Anomalies in semileptonic B decays

Fulvia De Fazio
INFN Bari

Outline

- brief overview/classification of flavour anomalies
- $R(D)$ & $R(D^*)$
- the case of V_{cb}
- new strategies to investigate semileptonic B decays

Based on P. Colangelo, FDF, PRD 2017
P. Colangelo, FDF, JHEP 2018

anomalies in B decays

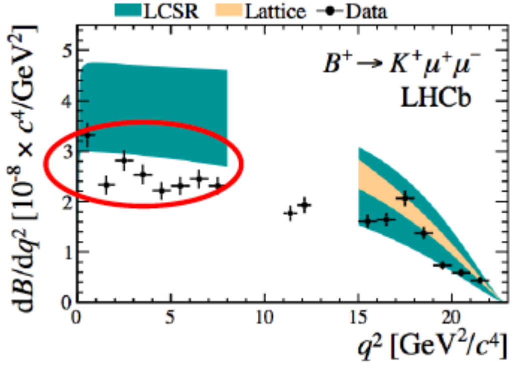
- In loop-induced modes : P_5' , R_K , R_{K^*}

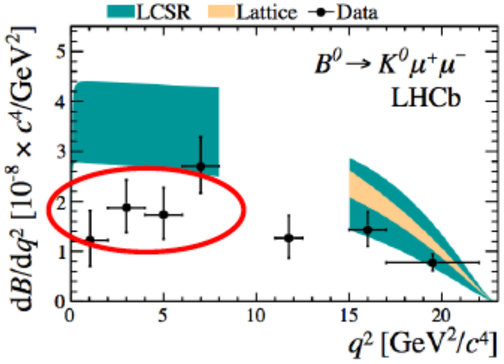
$$R_{K^{(*)}} = \left.\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)}\right|_{q^2 \in [q^2_{\min},\ q^2_{\max}]}$$

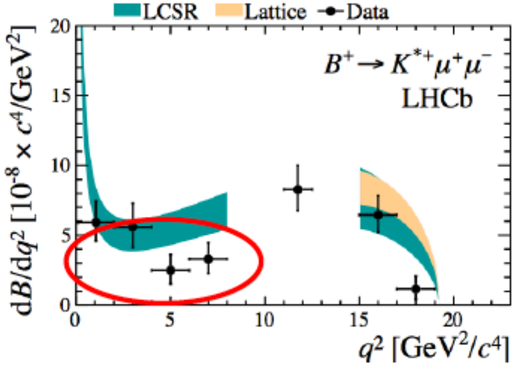
anomalies in loop-induced modes

b->s $\mu^+\mu^-$: measured BR are lower than SM predictions

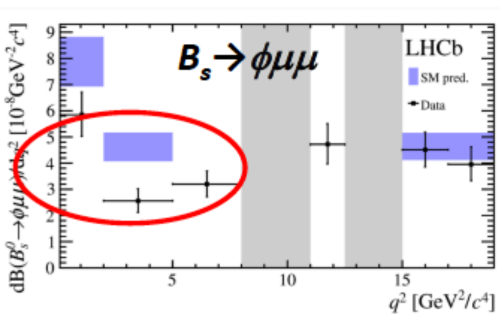
J. Serrano, talk @EPS2017



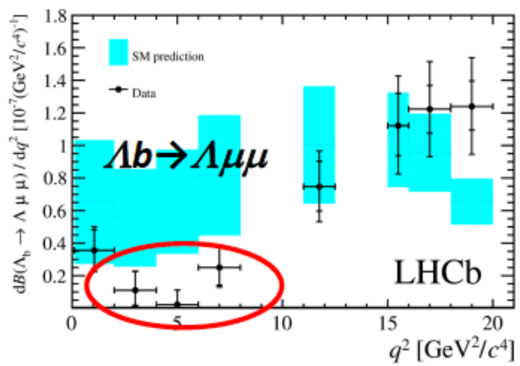




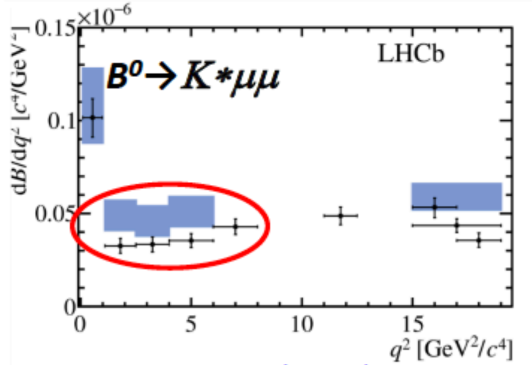
JHEP 06 (2014)133



JHEP 09 (2015)179

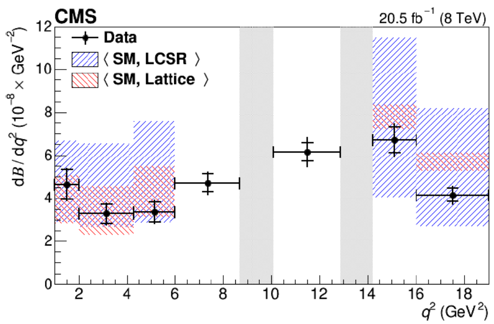


JHEP 06 (2015) 115



JHEP 11(2016)047

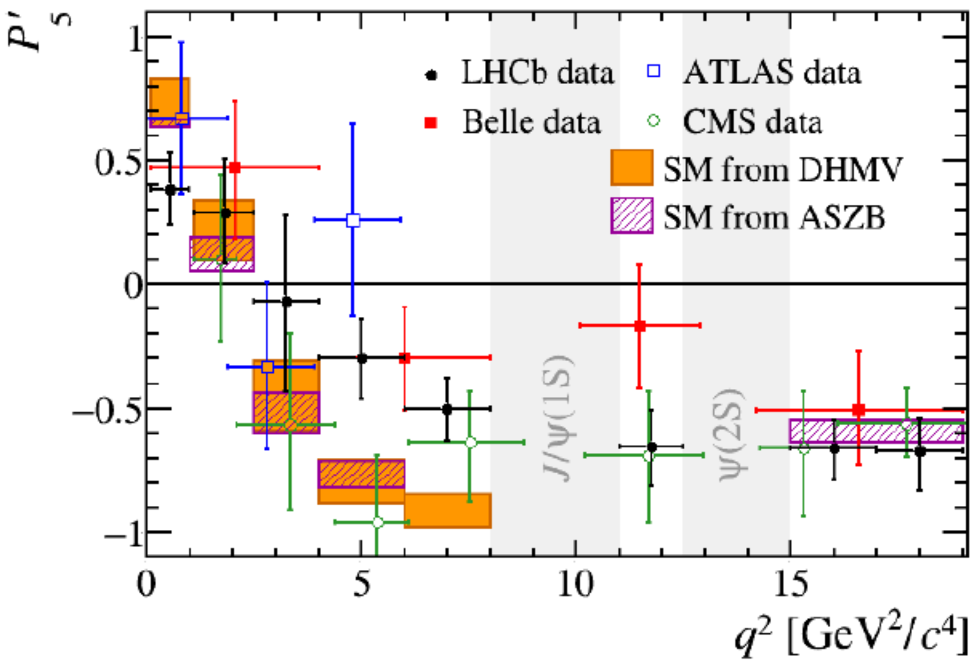
JHEP 04(2017)142



PLB 753 (2016) 424

anomalies in loop-induced modes

anomaly in the angular analysis in B->K* $\mu^+\mu^-$



anomalies in loop-induced modes

anomalous μ/e universality ratios:

$$R_{K^{(*)}} = \left.\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)}\right|_{q^2 \in [q^2_{\min},\, q^2_{\max}]}$$

S. Bifani et al. 1809.06229

Experiment (year)	H_s type	q^2 range [GeV^2/c^4]	Value
Belle (2009)	K	0.0 – kin. endpoint	$1.03 \pm 0.19 \pm 0.06$
Belle (2009)	K^*	0.0 – kin. endpoint	$0.83 \pm 0.17 \pm 0.08$
BaBar (2012)	K	0.10 – 8.12	$0.74^{+0.40}_{-0.31} \pm 0.06$
BaBar (2012)	K	> 10.11	$1.43^{+0.65}_{-0.44} \pm 0.12$
BaBar (2012)	K^*	0.10 – 8.12	$1.06^{+0.48}_{-0.33} \pm 0.08$
BaBar (2012)	K^*	> 10.11	$1.18^{+0.55}_{-0.37} \pm 0.11$
LHCb (2014)	K^+	1.0 – 6.0	$0.745^{+0.090}_{-0.074} \pm 0.036$
LHCb (2017)	K^{*0}	0.045 – 1.1	$0.66^{+0.11}_{-0.03} \pm 0.05$
LHCb (2017)	K^{*0}	1.1 – 6.0	$0.69^{+0.11}_{-0.07} \pm 0.05$

anomalies in B decays

- In tree-level B decays : R_D, R_{D*}

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)} \tau \nu_\tau)}{B(B \to D^{(*)} \ell \nu_\ell)}$$

- In loop-induced modes : P_5' , R_K , R_{K*}

$$R_{K^{(*)}} = \left.\frac{B(B \to K^{(*)} \mu^+ \mu^-)}{B(B \to K^{(*)} e^+ e^-)}\right|_{q^2 \in \left[q^2_{\min},\ q^2_{\max}\right]}$$

anomalies in B decays

- In tree-level B decays : R_D, R_{D*} $$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu_\tau)}{B(B \to D^{(*)}\ell\nu_\ell)}$$
- In loop-induced modes : P_5' , R_K , R_{K*} $$R_{K^{(*)}} = \left.\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)}\right|_{q^2\in\left[q^2_{\min},\ q^2_{\max}\right]}$$

long standing puzzles

- $|V_{cb}|$: tension between inclusive and exclusive determinations
- $|V_{ub}|$: tension between inclusive and exclusive determinations

anomalies in B decays

- In tree-level B decays : R_D, R_{D*}

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu_\tau)}{B(B \to D^{(*)}\ell\nu_\ell)}$$

- In loop-induced modes : P_5' , R_K , R_{K*}

$$R_{K^{(*)}} = \left.\frac{B(B \to K^{(*)}\mu^+\mu^-)}{B(B \to K^{(*)}e^+e^-)}\right|_{q^2\in[q^2_{\min},\ q^2_{\max}]}$$

long standing puzzles

- $|V_{cb}|$: tension between inclusive and exclusive determinations

- $|V_{ub}|$: tension between inclusive and exclusive determinations

questions to address

- are these tensions related?

- should we invoke LFU violation?

SM: ~~LFU~~ only in Yukawas

anomalies in B decays

- In tree-level B decays : R_D, R_{D*} ➔ violation of τ/μ, τ/e universality
- In loop-induced modes : P_5' , R_K , R_{K*} ➔ violation of μ/e universality

long standing puzzles

- $|V_{cb}|$: tension between inclusive and exclusive determinations
- $|V_{ub}|$: tension between inclusive and exclusive determinations

questions to address

- are these tensions related?
- should we invoke LFU violation?

SM: ~~LFU~~ only in Yukawas

anomalies in B decays

- In tree-level B decays : R_D, R_{D*} ➔ violation of τ/μ, τ/e universality this talk
- In loop-induced modes : P_5' , R_K , R_{K*} ➔ violation of μ/e universality

long standing puzzles

- $|V_{cb}|$: tension between inclusive and exclusive determinations this talk
- $|V_{ub}|$: tension between inclusive and exclusive determinations

questions to address

- are these tensions related?
- should we invoke LFU violation?

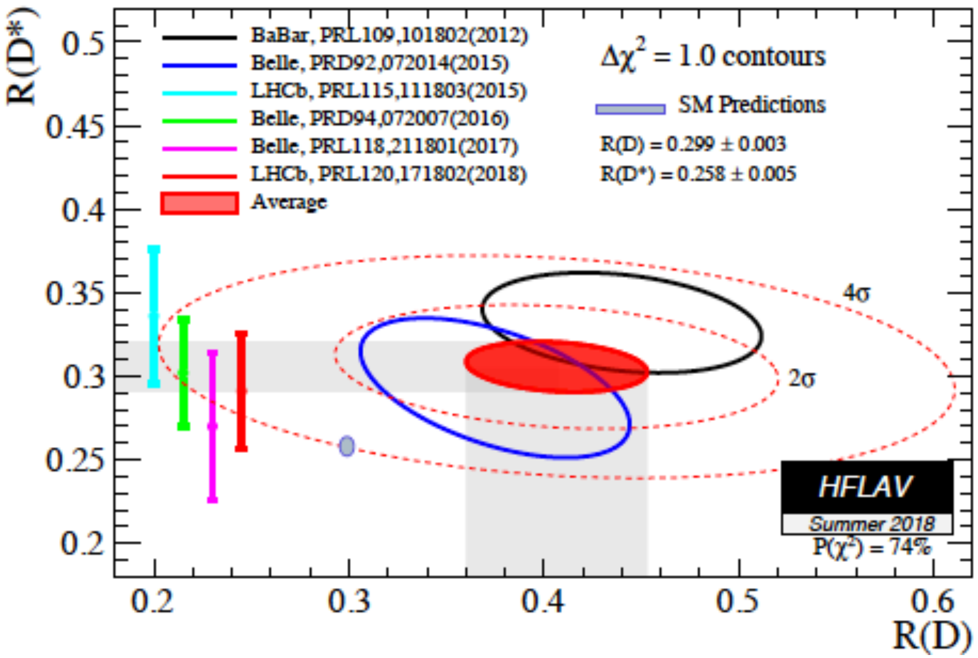
SM: ~~LFU~~ only in Yukawas

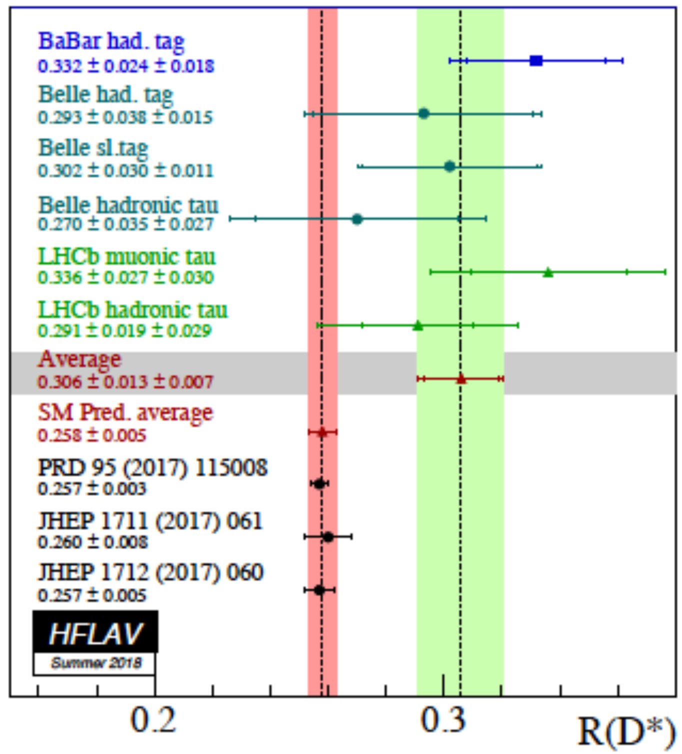
Latest news for R(D$^{(*)}$) & friends

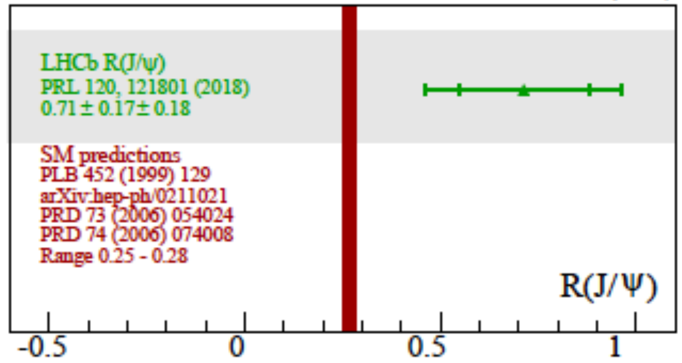
$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell)}$$

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

3.8σ deviation from SM (HFAG)





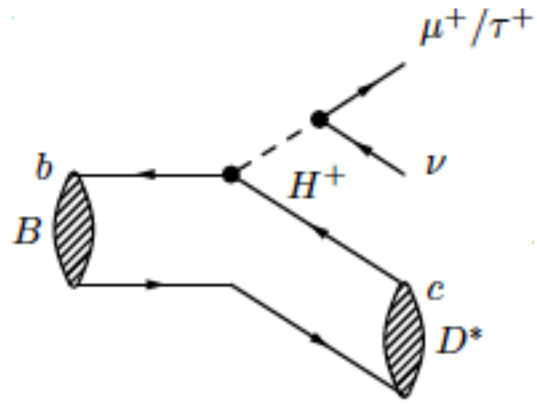


$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

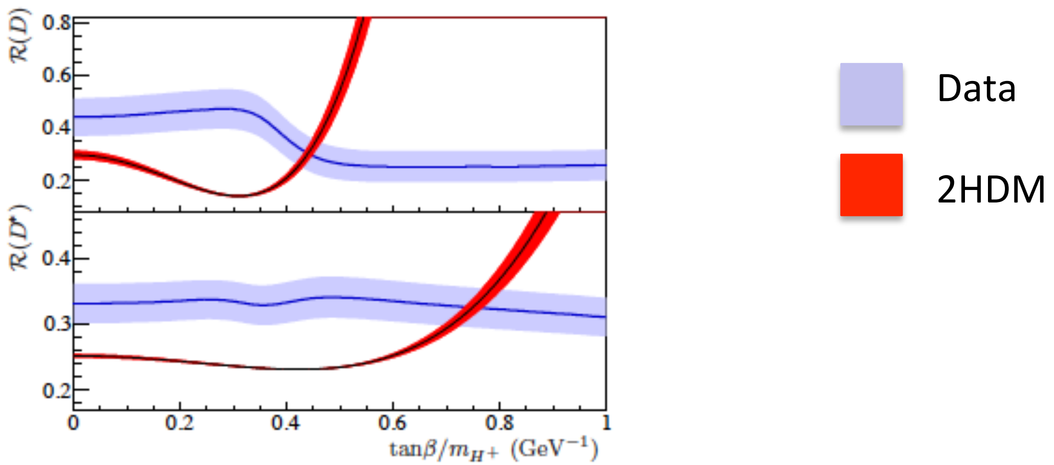
$R(D^{(*)})$

most "natural" explanation:
new scalars with couplings to leptons proportional to their mass

- would explain the enhancement of τ modes
- would enhance both semileptonic and purely leptonic modes



the simplest model (2HDM) excluded (BABAR):
no possibility to simultaneously reproduce R(D) and R(D*)



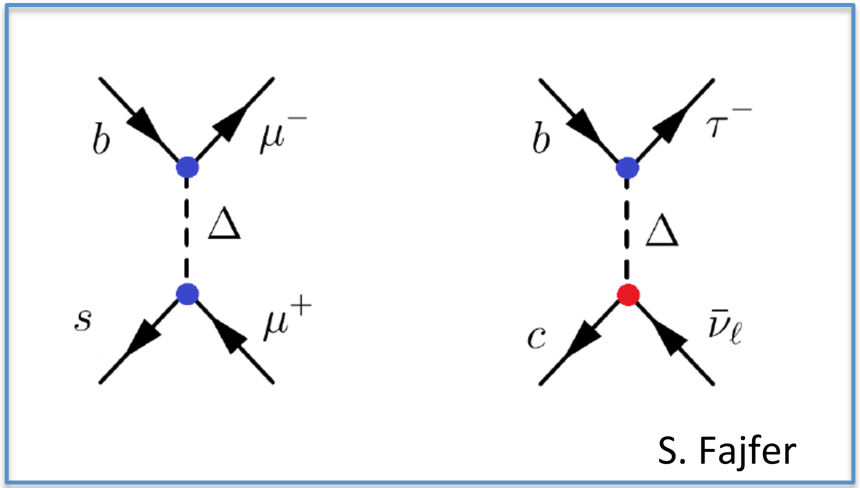
many other explanations put forward....

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

common solution to the $R(K^{(*)})$ tension -> new left-handed effective interaction

no effect observed in K, π decays -> NP mainly coupling to 3rd generation of q, ℓ

- ✧ new gauge bosons
- ✧ leptoquarks (scalar)
- ✧ leptoquarks (vector) -> may be either gauge bosons or vector mesons



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

- NP does not necessarily imply a unique mediator/a unique new structure
- bottom-up approach: no a priori identification of the model
  consider the new possible structures
  single out the most sensitive observables

τ lepton in the final state: allow to access more form factors
sensitive to the lepton mass

R(D(*))

P. Biancofiore, P. Colangelo, FDF , PRD 2013

- consider a NP scenario that enhances semileptonic modes but not leptonic ones
- predict the effects in other modes

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

new complex coupling: $\epsilon_T^{\mu,e}=0$, $\epsilon_T^{\tau} \neq 0$

charmed meson

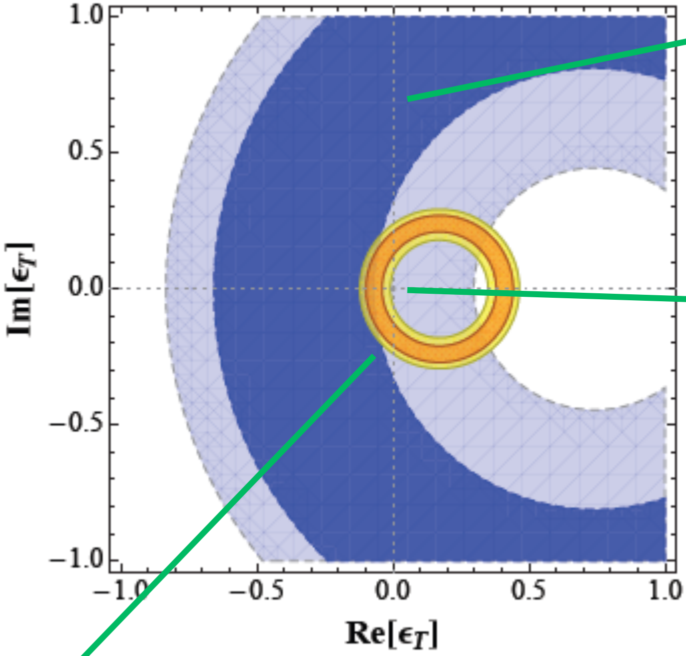
$$\frac{d\Gamma}{dq^2}(B \to M_c \ell \bar{\nu}_\ell) = C(q^2) \left[\frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{SM} + \underbrace{\frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{NP}}_{\propto |\epsilon_T|^2} + \underbrace{\frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{INT}}_{\propto \mathrm{Re}(\epsilon_T)} \right]$$

$$C(q^2) = \frac{G_F^2 |V_{cb}|^2 \lambda^{1/2}(m_B^2, m_{M_c}^2, q^2)}{192\pi^3 m_B^3} \left(1 - \frac{m_\ell^2}{q^2}\right)^2$$

$\propto |\epsilon_T|^2$

$\propto \mathrm{Re}(\epsilon_T)$

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

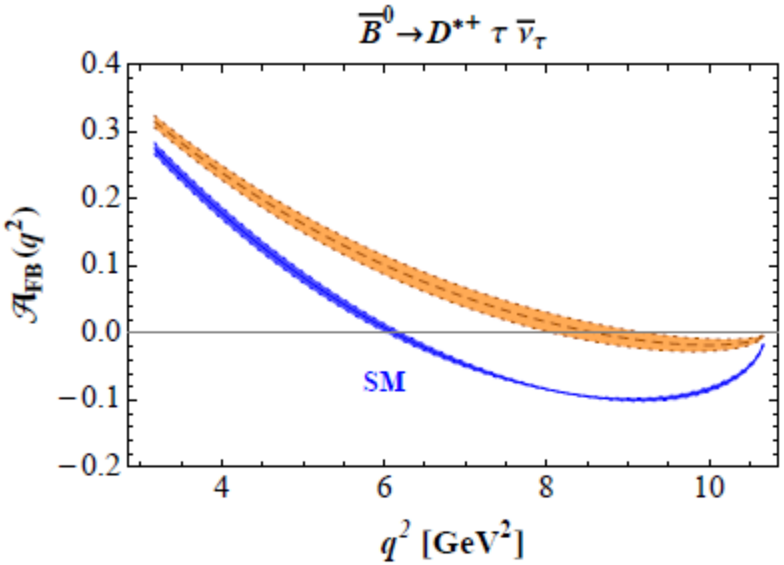


big circle: R(D) constraint

overlap region:
varying ε_T in this range
predictions for several observables

small circle: R(D*) constraint

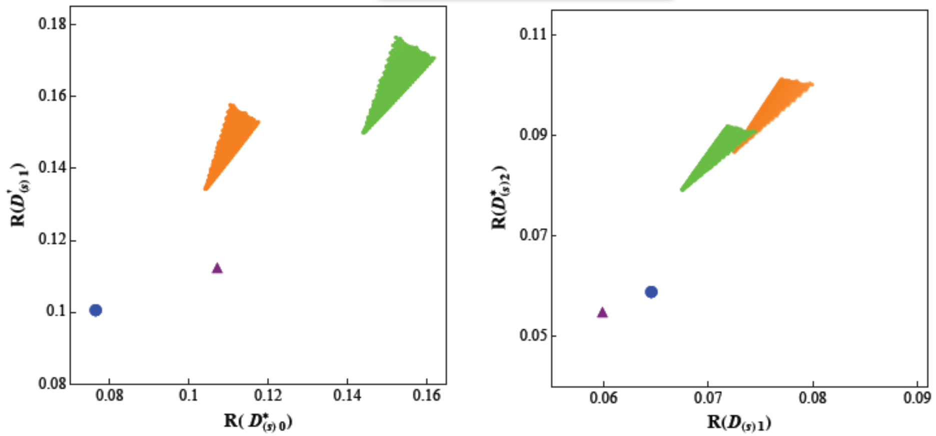
Ex: τ Forward-backward asymmetry



SM predicts a zero at $q^2 \approx 6.15$ GeV^2
in NP the zero is shifted to $q^2 \in [8.1, 9.3]$ GeV^2

$B \to D^{**} \tau \bar{\nu}_\tau$

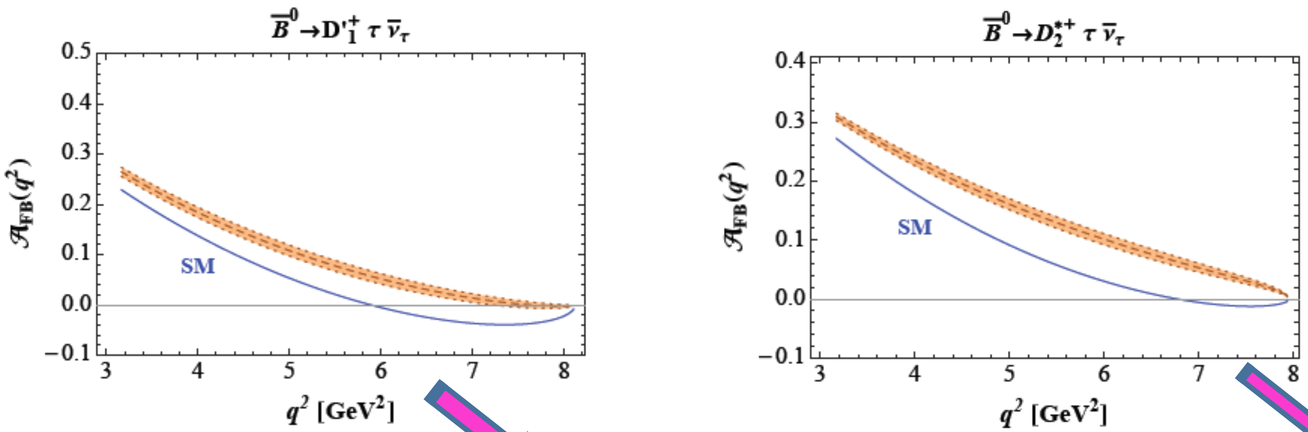
D^{**}= positive parity excited charmed mesons



orange = non strange
blue circle = SM
green = strange
triangle = SM

the inclusion of the tensor operator produces an increase in the ratios

forward-backward asymmetries



shift in the position of the zero

the zero disappears

$|V_{cb}|$

exclusive determinations from B systematically smaller than inclusive ones

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

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

Aoki et al. (lattice)

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

HFAG

are the tensions in $|V_{cb}|$ and $R(D^{(*)})$ related?

$|V_{cb}|$: argument against a NP explanation

A. Crivellin and S. Pokorski, PRL 114, 011802 (2015)

model independent parametrization of NP effects: write a generalized H_{eff}

- additional four-fermion operators (S,P,T)

- modified W-couplings

imply modified Z couplings if invariance under the SM gauge group is respected

$|V_{cb}|$: argument against a NP explanation

A. Crivellin and S. Pokorski, PRL 114, 011802 (2015)

model independent parametrization of NP effects: write a generalized H_{eff}

- additional four-fermion operators (S,P,T)

- modifie[illegible]-couplings

imply modified Z couplings if invariance under the SM gauge group is respected

$|V_{cb}|$: argument against a NP explanation

A. Crivellin and S. Pokorski, PRL 114, 011802 (2015)

model independent parametrization of NP effects: write a generalized H_{eff}

- additional four-fermion operators (S,P,T)

if massless leptons are considered
➔

- at zero recoil no interference between SM and NP contributions
- the NP effect is the same in all modes

$|V_{cb}|$

P. Colangelo, FDF, PRD 95, 011701(R) 2017

- include a new tensor operator in H_{eff}
- relax the assumption that it contributes only for τ lepton
- non vanishing m_ℓ $\ell = e, \mu, \tau$ and $m_e \neq m_\mu$

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

new structure-> new coupling

Inclusive B -> $X_c\, \ell \nu_\ell$ decay

Heavy Quark Expansion -> $\Gamma(H_Q)$ as series in powers of m_Q^{-1}

$$\boxed{\frac{d\Gamma}{d\hat{q}^2} = C(q^2)\left[\left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm SM} + |\epsilon_T|^2 \left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm NP} + {\rm Re}(\epsilon_T)\left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm INT}\right]} \qquad \hat{q}^2 = \frac{q^2}{m_b^2}$$

each of the three terms expanded in m_b^{-1}
α_s corrections included in the SM term

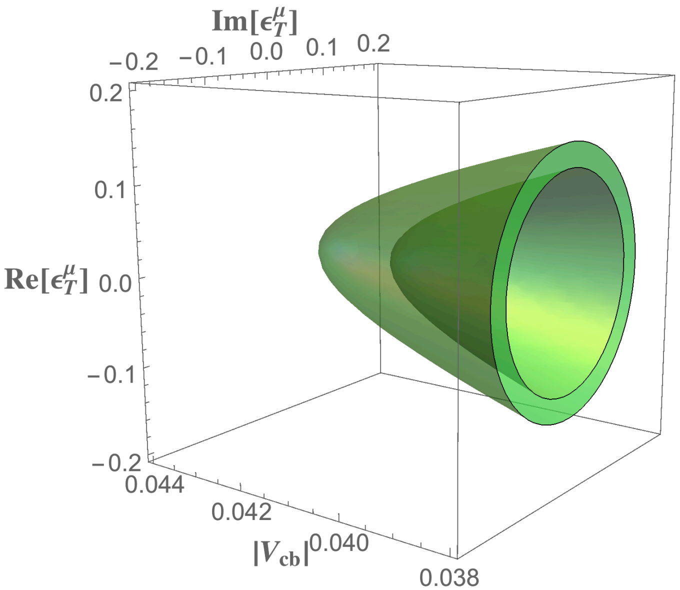
- prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^{ℓ}:
  three-parameter space $\boxed{({\rm Re}(\epsilon_T^{\ell}), {\rm Im}(\epsilon_T^{\ell}), |V_{cb}|)}$

- non vanishing lepton mass - distinguish between *e* and μ

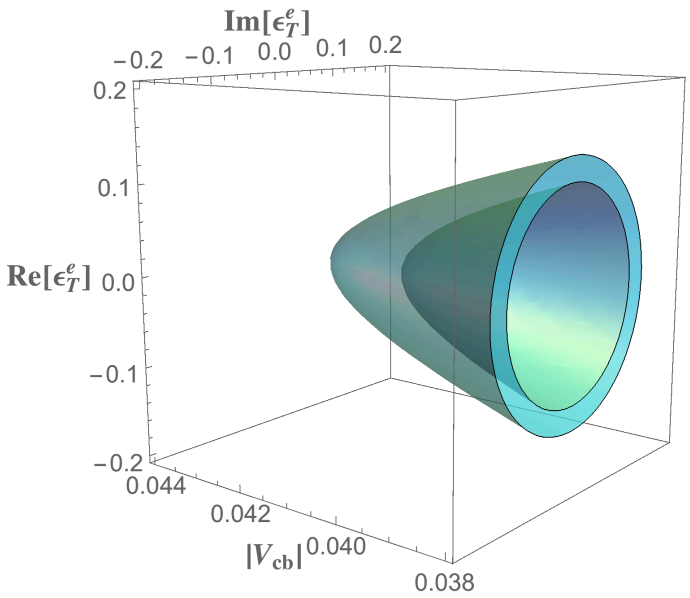
- result to be compared to experiment $\boxed{\mathcal{B}(B^+ \to X_c e^+ \nu_e) = (10.8 \pm 0.4) \times 10^{-2}}$ PDG

inclusive B -> $X_c \ell \nu_\ell$ decay: allowed regions

comparison with data at $1\,\sigma$



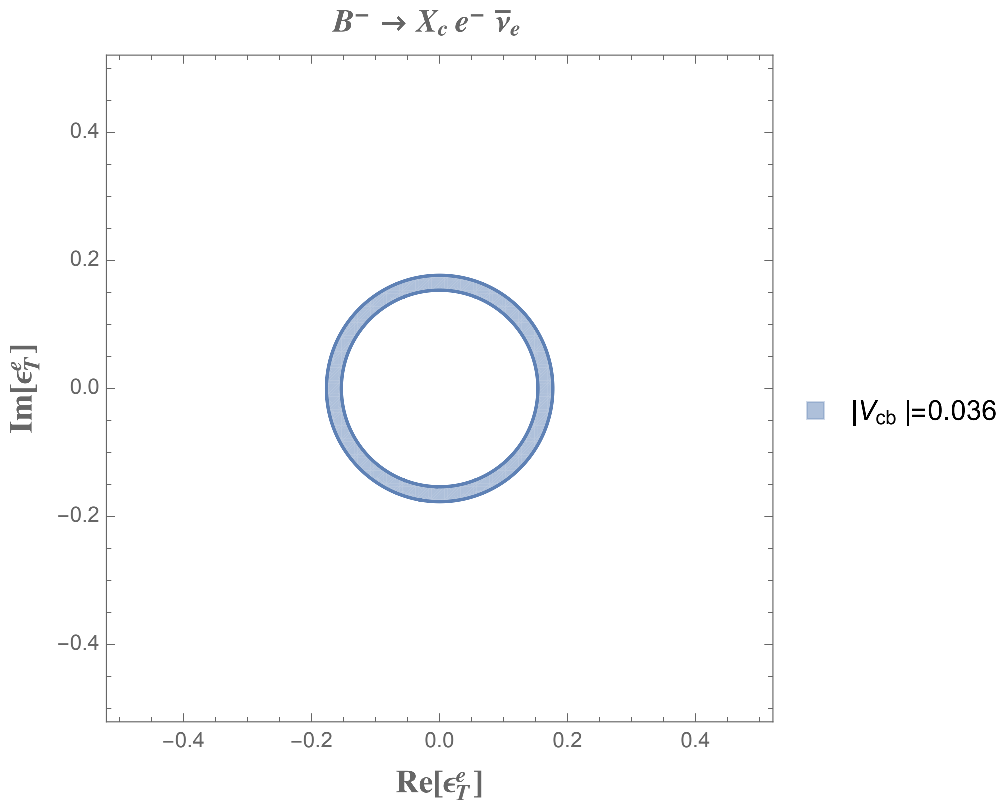
μ channel



e channel

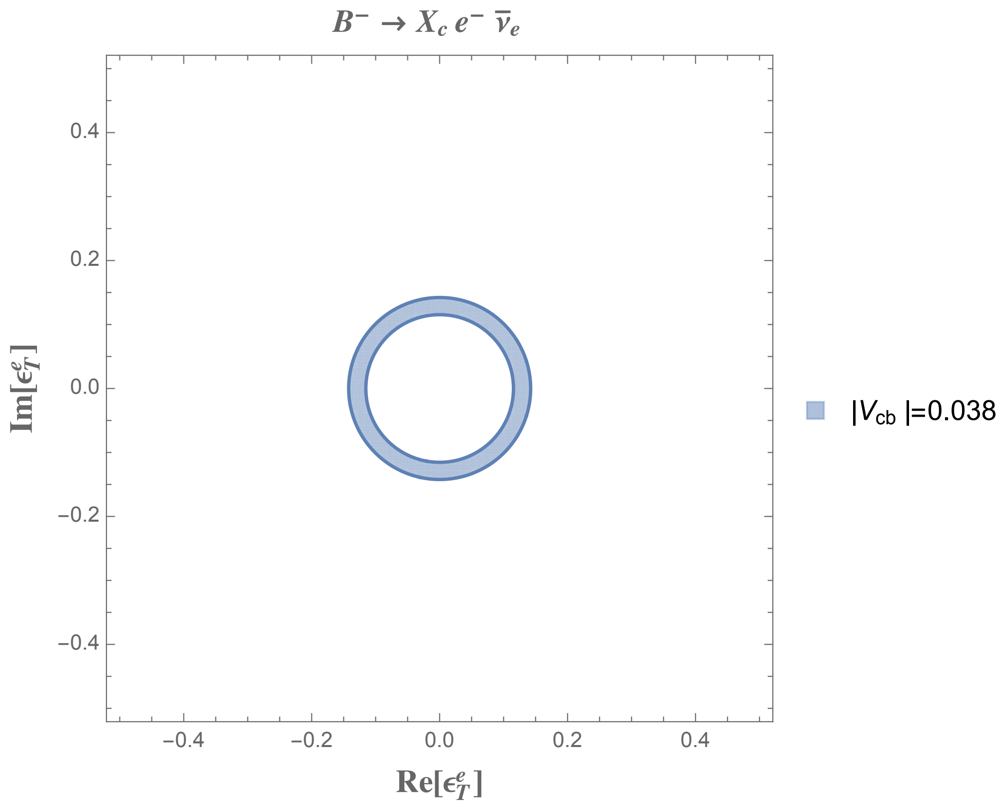
inclusive B -> $X_c \ell \nu_\ell$ decay: allowed regions

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



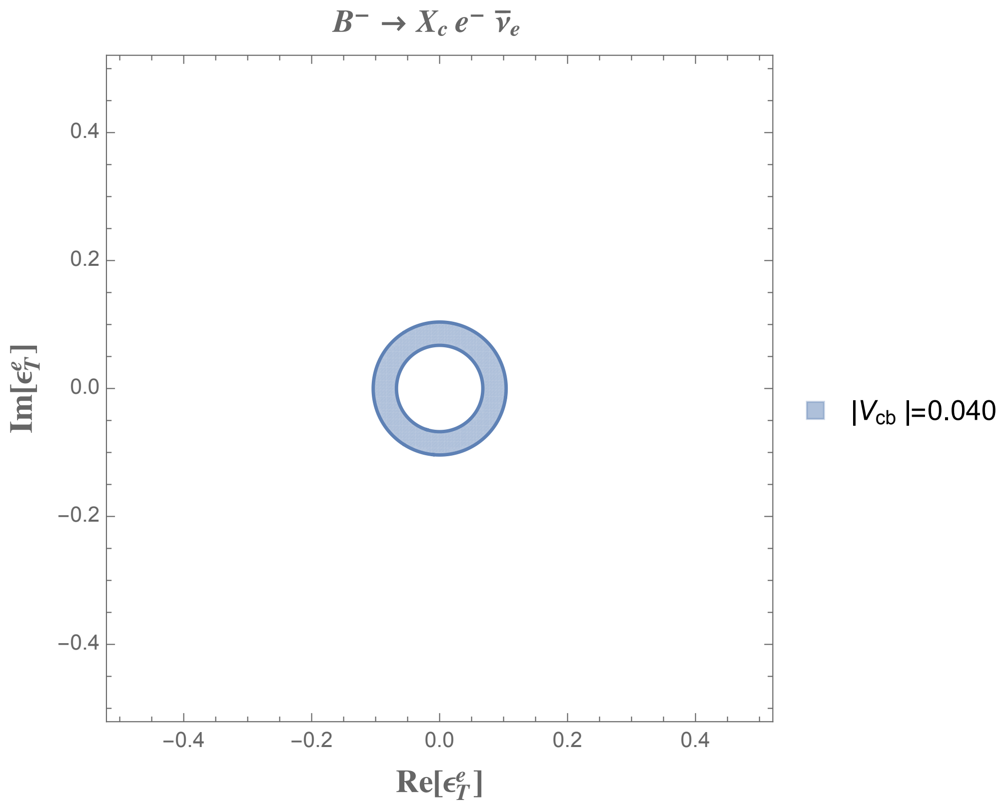
inclusive B -> $X_c\ \ell \nu_\ell$ decay: allowed regions

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



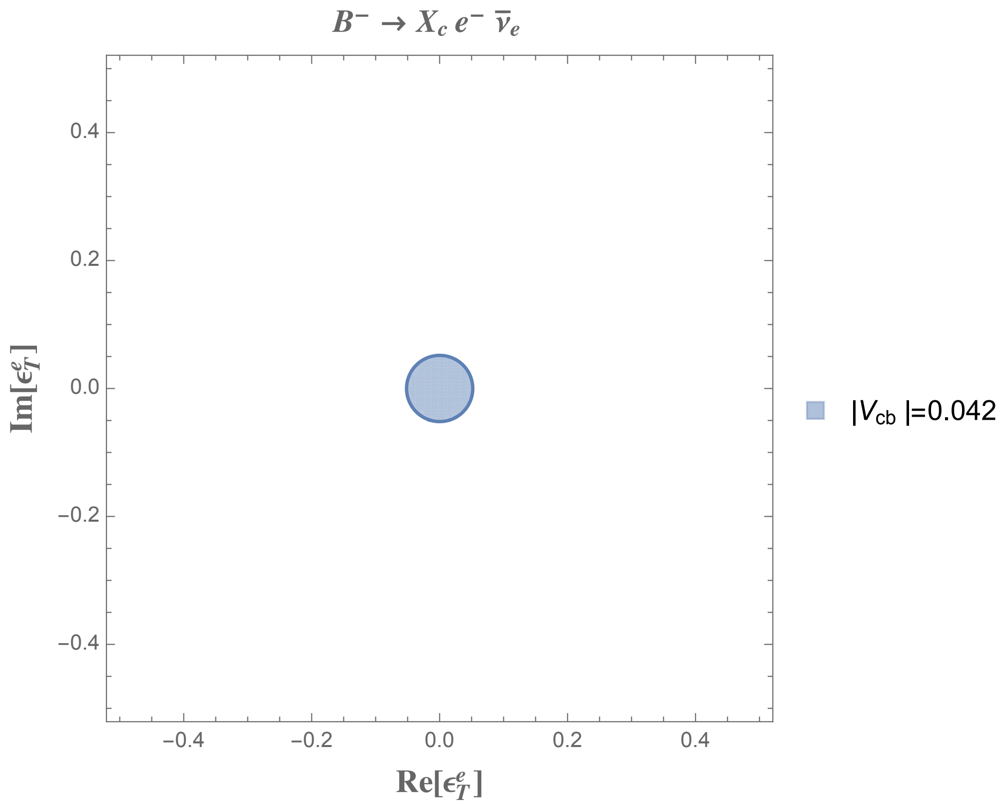
inclusive B -> $X_c\ \ell\nu_\ell$ decay: allowed regions

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



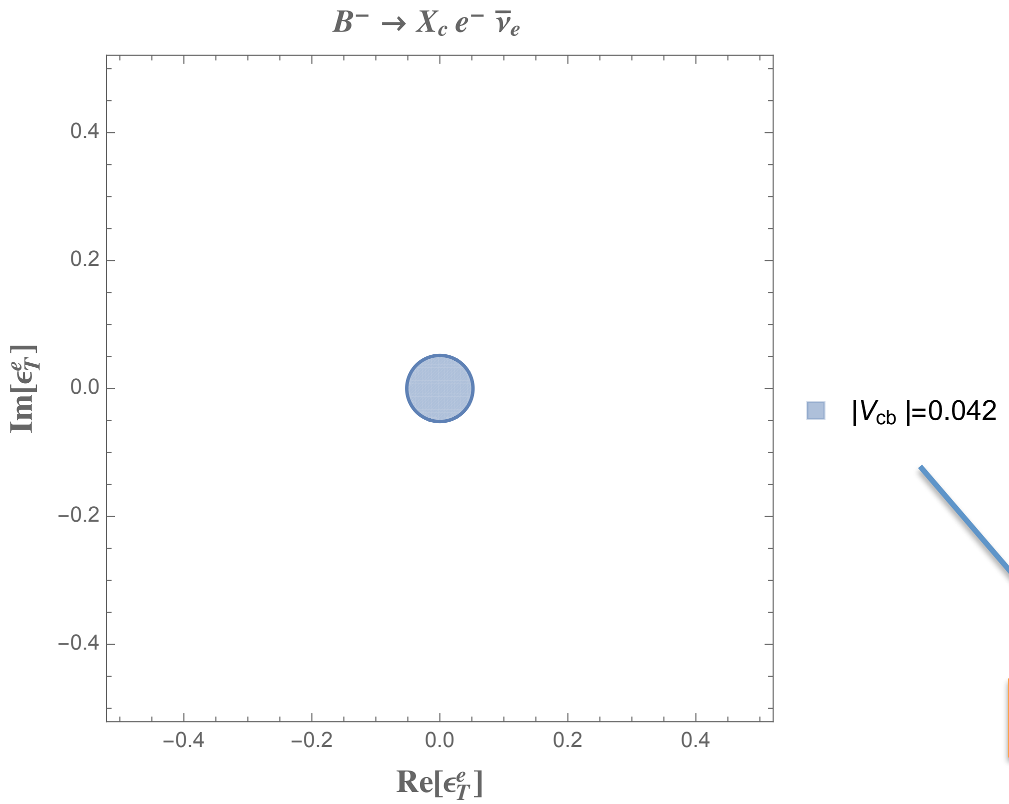
inclusive B -> $X_c\, \ell \nu_\ell$ decay: allowed regions

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



inclusive B -> $X_c\ \ell \nu_\ell$ decay: allowed regions

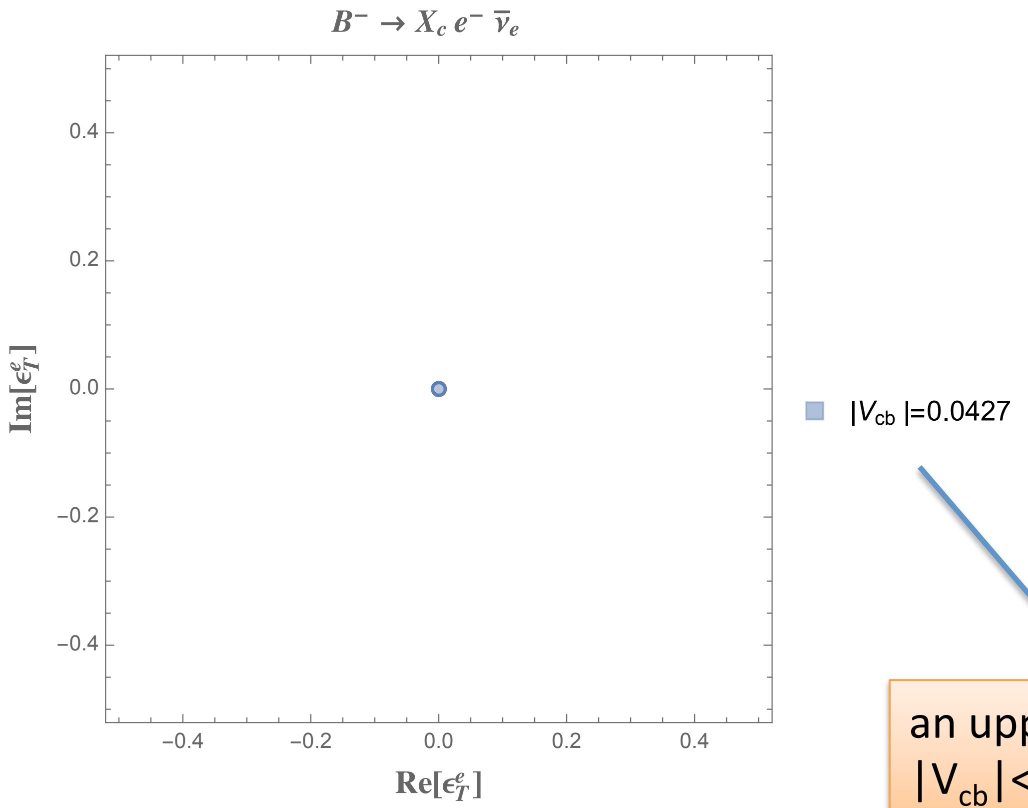
allowed values of ε_T^{ℓ} correlated to $|V_{cb}|$



quoted value for SM!

inclusive B -> $X_c\, \ell \nu_\ell$ decay: allowed regions

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



an upper limit is found: $|V_{cb}|<0.04273$

Exclusive B -> $D^{(*)} \ell \nu_\ell$ decay

$$\frac{d\Gamma}{dq^2}(B \to M_c \ell \bar{\nu}_\ell) = \left.\frac{d\Gamma}{dq^2}\right|_{SM} + \left.\frac{d\Gamma}{dq^2}\right|_{NP} + \left.\frac{d\Gamma}{dq^2}\right|_{INT}$$

- B ->D and B->D^*
- two sets of form factors: one for each structure in H_{eff}
- experimental data specific for *e* and μ available

B -> D $\ell \nu_\ell$

$$< D(p')|\bar{c}\gamma_\mu b|B(p)> \; = F_1(q^2)(p+p')_\mu + \frac{m_B^2 - m_D^2}{q^2}\left[F_0(q^2) - F_1(q^2)\right] q_\mu$$

$$< D(p')|\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b|B(p)> \; = \frac{F_T(q^2)}{m_B + m_D}\epsilon_{\mu\nu\alpha\beta}p'^\alpha p^\beta + i\frac{G_T(q^2)}{m_B+m_D}(p_\mu p'_\nu - p_\nu p'_\mu)$$

HQ relations: all form factors in terms of the Isgur Wise

- m_b^{-1} and α_s corrections known for F_1 and F_0
- leading order relations for F_T and G_T

M. Neubert,
Phys. Rep. 245 (1994) 259
I. Caprini, L. Lellouch, M. Neubert,
NPB 530 (1998) 153

- F_1 and F_0 from lattice
- HQ relations to derive F_T and G_T from F_1, F_0

J.A. Bailey et al.,
PRD 89 (2014) 114504

Compare to experiment:

BABAR Collab.,
PRD 79 (2009) 012002

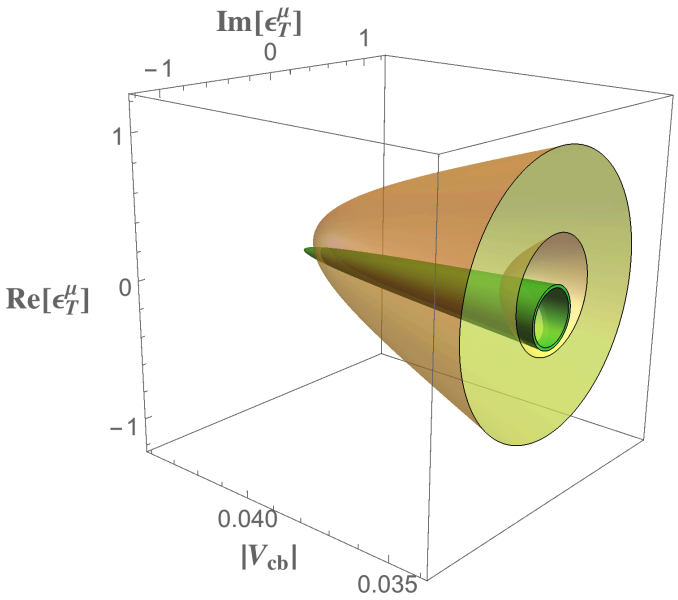
$$\mathcal{B}(B^- \to D^0\mu^-\bar{\nu}_\mu) = (2.25 \pm 0.04 \pm 0.17) \times 10^{-2}$$

$$\mathcal{B}(B^- \to D^0 e^-\bar{\nu}_e) = (2.38 \pm 0.04 \pm 0.15) \times 10^{-2}.$$

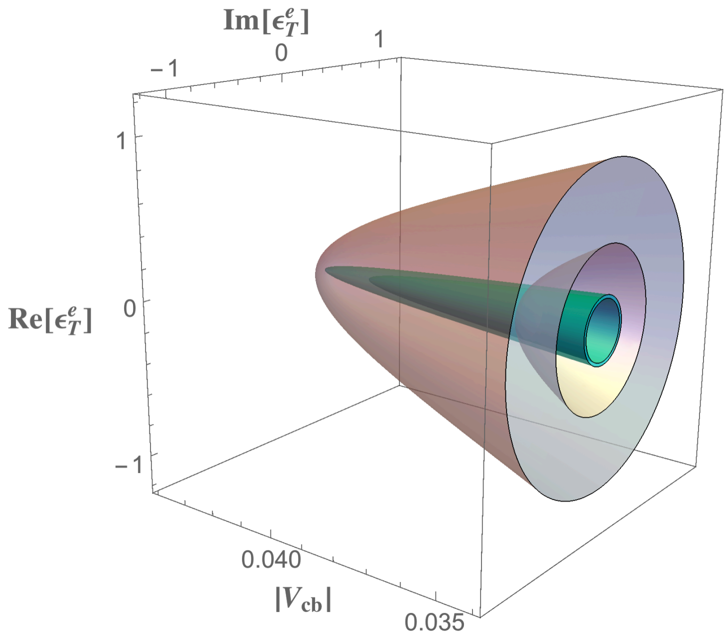
Theory prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^ℓ

$$(\mathrm{Re}(\epsilon_T^\ell), \mathrm{Im}(\epsilon_T^\ell), |V_{cb}|)$$

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



μ channel



e channel

inner regions: inclusive
outer regions: exclusive

role of the lepton mass:
the symmetry axes of the two regions do not coincide in the case of μ,
they are almost coincident for *e*

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

procedure adopted by BaBar $q^2 = m_B^2 + m_{D^{(*)}}^2 - 2m_B m_{D^{(*)}} w.$ BABAR, PRD79, 012002 (2009)

$$\frac{d\Gamma}{dw}(B \to D^*\ell\bar{\nu}_\ell) = \frac{G_F^2|V_{cb}|^2 m_B^5}{48\pi^3}(1-r^*)^2 r^{*3} W_{D^*}(w) h_{A_1}^2(w)\sqrt{w^2-1}\,(w+1)^2 \left\{\left[1+(1-R_2(w))\frac{w-1}{1-r^*}\right]^2 + 2\left[\frac{1-2wr^*+r^{*2}}{(1-r^*)^2}\right]\left[1+R_1(w)^2\frac{w-1}{w+1}\right]\right\}$$

$$R_2(w) = R_1(1) + 0.11(w-1) - 0.06(w-1)^2 \qquad R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

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

Parameters	De sample	$D\mu$ sample	Combined result
ρ_D^2	$1.22 \pm 0.05 \pm 0.10$	$1.10 \pm 0.07 \pm 0.10$	$1.16 \pm 0.04 \pm 0.08$
$\rho_{D^*}^2$	$1.34 \pm 0.05 \pm 0.09$	$1.33 \pm 0.06 \pm 0.09$	$1.33 \pm 0.04 \pm 0.09$
R_1	$1.59 \pm 0.09 \pm 0.15$	$1.53 \pm 0.10 \pm 0.17$	$1.56 \pm 0.07 \pm 0.15$
R_2	$0.67 \pm 0.07 \pm 0.10$	$0.68 \pm 0.08 \pm 0.10$	$0.66 \pm 0.05 \pm 0.09$
$\mathcal{B}(D^0\ell\bar{\nu})(\%)$	$2.38 \pm 0.04 \pm 0.15$	$2.25 \pm 0.04 \pm 0.17$	$2.32 \pm 0.03 \pm 0.13$
$\mathcal{B}(D^{*0}\ell\bar{\nu})(\%)$	$5.50 \pm 0.05 \pm 0.23$	$5.34 \pm 0.06 \pm 0.37$	$5.48 \pm 0.04 \pm 0.22$
χ^2/n.d.f. (probability)	416/468 (0.96)	488/464 (0.21)	2.0/6 (0.92)

$h_{A_1}^e(1)|V_{cb}| = (35.94 \pm 1.65) \times 10^{-3}$

$h_{A_1}^\mu(1)|V_{cb}| = (35.63 \pm 1.96) \times 10^{-3}$

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

compare experiment to theory when w->1:

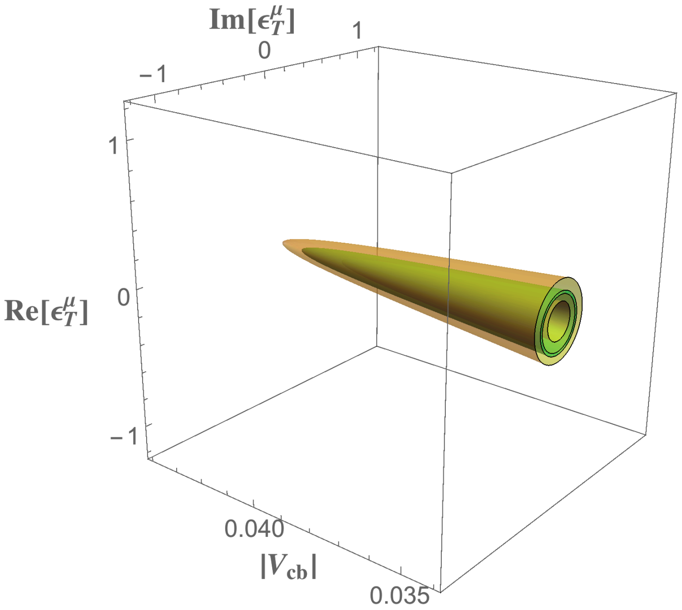
$$\frac{d\Gamma^{\rm th}}{dw}(B^- \to D^{*0}\ell^-\bar{\nu}_\ell)|_{w\to 1}$$
$$= \frac{G_F^2|V_{cb}|^2 m_{D^*}^2}{16\sqrt{2}\pi^3\ m_B}\sqrt{w-1}\left[1-\frac{m_\ell^2}{(m_B-m_{D^*})^2}\right]^2$$
$$\times\{(m_B+m_{D^*})^2[2(m_B-m_{D^*})^2+m_\ell^2]A_1(1)^2$$
$$+|\epsilon_T|^2 4[(m_B-m_{D^*})^2+2m_\ell^2][m_B\tilde{T}_1(1)+m_{D^*}\tilde{T}_2(1)]^2$$
$$-12{\rm Re}(\epsilon_T)(m_B^2-m_{D^*}^2)m_\ell A_1(1)[m_B\tilde{T}_1(1)+m_{D^*}\tilde{T}_2(1)]\}$$

- $A_1(1)$ known from lattice
- the others from HQ relations

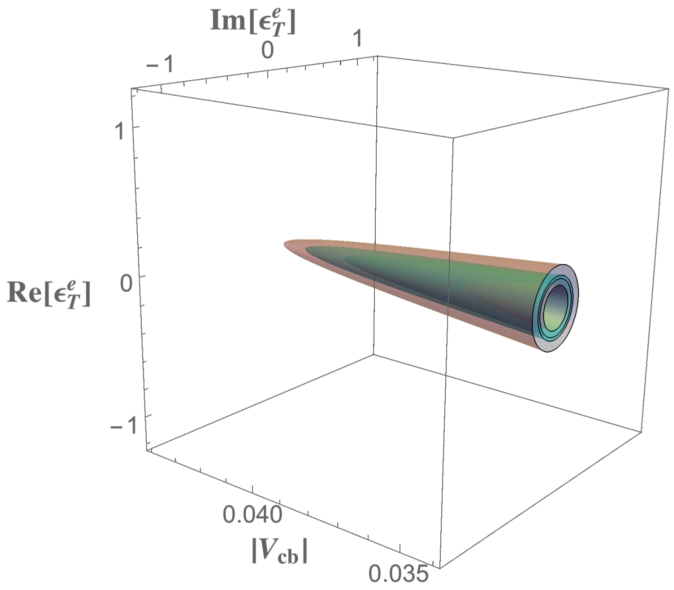
theory prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^ℓ

$$({\rm Re}(\epsilon_T^\ell), {\rm Im}(\epsilon_T^\ell), |V_{cb}|)$$

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



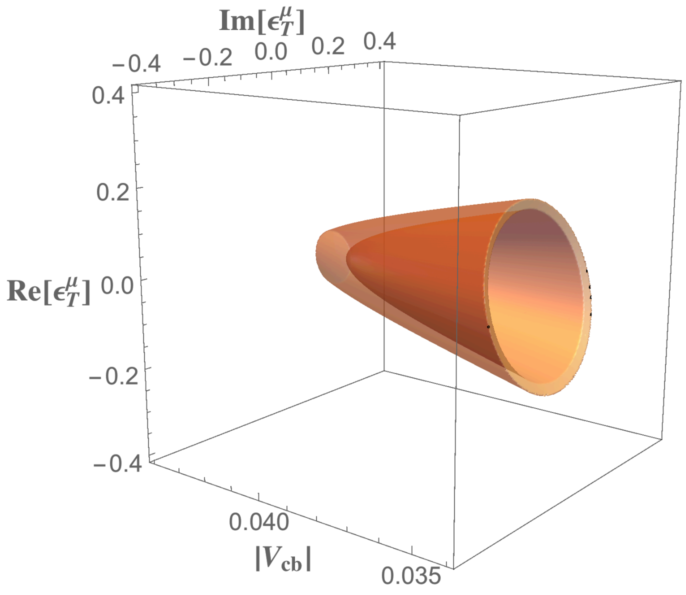
μ channel



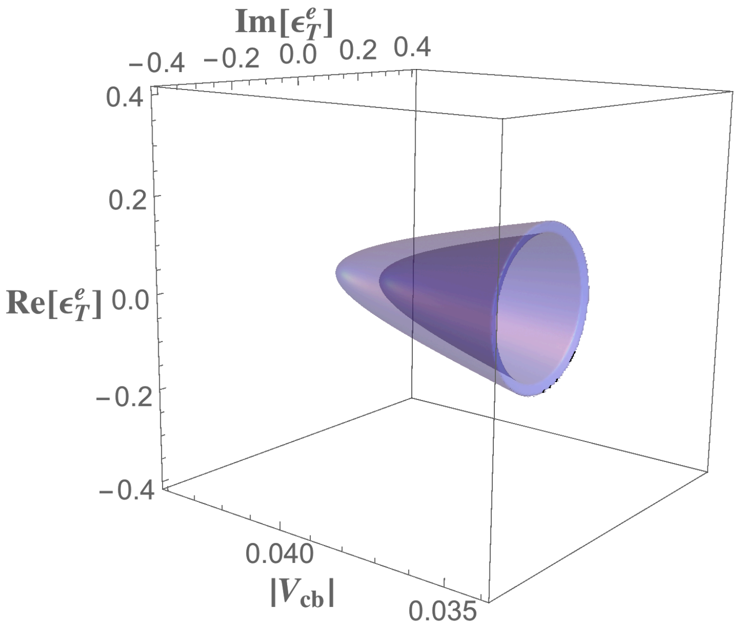
e channel

inner regions: inclusive mode
outer regions: exclusive mode

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



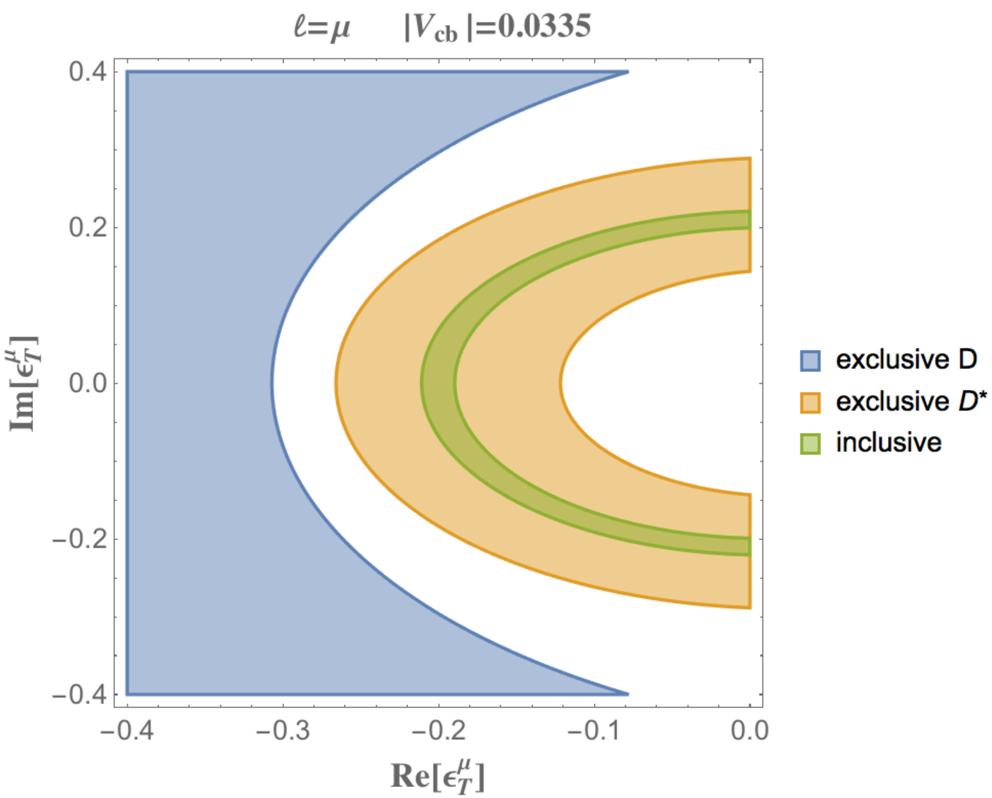
μ channel



e channel

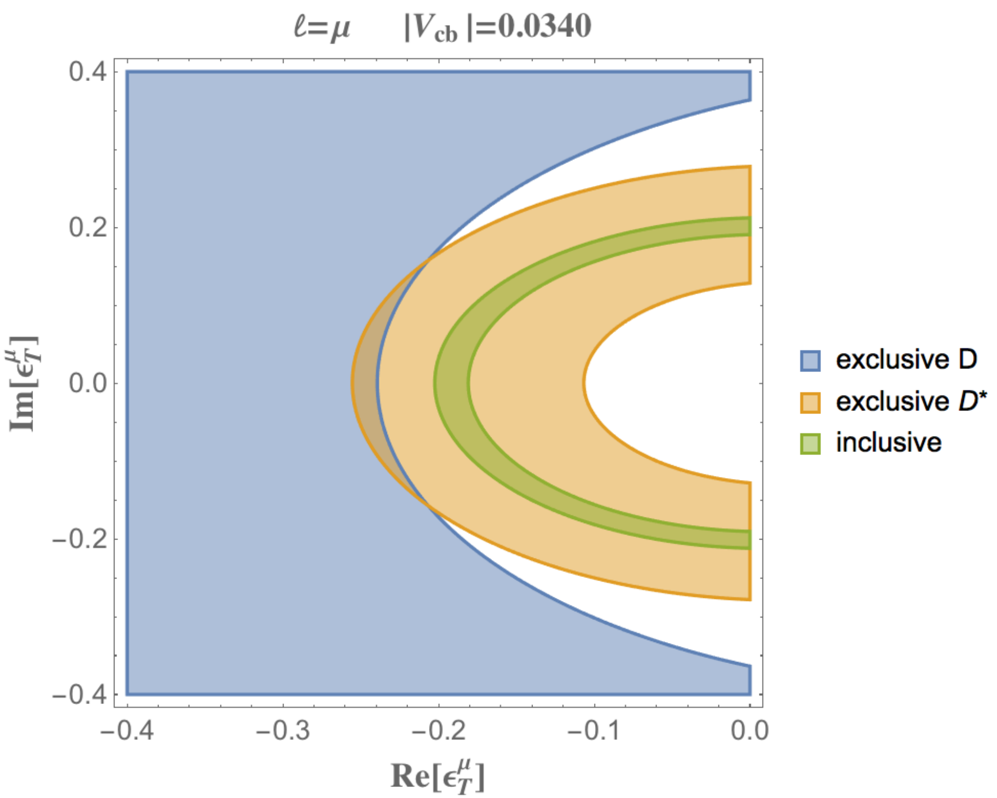
projections in the (Re ε_T, Im ε_T) plane

μ channel



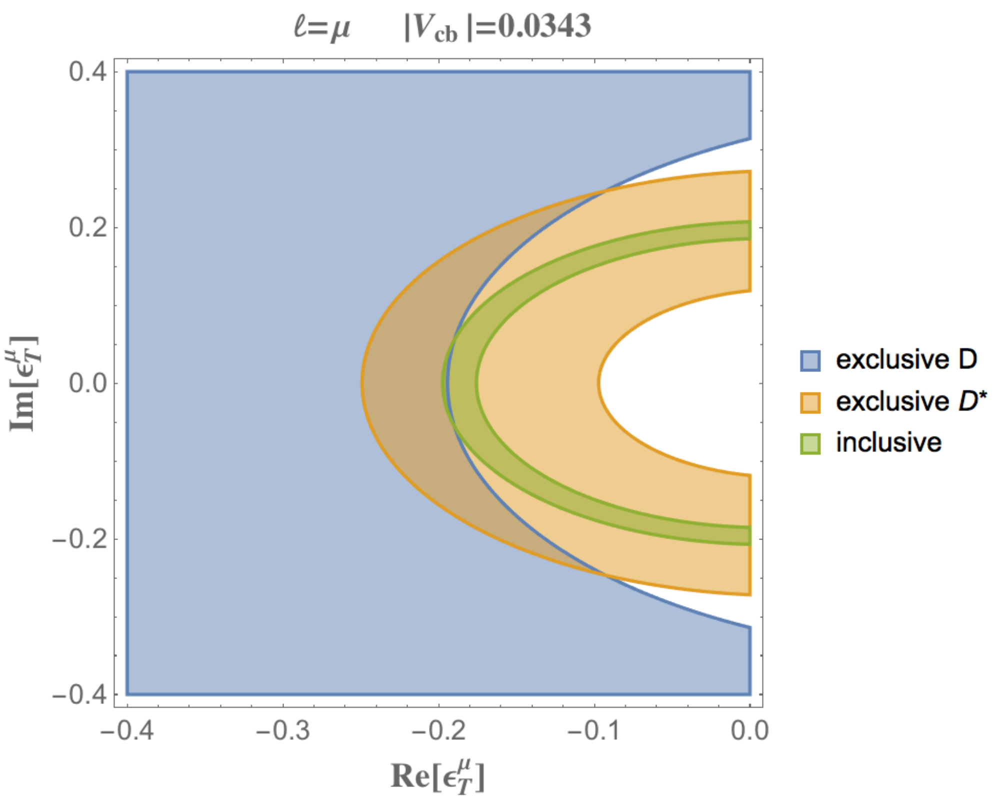
projections in the (Re ε_T, Im ε_T) plane

μ channel



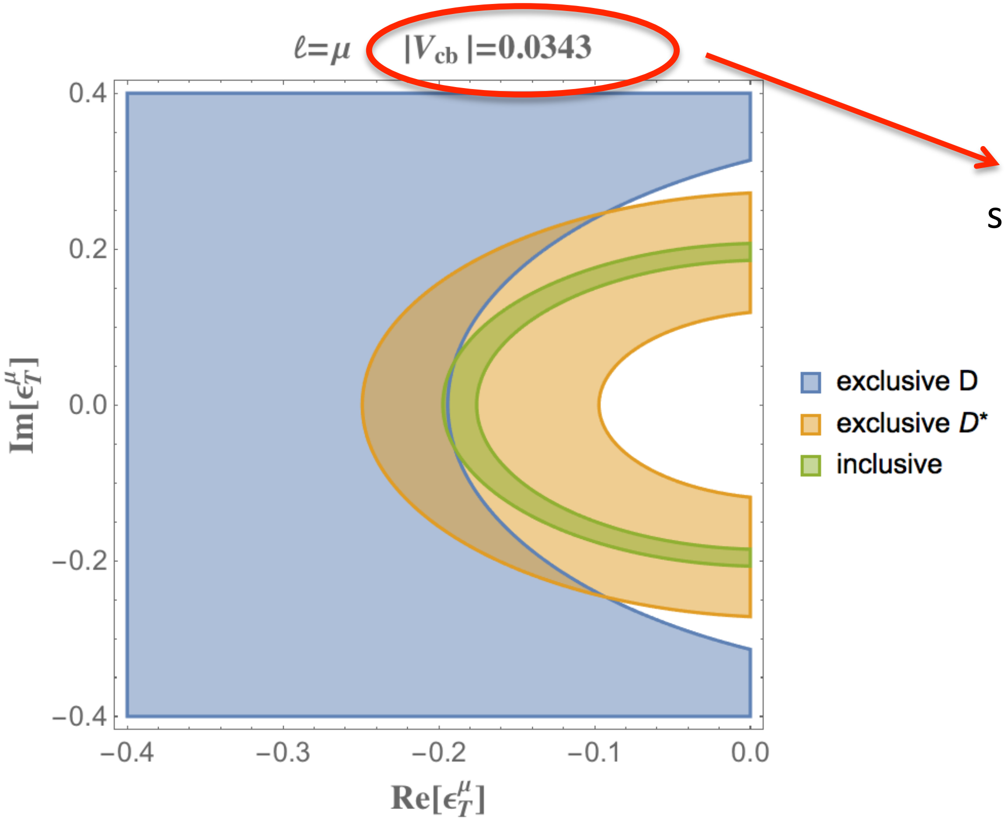
projections in the (Re ε_T, Im ε_T) plane

μ channel



projections in the (Re ε_T, Im ε_T) plane

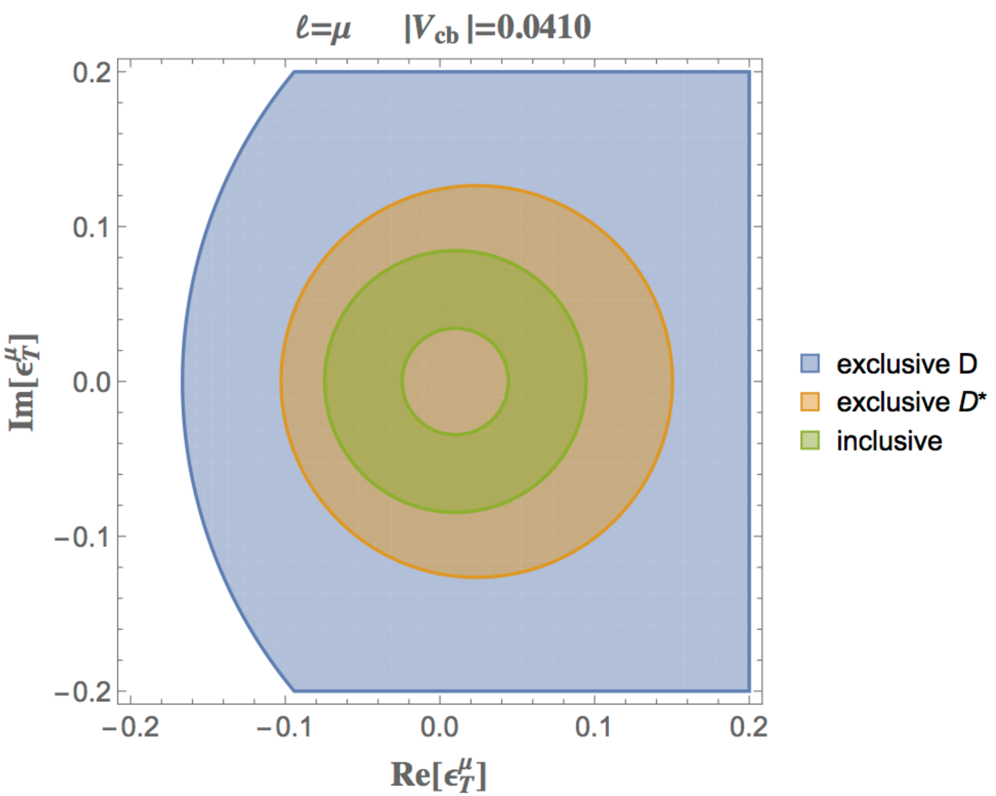
μ channel



smallest allowed value

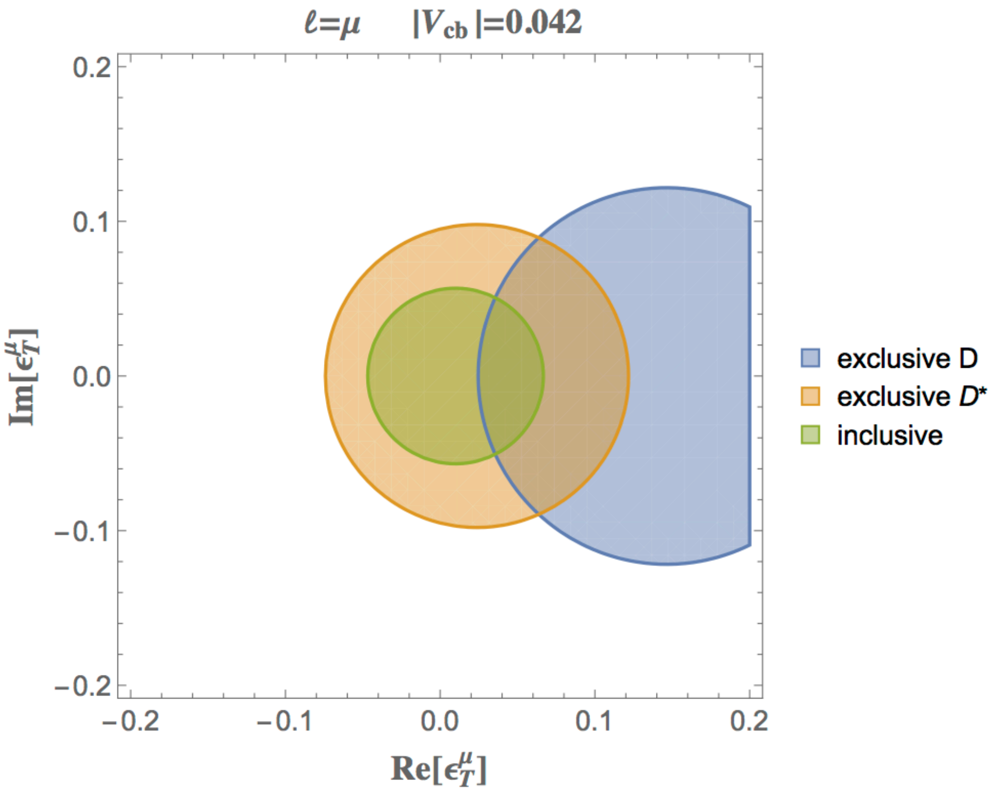
projections in the (Re ε_T, Im ε_T) plane

μ channel



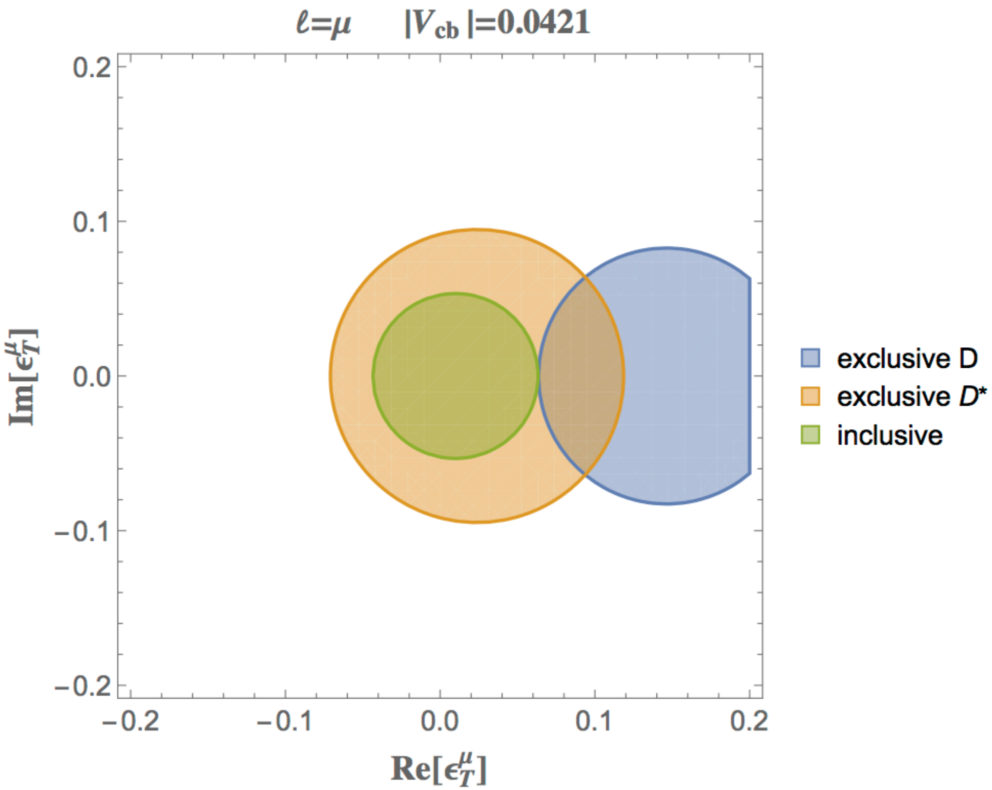
projections in the (Re ε_T, Im ε_T) plane

μ channel



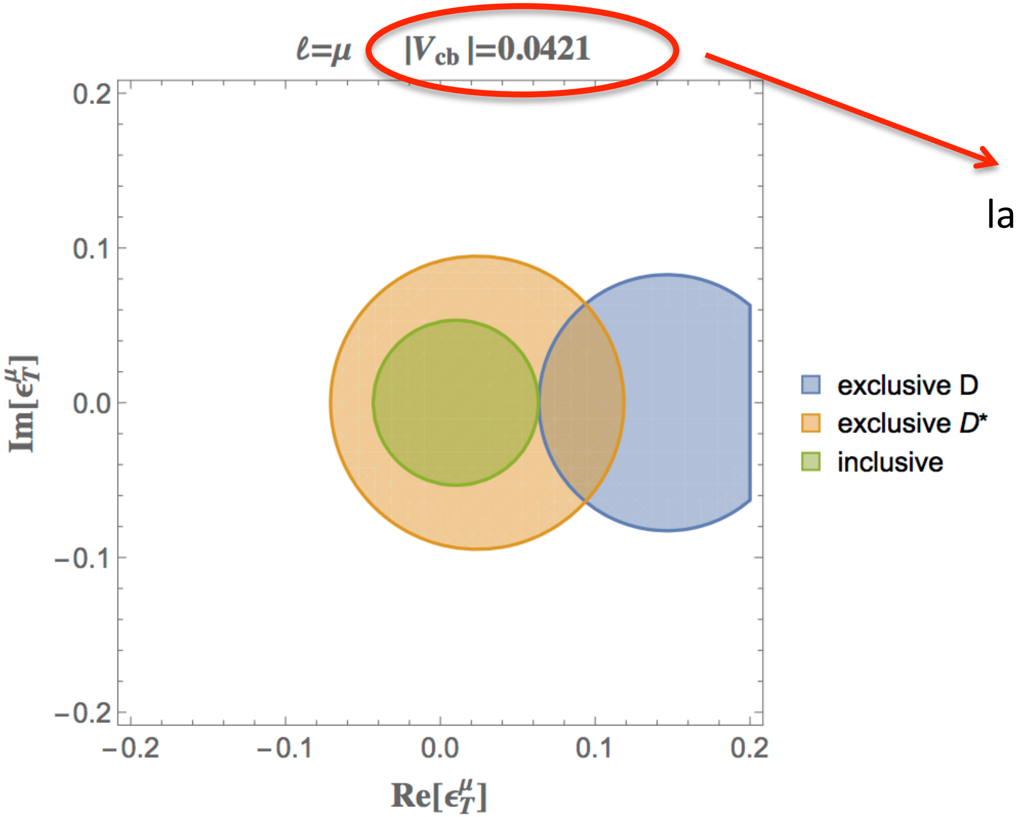
projections in the (Re ε_T, Im ε_T) plane

μ channel



projections in the (Re ε_T, Im ε_T) plane

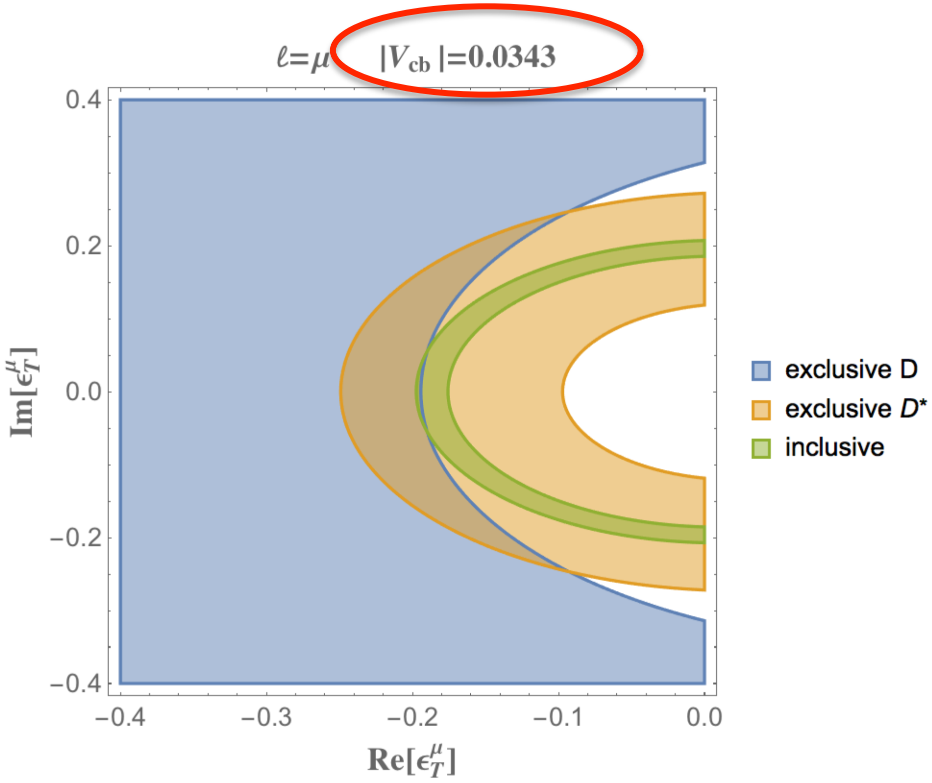
μ channel

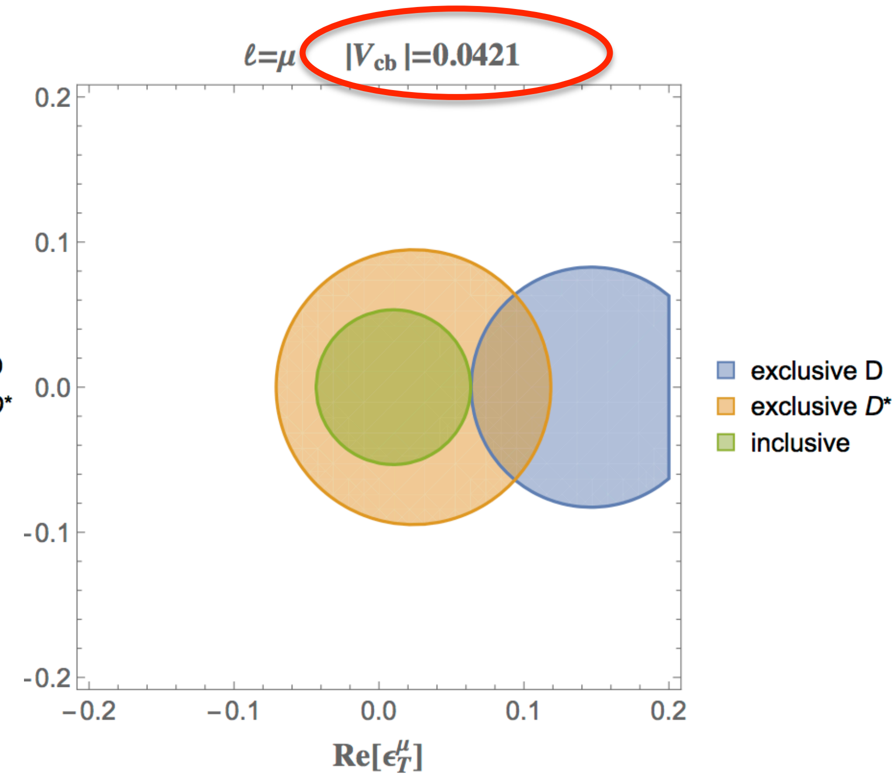


largest allowed value

projections in the (Re ε_T, Im ε_T) plane

μ channel

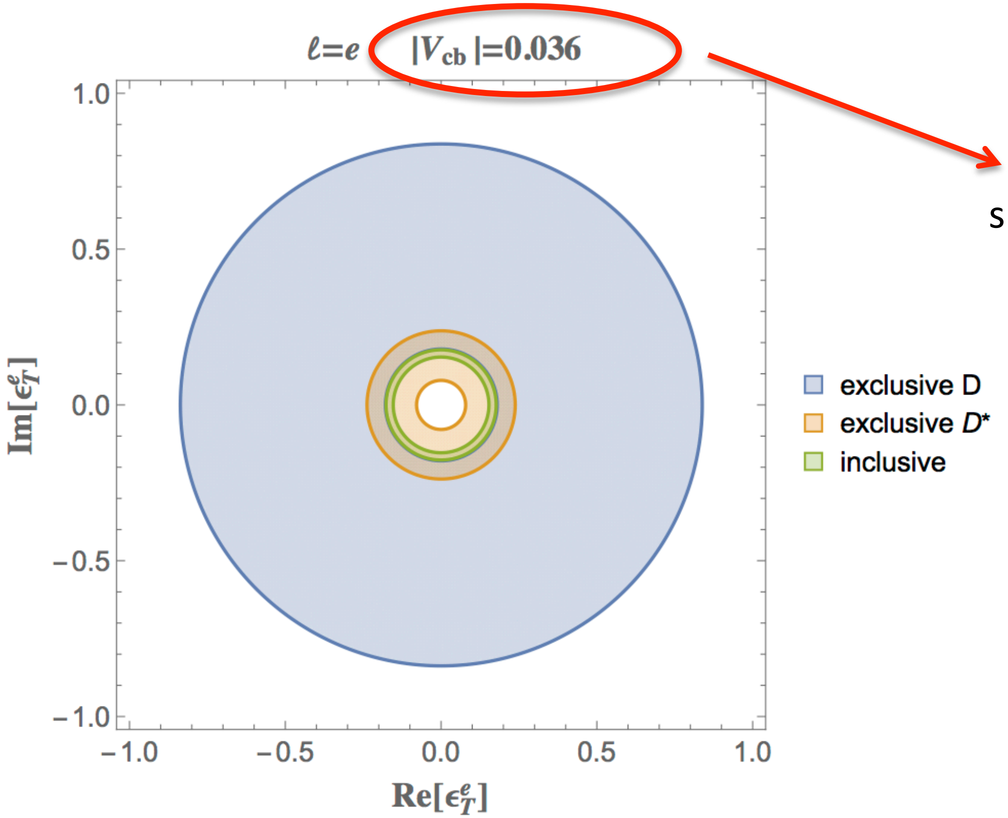




selected range $\boxed{|V_{cb}| \in [0.0343, 0.0421]}$

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

e channel



smallest allowed value

the largest value found from inclusive does not change

selected range $\boxed{|V_{cb}| \in [0.036, 0.0427]}$

V_{cb} range from both modes

μ channel

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

e channel

$$\boxed{|V_{cb}| \in [0.036, 0.0427]}$$

all constraints can be fulfilled in

$$\boxed{|V_{cb}| \in [0.036, 0.042]}$$

role of the NP contributions

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

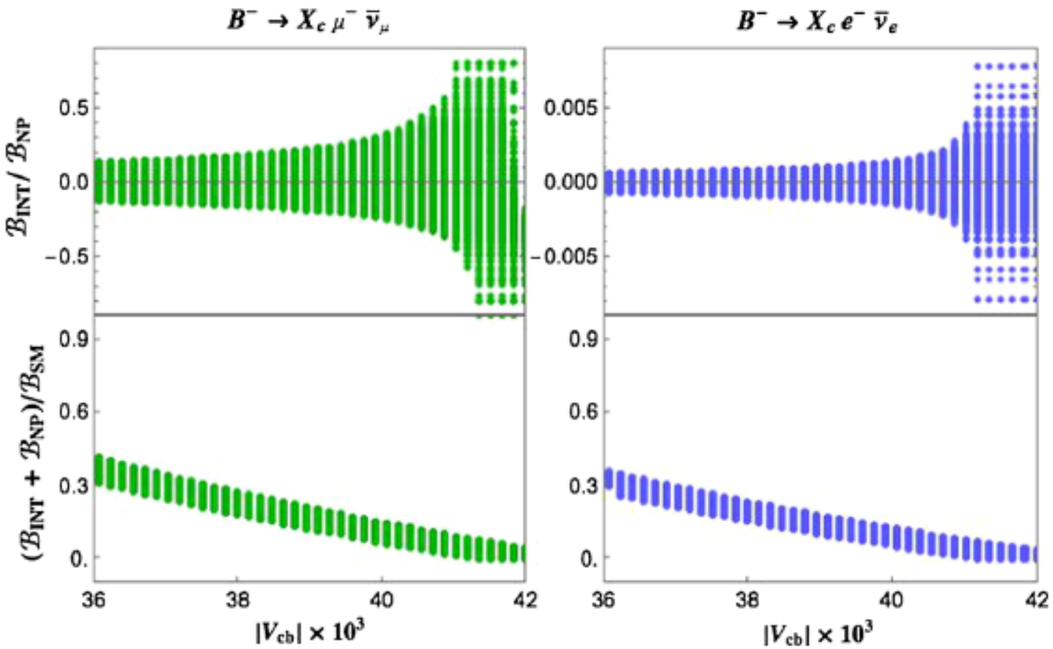
$$\frac{d\Gamma}{d\hat{q}^2} = C(q^2)\left[\left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm SM} + |\epsilon_T|^2 \left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm NP} + {\rm Re}(\epsilon_T)\left.\frac{d\tilde{\Gamma}}{d\hat{q}^2}\right|_{\rm INT}\right]$$

$\mathcal{B}_{\rm SM}$ $\mathcal{B}_{\rm NP}$ $\mathcal{B}_{\rm INT}$

compute varying Re(ε_T), Im(ε_T) and $|V_{cb}|$ only in the *allowed* region

role of the NP contributions

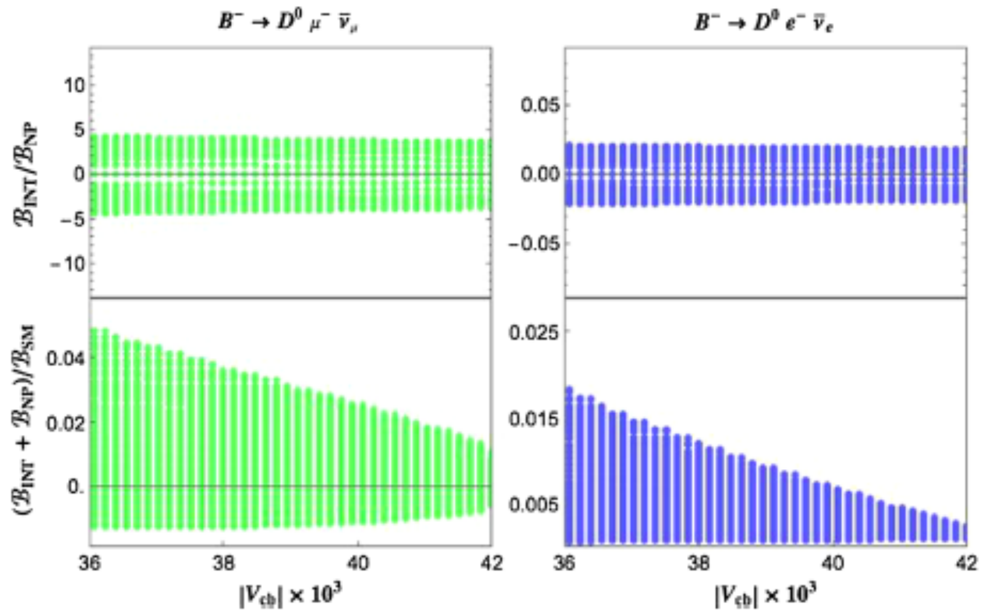
B -> $X_c \ell \nu_\ell$



- interference term can be sizable for μ
- the total NP contribution (NP+INT) is negligible for both e and μ when $|V_{cb}|$ is large

role of the NP contributions

B -> D $\ell \nu_\ell$



- interference term can be sizable for μ
- the total NP contribution (NP+INT) has a larger impact in the inclusive mode

the role of NP is different in different channels!
a NP H_{eff} might be at the origin of the $|V_{cb}|$ anomaly

A SM solution to the $|V_{cb}|$ puzzle?

Bigi, Gambino, Schacht, 1703.06124
Grinstein, Kobach, 1703.08170

fully differential decay rate
(Belle 1702.01521)

$$\frac{d\Gamma(\bar{B} \to D^* l \bar{\nu}_l)}{dw\, d\cos\theta_v\, d\cos\theta_l\, d\chi}$$

Boyd-Grinstein-Lebed (BGL) form factor parametrization instead of Caprini-Lellouch-Neubert (CLN)

differences:
CLN relies on HQET relations (4 parameter fit of the differential rate)
BGL based on unitarity, analiticity (as CLN)
BGL includes single particle (B_c^*) contributions (8 parameter fit)

BGL more conservative, data at low recoil better reproduced

➔ $|V_{cb}|$ from the fit with BGL closer to the inclusive determination
(with a larger uncertainty)

warning: only new Belle data considered

Semileptonic B decays

- what is the role of the FF parametrization?
- How to disentangle possible non-SM effects?

Semileptonic B decays

P. Colangelo, FDF, JHEP 06 (2018) 082

- what is the role of the FF parametrization?
- How to disentangle possible non-SM effects?

study of the fully differential decay rate in

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

relevant for $B_s \to D^*_s$ transitions

Semileptonic B decays

- compare SM predictions obtained using the BGL and the CLN parametrizations for the FF
- compare SM to a NP model

Semileptonic B decays

- compare SM predictions obtained using the BGL and the CLN parametrizations for the FF

- compare SM to a NP model

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

Semileptonic B decays

- compare SM predictions obtained using the BGL and the CLN parametrizations for the FF

- compare SM to a NP model

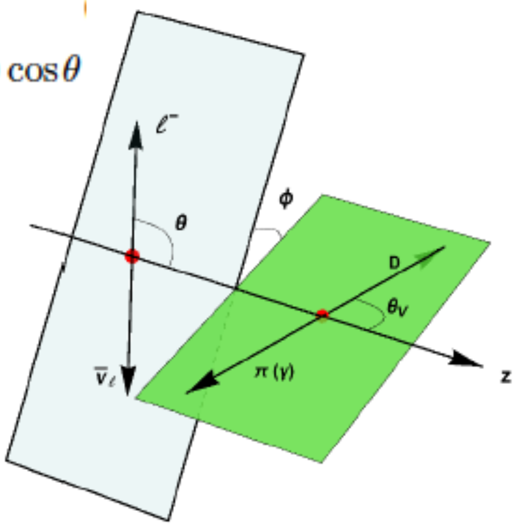
$$\boxed{H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{c}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell + \epsilon_T^\ell\, \bar{c}\sigma_{\mu\nu}(1-\gamma_5)b\, \bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell \right] + \text{h.c.}}$$

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

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

Semileptonic B decays

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



$$\frac{d^4\Gamma(\bar{B}\to D^*(\to D\gamma)\ell^-\bar{\nu}_\ell)}{dq^2\,d\cos\theta\,d\phi\,d\cos\theta_V} = \mathcal{N}_\gamma |\vec{p}_{D^*}| \left(1-\frac{m_\ell^2}{q^2}\right)^2 \Big\{ I_{1s}^\gamma \sin^2\theta_V + I_{1c}^\gamma (3+\cos 2\theta_V)$$
$$+ (I_{2s}^\gamma \sin^2\theta_V + I_{2c}^\gamma (3+\cos 2\theta_V))\cos 2\theta$$
$$+ I_3^\gamma \sin^2\theta_V \sin^2\theta \cos 2\phi + I_4^\gamma \sin 2\theta_V \sin 2\theta \cos\phi$$
$$+ I_5^\gamma \sin 2\theta_V \sin\theta \cos\phi + (I_{6s}^\gamma \sin^2\theta_V + I_{6c}^\gamma (3+\cos 2\theta_V))\cos\theta$$
$$+ I_7^\gamma \sin 2\theta_V \sin\theta \sin\phi \Big\}.$$

Semileptonic B decays

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

Angular coefficients

- depend on the hadronic form factors
- some vanish in the SM

$$\frac{d^4\Gamma(\bar{B}\to D^*(\to D\gamma)\ell^-\bar{\nu}_\ell)}{dq^2\, d\cos\theta\, d\phi\, d\cos\theta_V} = \mathcal{N}_\gamma |\vec{p}_{D^*}| \left(1-\frac{m_\ell^2}{q^2}\right)^2 \Big\{ I_{1s}^\gamma \sin^2\theta_V + I_{1c}^\gamma (3+\cos 2\theta_V)$$
$$+ (I_{2s}^\gamma \sin^2\theta_V + I_{2c}^\gamma (3+\cos 2\theta_V)) \cos 2\theta$$
$$+ I_3^\gamma \sin^2\theta_V \sin^2\theta \cos 2\phi + I_4^\gamma \sin 2\theta_V \sin 2\theta \cos\phi$$
$$+ I_5^\gamma \sin 2\theta_V \sin\theta \cos\phi + (I_{6s}^\gamma \sin^2\theta_V + I_{6c}^\gamma (3+\cos 2\theta_V)) \cos\theta$$
$$+ I_7^\gamma \sin 2\theta_V \sin\theta \sin\phi \Big\}.$$

Semileptonic B decays

- relations between the angular coefficients in the π case and in the γ case

$$\frac{I_{1s}^{\pi}}{4I_{1c}^{\gamma}} = \frac{I_{1c}^{\pi}}{2I_{1s}^{\gamma}} = \frac{I_{2s}^{\pi}}{4I_{2c}^{\gamma}} = \frac{I_{2c}^{\pi}}{2I_{2s}^{\gamma}} = \frac{I_{6s}^{\pi}}{4I_{6c}^{\gamma}} = \frac{I_{6c}^{\pi}}{2I_{6s}^{\gamma}} = -\frac{I_{3}^{\pi}}{2I_{3}^{\gamma}} = -\frac{I_{4}^{\pi}}{2I_{4}^{\gamma}} = -\frac{I_{5}^{\pi}}{2I_{5}^{\gamma}} = 1 .$$

- fit to the experimental fully differential decay distribution → angular coefficients → FF

Example: only SM

$$A_1(q^2) = \frac{1}{4(m_B + m_{D^*})}\left\{\sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} - \frac{I_{6s}^{\pi}}{q^2}} + \sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} + \frac{I_{6s}^{\pi}}{q^2}}\right\},$$

$$A_2(q^2) = \frac{(m_B + m_{D^*})}{4\lambda(m_B^2, m_{D^*}^2, q^2)}\left\{(m_B^2 - m_{D^*}^2 - q^2)\left[\sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} - \frac{I_{6s}^{\pi}}{q^2}} + \sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} + \frac{I_{6s}^{\pi}}{q^2}}\right]\right.$$
$$\left. - 4\sqrt{2} m_{D^*}\sqrt{q^2}\sqrt{-\frac{I_{2c}^{\pi}}{q^2 - m_\ell^2}}\right\},$$

$$V(q^2) = \frac{(m_B + m_{D^*})}{4\lambda^{1/2}(m_B^2, m_{D^*}^2, q^2)}\left\{\sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} - \frac{I_{6s}^{\pi}}{q^2}} - \sqrt{\frac{4I_{1s}^{\pi}}{m_\ell^2+3q^2} + \frac{I_{6s}^{\pi}}{q^2}}\right\},$$

$$A_0(q^2) = \frac{1}{2}\frac{\sqrt{q^2}}{\lambda^{1/2}(m_B^2, m_{D^*}^2, q^2)}\sqrt{\frac{(q^2 - m_\ell^2)\, I_{1c}^{\pi} + (q^2 + m_\ell^2)\, I_{2c}^{\pi}}{m_\ell^2(q^2 - m_\ell^2)}}.$$

BGL vs CLN

$$V(w) = \frac{R_1(w)}{R^*} h_{A_1}(w)$$
$$A_1(w) = \frac{w+1}{2} R^* h_{A_1}(w)$$
$$A_2(w) = \frac{R_2(w)}{R^*} h_{A_1}(w)$$
$$A_0(w) = \frac{R_0(w)}{R^*} h_{A_1}(w)$$

CLN

Exploits HQET relations

Quantities expanded for w->1

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

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

Fit by Belle Collaboration

$\lvert V_{cb}\rvert \times 10^3$	ρ^2	$R_1(1)$	$R_2(1)$
37.4 ± 1.3	1.03 ± 0.13	1.38 ± 0.07	0.87 ± 0.10

BGL

Exploits analiticity

FF expanded as

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

Blatsche factors

take into account poles associated to cb poles

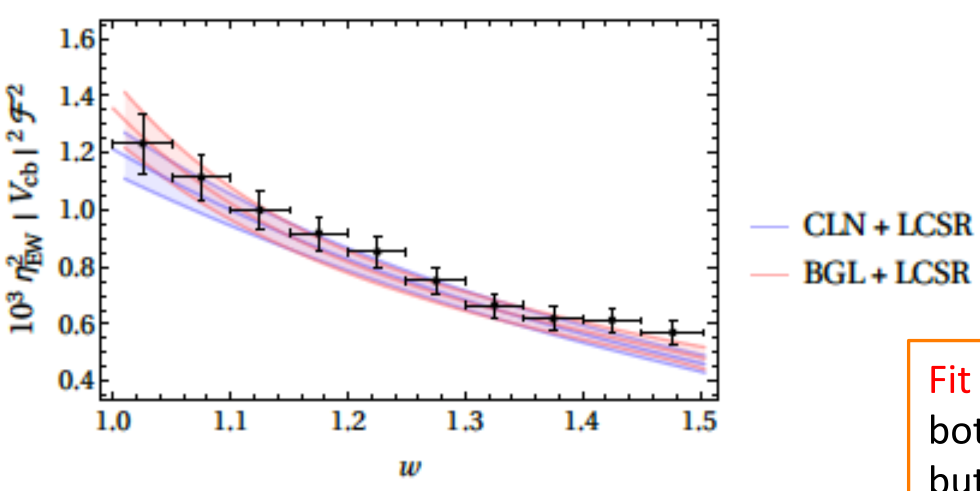
unitarity bounds

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

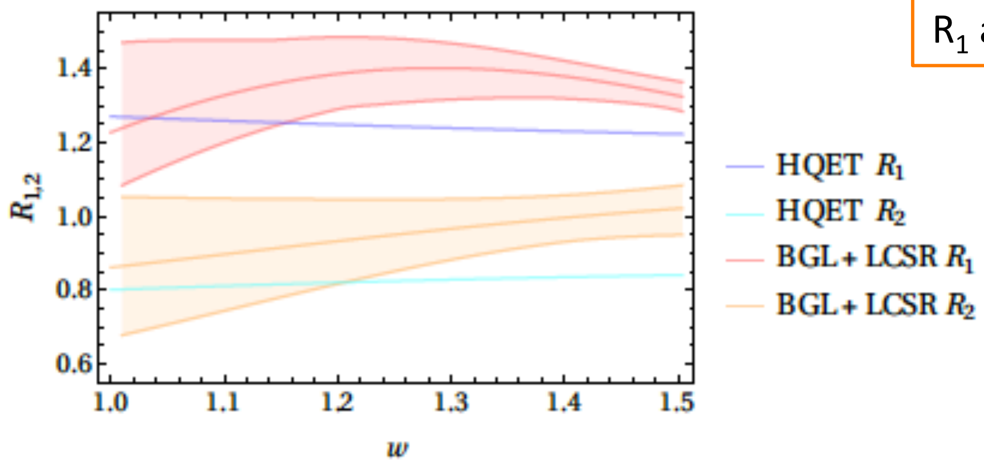
a_n n=0,1,2 fitted for all FFs

BGL vs CLN

from D. Bigi, P. Gambino, S. Schacht PLB 2017



(b)



Fit to the Belle data:
both parametrizations work well
but data at small w are better reproduced by BGL

R_1 and R_2 show deviations from their HQET results

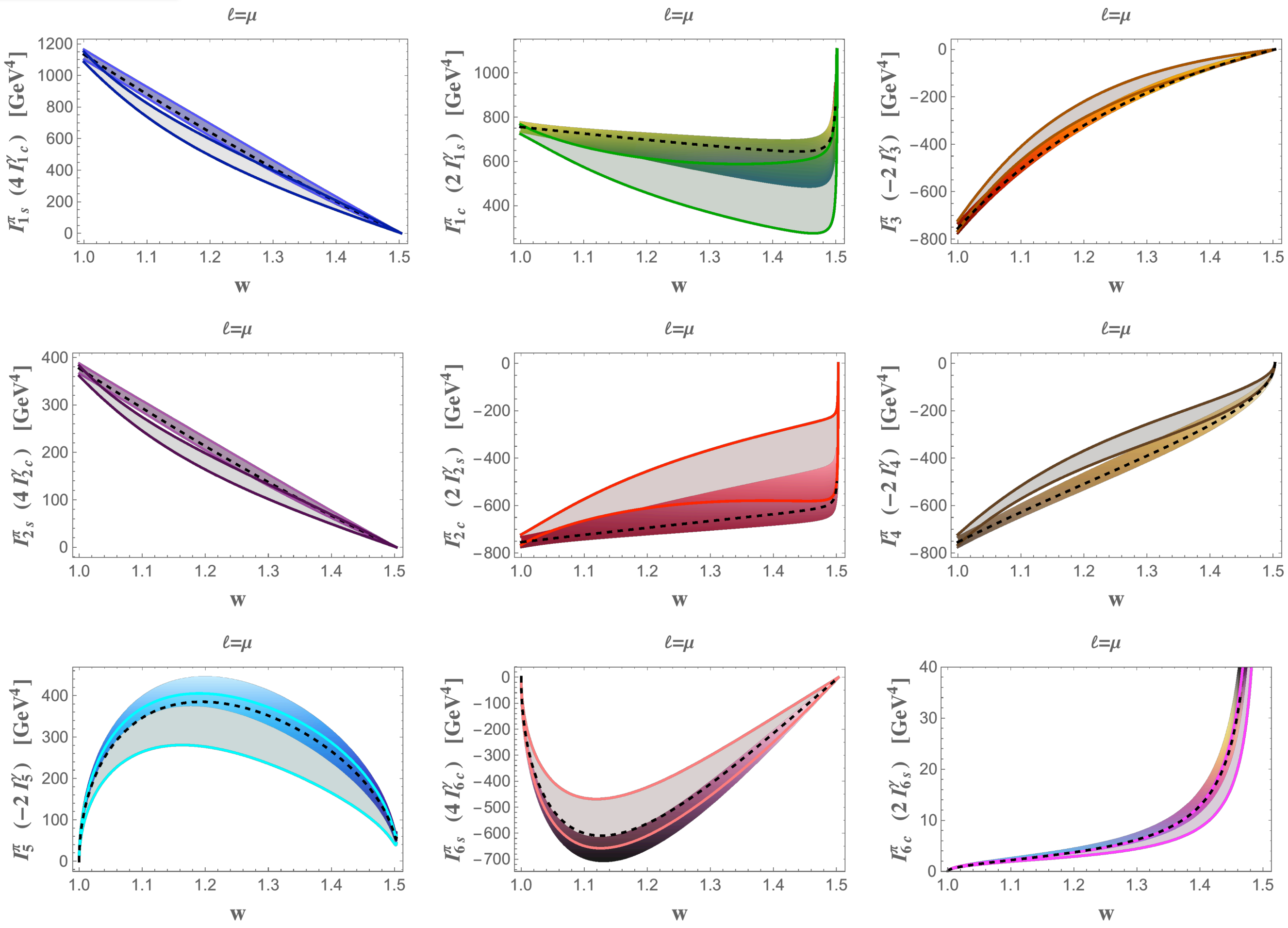
BGL vs CLN

angular coefficients could in principle allow the reconstruction of R_1 and R_2

$$R_1(w) = \frac{8q^2 m_B m_{D^*}(1+w)}{(m_\ell^2+3q^2)\lambda^{1/2}(m_B^2, m_{D^*}^2, q^2)} \frac{1}{I_{6s}^\pi} \left[\sqrt{(I_{1s}^\pi)^2 - \left(\frac{m_\ell^2+3q^2}{q^2}\right)^2 \frac{(I_{6s}^\pi)^2}{16}} - I_{1s}^\pi \right],$$

$$R_2(w) = \frac{2m_B m_{D^*}(1+w)}{\lambda(m_B^2, m_{D^*}^2, q^2)} \left[(m_B^2 - q^2 - m_{D^*}^2) \right.$$
$$\left. + 2\sqrt{2} m_{D^*} q^2 \sqrt{-\frac{q^2}{q^2-m_\ell^2} I_{2c}^\pi \frac{1}{I_{6s}^\pi}} \left(\sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2} - \frac{I_{6s}^\pi}{q^2}} - \sqrt{\frac{4I_{1s}^\pi}{m_\ell^2+3q^2} + \frac{I_{6s}^\pi}{q^2}} \right) \right].$$

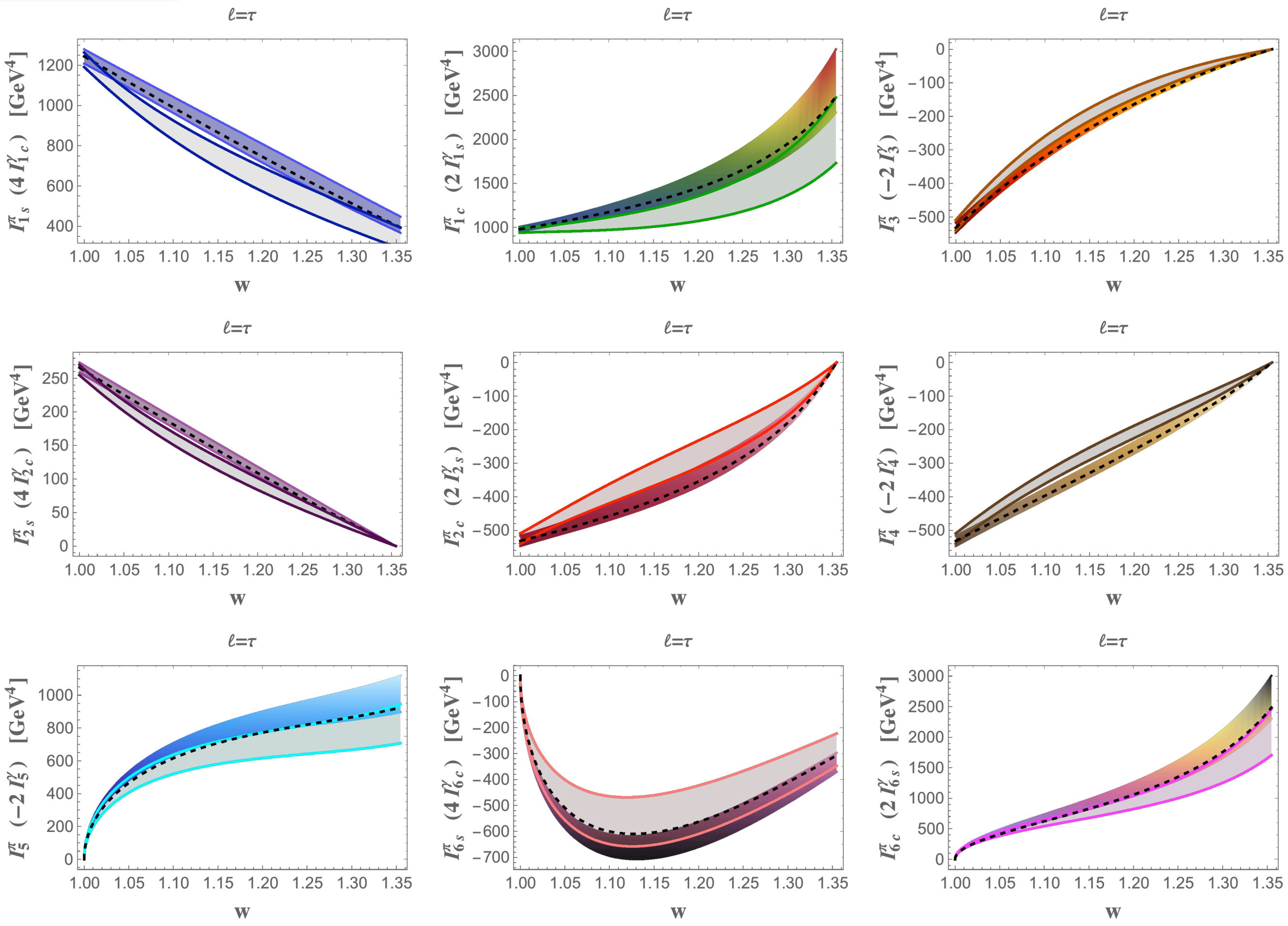
SM case: BGL vs CLN
μ case



Darker regions: CLN
Lighter regions: BGL

some of the structures are particularly sensitive to the choice of theparametrization

SM case: BGL vs CLN
τ case



Darker regions: CLN
Lighter regions: BGL

some of the structures are particularly sensitive to the choice of theparametrization

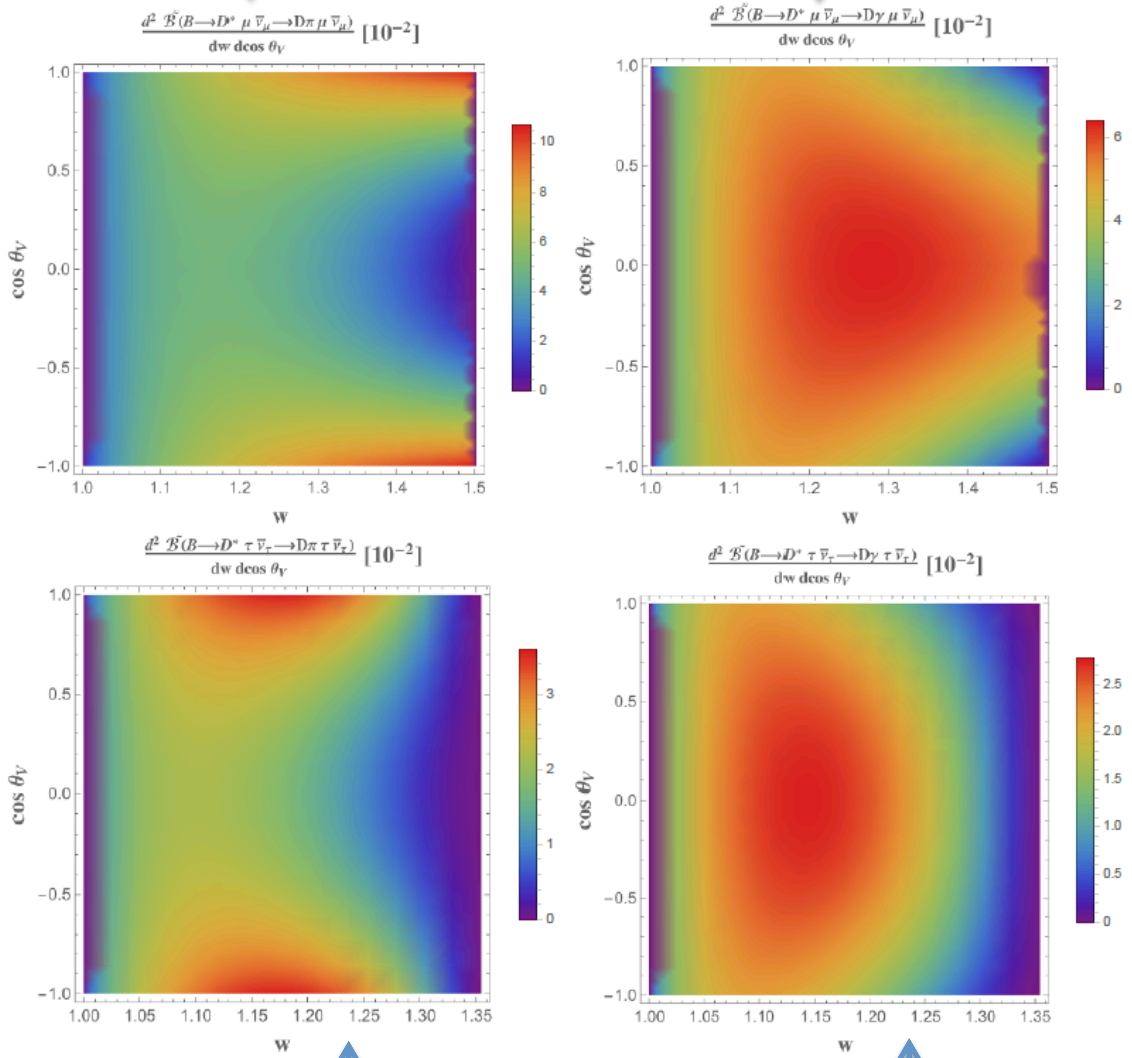
Exploiting both D^* ->D π and D^* ->D γ modes

D^* -> D π

D^* -> D γ

lepton=μ

lepton=μ



lepton=τ

lepton=τ

D^* -> D π

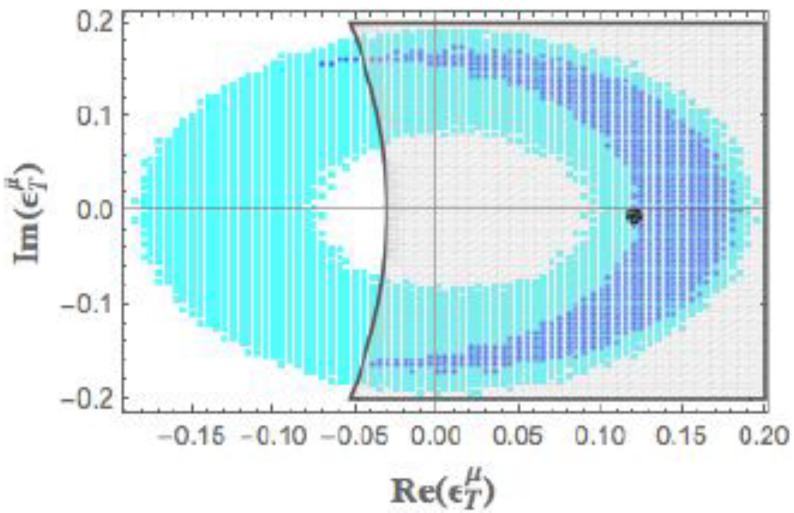
D^* -> D γ

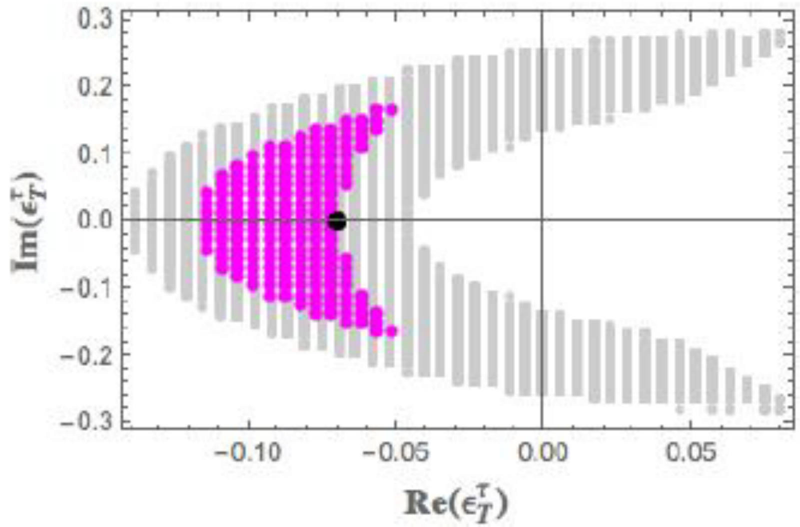
SM vs NP

- keep both ε_T^{μ} , ε_T^{τ} non vanishing
- choose ε_T^{μ} in the region already selected to fix the V_{cb} anomaly
- determine ε_T^{τ} to reproduce R(D) & R(D^*)

SM vs NP

- keep both ε_T^μ , ε_T^τ non vanishing
- choose ε_T^μ in the region already selected to fix the V_{cb} anomaly
- determine ε_T^τ to reproduce R(D) & R(D*)

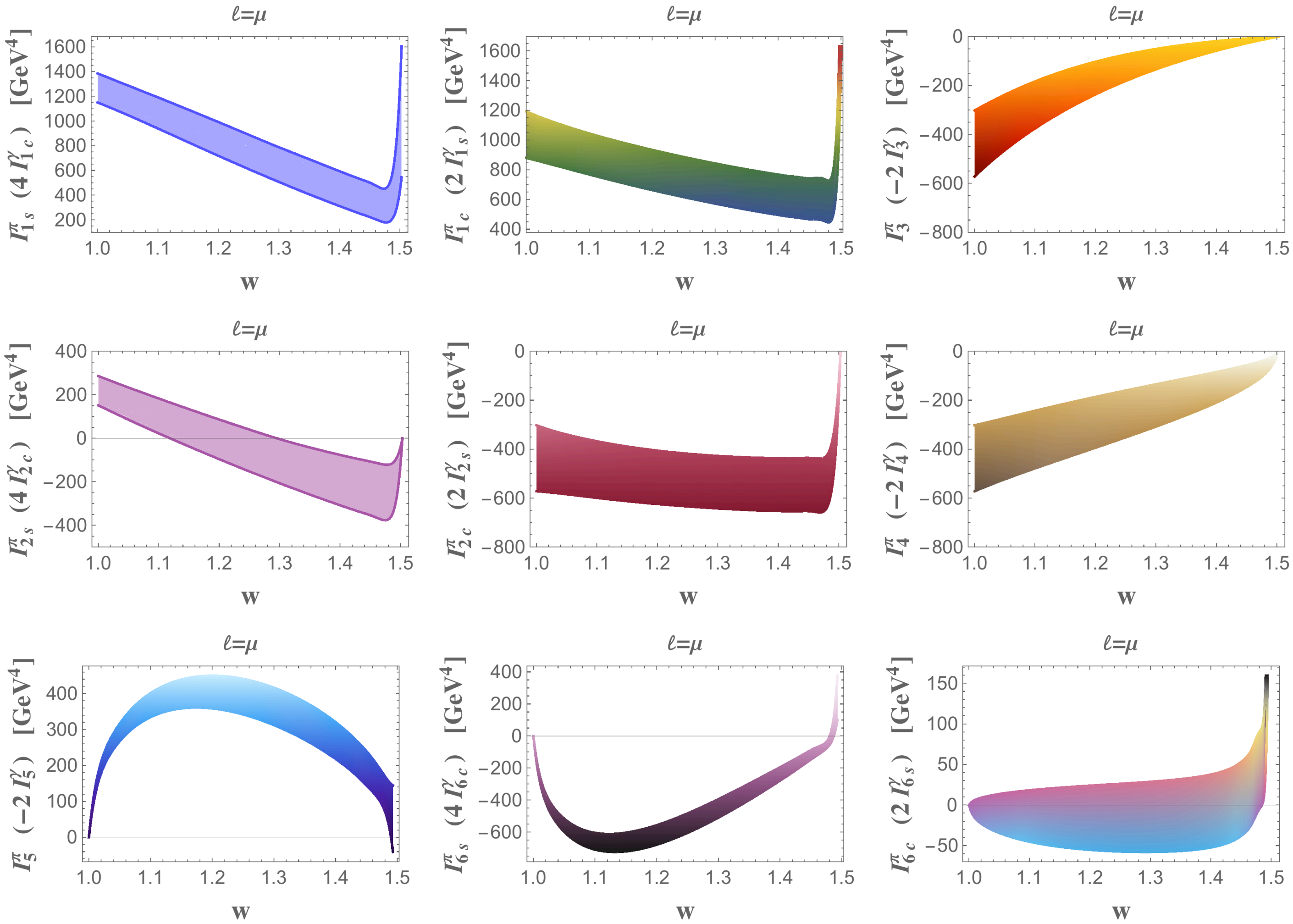




Darker regions: $\chi^2<1$

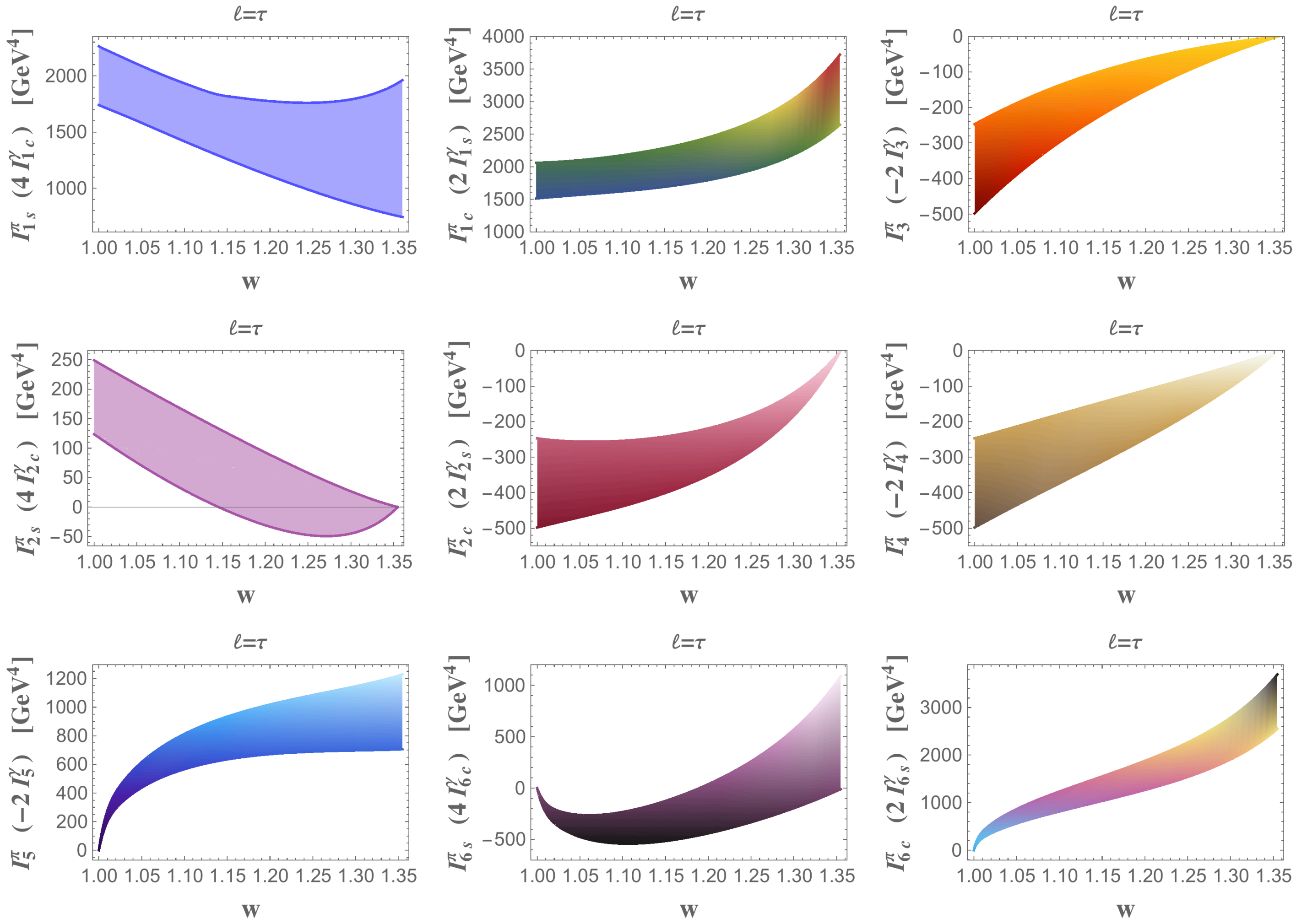
Black dots: benchmark points

SM vs NP
μ case



- angular coefficients computed varyng ε^T in the small χ^2 region
- NP modifies their size
- some coefficients display a zero absent in SM (I_{2s}^{π} or I_{2c}^{γ})

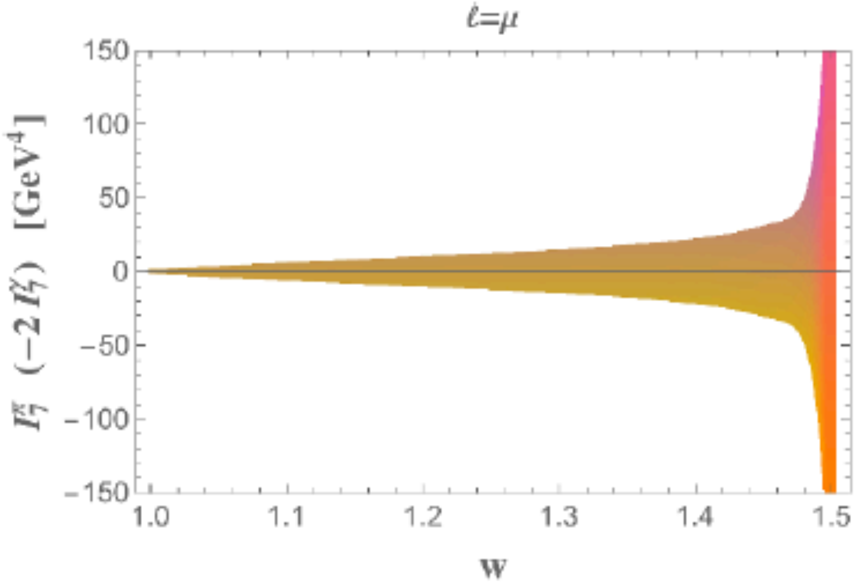
SM vs NP
τ case

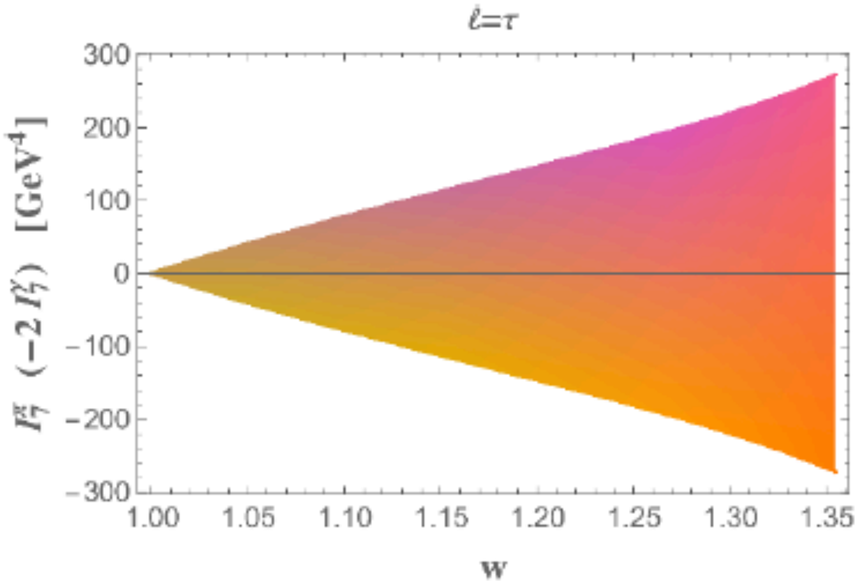


- angular coefficients computed varyng ε^T in the small χ^2 region
- NP modifies their size
- some coefficients display a zero absent in SM (I_{2s}^{π} or I_{2c}^{γ})

SM vs NP

I_7 is absent in the SM but not in NP





SM vs NP:
set of observables computed in the benchmark points

- q^2 – dependent Forward-Backward asymmetry:

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

- transverse forward-backward asymmetry (A_{FB} for transversely polarized D^*)

- D* polarization asymmetry

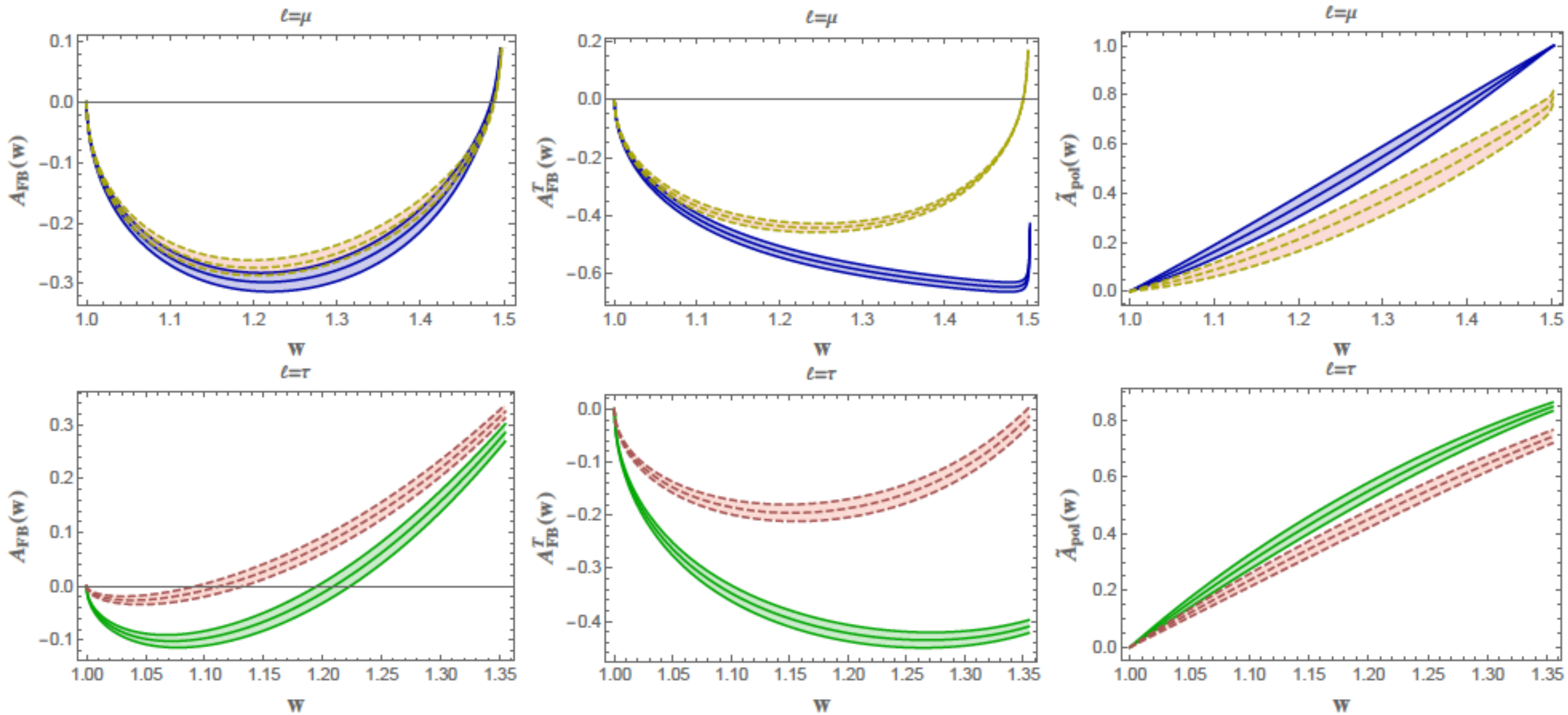
$$\frac{dA_{\rm pol}^{D^*}(q^2)}{dq^2} = 2\frac{d\Gamma_L}{dq^2}\Big/\frac{d\Gamma_T}{dq^2} - 1\,.$$

- $\cos(\theta_V)$ – dependent forward-backward asymmetry

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

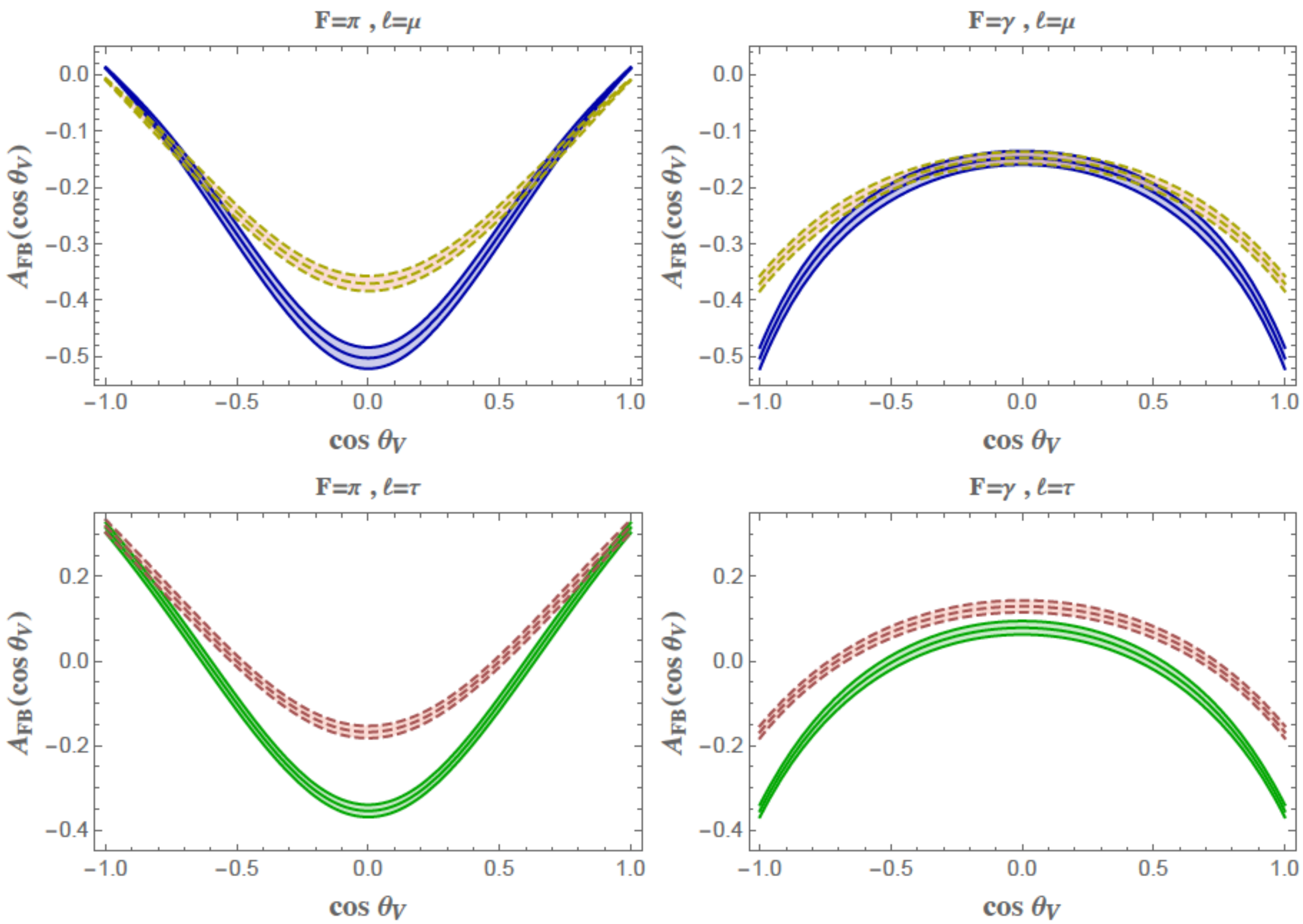
SM vs NP:
set of observables computed in the benchmark points

μ case
blue, solid=SM
yellow, dashed=SM+NP

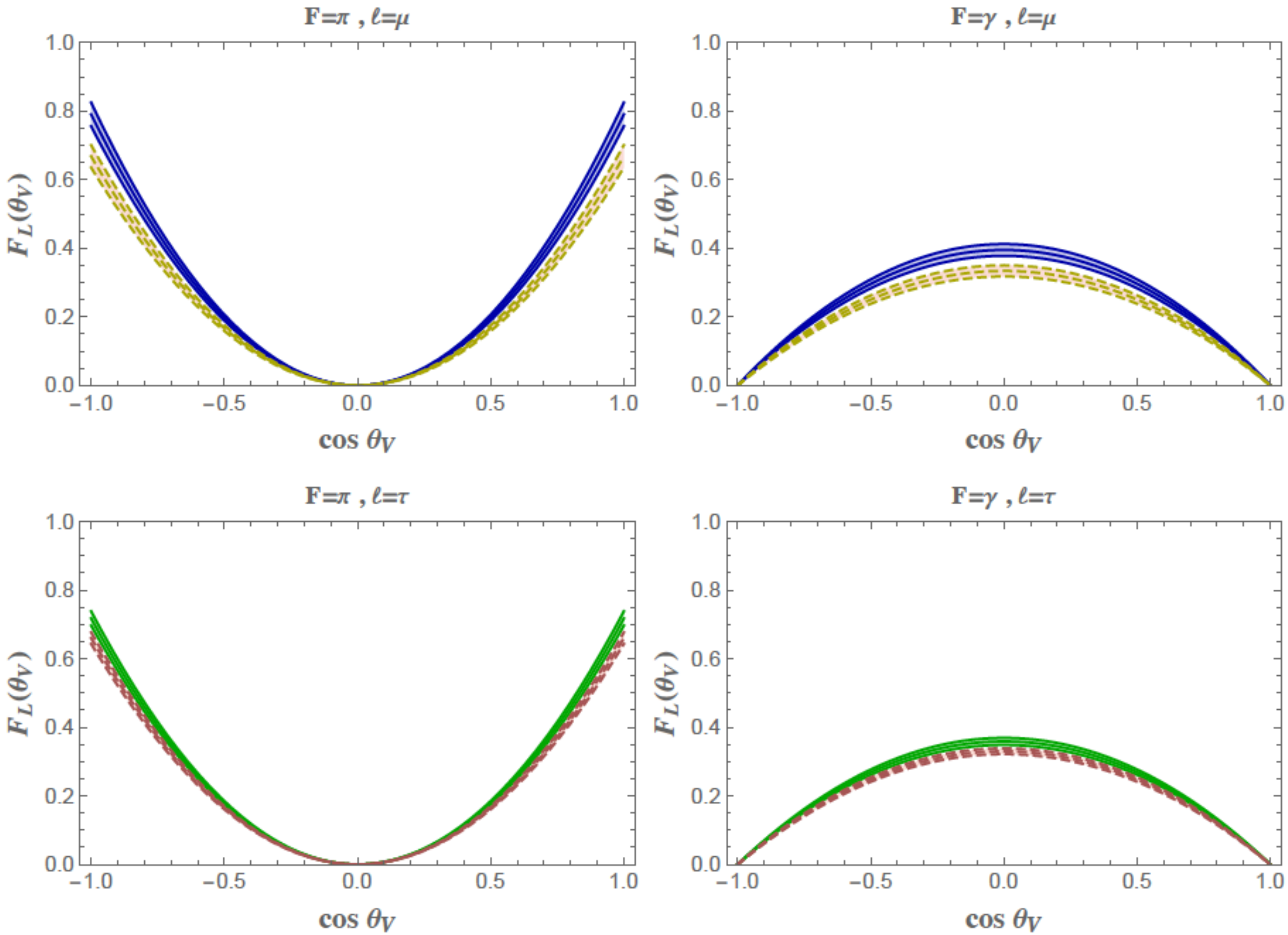


τ case
green, solid=SM
brown, dashed=SM+NP

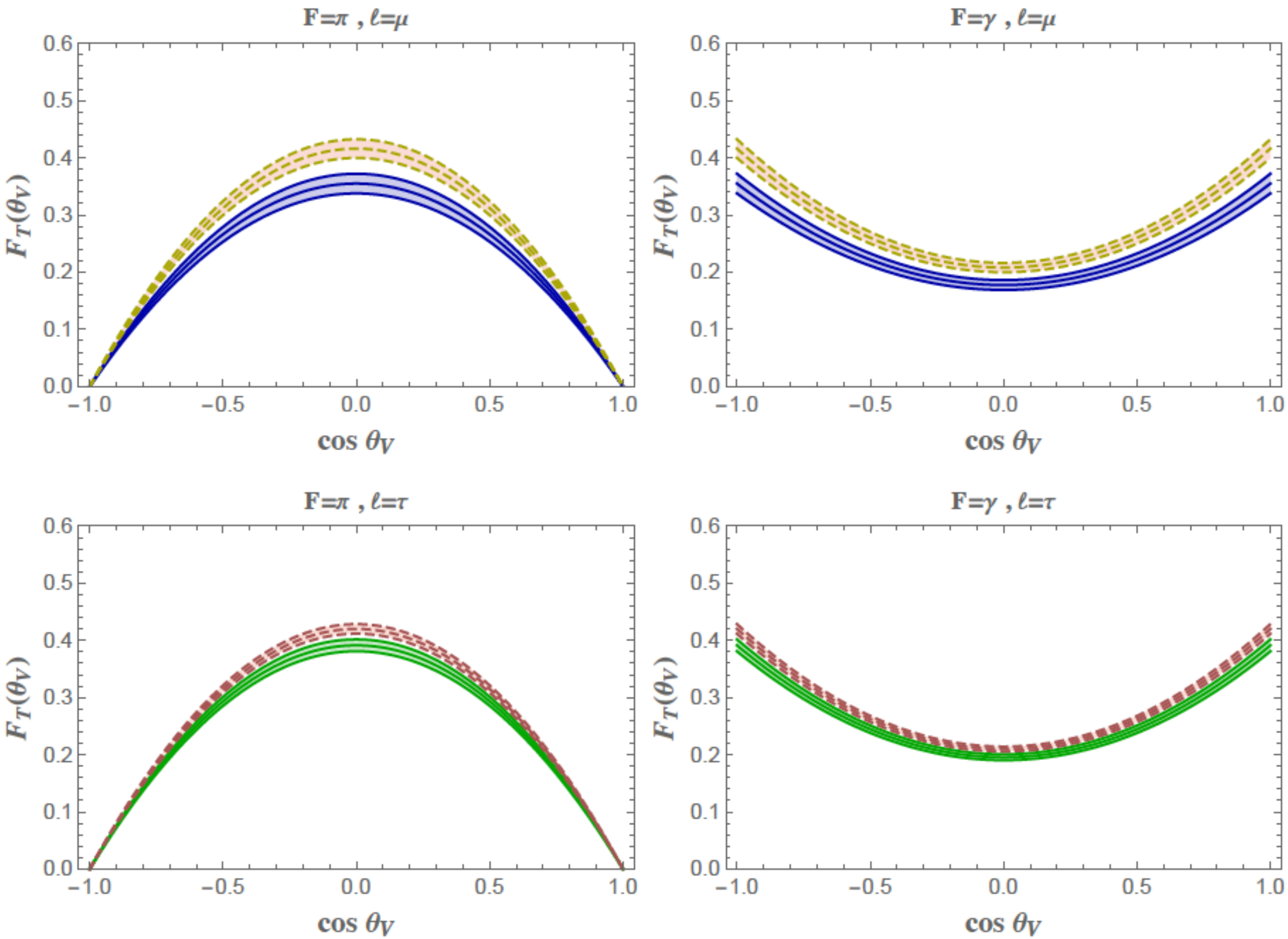
SM vs NP:
set of observables computed in the benchmark points



SM vs NP: D^* polarization fractions

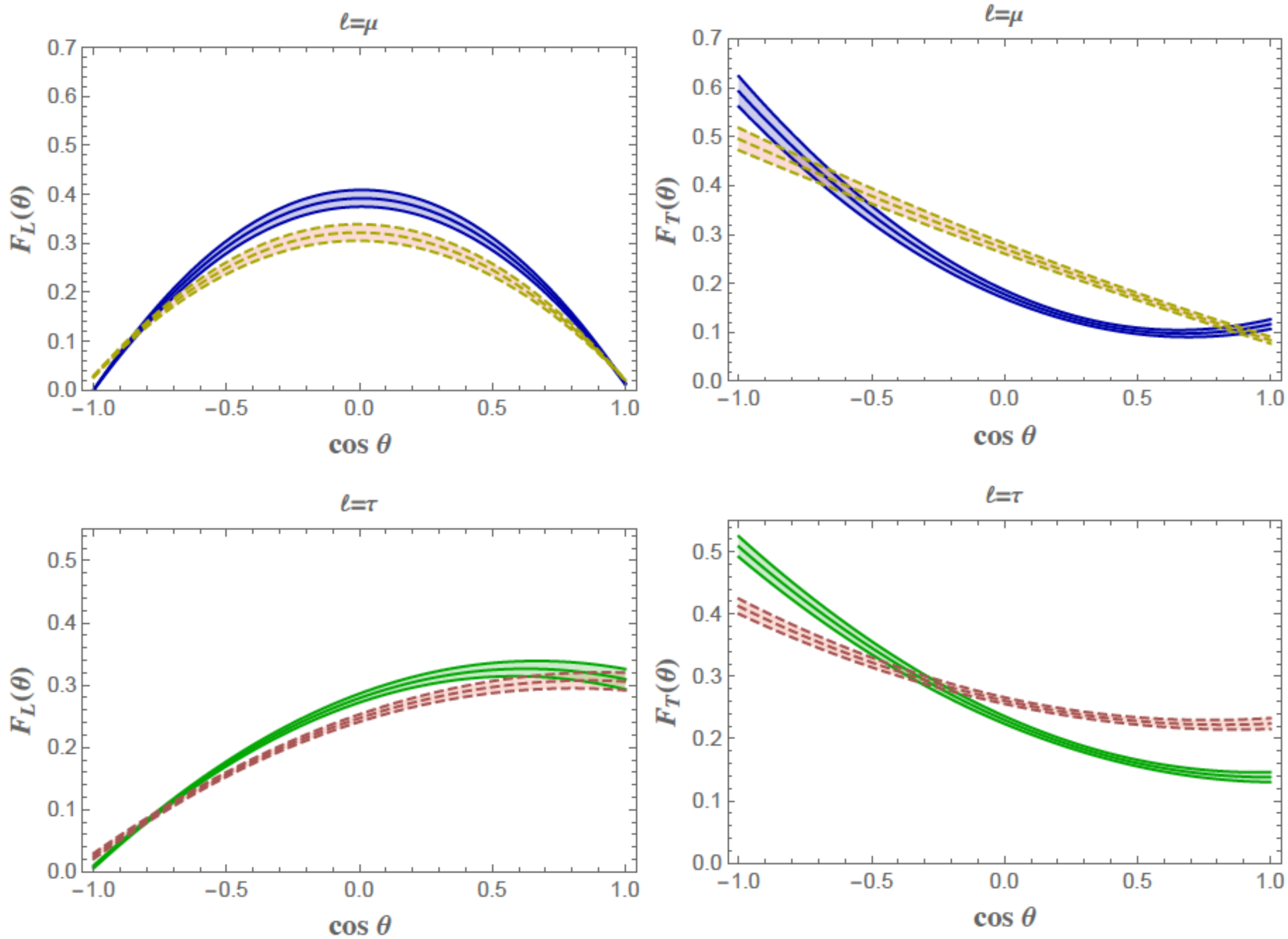


SM vs NP: D^* polarization fractions



SM vs NP: D^* polarization fractions

a particularly interesting case:
the convexity of the NP curve varies with ε_T



Tests of LFU

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

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

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

Challenging the lepton flavour universality opens new perspectives in NP searches

What is needed

- separate measurements for *e* and μ inclusive and exclusive B modes — V_{cb}
- new modes, e.g. measurements of B_s and Λ_b semileptonic decays — V_{cb}, $R(D^{(*)})$
- modes where the tensor operator does not contribute, i.e. $B_c \to \tau\, \nu_\tau$ — V_{cb}, $R(D^{(*)})$
- new observables where effects are expected, e.g. D_i^{**} (are F-B asymmetries accessible?) — V_{cb}, $R(D^{(*)})$
- Same breaking pattern in b->u transitions? — V_{ub}

A lot of surprises from three-level processes

The journey in search of phenomena beyond SM continues….