Recent results on (semi)leptonic B decays from Belle

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On behalf of the Belle collaboration

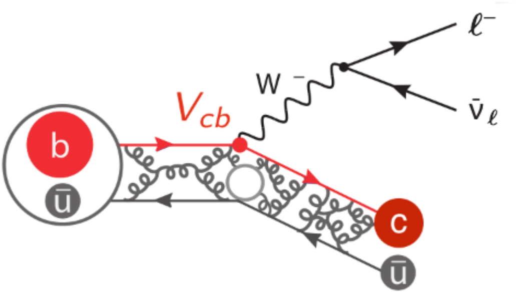
EPS-HEP in Venise, July 6th, 2017

BELLE

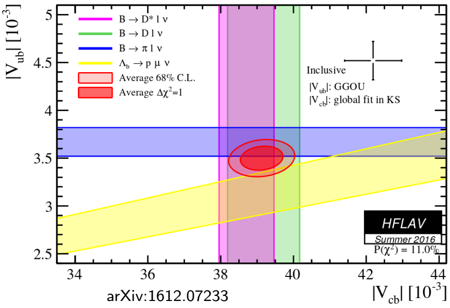
UNIVERSITÄT BONN

LAPP
Laboratoire d'Annecy-le-Vieux de Physique des Particules

- Decays with leptons precisely predicted in the Standard Model
- They have high branching fractions
- Leptonic and hadronic currents factorise



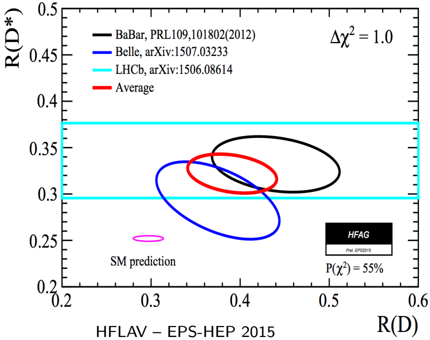
- Several tensions seen in B physics that can be tested using (semi)leptonic decays



arXiv:1612.07233

Tension: inclusive and exclusive

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



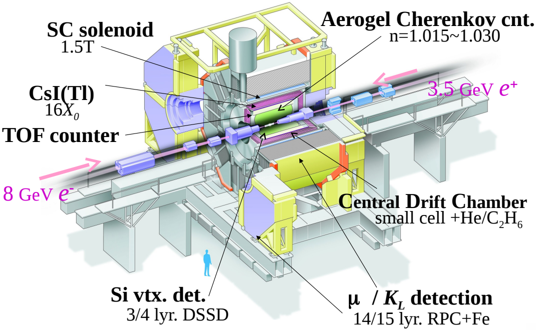
HFLAV – EPS-HEP 2015

World average at 4σ from SM

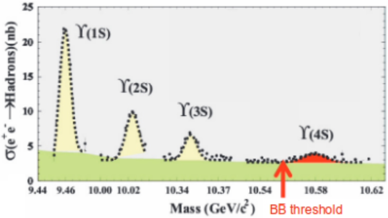
Outline

1. Measurement of $|V_{cb}|$ and form factors from $B \to D^* \ell \nu$
2. Recent measurement of $\mathcal{R}(D^{(*)})$
3. Measurement $B \to \eta(') \ell \nu$
4. Search for purely leptonic $B \to \mu \nu$ decays

Belle Detector



- 1999 to 2010 in Tsukuba, Japan
- At KEKB: asymmetric e^+e^- collider



- $\sqrt{s} = 10.58\,\text{GeV} = m(\Upsilon(4S))$
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \sim 100\%$
- Int. luminosity on $\Upsilon(4S)$: $711\,\text{fb}^{-1}$
- 772 Mio. $B\bar{B}$ pairs

Results from $B \to D^{(*)}\ell/\tau\nu$ decays

- Semileptonic $B \to D^{(*)}\ell\nu$ ($\ell = e, \mu$) allow for measurement of $|V_{cb}|$
- Measure hadronic form factor parameters
- Decays with τ leptons are sensitive to New Physics coupling 3rd generation
- Test lepton flavour universality

Systematics on $|V_{cb}|$, efficiencies, form factors, etc. cancel

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

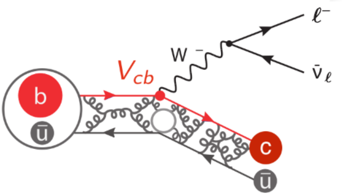
SM prediction

$\mathcal{R}(D^*) = 0.252 \pm 0.003$
$\mathcal{R}(D) = 0.300 \pm 0.008$

Heechang Na et al.
Svjetlana Fajfer et al.
Jernej F. Kamenik, Federico Mescia
Fermilab Lattice, MILC Collaborations

Form factor parameters measured from $B \to D^{(*)}\ell\nu$ decays used as input for prediction

Precise determination of the CKM matrix element $|V_{cb}|$ with $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle



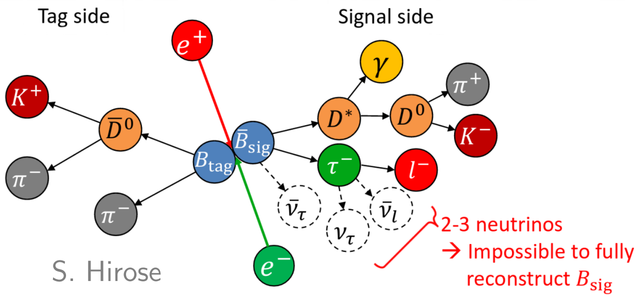
BELLE-CONF-1612

arXiv:1702.01521 [hep-ex] 14 Feb 2017

Analysis performed with hadronic tagging (fully reconstructed B_{tag}):

→ reduce non-B background

→ know kinematics of signal B



B_{tag} reconstructed in 1104 different hadronic decay modes

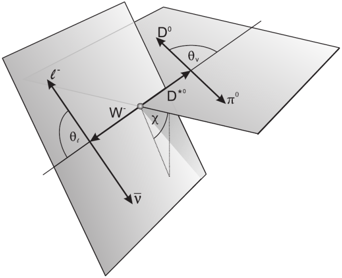
Efficiency: $\sim 10^{-3}$

- Performed using neural network
- Efficiency correction in MC using reference channel

$$\frac{d^4\Gamma(B \to D^*\ell\nu)}{dw\, d\cos\theta_v\, d\cos\theta_\ell\, d\chi} = f(|V_{cb}|^2, \underbrace{\rho^2_{D^*}, R_1, R_2}_{\text{form factor parameters}})$$

Kinematic variables:

- $w = \frac{m_B^2 - m_{D^*}^2 - q^2}{m_B m_{D^*}}$
- $\cos\theta_v$, $\cos\theta_\ell$, χ: decay angles



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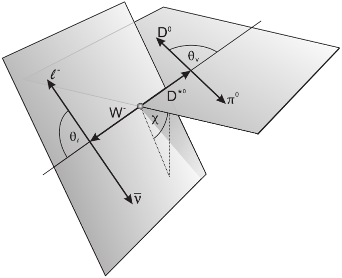

Kinematic variables:

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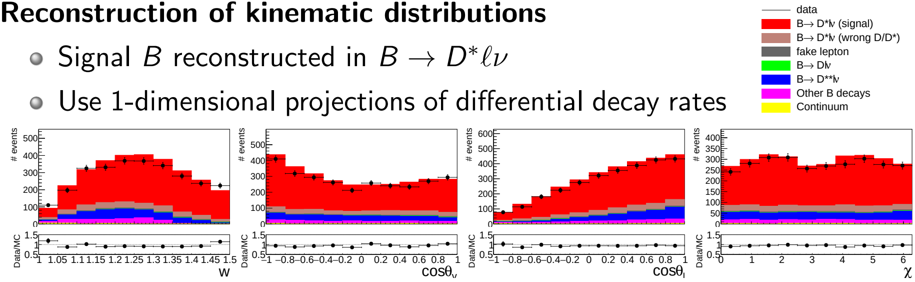
Reconstruction of kinematic distributions

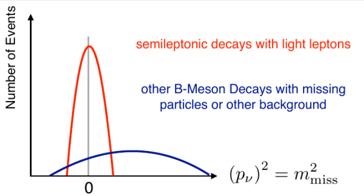
- Signal B reconstructed in $B \to D^*\ell\nu$
- Use 1-dimensional projections of differential decay rates

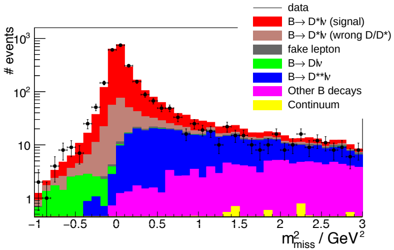


Signal extraction

- Single non-reconstructed particle in event: neutrino from signal decay

$$m^2_{miss} = (p_{\Upsilon(4S)} - p_{tag} - p_{D^*} - p_\ell)^2$$





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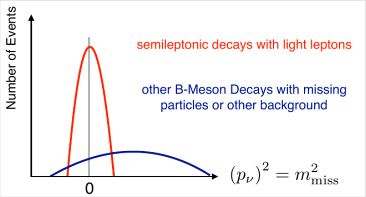
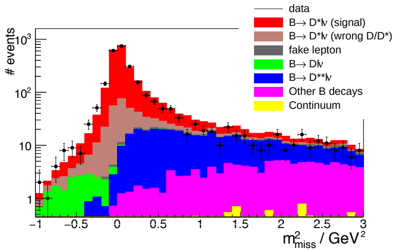
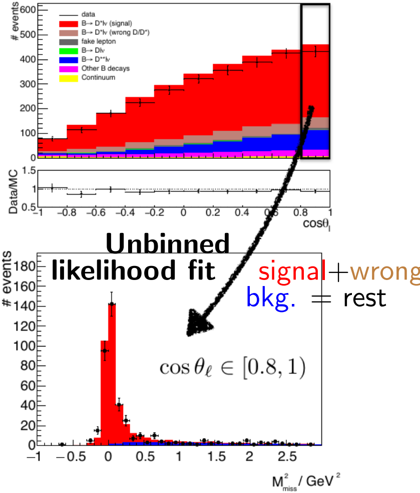
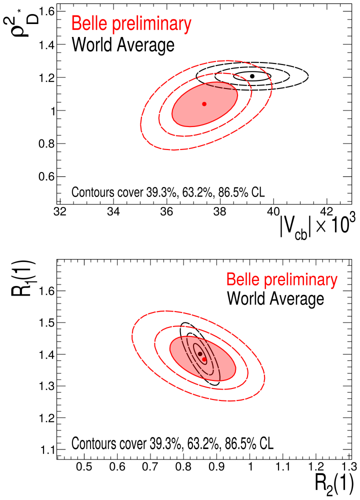






Parameter	Measurement	World average
$\lvert V_{cb}\rvert \cdot 10^3$	37.4 ± 1.2	39.2 ± 0.7
ρ^2_{D*}	1.04 ± 0.13	1.20 ± 0.03
R_1	1.38 ± 0.07	1.40 ± 0.03
R_2	0.86 ± 0.10	0.85 ± 0.02

CLN parametrisation



- Measured values can be used to calculate SM prediction of $\mathcal{R}(D^*)$
- Use additional FF R_0 from sum rules [arXiv:1203.2653]

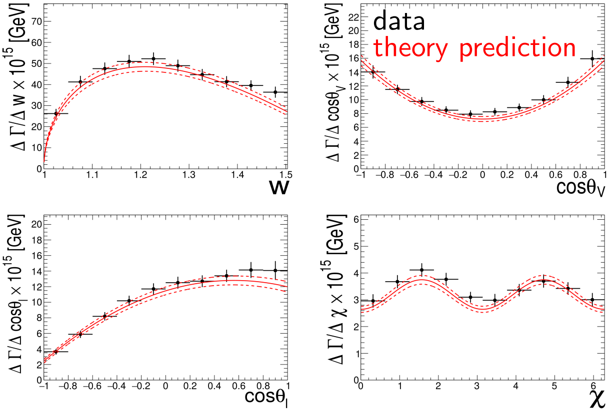
Prediction:

$$\mathcal{R}(D^*)_{\text{SM}} = 0.242 \pm 0.005$$

- Possibility to test compatibility with NP such as right-handed currents once calculations for FF available

Unfolding of the kinematic distributions

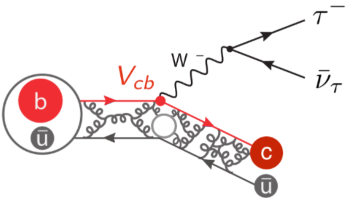
- Unfolded spectra provided: corrected for migration and acceptance
- Difference between inclusive and exclusive depends on parametrisation
- Work ongoing to extract $|V_{cb}|$ using BGL parametrisation



Follow up papers:
arXiv:1703.05330 (04/17)
arXiv:1703.06124 (04/17)
arXiv:1703.08170 (06/17)

→ Talk by Stefan Schacht
(https://indico.cern.ch/event/466934/contributions/2586301/)

Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method



Phys.Rev. D94 (2016) no.7, 072007 – Published 27 October 2016
arXiv:1607.07923 [hep-ex] 13 Dec 2016

Analysis strategy

- Analysis restricted to neutral $B^0\bar{B}^0$ pairs (due to high background)

Reconstruction

Semileptonic tag ($\epsilon \sim 10^{-2}$):	$B_{tag} \to D^*\ell\nu$		(1 neutrino)
Signal:	$B_{sig} \to D^*\tau\nu$	$\tau \to \ell\nu_\ell\nu_\tau$	(3 neutrino)
Normalisation:	$B_{sig} \to D^*\ell\nu$		(1 neutrino)

Analysis strategy

- Analysis restricted to neutral $B^0\bar{B}^0$ pairs (due to high background)

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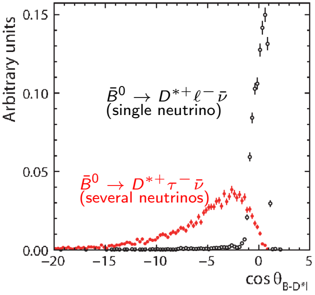
Separation of signal mode and normalisation mode

Angle betw. B and $D^*\ell$-system in $\Upsilon(4S)$ frame:

$$\cos\theta_{B-D^*\ell} = \frac{2E_{beam}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

- Assumes single neutrino
- Outside range $[-1, 1]$ for signal decay



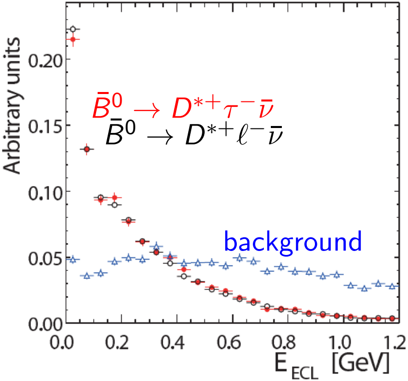
Signal extraction

- 2-dimensional extended binned likelihood fit to E_{ECL} and O_{NB}

E_{ECL}

Cluster energy not associated to event

- around zero for correct reconstruction
- flat for background



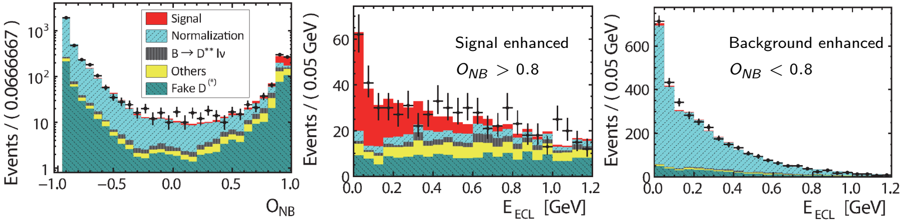
Efficiency: $\frac{\epsilon_{norm}}{\epsilon_{sig}} = 1.289 \pm 0.015$

O_{NB}: Neural network classifier

Signal likelihood using:

- $\cos\theta^{sig}_{B-D^*\ell\nu}$
- $m^2_{miss} = (2E_{beam} - \sum_i E_i)^2 - |\sum_i \vec{p}_i|^2$
- $E_{vis} = \sum_i E_i$

Fit to data:



$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau \to \ell\nu_\ell\nu_\tau)} \cdot \underbrace{\frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\text{determined from MC}} \cdot \underbrace{\frac{N_{sig}}{N_{norm}}}_{\text{from fit}}$$

Result

$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$ (agreement with SM: 1.6σ)

- Good agreement with previous Belle measurements

New Physics interpretation

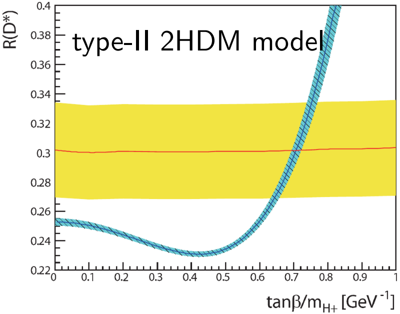
- Compatibility with New Physics tested in model independent way

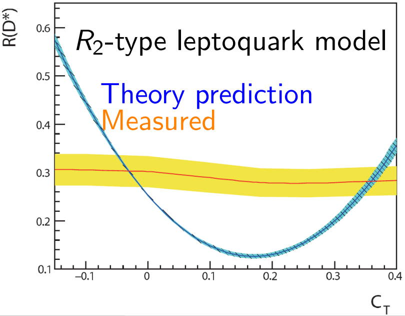
$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\mathcal{O}_{SM} + \sum_{\text{all}} C_X \mathcal{O}_X \right]$$

$\mathcal{O}_X$: all possible 4-fermion operator
C_X: Wilson coefficients

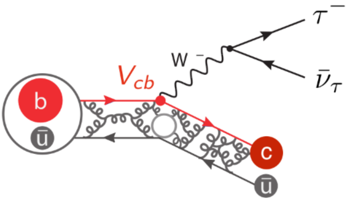
- Analysis repeated using MC for each of 6 $\mathcal{O}_X$ added one-by-one to constrain Wilson Coefficients

Examples of model interpretations:





Measurement of the τ lepton polarization and $\mathcal{R}(D^*)$ in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$



Phys. Rev. Lett. 118, 211801 Published 26 May 2017
arXiv:1612.00529 [hep-ex]

Measurement of τ lepton polarisation in $B \to D^* \tau \nu$

$$P_\tau(D^*) = \frac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}$$

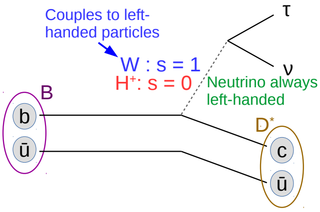
$\Gamma^\pm(D^*)$: $B \to D^* \tau \nu$ decay rate for τ helicity $= \pm\frac{1}{2}$

SM prediction

$$P_\tau(D^*) = -0.497 \pm 0.013$$

Tanaka & Watanabe (Phys. Rev. D 87, 034028, 2013)

τ polarisation sensitive to NP



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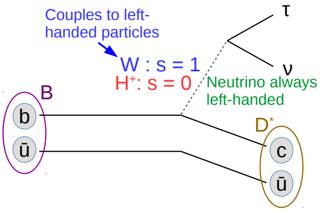
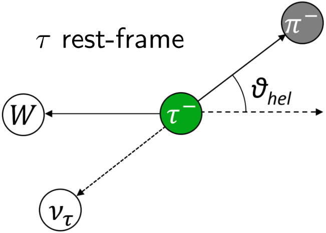


Measurement from two-body hadronic τ decays (hadronic tagging)

$$\frac{d\Gamma(D^*)}{d\cos\vartheta_{hel}} = \frac{\Gamma(D^*)}{2}\left[1 + \alpha P_\tau(D^*)\cos\vartheta_{hel}\right]$$

- α: sensitivity from τ decay mode ($\alpha \sim 0$ from leptonic τ decays)
- $\tau \to \pi\nu_\tau$ ($\alpha = 1$)
- $\tau \to \rho\nu_\tau$ ($\alpha = 0.45$)

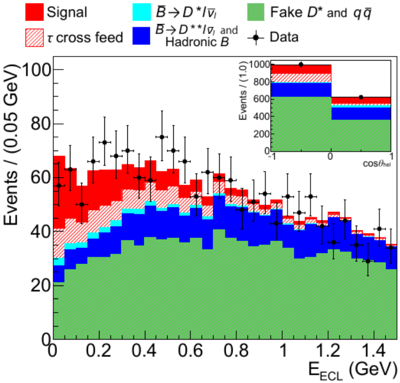


- Divide signal into forward ($\cos\vartheta_{hel} > 0$) and backward ($\cos\vartheta_{hel} < 0$) to calculate polarisation

$$P_\tau(D^*) = \frac{2(N_{sig}^F - N_{sig}^B)}{\alpha(N_{sig}^F + N_{sig}^B)}$$

8 categories

$$(B^\pm, \bar{B}^0) \otimes (\pi\nu_\tau, \rho\nu_\tau) \otimes (\text{frwd}, \text{bkwd})$$



- Likelihood fit in 2 steps:
  - to normalisation sample for $B \to D^*\ell\nu$ yield (using M_{miss}^2)
  - simultaneous fit to 8 signal samples (using E_{ECL})

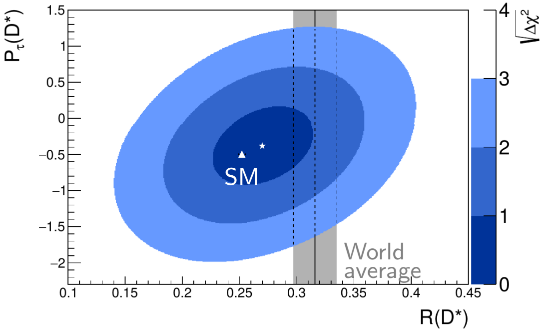
Results

- $\mathcal{R}(D^*)$ can be calculated as before from extracted yields
- Polarisation from forward/backward asymmetry

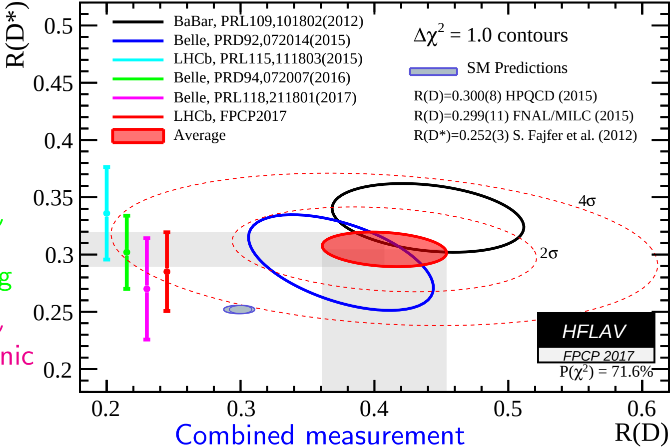
$$\frac{\epsilon_{norm}}{\epsilon_{sig}} = 0.97 \pm 0.02 \; (B^{\pm}, \tau \to \pi\nu)$$
$$= 1.21 \pm 0.03 \; (B^{0}, \tau \to \rho\nu)$$
$$= 3.42 \pm 0.07 \; (B^{\pm}, \tau \to \rho\nu)$$
$$= 3.83 \pm 0.12 \; (B^{0}, \tau \to \rho\nu)$$

Result

$$\mathcal{R}(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$



- Consistent with SM and previous measurements!
- Error can be reduced in Belle II



$B \to D^* \tau \nu$ with semi-leptonic tag

$B \to D^* \tau \nu$ with hadronic τ decays

Combined measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

Excess still 4σ: central value moved towards SM;

on $\mathcal{R}(D^*)$, discrepancy increased from 3.0σ to 3.4σ

Measurement of the decays $B \to \eta \ell \nu_\ell$ and $B \to \eta' \ell \nu_\ell$ in fully reconstructed events at Belle

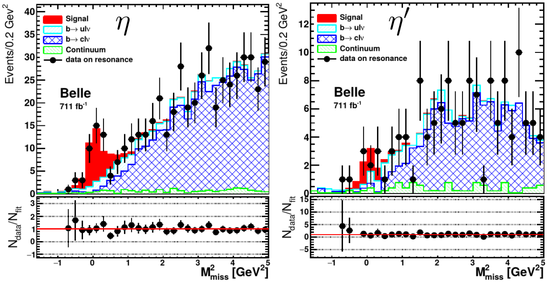
arXiv:1703.10216 – 29 March 2017
submitted to PRD(RC)

Overview and result

Important to know decay composition for signal model in inclusive $|V_{ub}|$ measurements → test tension between inclusive and exclusive

Reconstruction & signal extraction:

- Hadronic tagging to reduce background
- η: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
- η': $\eta' \to \eta\pi^+\pi^-$ with $\eta \to \gamma\gamma$



Binned likelihood fit on M^2_{miss} with 4 components

Results

$\mathcal{B}(B \to \eta \ell \nu_\ell) = (4.2 \pm 1.1 \pm 0.3) \cdot 10^{-5}$
$\mathcal{B}(B \to \eta' \ell \nu_\ell) < 0.72 \cdot 10^{-4}$ at 90% C.L.

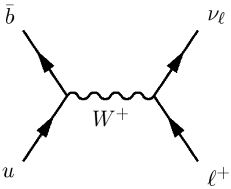
- Compatible with results from CLEO and BaBar
- Limited by stat. → significant improvement with Belle II

Search for $B \to \mu\nu$ decays at the Belle experiment

July 2017,
PRL journal publication in preparation

Motivation

- $\mathcal{B}(B \to \mu\nu)$ precisely predicted in the SM
- May increase significantly within NP models
- Limit (HFLAV, Nov 2016): $< 10 \cdot 10^{-7}$ (90% C.L.)



- New result from Belle: first measurement leading to branching fraction (not upper limit)

SM prediction

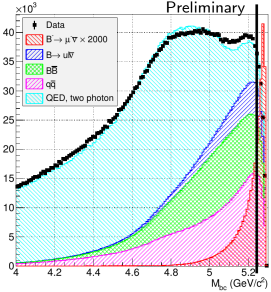
$$\mathcal{B}(B \to \mu\nu) = (3.80 \pm 0.31) \cdot 10^{-7}$$

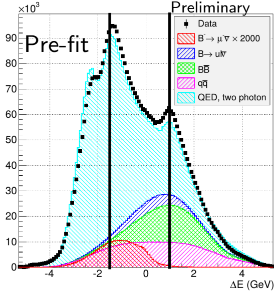
Input from:
Na et al., arXiv:1212.0586
Particle Data Group, Chin. Phys. C 40, no. 10, 100001 (2016)
Belle Collaboration, Phys. Rev. D 88, 032005 (2016)
Fermilab Lattice and MILC Coll. , Phys. Rev. D 92, 014024 (2015)

Untagged: all reco. particles except muon belong to 2^{nd} B

$$M_{bc} = \sqrt{E_{\text{beam}}^2 - \left(\sum_i \vec{p}_i^{\,*}\right)^2}$$

$$\Delta E = E_B - E_{\text{beam}}$$

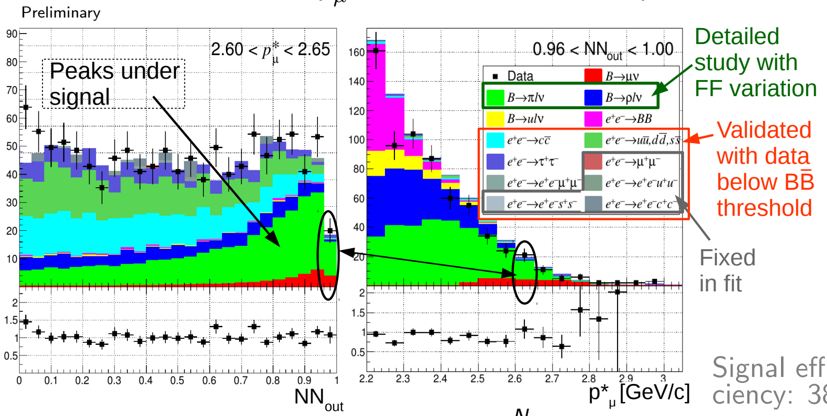




Signal selection

- Angle between $\vec{p}_\mu$ and thrust axis used to reduce jet-like continuum
- B rest-frame: $E_\mu = \frac{m_B}{2}$ (boosted in CMS: p_μ^*)
- p_μ^* side-bands used for validation
- Neural network trained for separation of signal from background

2-dim. binned likelihood fit in p_μ^* and neural network output



Signal efficiency: 38%

- Cancellation of systematics in ratio $R = \frac{N_{B\to\mu\nu}}{N_{B\to\pi\ell\nu}}$ (efficiency from $R_{\text{fit}}/R_{\text{MC}}$)

Preliminary results

$\mathcal{B}(B \to \mu\nu) = (6.46 \pm 2.22 \pm 1.55) \cdot 10^{-7}$

$\mathcal{B}(B \to \mu\nu) \in [2.9, 10.7]x10^-7$ at 90% C.L.

Consistent with SM!

Significance: 2.4σ

Will improve with Belle II...

Conclusion

- $|V_{cb}|$ and FF parameters from $B \to D^* \ell \nu$: agree with world average
- Unfolded differential decay rates: can be used to test different models

- Three measurements of $\mathcal{R}(D^{(*)})$, yielding compatible results
- First measurement of τ polarisation: agrees with the SM prediction

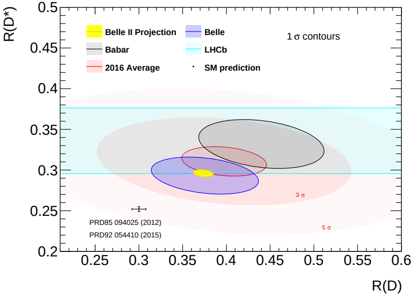
- First measurement of $B \to \eta^{(\prime)} \ell \nu_\ell$ by Belle

- First measurement of $B \to \mu\nu$ leading to a branching fraction

Prospects for Belle II:

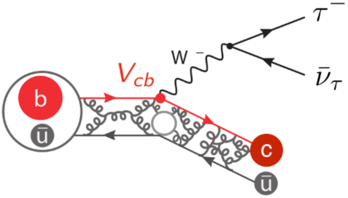
Observable	Belle / LHCb Measurements	Today	Belle II 5/ab	Belle II 50/ab
R(D)	0.403 +/- 0.040 +/- 0.024	12%	5.6%	3.2%
R(D*)	0.310 +/- 0.015 +/- 0.008	5.4%	3.9%	2.2%

For confirmed central value, would be possible to measure 9σ deviation from SM!



Backup

Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle



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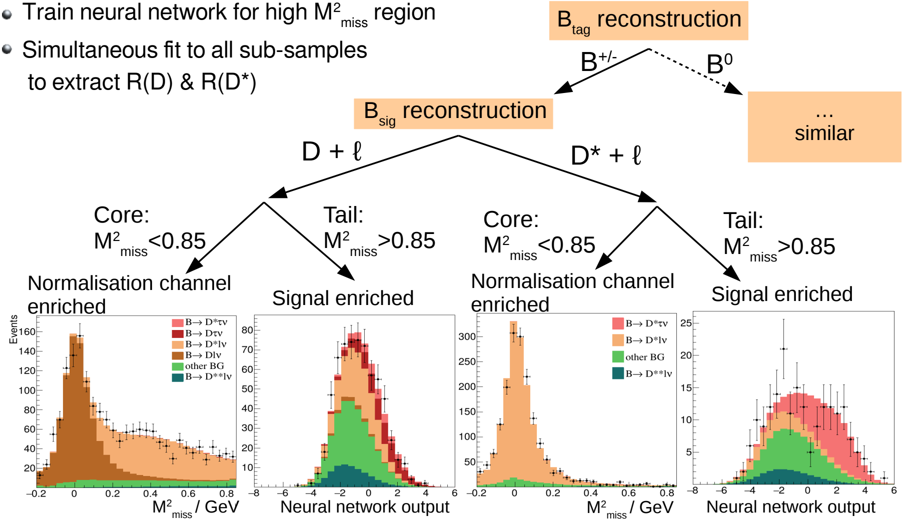
arXiv:1507.03233 [hep-ex] 12 July 2015

Simultaneous fit of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

- τ lepton reconstructed in $\tau \to \ell \, \nu_\ell \nu_\tau$
- Same reco. final state for signal and normalisation: use M^2_{miss} to separate them
- Train neural network for high M^2_{miss} region
- Simultaneous fit to all sub-samples
  to extract R(D) & R(D*)



Results and New Physics interpretation

Result

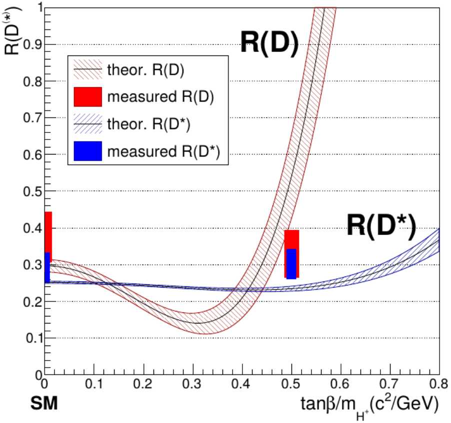
$\mathcal{R}(D) = 0.375 \pm 0.064 \pm 0.026$
$\mathcal{R}(D^*) = 0.293 \pm 0.038 \pm 0.015$

Agreement with SM: 1.8σ

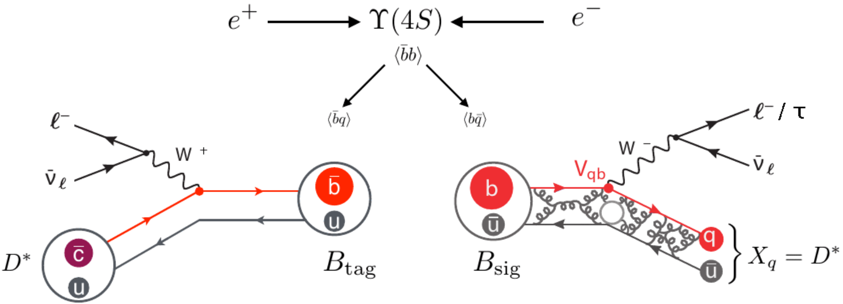
Test of type II 2HDM model:

- Acceptances & efficiencies depend model assumptions: fit repeated with MC generated with $\frac{\tan\beta}{m_{H^+}} = 0.5\,\text{GeV}^{-1}$
- Results:
  $\mathcal{R}(D) = 0.329 \pm 0.060 \pm 0.022$
  $\mathcal{R}(D^*) = 0.301 \pm 0.039 \pm 0.015$

$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau \to \ell\nu_\ell\nu_\tau)} \cdot \underbrace{\frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\text{determined from MC}} \cdot \underbrace{\frac{N_{sig}}{N_{norm}}}_{\text{from fit}}$$



- Reconstruct tagging B meson in $B \to D^* \ell \nu$
- Measurement statistically independent to those with hadronic tagging



Systematic uncertainties:

Error Source	$\Delta\mathcal{B}$ [%]
Tagging Calibration	3.6
$N_{B\bar{B}}$	1.4
f_{+0}	1.1
PDF shapes	0.9
$\mathcal{B}(D \to K\pi(\pi)(\pi))$	0.4
$\mathcal{B}(D^* \to D\,\pi)$	0.2
$\mathcal{B}(\bar{B} \to D^{**}\,\ell\,\bar{\nu}_\ell)$	0.2
e PID	0.2
μ PID	0.1
π_{slow} Eff.	0.1
$\mathcal{B}(\bar{B} \to D\,\ell\,\bar{\nu}_\ell)$	< 0.1
$B \to D^{(*,**)}\,\ell\,\bar{\nu}_\ell$ FFs	< 0.1
Lepton Fakerates	< 0.1
K PID	< 0.1
Total	4.2

Systematic uncertainties:

	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\text{eff}}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\text{eff}}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio f_{wc}	0.0	0.0	0.84
M^2_{miss} shape	0.6	1.0	0.00
o'_{NB} shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	−0.32

Systematic uncertainties:

	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC size for each PDF shape	2.2	2.5	3.9
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$	$^{+2.1}_{-0.0}$	$^{+2.8}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$	$^{+0.7}_{-1.3}$	$^{+2.2}_{-3.3}$
PDF shape and yields of fake $D^{(*)}$	1.4	1.6	1.6
PDF shape and yields of $B \to X_c D^*$	1.1	1.2	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2	1.5	1.9
Modeling of semileptonic decay	0.2	0.2	0.3
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$	$^{+4.1}_{-3.7}$	$^{+5.9}_{-5.8}$

τ lepton polarisation

Systematic uncertainties:

Source	rel. uncertainty on $\mathcal{R}(D^*)$	uncertainty on $P_\tau(D^*)$
Hadronic B decay composition	$^{+7.7}_{-6.9}\%$	$^{+0.13}_{-0.10}$
MC stat. for PDF construction	$^{+4.0}_{-2.8}\%$	$^{+0.15}_{-0.11}$
Semileptonic B decays	$\pm 3.5\%$	± 0.05
Fake D^* background	$\pm 3.4\%$	0.02
Other	$\pm 2.2\%$	± 0.03

Allowed regions for Wilson coefficients

Models or operators	Parameters	Allowed regions (68% C.L.)
$\mathcal{O}_{S_1}$	C_{S_1}	$[-4.25, -3.09], [+0.44, +1.57]$
$\mathcal{O}_{S_2}$	C_{S_2}	$[-1.56, -0.43], [+3.12, +4.28]$
$\mathcal{O}_{V_1}$	C_{V_1}	$[-2.15, -2.03], [+0.05, +0.15]$
$\mathcal{O}_{V_2}$	C_{V_2}	$[-0.17, 0.00], [+1.83, +1.96]$
$\mathcal{O}_T$	C_T	$[-0.06, -0.01], [+0.34, +0.39]$
R_2-type leptoquark	$C_T(= +C_{S_2}/7.8)$	$[-0.05, -0.01], [+0.34, +0.38]$
S_1-type leptoquark	$C_T(= -C_{S_2}/7.8)$	$[-0.07, -0.01], [+0.22, +0.28]$