Study of $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ decays and determination of $|V_{ub}|$

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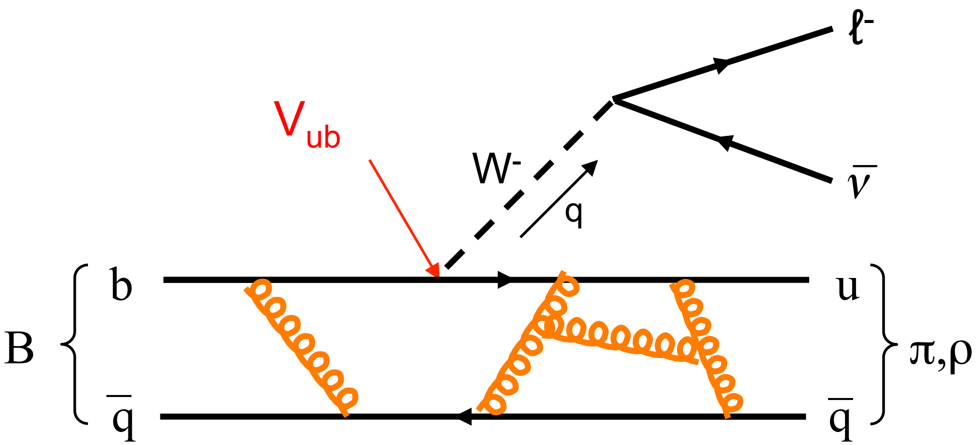
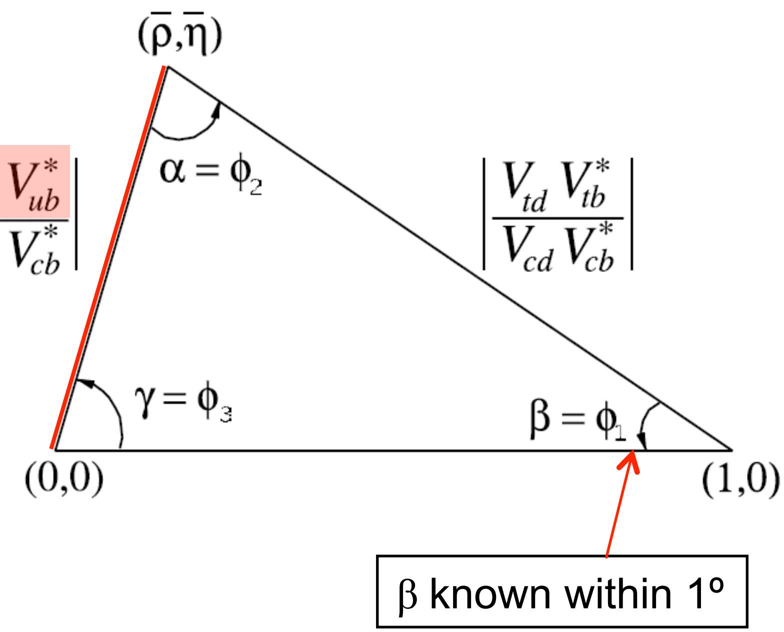
Motivation



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

$$B \to \rho \ell \nu : \frac{d\Gamma}{dq^2} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\rho| q^2 m_B^2}{96\pi^3} |F_\rho(q^2)|^2$$



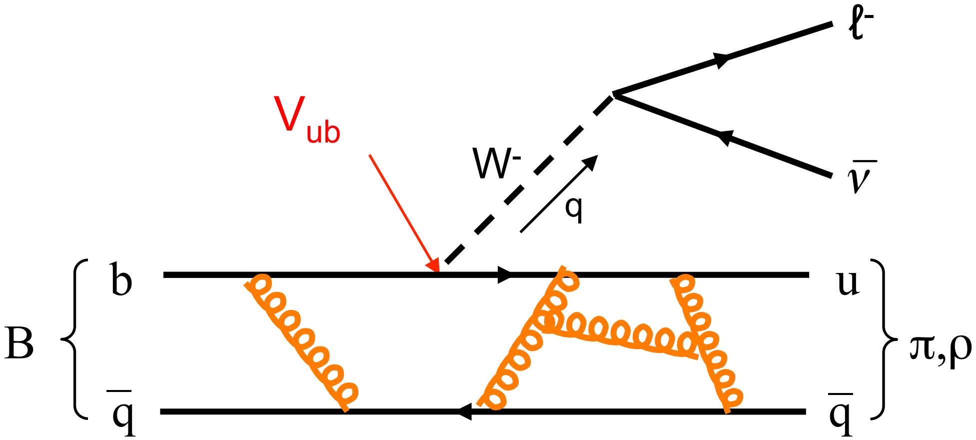
$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$ $\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$

Physics Goals

- Measure $|V_{ub}|$
- Test QCD calculations of form factors

Measure $\mathcal{B}(q^2)$ of $B \to (\pi^\pm/\pi^0/\rho^\pm/\rho^0)\ell\nu$

Data sample: 377 million $B\overline{B}$ pairs.

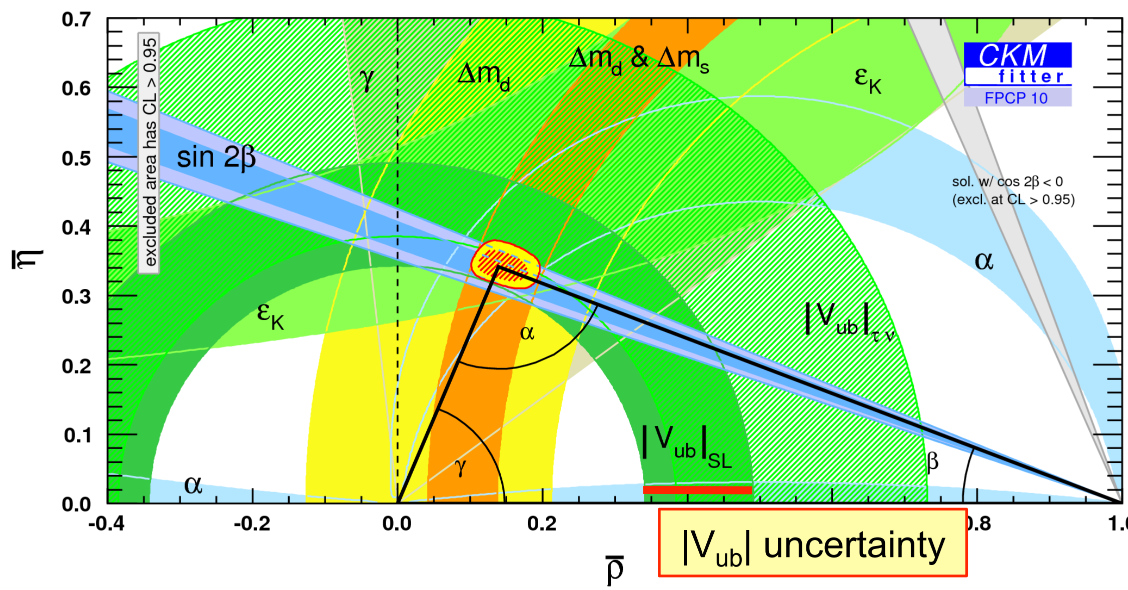


$$B \to \pi \ell \nu : \frac{d\Gamma}{dq^2} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |f_+(q^2)|^2$$

$$B \to \rho \ell \nu : \frac{d\Gamma}{dq^2} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\rho| q^2 m_B^2}{96\pi^3} |F_\rho(q^2)|^2$$

Physics Goals

- Measure $|V_{ub}|$
- Test QCD calculations of form factors

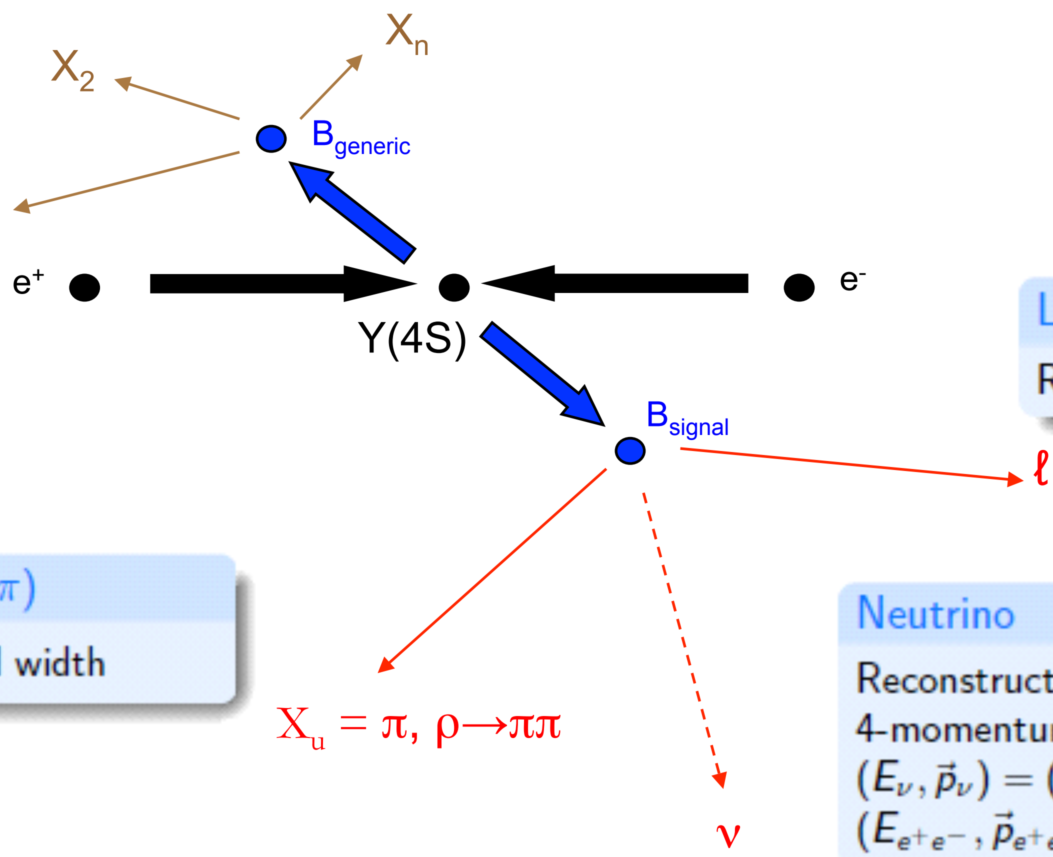


Measure $\mathcal{B}(q^2)$ of $B \to (\pi^\pm/\pi^0/\rho^\pm/\rho^0)\ell\nu$

Data sample: 377 million $B\overline{B}$ pairs.

Signal candidate selection

Untagged
non-signal B is not reconstructed



Lepton ($\ell = e, \mu$)

Require high momentum.

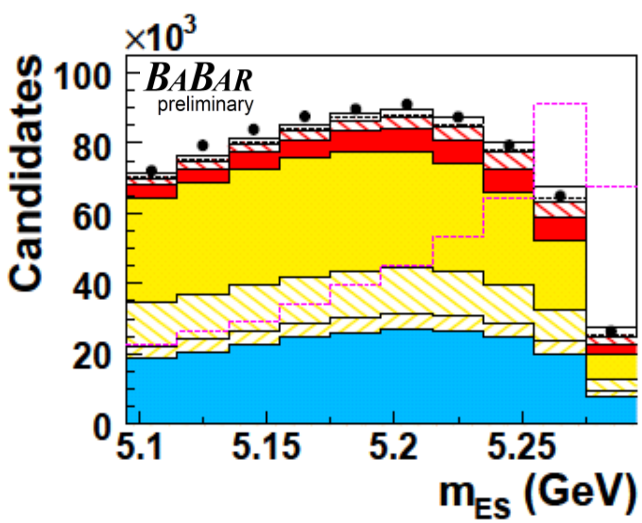
Hadron (π or $\rho \to \pi\pi$)

$|m_{\pi\pi} - m_\rho^{PDG}| \leq 1$ full width

Neutrino

Reconstructed from missing 4-momentum of event:

$(E_\nu, \vec{p}_\nu) = (E_{miss}, \vec{p}_{miss}) = (E_{e^+e^-}, \vec{p}_{e^+e^-}) - (\sum_i E_i, \sum_i \vec{p}_i)$



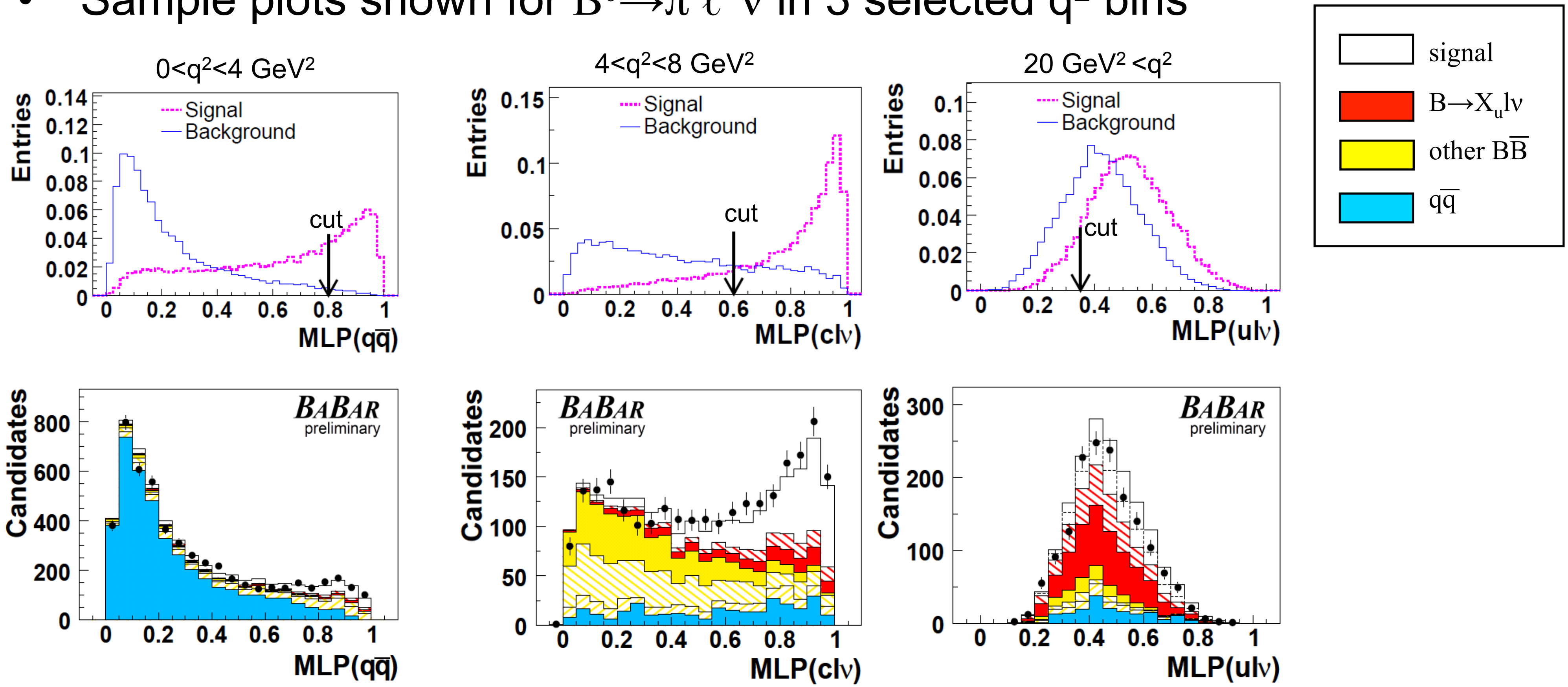
$B^0 \to \pi^- \ell^+ \nu$ after preselection

Sample components

- Signal: very small relative to bkgd.
- $B \to X_u l \nu$ ($X_u \neq \pi,\rho$): similar to signal
- other $B\bar{B}$: $B \to X_c l \nu$ control samples used as cross-check
- $e^+e^- \to q\bar{q}$ (q=u,d,s,c) continuum: off-resonance data used to correct fit variable shapes

Neural Net Background Suppression

- Neural nets trained against each of 3 backgrounds, in each q^2 bin
- Sample plots shown for $B^0 \to \pi^- \ell^+ \nu$ in 3 selected q^2 bins



Continuum background
Jet-like events differ from isotropic B decays

$B \to X_c l\nu$ background
largest background, $\Gamma(b \to cl\nu) \sim 50 \times \Gamma(b \to ul\nu)$

$B \to X_u l\nu$ background
Mostly at high q^2, hard to separate

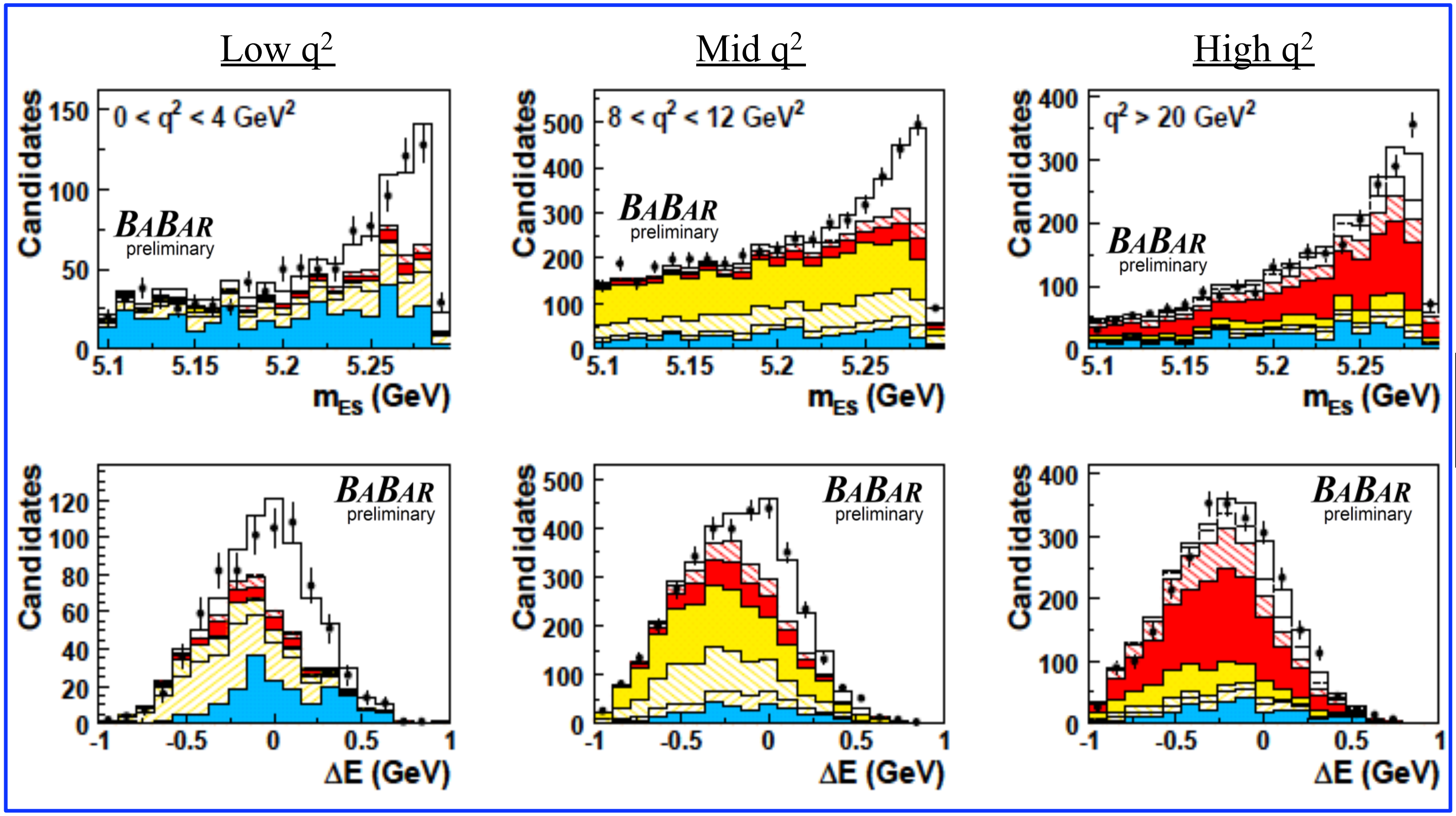
$B^0 \to \pi^- \ell^+ \nu$ S/B before NN = 3%
$B^0 \to \pi^- \ell^+ \nu$ S/B after NN = 12%

$B \to \pi \ell \nu$ YIELDS

binned ML fit in m_{ES}, ΔE, and q^2 for $B \to (\pi^{\pm}/\pi^{0}/\rho^{\pm}/\rho^{0})\ell\nu$ simultaneously, with isospin constraint

$B^0 \to \pi^- \ell^+ \nu$ in 6 q^2 bins

Backgrounds vary with q^2.



- signal
- $B \to X_u l \nu$
- other $B\overline{B}$
- $q\overline{q}$

$$m_{ES} = \sqrt{\left(\frac{s/2 + \vec{p}_{beams} \cdot \vec{p}_B}{E_{beams}}\right)^2 - \vec{p}_B^{\,2}}$$

Signal peaks at $m_{ES} \approx m_B = 5.28\ \mathrm{GeV}/c^2$

$$\Delta E = \frac{p_{beams} \cdot p_B}{\sqrt{s}} - \frac{\sqrt{s}}{2}$$

Signal peaks at $\Delta E = 0$

Single mode yields →

4-mode yield used to find BF →

$B^0 \to \pi^- \ell^+ \nu$	7181 ± 279
$B^+ \to \pi^0 \ell^+ \nu$	3446 ± 208
$B \to \pi \ell \nu$	10604 ± 376

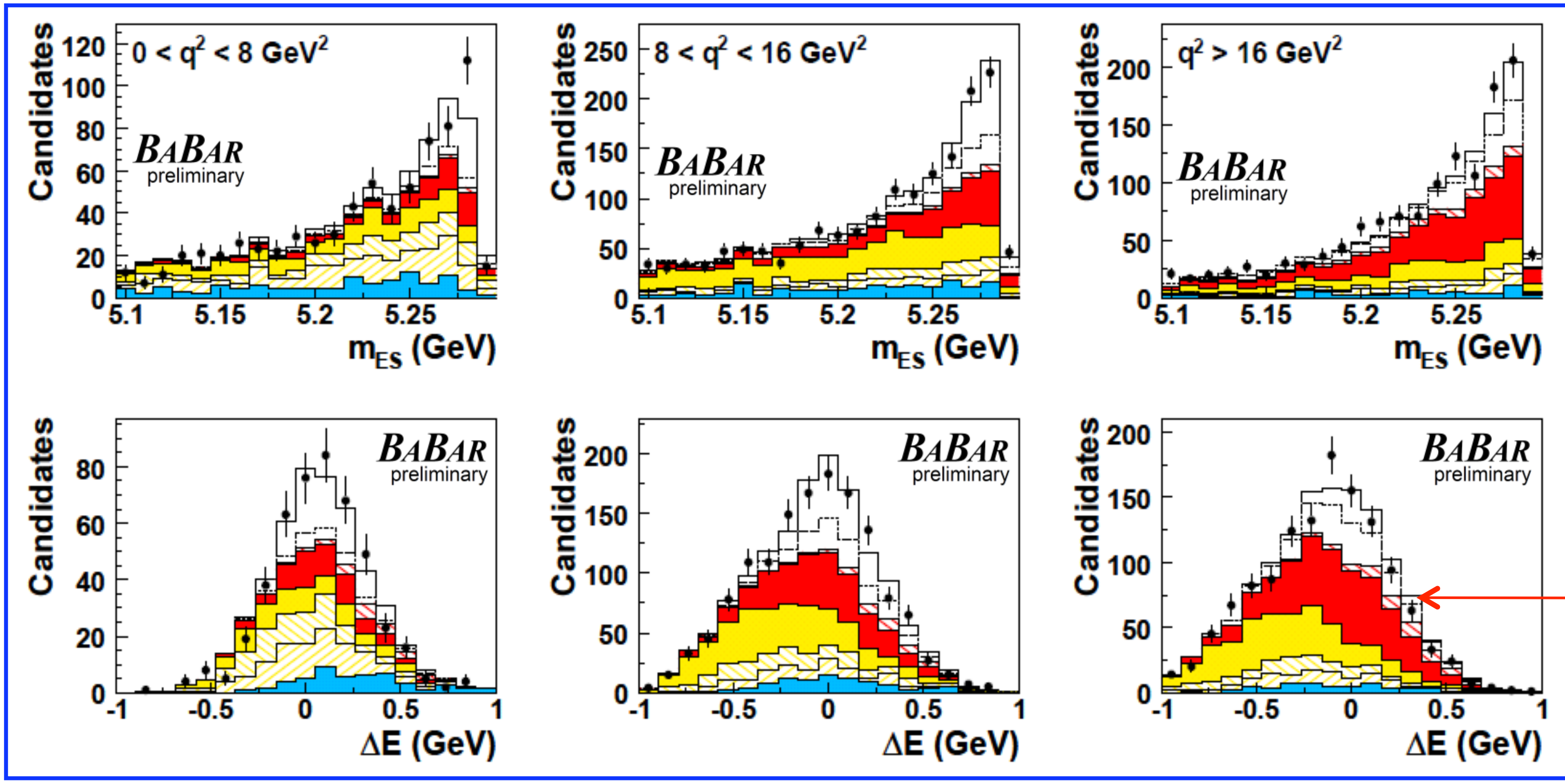
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.41 \pm 0.05_{stat} \pm 0.07_{syst}) \times 10^{-4}$$

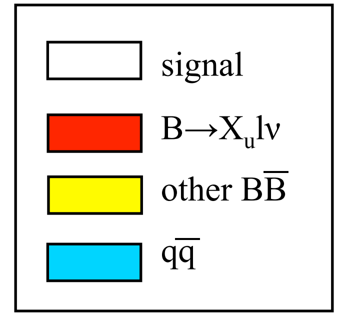
$\sigma_{stat} = 3.5\%$; $\sigma_{syst} = 5.0\%$; $\sigma_{tot} = 6.1\%$

$B \to \rho \ell \nu$ YIELDS

binned ML fit in m_{ES}, ΔE, and q^2 for $B \to (\pi^\pm/\pi^0/\rho^\pm/\rho^0)\ell\nu$ simultaneously, with isospin constraint

$B^0 \to \rho^- \ell^+ \nu$ in 3 q^2 bins





Large $B \to X_u l\nu$ background is highly correlated with signal and must be fixed in the fit.

$B^0 \to \rho^- \ell^+ \nu$	1577 ± 130
$B^+ \to \rho^0 \ell^+ \nu$	1970 ± 154
$B \to \rho \ell \nu$	3332 ± 286

Smaller yield than $B \to \pi l\nu$

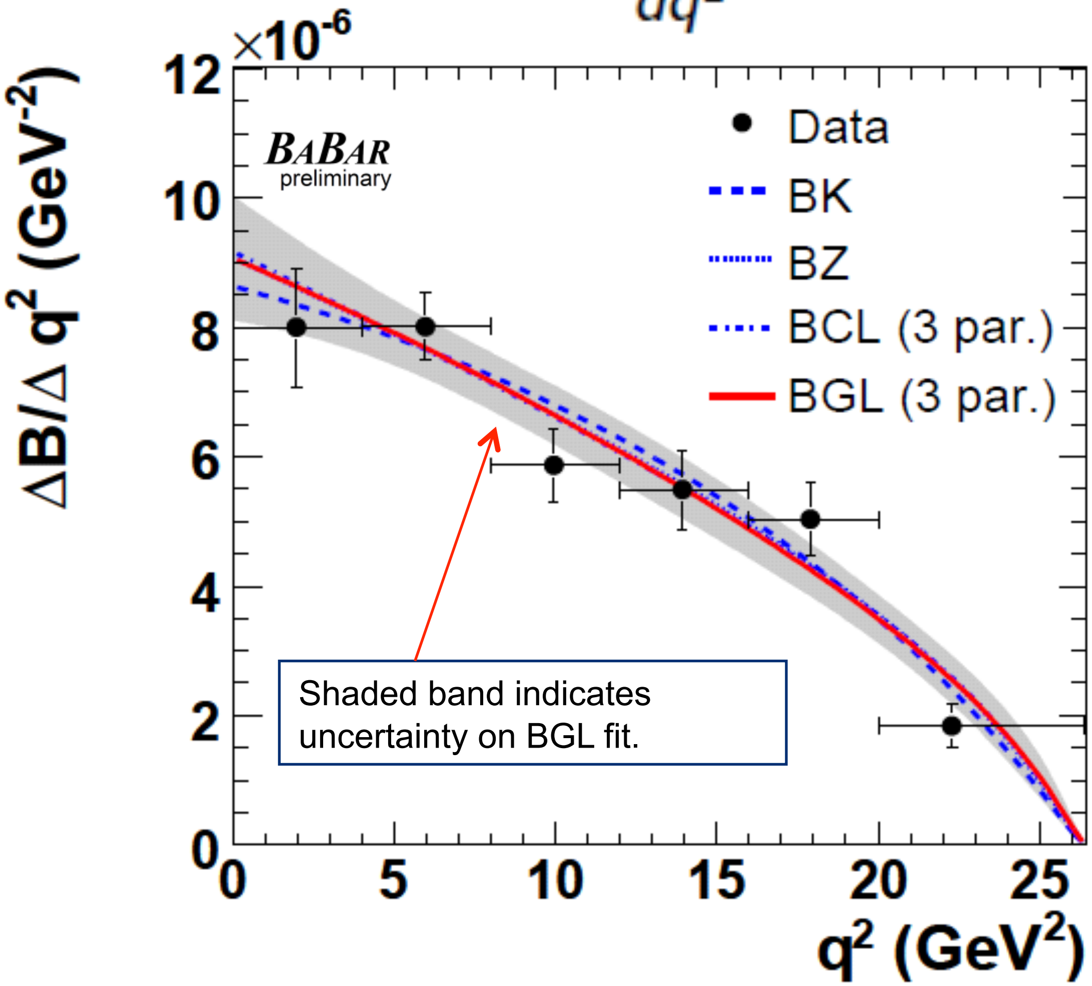
$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (1.75 \pm 0.15_{stat} \pm 0.27_{syst}) \times 10^{-4}$$

$\sigma_{stat} = 8.6\%$; $\sigma_{syst} = 15\%$; $\sigma_{tot} = 18\%$

Systematic errors	$B \to \pi \ell \nu$	$B \to \rho \ell \nu$
detector effects	3.2%	4.9%
K_L simulation	3.0%	7.5%
$B \to (\pi/\rho)\ell\nu$ FF	2.2%	9.4%
$B \to X_u \ell\nu$ bkgd.	0.9%	12.9%
$B \to X_c \ell\nu$ bkgd.	1.0%	1.5%
$q\bar{q}$ bkgd.	2.0%	4.0%
other effects	1.5%	2.5%
Total	5.0%	15.7%

Form factor parameterizations

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



Shaded band indicates uncertainty on BGL fit.

q^2 spectrum corrected for detector efficiency & resolution, bremsstrahlung, and radiative effects

$f_+(q^2)$ parameterizations

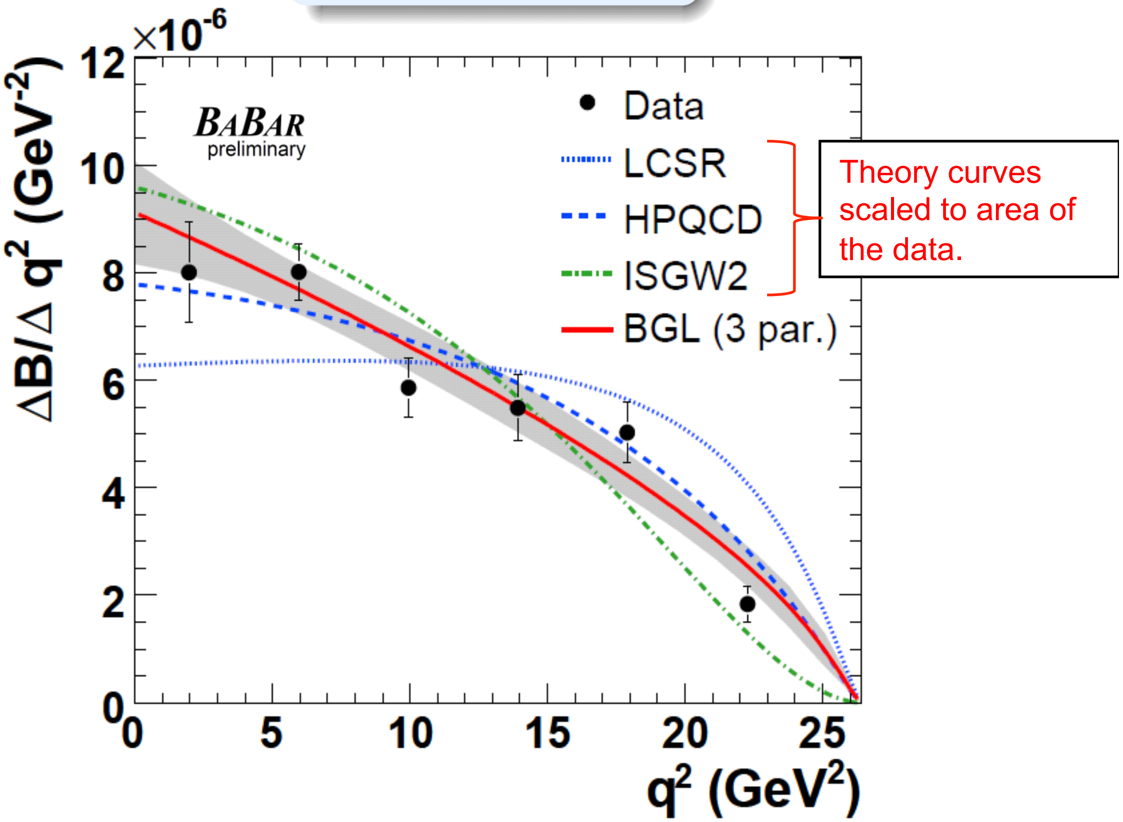
1 param.	Becirevic, Kaidalov (BK) Phys Lett B 478, 417 (2000)
2 param.	Ball, Zwicky (BZ) PLB 644, 38 (2007)
n param.	Bourrely, Caprini, Lellouch (BCL) PRD 79, 013008 (2009)
n param.	Boyd, Grinstein, Lebed (BGL) PRL 56, 303 (1997)

- BCL and BGL expansions avoid ad hoc assumptions and are based on fundamental QCD concepts.
- We use BGL 3-parameter fit as default (consistent with BGL 2-parameters).

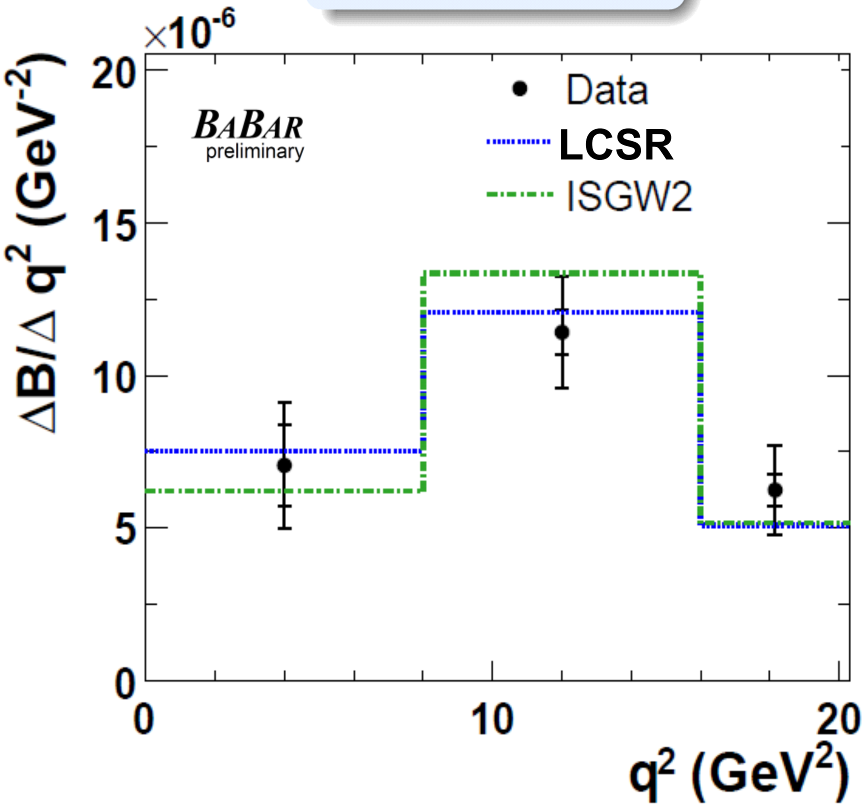
All 4 parameterizations agree with each other and are consistent with the data.

Comparison with theory

$B \to \pi \ell \nu$



$B \to \rho \ell \nu$



Probability of agreement with theory

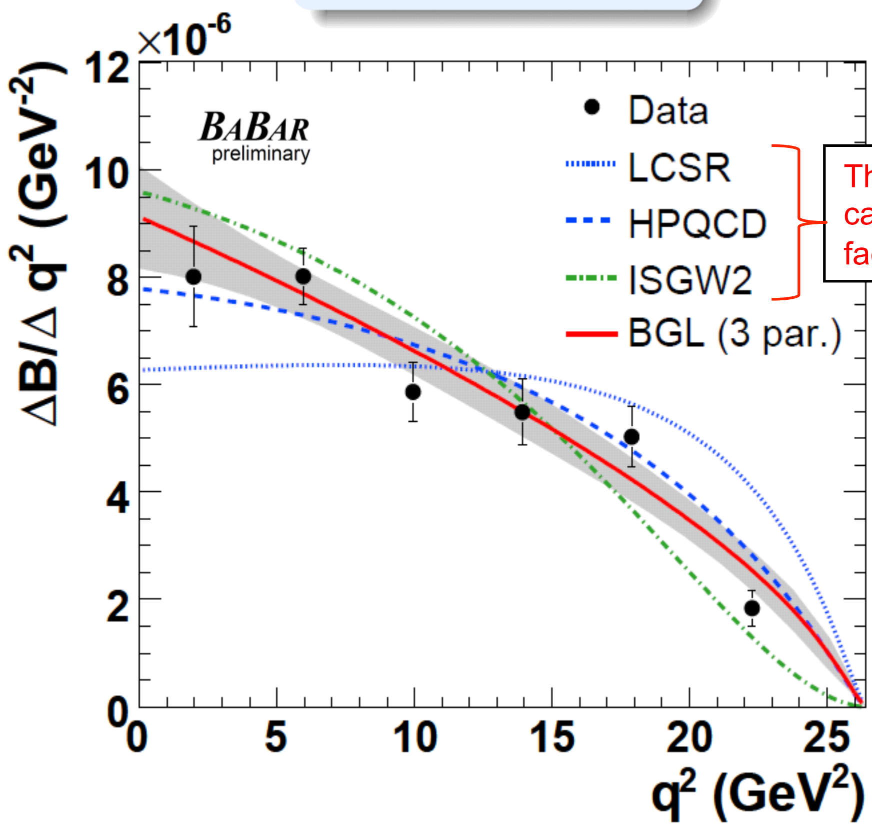
Calculation	Prob(χ^2, ndf)
HPQCD PRD 73, 074502 (2006)	13%
ISGW2 PRD 52, 2783 (1995)	0.2%
LCSR PRD 71, 014015 (2005)	$< 10^{-5}$

Errors too large to distinguish between $B \to \rho \ell \nu$ predictions.

- Probabilities exclude theory errors and use full q^2 range.
- Calculations valid only for partial q^2 range.

$|V_{ub}|$ FROM PARTIAL q^2 RANGE

$B \to \pi \ell \nu$



Solve rate equation for $|V_{ub}|$

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

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

Probability of agreement with theory

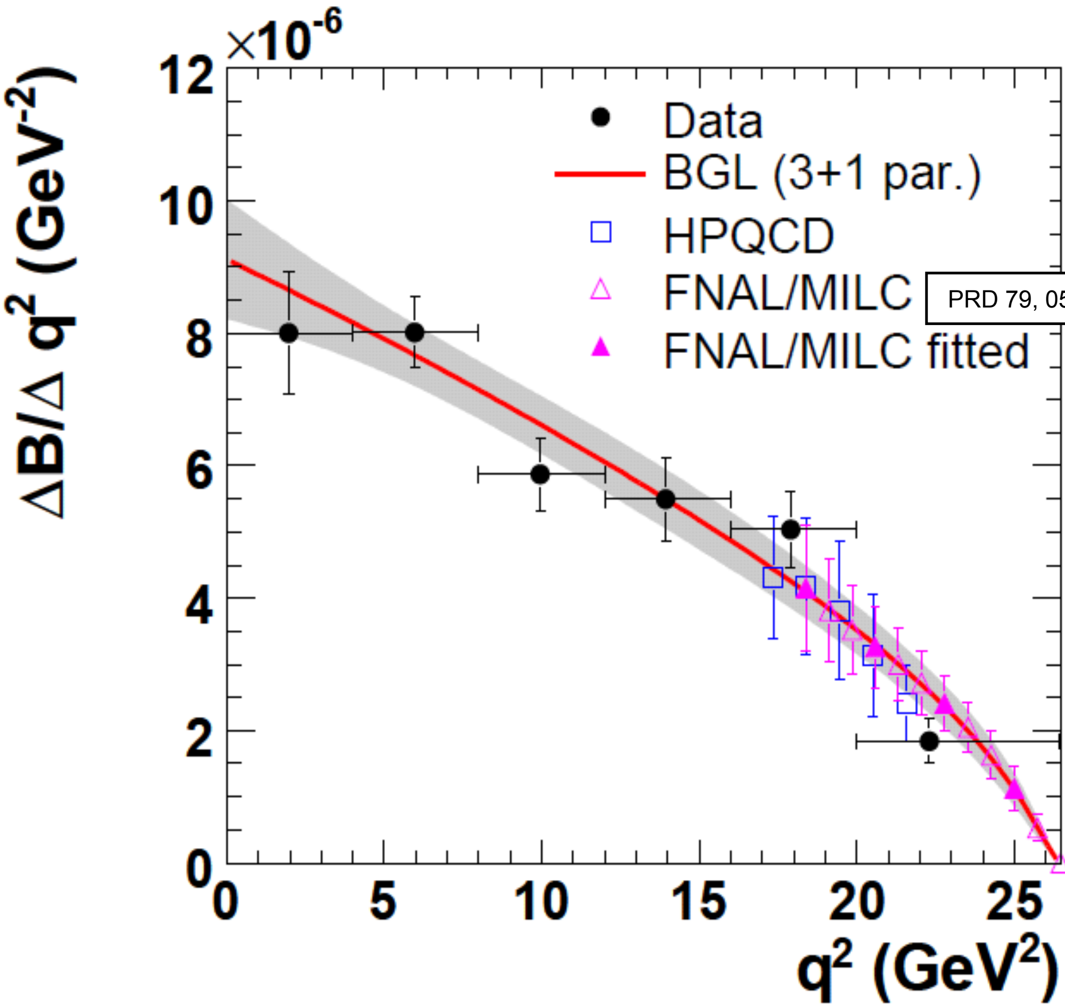
Calculation	Prob(χ^2, ndf)
HPQCD PRD 73, 074502 (2006)	13%
ISGW2 PRD 52, 2783 (1995)	0.2%
LCSR PRD 71, 014015 (2005)	$< 10^{-5}$

- Probabilities exclude theory errors and use full q^2 range.
- Calculations valid only for partial q^2 range.

		$\lvert V_{ub}\rvert (\times 10^{-3})$
LCSR	$(q^2 < 16\,\mathrm{GeV}^2)$	$3.63 \pm 0.12^{+0.59}_{-0.40}$
HPQCD	$(q^2 > 16\,\mathrm{GeV}^2)$	$3.21 \pm 0.17^{+0.55}_{-0.36}$

σ_{exp} = 3-5%; σ_{thy} = ~15%
Theory error dominates

$|V_{ub}|$ FROM FULL q^2 RANGE



PRD 79, 054507 (2009)

Simultaneous fit to data and theory

- 3 parameters: BGL quadratic polynomial
- 4th parameter: relative normalization between theory and data, $\alpha\ |V_{ub}|^2$
- Theory points are correlated, so not all are used in fit.

$$|V_{ub}| = (2.99 \pm 0.35) \times 10^{-3} \quad \text{HPQCD (1 point)}$$

$$|V_{ub}| = (2.92 \pm 0.37) \times 10^{-3} \quad \text{FNAL/MILC (1 point)}$$

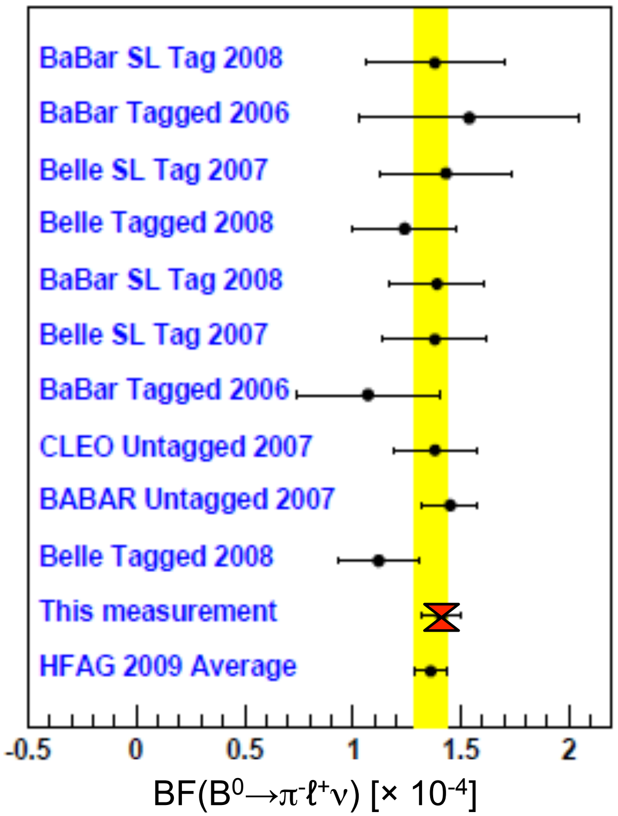
$$|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3} \quad \text{FNAL/MILC (4 points)}$$

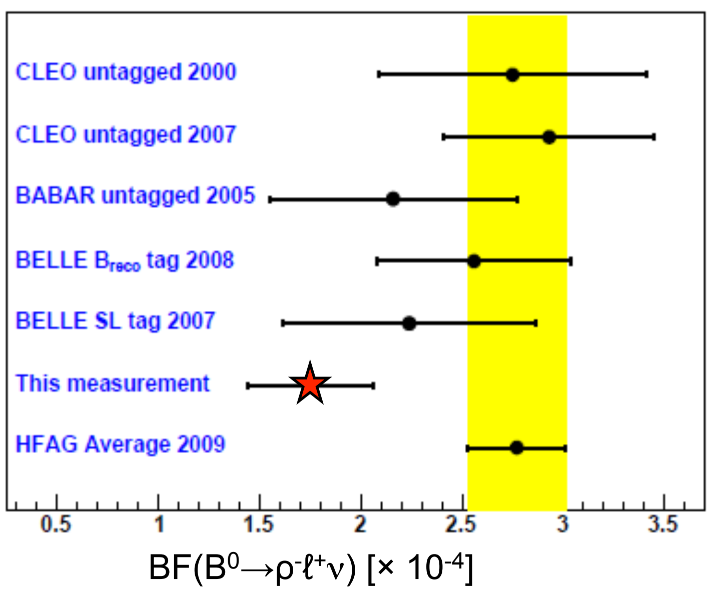
σ(data BF) = 3%
σ(data q^2 shape) = 5%
σ(theory FF norm.) = 8.5%
σ_{total} = 10.5%

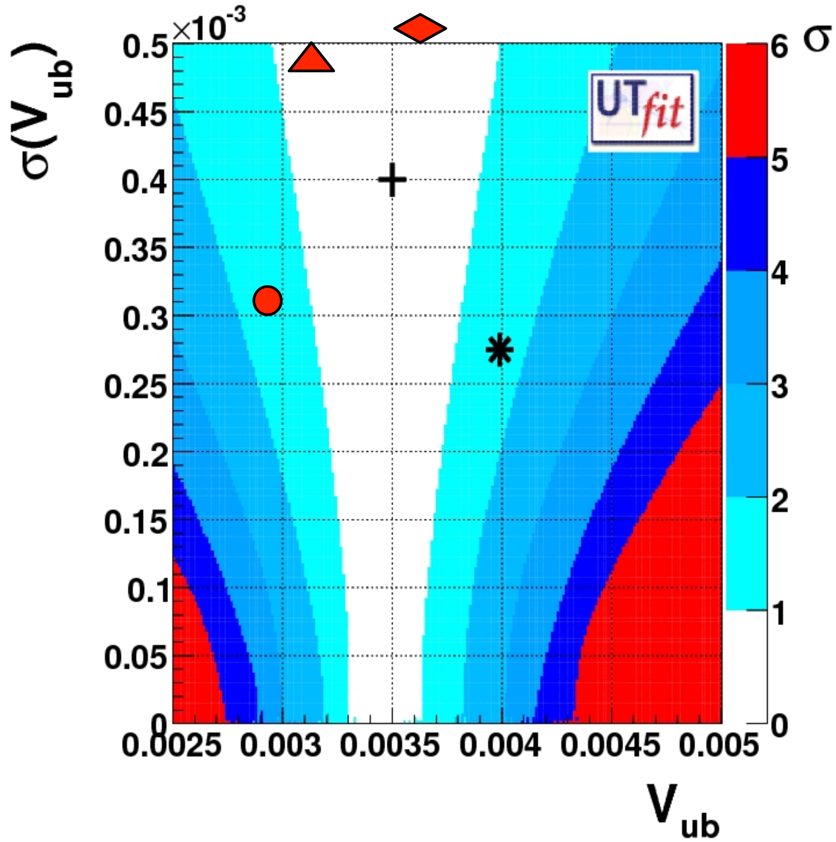
Errors reduced compared to $|V_{ub}|$ from partial q^2 range

Conclusion

- Most precise branching fraction measurements:
  - $BF(B^0 \to \pi^- \ell^+ \nu) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}$
  - $BF(B^0 \to \rho^- \ell^+ \nu) = (1.75 \pm 0.15 \pm 0.27) \times 10^{-4}$
- Tests of q^2 spectrum agreement with theoretical predictions.
- Determination of $|V_{ub}|$:
  - LCSR, low q^2 $= (3.63 \pm 0.12\ ^{+0.59}_{-0.40}) \times 10^{-3}$
  - HPQCD, high q^2 $= (3.21 \pm 0.17\ ^{+0.55}_{-0.36}) \times 10^{-3}$
  - FNAL/MILC, full q^2 $= (2.95 \pm 0.31) \times 10^{-3}$







UT Fit Values

✚ average exclusive

✸ average inclusive

Global "all other" fit = $(3.48 \pm 0.16) \times 10^{-3}$

Backup

FORM FACTOR PARAMETERIZATIONS

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

Becirevic-Kaidalov (BK)

$$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/m_{B^*}^2)(1 - \alpha_{BK} q^2/m_{B^*}^2)}$$

Ball-Zwicky (BZ)

$$f_+(q^2) = f_+(0)\left[\frac{1}{1 - q^2/m_{B^*}^2} + \frac{r_{BZ}\, q^2/m_{B^*}^2}{(1 - q^2/m_{B^*}^2)(1 - \alpha_{BZ} q^2/m_{B^*}^2)}\right]$$

Boyd, Grinstein, Lebed (BGL)

$$f_+(q^2) = \frac{1}{\mathcal{P}(q^2)\phi(q^2, q_0^2)} \sum_{k=0}^{k_{max}} a_k(q_0^2)[z(q^2, q_0^2)]^k$$

$$z(q^2, q_0^2) = \frac{\sqrt{m_+^2 - q^2} - \sqrt{m_+^2 - q_0^2}}{\sqrt{m_+^2 - q^2} + \sqrt{m_+^2 - q_0^2}}$$

Bourrely, Caprini, Lellouch (BCL)

$$f_+(q^2) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{k_{max}} b_k(q_0^2)\left[[z(q^2, q_0^2)]^k - (-1)^{k-k_{max}-1}\frac{k}{k_{max}+1}[z(q^2, q_0^2)]^{k_{max}+1}\right]$$

Red-highlighted variables vary in the fit.

Systematic uncertainties

From combined 4-mode fit

$B \to \pi \ell \nu$							
q^2 range (GeV^2)	0-4	4-8	8-12	12-16	16-20	>20	0-26.4
Track efficiency	3.4	1.5	2.3	0.1	1.5	2.8	1.9
Photon efficiency	0.1	1.4	1.0	4.6	2.8	0.3	1.8
Lepton identification	3.8	1.6	1.9	1.8	1.9	3.0	1.8
K_L efficiency	1.0	0.1	0.5	4.5	0.4	2.0	1.4
K_L shower energy	0.1	0.1	0.1	0.8	0.9	3.8	0.7
K_L spectrum	1.6	1.9	2.2	3.1	4.4	2.3	2.5
$B \to \pi \ell \nu FF f_+$	0.5	0.5	0.5	0.6	1.0	1.0	0.6
$B \to \rho \ell \nu FF A_1$	1.7	1.2	3.4	2.0	0.1	1.6	1.7
$B \to \rho \ell \nu FF A_2$	1.3	0.8	2.6	1.0	0.1	0.4	1.1
$B \to \rho \ell \nu FF V$	0.2	0.3	0.9	0.7	0.1	0.5	0.5
$\mathcal{B}(B^+ \to \omega \ell^+ \nu)$	0.1	0.1	0.1	0.2	0.3	1.5	0.2
$\mathcal{B}(B^+ \to \eta \ell^+ \nu)$	0.1	0.1	0.2	0.2	0.2	0.5	0.2
$\mathcal{B}(B^+ \to \eta' \ell^+ \nu)$	0.1	0.1	0.1	0.1	0.1	0.3	0.1
$\mathcal{B}(B \to X_u \ell \nu)$	0.2	0.1	0.1	0.1	1.1	1.6	0.4
$B \to X_u \ell \nu$ SF param.	0.4	0.1	0.2	0.2	0.5	4.2	0.7
$B \to D \ell \nu$ FF ρ_D^2	0.2	0.1	0.5	0.3	0.2	0.7	0.3
$B \to D^* \ell \nu$ FF R_1	0.1	0.4	0.8	0.6	0.3	0.6	0.5
$B \to D^* \ell \nu$ FF R_2	0.5	0.2	0.1	0.2	0.1	0.4	0.2
$B \to D^* \ell \nu$ FF $\rho_{D^*}^2$	0.7	0.2	0.6	0.8	0.4	1.1	0.6
$\mathcal{B}(B \to D \ell \nu)$	0.2	0.2	0.3	0.4	0.5	0.5	0.3
$\mathcal{B}(B \to D^* \ell \nu)$	0.4	0.1	0.3	0.3	0.3	0.7	0.3
$\mathcal{B}(B \to D^{**} \ell \nu)_{\text{narrow}}$	0.4	0.1	0.1	0.3	0.1	0.5	0.2
$\mathcal{B}(B \to D^{**} \ell \nu)_{\text{broad}}$	0.1	0.1	0.1	0.5	0.1	0.2	0.2
Secondary leptons	0.5	0.2	0.3	0.2	0.2	0.7	0.3
Continuum	5.3	1.0	2.6	1.8	3.1	6.1	2.0
Bremsstrahlung	0.3	0.1	0.1	0.1	0.1	0.4	0.2
Radiative corrections	0.5	0.1	0.1	0.2	0.2	0.6	0.3
$N_{B\bar{B}}$	1.2	1.0	1.2	1.2	1.1	1.6	1.2
B lifetimes	0.3	0.3	0.3	0.3	0.3	0.7	0.3
$f_{\pm}/f_{00}$	1.0	0.4	0.8	0.8	0.5	1.3	0.8
Total syst. error	8.2	3.9	6.7	8.3	6.9	10.6	5.0

$B \to \rho \ell \nu$				
q^2 range (GeV^2)	0-8	8-16	>16	0-20.3
Track efficiency	3.2	2.9	0.3	2.5
Photon efficiency	2.6	2.0	2.6	2.4
Lepton Identification	5.7	3.0	4.0	3.4
K_L efficiency	10.3	1.2	4.9	4.8
K_L shower energy	1.6	0.8	1.0	1.1
K_L spectrum	4.2	6.1	7.0	5.7
$B \to \pi \ell \nu$ FF f_+	0.1	0.1	0.7	0.2
$B \to \rho \ell \nu$ FF A_1	10.7	6.6	4.5	7.5
$B \to \rho \ell \nu$ FF A_2	8.5	3.8	0.8	4.7
$B \to \rho \ell \nu$ FF V	3.4	3.0	3.6	3.2
$\mathcal{B}(B^+ \to \omega \ell^+ \nu)$	0.7	0.7	3.4	1.2
$\mathcal{B}(B^+ \to \eta \ell^+ \nu)$	0.8	0.1	0.6	0.4
$\mathcal{B}(B^+ \to \eta' \ell^+ \nu)$	0.8	0.5	1.2	0.7
$\mathcal{B}(B \to X_u \ell \nu)$	7.4	7.3	10.6	8.0
$B \to X_u \ell \nu$ SF param.	11.9	7.6	12.8	10.0
$B \to D \ell \nu$ FF ρ_D^2	0.9	0.2	0.1	0.4
$B \to D^* \ell \nu$FF R_1	0.7	0.1	0.3	0.3
$B \to D^* \ell \nu$FF R_2	1.7	0.1	0.2	0.6
$B \to D^* \ell \nu$FF $\rho_{D^*}^2$	2.0	0.2	0.1	0.7
$\mathcal{B}(B \to D \ell \nu)$	1.6	0.3	0.1	0.7
$\mathcal{B}(B \to D^* \ell \nu)$	0.5	0.1	0.3	0.3
$\mathcal{B}(B \to D^{**} \ell \nu)_{\text{narrow}}$	1.3	0.1	0.1	0.5
$\mathcal{B}(B \to D^{**} \ell \nu)_{\text{broad}}$	0.7	0.1	0.1	0.3
Secondary leptons	1.5	0.1	0.1	0.5
Continuum	8.9	3.8	5.0	4.0
Bremsstrahlung	0.9	0.1	0.2	0.4
Radiative corrections	1.3	0.1	0.7	0.6
$N_{B\bar{B}}$	2.7	2.0	2.5	2.3
B lifetimes	1.5	0.4	0.4	0.7
$f_{\pm}/f_{00}$	1.2	0.1	0.1	0.4
Total syst. error	26.1	16.1	21.3	15.7