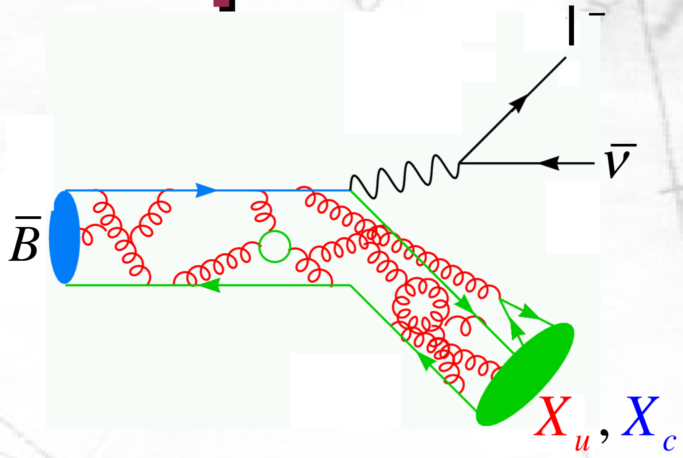
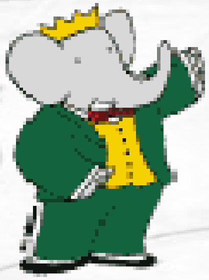
Semileptonic B Decays at BaBar





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representing the *BaBar* Collaboration

KEK, January 10 2008

Outline

- Introduction
  - Motivations
  - BaBar
  - Experimental approach
- Inclusive decays
  - Determination of $|V_{cb}|$
  - Determination of $|V_{ub}|$
- Exclusive Decays
  - $D^{(*(*))}\ell\nu$
  - $\pi(\eta^{(')})\ell\nu$
- Conclusions

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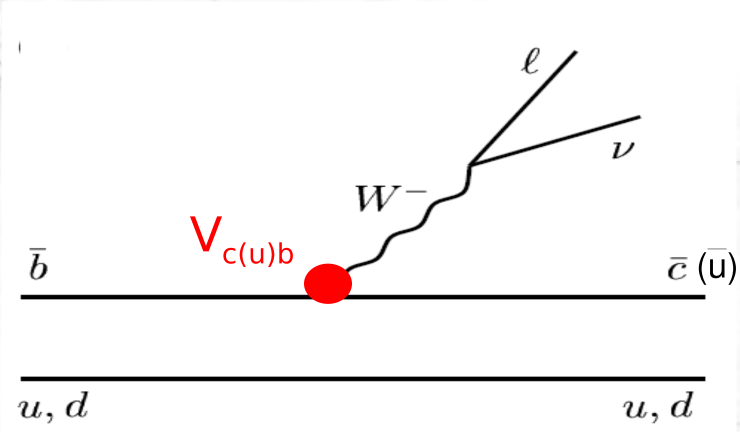
Semileptonic Decays

$b \to c\ell\nu, u\ell\nu$



- Semileptonic decays are an important tool to study:
  - CKM matrix elements
  - Heavy quark parameters (eg. b, c quark masses)
  - QCD Form Factors
  - New Physics

Framework: the CKM Matrix

- B^+ and B^0 are the most accessible 3rd-generation particles
- Their decays allow detailed studies of the CKM matrix

$$L = -\frac{g}{\sqrt{2}}\begin{pmatrix}\bar{u}_L & \bar{c}_L & \bar{t}_L\end{pmatrix}\gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

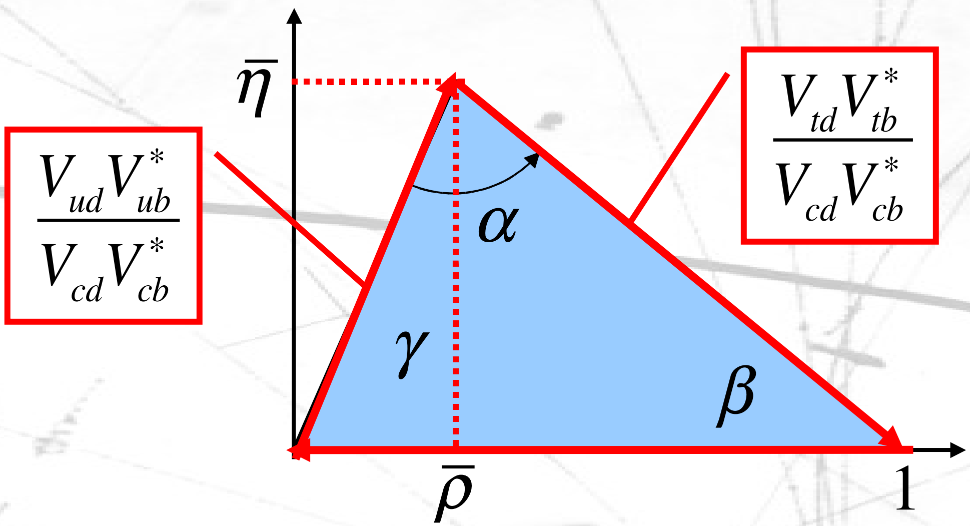
- Unitary matrix
- V_{CKM} connects the weak to the mass eigenstates
- 3 real parameters + 1 complex phase

The only source of ~~CP~~ in the Minimal SM

- Is this the complete description of the CP violation?
  - Is everything consistent with a single unitary matrix?

Representation: the Unitarity Triangle

- Unitarity of V_{CKM} ➡ $V^{\dagger}_{\mathrm{CKM}} V_{\mathrm{CKM}} = 1$ ➡ $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$
  - This is neatly represented by the familiar Unitarity Triangle



$$\alpha\ (\phi_2) = \arg\left[-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right]$$

$$\beta\ (\phi_1) = \arg\left[-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right]$$

$$\gamma\ (\phi_3) = \arg\left[-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right]$$

  - Angles α, β, γ can be measured with ~~CP~~ of *B* decays

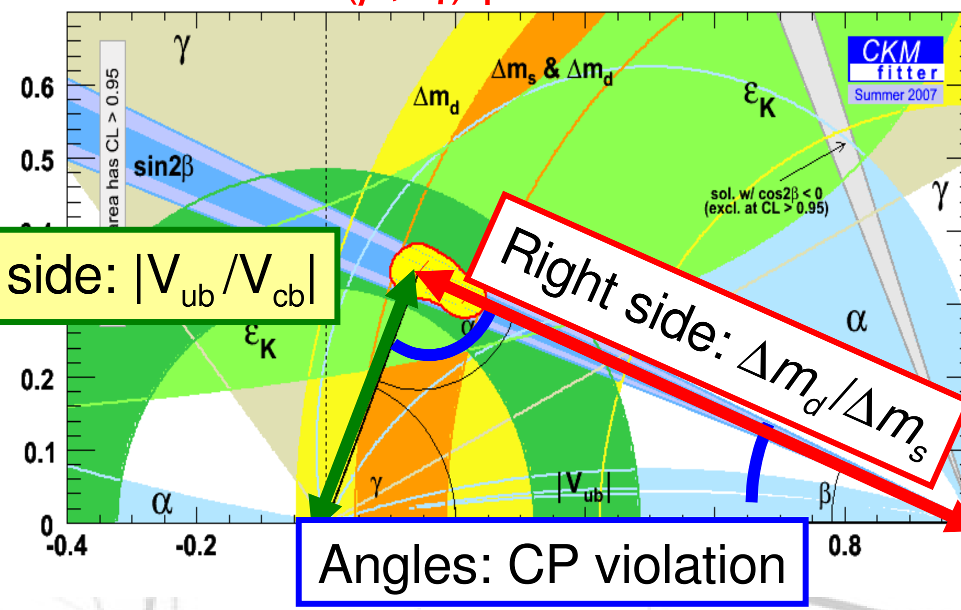
$|V_{ub}/V_{cb}|$

- Compare the measurements on the (ρ, η) plane
  - The [yellow ellipse] tells us this is true as of today: still large enough to hide new physics!
  - We need the green ring thinner
- Left side of the Triangle is

$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \left|\frac{V_{ub}}{V_{cb}}\right| \frac{1}{\tan\theta_C}$$

Measurement of $|V_{ub}/V_{cb}|$ is complementary to sin2β

(ρ, η) plane:



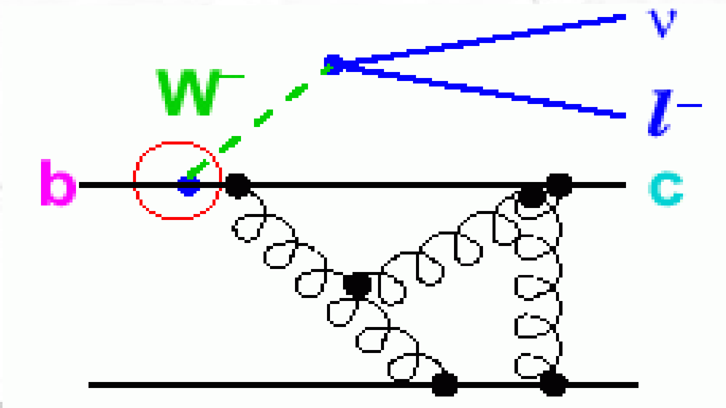
Goal: Accurate determination of both $|V_{ub}/V_{cb}|$ and sin2β

sinβ (all charmonium) = 0.680±0.025 ~ percentage error: 3.7% (HFAG)

HFAG = Heavy Flavour Averaging Group

Semileptonic B Decays

- Natural probe for $|V_{ub}|$ and $|V_{cb}|$
- Decay rate $\Gamma_{c(u)} \equiv \Gamma(b \to c(u)\ell\nu) \propto |V_{c(u)b}|^2$



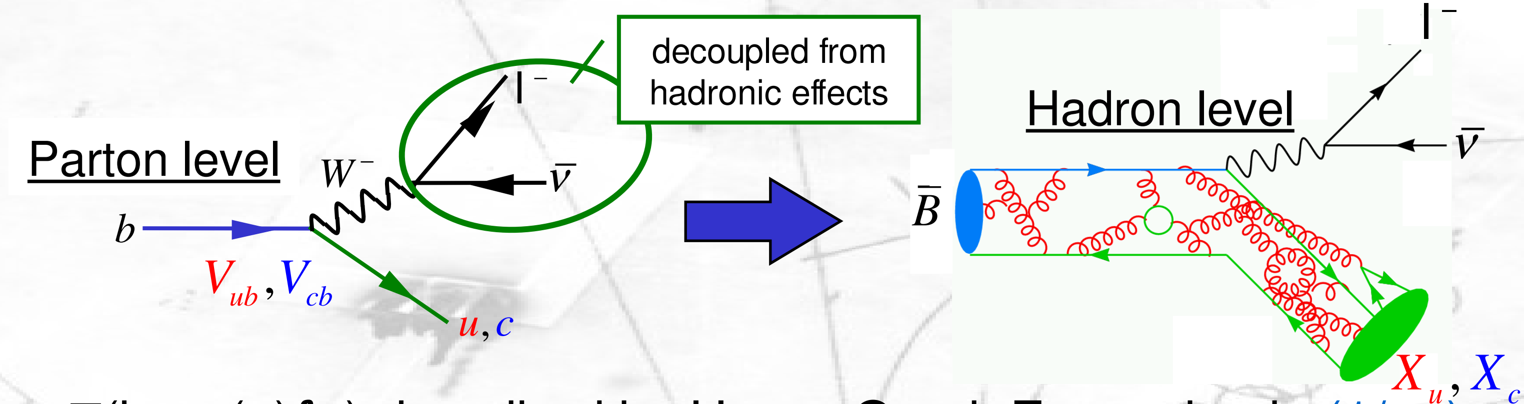
PDG 2006

Decay Mode	Branching Fraction
$B^+ \to l^+\nu_l$ + anything	10.9 ± 0.4 %
$B^+ \to \bar{D}^*(2007)^0\ell^+\nu_\ell$	(6.5 ± 0.5) %
$B^+ \to \bar{D}^0\ell^+\nu_\ell$	(2.15 ± 0.22) %
$B^+ \to \bar{D}_1(2420)^0\ell^+\nu_\ell$	(0.56 ± 0.16) %
$B^+ \to \bar{D}_2(2460)^0\ell^+\nu_\ell$	< 0.8% @90CL
$B^+ \to D^-\pi^+\ell^+\nu_\ell$	(0.53 ± 0.10) %
$B^+ \to D^{*+}\pi^+\ell^+\nu_\ell$	(0.64 ± 0.15) %
$B^+ \to \bar{D}^{(*)}n\pi\ell^+\nu_\ell$	??

- Γ_c larger than Γ_u by a factor ~50
  - ➜ Extracting $b \to u\ell\nu$ signal challenging
- Sensitive to hadronic effects
  - ➜ Must understand them to extract $|V_{ub}|$, $|V_{cb}|$

Total $b\to c(u)\ell\nu$ Rate

Tree level, short distance (perturbative) + long distance (non perturbative):



- $\Gamma(b\to c(u)\ell\nu)$ described by Heavy Quark Expansion in $(1/m_b)^n$ and α_s^k

$$\Gamma(B\to X_{c(u)}\ell\nu)=G_F^2 m_b^5/192\pi^3|V_{c(u)b}|^2[1+A_{ew}]A_{pert}A_{nonpert}$$

- free quark decay: $G_F^2 m_b^5/192\pi^3|V_{c(u)b}|^2$
- perturbative corrections (α_s^k dependent): $[1+A_{ew}]A_{pert}$
- Non-perturbative power corrections ($(1/m_b)^n$ dependent): $A_{nonpert}$

- Non-perturbative parameters need to be measured.
- They depend on the expansion, which depends on the m_b definition
- Similar expression for $b\to s\gamma$.

Moments in $B\to X_{c(u)}\ell\nu$ decays

Moments evaluated on the full lepton/mass spectrum or part of it: $p_\ell > p_{min}$ in the B rest frame

Lepton moments: $$\langle E_l^n \rangle = \frac{1}{\Gamma_{c(u)}} \int \left(E_l - \langle E_l \rangle \right)^n \frac{d\Gamma_{c(u)}}{dE_l} dE_l$$

Hadronic mass moments: $$\langle m_X^n \rangle = \frac{1}{\Gamma_{c(u)}} \int m_X^n \frac{d\Gamma_{c(u)}}{dm_X} dm_X$$

Moments are related to non-perturbative parameters

For comparison with data, use low-order moments of inclusive distributions over large ranges on phase space to avoid problem with quark-hadron duality

Similarly, moments in the photon energy are calculated for $b\to s\gamma$

Calculations available in "kinetic" (Benson, Bigi, Gambino, Mannel, Uraltsev, Nucl. Phys. B665:367) and "1S" (Bauer, Ligeti, Luke, Manohar, Trott, Phys. Rev. D70:094017,2004) mass schemes

> 60 measured moments available form DELPHI, CLEO, BABAR, Belle, CDF

Exclusive Measurements

- Matrix element for semileptonic decays:

$$\mathcal{M}(M_{Q\bar{q}} \to X_{q'\bar{q}}\ell^-\overline{\nu}_\ell) = -i\frac{G_F}{\sqrt{2}}V_{q'Q}L^\mu H_\mu$$

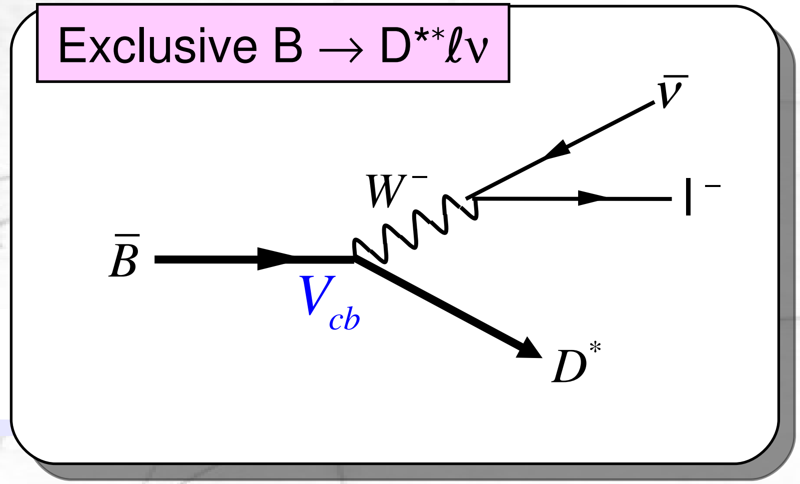
- Leptonic current exactly known:

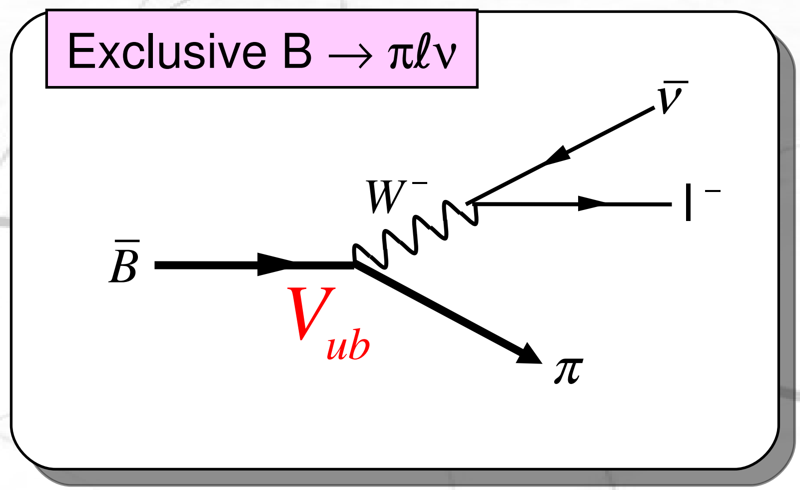
$$L^\mu = \bar{u}_\ell\gamma^\mu(1-\gamma_5)v_\nu$$

- Hadronic current described by Form Factors (FF), functions of squared momentum transfer q^2:

$$\langle P'(p')|V^\mu|P(p)\rangle = f_+(q^2)(p+p')^\mu + f_-(q^2)(p-p')^\mu$$

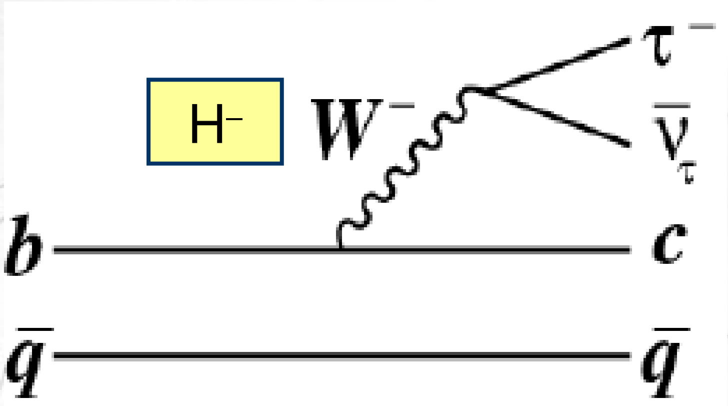
➔ Exclusive rates determined by $|V_{c(u)b}|$ and Form Factors (FF), which represent the probability that the heavy-quark combine to form the selected final state particle.
  - Theoretically calculable at kinematical limits
    - Lattice QCD works if D^* or π is ~ at rest relative to B
  - Empirical extrapolation is necessary to extract $|V_{c(u)b}|$ from measurements
- Measure differential rates to constrain the FF shape, then use FF normalization from the theory for $|V_{c(u)b}|$





New Physics, $B \to D^{(*)} \tau \nu$

- Same Feynman diagram as the light leptons (e, μ), but the decays can also be mediated by a charged Higgs boson.



- Very clean probe of New Physics:
  - NP contributes at tree level
  - Measurements of FF's for light leptons allow for very precise prediction of the τ-hadronic behaviour
  - Spin zero Higgs does not couple to all the helicity states, affect D and D^* differently, τ polarization.

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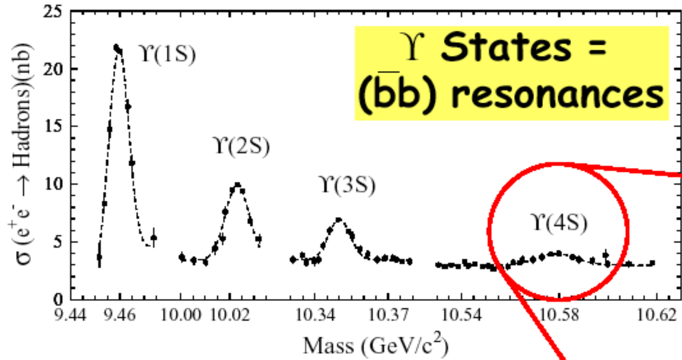
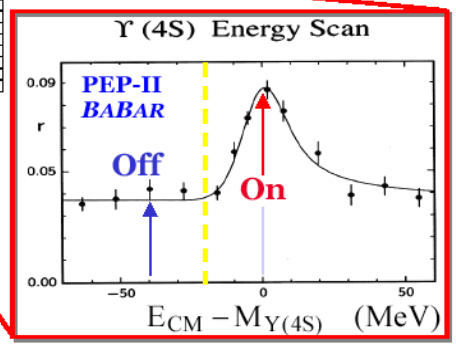
PEPII at SLAC and BaBar





Cross Sections at $\Upsilon(4S)$:

$b\bar{b} \sim 1.1$ nb

continuum background:
- $c\bar{c} \sim 1.3$ nb
- $d\bar{d}, s\bar{s} \sim 0.3$ nb
- $u\bar{u} \sim 1.4$ nb

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$
$L = 1$ state

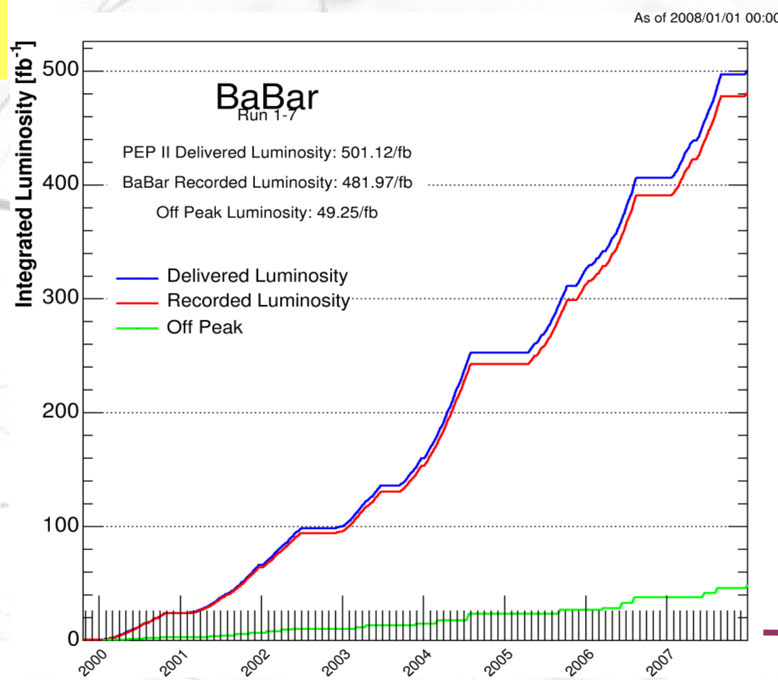
- B-factories: run @ Y(4S)
- BaBar (BELLE) asymmetric factory: 9 GeV e^- on 3.1 GeV e^+, Y(4S) boost: $\beta\gamma \sim 0.56$

Peak luminosity:

1.2×10^{34} cm^{2}s^{-1}

Integrated luminosity:
482 fb^{-1} (Jan 1, 2008)

Analyses presented here: 79-382 fb^{-1}



The BaBar Detector

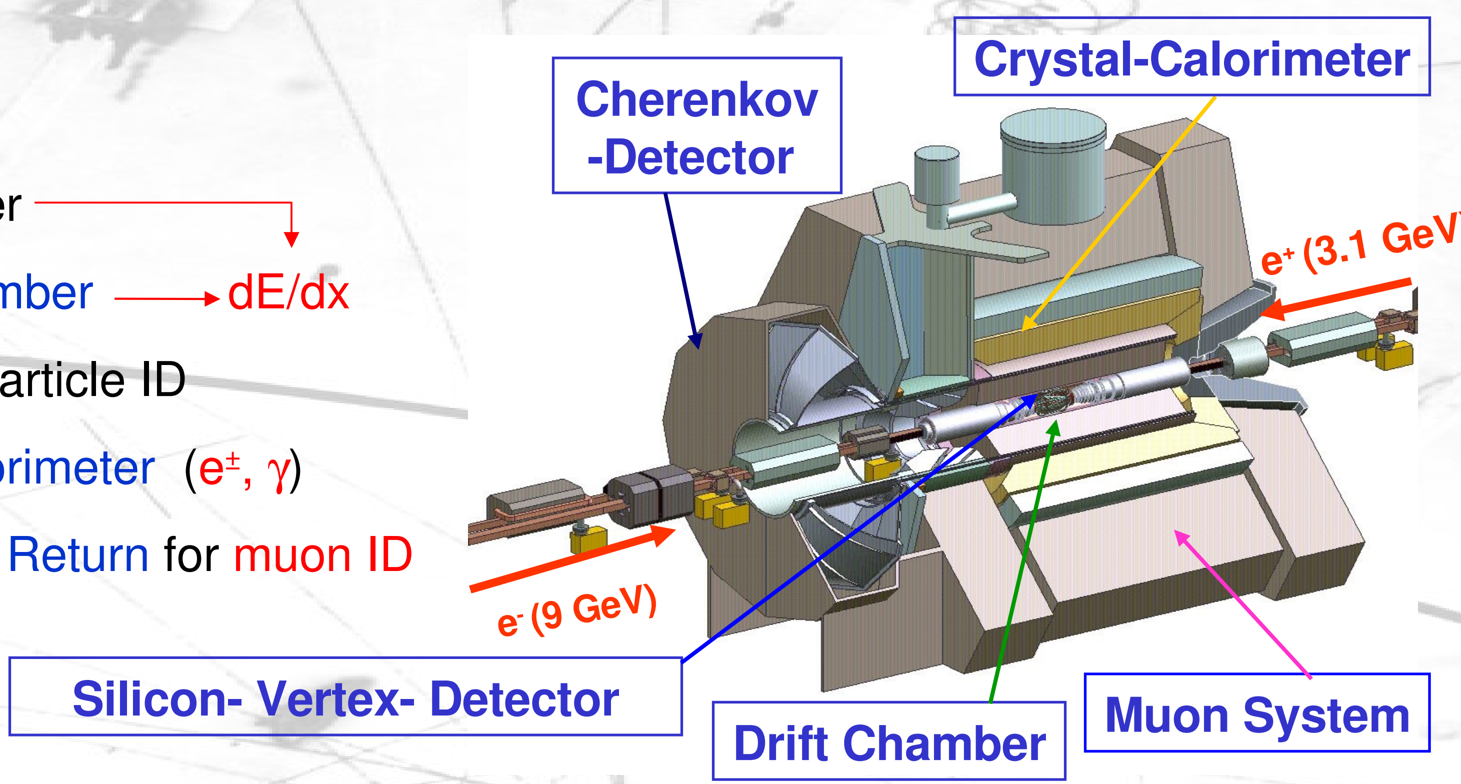
$B \to X_{c,u}\, \ell\, \nu$

$\to \pi^{\pm}$'s, $K^{\pm}$'s, γ's

$\ell = e, \mu, \tau$

- Good e, μ ID ($p^*_{\ell} > 1$GeV)
- Good hadron ID (e.g. π/K separation)
- Angular coverage ≈ 91% of 4π in CMS (challenge for ν reconstruction)

- 5-layer SVT tracker → dE/dx
- 40-layer Drift Chamber → dE/dx
- DIRC (RICH) for particle ID
- CsI(Tl) crystal calorimeter ($e^{\pm}$, γ)
- Instrumented Flux Return for muon ID



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Approaches to Measuring $B \to X\ell\nu$

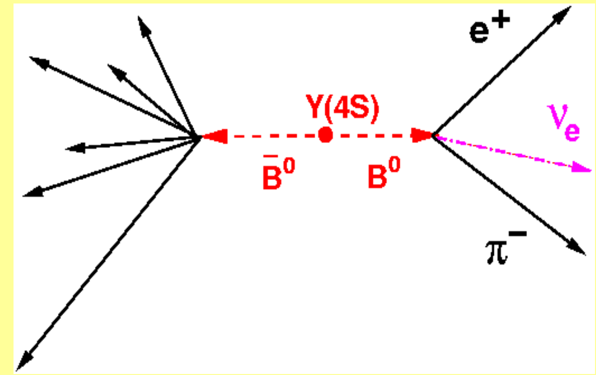
Signal example: $B \to \pi \ell \nu$

(Un)tagged B

Untagged
- Initial 4-momentum known
- Missing 4-momentum = ν
- Reconstruct $B \to X\ell\nu$ using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$

Pros
- High efficiency

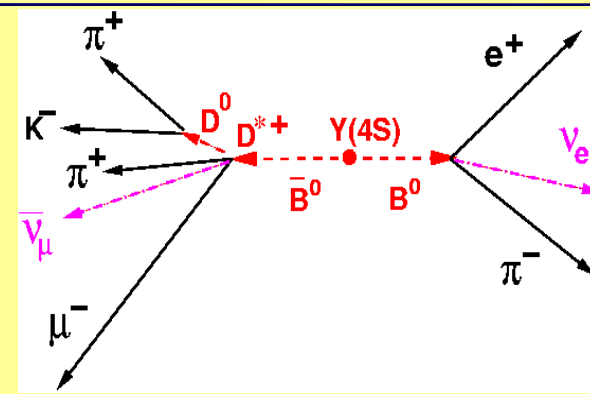
Cons
- ν resolution problematic
- Rel. high backgrounds (relatively low purity)



Semileptonic (SL) Tag
- One B reconstructed in a selection of $D^{(*)}\ell\nu$ modes
- Two missing ν in event
- Use kinematic constraints

Pros
- Lower backgrounds (higher purity)

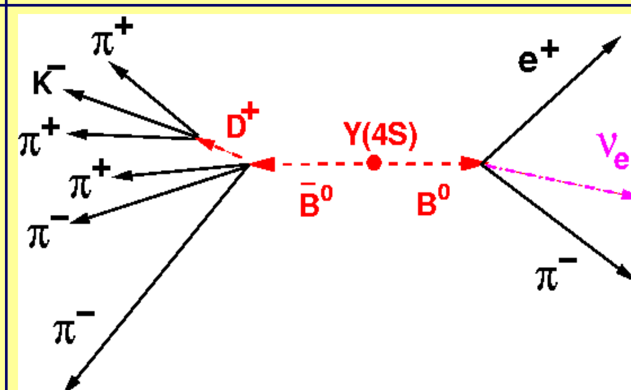
Cons
- Relatively low efficiency



Full Recon Tag (Breco)
- One B reconstructed completely in known $b \to c$ mode.
- Many modes used.

Pros
- Very good ν resolution
- Very low backgrounds

Cons
- Very low efficiency



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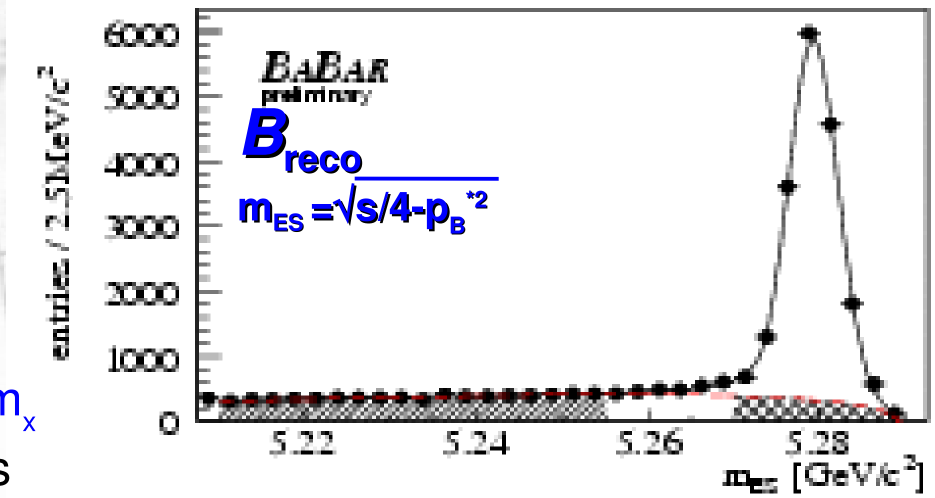
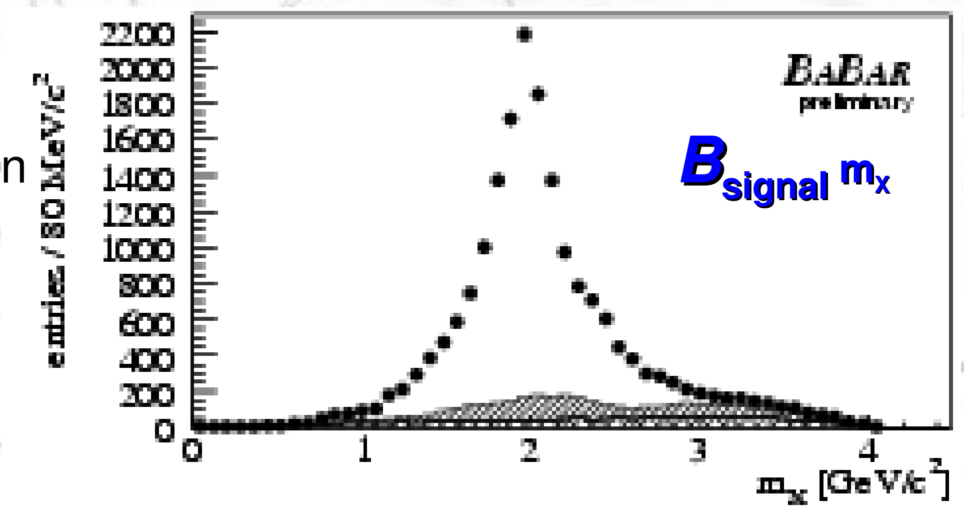
airXiv:0707.2670 [hep-ex]

Moments in $B \to X_c \ell\nu$ decays

232M $B\overline{B}$

- B-reco. Subtract background with m_{ES}
- 1 lepton (e,μ) in recoil with energy $P_\ell > 0.8$ GeV in B-rest frame
- Remaining charged and neutral particles form inclusive X_c system
- Measure moments of hadronic mass m_x and mixed mass-and-energy moments for several lower cuts on P_ℓ
- Improve resolution with kinematic fit
  - energy-momentum conservation
  - E_{miss}, p_{miss} consistent with ν
- Correct X_c system for bias due to unmeasured particles
- Dominant systematic uncertainty: efficiency on inclusive event reconstruction



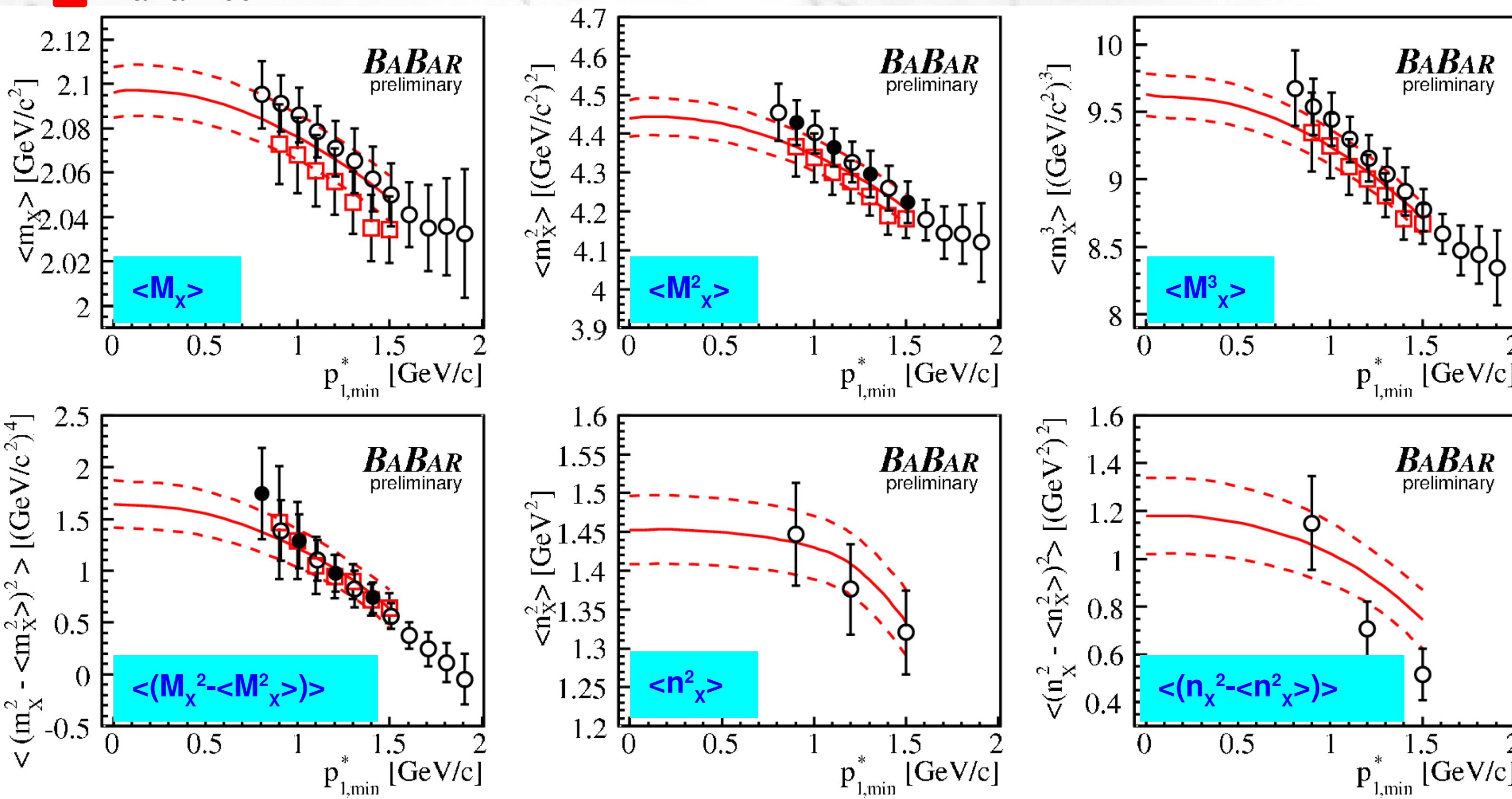


airXiv:0707.2670 [hep-ex]

Measured Moments

●○ This measurement (open symbols not fitted)

□ *BaBar* 2004



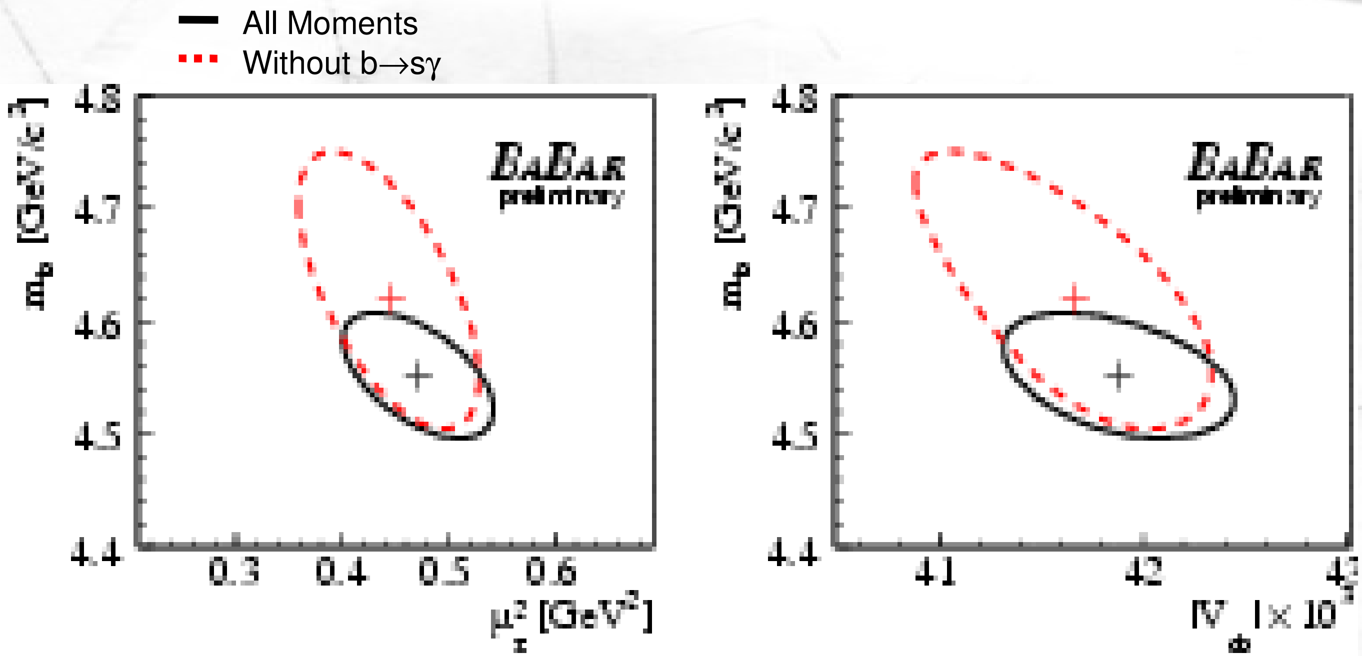
$n_x = m_x^2c^4 - 2\tilde{\Lambda}E_x + \tilde{\Lambda}$

($\tilde{\Lambda}$=0.65 GeV)

- Moments integrated over data for various lepton cuts over the same mass or lepton energy distribution (all points highly corrrelated)
- Each observable has a different dependence on $|V_{cb}|$, m_b, m_c, and several non-perturbative params
- Parameters determined by a global fit over ● points
- The ○ points, not used in the fit, agree well with the fit results

Global OPE Fit – Kinetic Scheme

- 27 input moments:
  - 8 mass moments (this analysis)
  - 13 E_l moments (Phys. Rev. D69 111104 (2004))
  - 6 E_γ moments (Phys. Rev. D 72, 052004 (2005), Phys. Rev. Lett. 97 171803 (2006))
- Further input: τ_B
- 8 fit parameters:
  - $|V_{cb}|$, m_b, m_c, $\mathcal{B}_{sl}$
  - 4 HQE parameters



- Fit results:

$|V_{cb}| = (41.88 \pm 0.44_{exp} \pm 0.35_{theo} \pm 0.59_{\Gamma SL})10^{-3}$ (1.9% total error)

$m_b = (4.55 \pm 0.038_{exp} \pm 0.040_{theo})$ GeV (1.2% total error)

$m_c = (1.070 \pm 0.038_{exp} \pm 0.040_{theo})$ GeV

$\mathcal{B}_{SL} = (10.597 \pm 0.171_{exp} \pm 0.053_{theo})$ %

$m^2_\pi = (0.471 \pm 0.034_{exp} \pm 0.062_{theo})$ GeV²

$m^2_G = (0.330 \pm 0.042_{exp} \pm 0.043_{theo})$ GeV²

$\rho^3_D = (0.220 \pm 0.021_{exp} \pm 0.042_{theo})$GeV³

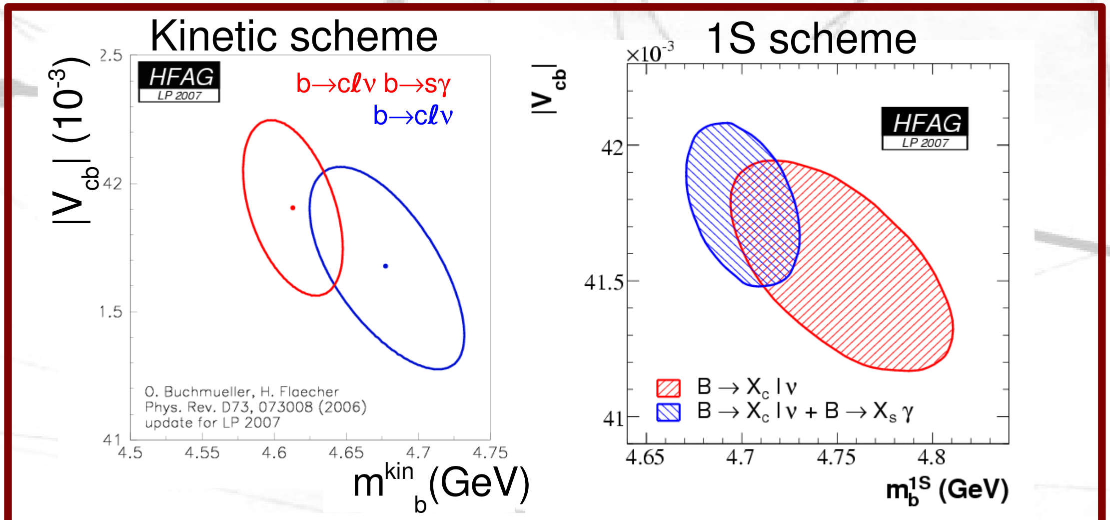
$\rho^3_{LS} = -(0.159 \pm 0.081_{exp} \pm 0.050_{theo})$GeV³

non-perturbative params

OPE Global Fits

- More results from global fits in the kinetic and 1S schemes are available. Recent averages performed by the HFAG
- A pattern is present: results with $b \to c\ell\nu$ and $b \to s\gamma$ moments differ from results with $b \to c\ell\nu$ moments only (except in hep-ex/0611047, but larger errors).
- HFAG results for Lepton Photon:

	m_b (GeV)	m_b (GeV)
	$b \to c\ell\nu$ $b \to s\gamma$	$b \to c\ell\nu$
Kinetic scheme	4.613 ± 0.035	4.677 ± 0.053
1S scheme	4.701 ± 0.030	4.751 ± 0.058



- Large uncertainties due to the ansatz and missing terms
- Different values of m_b impact the determination of $|V_{ub}|$ from inclusive decays

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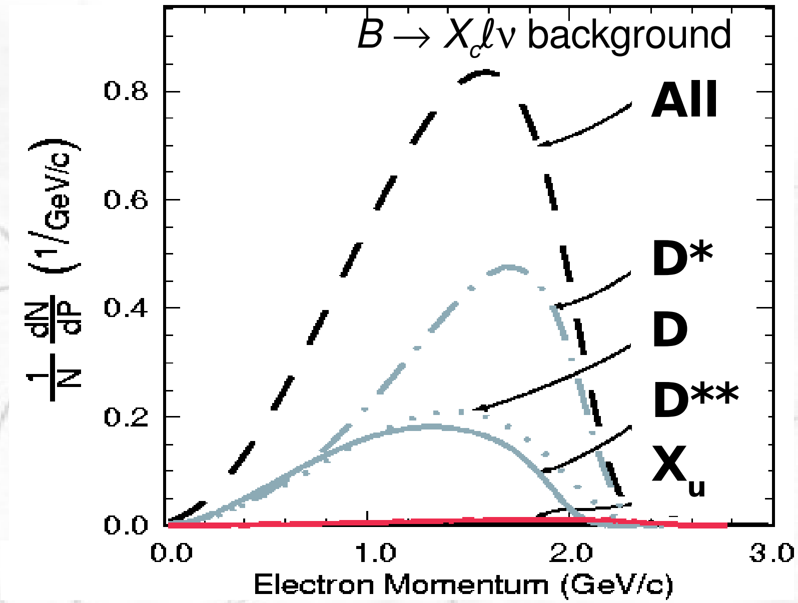
$B \to X_u \ell \nu$ rate

- $B \to X_c \ell \nu$ background is about 50 times larger than $B \to X_u \ell \nu$
- Major experimental challenge is to separate $B \to X_c \ell \nu$ background from signal
- This is achieved in region of phace space where the $B \to X_c \ell \nu$ background is suppressed $\to$ partial decay rate

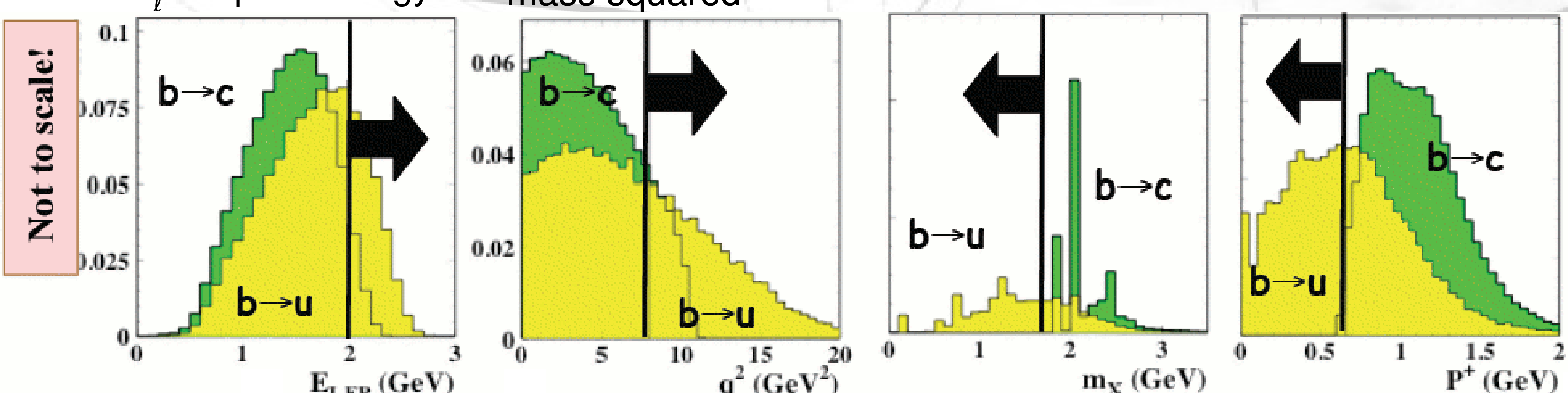


E_ℓ = lepton energy

q^2= lepton-neutrino mass squared

M_X = hadronic mass

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

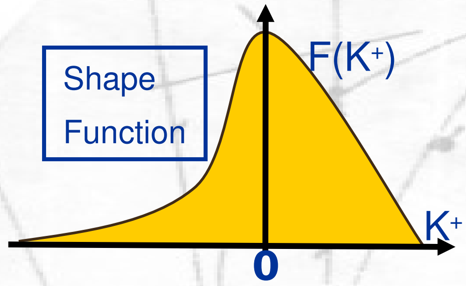


Restriction of the phase-space is a challenge to theory!

$B \to X_u \ell \nu$ theory: OPE approach

Restrict kinematics to suppress background from $B \to X_c \ell \nu$: OPE convergence is compromised! Need light-cone distribution (shape) function of b quark:

Detailed shape not constrained, in particular the low tail. Needs to be determined by data



Mean and r.m.s. are known from the moments!

Four approaches:

- 3-scale OPE based on HQET, SCET: Bosch, Lange, Neubert, Paz (BLNP) [PRD 72:073006 (2005)]
- Relate $b \to u \ell \nu$ directly to $b \to s \gamma$: Lange, Neubert, Paz (LNP) [JHEP 0510:084, 2005], Leibovich, Low, Rothstein (LLR) [PLB 486:86]
- Select phase space in m_X-q^2 with reduced SF dependence: Bauer, Ligeti, Luke (BLL) [PRD 64:113004 (2001)]
- Kinetic scheme: P.Gambino, P.Giordano, G.Ossola, N.Uraltsev (GGOU) [JHEP10(2007)058] (very recent!)

$B \to X_u \ell \nu$ theory: parton-level approach

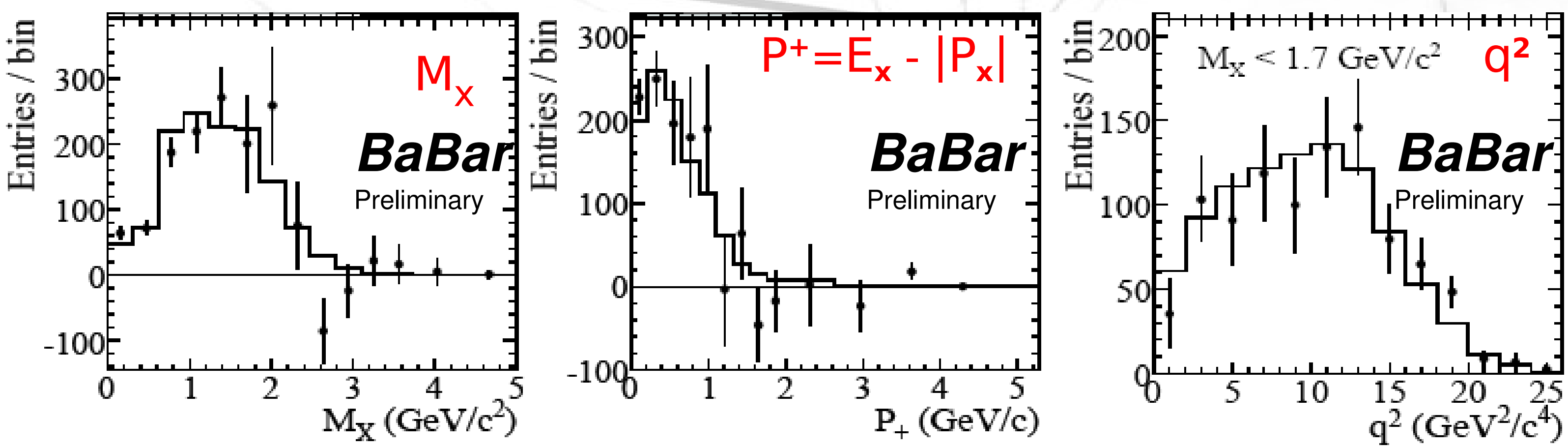
- On-shell calculation framework
- Use perturbation QCD, with inclusive hadron final states coming from gluon radiation, as $m_b >> \Lambda$ (hadronic scale)
- The perturbative expansion of spectra in the threshold region is affected by large logarithms, to be resummed
- No Shape Function is introduced, but a modelling of non-perturbative QCD effects is adopted.
- Two approaches:
  - Dressed Gluon Exponentiation: J.R. Andersen and E. Gardi (DGE) [JHEP 0601:097 (2006)]
  - Analytic Coupling: U. Aglietti, G. Ferrera, G. Ricciardi (AC) [Phys.Rev. D74 (2006) 034006, Phys.Rev. D74 (2006) 034005, Phys.Rev. D74 (2006) 034004]

$B \to X_u \ell \nu$: fully tagged B

arXiv:0708.3702 [hep-ex]
submitted to PRL

- Fully reconstructed B
- Events identified fitting the m_{ES} distribution
- Normalize to semileptonic events to be independent of tagging efficiency
- Use 3 kinematic variables to distinguish $b \to c \ell \nu$ from $b \to u \ell \nu$: M_x, P^+, M_x-q^2
- Major systematic errors from: detector, m_{ES} fits, MC stat.

Variables	$X_u \ell \nu$ events	$\Delta\mathcal{B}(10^{-3})$
M_x	803 ± 60	$1.18 \pm 0.09_{stat} \pm 0.07_{syst} \pm 0.01_{theo}$
P^+	633 ± 63	$0.95 \pm 0.10_{stat} \pm 0.08_{syst} \pm 0.01_{theo}$
M_x, q^2	562 ± 55	$0.76 \pm 0.08_{stat} \pm 0.07_{syst} \pm 0.02_{theo}$



382M $B\bar{B}$

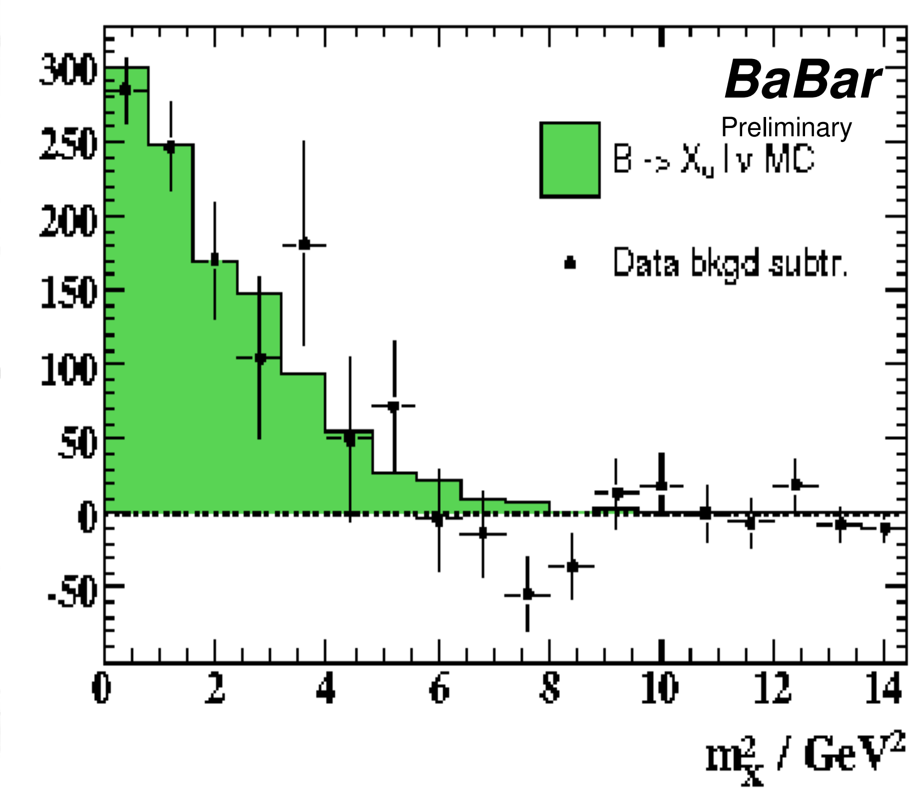
Measured Distributions, not efficiency corrected

$B \to X_u \ell \nu$ m_x moments

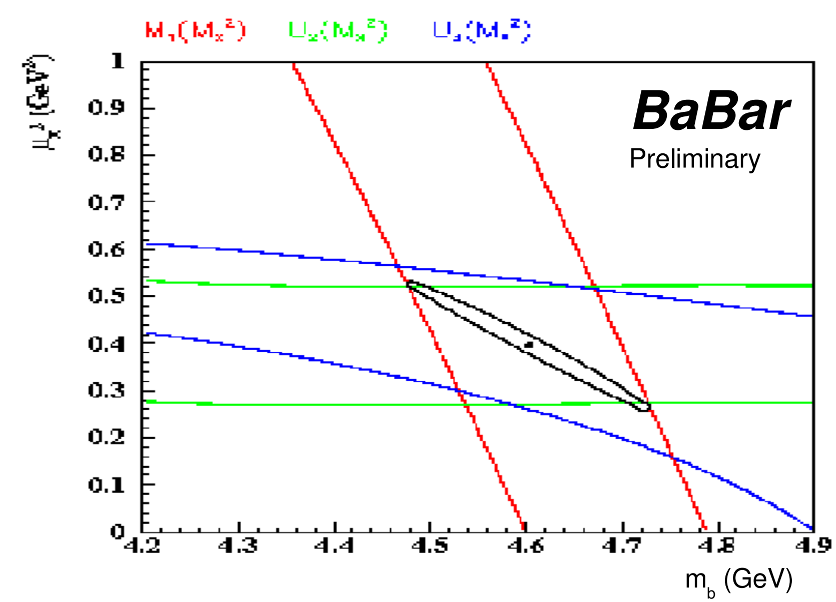
Preliminary. Presented at Hadron07

347M $B\bar{B}$

- Analysis approach similar to arXiv:0708.3702 [hep-ex]
- Unfold the m_X spectrum for detector acceptance, efficiency and resolution.
- Extract mass moments with upper cut $m_X^2 < 6.2$ GeV^2



- $M_1 = (1.96 \pm 0.34_{stat} \pm 0.53_{syst})$ GeV^2
- $U_2 = (1.92 \pm 0.59_{stat} \pm 0.87_{syst})$ GeV^4
- $U_3 = (1.79 \pm 0.62_{stat} \pm 0.78_{syst})$ GeV^6



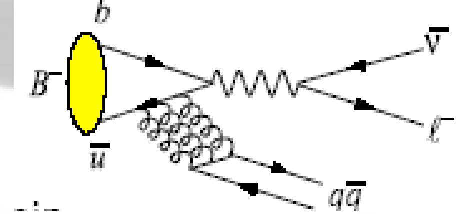
Theory calculations used:
Gambino, Ossola, Uraltsev hep-ph/0505091

First measurement of m_b in $X_u \ell \nu$ (but large errors):
$m_b = 4.604 \pm 0.025_{stat} \pm 0.193_{mom.\ syst} \pm 0.097_{syst}$ GeV

arXiv:0708.1753 [hep-ex]

383M $B\bar{B}$

Weak Annihilation

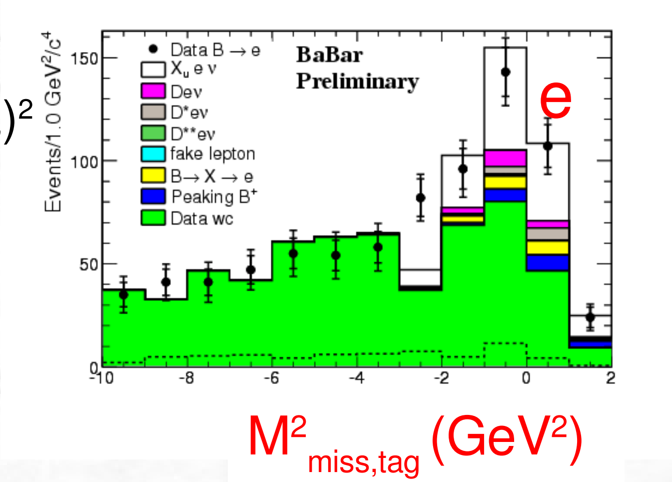


Small contribution to $B \to X_u \ell \nu$ decay (<3% of total rate)

– Compare $B^0 \to X_u \ell \nu$ partial rate to charge-averaged $B \to X_u \ell \nu$ rate in WA-enhanced region (large p_ℓ and large q^2)

- Tagging: $B^0 \to D^{*+} \ell^- \nu X$ with partial D^* reconstruction
- Neutrino mass derived from kinematics $m_\nu^2 = (P_B - P_{D^*} - P_\ell)^2$
- Measure $\mathcal{B}$ for $P_\ell > 2.2\text{-}2.4$ GeV

ΔP_ℓ	$\Delta\mathcal{B}(B^0) \cdot 10^4$
$2.2 - 2.6\ \mathrm{GeV}/c$	$2.62 \pm 0.33 \pm 0.16$
$2.3 - 2.6\ \mathrm{GeV}/c$	$1.30 \pm 0.21 \pm 0.07$
$2.4 - 2.6\ \mathrm{GeV}/c$	$0.76 \pm 0.15 \pm 0.05$



- Extract charge asymmetry, using info from untagged $B \to u \ell \nu$ from endpoint analysis (Phys.Rev.D73:012006,2006)

$$A^{+/0} = \frac{\Delta\Gamma^+ - \Delta\Gamma^0}{\Delta\Gamma^+ + \Delta\Gamma^0}$$

- Limit on contribution from WA for interval $2.3 < E_l < 2.6$ GeV:

$$\frac{|\Gamma_{WA}|}{\Gamma_u} = \frac{2 \cdot f_u(\Delta P_\ell)}{f_{WA}(\Delta P_\ell)} \cdot A^{+/0} < \frac{3.8\ \%}{f_{WA}(2.3 - 2.6)}, \quad \text{at } 90\%\ \text{C.L.}$$

$\Gamma_{WA} = \Gamma^+ - \Gamma^0$

$f_{WA}(\Delta P_\ell)$= fraction of WA in interval ΔP_ℓ

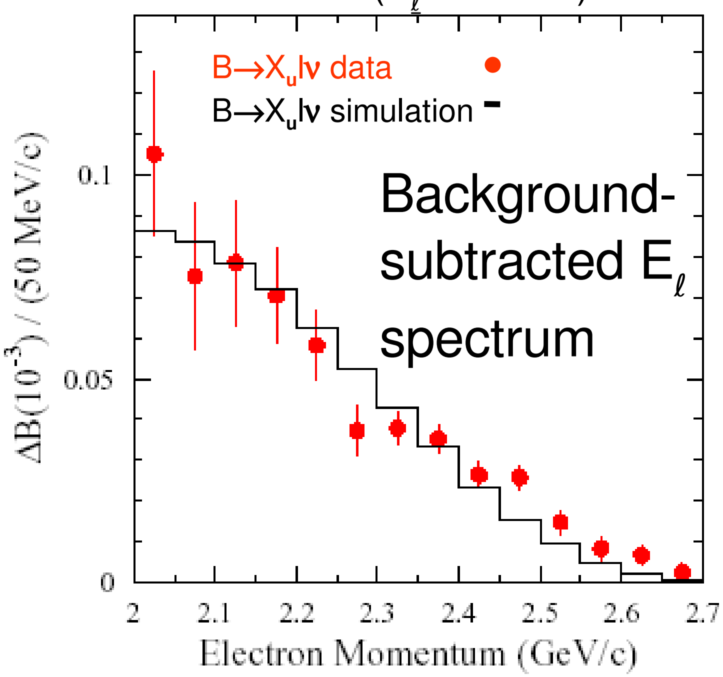
$B \to X_u \ell \nu$ E_ℓ analyses

- The E_ℓ (endpoint) analysis is the original method to study $B \to X_u \ell \nu$
- Two untagged analyses so far
- Identify high energy lepton (electron, plenty of statistics)
- Very high background from $B \to X_c \ell \nu$!
- Accurate subtraction of the background is crucial
- Missing momentum used for determining q^2

Phys.Rev.D73:012006,2006

88M $B\bar{B}$

- $S/B \sim 1/15$ ($E_\ell > 2$ GeV)

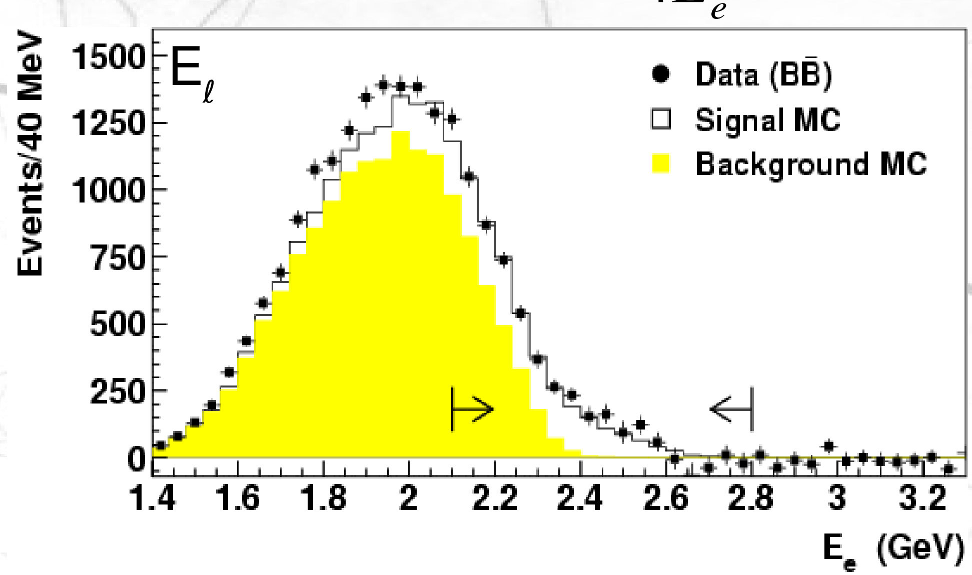


Phys.Rev.Lett.95:111801,2005

88M $B\bar{B}$

- Suppress background using:

$$s_h^{max} = m_B^2 + q^2 - 2m_B\left(E_e + \frac{q^2}{4E_e}\right)$$

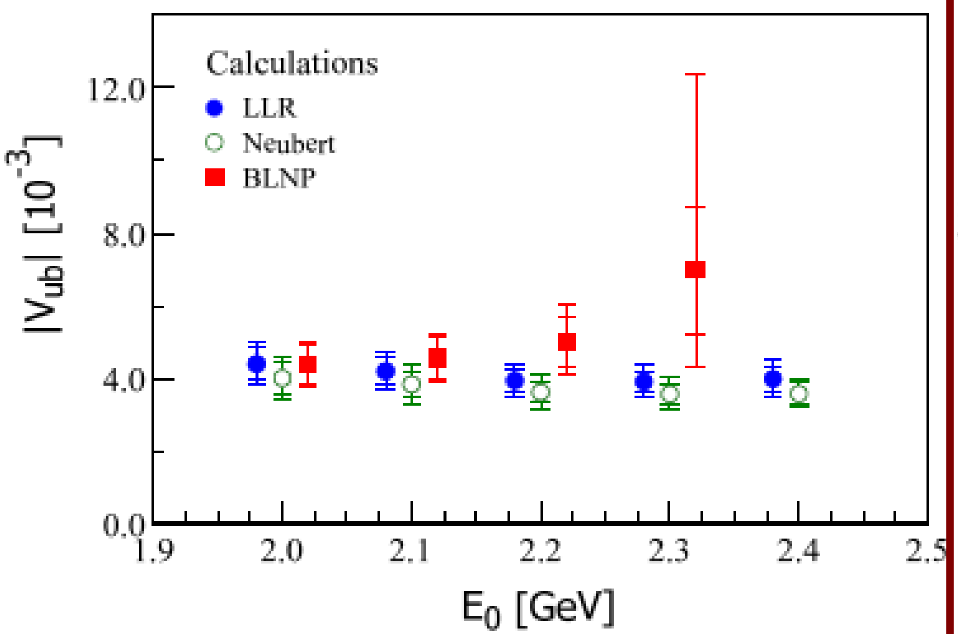


SF independent analyses

- Assumption that QCD interactions affecting b→sγ and b→uℓν are the same
- Take ratio of weighted b→sγ and b→uℓν decay rates
- b→sγ spectrum from Phys. Rev. D72 (2005) 052004
- Two BaBar analyses:

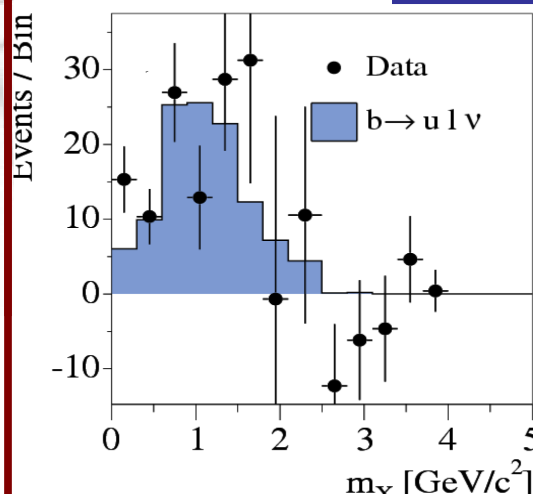
arXiv:hep-ph/0702072v1
accepted by PRD

- Using the endpoint spectrum, $|V_{ub}|$ is
- calculated as a function of E_ℓ
- Consistent results except at high E_ℓ

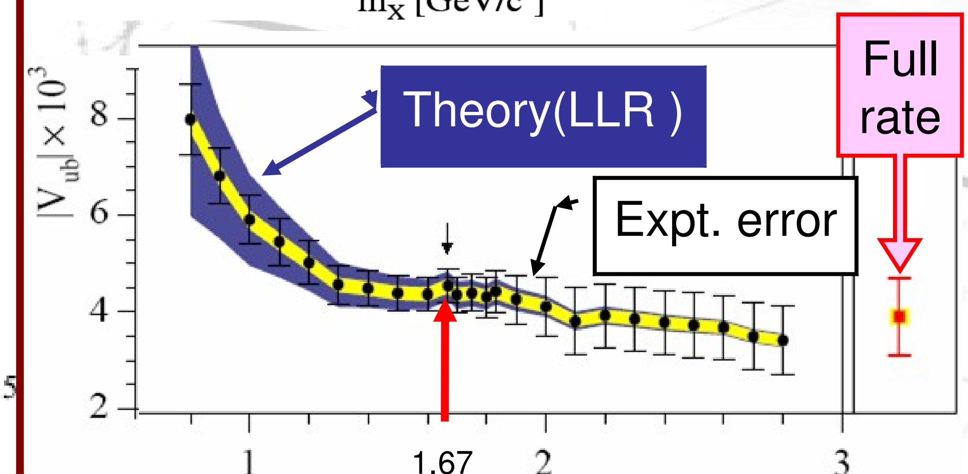


Phys.Rev.Lett. 96 (2006) 221801

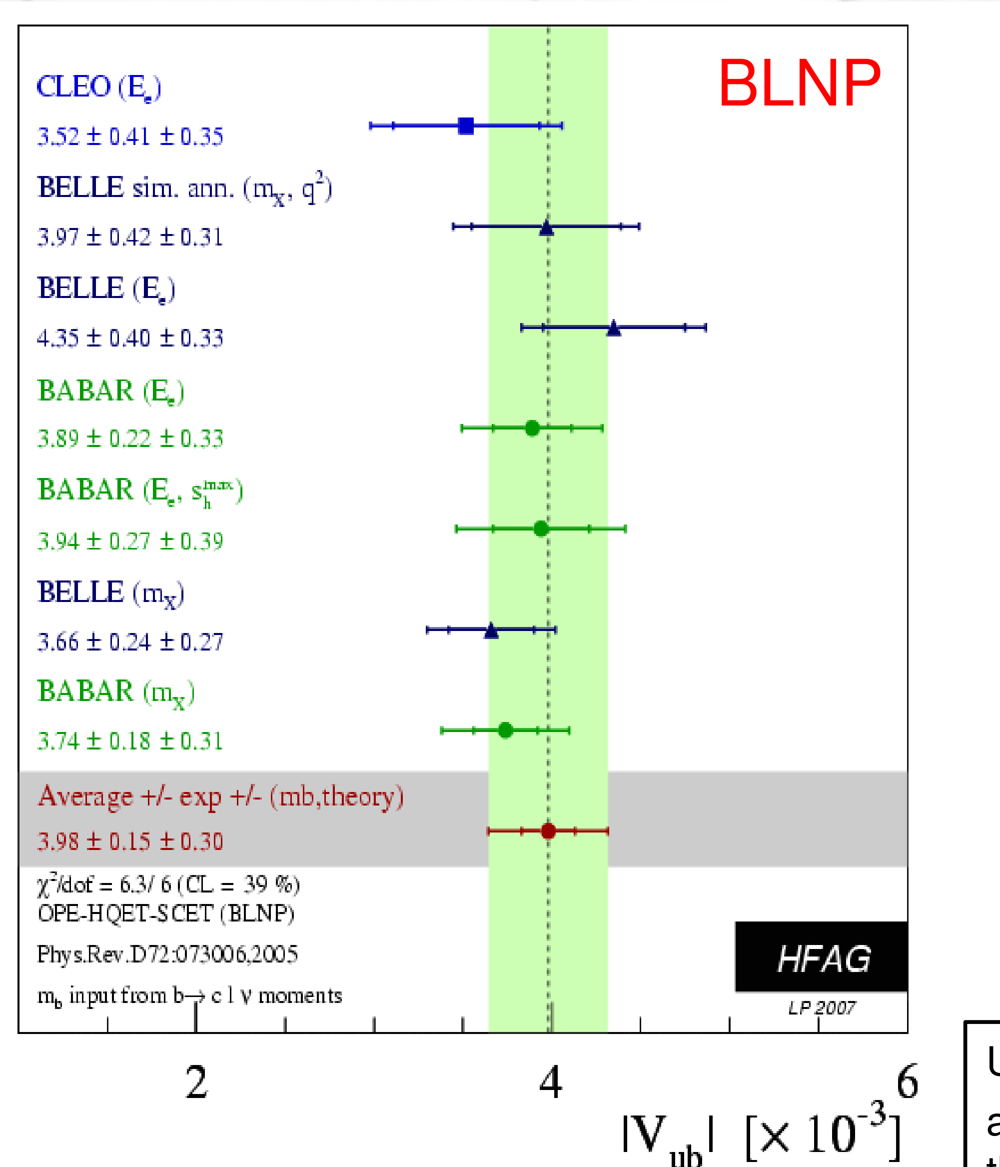
88.9M $B\bar{B}$



- Select Breco events and measure m_X
- Statistic limited analysis



$|V_{ub}|$ results



Plethora of theoretical approaches $\rightarrow$ plethora of $|V_{ub}|$ values for each analysis

Current approach is either to quote all the values or just BLNP (OPE)

BLNP: m_b from $b \to c\ell\nu$ moments:

$|V_{ub}| = (3.98 \pm 0.15 \pm 0.30)\ 10^{-4}$

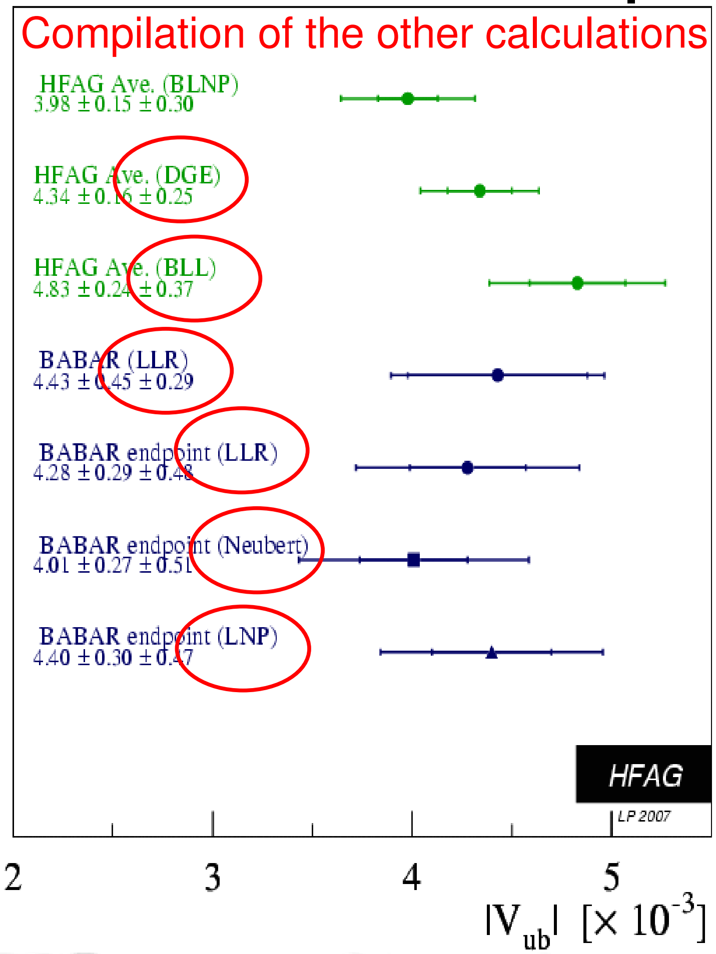
BLNP: m_b from $b \to cl\nu$ and $b \to s\gamma$ moments can't be used because of uncontrolled theoretical errors for the $b \to s\gamma$ moments. $|V_{ub}|$ value using $b \to cl\nu$ and $b \to s\gamma$ was:

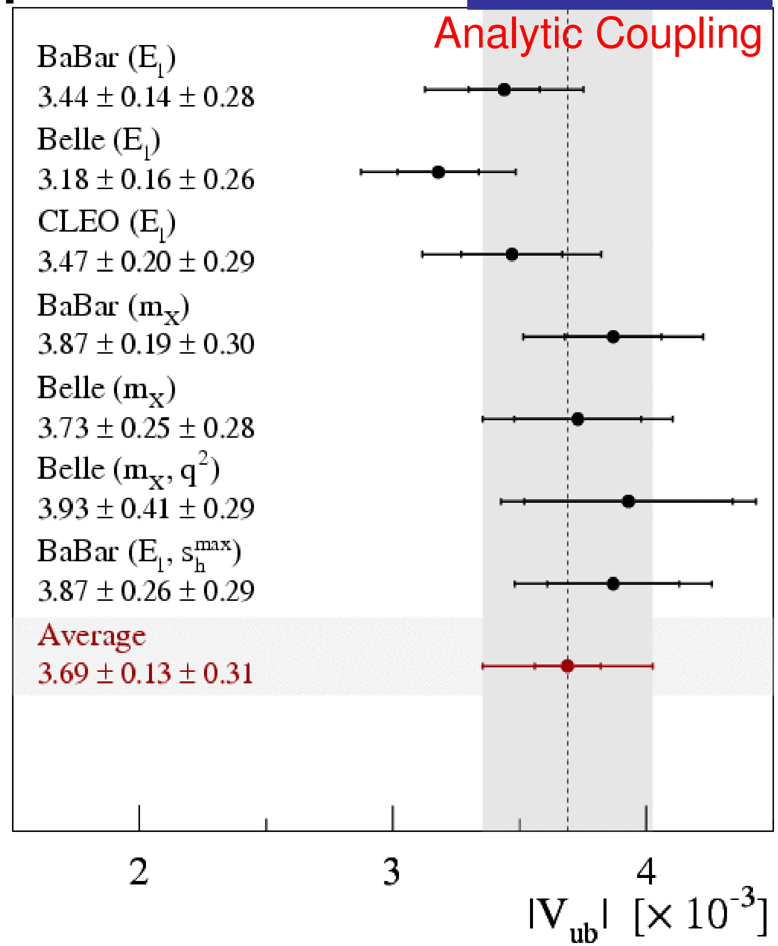
$|V_{ub}| = (4.31 \pm 0.17 \pm 0.35)\ 10^{-3}$

Use only the partial $\mathcal{B}$ from m_X for the Breco analyses as experimental correlation among the variables are not published

More $|V_{ub}|$ results

arXiv:0711:0860





- Results vary from 4.83×10^{-3} (BLL) to 3.69×10^{-3} (AC)
- b-quark masses approaches and dependences different.
- Aim for the near future: to quote one value of $|V_{ub}|$
- $|V_{ub}|$ average using the Kinetic scheme (P.Gambino, P.Giordano, G.Ossola, N.Uraltsev, [JHEP10(2007)058]) is being computed.

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  - Experimental approach
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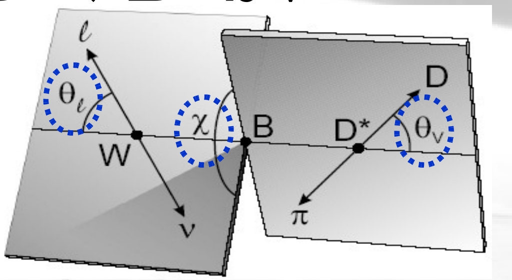
  - Determination of $|V_{cb}|$
  - Determination of $|V_{ub}|$
- Exclusive Decays
  - $D^{(*(*))}\ell\nu$
  - $\pi(\eta^{(')})\ell\nu$
- Conclusions

$|V_{cb}|$ and Form Factors from $B \to D^* \ell \nu$

- Differential decay rate :

Form Factors — Phase Space

$$\frac{d\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{G_F^2|V_{cb}|^2}{48\pi^3} F(w,\theta_\ell,\theta_V,\chi)\, G(w)$$



D* boost in the B rest frame

$$w \equiv \frac{M_B^2 + M_{D^*}^2 - q^2}{2 M_B M_{D^*}}$$

- HQ symmetry (b and c mass infinite) predicts a unique universal FF, normalized to 1.0 at zero recoil.
- QCD (and QED) correction to F(1) needed!
- $F(w,\theta_l,\theta_v,\chi)$ incorporates 3 non-trivial form factors, $A_1(w)$, $A_2(w)$, $V(w)$
- HQET relates the 3 FF's to each other through HQS, but leaves 3 free parameters to be determined experimentally. They are:

  Amplitude ratios: $R_1(w)=V/A_1$

  $R_2(w)=A_2/A_1$

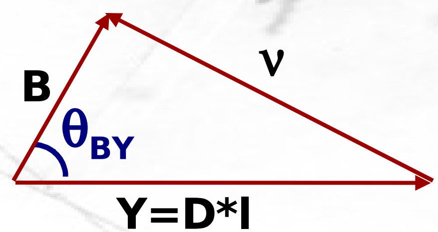
  Curvature $\rho^2=-dF/dw|_{w=1}$

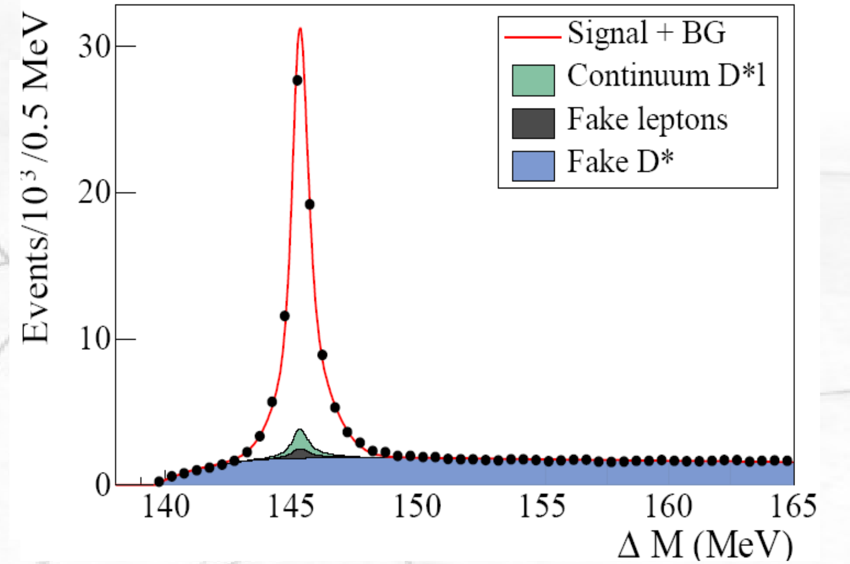
- Using a parametrization by CLN (Caprini, Lellouch, Neubert, NPB530, (1998) 153): three parameters need to be extracted from data $R_1(1)$, $R_2(1)$ and ρ^2.
- Goal is to determine $R_1(w)$, $R_2(w)$, ρ^2
- There are 4 observables: w and 3 angles (θ_l, χ, θ_v)

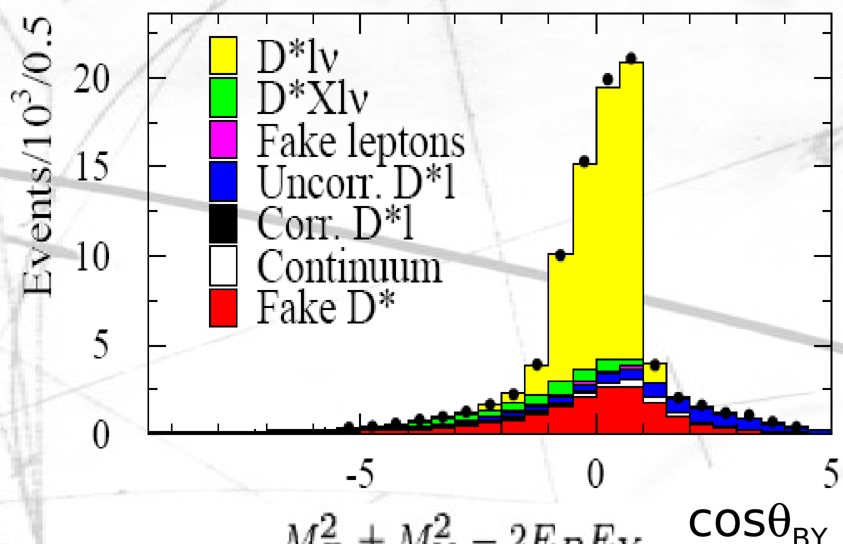
$B^0 \to D^{*+} \ell \nu$ Selection

Select $B^0 \to D^{*+} \ell \nu$ $(D^{*+} \to D^0\pi^+)$ events with $p^*_\ell > 1.2$ GeV

Estimate backgrounds (comb., D**) from $\Delta M = M(D^*)-M(D)$ and $\cos\theta_{BY}$







$$\cos\theta_{BY} = -\frac{M_B^2 + M_Y^2 - 2E_B E_Y}{2p_B p_Y}$$

<u>Two BABAR analyses:</u>

(1) Three D modes: $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, χ^2 fit to 1D projections

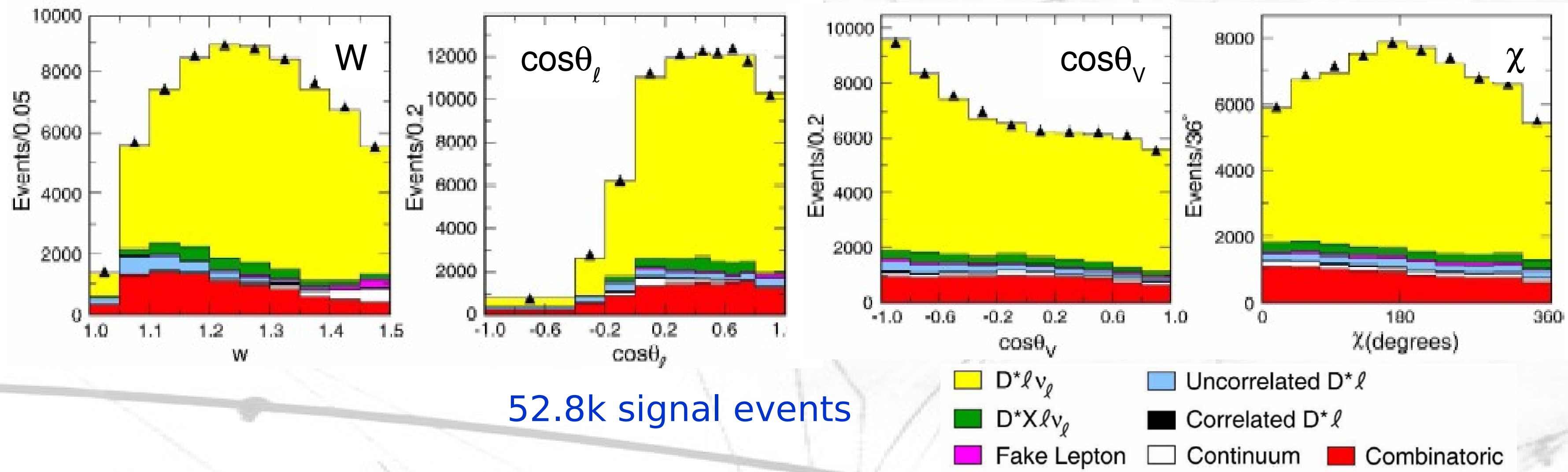
(2) One D mode: $D^0 \to K\pi$, 4D maximum Likelihood fit

$B \to D^*$ Form Factors: 1D Projections

- Simultaneous χ^2 fit of 1D projections in three variables w, $\cos\theta_l$, $\cos\theta_V$ (integrated over angle χ)

79M $B\bar{B}$

- First simultaneous measurement of form factors and $|V_{cb}|$, fully accounting for all correlations



52.8k signal events

- Final results combined with Phys.Rev. D74 (2006) 092004 (which uses a full 4D fit) to give a combined value of the form factors:

$\rho^2 = 1.179 \pm 0.048 \pm 0.028$ $\quad$ $R_1(1) = 1.417 \pm 0.061 \pm 0.044$

$R_2(1) = 0.836 \pm 0.037 \pm 0.022$ $\quad$ $F(1)|V_{cb}| = (34.7 \pm 0.3 \pm 1.1)\ 10^{-3}$

Syst. Uncertainties dominated by detector efficiencies, Bg, R_1, R_2

New BaBar FF are ~5 times better than the old ones from CLEO (with ~3 fb^{-1})

226M $B\bar{B}$

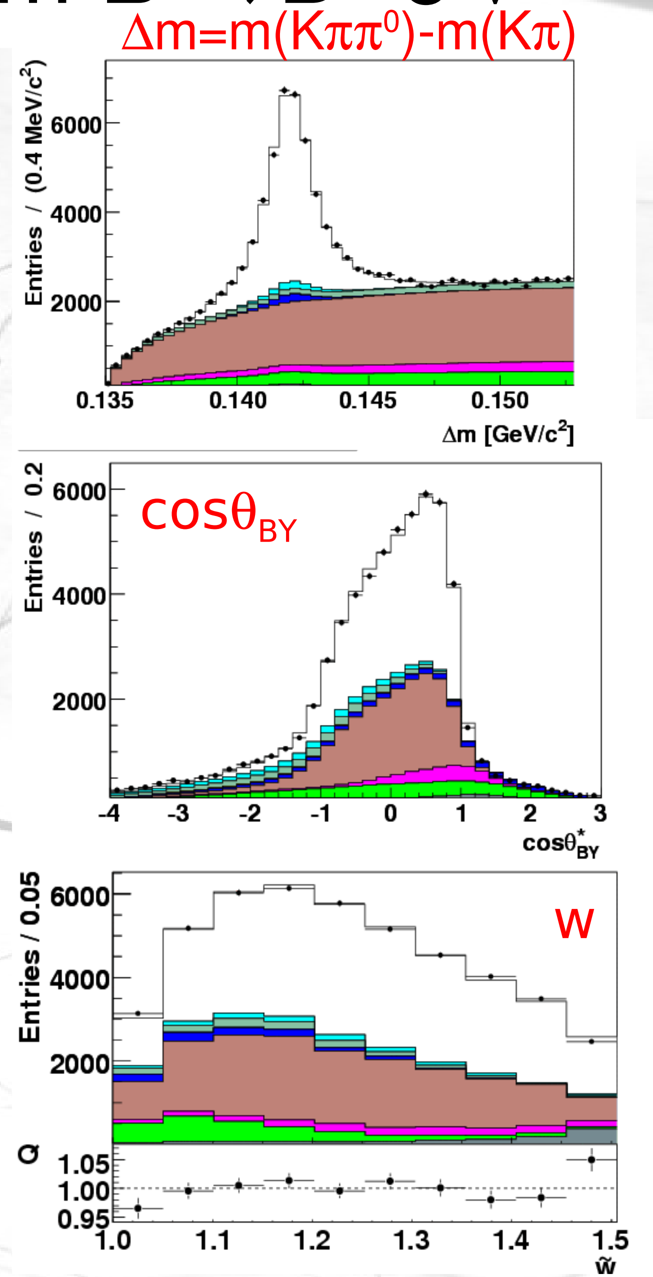
arXiv:0712.3493 [hep-ex]

$|V_{CB}|$ and Form Factors from $B^- \to D^{*0} e^- \nu$

- Look at decay chain: $D^{*0} \to \pi^0 D^0$ and $D^0 \to K^- \pi^+$
- Discriminating variables: Δm, $\cos\theta_{BY}$
- Binned maximum likelihood fit in Δm, $\cos\theta_{YB}$ and ω
- 23500 ± 330 signal events from the fit
- Main background: mis-reconstructed $B^{0\pm} \to D^{*0\pm} e\text{-}\nu$
- Main systematic uncertainties:
  - π^0 reconstruction efficiency
  - $\mathcal{B}(D^{*0} \to \pi^0 D^0)$
  - $R_1(1)$ and $R_2(1)$ for ρ^2
- Results:

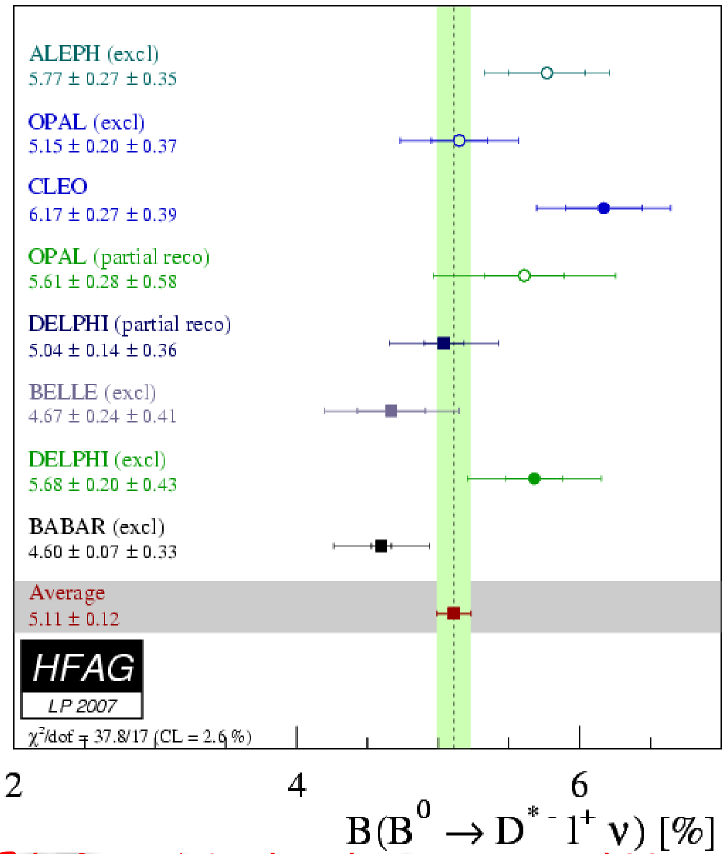
- $F(1)|V_{cb}| = (35.9 \pm 0.6 \pm 1.4)\ 10^{-3}$
- $\rho^2 = 1.16 \pm 0.06 \pm 0.08$
- $\mathcal{B}(B^- \to D^{*0} e^- \nu) = (5.56 \pm 0.08 \pm 0.41)\%$

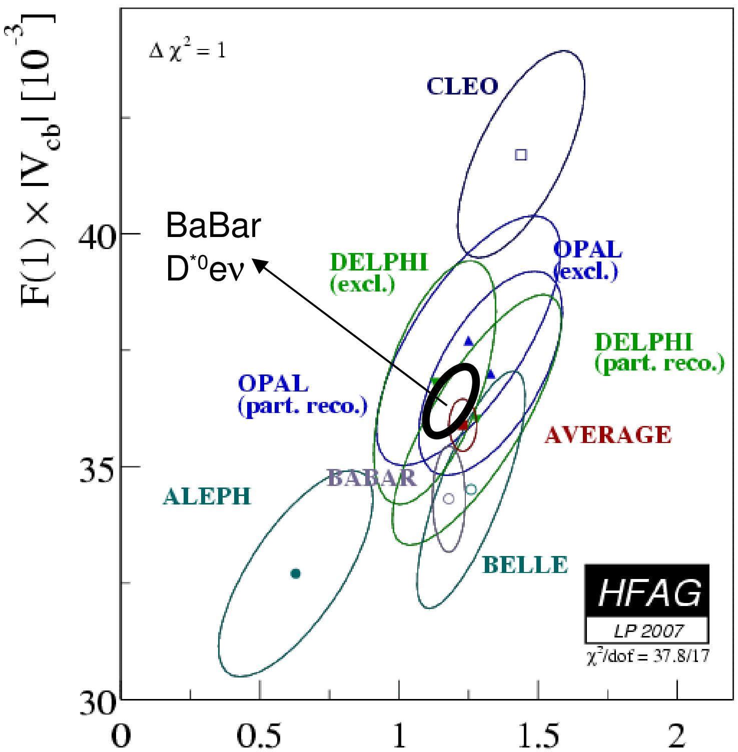
in agreement with PDG values of $\mathcal{B}(B^0 \to D^{*-} e^+ \nu)$



BABAR Results vs. World Average

- Global multidimensional fit (arXiv:0712.3493, $B \to D^{*0} e\nu$ not yet included)





$F(1)|V_{cb}| = (35.89 \pm 0.56)\ 10^{-3}$ ρ^2

$\rho^2 = 1.23 \pm 0.05$

$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu) = (5.11 \pm 0.12)\%$

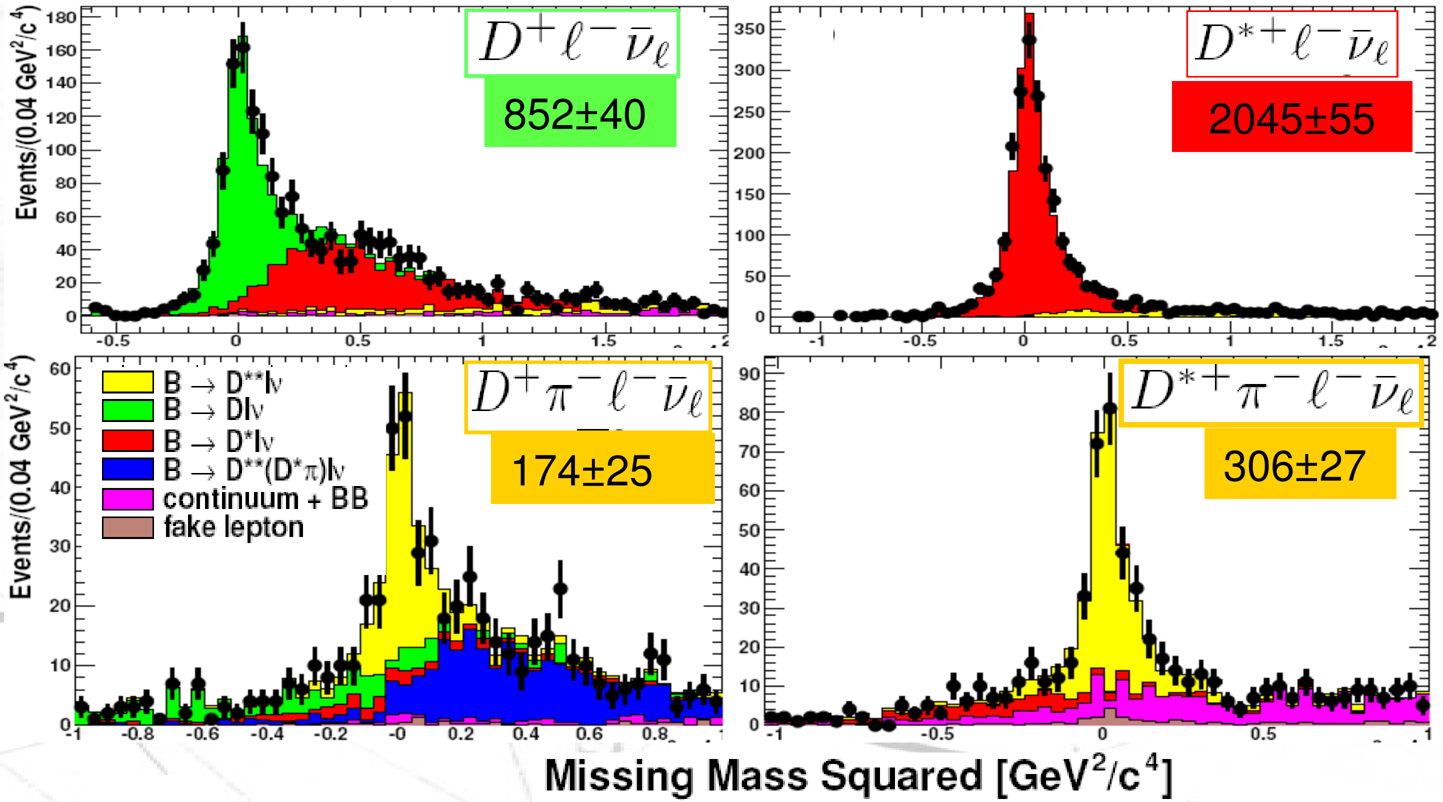
- Improved precision: 2.1% (Winter 2006) → 1.6% (now) on $F(1)|V_{cb}|$
- Using $F(1) = 0.919 + 0.033$ (Hashimoto et al PRD66 104503): $|V_{cb}| = (39.1 + 0.6 + 1) 10^{-3}$
- While from inclusive decays (kin. scheme) $|V_{cb}| = (41.68 + 0.39 + 0.58) 10^{-3}$
- Discrepancy between inclusive and exclusive $|V_{cb}|$

341M $B\overline{B}$

arXiv:0712.3503 [hep-ex] submitted to PRL

Branching Fractions for $B \to D/D^*/D\pi/D^*\pi\ell\nu$

- Breco sample
- reconstruct e, μ in the recoil
- reconstruct $D^{(*)(0)(\pm)}$ in the recoil
- extract signal by fitting missing mass squared
- dominant syst due to Breco, $\mathcal{B}(D^{(*)(0)(\pm)})$ and track reconstr.



$$\mathcal{B}(B^- \to D^{(*)}\pi\ell^-\bar{\nu}_\ell) = (1.52 \pm 0.12_{stat.} \pm 0.10_{syst.})\%$$
$$\mathcal{B}(\overline{B}^0 \to D^{(*)}\pi\ell^-\bar{\nu}_\ell) = (1.37 \pm 0.17_{stat.} \pm 0.10_{syst.})\%,$$

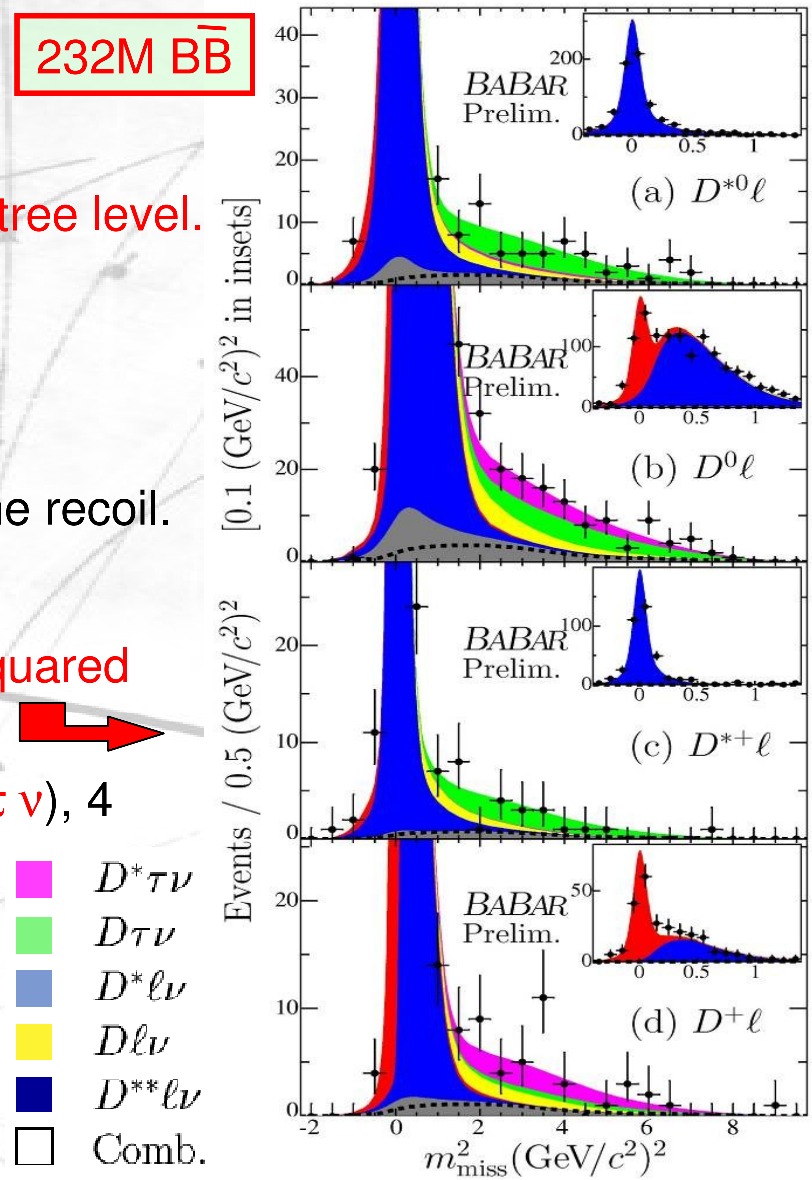
Results consistent with isospin symmetry, but $\Delta_{excl-incl.} = (1.2 \pm 0.4)\%$!

arXiv:0709.1698 [hep-ex]
accepted by PRL

Observation of $B \to D^{(*)}\tau\nu$

232M $B\bar{B}$

- Large τ mass gives sensitivity to new physics at tree level. Eg charged Higgs boson
- Very challenging: $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$ produce two additional neutrinos
- Select Breco events. Identify $D^{(*)}$ plus lepton in the recoil.
- Maximum likelihood fit with:
  - two discriminating variables missing mass squared squared and lepton energy
  - 8 channels: 4 signal ($D^0\tau\nu$, $D^{*0}\tau\nu$, $D^+\tau\nu$, $D^{*+}\tau\nu$), 4 background $B \to D^{**}\ell\nu$.

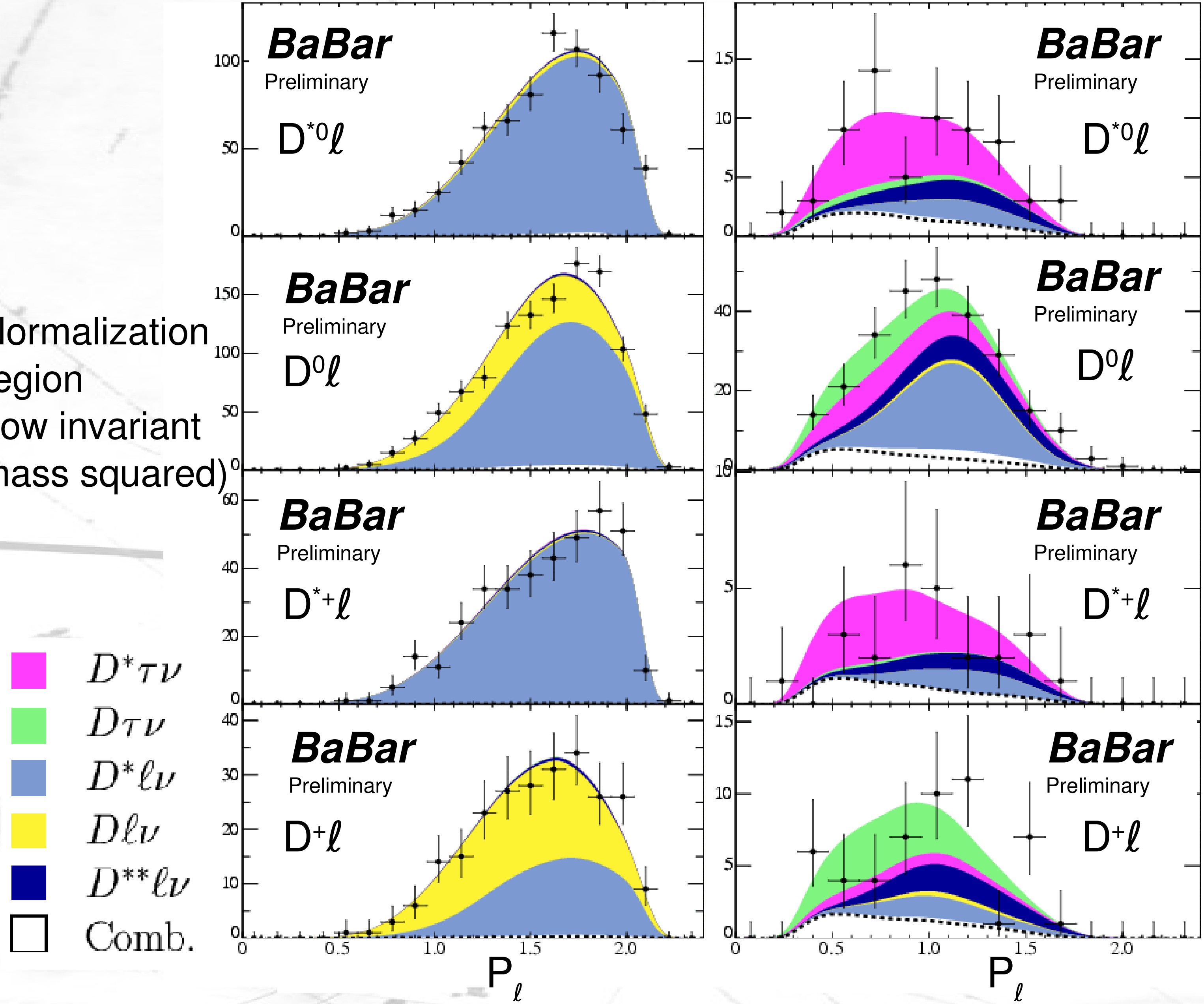


$D^{(*)}\tau\nu$ – fit results

arXiv:0709.1698 [hep-ex]
accepted by PRL

Normalization region (low invariant mass squared)

Signal region (high invariant mass squared)



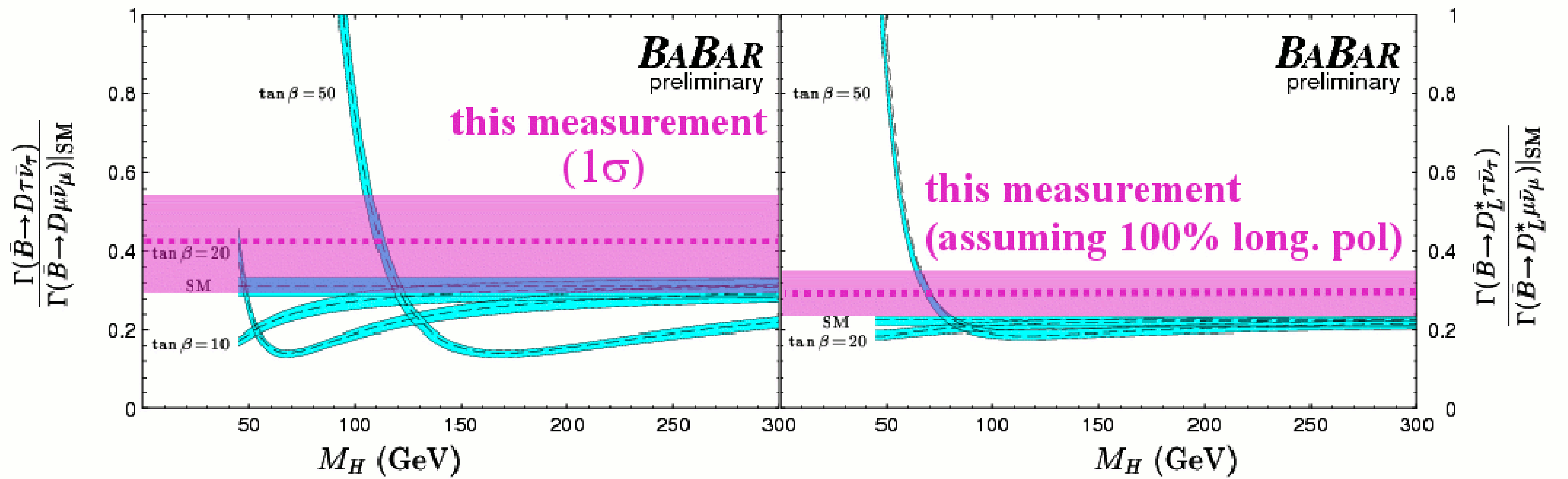
arXiv:0709.1698 [hep-ex]
accepted by PRL

Observation of B → $D^{(*)}\tau\,\nu$

Confirmation of Belle observation in D^{*+}, ***first observation of D^{*0}*** *and* ***first evidence for the D modes.***

Main systematic errors from PDF parametrization, combinatoric background parametrization

Mode	R [%]	$\mathcal{B}$ [%]	
$B\to D\tau^-\overline{\nu}_\tau$	41.6±11.7±5.2	$0.86\pm0.24\pm0.11\pm0.06$	3.6 σ
$B\to D^*\tau^-\overline{\nu}_\tau$	29.7± 5.6±1.8	$1.62\pm0.31\pm0.10\pm0.05$	6.2 σ



Model: type-II 2HDM, Tanaka Z Phys. **C67** 321 (1995)

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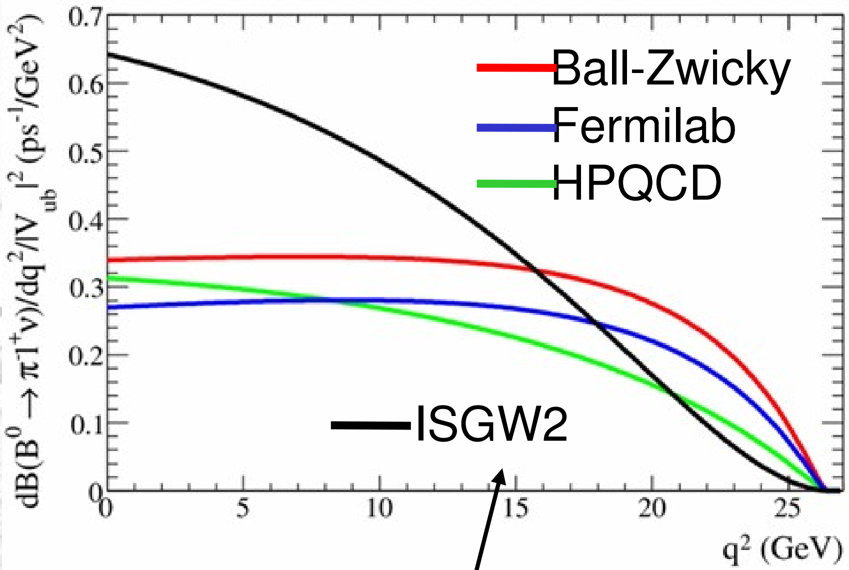
Exclusive $B \to \pi\ell\nu$

- $B \to \pi\ell\nu$ rate is given by

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

One FF for $B \to \pi\ell\nu$ with massless lepton

- Form factor $f_+(q^2)$ has been calculated using
  - Lattice QCD
    - Unquenched calculations by Fermilab (hep-lat/0409116) and HPQCD (PRD73:074502)
    - ±12% for $q^2 > 16$ GeV^2
  - Light Cone Sum Rules
    - Ball & Zwicky (PRD71:014015)
    - ±13% for $q^2 < 16$ GeV^2



Quark model, PRD52 (1995) 2783

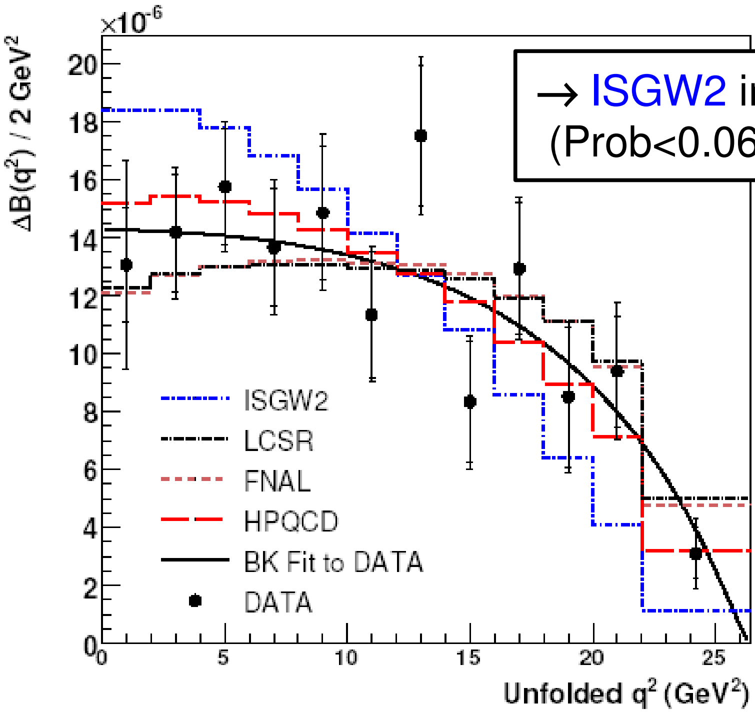
PRL 98, 091801 (2007)

Loose untagged $B \to \pi^+ \ell \nu$

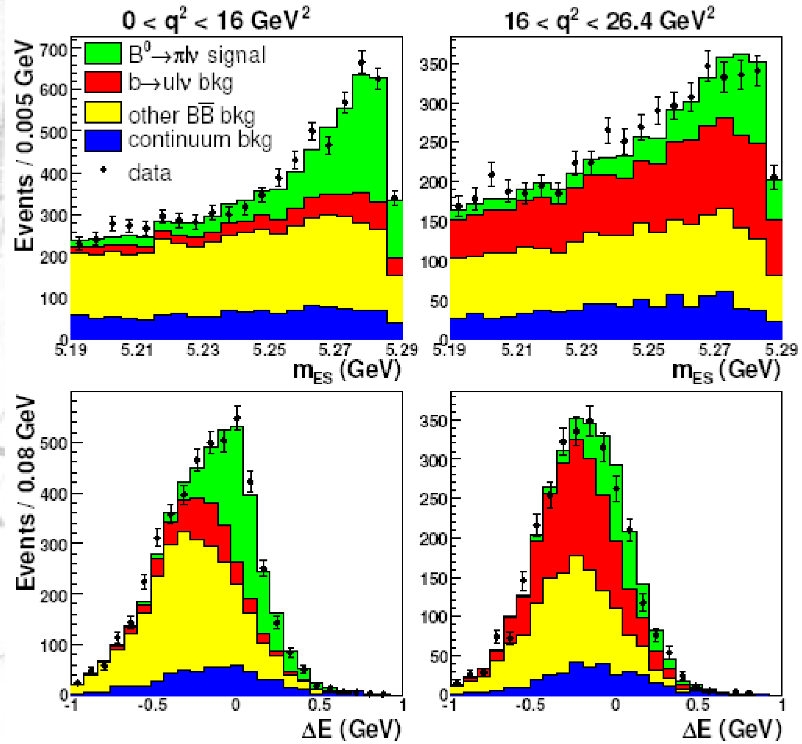
206M $B\bar{B}$

- No Tag
- No *neutrino tight quality* cuts (increase signal efficiency)
- 12 q^2 bins
- Smallest statistical and systematic uncertainties of all individual published $B \to \pi \ell \nu$ measurements
- Larger systematic error due to fit

$\mathcal{B}(B \to \pi^+ \ell \nu) = (1.46 \pm 0.07_{stat} \pm 0.08_{syst}) 10^{-4}$



→ ISGW2 incompatible (Prob<0.06%)



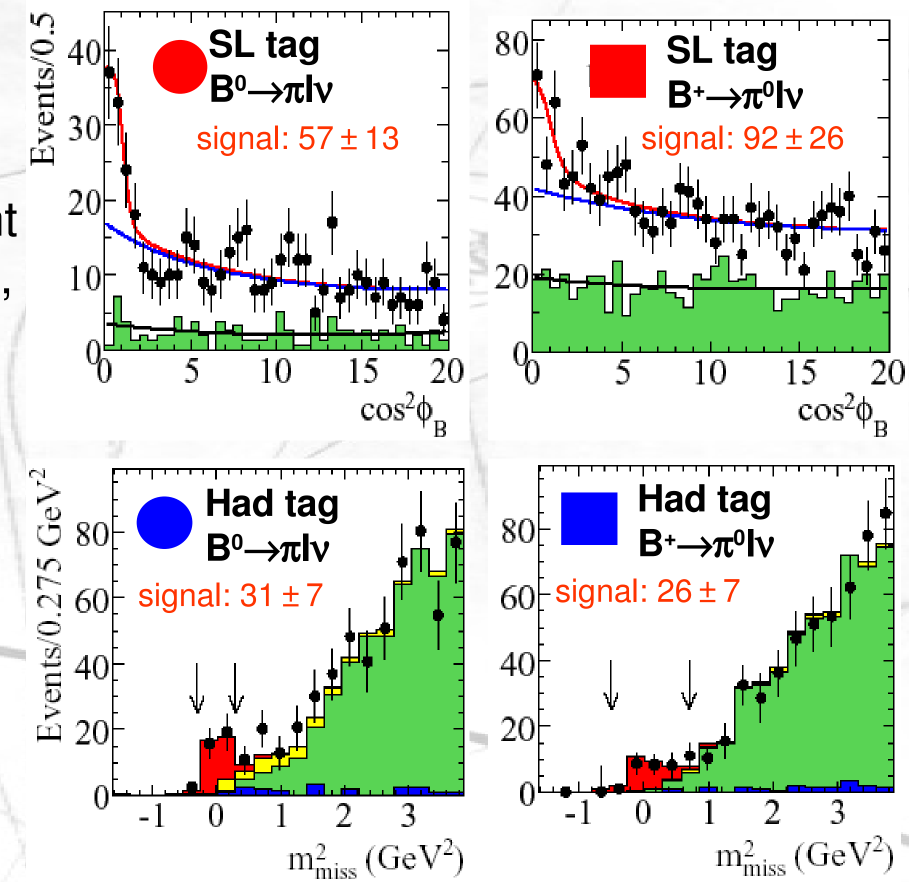
PRL 97,211801 (2006)

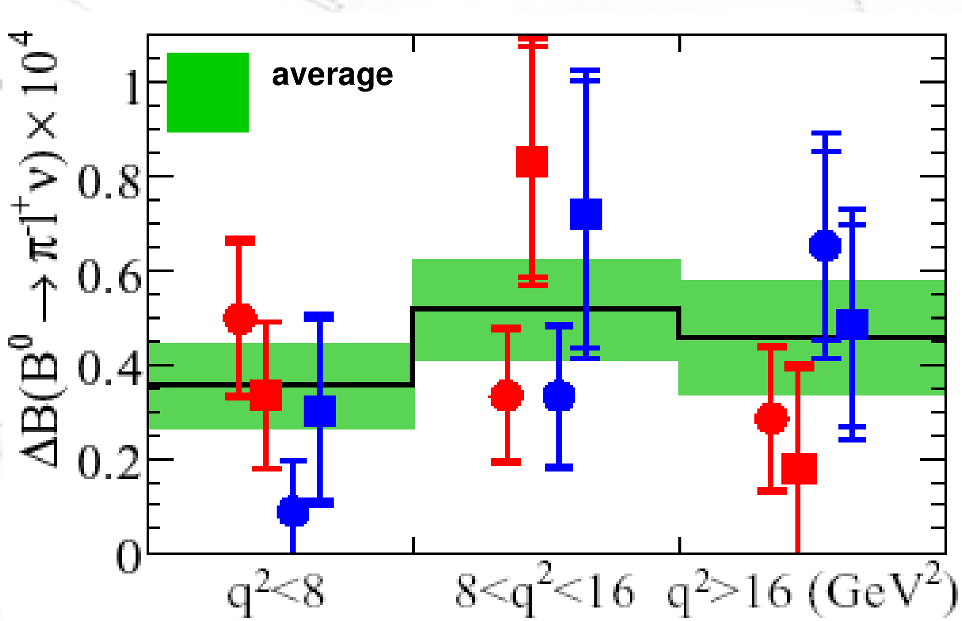
211M $B\bar{B}$

Tagged $B \rightarrow \pi^{0/+} \ell \nu$

ϕ_B is the angle between the directions of the two B mesons.

- Fully (hadronic) and semileptonic tags
- Neutral and charged pion
- 3 q^2 bins
- Dominated by statistical error for the moment
- Main syst errors: signal MC stat., signal PDF, photon and π^0 reconstruction.

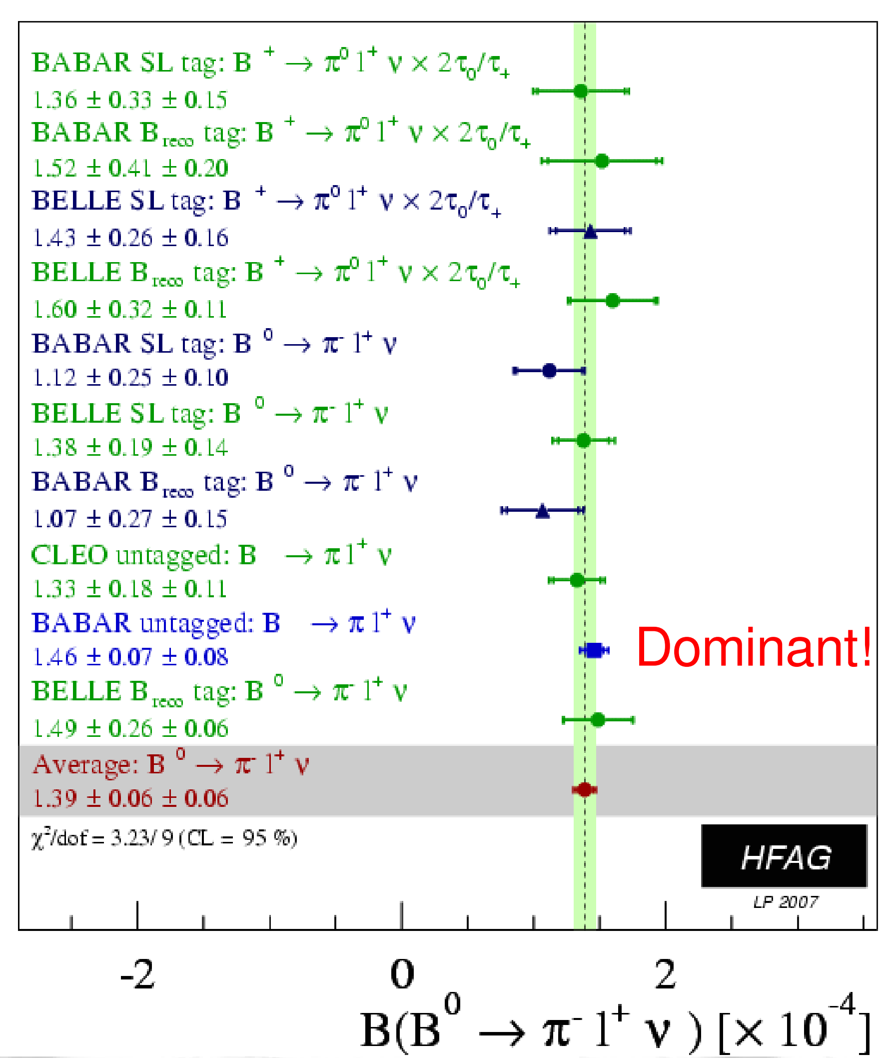


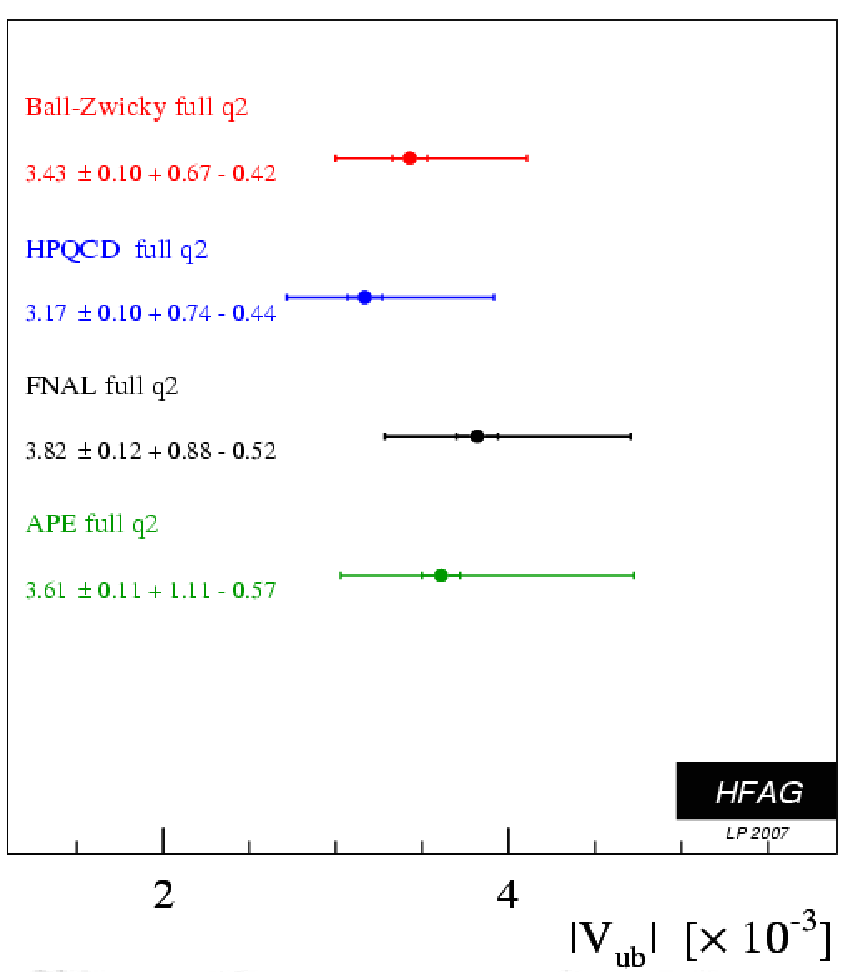


Total B comparable with untagged analysis

$\mathcal{B}(B \rightarrow \pi^+ \ell \nu) = (1.33 \pm 0.17_{stat} \pm 0.11_{syst}) 10^{-4}$

Exclusive $|V_{ub}|$: Summary





HFAG branching fraction average:

$\mathcal{B}(B \to \pi^+ \ell \nu) = (1.39 \pm 0.06_{stat} \pm 0.06_{syst}) 10^{-4}$

$|V_{ub}|$:

- Small experimental errors
- Large theoretical error on FF
- Theory error needs to improve!

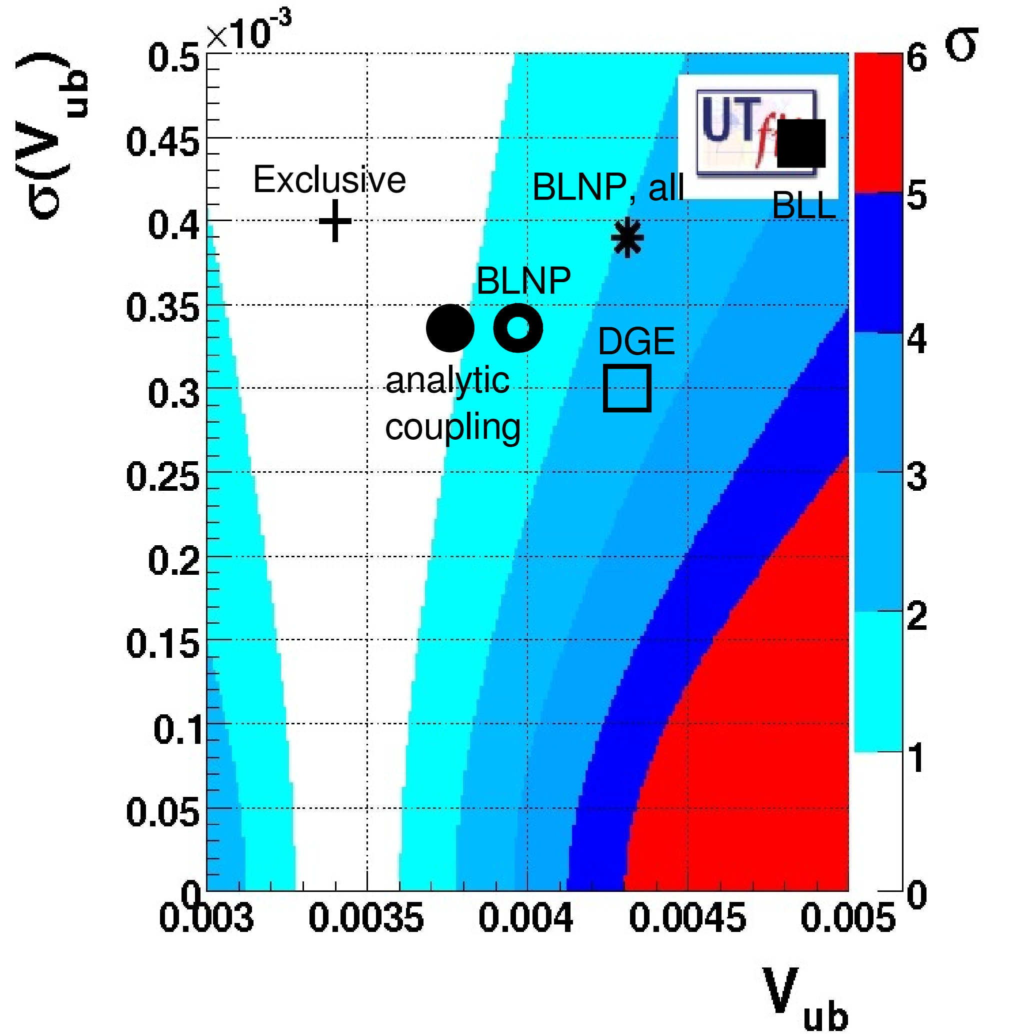
$|V_{ub}|$: CKM consistency

• Most probable value of $|V_{ub}|$ from measurements of other CKM parameters Standard Model and from the exclusive final states favours a value ~ $3.5*10^{-3}$

• Steady work in the inclusive decays to improve current calculations of $|V_{ub}|$

• "Tension" with exclusive decays not there anymore for some calculations

• Still work on the experimental and theoretical side needed to understand current results



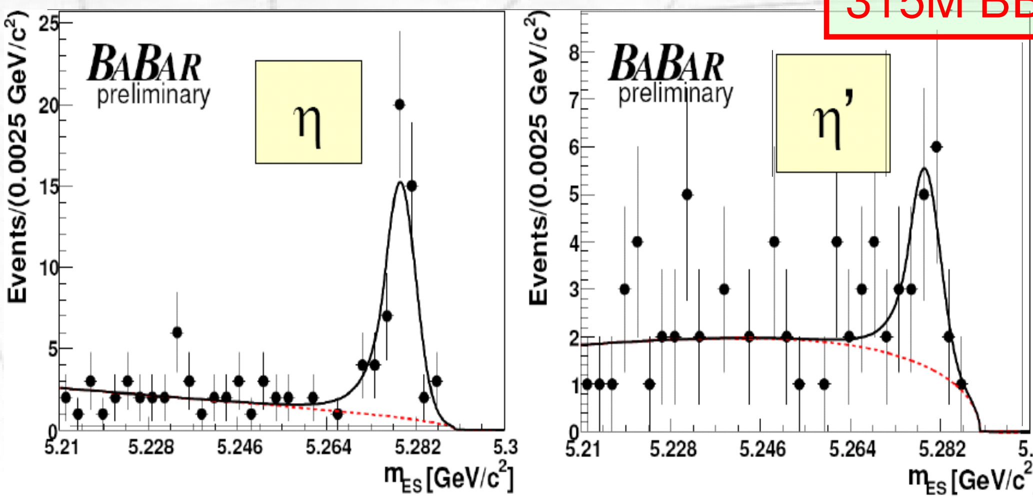
$|V_{ub}|$ values obtained with other methods have larger errors than $0.5 \bullet 10^{-3}$.

Other Modes: $B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$

Independent measurements of various $B \to X_u \ell \nu$ decay modes important to further constraint theoretical models

- Hadronic tag
- Reconstruction of signal B:
  - → Lepton momentum $p^* > 0.5$ GeV for electrons $p^* > 0.8$ GeV for muons
  - → Meson reconstructed in
    - $\eta \to \gamma\gamma$
    - $\eta \to \pi^+\pi^-\pi^0$
    - $\eta \to \pi^0\pi^0\pi^0$
    - $\eta' \to \rho\gamma$
    - $\eta' \to \eta\pi^+\pi^-$
- fit to m_B distributions to extract signal yields

315M $B\bar{B}$



$\mathcal{B}(B^+ \to \eta\, l^+\nu) < 1.4 \times 10^{-4}$ (90% *CL*)

$\mathcal{B}(B^+ \to \eta l^+\nu) = (0.84 \pm 0.27_{stat} \pm 0.21_{syst})10^{-4}$

$\mathcal{B}(B^+ \to \eta'\, l^+\nu) < 1.3 \times 10^{-4}$ (90% *CL*)

Need more data!

Outline

- Introduction
  - Motivations
  - BaBar
  - Experimental approach
- Inclusive decays
  - Determination of $|V_{cb}|$
  - Determination of $|V_{ub}|$
- Exclusive Decays
  - $D^{(*(*))}\ell\nu$
  - $\pi(\eta^{(')})\ell\nu$
- Conclusions

Summary

- Very significant improvements of understanding semileptonic B decays in the past 5 years!
- Challenge of QCD corrections is being addressed.
- High order terms in OPE calculations are needed. Special treatment for $B \to X_s\gamma$ required.
- Experimentally, $B \to X_u\ell\nu$ measurements can be improved with higher statistics and reduced systematics.
- Exclusive measurements: needed improved normalization of FF by theory
- Current differences between exclusive and inclusive measurements may be of both theory and experimental nature.
- Tight scrutiny needed to arrive at a more stringent test of the CKM matrix in the future!
- First evidence of $B \to D\tau\nu$!