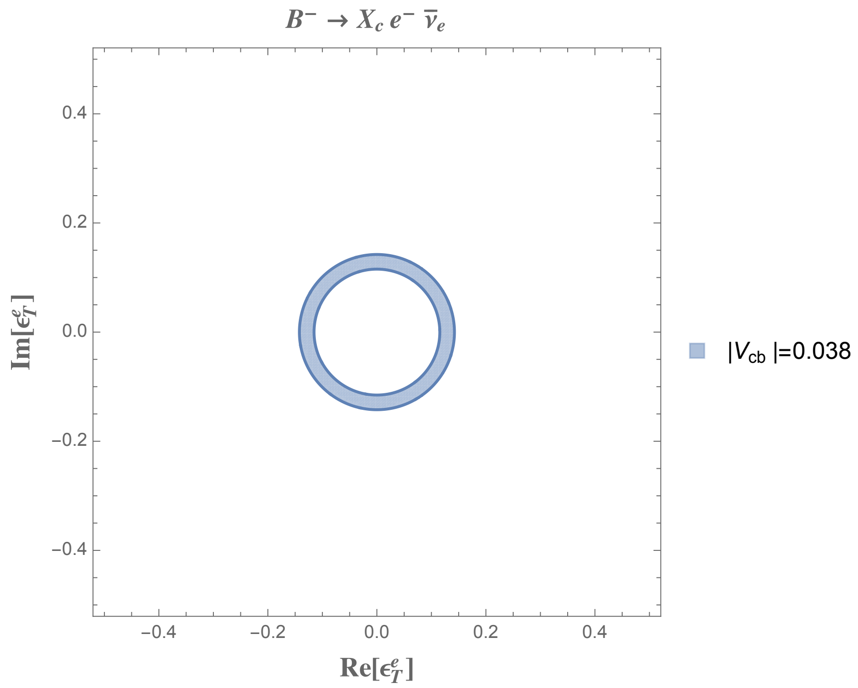


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

$B \to X_c \, \ell \nu_\ell$
allowed regions in parameter space

allowed ε_T^ℓ correlated to $|V_{cb}|$



De Fazio PC, PRD 95, 011701(R)

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$B \to X_c \, \ell \nu_\ell$
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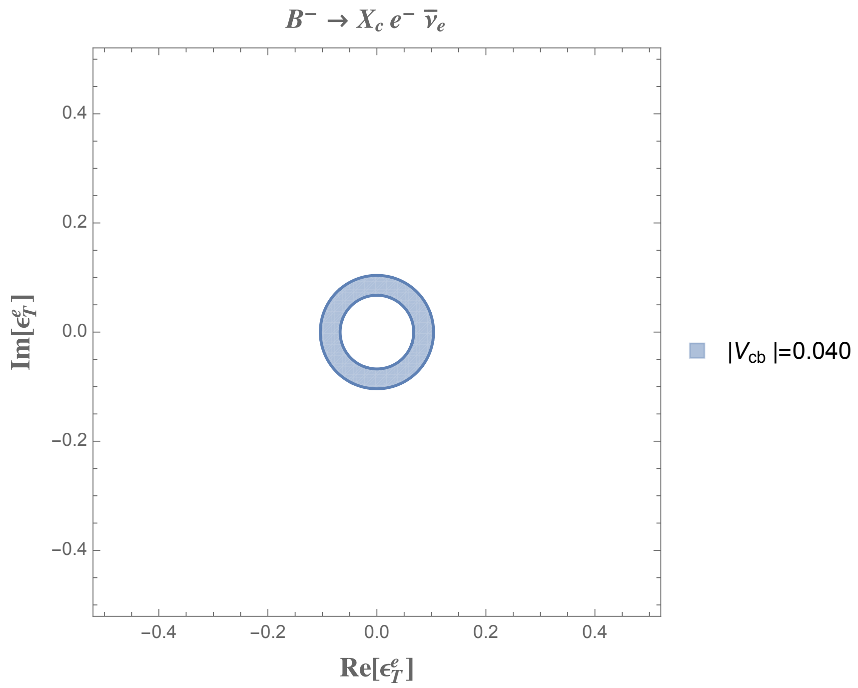

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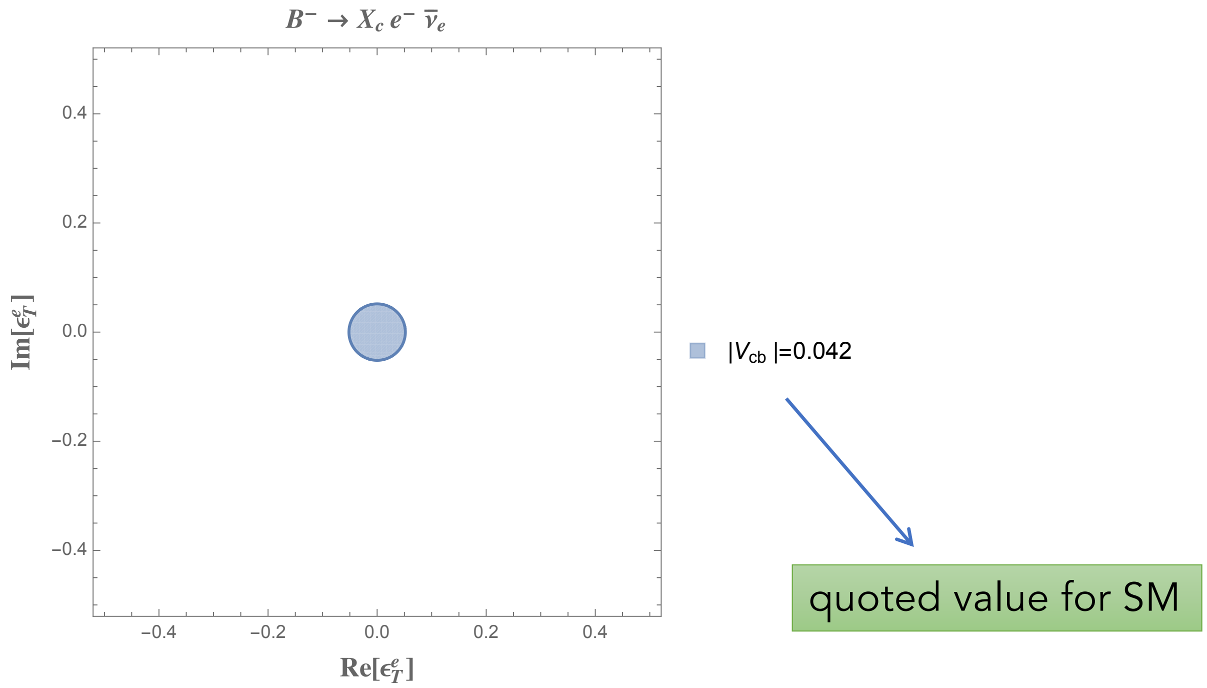
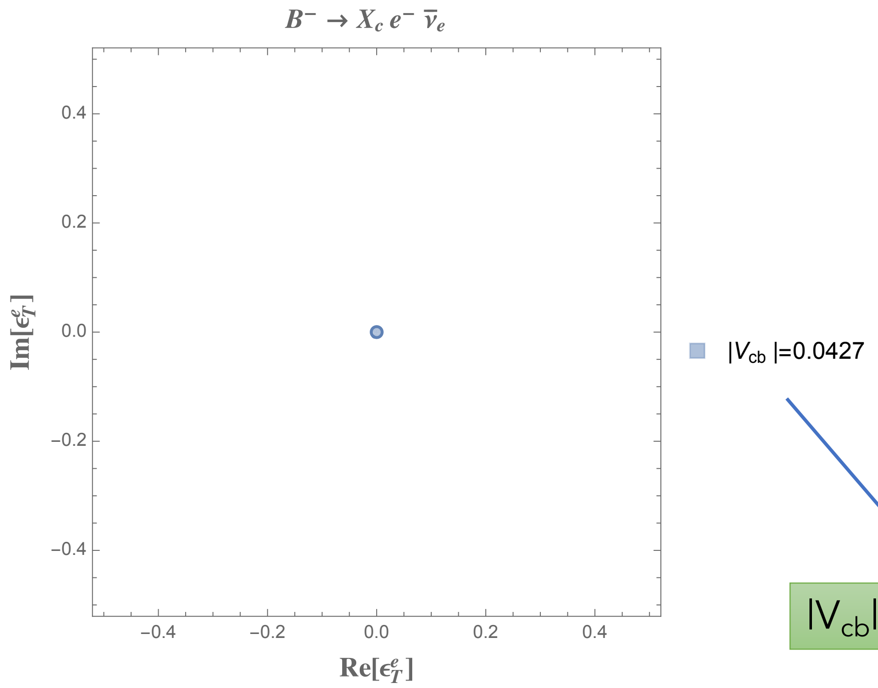


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

$B \to X_c \ell \nu_\ell$
allowed regions in parameter space

allowed ε_T^ℓ correlated to $|V_{cb}|$



$|V_{cb}|<0.04273$

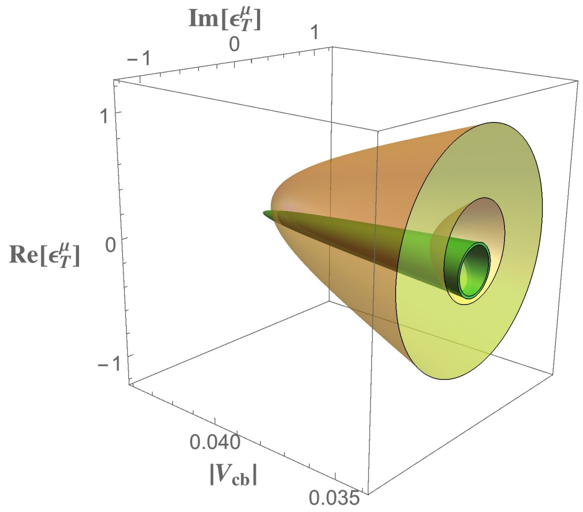
De Fazio PC, PRD 95, 011701(R)

Possible connection with the |V$_{cb}$| puzzle

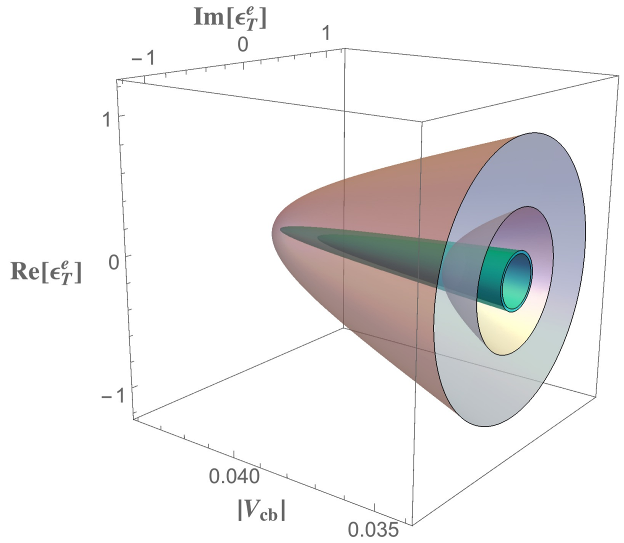
$B \to D \ell \nu_\ell$ + $B \to X_c \ell \nu_\ell$: allowed regions

$$B\left(B^+ \to \bar{D}^0 e^+ \nu_e\right) = \left(2.38 \pm 0.04 \pm 0.15\right) \times 10^{-2}$$

$$B\left(B^+ \to \bar{D}^0 \mu^+ \nu_\mu\right) = \left(2.25 \pm 0.04 \pm 0.17\right) \times 10^{-2}$$



μ mode



e mode

inner regions: inclusive
outer regions: exclusive

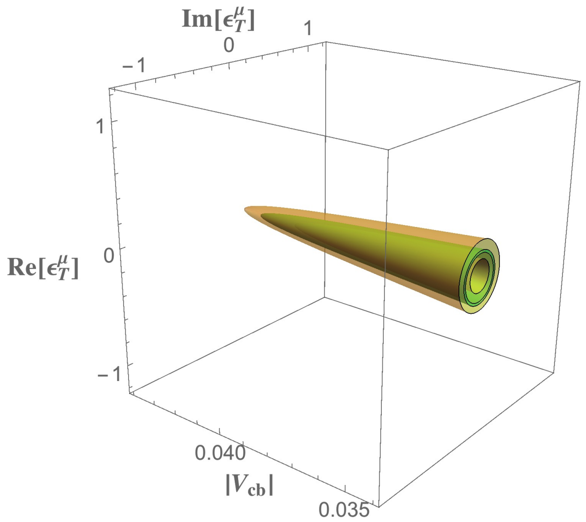
effect of the lepton mass:
the symmetry axes of the two regions do not coincide in the case of μ

De Fazio PC, PRD 95, 011701(R)

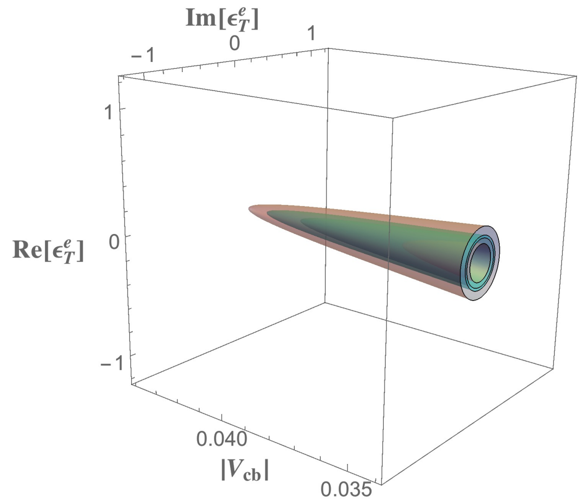
Possible connection with the $|V_{cb}|$ puzzle

$B \to D^* \ell \nu_\ell + B \to X_c \ell \nu_\ell$

$$B\left(B^+ \to \bar{D}^{*0} e^+ \nu_e\right) = (5.50 \pm 0.05 \pm 0.23) \times 10^{-2}$$
$$B\left(B^+ \to \bar{D}^{*0} \mu^+ \nu_\mu\right) = (5.34 \pm 0.06 \pm 0.37) \times 10^{-2}$$



μ mode



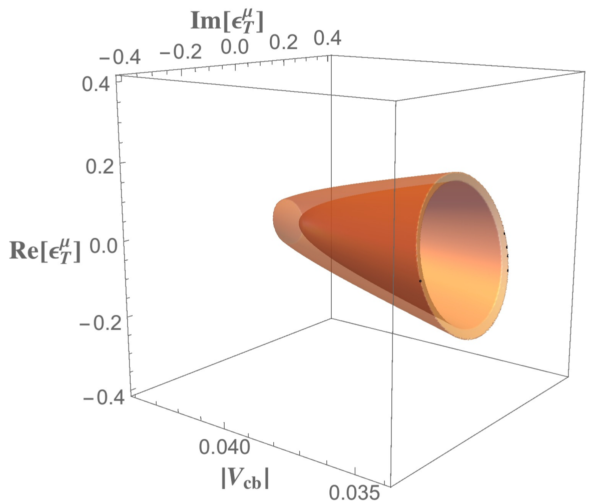
e mode

inner regions: inclusive
outer regions: exclusive

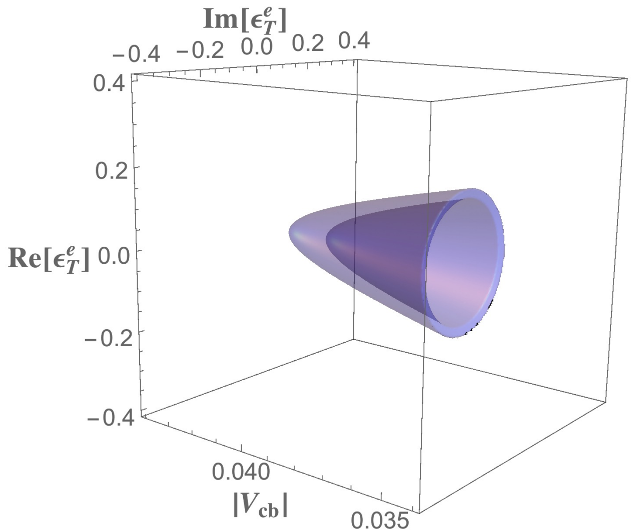
De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

$B \to D \ell \nu_\ell + B \to D^* \ell \nu_\ell + B \to X_c \ell \nu_\ell$



μ mode



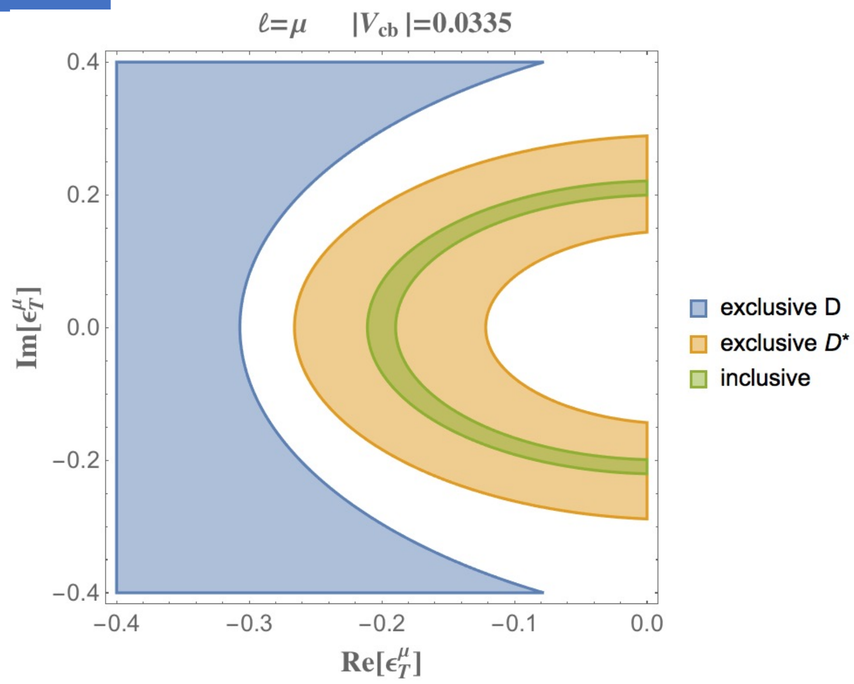
e mode

De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

projections in the (Re ε_T, Im ε_T) plane

μ mode

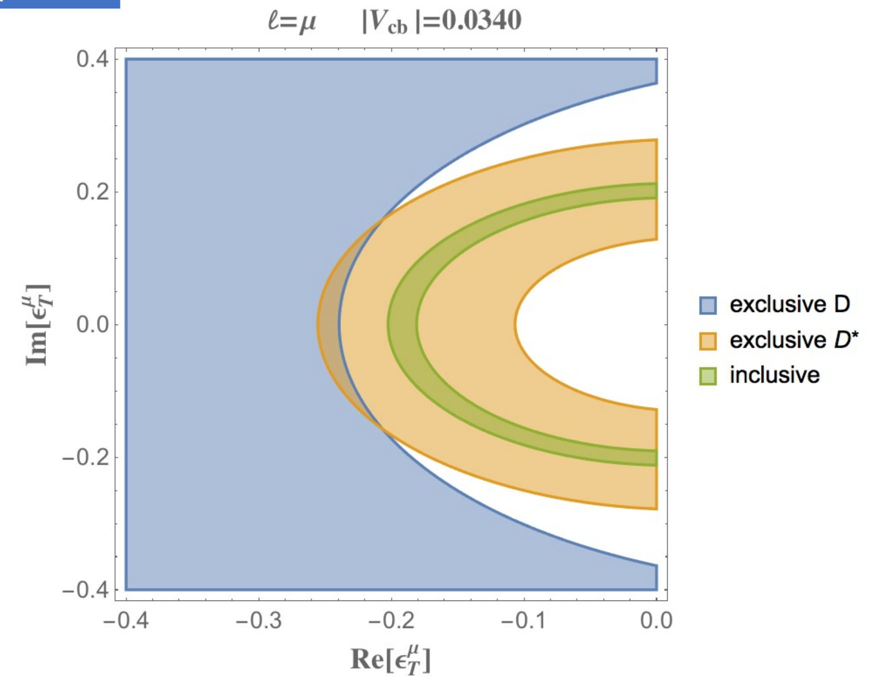


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

projections in the (Re ε_T, Im ε_T) plane

μ mode

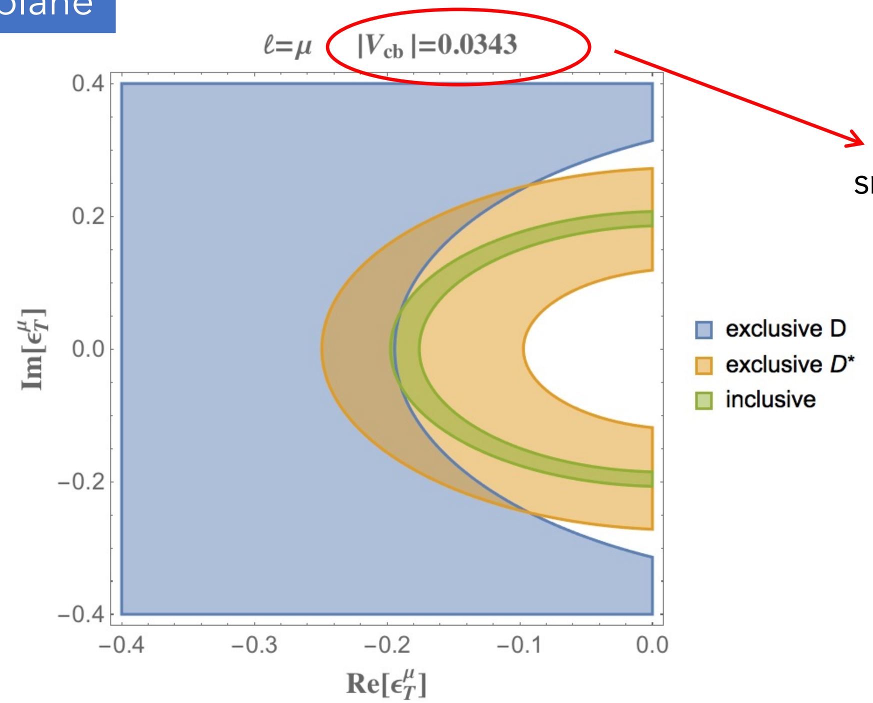


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

projections in the (Re ε_T, Im ε_T) plane

μ mode



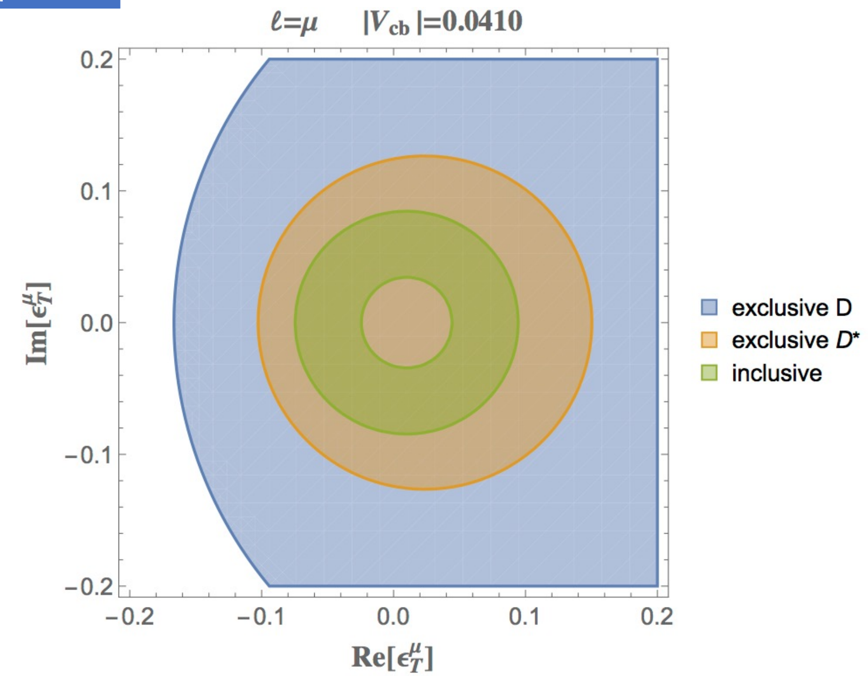
smallest allowed value

De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

projections in the (Re ε_T, Im ε_T) plane

μ mode

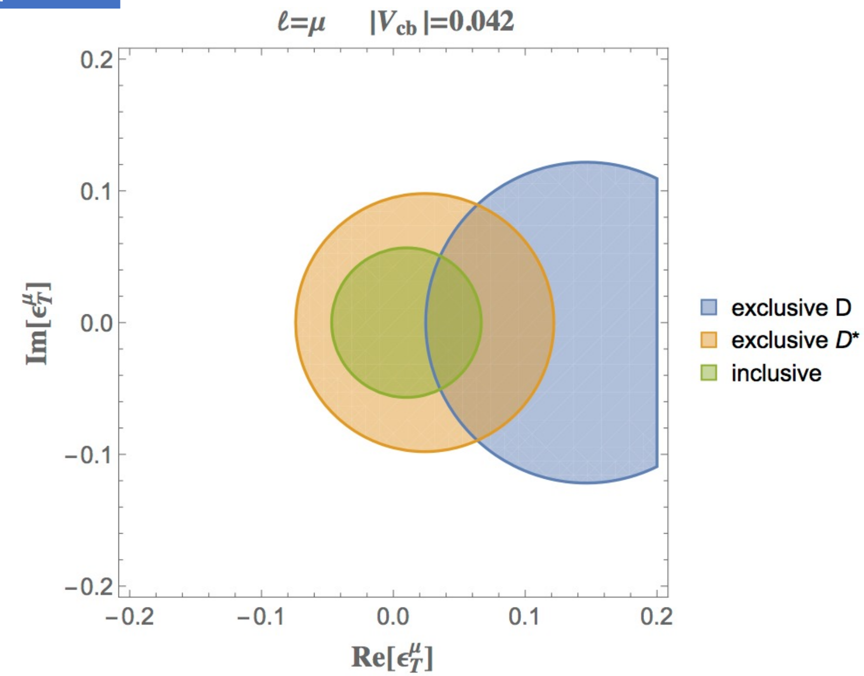


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

projections in the (Re ε_T, Im ε_T) plane

μ mode

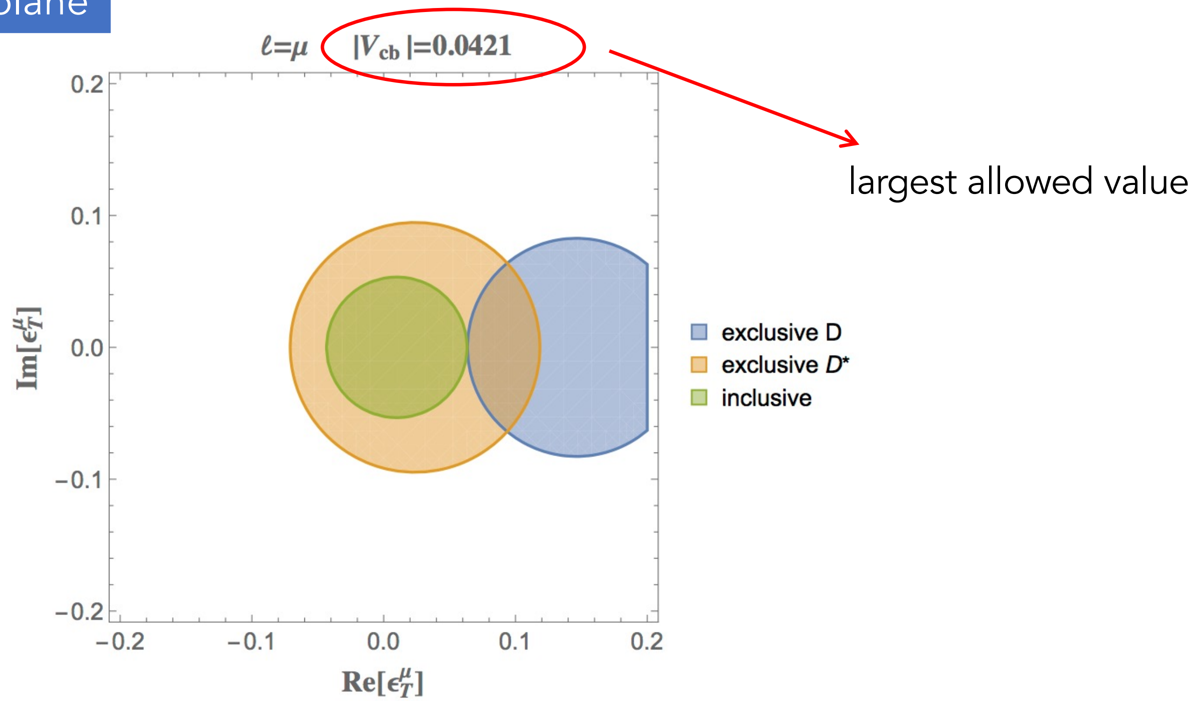


De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle

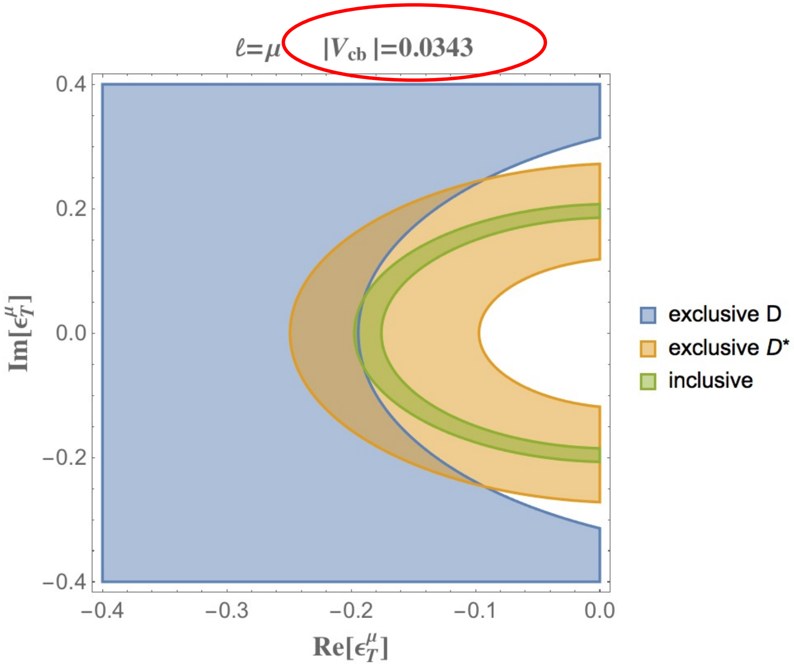
projections in the ($\text{Re}\ \varepsilon_T$, $\text{Im}\ \varepsilon_T$) plane

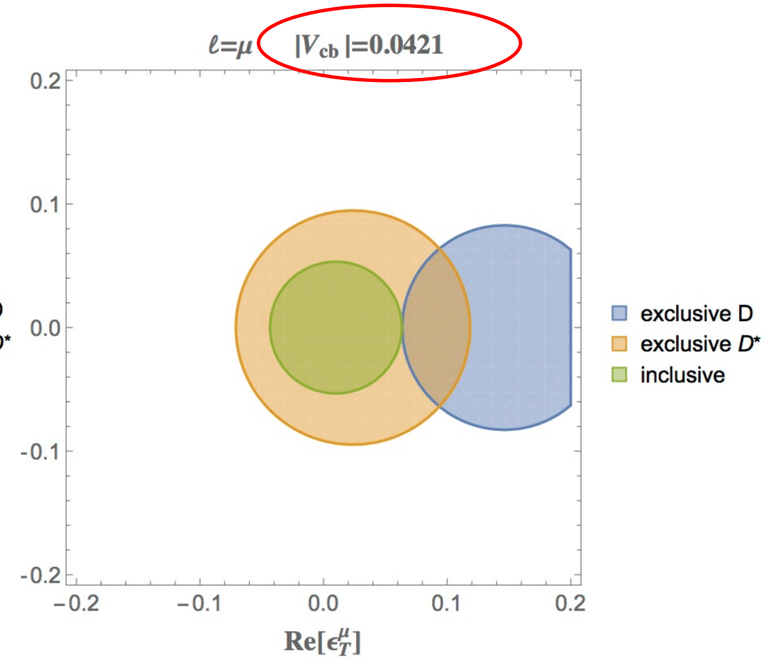
μ mode



De Fazio PC, PRD 95, 011701(R)

Possible connection with the $|V_{cb}|$ puzzle





μ mode

$|V_{cb}| \in [0.0343, 0.0421]$

e mode

$|V_{cb}| \in [0.0360, 0.0427]$

all constraints fulfilled for $|V_{cb}| \in [0.036, 0.042]$

SM-NP interference sizable for μ

Conclusions

Inclusive heavy hadron decays

- important for $|V_{cb}|$ and $|V_{ub}|$ determinations
- testing ground for NP

Improvements

- new results for heavy baryons: hadronic matrix elements for a polarized baryon at $O(1/m_b^3)$ including all BSM D=6 operators
- fully differential distribution for non-vanishing m_l

- New clean observable testing LFU: ratio of the slope parameter in the cos (θ_P) distribution correlated with $R(\Lambda_b)$ shows a pattern of deviation from SM
Measurement accessible at the future lepton colliders (ILC, FCC-ee)

A precise determination of the nonperturbative parameters for heavy baryons is mandatory

$\hat{\mu}_\pi^2$ $\hat{\rho}_D^3$ $\hat{\rho}_{LS}^3$

The possibility of a NP origin of the tensions in the CKM matrix elements, related to the R(D) anomalies, should not be discarded