Semileptonic B decays: features – anomalies - challenges

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outline

- tensions and anomalies in semileptonic B decays
- model independent analyses
- which model beyond SM?

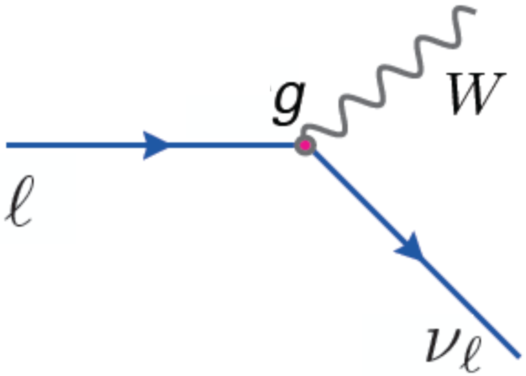
based on F. De Fazio, F. Loparco & PC:
arxiv:1906.07068; JHEP 1806, 082; PRD 95, 011701(R)

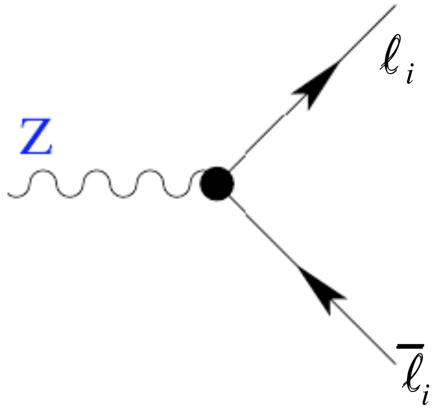
Helmoltz – DIAS International Summer School
Quantum Field Theory at the Limits:
From strong fields to heavy quarks
Dubna, July 22 – August 2, 2019

$SU(2)_L \times U(1)_Y$

Lepton Flavour Universality

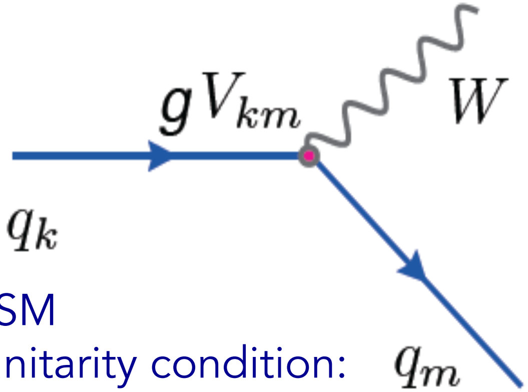
same couplings of the lepton generations to the gauge bosons





charged current quark transitions

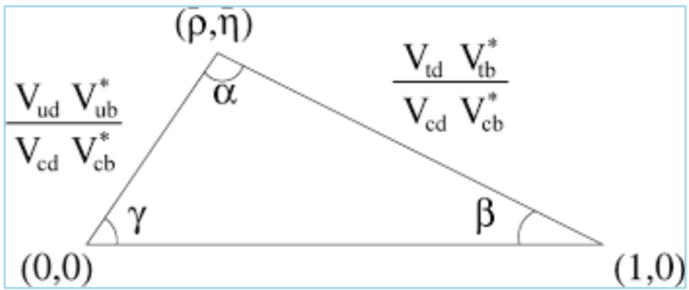
unitary V_{CKM}



elements are parameters of the SM

relations provided by unitarity condition: unitarity triangles

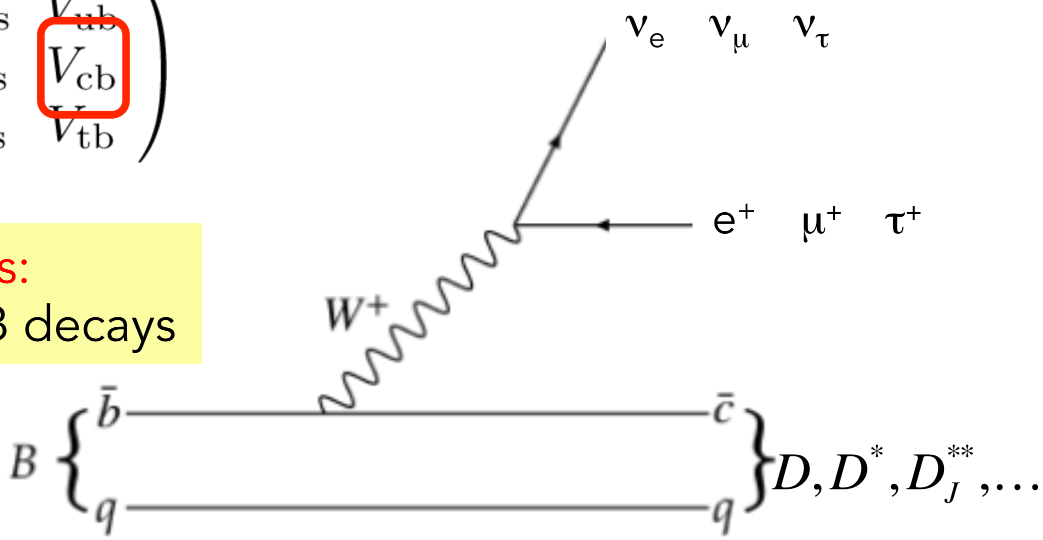
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

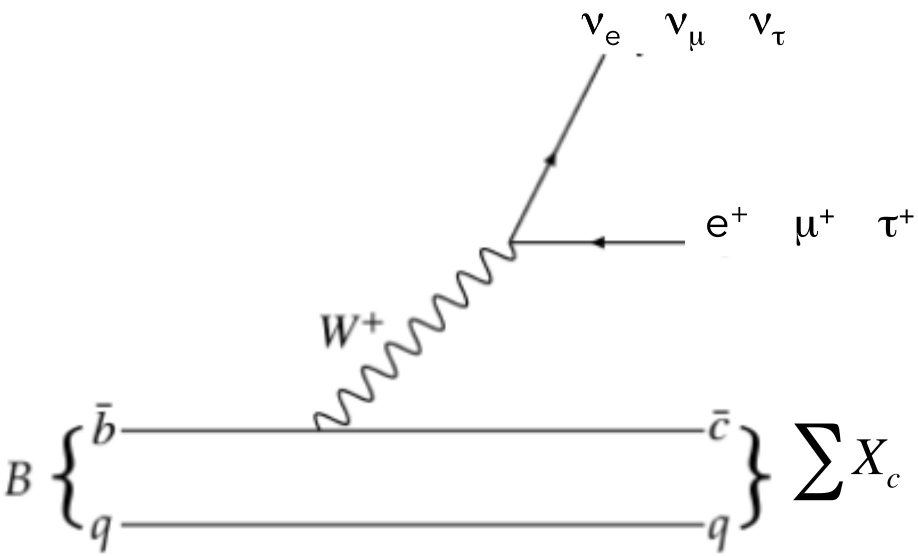


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

$|V_{cb}|$ measurements:
use semileptonic B decays

exclusive processes

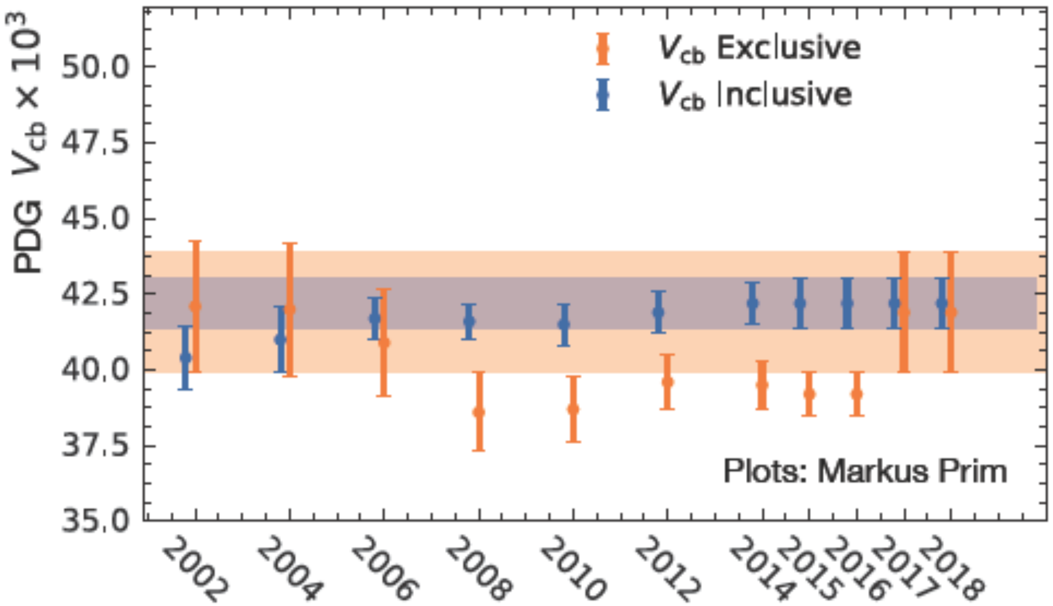




inclusive mode

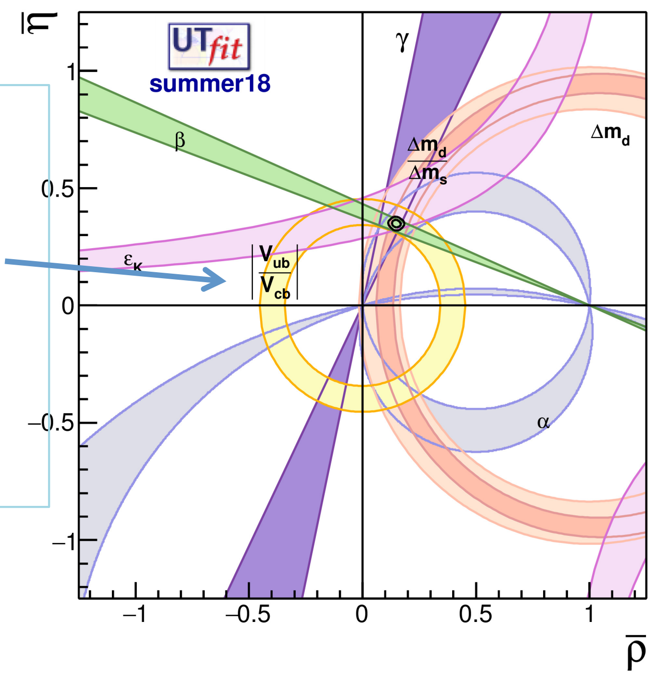
other b decay modes (B_c purely leptonic, Λ_b->Λ_c …) more rare or less precise

$|V_{cb}|_{excl}$ vs $|V_{cb}|_{incl}$

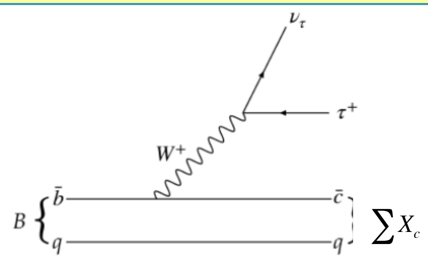


$|V_{cb}|$ important parameter

- $|V_{ub}|/|V_{cb}|$ constrains the UT triangle
- rare decays $|V^{*}_{tb}\ V_{ts}|^2$ -> $|V_{cb}|^2\ (1+O(\lambda^2))$
- …..



inclusive width
computed using OPE



$$\Gamma \propto \sum_X (2\pi)^4 \delta^4(P_B - P_X) |\langle X | \mathcal{H}_{eff} | B(v) \rangle|^2$$
$$= \int d^4x \, \langle B(v) | \mathcal{H}_{eff}(x) \mathcal{H}^\dagger_{eff}(0) | B(v) \rangle$$
$$= 2\,\mathrm{Im} \int d^4x \, \langle B(v) | T\{\mathcal{H}_{eff}(x) \mathcal{H}^\dagger_{eff}(0)\} | B(v) \rangle$$
$$= 2\,\mathrm{Im} \int d^4x \, e^{-im_b v\cdot x} \langle B(v) | T\{\widetilde{\mathcal{H}}_{eff}(x) \widetilde{\mathcal{H}}^\dagger_{eff}(0)\} | B(v) \rangle$$

Shifman Vainshtein Uraltsev
Georgi Bigi Chay Manohar
Wise Neubert Mannel
Gambino

$$\int d^4x e^{im_b vx} T\{\widetilde{\mathcal{H}}_{eff}(x) \widetilde{\mathcal{H}}^\dagger_{eff}(0)\}$$
$$= \sum_{n=0}^{\infty} \left(\frac{1}{2m_Q}\right)^n C_{n+3}(\mu) \mathcal{O}_{n+3}$$

OPE

$$\Gamma = \Gamma_0 + \frac{1}{m_Q}\Gamma_1 + \frac{1}{m_Q^2}\Gamma_2 + \frac{1}{m_Q^3}\Gamma_3 + \cdots$$

free quark decay width — vanishes — power corrections

each Γ_i expanded in α_s

input

- m_b m_c α_s
- non perturbative parameters

$$\Gamma_2: \quad \begin{cases} 2M_H \mu_\pi^2 = -\langle H(v) | \bar{Q}_v (iD)^2 Q_v | H(v) \rangle \\ 2M_H \mu_G^2 = \langle H(v) | \bar{Q}_v \sigma_{\mu\nu} (iD^\mu)(iD^\nu) Q_v | H(v) \rangle \end{cases}$$

$$\Gamma_3: \quad \begin{cases} 2M_H \rho_D^3 = -\langle H(v) | \bar{Q}_v (iD_\mu)(ivD)(iD^\mu) Q_v | H(v) \rangle \\ 2M_H \rho_{LS}^3 = \langle H(v) | \bar{Q}_v \sigma_{\mu\nu} (iD^\mu)(ivD)(iD^\nu) Q_v | H(v) \rangle \end{cases}$$

Γ_4: 5 parameters

width, spectrum and moments → $|V_{cb}|$

HQE parameters

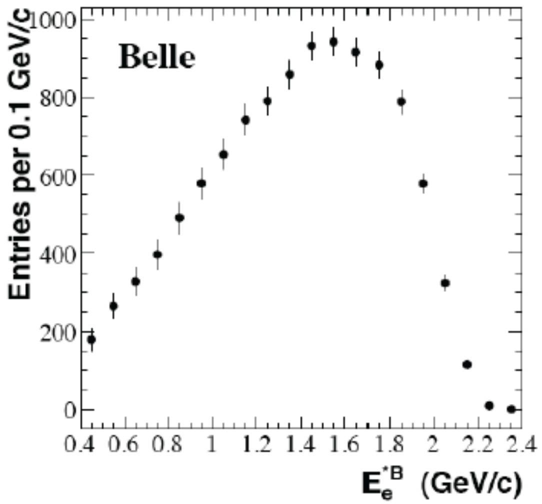
E_l charged lepton energy

M_x hadronic invariant mass

$$|V_{cb}|_{incl} = (42.46 \pm 0.88) \times 10^{-3}$$

$$\langle M_X^n \rangle = \frac{1}{\Gamma} \int dM_X \, M_X^n \int_{E_{cut}} dE_\ell \, \frac{d^2\Gamma}{dM_x \, dE_\ell}$$

$$\langle E_\ell^n \rangle = \frac{1}{\Gamma} \int dM_X \int_{E_{cut}} dE_\ell \, E_\ell^n \frac{d^2\Gamma}{dM_x \, dE_\ell}$$

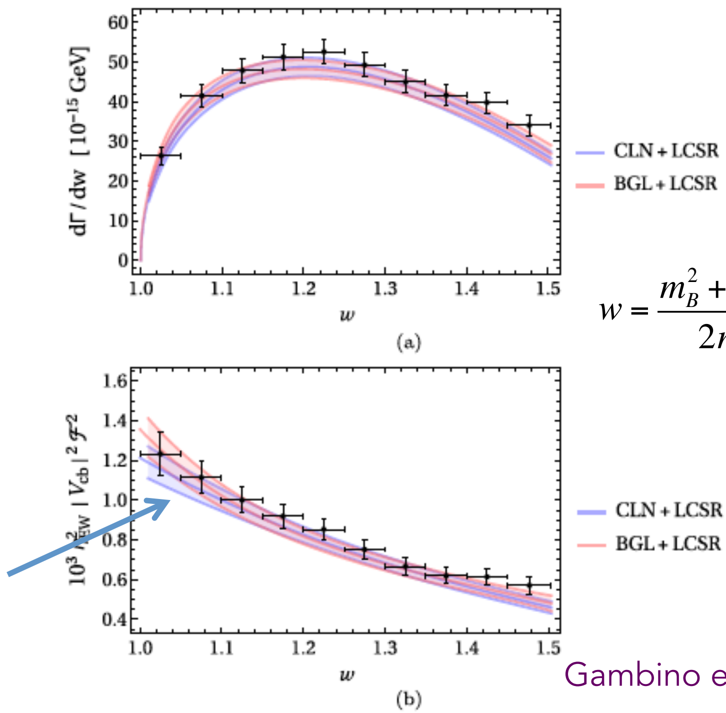


lepton energy spectrum

$|V_{cb}|$ from $\bar{B} \to D^* \ell \bar{\nu}_\ell$

Th. uncertainties in hadronic form factors

lepton pair invariant mass distribution



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

behaviour close to to q^2_{max} extrapolated

-> $|V_{cb}|^2 F(1)^2$

Gambino et al

F(1)=1 in the large m_Q limit

from lattice QCD: F(1)=0.906(13) (FNAL/MILC)

F(1)=0.895(26) (HPQCD)

no $O(1/m_Q)$ corrections at q^2_{max}

$$\langle D^*(p_{D^*},\epsilon)|\bar{c}\gamma_\mu(1-\gamma_5)b|\bar{B}(p_B)\rangle = -\frac{2V(q^2)}{m_B+m_{D^*}} i\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p_B^\alpha p_{D^*}^\beta - \left\{(m_B+m_{D^*})\left[\epsilon^*_\mu - \frac{(\epsilon^*\cdot q)}{q^2}q_\mu\right]A_1(q^2) - \frac{(\epsilon^*\cdot q)}{m_B+m_{D^*}}\left[(p_B+p_{D^*})_\mu - \frac{m_B^2-m_{D^*}^2}{q^2}q_\mu\right]A_2(q^2) + (\epsilon^*\cdot q)\frac{2m_{D^*}}{q^2}q_\mu A_0(q^2)\right\} \quad (2.24)$$

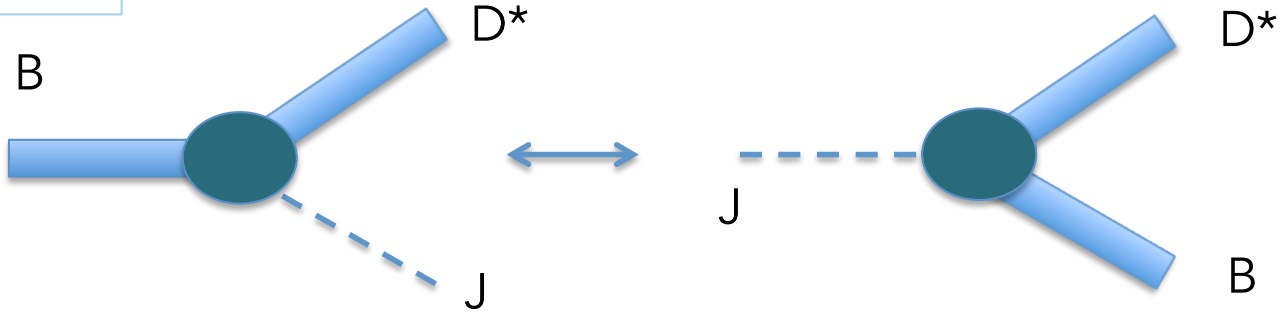
SM

$$\langle D^*(p_{D^*},\epsilon)|\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b|\bar{B}(p_B)\rangle = T_0(q^2)\frac{\epsilon^*\cdot q}{(m_B+m_{D^*})^2}\epsilon_{\mu\nu\alpha\beta}p_B^\alpha p_{D^*}^\beta + T_1(q^2)\epsilon_{\mu\nu\alpha\beta}p_B^\alpha\epsilon^{*\beta} + T_2(q^2)\epsilon_{\mu\nu\alpha\beta}p_{D^*}^\alpha\epsilon^{*\beta} + i\left[T_3(q^2)(\epsilon^*_\mu p_{B\nu}-\epsilon^*_\nu p_{B\mu}) + T_4(q^2)(\epsilon^*_\mu p_{D^*\nu}-\epsilon^*_\nu p_{D^*\mu}) + T_5(q^2)\frac{\epsilon^*\cdot q}{(m_B+m_{D^*})^2}(p_{B\mu}p_{D^*\nu}-p_{B\nu}p_{D^*\mu})\right].$$

NP

FF parametrization

crossing +
analyticity



physical semileptonic region

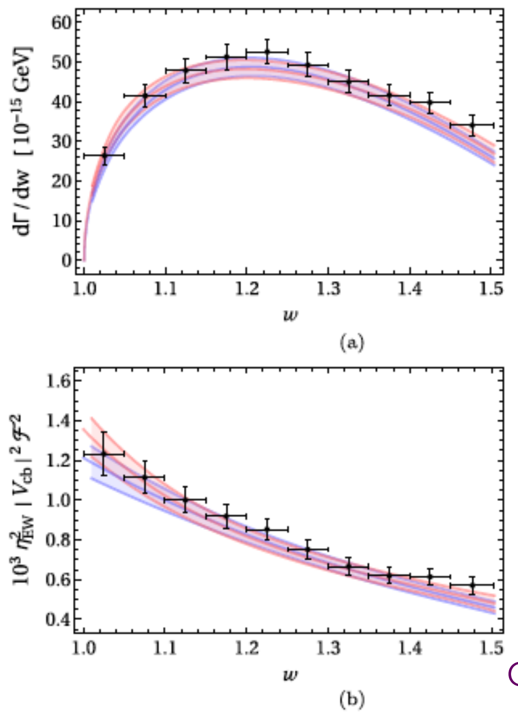
$$m_\ell^2 \le q^2 \le (m_B - m_{D^*})^2$$

two-point corr. cut

$$q^2 \ge (m_B + m_{D^*})^2$$

$|V_{cb}|$ from $\bar{B} \to D^* \ell \bar{\nu}_\ell$

Th. uncertainties in hadronic form factors
- value at maximum q^2 F(1)
- shape close to maximum q^2



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

Gambino et al.

Caprini Lellouch Neubert

CLN: Heavy Quark Theory relations

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right]$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$
$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2,$$

5 parameters

Boyd Grinstein Lebed

BGL: analiticity + crossing symm.

$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{N} a_n z^n.$$

$$\sum_{n=0}^{N} |a_n|^2 \leq 1$$

$$z = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$
$$t_\pm = (M_B \pm M_{D^*})^2$$
$$t_0 = t_+ - \sqrt{t_+(t_+ - t_-)}$$

Blatsche factors ($B^{(n)}_c$ poles) + phase space functions

parameters

$|V_{cb}|_{excl}$ vs $|V_{cb}|_{incl}$

$$|V_{cb}|^{D^*}_{excl} = (39.27 \pm 0.56_{th} \pm 0.49_{exp}) \times 10^{-3}$$

$$|V_{cb}|^{D}_{excl} = (40.85 \pm 0.98) \times 10^{-3}$$

LQCD+CLN+BABAR+Belle+LHCb

CLN: Caprini Lellouch Neubert

Gambino et al
Grinsten et al
Berlochner et al

$$|V_{cb}|^{D^*}_{excl} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$$

LQCD+BGL+Belle (dataset in 1701.0827)

BGL: Boyd Grinstein Lebed

new BABAR and Belle

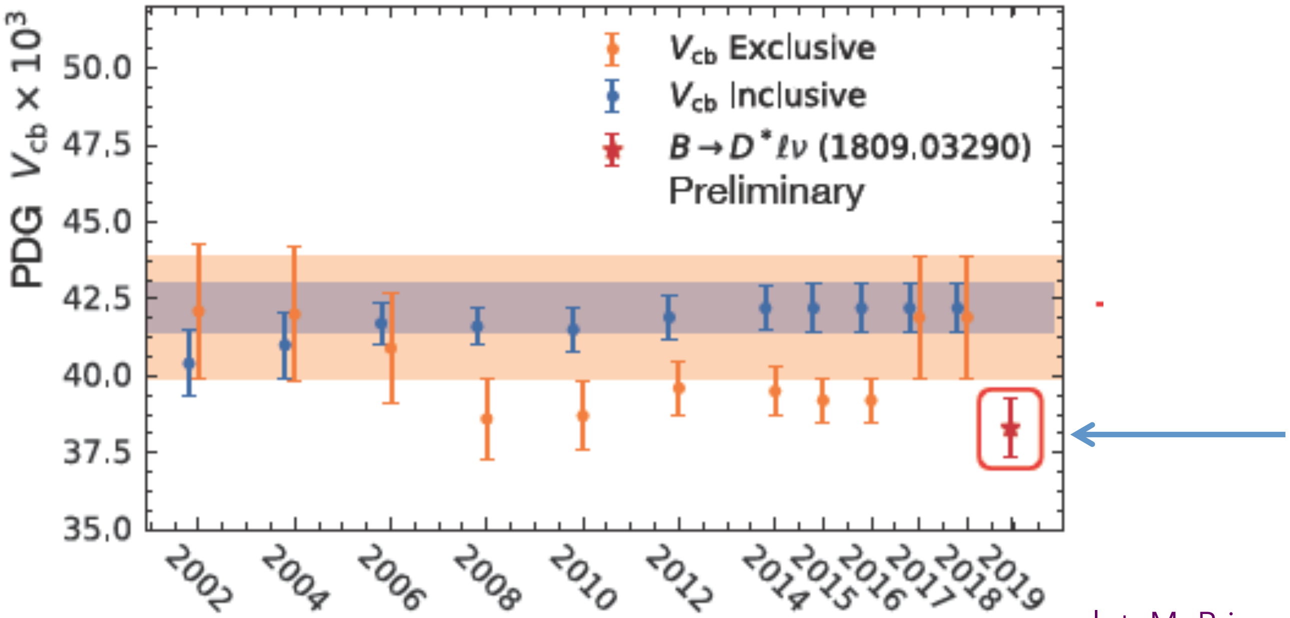
$$|V_{cb}|^{D^*}_{excl} = (38.36 \pm 0.90) \times 10^{-3}$$

LQCD+BGL+BABAR (1903.10002)
LQCD+BGL+Belle (1809.03290)

$$|V_{cb}|_{incl} = (42.46 \pm 0.88) \times 10^{-3}$$

Heavy FLavour AVeraging group

$|V_{cb}|_{excl}$ vs $|V_{cb}|_{incl}$



plot: M. Prim

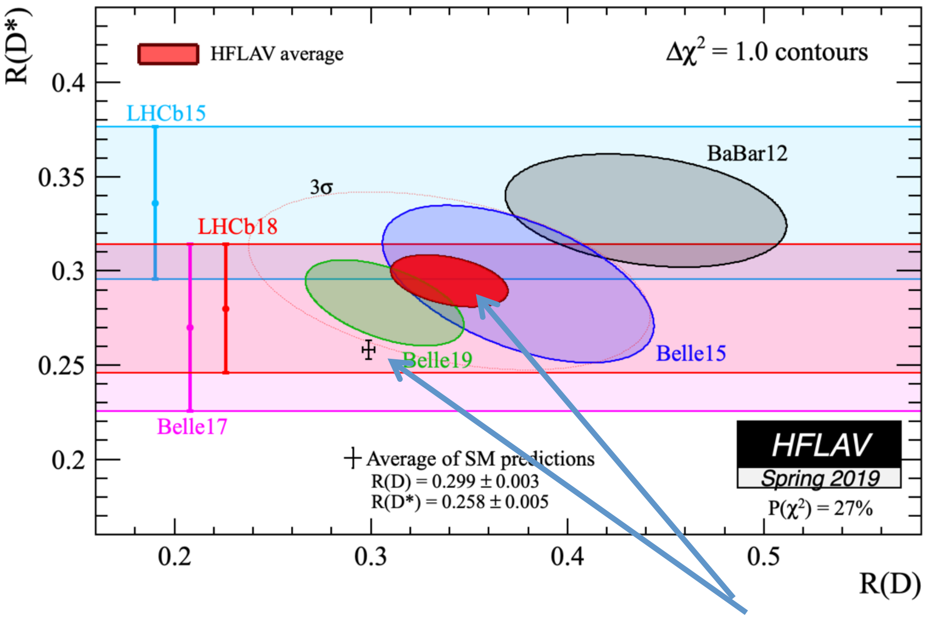
- confirmation of the lattice QCD result for F(1) required (SM solution of the puzzle)
- however, another anomaly has been detected in b –> c semileptonic modes

anomalies in R(D$^{(*)}$)

$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell)}$$

$$\mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell)}$$

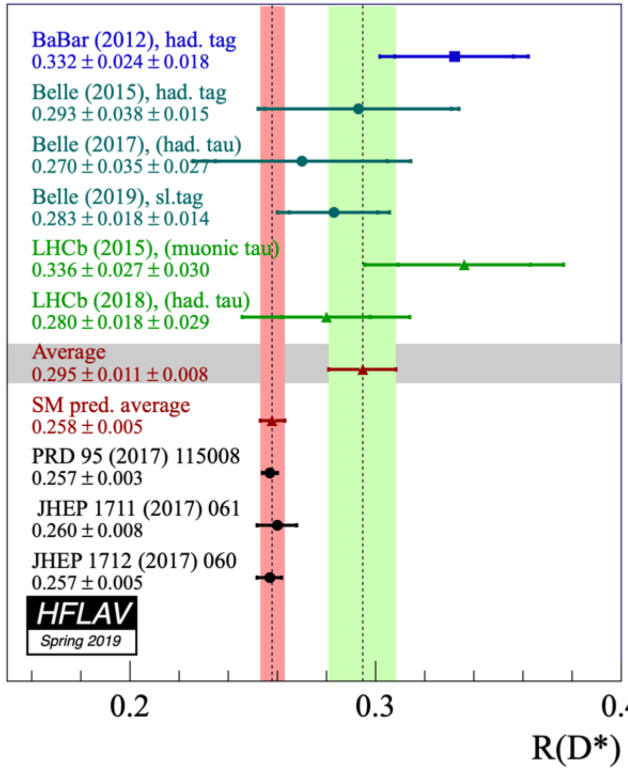
l=e, μ

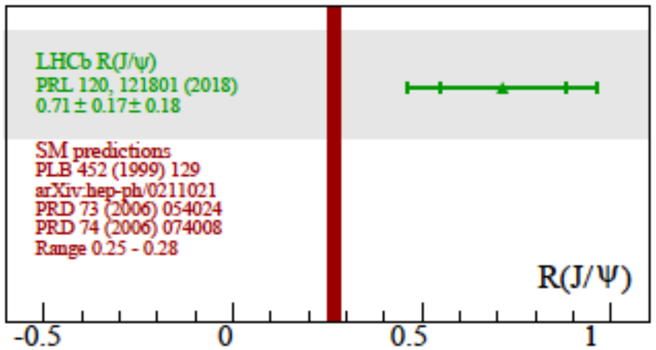


3.1 σ from SM

Fajfer et al.

form factor uncertainties largely cancel out in the ratios





$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$$

M. Ivanov et al.

➔τ/μ,e universality questioned

SM or BSM effects?

Are the $R(D^{(*)})$ and $|V_{cb}|$ issues different problems
or
are they related?

SM successful theory of physics phenomena up to the ew scale

SM not expected to hold much above that scale, but its (eventual) extension is unknown

pragmatic approach

experimental input (anomalies)

SM-EFT model independent analysis

simplified BSM Models

more fundamental NP models (accounting for the origin of flavour, …)

$$L_{eff} = L_{SM} + \sum \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^d$$

← SM operators

$$A = A_{SM} + \frac{c}{\Lambda^2}$$

← process dependent (c)

← new energy scale (Λ)

Buchmuller and Wyler
Grzadkowski et al.
Contino et al. , …

flavour ansatz: NP mainly coupled to the third fermion family

R(D(*)) consider additional operators

example: operator enhancing B to τ semileptonic modes and leaving $\tau(B_c)$ quite unaffected

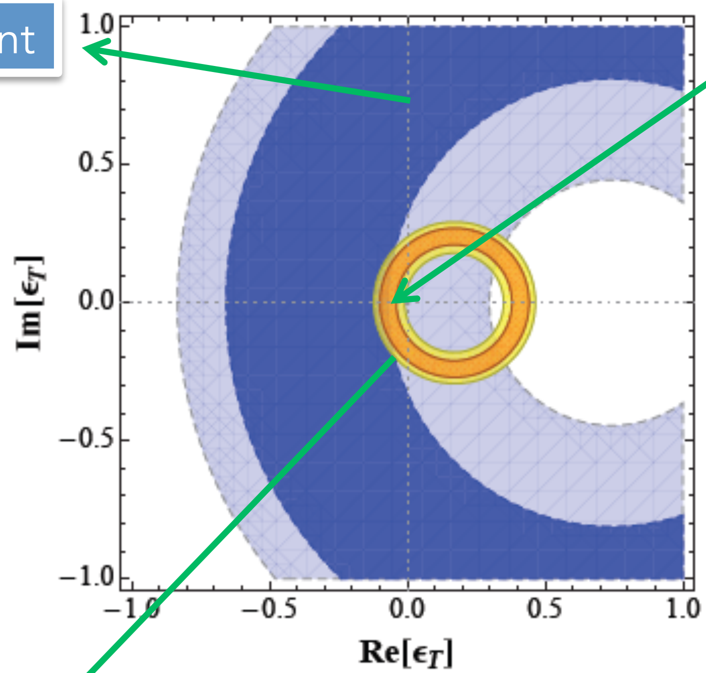
Biancofiore De Fazio PC

$$H_{eff} = H_{eff}^{SM} + H_{eff}^{NP} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{c}\gamma_\mu (1-\gamma_5) b \, \bar{\ell}\gamma^\mu (1-\gamma_5)\bar{\nu}_\ell + \epsilon_T^\ell \, \bar{c}\sigma_{\mu\nu}(1-\gamma_5) b \, \bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\bar{\nu}_\ell \right]$$

$\varepsilon_T^{\mu,e}=0, \ \varepsilon_T^{\tau} \neq 0$

common range

R(D) constraint



R(D*) constraint

analyze the phenomenological consequences

$|V_{cb}|$ problem

arguments against a NP option

- for H_{eff} with new four-fermion operators (S,P,T) and massless leptons, at zero recoil no interference between SM and NP contributions
- same NP effect in all modes

Crivellin Pokorski, PRL 114, 011802 (2015)

The arguments can be evaded:

- consider new operators in H_{eff} (example: tensor)
- relax the assumption that it contributes only for τ lepton
- keep non vanishing m_ℓ $\ell=e,\mu,\tau$ and $m_e \neq m_\mu$

De Fazio PC, PRD 95, 011701(R)

same NP example:

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}[\bar{c}\gamma_\mu(1-\gamma_5)b\bar{\ell}\gamma^\mu(1-\gamma_5)\bar{\nu}_\ell \quad + \epsilon_T^\ell \bar{c}\sigma_{\mu\nu}(1-\gamma_5)b\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\bar{\nu}_\ell]$$

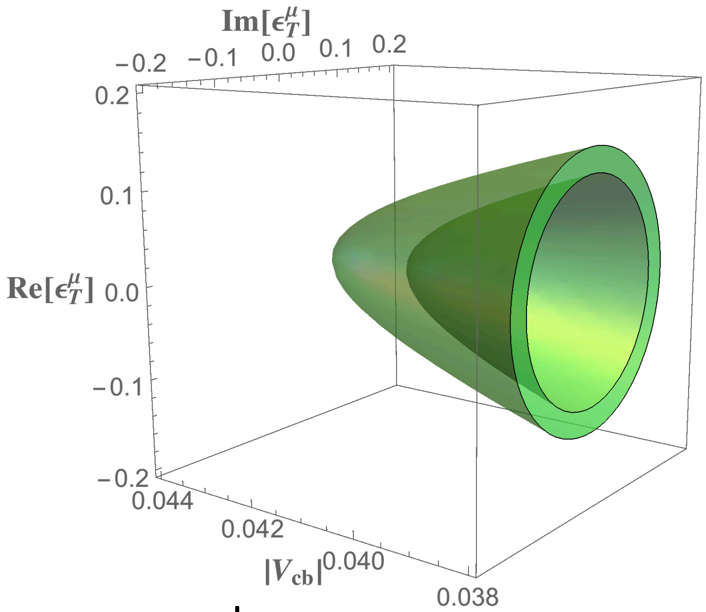
B -> $X_c \ell \nu_\ell$

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

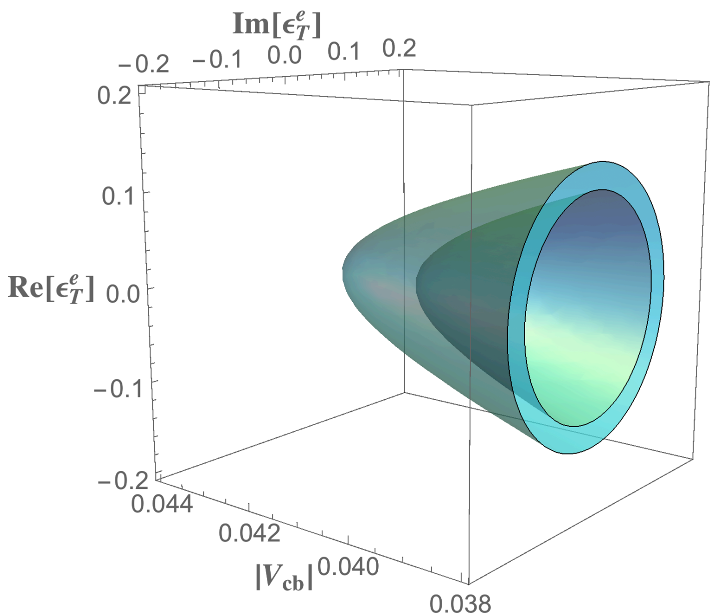
$\Gamma_{SM,\ NP,\ INT}$ expanded in $1/m_Q$

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

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



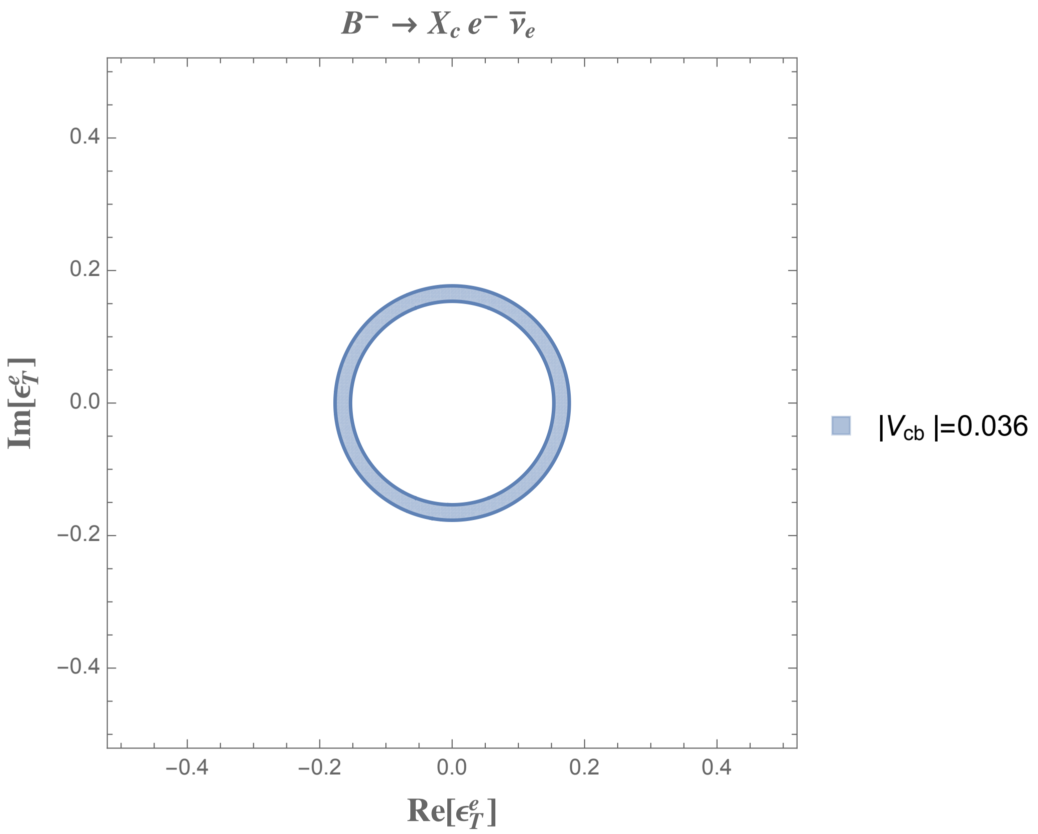
μ mode



e mode

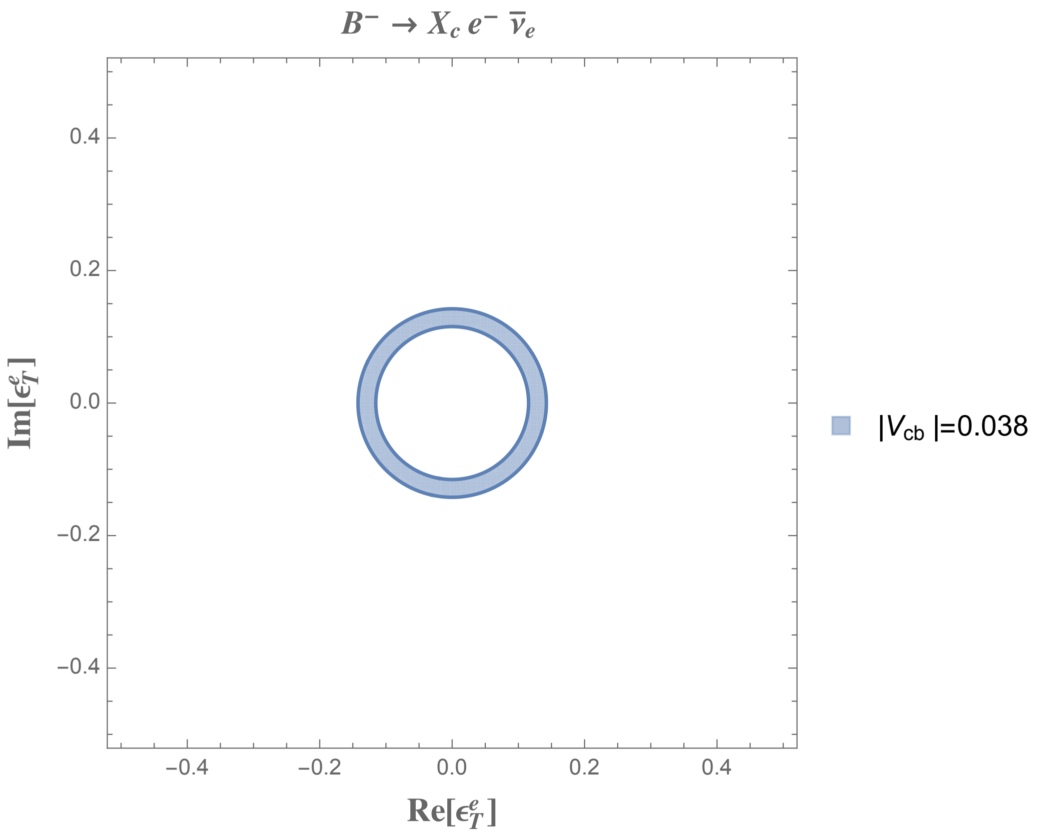
$B \to X_c \ell \nu_\ell$
allowed regions in parameter space

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



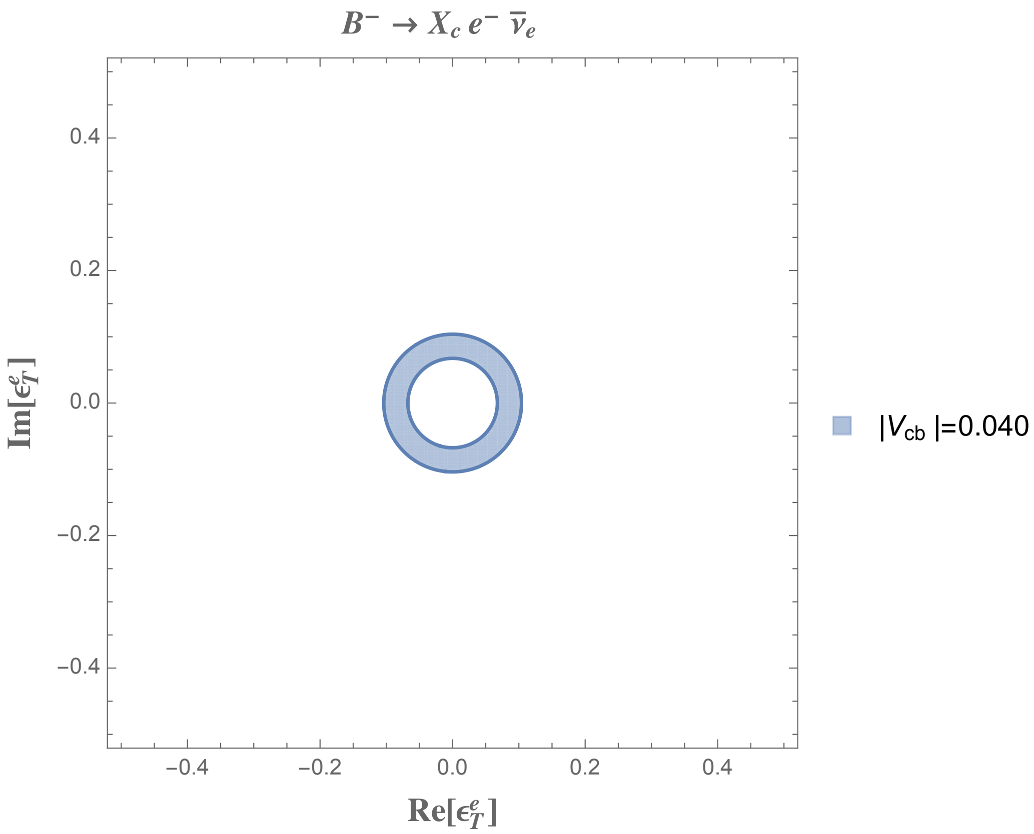
B -> $X_c \ell \nu_\ell$
allowed regions in parameter space

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



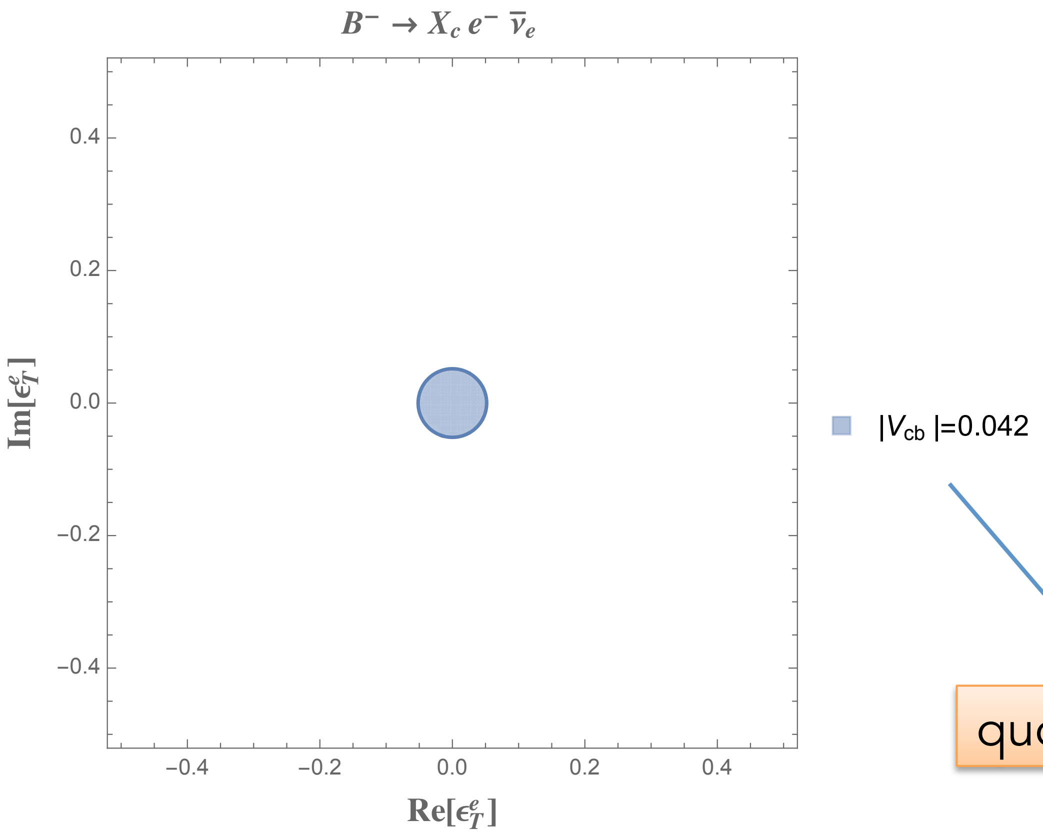
$B \to X_c \ell \nu_\ell$
allowed regions in parameter space

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



B -> $X_c\ \ell\nu_\ell$
allowed regions in parameter space

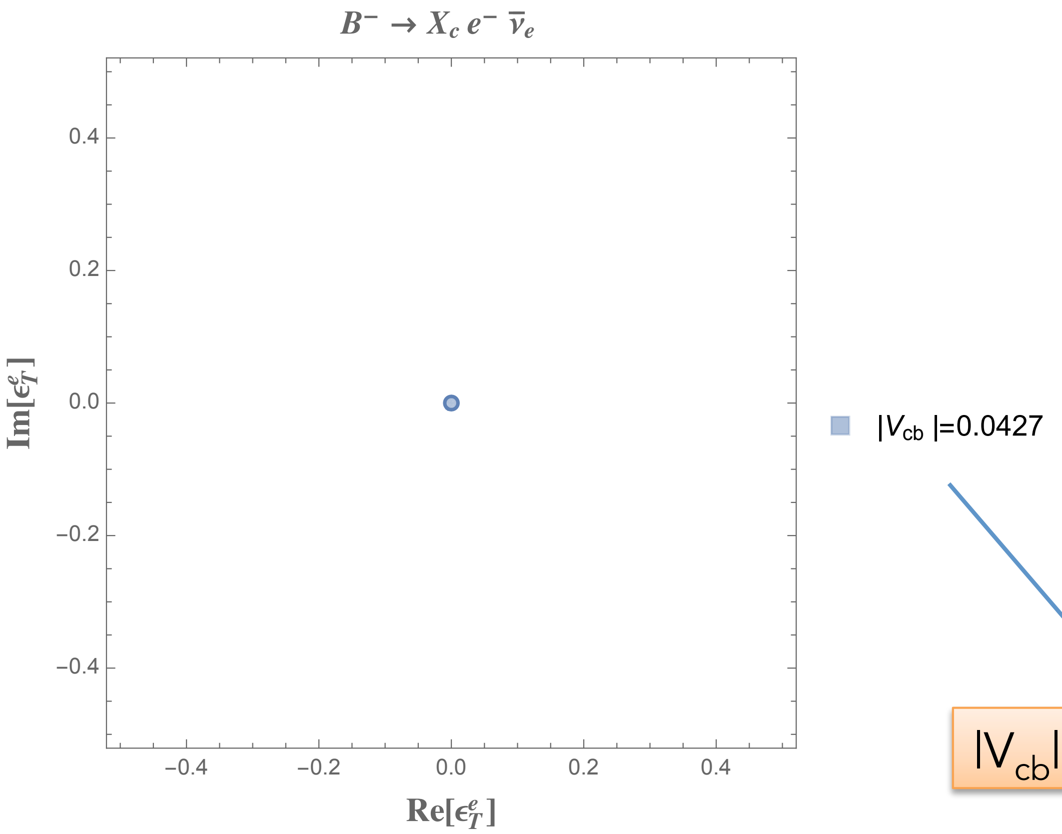
allowed ε_T^ℓ correlated to $|V_{cb}|$



quoted value for SM

B -> $X_c \ell \nu_\ell$
allowed regions in parameter space

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

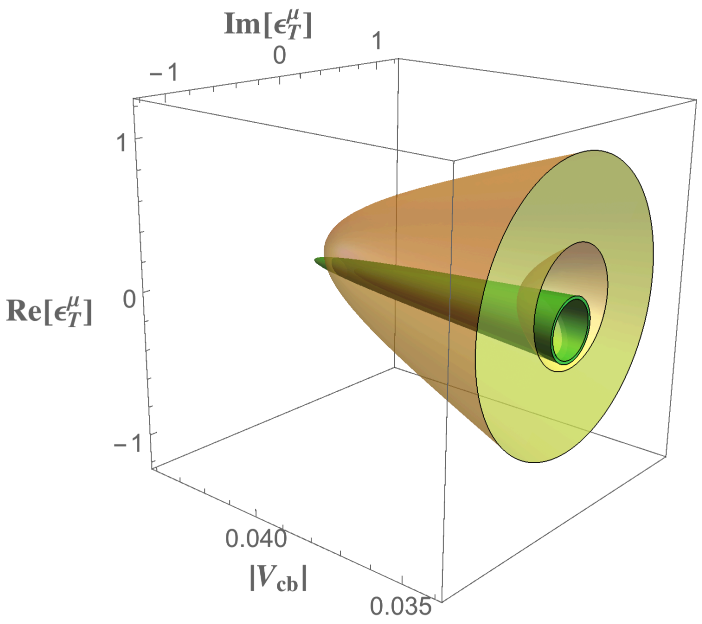


$|V_{cb}|$<0.04273

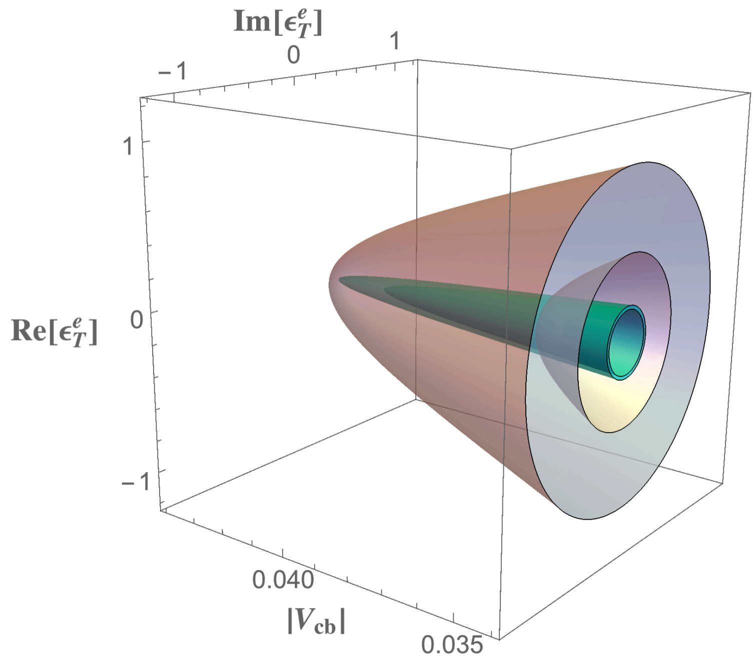
B -> D $\ell\nu_\ell$ + B -> X_c $\ell\nu_\ell$: allowed regions

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

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



μ mode



e mode

inner regions: inclusive
outer regions: exclusive

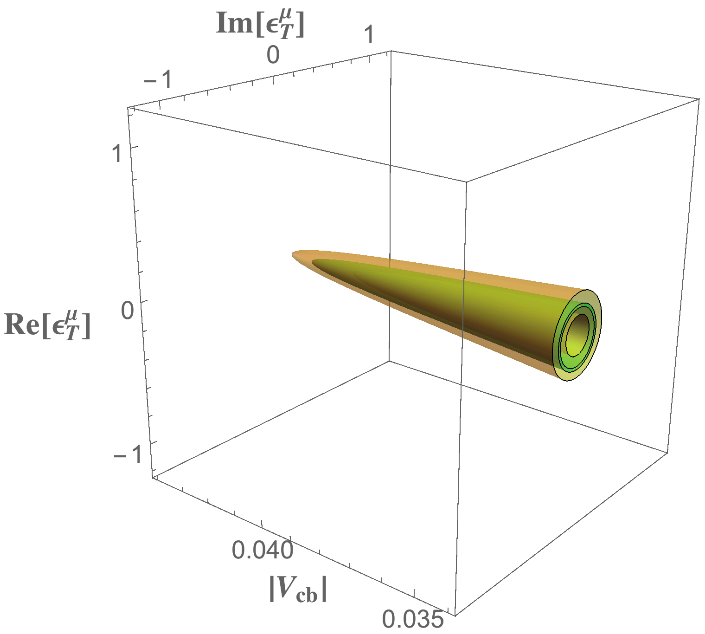
effect of the lepton mass:
the symmetry axes of the two regions do not coincide in the case of μ

B -> D* $\ell\nu_\ell$ + B -> X_c $\ell\nu_\ell$

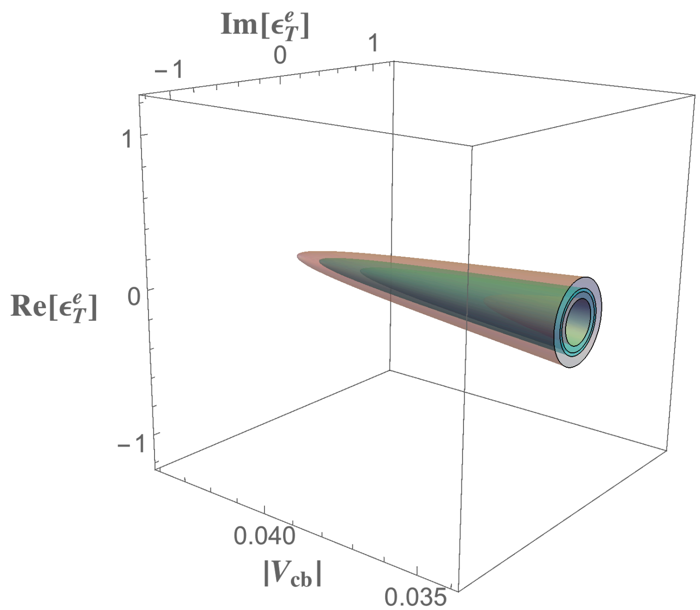
$$B\left(B^{+}\to\bar{D}^{*0}e^{+}\nu_{e}\right)=\left(5.50\pm0.05\pm0.23\right)\times10^{-2}$$

$$B\left(B^{+}\to\bar{D}^{*0}\mu^{+}\nu_{\mu}\right)=\left(5.34\pm0.06\pm0.37\right)\times10^{-2}$$

BABAR, PRD79, 012002 (2009)



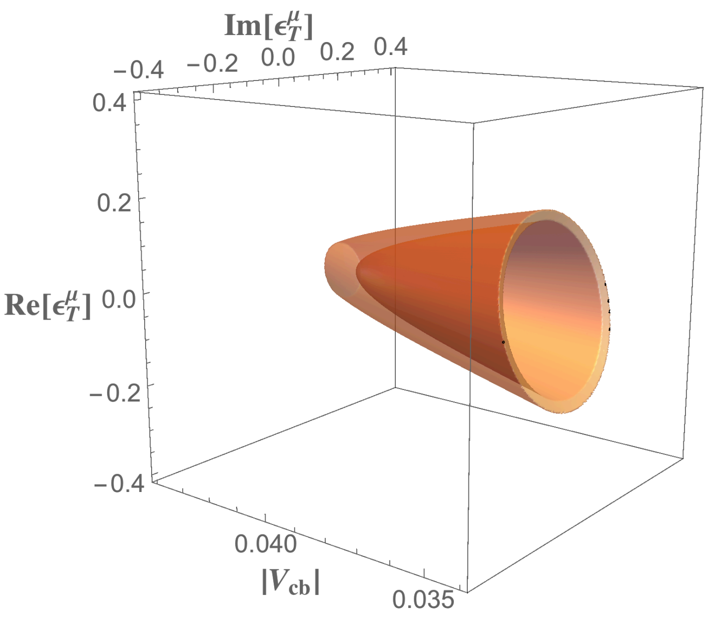
μ mode



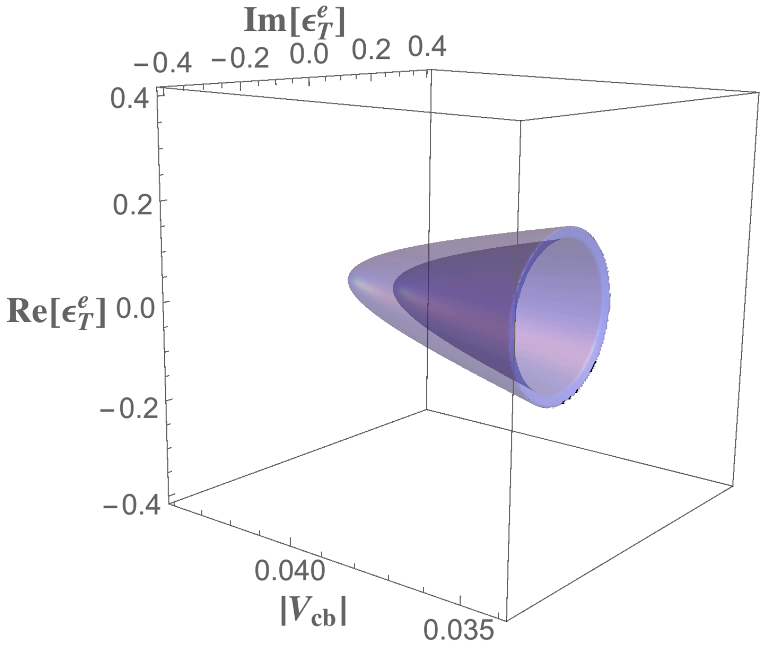
e mode

inner regions: inclusive
outer regions: exclusive

B -> D $\ell\nu_\ell$ +B -> D* $\ell\nu_\ell$ + B -> X_c $\ell\nu_\ell$



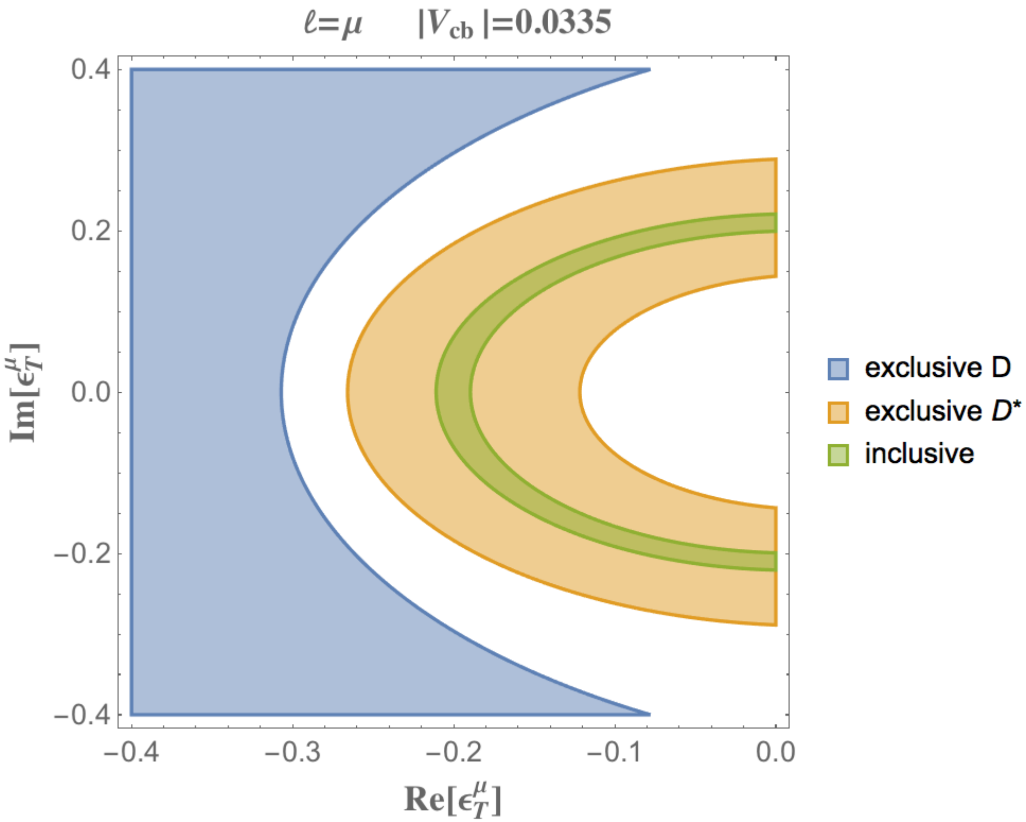
μ mode



e mode

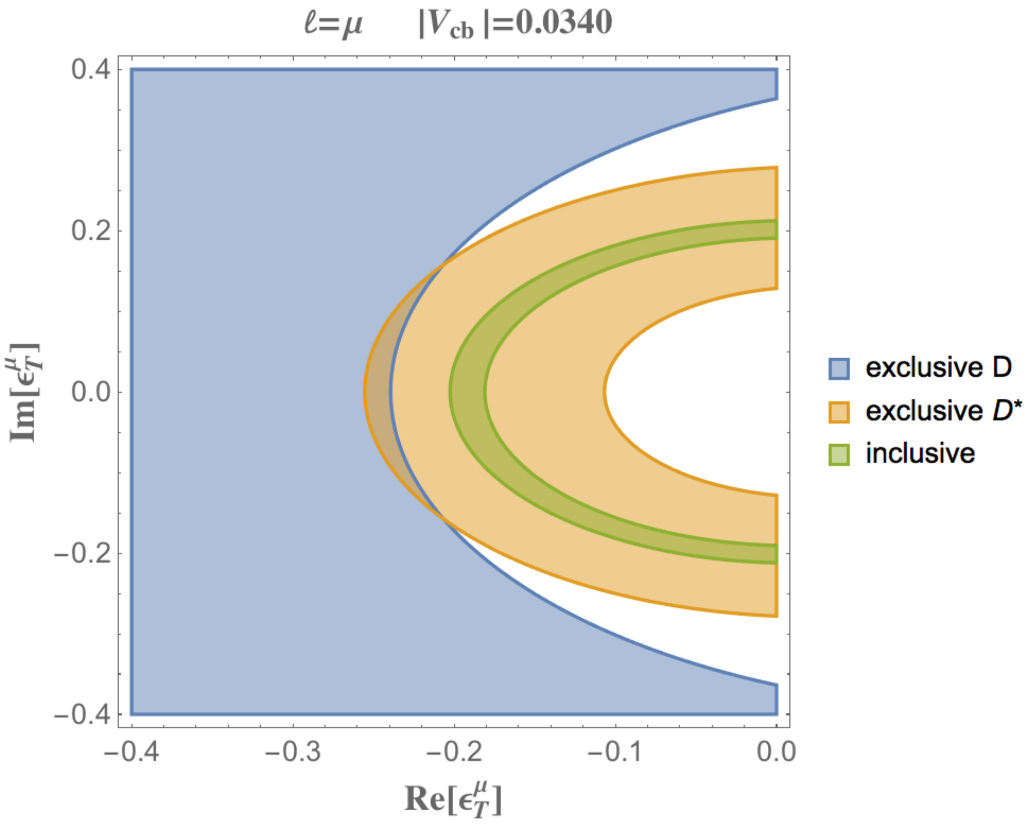
projections in the (Re ε_T, Im ε_T) plane

μ mode



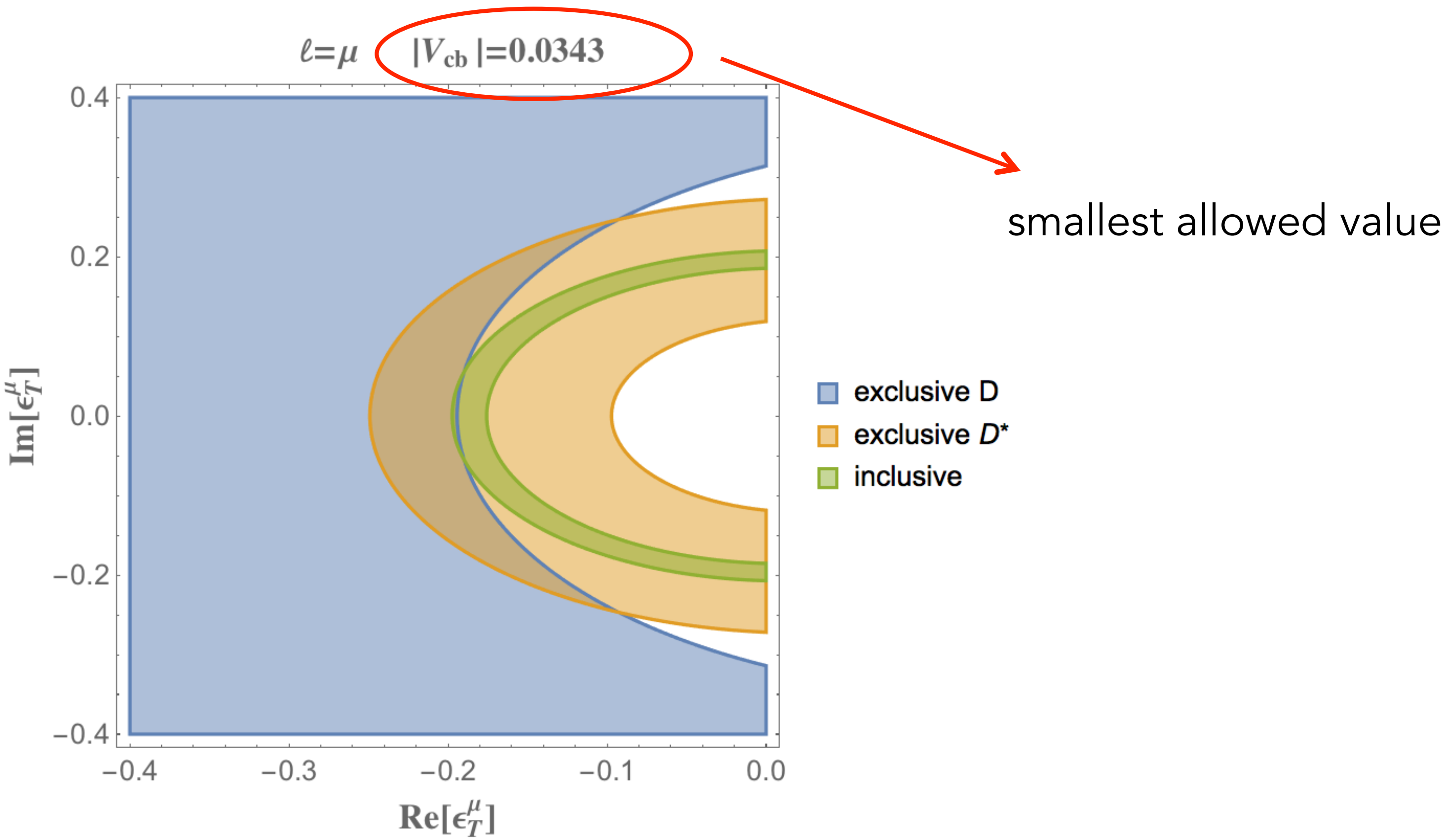
projections in the (Re ε_T, Im ε_T) plane

μ mode



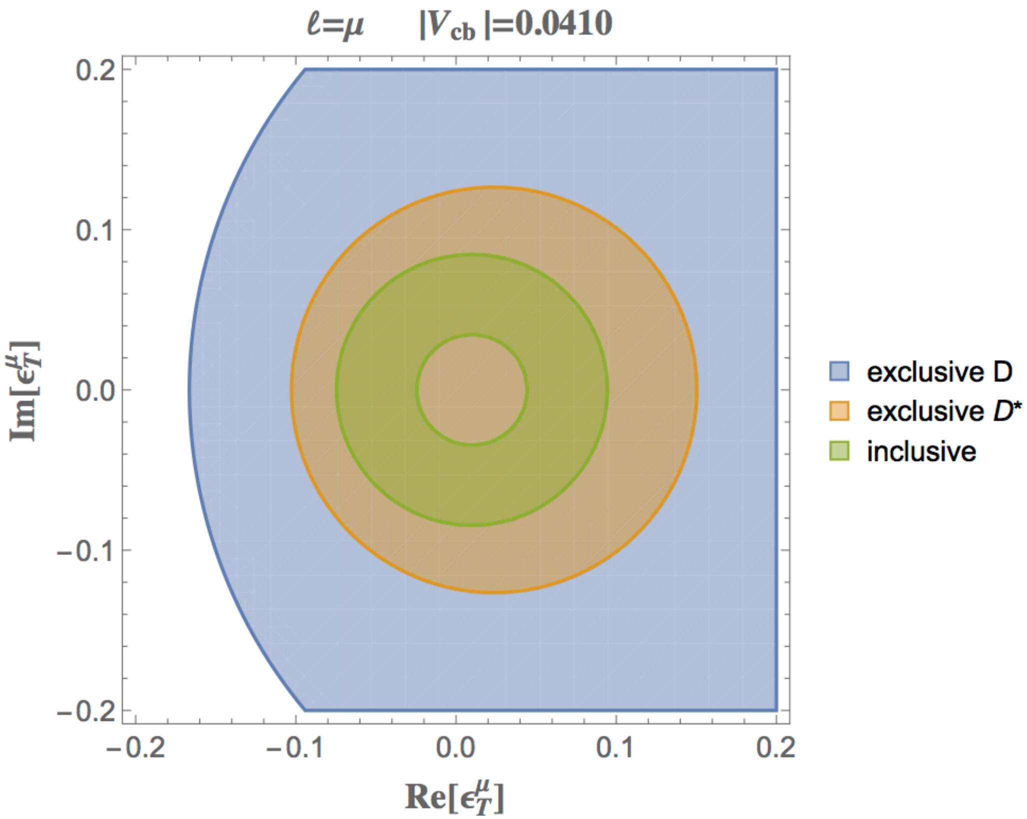
projections in the (Re ε_T, Im ε_T) plane

μ mode



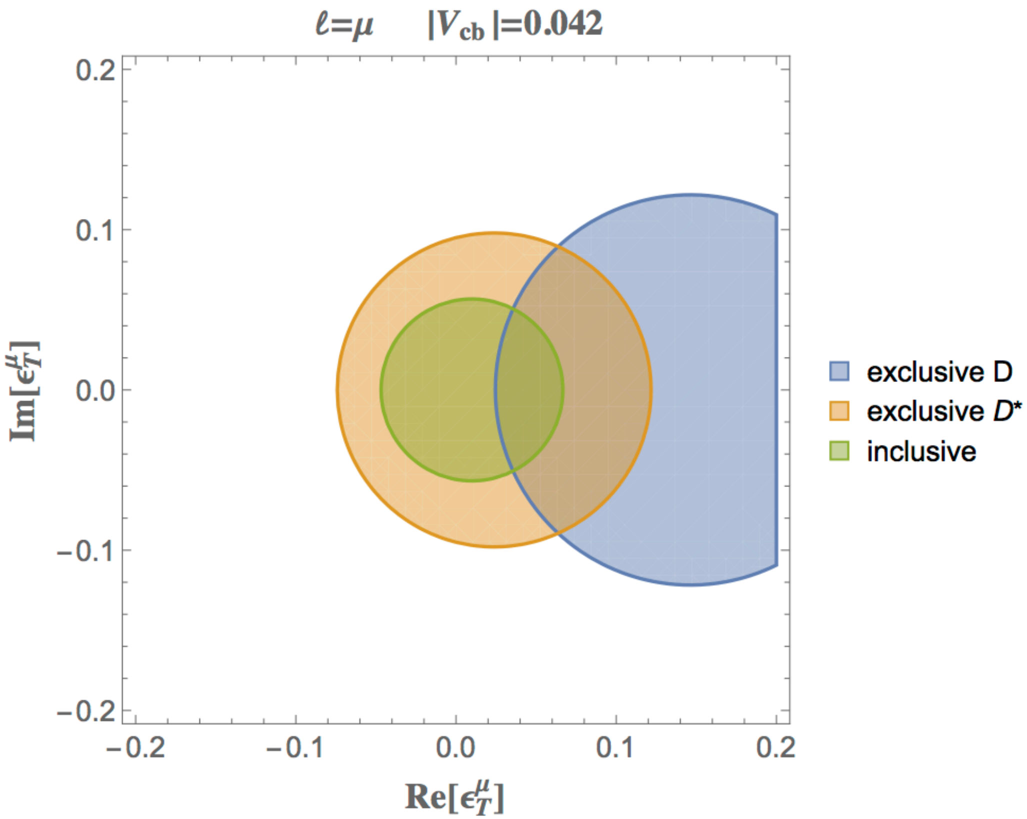
projections in the (Re ε_T, Im ε_T) plane

μ mode



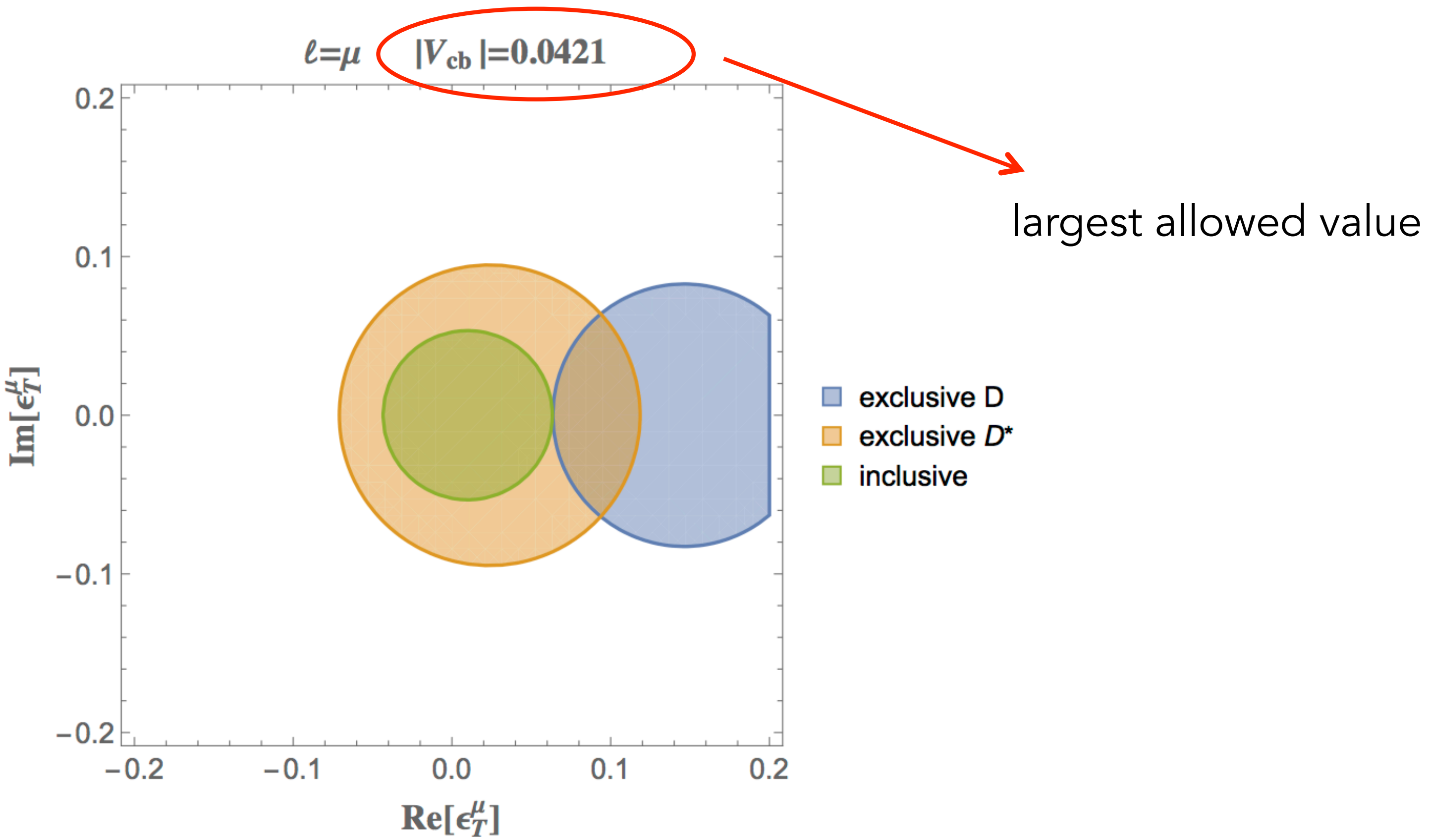
projections in the (Re ε_T, Im ε_T) plane

μ mode



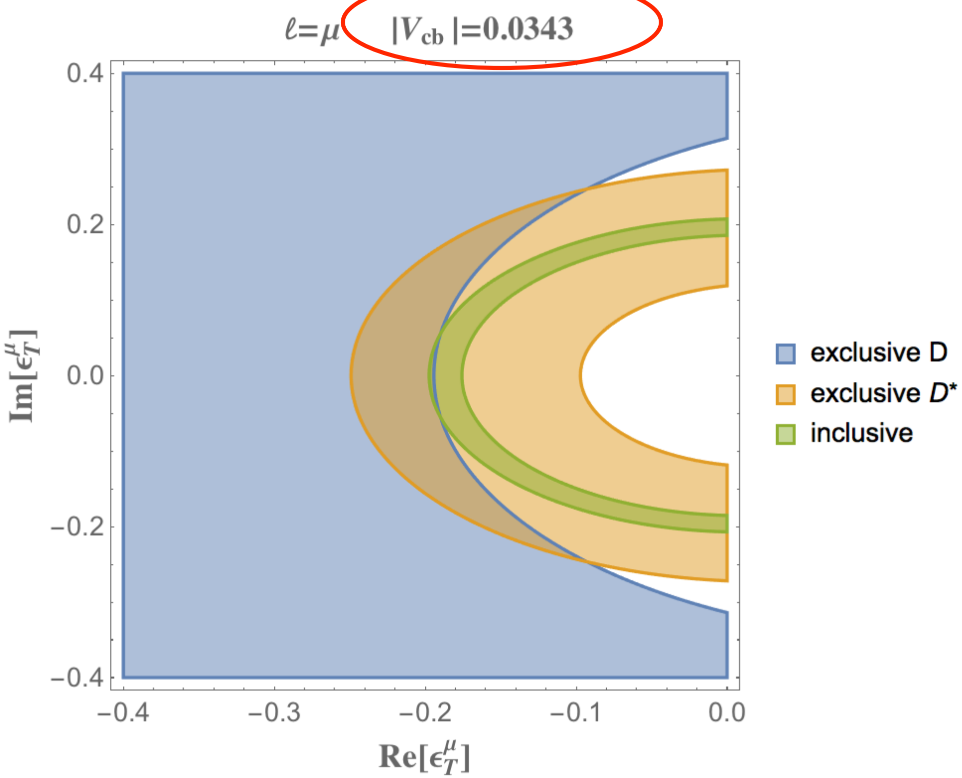
projections in the (Re ε_T, Im ε_T) plane

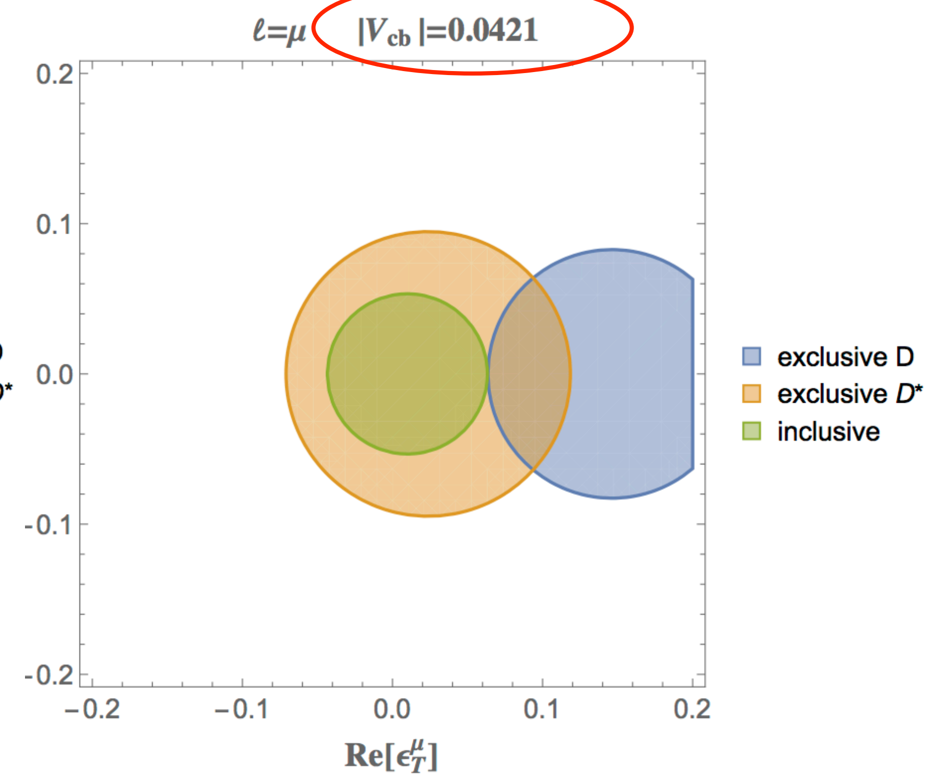
μ mode



projections in the (Re ε_T, Im ε_T) plane

μ mode





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

a connection between $R(D^{(*)})$ and $|V_{cb}|$ could be found

impact on observables in exclusive processes

$\bar{B} \to D^*(D\pi)\ell^-\bar{\nu}_\ell$ $\bar{B} \to D^*(D\gamma)\ell^-\bar{\nu}_\ell$

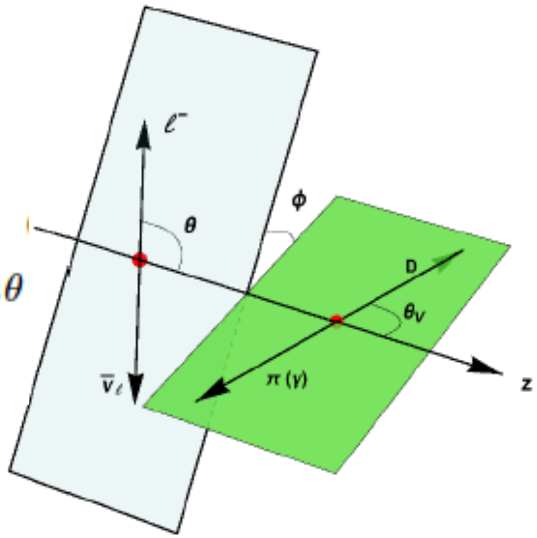
De Fazio PC JHEP 1806, 082

important for $B_s \to D^*_s$

- effects of FF parametrization: BGL vs CLN
- disentangling SM from NP - example: tensor case

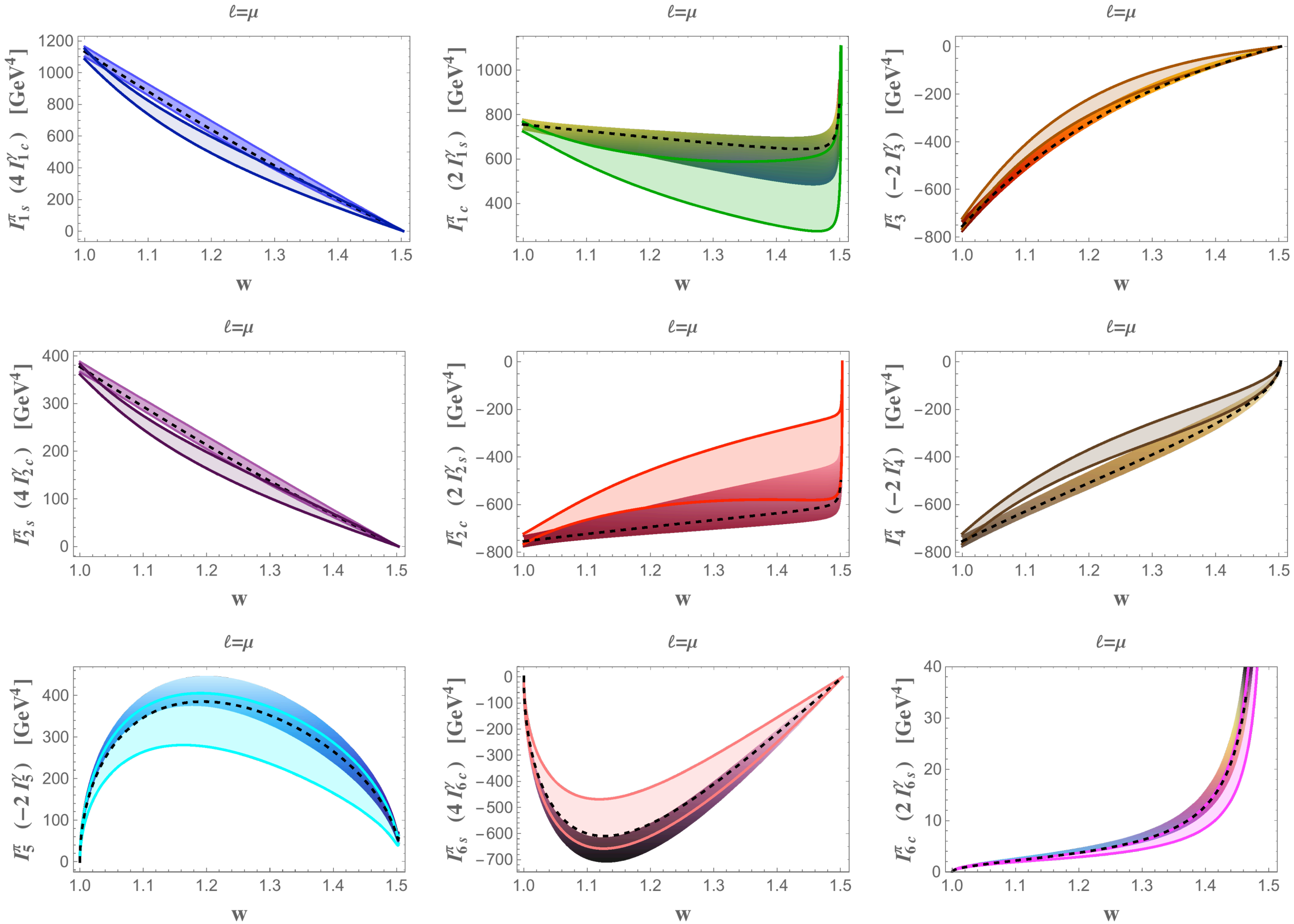
four dimensional decay distribution

$$\frac{d^4\Gamma(\bar{B}\to D^*(\to D\pi)\ell^-\bar{\nu}_\ell)}{dq^2\,d\cos\theta\,d\phi\,d\cos\theta_V} = \mathcal{N}_\pi|\vec{p}_{D^*}|\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{I_{1s}^\pi\sin^2\theta_V + I_{1c}^\pi\cos^2\theta_V + \left(I_{2s}^\pi\sin^2\theta_V + I_{2c}^\pi\cos^2\theta_V\right)\cos 2\theta + I_3^\pi\sin^2\theta_V\sin^2\theta\cos 2\phi + I_4^\pi\sin 2\theta_V\sin 2\theta\cos\phi + I_5^\pi\sin 2\theta_V\sin\theta\cos\phi + \left(I_{6s}^\pi\sin^2\theta_V + I_{6c}^\pi\cos^2\theta_V\right)\cos\theta + I_7^\pi\sin 2\theta_V\sin\theta\sin\phi\Big\},$$



angular coefficient functions
- sensitive to FF parametrization
- some of them vanish in SM
- relations between Dπ and Dγ modes

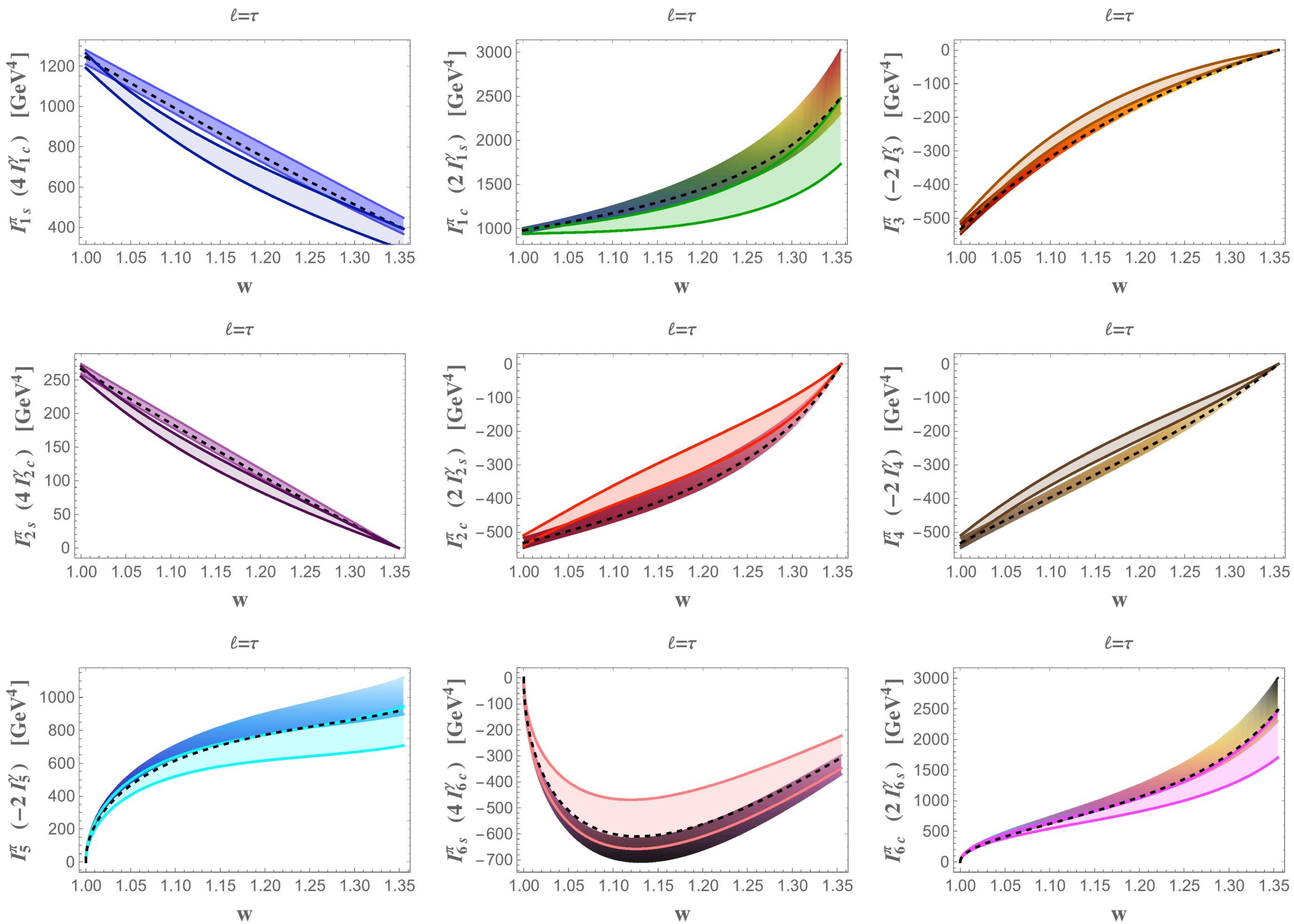
SM: BGL vs CLN
μ mode



darker regions: CLN
lighter regions: BGL

there are coefficients more sensitive to the parametrization

SM: BGL vs CLN
τ mode



darker regions: CLN
lighter regions: BGL

there are coefficients more sensitive to the parametrization

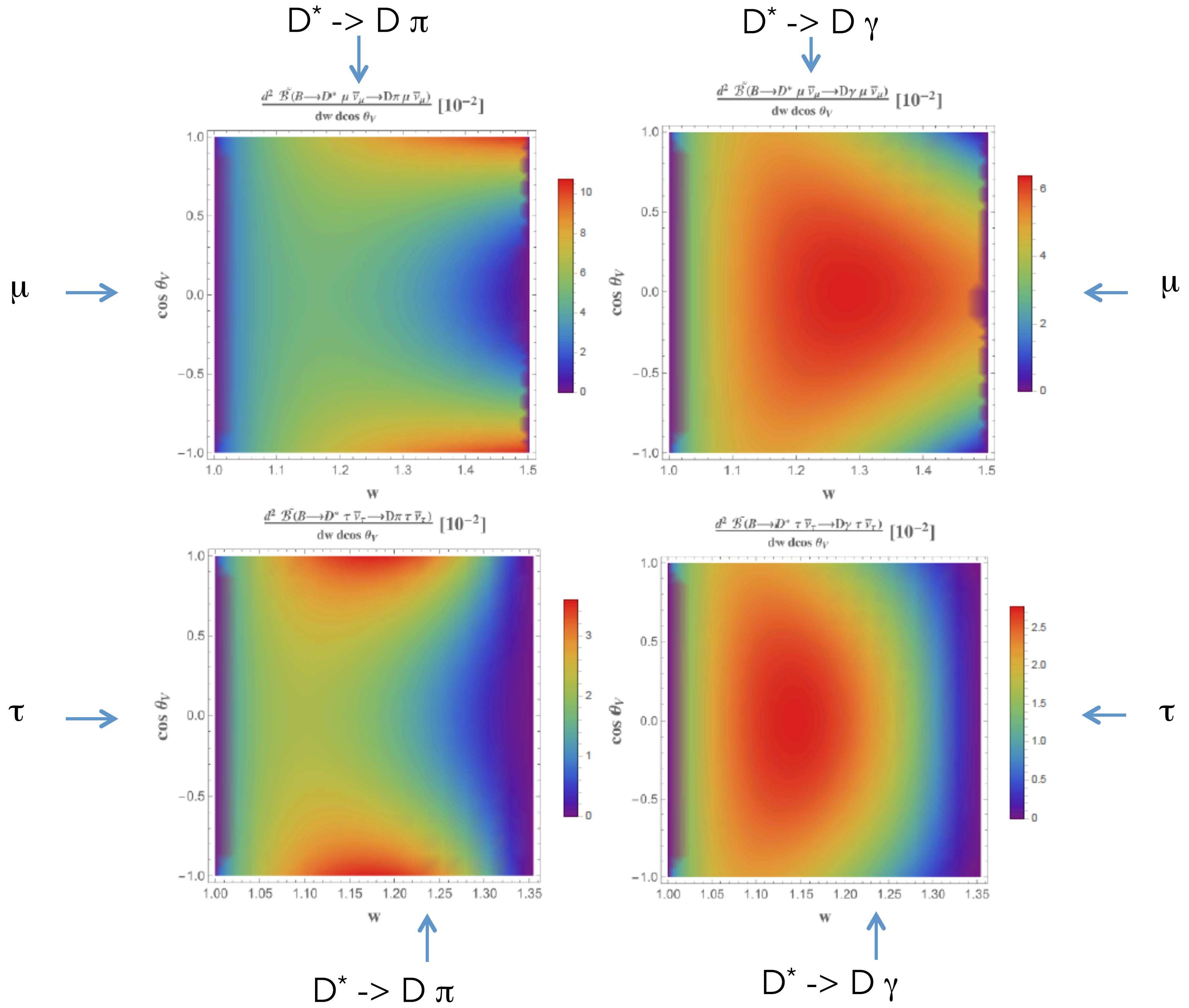
$\bar{B} \to D^*(D\pi)\ell^-\bar{\nu}_\ell$ $\bar{B} \to D^*(D\gamma)\ell^-\bar{\nu}_\ell$

- fit of the experimental differential distribution ➔ angular coefficients ➔ FF

SM

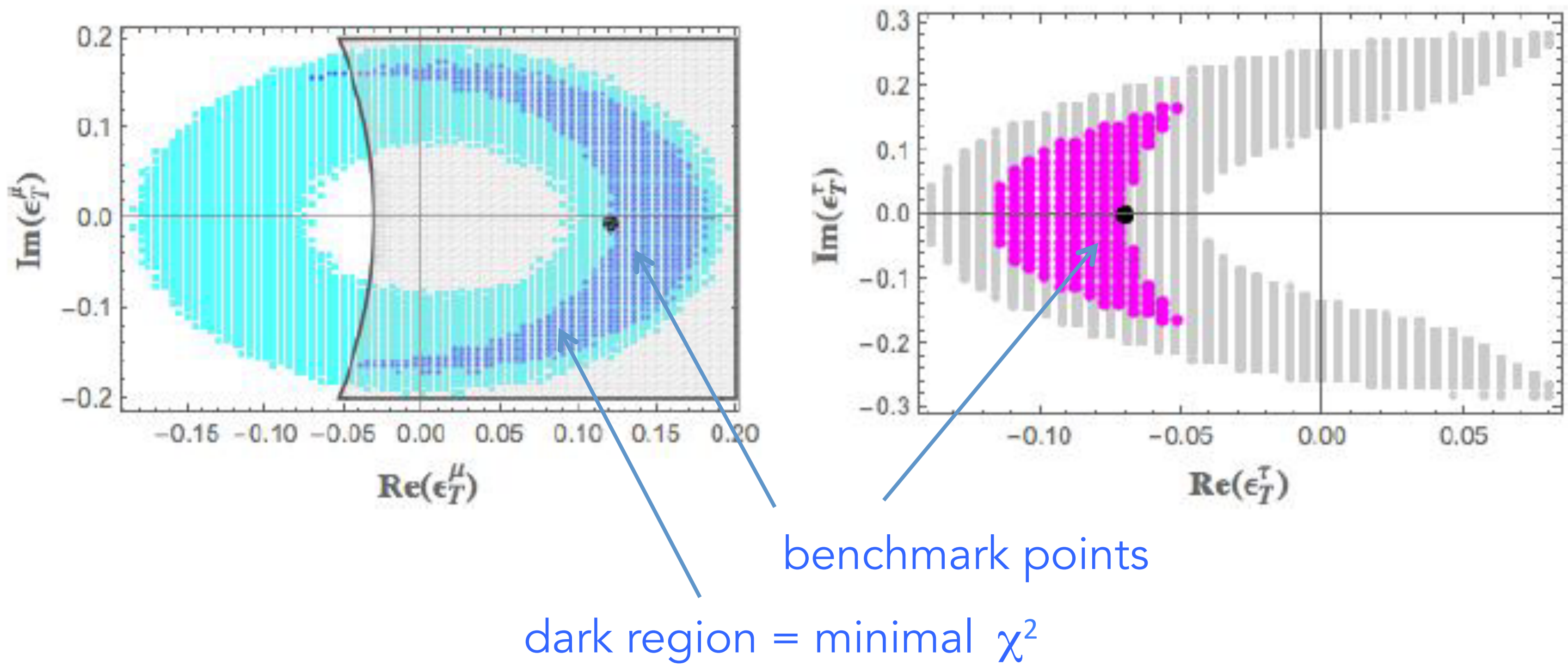
$$\begin{aligned}
A_1(q^2) &= \frac{1}{4(m_B+m_{D^*})}\left\{\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}-\frac{I_{6s}^\pi}{q^2}}+\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}+\frac{I_{6s}^\pi}{q^2}}\right\},\\
A_2(q^2) &= \frac{(m_B+m_{D^*})}{4\lambda(m_B^2,\,m_{D^*}^2,\,q^2)}\left\{(m_B^2-m_{D^*}^2-q^2)\left[\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}-\frac{I_{6s}^\pi}{q^2}}+\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}+\frac{I_{6s}^\pi}{q^2}}\right]\right.\\
&\quad\left.-4\sqrt{2}m_{D^*}\sqrt{q^2}\sqrt{-\frac{I_{2c}^\pi}{q^2-m_\ell^2}}\right\},\\
V(q^2) &= \frac{(m_B+m_{D^*})}{4\lambda^{1/2}(m_B^2,\,m_{D^*}^2,\,q^2)}\left\{\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}-\frac{I_{6s}^\pi}{q^2}}-\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2}+\frac{I_{6s}^\pi}{q^2}}\right\}, \qquad (3.8)\\
A_0(q^2) &= \frac{1}{2}\frac{\sqrt{q^2}}{\lambda^{1/2}(m_B^2,\,m_{D^*}^2,\,q^2)}\sqrt{\frac{(q^2-m_\ell^2)\,I_{1c}^\pi+(q^2+m_\ell^2)\,I_{2c}^\pi}{m_\ell^2(q^2-m_\ell^2)}}.
\end{aligned}$$

complementarity D* ->D π with D* ->D γ



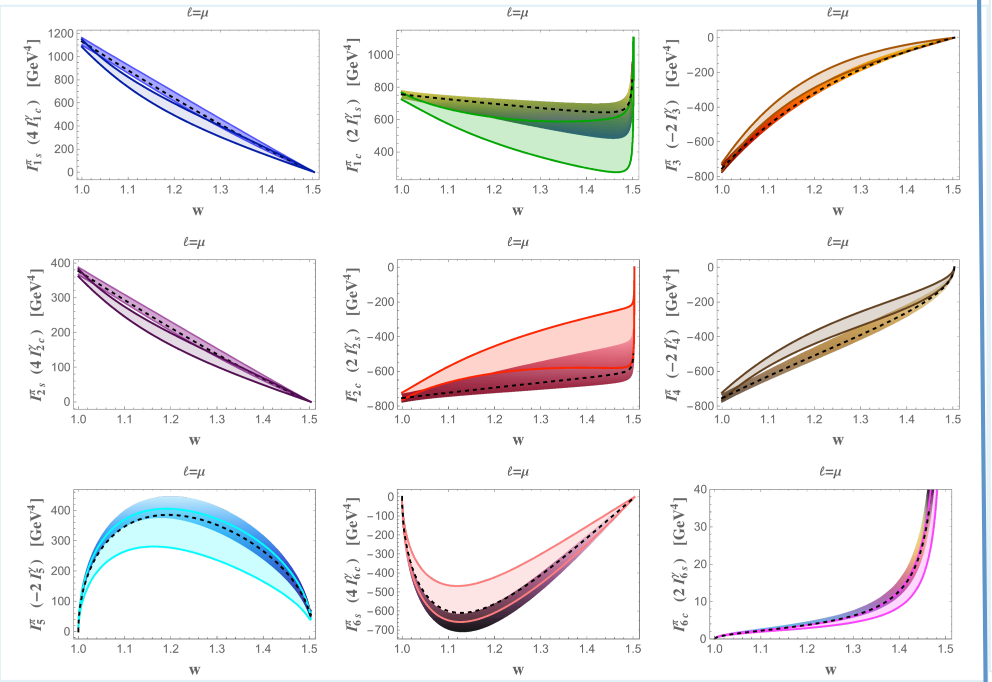
SM vs NP

- ε_T^{μ} , ε_T^{τ} non vanishing
- choose ε_T^{μ} in the region to fix the $|V_{cb}|$ tension
- determine ε_T^{τ} to reproduce R(D) & R(D*)

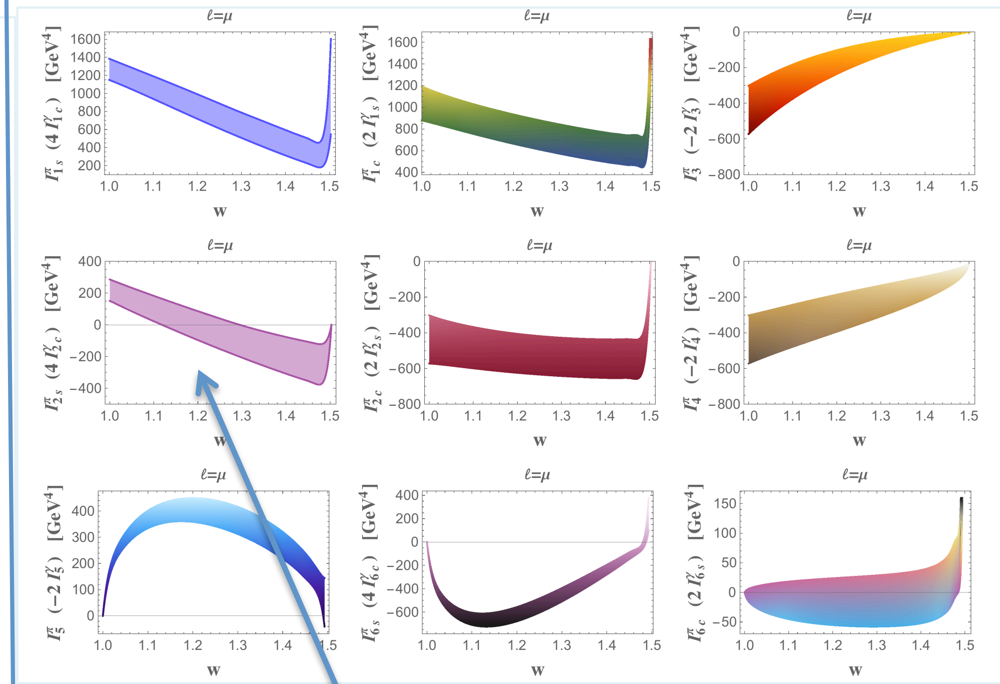


SM vs NP
μ mode

SM



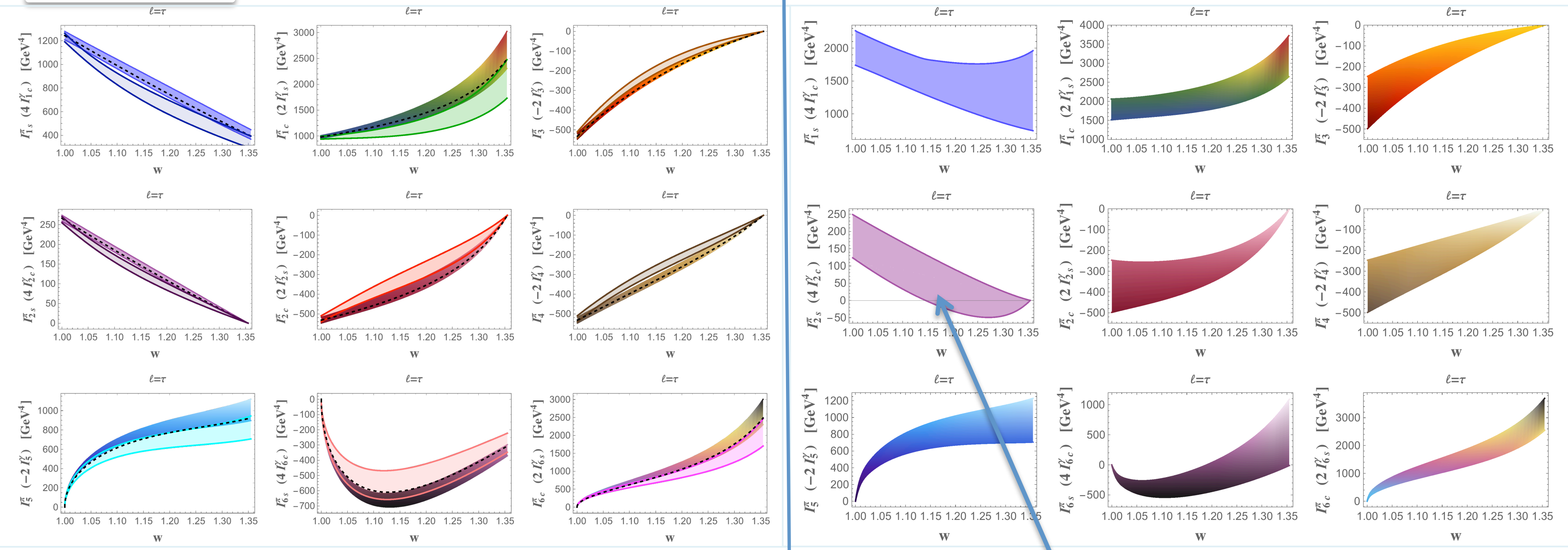
NP



size modified in NP
some coefficients display a zero absent in SM (I_{2s}^{π} or I_{2c}^{γ})

SM vs NP
τ mode

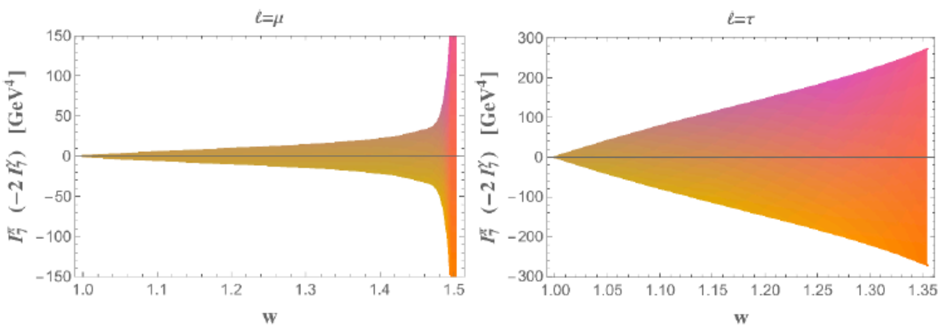
SM | NP



size modified in NP

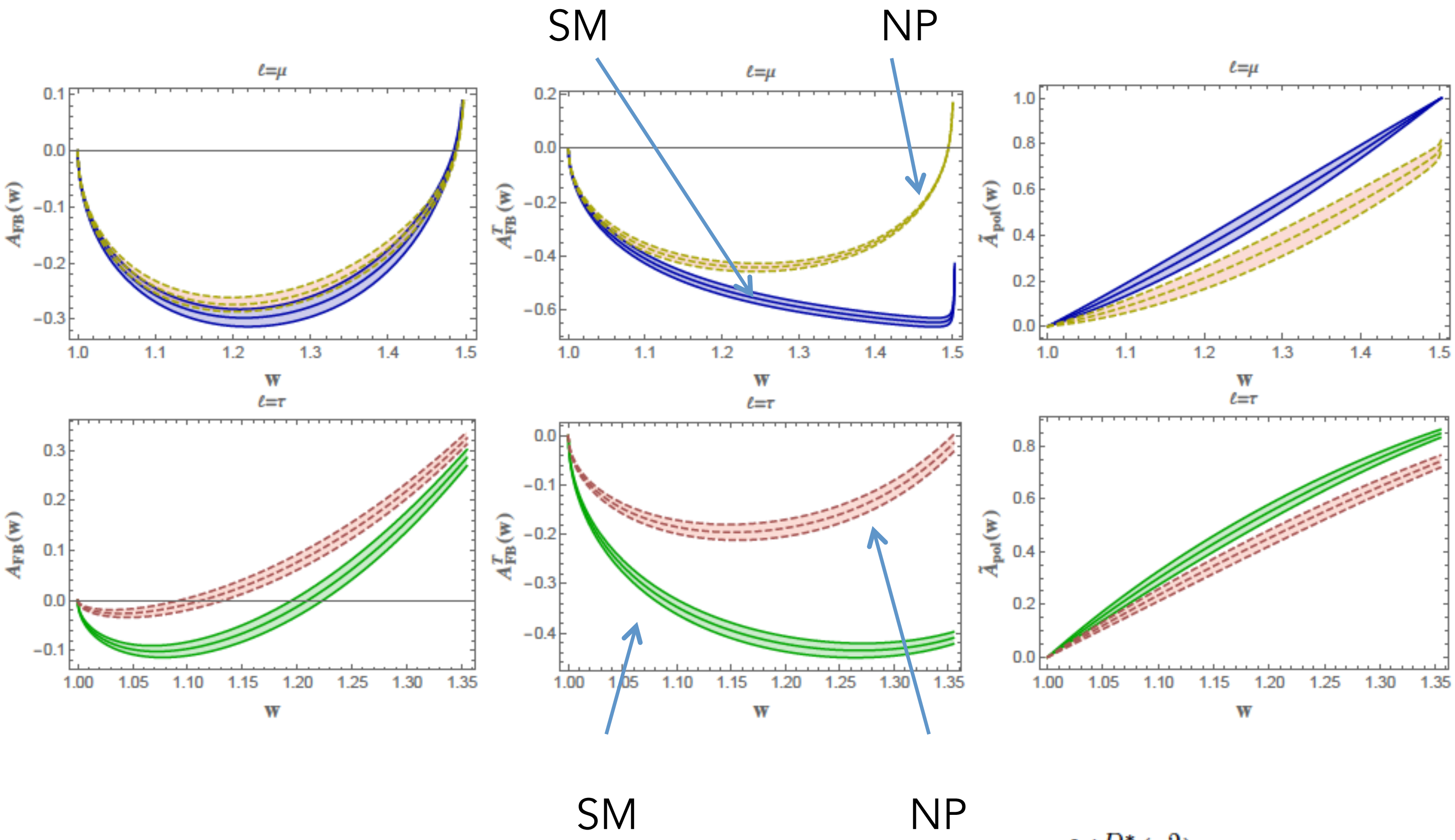
some coefficients display a zero absent in SM (I_{2s}^{π} or I_{2c}^{γ})

I_7 vanishes in SM, not in NP



SM vs NP at the benchmark points

$$A_{\rm FB}(q^2) = \left[\int_0^1 d\cos\theta\,\frac{d^2\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d\cos\theta\,\frac{d^2\Gamma}{dq^2 d\cos\theta}\right] / \frac{d\Gamma}{dq^2}\,.$$

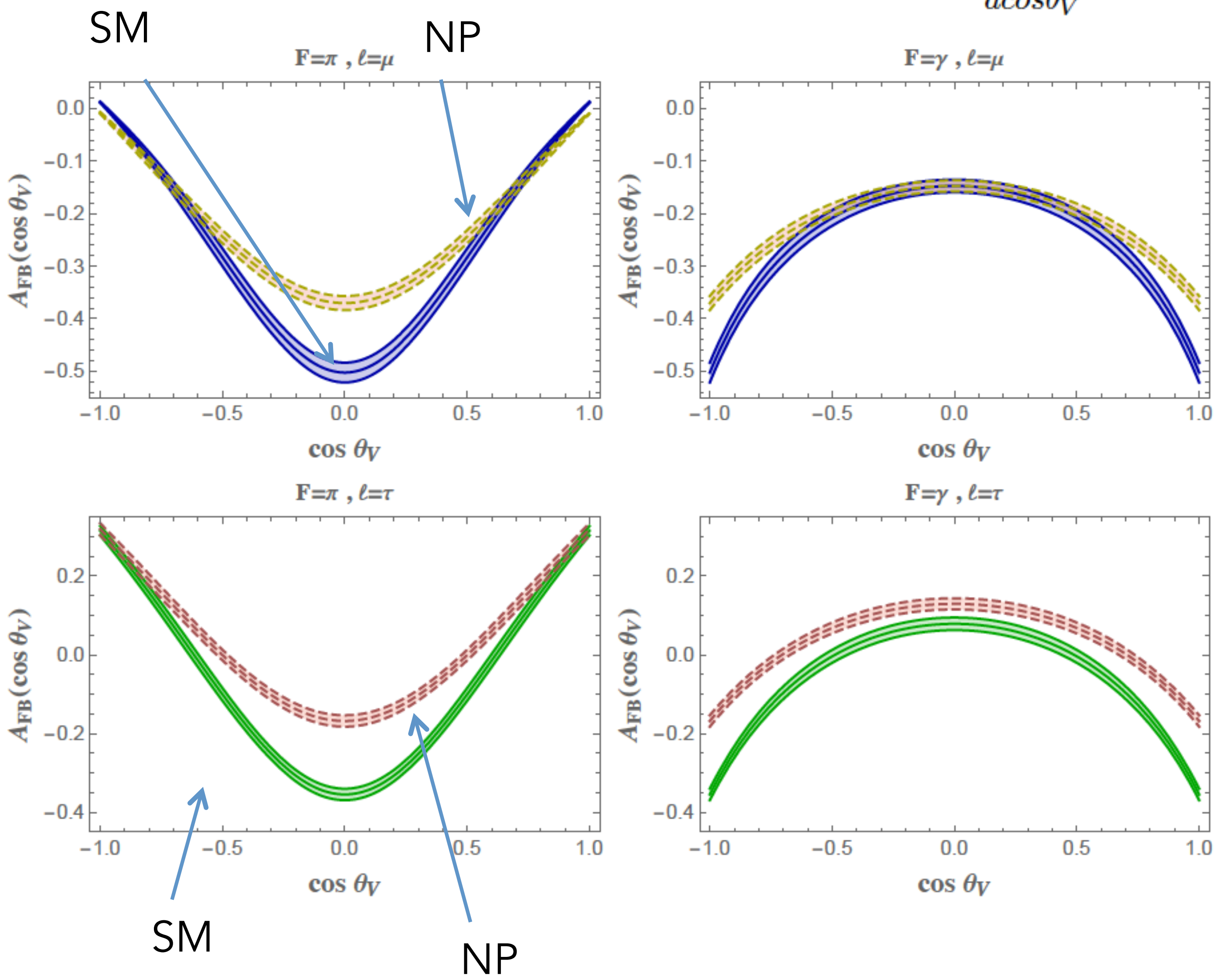


transverse A_{FB}

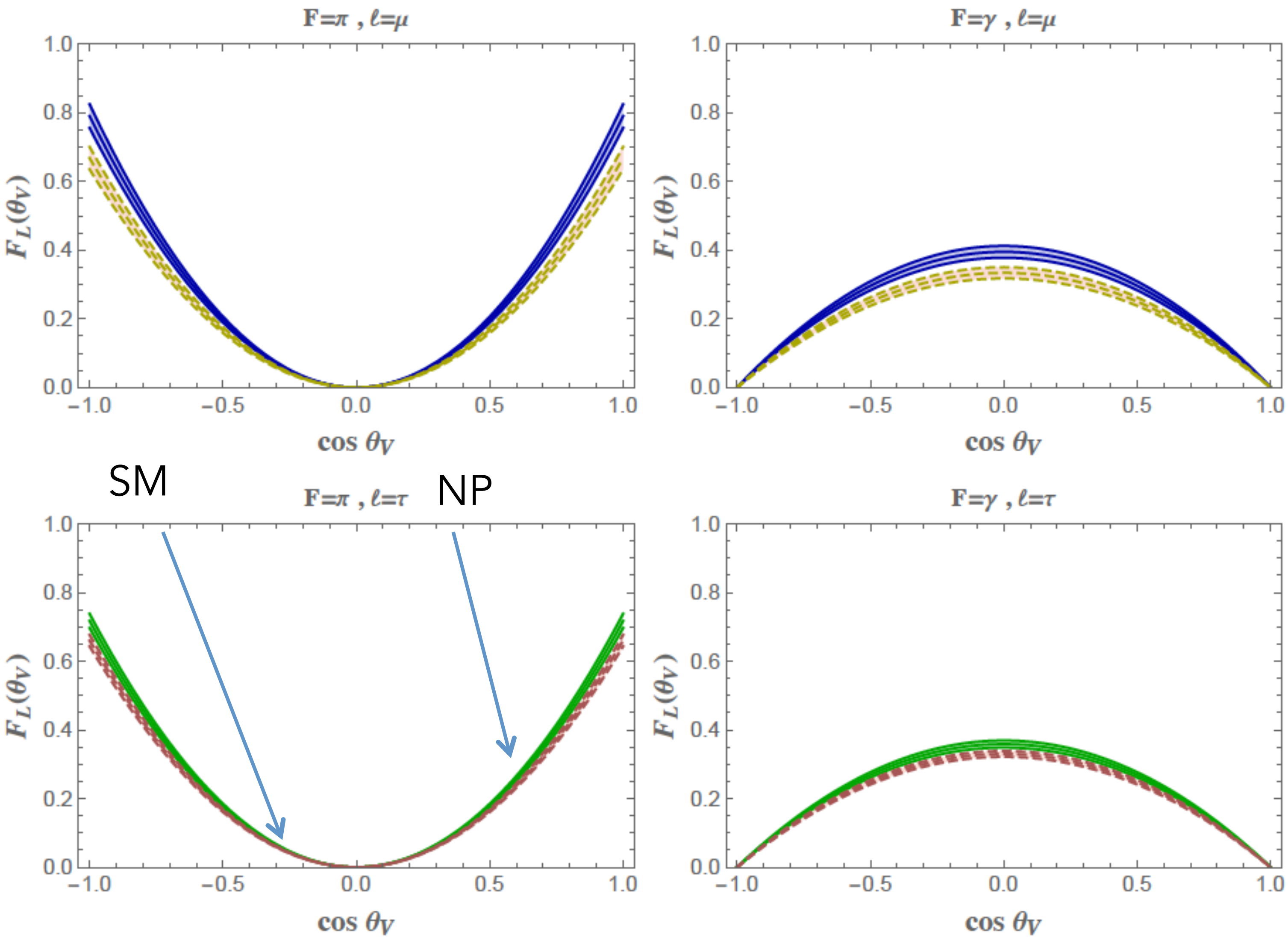
$$\frac{dA^{D^*}_{\rm pol}(q^2)}{dq^2} = 2\frac{d\Gamma_L}{dq^2} / \frac{d\Gamma_T}{dq^2} - 1\,.$$

SM vs NP at the benchmark points

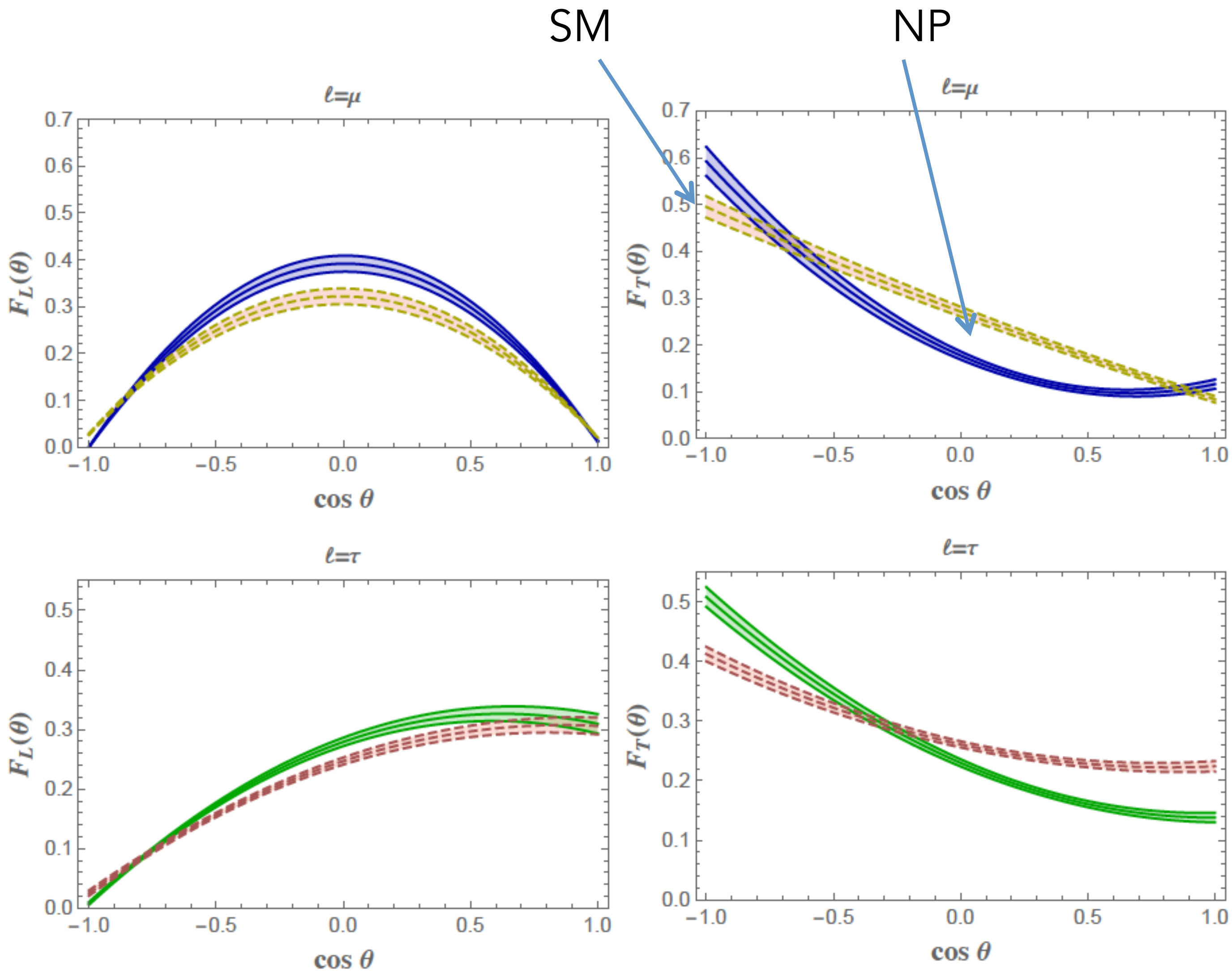
$$A_{\rm FB}(cos\theta_V) = \frac{\left[\int_0^1 dcos\,\theta \frac{d^2\Gamma}{dcos\theta_V\, dcos\,\theta} - \int_{-1}^0 dcos\,\theta \frac{d^2\Gamma}{dcos\theta_V\, dcos\,\theta}\right]}{\frac{d\Gamma}{dcos\theta_V}}.$$



D* polarization fractions



D* polarization fractions



tests of LFU using the angular coefficient functions

$$R_i^{\ell_1 \ell_2} = \frac{\int_{w=1}^{w_{\max}(\ell_1)} (\tilde{I}_i^{\pi}(w))_{\ell_1} dw}{\int_{w=1}^{w_{\max}(\ell_2)} (\tilde{I}_i^{\pi}(w))_{\ell_2} dw}$$

$$\tilde{I}_i = \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |\vec{p}_{D^*}|_{BRF}\, I_i$$

SM

	$\ell_1 = \tau\,,\, \ell_2 = \mu$	$\ell_1 = \tau\,,\, \ell_2 = e$	$\ell_1 = \mu\,,\, \ell_2 = e$
R^π_{1s}	0.263 ± 0.006	0.262 ± 0.005	0.9957 ± 0.0001
R^π_{1c}	0.28 ± 0.02	0.28 ± 0.02	1.008 ± 0.004
R^π_{2s}	0.134 ± 0.003	0.133 ± 0.003	0.9923 ± 0.0002
R^π_{2c}	0.079 ± 0.005	0.077 ± 0.005	0.975 ± 0.002
R^π_{3}	0.153 ± 0.004	0.152 ± 0.004	0.9932 ± 0.0002
R^π_{4}	0.112 ± 0.004	0.111 ± 0.004	0.9891 ± 0.0004
R^π_{5}	0.30 ± 0.02	0.30 ± 0.02	0.999 ± 0.001
R^π_{6s}	0.197 ± 0.004	0.196 ± 0.004	0.9943 ± 0.0001
R^π_{6c}	5.90 ± 0.45	76000 ± 7000	12900 ± 200

NP

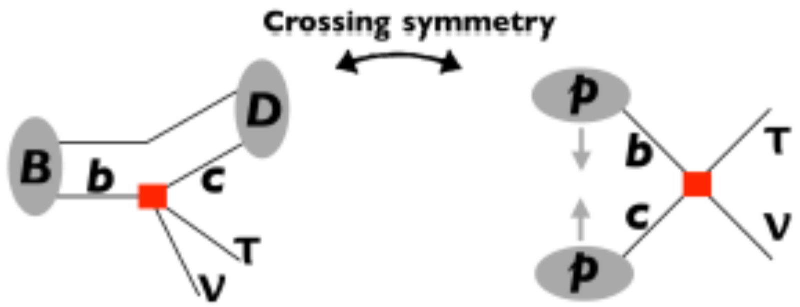
	$\ell_1 = \tau\,,\, \ell_2 = \mu$	$\ell_1 = \tau\,,\, \ell_2 = e$	$\ell_1 = \mu\,,\, \ell_2 = e$
R^π_{1s}	0.32 ± 0.01	0.304 ± 0.008	0.957 ± 0.002
R^π_{1c}	0.36 ± 0.03	0.34 ± 0.02	0.956 ± 0.003
R^π_{2s}	0.37 ± 0.02	0.38 ± 0.02	1.04 ± 0.01
R^π_{2c}	0.082 ± 0.006	0.080 ± 0.006	0.973 ± 0.002
R^π_{3}	0.183 ± 0.005	0.182 ± 0.005	0.9932 ± 0.0002
R^π_{4}	0.131 ± 0.005	0.130 ± 0.005	0.9890 ± 0.0004
R^π_{5}	0.35 ± 0.03	0.33 ± 0.03	0.96 ± 0.01
R^π_{6s}	0.150 ± 0.006	0.152 ± 0.006	1.012 ± 0.003
R^π_{6c}	-11.6 ± 1.5	-944 ± 40	81.2 ± 9.1
R^π_{7}	0	0	184 ± 2

new measurement
Belle 2018

$$\frac{B(B^0 \to D^{*-} e^+ \nu_e)}{B\left(B^0 \to D^{*-} \mu^+ \nu_\mu\right)} = 1.01 \pm 0.01 \pm 0.03$$

collider constraints on the new operators:

crossing symmetry connects to mono-tau events at the LHC



Camalich Grejio Ruiz Alvarez

excess in pp -> τ + trasverse missing energy should be observed

synergy between pp and B physics

- 4d angular distributions in $\bar{B} \to D^*(D\pi)\ell\bar{\nu}_\ell$ $\bar{B} \to D^*(D\gamma)\ell\bar{\nu}_\ell$ can disentangle non SM effects

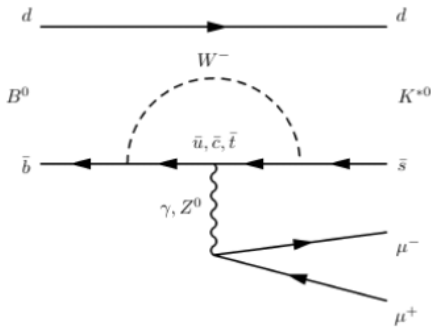
- as alternative to conventional SM solutions, a NP option to solve the $|V_{cb}|_{excl}$ vs $|V_{cb}|_{incl}$ tension seems still viable, related to $R(D^{(*)})$

- precision era: importance of separate theoretical and experimental analyses for electrons – muons - taus

} example

see also Becirevic et al.

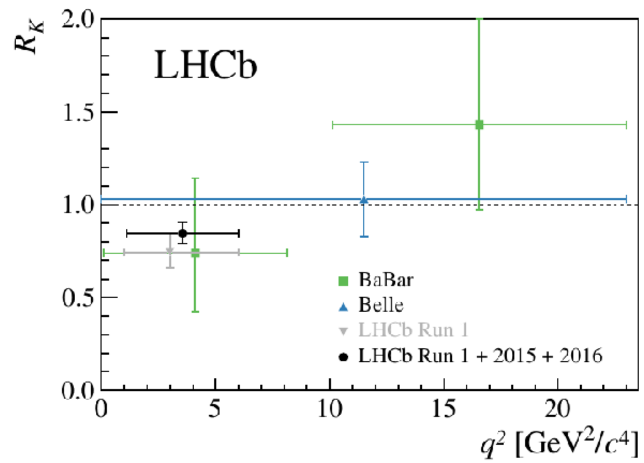
LFU anomalies in FCNC processes



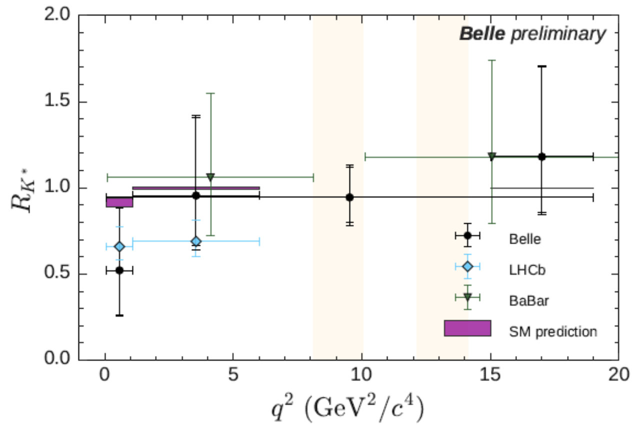
$$R(K^{(*)}) = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)} = 1 \pm \underbrace{O(10^{-3})}_{\text{neglect lepton mass}} \pm \underbrace{O(10^{-2})}_{\text{QED}}$$

Bordone Isidori Pattori

- R(K): 2.5 σ from SM
- R(K*) (2 bins of q²): 2.6 σ

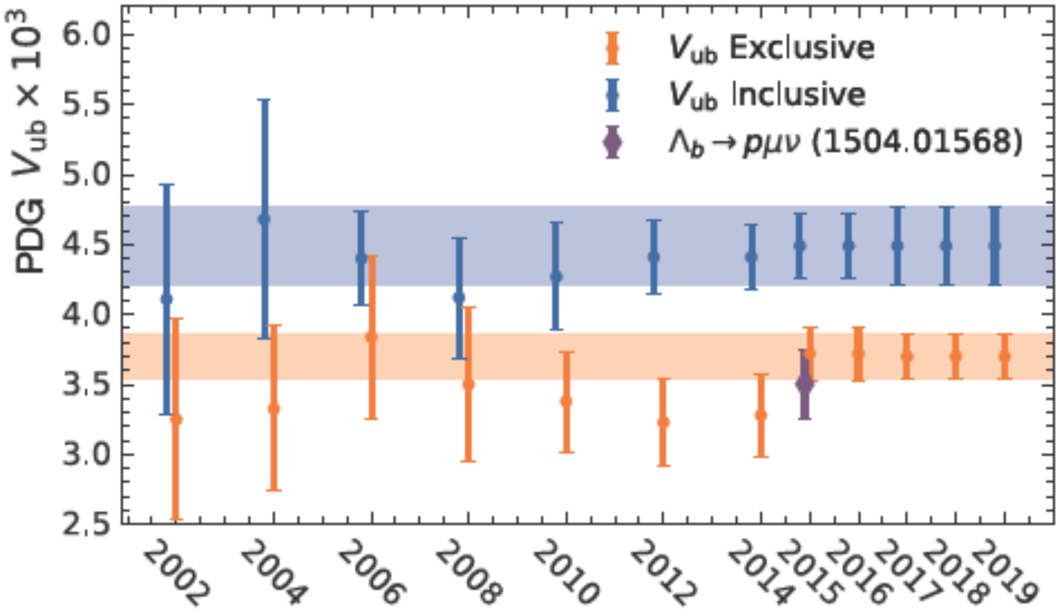


$$R(K) = 0.846^{+0.060}_{-0.054}(stat)^{+0.016}_{-0.014}(syst)$$



CKM suppressed b->u transition

tension in $|V_{ub}|_{excl}$ vs $|V_{ub}|_{incl}$



plot: M. Prim

no tests of LFU: R(π) R(ρ)

Include in the SM effective Hamiltonian all D=6 operators

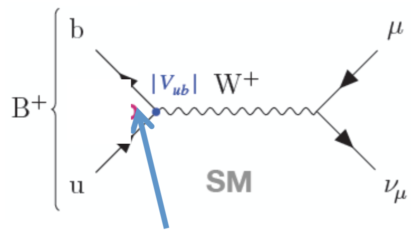
De Fazio Loparco PC

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

- experimental bounds
- consequences

$B^- \to \ell \bar\nu_\ell$

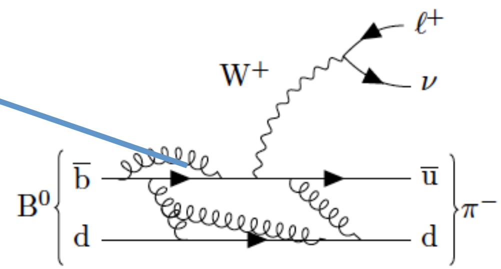
$$\Gamma(B^-\to\ell^-\bar\nu_\ell) = \frac{G_F^2 |V_{ub}|^2 f_B^2 m_B^3}{8\pi} \left(1-\frac{m_\ell^2}{m_B^2}\right)^2 \left| \left(\frac{m_\ell}{m_B}\right) (1+\epsilon_V^\ell) + \frac{m_B}{m_b+m_u}\epsilon_P^\ell \right|^2$$



$$\langle 0|\bar u \gamma_\mu \gamma_5 b|\bar B(p)\rangle = i\, f_B p_\mu$$

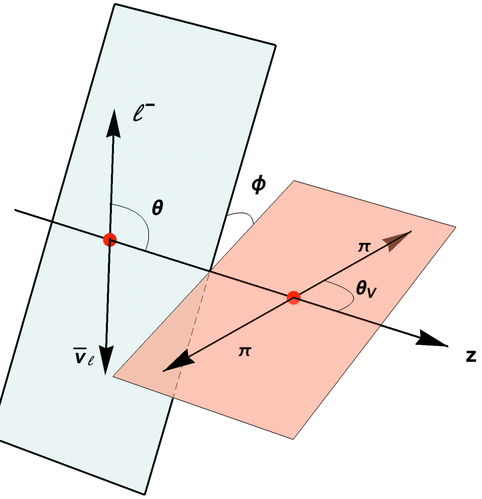
$\bar B \to \pi \ell \bar\nu_\ell$

$$\frac{d\Gamma}{dq^2}(\bar B\to\pi\ell^-\bar\nu_\ell) = \frac{G_F^2|V_{ub}|^2 \lambda^{1/2}(m_B^2,m_\pi^2,q^2)}{128 m_B^3 \pi^3 q^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2$$
$$\times \Bigg\{ \left| m_\ell (1+\epsilon_V^\ell) + \frac{q^2 \epsilon_S^\ell}{m_b - m_u}\right|^2 (m_B^2-m_\pi^2)^2 f_0^2(q^2) + \lambda(m_B^2,m_\pi^2,q^2)\left[\frac{1}{3}\left| m_\ell(1+\epsilon_V^\ell) f_+(q^2) + \frac{4q^2}{m_B+m_\pi}\epsilon_T^\ell f_T(q^2)\right|^2 + \frac{2q^2}{3}\left|(1+\epsilon_V^\ell) f_+(q^2) + 4\frac{m_\ell}{m_B+m_\pi}\epsilon_T^\ell f_T(q^2)\right|^2\right]\Bigg\} \,.$$



$\bar{B} \to \rho(770)\ell\bar{\nu}_\ell$

$$\frac{d^4\Gamma(\bar{B}\to\rho(\to\pi\pi)\ell^-\bar{\nu}_\ell)}{dq^2\,d\cos\theta\,d\phi\,d\cos\theta_V} = \mathcal{N}_\rho|\vec{p}_\rho|\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{I_{1s}^\rho\sin^2\theta_V + I_{1c}^\rho\cos^2\theta_V$$
$$+\left(I_{2s}^\rho\sin^2\theta_V + I_{2c}^\rho\cos^2\theta_V\right)\cos 2\theta$$
$$+ I_3^\rho\sin^2\theta_V\sin^2\theta\cos 2\phi + I_4^\rho\sin 2\theta_V\sin 2\theta\cos\phi$$
$$+ I_5^\rho\sin 2\theta_V\sin\theta\cos\phi + \left(I_{6s}^\rho\sin^2\theta_V + I_{6c}^\rho\cos^2\theta_V\right)\cos\theta$$
$$+ I_7^\rho\sin 2\theta_V\sin\theta\sin\phi\Big\}\,,$$



$\bar{B} \to a_1(1260)\ell\bar{\nu}_\ell$

$$\frac{d^4\Gamma(\bar{B}\to a_1(\to\rho_{\|(\perp)}\pi)\ell^-\bar{\nu}_\ell)}{dq^2\,d\cos\theta\,d\phi\,d\cos\theta_V} = \mathcal{N}_{a_1}^{\|(\perp)}|\vec{p}_{a_1}|\left(1-\frac{m_\ell^2}{q^2}\right)^2\Big\{I_{1s,\|(\perp)}^{a_1}\sin^2\theta_V + I_{1c,\|(\perp)}^{a_1}(3+\cos 2\theta_V)$$
$$+\left(I_{2s,\|(\perp)}^{a_1}\sin^2\theta_V + I_{2c,\|(\perp)}^{a_1}(3+\cos 2\theta_V)\right)\cos 2\theta$$
$$+ I_{3,\|(\perp)}^{a_1}\sin^2\theta_V\sin^2\theta\cos 2\phi + I_{4,\|(\perp)}^{a_1}\sin 2\theta_V\sin 2\theta\cos\phi$$
$$+ I_{5,\|(\perp)}^{a_1}\sin 2\theta_V\sin\theta\cos\phi$$
$$+\left(I_{6s,\|(\perp)}^{a_1}\sin^2\theta_V + I_{6c,\|(\perp)}^{a_1}(3+\cos 2\theta_V)\right)\cos\theta$$
$$+ I_{7,\|(\perp)}^{a_1}\sin 2\theta_V\sin\theta\sin\phi\Big\}\,.$$

the new operators contribute in different ways to the different processes

	ϵ_V^ℓ	ϵ_S^ℓ	ϵ_P^ℓ	ϵ_T^ℓ
$B^- \to \ell^- \bar{\nu}_\ell$	✔		✔	
$\bar{B} \to \pi \ell^- \bar{\nu}_\ell$	✔	✔		✔
$B \to \rho \ell \bar{\nu}_\ell$	✔		✔	✔
$B \to a_1 \ell \bar{\nu}_\ell$	✔	✔		✔

data

$$B\left(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell\right) = \left(1.50 \pm 0.06\right) \times 10^{-4}$$

$$B\left(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell\right) = \left(2.94 \pm 0.21\right) \times 10^{-4}$$

$$B\left(B^- \to \mu^- \bar{\nu}_\ell\right) = \left(6.46 \pm 2.2 \pm 1.60\right) \times 10^{-7}$$

$$\left[2.0, 10.7\right] \times 10^{-7} \quad \text{at } 90\%\text{CL}$$

$$B\left(B^- \to \tau^- \bar{\nu}_\ell\right) = \left(1.09 \pm 0.24\right) \times 10^{-4}$$

$$B\left(B^- \to e^- \bar{\nu}_\ell\right) < 9.8 \times 10^{-7}$$

$$B\left(\bar{B}^0 \to \pi^+ \tau^- \bar{\nu}_\ell\right) < 2.5 \times 10^{-4}$$

B->π form factors

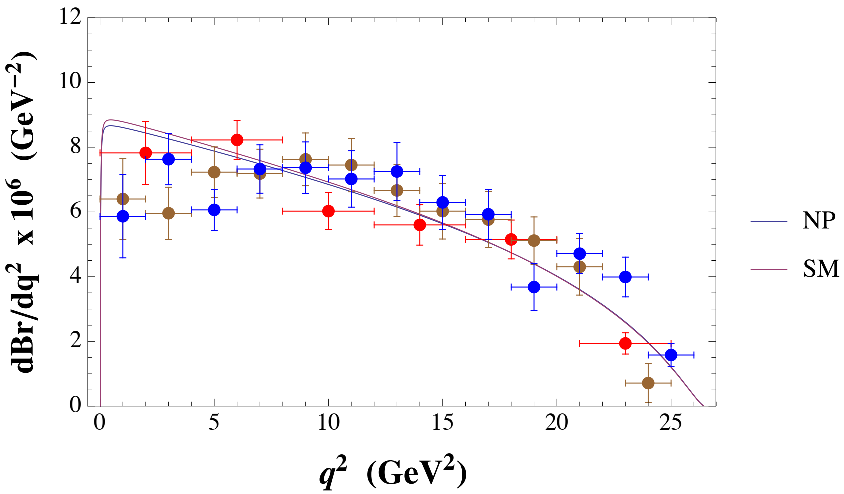
$$f_{+,T}(t) = \frac{1}{1 - \frac{q^2}{m^2_{pole}}} \sum_{n=0}^{N-1} a_n \left[z(t)^n - \frac{n}{N}(-1)^{n-N} z(t)^N \right]$$

$$f_0(t) = \sum_{n=0}^{N-1} a_n z(t)^n, \qquad z(t) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}.$$

LCSR + Lattice QCD

Khodjamirian et al.
FLAG

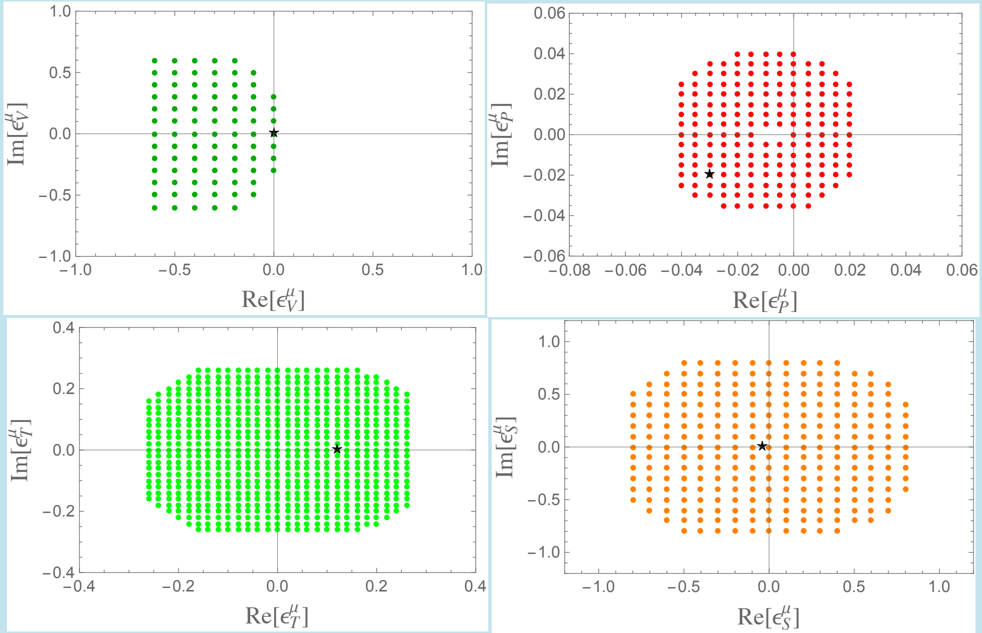
	$f_+^{B\to\pi}$	$f_0^{B\to\pi}$	$f_T^{B\to\pi}$
a_0	0.416 (20)	0.492 (20)	0.400 (21)
a_1	−0.430	−1.35	−0.50
a_2	0.114	2.50	0.00076
a_3			0.534

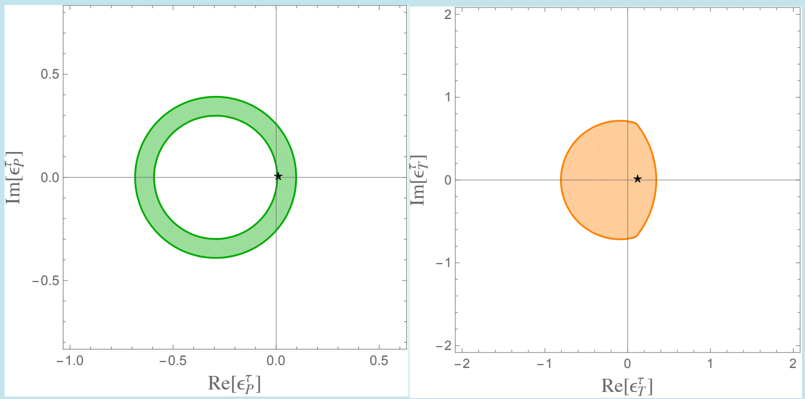


B->ρ form factors from Light Cone QCD sum rules

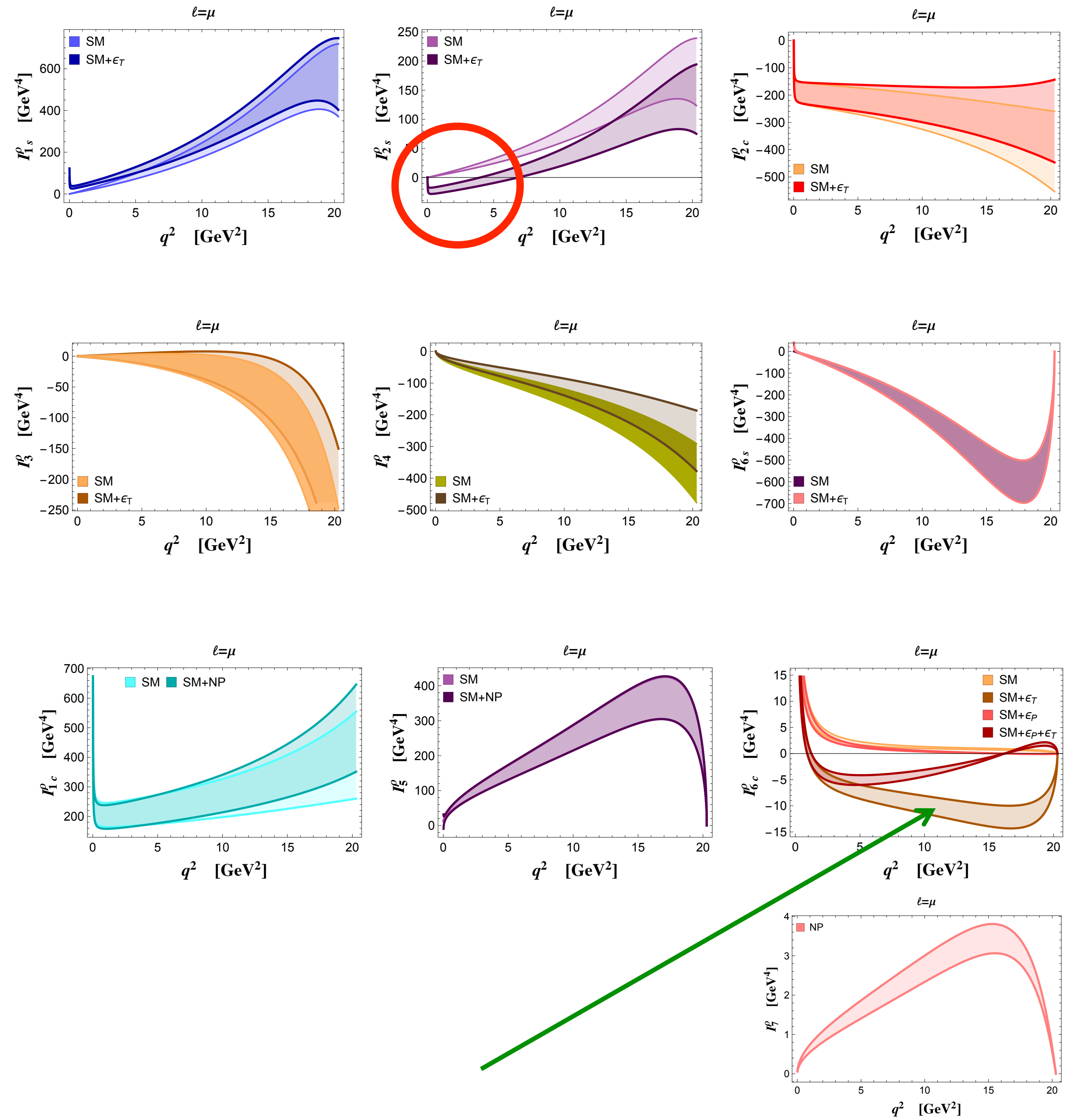
Ball Zwicky Straub et al

parameter space

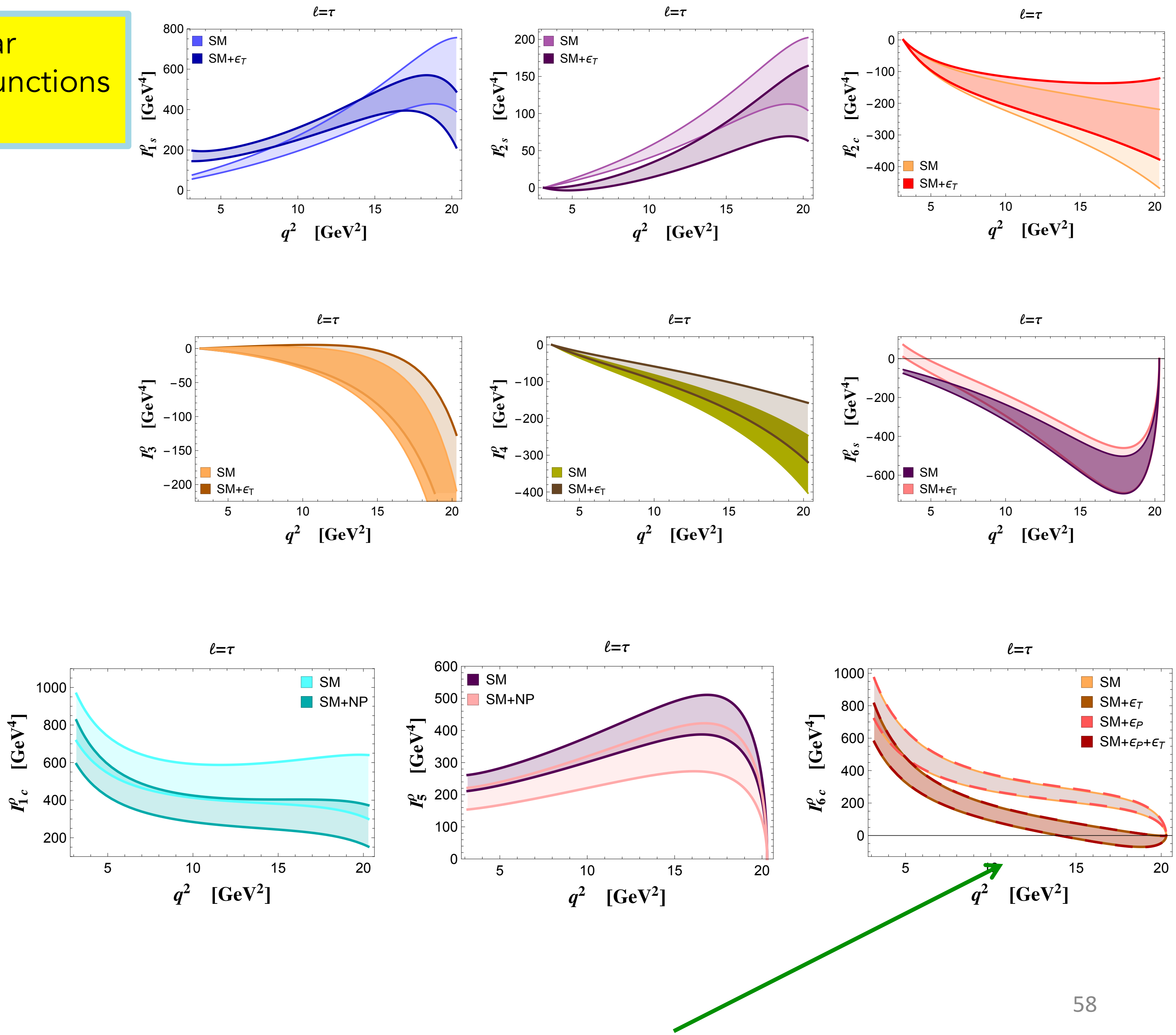




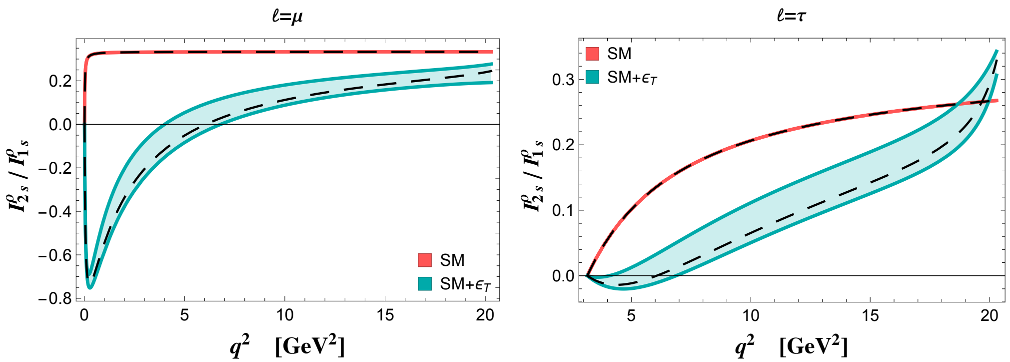
B-> ρ angular coefficient functions μ mode



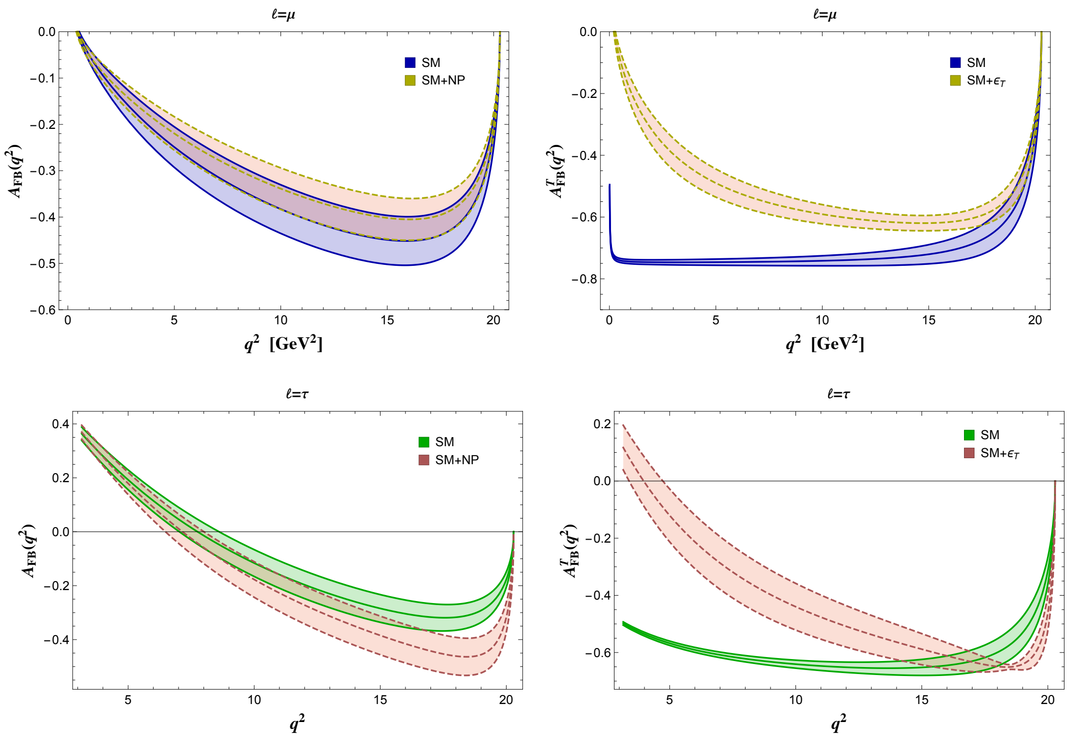
B-> ρ angular coefficient functions τ mode



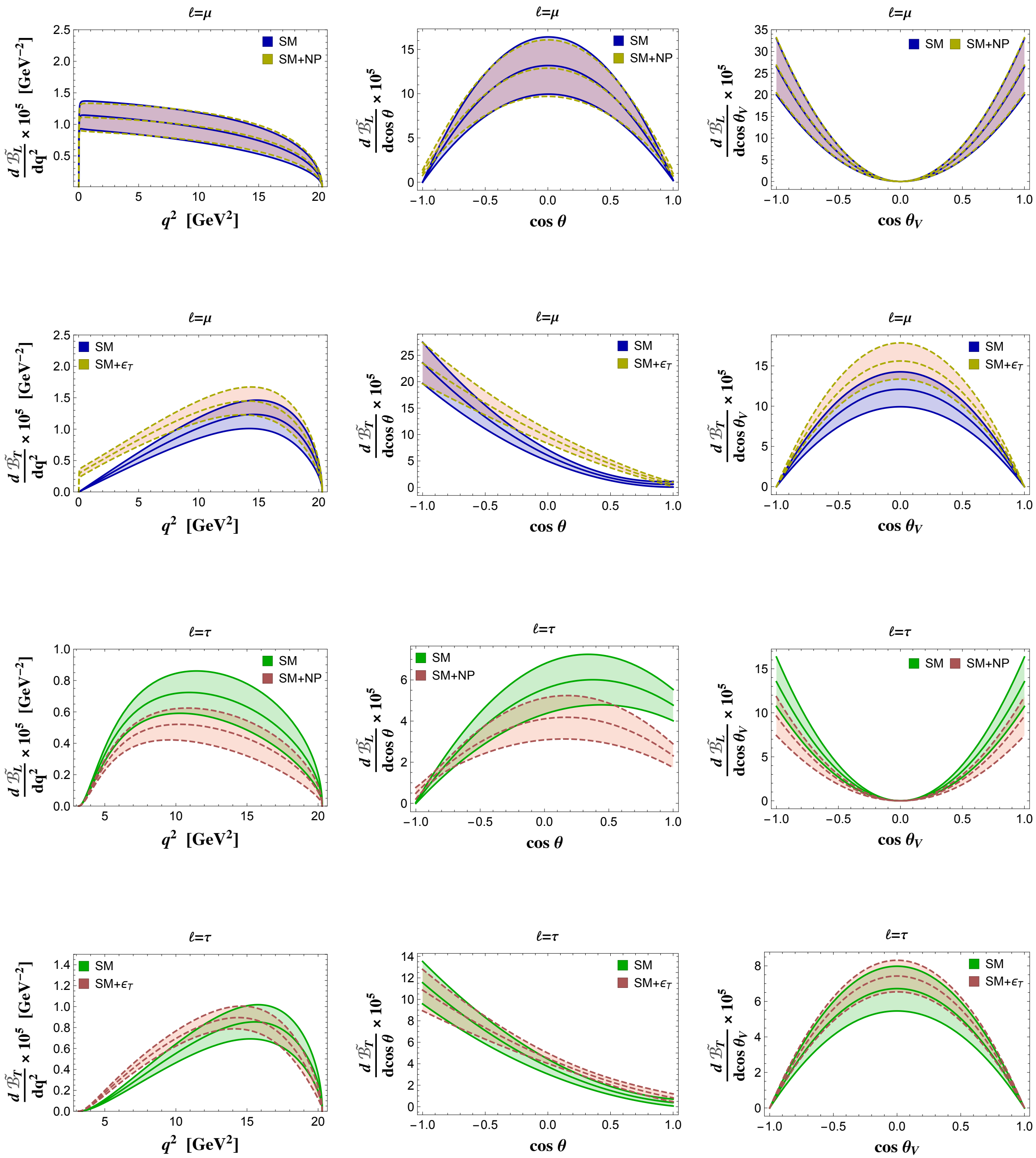
$$R^{\rho}_{2s/1s}(q^2) = \frac{I^{\rho}_{2s}(q^2)}{I^{\rho}_{1s}(q^2)}$$



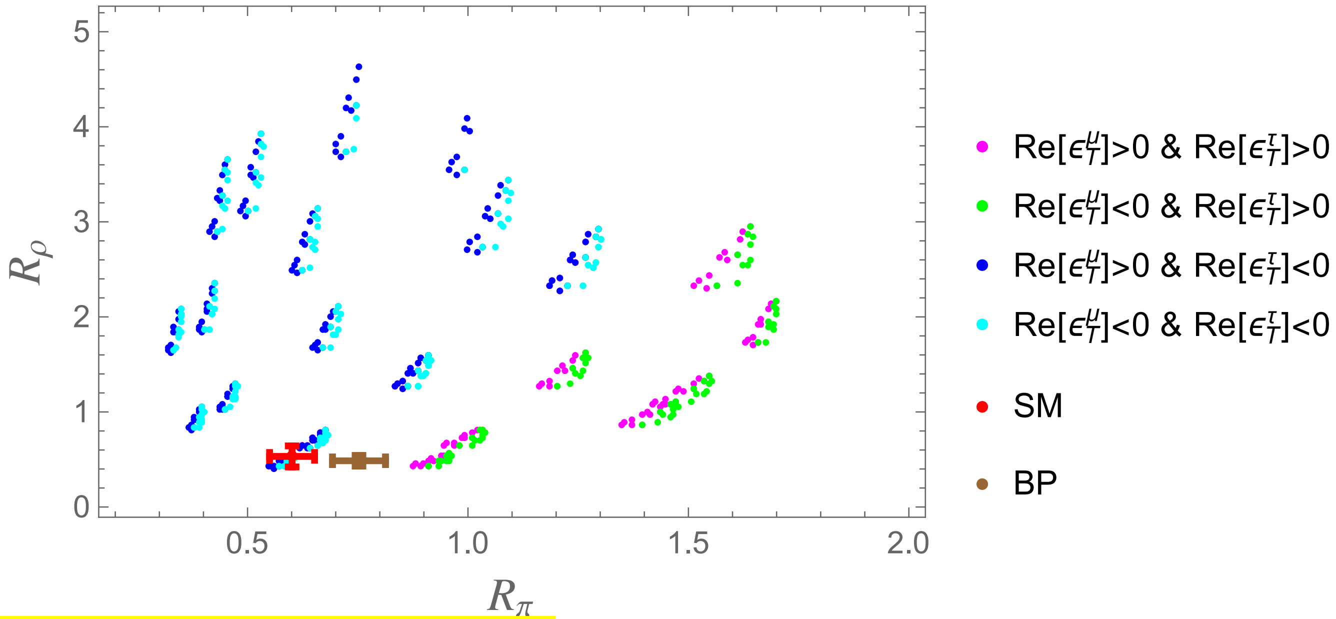
charged lepton
FB asymmetry



distributions



R(ρ) vs R(π)



large deviations are possible for tauonic modes

Which SM extension? simplified BSM models

Scrutinized candidates:

Spin 0, 1 leptoquark (LQ) → predicted in GUT/compositeness frameworks coupled to quarks and leptons

$$L = y_{ij}\bar{Q}_i S_3 L_j + z_{ij}\bar{Q}_i S_3 Q_j + h.c.$$

$$\frac{1}{\Lambda^2}\left(\bar{c}\gamma^\mu P_L b\right)\left(\tau\gamma^\mu P_L \upsilon\right) + tensor + ..$$

O(2 TeV)

SU(2) singlet vector leptoquark U_1 — Aebisher et al., Alonso et al., Barbieri et al., Calibbi et al.,Fajfer et al., Hiller et al., Bhattacharaya et al., Buttazzo et al.,…

SU(2) triplet scalar leptoquark S_3 — Kowalska et al., Dorsnee et al., Becirevic et al.,…

major focus on FCNC anomalies

331 models — Buras De Fazio Girrbach…

…………..

CONCLUSIONS & CHALLENGES

- Flavour a puzzling sector of the Standard Model
- Anomalies have been observed: they look quite robust (but no disagreement with SM at 5σ) and seem to follow a coherent pattern, pointing to BSM
- New precision measurements foreseen in the next future (LHCb, Belle II, and searches for signatures in pp)
- Theoretical efforts required for more precise predictions, to identify the regularities and to explore the possible new paths.