Theory overview of the tree-level B decays

Fulvia De Fazio
INFN Bari

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

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questions to address

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

SM: ~~LFU~~ only in Yukawas

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SM: ~~LF~~U only in Yukawas

b --> c ℓ ν decays

tensions:

- ratios $R(D^{(*)})$ deviate from SM predictions ($\approx 3.9\sigma$)
- long standing issue:
  discrepancy in $|V_{cb}|$ determinations from inclusive and exclusive B modes ($\approx 3.1\sigma$)

impact on other flavour observables, i.e. ε_K

anomalies in semileptonic transitions:
is NP hiding under tree-level processes?

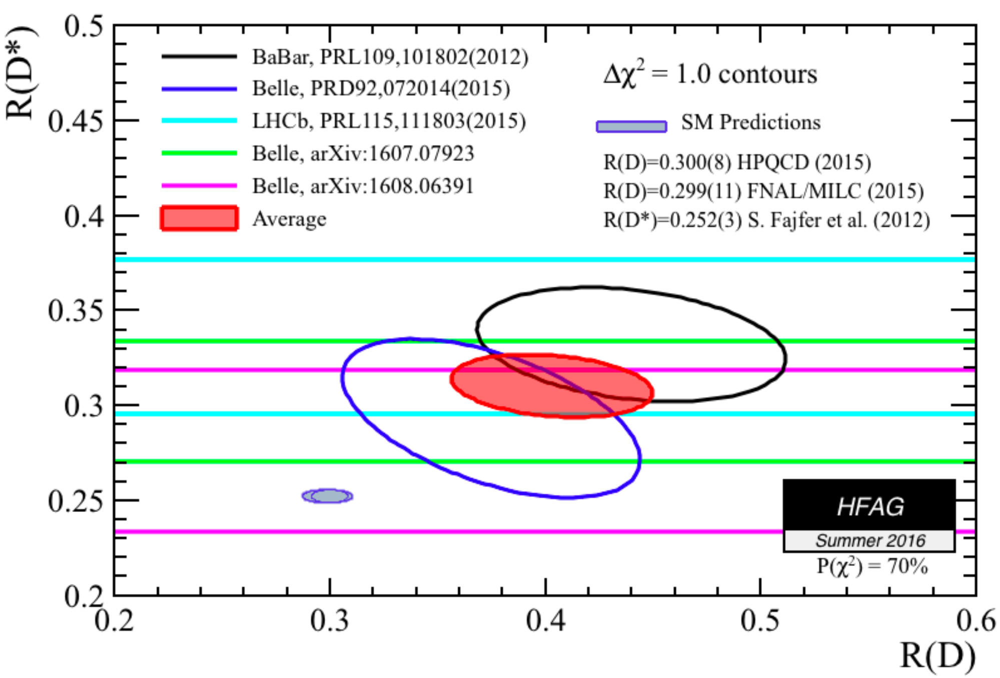
R(D$^{(*)}$)

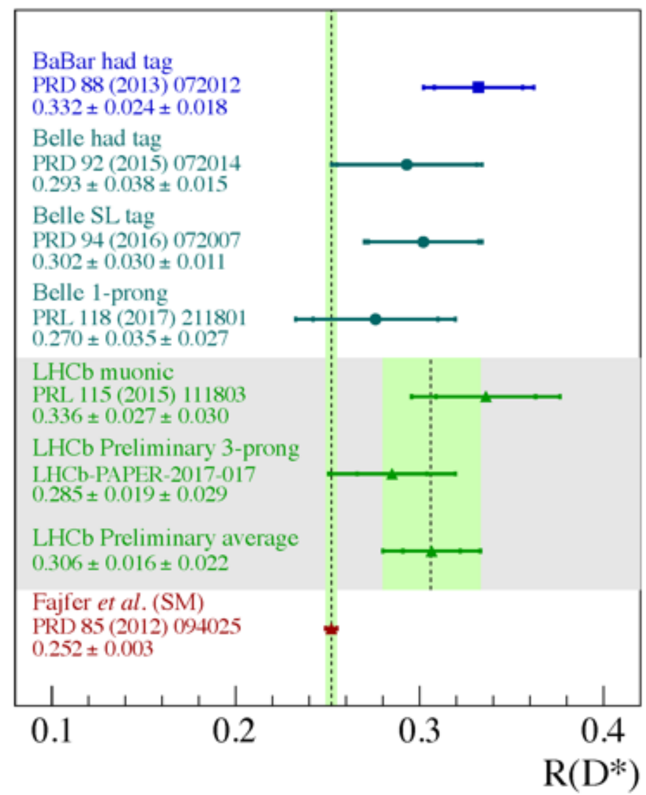
SM

$$\mathcal{R}^0(D)\Big|_{SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell)}\Big|_{SM} = 0.324 \pm 0.022$$

$$\mathcal{R}^0(D^*)\Big|_{SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)}\Big|_{SM} = 0.250 \pm 0.003$$

present scenario
HFAG quotes 3.9σ deviation
from SM

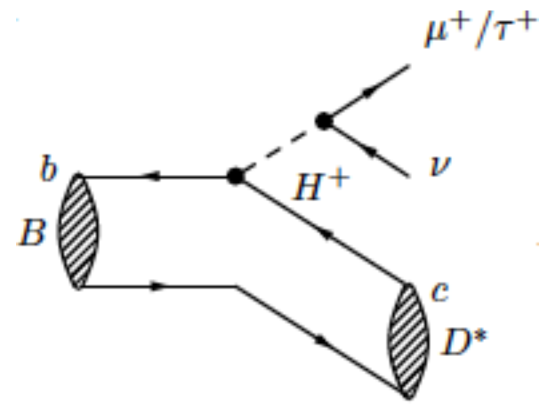




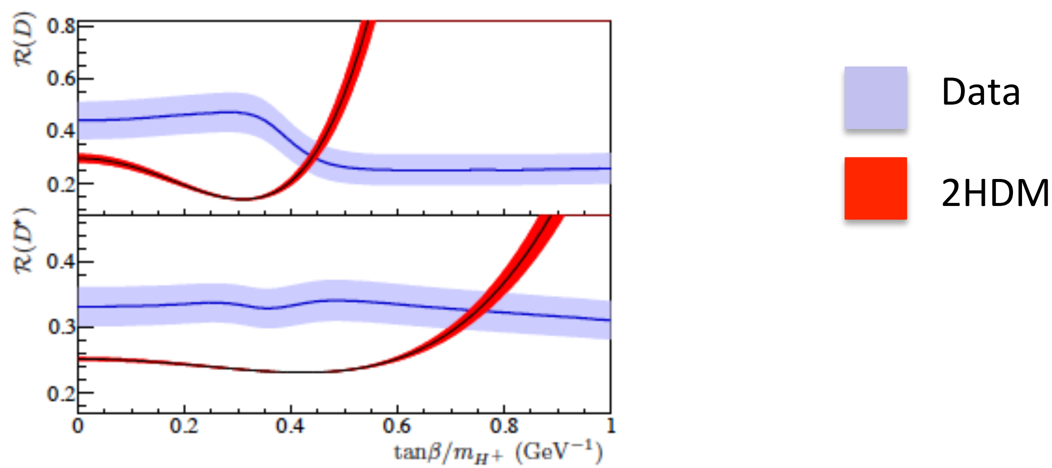
R(D$^{(*)}$)

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$^{(*)}$)

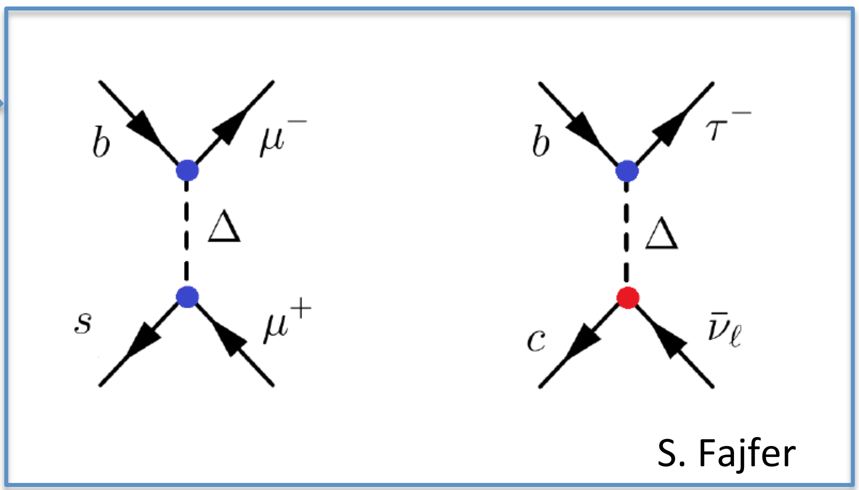
common solution to the R(K$^{(*)}$) tension -> new left-handed effective interaction

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



Contribution
to charged & neutral currents

- constraints from direct searches of resonances in $\tau^+\tau^-$ inv. mass
  Faroughy et al. PLB 2017

- constraints from B-Bbar mixing

  not for vector –coloured LQ
  Buttazzo et al 1706.07808

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

- 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

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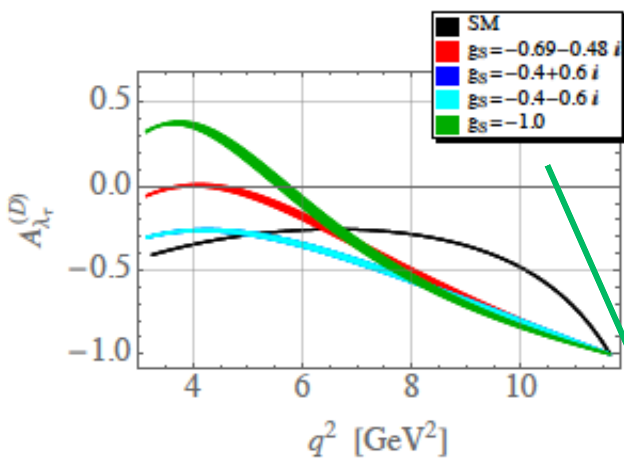
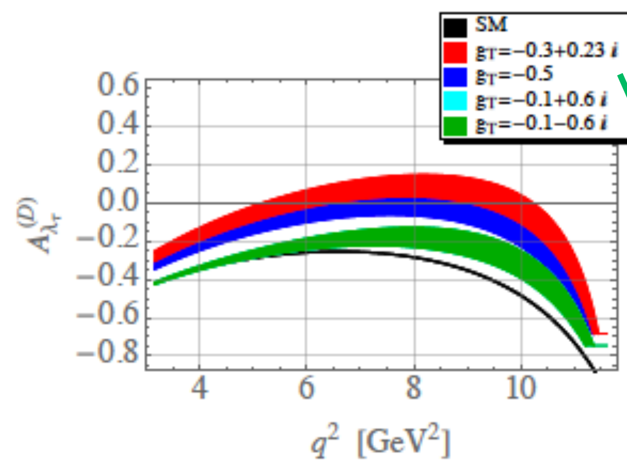
τ lepton in the final state: allow to access more form factors
sensitive to the lepton mass: lepton polarization asymmetry



new scalar contribution



new tensor contribution

Becirevic et al, 2016

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

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

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

charmed meson

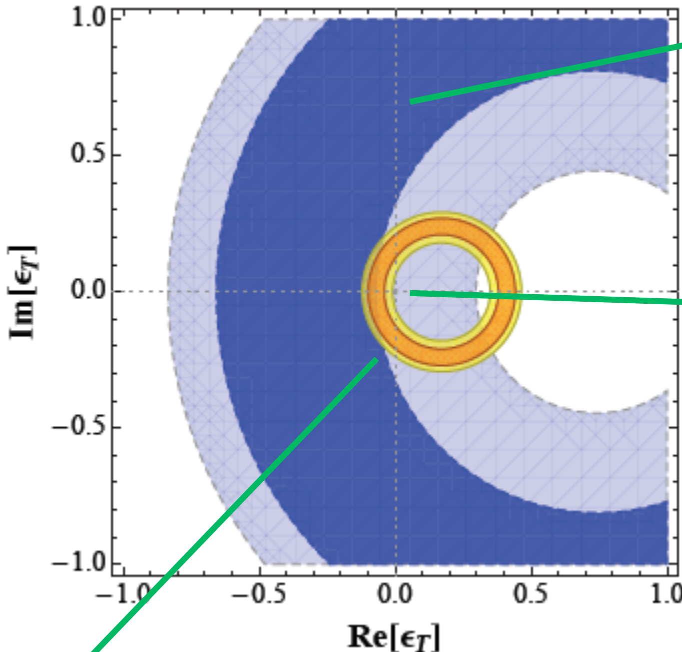
$$\frac{d\Gamma}{dq^2}(B \to M_c \ell \bar{\nu}_\ell) = C(q^2) \left[\frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{SM} + \frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{NP} + \frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{INT} \right]$$

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

$\propto |\varepsilon_T|^2$

$\propto$ Re(ε_T)

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

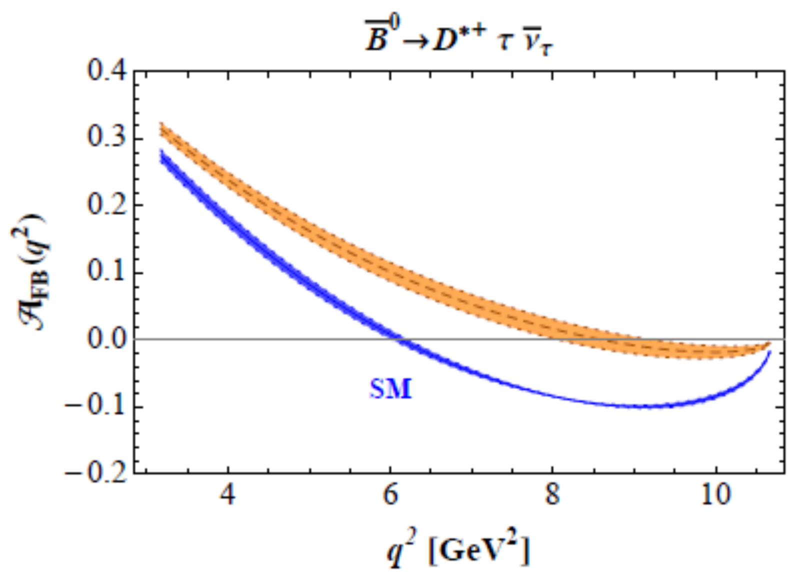


big circle: $R(D)$ constraint

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

small circle: $R(D^*)$ constraint

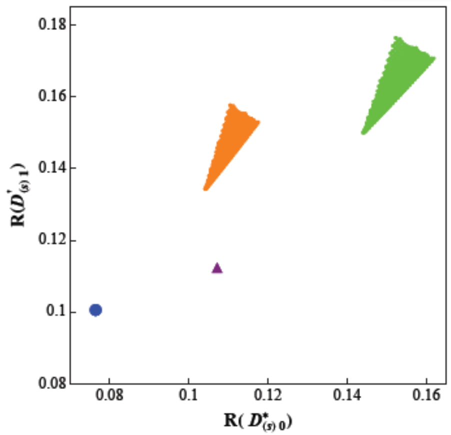
Ex: τ Forward-backward asymmetry

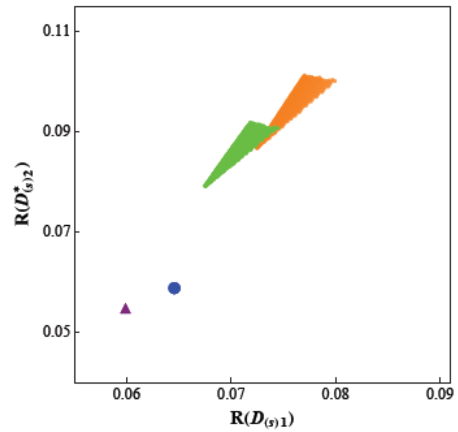


SM predicts a zero at $q^2 \approx 6.15$ GeV^2
in NP the zero is shifted to $q^2 \in [8.1, 9.3]$ GeV^2

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

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

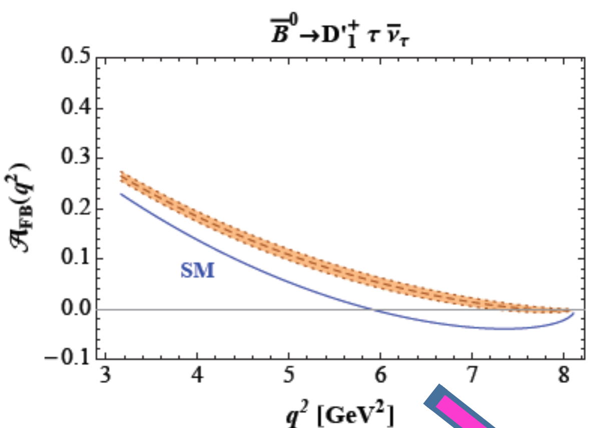


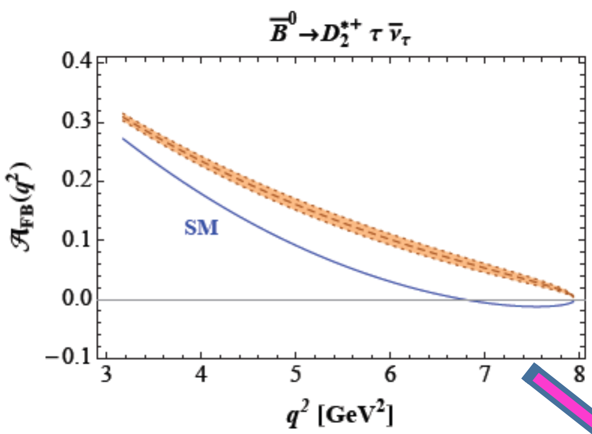


orange = non strange
blue circle = SM
green = strange
triangle = SM

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

$$|V_{cb}|_{\rm excl} = (39.78 \pm 0.42) \times 10^{-3}$$

C. DeTar, LeptonPhoton2015

$$|V_{cb}|_{\rm incl} = (42.21 \pm 0.78) \times 10^{-3}.$$

A. Alberti et al., PRL 114 (2015) 061802
P. Gambino et al., PRD 94 (2016) 014031

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

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- 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}

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

$$\hat{q}^2 = \frac{q^2}{m_b^2}$$

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

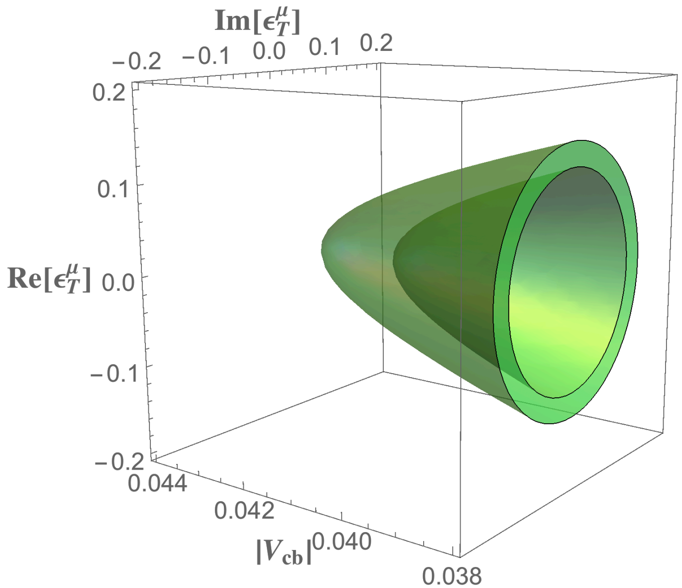
- prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^ℓ :
  three-parameter space $\boxed{(\mathrm{Re}(\epsilon_T^\ell), \mathrm{Im}(\epsilon_T^\ell), |V_{cb}|)}$

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

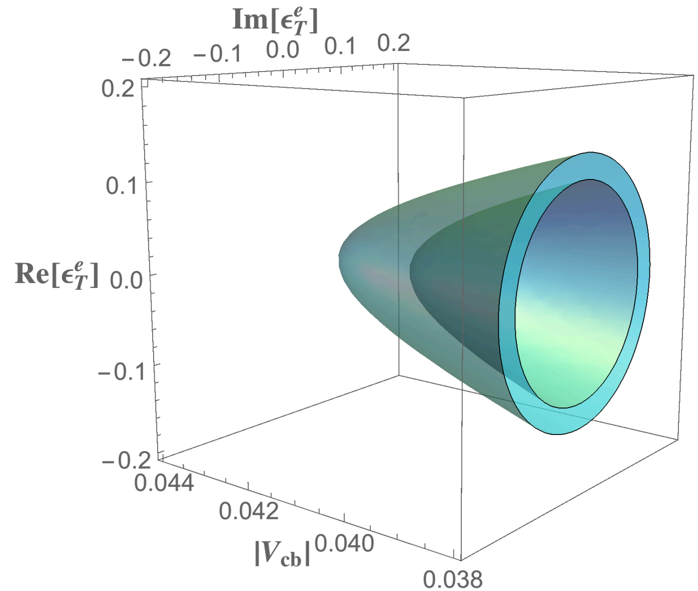
- result to be compared to experiment $\boxed{\mathcal{B}(B^+ \to X_c e^+ \nu_e) = (10.8 \pm 0.4) \times 10^{-2}}$ PDG

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

comparison with data at $1\,\sigma$



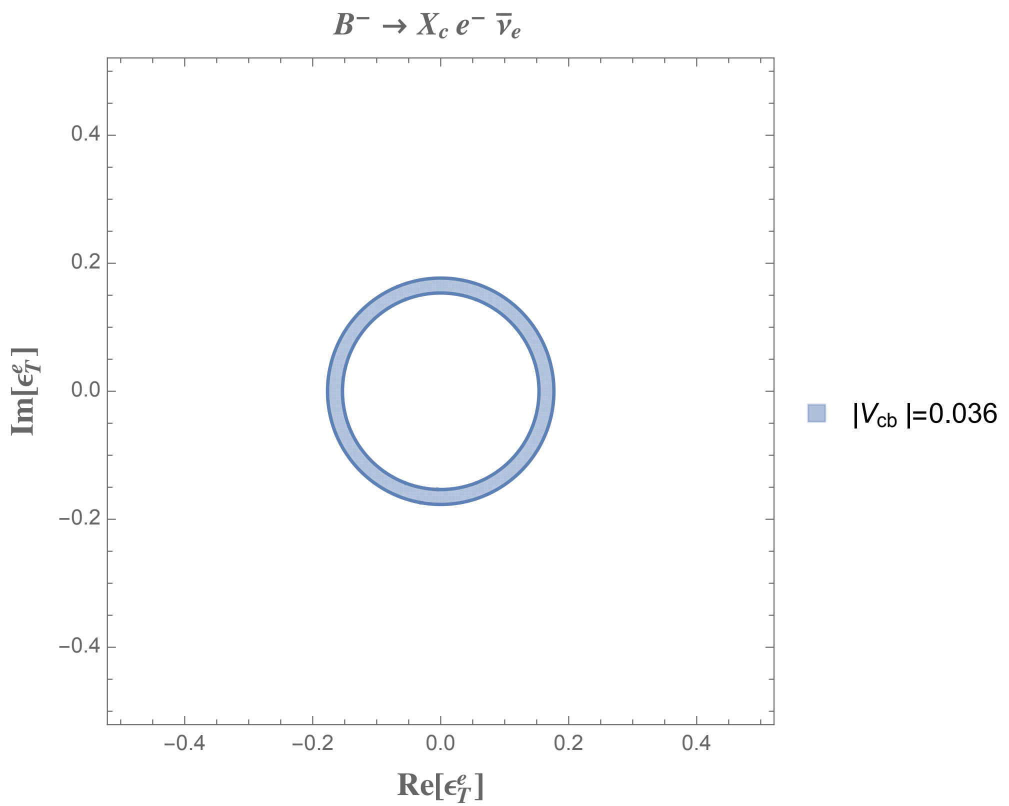
μ channel



e channel

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

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



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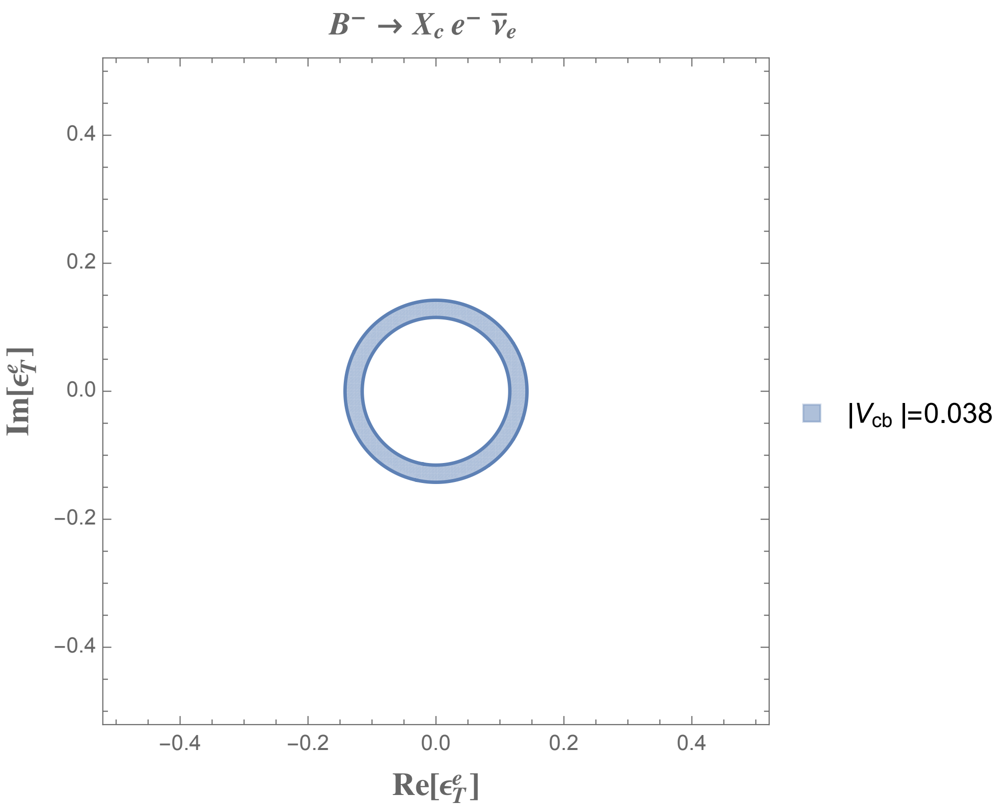
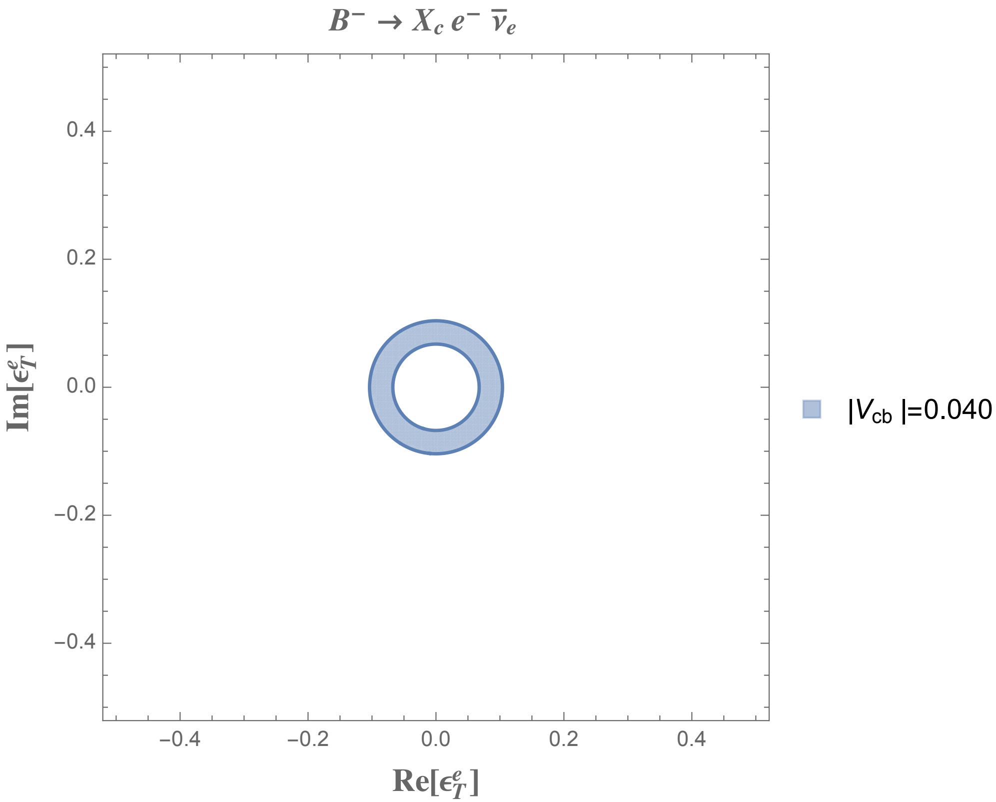


inclusive B -> $X_c\, \ell \nu_\ell$ decay:
allowed regions

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



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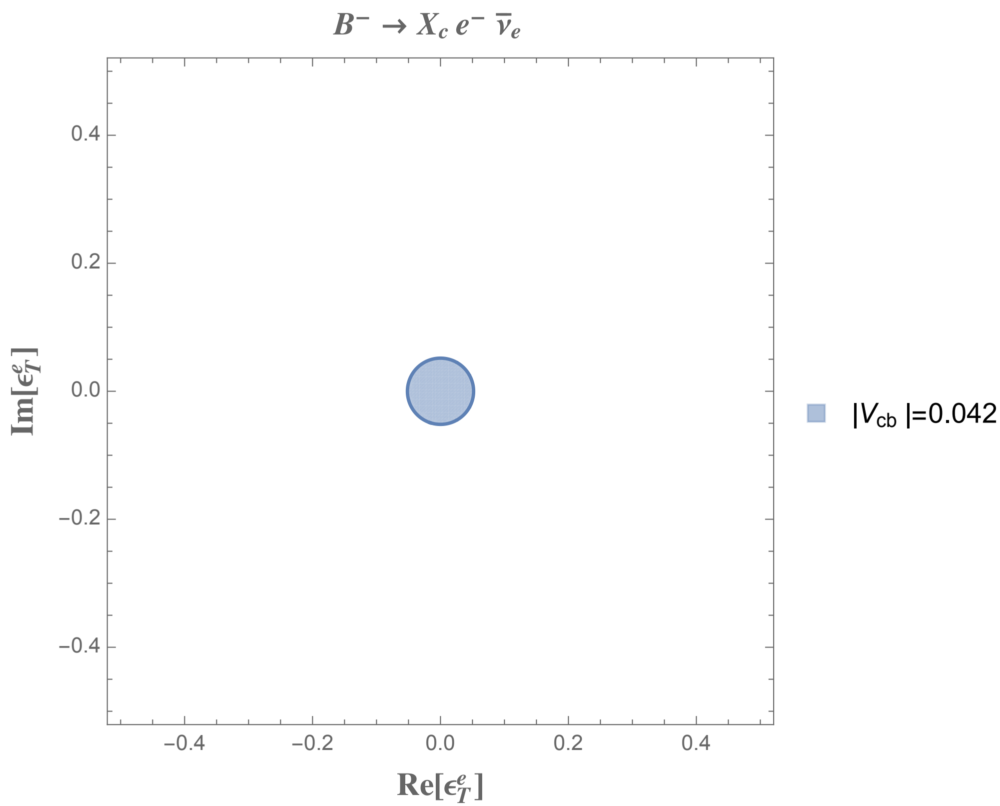

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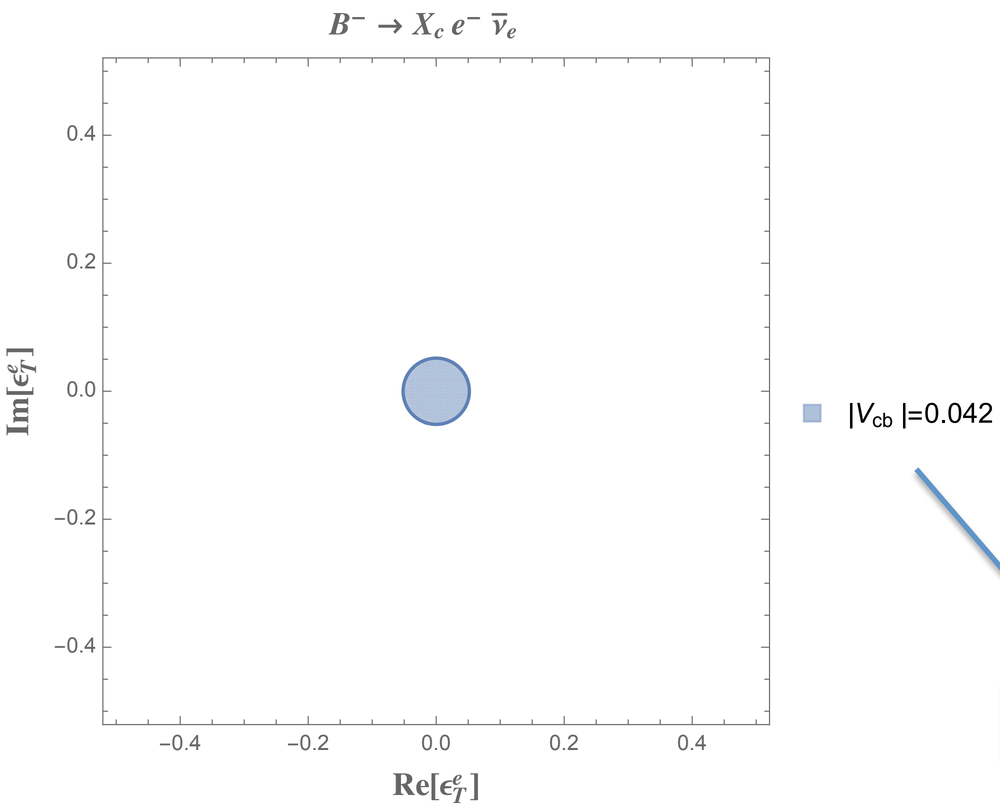
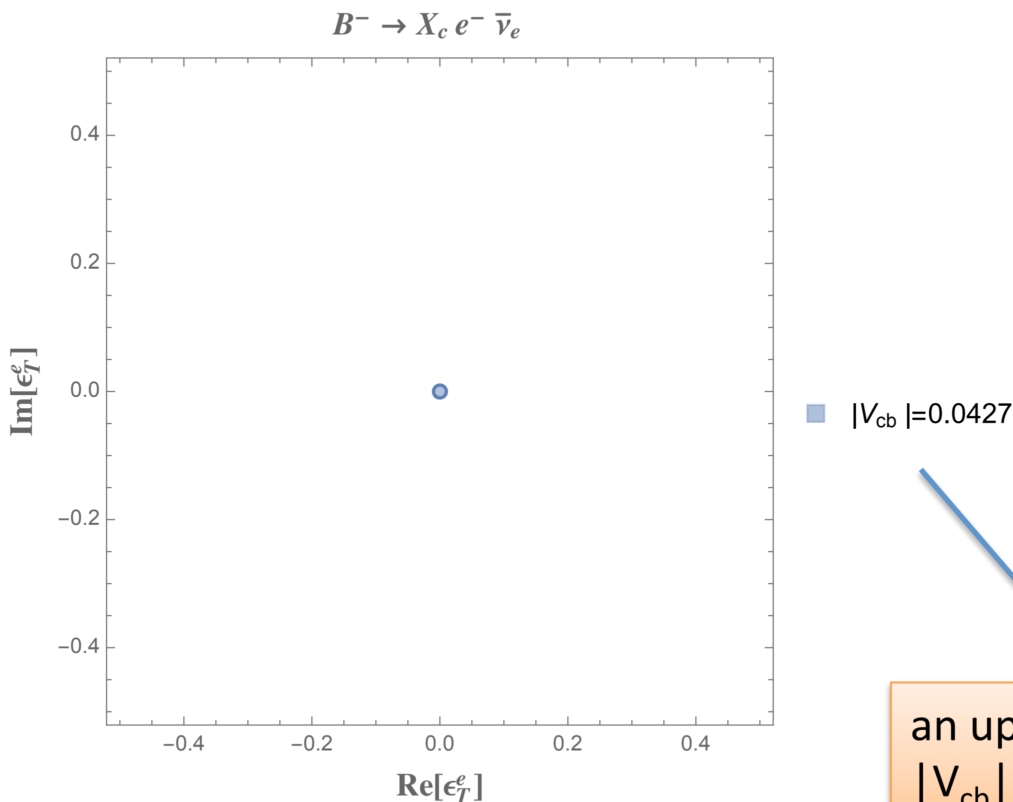


quoted value for SM!

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

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

- 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

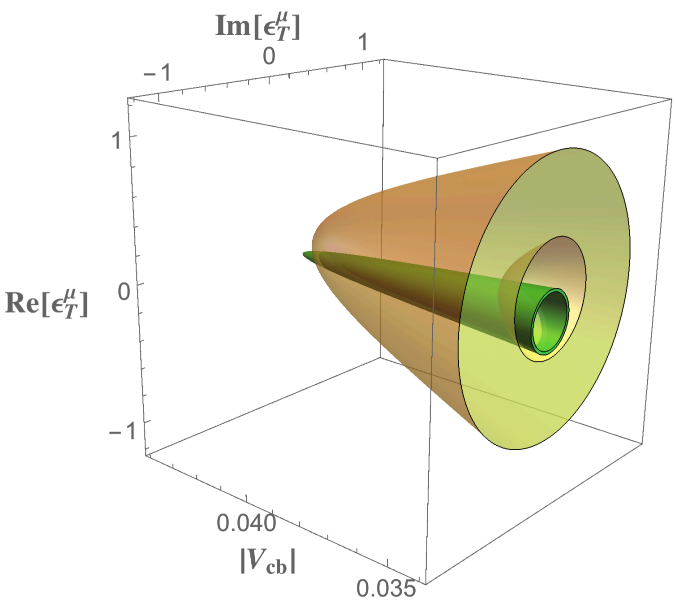
$$\mathcal{B}(B^- \to D^0\mu^-\bar{\nu}_\mu) = (2.25 \pm 0.04 \pm 0.17) \times 10^{-2}$$

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

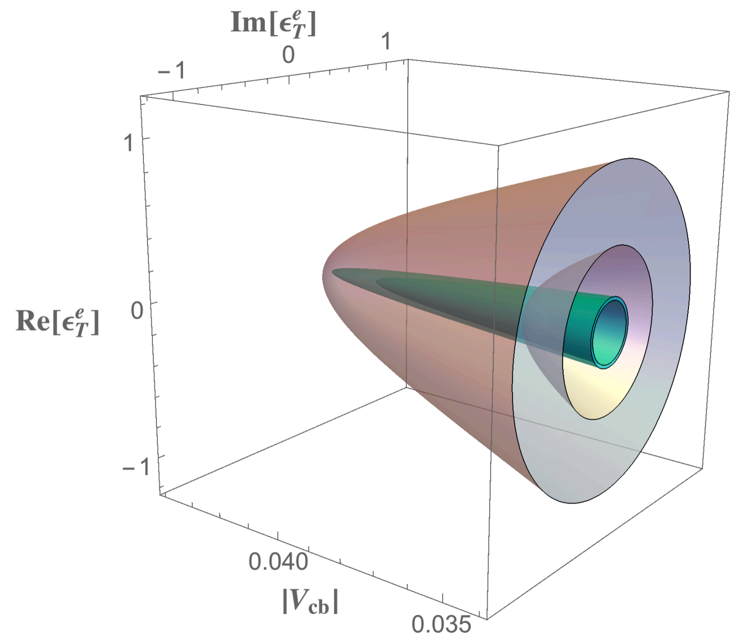
Theory prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^ℓ

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

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

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

procedure adopted by BaBar

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

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)

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

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

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

compare experiment to theory when w->1:

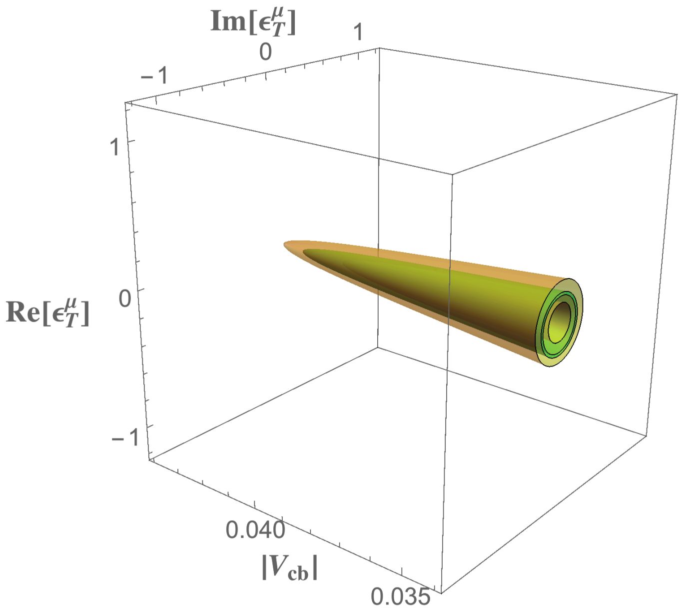
$$
\begin{aligned}
&\frac{d\Gamma^{\rm th}}{dw}(B^- \to D^{*0}\ell^-\bar{\nu}_\ell)|_{w\to 1} \\
&= \frac{G_F^2 |V_{cb}|^2 m_{D^*}^2}{16\sqrt{2\pi}^3\, m_B}\sqrt{w-1}\left[1-\frac{m_\ell^2}{(m_B-m_{D^*})^2}\right]^2 \\
&\quad \times\{(m_B+m_{D^*})^2[2(m_B-m_{D^*})^2+m_\ell^2]A_1(1)^2 \\
&\quad +|\epsilon_T|^2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

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

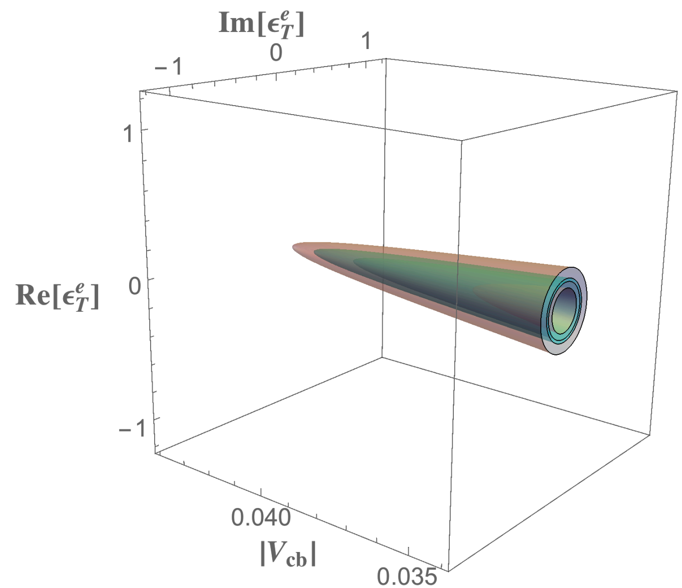
theory prediction depends on $|V_{cb}|$ and on the complex parameter ε_T^ℓ

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

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



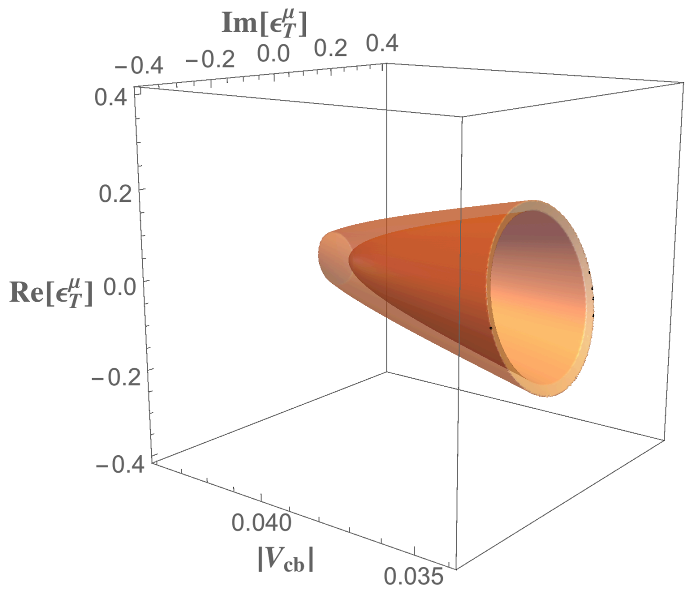
μ channel



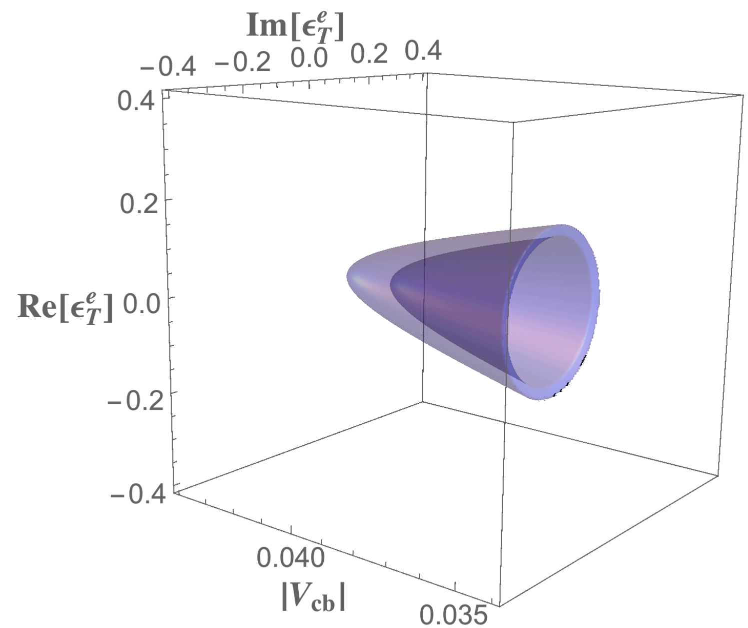
e channel

inner regions: inclusive mode
outer regions: exclusive mode

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



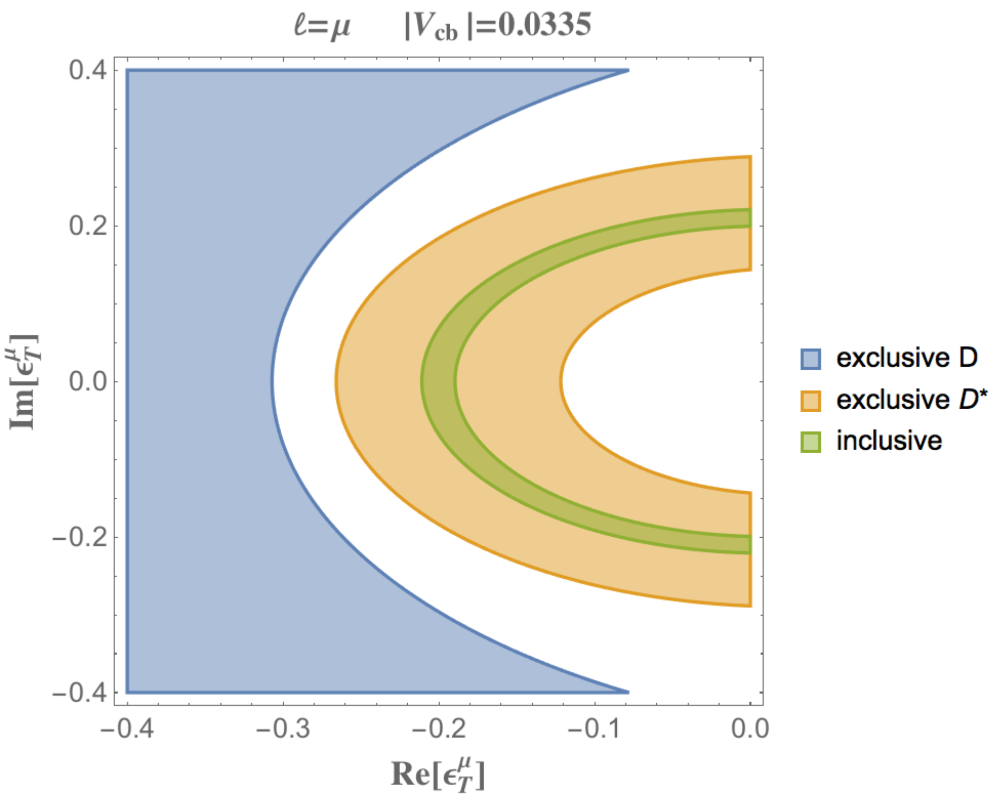
μ channel



e channel

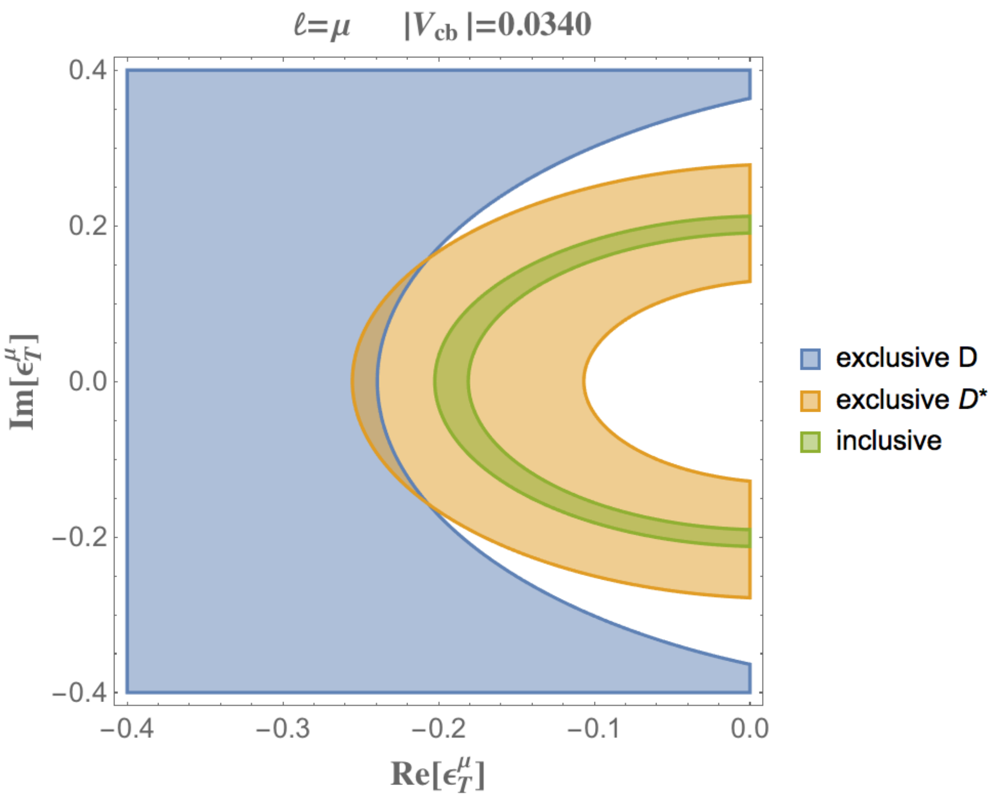
projections in the (Re ε_T, Im ε_T) plane

μ channel



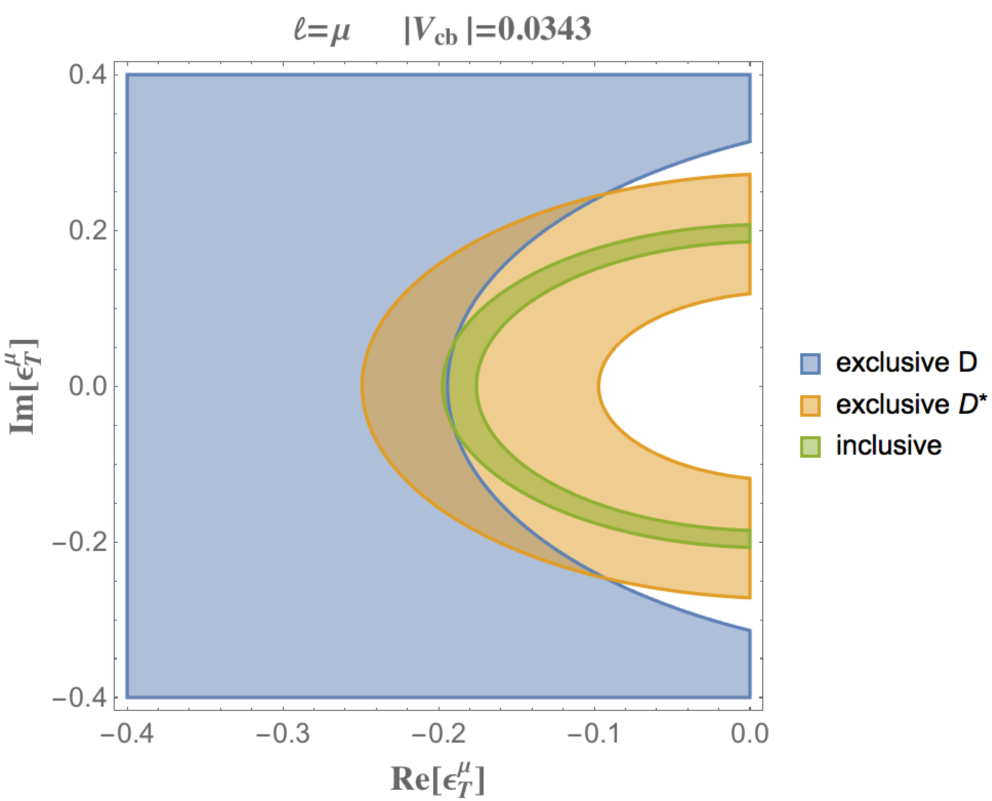
projections in the (Re ε_T, Im ε_T) plane

μ channel



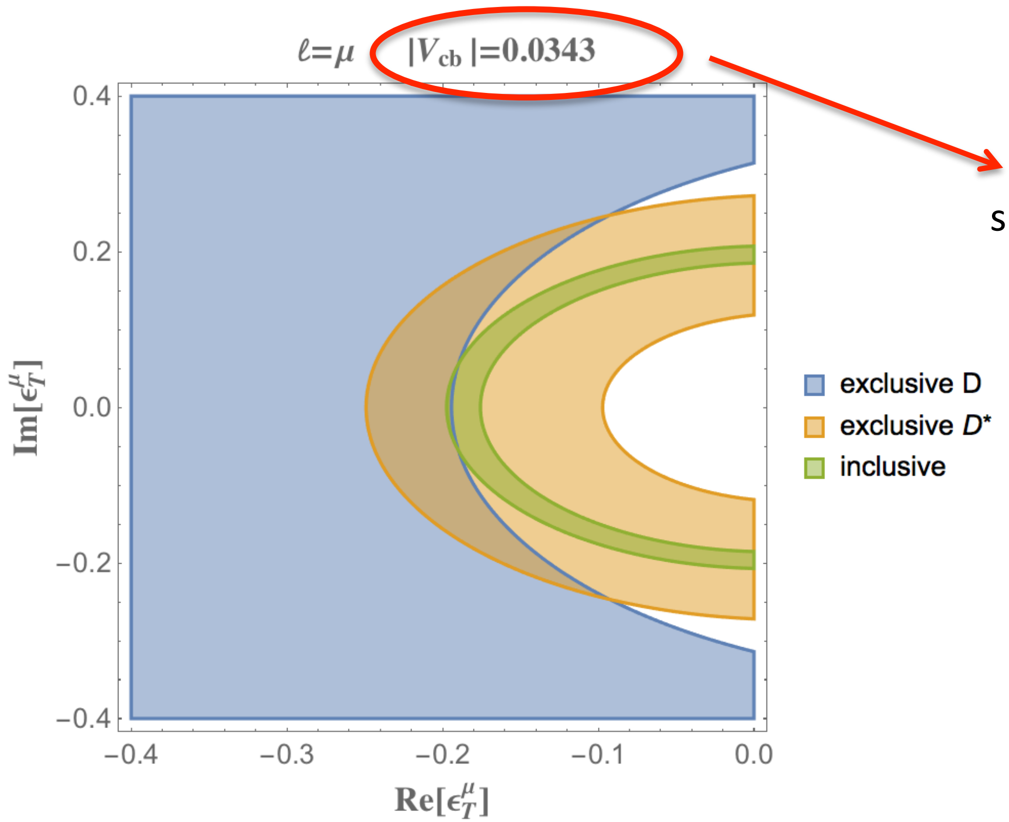
projections in the (Re ε_T, Im ε_T) plane

μ channel



projections in the (Re ε_T, Im ε_T) plane

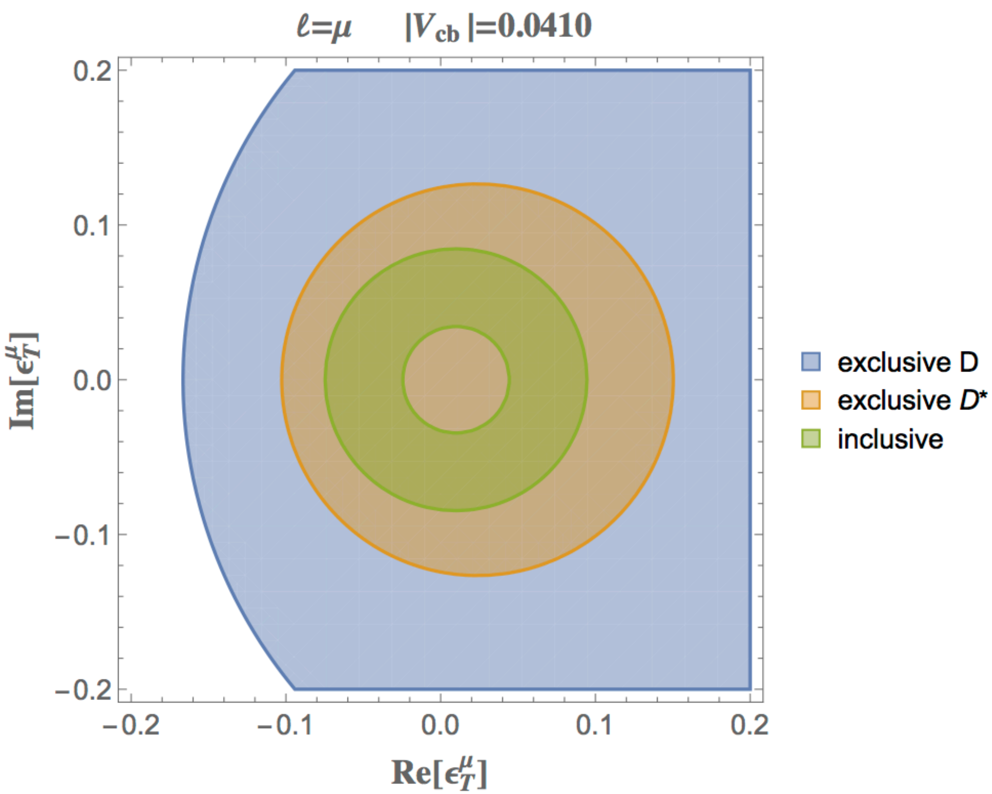
μ channel



smallest allowed value

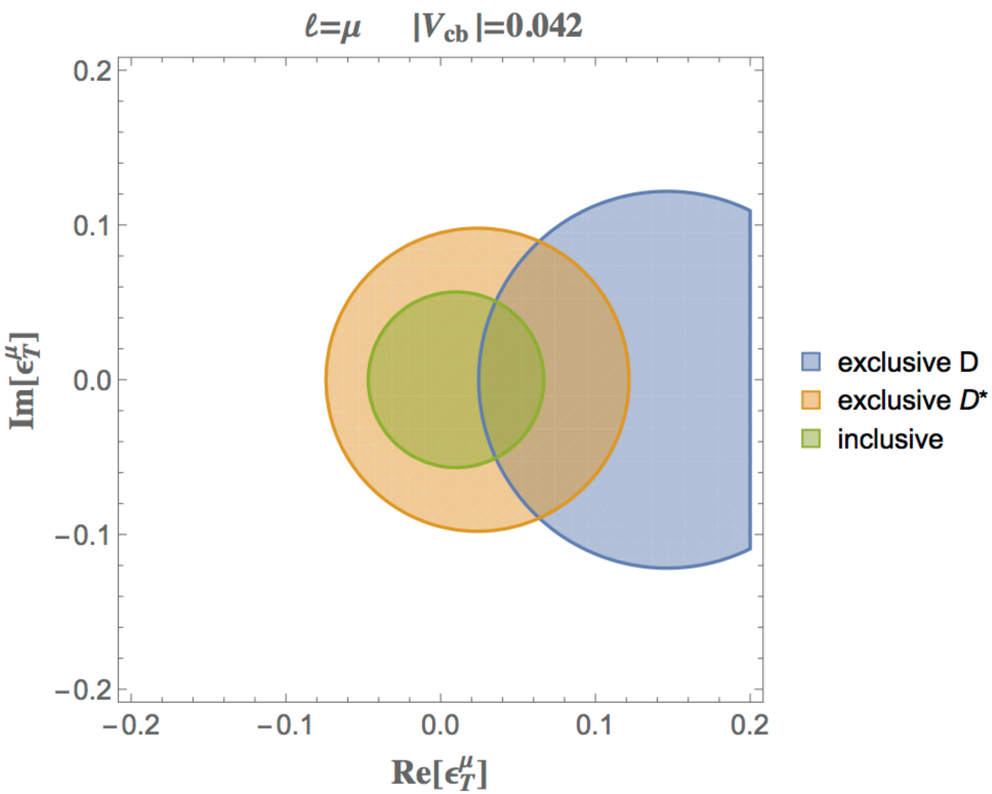
projections in the (Re ε_T, Im ε_T) plane

μ channel



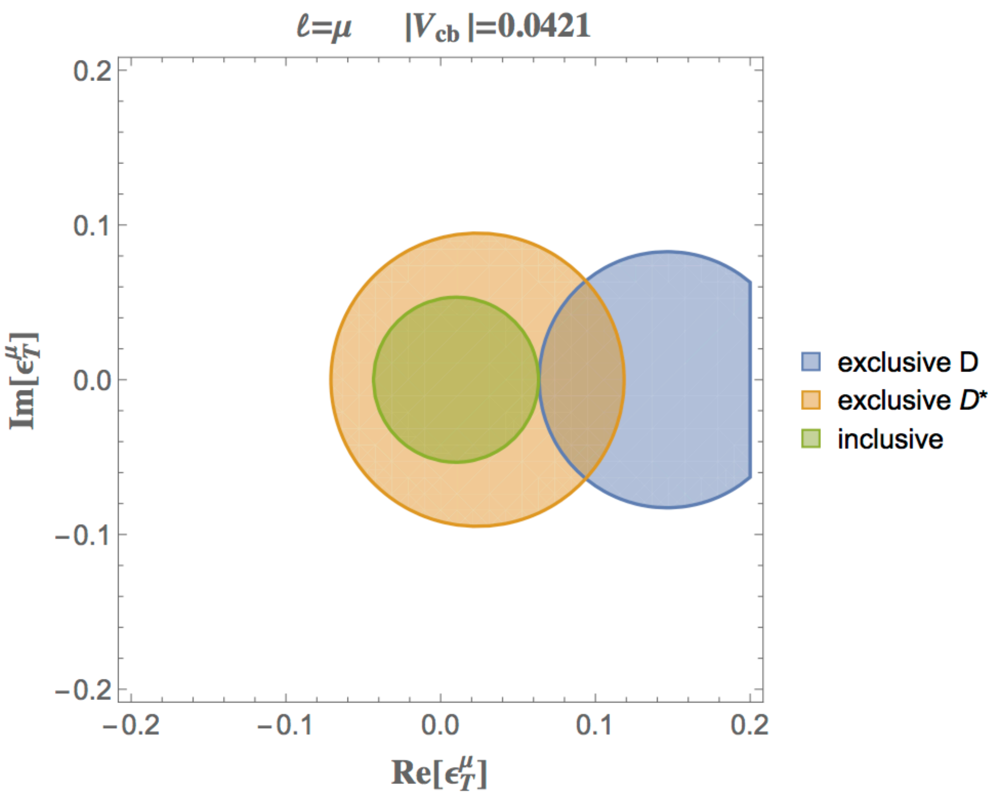
projections in the (Re ε_T, Im ε_T) plane

μ channel



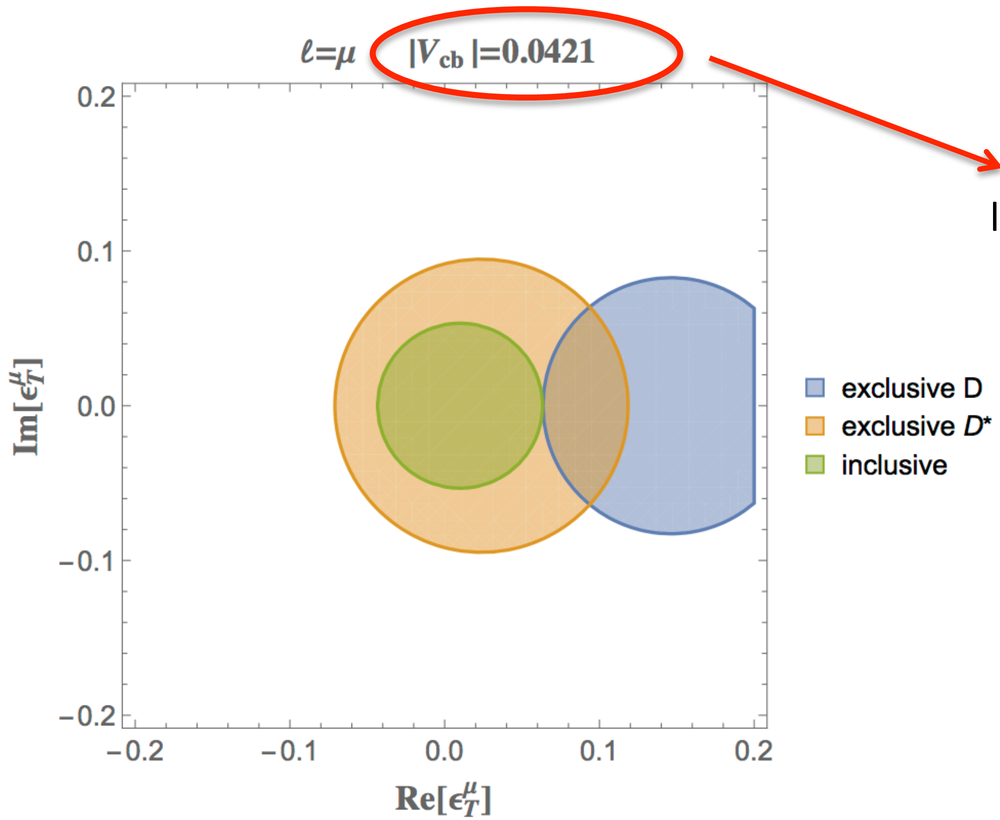
projections in the (Re ε_T, Im ε_T) plane

μ channel



projections in the (Re ε_T, Im ε_T) plane

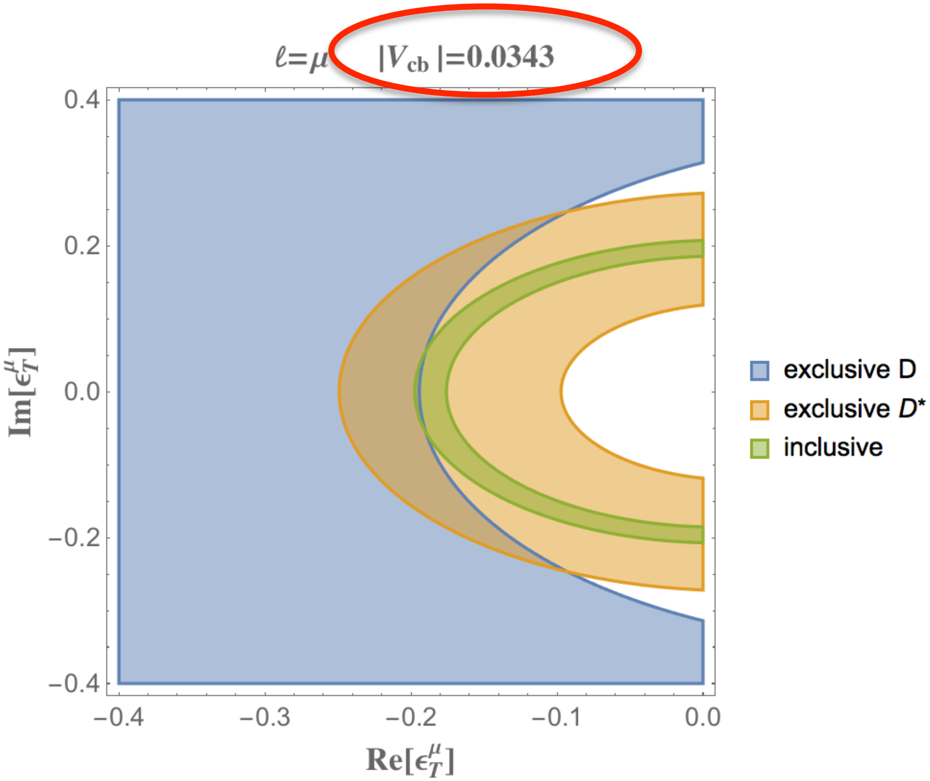
μ channel

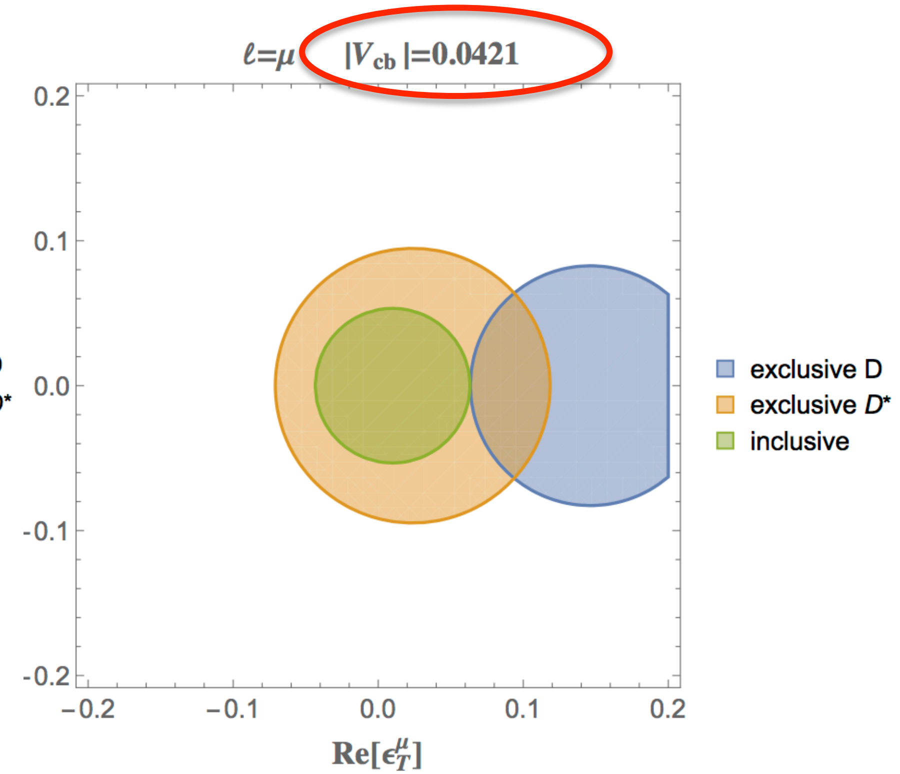


largest allowed value

projections in the (Re ε_T, Im ε_T) plane

μ channel

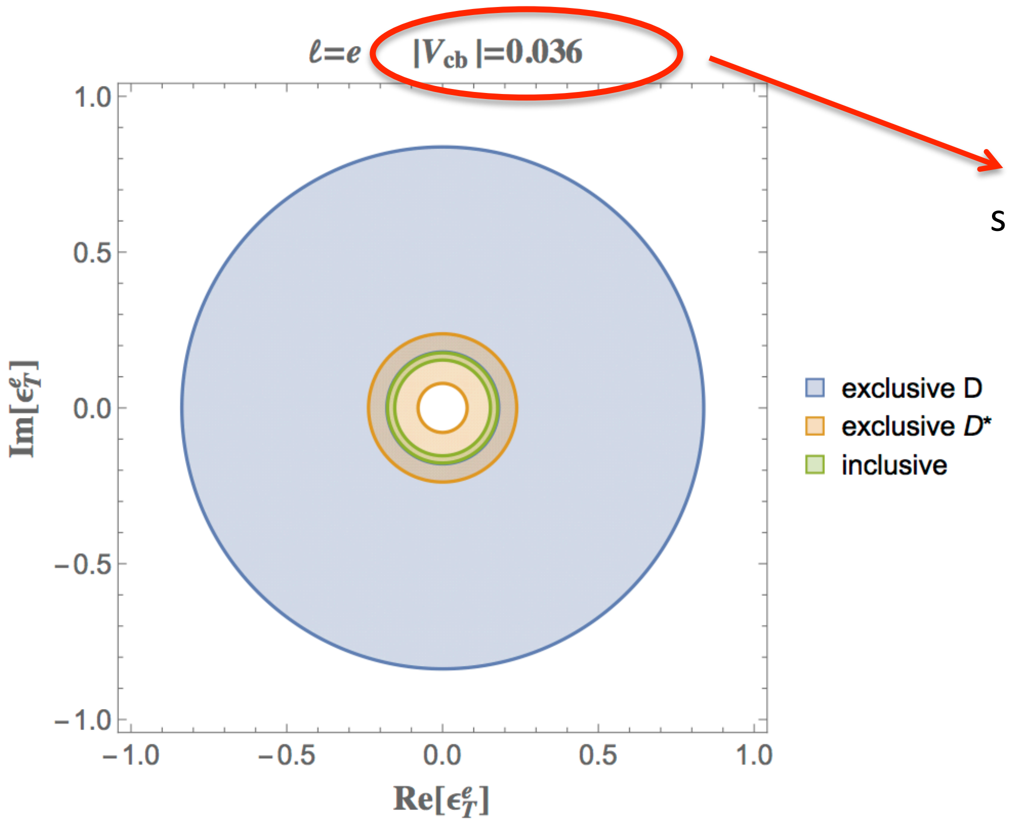




selected range $\boxed{|V_{cb}| \in [0.0343, 0.0421]}$

projections in the (Re ε_T, Im ε_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

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

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

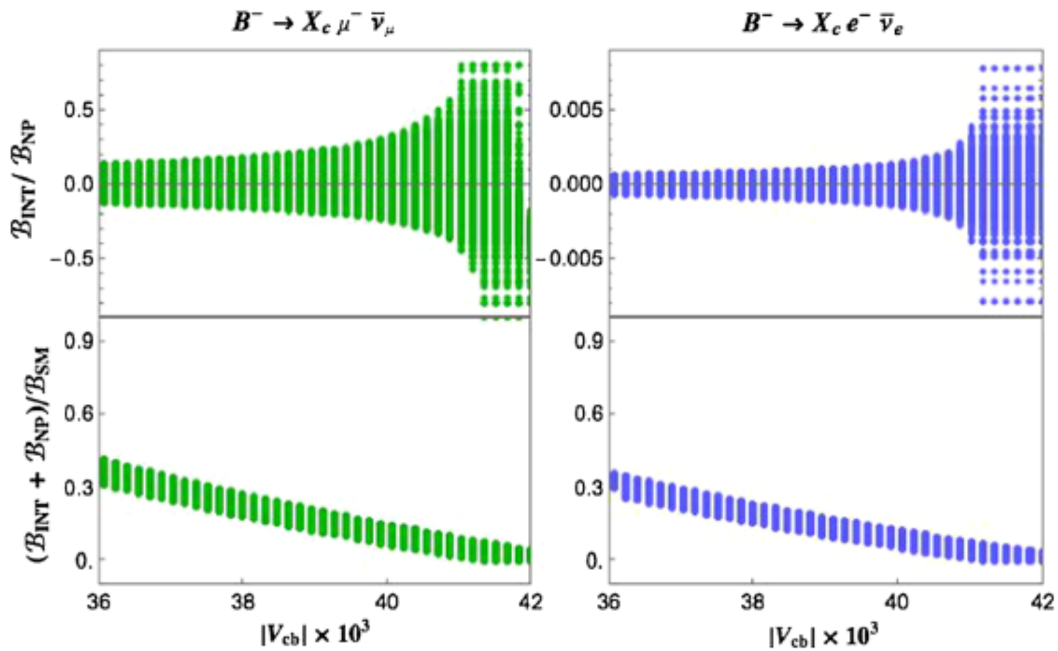
$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$

$\mathcal{B}_{\mathrm{SM}} \qquad \mathcal{B}_{\mathrm{NP}} \qquad \mathcal{B}_{\mathrm{INT}}$

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

role of the NP contributions

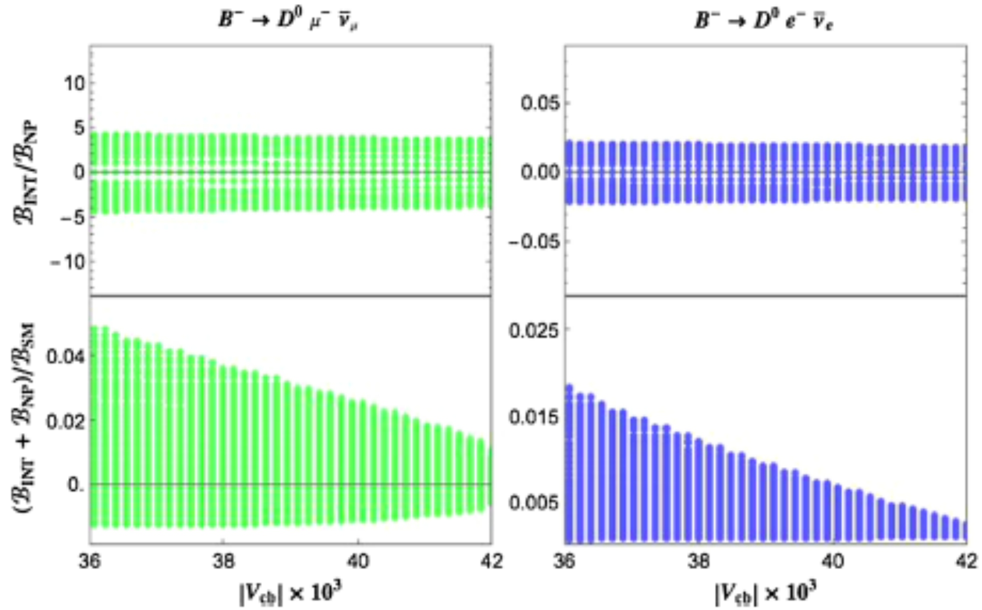
B -> $X_c\, \ell \nu_\ell$



- 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

talk by Schacht

A few words about V_{ub}

- Inclusive determination from B-> X_u l ν -> OPE : the same parameters! requires shape function (moments related to the OPE parameters)
- Exclusive: from B-> π l ν, Λ_b –> p l ν : requires FF
- Exclusive leptonic: from B -> τ ν : requires f_B

Inclusive vs exclusive:
recent lattice calculation of B-> π FF point to larger values of $|V_{ub}|_{excl}$
discrepancy still at 3 σ level

If LFU violation exists in b -> c we should probably see it also in b->u

universal breaking pattern?

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

A lot of surprises from three-level processes

The journey in search of phenomena beyond SM continues….