B decays with missing energy: a powerful lens for New Physics

Alan Schwartz
University of Cincinnati, USA

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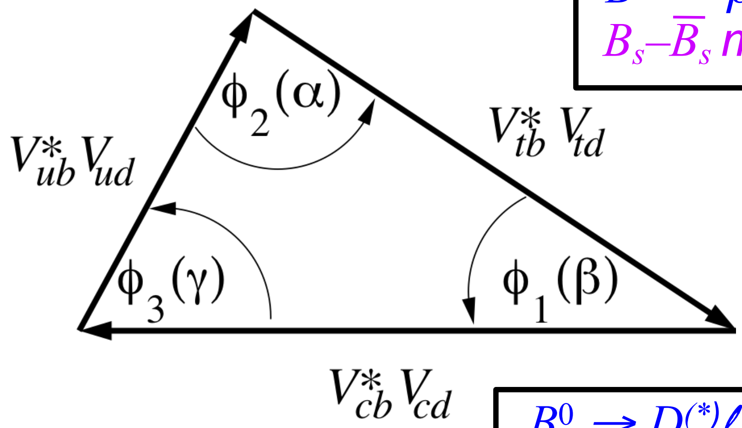
- *overview*
- *exclusive and inclusive $|V_{cb}|$*
- *exclusive and inclusive $|V_{ub}|$*
- *other (Λ_b, τ) measurements of $|V_{ub}|$*
- *$R(D)$, $R(D^*)$*
- *forefront searches ($h\nu\nu$, $\tau^+\tau^-$, $\mu^+\nu$)*

Determining sides of the Unitarity Triangle

Belle
LHCb



$B^0 \to \rho^0\gamma$
B_s–$\overline{B}_s$ mixing

Jubb et al., Nucl. Phys. B 915, 431 (2017)
Artuso et al., RMP 88, 045002 (2016)
Lenz, Nierste, arXiv:1102.4274 (2011)
FNAL/MILC, PRD 93, 113016 (2016)
FLAG, EPJC 77, 112 (2017)

$B^0 \to \pi\, \ell^+ \nu$
$B^0 \to X_u\, \ell\, \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p\, \ell^+ \nu$

Bourrely et al., PRD 79, 013008 (2009)
FLAG, arXiv:1607.00299 (2016)
Bharucha, JHEP 05, 092 (2012)
Detmold et al., PRD 92, 034503 (2015)
Faustov and Galkin, PRD 94, 073008 (2016)

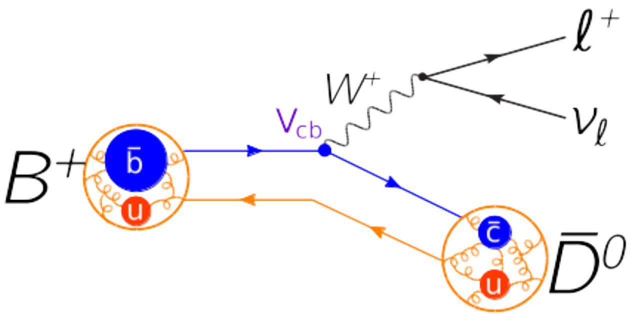
Lange et al. (BLNP), PRD 72, 073006 (2005)
Andersen, Gardi (DGE), JHEP 601, 97 (2006)
Gambino et al. (GGOU), JHEP 10, 058 (2007)
Aglietti et al. (ADFR), EPJ C59 (2009)
Bauer et al. (BLL), PRD 64, 113004 (2001)

$B^0 \to D^{(*)}\ell\, \nu$
$B^0 \to X_c\, \ell\, \nu$ (ℓ energy, hadron mass moments)
$B^0 \to X_s\, \gamma$ (γ energy moments)

Caprini et al., Nucl. Phys. B530, 153 (1998)
FNAL/MILC, PRD 89, 114504 (2014)
FNAL/MILC, PRD 92, 034506 (2015)
Benson et al., Nucl. Phys. B665, 367 (2003)
Gambino, Uraltsev, EPJ C34, 181 (2004)
Gambino, JHEP 09, 055 (2011)
Alberti et al., PRL 114, 061802 (2015)
Bauer, Ligeti, et al., PRD 70, 094017 (2004)
Gambino and Schwanda, PRD 89, 014002 (2014)

Exclusive $|V_{cb}|$

$|V_{cb}|$ from $B \to D^{(*)} l \nu$



Define kinematics in terms of w, rather than q^2:

$$w \equiv v_B \cdot v_D = \frac{M_B^2 + M_D^2 - q^2}{2 M_B M_D}$$

$q^2 = (P_B - P_D)^2 = (P_l + P_\nu)^2$

$q^2 = 0 \rightarrow w_{max} = 1.6$

$q^2_{max} \rightarrow w = 1$

$B \to D l \nu$ decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} m_D^3 (M_B + m_D)^2 (w^2 - 1)^{3/2} |V_{cb}|^2 \eta_{EW}^2 G^2(w)$$

form factor

Caprini, Lelouch, Neubert:

$$G(w \to z) = G(1)\left[1 - 8\rho^2 z + (51\rho^2 - 10) z^2 - (252\rho^2 - 84) z^3\right]$$

$B \to D^* l \nu$ decay rate:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} M_{D^*}^3 (M_B - m_{D^*})^2 |V_{cb}|^2 \eta_{\rm EW}^2 \sqrt{w^2 - 1}(w+1)^2 \times$$
$$h_{A_1}^2(w)\left\{2\left[\frac{1 - 2wr + r^2}{(1-r)^2}\right]\left[1 + R_1^2(w)(w-1)\right] + \left[1 + (1 - R_2(w))\frac{w-1}{1-r}\right]^2\right\}$$

form factors

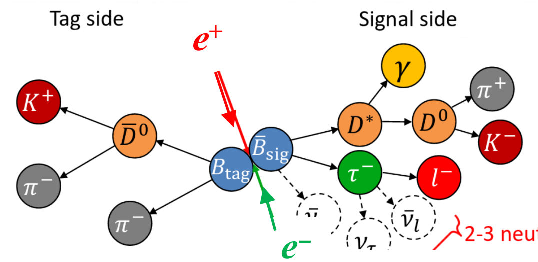
$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15) z^2 - (231\rho^2 - 91) z^3\right]$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$
$$R_2(w) = R_2(1) - 0.11(w-1) + 0.06(w-1)^2$$

$|V_{cb}|$ from $B \to D l \nu$

711 fb^{-1} — Glattauer at al. (Belle), PRD 93, 032006 (2016)

$B \to D \ell \nu$ Reconstruction:

Divide event into 2 hemispheres: "signal" side and "flavor tag" side. Tag side is fully reconstructed (using neural net)



charged tags

$B^- \to D^{*0}\pi^-$
$B^- \to D^{*0}\pi^-\pi^0$
$B^- \to D^{*0}\pi^-\pi^+\pi^-$
$B^- \to D^{*0}\pi^-\pi^+\pi^-\pi^0$

$B^- \to D^0\pi^-$
$B^- \to D^0\pi^-\pi^0$
$B^- \to D^0\pi^-\pi^+\pi^-$

$B^- \to D^{*0}D_s^{*-}$
$B^- \to D^{*0}D_s^-$
$B^- \to D^0 D_s^{*-}$
$B^- \to D^0 D_s^-$

$B^- \to J/\psi\, K^-$
$B^- \to J/\psi\, K^-\pi^+\pi^-$
$B^- \to J/\psi\, K^-\pi^0$
$B^- \to J/\psi\, K_S\pi^-$

$B^- \to D^0 K^-$
$B^- \to D^+\pi^-\pi^-$

neutral tags

$B^0 \to D^{*+}\pi^-$
$B^0 \to D^{*+}\pi^-\pi^0$
$B^0 \to D^{*+}\pi^-\pi^+\pi^-$
$B^0 \to D^{*+}\pi^-\pi^+\pi^-\pi^0$

$B^0 \to D^+\pi^-$
$B^0 \to D^+\pi^-\pi^0$
$B^0 \to D^+\pi^-\pi^+\pi^-$

$B^0 \to D^{*+}D_s^{*-}$
$B^0 \to D^{*+}D_s^-$
$B^0 \to D^+ D_s^{*-}$
$B^0 \to D^+ D_s^-$

$B^0 \to J/\psi\, K_S$
$B^0 \to J/\psi\, K^-\pi^+$
$B^0 \to J/\psi\, K_S\pi^+\pi^-$

$B^0 \to D^0\pi^0$

charged signals

$D^+ \to K^-\pi^+\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$
$D^+ \to K^-\pi^+\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+$

$D^+ \to K_S\pi^+$
$D^+ \to K_S\pi^+\pi^0$
$D^+ \to K_S\pi^+\pi^+\pi^-$
$D^+ \to K_S K^+$

$D^+ \to \pi^+\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$

neutral signals

$D^0 \to K^-\pi^+$
$D^0 \to K^-\pi^+\pi^0$
$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$

$D^0 \to K_S\pi^+\pi^-$
$D^0 \to K_S\pi^+\pi^-\pi^0$
$D^0 \to K_S\pi^0$

$D^0 \to K^-K^+$
$D^0 \to \pi^+\pi^-$
$D^0 \to K_S K_S$
$D^0 \to \pi^0\pi^0$
$D^0 \to K_S\pi^0\pi^0$

$D^0 \to \pi^+\pi^+\pi^0$

Note: over 1000 decay topologies considered.
[This is straightforward at an e^+e^- machine but very difficult at a hadron machine]

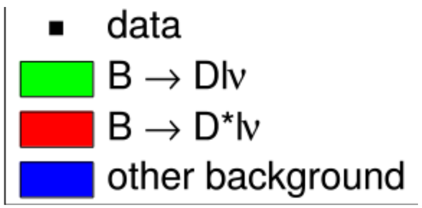
$|V_{cb}|$ from $B \to D l \nu$

$B \to D \ell \nu$ Reconstruction:

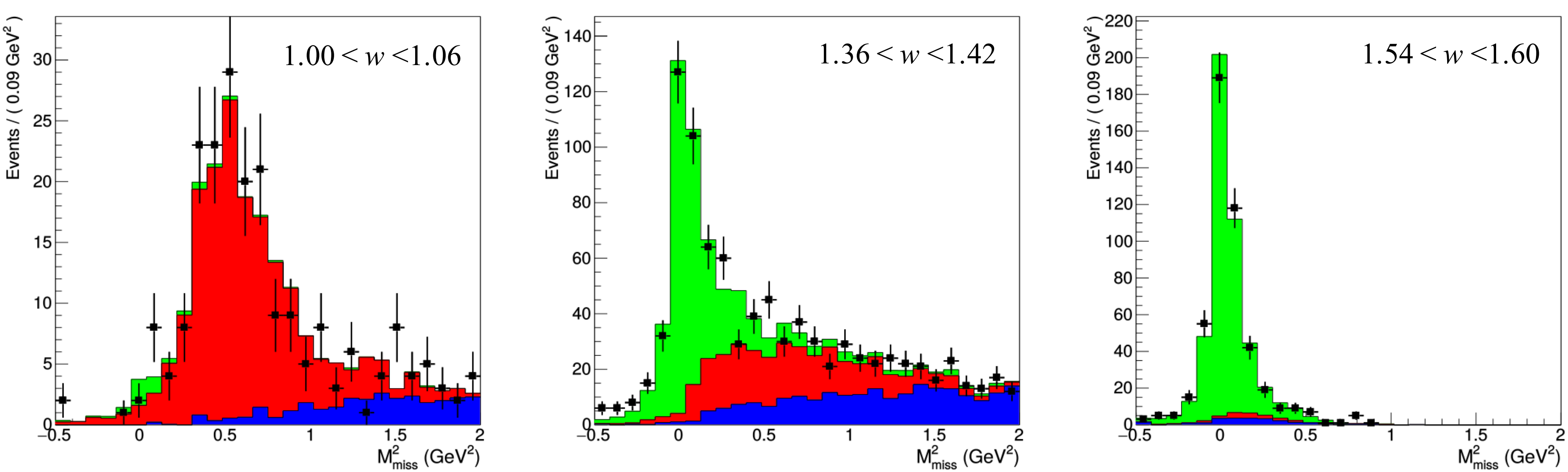
After tag side reconstructed, tracks are "removed" and signal side D reconstructed. After D reconstructed, e or μ is added to decay and missing mass calculated:

$$M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$$

Missing mass spectrum (in bins of w) is fit for signal yield; from signal yield one calculates $\Delta\Gamma/\Delta w$.



$B^0 \to D^+ e^- \nu$

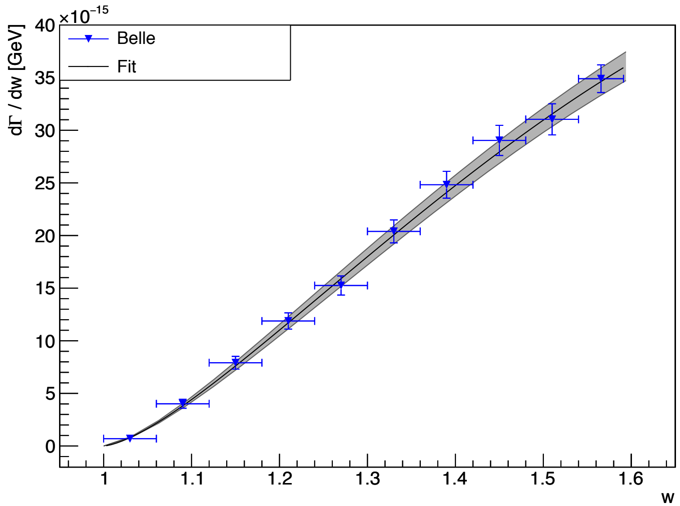


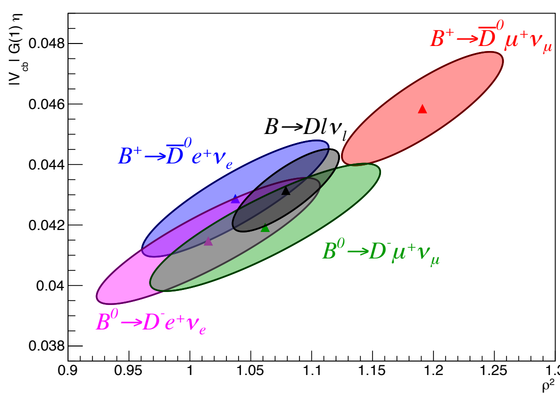
$|V_{cb}|$ from $B \to D l \nu$

711 fb^{-1}

Glattauer at al. (Belle), PRD 93, 032006 (2016)

Results: CLN *(2 params, heavy quark symmetry)*

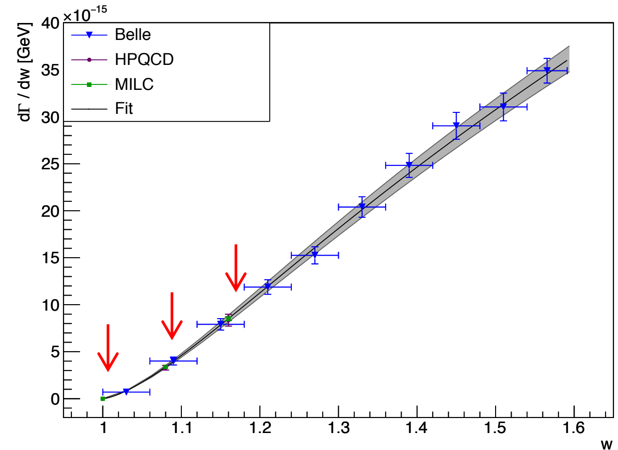




$|V_{cb}|\, \eta_{EW} = (40.12 \pm 1.34) \times 10^{-3}$

Using G(1) = 1.0541 ± 0.0083 [MILC, PRD 92, 034506, (2015)]
η_{EW} = 1.0066 ± 0.0050 [Sirlin, Nucl. Phy. B196, 83 (1982)]

BGL *(more params, less constraints)*
3 lattice QCD calculated points are also fitted:



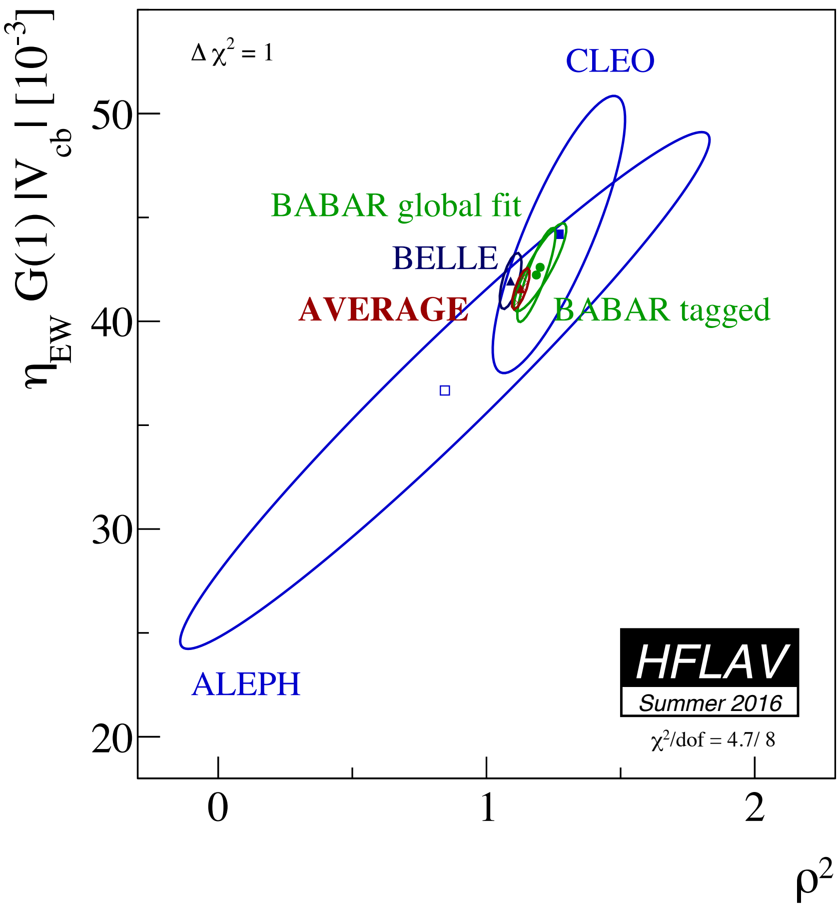
MILC data from PRD 92, 034506, (2015)
HPQCD data from PRD 92, 054510, (2015)

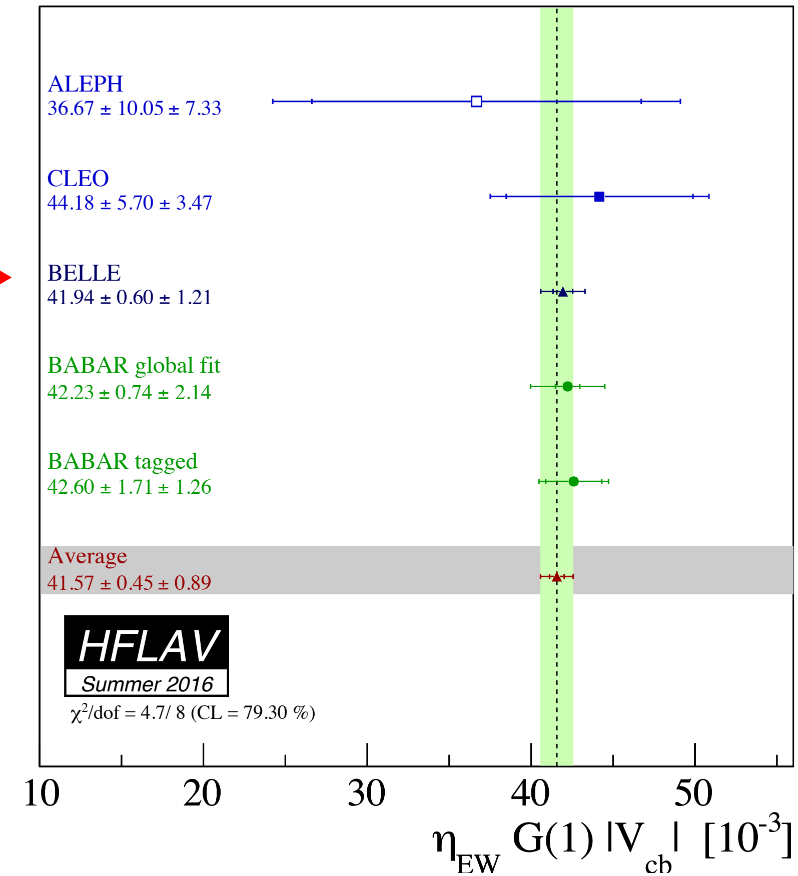
$|V_{cb}|\, \eta_{EW} = (41.10 \pm 1.14) \times 10^{-3}$

$$\begin{aligned} \mathcal{B}(B^0 \to D^- \ell^+ \nu) &= (2.35 \pm 0.04 \pm 0.11)\% \\ \mathcal{B}(B^+ \to \overline{D}{}^0 \ell^+ \nu) &= (2.67 \pm 0.04 \pm 0.12)\% \\ \mathcal{B}(B \to D \ell^+ \nu) &= (2.43 \pm 0.03 \pm 0.10)\% \end{aligned}$$

$|V_{cb}|$ from $B \to D l \nu$

Heavy Flavor Averaging Group (HFLAV)
arXiv: 1612.07233 (to appear in EPJC)





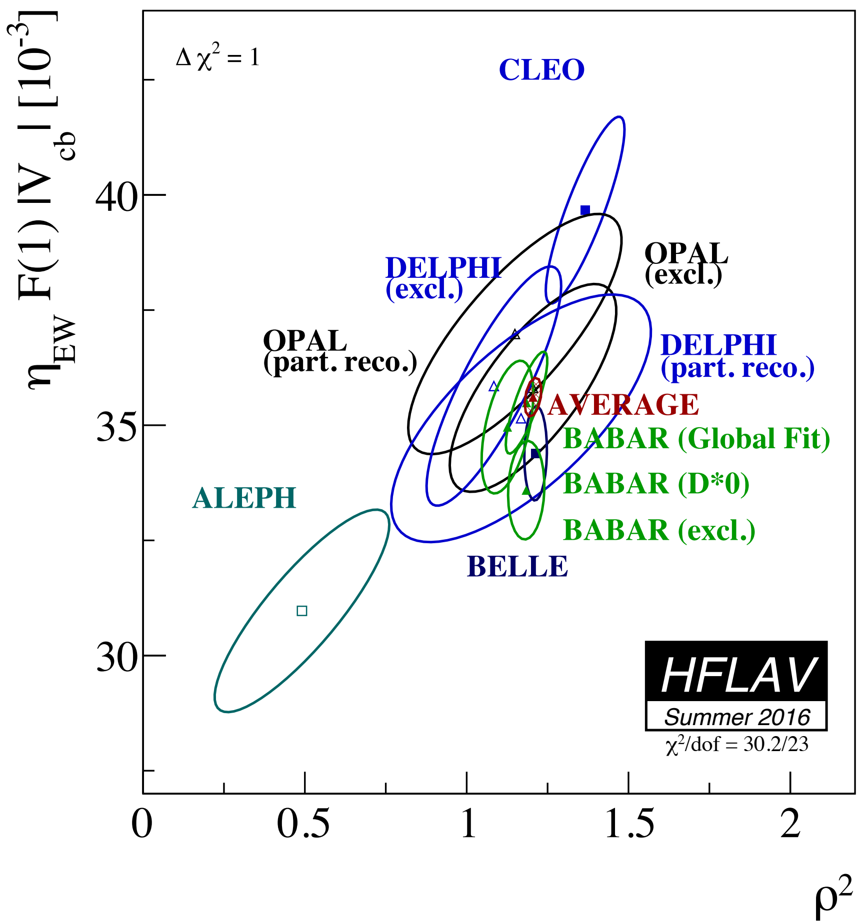
Using $G(1) = 1.0541 \pm 0.0083$ [MILC, PRD 92, 034506, (2015)]

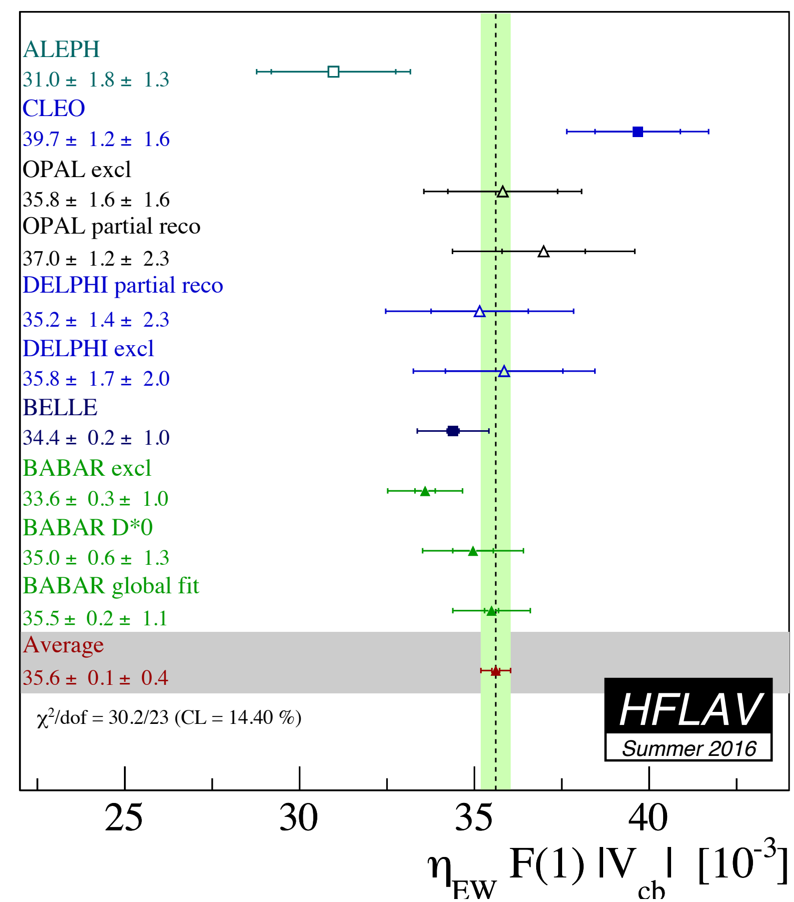
$\eta_{EW} = 1.0066 \pm 0.0050$ [Sirlin, Nucl. Phy. B196, 83 (1982)]

$\Rightarrow$ $|V_{cb}| = (39.18 \pm 0.94_{exp} \pm 0.36_{th}) \times 10^{-3}$

$|V_{cb}|$ from $B \to D^* l\nu$

Heavy Flavor Averaging Group (HFLAV)
arXiv: 1612.07233 (to appear in EPJC)





Using $\eta_{EW}F(1) = 0.912 \pm 0.014$ [FNAL-MILC, PRD 89, 114504, (2014)]

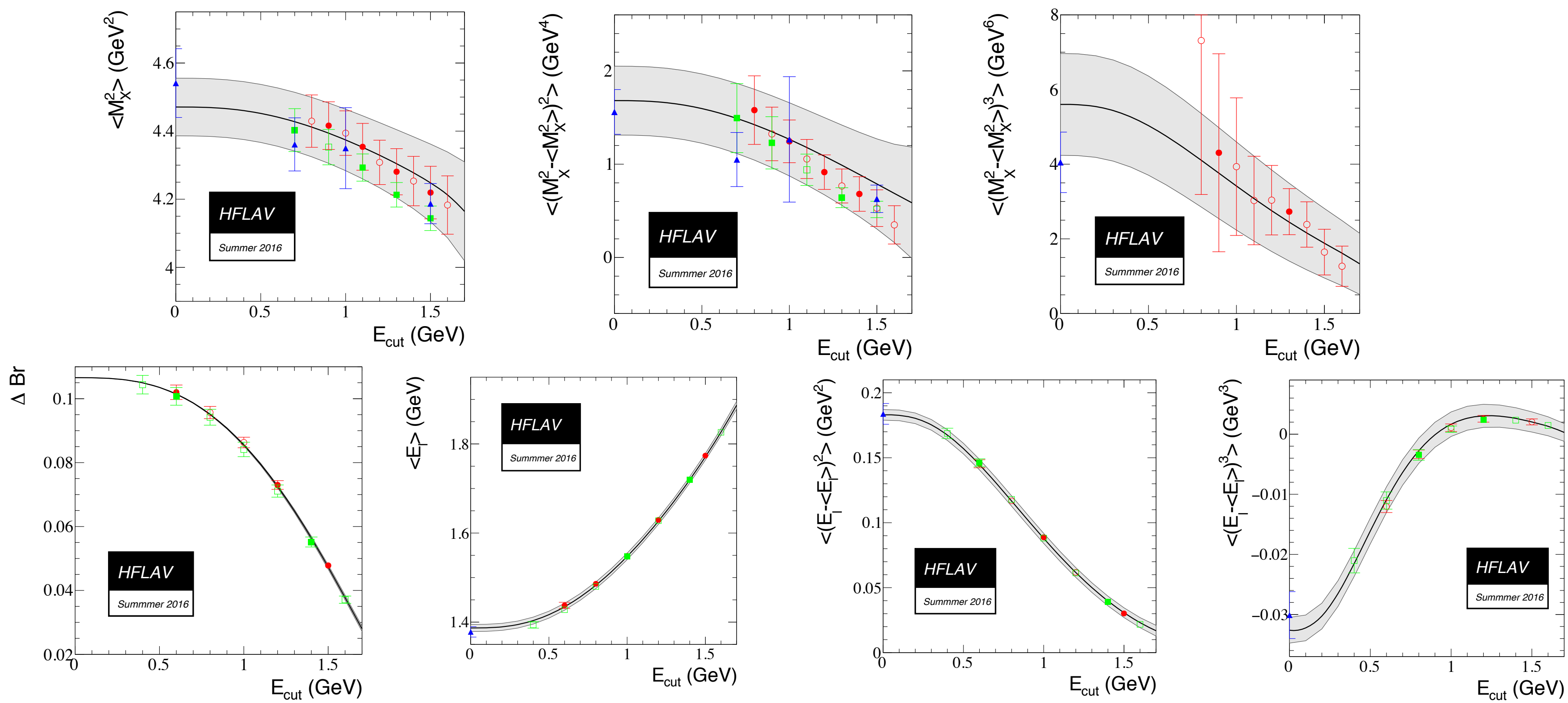
$\Rightarrow$ $|V_{cb}| = (39.05 \pm 0.47_{exp} \pm 0.58_{th}) \times 10^{-3}$

Inclusive $|V_{cb}|$

$|V_{cb}|$ from inclusive $B \to X_c l\nu$

HFLAV arXiv: 1612.07233
(to appear in EPJC)

Global fit: Use OPE to describe $b \to c$ transitions. Two renormalization schemes used to describe non-perturbative parameters: "kinetic scheme" and "1S" scheme. Observables fit are recoil mass moments $\langle M_X^n \rangle$ (n=2,4,6) and charged lepton moments $\langle E_l^n \rangle$ (n=0,1,2,3). Moments are calculated + fit for different E_l^{min} values:



Kinetic scheme: Gambino, JHEP 09, 055, (2011); Alberti, Gambino, Healey, and Nandi, PRL 114, 061802, (2015)

$|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3}$

1S scheme: Bauer, Ligeti, Luke, Manohar, and Trott, PRD 70, 094017, (2004); Belle, PRD 78, 032016, (2008)

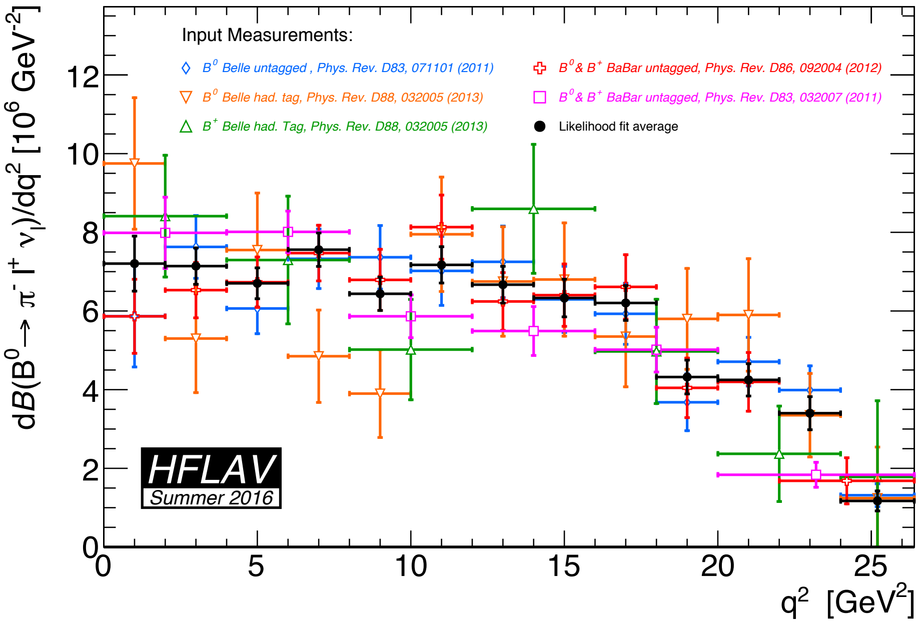
$|V_{cb}| = (41.98 \pm 0.45) \times 10^{-3}$

Exclusive $|V_{ub}|$

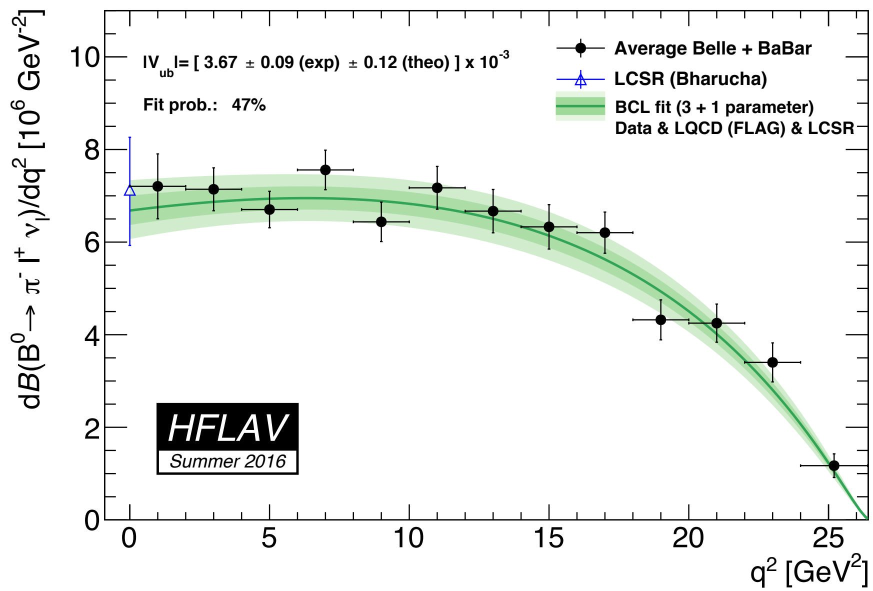
$|V_{ub}|$ via exclusive $B \to \pi l \nu$

***HFLAV** arXiv: 1612.07233*
(to appear in EPJC)

***(1) five $B^{(+0)} \to \pi^{(0+)} l\nu$ analyses:** hadronic tagged, untagged. Fit for averaged q^2 spectrum*



***(2)** Use BCL parametrization of form factor, fit averaged q^2 spectrum for BCL parameters and $|V_{ub}|$ [Bourrely, Caprini, Lellouch, PRD 79, 013008 (2009)]*



$$\chi^2 = \left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right)^T C^{-1} \left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right) + \chi^2_{\rm LQCD} + \chi^2_{\rm LCSR}$$

$$\chi^2_{\rm LQCD} = \left(\vec{b} - \vec{b}_{\rm LQCD}\right)^T C^{-1}_{\rm LQCD} \left(\vec{b} - \vec{b}_{\rm LQCD}\right)$$

$$\chi^2_{\rm LCSR} = \left(f_+^{\rm LCSR} - f_+(q^2 = 0; \vec{b})\right)^2 / \sigma^2_{f_+^{\rm LCSR}}$$

***Lattice:** Aoki et al., (FLAG), EPJC 77, 112, (2017)*
***LCSR:** Bharucha, JHEP 05, 092, (2012)*

$|V_{ub}| = (3.67 \pm 0.09_{\rm exp} \pm 0.12_{\rm th}) \times 10^{-3}$

Inclusive $|V_{ub}|$

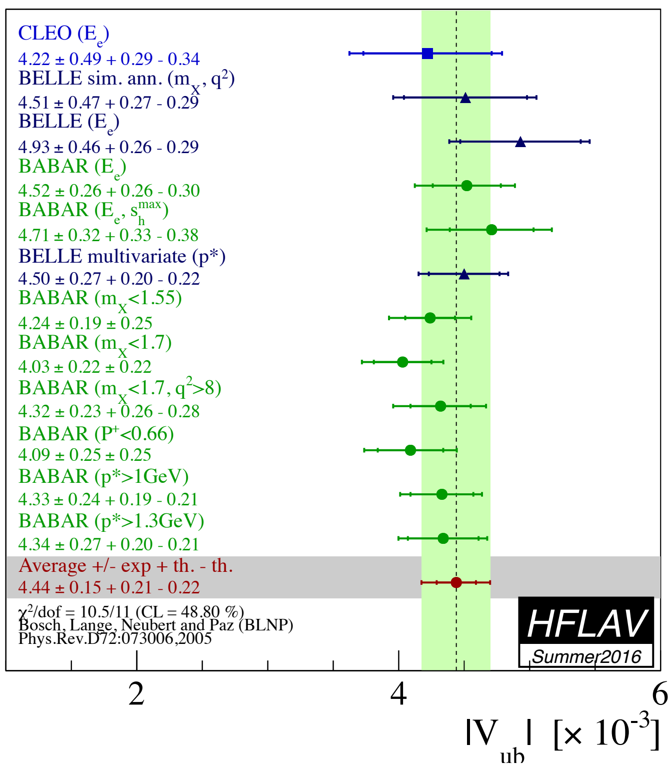
$|V_{ub}|$ via inclusive $B \to X_u l\nu$

HFLAV *arXiv: 1612.07233*
(to appear in EPJC)

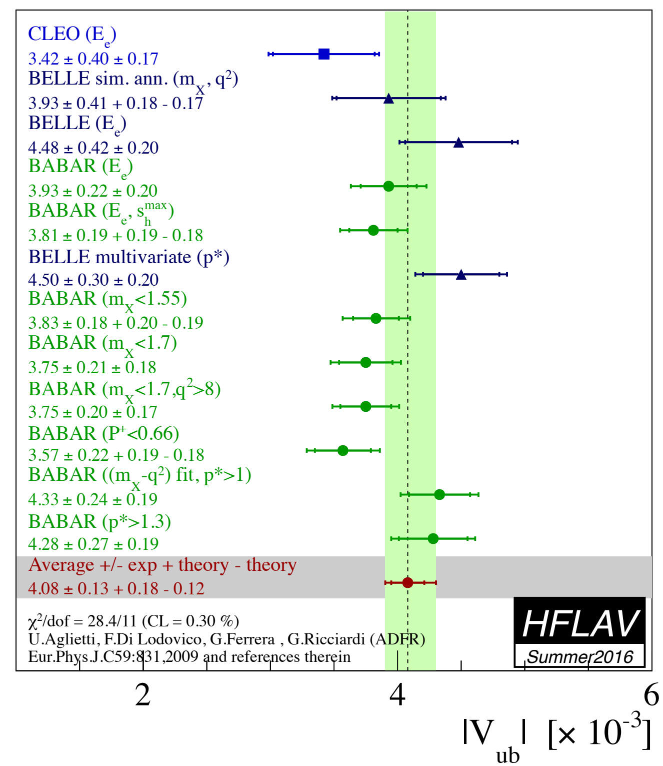
To reduce large backgrounds from $B \to X_c l\nu$, one must make cuts that severely restrict the acceptance. To extrapolate partial rates for measured regions into unmeasured regions requires "shape functions" calculated from theory. Five theory models are used.

BLNP:	*Bosch, Lange, Neubert, Paz, Nucl. Phys. B699, 335, (2004)*
DGE:	*Andersen, Gardi, JHEP 0601:097 (2006)*
GGOU:	*Gambino, Giordano, Ossola, Uraltsev, JHEP 0710:058 (2007)*
ADFR:	*Aglietti, Di Lodovico, Ferrera , Ricciardi, EPJC 59, 831 (2009)*
BLL:	*Bauer, Ligeti Luke, PRD 64:113004 (2001)*

BLNP



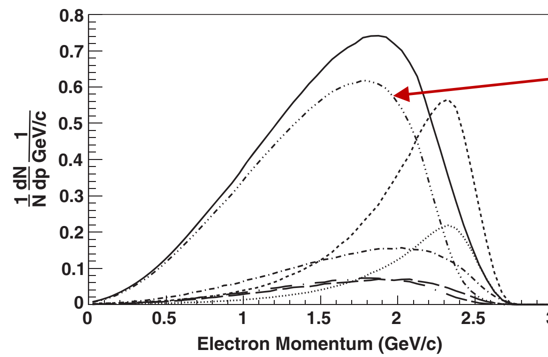
ADFR

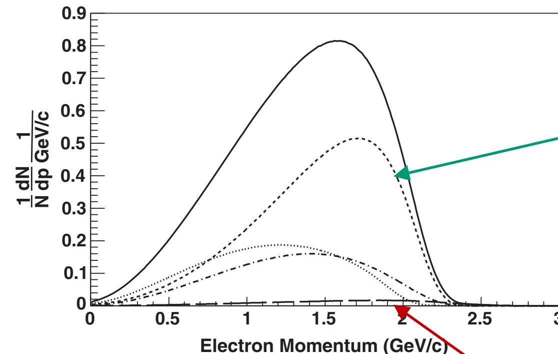


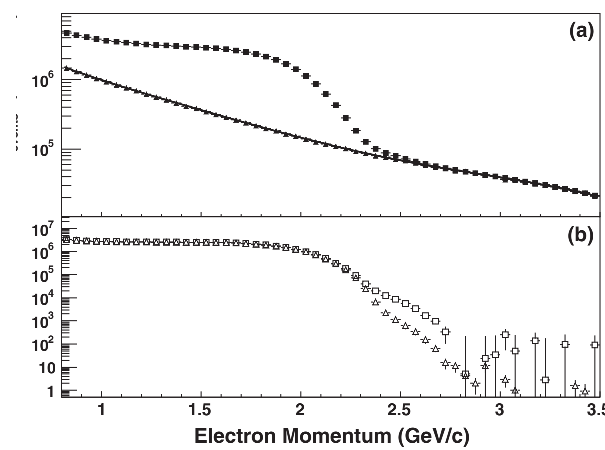
$|V_{ub}|$ via $B \to X_u l\nu$: final BaBar result

425 fb^{-1} Lees et al., PRD 95, 072001 (2017)

- *measure branching fraction for inclusive $B \to X_u e^+ \nu$, from this extract $|V_{ub}|$*
- *spectrum is well-dominated by $B \to X_c e^+ \nu$, except near endpoint region 2.3-2.6 GeV/c. Thus measurement relies on good understanding of shapes of all signal and background contributions. Input shape of $B \to X_u e^+ \nu$ spectrum is taken from 4 QCD theory calculations:*
  - *De Fazio, Neubert, JHEP 06 (1999) 017*
  - *Bosch, Lange, Neubert, Paz, Nucl. Phys. B699, 335 (2004) Bosch, Neubert, Paz, JHEP 11 (2004) 073;*
  - *Gambino, Biordano, Ossola, Uraltsev, JHEP 10 (2007) 058 Gambino, JHEP 09 (2011) 055;*
  - *Andersen, Gardi, JHEP 01 (2006) 097, JHEP 01 (2007) 029 Gardi, arXiv:0806.4524*
- *Analysis uses NN to reduce continuum background, but then must subtract remaining continuum background using off-resonance data) to see BB spectrum*
- *Binned fit is performed over range 0.8-3.5 GeV/c, floated parameters are $B \to D^{(*)(*)} e^+ \nu$ background normalizations and $B \to X_u e^+ \nu$ signal. Events in region 2.1-2.7 GeV/c are combined into one bin.*





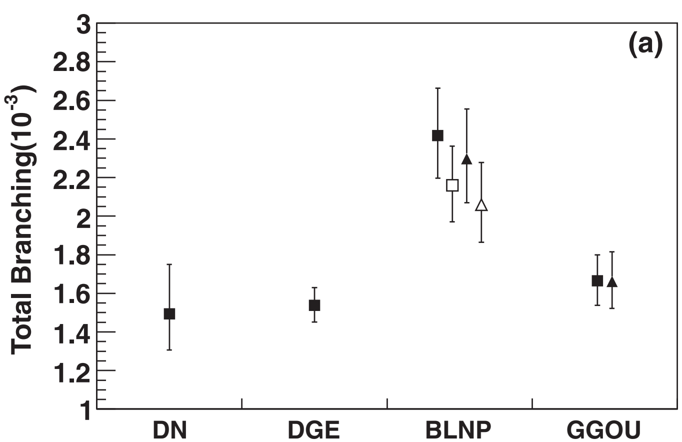


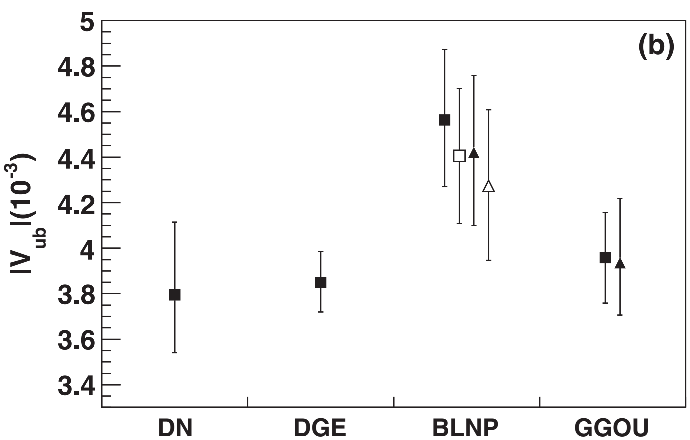
$|V_{ub}|$ via $B \to X_u l\nu$: final BaBar result

425 fb^{-1} Lees et al., PRD 95, 072001 (2017)

Fit results:

	DN	BLNP$_{\mu_i=2.0\text{ GeV}}$ m_c constraint	GGOU m_c constraint	DGE
$X_u e\nu$	0.149 ± 0.005	0.240 ± 0.008	0.166 ± 0.006	0.153 ± 0.005
$De\nu$	2.233 ± 0.090	2.197 ± 0.088	2.226 ± 0.089	2.230 ± 0.089
$D^* e\nu$	5.612 ± 0.049	5.424 ± 0.049	5.579 ± 0.048	5.611 ± 0.048
$D^{(*)}\pi e\nu$	<0.052	<0.025	<0.050	<0.075
$D^{**} e\nu$	2.285 ± 0.071	2.540 ± 0.075	2.331 ± 0.070	2.287 ± 0.070
$D'^{(*)} e\nu$	0.046 ± 0.011	0.023 ± 0.011	0.041 ± 0.011	0.045 ± 0.011
$D \to e$	0.982 ± 0.005	0.968 ± 0.005	0.980 ± 0.005	0.982 ± 0.005
$r_L / r_L^{(0)}$	1.0002 ± 0.0007	1.0002 ± 0.0007	1.0002 ± 0.0007	1.0002 ± 0.0007
$\chi^2_{\text{ON}} + \chi^2_{\text{OFF}} + \chi^2_{\text{constraints}}$	$27.4 + 69.7 + 0.1$	$31.9 + 70.9 + 0.2$	$27.8 + 69.9 + 0.1$	$26.8 + 69.7 + 0.1$
$\chi^2 / N_{\text{d.o.f.}}$	$97.2/85$	$102.9/85$	$97.8/85$	$96.6/85$

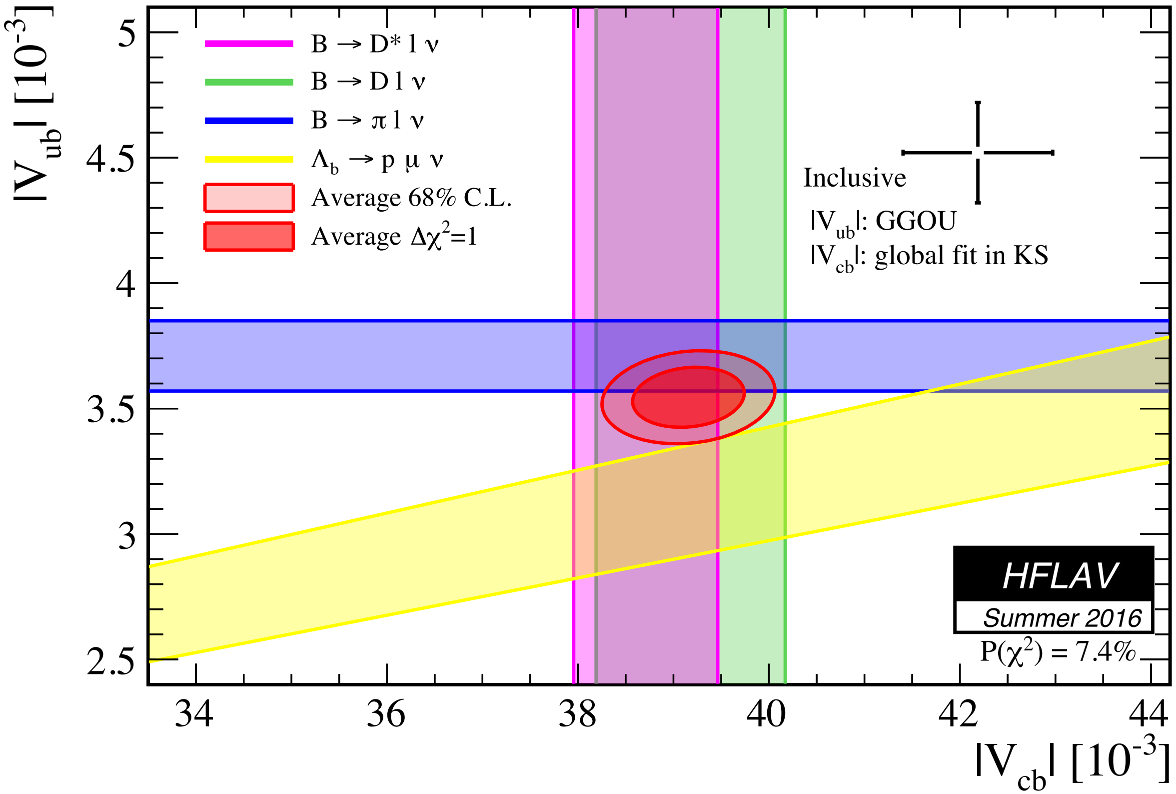




HFLAV WA: (arXiv: 1612.07233)

Framework	V_{ub} $[10^{-3}]$
BLNP	$4.44 \pm 0.15^{+0.21}_{-0.22}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.52 \pm 0.15^{+0.11}_{-0.14}$
ADFR	$4.08 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$

Puzzle: Inclusive vs. Exclusive $|V_{cb}|$, $|V_{ub}|$



Latest lattice results:
Bailey (MILC), PRD 89, 114504 (2014)
Bailey (FNAL/MILC), PRD 92, 034506 (2015)
Aoki (FLAG), EPJC 77, 112 (2017)
Detmold et.al., PRD 92, 034503 (2015)

	Exclusive (%)	Inclusive (%)	Diffference
$\lvert V_{cb}\rvert$	3.905 ± 0.047 ± 0.058 ($D^*\ell\nu$) 3.918 ± 0.094 ± 0.031 ($D\ell\nu$)	4.219 ± 0.078 (“kinetic scheme”) 4.198 ± 0.045 (“1S scheme”)	(2.4 – 3.4) σ
$\lvert V_{ub}\rvert$	0.368 ± 0.010 ± 0.012 ($\pi\ell\nu$)	0.452 ± 0.015 ± 0.014 ($X_u\ell\nu$)	3.3 σ

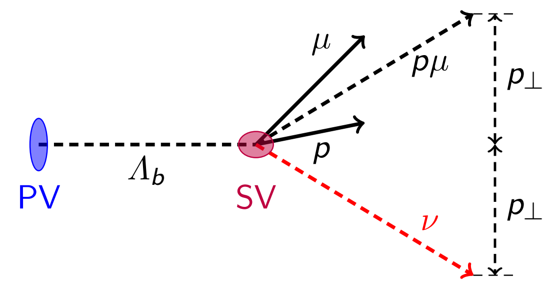
Other measurements of $|V_{ub}|$

LHCb: $|V_{ub}|$ from $\Lambda_b \to p\ell^- \nu$ decays

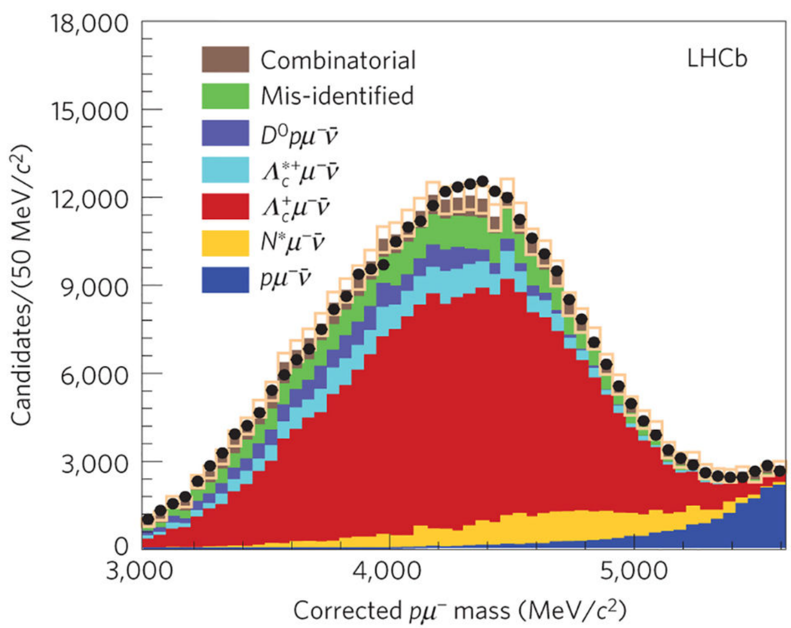
Aaij (LHCb), Nature Phys. 11, 743, (2015)

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu})_{q^2>15\ \mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\bar{\nu})_{q^2>7\ \mathrm{GeV}^2}} = \frac{N_{p\mu^-\bar{\nu}}}{N_{\Lambda_c\mu^-\bar{\nu}}}\left(\frac{\varepsilon_{\Lambda_c\mu^-\bar{\nu}}}{\varepsilon_{p\mu^-\bar{\nu}}}\right) = \frac{|V_{ub}|^2}{|V_{cb}|^2}\, R_{\mathrm{lattice}}$$

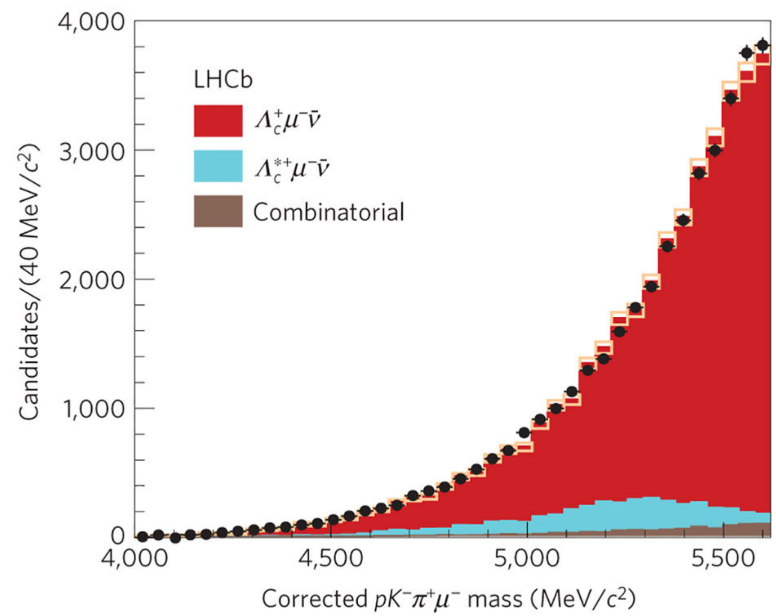
$$M_{\mathrm{corr}} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



$\Lambda_b \to p\ell^- \nu$



$\Lambda_b \to \Lambda_c \ell^- \nu$



LHCb: $|V_{ub}|$ from $\Lambda_b \to p\ell^- \nu$ decays

Aaij (LHCb), Nature Phys. 11, 743, (2015)

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu})_{q^2>15\ \mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\bar{\nu})_{q^2>7\ \mathrm{GeV}^2}} = \frac{N_{p\mu^-\bar{\nu}}}{N_{\Lambda_c\mu^-\bar{\nu}}}\left(\frac{\varepsilon_{\Lambda_c\mu^-\bar{\nu}}}{\varepsilon_{p\mu^-\bar{\nu}}}\right) = \frac{|V_{ub}|^2}{|V_{cb}|^2} R_{\mathrm{lattice}}$$

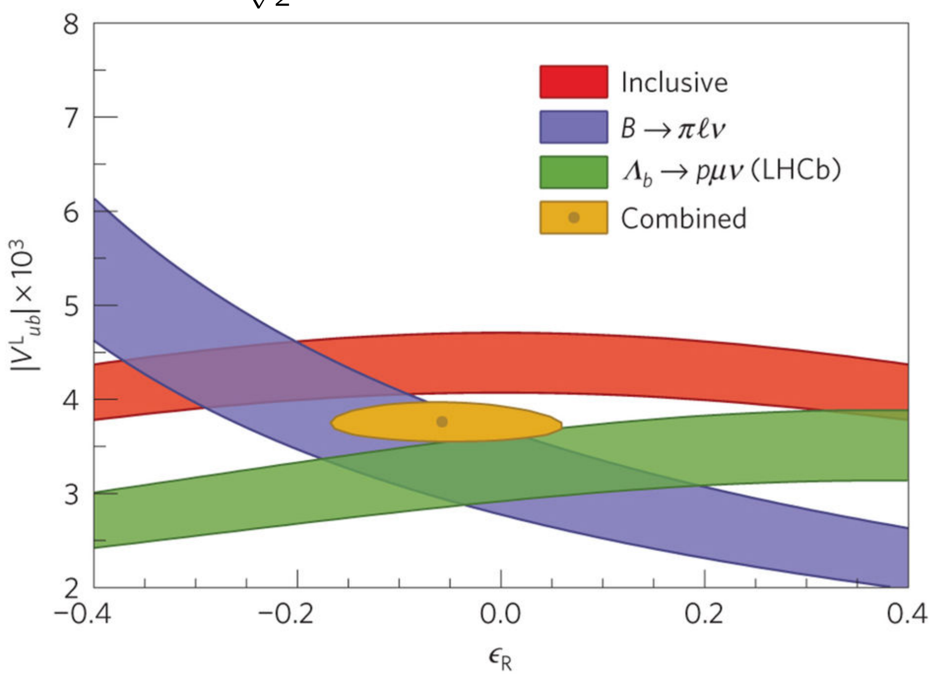
$$\Rightarrow \quad (0.95 \pm 0.04 \pm 0.07) \times 10^{-2} = \frac{|V_{ub}|^2}{|V_{cb}|^2}(1.471 \pm 0.095 \pm 0.109)$$

Detmold, Lehner, Meinel, PRD 92, 034503, (2015)

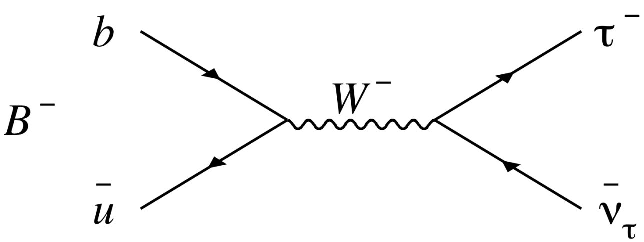
$$\Rightarrow \quad \frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.004_{\mathrm{exp}} \pm 0.004_{\mathrm{form\ factors}}$$

Can constrain right-handed currents (NP):

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L l) + h.c.$$



$|V_{ub}|$ via $B^+ \to \tau^+\nu$



Aubert et al., PRD 81, 051101 (2010) 418 fb^{-1} $D^0\ell$ tag
Lees et al., PRD 88, 031102 (2013) 426 fb^{-1} hadr.tag

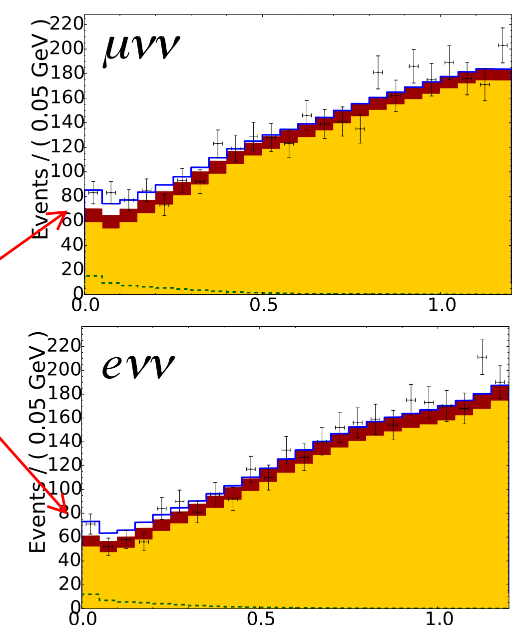
Hara et al., PRD 82, 071101 (2010) 605 fb^{-1} semi.tag
Hara et al., PRL 110, 131801 (2013) 711 fb^{-1} had.tag
Kronenbitter et al., PRD 92, 051102 (2015) 711 fb^{-1} semi.tag

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

PRD 92, 051102 (2015):

- $B^+ \to D^{(*)0}\ell^+\nu$, $D^{*0} \to D^0\gamma$, $D^0\pi^0$; $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$...
- $\tau^- \to \mu^-\nu\nu$, $e^-\nu\nu$, $\pi^-\nu$, $\rho\nu$ (1 charged track)
- large backgrounds from $b \to c$ (BB) and continuum
- signal is obtained by fitting the ECL (electromagnetic calorimeter energy) distribution: peak new zero indicates $\tau \to \ell\nu\nu$, $\pi\nu$ decay.
- ECL simulation is validated with identically tagged $B^+ \to D^{(*)0}\ell^+\nu$ control sample

222 ± 50
(all chan.)
3.8σ



Excess calorimeter energy (GeV)

$|V_{ub}|$ via $B^+ \to \tau^+\nu$

Kronenbitter et al., PRD 92, 051102 (2015):

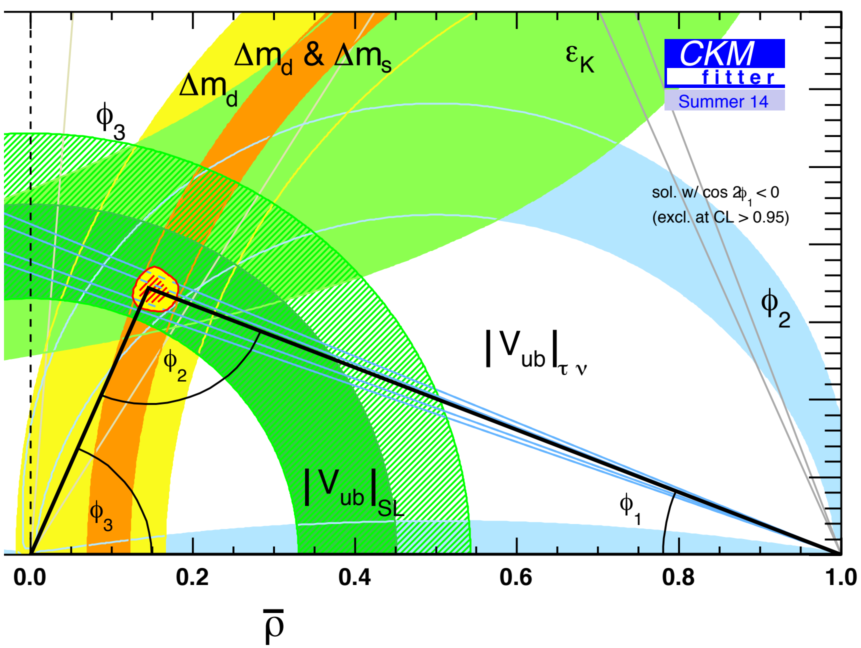
$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$$

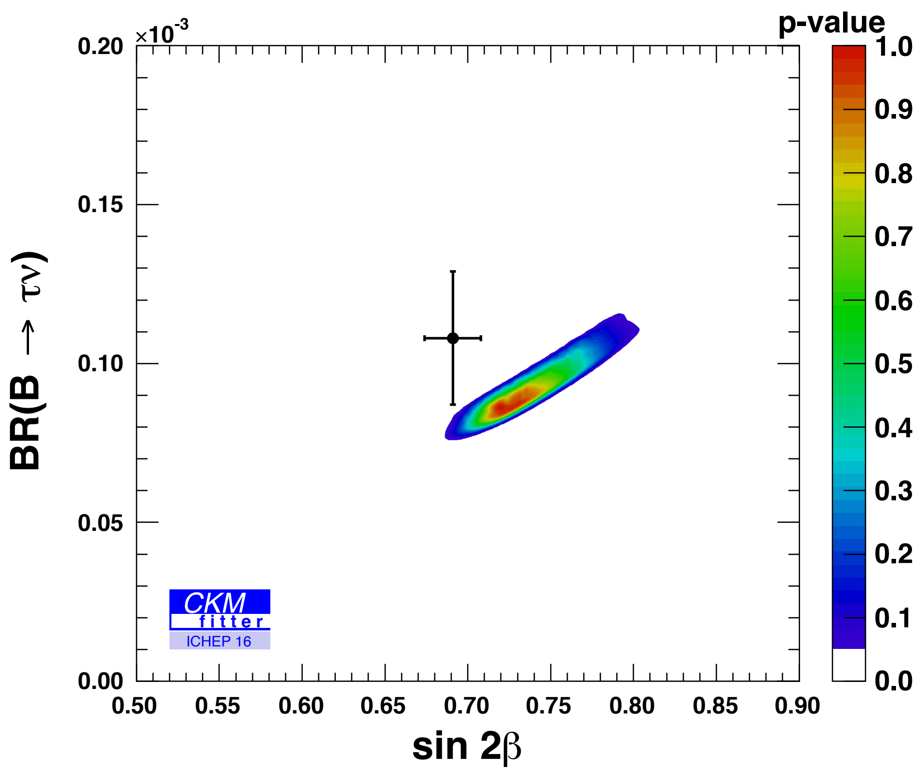
World average:

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.06 \pm 0.19) \times 10^{-4}$$

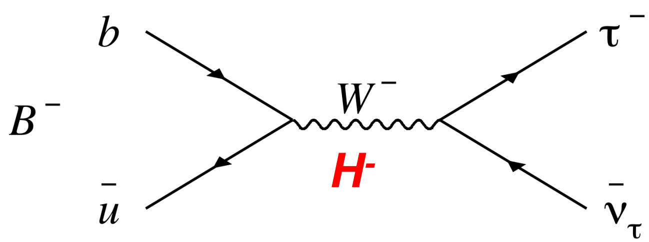
$\Rightarrow$ $\boxed{|V_{ub}| = (4.28\,^{+0.39}_{-0.43}) \times 10^{-3}}$ *using* $f_B = (190.5 \pm 4.2)$ *MeV (PDG14)*

There is tension coming from $|V_{td}|$ *measured in* B^0-$\bar{B}^0$ *mixing,* ϕ_1 (β) *and* ϕ_2 (α)*:*





Constraint on Type II charged Higgs: $B^+ \to \tau^+ \nu$

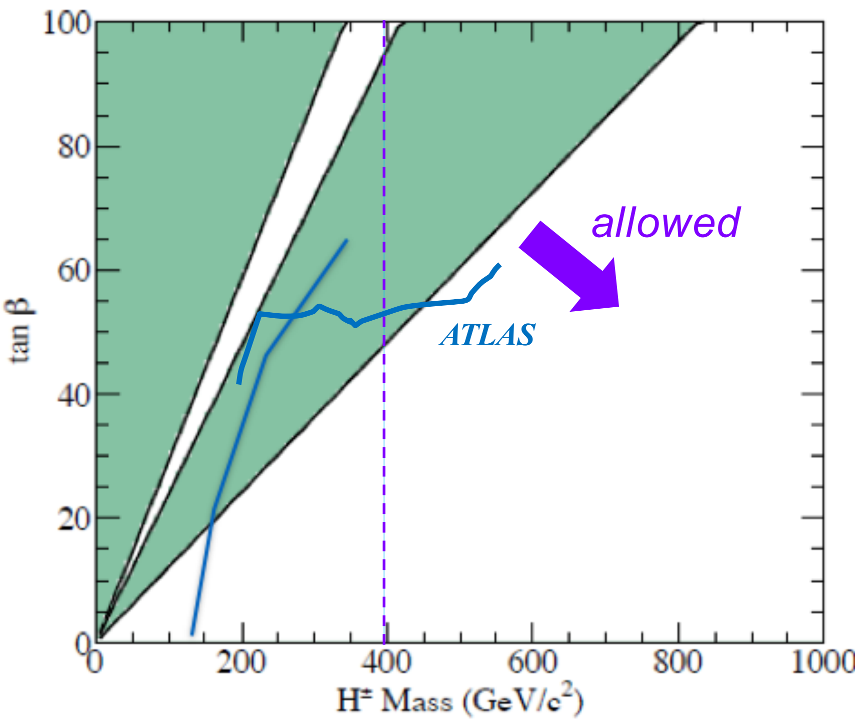


2-Higgs doublet model:

$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \cdot \left(1 - m_B^2 \frac{\tan^2\beta}{m_H^2}\right)^2$$

Taking f_B *= (190.5 ± 4.2) MeV and* $|V_{ub}|$ *= (4.13 ± 0.49) x* 10^{-3} *(PDG14) gives*
$\mathcal{B}_{SM} = (1.09\ ^{+0.27}_{-0.24}) \times 10^{-4}$

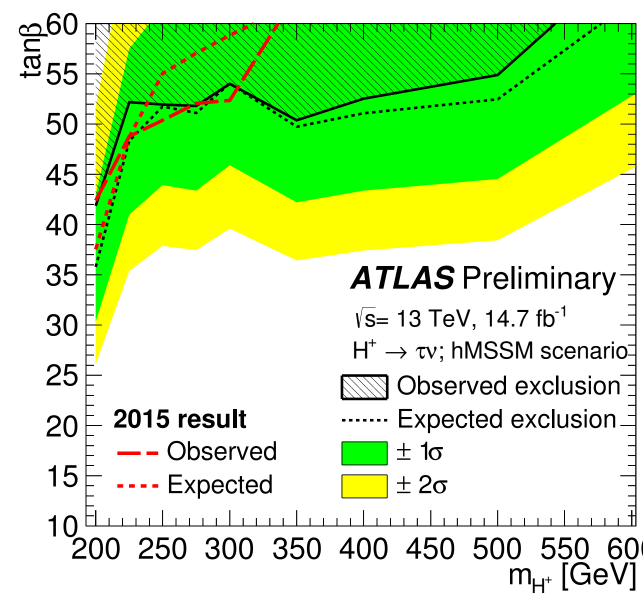
⇒ *WA* $\mathcal{B} = (1.06 \pm 0.19) \times 10^{-4}$ *gives a constraint in the* $\tan\beta$-m_H *plane:*



current measured value of $\mathcal{B}(b \to s\gamma)$ *excludes* m_H*<400 GeV/c² for all tanβ.*

Theory: Hermann, Misiak,& Steinhauser, JHEP 1211 (2012) 036; Misiak et al., PRL 98, 022002 (2007)

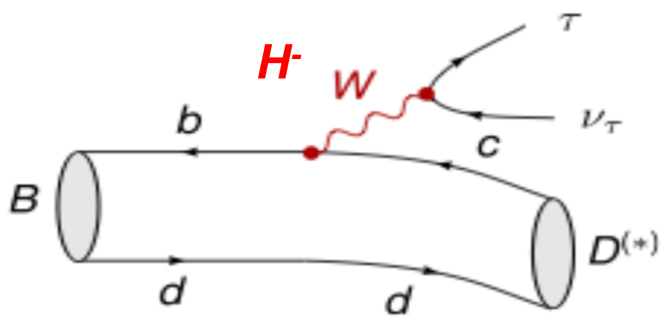
Compare to direct search at LHC (Jochen Meyer, PIC 2017):



$R(D)$ and $R(D^*)$

(tests of lepton universality)

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

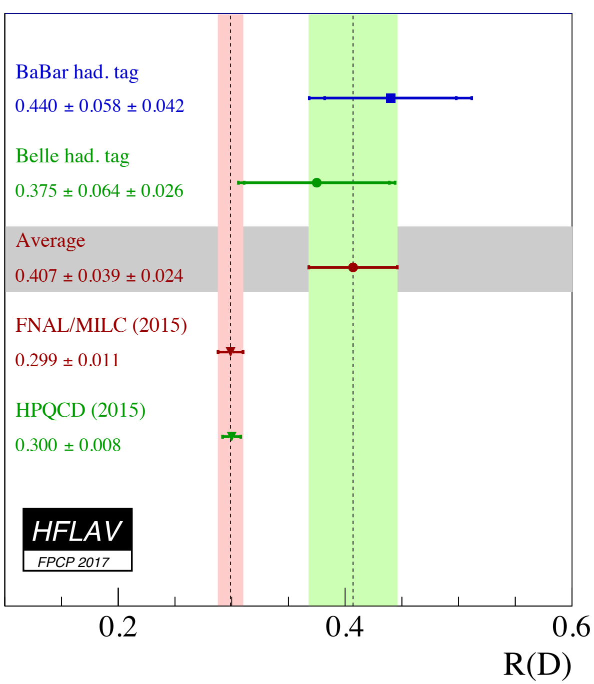


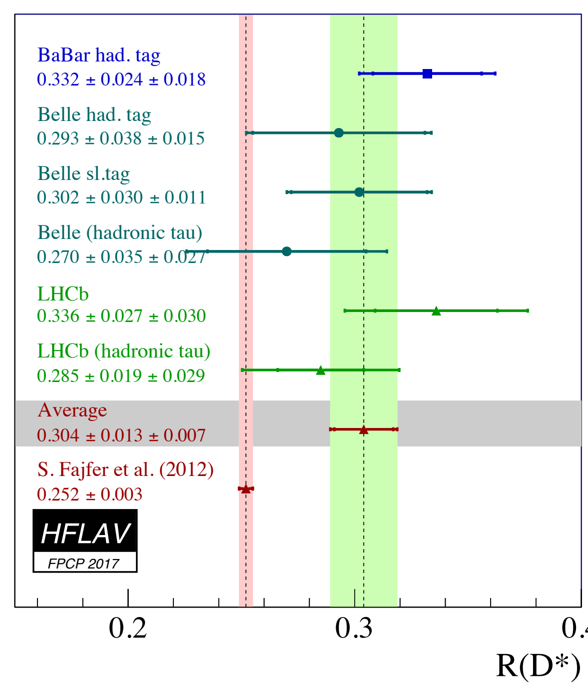
$B \to D^{(*)}\tau\nu$ can also receive contribution from a charged Higgs, changing the rate, q^2 distribution, etc.

Define ratios:

$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\ell\nu)} \qquad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

Uncertainties from form factors and V_{cb} drop out $\Rightarrow$ ratios test lepton universality.
Measured values of have traditionally been above SM prediction:





NEW: FPCP 2017

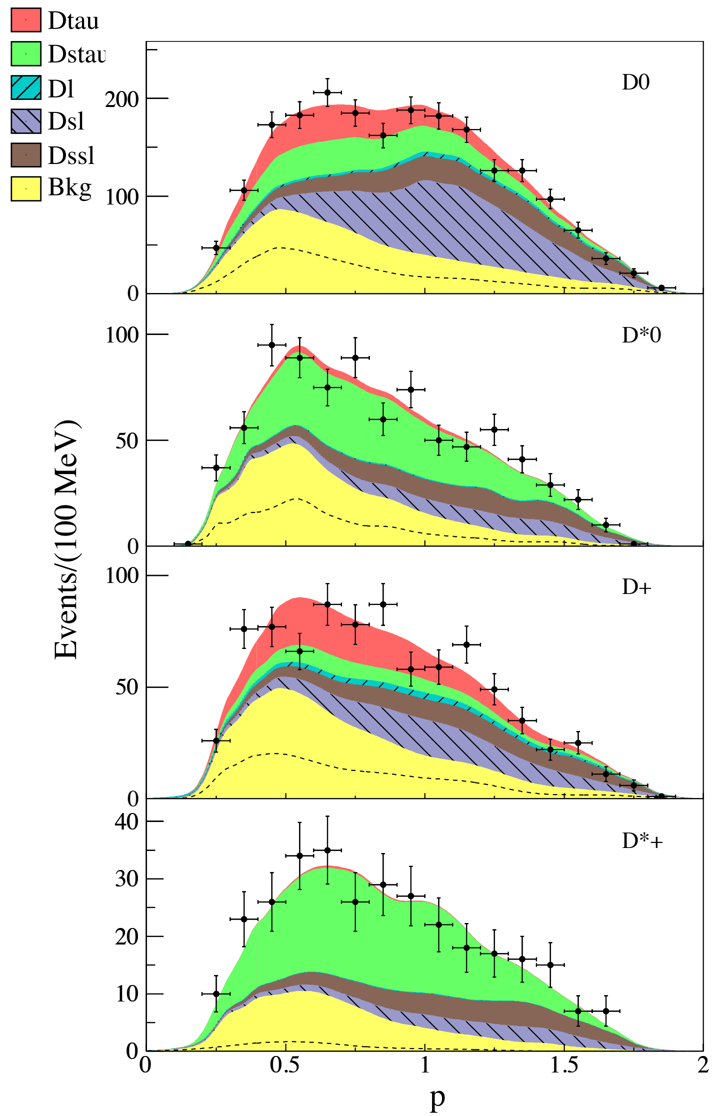
$B \rightarrow D^{(*)}\tau\nu$: first discrepancy

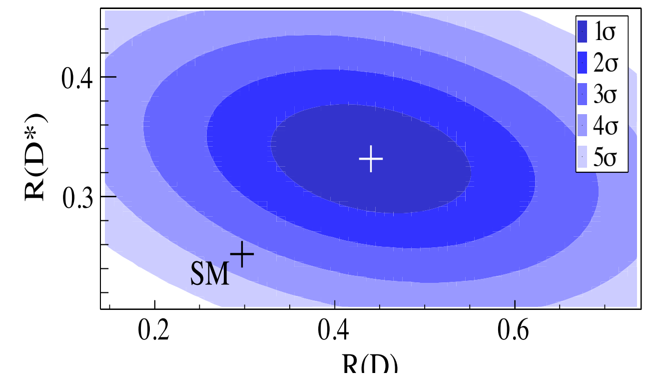
426 fb^{-1} *Lees et al., PRD 88, 072012 (2013); PRL 109, 101802 (2012)*

- *Fully reconstruct hadronic decay on tag side (1680 possible final states)*
- *Reconstruct $D\mu$ or De on signal side.*
- *Perform 2-d fit to lepton momentum spectrum and missing mass:*

$$M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$$

- *To control poorly known $B \rightarrow D^{**}(\ell/\tau)\nu$ backgrounds that enter signal sample via $D^{**} \rightarrow D^{(*)}\pi^0$ decays, require $D\pi^0\mu$, $D\pi^0 e$ on signal side, simultaneously fit those samples (8 samples simultaneously fit)*





$$\mathcal{R}_{D^*} = 0.332 \pm 0.024 \pm 0.018$$
$$\mathcal{R}_{D} = 0.440 \pm 0.058 \pm 0.042$$

Notably higher than SM prediction:

$$\mathcal{R}^{SM}_{D^*} = 0.252 \pm 0.003$$
$$\mathcal{R}^{SM}_{D} = 0.297 \pm 0.017$$

Updated from Fajfer, Kamenik, & Nisandzic, PRD 85, 094025 (2012); Kamenik and Mescia, PRD 78, 014003 (2008)

$B \to D^{(*)}\tau\nu$: results confirmed by Belle

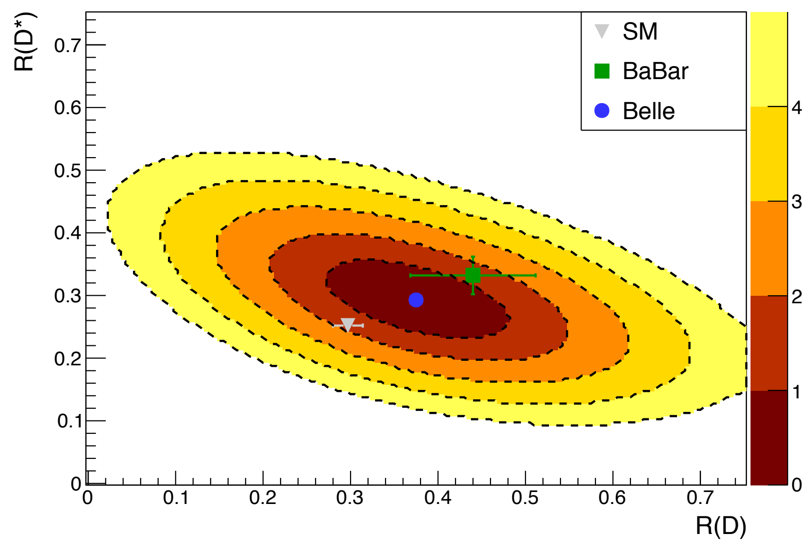
711 fb^{-1} Huschle, PRD 92, 072014 (2015)

$$\mathcal{R}_{D^*} \equiv \frac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^* \ell\nu)} \qquad \mathcal{R}_D \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

- Use hadronically tagged events (as done for $B \to D\ell\nu$ analysis, 1149 possible states)
- On signal side consider only $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, select $D^{(*)}\mu$ and $D^{(*)}e$ on signal side
- calculate missing mass squared: $M^2_{\rm miss} = \left(P_{\rm beam} - P_D - P_\ell\right)^2$
- for $M^2_{miss} < 0.85$ ($B \to D^{(*)}\ell\nu$ dominated), fit M^2_{miss} spectrum directly for $B \to D\ell\nu$ yield
- for $M^2_{miss} > 0.85$ ($B \to D^{(*)}\tau\nu$ dominated), fit a NN spectrum to obtain $B \to D^{(*)}\tau\nu$ yield, because M^2_{miss} cannot discriminate between $D^{(*)}\tau\nu$ signal and $D^{**}\ell\nu$ background. NN has 8 inputs, but most discrimination power comes from E_{ECL} (unassociated energy in calorimeter) and p_ℓ^* (lepton momentum in CM frame)

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

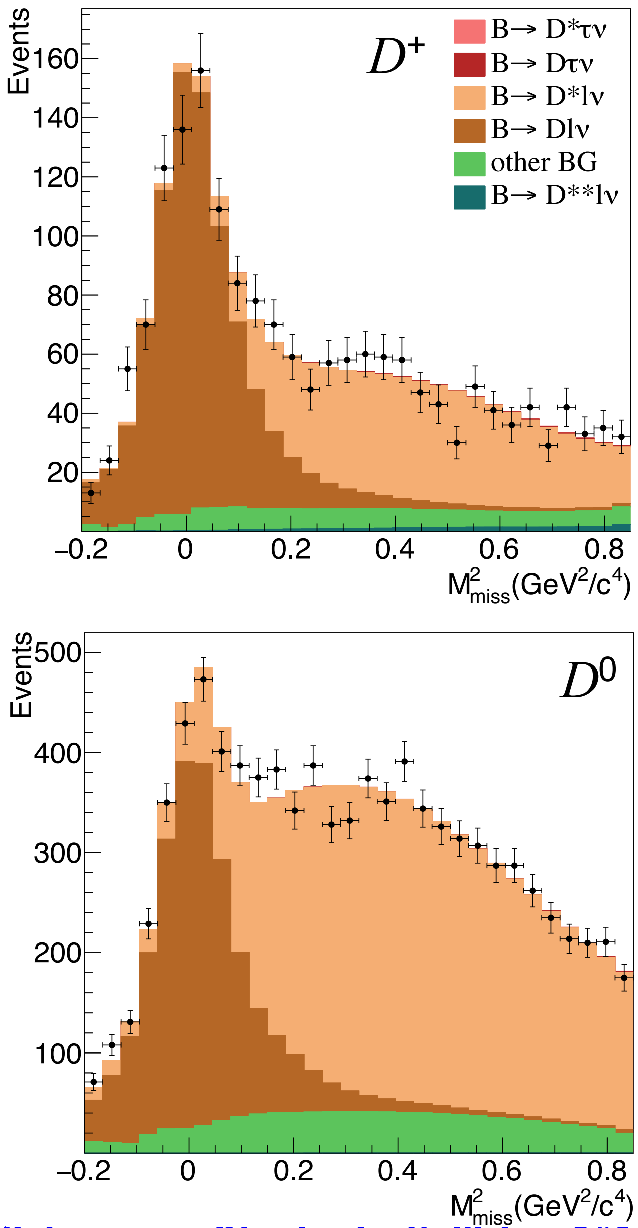
Also higher than SM: $\mathcal{R}^{SM}_{D^*} = 0.252 \pm 0.003$, $\mathcal{R}^{SM}_D = 0.297 \pm 0.017$



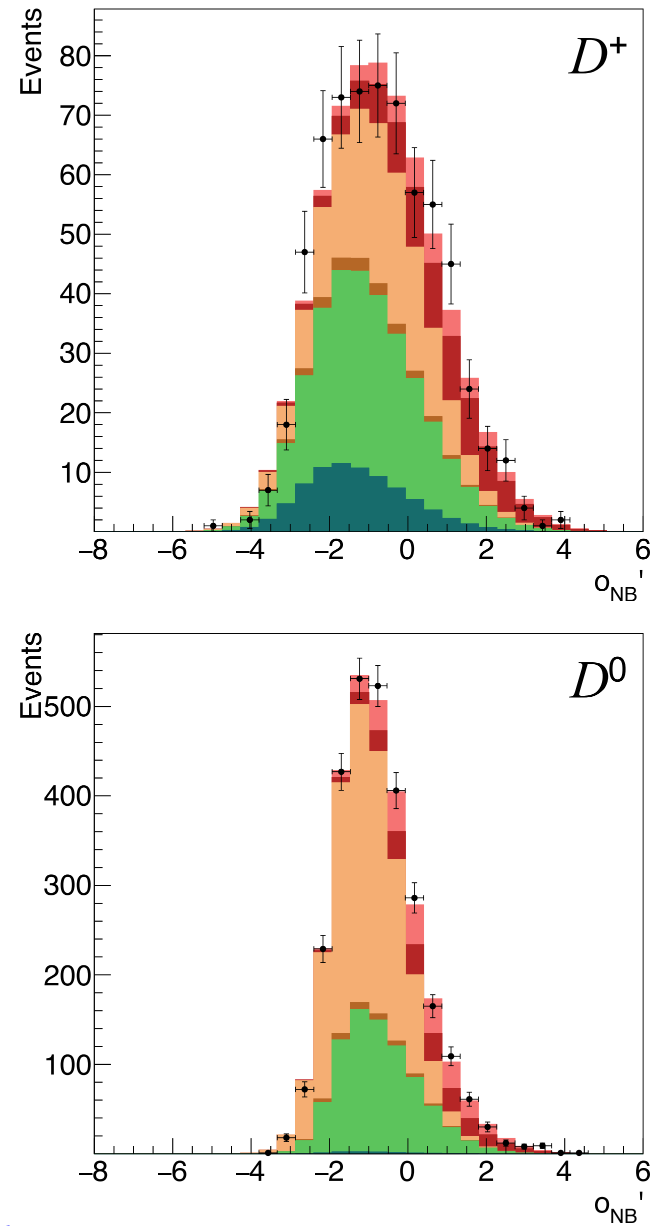
$B \rightarrow D^{(*)}\tau\nu$ (cont'd)

711 fb^{-1} Huschle et al. (Belle), PRD 92, 072014 (2015)

M^2_{miss}



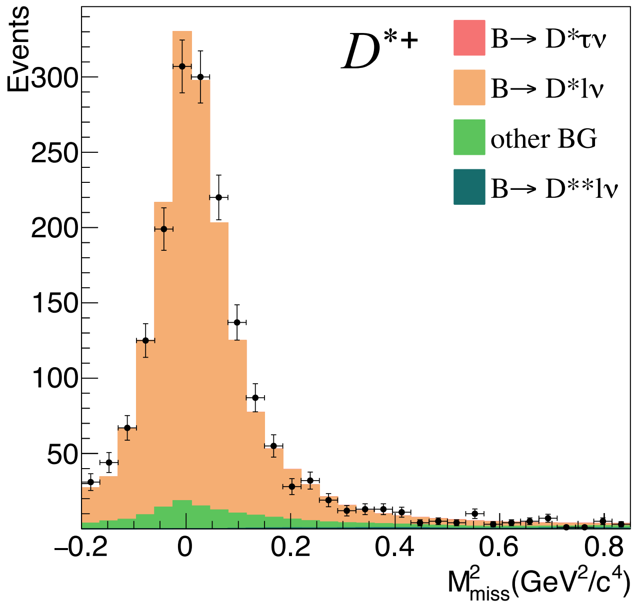
NN (M^2_{miss} > 0.85)

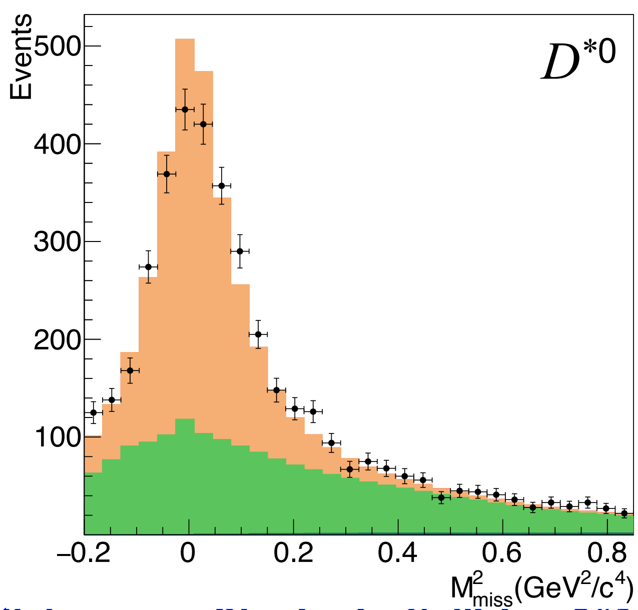


$B \to D^{(*)} \tau \nu$ (cont'd)

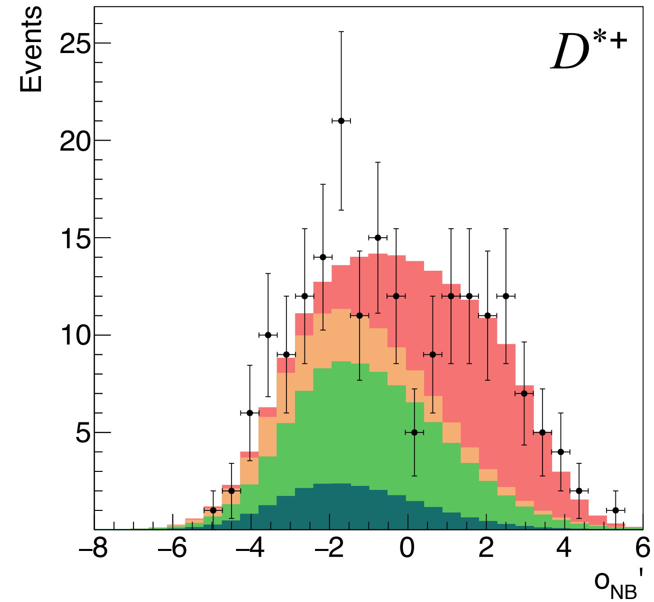
711 fb^{-1} Huschle et al. (Belle), PRD 92, 072014 (2015)

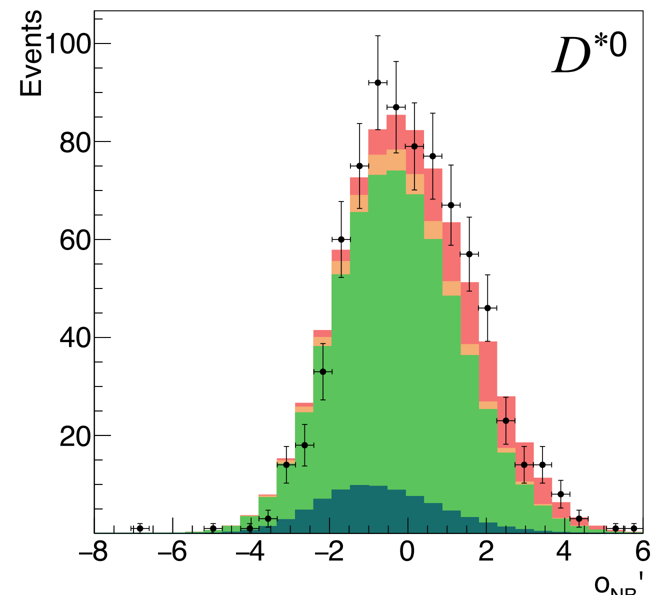
M^2_{miss}





NN (M^2_{miss} > 0.85)





$B \to D^{(*)}\tau\nu$: constraint on Type II charged Higgs

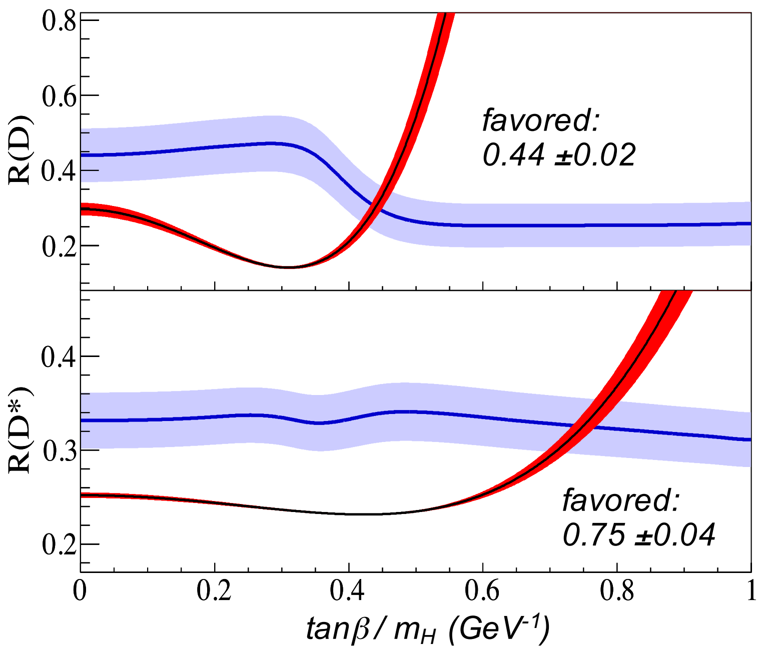
2-Higgs doublet model:

$$\mathcal{R}_{D^{(*)}}^{2HDM} = \mathcal{R}_{D^{(*)}}^{SM} + A_{(*)}\left(\frac{\tan\beta}{m_H}\right)^2 + B_{(*)}\left(\frac{\tan\beta}{m_H}\right)^4$$

	D^*	D
$\mathcal{R}^{SM}$	0.252 ± 0.003	0.297 ± 0.017
A	-0.230 ± 0.029	-3.25 ± 0.32
B	0.643 ± 0.085	16.9 ± 2.0

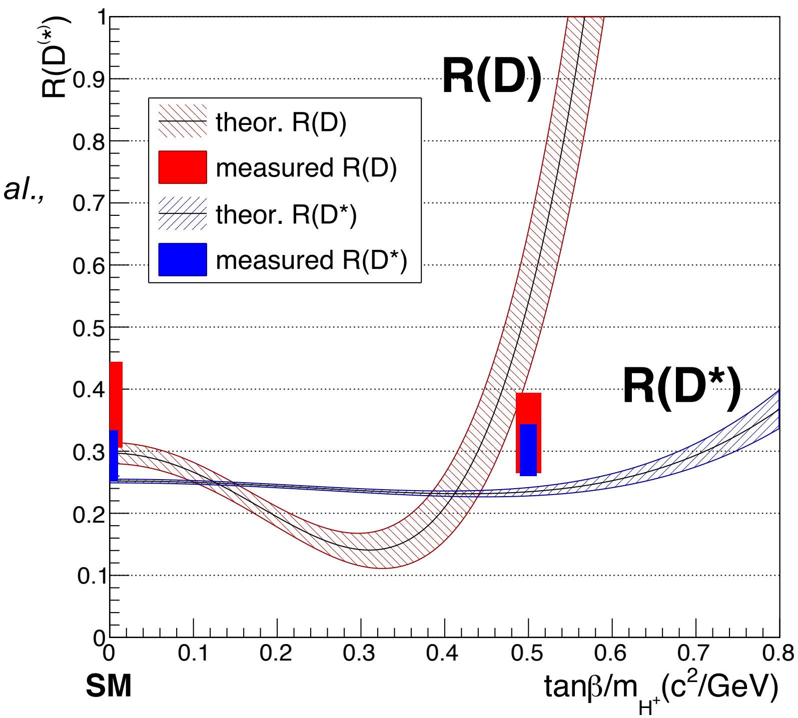
For a Type II charged Higgs doublet model (2HDM), the kinematic distribution of the $\tau\nu$ changes, and thus the PDFs used to fit the data changes $\rightarrow$ must refit $\Rightarrow$ results depend on $\tan\beta/M_H$.

Lees et al., PRD 88, 072012 (2013); PRL 109, 101802 (2012)



Results inconsistent with 2HDM at 3.1σ level

Huschle et al., PRD 92, 072014 (2015)



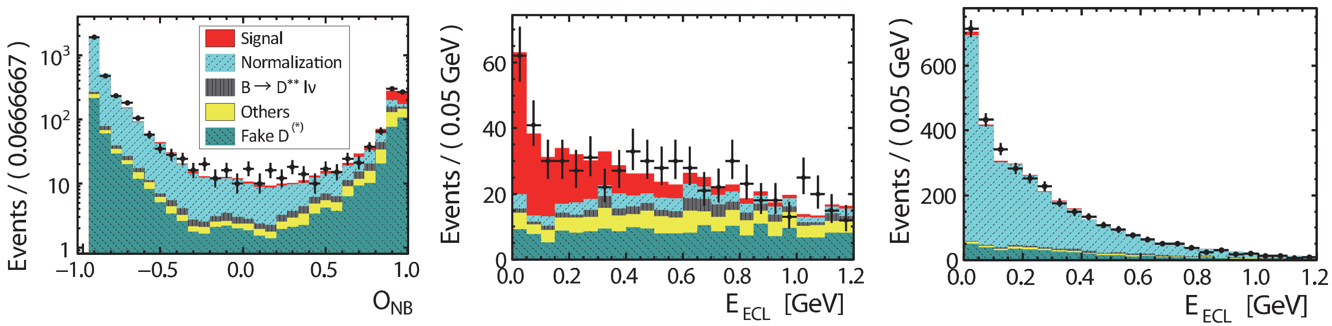
Results consistent with 2HDM

$$\mathcal{R}_{D^*}^{(2HDM)} = 0.301 \pm 0.039 \pm 0.015$$
$$\mathcal{R}_{D}^{(2HDM)} = 0.329 \pm 0.060 \pm 0.022$$

$B \to D^{(*)}\tau^+\nu$: two more Belle analyses

711 fb^{-1} Sato et al., PRD 94, 072007 (2016)

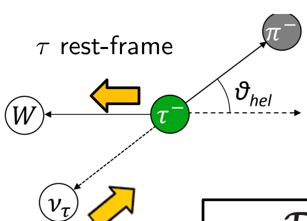
- Use semileptonically tagged events: $B_{tag} \to D^{*+}\ell^- \nu$
- On signal side consider only $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, select $D^{(*)}\mu$ and $D^{(*)}e$ on signal side
- most discrimination power comes from E_{ECL} (unassociated energy in calorimeter)



$$\mathcal{R}_{D^*} = 0.302 \pm 0.030 \pm 0.011$$

711 fb^{-1} Hirose et al., PRL 118, 211801 (2017); arXiv:1709.00129

- Use hadronically tagged events (1104 possible states); On signal side: $\tau \to \pi^- \nu$, $\tau \to \rho^- \nu$
- Measure τ polarization via helicity angle: $P_\tau \equiv \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$



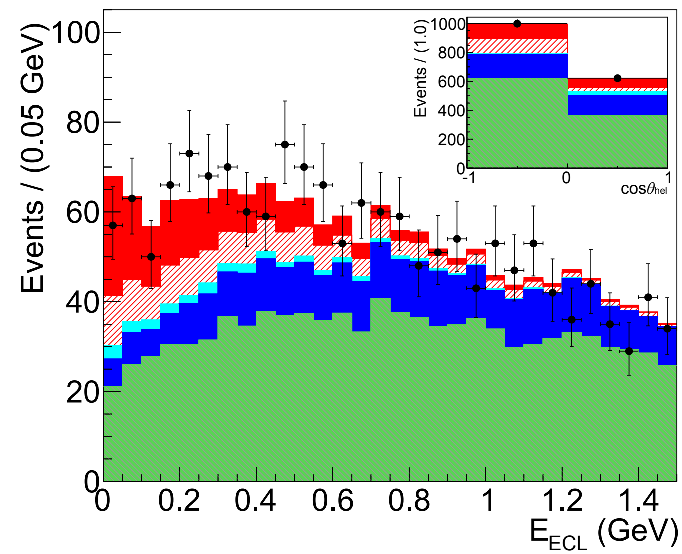
$$\frac{d\Gamma}{d\cos\theta_h} \propto 1 + \alpha P_\tau \cos\theta_h$$

$$\left(\begin{array}{l} \tau \to \pi\nu:\ \alpha = 1 \\ \tau \to \rho\nu:\ \alpha = 0.45 \end{array} \right)$$

$$\mathcal{R}_{D^*} = 0.270 \pm 0.035 \,^{+0.028}_{-0.025}$$

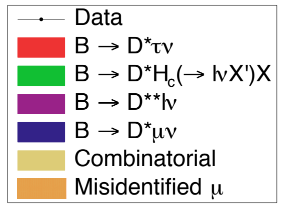
$$P_\tau(D^*) = -0.38 \pm 0.51 \,^{+0.21}_{-0.16}$$

SM: -0.497

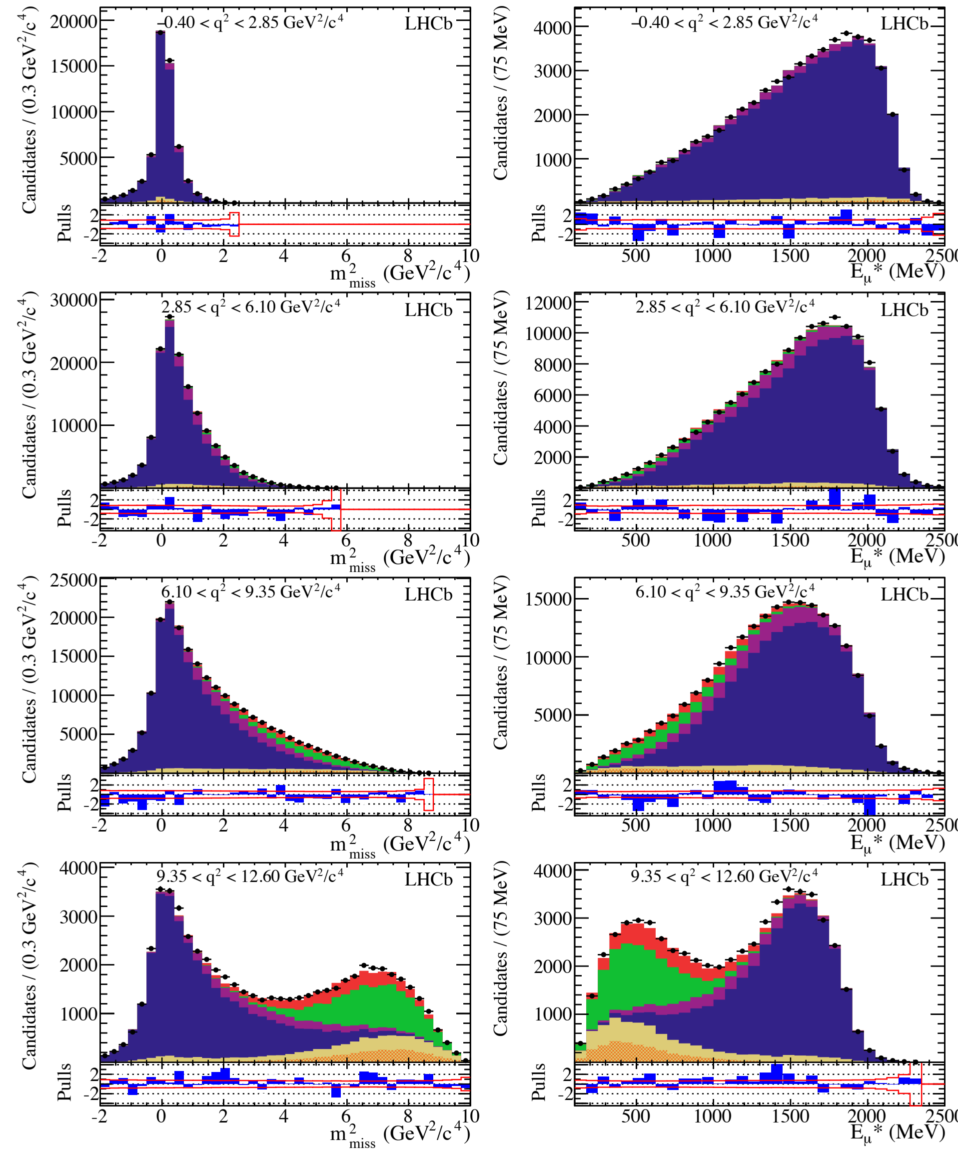


$B \to D^{*}\tau^{+}\nu$: LHCb results

3.0 fb^{-1} Aaij et al., PRL 115, 111803 (2015)



- *select signal via* $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+,\ \tau^- \to \mu^-\nu$ *, normalization is* $B \to D^{*+}\mu^-\nu$
- *require* $K^-\pi^+\pi^+\mu^-$ *be isolated from other tracks to reject:*
  $B \to D^{**}[\to D^{*-}\pi(\pi)]\ \mu^+\nu$
  $B \to D^{*-}H_c\ [H_c \to \mu^+\nu X]\ X$
  $B_s \to [D_{s1}(2536),\ D_{s2}(2573)]\ \mu^+\nu$
- *reverse isolation cut and use* $B \to D^{*+}\mu^-\pi$, $D^{*+}\mu^-\pi\pi$, $B \to D^{*+}\mu^-K$ *control samples to study these backgrounds*
- *dominant systematic comes from hadrons misidentified as muons (use* $B \to D^{*+}h^-$ *control sample to study this)*
- *define* $m^2_{miss} = (P_B - P_{D^*} - P_\mu)^2$ *and* $q^2 = (P_B - P_{D^*})^2$*, count signal via binned ML fit to* m^2_{miss} *,* q^2*, and* E^*_μ
- *Fit finds 363000* $B \to D^{*+}\mu^-\nu$ *, 16500* $B \to D^{*+}\tau^-\nu$



$$\mathcal{R}_{D^*} = 0.336 \pm 0.027 \pm 0.030$$

$B \to D^* \tau^+ \nu$: LHCb results

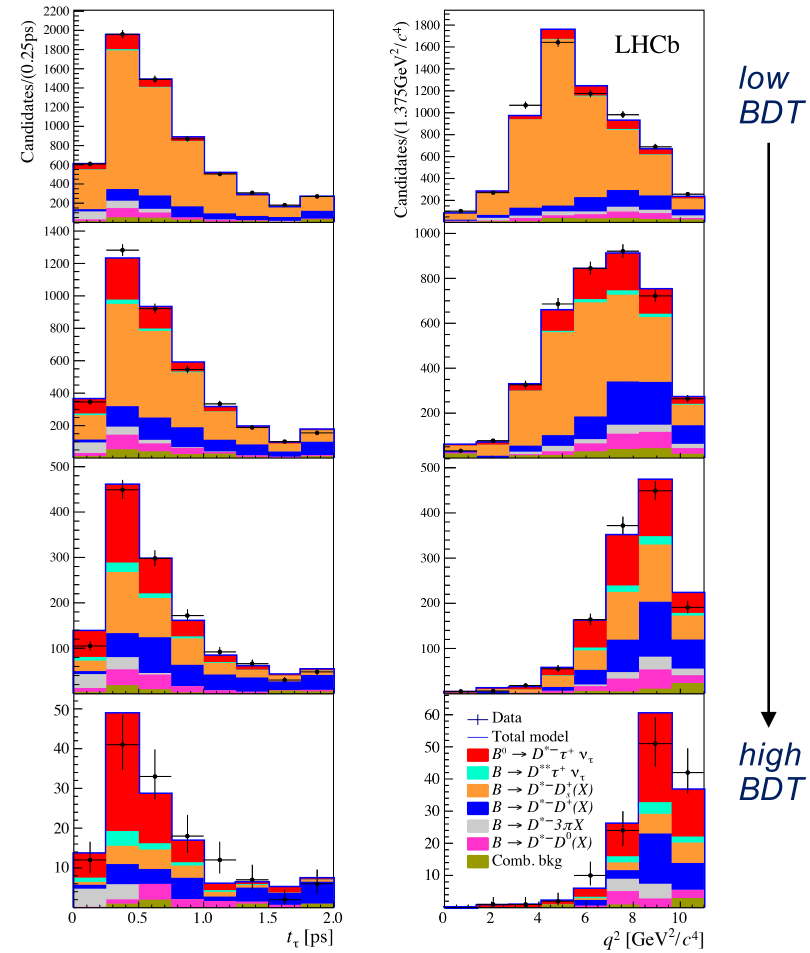
3.0 fb^{-1} Aaij et al., arXiv:1708.08856 (first presented at FPCP 2017)

- select signal via $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$, $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu$,
  $\Rightarrow$ normalization is $B \to D^{*+} \pi^- \pi^+ \pi^-$

$$\mathcal{K}_{D^*} = \frac{\mathcal{B}(B^0 \to D^{*+} \tau^- [\to \pi^+ \pi^- \pi^- \nu] \bar{\nu})}{\mathcal{B}(B^0 \to D^{*+} \pi^+ \pi^- \pi^-)}$$

$$= R_{D^*} \times \frac{\mathcal{B}(B^0 \to D^{*+} \pi^+ \pi^- \pi^-)}{\mathcal{B}(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

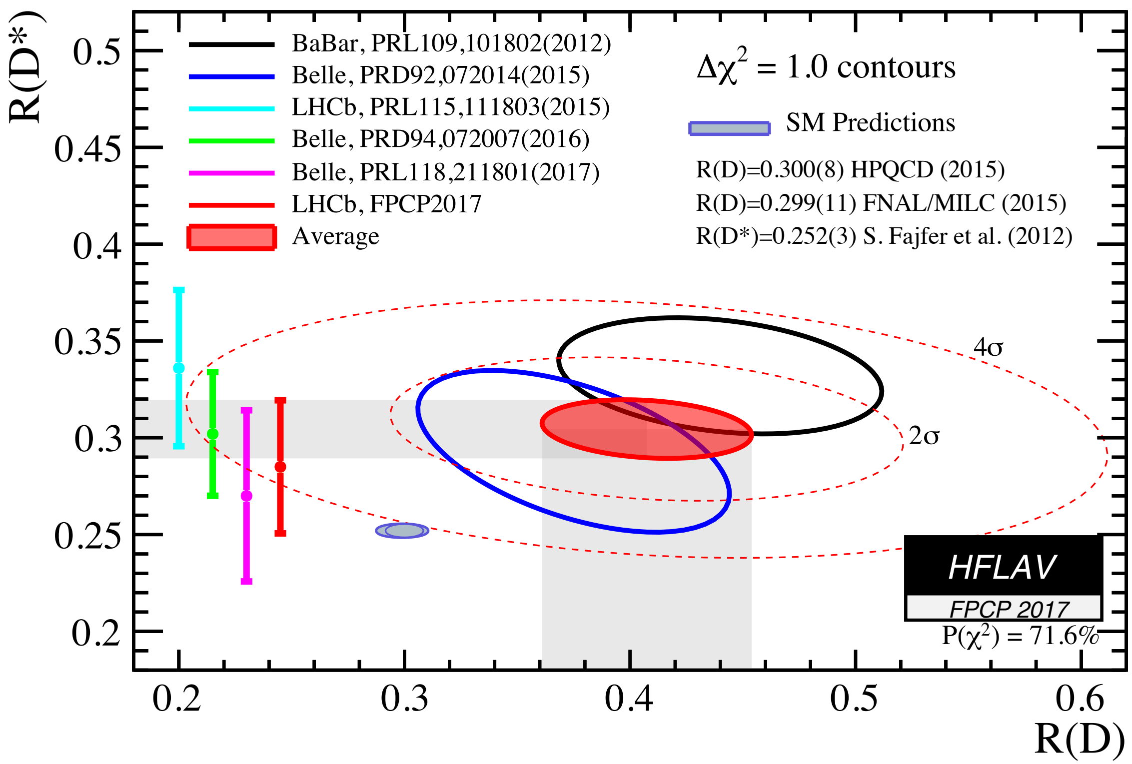
- require $\pi^+\pi^+\pi^-$ vertex be downstream (separated) from D^* decay vertex to reject $B \to D^* \pi^+ \pi^+ \pi^- X$. This rejects background by ~1000, but $\varepsilon_{sig} = 0.35$
- still have backgrounds from $B \to D^{*+} D_{(s)} [\to \pi^+ \pi^+ \pi^- X] X$. Use BDT to reject these. Take admixture (=shapes) of the remaining background from fitting a $D_{(s)} \to \pi^+ \pi^+ \pi^-$-selected control sample
- dominant systematic comes from $B \to D^{*+} D_{(s)} [\to \pi^+ \pi^+ \pi^- X] X$ decays and ε_{ratio}. Also notable systematic from residual $B \to D^* \pi^+ \pi^+ \pi^- X$
- count signal via binned ML fit to t_τ, q^2, and BDT output.
- Fit finds 17660 $B \to D^{*+} \pi^- \pi^+ \pi^-$, 1273 $B \to D^{*+} \tau \nu$



$$\mathcal{K}_{D^*} = 1.93 \pm 0.13 \pm 0.17$$
$$\mathcal{R}_{D^*} = 0.285 \pm 0.019 \pm 0.025 \pm 0.0$$

Overall LHCb average: $\mathcal{R}_{D^*} = 0.306 \pm 0.016 \pm 0.022$

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



Data is 3.9σ above theory;

χ^2 = 18.8 for 2 d.o.f;

p-value = 8.3 x 10^{-5}

LHCb run II data, Belle II should resolve this

SM Predictions:
R(D) =0.297 +- 0.017 [Kamenik & Mescia, PRD 78, 014003 (2008)]
R(D)=0.252 +- 0.003 [Fajfer et al., PRD 85, 094025 (2012)]*

More Recent SM Predictions (Lattice):
R(D) =0.299 +- 0.011 [Bailey et al. (FNAL/MILC), arXiv:1503.07237]
R(D) =0.300 +- 0.008 [Na et al. (HPQCD), arXiv:1505.03925]

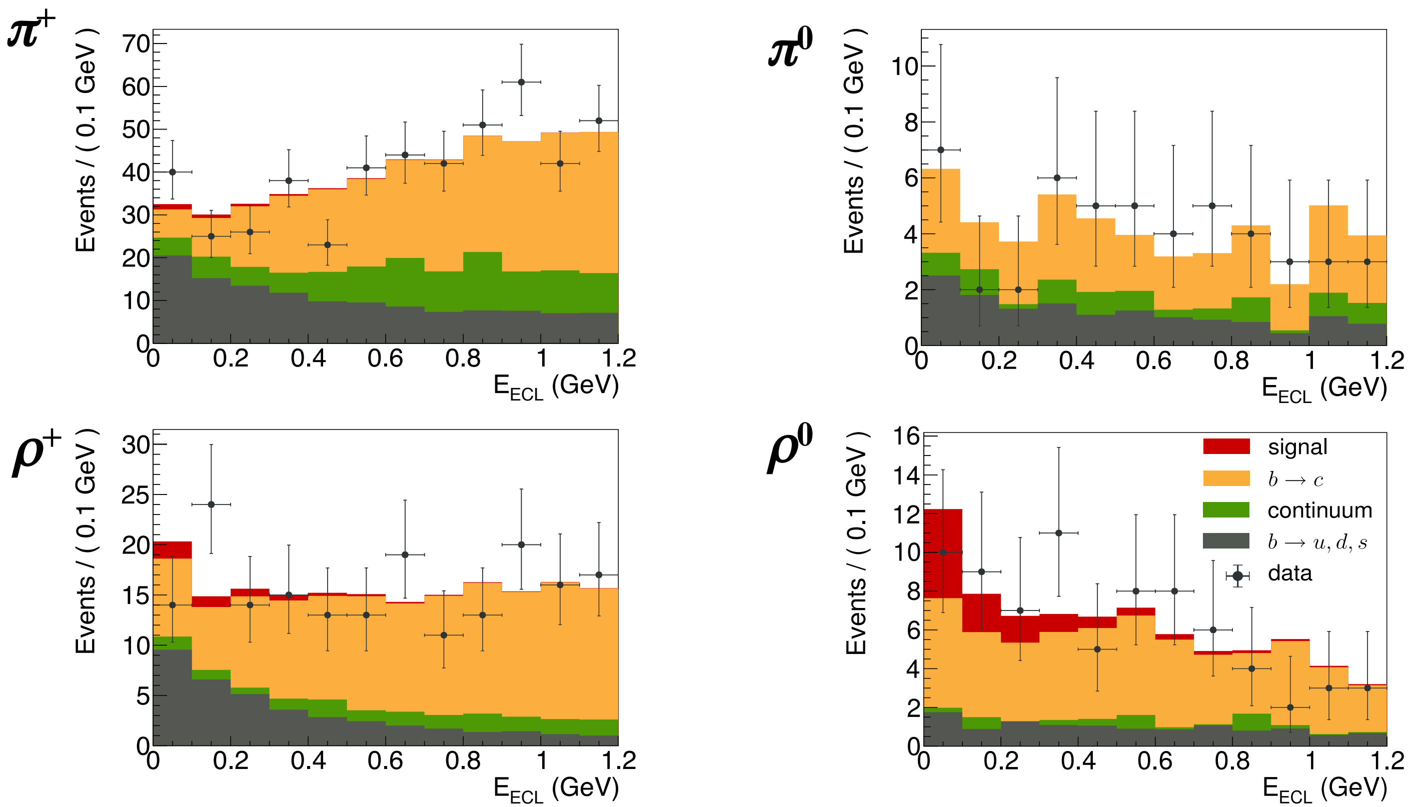
“Forefront” decays

(hard)

$B \rightarrow h\nu\nu$ $(h = \pi^+, \pi^0, \rho^+, \rho^0, K^+, K_S, K^{*0}, K^{*+})$

711 fb^{-1} Grygier et al. (Belle), arXiv:1702.05224 (2017), to appear in PRD

- ***Semileptonic tag:*** *use Neural Network (NN) to identify $B \rightarrow D^{(*)}l\nu$ decay on tagging side. Including D^0 and D^+ modes, there are 108 different decay channels considered.*
- *Require only relevant tracks on signal side: no extra tracks, extra π^0's, or K_L's.*
- *Suppress continuum background (uu, dd, ss, cc) with a second NN based on Fox-Wolfram moments, event topology*
- *Reject backgrounds with a third NN based on 17-31 kinematic variables*
- *Fit E_{ECL} (unassociated energy in the calorimeter) distribution for signal*



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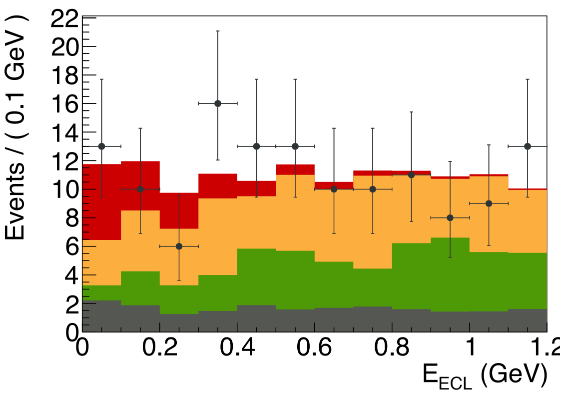
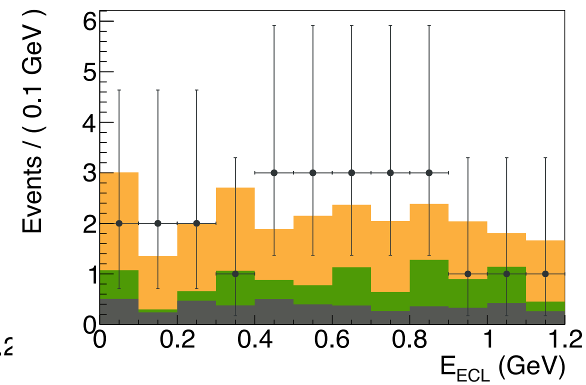
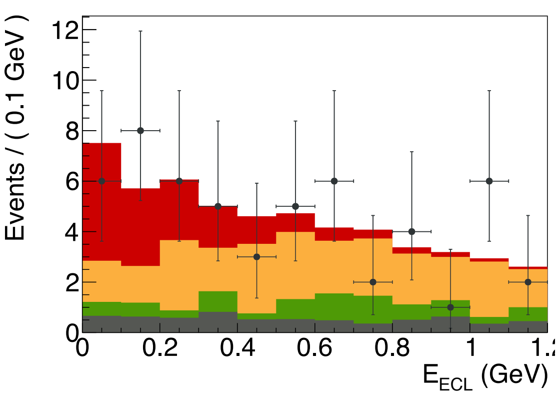
K^+



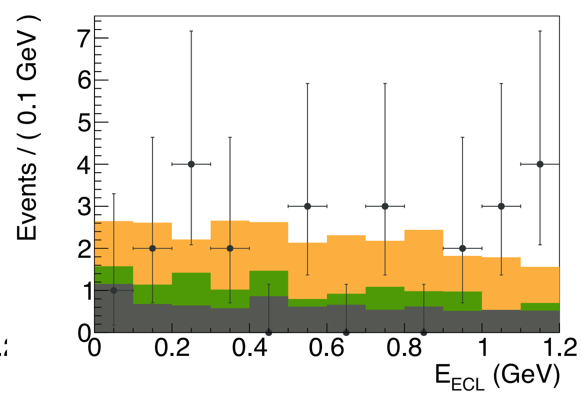
K_S

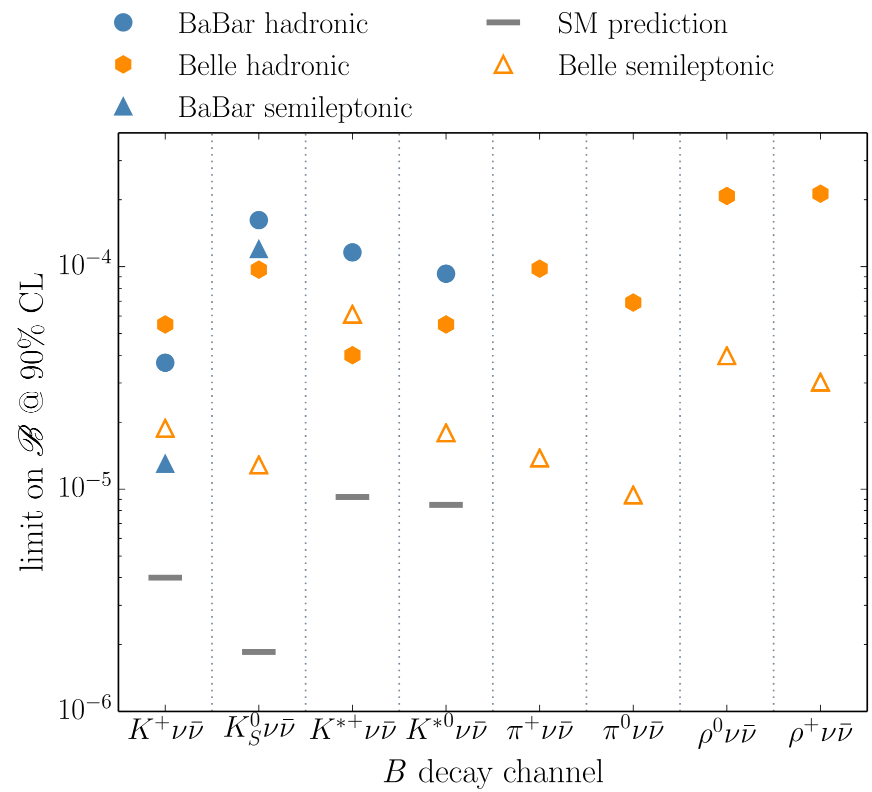


K^{*+}



K^{*0}





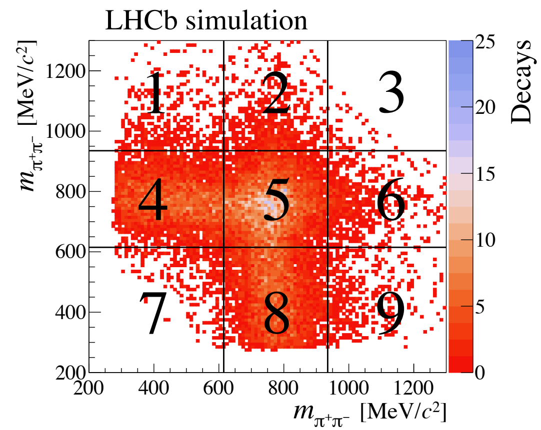
- *no signals observed*
- *most limits are the world's best*
- *limits are a factor of 2.7 (K^*) – 3.9 (K) above SM prediction*

$\Rightarrow$ *Belle II should get to SM level*

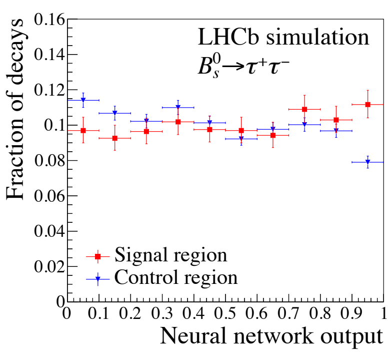
$B_{(s)} \to \tau^+\tau^-$

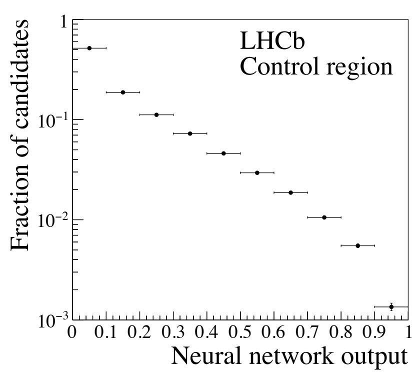
$3.0\ fb^{-1}$ *Aaij et al., PRL 118, 251802 (2017)*

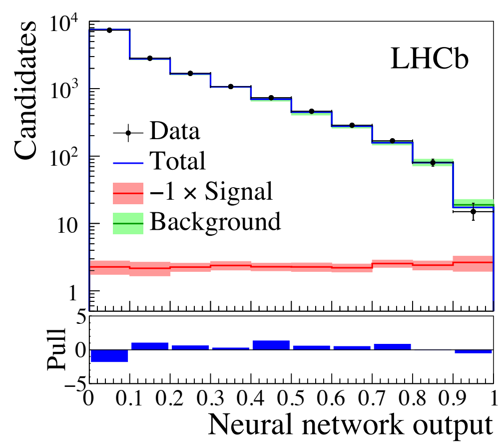
- *reconstruct $\tau^+ \to \pi^+\pi^-\pi^+\nu$, requiring good 3-track vertices*
- *normalize sensitivity to $B^0 \to D^- D_s^+$, with $D^- \to K^+\pi^-\pi^-$, $D_s^+ \to K^+K^-\pi^-$*
- *As $\tau^+ \to \pi^+\pi^-\pi^+\nu$ proceeds mainly via $\tau^+ \to a_1(1260)\nu \to \rho^0\pi^+\nu$, divide $B^0 \to \tau^+\tau^-$ candidates into 9 bins based on $\pi^+\pi^-$ mass; require both τ candidates to be in bin 5; background is modeled from (4,5,8)x(4,8)*
- *require isolation cuts based on tracks, calorimeter energy*
- *impose cut on 7-input NN1*
- *signal yield is determined from binned ML fit to 29-input NN2 output*

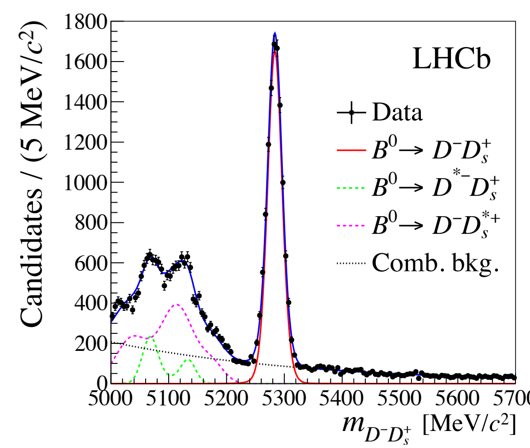


$$\mathcal{N}^{SR}_{data} = s\mathcal{N}^{SR}_{sim} + f_b\left(\mathcal{N}^{CR}_{data} - s\frac{\varepsilon^{CR}}{\varepsilon^{SR}}\mathcal{N}^{CR}_{sim}\right)$$









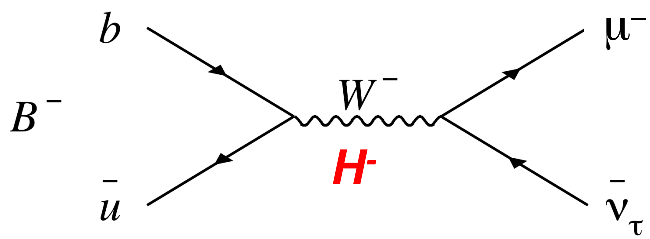
Results:

$$B^0 \to \tau^+\tau^- : \quad s = -15^{+80}_{-70} \quad \mathcal{B} < 1.6 \times 10^{-3} \quad (90\%\ \text{C.L.})$$
$$B^0_s \to \tau^+\tau^- : \quad s = -23^{+75}_{-66} \quad \mathcal{B} < 5.2 \times 10^{-3} \quad (90\%\ \text{C.L.})$$

SM: $(1\text{-}2) \times 10^{-8}$

$B^- \to \mu^- \nu$

711 fb^{-1} PRELIMINARY



$$\mathcal{B}(B \to \mu^+ \nu) = \frac{G_F^2 m_B}{8\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

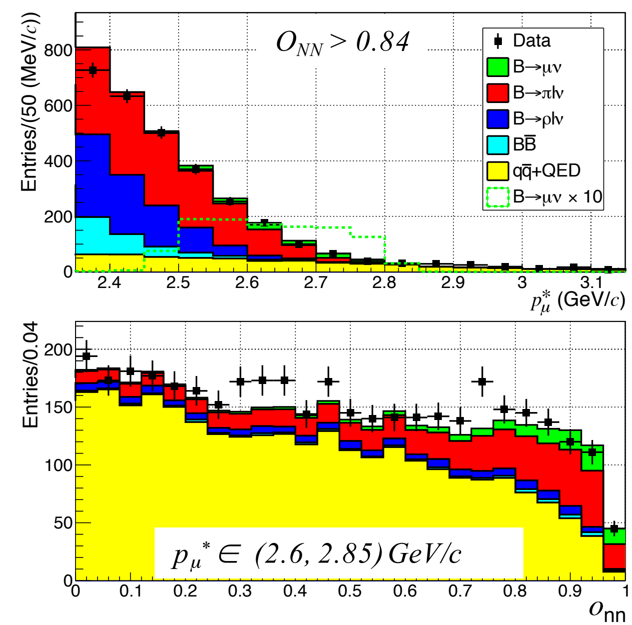
- require well-identified muon in momentum range 2.2-4.0 GeV/c (“monochomatic” range: 2.4776-2.812)
- opposite side B is not reconstructed; require this side to satisfy $M_{bc} > 5.1$ GeV/c^2 and $\Delta E \in (-3, 2)$ GeV
- to reduce remaining 3-orders of magnitude background, use 14-input Neural Network (NN)
- signal is counted via 2-D binned ML fit to O_{NN} and p_μ^* . Fit parameter is the ratio $N(B \to \mu^- \nu)/N(B \to \pi \mu^- \nu)$

$$M_{bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$

PRELIMINARY

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

(2.4σ significance)



Summary

- Decays with neutrinos (semileptonic and leptonic decays) provide an important way to constrain the CKM unitarity triangle (measuring sides) and search for new physics (e.g., charged Higgs). This is complementary to measuring the internal angles.
- The current data shows notable discrepancies:

  Inclusive $|V_{cb}|$ is higher than exclusive $|V_{cb}|$ by $2.4–3.4\sigma$

  Inclusive $|V_{ub}|$ is higher than exclusive $|V_{ub}|$ by 3.3σ

  R(D) and R(D*) are both higher than the SM prediction, which has little uncertainty. The difference is 3.9σ

  The $B^+ \to \tau^+ \nu$ branching fraction is ~2σ higher than the SM prediction

  Data not consistent with a 2-Higgs doublet model
- Two major upgrades in progress:

  at KEK in 2010-18 → Super B factory: $\mathcal{L} \times 40 \Rightarrow 50\ ab^{-1}$. Essentially a new experiment, most detector components and electronics are replaced. First data in 2019

  at LHCb: Phase 1 upgrade during Long Shutdown #2 (2019-20) to take data for Runs 3 (2021-23) and 4 (2027-29)

These will allowed greatly improved sensitivity to new physics, should notably over-constrain the Unitarity triangle, and should resolve the above puzzles

Extra

Extra Slides

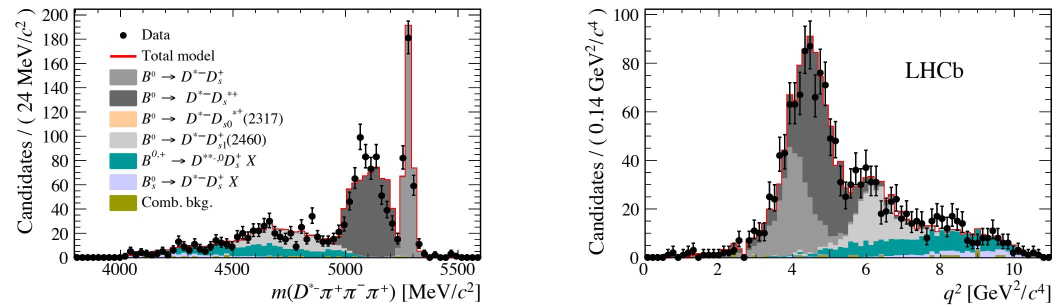
$B \to D^* \tau^+ \nu$: LHCb results

3.0 fb^{-1} *Aaij et al., arXiv:1708.08856 (first presented at FPCP 2017)*

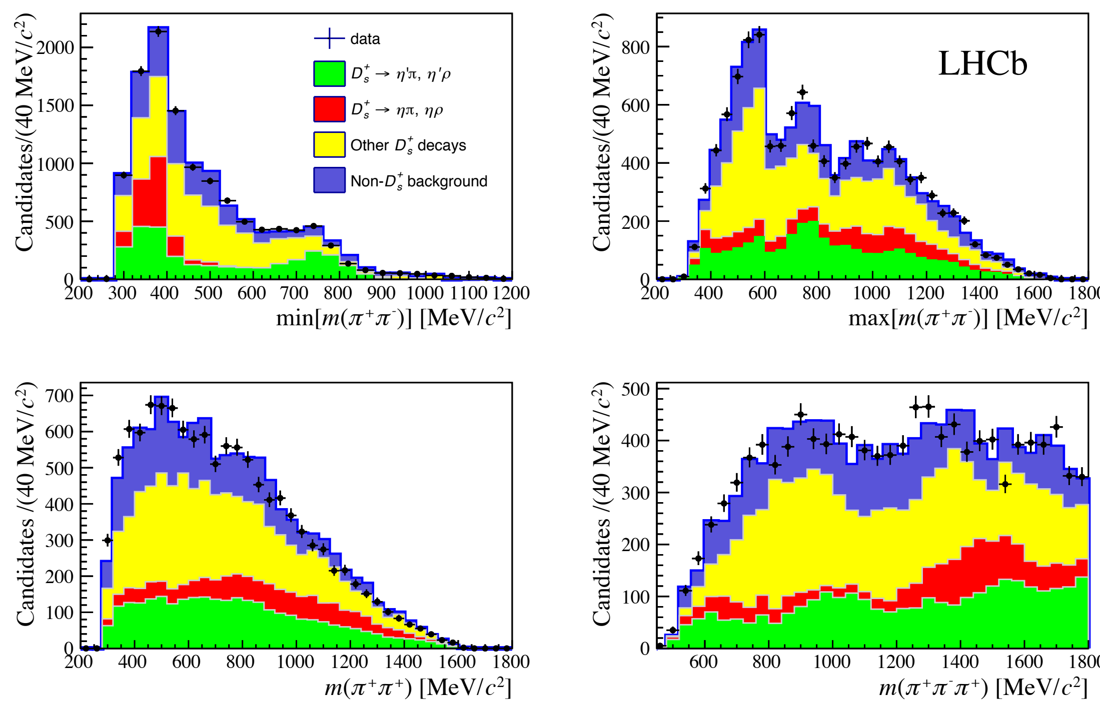
Backgrounds from

$B \to D^{*+} D_{(s)} [\to \pi^+\pi^+\pi^- X] X$:

Use BDT to reject these. Take admixture (=shapes) of the remaining background from fitting a $D_{(s)} \to \pi^+\pi^+\pi^-$-selected control sample:



Tuning D_s decay model using another data control sample:



Missing Energy decays in Belle II

arXiv:1002.5012 (Belle II)

arXiv:1008.1541 (SuperB)

errors.

	Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$ [10]	1.8%	1.4%
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$ [5]	3.4%	3.0%
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 27\%)$ [26]	10%	3%
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.2%	2.5%
	$R(B \to D^*\tau\nu)^\dagger$	$0.332(1 \pm 9.0\%)$ [29]†	2.9%	1.6%
	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [10^{-6}]	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 ($B \to X_s\ell\ell$)	~20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	–	< 2 [44]‡	–