Semileptonic B-decays (b to u transition)

Outline

- Inclusive b to u decays
- Exclusive b to u decays
- Summary

(nothing new since ICHEP06)

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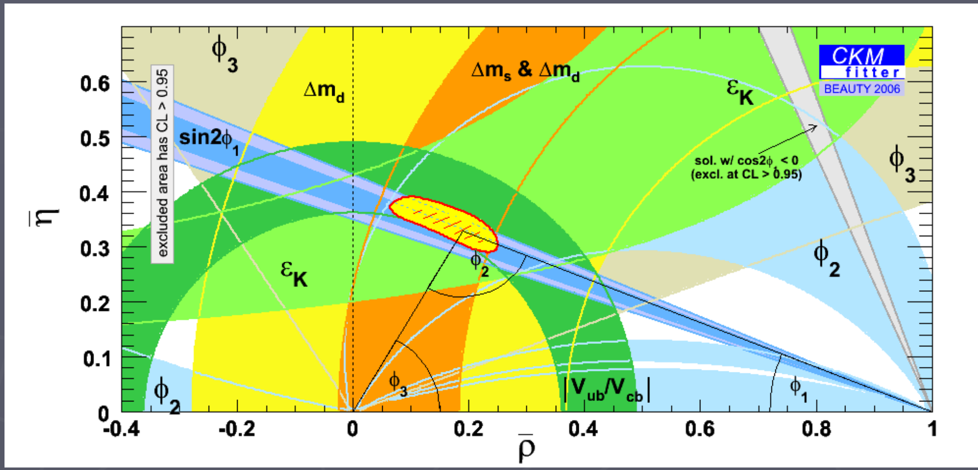
Heavy Quarks and Leptons
16.10 ~ 20.10 2006 Munich, Germany

Status of $|V_{ub}|$

Measurements of $|V_{ub}|$ provide
independent crosscheck
of the unitary trangle (UT)

With ϕ_3, $|V_{ub}|$ can
constrain UT from tree level
processes alone

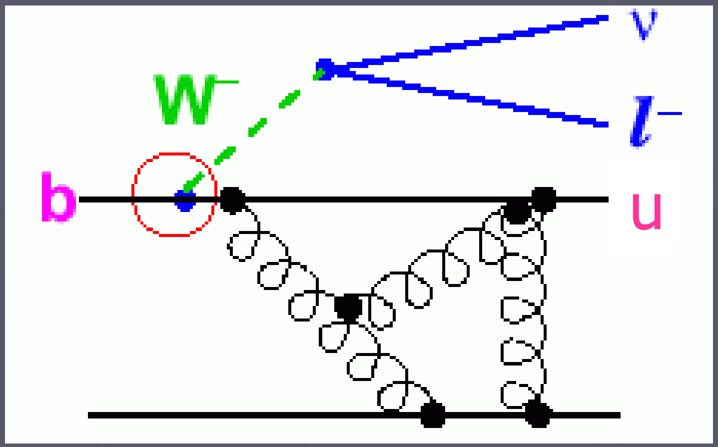


$\delta|V_{ub}| \sim 2\%$ is established firmly by now

$|V_{ub}|$ from $B \to X_u \ell \nu$ inclusive measurements
:precision about 7%
accessing fraction of phase space → shape function is usually required

$|V_{ub}|$ from exclusive decays $B \to \pi\ell\nu, \rho\ell\nu, \ldots$
:precision worse than 10%
form factor has to be calculated → model dependence is introduced

$|V_{ub}|$ from semileptonic B-decays

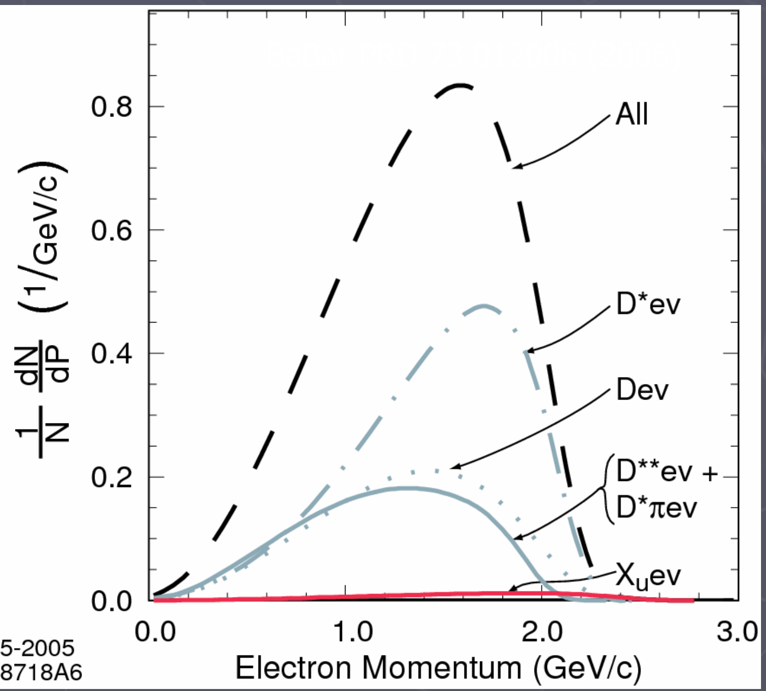


Semileptonic inclusive rates depend only on CKM matrix element and quark mass

$$\Gamma(b \to u\ell\bar{\nu}) = \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$$

hadron level easy to calculate in OPE (<5% error)

$$|V_{ub}| = 0.00424 \left\{ \frac{\mathcal{B}(B \to X_u\ell\nu)}{0.02} \frac{1.61 \text{ ps}}{\tau_b} \right\}^{\frac{1}{2}} \times (1.0 \pm 0.012_{QCD} \pm 0.022_{HQE})$$



But the problem is:

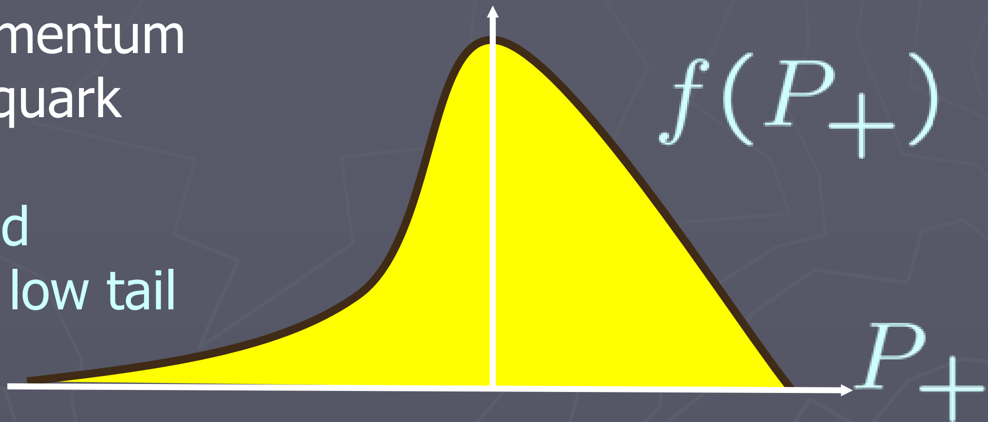
$$\Gamma(b \to c\ell\nu) \sim 50\Gamma(b \to u\ell\nu)$$

OPE does not work on limited phase space

$|V_{ub}|$: inclusive determination

Limited phase space to reduce the b to c transition background→ OPE fails
Non perturbative **Shape Function** to extrapolate to the full phase space

Shape function: lightcone momentum distribution function of the b quark inside the meson
Detailed shape not constrained theoretically, in particular the low tail

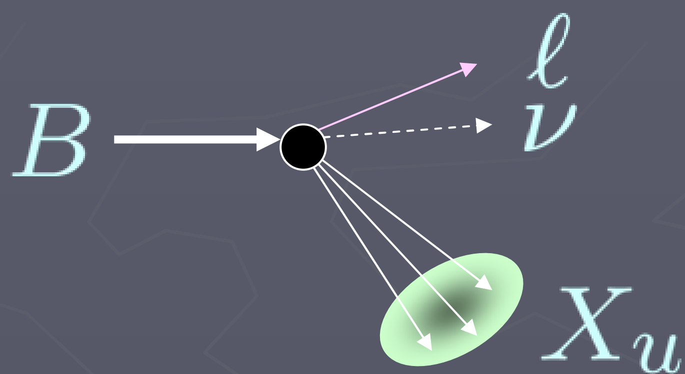


Shape function need to be determined from experimental data

Theoretical frameworks used by HFAG
BLNP : B. O. Lange, M. Neubert and G. Paz, PRD 72 073006 (2005)
DGE : J. R. Anderson and E. Gardi, JHEP 0601:097 (2006)
BLL : C. W. Bauer, Z. Ligeti and M. E. Luke, PRD 64 113004 (2001)
Also
(*) LLR : A. K. Leibovich, I. Low and I. Z. Rothstein, PLB 486 86 (2000)
→ for BaBar's new analysis (less dependence on SF)

Inclusive $B \to X_u \ell \nu$

$m_u \ll m_c$ → Exploits different kinematics



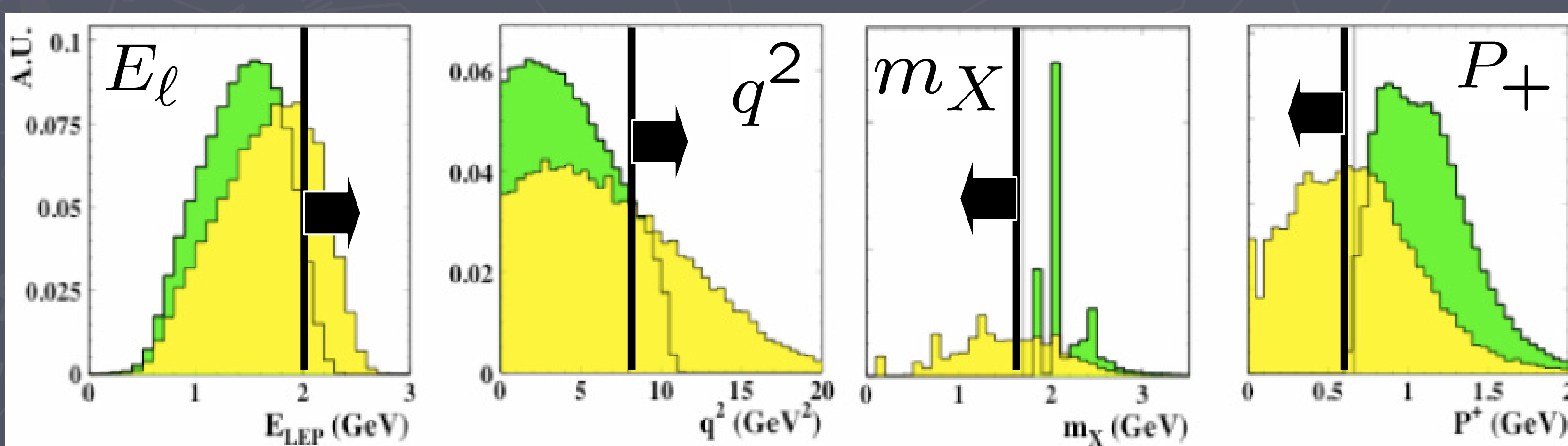
E_ℓ : lepton energy

q^2 : lepton-neutrino mass squared

m_X : mass of the hadronic system

$$P_+ = E_X - |\vec{P}_X|$$

Signal events have smaller m_X and P_+ → Larger E_ℓ and q^2



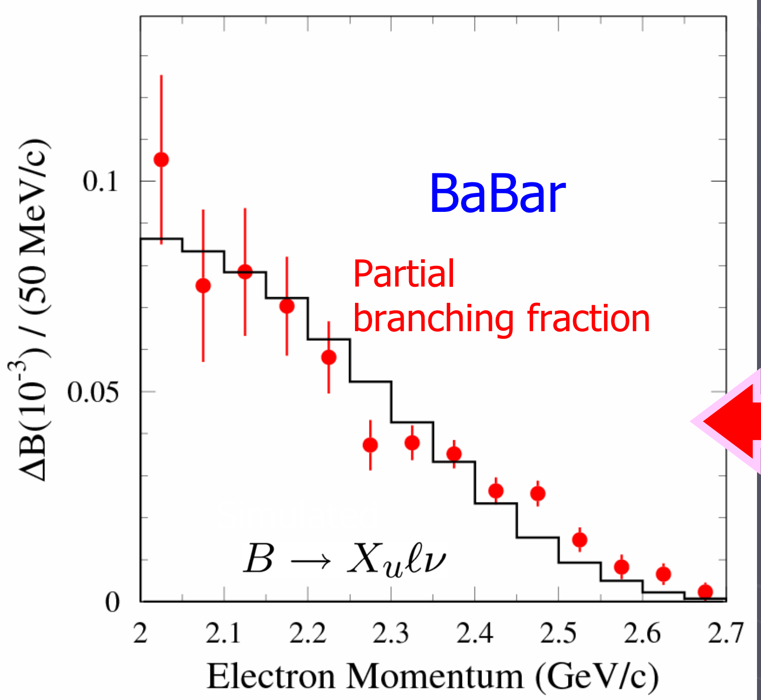
Lepton Endpoint

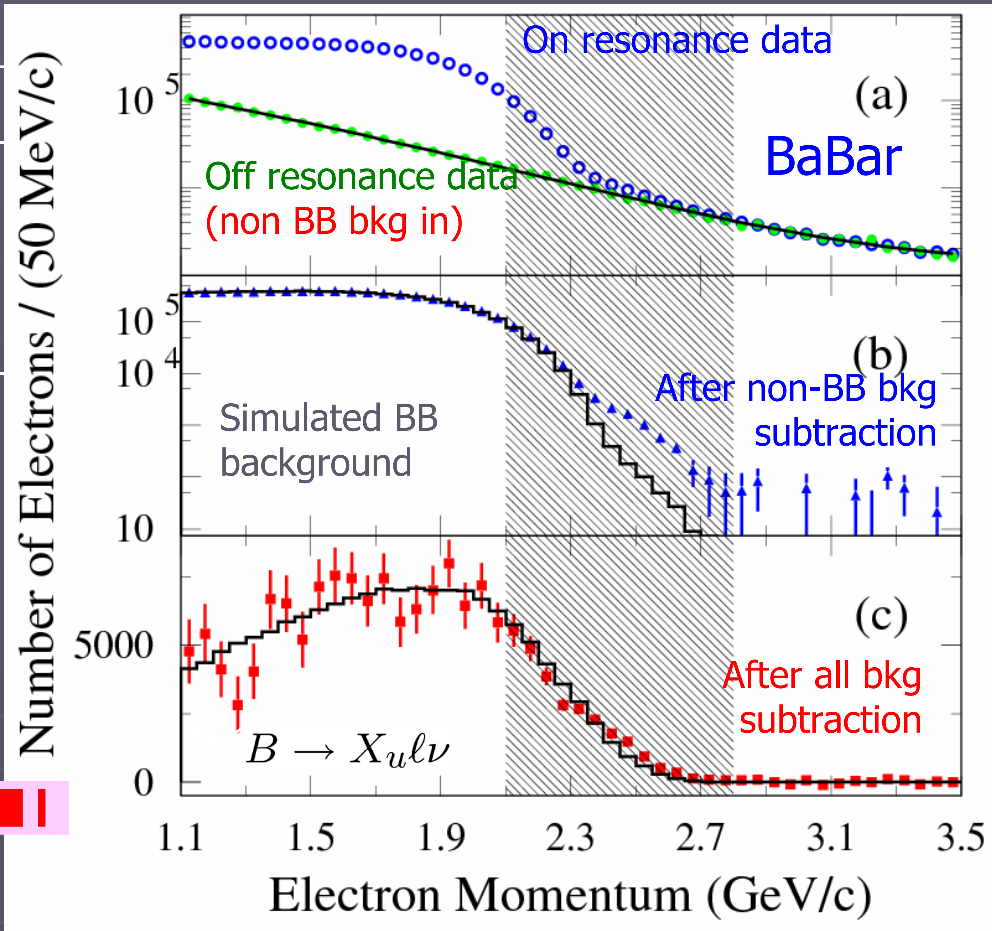
CLEO PRL 88 231803 (2002)
Belle PLB 621 28 (2005)
BaBar PRD 73 012006 (2006)

First pioneered by CLEO

Subtraction of backgrounds crucial!

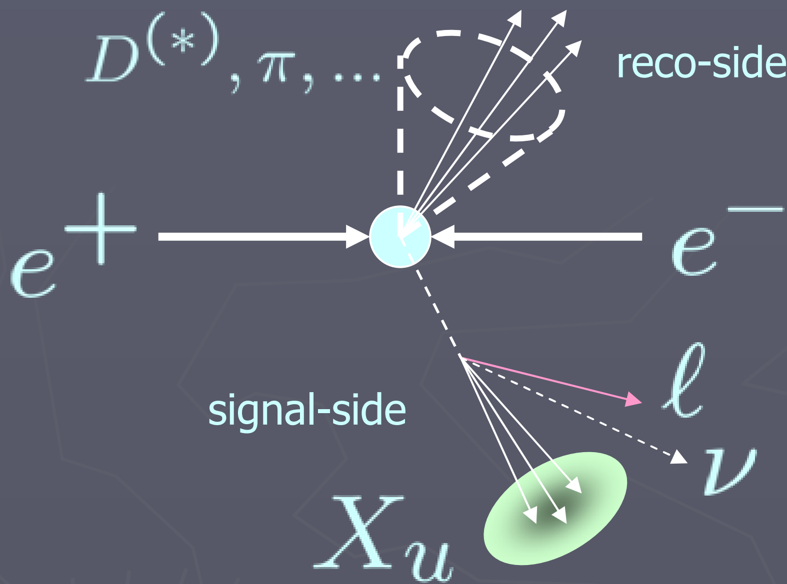
data	$\Delta\mathcal{B}(10^{-4})$	E_ℓ >
CLEO 9/fb	2.30 ± 0.15 ± 0.35	2.1 GeV
Belle 27/fb	8.47 ± 0.37 ± 1.53	1.9
BaBar 80/fb	5.72 ± 0.41 ± 0.65	2.0





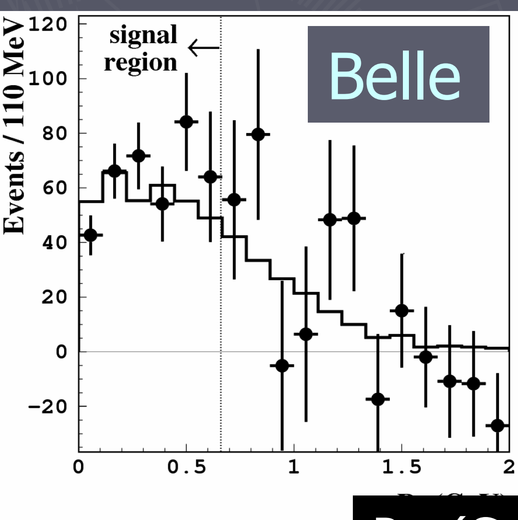
Measurements of m_X, P_+, q^2

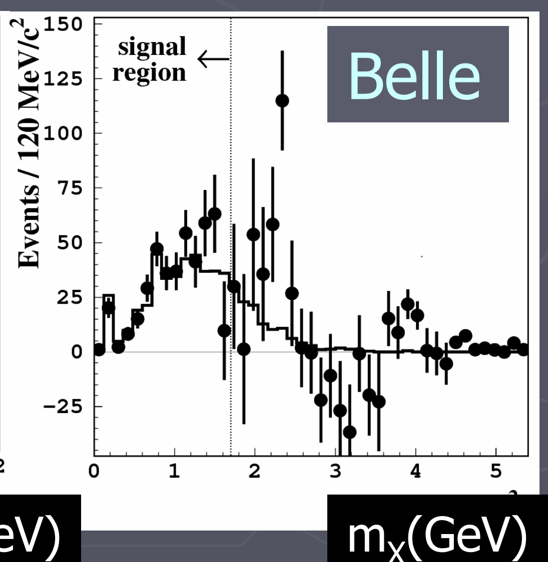
Belle PRL 95 241801 (2005)
BaBar hep-ex/0507017



Reconstruct all decay products to measure m_X, P_+, q^2

1) Fully reconstruct B meson
   - flavor and momentum known
   - maximum purity but low efficiency
2) D(*) tag in reco-side
   - lower purity but efficiency improved



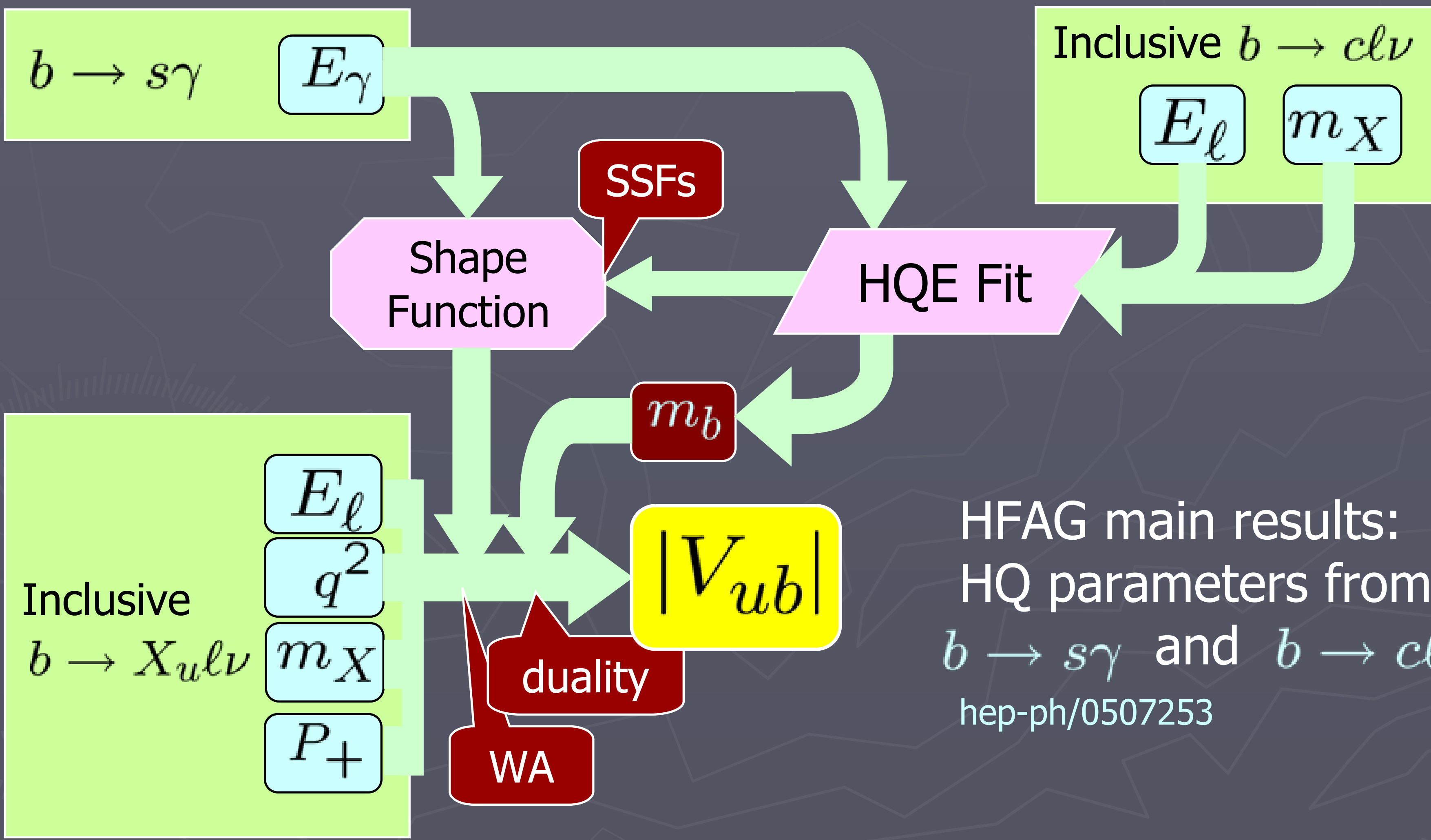


data	Phase space	$\Delta\mathcal{B}(10^{-4})$
Belle 253/fb	m_X<1.7	12.4±1.1±1.0
	m_X<1.7,q^2>8	8.4±0.8 ±1.0
	P+<0.66	11.0±1.0 ±1.6
BaBar 211/fb	m_X<1.7,q^2>8	8.7±0.9 ±0.9 (preliminary)

First measurement of P+ (Belle)
Errors are larger than endpoint results

Extracting $|V_{ub}|$ from partial branching fraction

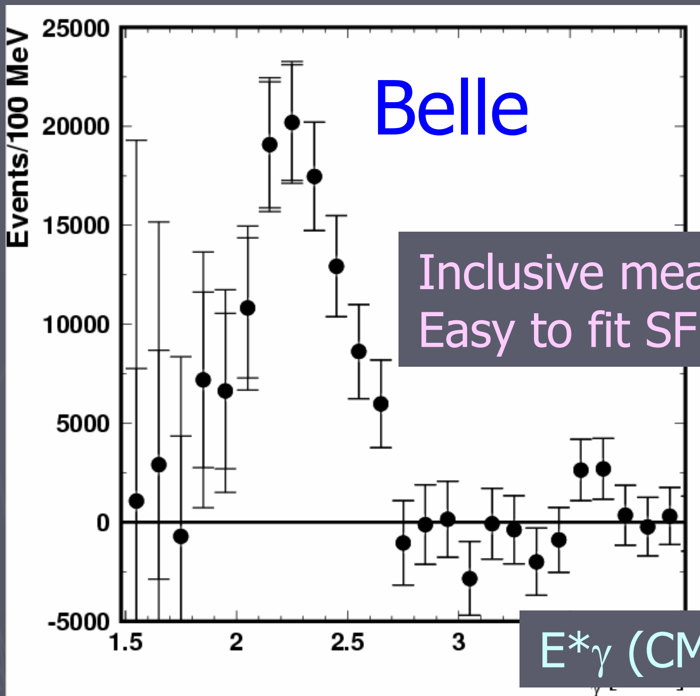
("Morii diagram")



HFAG main results:
HQ parameters from $b \to s\gamma$ and $b \to c\ell\nu$
hep-ph/0507253

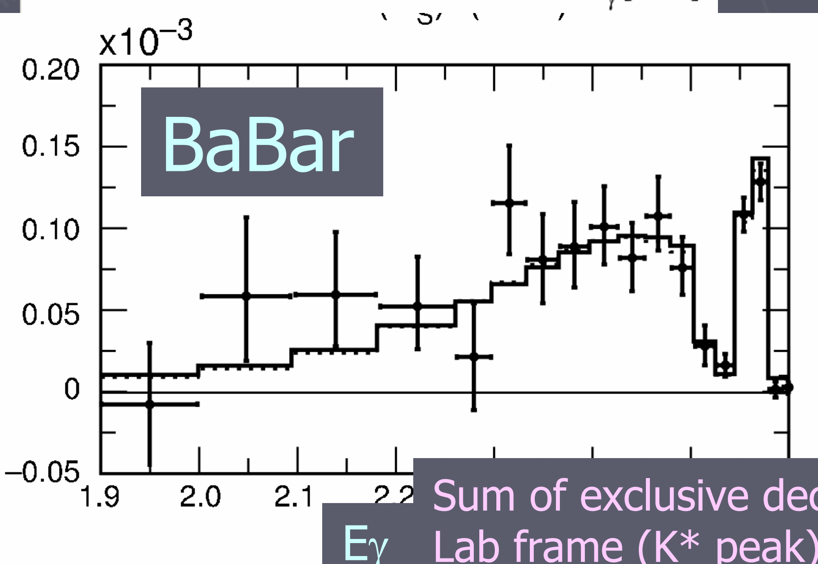
Fitting the Shape Function

Belle PRL 93 061803 (2004)
BaBar PRD 72 052004 (2005)



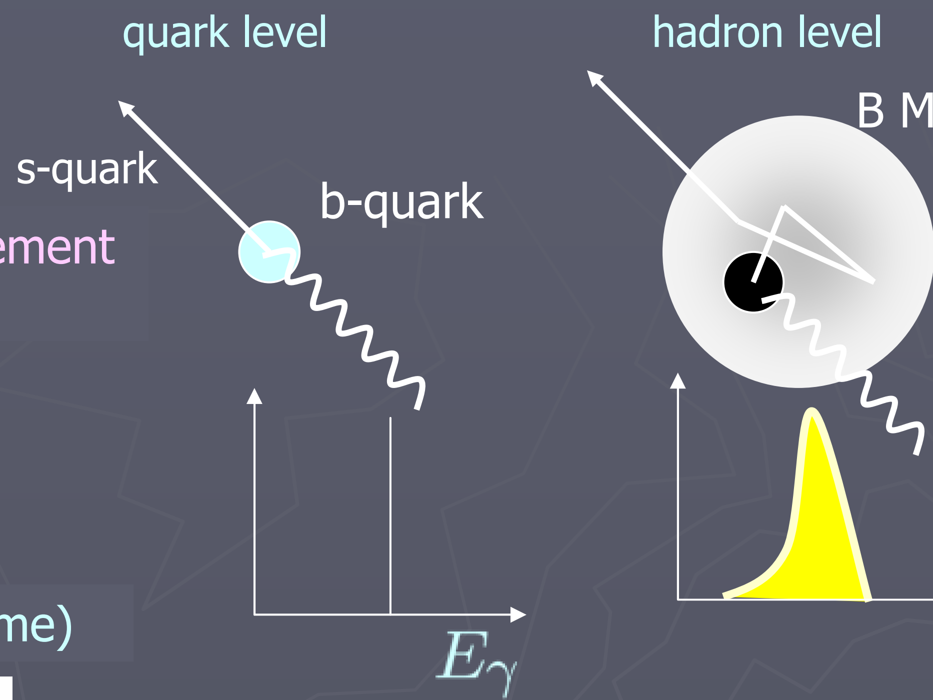
Inclusive measurement
Easy to fit SF

$E^*\gamma$ (CM frame)



$E\gamma$

Sum of exclusive decays
Lab frame (K* peak)



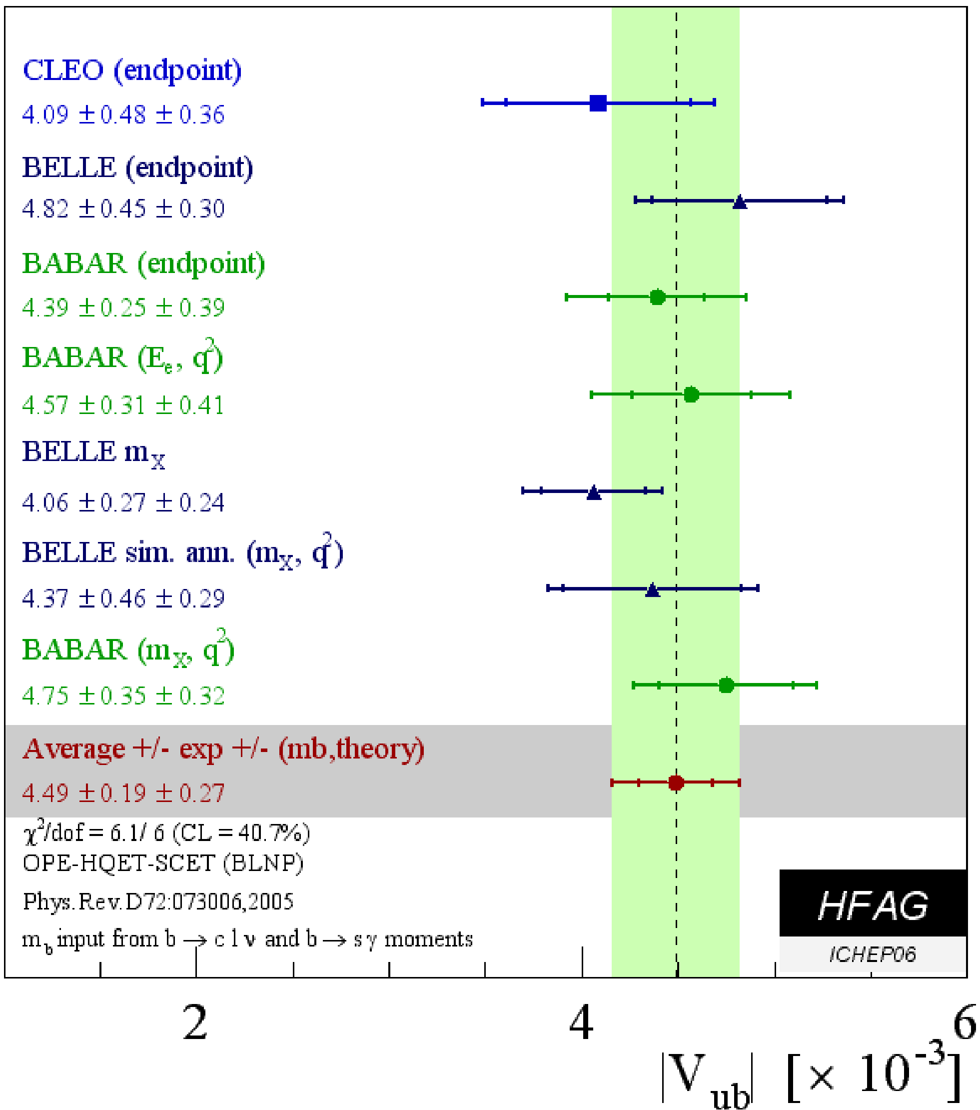
Need to parameterize SF
(shape is not known a priori)

Sub-leading shape function is considered (BLNP)

HQ parameters can be extracted from the
photon spectrum in $b \longrightarrow s\gamma$ or
lepton spectrum in $b \longrightarrow c\ell\nu$

Inclusive $|V_{ub}|$: BLNP framework

$$|V_{ub}|_{\text{BLNP}} = (4.49 \pm 0.19_{\text{exp}} \pm 0.27_{\text{theory}}) \times 10^{-3}$$



$$m_b(\text{SF}) = 4.60 \pm 0.04 \text{ GeV}$$
$$\mu_\pi^2(\text{SF}) = 0.20 \pm 0.04 \text{ GeV}^2$$

The total error in percentage:

$$\delta|V_{ub}| = \pm 7.3\%$$

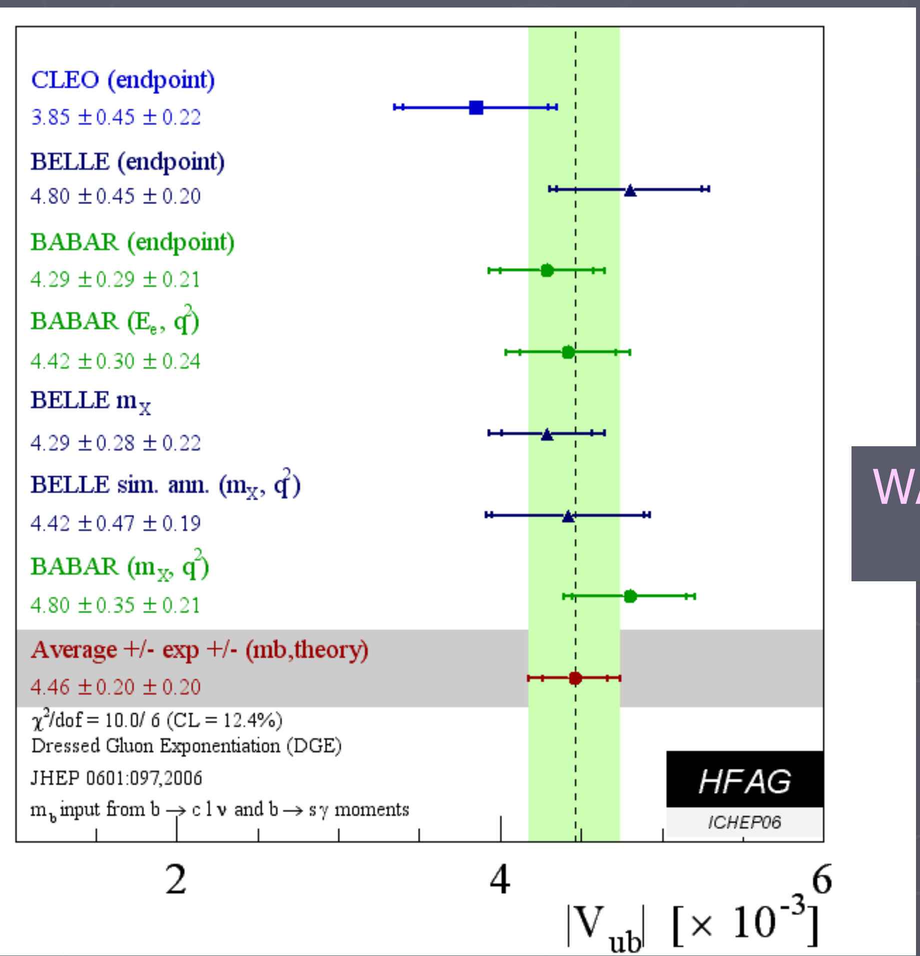
statistical	2.2%
Expt. systematic	2.8%
$b \to c\ell\nu$ model	1.9%
$b \to u\ell\nu$ model	1.6%
HQ parameters	4.2%
Subleading SF + Perturbative	3.8%
Weak Annihilation	1.9%

Theoretical uncertainty is larger (not by a lot)

Inclusive $|V_{ub}|$: DGE framework

Dressed Gluon Exponentiation (DGE): on-shell b-quark calculation converted into hadronic variables used as approximation to the meson decay spectrum

$$|V_{ub}|_{\mathrm{DGE}} = (4.46 \pm 0.20_{\mathrm{exp}} \pm 0.20_{\mathrm{theory}}) \times 10^{-3}$$



$m_b(\overline{\mathrm{MS}}) = 4.20 \pm 0.04 GeV$

$$\delta|V_{ub}| = \pm 6.3\%$$

WA missing here

statistical	1.8%
Expt. systematic	2.5%
$b \to c\ell\nu$ model	2.3%
$b \to u\ell\nu$ model	2.3%
$m_b(\mathrm{R\_CUT})$	1.2%
$\alpha_s(\mathrm{R\_CUT})$	1.0%
Total SL width	3.0%
DGE theory	2.9%

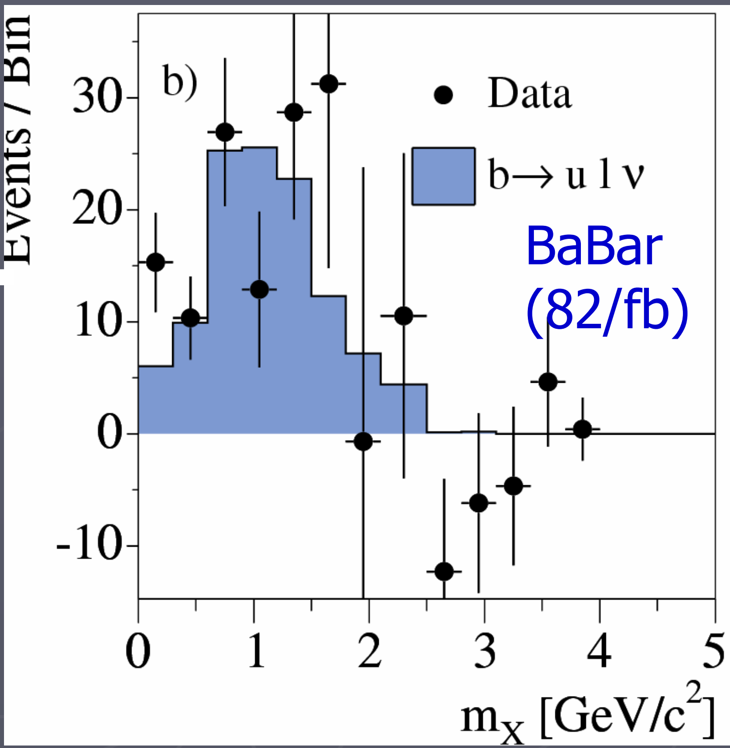
m_X + weighted E_γ in $b \to s\gamma$

BaBar PRL 96 222801 (2006)

Instead of
- assume ad-hoc model for SF and
- get model parameters from b→c and B→sγ

→ Directly use measured photon energy spectrum in b→ sγ (LLR approach)

→ residual SF dependence via signal MC

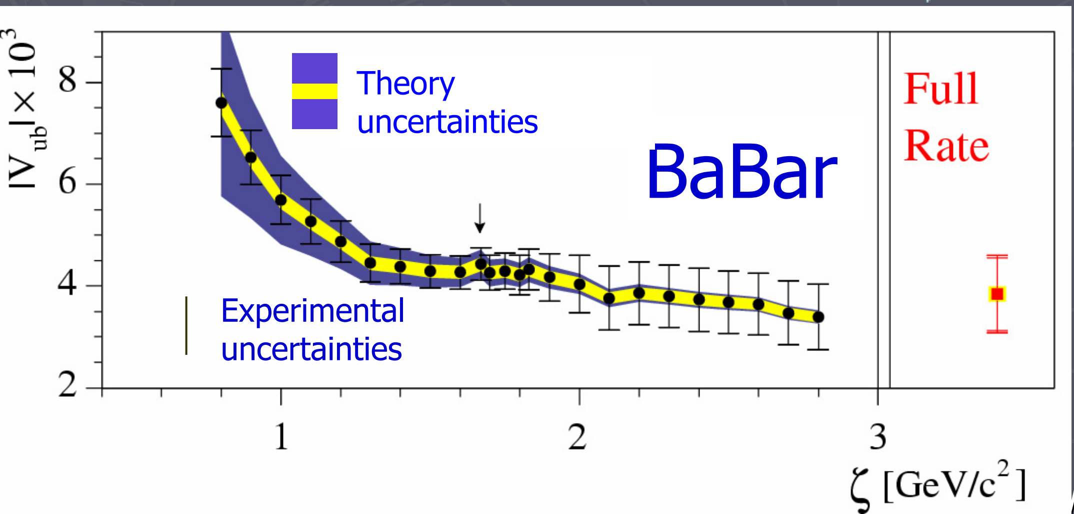


$$\frac{|V_{ub}|}{|V_{ts}|} = \left\{ \frac{6\alpha(1 + H^{\gamma}_{\text{mix}})(C_7^{(0)})^2}{\pi[I_0(\zeta) + I_+(\zeta)]} \times \delta R_u(\zeta) \right\}^{1/2}$$

$\delta R_u(\zeta)$: partial decay rate of $b \to u\ell\nu$

H^{γ}_{mix} : interferences btw EM penguin O_7 w/ O_2 and O_8

I_0, I_+ : weights from $d\Gamma^{\gamma}/dE_\gamma$ in $b \to s\gamma$



Choose : ζ

→ Total error is minimal

→ $\zeta = 1.67 \text{GeV}/c^2$

$$|V_{ub}| = (4.43 \pm 0.38_{\text{stat}} \pm 0.25_{\text{syst}} \pm 0.29_{\text{th}}) \times 10^{-3}$$

BaBar PRL 96 222801 (2006)

m_X with large acceptance

OPE allows to extract $|V_{ub}|$ with ~ 5% error

→ measure entire m_X spectrum up to 2.5 GeV
→ This gives acceptance ~ 97%

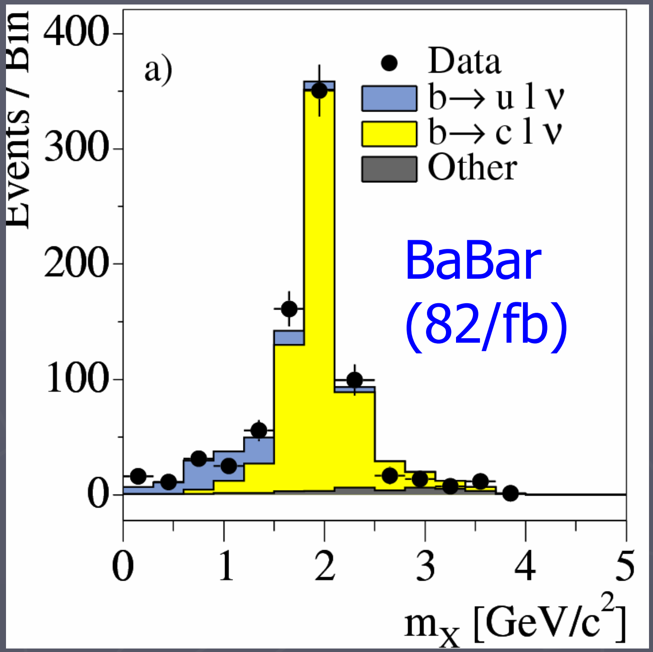
No shape function in extraction of $|V_{ub}|$

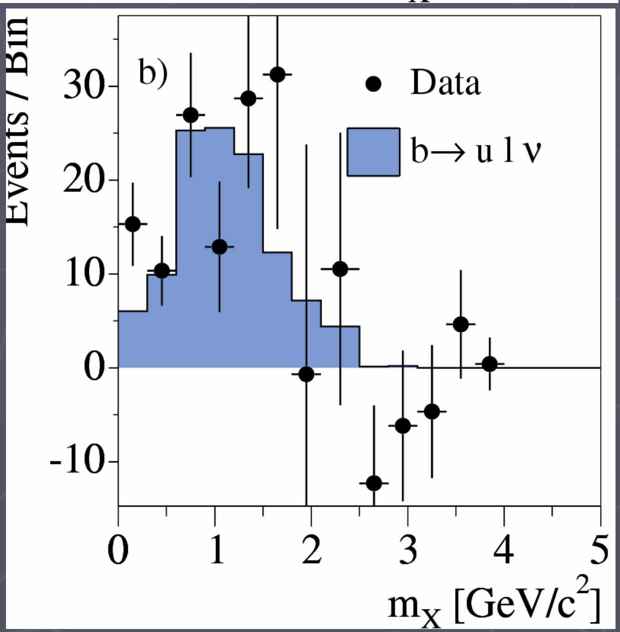
- Residual SF dependence via signal MC
  systematic: 5.0%

- Need to subtract b→c background
  systematic: 3.8%
  increased statistical uncertainty

$$|V_{ub}| = (3.84 \pm 0.70_{\text{stat}} \pm 0.30_{\text{syst}} \pm 0.10_{\text{theory}}) \times 10^{-3}$$

↑ Improvement in theory uncertainty

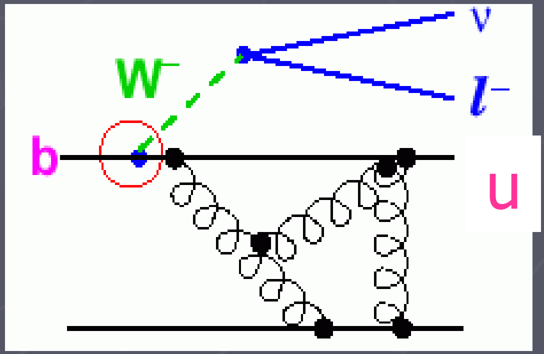




Exclusive decays to $|V_{ub}|$

measure exclusive final states
- good suppression of b→c decays, high signal-to-background
- small branching fraction $O(10^{-4})$ → need high statistics

require unknown form factor to extract $|V_{ub}|$
(complication due to QCD)



need to measure q^2 i.e. either 4-momentum of ν or B

Channel $B \to \pi \ell \nu$ is the most promising for $|V_{ub}|$
- one dominant form factor $f_+(q^2)$
- q^2 shape and normalization needed

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

Determining the Form Factors

- Earlier predictions made with quark models e.g. ISGW2
- Lattice QCD
  - ✓ makes predictions at high q^2 ($q^2 > \sim 16$ GeV^2)
  - ✓ unquenched calculations have become available recently

    e.g. HPQCD PRD 73, 074502 (2006)

    FNAL NP Proc. Suppl. 140, 461 (2005)

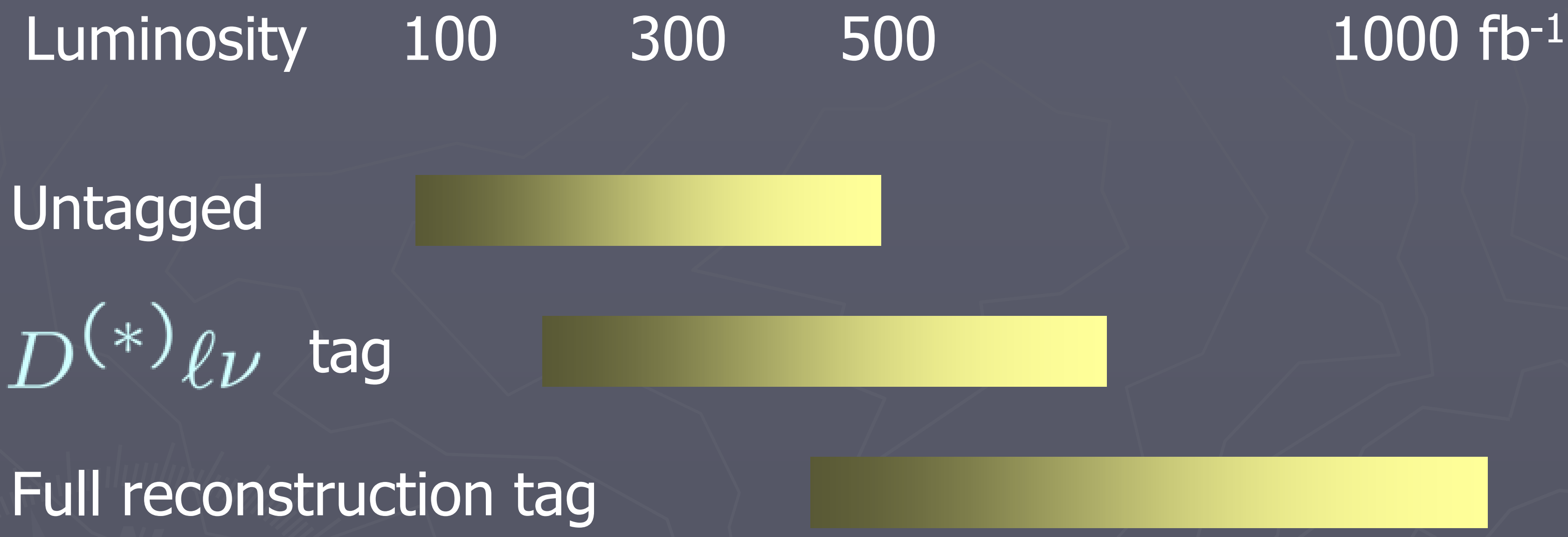
- Light Cone Sum Rules (LCSR)
  - ✓ makes predictions at low q^2 ($q^2 < \sim 14$ GeV^2)

    e.g. Ball & Zwicky PRD 71 014015 (2005), PRD 71, 014029 (2005)

- Parameterization has been used to extend Lattice QCD or LCSR to full q^2 range

- The normalization of FF becomes main issue when extracting $|V_{ub}|$

Range of Applicability of Method



Not an absolute but illustrative statement

Full reconstruction tag will become method of choice soon

Note:

Belle 642 fb-1

BaBar 406 fb-1 **(now reached 1/ab for combined data)**

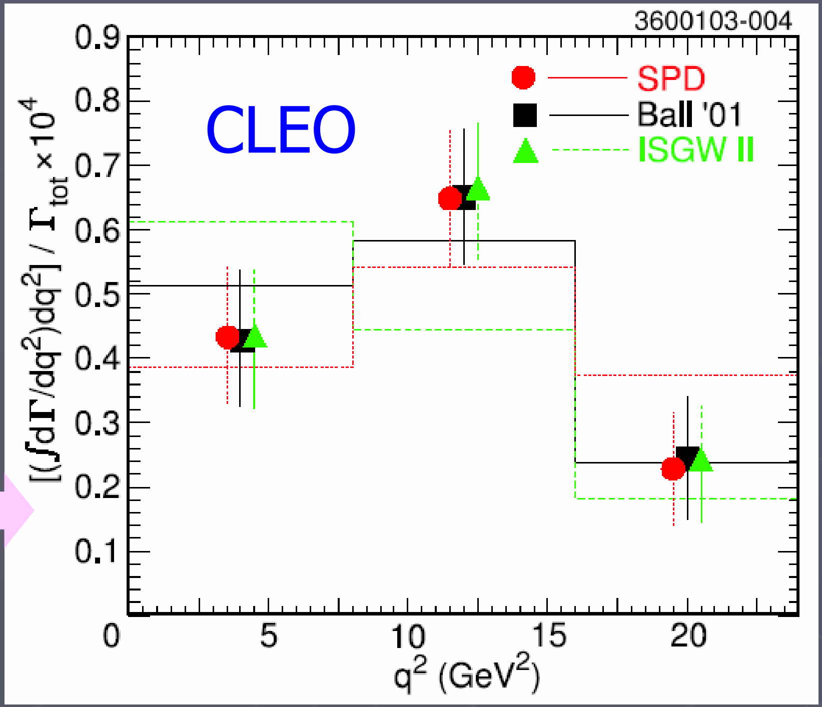
CLEO PRD 68 072003 (2003)

CLEO untagged $B \to \pi \ell \nu$

FF models enter extraction of BF through

- ✓ signal efficiency from MC
- ✓ b→u crossfeed and b→c

π^+ result



$$\mathcal{B}(B \to \pi^- \ell^+ \nu) = (1.33 \pm 0.18_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.01_{\text{FF sig}} \pm 0.07_{\text{FF crossfeed}}) \times 10^{-4}$$

$$|V_{ub}| = (3.17 \pm 0.17^{+0.16+0.53}_{-0.17-0.39} \pm 0.03) \times 10^{-3}$$

stat syst theory FF shape

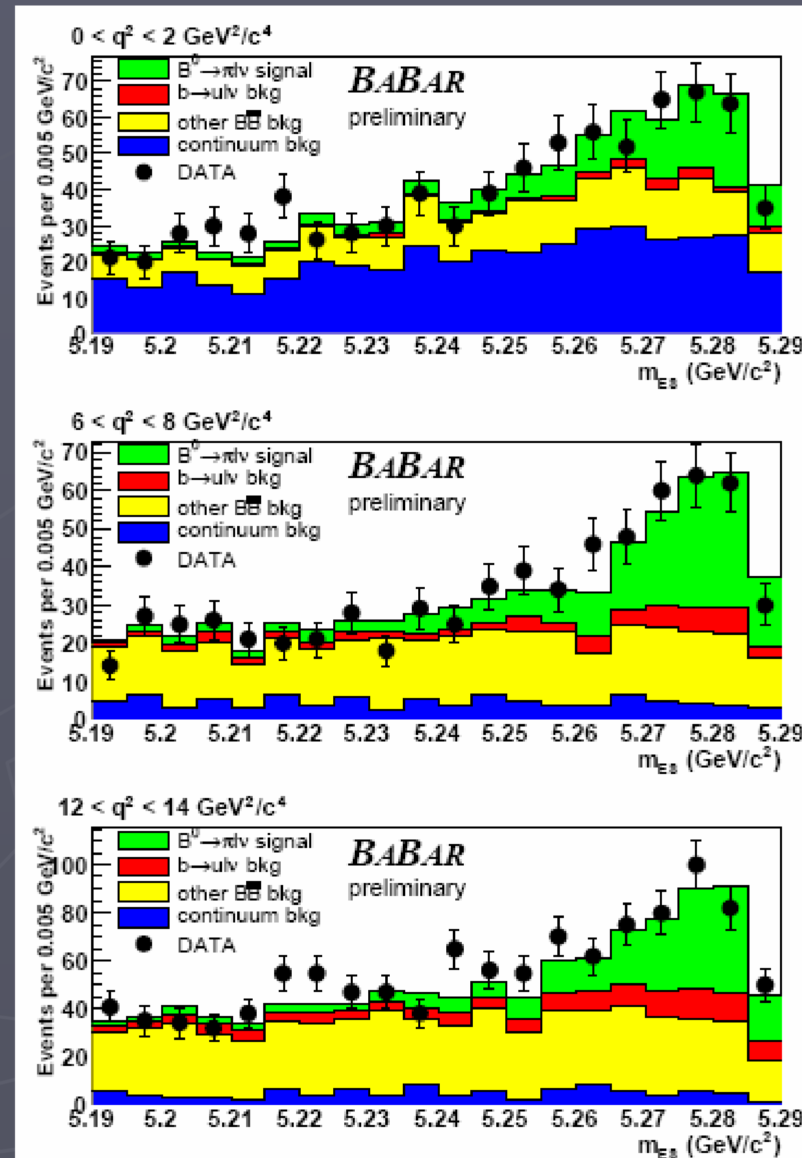
(π and ρ mode combined) LCSR+LQCD

BaBar hep-ex/0607060

BaBar untagged $B \to \pi \ell \nu$ preliminary

Updated from the last pub (PRD72051102)
: now **227 BB pairs** used

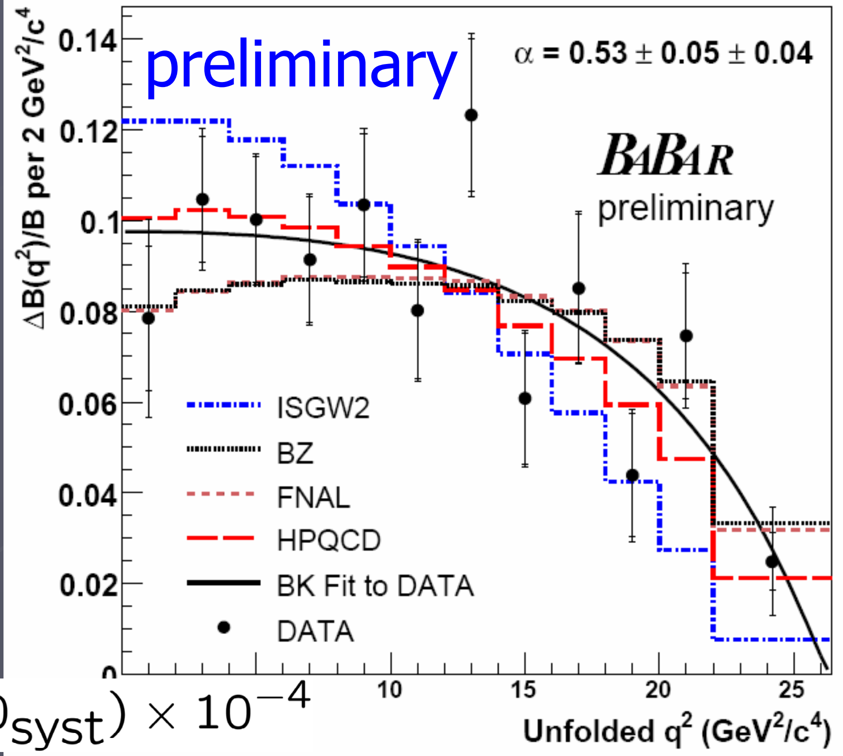
- use much looser ν reconstruction to improve signal efficiency
- no harsh cut on $|m^2_{miss}/E_{miss}|$
- calculate q^2 from B momentum in "average" B-frame + unfolding
  → q^2 resolution still good (~400 MeV)
- more parameters for background
  → reduced systematics
- 5 times the signal yield: 25/fb-1
- 12 bins in q^2



BaBar hep-ex/0607060

BaBar untagged $B \to \pi \ell \nu$

- ISGW2 is incompatible with the data
- LQCD & LCSR consistent with BaBar data
- Covariance matrices are included in preprint → theorists can use for analyses
- use BK parameterization for $f_+(q^2,\alpha)$



$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.44 \pm 0.08_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-4}$$

QCD calculations	Stat+syst. errors χ^2	Stat+syst. errors Prob(χ^2)%
ISGW2	34.1	0.07
Ball-Zwicky	13.0	37.2
FNAL	12.5	41.0
HPQCD	10.2	60.2

	q^2	$\lvert V_{ub}\rvert (10^{-3})$	
Ball-Zwicky	<16	3.6±0.1±0.1+0.6-0.4 (uncertainty in FFs)	→ LCSR
HPQCD	>16	4.1±0.2±0.2+0.6-0.4	Lattice QCD
FNAL	>16	3.6±0.2±0.2+0.6-0.4	Lattice QCD

Belle hep-ex/060424
Submitted to PLB

Belle $B \to \pi/\rho\ell\nu$ with $D^{(*)}\ell\nu$ tag

Ratios of decay rates are measured and found to be consistent with isospin relations

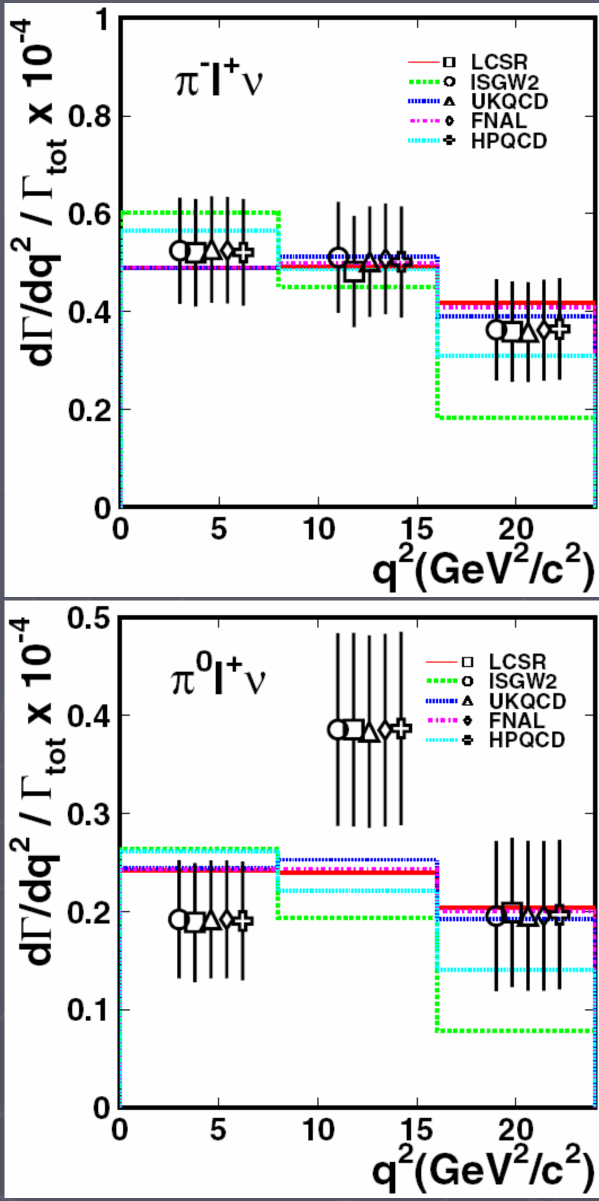
$$\frac{\Gamma(B^0 \to \pi^-\ell^+\nu)}{\Gamma(B^+ \to \pi^0\ell^+\nu)} = (1.92 \pm 0.43 \pm 0.28)$$

$$\frac{\Gamma(B^0 \to \rho^-\ell^+\nu)}{\Gamma(B^+ \to \rho^0\ell^+\nu)} = (1.74 \pm 0.53 \pm 0.33)$$

$|V_{ub}|$ from $q^2>16$ GeV^2 region, π^-, π^0 combined

	q^2(GeV^2)	$\lvert V_{ub}\rvert(10^{-3})$
FNAL	>16	3.60±0.41±0.20+0.62-0.41(LQCD)
HPQCD	>16	4.03±0.46±0.22+0.59-0.41(LQCD)

This gives ~13% experimental uncertainty on $|V_{ub}|$



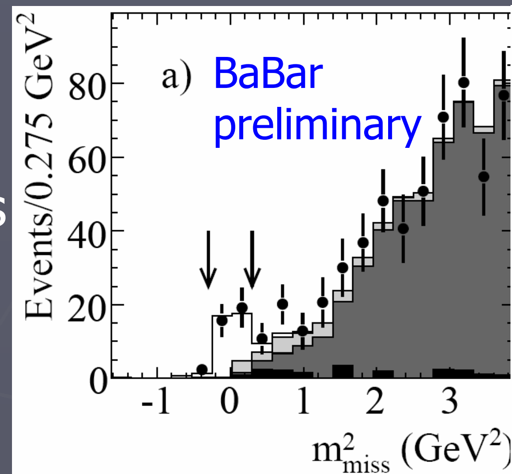
BaBar $B \to \pi/\rho\ell\nu$ with had. + SL tag combined

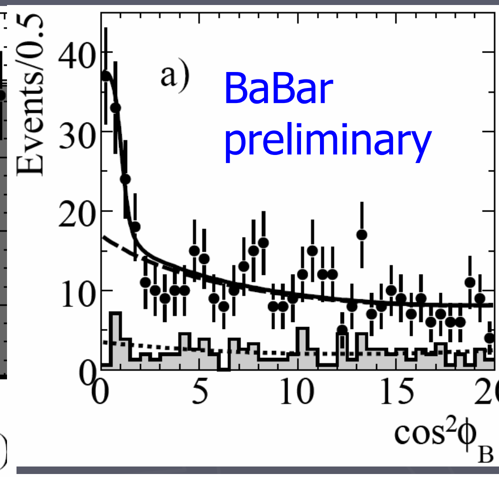
BaBar hep-ex/0607089

Using 215/fb of data

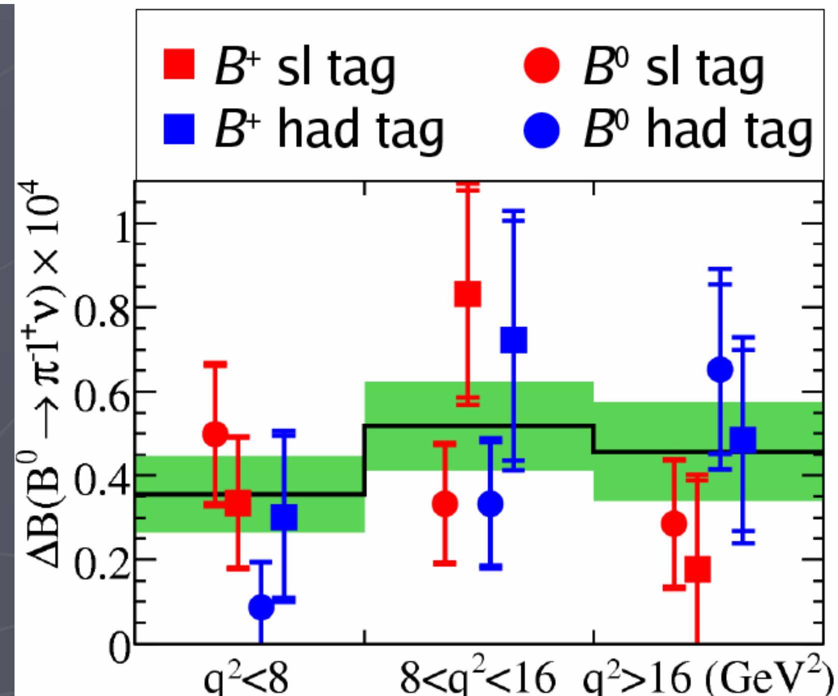
Need to combine 4 measurements
- 2 x B-flavors:
  - charged and neutral B
- 2 x tagging methods
  - hadronic and semileptonic

→ minimize total error in each bin of q^2



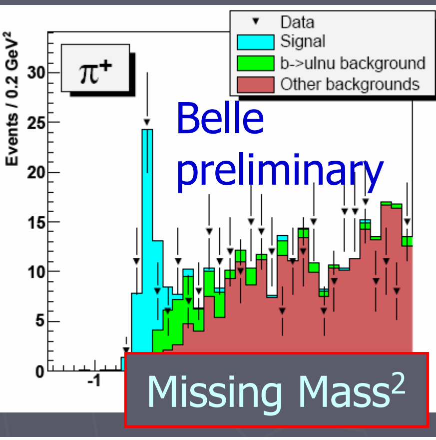


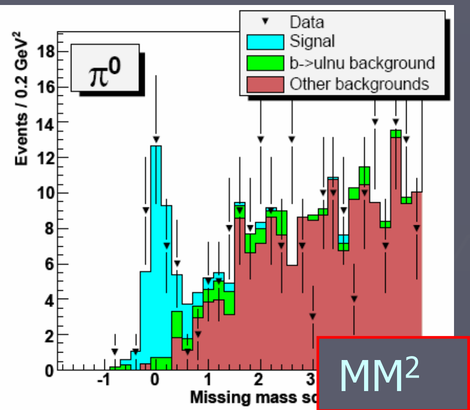
	q^2(GeV^2)	$\|V_{ub}\|(10^{-3})$
Ball-Zwicky	<16	3.2±0.2±0.1+0.5-0.4 (uncertainty in FFs)
HPQCD	>16	4.5±0.5±0.3+0.7-0.5
FNAL	>16	4.0±0.5±0.3+0.7-0.5
APE	>16	4.1±0.5±0.3+1.6-0.7

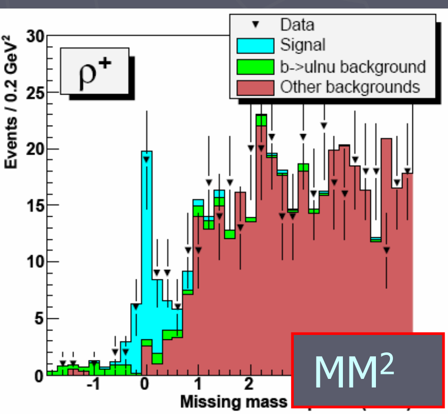


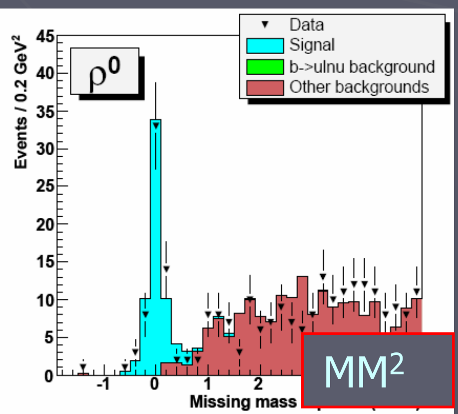
Belle $B \to \pi/\rho/\omega\ell\nu$ with full reco tag

Belle-CONF-0666



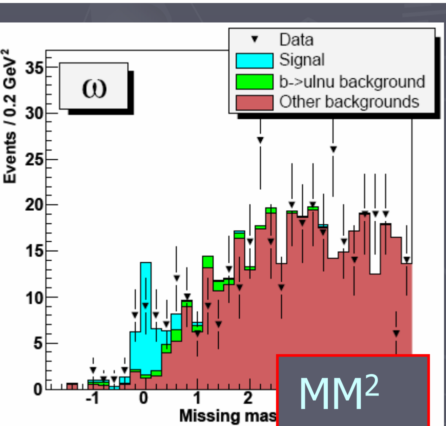






- Using 497/fb of data
- Reconstruct the hadronic decay of B first
- Identify a lepton and search for light mesons
- Extract yield from the missing mass squared distributions

→ **high purity signal obtained**



Belle preliminary

$$\mathcal{B}(B^0 \to \pi^-\ell^+\nu) = (1.49 \pm 0.26_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \pi^0\ell^+\nu) = (0.86 \pm 0.17_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$

Summary of Exclusive $\mathcal{B}(B \to \pi^- \ell^+ \nu)$

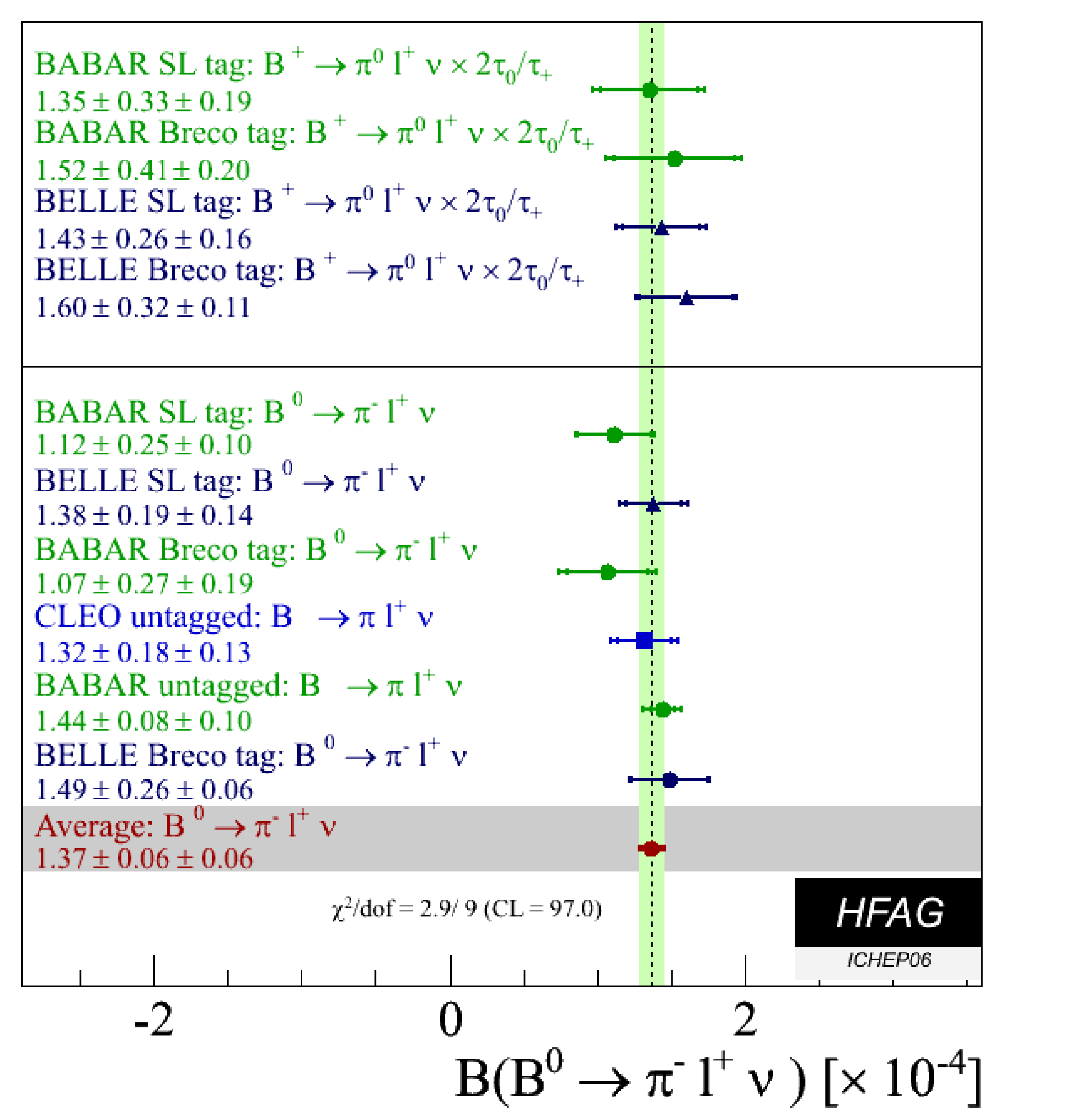
HFAG ICHEP 2006

Average $\mathcal{B}(B \to \pi^- \ell^+ \nu)$

$(1.37 \pm 0.06 \pm 0.06) \times 10^{-4}$

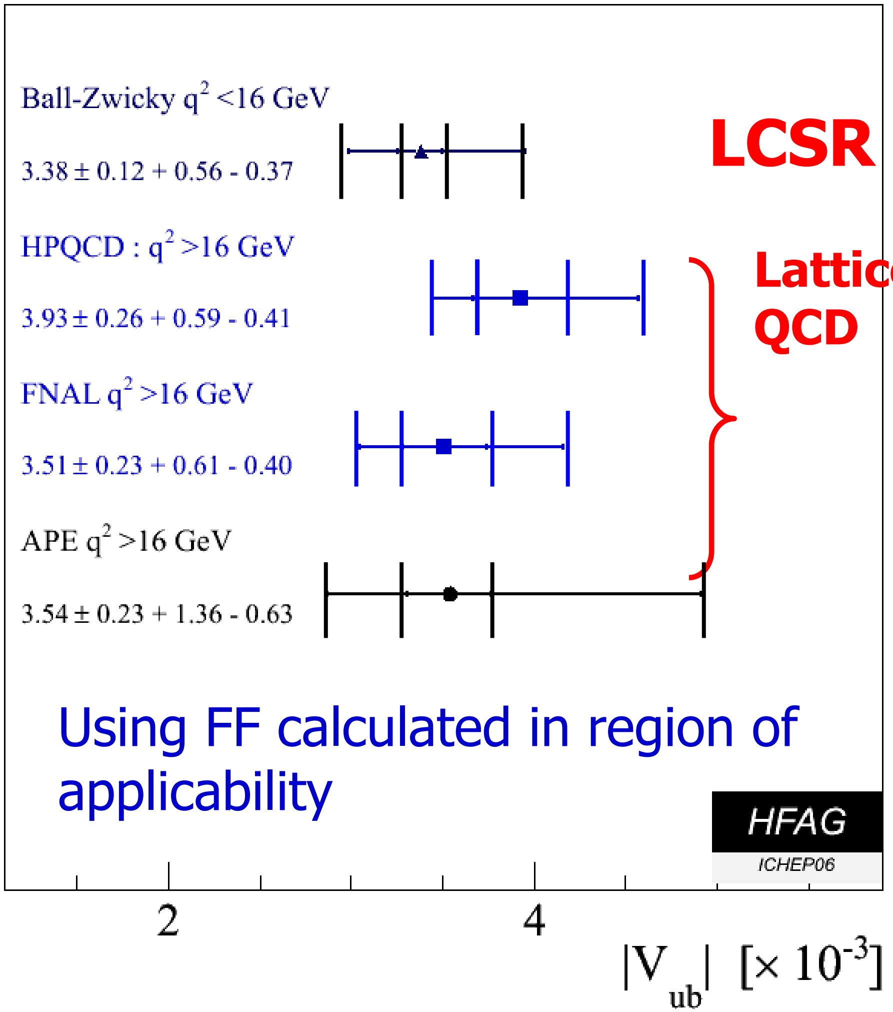
Note: updated Belle SL tag result now included

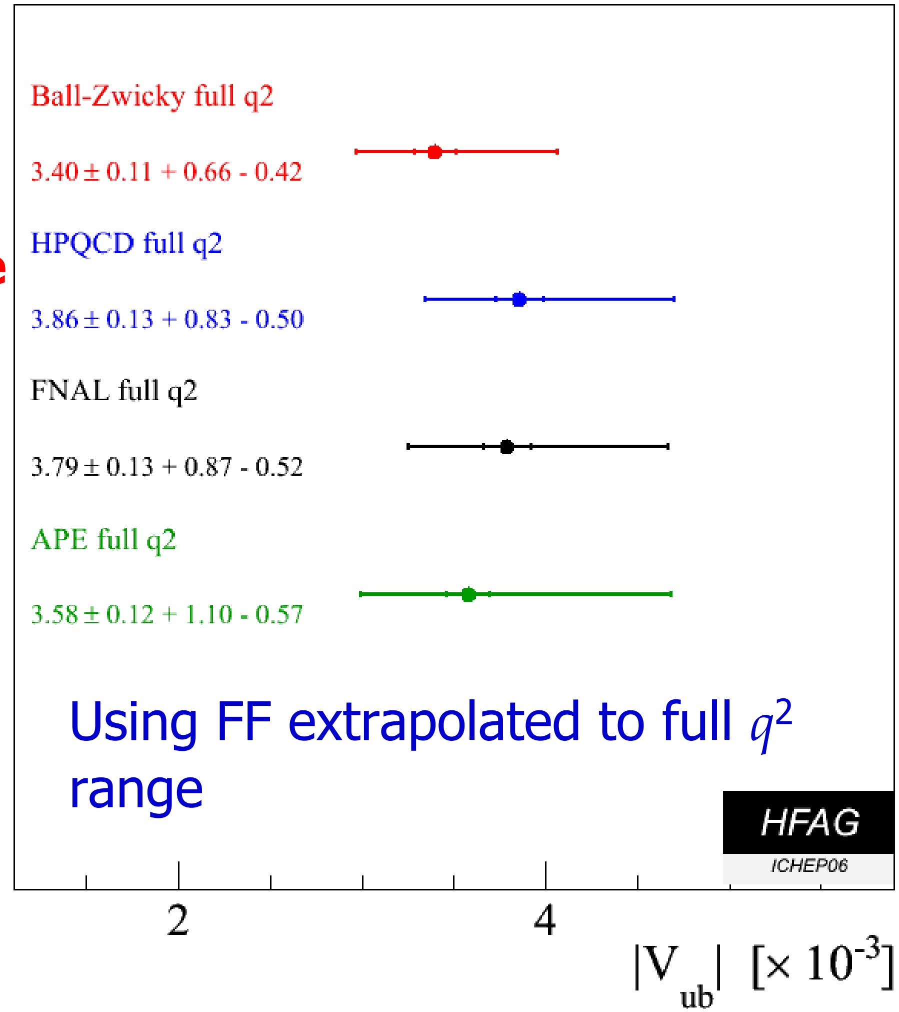
Untagged analyses currently the most precise



Summary of $|V_{ub}|$ from Exclusive Decays

HFAG ICHEP 2006 (+ my bars for clarity)





Summary

- Inclusive measurements $|V_{ub}|$ ~ 7 % precision
  - ✓ shape function is one of main issues
  - ✓ Error is more or less equally shared by exp. and theory
  - ✓ BaBar's new result (LLR) looks promising
    - has residual SF dependence

- Exclusive measurements $|V_{ub}| > 10$ %
  - ✓ Form factor calculation is the main issue
  - ✓ Theoretical uncertainty is dominant

Question: $|V_{ub}| < 5$ % error achievable?

CLEO PRD 68 072003 (2003)

CLEO untagged $B \to \pi \ell \nu$

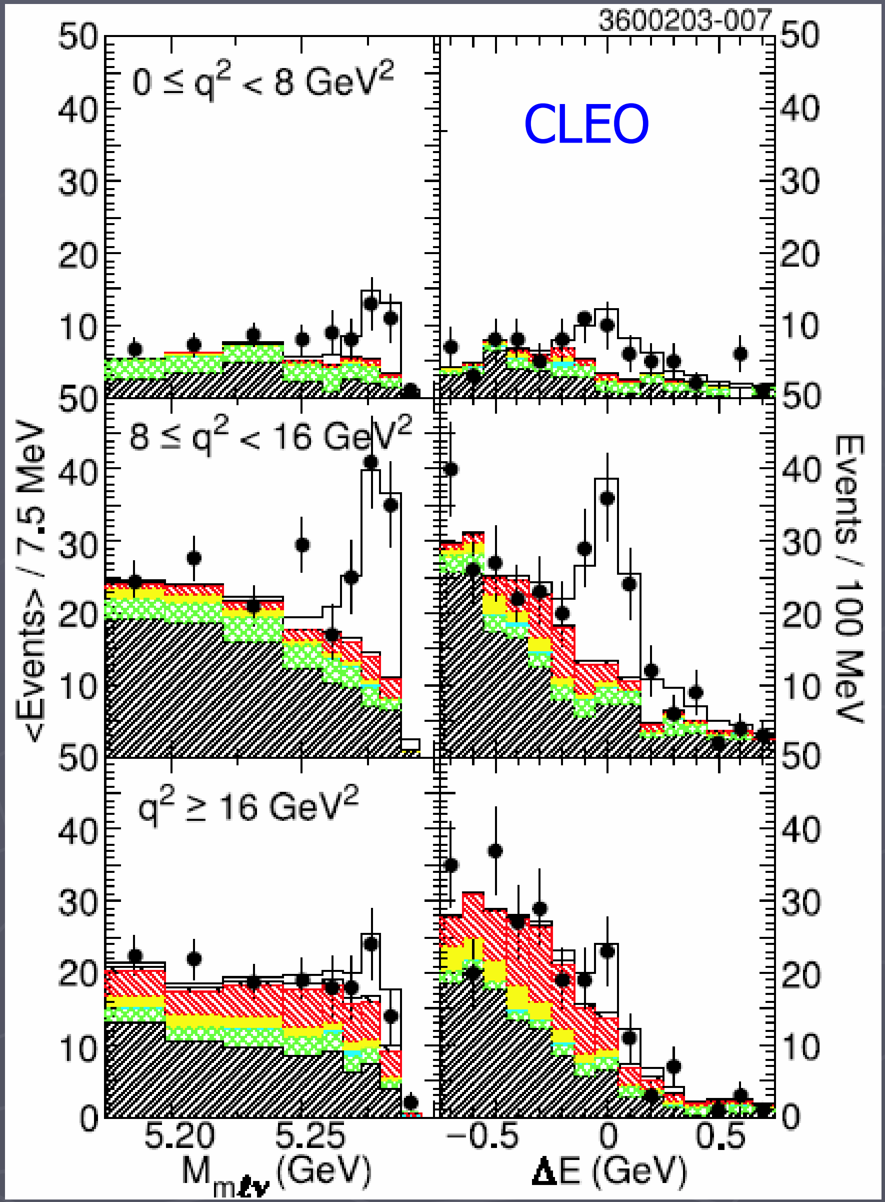
Search and fit for yields across a number of exclusive modes

$$\pi^+, \pi^0, \rho^+, \rho^0, \omega, \eta$$

Isospin constraints imposed in fits on 9.7 x 10^6 BB pairs

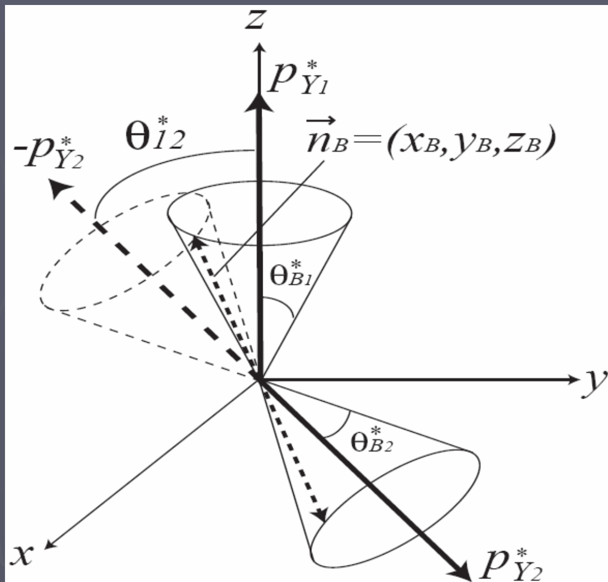
Extract partial branching fraction in 3 q2 bins for π^+ and ρ^+

π^+ result



Belle hep-ex/060424
Submitted to PLB

Belle $B \to \pi/\rho\ell\nu$ with $D^{(*)}\ell\nu$ tag



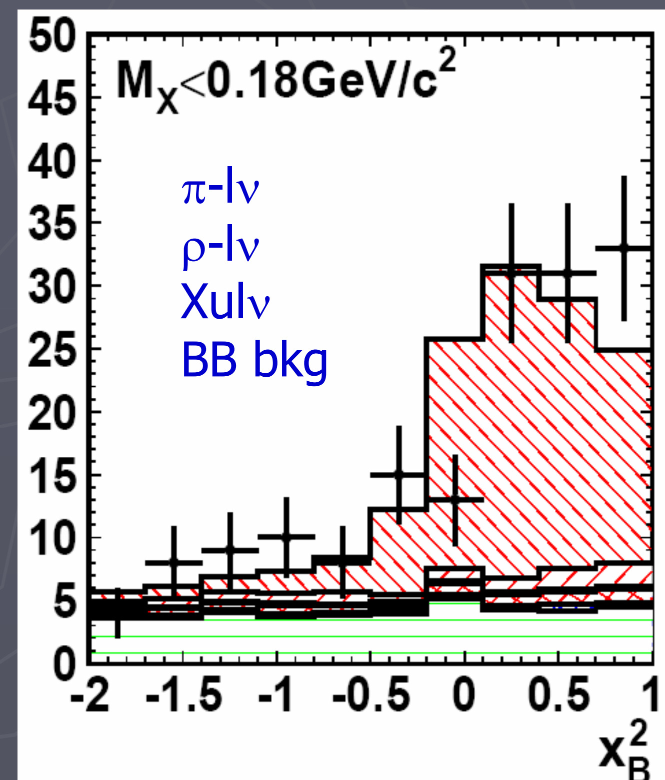
Using 253/fb (275 million BB events)

- Reconstruct tag side first $B \to D^{(*)}\ell\nu$
- Identify leptons
- Look for π or ρ in the remaining particles

Select events using kinematical variables

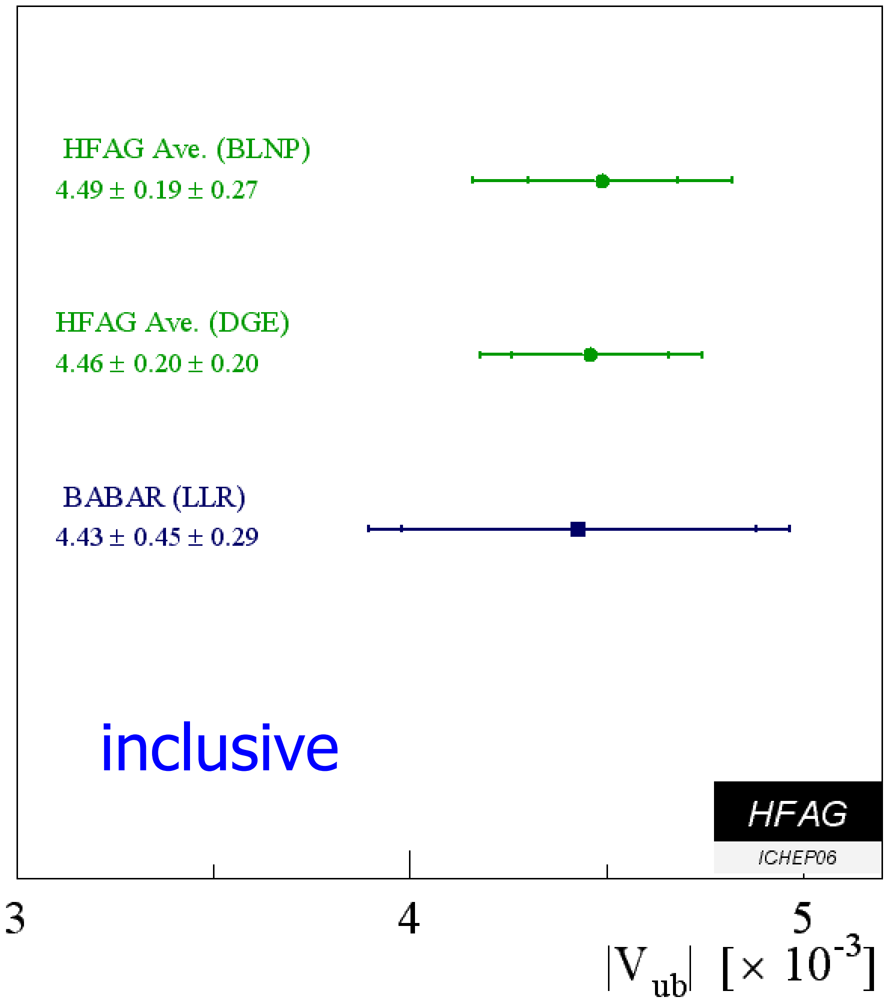
$$x_B^2 = 1 - \frac{1}{\sin^2\theta^*_{12}}(\cos^2\theta^*_{B1} + \cos^2\theta^2_{B2} - 2\cos\theta^*_{B1}\cos\theta^*_{B2}\cos\theta^*_{12}) > -2$$

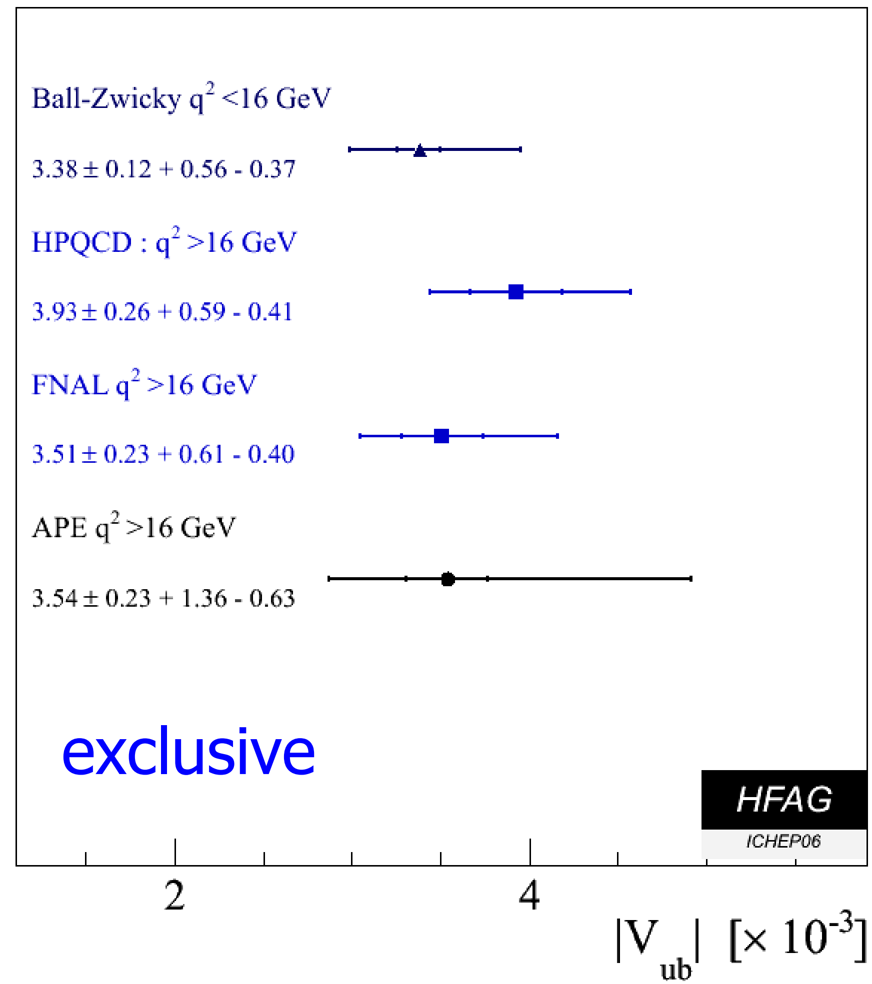
Extract the signal in (x^2_B, m_X) plane with 4 signal and 3 bkg components



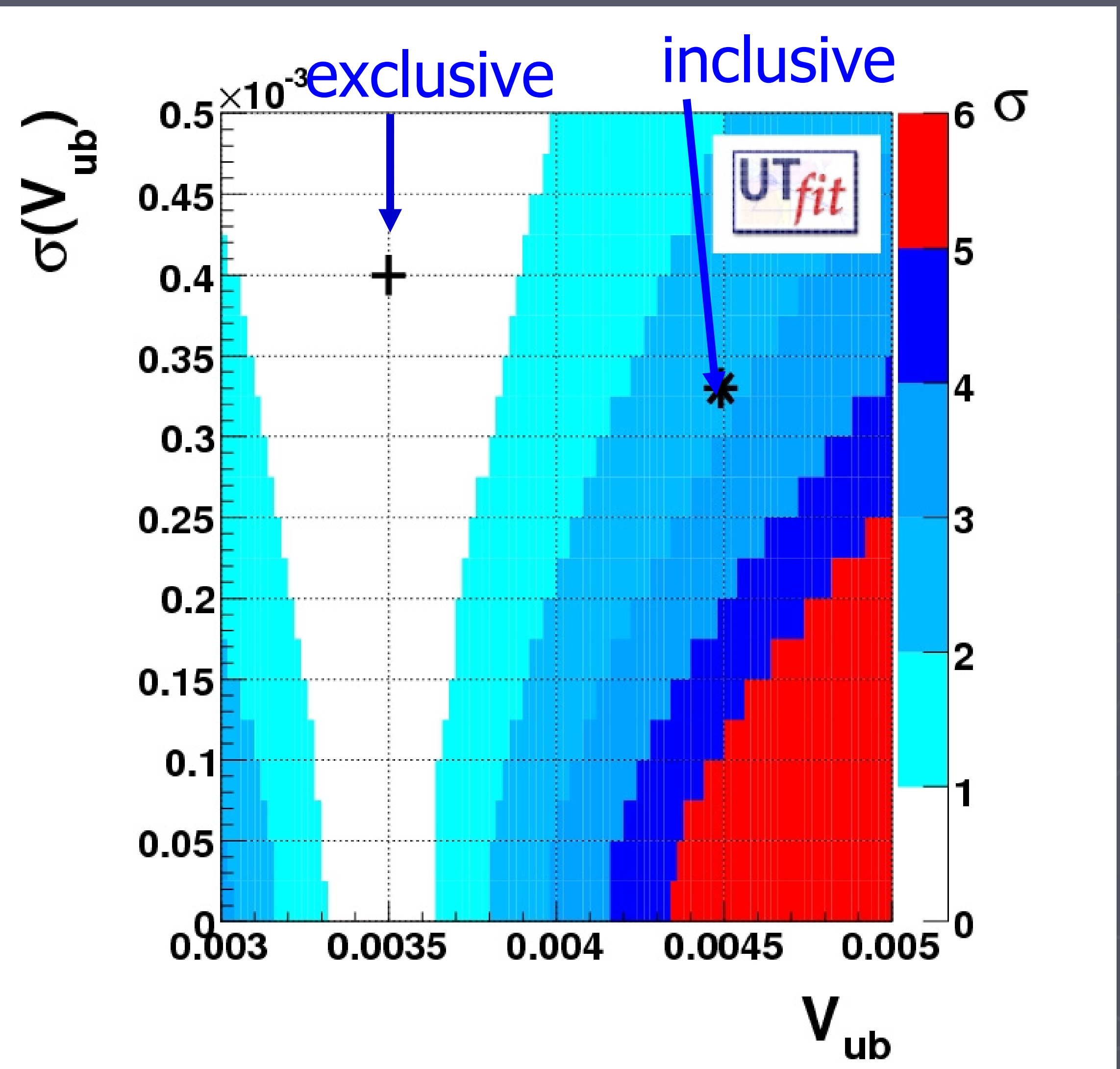
$|V_{ub}|$: inclusive vs exclusive

HFAG ICHEP 2006





$|V_{ub}|$: direct vs. indirect



Indirect measurements constrain $|V_{ub}|$

→ indicated as bands in the plot

There are two direct measurements

+: exclusive *:inclusive

The present value of $\sin 2\phi_1$ is more compatible with exclusive determination of $|V_{ub}|$