Theory status and latest developments in NP searches with **semileptonic *b* decays**

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(from last Friday on)

CKM fitter

UK Flavour 2017, Durham

Outline

1. Introduction
2. Theoretical status of $V_{(u,c)b}$
3. Theoretical status of τ/ℓ ratios
4. Constraining NP in $b \to c\tau\nu$

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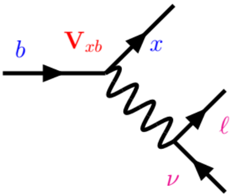
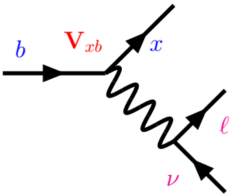
Cross-road



Why (semi)leptonic b decays:

- Laboratory: creating and improving tools for QCD

Cross-road



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- Extracting fundamental parameters: CKM matrix

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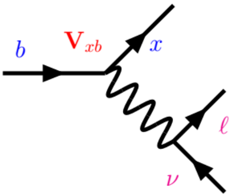

Why (semi)leptonic *b* decays:

- Laboratory: creating and improving tools for QCD
- Extracting fundamental parameters: CKM matrix
- Going Beyond the Standard Model: indications of LFUV

Important progresses in the *theoretical* front

Notably Lattice QCD [Talk by Chris Bouchard]

Important progresses in the *experimental* front

BaBar, Belle, LHCb [Talk by Mika Vesterinen]

Here, a review:

Brief **overview of** $V_{(u,c)b}$ **and** $R_{D^{(*)}}$

Developments in **NP searches**

Outline

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- $\sim$ theo. frameworks for **charmed** and **charmless** modes, but different tools for **inclusive** and **exclusive**

Exclusive

HQS (∞ mass limit) underlying HQET

e.g., in the HQ limit, $\mathcal{F}^{B\to D^*}(w) = \mathcal{G}^{B\to D}(w) = \xi_{IW}(w)$

Inclusive

HQE leads to a systematic OPE in powers of $1/m_b$

Exclusive V_{cb} extraction: $B \to D^* \ell \nu$

$$\frac{d\Gamma}{dw} \propto \eta_{EW}^2 \mathcal{F}(w)^2 |V_{cb}|^2 \,, \quad w = v_B \cdot v_{D^*} \,,$$

$$\text{where } 1 \leq w \leq (m_B^2 + m_{D^*}^2)/(2 m_B m_{D^*})$$

- In the limit $m_{b,c} \to \infty$, single FF (axial-vector) $\mathcal{O}(\Lambda_{QCD}^n / m_{b,c}^n)$ corrections: for the normalization @ $w = 1$ and the shape of the FF as a function of w
- Lattice QCD, $\mathcal{F}(1) = 0.906 \pm 0.013$ [Fermilab/MILC'14]

$$|V_{cb}| = (39.05 \pm 0.47_{\text{exp}} \pm 0.58_{\text{lattice,EW}}) \times 10^{-3} \;\; (\textbf{CLN})$$

[HFAG'16]

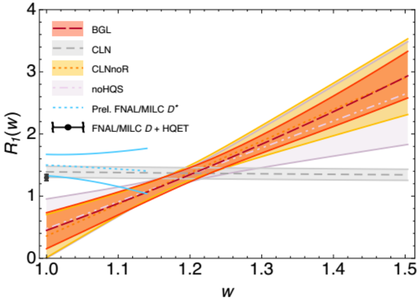
Exclusive V_{cb} extraction: $B \to D^*\ell\nu$

- Parameterizations of the FFs as a function of the recoil
  CLN model dependent/**BGL** model independent
- Important tensions among **CLN**/**BGL** for latest Belle
  BGL in agreement w/ $|V_{cb}|_{incl.}$, but large tensions w/ HQS

[Belle'17,Bigi+'17,Grinstein+'17,Bernlochner+'17]

Preliminary $B \to D^*\ell\nu$ beyond zero-recoil from Lattice talk

[Bernlochner+'17]



Exclusive V_{cb} extraction: $B \to D\ell\nu$

$$\frac{d\Gamma}{dw} \propto \eta_{EW}^2 \mathcal{G}(w)^2 |V_{cb}|^2, \qquad \text{w/ } \mathcal{G} \text{ function of } f_+ \text{ and } f_0$$

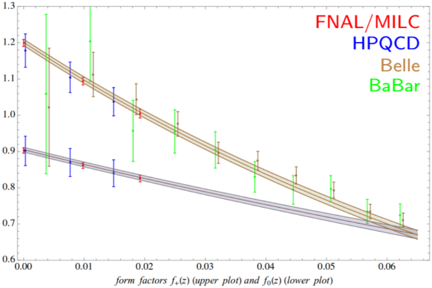
$$|V_{cb}| = (40.49 \pm 0.97) \times 10^{-3}$$

(**BGL** & *Bigi*, *Gambino*)

[HPQCD'15,Fermilab/MILC'15,Bigi+'16]

Competitive precision w/ $B \to D^*$

CLN/**BGL** are consistent



Inclusive V_{cb} extraction

$$\Gamma \propto |V_{cb}|^2 \left[\sum_i \mathbf{C_0^{(i)}} \frac{\alpha_s^i}{\pi} + \frac{\mathcal{O}(\mu^2)}{m_b^2} \sum_i \mathbf{C_2^{(i)}} \frac{\alpha_s^i}{\pi} + \frac{\mathcal{O}(\rho^3)}{m_b^3} \sum_i \mathbf{C_3^{(i)}} \frac{\alpha_s^i}{\pi} + \ldots\right]$$

- Terms $\mathcal{O}(\alpha_s \mu^2 / m_b^2)$ for the dimension 5 chromomagnetic op., $\mu_G^2 \equiv \langle B|\bar{b}(iD_\perp^\mu)(iD_\perp^\nu)\sigma_{\mu\nu} b|B\rangle \qquad (D_\perp^\mu = (g_{\mu\nu} - v_\mu v_\nu)D^\mu)$

  [Alberti+'14,Mannel+'15]

- Estimate terms $\mathcal{O}(1/m_b^{4,5})$ [Gambino+'16]

  Main uncertainties: higher-order perturbative $(\alpha_s^3, \alpha_s/m_b^3)$ and non-perturbative corrections

Inclusive V_{cb} extraction

- Semileptonic moments $\langle E_e^n \rangle_{E_e > E_{max}}$, $n = 0, 1, 2, \ldots$, etc.

$$\langle E_e^n \rangle_{E_e > E_{cut}} = \int_{E_{cut}}^{E_{max}} \frac{d\Gamma}{dE_e} E_e^n dE_e / \int_{E_{cut}}^{E_{max}} \frac{d\Gamma}{dE_e} dE_e$$

- Fit including $(1, \alpha_s, \alpha_s^2)$, $(1, \alpha_s)/m_b^2$, $1/m_b^3$ terms

$$|V_{cb}| = (42.19 \pm 0.78_{\text{fit,theory}}) \times 10^{-3} \ \ (m_b^{kin})$$ [HFAG'16]

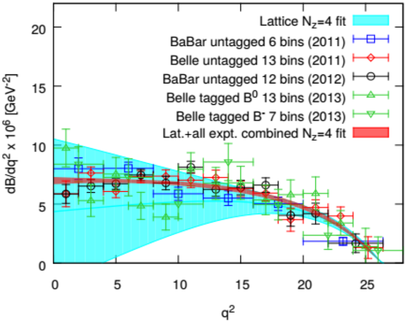
- Unc. dominated by theory unc. for the measured moments

Exclusive V_{ub} extraction

$B \to \pi \ell \nu$

Simultaneous fit to Lattice and differential rates data:

$$|V_{ub}| = (3.72 \pm 0.16_{\rm expt,lat.}) \times 10^{-3}$$
$(BCL \,\&\, FNAL/MILC)$

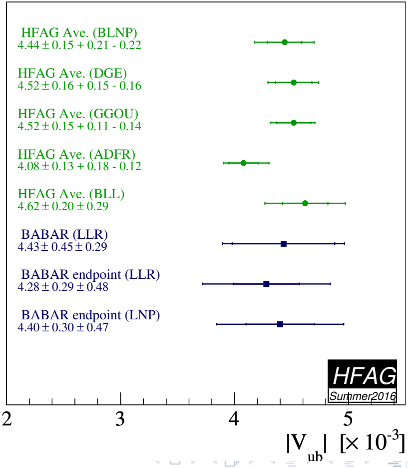


[Fermilab/MILC'15]

Inclusive V_{ub} extraction

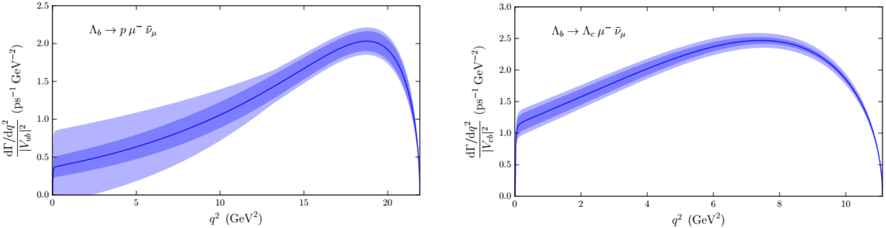
Huge background from $B \to X_c \ell \bar{\nu}_\ell$: more complex handling of non-perturbative effects

Different theoretical methods lead to similar extractions



Semileptonic b-baryon decays: excl. $|V_{ub}|/|V_{cb}|$

$\Lambda_b^0 \to (p, \Lambda_c^+)\mu^-\bar{\nu}$



- $\Lambda_b^0 \to (p, \Lambda_c^+)\mu^-\bar{\nu}$ peak at large recoil: Lattice specially suitable
- Lattice FFs for baryon decays [Detmold+'15,Meinel'16; tensor: Datta+'17]

  Six in total for each channel (3 vector, 3 axial-vector)

Semi-leptonic B-baryon decays: excl. $|V_{ub}|/|V_{cb}|$

- LHCb: measurement of $\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\bar{\nu})_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\bar{\nu})_{q^2>7\,\mathrm{GeV}^2}}$

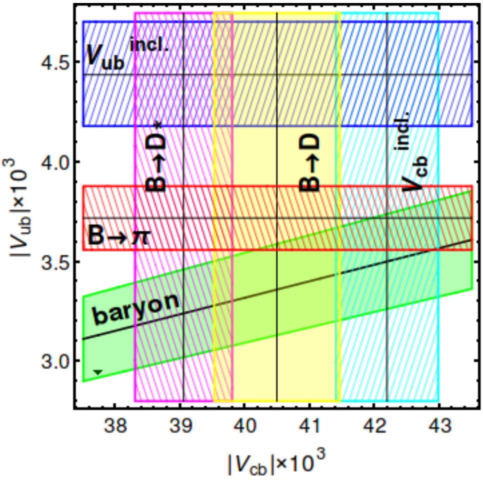
  First determination of $|V_{ub}|/|V_{cb}|$ at a hadron collider

$$|V_{ub}|/|V_{cb}| = 0.083 \pm 0.004_{\mathrm{expt}} \pm 0.004_{\mathrm{lattice}} \quad (\textit{Detmold et al.})$$

- **Similar unc.** compared to inclusive and exclusive determinations

PDG15: $\frac{|V_{ub}|}{|V_{cb}|} = 0.107 \pm 0.006$ (incl.), $\frac{|V_{ub}|}{|V_{cb}|} = 0.095 \pm 0.005$ (excl.)

- 1σ bands (no distinction of statistical and theoretical uncs.)



- Exclusive $|V_{ub}|$, inclusive $|V_{cb}|$, and $|V_{ub}|/|V_{cb}|$ from B-baryon decays favored by **indirect** predictions

[CKMfitter, UTfit; by ICHEP 16]

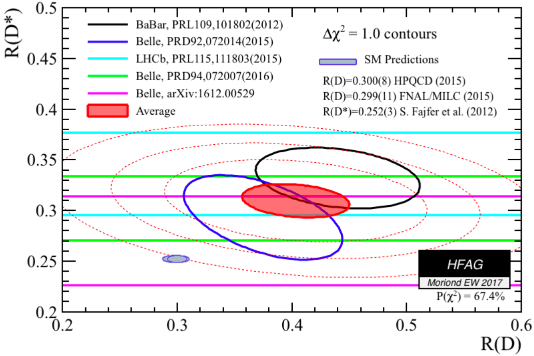
Outline

Tau rates

$B \to D^{(*)}\ell\nu$

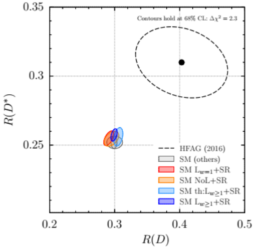
$$\frac{d\Gamma_\ell}{dq^2} \propto \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left(|H_+|^2 + |H_-|^2 + |H_0|^2\right)\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2}|H_t|^2\right]$$

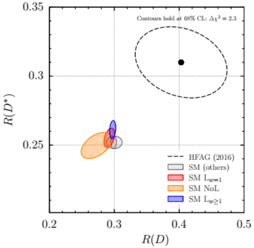
- τ contributions: Sensitive to H_t
- Ratios of Γ_ℓ: Tension with SM $\to$ **LFUV**



Combined fit R_D and R_{D^*}

- HQET to $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}, \alpha_s)$ [Bernlochner+'1703,'1708]
- Global fit: $|V_{cb}|$, $\mathcal{G}(1)$, $\mathcal{F}(1)$, slope of ξ_{IW}, sub-leading IW funcs.
- No inconsistencies between data, LQCD results and QCDSR





Most precise prediction ($\mathrm{L}_{w\geq1} + \mathrm{SR}$ = expt. data and all LQCD and QCDSR):

$\mathbf{R_D} = \mathbf{0.299(3)}$ and

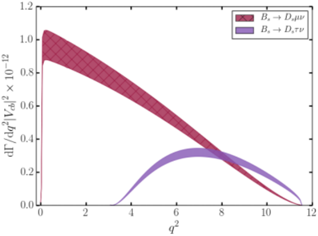
$\mathbf{R_{D^*}} = \mathbf{0.257(3)}$, corr $= \mathbf{44\%}$

($|V_{cb}| = (39.3\pm1.0)\times10^{-3}$)

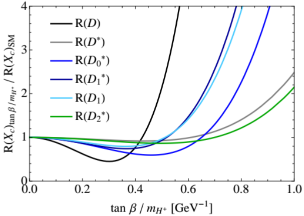
Prospects on other ratios

$$R(D_s) = \frac{\mathcal{B}(B_s \to D_s \tau\nu)}{\mathcal{B}(B_s \to D_s \ell\nu)} = 0.314 \pm 0.006_{\text{lattice}}$$

[Monahan+'16,'17]



type-II 2HDM



$$R(\textstyle\sum_{\{D_0^*, D_1^*, D_1, D_2^*\}} D^{**}) = 0.085 \pm 0.012\,,$$

w/ subleading IW functions estimated

[Bernlochner+'16,Monahan+'16,'17]

Also, $R(\Lambda_c) = 0.33 \pm 0.01$ [Detmold+'1503.01421,Datta+'17]

Outline

$b \to c\tau\bar{\nu}_\tau$ at low energies

Charged currents:

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+\epsilon_{\mathbf{L}})\,\bar{\tau}\gamma_\mu P_L\nu_\tau \cdot \bar{c}\gamma^\mu P_L b + \epsilon_R\bar{\tau}\gamma_\mu P_L\nu_\tau \cdot \bar{c}\gamma^\mu P_R b$$
$$+\epsilon_T\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau \cdot \bar{c}\sigma^{\mu\nu}P_L b + \epsilon_{S_L}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_L b + \epsilon_{S_R}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_R b\Big] + \text{h.c.}$$

Different phenomenological aspects for the NP $\epsilon_{\mathbf{L}}$, ϵ_R, ϵ_{S_L}, ϵ_{S_R}, ϵ_T

B_c lifetime

Valuable info. for constraining chiral-enhanced pseudo-scalar NP

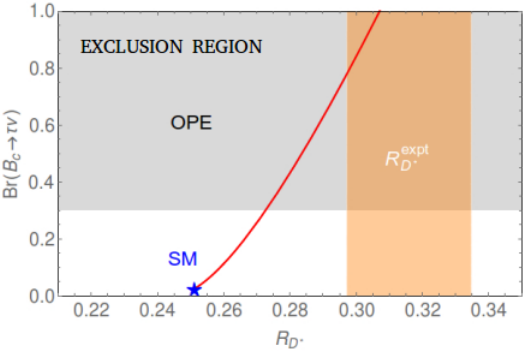
$\tau_{B_c}^{\rm OPE} \overset{SM}{=} 0.52^{+0.18}_{-0.12}\ {\rm ps} \Rightarrow$

[Bigi'95,Beneke+'96,C.-H. Chang+'00]

$\mathcal{B}(B_c^- \to \tau\nu) \lesssim 30\%$

Suppressed coupling

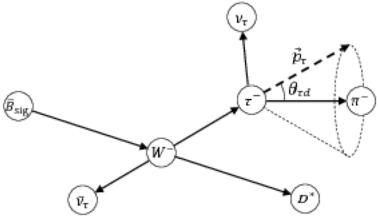
$\epsilon_{S_L} - \epsilon_{S_R}$



[Alonso+'16; see also, Akeroyd+'17]

τ-lepton polarization in $\bar{B}^0 \to D^*\tau^-\bar{\nu}_\tau$

- First meas. of the τ longitudinal polarization in $\bar{B}^0 \to D^*\tau^-\bar{\nu}$ through $\tau^- \to \pi^-\nu_\tau$, $\tau^- \to \rho^-\nu_\tau$ [Belle'16,'17]

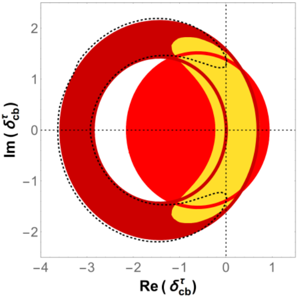


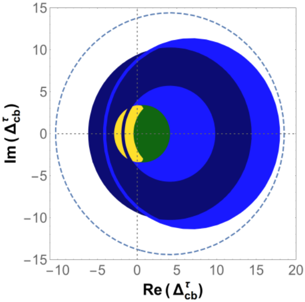
- The distribution of $\cos(\theta_{\tau d})$ gives the polarization
- SD information carried out by the polarizations of the τ-lepton

[Ivanov+'17]

Constraints on NP: longitudinal polarization

$$\delta^{\tau}_{cb} \propto (\epsilon_{S_L} + \epsilon_{S_R}) \quad \text{and} \quad \Delta^{\tau}_{cb} \propto (\epsilon_{S_L} - \epsilon_{S_R})$$

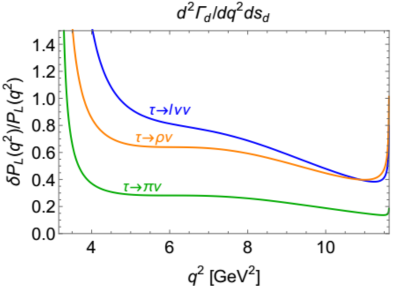


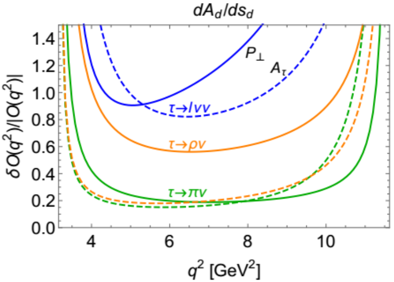


Dark red/blue rings: $R(D^{(*)})$; *light* red/blue disks: q^2-distribution of $B \to D^{(*)}\tau\nu$; green disk: $\mathcal{B}(B_c \to \tau\nu)$; dotted area: includes $\frac{\mathcal{B}(B\to\tau\nu)}{\mathcal{B}(B\to\pi\ell\nu)}$; dashed circle: $P_L(D^*)$ [Celis+'16]

τ-lepton polarization in $B \to D\tau\nu$

- Final-state $\tau \to d\nu_\tau(\bar{\nu}_\ell)$, $d = \{\pi, \rho, \ell\}$: **self-analyzer** [Alonso+'17]
  $\Gamma_d(\tau \to d) \Rightarrow P_L$, and $A_d(q^2) = F_A^d A_\tau(q^2) + F_\perp^d P_\perp(q^2)$
  A_τ: FB asym.; $P_\perp$: perpendicular pol. (e.g. in the plane $\pi\nu_\tau$)
- **Belle II** (full operation): $\tau \to \pi\nu_\tau$, uncertainties $\lesssim \mathcal{O}(10\ \%)$



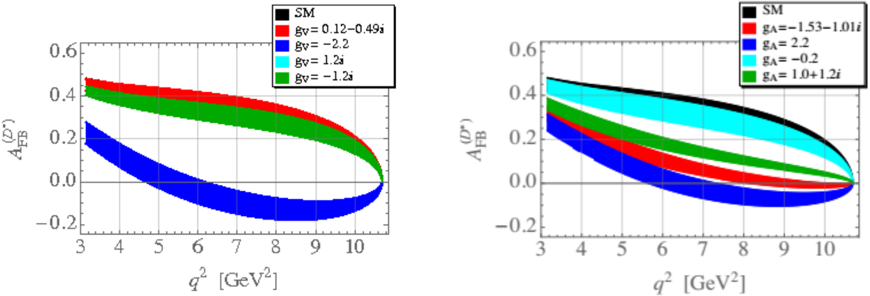


$s_d = E_d/\sqrt{q^2}$ (in the $\tau\bar{\nu}_\tau$ rest-frame)

Angular observables

Some benefits:

Distinguishing NP scenarios, e.g., FB asym. τ



[Bečirević+'16]

$$g_V = \epsilon_L + \epsilon_R\,, \qquad g_A = \epsilon_R - \epsilon_L$$

Correlations w/ rare decays

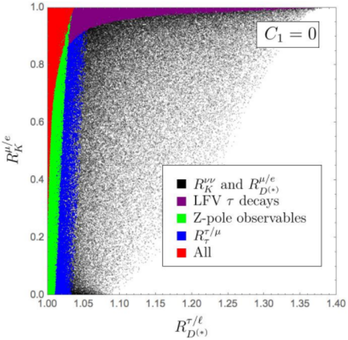
Anomalies in B decays intermediated by neutral currents, $R_{K^{(*)}}$

At energies $\gg v_{EW}$:

$$\mathcal{L}^0_{NP} = \frac{1}{\Lambda^2}\left(C_1\,\bar{q}'_{3L}\gamma^\mu q'_{3L}\cdot\bar{\ell}'_{3L}\gamma_\mu\ell'_{3L} + C_3\,\bar{q}'_{3L}\gamma^\mu\tau^a q'_{3L}\cdot\bar{\ell}'_{3L}\gamma_\mu\tau^a\ell'_{3L}\right)$$

EW corrections:
LNV four-lepton ops.,
corrections
to Z coupling, etc.

[Glashow+'14,Feruglio+'16,'17]



Concluding remarks

- Reason for the **excl. vs. incl. tensions**?
- **Physics underlying** $R(D^{(*)})$: SM? NP? stat., syst. effects?
- **Common origin for all** B **anomalies**, $R(D^{(*)})$ and $R(K^{(*)})$?

$\rightarrow$ Perhaps more questions than answers, but important progresses are continuously made!

Obviously, very exciting times are foreseen w/ improved LQCD (e.g. $B \rightarrow D^*$ beyond zero-recoil, etc.), further Belle/LHC analyses and Belle II (e.g. new tau observables, etc.)

Thanks

(and apologies for possibly missing references!)

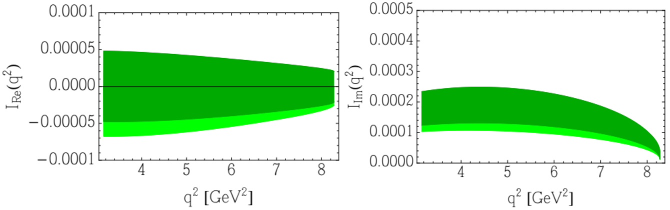
Angular observables

- Benefits: interference between $D^* \to D\pi$ and $D_0^* \to D\pi$
  Predictions rely on (naive) Breit-Wigner assumption for D_0^*

$$(I_{Re}(q^2), I_{Im}(q^2)) = \frac{1}{d\Gamma/dq^2} \int_{(m_{D^*}-\delta)^2}^{(m_{D^*}+\delta)^2} (b_\chi^c, b_\chi^s) dm_{D\pi}^2 \,,$$

$$\text{w/ } (b_\chi^c, b_\chi^s) \text{ function of } BW_{D^*} \times BW_{D_0^*}$$

- $(I_{Re}(q^2), I_{Im}(q^2))$ small for different δ, and $\epsilon_L, \epsilon_R, \epsilon_{S_L}, \epsilon_{S_R}, \epsilon_T \approx 1$



[1602.03030]

Quantity	g_V	g_A	g_S	g_P	g_T
A_{FB}^{D}	$\times$	–	$\star\star\star$	–	$\star$
$A_{\lambda_\tau}^{D}$	$\times$	–	$\star\star\star$	–	$\star\star$
$A_{FB}^{D^*}$	$\star$	$\star\star\star$	–	$\star\star\star$	$\star$
$A_{\lambda_\tau}^{D^*}$	$\times$	$\times$	–	$\star\star$	$\star$
$R_{L,T}$	$\times$	$\times$	–	$\star\star$	$\star\star$
A_5	$\star\star$	$\star\star$	–	$\star$	$\star\star\star$
C_χ	$\star$	$\times$	–	$\star\star$	$\star\star$
S_χ	$\star\star\star$	$\star\star\star$	–	$\times$	$\star\star\star$
A_8	$\star\star$	$\star\star$	–	$\star\star$	$\star\star\star$
A_9	$\star$	$\star$	–	$\star\star$	$\star\star$
A_{10}	$\star\star$	$\star\star$	–	$\times$	$\star\star$
A_{11}	$\times$	$\times$	–	$\star\star$	$\star\star$

Table 1: *Sensitivity to $g_i \neq 0$: $\times$ stands for "not sensitive", and $\star\star\star$ for "maximally sensitive".*

[1602.03030]

	BELLE I [total]	BELLE II [1 year]	BELLE II [total]
$\mathcal{L}$ [ab^{-1}]/N [events]	1/60	5/300	50/3000
$\delta P_L/P_L$	$\{0.21, 0.49, 0.62\}$	$\{0.10, 0.22, 0.28\}$	$\{0.03, 0.07, 0.09\}$
$\delta P_\perp/\lvert P_\perp\rvert$	$\{0.62, 1.8, 4.0\}$	$\{0.28, 0.81, 1.8\}$	$\{0.09, 0.25, 0.57\}$
$\delta A_\tau/\lvert A_\tau\rvert$	$\{0.74, 0.69, 2.8\}$	$\{0.33, 0.31, 1.3\}$	$\{0.11, 0.10, 0.40\}$

TABLE I: Relative statistical uncertainties on the τ polarizations, P_L and $P_\perp$, and angular asymmetry, A_τ, in $B^- \to D^0\tau^-\bar{\nu}_\tau$ for different τ decays $\{\tau \to \pi\nu, \tau \to \rho\nu, \tau \to \ell\nu\bar{\nu}\}$. Predictions are given for the full data set from BELLE I and projections for BELLE II.

[1702.02773]