



OAW
Austrian Academy
of Sciences

Measurement of the sides of the UT ($|V_{cb}|$ and $|V_{ub}|$) at the B factories

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Austrian Academy of Sciences

Representing the Belle collaboration

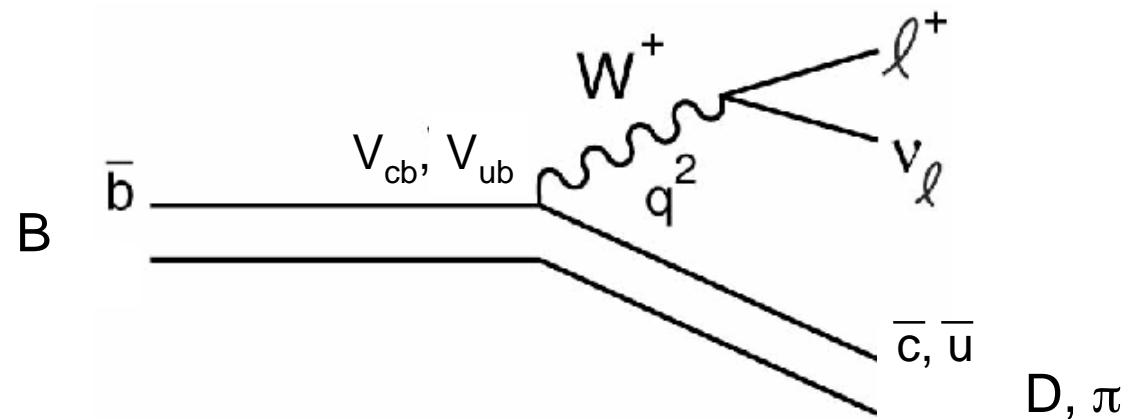


Second Workshop on Theory,
Phenomenology and Experiments
in Heavy Flavour Physics

June 16-18 2008, Capri, Italy

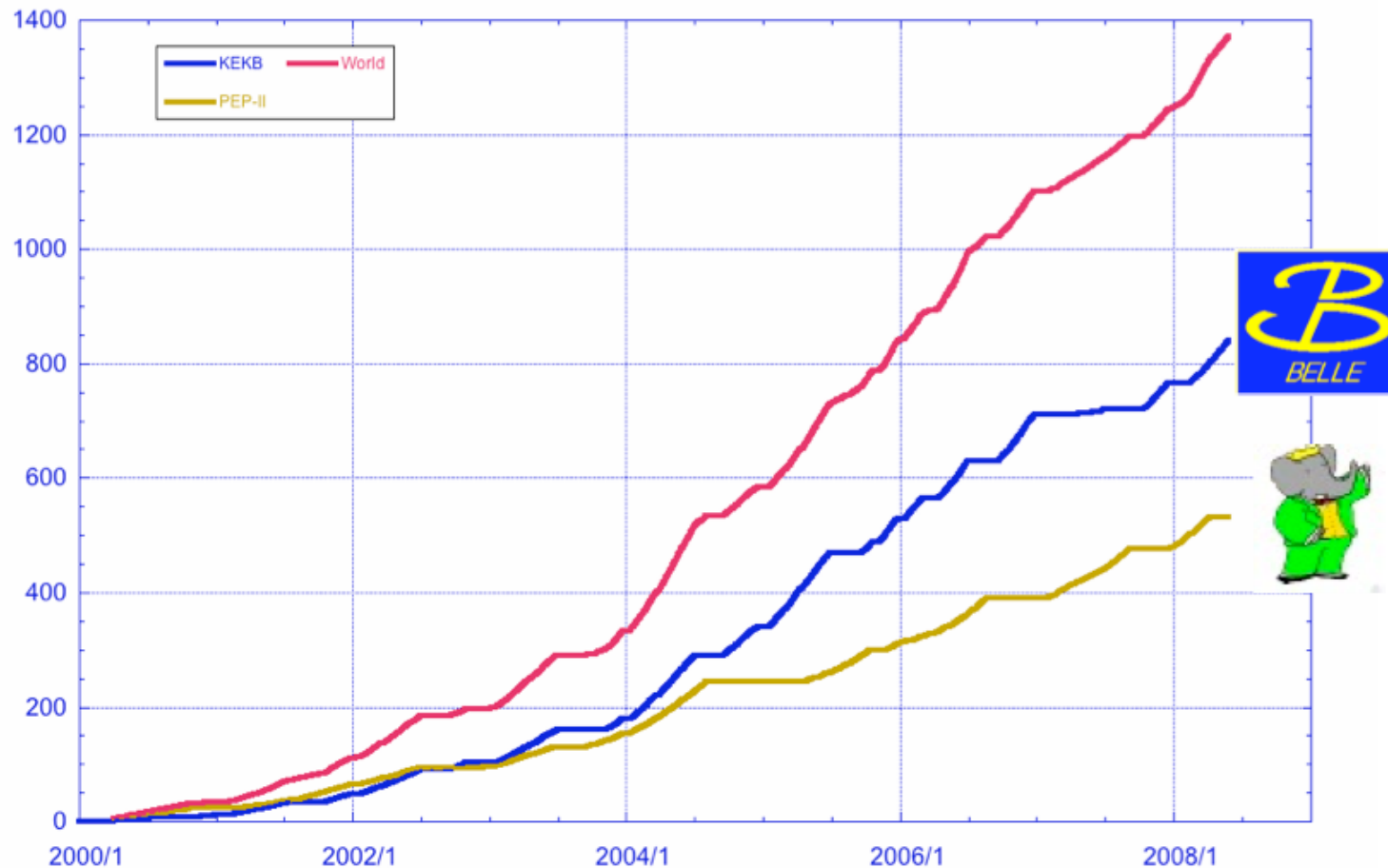
Semileptonic decays

- At the B factories, $|V_{cb}|$ and $|V_{ub}|$ are determined from **semileptonic B decays**



- “**Old physics**”: tree diagrams, no ‘pollution’ from New Physics
- A precise determination of $|V_{ub}/V_{cb}|$ is crucial to be able to observe deviations from the CKM mechanism due to New Physics

Belle and BaBar



840/fb total
750/fb on Y(4S)

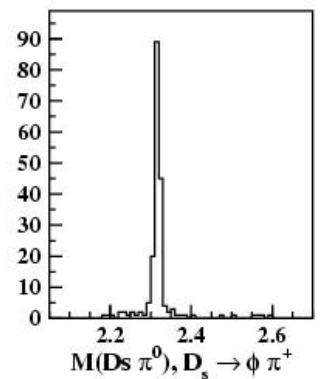
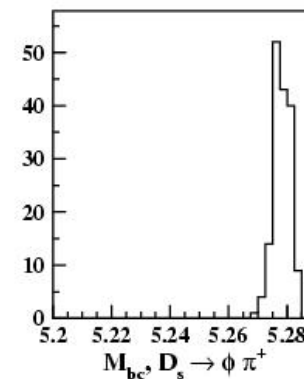
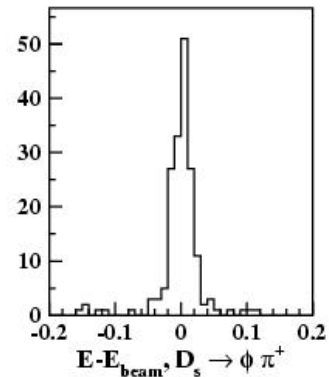
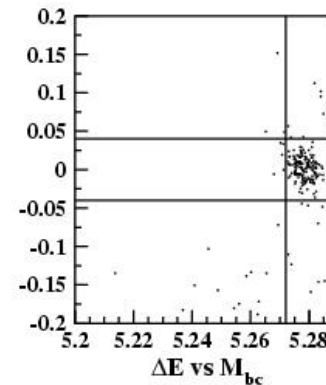
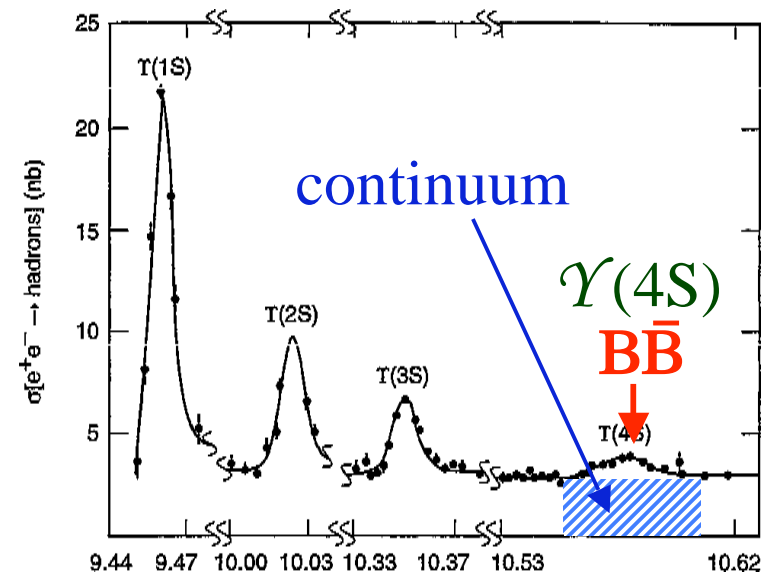
531/fb total
433/fb on Y(4S)

- At the $Y(4S)$, $B\bar{B}$ are produced at threshold
- This allows to
 - Select a B signal using two nearly independent variables

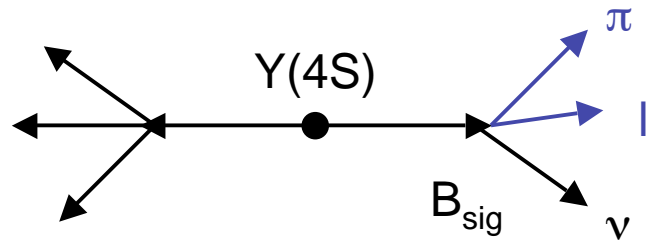
$$M_B = \sqrt{(E_{beam}^*)^2 - (\sum P_i)^2}$$

$$\Delta E = \sum E_i - E_{beam}^*$$

- Determine the 4-momentum of one B by reconstructing the other
- Distinguish $B\bar{B}$ (spherical) from continuum events (jet-like)

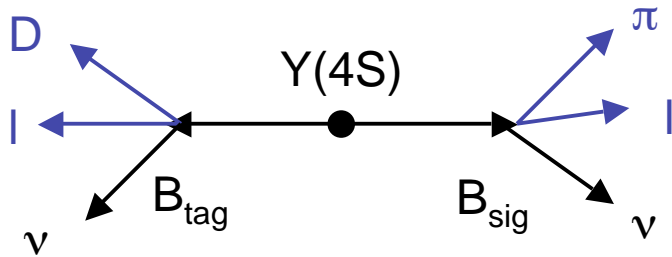


Tagging



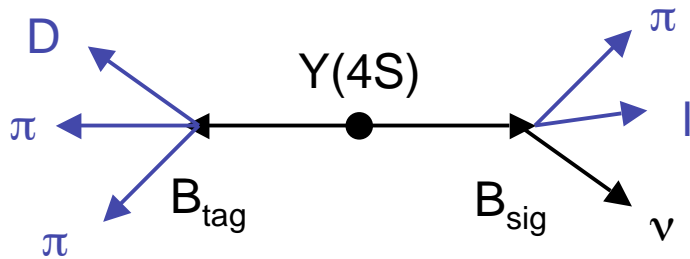
Untagged

- Only signal reconstructed
- High efficiency



Semileptonic tag

- Good statistics, clean events
- Kinematics not fully reconstructed



Fullrecon tag

- Kinematics fully known
- Low statistics

Efficiency



Purity

$|V_{cb}|$ from exclusive
semileptonic B decays

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

Differential width

- Decay rate for $B \rightarrow D^{(*)} \ell \bar{\nu}_\ell$

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

$$\frac{d\Gamma}{dw}(\bar{B} \rightarrow D \ell \bar{\nu}_\ell) =$$

$$\frac{G_F^2}{48\pi^3} |V_{cb}|^2 (m_B + m_D)^2 m_D^3 (w^2 - 1)^{3/2} (\mathcal{G}(w))^2 \quad w \equiv v \cdot v'$$

form factor

- Form factor parameterization based on HQET and dispersion relations [Caprini et al., Nucl. Phys. B530, 153 (1998)]
- Experiments perform a fit to $d\Gamma/dw$ and extract $F(1)|V_{cb}|$ and $G(1)|V_{cb}|$

BaBar $B^0 \rightarrow D^{*-} l^+ \nu$

[Phys. Rev. D77, 032002 (2008)]

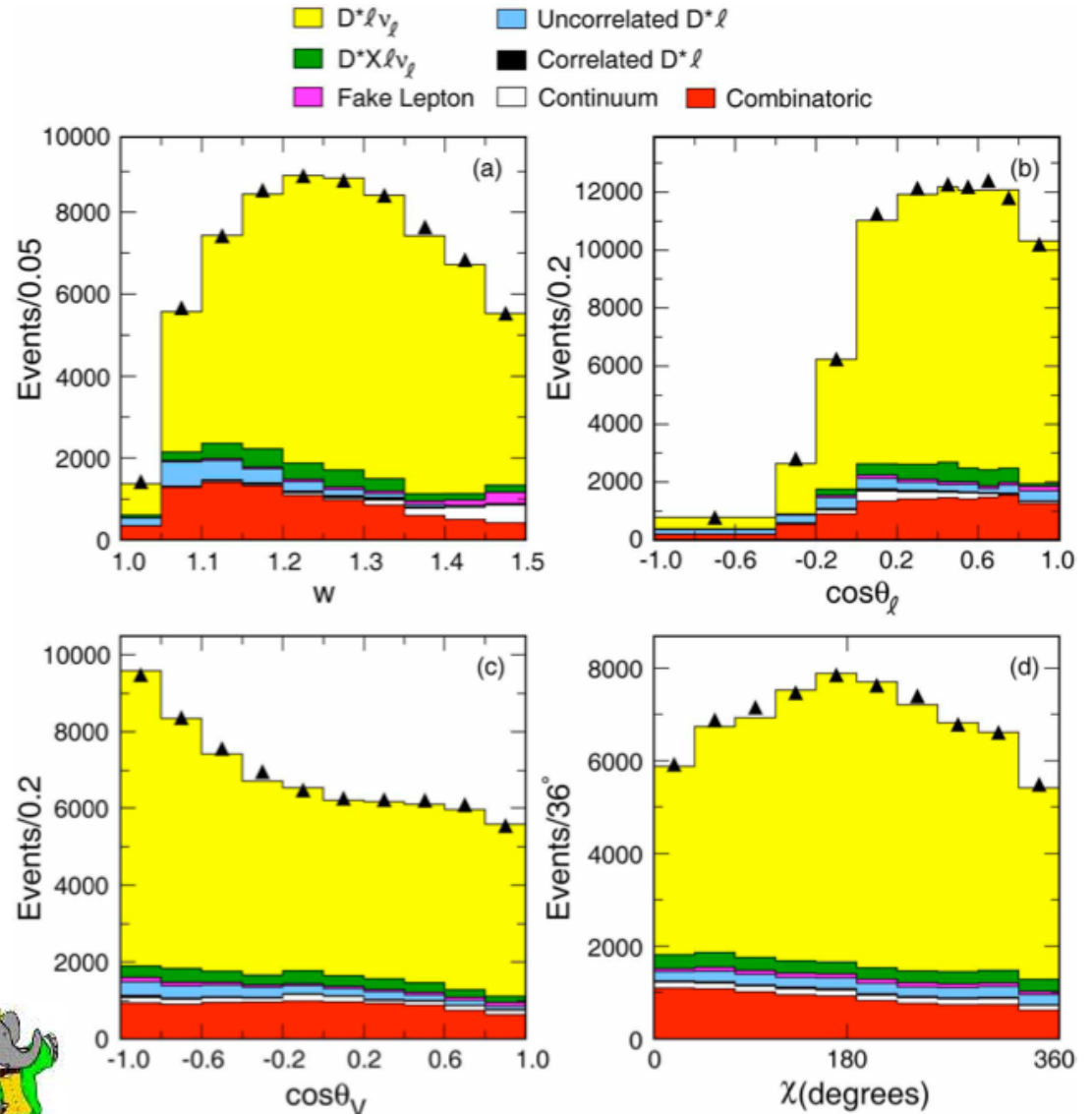
- 79/fb on Y(4S) data
- Untagged measurement based on about 52,800 reconstructed $B^0 \rightarrow D^{*-} l^+ \nu$ decays
- Fit to the full (4-dimensional) differential width

$$\mathcal{F}(1)|V_{cb}| = (34.4 \pm 0.3 \pm 1.1) \times 10^{-3}$$

$$\rho^2 = 1.191 \pm 0.048 \pm 0.028$$

$$R_1(1) = 1.429 \pm 0.061 \pm 0.044$$

$$R_2(1) = 0.827 \pm 0.038 \pm 0.022.$$



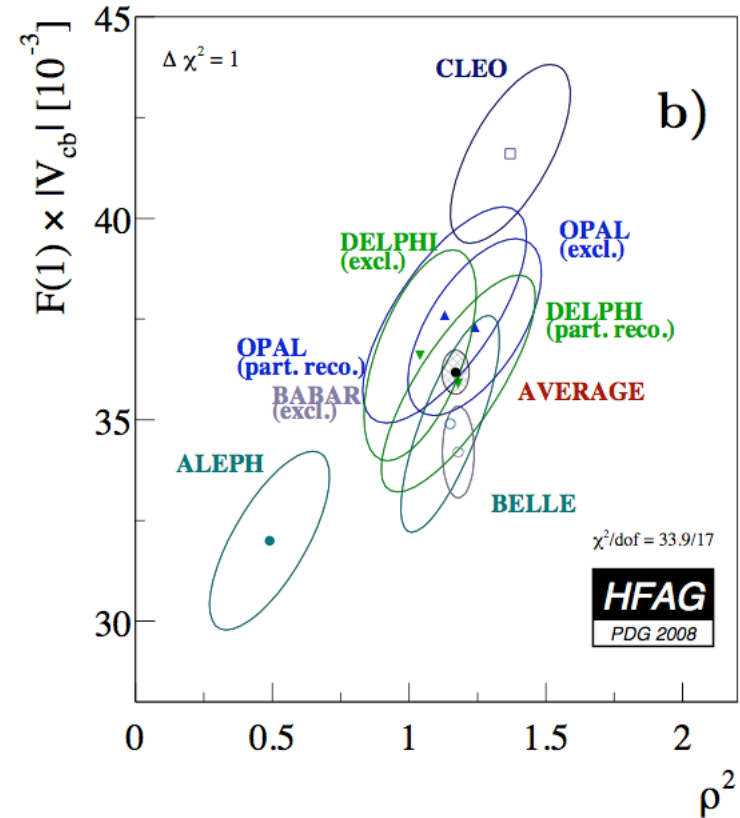
$|V_{cb}|$ from $B^0 \rightarrow D^{*-} l^+ \nu$

- HFAG 2008 average

$$F(1)|V_{cb}| = (36.18 \pm 0.55) \times 10^{-3}$$

$$\chi^2/\text{dof.} = 33.9/17$$

(CL=0.008%)

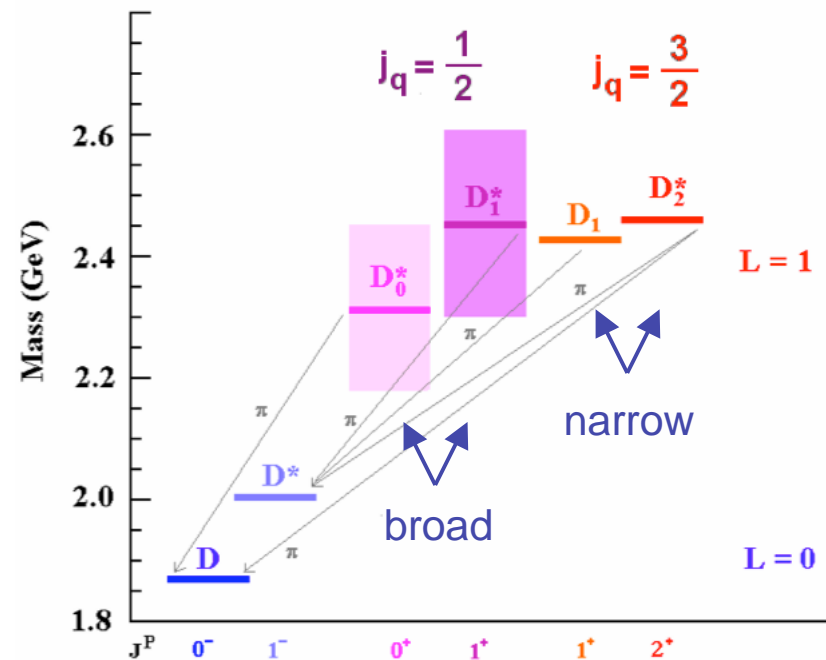


lattice	F(1)	$ V_{cb} $ exclusive (10^{-3})
Hashimoto et al. [PRD66, 104503 (2002)]	0.919 \pm 0.033	39.37 \pm 0.60(exp) \pm 1.41(th)
Laiho et al. [PoS LATTICE2007, 358 (2006)]	0.930 \pm 0.022	38.90 \pm 0.59(exp) \pm 0.92(th)

$$B \rightarrow D^{**} l \nu$$

- Two mysteries
 - Sum of exclusives modes does not add up to inclusive
 - Theory predicts that the narrow D^{**} states dominate, in contrast to the experiment
- [Bigi et al., arXiv:0708.1621]

BR[%] HFAG ave.	B^0	B^+
D^*	5.16 ± 0.11	6.07 ± 0.29
D	2.17 ± 0.12	2.27 ± 0.11
$D\pi$	0.43 ± 0.06	0.42 ± 0.05
$D^*\pi$	0.49 ± 0.08	0.61 ± 0.05
Σ Exclusive (measured)	8.25 ± 0.19	9.37 ± 0.32
inclusive	10.33 ± 0.28	10.99 ± 0.28
Inclusive - Σ Exclusive	2.08 ± 0.34	1.62 ± 0.42

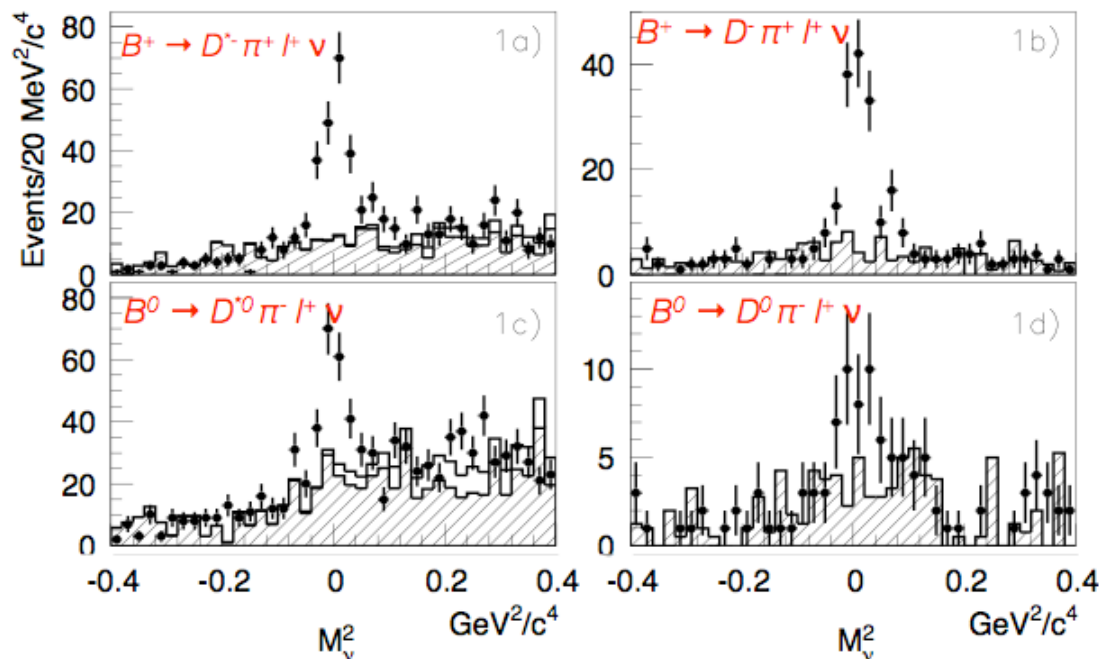


Belle $B \rightarrow D^{**} \nu$

[Phys. Rev. D77, 091503 (2008)]



- 605/fb of Y(4S) data
- Full reconstruction tag
- Reconstruct $D^{(*)}\pi l$ on the signal side



▨ $\Delta E + M(D) - \Delta E, M(D)$ sidebands
□ Fakes, Feed down

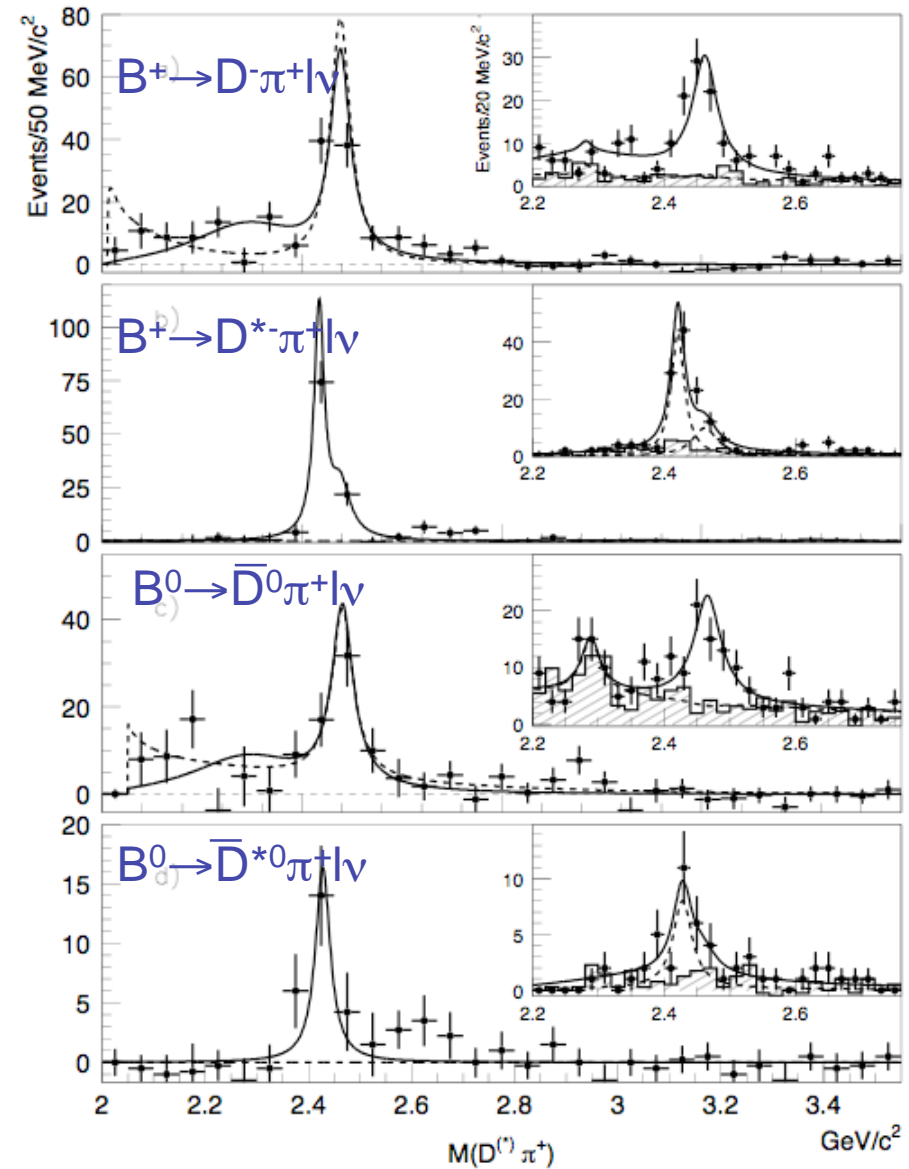
Signal window: $|M_\nu^2| < 0.1 \text{ GeV}^2$

Missing mass $M_\nu^2 = (P_{\text{beams}} - P_{\text{tag}} - P_{\text{sl}})^2$

Fit to $M[D(^*)\pi^+]$

	Mode	Yield	$\mathcal{B}(\text{mode}),\%$	Signif.
$D\pi$	$B^+ \rightarrow \bar{D}_0^{*0} \ell^+ \nu$	102 ± 19	$0.24 \pm 0.04 \pm 0.06$	5.4
	$B^+ \rightarrow \bar{D}_2^{*0} \ell^+ \nu$	94 ± 13	$0.22 \pm 0.03 \pm 0.04$	8.0
	$B^0 \rightarrow D_0^{*-} \ell^+ \nu$	61 ± 22	$0.20 \pm 0.07 \pm 0.05$	2.6
	$B^0 \rightarrow D_2^{*-} \ell^+ \nu$	68 ± 13	$0.22 \pm 0.04 \pm 0.04$	5.5
$D^*\pi$	$B^+ \rightarrow \bar{D}_1^{*0} \ell^+ \nu$	-5 ± 11	< 0.07 @ 90% C.L.	
	$B^+ \rightarrow \bar{D}_1^{*0} \ell^+ \nu$	81 ± 13	$0.42 \pm 0.07 \pm 0.07$	6.7
	$B^+ \rightarrow \bar{D}_2^{*0} \ell^+ \nu$	35 ± 11	$0.18 \pm 0.06 \pm 0.03$	3.2
	$B^0 \rightarrow D_1^{*-} \ell^+ \nu$	4 ± 8	< 0.5 @ 90% C.L.	
	$B^0 \rightarrow D_1^{*-} \ell^+ \nu$	20 ± 7	$0.54 \pm 0.19 \pm 0.09$	2.9
	$B^0 \rightarrow D_2^{*-} \ell^+ \nu$	1 ± 6	< 0.3 @ 90% C.L.	

- Contribution of broad and narrow states is of similar order



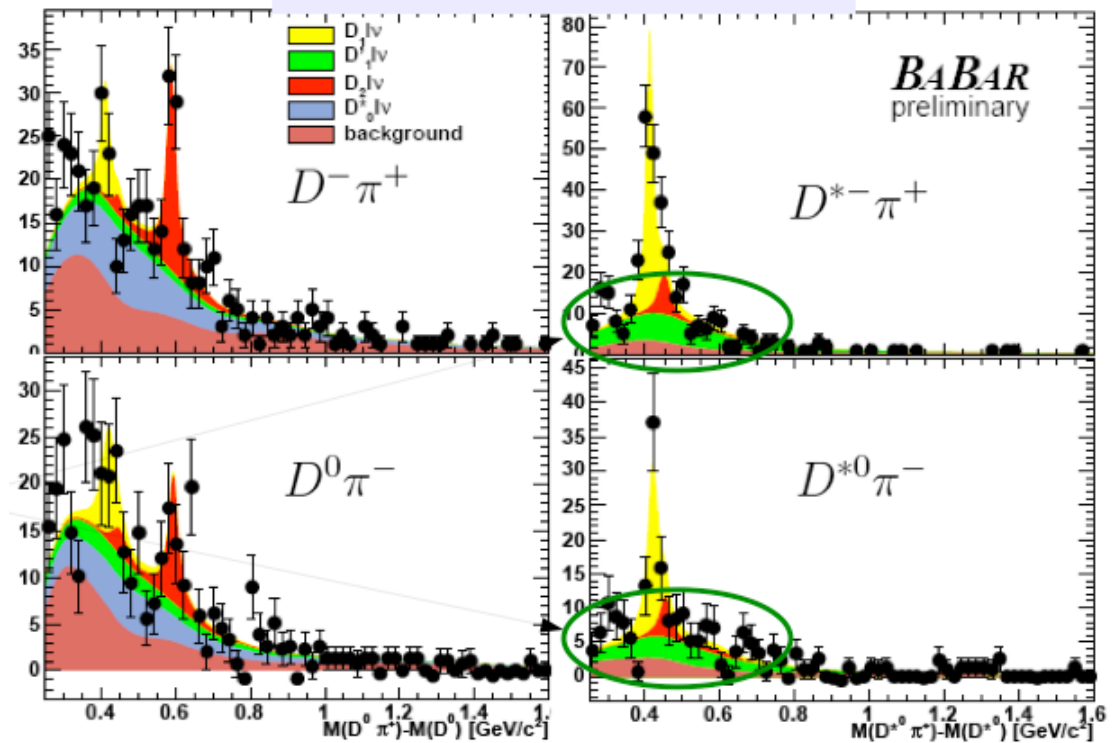
BaBar $B \rightarrow D^{**} \ell \nu$

Moriond preliminary



$D_1' \ell \nu$ component
(6 sigma signal)

Brand new for Moriond '08



Decay Mode	$B (\bar{B} \rightarrow D^{**} \ell^- \bar{\nu}_\ell) \times B (D^{**} \rightarrow D^{(*)} \pi) \%$ (BELLE)	BABAR Branching Fraction
<i>Dπ invariant mass fit</i>		
$B^- \rightarrow D_0^{*0} \ell^- \bar{\nu}_\ell$	$0.24 \pm 0.04 \pm 0.06$	$0.28 \pm 0.05 \pm 0.04$
$B^- \rightarrow D_2^{*0} \ell^- \bar{\nu}_\ell$	$0.22 \pm 0.03 \pm 0.04$	$0.16 \pm 0.03 \pm 0.01$
$\bar{B}^0 \rightarrow D_0^{*+} \ell^- \bar{\nu}_\ell$	$0.20 \pm 0.07 \pm 0.05$	$0.47 \pm 0.09 \pm 0.07$
$\bar{B}^0 \rightarrow D_2^{*+} \ell^- \bar{\nu}_\ell$	$0.22 \pm 0.04 \pm 0.04$	$0.08 \pm 0.04 \pm 0.02$
<i>D*π invariant mass fit</i>		
$B^- \rightarrow D_1^{*0} \ell^- \bar{\nu}_\ell$	< 0.07 @ 90CL	$0.27 \pm 0.05 \pm 0.05$
$B^- \rightarrow D_1^0 \ell^- \bar{\nu}_\ell$	$0.42 \pm 0.07 \pm 0.07$	$0.29 \pm 0.03 \pm 0.03$
$B^- \rightarrow D_2^{*0} \ell^- \bar{\nu}_\ell$	$0.18 \pm 0.06 \pm 0.03$	$0.07 \pm 0.01 \pm 0.01$
$\bar{B}^0 \rightarrow D_1^{*+} \ell^- \bar{\nu}_\ell$	< 0.5 @ 90CL	$0.37 \pm 0.07 \pm 0.05$
$\bar{B}^0 \rightarrow D_1^+ \ell^- \bar{\nu}_\ell$	$0.54 \pm 0.19 \pm 0.09$	$0.25 \pm 0.05 \pm 0.03$
$\bar{B}^0 \rightarrow D_2^{*+} \ell^- \bar{\nu}_\ell$	< 0.3 @ 90CL	$0.04 \pm 0.02 \pm 0.01$

$|V_{cb}|$ from inclusive
decays $B \rightarrow X_c \ell \nu$

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

Semileptonic width

- $\Gamma(B \rightarrow X_c | \nu)$ can be systematically calculated in the framework of **operator product expansion (OPE)**

$$\Gamma_{sl}(b \rightarrow c) = \frac{G_F^2 m_b^5(\mu)}{192 \pi^3} |V_{cb}|^2 (1 + A_{ew}) A^{\text{pert}}(r, \mu)$$

$$\left[z_0(r) \left(1 - \frac{\mu_\pi^2(\mu) \mu_G^2(\mu) + \frac{\rho_D^3(\mu) + \rho_{LS}^3(\mu)}{m_b(\mu)}}{2m_b^2(\mu)} \right) - 2(1-r)^4 \frac{\mu_G^2(\mu) \frac{\rho_D^3(\mu) + \rho_{LS}^3(\mu)}{m_b(\mu)}}{m_b^2(\mu)} + d(r) \frac{\rho_D^3(\mu)}{m_b^3(\mu)} + \dots \right]$$

from [Benson et al.,
Nucl. Phys. B665,
367 (2003)]

$$r = m_c^2(\mu) / m_b^2(\mu)$$

○ ... HQ parameters (non-calculable; contain soft QCD physics)

- At each order in $1/m_b$, the expectation values of local operator products (**heavy quark parameters**) are multiplied by perturbatively calculable coefficients
- Other inclusive observables (moments) in $B \rightarrow X_c | \nu$ and $B \rightarrow X_s \gamma$ decays have **OPEs with the same HQ parameters**

Global analysis of B decays

- Dedicated predictions for each observable
 - $\langle E^n \rangle_{E_l > E_{cut}} = f^{(n)}(E_{cut}, m_b, \text{HQ param.})$
 - $\langle M^{2n}_X \rangle_{E_l > E_{cut}} = g^{(n)}(E_{cut}, m_b, \text{HQ param.})$
 - $\langle E^n_\gamma \rangle_{E_\gamma > E_{cut}} = h^{(n)}(E_{cut}, m_b, \text{HQ param.})$
- Determine HQ parameters by performing a fit to all available moment measurements
- Available calculations
 - Kinetic running mass [P.Gambino, N.Uraltsev, Eur.Phys.J. C34, 181 (2004); D.Beson, I.Bigi, N.Uraltsev, Nucl.Phys. B710, 371 (2005)]
 - 1S mass [C.Bauer, Z.Ligeti, M.Luke, A.Manohar, M.Trott, Phys.Rev. D70, 094017 (2004)]

	Kinetic scheme	1S scheme
O(1)	m_b, m_c	m_b
O(1/m ² _b)	μ^2_π, μ^2_G	λ_1, λ_2
O(1/m ³ _b)	ρ_D, ρ_{LS}	ρ_1, τ_{1-3}

Available measurements

BaBar	$\langle E^n_l \rangle$: $n=0,1,2,3$ [PRD 69, 111104 (2004)] $\langle M^{2n}_X \rangle$: $n=1,2$ [PRD 69, 111103 (2004)] $\langle E^n_\gamma \rangle$: $n=1,2$ [PRL 97, 171803 (2006)] and [PRD 72, 052004 (2005)]
Belle	$\langle E^n_l \rangle$: $n=0,1,2,3$ [PRD 75, 032001 (2007)] $\langle M^{2n}_X \rangle$: $n=1,2$ [PRD 75, 032005 (2007)] $\langle E^n_\gamma \rangle$: $n=1,2$ [arXiv:0804.1580] preliminary
CDF	$\langle M^{2n}_X \rangle$: $n=1,2$ [PRD 71, 051103 (2005)]
CLEO	$\langle M^{2n}_X \rangle$: $n=1,2$ [PRD 70, 032002 (2004)] $\langle E^n_\gamma \rangle$: $n=1$ [PRL 87, 251807 (2001)]
DELPHI	$\langle E^n_l \rangle$: $n=1,2,3$ $\langle M^{2n}_X \rangle$: $n=1,2$ [EPJ C45, 35 (2006)]

- 70 measurements in total

$|V_{cb}|$ and m_b

Kinetic scheme ($X_c l \nu + X_s \gamma$ data)

$$|V_{cb}| = (41.55 \pm 0.43_{\text{fit}} \pm 0.08_{\tau_B} \pm 0.58_{\text{th}}) \times 10^{-3}$$

$$m_b^{\text{kin}} = 4.613 \pm 0.033 \text{ GeV}$$

$$m_c^{\text{kin}} = 1.178 \pm 0.049 \text{ GeV}$$

$$\chi^2/\text{ndf.} = 30.6 / (70-7)$$

preliminary

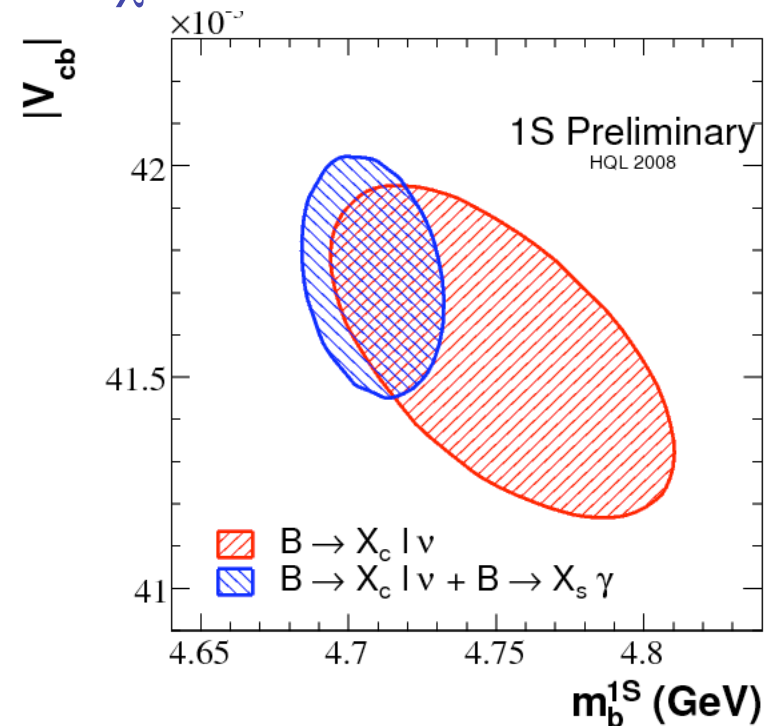
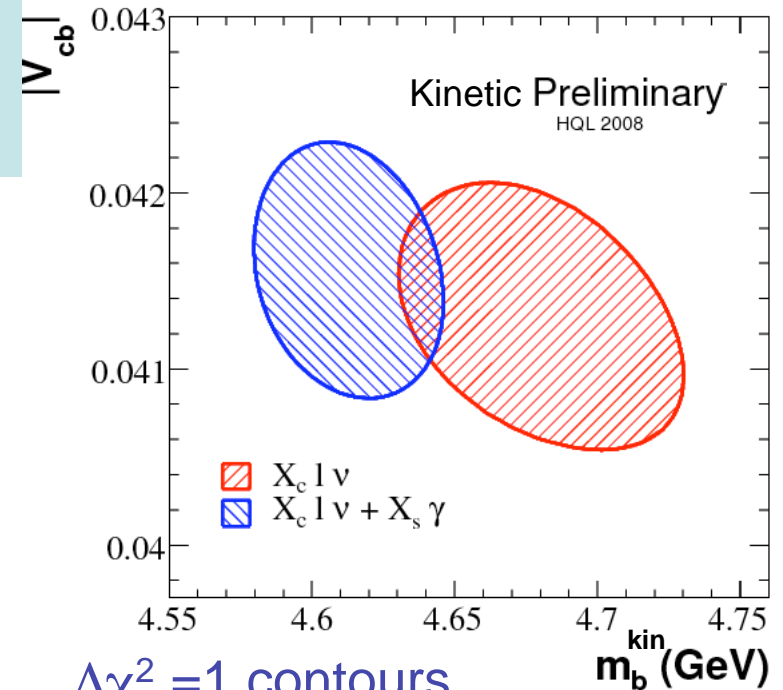


1S scheme ($X_c l \nu + X_s \gamma$ data)

$$|V_{cb}| = (41.74 \pm 0.29_{\text{fit}} \pm 0.08_{\tau_B}) \times 10^{-3}$$

$$m_b^{1S} = 4.708 \pm 0.024 \text{ GeV}$$

$$\chi^2/\text{ndf.} = 26.1 / (70-7)$$

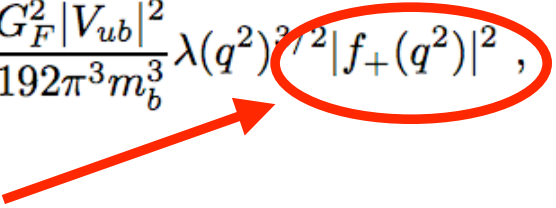


$|V_{ub}|$ from exclusive
semileptonic decays $b \rightarrow u$

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

$B \rightarrow \pi \ell \nu$

- Decay width

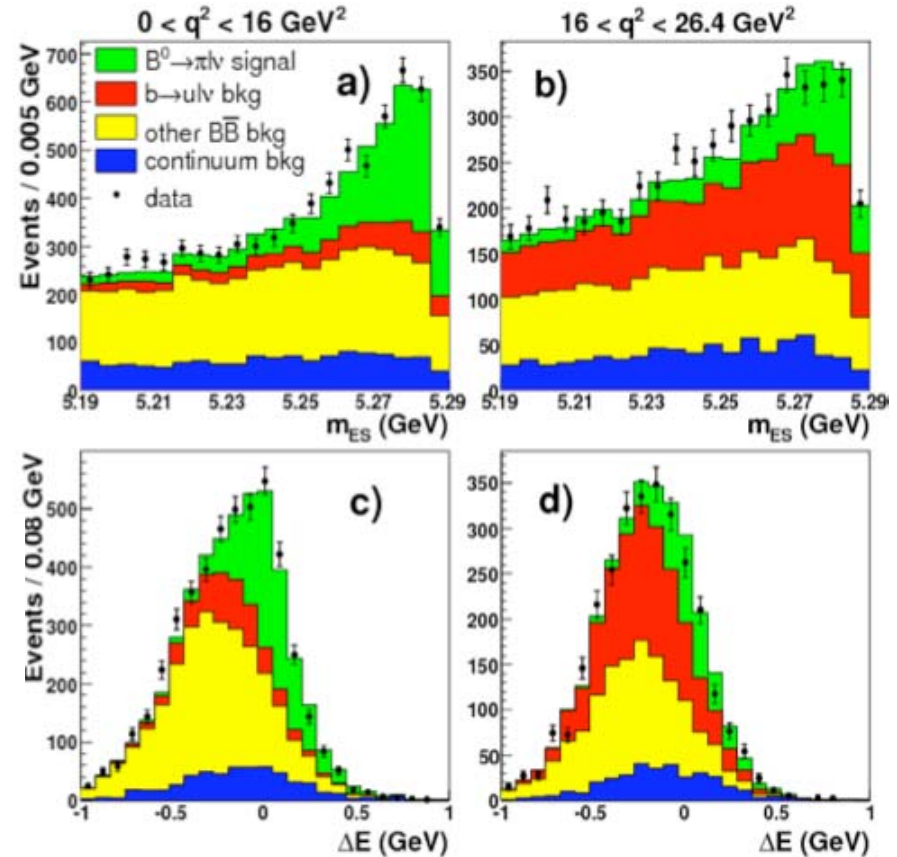
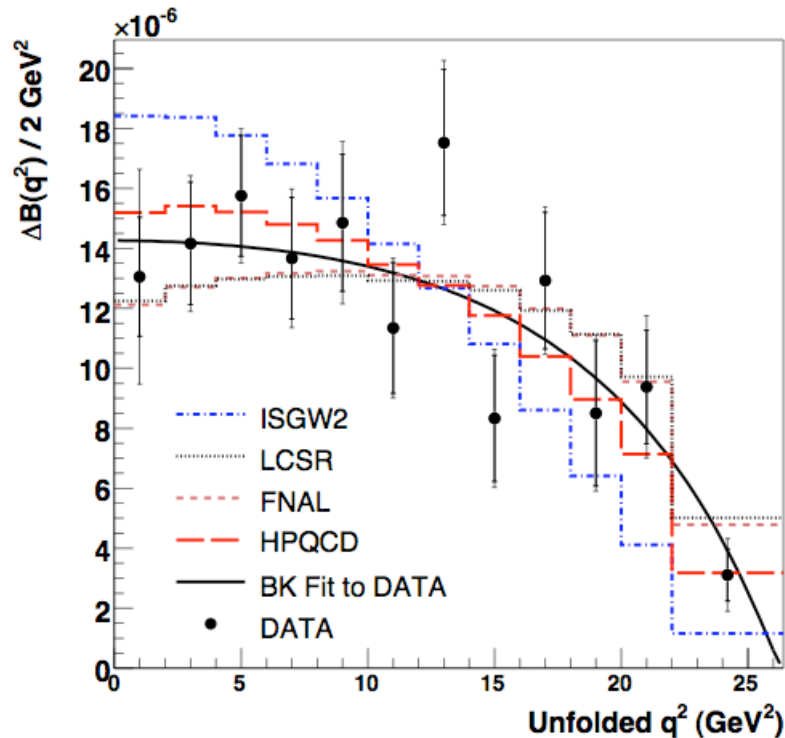
$$\frac{d\Gamma(B \rightarrow \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 m_b^3} \lambda(q^2)^{3/2} |f_+(q^2)|^2, \quad q^2 = (p_\ell + p_\nu)^2$$


- Need form factor shape and normalization for $|V_{ub}|$
- Available form factor calculations
 - Relativistic quark models
 - ISGW2 [Phys. Rev. D52, 2783 (1995)]
 - Light cone sum rules (LCSR) in the region $q^2 < 14 \text{ GeV}^2$
 - Ball-Zwicky [Phys. Rev. D71, 014015 (2005)]
 - Lattice QCD in the region $q^2 > 16 \text{ GeV}^2$
 - HPQCD [Phys. Rev. D73, 074502 (2006)]
 - FNAL [Nucl. Phys. Proc. Suppl. 140, 461 (2005)]

BaBar $B^0 \rightarrow \pi^- \ell^+ \nu$

[Phys. Rev. Lett. 98, 091801 (2007)]

- Based on 206/fb
- Untagged measurement; loose requirements for neutrino reconstruction
- Measurement of the q^2 -distribution



$$Br = (1.46 \pm 0.07_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-4}$$

$$\Delta Br(q^2 > 16 \text{ GeV}^2) =$$

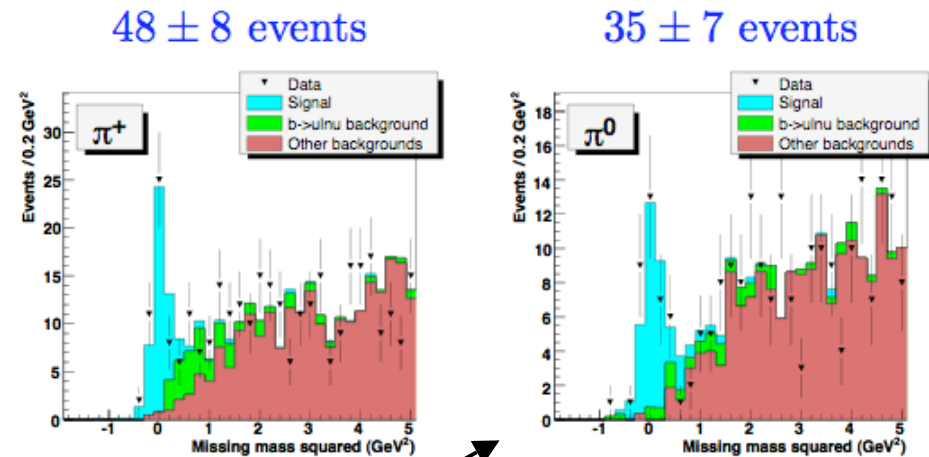
$$(0.38 \pm 0.04_{\text{stat}} \pm 0.03_{\text{syst}}) \times 10^{-4}$$

Belle $B \rightarrow \pi \ell \nu$

[hep-ex/0610054] preliminary



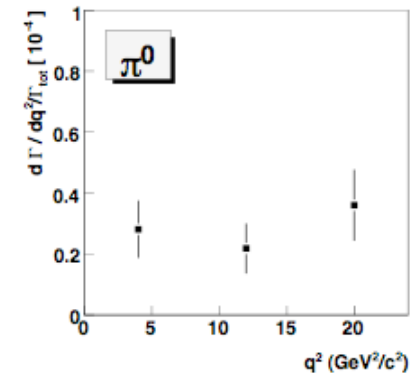
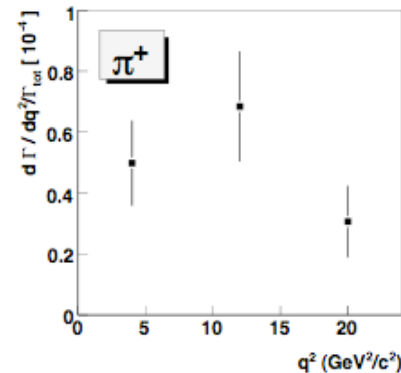
- Based on 497/fb
- Use of full reconstruction tag



$$P_{miss}^2 = (P_{\Upsilon(4S)} - P_{Breco} - P_{Xu} - P_{\ell})^2 = m_{miss}^2$$

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

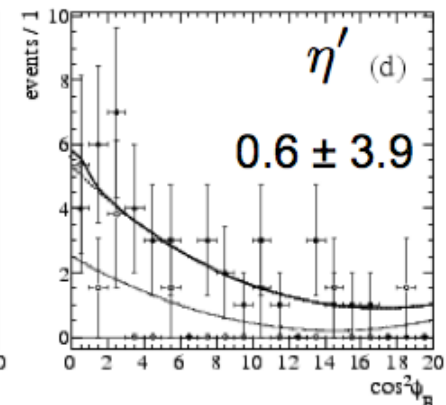
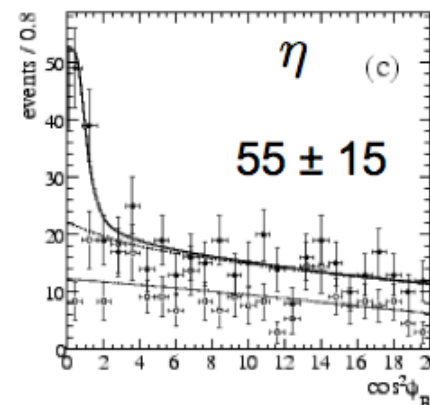
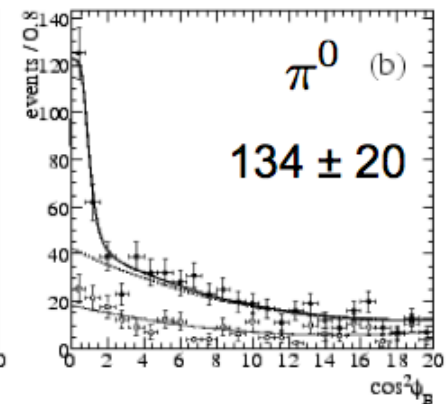
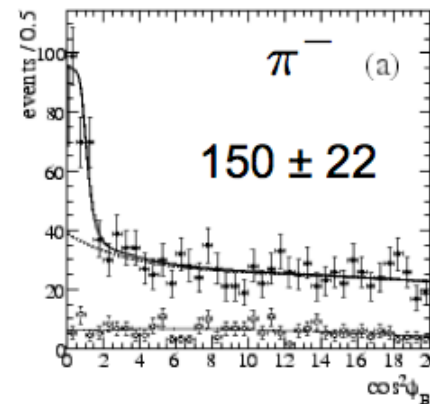
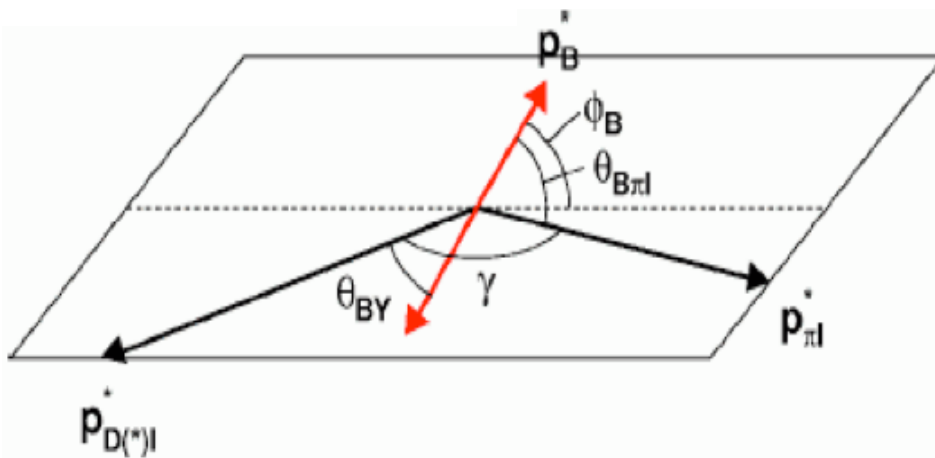
$$\mathcal{B}(B^+ \rightarrow \pi^0 \ell^+ \nu) = (0.86 \pm 0.17(stat) \pm 0.06(syst)) \times 10^{-4}$$



BaBar $B \rightarrow (\pi, \eta, \eta') \ell \nu$

[arXiv:0805.2408]

- Based on 348/fb
- Semileptonic tag: reconstruct $D^{(*)} \ell$ and (π, η, η')
- Extract yield from fit to $\cos^2 \phi_B$



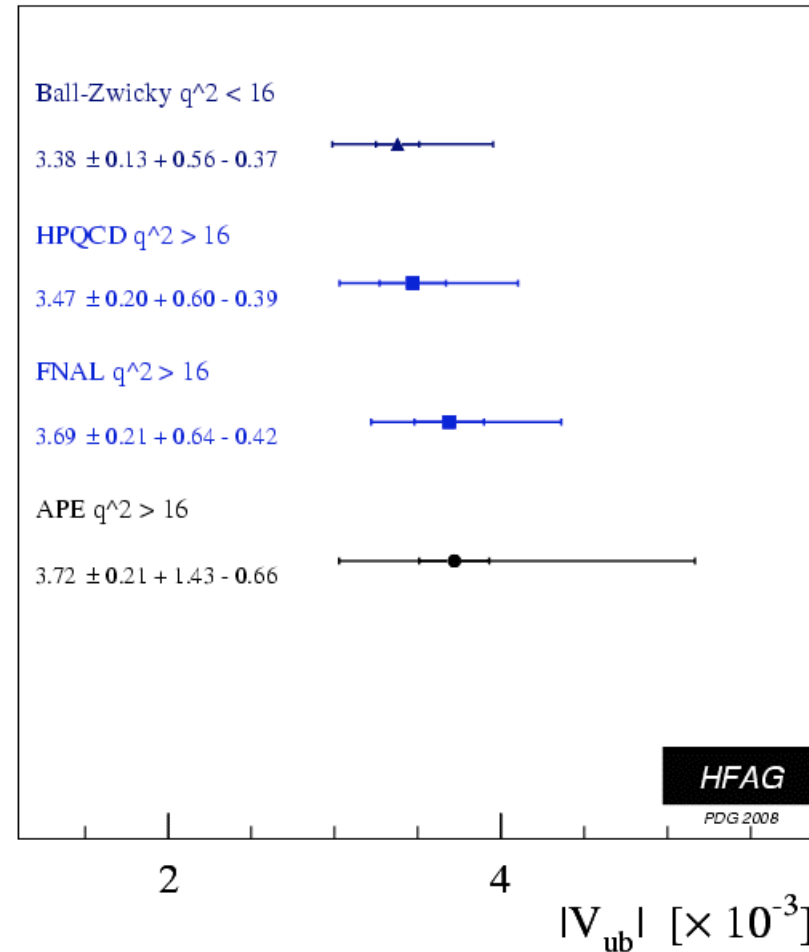
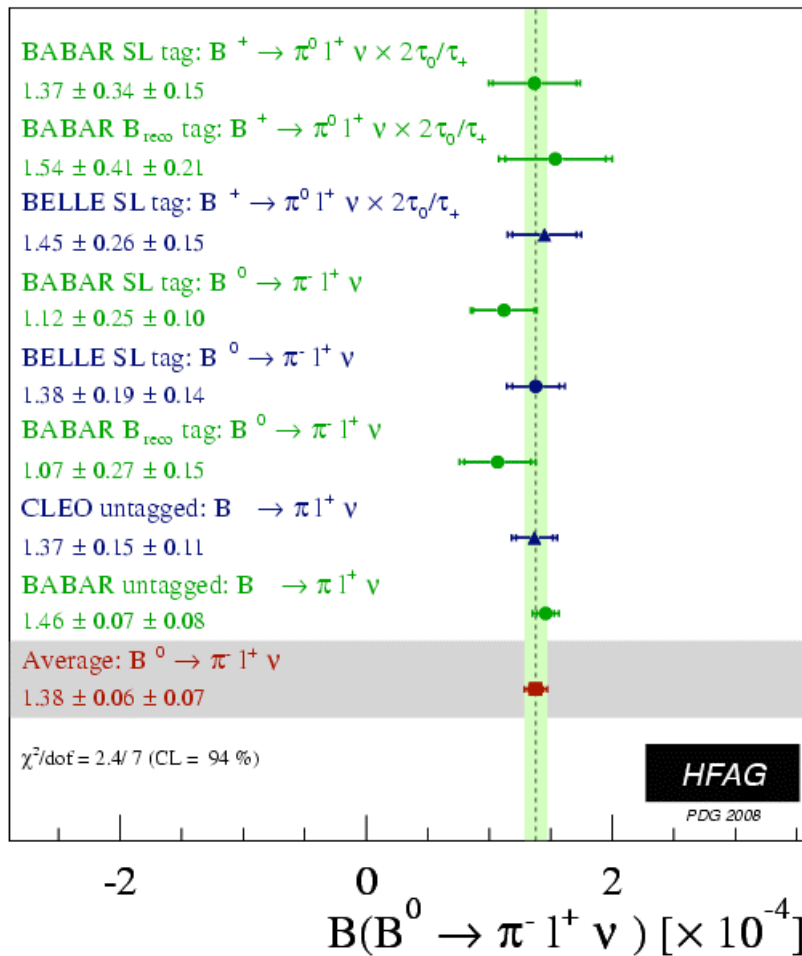
$$\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.37 \pm 0.21 \pm 0.07) \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \pi^0 \ell^+ \nu) = (0.96 \pm 0.15 \pm 0.07) \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \eta \ell^+ \nu) = (0.69 \pm 0.20 \pm 0.30) \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \eta' \ell^+ \nu) < 0.47 \times 10^{-4}$$

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



Experimental uncertainty $\sim 4\text{-}6\%$
 F.F. normalization uncertainty $\sim 13\text{-}15\%$

$|V_{ub}|$ from inclusive
decays $B \rightarrow X_u | \nu$

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

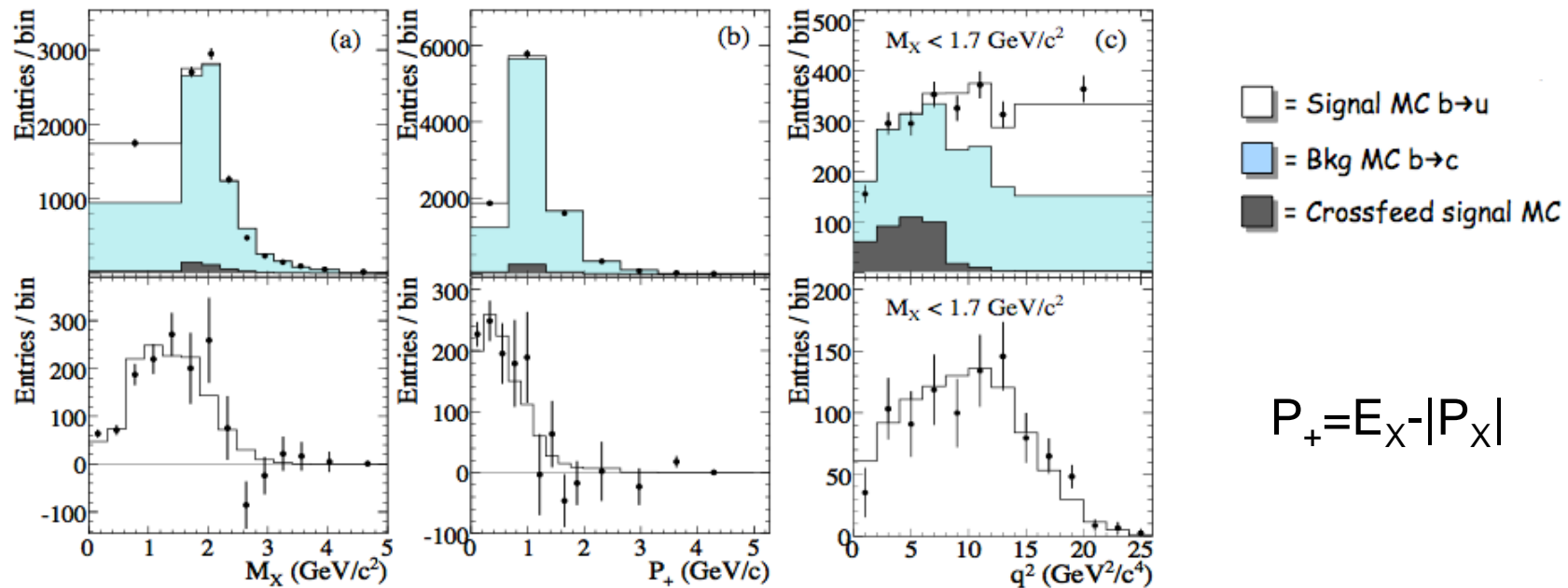
Theoretical calculations

- Also based on the OPE, as for $B \rightarrow X_c l \nu$ decays
- Experimental cuts to enhance $X_u l \nu$ and suppress $X_c l \nu$ compromise the convergence of the OPE \Rightarrow need **shape function**
- (Leading order) shape function parameter can be determined from $B \rightarrow X_s \gamma$ and/or $B \rightarrow X_c l \nu$ data
- Available theory calculations
 - Bosch, Lange, Neubert, Paz (BLNP) [[Phys.Rev. D72, 073006 \(2005\)](#)]
 - Anderson, Gardi (DGE) [[JHEP 0601:097 \(2006\)](#)]
 - Gambino, Giordano, Ossola, Uraltsev (GGOU) [[JHEP 0710:058 \(2007\)](#)]
 - Aglietti, Di Lodovico, Ferrera, Ricciardi (AC) [[arXiv:0711.0860](#)]
 - Bauer, Ligeti, Luke (BLL) [[Phys.Rev. D64, 113004 \(2001\)](#)]

BaBar $B \rightarrow X_u \nu$

[Phys. Rev. Lett. 100, 171802 (2008)]

- Based on 347/fb
- Fullrecon tag



$$M_X < 1.55 \text{ GeV}/c^2$$

$$M_X < 1.7 \text{ GeV}/c^2, q^2 > 8.0 \text{ GeV}^2/c^4$$

$$P_+ < 0.66 \text{ GeV}/c,$$

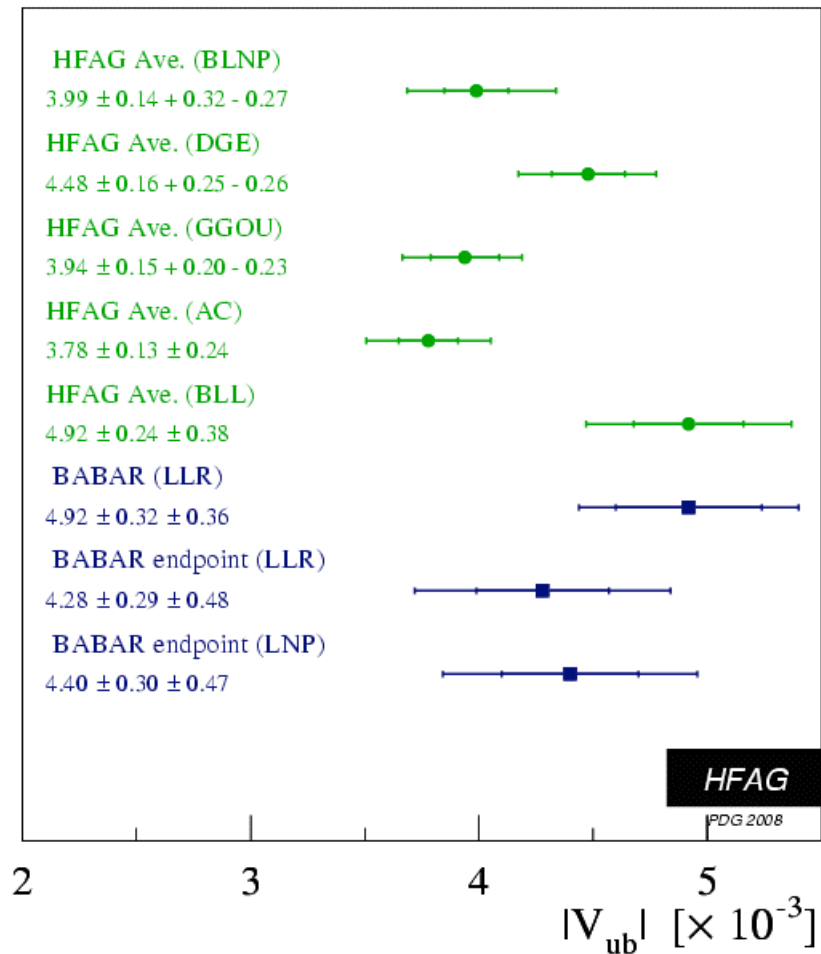
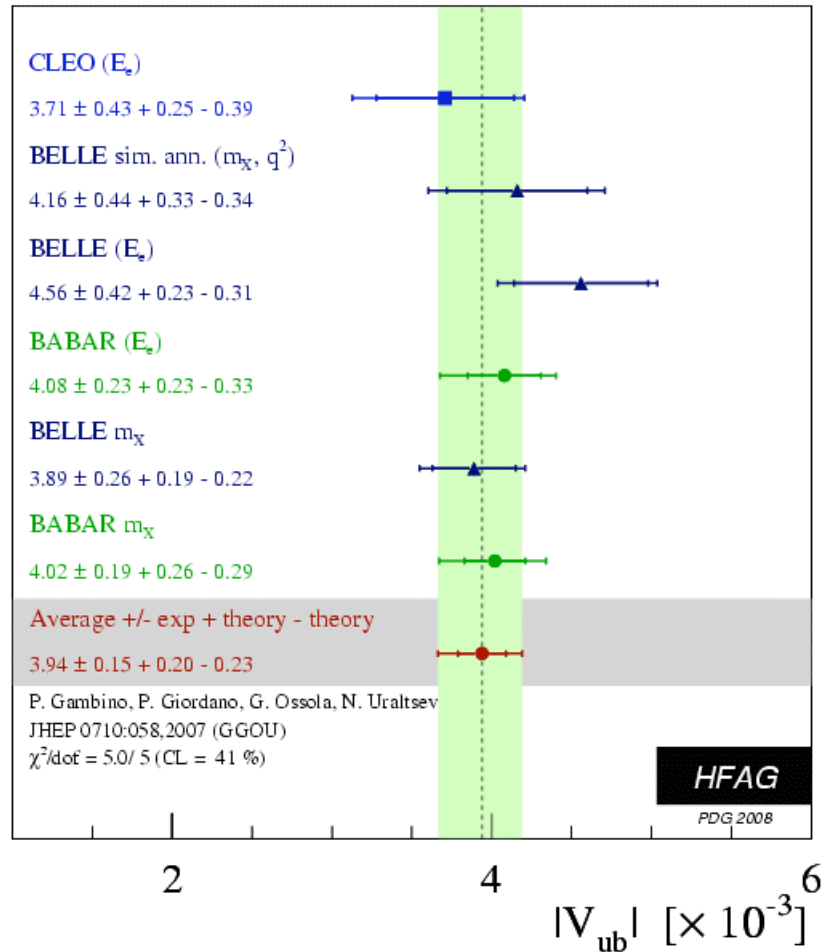
$$\Delta\mathcal{B} = (1.18 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{syst.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$$

$$\Delta\mathcal{B} = (0.81 \pm 0.08_{\text{stat.}} \pm 0.07_{\text{syst.}} \pm 0.02_{\text{theo.}}) \times 10^{-3}$$

$$\Delta\mathcal{B} = (0.95 \pm 0.10_{\text{stat.}} \pm 0.08_{\text{syst.}} \pm 0.01_{\text{theo.}}) \times 10^{-3}$$

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

GGOU framework



Can we trust in the theory error?

Summary and outlook

- $|V_{cb}|$ inclusive
 - consistency between different frameworks

	$ V_{cb} $ inclusive (10^{-3})
Kinetic scheme	41.55 +/- 0.43(fit) +/- 0.08(τ_B) +/- 0.58(th)
1S scheme	41.74 +/- 0.29(exp) +/- 0.08(τ_B)

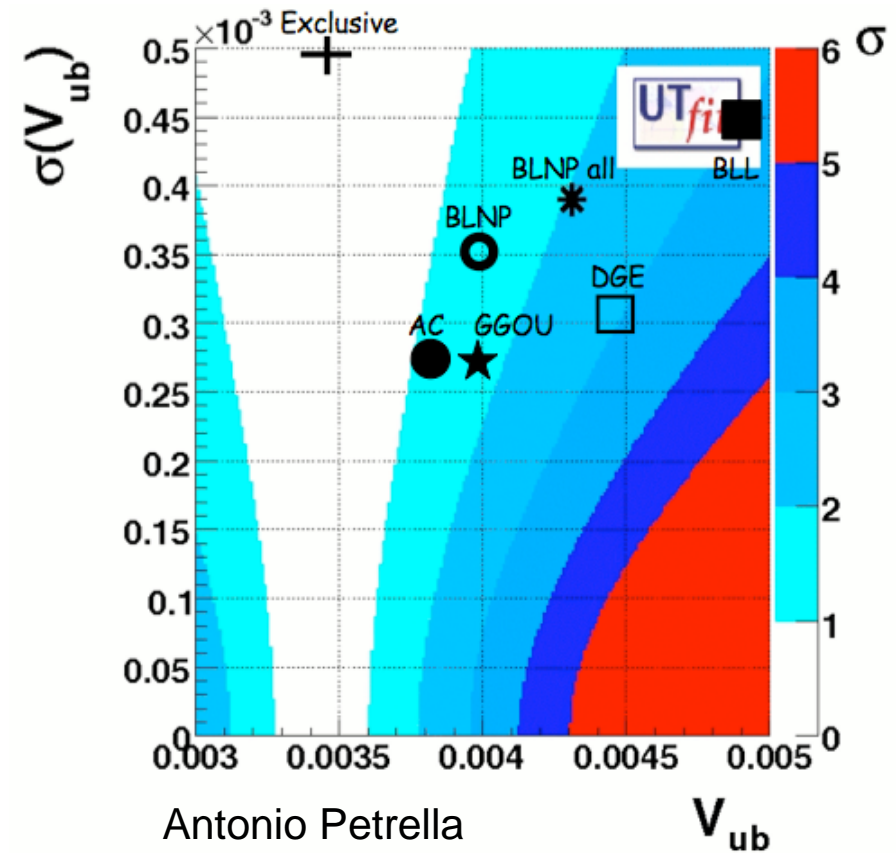
- $|V_{cb}|$ exclusive
 - Certain tension with $|V_{cb}|$ inclusive
 - New $B \rightarrow D_l \nu$ measurements might tell us more

F(1)	$ V_{cb} $ exclusive (10^{-3})
Hashimoto et al.	39.37 +/- 0.60(exp) +/- 1.41(th)
Laiho et al.	38.90 +/- 0.59(exp) +/- 0.92(th)

1.5 sigma

2.5 sigma

- $|V_{ub}|$ exclusive
 - Form factor uncertainty still large
 - Experiment can help by measuring F.F. shapes
- $|V_{ub}|$ inclusive
 - Why give different calculations different answers for $|V_{ub}|$ incl.?



Backup slides

The CKM mechanism

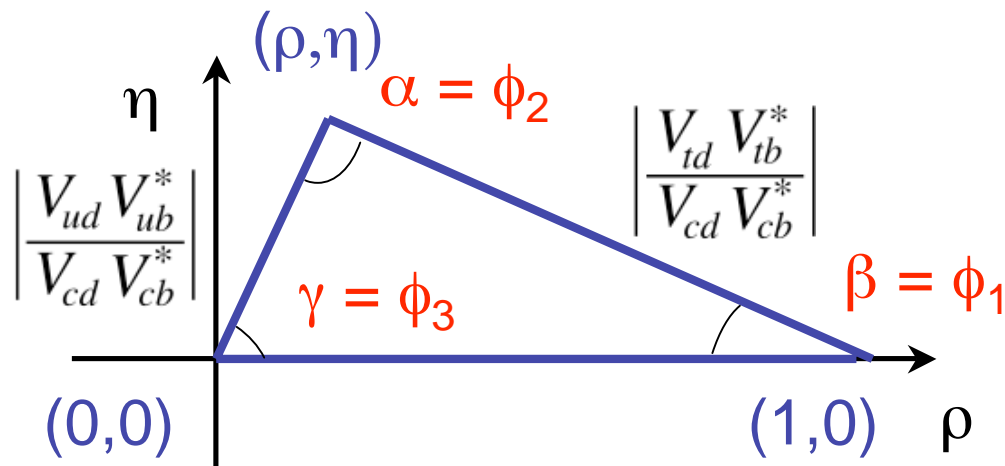
- The charged current interaction in the SM

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_{Li}} \gamma^\mu (V_{\text{CKM}})_{ij} d_{Lj} W_\mu^\pm + \text{h.c.}$$

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

[Kobayashi, Maskawa, Prog. Theor. Phys. 49, 652 (1973)]

- V_{CKM} is a unitary 3x3 matrix; it contains three real parameters and one complex phase
- Its unitarity is commonly represented by the unitarity triangle



$$\alpha \equiv \phi_2 \equiv \arg \left(-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right)$$

$$\beta \equiv \phi_1 \equiv \arg \left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

$$\gamma \equiv \phi_3 \equiv \arg \left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$