Semileptonic decays at the e^+e^- B factories

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On behalf of the Belle and BaBar Collaborations

FPCP 2018

Hyderabad, July 14, 2018

Outline

1. CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$

- Exclusive $|V_{cb}|$
  - $B \to D^* \ell \nu$: New model-independent measurement **(Belle 2018)** **NEW**
- Inclusive $|V_{ub}|$
  - Updated electron endpoint analysis **(BaBar 2017)**
- Exclusive $|V_{ub}|$
  - First had.-tag measurement of $B \to \eta \ell \nu$, $B \to \eta' \ell \nu$ **(Belle 2017)**

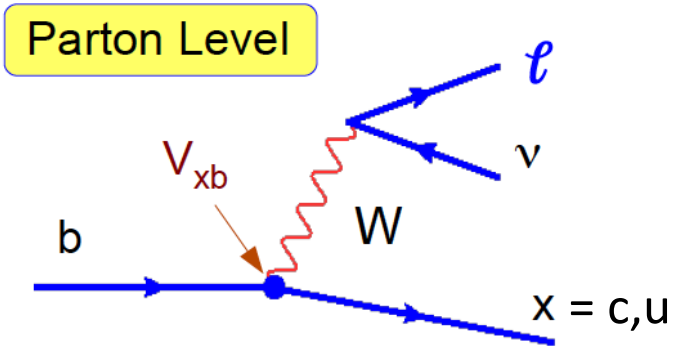
2. Semileptonic B decays with τ leptons

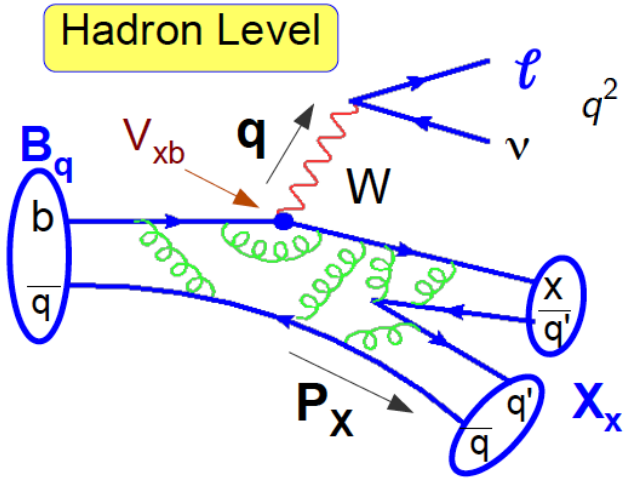
- R(D) and R(D*)
  - τ polarization in $B \to D^* \tau \nu$ **(Belle 2017/18)**

3. Higher charm resonances D**

- New $B \to D^{(*)} \pi \ell \nu$ measurements **(Belle 2018)** **NEW**

Semileptonic B decays

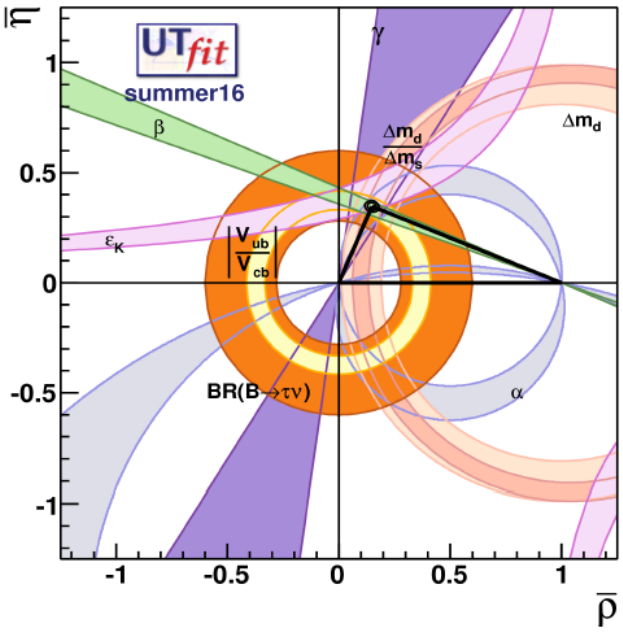




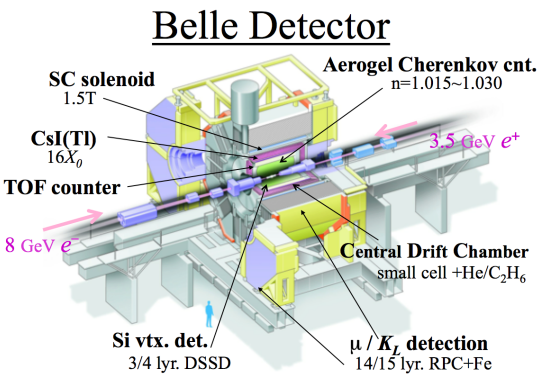
- Ideally suited to determine CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$

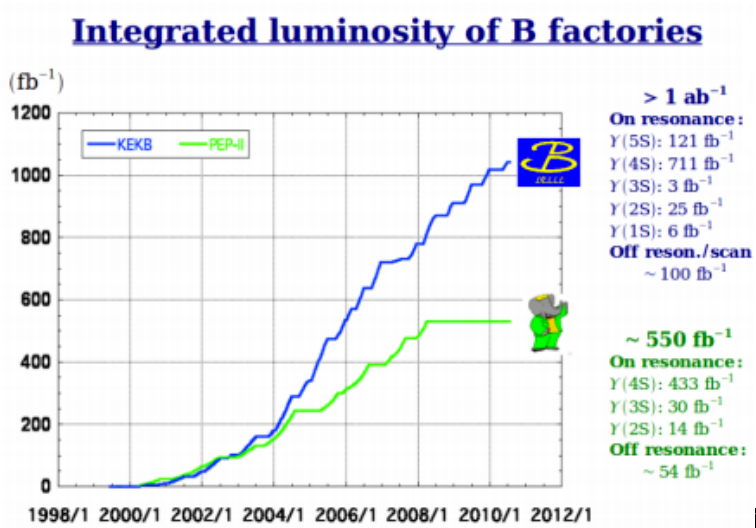
- **Inclusive** decays: $B \to X_{u,c}\ell\nu$
  - QCD corrections to parton level decay rate
  - Operator Product Expansion (OPE) in α_S and Λ/m_b

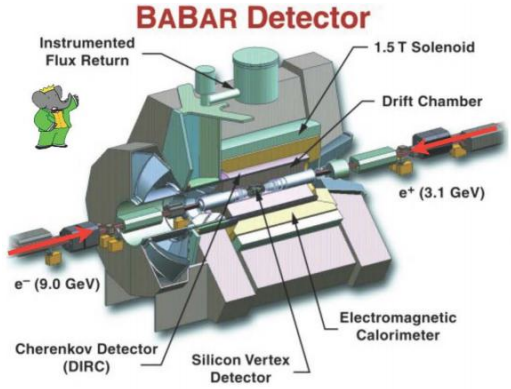
- **Exclusive** decays: $B \to D/D^*/\ldots\ell\nu$, $B \to \pi/\rho/\ldots\ell\nu$
  - QCD contributions parametrized in form factors
  - Lattice QCD (high q^2) or LCSR (low q^2)

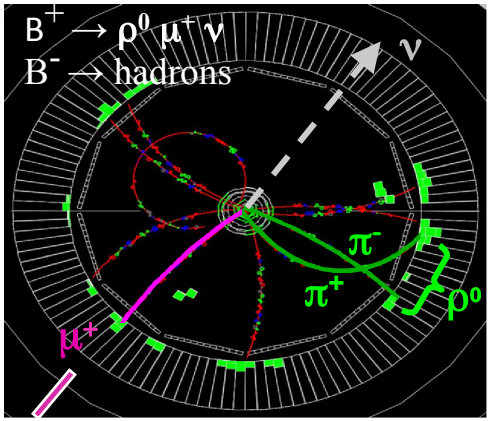


The e^+e^- B Factories







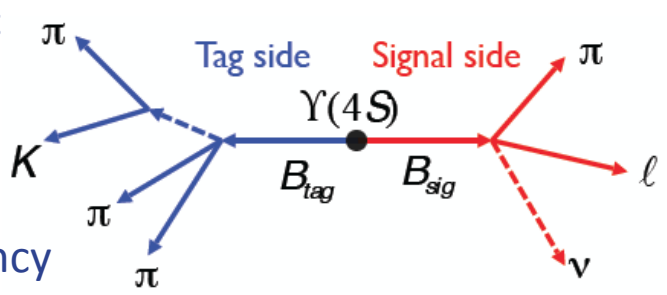


- Clean environment
  - efficient detection of neutral particles (γ, π^0, η, …)

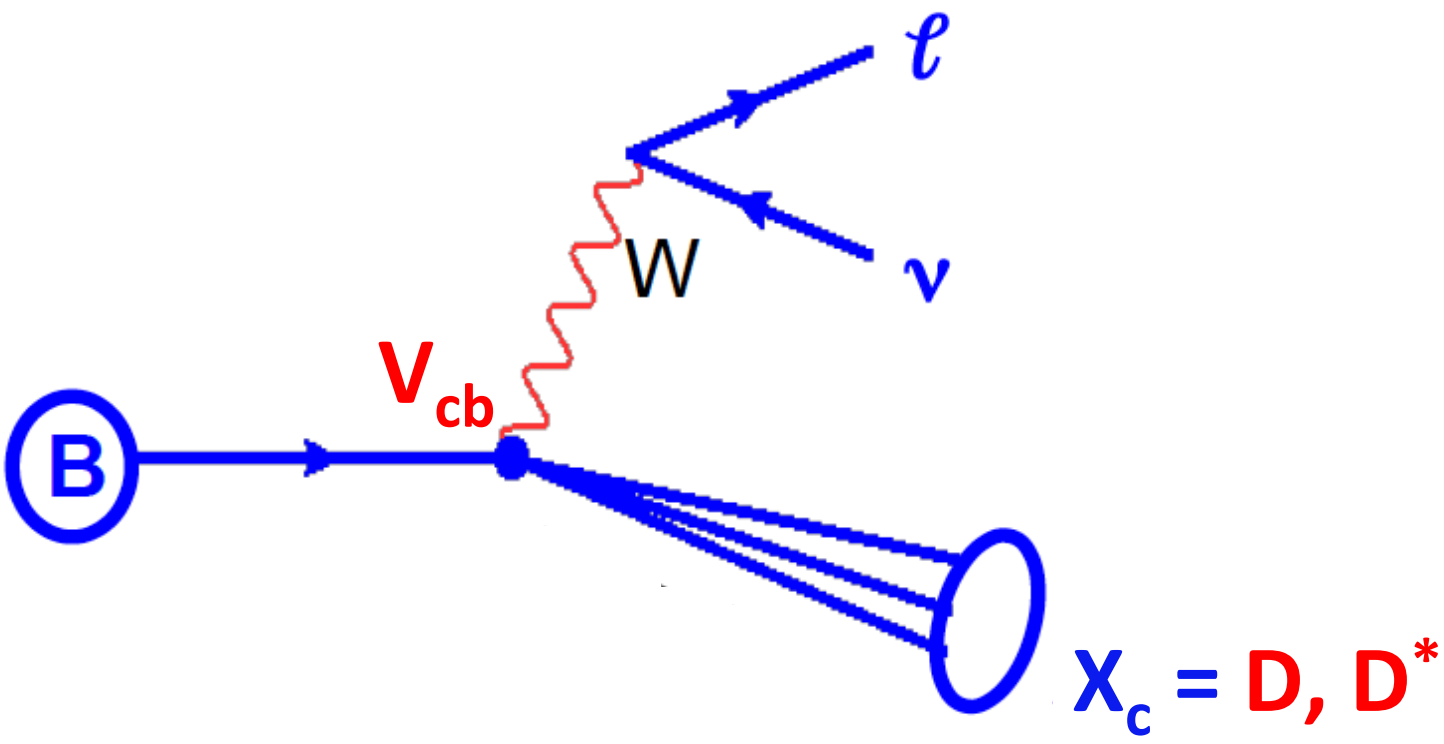
- Full-reconstruction B tagging

  ⇒ Powerful tool to measure:
  - decays with missing energy
  - inclusive decays

~ 1000 hadronic decay modes

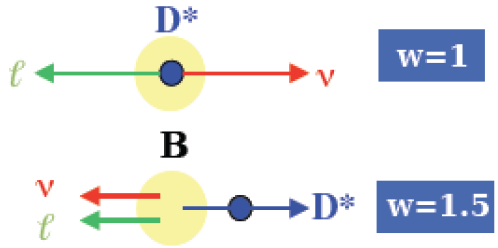


Tagging Efficiency ~ few ‰


ℓ
ν
W
V cb
B
X c = D, D*

$B \to D^{(*)}\ell\nu$: Rates and form factors

$B \to D\ell\nu$: $$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} m_D^3 (m_B + m_D)^2 (w^2-1)^{3/2} |V_{cb}|^2 G^2(w)$$



$B \to D^*\ell\nu$: $$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 (w^2-1)^{1/2} \chi(w) |V_{cb}|^2 F^2(w)$$

Form factor parametrizations

- CLN: *Caprini, Lellouch, Neubert, Nucl.Phys.B530, 153 (1998)*

$B \to D\ell\nu$

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

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

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

- BGL: *Boyd, Grindstein, Lebel, Phys.Rev.Lett. 74, 4603 (1995)*

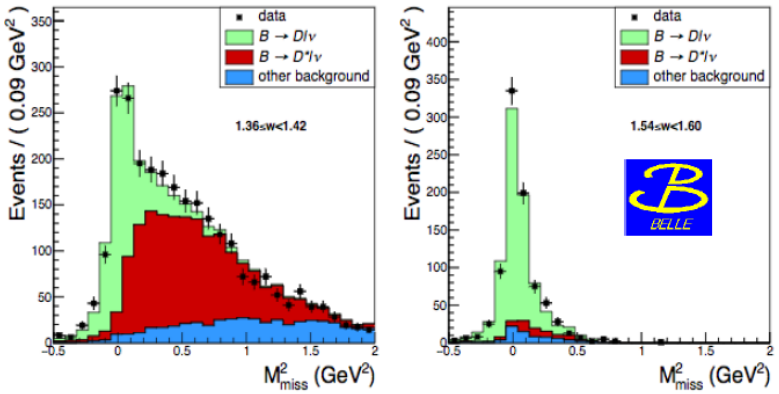
$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

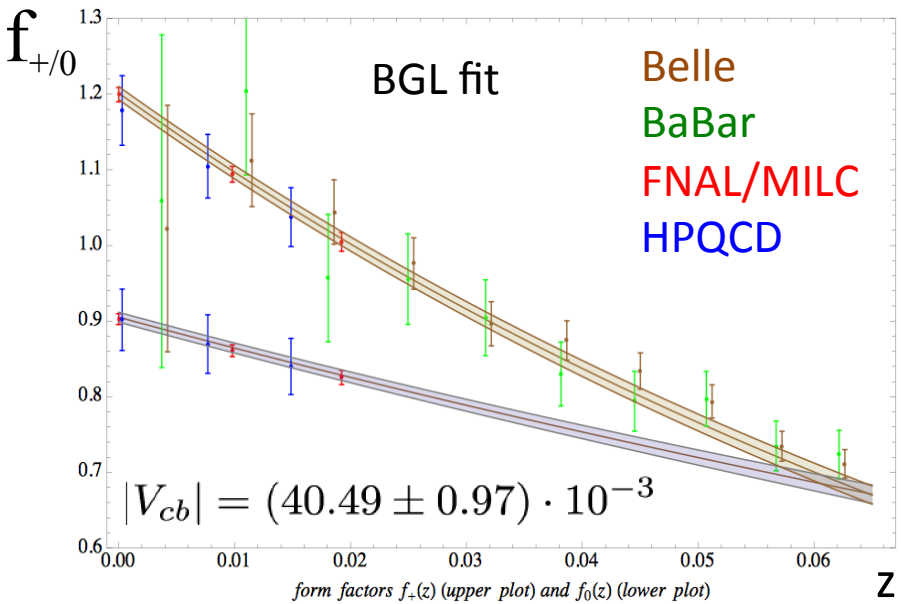
$B \to D^{(*)} \ell \nu$

$B \to D \ell \nu$

- Hadronic tag ⇒ fit M^2_{miss} in bins of w

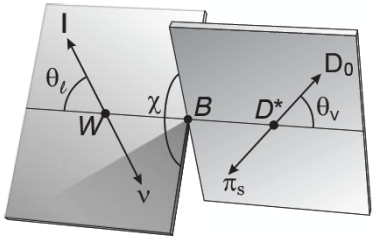
Phys. Rev. D 93, 032006 (2016)





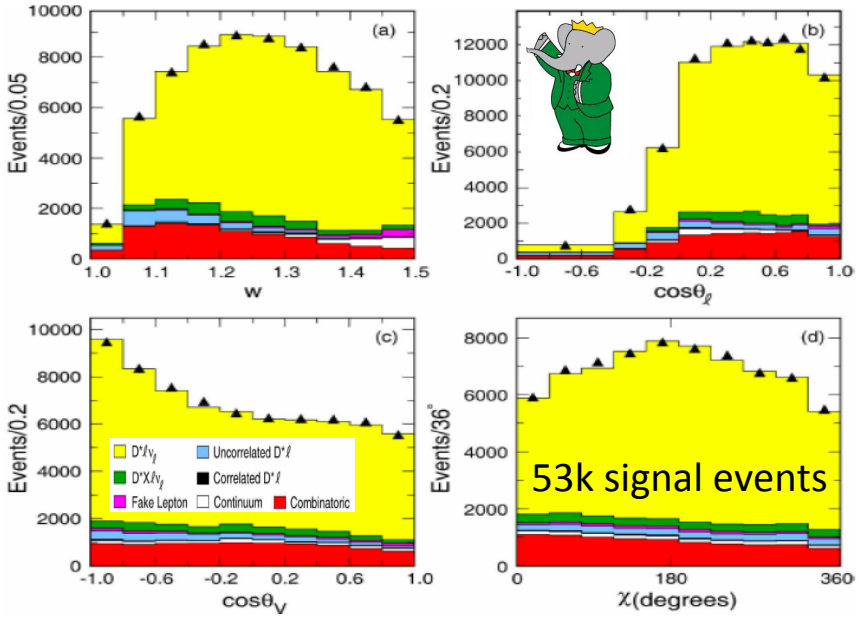
Bigi, Gambino Phys.Rev.D 94,094008(2016)

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

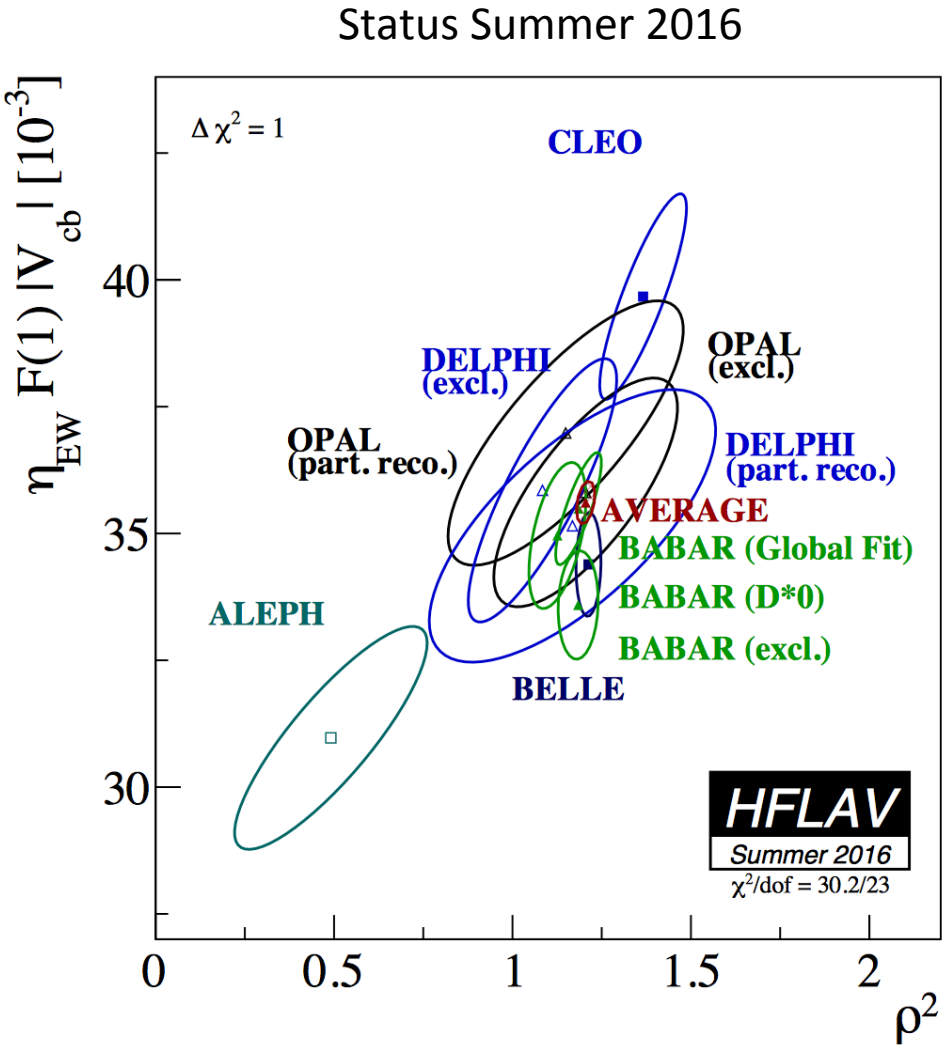


- Untagged
- Fit 1D projections of w, $\cos\Theta_\ell$, $\cos\Theta_V$, χ to extract ρ^2, $R_1(w)$, $R_2(w)$ and $F(1)|V_{cb}|$
- Account for bin-by-bin correlations

Phys.Rev.D77:032002,2008



$B \to D^* \ell \nu$: Status 2016



- As of summer 2016, all $B \to D^* \ell \nu$ analyses based on CLN parametrization

- HFLAV average using CLN:

$$\begin{aligned} \eta_{EW}\mathcal{F}(1)|V_{cb}| &= (35.61 \pm 0.43) \times 10^{-3} , \\ \rho^2 &= 1.205 \pm 0.026 , \\ R_1(1) &= 1.404 \pm 0.032 , \\ R_2(1) &= 0.854 \pm 0.020 , \end{aligned}$$

- With unquenched LQCD calculation of F(w) at w=1 from FNAL/MILC:

Bailey et al., Phys.Rev.D89,114504(2014)

$$|V_{cb}| = (38.71 \pm 0.47_{\rm exp} \pm 0.59_{\rm th}) \times 10^{-3}$$

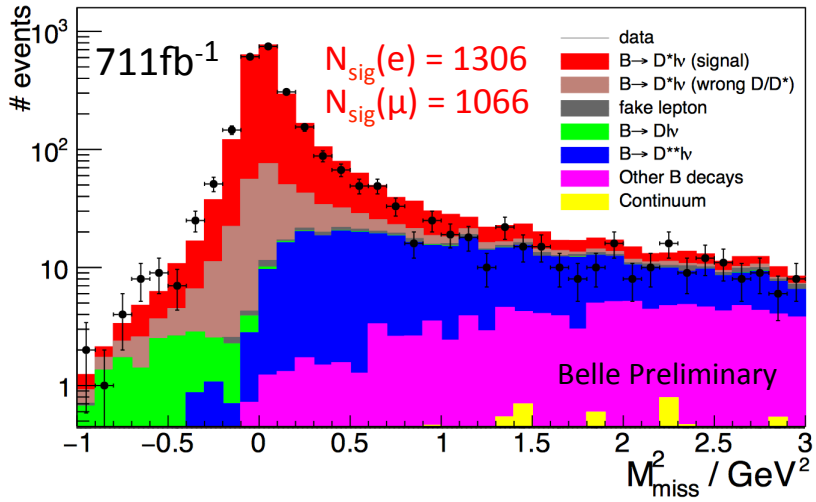
Old data cannot easily be re-analyzed with different parametrizations

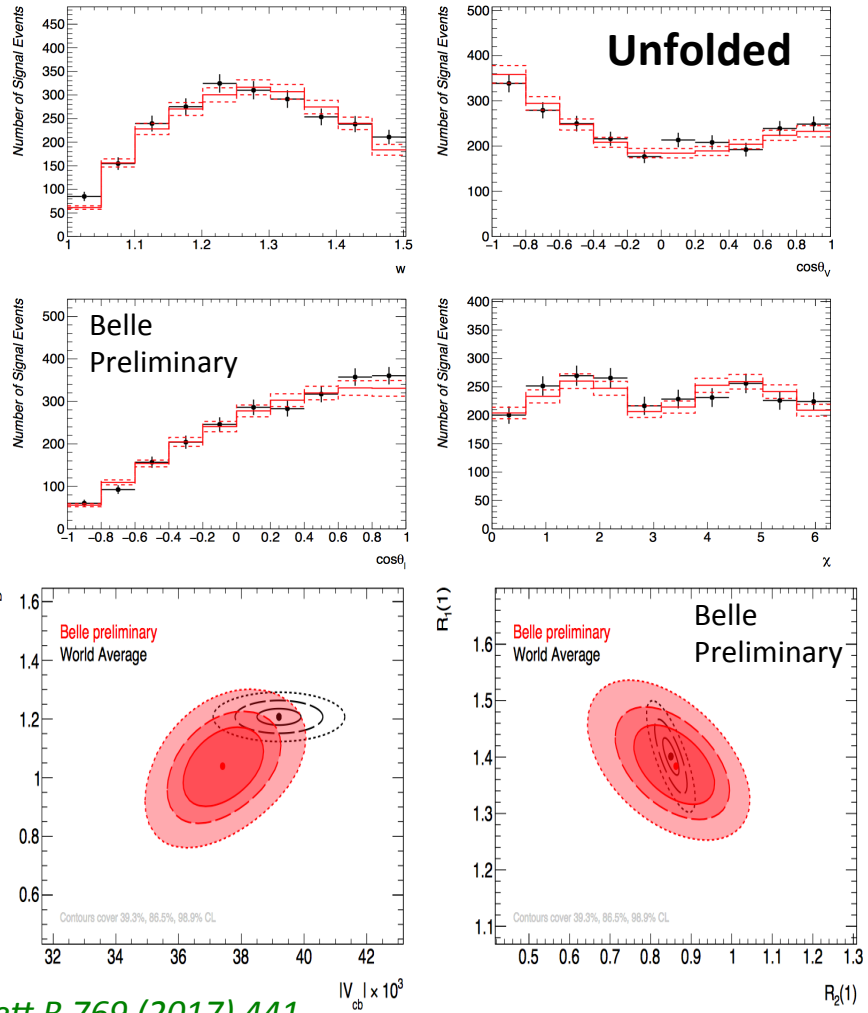
⇒ new "model-independent" analyses using BGL

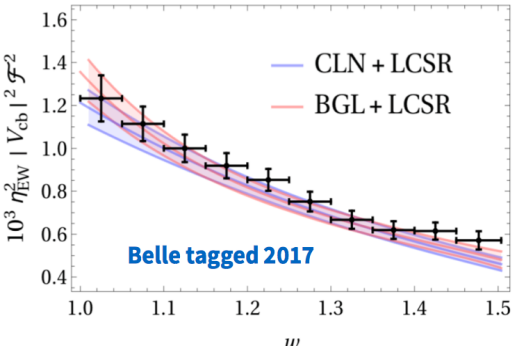
Model-independent analysis: Tagged $B \to D^{*}\ell\nu$

Belle Prelim. Results, arXiv:1702.01521 [hep-ex]

- Hadronic B tags
- Signal extracted from unbinned max-LH fit to M^2_{miss} in 4 × 10 bins of w, 3 angles
- **Unfolding** of kinematic distributions







Bigi, Gambino, Schacht Phys.Lett B 769 (2017) 441

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)

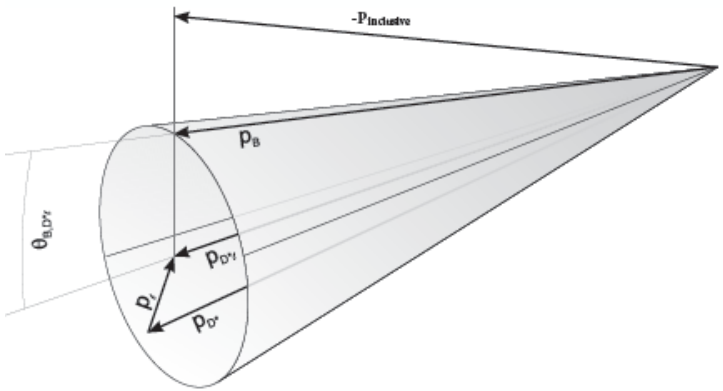
BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\ (^{+20}_{-21})$	$0.0404\ (^{+16}_{-17})$

Model-independent analysis: Untagged $B \to D^* \ell \nu$

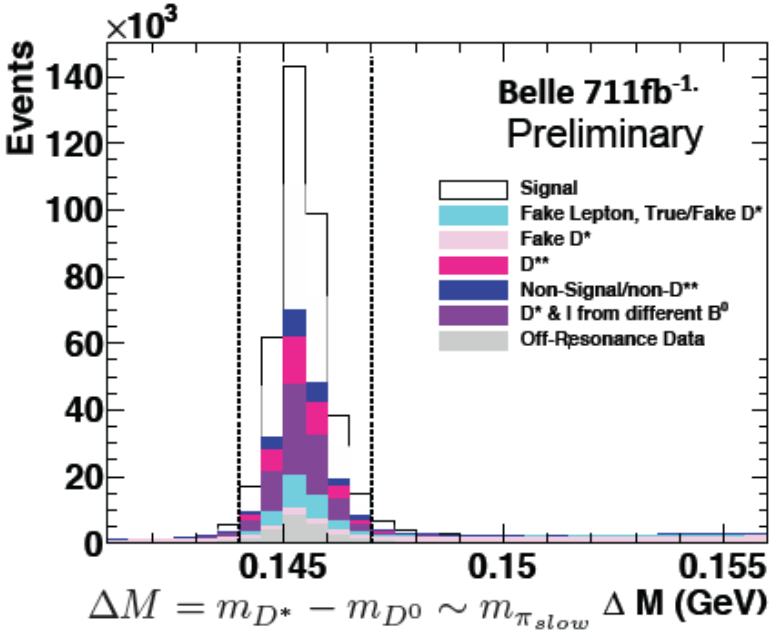
NEW! Prelim. results presented at ICHEP 2018

- $P_\ell^* > 0.85$ GeV (ℓ = e, μ)
- $144 < m_{D^*} - m_D < 147$ MeV
- $|\cos\Theta_{B\text{-}D^*\ell}| < 1.0$

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



$$\vec{p}_{inclusive} = \vec{p}_{beam} - \sum \vec{p}_i$$



N($B \to D^* e\nu$) = 91381

N($B \to D^* \mu\nu$) = 89965

- Simultaneous fit of 1D projections of w, $\cos\Theta_l$, $\cos\Theta_V$, χ to extract form-factor parameters and $F(1)|V_{cb}|$ using both CLN and BGL (n=3) param.

Model-independent analysis: Untagged $B \to D^* \ell \nu$

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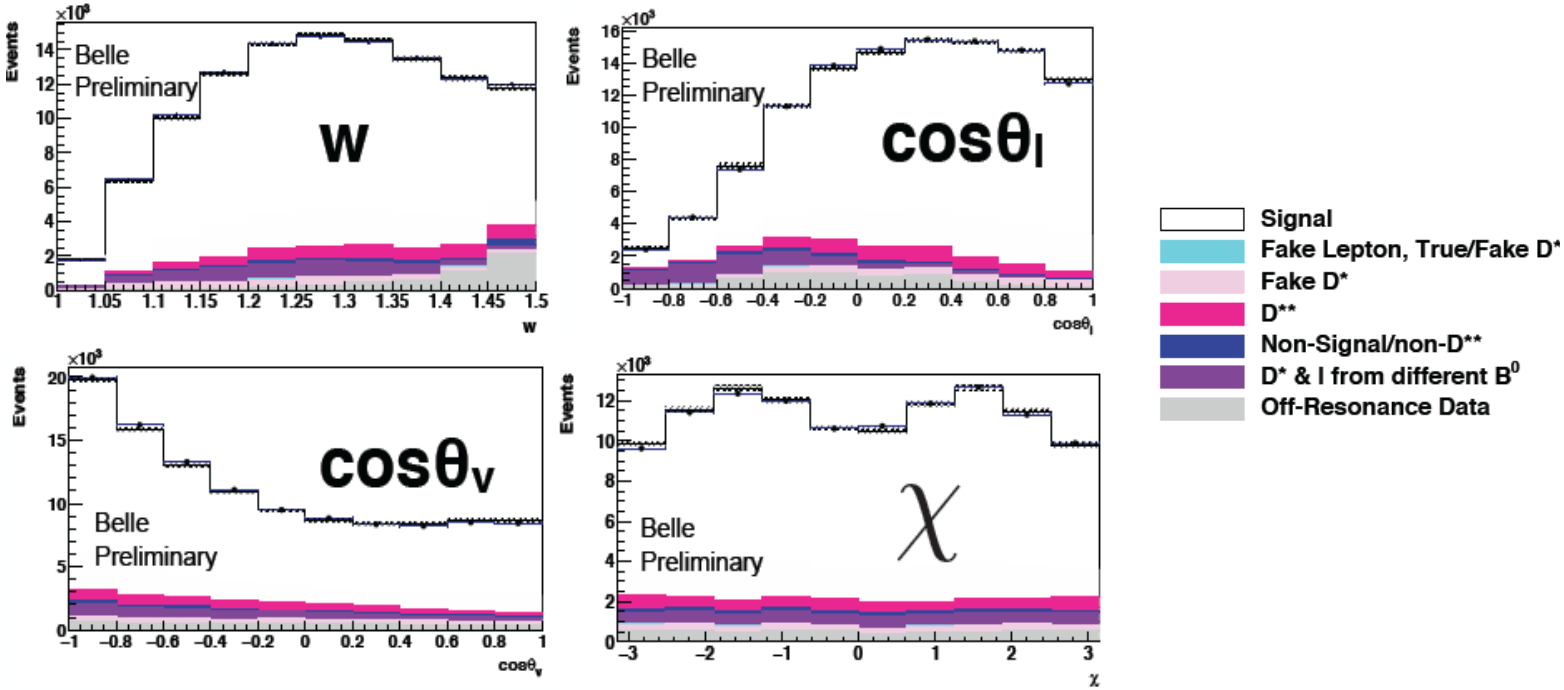


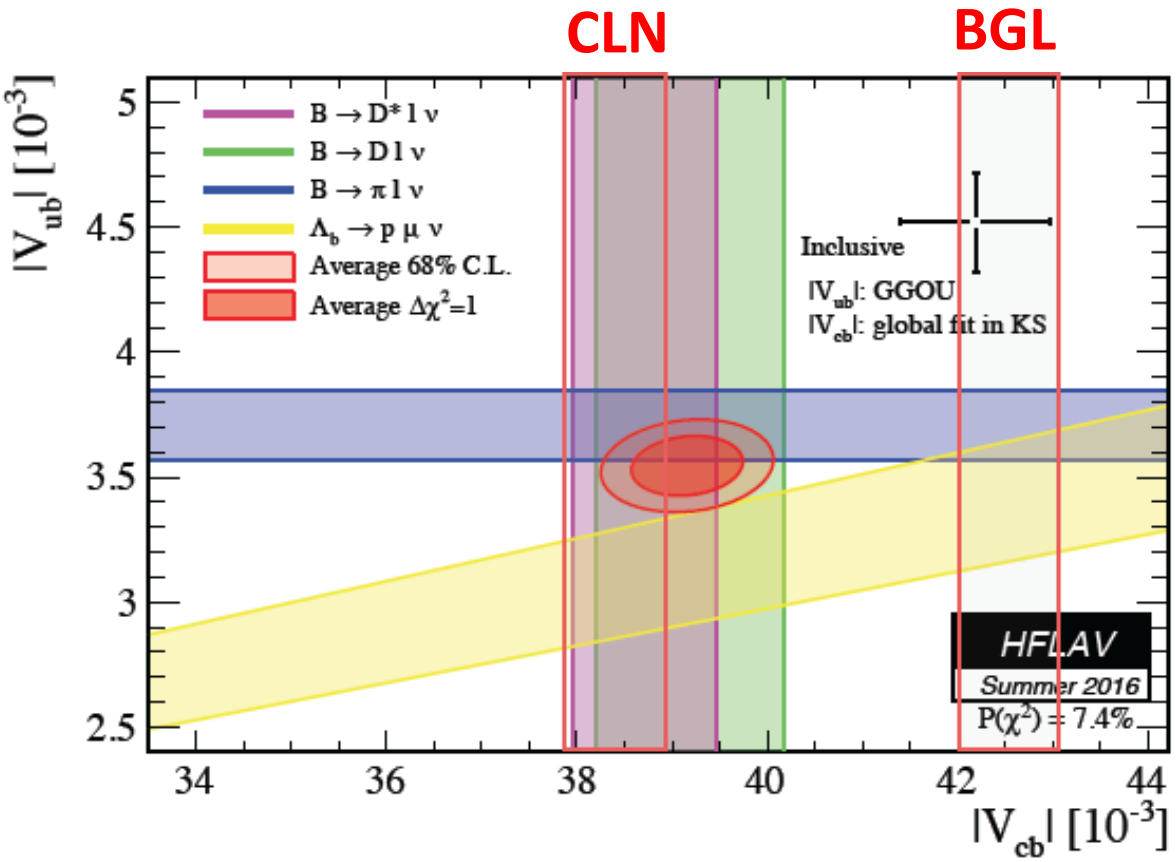
	Belle untagged	Belle had. tag	HFLAV average
		CLN	
ρ_{D^*}	1.106 ± 0.032	1.17 ± 0.15	1.21 ± 0.03
$R_1(1)$	1.229 ± 0.029	1.39 ± 0.09	1.40 ± 0.03
$R_2(1)$	0.852 ± 0.022	0.91 ± 0.08	0.85 ± 0.02
$\lvert V_{cb} \rvert \times 10^3$	38.4 ± 0.87	38.2 ± 1.5	39.2 ± 0.7
		BGL	
$\lvert V_{cb} \rvert \times 10^3$	42.5 ± 0.97	41.7 ± 2.0	–

"New $|V_{cb}|$ status"

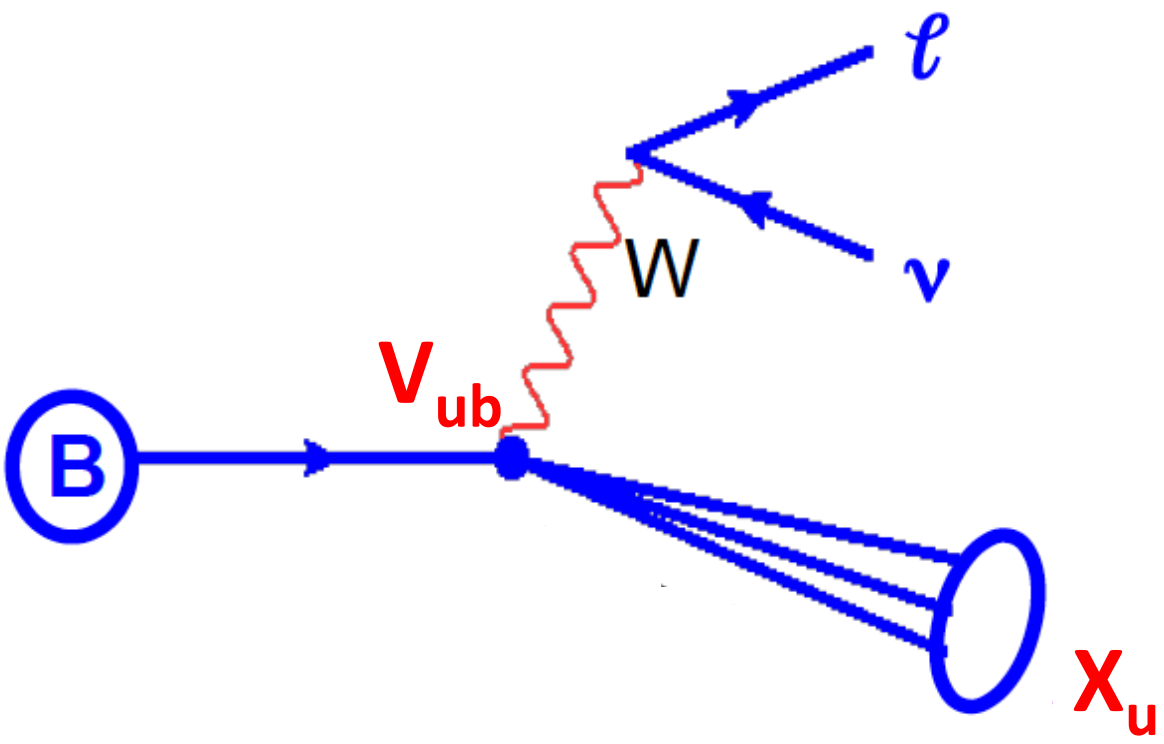
$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ **Inclusive $|V_{cb}|$**

$|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (BGL)**

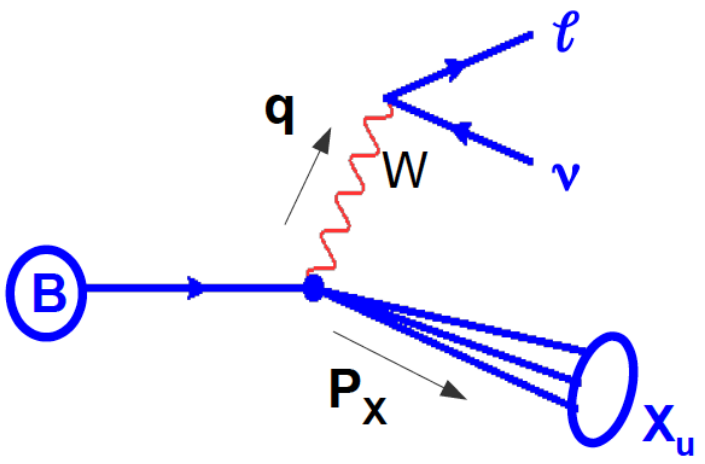
$|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (CLN)**



BGL fit for $B \to D^* \ell \nu$ in good agreement with inclusive result!


ℓ
ν
W
V_{ub}
B
X_u

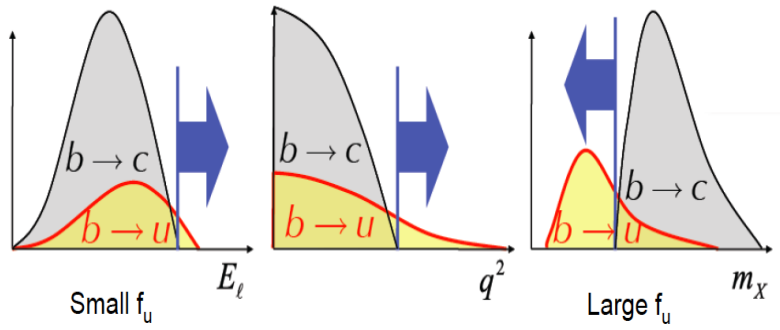
Inclusive $B \to X_u \ell \nu$

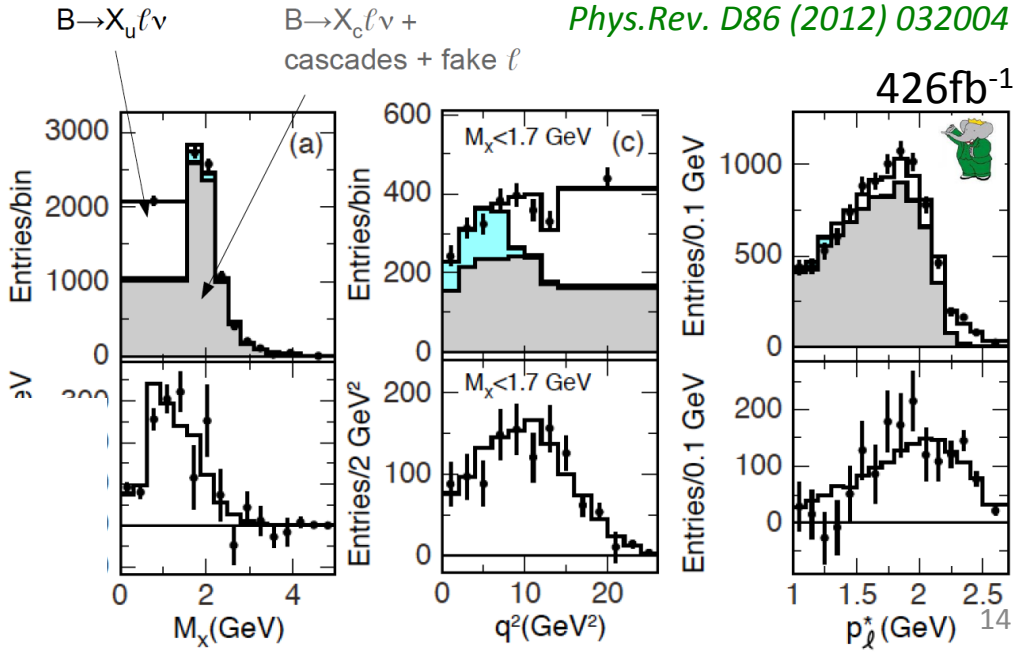


- Large background from $B \to X_c \ell \nu$
- Extract signal in kinematic variables ($m_u < m_c$)
- Restricted phase space region (fraction f_u) problematic for partial rate calculation
  - Non-perturbative shape function needed
  - Universal only at leading order in Λ/m_b

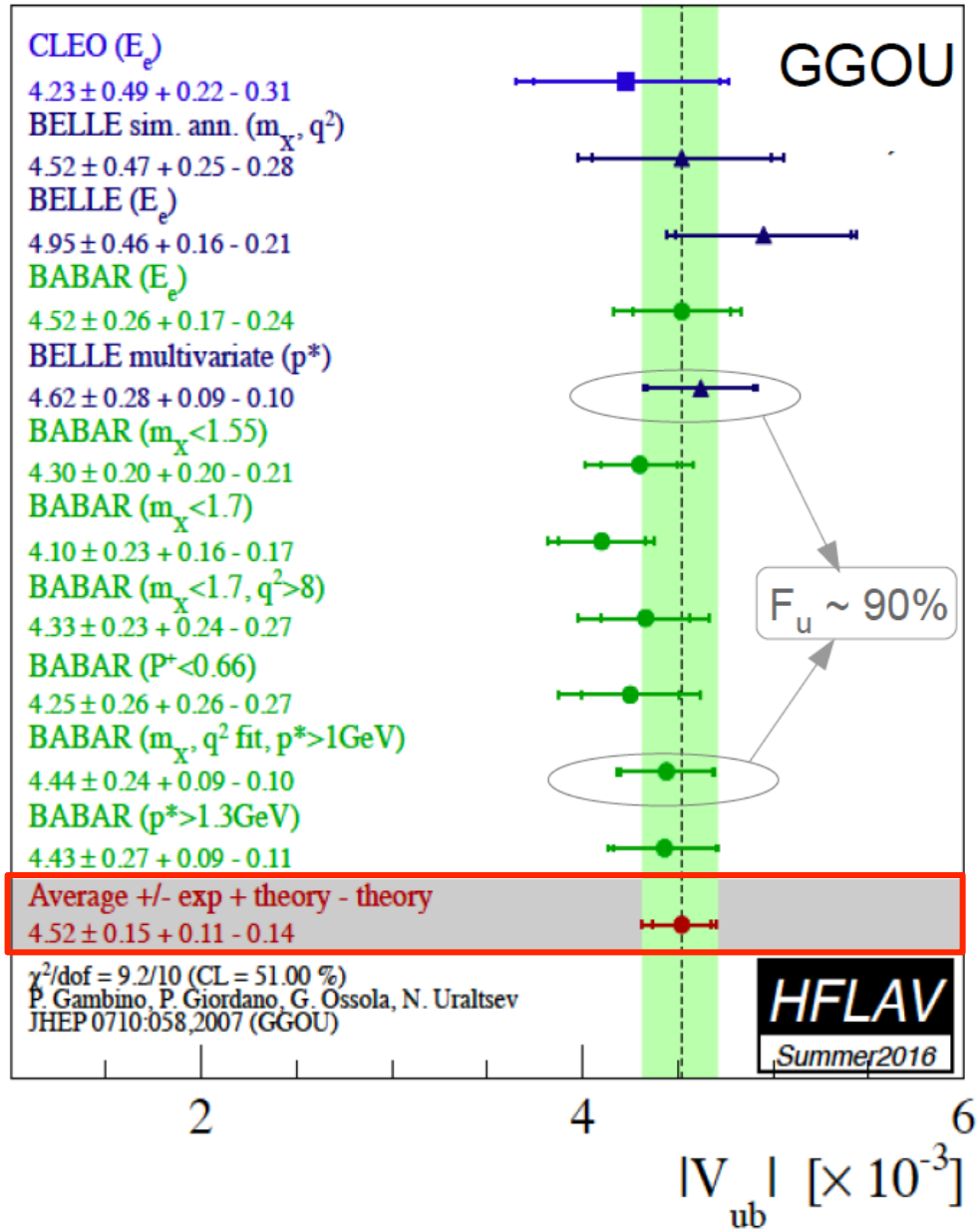
$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2}{192\pi^3} m_b^5 |V_{ub}|^2 A_{ew} \; A_{pert} A_{non-pert}$$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Delta\Gamma_{theory}}}$$





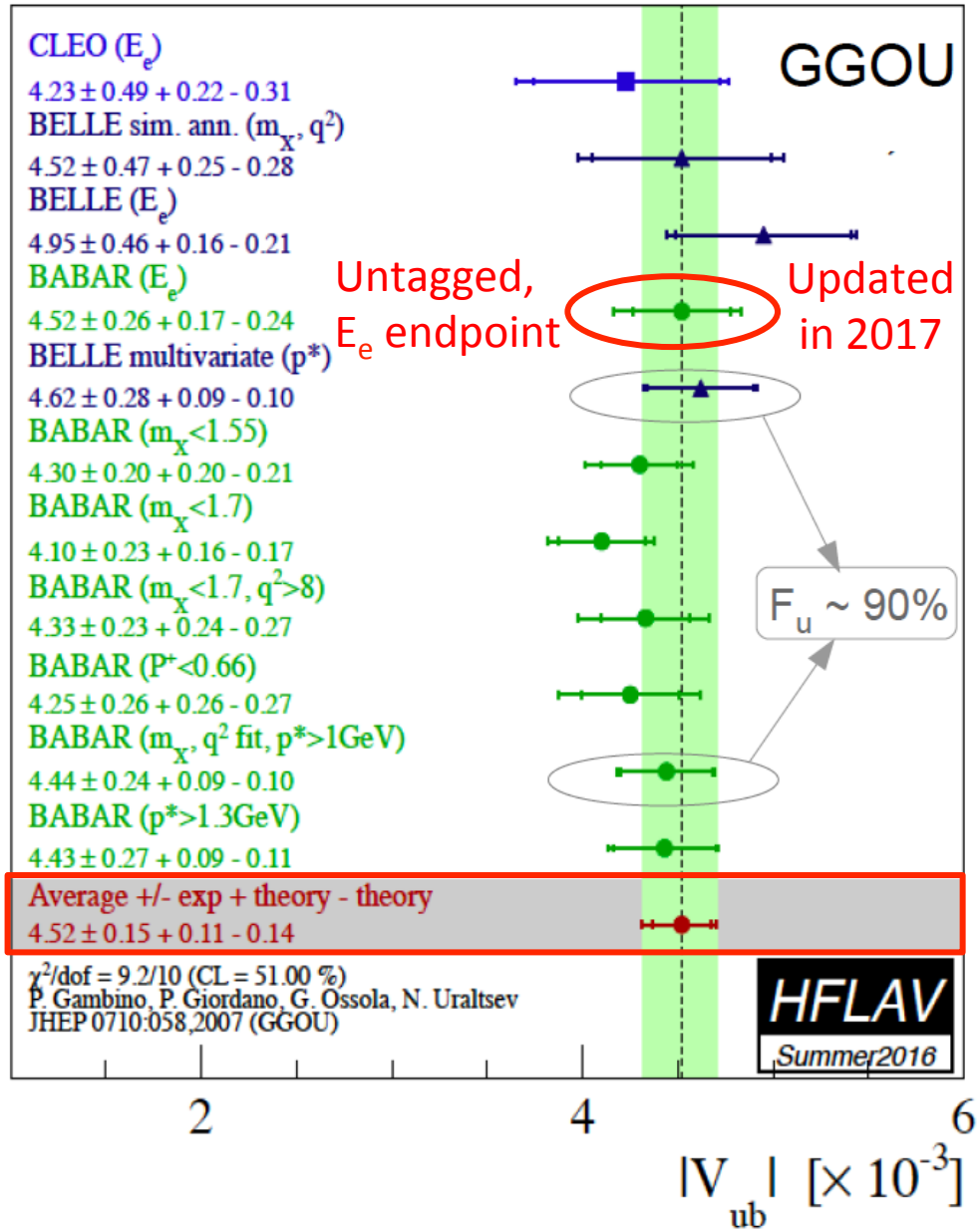
$|V_{ub}|$ from inclusive decays



- Consistent $|V_{ub}|$ results for
  - Belle and BaBar
  - Different kinematic regions
  - Different theory calculations

Framework	$\lvert V_{ub}\rvert[10^{-3}]$
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)	$4.62 \pm 0.20 \pm 0.29$

$|V_{ub}|$ from inclusive decays



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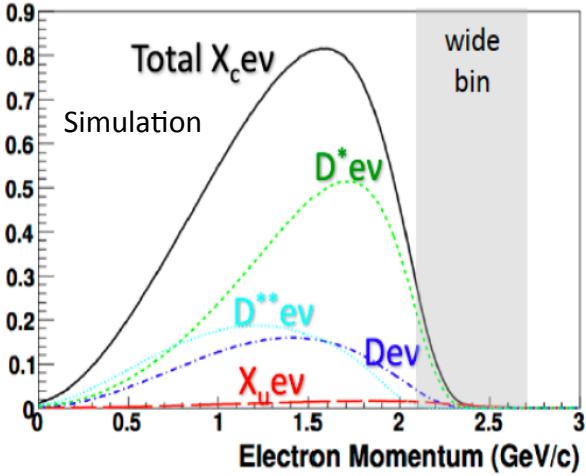
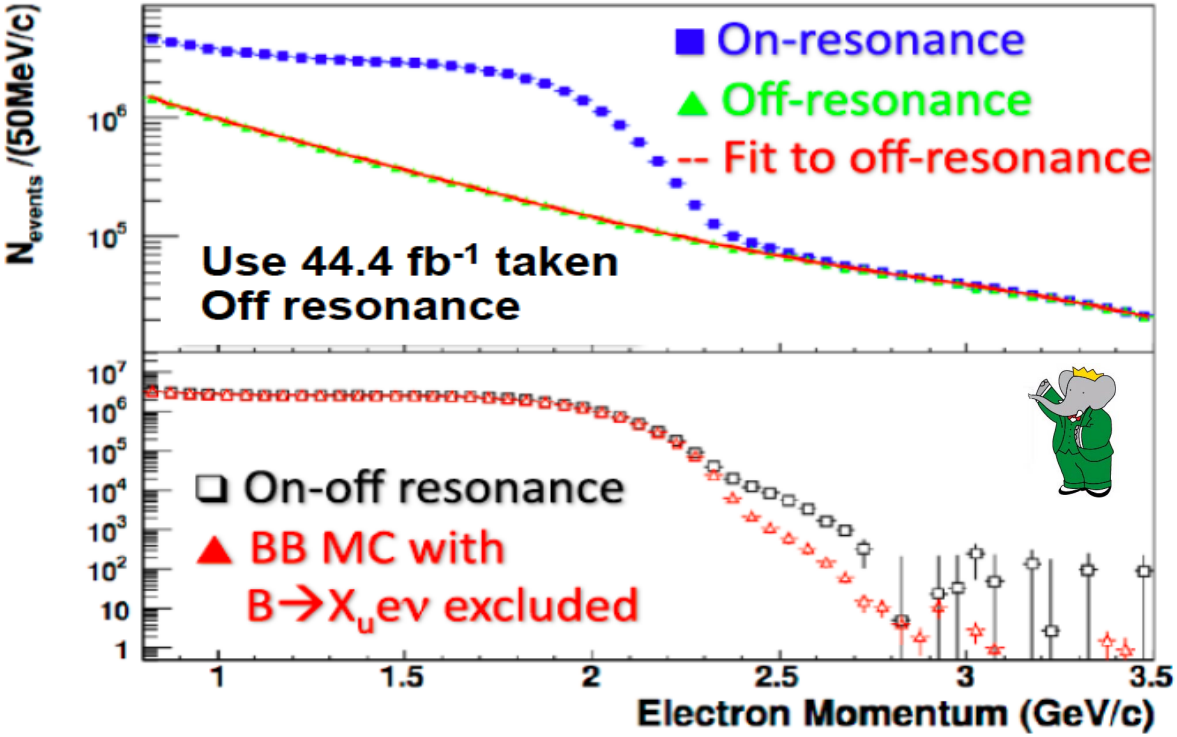
Inclusive $B \to X_u \ell \nu$: Updated E_e endpoint analysis

Phys.Rev.D 95, 072001 (2017)

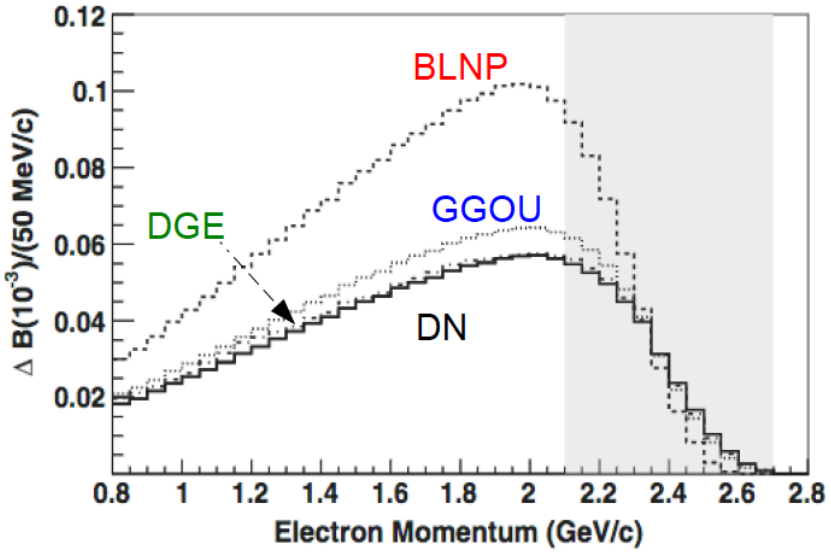
- Untagged inclusive measurement of E_e spectrum by BaBar
- Signal extracted in simul. fit to Y(4S) and off-res. data
  - Contiuum (exponential form with 5 par.)
  - $B \to X_u \ell \nu$ signal
  - $B \to X_c \ell \nu$ components (X_c = D, D^*, D^{**}, $D^{(*)}\pi$, $D'^{(*)}$)
  - Secondary leptons $b \to c \to \ell$





- E_e range: 0.8 – 2.7 GeV
  - Lower limit varied from 0.8 up to 2.1 GeV for ΔB and $|V_{ub}|$ extraction

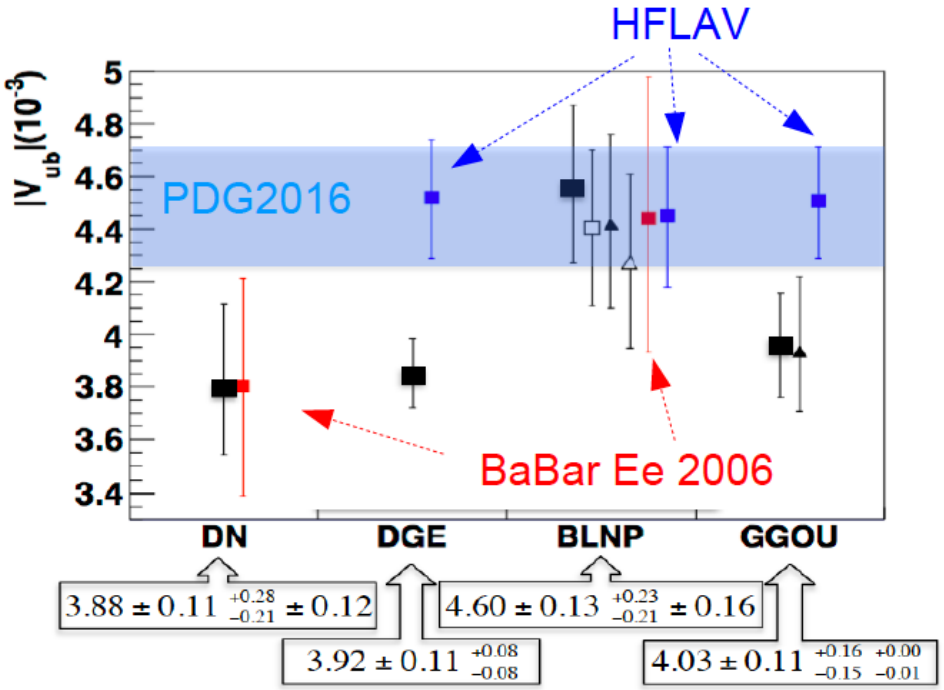
Inclusive $B \to X_u \ell \nu$: Updated E_e endpoint analysis

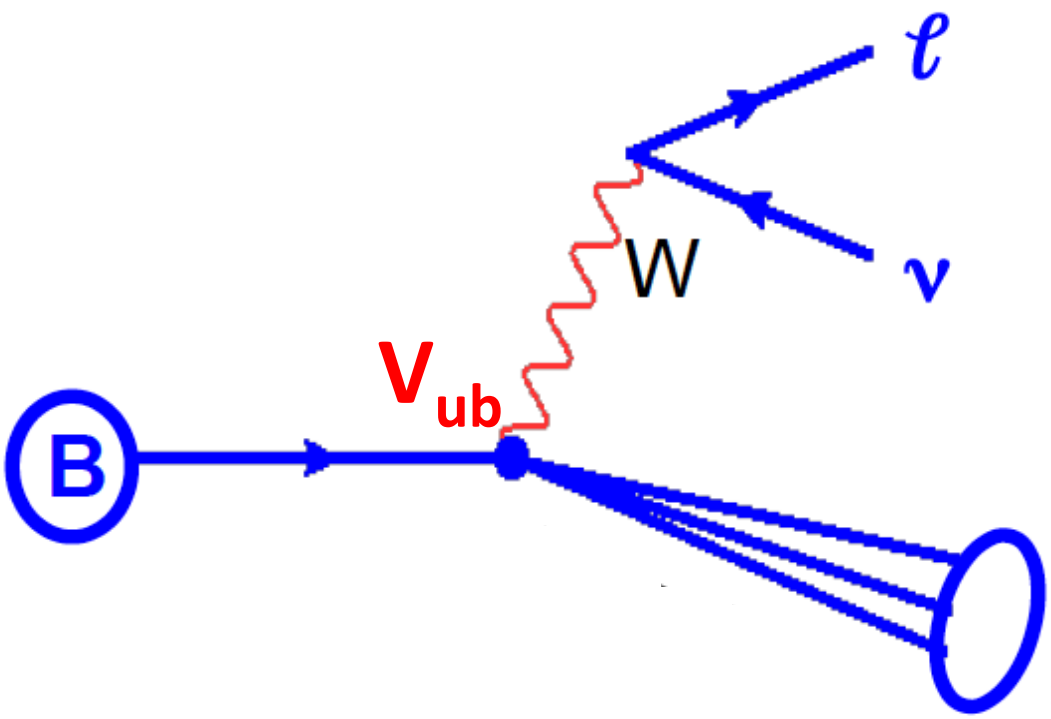


- Highest signal sensitivity in bin 2.1-2.7 GeV
- 4 theory calculations used as signal model

  ⇒ different partial rate predictions in 2.1-2.7 GeV bin

- Results for DN, DGE, GGOU agree with each other, BLNP higher
- Lower $|V_{ub}|$ than in previous measurements (except for BLNP)
- $|V_{ub}|$ results obtained from [0.8;2.7] ~ 1% higher than from [2.1;2.7]



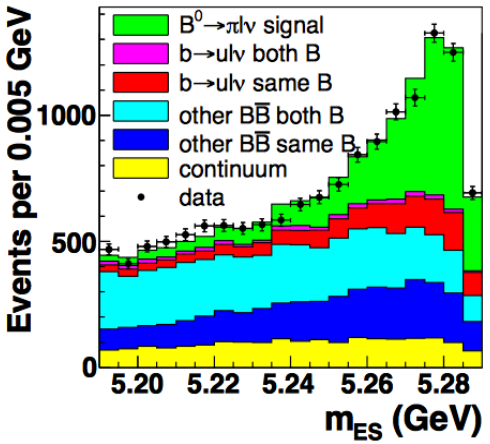


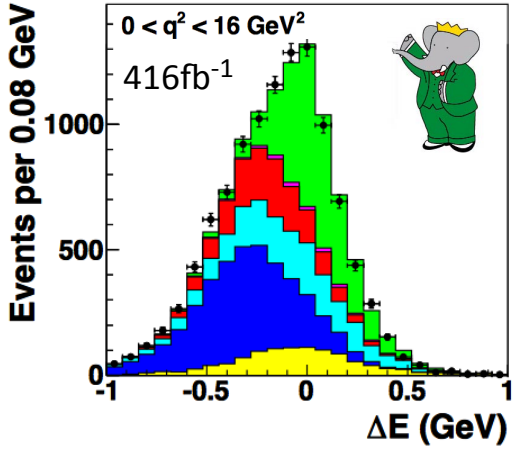
$X_c = \pi, \eta, \eta', \ldots$

$|V_{ub}|$ from $B \to \pi \ell \nu$

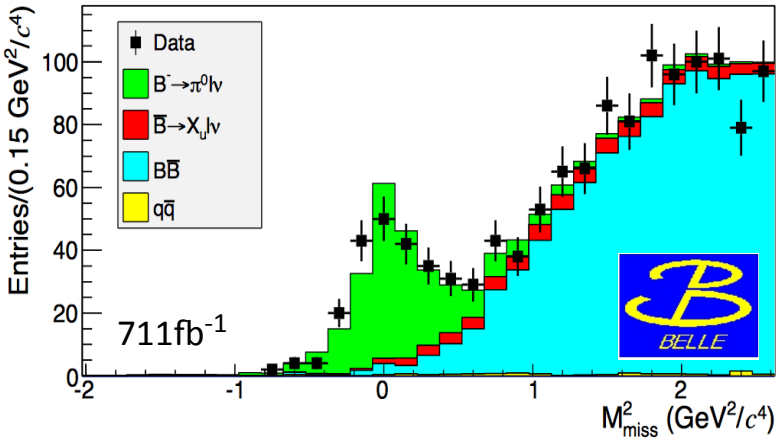
$$\frac{d\Gamma}{dq^2}(B^0 \to \pi^- \ell^+ \nu) = \frac{G_F}{24\pi^3} p_\pi^3 \; |V_{ub}|^2 \; |f_+(q^2)|^2$$

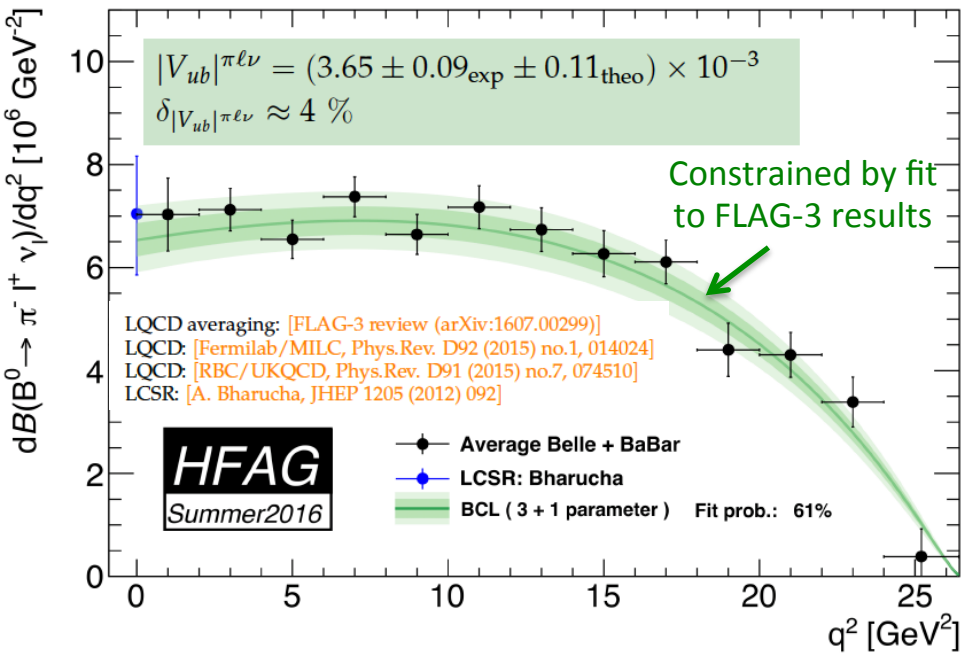
Untagged





Had. B tags





Form factor parametrization: BCL

Bourrely, Caprini, Lellouch, PRD79, 013008 (2009)

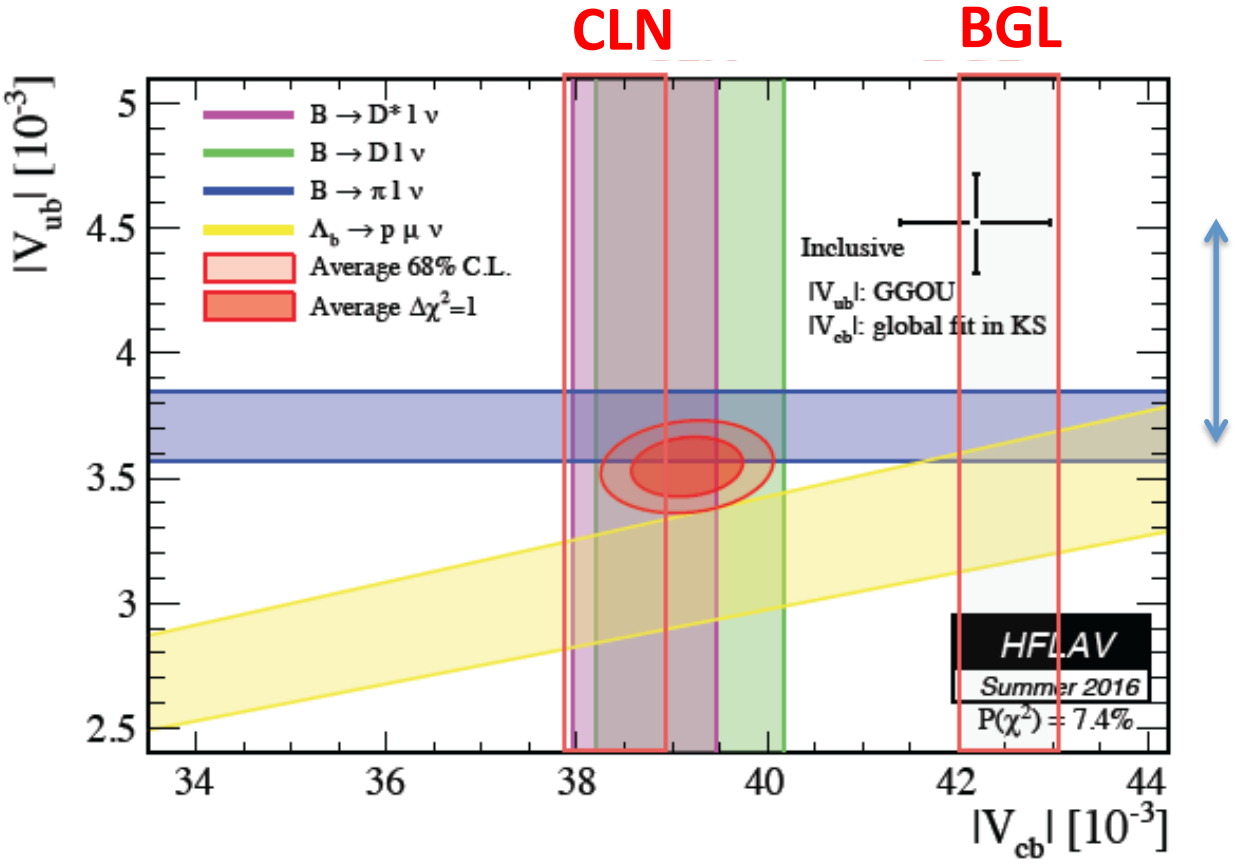
$$f_+(q^2, \vec{b}) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{K} b_k(t_0)\, z(q^2)^k$$

Parameter	Value
$\|V_{ub}\|$	$(3.65 \pm 0.14) \times 10^{-3}$
b_1^+	0.421 ± 0.017
b_2^+	-0.390 ± 0.033
b_3^+	-0.650 ± 0.126

Status of $|V_{ub}|$

$|V_{ub}| = (4.52 \pm 0.15 \pm 0.22) \times 10^{-3}$ inclusive average (GGOU)

$|V_{ub}| = (3.65 \pm 0.09 \pm 0.11) \times 10^{-3}$ $B \to \pi \ell \nu$ average (FLAG + LCSR)

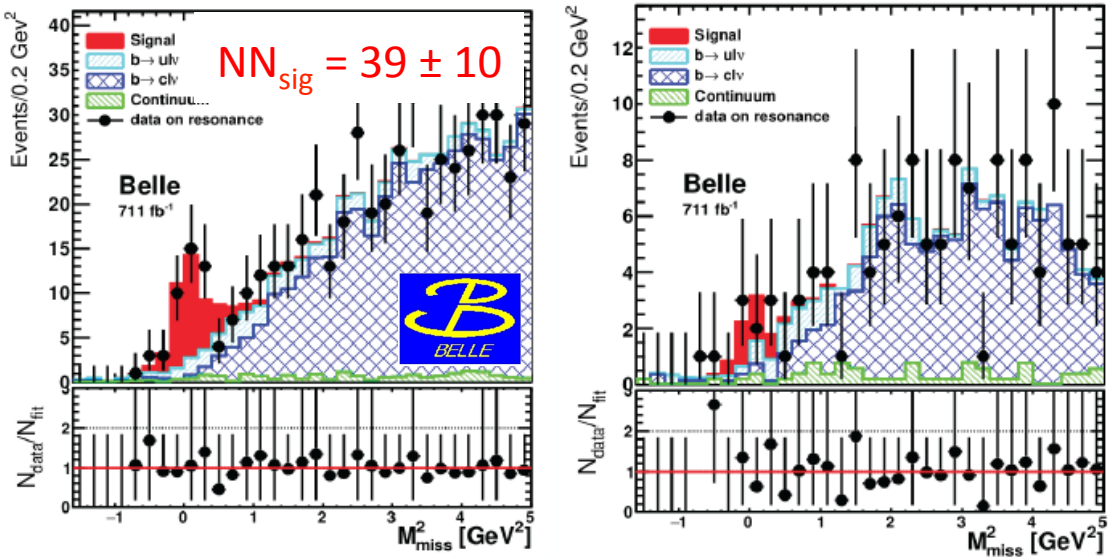


Persistent exclusive-inclusive discrepancy for $|V_{ub}|$ at ~3σ level!

Decays to heavier charmless resonances: η, η'

- Measure decays to higher-mass charmless resonances
  ⇒ better understand composition of inclusive $B \to X_u \ell\nu$ rate
- New measurement of $B \to \eta/\eta'\ell\nu$ with hadronic tags *Phys.Rev.D96, 091102(R) (2017)*

$B \to \eta\ell\nu$ **$B \to \eta'\ell\nu$**



$\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$

$\eta' \to \pi^+\pi^-\eta,\ \eta\gamma$

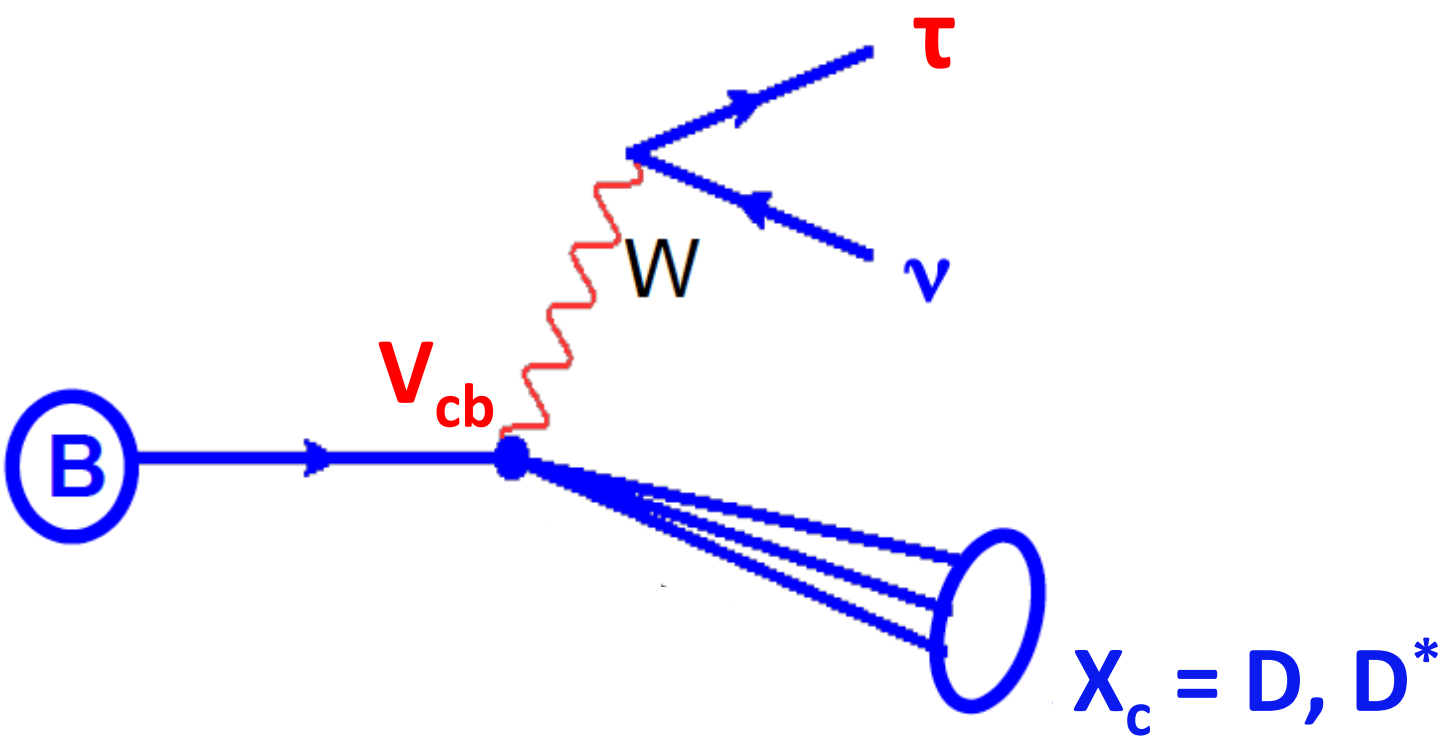
$$\mathcal{B}(B^+ \to \eta\ell^+\nu) = (4.2 \pm 1.1_{stat} \pm 0.3_{syst}) \times 10^{-5}$$
$$\mathcal{B}(B^+ \to \eta'\ell^+\nu) < 0.72 \times 10^{-4} \quad 90\% \text{ C.L.}$$

$$|V_{ub}| = (3.59 \pm 0.58_{stat} \pm 0.13_{syst}\,^{+0.29}_{-0.32\,theo}) \times 10^{-3}$$

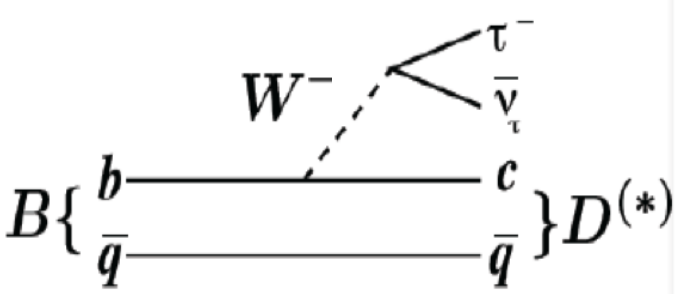
Significance: 3.7σ

$|V_{ub}|$ from LCSR

P. Ball, G. Jones, JHEP 08 (2007) 025


τ
W
ν
V_{cb}
B
X_c = D, D^*

Semileptonic decays with τ lepton: $B \to D^{(*)}\tau\nu$



Measure BF ratio:

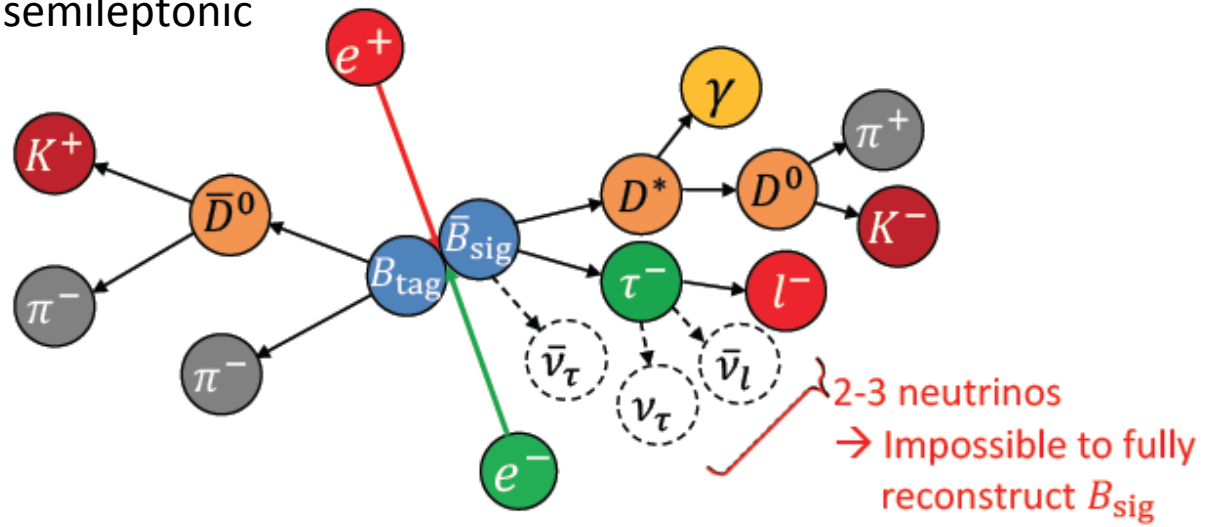
$$R(D^{(*)}) \equiv \frac{BF(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{BF(B \to D^{(*)}l^-\bar{\nu}_l)}$$

Tag side:

- Inclusive
- hadronic
- semileptonic

Signal side:

- $\tau \to \ell\nu\nu$
- $\tau \to \pi\nu$, $\rho\nu$

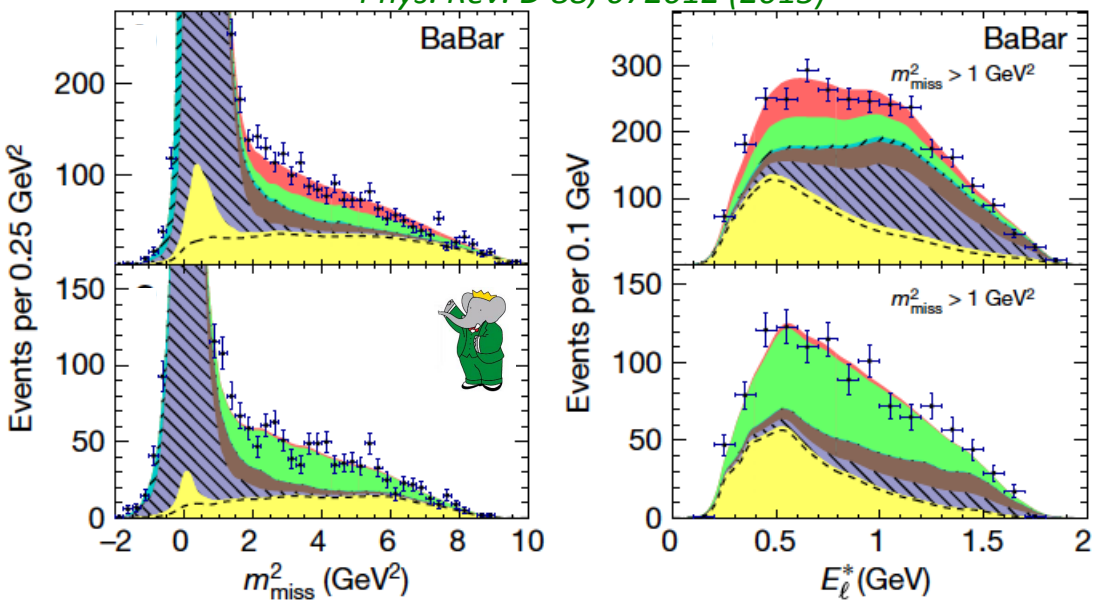


Semileptonic decays with τ lepton: $B \to D^{(*)}\tau\nu$

Experiment	Tag method	τ mode	R_D	R_{D^*}
Belle 07*	Inclusive	e ν ν, π ν	0.38±0.11	0.34±0.08
Belle 10*	Inclusive	l ν ν, π ν		
Babar 12	Hadronic	l ν ν	0.440±0.058±0.042	0.332±0.024±0.018
Belle 15	**Hadronic**	**l ν ν**	**0.375±0.064±0.026**	**0.293±0.038±0.015**
Belle 16	**Semileptonic**	**l ν ν**	**IN PROGRESS**	**0.302±0.030±0.011**
Belle 17	**Hadronic**	**π ν, ρ ν**	**-**	**0.270±0.035±0.027**
LHCb 16	-	l ν ν	-	0.336±0.027±0.030
LHCb 17		3 π ν	-	0.286±0.019±0.033
Belle ave.	**SL+Had**	**-**	**0.374±0.061**	**0.292±0.020±0.012**

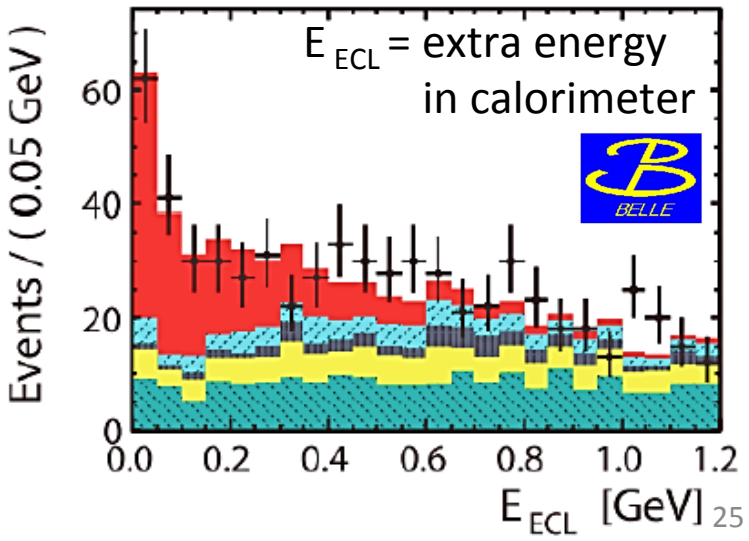
Hadronic B tag

Phys. Rev. D 88, 072012 (2013)



Semileptonic B tag

Phys.Rev. D94,072007 (2016)



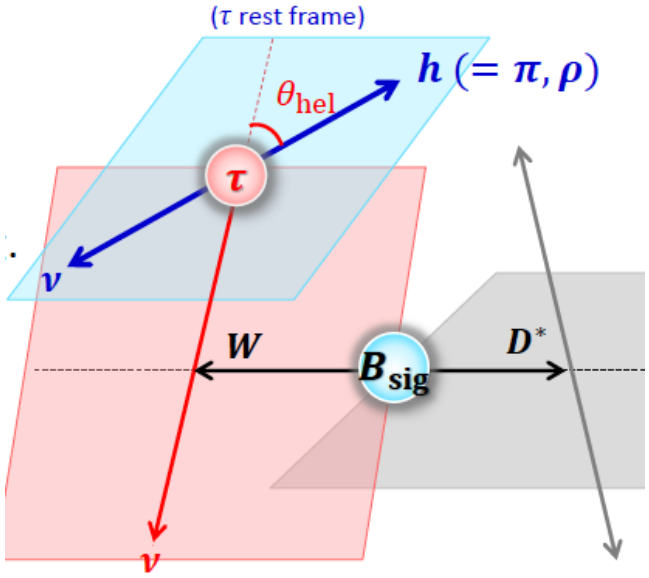
τ polarization in $B \to D^{*}\tau\nu$ with $\tau \to \pi/\rho\nu$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{\mathrm{hel}})$$

- Tau helicity angle ($\cos\Theta_{\mathrm{hel}}$) sensitive to P_τ
- 4-momentum of signal B can be determined with hadronic B tagging
  ⇒ reco. of 4-momentum transfer **q**
  ⇒ allows for boost into W rest frame
- Use 1-Prong hadronic tau decays:

$$\tau \to h\nu, \quad h = \pi^-, \rho^- (\to \pi^-\pi^0)$$

$$\alpha = \begin{cases} 1 & \text{for } \tau \to \pi^- \\ 0.45 & \text{for } \tau \to \rho^- \end{cases}$$

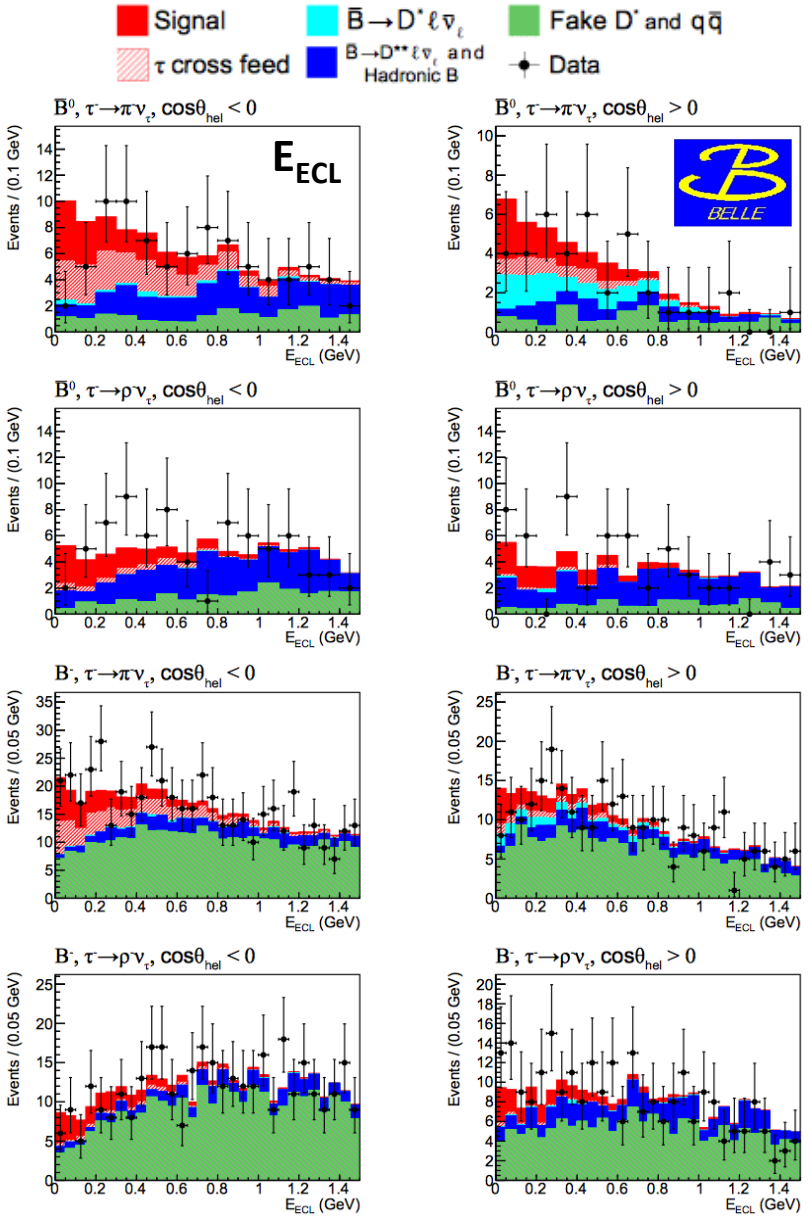


Integration over "fwd/bwd region" yields:

$$P_\tau(D^*) = \frac{2}{\alpha}\frac{N_{\mathrm{sig}}(\cos\theta_{\mathrm{hel}} > 0) - N_{\mathrm{sig}}(\cos\theta_{\mathrm{hel}} < 0)}{N_{\mathrm{sig}}(\cos\theta_{\mathrm{hel}} > 0) + N_{\mathrm{sig}}(\cos\theta_{\mathrm{hel}} < 0)}$$

τ polarization in $B \to D^{*}\tau\nu$ with $\tau \to \pi/\rho\nu$

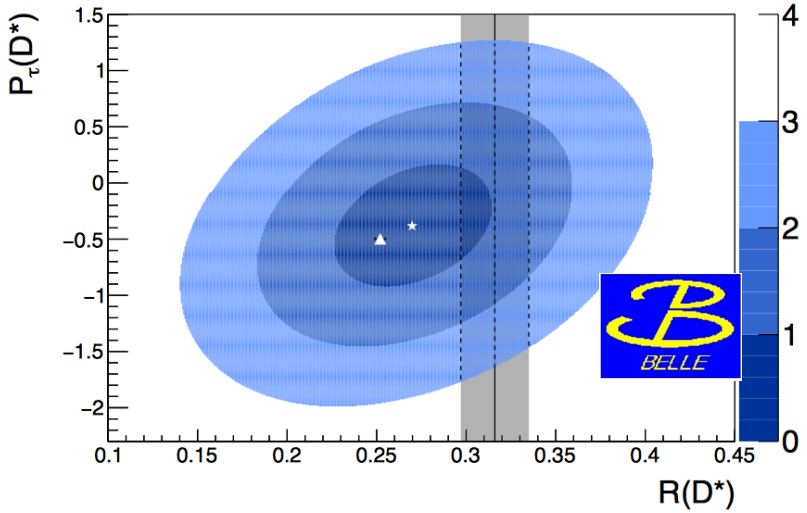
- Belle performed **first measurement** of τ polarization in semileptonic B



Phys.Rev.D97, 012004 (2018)

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

$P_\tau(D^*) > 0.5$ excluded at 90% CL

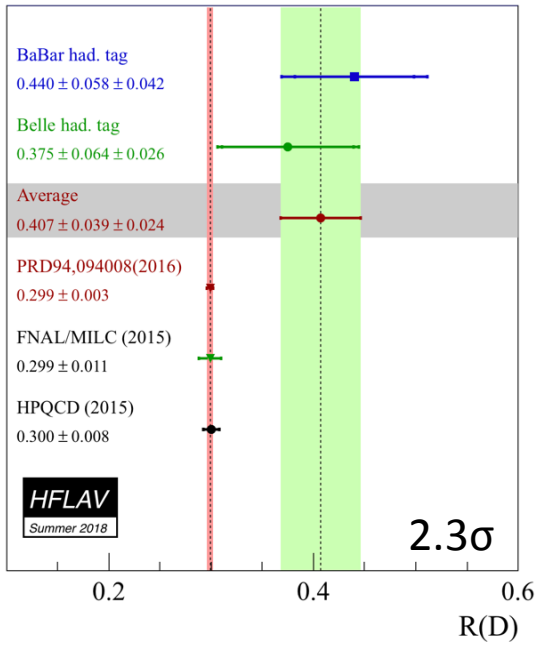


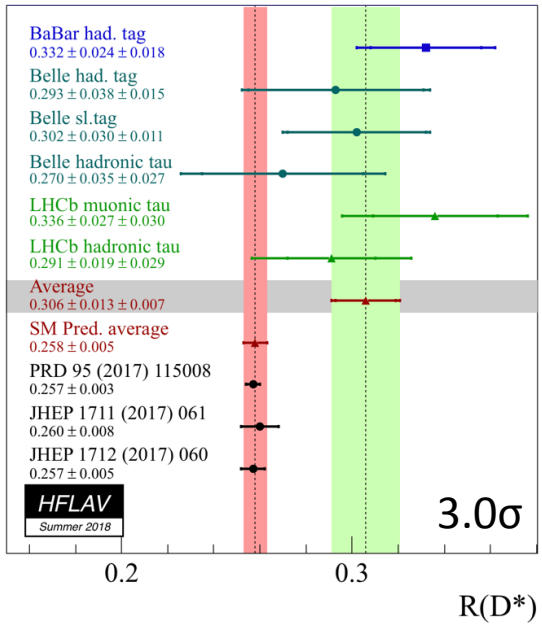
SM prediction:

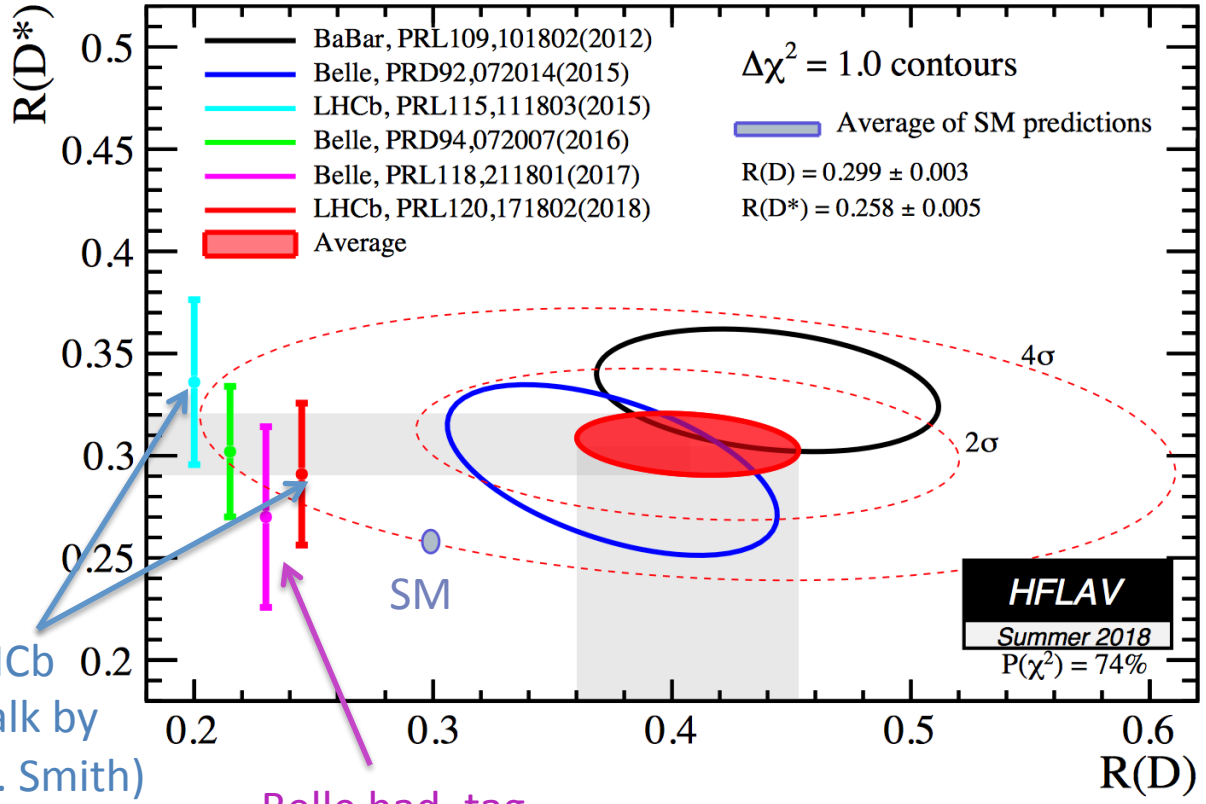
$R(D^*)$	=	0.252 ± 0.003	Fajfer, Kamenik, Nisandzic, Phys.Rev. D85, 094025 (2012)
$P_\tau(D^*)$	=	-0.497 ± 0.013	Tanaka and Watanabe, Phys.Rev. D87, 034028 (2013)

Results are in good agreement with SM prediction (within 0.6σ)

Status of R(D(*)) results





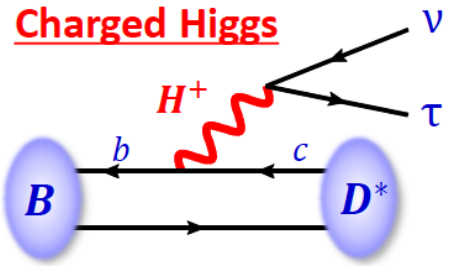


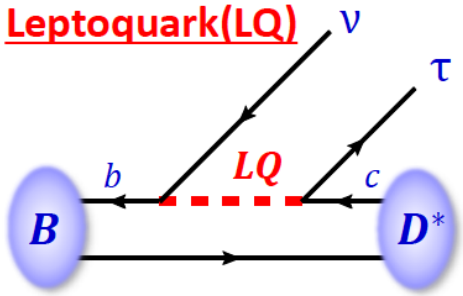
LHCb (talk by M. Smith)

Belle had. tag (τ polarization)

Deviation from SM prediction: 3.9 σ

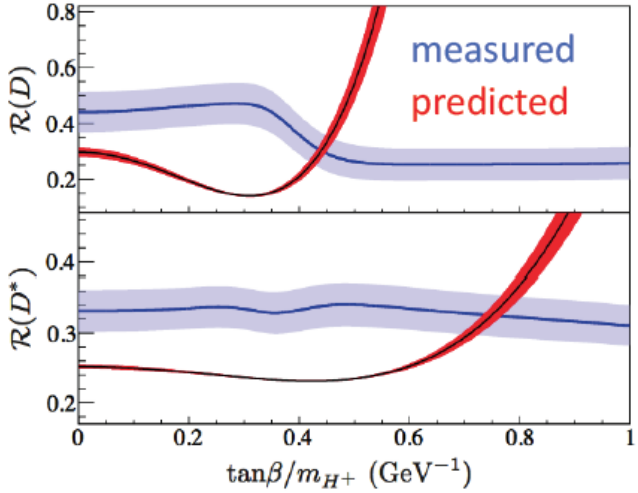
New-physics interpretations: Some examples



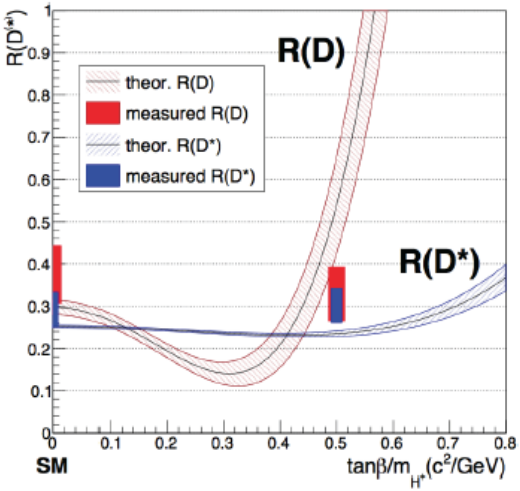


Examples:

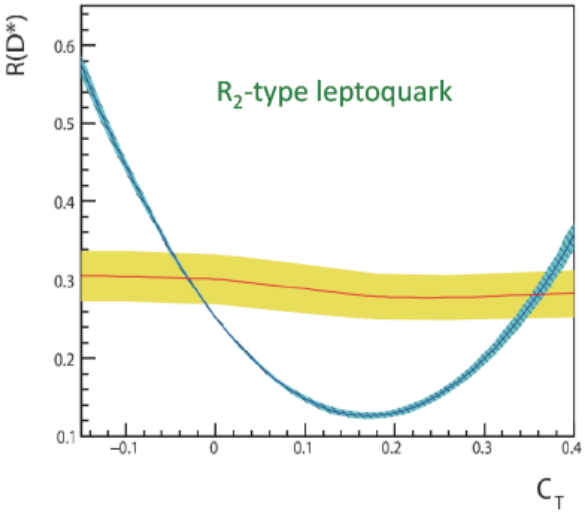
BaBar disfavours 2HDM type II



Belle more compatible



Belle studied two 2 types of leptoquark models. Results allow additional contribution from scalar and vector operators



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

	Experiment	SL tag R_{D^*}	Had tag R_{D^*}, $\tau \to h\,\nu$	Had tag R_{D^*}, $\tau \to l\,\nu\,\nu$	Had tag R_D, $\tau \to l\,\nu\,\nu$
1	MC statistics	2.2	3.5	-	-
2	**B → D** l ν modelling**	**+1, -1.7**	**2.4**	**1.5**	**4.2**
3	B → D* l ν	+1.3, -0.2	2.3	-	-
4	**D** decay modes**	**(in 2)**	**(in 2)**	**1.3**	**3.0**
5	**Hadronic B decays**	**1.1**	**7.3**	**-**	**-**
6	**B → D** τ ν**	**(in 2)**	**(in 2)**	**-**	**-**
7	Fake $D^{(*)}$	1.4	0.2	0.3	0.5
8	Fake lepton	-	-	0.6	0.5
9	Lepton ID	1.2	1.8	0.5	0.5
10	τ Br	0.2	0.3	0.2	0.2
11	Other	-	2.3	-	-
	Total	3.5	9.9	5.2	7.1

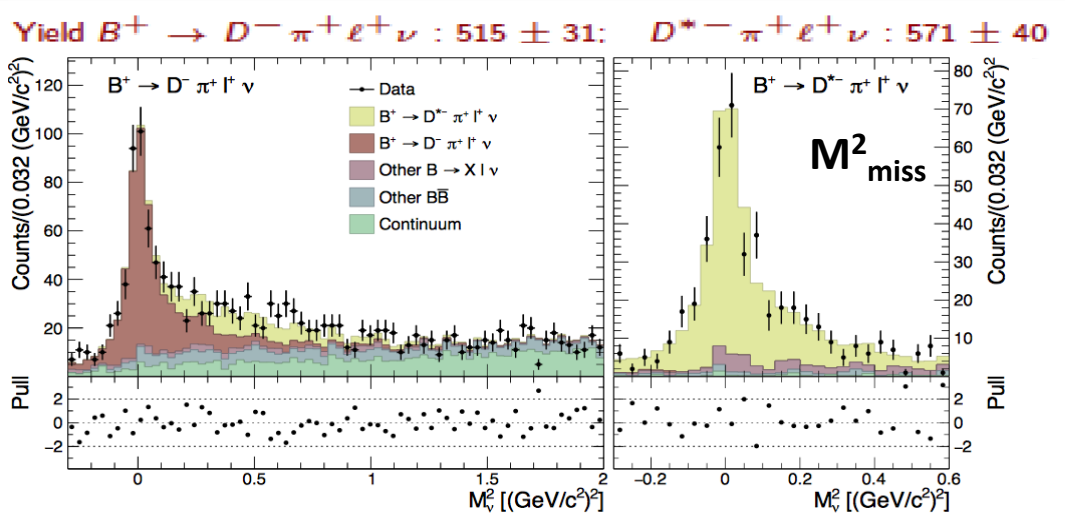
Better knowledge of semileptonic B decays to D^{**} would be helpful!

Higher charm resonances D^{**}: $B \to D^{(*)}\pi\ell\nu$

- New hadronic-tag analysis of $B \to D^{(*)}\pi\ell\nu$ by Belle
  - Dominated by D^{**}
  - $B \to D\pi\ell\nu$ and $B \to D^{*}\pi\ell\nu$ fitted simultaneously

arXiv:1803.06444 [hep-ex]
accepted by PRD

$D^{*0} \to D^0\pi^0$, $D^{*+} \to D^+\pi^0, D^0\pi^+$
6 D^0, 4 D^+ decay modes



Higher charm resonances D^{**}: $B \to D^{(*)}\pi\ell\nu$

Results *arXiv:1803.06444 [hep-ex], accepted by PRD*

Comparison with HFLAV 2016

$$\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu) = [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})] \times 10^{-3},$$ $[4.1 \pm 0.5] \times 10^{-3}$

$$\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu) = [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3},$$ $[4.2 \pm 0.6] \times 10^{-3}$

$$\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu) = [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3},$$ $[6.0 \pm 0.6] \times 10^{-3}$

$$\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu) = [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}.$$ $[4.7 \pm 0.8] \times 10^{-3}$

Compatible with world average, with comparable/somewhat improved precison

- Useful input to understand incl.- sum of excl. gap for $B \to X_c\ell\nu$
- Potential future improvement: Include $D^{(*)}\pi\pi$, as done by BaBar *PRL 116, 041801*

Conclusions

- Inclusive-exclusive difference for $|V_{cb}|$ maybe solved
  - BGL fit in new high-statistics $B \to D^* \ell \nu$ analysis from Belle compatible with inclusive $|V_{cb}|$
- Inclusive-exclusive difference for $|V_{ub}|$ persistent (~ 3σ)
  - Interesting results from electron endpoint studies by BaBar
- First measurement of $B \to \eta \ell \nu$, $B \to \eta' \ell \nu$ with had. tags by Belle
- R(D) and R(D*) measurements one of the highlights at the B factories
  - New dimension to search for NP in sl. B decays with taus $\to \tau$ polarization
- New $B \to D^{(*)} \pi \ell \nu$ branching fraction measurement from Belle
  - Critical input to background modeling in R(D*) measurement