Towards precision in $|V_{cb}|$ and $|V_{ub}|$ measurements

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on behalf of the Belle collaboration

Precision theory for precise measurements at the LHC and future colliders
Quy-Nhon, Vietnam
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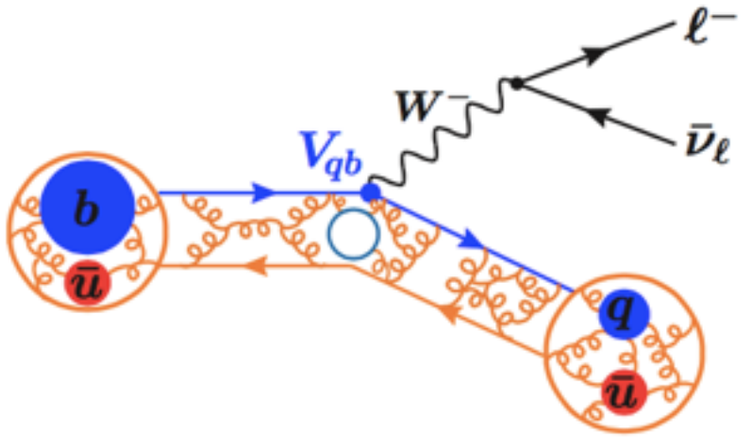
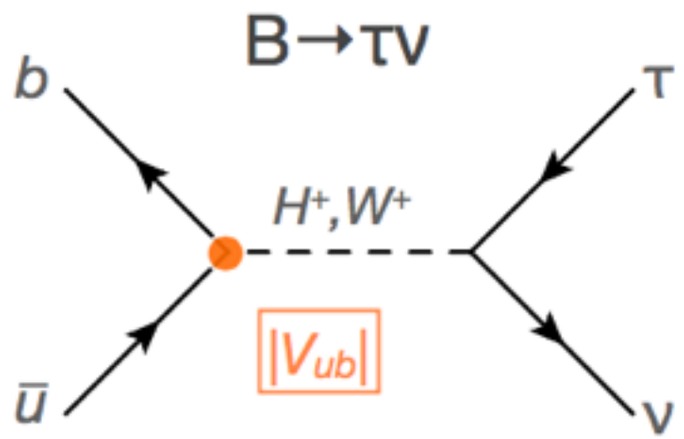
$|V_{ub}|$ and $|V_{cb}|$





Experimental measurements

$|V_{cb}|$ Semileptonic

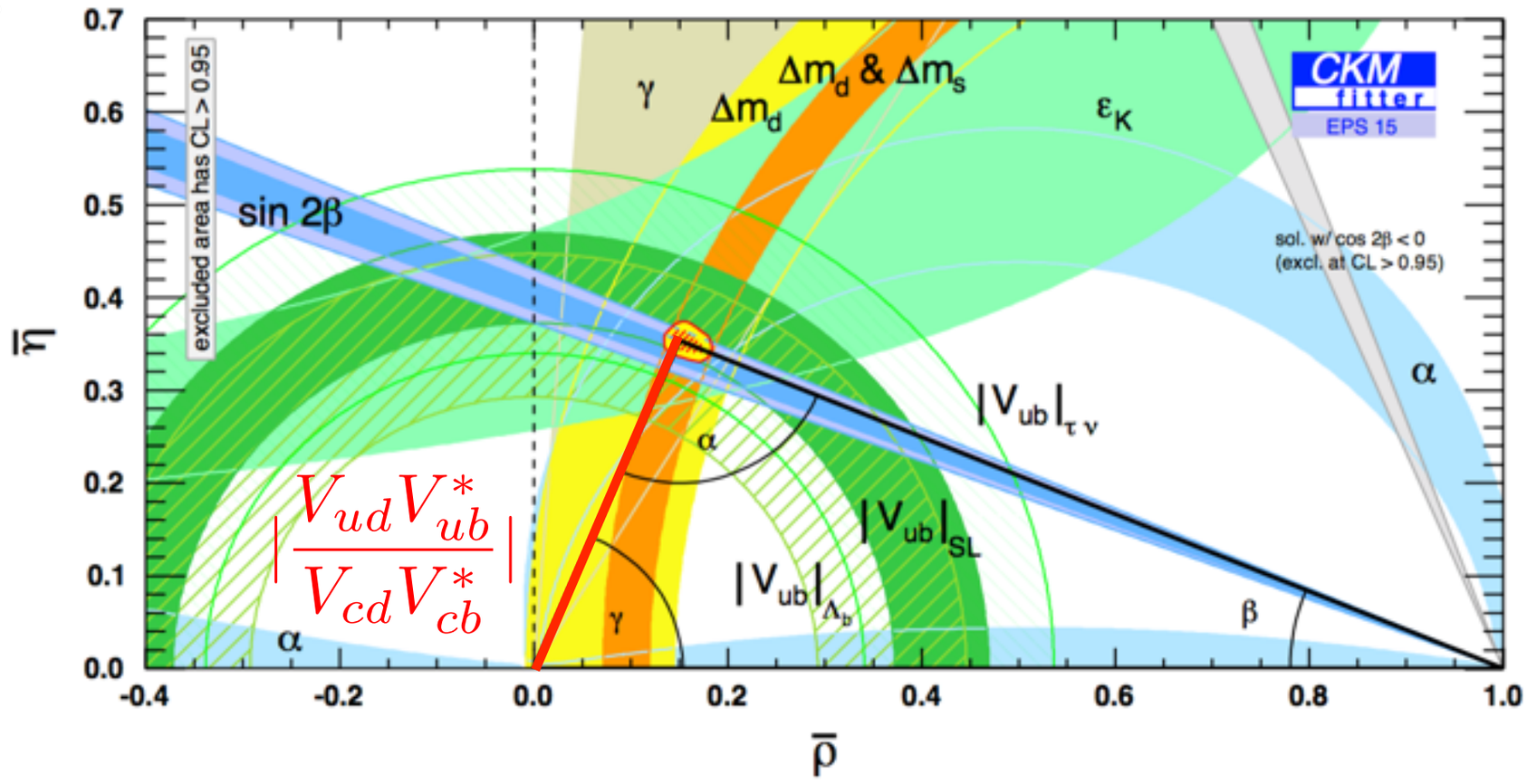
Inclusive: $B \to X_c l \nu$

Exclusive: $B \to D^{(*)} l \nu$

$|V_{ub}|$ Seimileponic

Inclusive: $B \to X_u l \nu$

Exclusive: $B \to \pi l \nu$



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

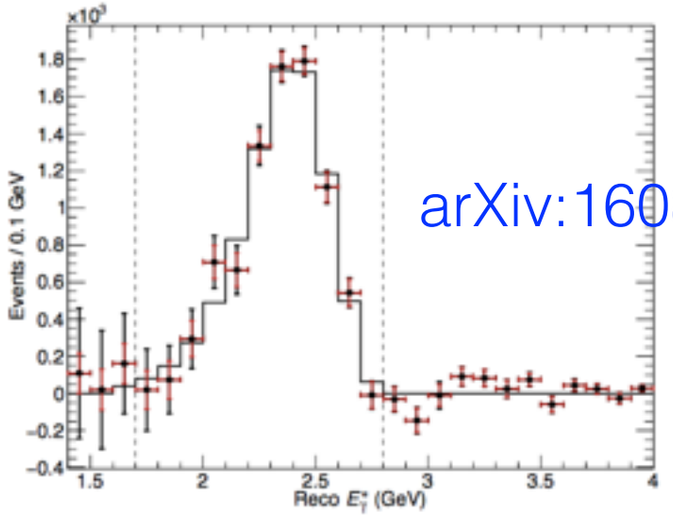
- Total semileptonic decay width with Operator Product Expansion (OPE)

$$\Gamma_{SL} = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3}(1 + A_{ew})A_{per} \times [c_0(r) + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{SL}^3}{m_b^3}) + ...]$$

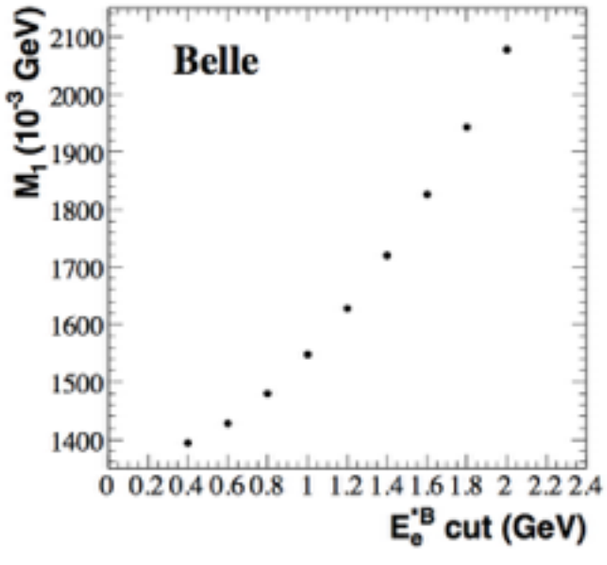
non-perturbative input

r=m_c/m_b, heavy quark parameters $\mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{SL}^3$

- Moments of spectrums Lepton energy, hadronic mass, and photon-energy ($B \to X_s\gamma$)
  - n^{th} moment of observables e.g. Lepton energy: $\langle E_\ell^n \rangle = \frac{1}{\Gamma_{E_\ell > E_{cut}}} \int_{E_\ell > E_{cut}} E_\ell^n \frac{d\Gamma}{dE_\ell} dE_\ell$
  - Similar expansion as Γ_{SL}: $f(E_{cut}, m_c, m_b, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{SL}^3)$
  - Use these moments to extract the quark masses and heavy quark parameters



arXiv:1608.02344



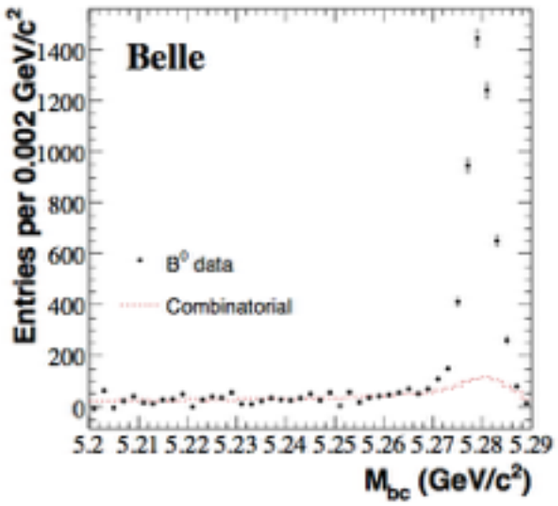
Experimental measurements $\mathrm{B} \to \mathrm{X_c}\ell\nu$

- Tag B meson with hadronic decays

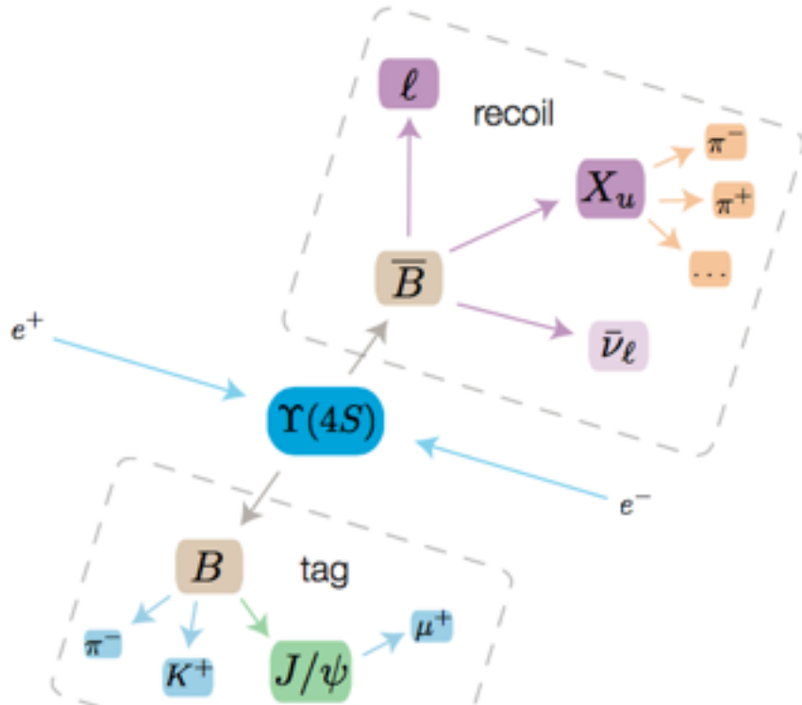
$$\mathrm{B_{tag}} \to \mathrm{D}^{(*)}\mathrm{Y}$$

$$M_{\mathrm{bc}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_B)^2}$$

$$\Delta E = E^*_B - E^*_{\mathrm{beam}}$$

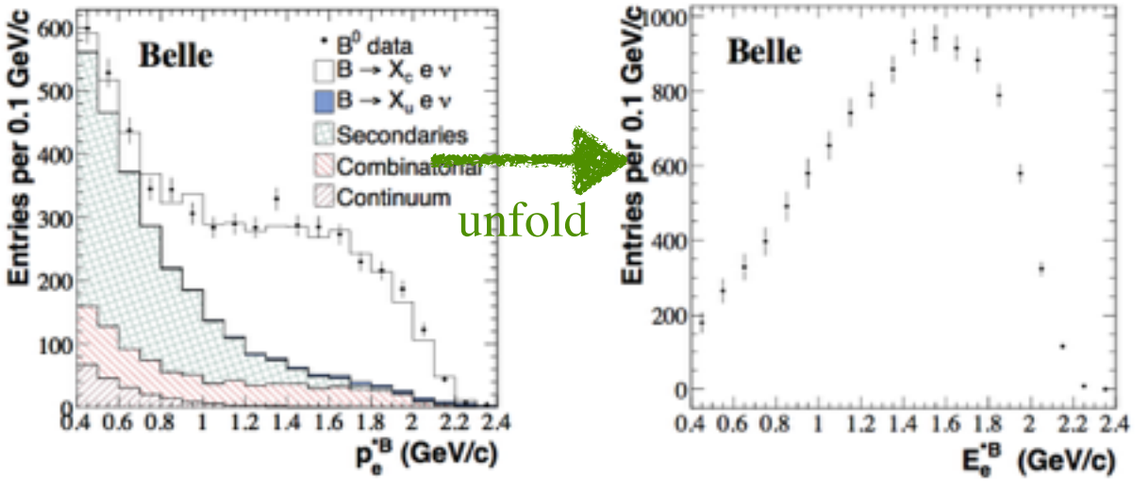


Belle, PRD 75, 032001 (2007)



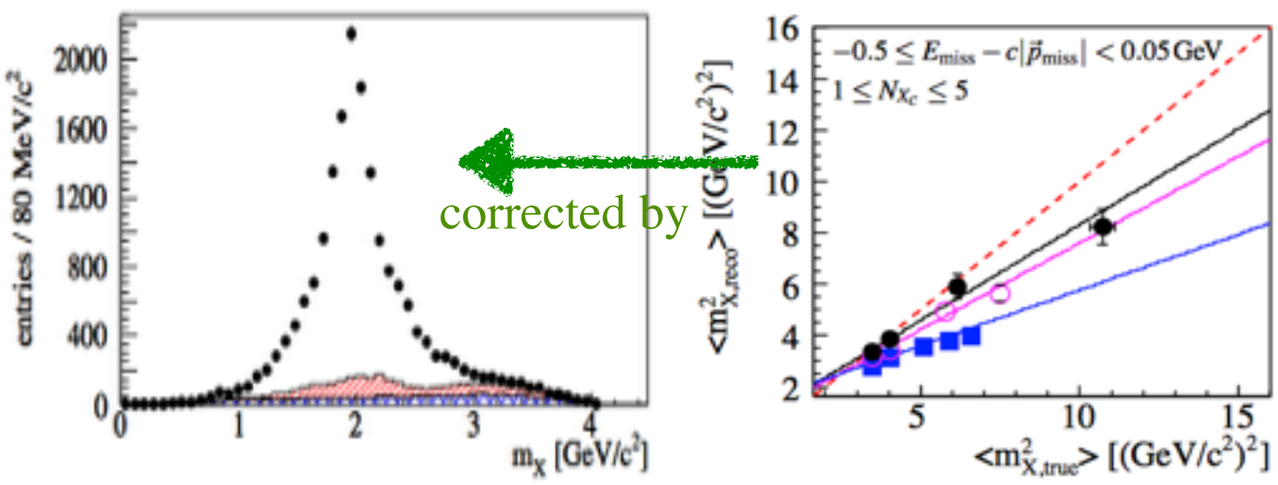
- Reconstruct X_c with the rest particles not used for B_{tag} and lepton
- Extraction of moments of lepton energy and hadronic mass
  - Reconstructed spectrum → True spectrum: detectors resolution, selection efficiency, QED radiative effect

Belle: Unfolding



Belle, PRD 75, 032001 (2007)

Babar: Linear correction



Babar, PRD 81, 032003 (2010)

$|V_{cb}|$ determination from $B \to X_c \ell \nu$

- Global Fitting: fit to the moments of lepton energy and hadronic mass with different energy cut with some parameters constrains.

- Theoretical expressions
  - Kinetic scheme, 1S
  - Fit to the measurements from different experiments
  - Fitting results are consistent

	$\|V_{cb}\|$ (10^{-3})	m_b (GeV)	note
Kinetic scheme	42.46±0.88	4.541±0.023	m_c constrain HFAG 2014
	42.21±0.78	4.553±0.020	m_c constrain PRL 114, 061802 (2015) higher order correction $\mathcal{O}(\alpha_s \Lambda_{QCD}^2/m_b^2)$
1S	41.98±0.45	4.691±0.037	combine $B \to X_s \gamma$ HFAG 2014

$|V_{cb}|=(42.21\pm0.78)\times10^{-3}$

$|V_{cb}|$ determination from exclusive $B \to D^{(*)}\ell\bar{\nu}_\ell$

- Differential decay ratio in the limit of very small lepton masses :

ω: the Lorentz boost of D meson in the B rest frame

$$w = V_B \cdot V_D = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2m_B m_{D^{(*)}}}$$

$$\frac{d\Gamma}{dw}(\bar{B} \to D^*\ell\bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(w^2-1)^{1/2}P(w)(\eta_{\rm ew}\mathcal{F}(w))^2$$

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

- Parameterization of the form factors in the framework of Heavy Quark Effective Theory

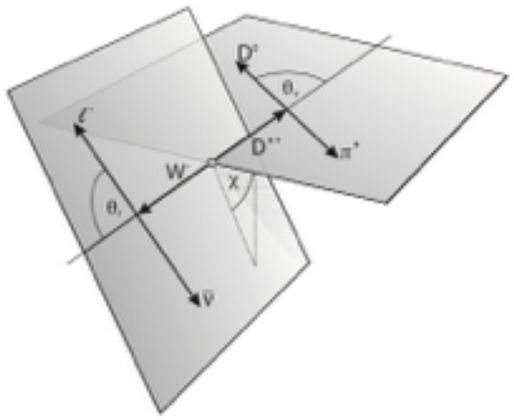
$$\mathcal{F}(w) : \mathcal{F}(1), \rho^2, R_1(1), R_2(1)$$
$$\mathcal{G}(w) : \mathcal{G}(1), \rho^2$$

- The form factor normalisation at ω=1 (zero-recoil) computed by Lattice QCD

$\mathcal{F}(1) = 0.906 \pm 0.013$ PRD.89, 114504(2014)

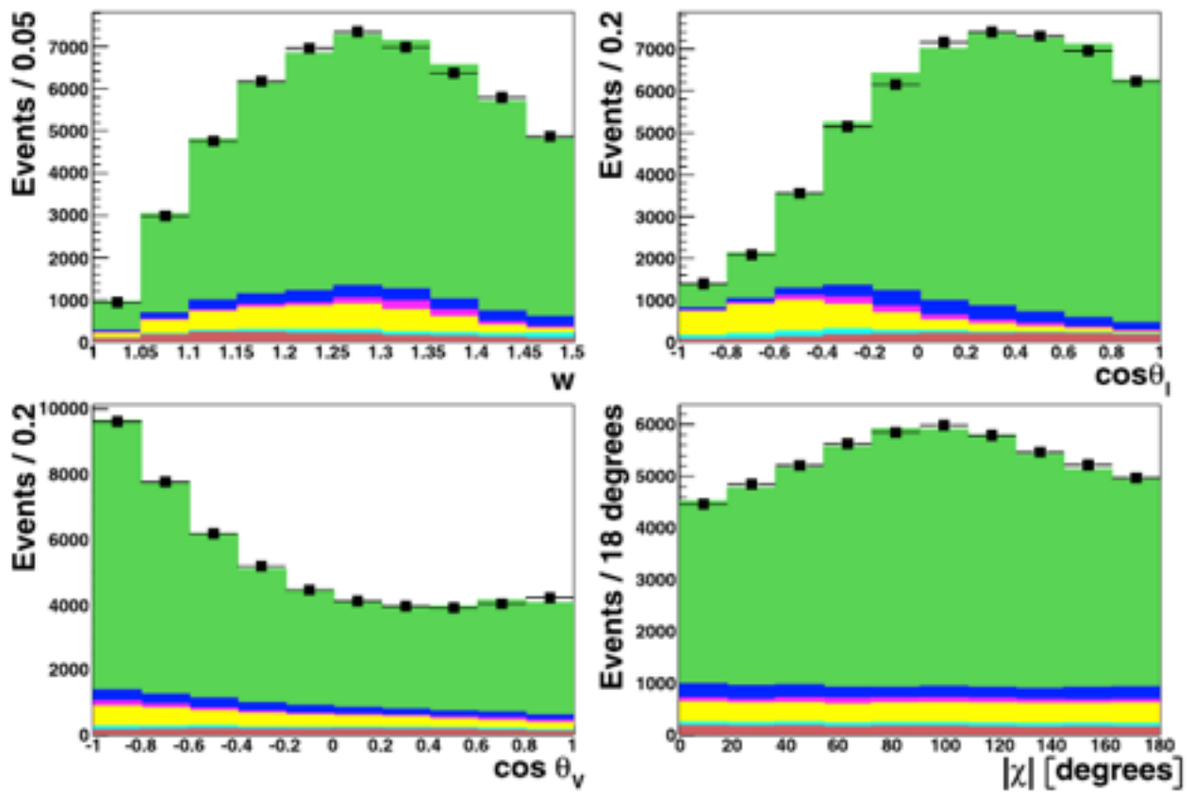
$\mathcal{G}(1) = 1.0528 \pm 0.0082$ Fermilab/MILC: PR D92, 034506, 2015

Experimental measurements $\bar{B} \to D^* \ell \bar{\nu}_\ell$

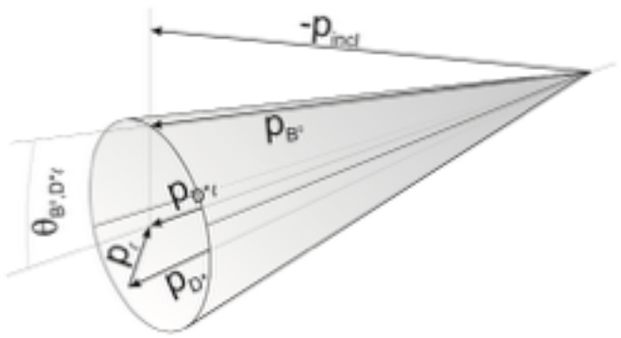


- Kinematics of the decay is characterized by four variables ω, θ_l, θv, |χ|
- Fit to ω, cos(θ_l), cos(θv), |χ|

Belle, PRD82, 112007 (2010)



- Untagged (Belle), determine B rest frame with the rest particles based on the feature that B direction lie on a cone around the (D*l)-axis



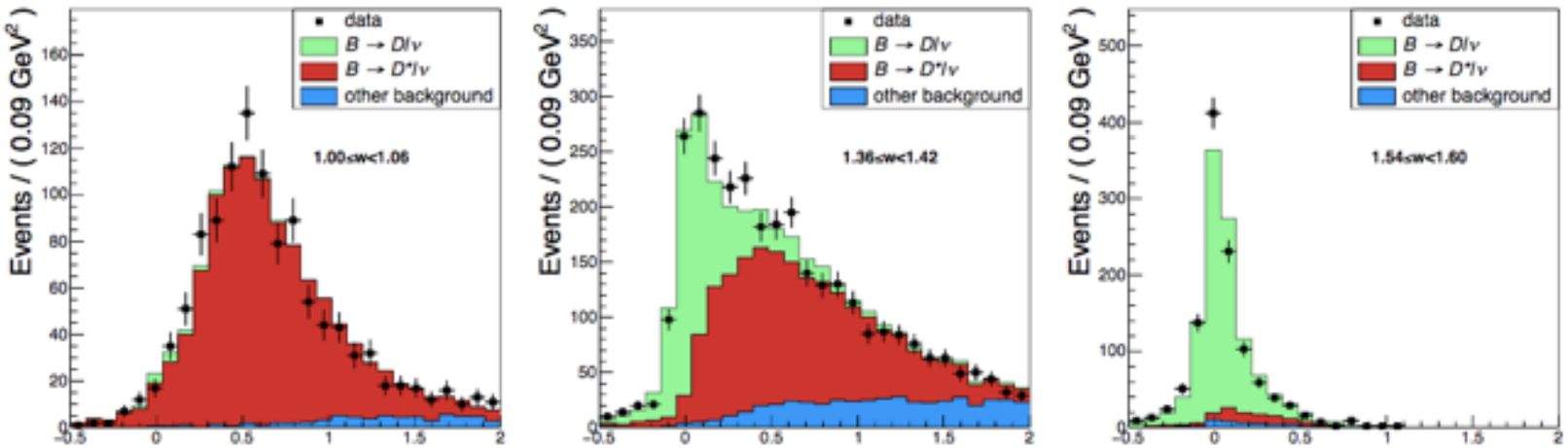
$B \to D^* \ell \nu$	$\mathcal{B}$ (%)	$\eta_{\rm EW}\mathcal{F}(1)\lvert V_{cb}\rvert$ (10^{-3})	$\rho^2_{D^*}$
CLEO untagged (Briere *et al.*, 2002)	$5.62 \pm 0.18 \pm 0.26$	$39.94 \pm 1.23 \pm 1.63$	$1.37 \pm 0.09 \pm 0.09$
Belle untagged (Dungel *et al.*, 2010)	$4.56 \pm 0.03 \pm 0.26$	$34.60 \pm 0.17 \pm 1.02$	$1.21 \pm 0.03 \pm 0.01$
BABAR untagged $B^0 \to D^{*-}\ell^+\nu$ (Aubert *et al.*, 2008b)	$4.54 \pm 0.04 \pm 0.25$	$33.94 \pm 0.30 \pm 0.99$	$1.19 \pm 0.05 \pm 0.03$
BABAR untagged $B^+ \to \overline{D}^{*0}\ell^+\nu$ (Aubert *et al.*, 2008d)	$4.97 \pm 0.07 \pm 0.34$	$35.22 \pm 0.59 \pm 1.33$	$1.13 \pm 0.06 \pm 0.06$
BABAR global fit (Aubert *et al.*, 2009d)	$4.95 \pm 0.02 \pm 0.20$	$35.76 \pm 0.20 \pm 1.10$	$1.19 \pm 0.02 \pm 0.06$
HFAG average (Amhis *et al.*, 2014)	$4.93 \pm 0.01 \pm 0.11$	$35.81 \pm 0.11 \pm 0.44$	$1.21 \pm 0.02 \pm 0.02$

- Systematic errors are dominant: tracking, particle ID, branching fractions of D(*) decay…

Experimental measurements $\bar{B} \to D\ell\bar{\nu}_\ell$

- Extract signals
  - hadronic tag another B
  - identify signal with $m^2_{miss} = (p(\Upsilon) - p(B_{tag}) - p(D) - p\ell)^2$

Belle: PRD 93.032006 (2016)

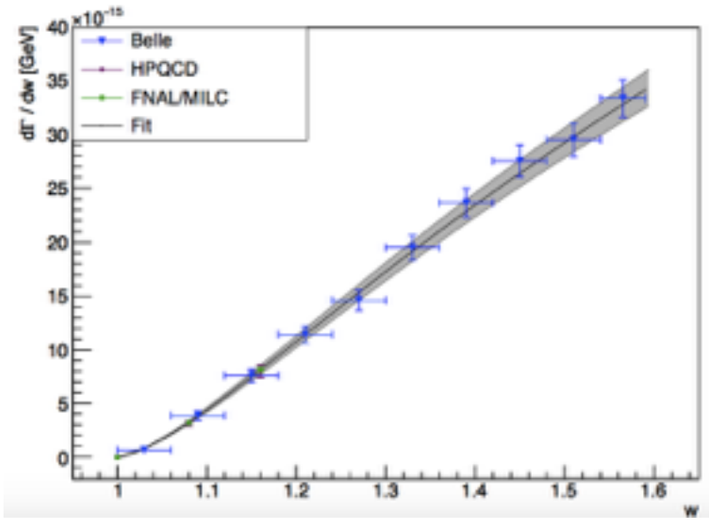


- Parameterisation of form factor $\mathcal{G}(\omega)$
  - CLN: $\mathcal{G}(1), \rho^2$

$$\eta_{\rm EW}\mathcal{G}(1)|{\rm V_{cb}}| = (42.29 \pm 1.37) \times 10^{-3}$$
$$\rho^2 = 1.09 \pm 0.05$$

  - Model-independent BGL fit

Combined fit to experimental data and calculation from lattices QCD data (FNAL/MILC and HPQCD)



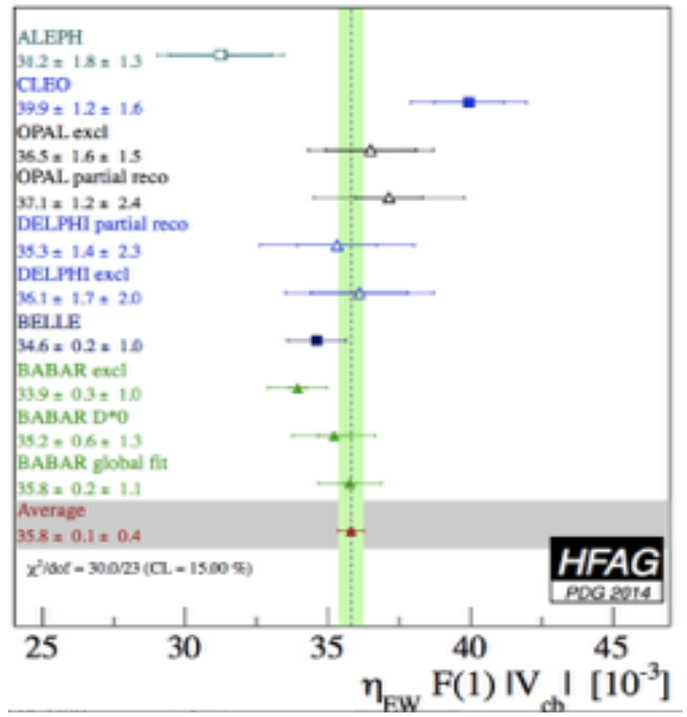
Lattice data	$\eta_{\rm EW}\lvert V_{cb}\rvert[10^{-3}]$
FNAL/MILC [15]	40.96 ± 1.23
HPQCD [32]	41.14 ± 1.88
FNAL/MILC & HPQCD [15, 32]	41.10 ± 1.14

Exclusive Average

$\bar{B} \to D^* \ell \bar{\nu}_\ell$

$|V_{cb}| = (38.9 \pm 0.5 \pm 0.5 \pm 0.2) \times 10^{-3}$

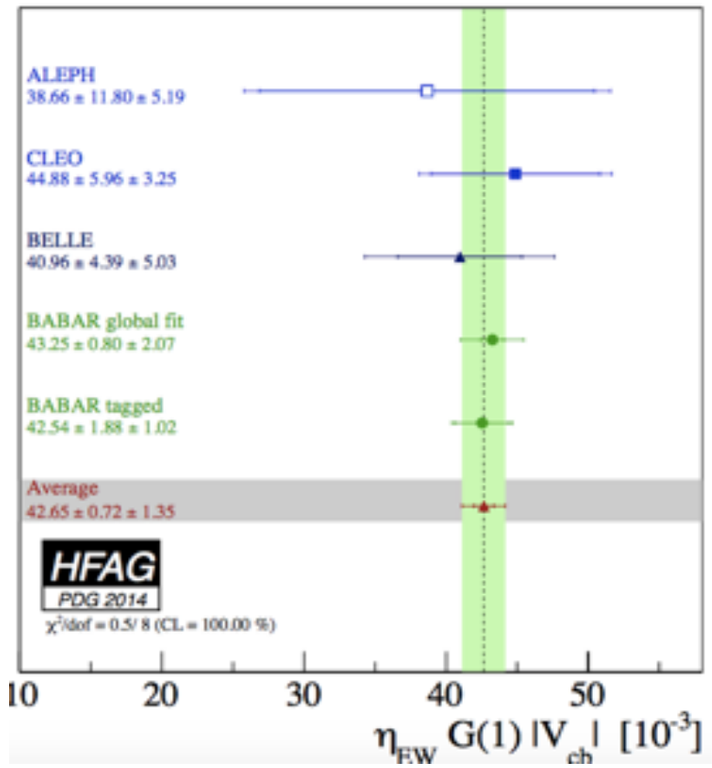
- HFAG 2014: $\eta_{\rm ew}\mathcal{F}(1)\,|V_{cb}| = (35.81 \pm 0.45) \times 10^{-3}$
- LQCD: $\mathcal{F}(1) = 0.906 \pm 0.013$
- Leading EW correction η_{ew} = 1.015±0.005



$\bar{B} \to D \ell \bar{\nu}_\ell$

$|V_{cb}| = (40.0 \pm 1.4 \pm 0.3 \pm 0.2) \times 10^{-3}$

- HFAG 2014: $\eta_{\rm ew}\mathcal{G}(1)|V_{cb}| = (42.65 \pm 1.53) \times 10^{-3}$
- LQCD: $\mathcal{G}(1) = 1.0528 \pm 0.0082$
- Leading EW correction η_{ew} = 1.012±0.005



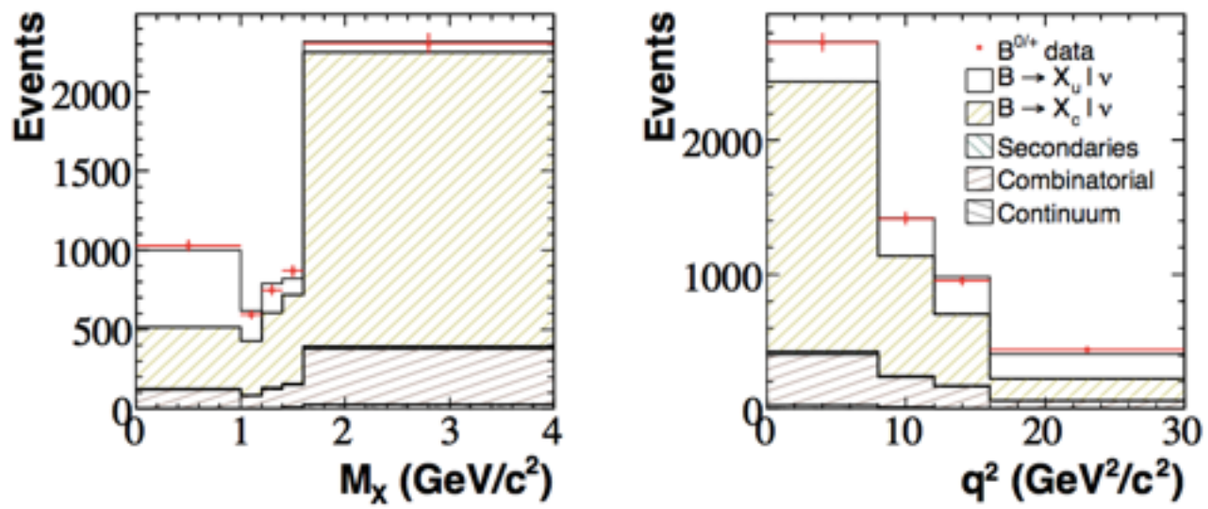
PDG 2015: average of the results from B→Dlν and B→D*lν

$$\boxed{|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3}}$$

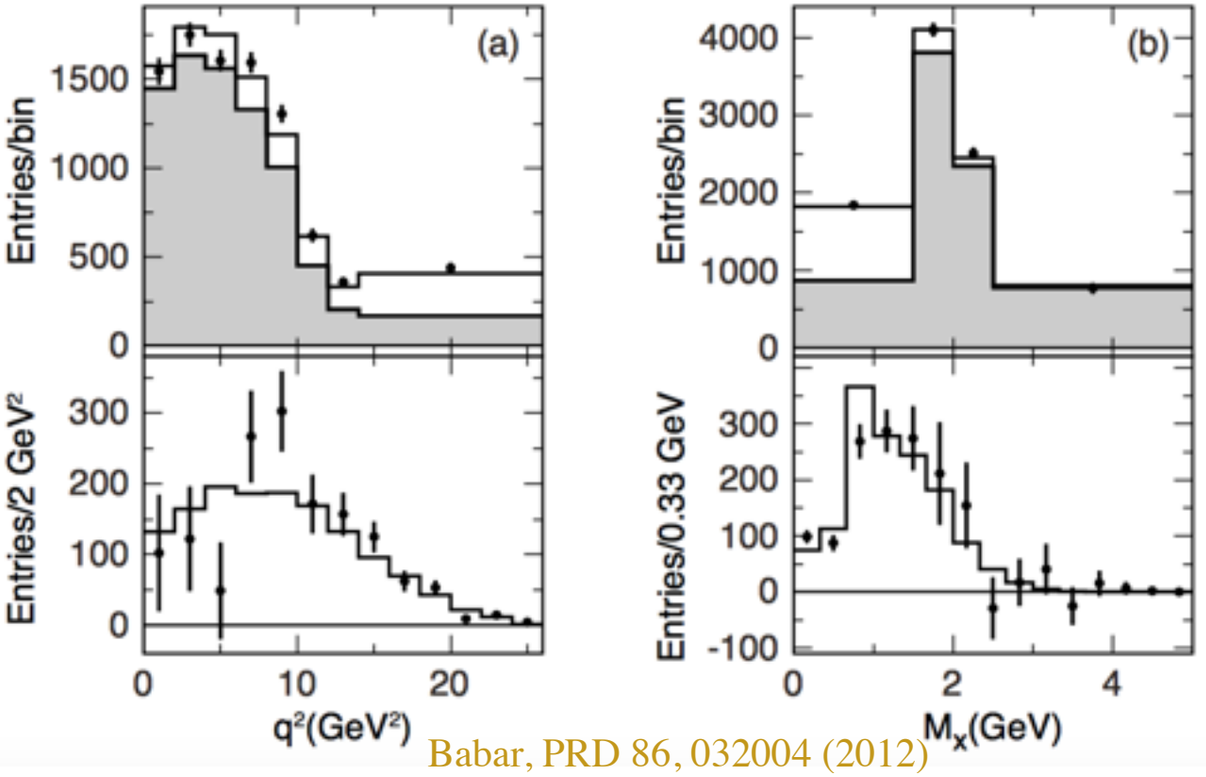
$B \to X_u l \nu$ Experimental measurements

- Tag lepton in signal B side, tag another B meson with Hadronic decays $B \to D^{(*)} Y$
- Kinematic properties : $(M_X, q^2, p_\ell^*, P_+, MM^2, etc.)$
- Challenge: background from $B \to X_c l \nu$, $\Gamma(b \to c\ell\nu) \approx 50 \times \Gamma(b \to u\ell\nu)$
- More kinematic variables are used to further suppress background, Belle: BDT, Babar: Cut based selection
- $p_\ell^* > 1.0\mathrm{GeV}$ in the B rest frame, cover 90% of $B \to X_u l \nu$ phase space

Dominent Systematic sources	Belle(%)	Babar(%)
$B \to X_u l \nu$ shape function	3.6	5.4
Exclusive $B \to X_u l \nu$	4.9	1.9
Background simulation ($D^{(*)}$)	1.7	2.7
Detector effects	3.1	3.4
BDT	3.1	-



Belle, PRL 104 (2010)



Babar, PRD 86, 032004 (2012)

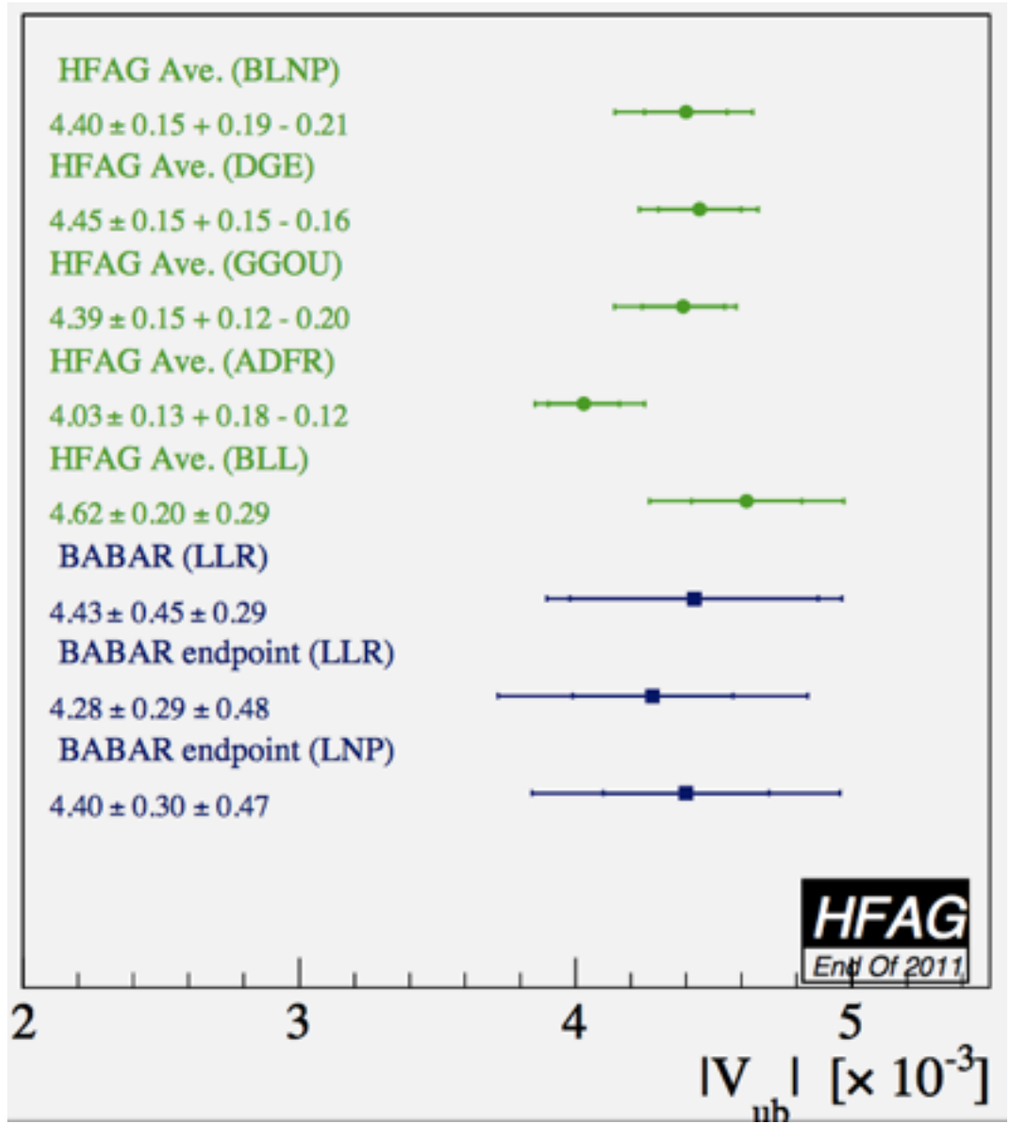
$|V_{ub}|$ determination from $B \to X_u l \nu$

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

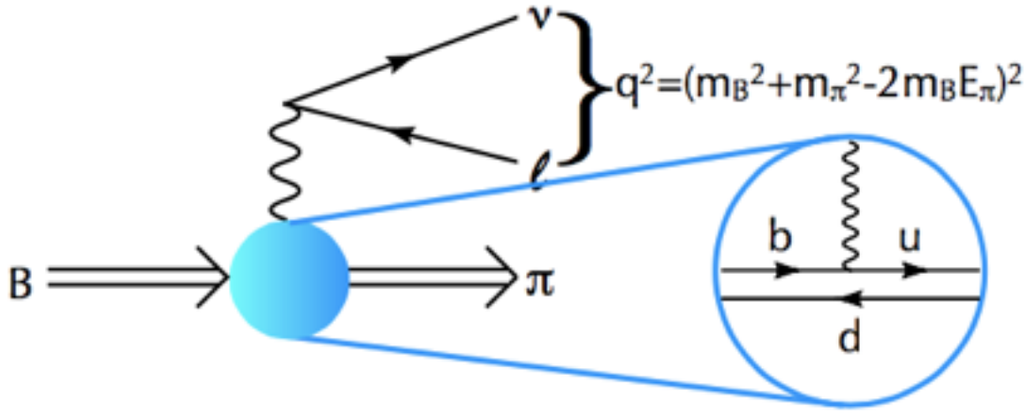
- $\Delta\Gamma_{\text{theory}}$ is the predicated $B \to X_u l \nu$ partial rate in the given phase space region
- Theoretical calculations from BLNP, DGE, ADFR, GGOU…
- Agreement between different calculations

PDG 2015

$$|V_{ub}| = (4.49 \pm 0.16_{\text{exp}} \; {}^{+0.16}_{-0.18} \, \text{theo}) \times 10^{-3}$$



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



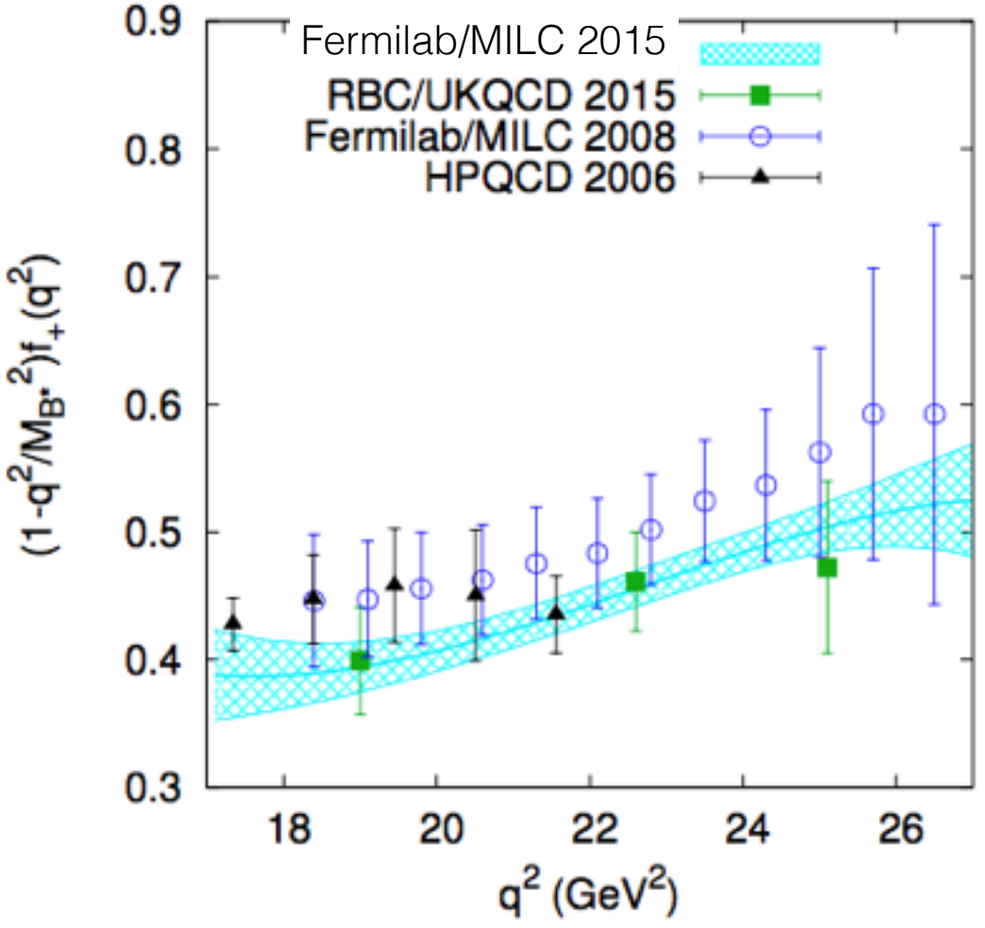
$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\boldsymbol{p}_\pi|^3 |f_+(q^2)|^2$$

$$|V_{ub}| = \sqrt{\frac{C_v \Delta\mathcal{B}}{\tau_B \Delta\zeta}} \qquad \Delta\zeta = \int d\Gamma / |V_{ub}|^2$$

- Form factor calculation

  - Lattice QCD: FNAL/MILC, HPQCD, RBC/UKQCD

  - Light Cone Sum Rules (LCSR): Ball/ Zwicky, Bharucha



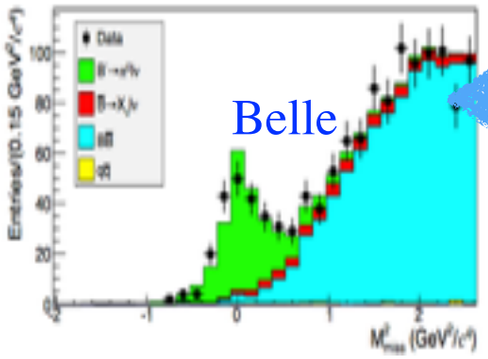
B→πlν Experimental Measurements

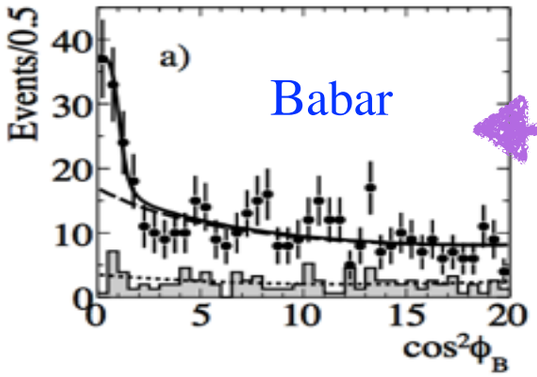
Three methods of identifying signals: *Untagged, Hadronic tag, Semileptonic tag*

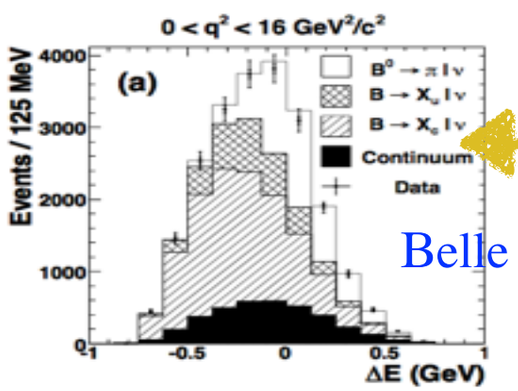
- *Had. tag*
  - Hadronic decaies
  - Missing mass
  - efficiency: Belle: ~0.2%, Babar:B^0~0.3%, B^+~0.5%
  - Dominant Uncertainty: Tag calibration

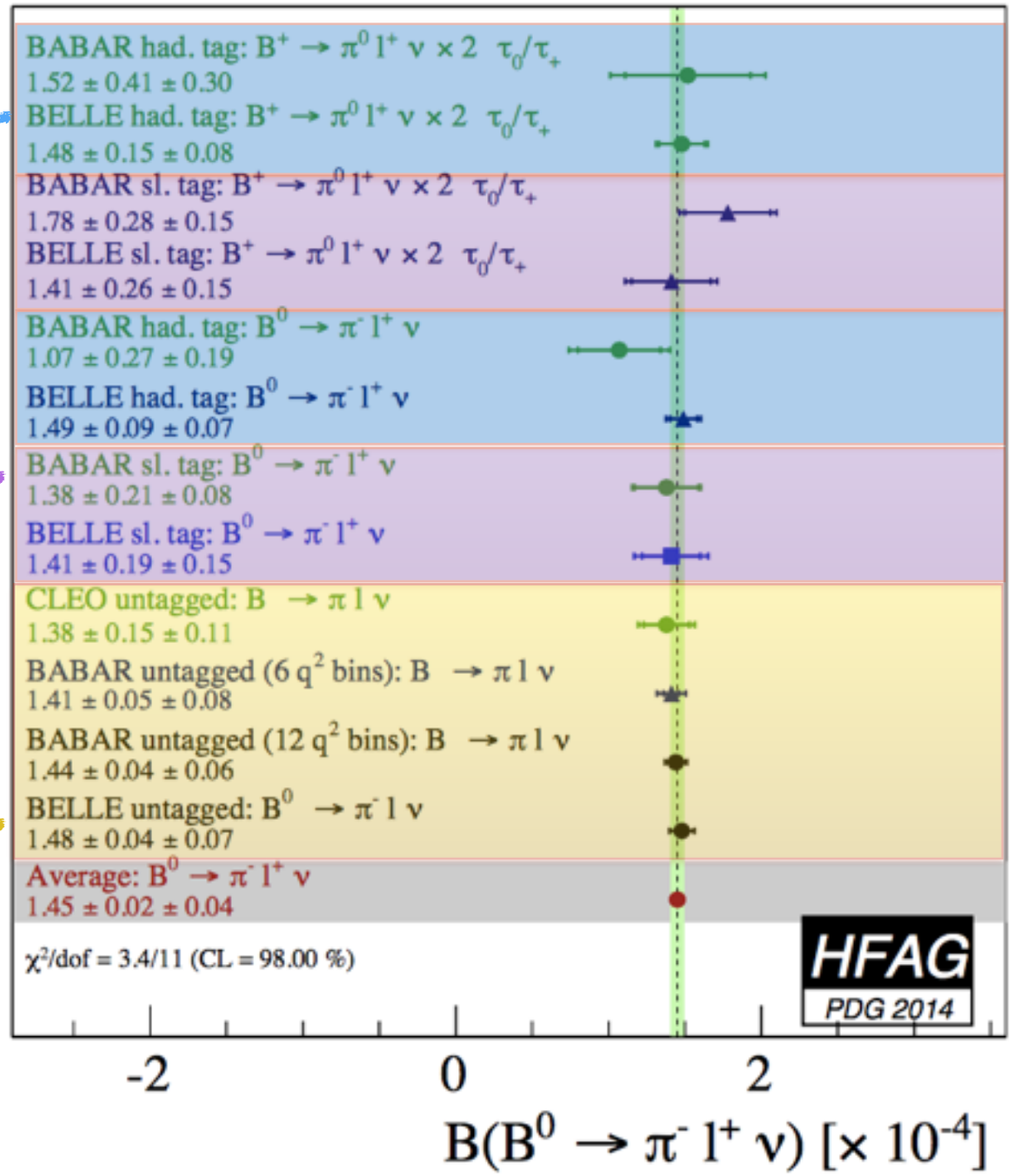
- *S.L. tag*
  - tag B→$D^{(*)}$1ν
  - extract signal yield by using the kinematic feature of the double semileptonic decay
  - efficiency: Belle~0.2%, Babar:B^0(B^+) ~0.1%(0.3%)

- *Untagged*
  - determine neutrino four-momentum with the momenta of all particles and beam particles
  - efficiency: Belle~9%, Babar:B^0(B^+) ~7%(5%)
  - Dominent uncertainty: Detector effects, b→ulν background





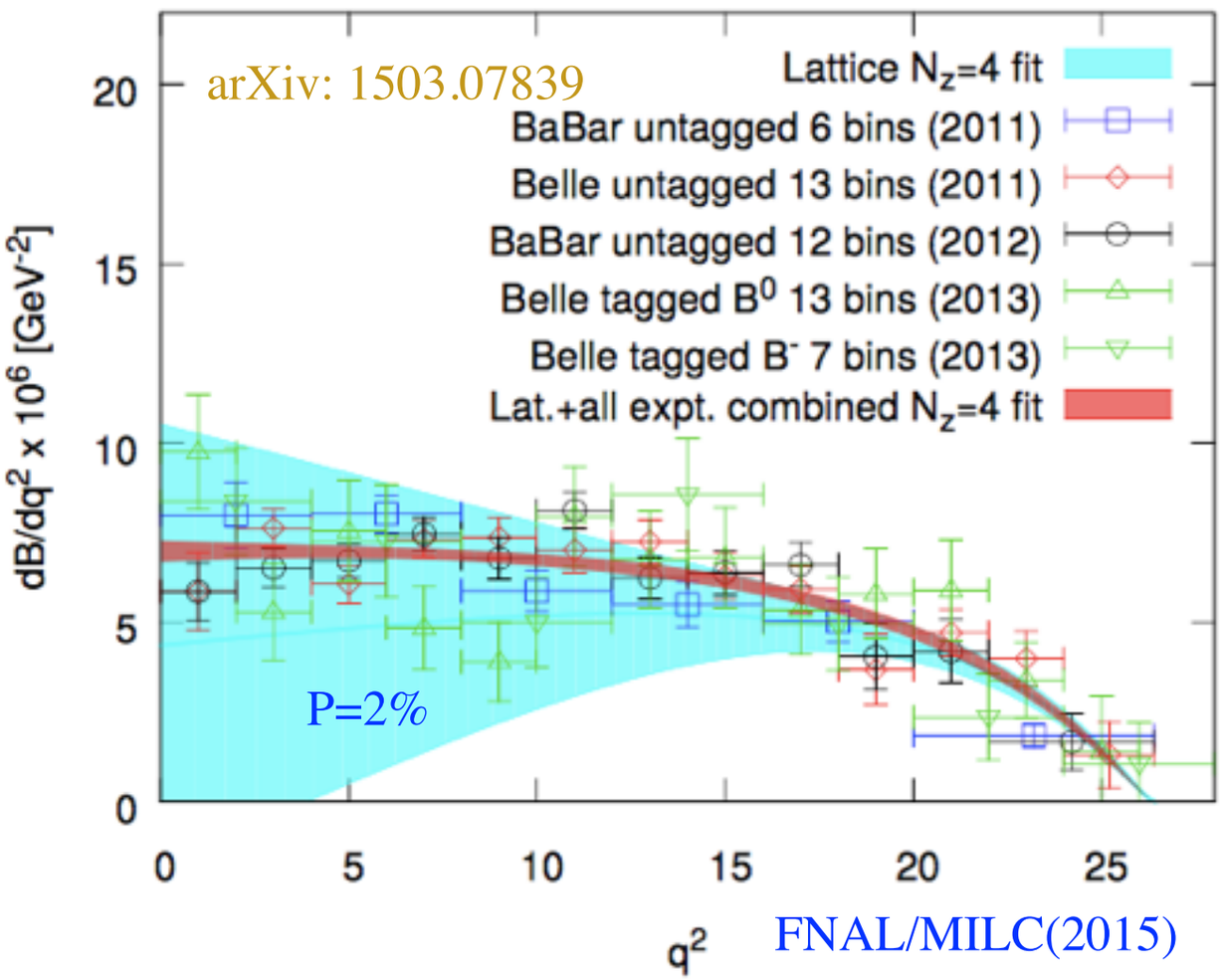




$|V_{ub}|$ determination from $B \to \pi l \nu$

- Combined fit to experimental partial rates and theoretical calculation versus q^2
  - different experimental measurements
  - calculation from Lattice QCD
  - fit to full q^2 region
  - most precise determination σ~4%, σ(experimental) ~ σ(QCD)

$$|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$$



$|V_{ub}|$ determination from baryonic decay $\Lambda_b \to p\mu\nu_\mu$

$\Lambda_b \to p\mu\nu_\mu$ @LHCb

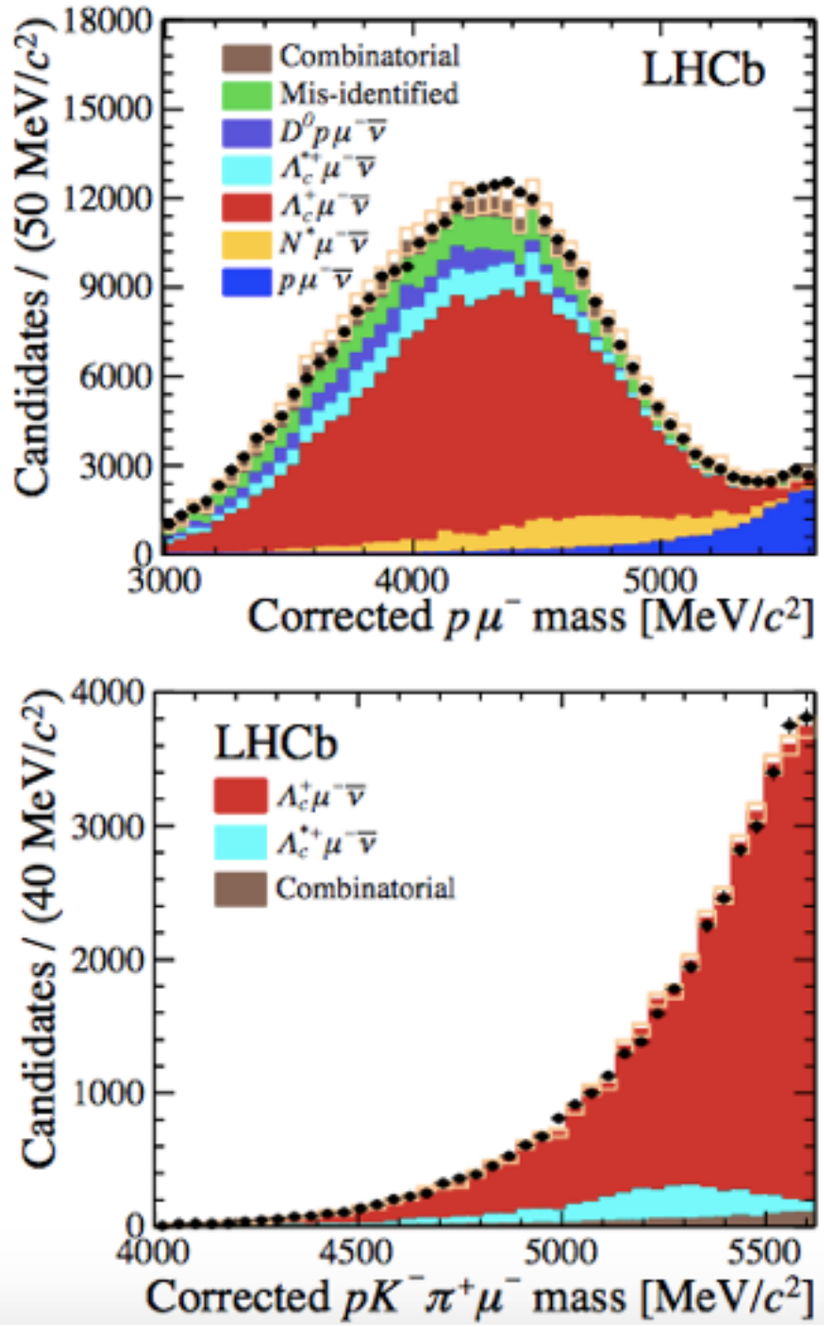
- Measure $|V_{ub}|/|V_{cb}|$ with $\Lambda_b \to p\mu\nu_\mu$, $\Lambda_b \to (\Lambda_c \to pK\pi)\mu\nu_\mu$.
- Cancel some of experimental uncertainties.
- Determine $|V_{ub}|$ with $|V_{cb}|$ from experiment

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{(PDG 2014)}$$

$$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.16(\text{LQCD}) \pm 0.06(\text{norm})) \times 10^{-3}$$

- Consistent with $|V_{ub}|$ determined by exclusive B decays



LHCb, arXiv: 1504,01568

Summary

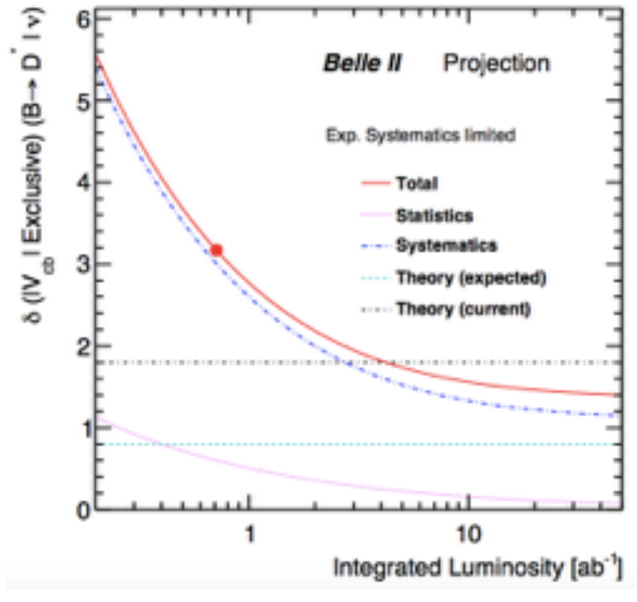
- $|V_{cb}|$ and $|V_{ub}|$ are measured with different methods
  - Inclusive $B \to X_c l\nu$, $B \to X_u l\nu$, Hadronic tag, Semileptonic tag, Untagged.
  - Exclusive $B \to D^{(*)} l\nu$, $B \to \pi l\nu$
- Inclusive-Exclusive tension in both $|V_{cb}|$ and $|V_{ub}|$ still exist.

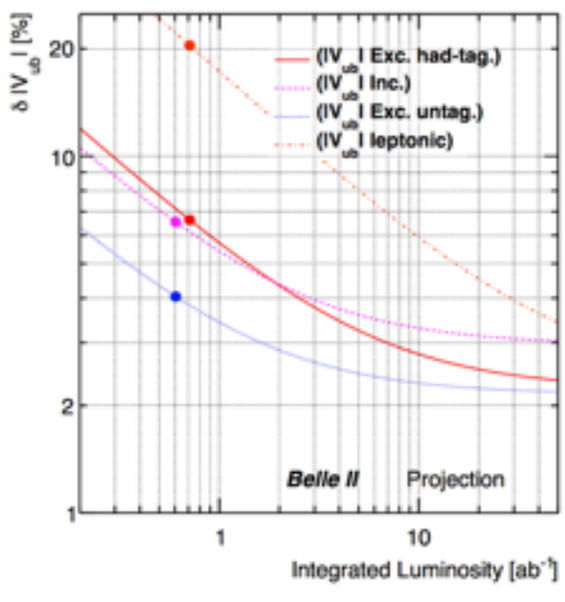
	Measurements (10^{-3})	δV/V
$\|V_{ub}\|$ Inc.	4.49±0.23	6%
$\|V_{ub}\|$ Exc.	3.72±0.16	4%
$\|V_{cb}\|$ Inc.	42.21±0.78	2%
$\|V_{cb}\|$ Exc.	39.2±0.7	2%

2.8σ

2.9σ

- Belle II will provide more precise measurements.



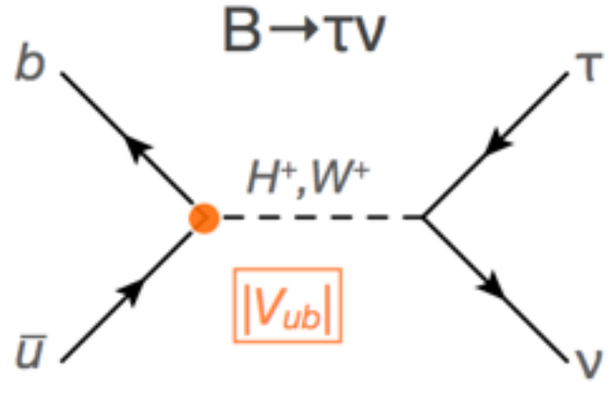


Back up

Experimental measurement $B \to \tau\nu_\tau$

$B \to \tau\nu_\tau$

- SM: $B(B \to \tau\nu_\tau) \propto (f_B|V_{ub}|)^2$
- Sensitive to New Physics: H^+
- B_{sig}: $\tau \to (e, \mu)\nu\nu$, $(\pi, \rho)\nu$, Hadronic tag B_{tag}
- Evidence: Belle~3.0σ, Babar~3.8σ

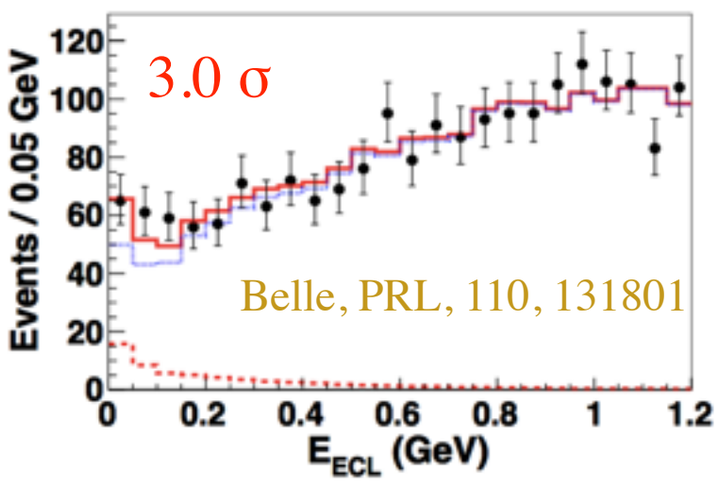


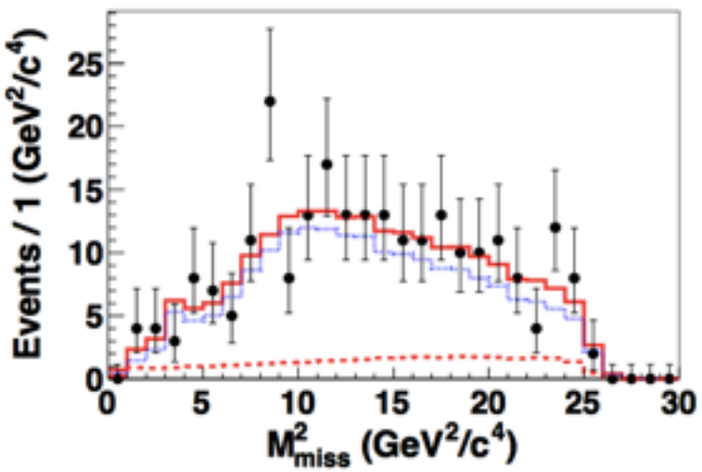
Belle

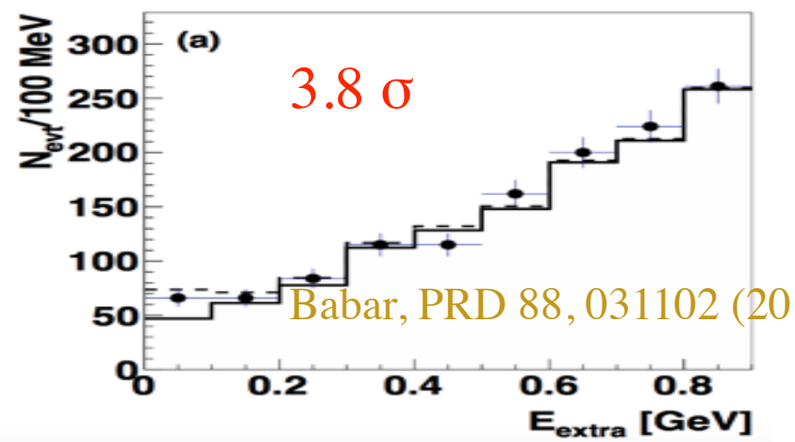
$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$

Babar

$$\mathcal{B}(B^+ \to \tau^+ \nu) = (1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})) \times 10^{-4}$$







Measurements from B→(ρ,ω,η,η')lν

Measurement: