B decays and CKM

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Outline

CKM overview

Determination of $|V_{cb}|$:

- $B \to D\, l\, \nu$ and $B \to D^*\, l\, \nu$ decays

Determination of $|V_{ub}|$:

- inclusive $B \to X_u\, l\, \nu$ branching fraction measurements
- exclusive $B \to (\pi,\rho)\, l\, \nu$ decays
- $B^+ \to \tau^+ \nu$

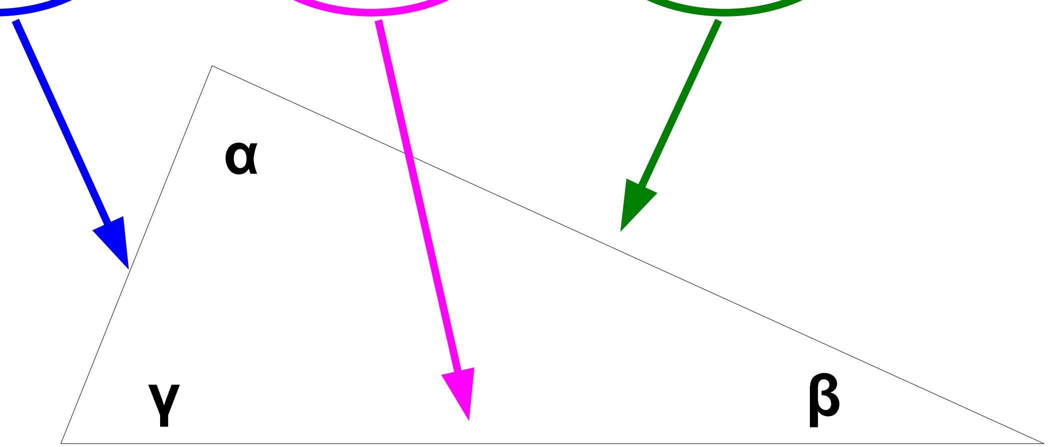
B decays and CKM

CKM matrix parametrizes the mixing of quark flavours via weak interaction

- Unitary by construction, implying non-trivial relationships between elements

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

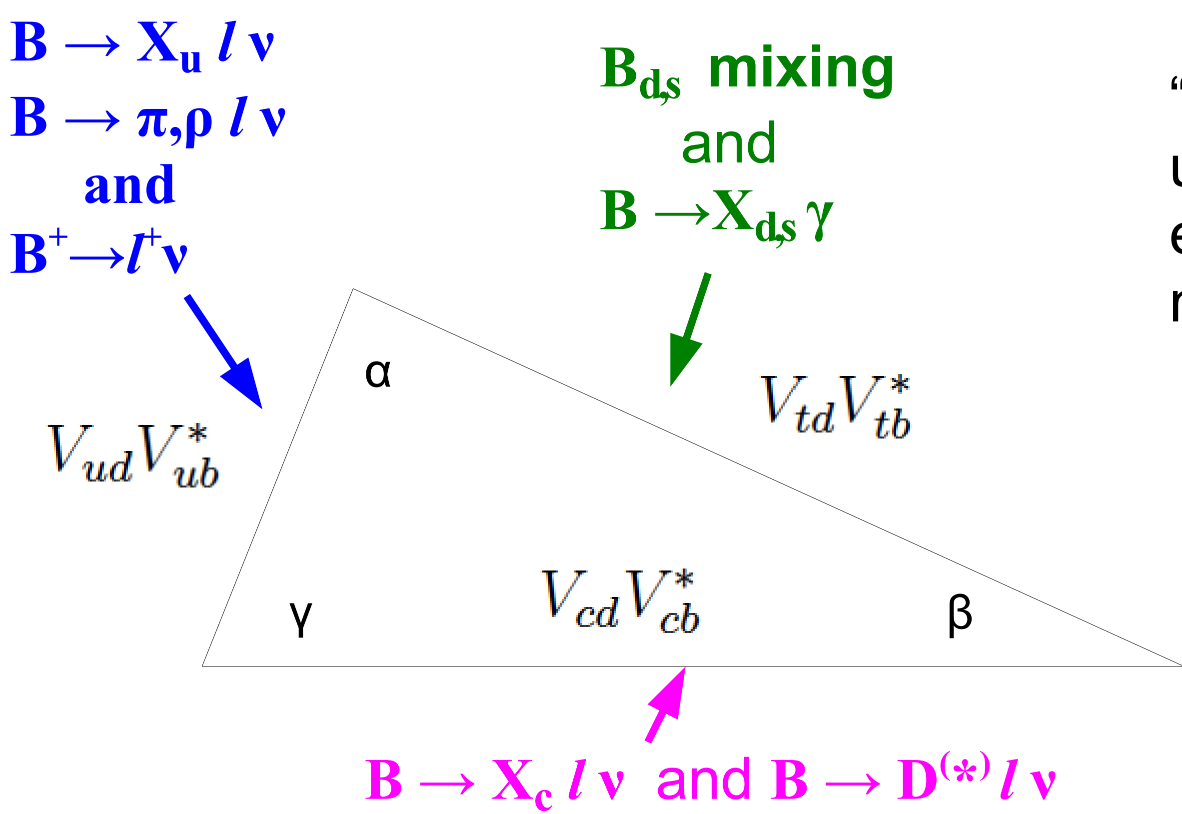


- Angles related to CP violation measurements
- Lengths of sides related to magnitudes of CKM elements (i.e. CP conserving measurements)

B decays and CKM

CP conserving B physics measurements probe the range of 3rd generation CKM elements through both tree and one-loop processes

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



"Redundant" determinations using theoretically and experimentally independent methods

- Validate methodology and can be interpreted in context of new physics models

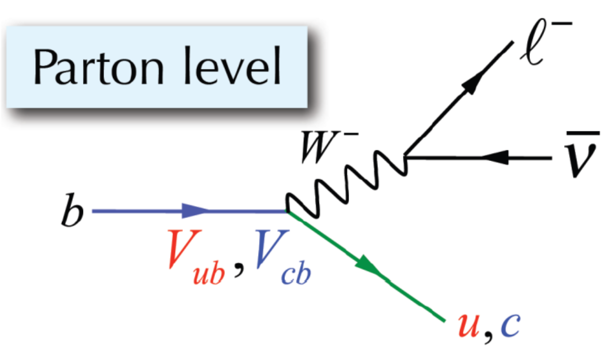
Determining CKM elements

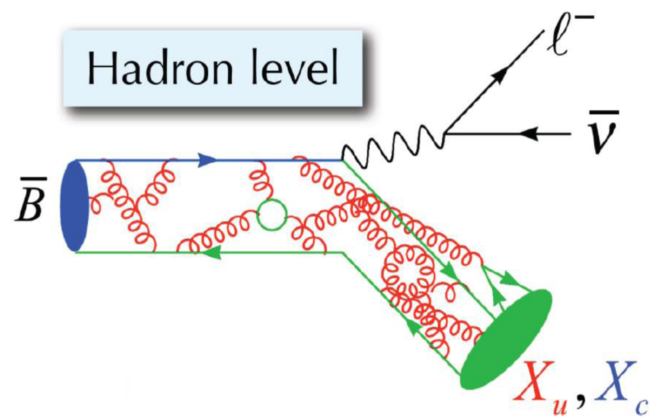
Semileptonic B decays give direct access to CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$:

$$M(M_{Q\bar{q}} \rightarrow X_{q'\bar{q}}\, l\bar{\nu}) = -i\frac{G_F}{\sqrt{2}} V_{q'Q} L^{\mu} H_{\mu}$$

$$L^{\mu} = \bar{u}_l \gamma^{\mu}(1-\gamma_5)v_{\nu} \qquad H_{\mu} = \left\langle X \middle| \bar{q}'\gamma_{\mu}(1-\gamma_5)Q \middle| M \right\rangle$$

- Challenge is to understand hadronic current (lattice QCD, HQET etc)

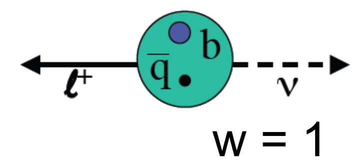




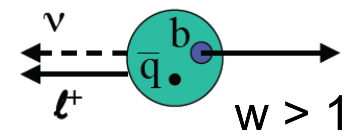
- Independent theoretical approaches for inclusive (OPE) and exclusive B decay processes (form factors)

$|V_{cb}|$ from exclusive decays

Exclusive $|V_{cb}|$ determinations are based on $B \to D l \nu$ and $B \to D^* l \nu$ differential decay rate measurements



- Limitation is knowledge of $B \to D^{(*)}$ form factors:



$$\frac{d\Gamma}{dw}(\overline{B} \to D\ell\overline{\nu}_\ell) = \frac{G_F^2}{48\pi^3\hbar} M_D^3 (M_B + M_D)^2 (w^2-1)^{3/2} | V_{cb} |^2 \mathcal{G}^2(w)$$

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

$$\omega = v_B \cdot v_{D^{(*)}}$$

Form factors become unity at zero-recoil in heavy quark limit; corrections computed on lattice

$|V_{cb}|$ extracted by extrapolating the differential decay rate to w = 1

- Requires assumption about shape of form factor:
  - BABAR/Belle use parametrization characterized by form factor slope parameter ρ^2 (and $\mathbf{R_1}$, $\mathbf{R_2}$ in D* decays)

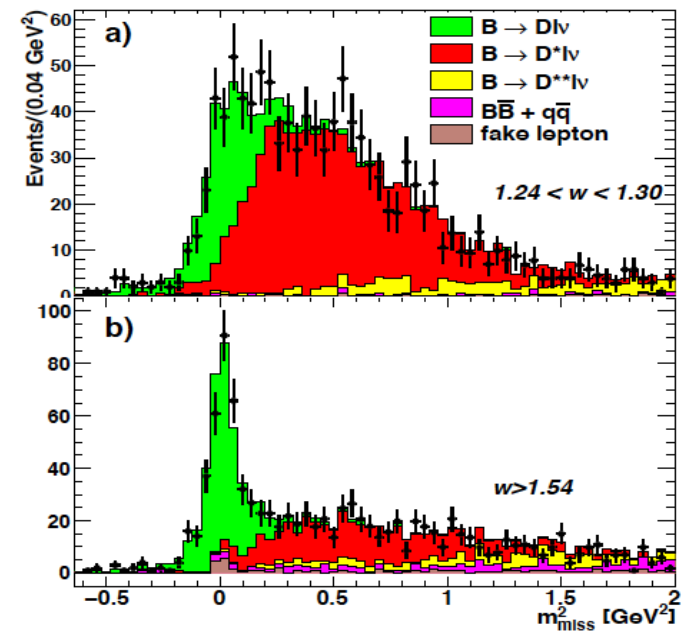
Caprini et al., Nucl. Phys B530, 153 (1998)

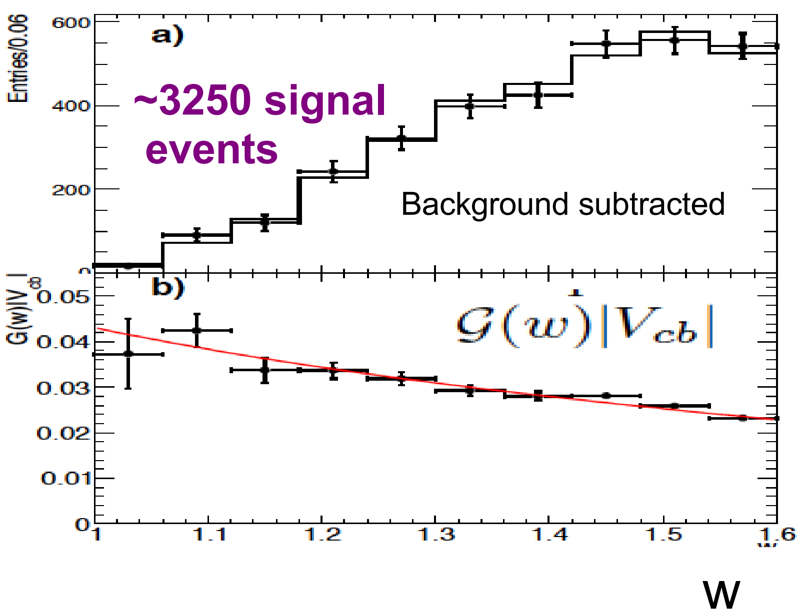
$|V_{cb}|$ from $B\to Dl\nu$

PRL 104, 011802 (2010)

BABAR measurement of $B\to Dl\nu$ based on 460×10^6 BB pairs using exclusive reconstruction of the accompanying **hadronic B decay**

- Background from $B\to D^*l\nu$ due to missing slow π^0
- Extract differential branching fraction from fit to missing mass spectrum in 10 bins of w



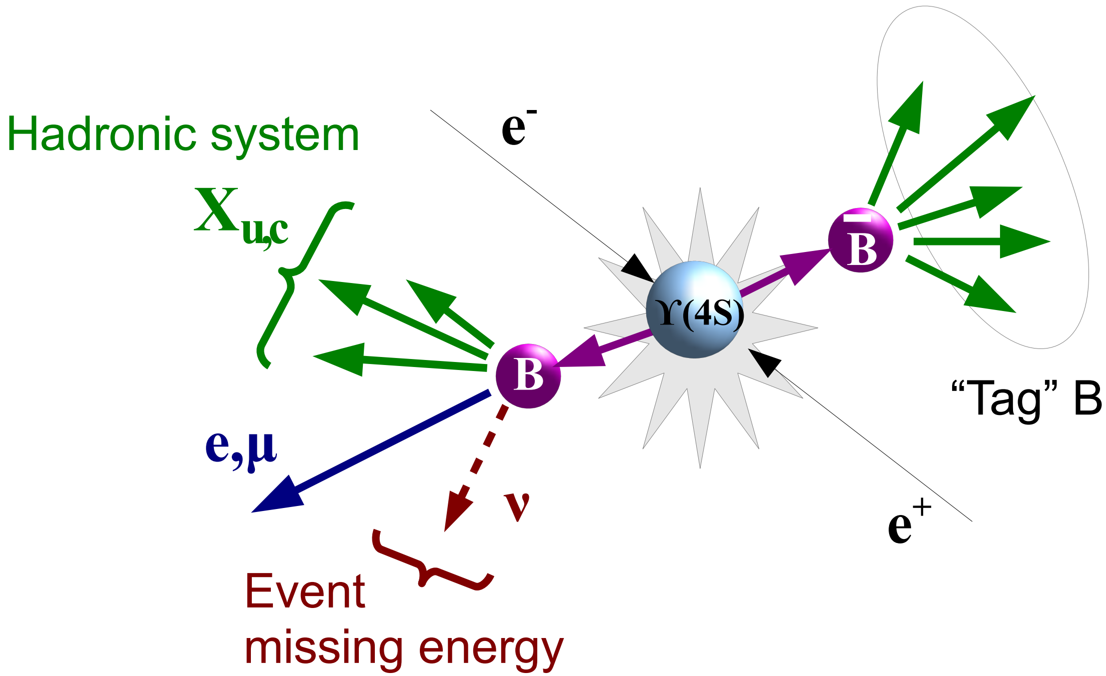


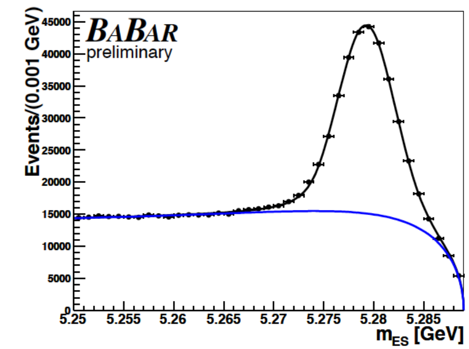
Most precise determination of $B\to Dl\nu$ branching fraction to date

$$\mathcal{B}(B\to Dl^+\nu) = (2.17 \pm 0.06 \pm 0.09)\%$$

$$G(1)|V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$$
$$\rho^2 = 1.20 \pm 0.09 \pm 0.04$$

Methodology





$$m_{\rm ES} \equiv \sqrt{E^{*2}_{\rm beam} - {\rm p}^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

Advantage:

- Improved knowledge of signal kinematics, missing energy and suppression of combinatorial backgrounds

Disadvantage:

- Low tag reconstruction efficiency

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

PRL 104, 011802 (2010)

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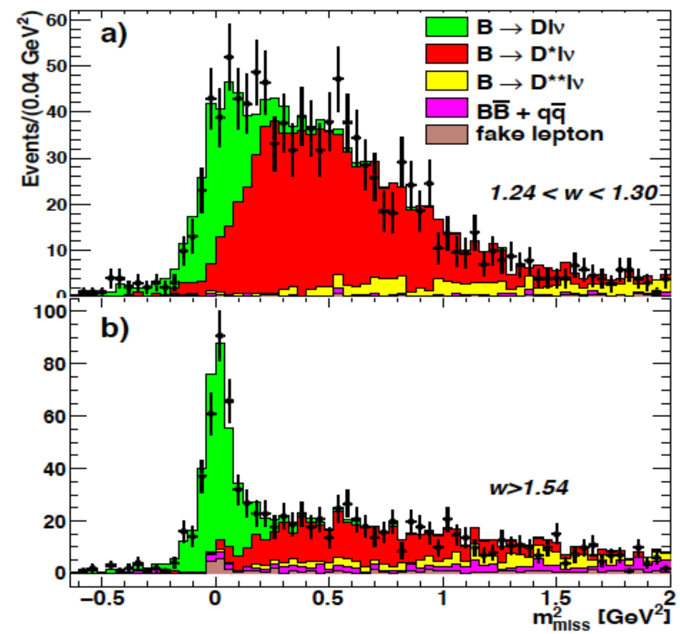
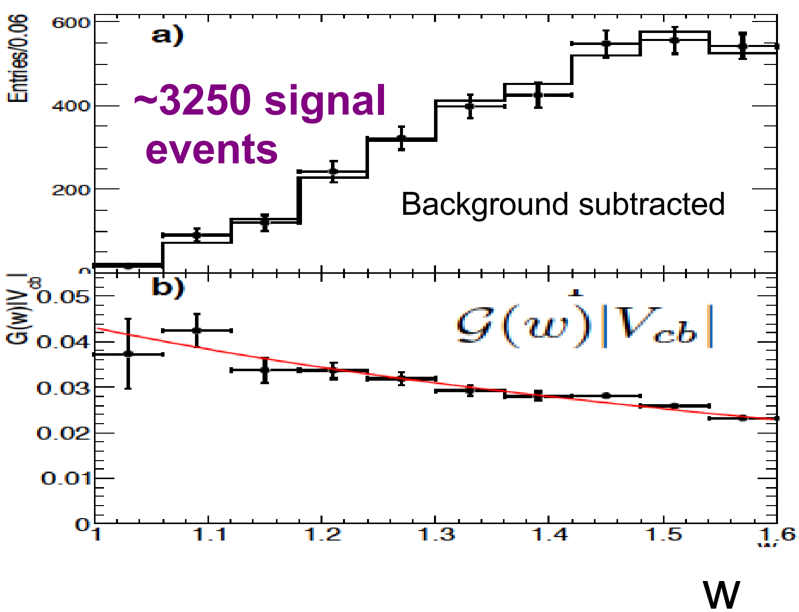




Most precise determination of $B \to D l \nu$ branching fraction to date

$$\mathcal{B}(B \to D l^+ \nu) = (2.17 \pm 0.06 \pm 0.09)\%$$

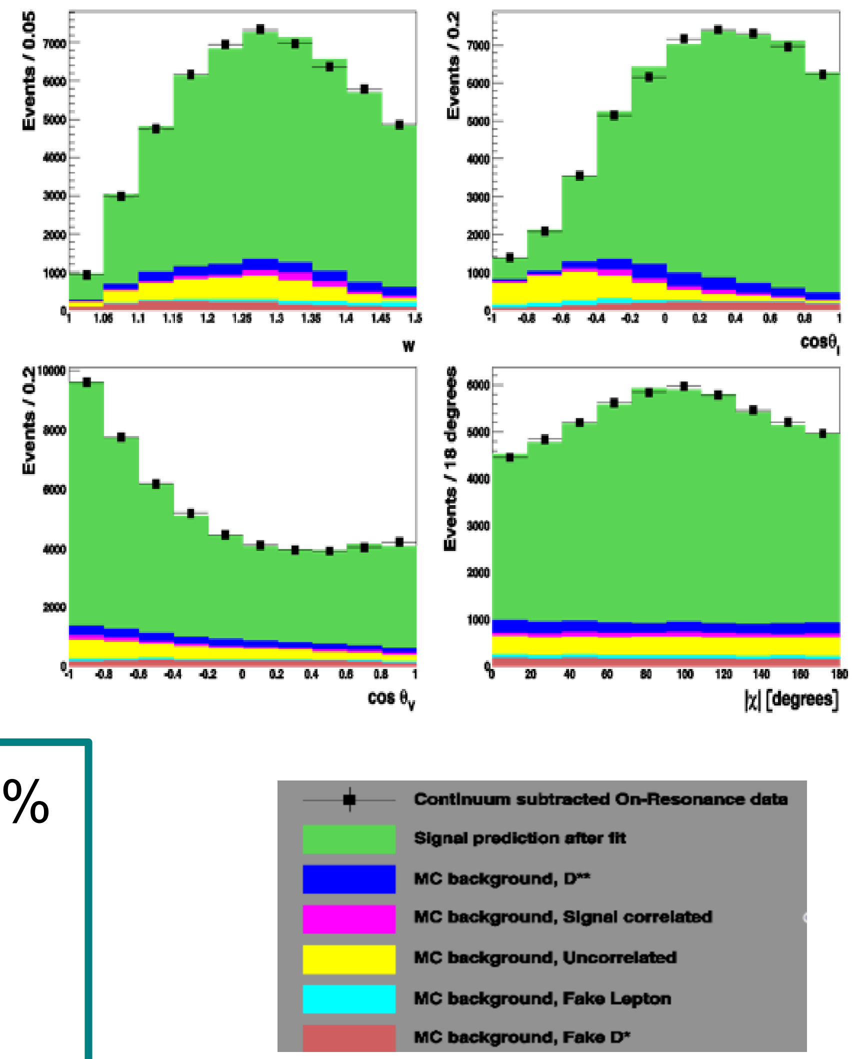
$$G(1)|V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$$
$$\rho^2 = 1.20 \pm 0.09 \pm 0.04$$

$|V_{cb}|$ from $B^0 \to D^{*-} l^+ \nu$

http://belle.kek.jp/results/summer10/dstlnu/

New untagged $B^0 \to D^{*-} l^+ \nu$ measurement based on 711 fb^{-1} of Belle data

- Consider only $D^{*+} \to D^0 \pi^+$; $D^0 \to K^- \pi^+$ (and charge conjugate) modes, with no tag B reconstruction
  - about 120,000 $B^0 \to D^{*-} l^+ \nu$ decays selected in total
- Extract branching fraction from fits to w and angles ($\cos\theta_l$, $\cos\theta_V$, χ) characterizing the D^* decay



$$\mathcal{B}(B^0 \to D^{*-} l^+ \nu) = (4.56 \pm 0.03 \pm 0.26)\%$$

$$F(1)|V_{cb}| = 34.5 \pm 0.2 \pm 1.0$$
$$\rho^2 = 1.214 \pm 0.034 \pm 0.009$$
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018$$
$$R_2(1) = 0.864 \pm 0.024 \pm 0.008$$

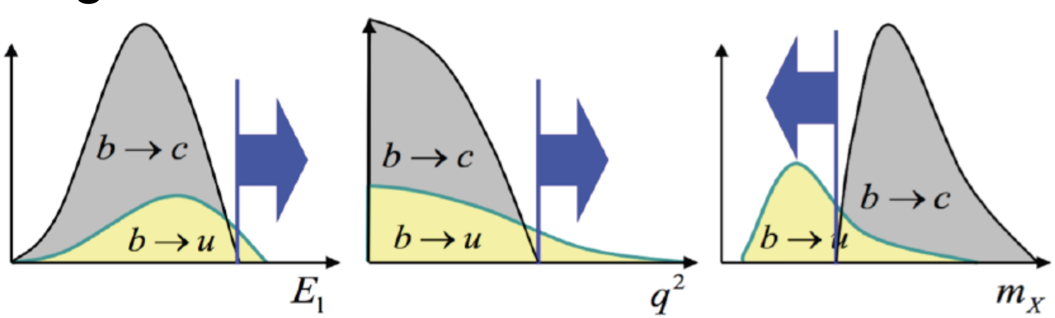
Measurement of $|V_{ub}|$

$$\Gamma(\bar{B} \to X_u \ell \bar{\nu}) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(1/m_b^2) + \text{h.c.}\right]$$

Challenge for $B \to X_u l\nu$ determination due to background from CKM-favored $B \to X_c l\nu$ decays:

$$\frac{\Gamma(b \to u\ell\nu)}{\Gamma(b \to c\ell\nu)} \approx \frac{|V_{ub}|}{|V_{cb}|} \approx \frac{1}{50}$$

- convergence of Heavy Quark Expansion spoiled in partial rate calculations, but kinematic selection required to suppress backgrounds:



p_ℓ^* lepton momentum
M_X hadronic invariant mass
q^2 squared momentum transfer
$P_+ = E_X - |p_X|$ light-cone momentum

- introduces dependencies on non-perturbative shape functions to account for efficiency loss in inaccessible regions of phase space)

$\Rightarrow$ Tradeoff between extending measurements into higher backgrounds regions and increased theory uncertainties on $|V_{ub}|$ extraction

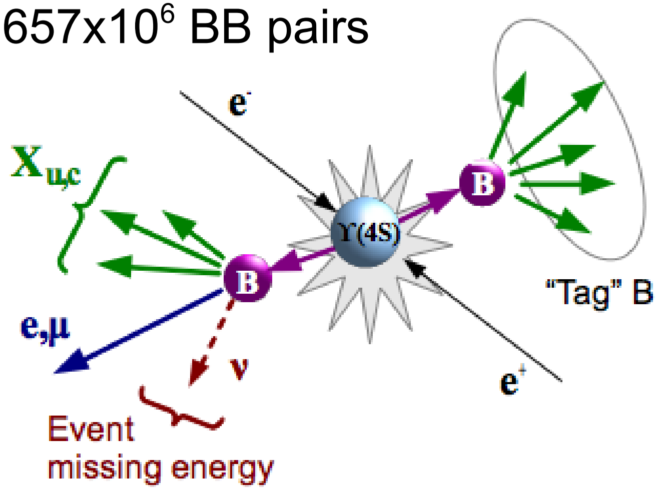
Inclusive $|V_{ub}|$

PRL 104:021801 (2010)

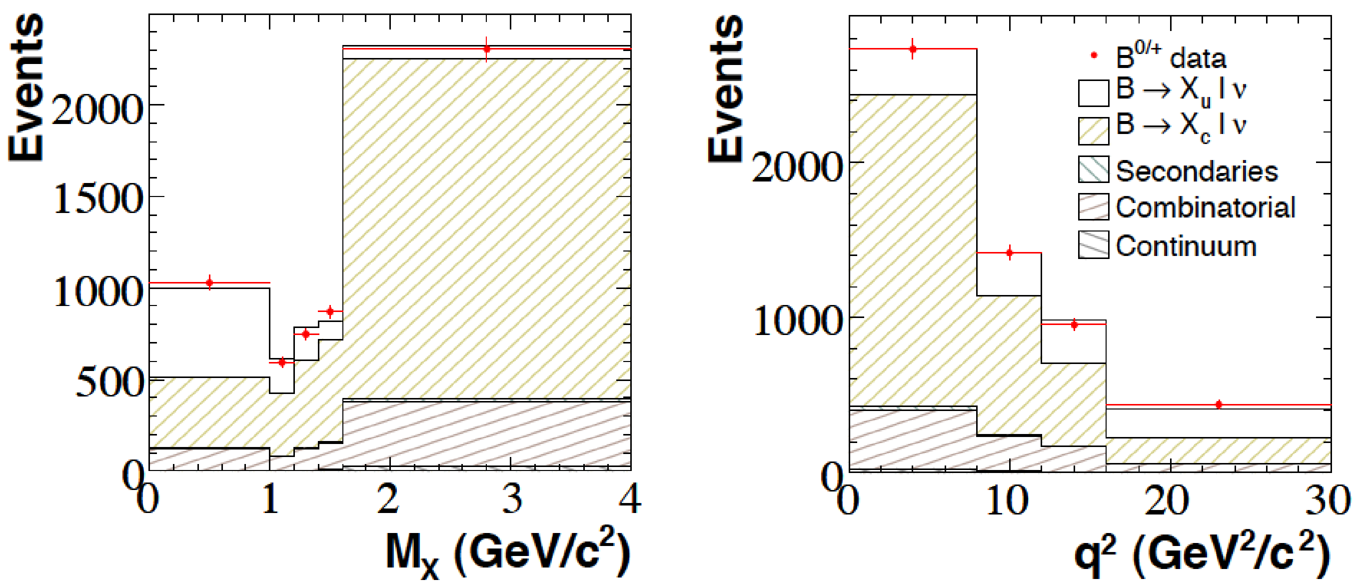
Belle $|V_{ub}|$ measurement based on inclusive $B \to X_u l\nu$ with hadronic tag reconstruction

- p_ℓ^* > 1.0 GeV/c
- Suppression of $B \to X_c l\nu$ background via 20-input Boosted Decision Tree

657x10[6] BB pairs



Yield extracted from 2D fit to M_X, q^2 with background floated:

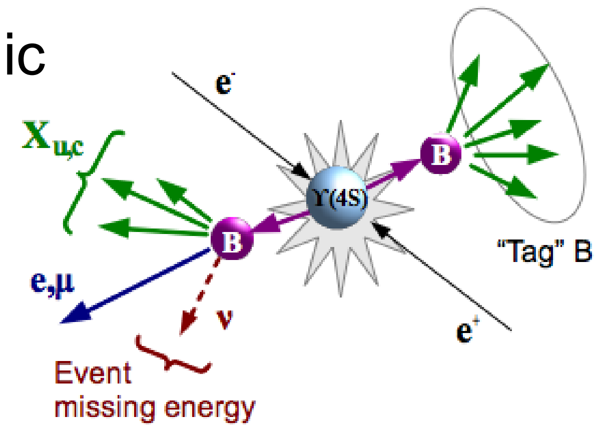


Analysis accesses ~90% of available $B \to X_u l\nu$ phase space

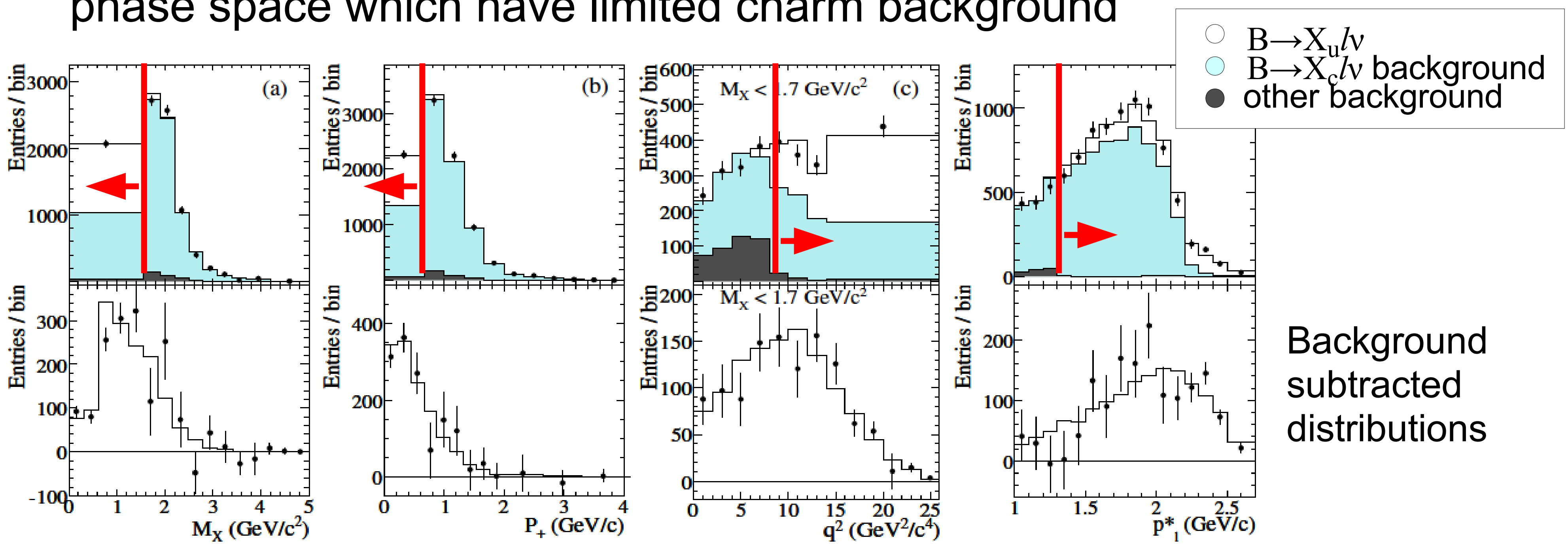
Inclusive $|V_{ub}|$

New BABAR measurement of $B \to X_u l \nu$ using hadronic tag reconstruction (468 x 10^6 BB pairs)

- p_ℓ^* > 1.0 GeV/c
- Cut-based selection using similar variables as Belle multivariate analysis



- Measure partial branching fractions in six regions of phase space which have limited charm background



Background subtracted distributions

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

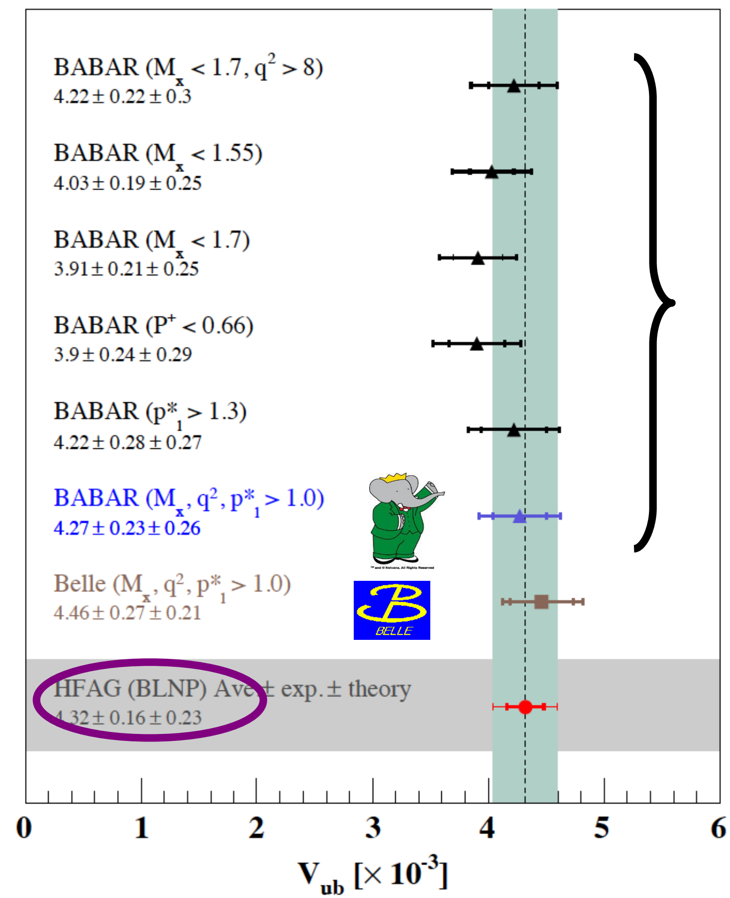
M. Sigamani
ICHEP 732 (2010)

$$\Delta\mathcal{B}(B \to X_u \ell\nu; p_\ell^* > 1.0\ \mathrm{GeV}/c) =$$
$$(1.80 \pm 0.13 \pm 0.15) \times 10^{-3}$$
$$(1.96 \pm 0.17 \pm 0.16) \times 10^{-3}$$

Most precise BABAR value obtained for full M_X, q^2 determination with $p_\ell^* > 1.0$ GeV/c

- Equivalent phase space coverage to Belle analysis
- Significantly reduced theory uncertainties compared with other methods

Partial branching fraction measurements translated into values of $|V_{ub}|$ using theoretical models (BLNP, GGOU, DGE ADFR



BABAR preliminary

(not included In HFAG average)

$|V_{ub}|$ from $B \to (\pi,\rho) l \nu$

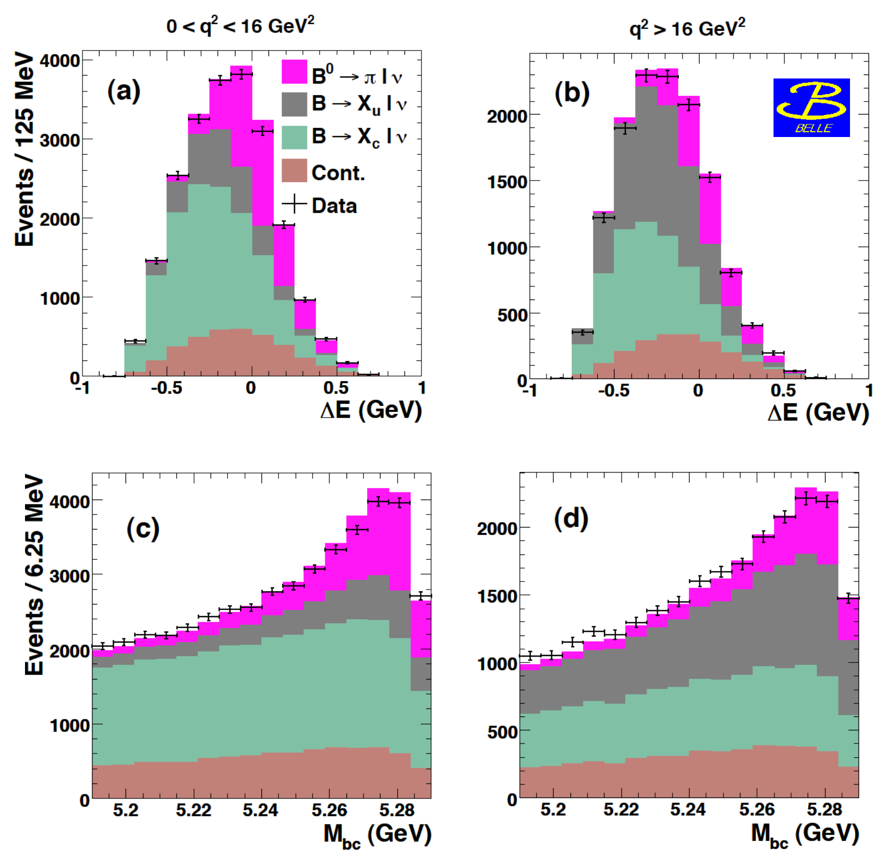
$|V_{ub}|$ can be extracted from measurements of exclusive $B \to \pi\, l\, \nu$ and $B \to \rho\, l\, \nu$ differential branching fractions

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

- theory input needed for form factor $f_+(q^2)$ determination

New preliminary Belle measurement based on 605 fb^{-1} of data:

$B(B^0 \to \pi^- l^+ \nu) =$
$(1.49 \pm 0.04 \text{ stat} \pm 0.07 \text{ syst}) \times 10^{-4}$



http://belle.kek.jp/results/summer10/b2pilnu/

$|V_{ub}|$ from $B \to (\pi,\rho) l \nu$

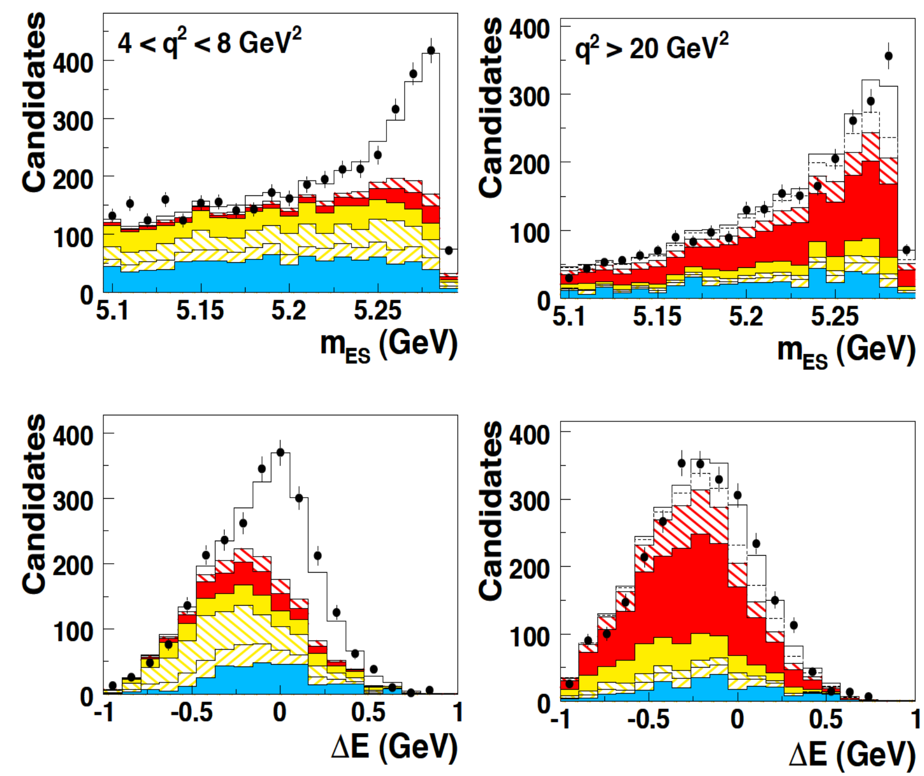
BABAR measurement of $B \to (\pi^{\pm}, \pi^0, \rho^{\pm}, \rho^0)\, l\nu$ based on 337×10^6 BB pairs

- Neutrino inferred from total event missing momentum vector
- Multivariate (NN) selection to suppress large $B \to X_c l\nu$ background as well as continuum and other $B \to X_u l\nu$ backgrounds
- Branching fractions extracted from simultaneous fit with isospin constraint in m_{ES}, ΔE and q^2 :

$$B(B^0 \to \pi^- l^+ \nu) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}$$
$$B(B^0 \to \rho^- l^+ \nu) = (1.75 \pm 0.15 \pm 0.27) \times 10^{-4}$$

BABAR
preliminary

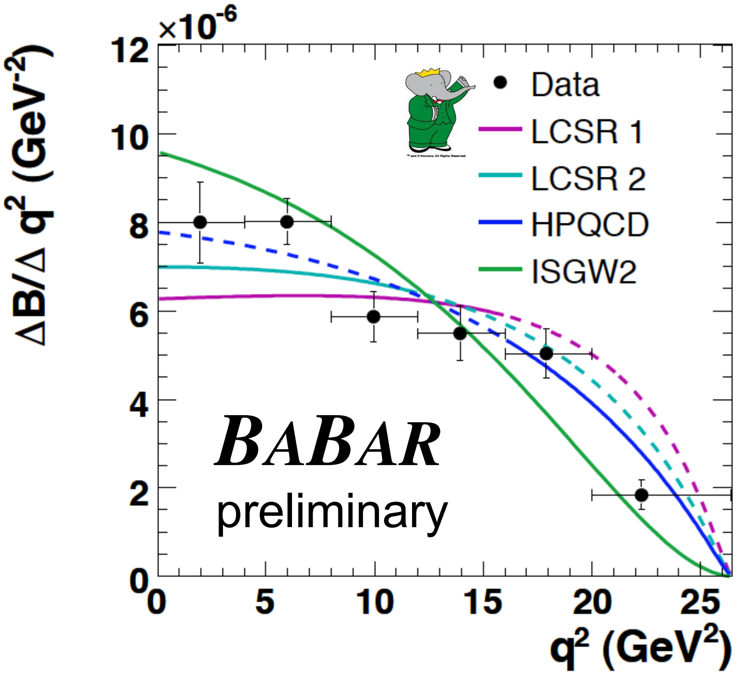
arXiv:1005.3288[hep-ex]



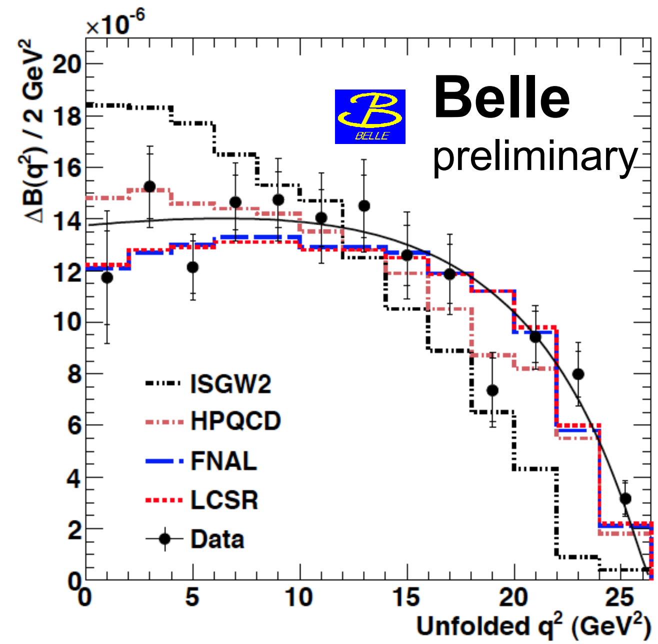
$B^0 \to \pi^- l^+ \nu$ (intermediate and high q^2 regions)

$|V_{ub}|$ from $B\to(\pi,\rho)l\,\nu$

Extract shape of the $B\to\pi l\nu$ form factor $f_+(q^2)$ from differential branching fraction spectrum:



Extract $|V_{ub}|$ by integrating **form factor predictions** over relevant q^2 range



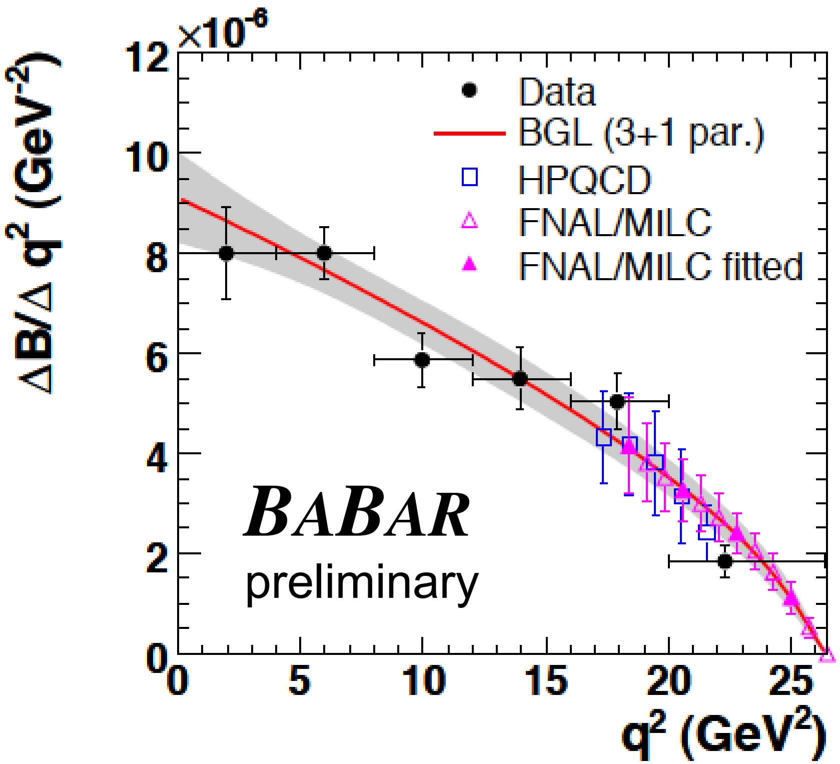
	q^2 Range (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
LCSR 1	$0-16$	1.10 ± 0.07	5.44 ± 1.43	$3.63\pm0.12^{+0.59}_{-0.40}$
LCSR 2	$0-12$	0.88 ± 0.06	$4.00^{+1.01}_{-0.95}$	$3.78\pm0.13^{+0.55}_{-0.40}$
HPQCD	$16-26.4$	0.32 ± 0.03	2.02 ± 0.55	$3.21\pm0.17^{+0.55}_{-0.36}$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(q^2_{min},q^2_{max})}{\tau_0\ \Delta\zeta(q^2_{min},q^2_{max})}}$$

$$\Delta\zeta(q^2_{min},q^2_{max}) = \frac{G_F^2}{24\pi^3}\int_{q^2_{min}}^{q^2_{max}} p_\pi^3|f_+(q^2)|^2dq^2$$

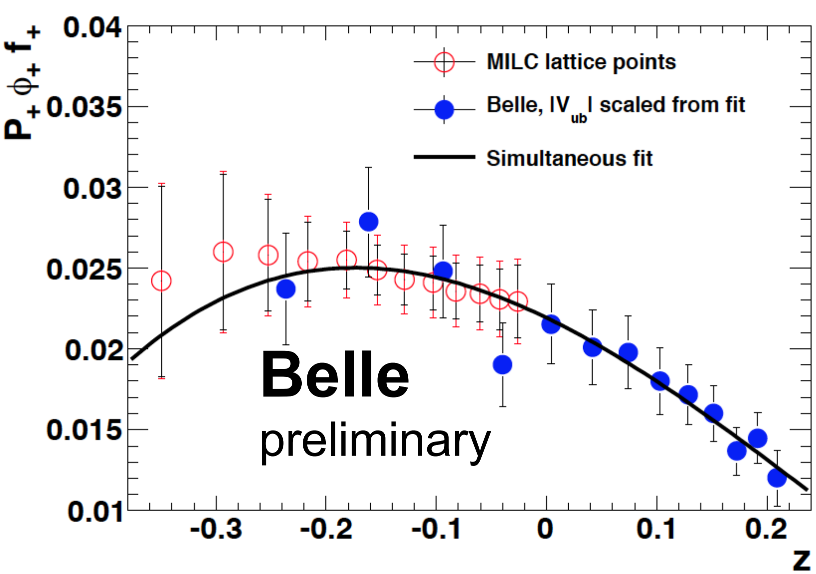
$|V_{ub}|$ from $B \to (\pi,\rho) l \nu$

$|V_{ub}|$ from alternatively be extracted from a simultaneous fit to data and lattice (FNAL/MILC):



$|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$

$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$



$f_+(q^2)$ expressed in terms of z to to remove known QCD effects

$|V_{ub}|$ summary

$|V_{ub}| = (4.46 \pm 0.27 \pm 0.24) \times 10^{-3}$

Inclusive $B \to X_u l \nu$ (p_ℓ^* > 1.0 GeV/c, M_X, q^2 fit)

$|V_{ub}| = (4.32 \pm 0.16 \pm 0.23) \times 10^{-3}$

Inclusive $B \to X_u l \nu$ HFAG average

$|V_{ub}| = (4.27 \pm 0.23 \pm 0.26) \times 10^{-3}$ New

Inclusive $B \to X_u l \nu$ (p_ℓ^* > 1.0 GeV/c, M_X, q^2 fit)

BLNP

$|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$

Exclusive $B \to \pi l \nu$ (fit with lattice)

$|V_{ub}| = (3.40 \pm 0.20) \times 10^{-3}$

Exclusive $B \to \pi l \nu$ HFAG average (HPQCD)

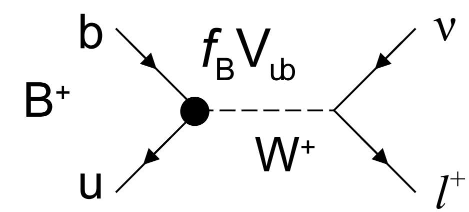
$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$ New

Exclusive $B \to \pi l \nu$ (fit with lattice)

- Significant improvements in techniques for $|V_{ub}|$ extraction in recent years, but long-standing discrepancy between inclusive and exclusive determinations persists

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

Theoretically clean determination of $|V_{ub}|$ from helicity suppressed leptonic modes



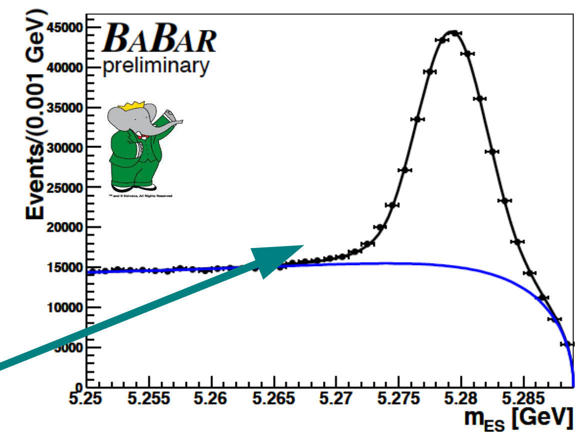
$$\mathcal{B}r(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} |V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

Experimental challenge due to small branching fractions and limited kinematic information

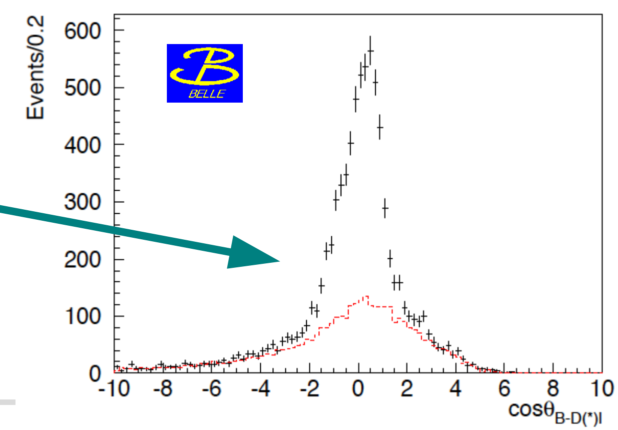
– $B \to \tau\nu$ most accessible mode at B factories

- Possible to use both hadronic and semileptonic reconstruction of tag B:

$$\begin{aligned} m_{\mathrm{ES}} &\equiv \sqrt{E_{\mathrm{beam}}^{*2} - \mathrm{p}_B^{*2}} \\ \Delta E^* &\equiv E_B^* - E_{\mathrm{beam}}^* \end{aligned}$$



$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}^{\mathrm{cms}} E_{D^{(*)}\ell}^{\mathrm{cms}} - m_B^2 - M_{D^{(*)}\ell}^2}{2P_B^{\mathrm{cms}} \cdot P_{D^{(*)}\ell}^{\mathrm{cms}}}$$



- Essentially no additional loss of kinematic information from use of $B \to D^{(*)} l \nu$ tags

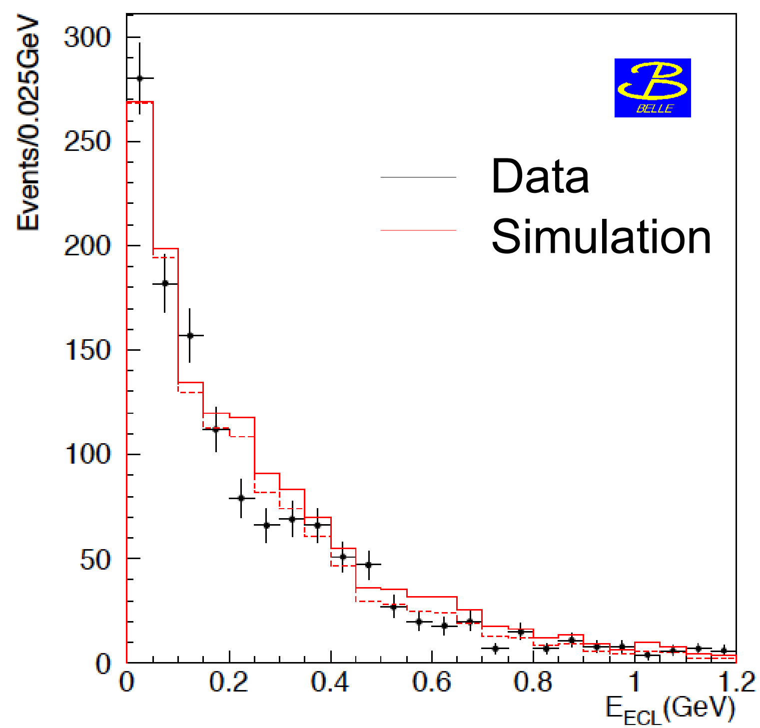
$|V_{ub}|$ and $B^+ \to \tau^+ \nu$

Topological selection of τ decay candidates in e,μ,π and ρ modes from particles not associated with the tag B candidate

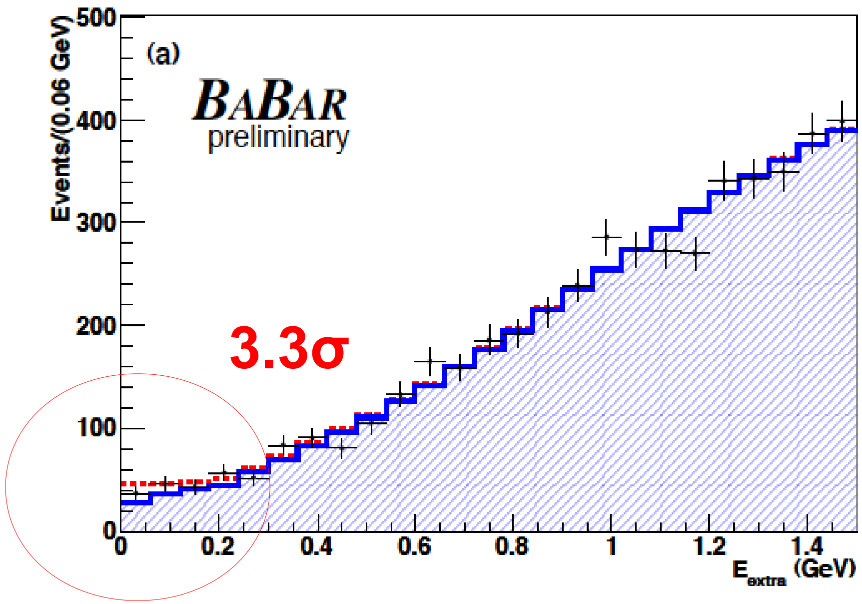
- Signal $B^+ \to \tau^+ \nu$ events expected to have little or no other activity in the detector, while backgrounds have higher multiplicity

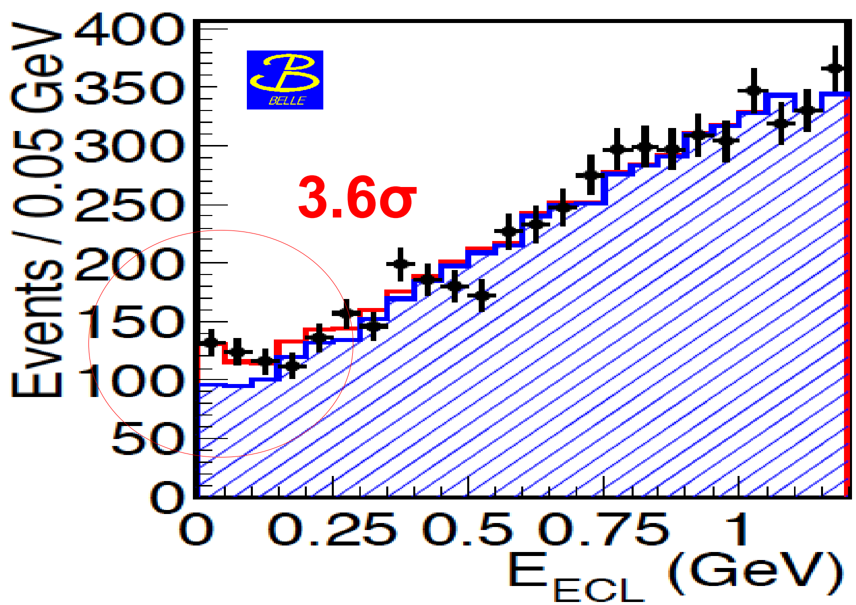
Characterize additional activity by E_{extra} (summed energy of all remaining calorimeter activity)

- Validate E_{extra} shape using samples in which the second B is exclusively reconstructed



$|V_{ub}|$ and $B^+ \rightarrow \tau^+ \nu$





arXiv:1008.0104 [hep-ex]

Decay Mode	$\epsilon \times 10^{-4}$	Branching Fraction $(\times 10^{-4})$
$\tau^+ \rightarrow e^+ \nu \bar{\nu}$	2.73	$0.39^{+0.89}_{-0.79}$
$\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$	2.92	$1.23^{+0.89}_{-0.80}$
$\tau^+ \rightarrow \pi^+ \nu$	1.55	$4.0^{+1.5}_{-1.3}$
$\tau^+ \rightarrow \rho^+ \nu$	0.85	$4.3^{+2.2}_{-1.9}$
combined	8.05	$1.80^{+0.57}_{-0.54}$

- Both results consistent with previously published SL tag analysis and Belle hadronic tag analyses*

arXiv:1006.4201v1 [hep-ex]

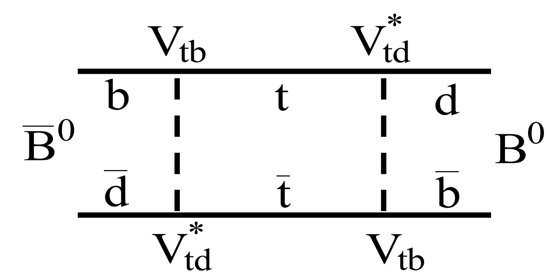
Decay Mode	Signal Yield	ε, 10^{-4}	$\mathcal{B}$, 10^{-4}
$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$	73^{+23}_{-22}	5.9	$1.90^{+0.59+0.33}_{-0.57-0.35}$
$\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$	12^{+18}_{-17}	3.7	$0.50^{+0.76+0.18}_{-0.72-0.21}$
$\tau^- \rightarrow \pi^- \nu_\tau$	55^{+21}_{-20}	4.7	$1.80^{+0.69+0.36}_{-0.66-0.37}$
Combined	143^{+36}_{-35}	14.3	$1.54^{+0.38+0.29}_{-0.37-0.31}$

* K. Ikado et al., Phys. Rev. Lett. 97, 251802 (2006)
B. Aubert et al., Phys. Rev. D 81, 051101(R) (2010)

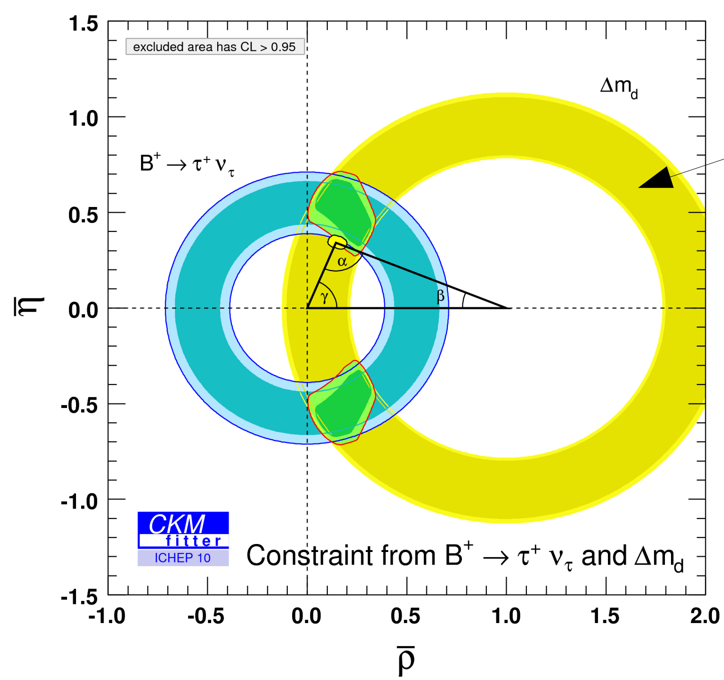
$|V_{ub}|$ and $B^+ \to \tau^+ \nu$

- Combination of all four (statistically independent) measurements yields

$$B(B^+ \to \tau^+ \nu) = (1.68 \pm 0.31) \times 10^{-4}$$



- Comparison with B mixing measurements permits cancelation of parametric uncertainty from f_B



$$\Delta m_d = \frac{G_F^2}{6\pi^2} \eta_B m_{B_d} f_{B_d}^2 B_d m_W^2 S(x_t) |V_{td} V_{tb}^*|^2$$

$$\eta_B = 0.551 \pm 0.007 \qquad S(x_t) \approx 0.784 x_t^{0.76} \qquad x_t = \overline{m}_t^2 / m_W^2$$

- “Tension” with respect to indirect $|V_{ub}|$ determination from sin2β at the level of ~2.5σ

CKMfitter Group (J. Charles et al.),
Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],

Conclusions

Measurements of CKM element magnitudes provide an important counterpoint to CP violation studies at B factories and hadron colliders

- Substantial improvements in experimental techniques and theoretical input in recent years have resulted in significantly decreased uncertainties on $|V_{cb}|$ and $|V_{ub}|$ determinations

- Discrepancies persist between inclusive and exclusive determinations, as well as between $|V_{ub}|$ measurements and the unitarity triangle fit driven by sin2β

- Recent (and internally consistent) $B^+ \to \tau^+ \nu$ measurements also favouring large $|V_{ub}|$