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Impact of leptonic τ decays on the distribution of $\overline{B} \to D\mu\overline{\nu}$ decays

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based on 1602.06143 with Marzia Bordone and Gino Isidori

Theorieseminar
Dortmund, 31.03.2016

Motivation

Setting the stage

- semileptonic $b \to c$ transitions long-time focus of particle physics
  - accessible at B factories BaBar and Belle (II), and most recently LHCb
  - allow to constrain CKM element V_{cb}
  - confirmation of KM mechanism lead to nobel prize for KM in 2008

- over recent years, two further points of interest developed
  - tension between extracted value of $|V_{cb}|$ from exclusive and inclusive decays
  - ratio exclusive $b \to c\tau\nu$ / exclusive $b \to c\mu\nu$ exceeds SM expectations

five slides to illustrate these points of interest

Inclusive vs. exclusive

Inclusive decays

- requires knowledge of hadronic tensor

$$W^{\mu\nu} \equiv \frac{1}{M_B} \int \mathrm{d}^4x\, e^{-iq\cdot x}\, \mathrm{Im}\langle \overline{B}|\mathcal{T}\left\{\overline{b}(x)\gamma^\mu P_L c(x), \overline{c}(0)\gamma^\nu P_L b(0)\right\}|\overline{B}\rangle$$

- operator product expansion in α_s, $1/m_b$ and $1/m_c$ yields (schematically)

$$\Gamma(\overline{B} \to X_c\mu\overline{\nu}) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \left[a_0\left(1 + \frac{\mu_\pi^2}{2m_b^2}\right) + a_2\frac{\mu_G^2}{2m_b^2} + a_3\frac{\overline{\rho}_3}{2m_b^3} + a_4\frac{\overline{\rho}_4}{2m_b^4}\right]$$

- coefficients a_k are perturbatively expanded in α_s
  - a_0 known up to $O\left(\alpha_s^2\right)$ [van Rittbergen 1999; Pak,Czarnecki 2008; Melnikov 2008]
  - a_2 recently calculated up to $O\left(\alpha_s\right)$ [Mannel,Pivovarov,Rosenthal 1506.08167]
  - $\overline{\rho}_3$ represents two further operators
  - $\overline{\rho}_4$ represents seven additional operators [Mannel,Turczyk,Uraltsev 1009.4622]
- good rate of convergence of and within coefficients a_k
  - good theory control in extraction of $|V_{cb}|$

Inclusive vs. exclusive

Exclusive decays

– exclusive semileptonic decays follow entirely different approach

– need hadronic matrix element (HME) $q^2 \equiv (p-k)^2$

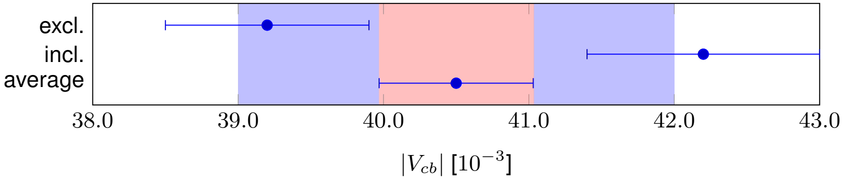
$$\langle D(k)|\bar{c}\gamma^\mu b|\overline{B}(p)\rangle = f_+(q^2)\left[(p+k)^\mu - \frac{M_B^2 - M_D^2}{q^2}q^\mu\right] + f_0(q^2)\frac{M_B^2 - M_D^2}{q^2}q^\mu$$

  – similarly but more complicated for D^*, all four D^{**} states, etc.
  – V_{cb} only extracted from D and D^*, since their HMEs most reliable

– form factors f_+, f_0 only accessible through non-perturbative methods

  – lattice QCD [e.g. Heechang,Bouchard,Lepage,Monahan,Shigemitsu 1505.03925]
  – QCD sum rules on the light-cone with B-meson LCDAs [Faller,Khodjamirian,Klein,Mannel 0809.0222]
  – QCD sum rules at zero hadronic recoil [Bigi,Shifman,Uraltsev,Vainshtein hep-ph/9405410]

Inclusive vs. exclusive



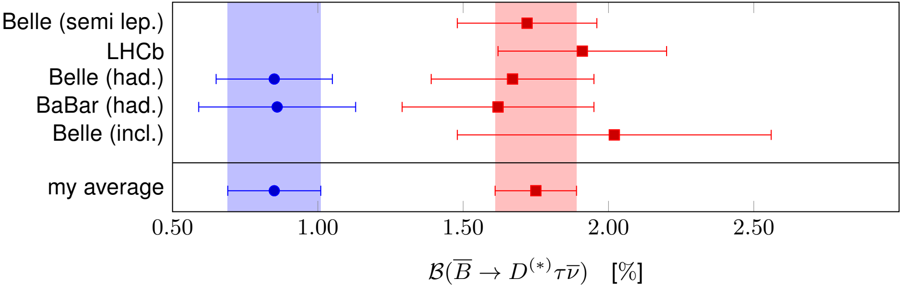
p value: 0.33%

naive weighted average, average w/ scale factor

- extracted values exhibit $99.67\% \approx 3\sigma$ tension [PDG 2014 & 2015 part. upd.]
- in addition: sum of exlusive semileptonic $\mathcal{B}$s does not saturate inclusive measurement
  - $\overline{B} \to D'^{(*)}\mu\overline{\nu}$ might close the gap [Bernlochner,Ligeti,Turczyk 1202.1834]

Exclusive semitauonic decays

data since 2007



sum of excl. modes: $(2.60 \pm 0.21)\,\%$

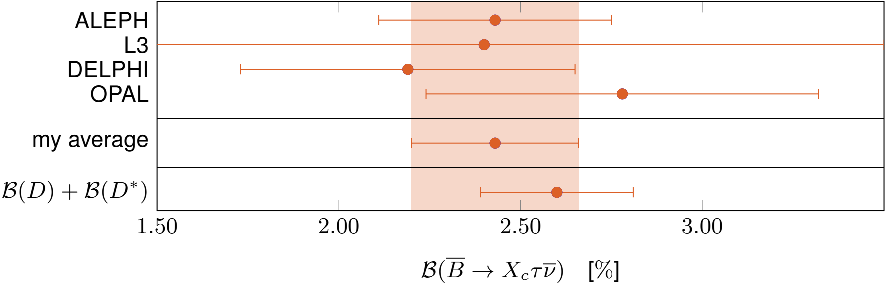
some entries calculated using world averages on $\mathcal{B}(\overline{B} \to D^{(*)}\mu\overline{\nu})$

$\overline{B} \to D\ \tau\nu$
$\overline{B} \to D^{*}\tau\nu$

[Belle (incl.) 0706.4429; BaBar (had.) 0709.1698; Belle (had.) 1507.03233; LHCb 1506.08614; Belle (semi lep.) 1603.06711]

Inclusive semitauonic decays

from LEP experiments



- sum of $D^{(*)}$ modes saturates inclusive rate of $(2.43 \pm 0.23)\%$
  - very little space for orbitally excited D^{**} modes,
  - $\mathcal{B}(\overline{B} \to D^{**} \mu \nu) \approx 0.79\%$ — assuming $\mathcal{B}(D^{**} \to D^{(*)} \pi) = 1$
  - maybe $R_{D^{**}}$ suppressed?
- updated inclusive measurement needed to settle questions (→ Belle II)

[OPAL hep-ex/0108031; DELPHI Phys.Lett. B496 (200) 43-48; L3 Z. Phys. C71 (1996) 379-390; ALEPH hep-ex/0010022]

Reasons?

(personally biased) list of possible reasons

$V_{cb}, R_{D^{(*)}}$ lattice QCD does not understand the form factors well enough

- underestimating form factors for time-like polarization?

V_{cb} model dependence of experimental q^2 spectrum in $\overline{B} \to D\mu\overline{\nu}$

- existing results explicitly use HQET prediction in fitting the q^2 spectrum
- new Belle (semi lep.) result is the only exception

more info in backups

$V_{cb}, R_{D^{(*)}}$ $\overline{B} \to D^{(*)}\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$ background not well-enough understood

- focus of the following exploratory study
- using $\overline{B} \to D\tau\overline{\nu}$ due to its simple hadronic matrix element

Impact of leptonic τ decays

Experimental PoV

- no hard criterium to distinguish $\overline{B} \to D\mu\overline{\nu}$ from $\overline{B} \to D\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$
- experiment sees neutrino-inclusive decay rate

$$\frac{d\Gamma(\overline{B} \to D\mu X_{\overline{\nu}})}{dq^2\, d\cos\theta_{[\mu]}} \equiv \frac{d\Gamma(\overline{B} \to D\mu\overline{\nu}_\mu)}{dq^2\, d\cos\theta_{[\mu]}} + \frac{d\Gamma(\overline{B} \to D\tau(\to \mu\overline{\nu}_\mu\nu_\tau)\overline{\nu}_\tau)}{dq^2\, d\cos\theta_{[\mu]}}$$
$$\equiv \frac{d\Gamma_1}{dq^2\, d\cos\theta_{[\mu]}} + \frac{d\Gamma_3}{dq^2\, d\cos\theta_{[\mu]}}$$

  - analytical results for Γ_3 not used in experimental analysis
  - first considered in this work

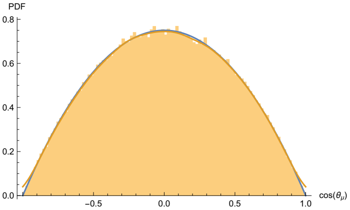
for NP contributions see also [Alonso,Kobach,Camalich 1602.07671]

- varying means to statistically disentangle both decays
  - Belle (II) uses NeuroBayes ($\to$ black box)

Signal 1: $\overline{B} \to D\mu\overline{\nu}$

$$\overline{B}(p) \;\to\; D(k)\;\mu(q_{[\mu]})\;\overline{\nu}(q_{[\overline{\nu}_\mu]})$$

- pseudo-scalar to pseudo-scalar transition
  - one hadronic form factors f_+
  - second form factor f_0 enters only m_μ^2/q^2 suppressed
- simple kinematics:
  - momentum transfer $q^2 = (p-k)^2$
  - muon helicity angle $\cos\theta_{[\mu]}$ in $\mu\overline{\nu}$ RF
- distribution in $\theta_{[\mu]}$



$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_{[\mu]}} = a + b\cos\theta_{[\mu]} + c\cos^2\theta_{[\mu]}$$

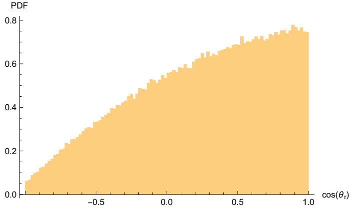
$$= a\sin^2\theta_{[\mu]} + O\left(m_\mu^2/q^2\right)$$

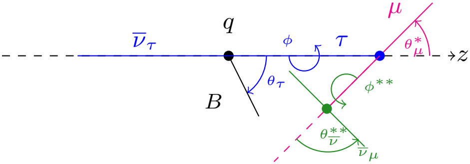
- a, b, c: functions of q^2

Signal 2: $\overline{B} \to D\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$

$$\overline{B}(p) \to D(k)\ \mu(q_{[\mu]})\ \overline{\nu}_\mu(q_{[\overline{\nu}_\mu]})\nu_\tau(q_{[\nu_\tau]})\overline{\nu}_\tau(q_{[\overline{\nu}_\tau]})$$

- hadronic matrix element
  - both form factors contribute
- complicated kinematics:
  - momentum transfer $q^2 = (p-k)^2$
  - $\overline{\nu}\nu$ mass $q^2_{[\nu_\tau \overline{\nu}_\mu]}$
  - five angles





Signal 2: $\overline{B} \to D\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$

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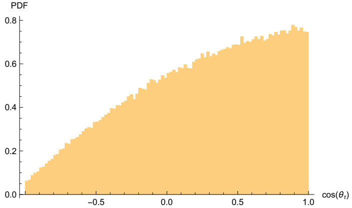
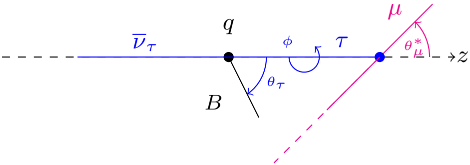
  - five angles, only 3 of which are needed for pheno studies





Signal 2: $\overline{B} \to D\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$

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- complicated kinematics:
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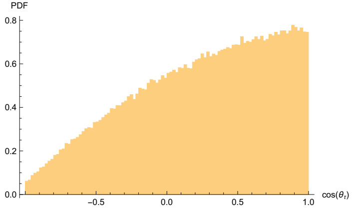
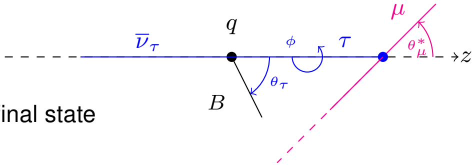


$$\frac{d^5\Gamma_3}{dq^2 dq^2_{[\nu_\tau\overline{\nu}_\mu]} d^2\Omega d\Omega^*} = \frac{\tilde{\Gamma}_3}{\pi m_\tau^8 q^6}\Big[A + B\cos\theta_{[\tau]} + C\cos^2\theta_{[\tau]} + \big(D\sin\theta_{[\tau]} + E\sin\theta_{[\tau]}\cos\theta_{[\tau]}\big)\cos\phi\Big]$$

$A, \ldots, E$ are functions of q^2, $q^2_{[\nu_\tau\overline{\nu}_\mu]}$ and $\cos\theta^*_{[\mu]}$

Observables



$\cos\theta_{[\mu]}$: muon helicity angle

- physical observable only in the 1ν final state
- defined in q rest frame
  - in terms of Lorentz invariants

$$\cos\theta_{[\mu]} \equiv 2\frac{\left(q - 2q_{[\mu]}\right)\cdot k}{\sqrt{\lambda}}$$

  - 3ν case: $\theta_{[\mu]} \neq \theta^*_{[\mu]}$

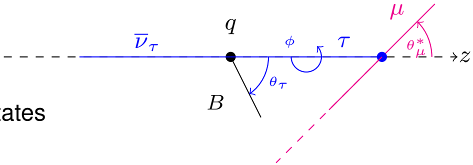
see backups for functional dep.

- boundaries

$$-1 \leq \cos\theta_{[\mu]} \leq 1 \qquad \text{for } 1\nu \text{ final state}$$
$$-1 \leq \cos\theta_{[\mu]} \lesssim 56.7 \qquad \text{for } 3\nu \text{ final state}$$

  - upper bounds very different from each other
  - not suitable for common parametrization

Observables



E_μ: muon energy in B rest frame

- physical observable for both final states
- defined in $\overline{B}$ rest frame
  - in terms of Lorentz invariants

$$E_\mu \equiv \frac{p \cdot q_{[\mu]}}{M_B}$$

- boundaries

$$m_\mu \approx 0 \leq E_\mu \lesssim 2.31\text{GeV} \qquad \text{for } 1\nu \text{ final state}$$

$$m_\mu \approx 0 \leq E_\mu \lesssim 2.26\text{GeV} \qquad \text{for } 3\nu \text{ final state}$$

  - upper bounds very similar for both final states
  - suggests common parametrization of E_μ dependence

Neutrino-inclusive decay

aim: obtain normalized, differential decay widths for the neutrino-inclusive decay

- decay widths in terms of $\cos\theta_{[\mu]}$ and E_μ yield complicated expressions

[see Alonso,Kobach,Camalich 1602.07671]

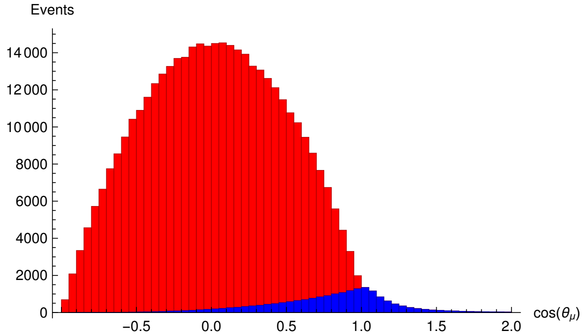
- our approach: Monte Carlo simulations of pseudo events
  - implement signal PDFs in EOS, including dependence on form factor parameters

    [DvD et al. http://github.com/eos/eos]
  - draw $\approx 4 \cdot 10^6$ pseudo events of $(q^2, \cos\theta_{[\mu]})$ for the 1ν final state
  - draw $\approx 4 \cdot 10^6$ pseudo events of $(q^2, q^2_{[\nu_\tau \overline{\nu}_\mu]}, \Omega, \Omega^*)$ for the 3ν final state

    Ω, Ω^*: solid angles
  - compute observable of interest for each set of pseudo events
  - combine sets with weights

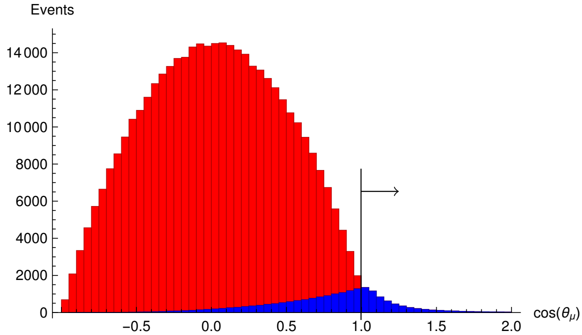
$$\omega_1 = \frac{1}{1 + R_D\, \mathcal{B}(\tau \to \mu\nu\overline{\nu})} \qquad \omega_3 = 1 - \omega_1$$

Distribution in $\cos\theta_{[\mu]}$



neutrino-inclusive, 3ν final state

Distribution in $\cos\theta_{[\mu]}$

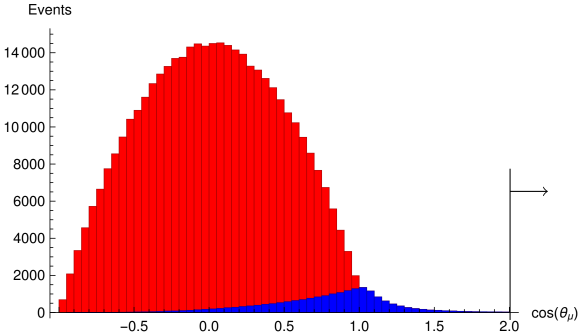


neutrino-inclusive, 3ν final state

Heavy tails

$\cos\theta_{[\mu]} > 1$ $\quad 32.3\%$ of 3ν ev.

Distribution in $\cos\theta_{[\mu]}$



neutrino-inclusive, 3ν final state

Heavy tails

$\cos\theta_{[\mu]} > 1$ 32.3% of 3ν ev.

$\cos\theta_{[\mu]} > 2$ $\approx 2\%$ of 3ν ev.

New method to extract $R_D\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$

- cash in on heavy tail of $B \to D\mu X_{\bar{\nu}}$, and turn it into new method to extract R_D
- we suggest measurement of

$$\rho_D^{\exp} \equiv \frac{\text{\#of } X_\nu \text{ events with } \cos\theta_\mu > 1}{\text{total \# of } X_\nu \text{ events}}$$

- precise calculation possible for

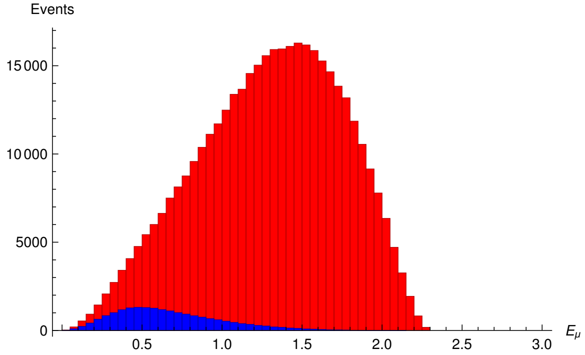
$$\rho_D^0 \equiv \frac{\text{\#of } 3\nu \text{ events with } \cos\theta_\mu > 1}{\text{total \# of } 3\nu \text{ events}} = 0.323 \pm 0.002 \quad (0.6\%)$$

  - uncertainty statistical
  - parametric uncertainty (form factors) within ± 0.002
- combine to extract

$$R_D\mathcal{B}(\tau \to \mu\bar{\nu}\nu) = \frac{\rho_D^{\exp}}{\rho_D^0 - \rho_D^{\exp}}$$

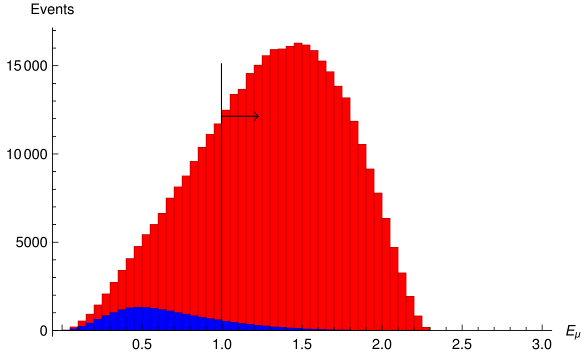
- will probably also work for other charmed hadrons: D^*, Λ_c

Distribution in E_μ



neutrino-inclusive, 3ν final state

Distribution in E_μ



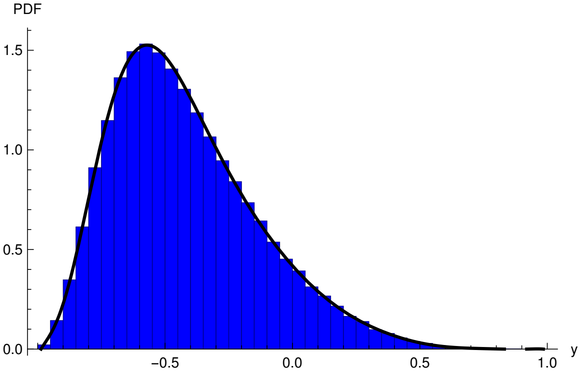
neutrino-inclusive, 3ν final state

Background

$E_\mu > 1$ $\approx 15\%$ of 3ν ev.
$\approx 0.8\%$ background

- parametrization of background PDF (and numeric results) in the paper
- allows fit of 3ν to 1ν ratio to data

Distribution in E_μ



$y \equiv 2E_\mu/E_\mu^{\text{max}} - 1$ ansatz: Legendre polynomials

$-1 \leq y \leq +1$

Background

$E_\mu > 1$ $\approx 15\%$ of 3ν ev.

$\approx 0.8\%$ background

- parametrization of background PDF (and numeric results) in the paper
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Implications for extraction of $|V_{cb}|$

– for last slide, let's assume $R_D \neq R_D^{\text{SM}}$, and let $\Delta R_D = R_D - R_D^{\text{SM}}$

– influences $|V_{cb}|^{\text{incl}}$ extraction
  – in simulation of $B \to X_c \mu \overline{\nu}$ backgrounds $R_{D^{(*)}}^{\text{SM}}$ is used
  – let $\Delta|V_{cb}|^{\text{(incl.)}} = |V_{cb}|^{\text{(exp)}} - |V_{cb}|^{\text{(true)}}$
  – we find for the maximal shift

$$\frac{\Delta|V_{cb}|^{\text{(incl.)}}}{|V_{cb}|} = \frac{1}{2}\Delta R_D \mathcal{B}(\tau \to \mu\overline{\nu}\nu) \approx 0.9\%\,,$$

  – not far from combined theory and experimental error on $|V_{cb}|^{\text{(incl.)}}$

[PDG 2014 and 2015 part. upd.]

  – important to study in more detail for future Belle II analyses

Summary and outlook

- lots of interesting things happening in b-physics right now
  $b \to c\tau\nu$ definitely among those

- we investigated $\overline{B} \to D\tau(\to \mu\overline{\nu}\nu)\overline{\nu}$ and its impact on the extraction of V_{cb} and R_D
  - analytic results can be used to check experimental Monte Carlo studies
  - numeric results for PDF of the 3ν background

- outlined a new method to extract R_D from $\cos\theta_{[\mu]}$ distribution of the neutrino-inclusive decay

- currently adapting method to $\overline{B} \to D^*\tau\nu$, with emphasis on underconstrained $\overline{B}$ momentum at LHCb

[Bordone,Chraszcz,DvD w.i.p.]

Appendix

Model-dependence of exclusive $\overline{B} \to D\mu\overline{\nu}$ measurements

- q^2 spectrum of the decay is relevant to extraction of V_{cb} and form factor ratios ($\to$ crosscheck of R_D inputs)

- Belle analyses do not provide histograms of observables as functions of q^2
  [e.g. Belle hep-ex/0111082]
  - (personally) could not find BaBar analysis that do, either!
  - only fits of HQET-inspired parametrization (to leading power in $1/m_b$!) are available
  - ditto for $\overline{B} \to D^*$

- according to sources within Belle, reanalysis of the data is not possible
  - new Belle analyses do provide the “raw” q^2 spectrum [e.g. Belle (semi lep.) 1603.06711]

Observables

1ν

$$E_\mu\Big|_{1\nu} = \frac{1}{4M_B}\left[(M_B^2 - M_P^2 + q^2) - \sqrt{\lambda}\cos\theta_\mu\right] ,$$

3ν

$$\cos\theta_{[\mu]}\Big|_{3\nu} = 2\beta_{\nu\overline{\nu}}\Bigg\{\left(\frac{(1-2\beta_{\nu\overline{\nu}})}{\beta_{\nu\overline{\nu}}} + 2\beta_\tau\right)\frac{M_B^2 - M_P^2 - q^2}{2\sqrt{\lambda}} + \beta_\tau\cos\theta_{[\tau]}$$

$$-\left(2\beta_\tau\frac{M_B^2 - M_P^2 - q^2}{2\sqrt{\lambda}} - (1-\beta_\tau)\cos\theta_{[\tau]}\right)\cos\theta^*_{[\mu]} - \sqrt{1-2\beta_\tau}\sin\theta^*_{[\mu]}\sin\theta_{[\tau]}\cos\phi\Bigg\}$$

$$E_\mu\Big|_{3\nu} = \frac{\beta_{\nu\overline{\nu}}}{2M_B}\Big[(M_B^2 - M_P^2 + q^2)((1-\beta_\tau) + \beta_\tau\cos\theta^*_{[\mu]})$$

$$-\sqrt{\lambda}(\beta_\tau + (1-\beta_\tau)\cos\theta^*_{[\mu]})\cos\theta_{[\tau]} + \sqrt{1-2\beta_\tau}\sqrt{\lambda}\sin\theta^*_{[\mu]}\sin\theta_{[\tau]}\cos\phi\Big]$$

with $\lambda = \lambda(M_B^2, M_D^2, q^2)$ the Källèn function

The case of $\overline{B} \to \pi\tau\overline{\nu}$

- $D \to \pi$ easy enough
- however, small mass of π makes for some numerical changes
- tail $\cos\theta_{[\mu]} > 1$ very light: $\approx 3.3\%$
  new method will probably not work for pions
- distribution in E_μ broader
  - $R_\pi \approx 0.7$ larger, thus control of subtraction much more important!
  - background PDF parametrization should work as well as for D