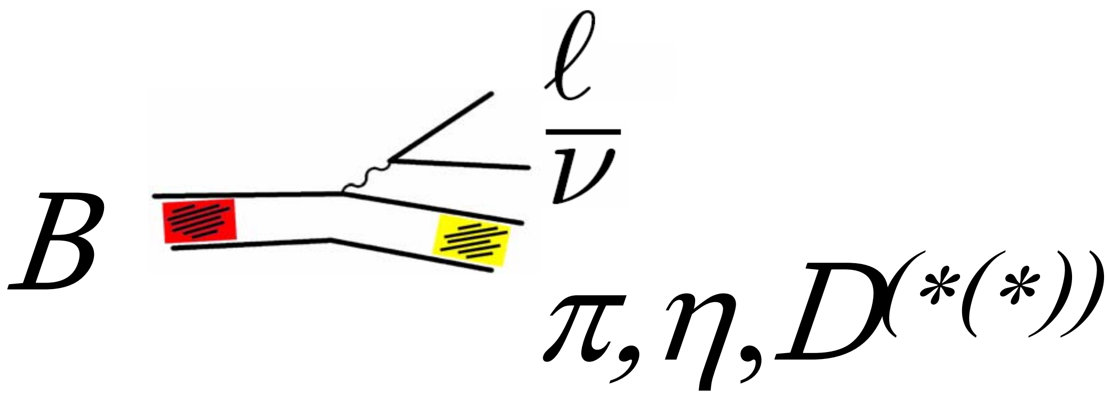
Progress in Semileptonic Decays with BABAR



Jochen Dingfelder,

SLAC, Stanford University

Outline of this Talk

- Introduction:

Semileptonic Decays - Overview & Motivation

PEP-II and BaBar - Status

- Exclusive Semileptonic B decays:

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

$B \to D^{**} l \nu$ narrow states

DPF'06 $B \to D/D^*/D^{**} l \nu$

$B \to \pi l \nu$

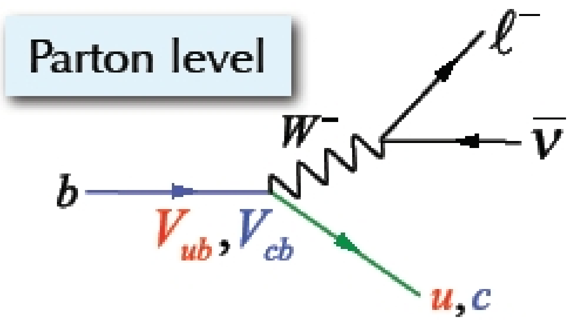
- Exclusive Semileptonic D decays:

$D \to K l \nu$

$D_s \to \phi l \nu$

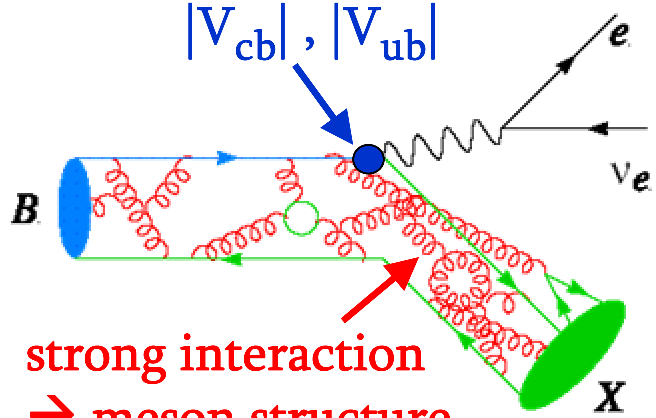
Why Study Semileptonic Decays ?

- Semileptonic decays $B \to X_{c,u} \ell \nu$ offer clear view of the b quark in the B meson
- Leptonic and hadronic currents factorize!



electroweak interaction → coupling

$|V_{cb}|$, $|V_{ub}|$



E_ℓ

$q^2 = (p_\ell + p_\nu)^2$
$= (p_B - p_X)^2$

M_X

strong interaction
→ meson structure

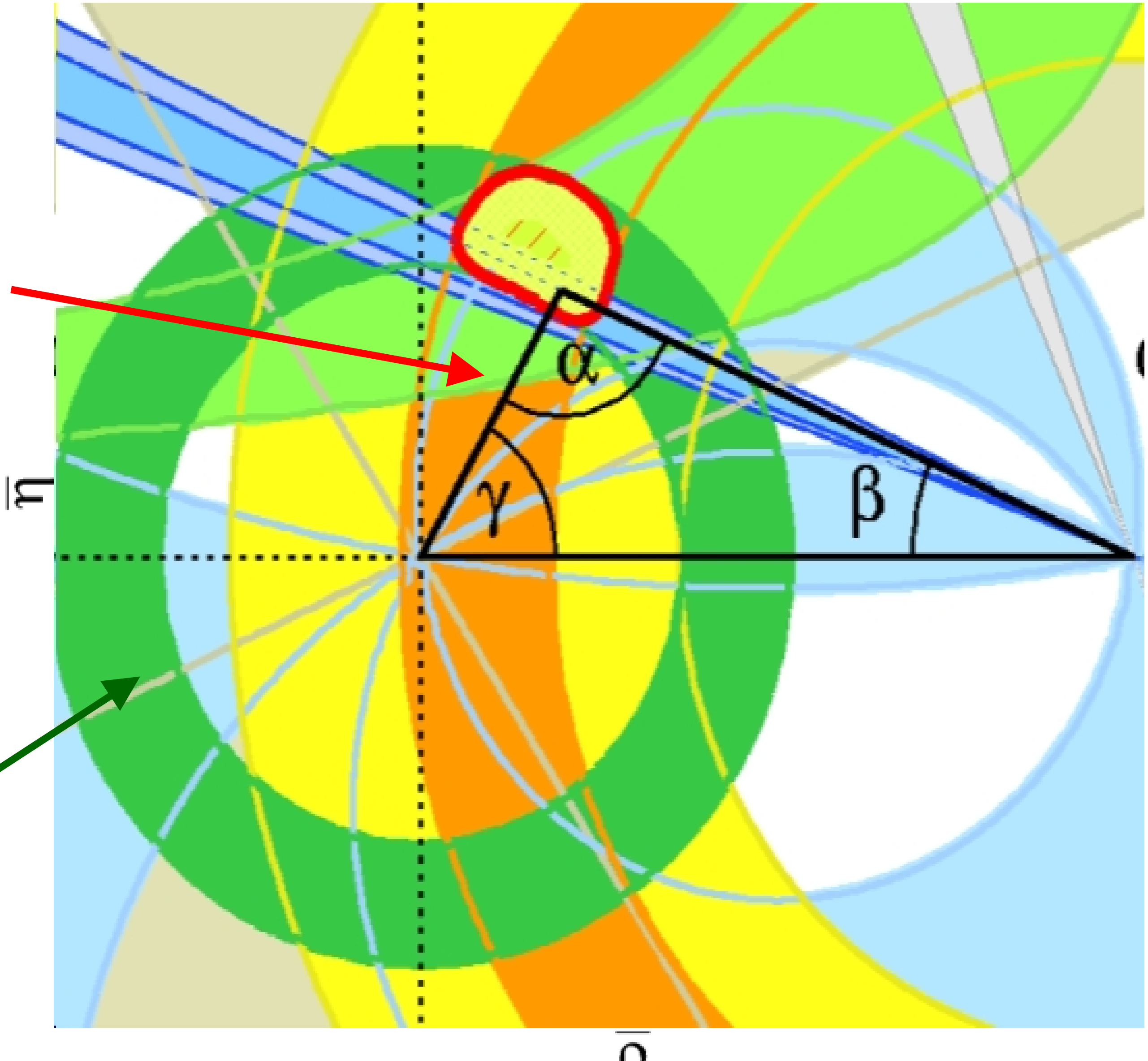
- Two experimental approaches:

Inclusive Decays	Exclusive Decays
➢ Large signal rate, high bkg	➢ Lower signal rate, better bkg reduction
➢ Total rate calculated with HQE	➢ Need Form Factors to describe hadronization process
➢ Need Shape Function (b-quark motion in B meson) → smears kin. spectra.	➢ Measurement as function of q^2, angles

Constraining the Unitarity Triangle

Constraints on Unitarity Triangle

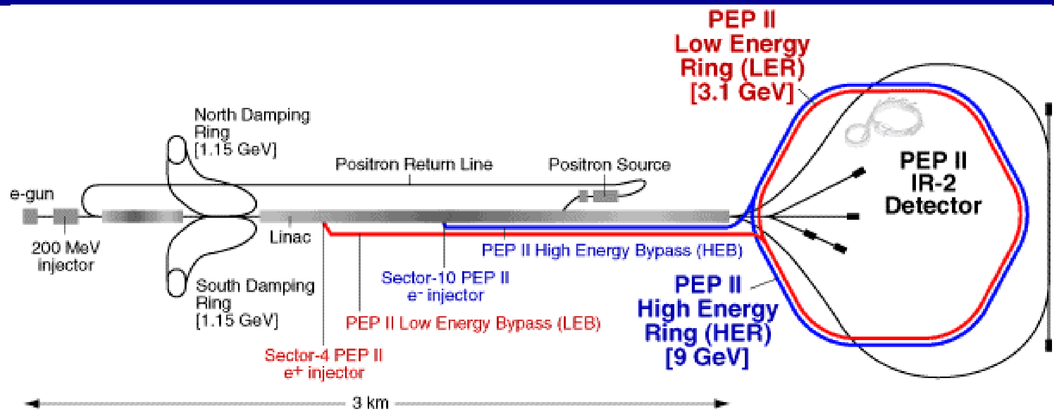
Getting small … but still some space for New Physics!



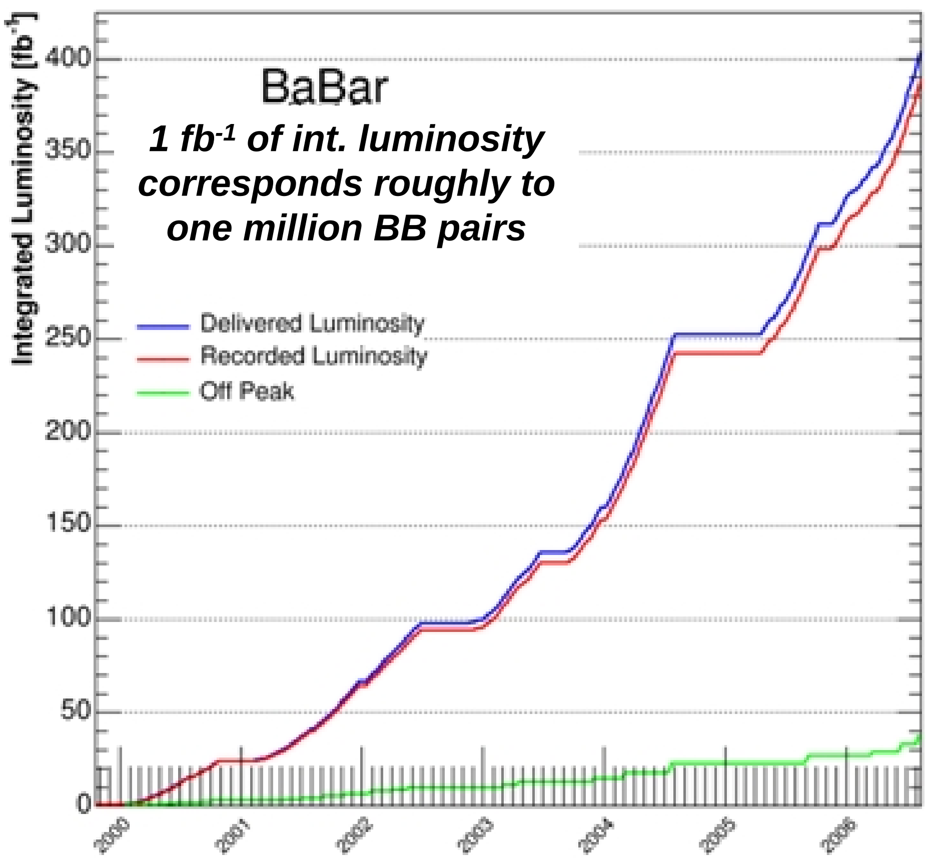
Measurement of $|V_{ub} / V_{cb}|$ complementary to sin2β

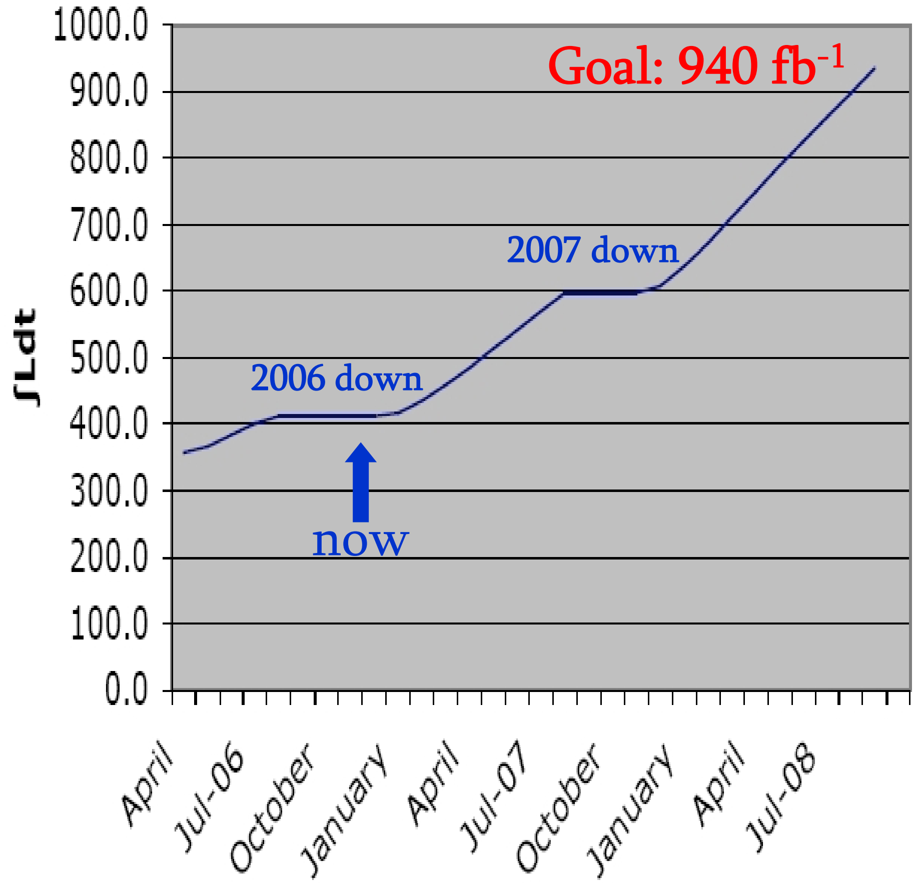
Current precision: $|V_{cb}|$: ~ 2% , $|V_{ub}|$ ~ 7-8% (from inclusive)

Towards 1/ab … PEP-II Performance & Plans



August 2006	PEP-II
L_{peak} [$cm^{-1}s^{-1}$]	12.1×10^{33}
$\int L\ dt$ [fb^{-1}]	410





Our Research Tools

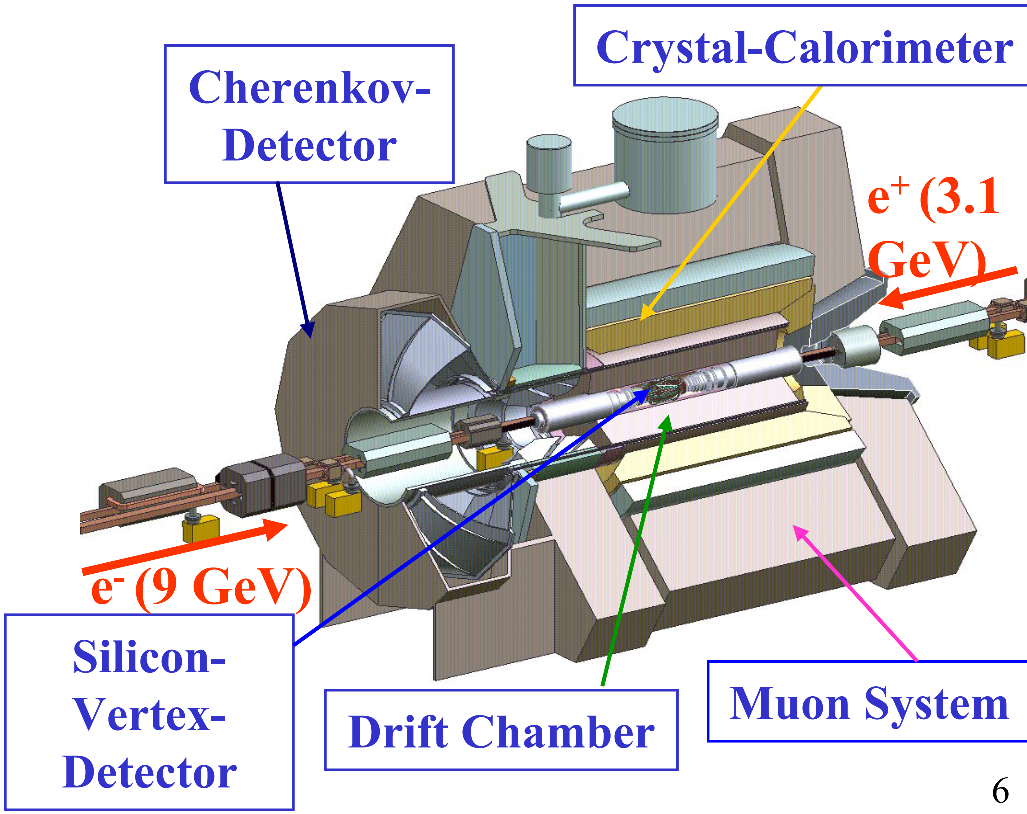
$B \rightarrow X_{c,u}\,\ell\,\nu$

$\rightarrow \pi^{\pm}$'s, $K^{\pm}$'s, γ's

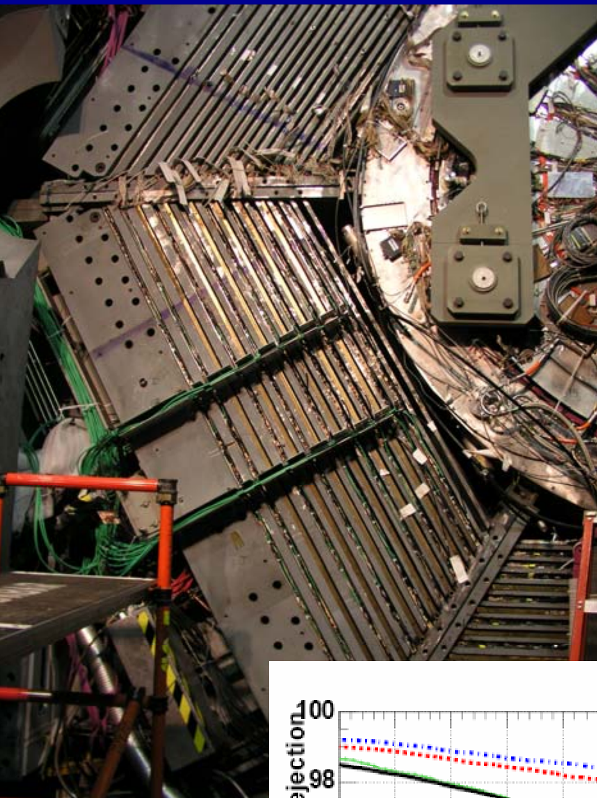
$\ell = e, \mu$

- Good e, μ ID ($p^*_l > 1$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



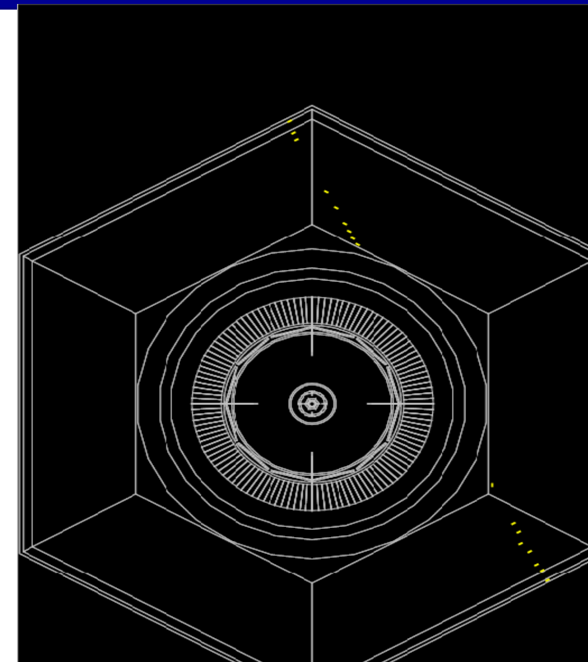
BABAR's New Muon System

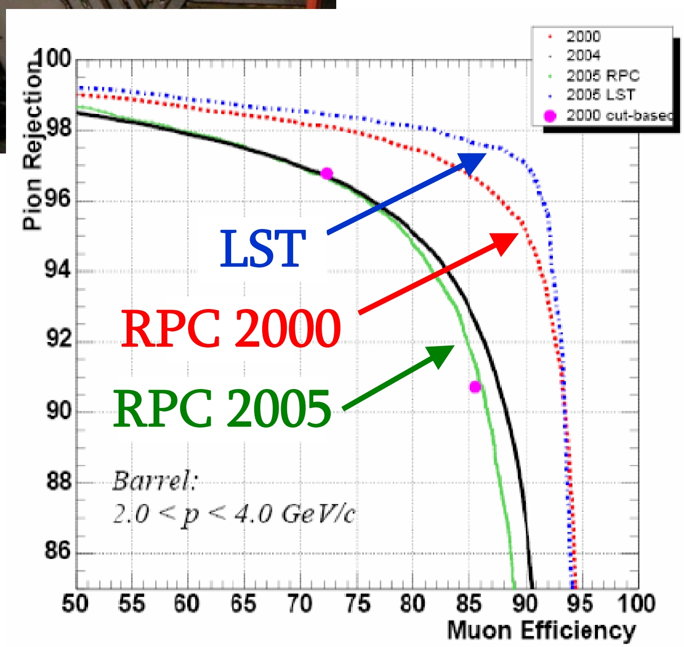


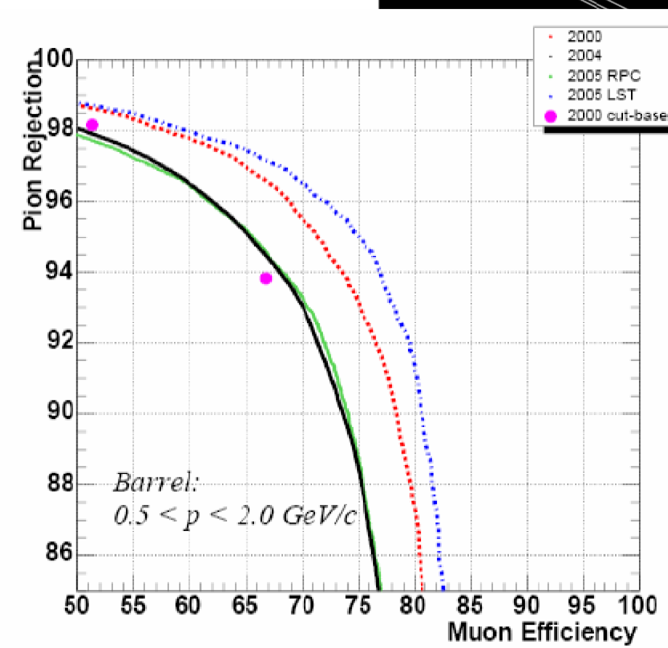
Replaced RPC's
by
12 layers of LST's

Installation complete on
11/13/06

Cosmics seen
11/16/06

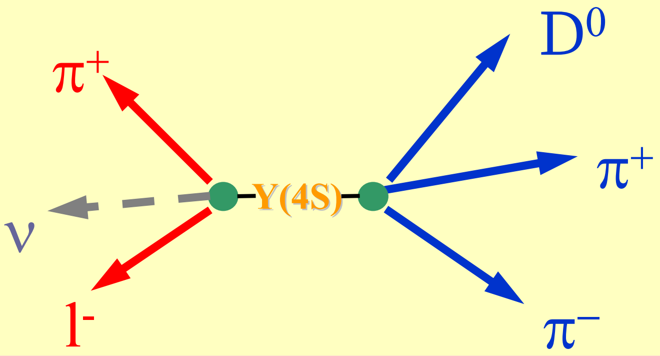






Tagging Methods

$$\Upsilon(4S) \rightarrow B\,\overline{B}$$

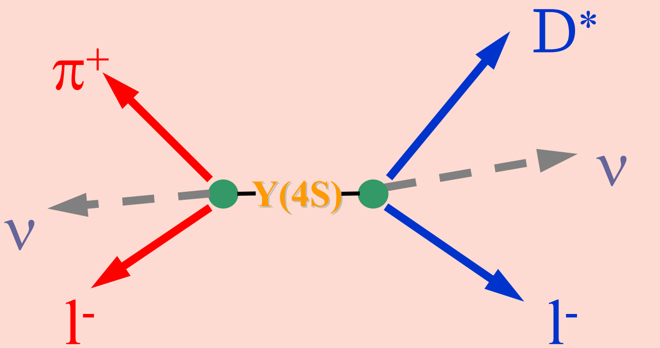


Hadronic Tag:

Fully reconstruct hadronic decay of one B:

$B \rightarrow D^{(*)} + (\pi^+,\pi^0,K^+,K^0)$ ≈ 1000 modes

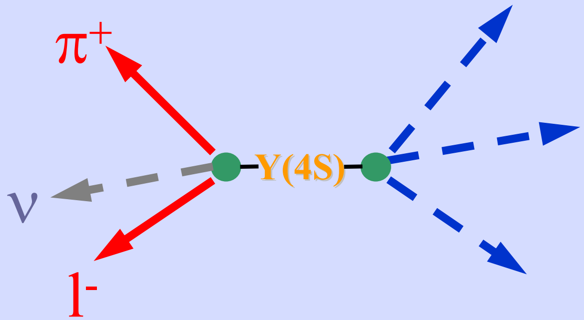
→ know kinematics, charge, flavor of B



Semileptonic Tag:

Reconstruct $B \rightarrow D^{(*)}\,l\,\nu$ and study recoil

Two ν → tag-B kinematics incomplete



No Tag:

High statistics

High backgrounds and cross-feed

→ Fully reconstruct signal side (ν reco.)

Exclusive Measurements

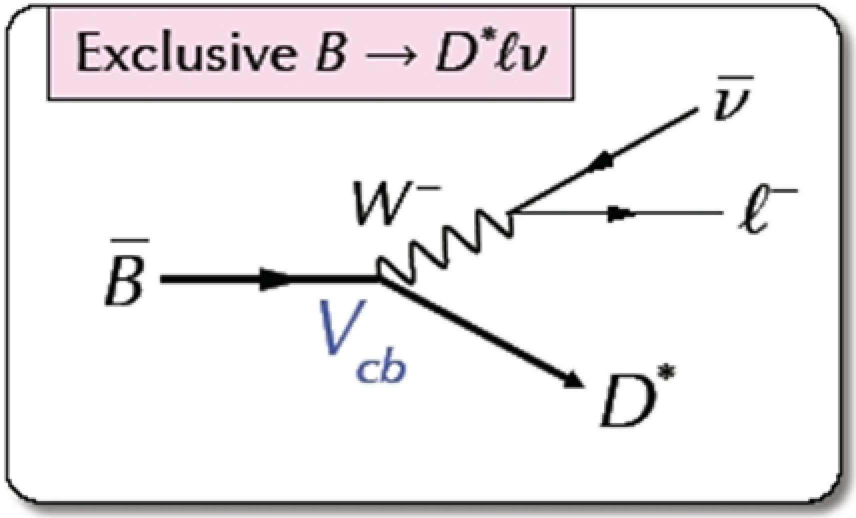
- Exclusive rates determined by $|V_{xb}|$ and form factors (describe hadronization)
- FF's calculated by LQCD, Light-cone sum rules, etc.

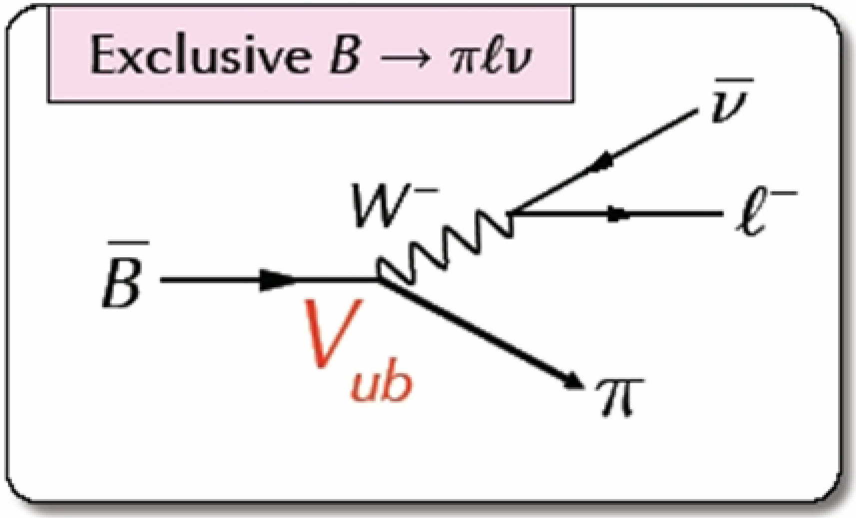
Why study exclusive decays?

→ Learn about QCD effects in semileptonic decays and compare with theoretical predictions

→ Theory uncertainies complementary to inclusive approach

→Good to have an independent cross-check!



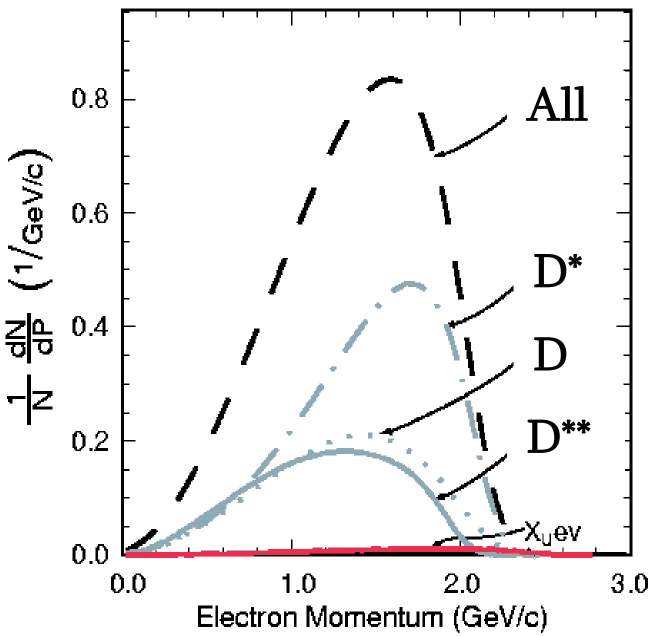


Motivation for Exclusive $B \to X_c \ell \nu$

(1) LQCD calculations are making progress … will push error on $|V_{cb}|$ closer to inclusive result in the (near) future: $B \to D$: 1-2% , $B \to D^*$: 2-3% ?

(2) Better understanding of $B \to D^{(*(*))} l \nu$ background for $|V_{ub}|$

(3) Sum of exclusive states does not saturate total branching fraction:



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) %
$B^+ \to \bar{D}^{(*)} n\pi \ell^+ \nu_\ell$	??

PDG 2006:
5 (10)% mismatch
for B^+ (B^0)

→ Subtracting D and D*, there are 2.5-3% missing!

→ Large non-resonant contribution ?

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

- The decay rate is:

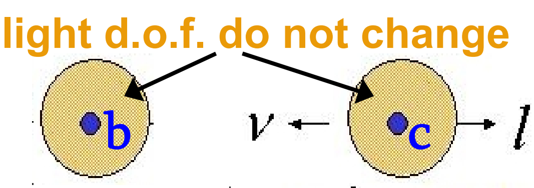
$$\frac{d\Gamma}{dq^2} \propto G(q^2)\,|V_{cb}|^2\,|f(q^2)|^2$$

Phase space

Form factor

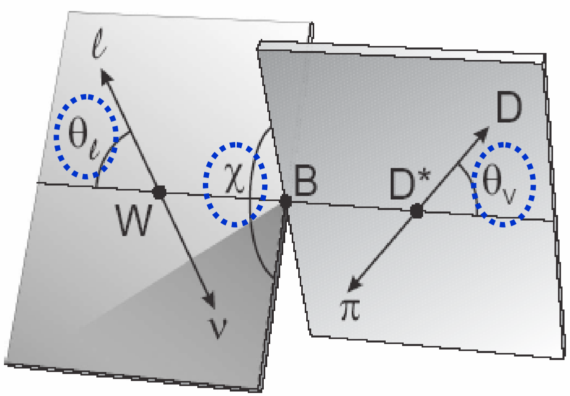
Here we use w = D^* boost in B rest frame

- f (w=1) = 1 in heavy-quark limit
  Lattice QCD says: $f(1) = 0.919^{+0.030}_{-0.035}$ Hashimoto et al, PRD 66 (2002) 014503



- Shape of f (w) expressed in terms of three parameters:
  ρ^2 (slope at w=1) , R1 , R2 (form-factor ratios)

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2 d\cos\theta_\ell d\cos\theta_V d\chi} = \frac{3G_F^2|V_{cb}|^2 P_{D^*} q^2}{8(4\pi)^4 M_B^2} \times$$
$$\{H_+{}^2(1-\cos\theta_\ell)^2\sin^2\theta_V + H_-{}^2(1+\cos\theta_\ell)^2\sin^2\theta_V$$
$$+4H_0{}^2\sin^2\theta_\ell\cos^2\theta_V - 2H_+H_-\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi$$
$$-4H_+H_0\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi$$
$$+4H_-H_0\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\}$$



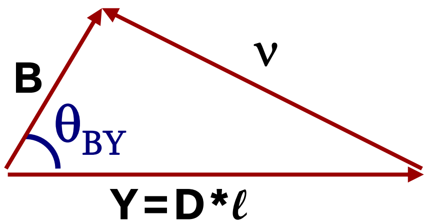
- $H_{+,-,0}$ contain three FF's $A_1(w)$, $A_2(w)$, $V(w)$

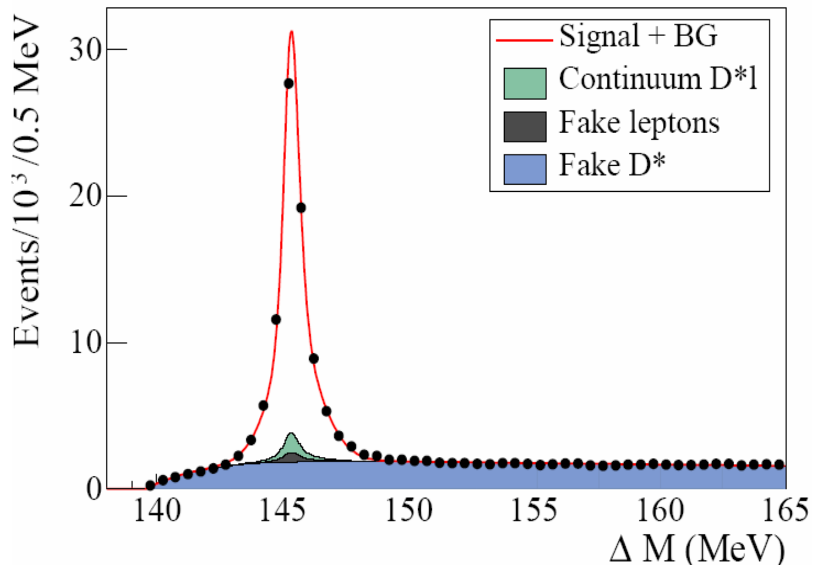
$$A_2(w) = \frac{\boxed{R_1(w)}}{R^{*2}}\frac{2}{w+1}A_1(w) \quad V(w) = \frac{\boxed{R_2(w)}}{R^{*2}}\frac{2}{w+1}A_1(w)$$

Measure angles θ_ℓ , θ_V , χ
→ determine ρ^2, R1, R2

$B^0 \to D^{*+} \ell \nu$ 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 $\cos\theta_{BY}$





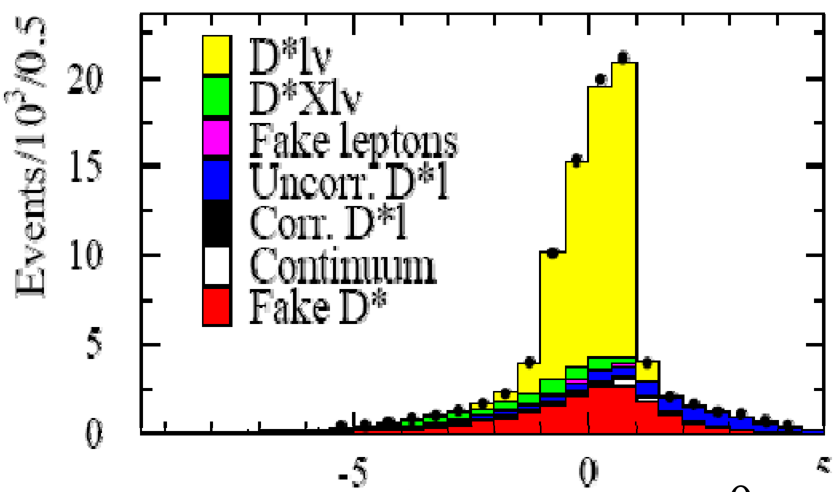
<ins>Two BABAR analyses:</ins>

(1) Three D modes: $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$

χ^2 fit to 1D projections in …

(2) One D mode: $D^0 \to K\pi$,

4D max. LH fit

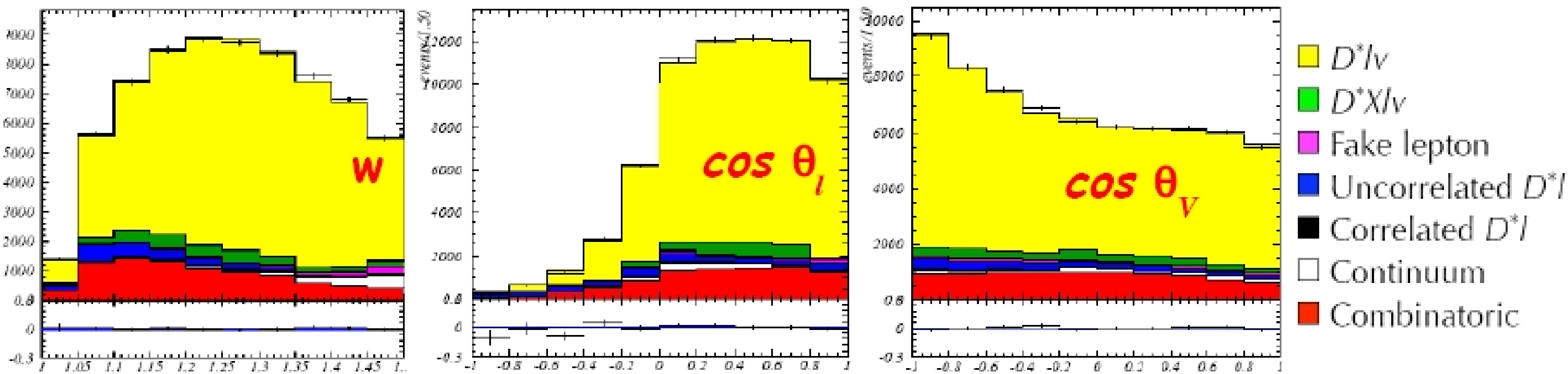


$$\cos\theta_{BY} = -\frac{M_B^2 + M_Y^2 - 2E_B E_Y}{2 p_B p_Y}$$

$B \rightarrow D^*$ 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)
- First simultaneous measurement of form factors and $|V_{cb}|$, fully accounting for all correlations

69k signal events

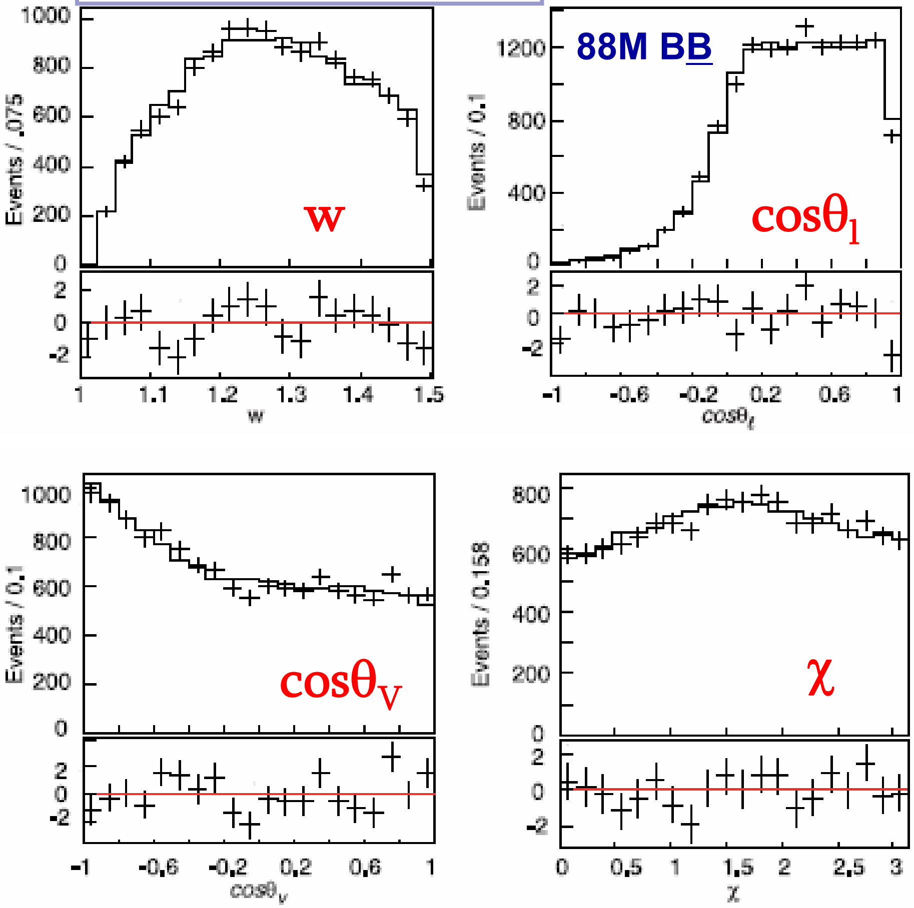


$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$$

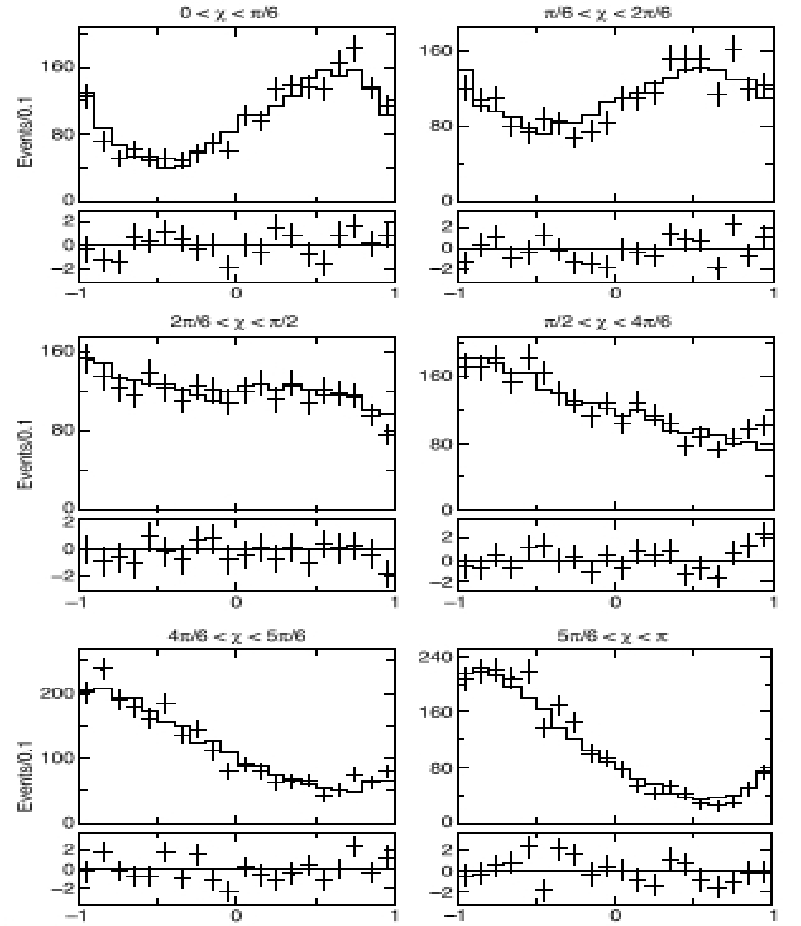
$B \to D^*$ Form Factors : Full 4D Fit

1D projections of fit result:

16k signal events



$\cos\theta_V$ in 6 bins of angle χ



- Fit in $6 \times 6 \times 6 \times 6$ bins: $\chi^2/\mathrm{ndf} = 1337/1291$ (Prob. = 19%)
- Reproduces details of correlations (also angle χ contains valuable information)

BABAR Results vs. World Average

Combination of the (stat. weakly correl.) BABAR results

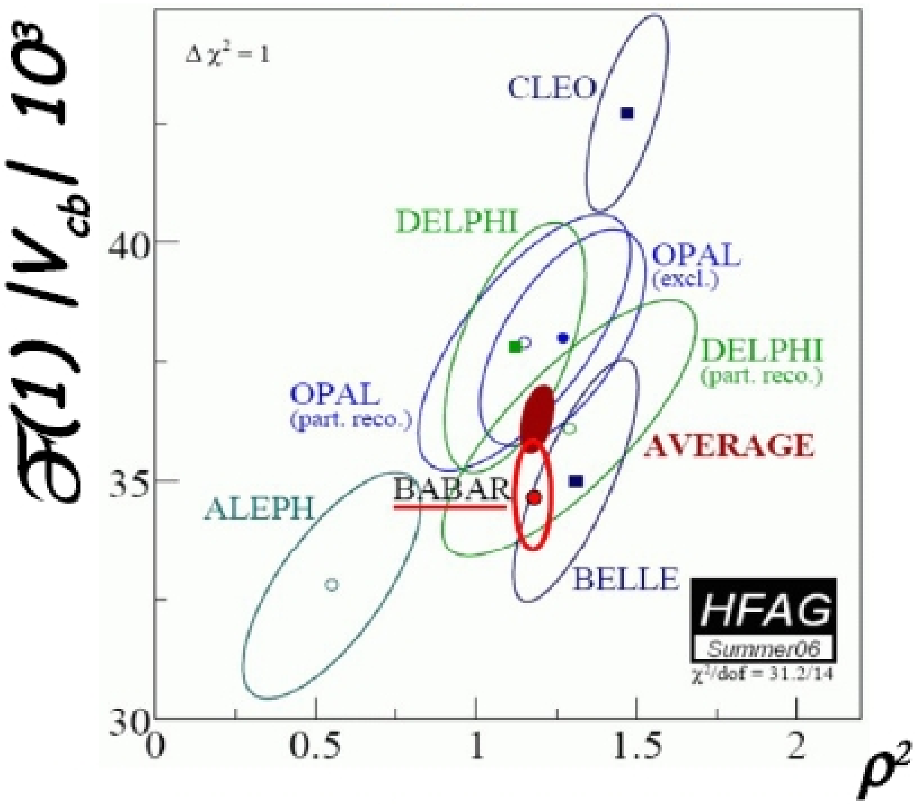
$R_1 = 1.417 \pm 0.061 \pm 0.044$

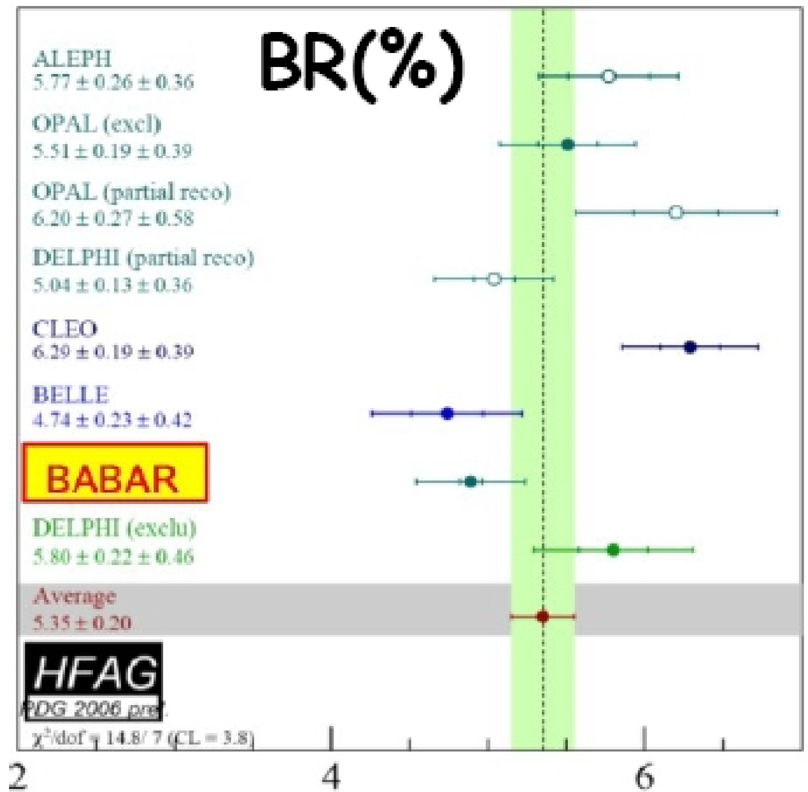
$R_2 = 0.836 \pm 0.037 \pm 0.022$

$\rho^2 = 1.179 \pm 0.048 \pm 0.028$

$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$

$\mathcal{B}(B^0 \to D^* l \nu_l) = (4.77 \pm 0.04 \pm 0.39)\%$



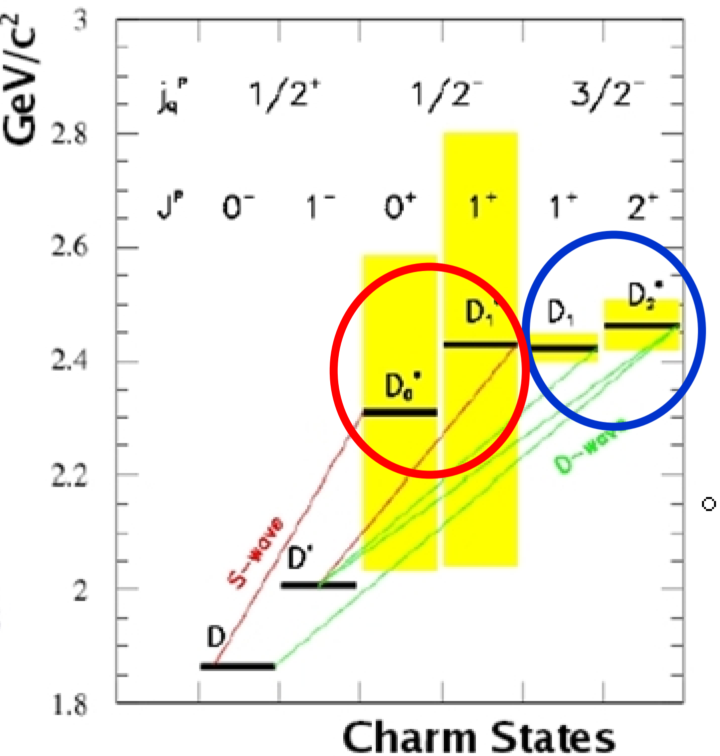


- Form factors 5 × more precise than former CLEO results
- Improved $|V_{cb}|$ syst error (since R1, R2 are significant contributions)

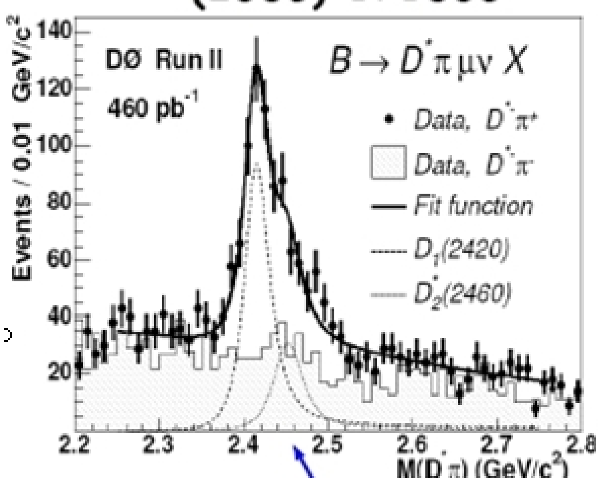
Higher Resonances – D** and Friends

- Use D** as nickname for states D*(nπ) with n>0, including:
  - narrow resonances D_1, D_2^*
  - broad resonances D_0^*, D_1^*
  - non-resonant ?
- So far, little is know about the D**
- Uncertainty of D_1, D_2^* branching fractions still ~ 20-30%

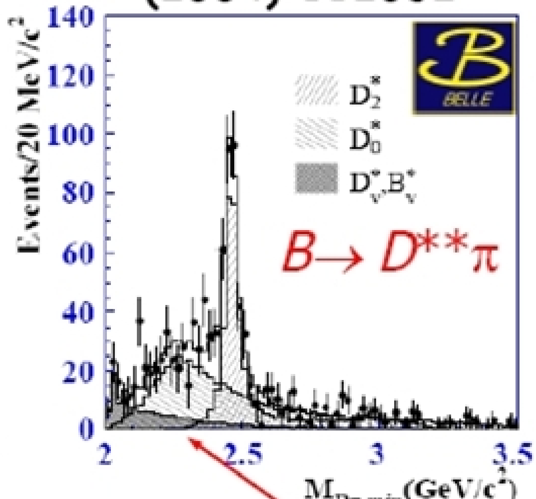
To see what he could see?



Abazov et al, PRL 95 (2005) 171803



Abe et al, PRD 69 (2004) 112002



narrow D_1, D_2^*

broad D_0^*, D_1^*

D^{**} Narrow States : Selection

New!

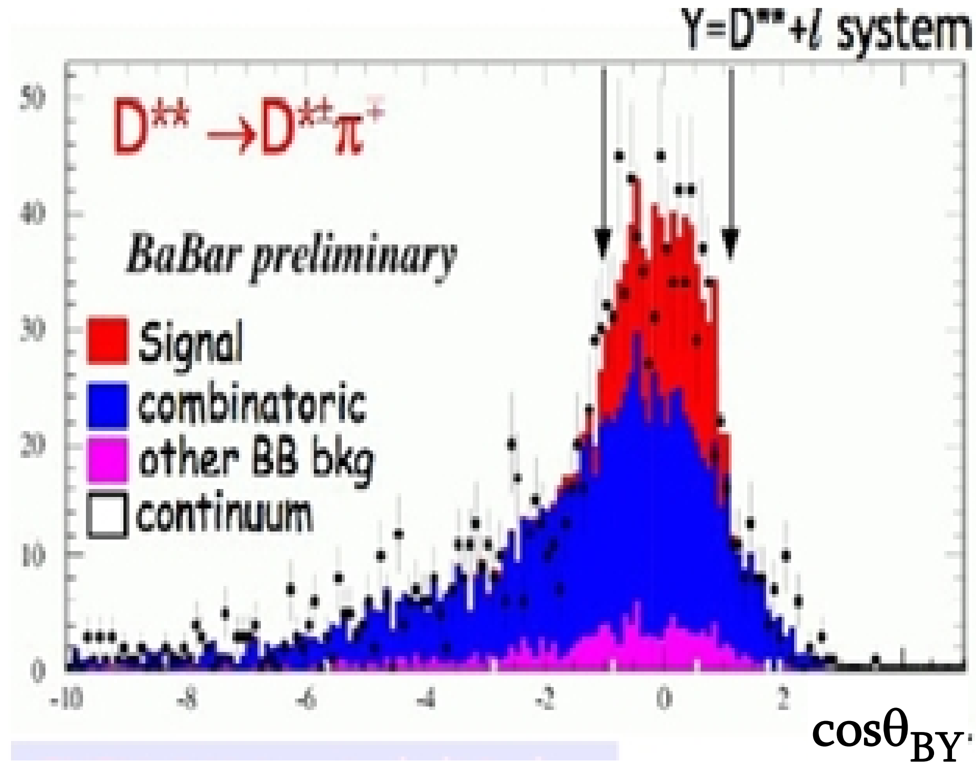
- Untagged analysis
- Use only "easy" decay modes: $D_2^{*0} \rightarrow D^{(*)+}\pi^+$ $\quad D_2^{*+} \rightarrow D^{(*)0}\pi^+$

  $D_1^0 \rightarrow D^{*+}\pi^-$ $\quad D_1^+ \rightarrow D^{*0}\pi^+$

- $p^*_1 > 0.8$ GeV
- Large cominatoric background

  → $|\cos\theta_{BY}| < 1.2$

$\varepsilon(D^{*\pm}\pi^{\mp})=(6.54 \pm 0.28)\%$
$\varepsilon(D^{*0}\pi^{\pm})=(5.26 \pm 0.41)\%$
$\varepsilon(D^{\pm}\pi^{\mp})=(7.59 \pm 0.67)\%$
$\varepsilon(D^{0}\pi^{\pm})=(14.77 \pm 1.46)\%$

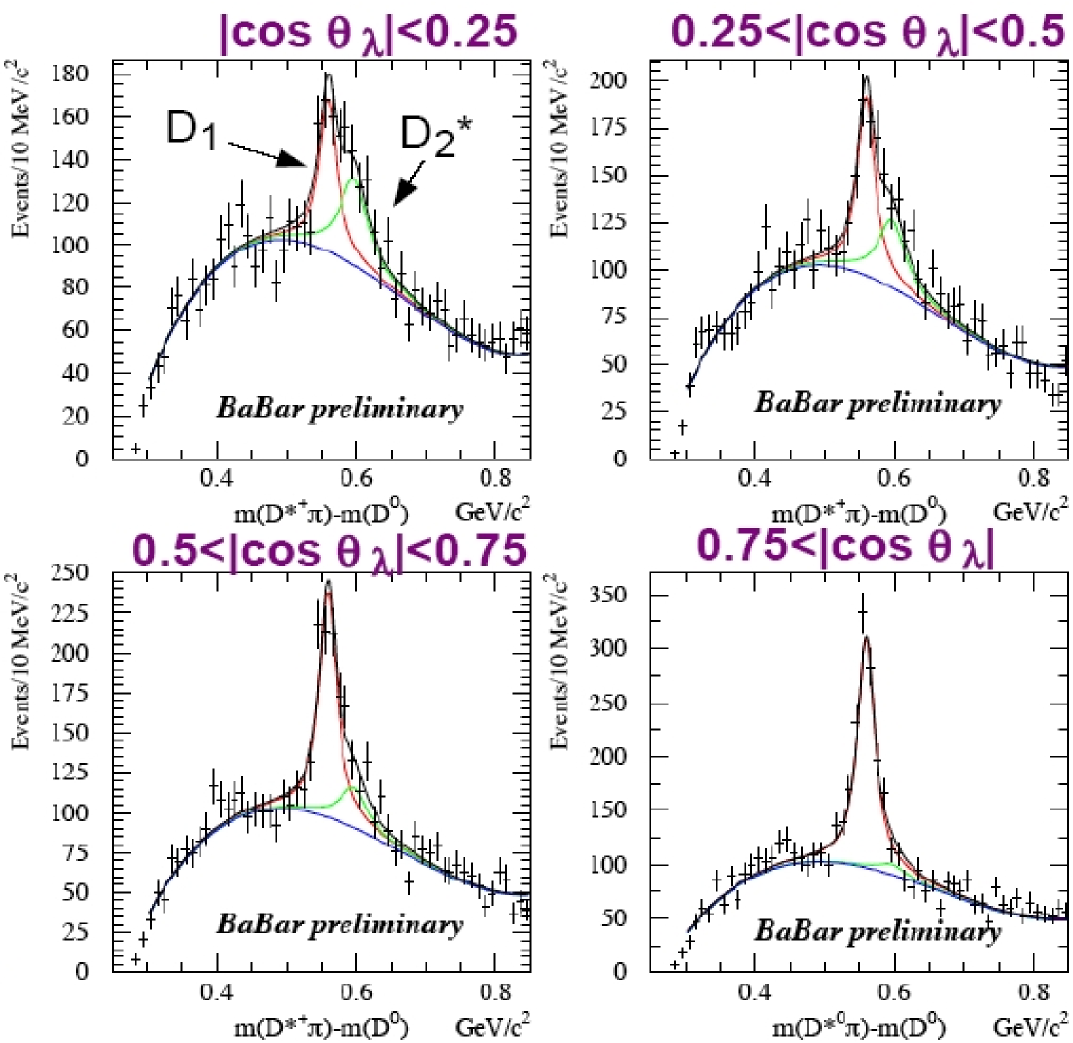


D** Narrow States : Signal Extraction

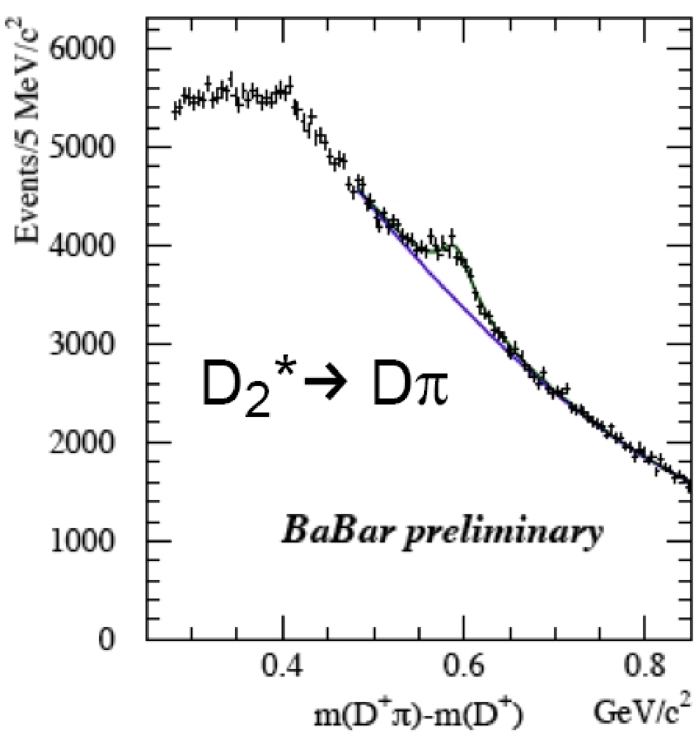
- Simultaneous fit of D_1 and D_2^* in $\Delta M = M(D^{**})-M(D^{(*)})$
- Use 4 D* helicity (λ) bins to separate the two states:

$\lambda(D_1) \sim 1+A\cos^2\theta_\lambda$

$\lambda(D_2^*) \sim \sin^2\theta_\lambda$



$D^{**} \to D\pi$



D** Narrow States : Results

- Fit 12 parameters : 5 branching fractions
  4 widths, 2 masses,
  and A

$$\mathcal{B}(B^- \to D_1^0 l^- \nu) = (4.48 \pm 0.26(stat.) \pm 0.35(syst.)) \cdot 10^{-3}$$

$$\mathcal{B}(B^- \to D_2^{*0} l^- \nu) = (3.54 \pm 0.32(stat.) \pm 0.54(syst.)) \cdot 10^{-3}$$

$$\mathcal{B}(B^0 \to D_1^- l^+ \nu) = (3.64 \pm 0.32(stat.) \pm 0.49(syst.)) \cdot 10^{-3}$$

$$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu) = (2.70 \pm 0.35(stat.) \pm 0.43(syst.)) \cdot 10^{-3}$$

$$\mathcal{B}(D_2^* \to D\pi) = 0.69 \pm 0.03$$

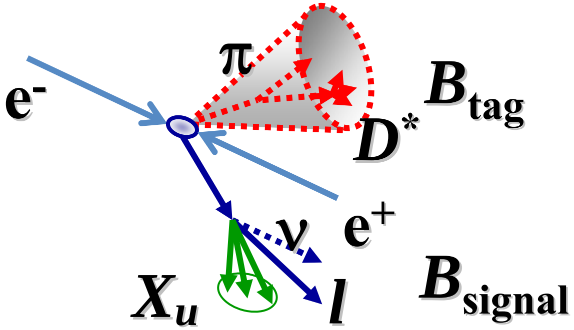
$$A = 2.75 \pm 0.44$$

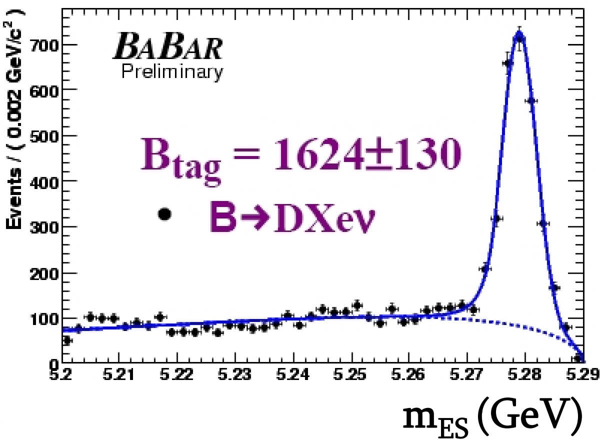
$$\frac{\chi^2}{ndf} = \frac{698.4}{600}$$

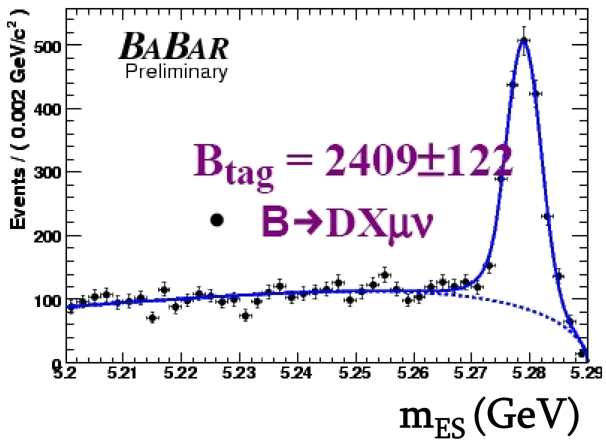
- Error on BF improved to 10-15%

$B \to D/D^*/D^{**}l\nu$ with Hadronic Tag

- Start with selection of "signal-side" D ℓ combination (D/D*/D** all decay through a D)
- Then fully reconstruct tag B from remaining particles in the event (increases efficiency)







$p_{e/\mu} > 0.6\ GeV$

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K_S\pi^+\pi^-(\pi^0), K_S\pi^0, KK, \pi\pi, K_SK_S$

$D^+ \to K^-\pi^+\pi^+(\pi^0), K_S\pi^+(\pi^0), K_S\pi^+\pi^-\pi^+, K_SK^+, K^+K^-\pi^+$

- Extract D, D*, D** components using kinematics and topology
  - Weak sensitivity to D** decay mode or compostition:

$$D^{**} = D_{narrow} + D_{broad} + D_{non\text{-}res}$$

  - Can only determine relative fractions, not absolute branching fractions

Fitting the Various Contributions

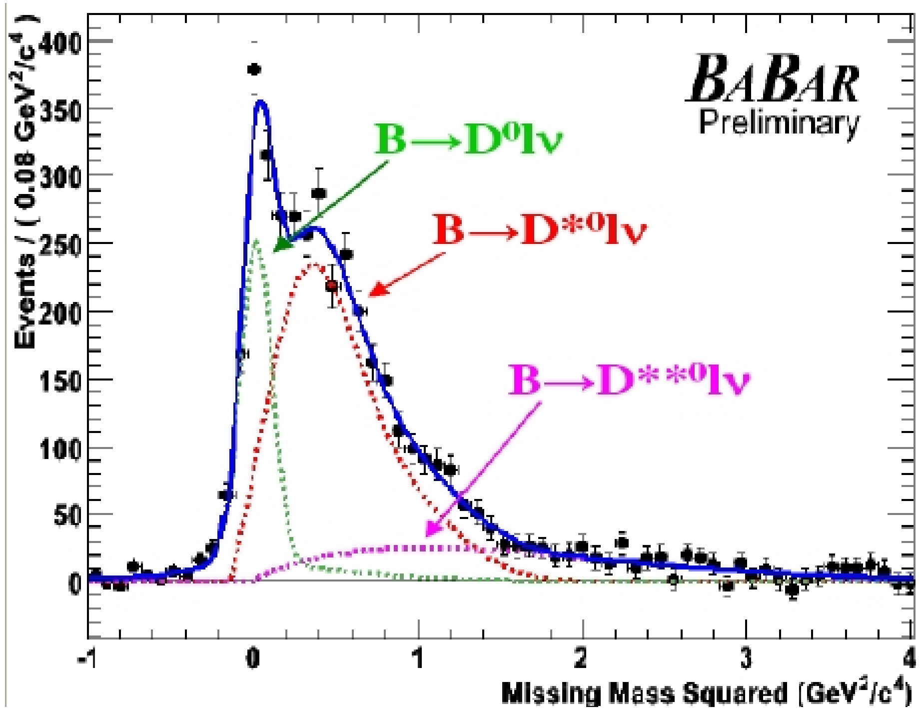
- Global χ^2 fit to "inclusive" distributions:

P_{lepton}

= 0 (Mass²(ν)) for B->Dlν

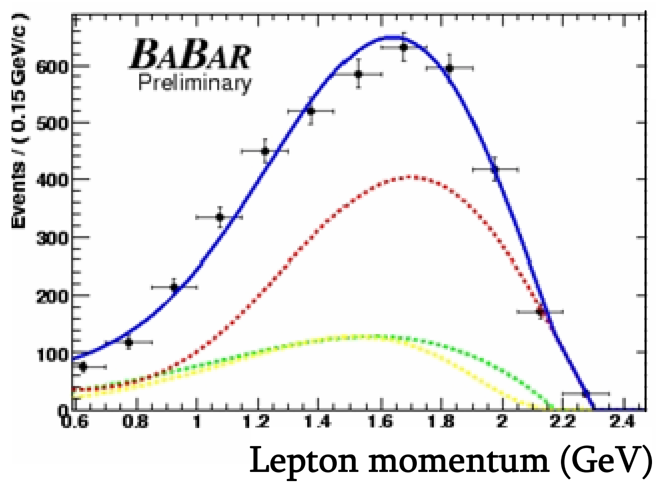
$$M^2_{miss} = (p(\Upsilon) - p(B_{tag}) - p(D) - p_l)^2$$

N (residual charged tracks), remove B_{tag}, D and l



- Shapes of exclusive distributions (PDF's) obtained from enhanced data samples (→ reduces dependence on simulation)

$$\boxed{\begin{aligned} B \to DXl\nu = \; & B \to Dl\nu \\ & + B \to D^* l\nu \\ & + B \to D^{(*)}\pi l\nu \end{aligned}}$$



- Fit rates, feed-down, PDF shape parameters

$B \to D/D^*/D^{**}l\nu$: Results

- Measured ratios of decay rates:

$$\Gamma(B^- \to D^0 l\nu)/\Gamma(B^- \to DX l\nu) = 0.210 \pm 0.017(stat.) \pm 0.021(syst.)$$

$$\Gamma(B^- \to D^{*0} l\nu)/\Gamma(B^- \to DX l\nu) = 0.611 \pm 0.021(stat.) \pm 0.027(syst.)$$

$$\Gamma(B^- \to D^{**0} l\nu)/\Gamma(B^- \to DX l\nu) = 0.173 \pm 0.017(stat.) \pm 0.021(syst.)$$

- If we assume that the 3 contributions saturate total $B \to X_c l\nu$ branching fraction, compute absolute branching fractions:

$$BR(B^- \to X_c l\nu) = (10.9 \pm 0.04)\ \%$$

$$BR(B^- \to D^0 l\nu) = 2.23 \pm 0.19(stat.) \pm 0.23(syst.)\ \%$$

$$BR(B^- \to D^{*0} l\nu) = 6.81 \pm 0.23(stat.) \pm 0.30(syst.)\ \%$$

$$BR(B^- \to D^{**0} l\nu) = 1.93 \pm 0.19(stat.) \pm 0.23(syst.)\ \%$$

- Only ~ 1.7% in the higher mass stuff, while we expect ~ 3% … if multiple π contribution is small … !

Comparison Belle and BABAR

BABAR hep-ex 0607067

$BR(B^- \to D^0 l\nu) = 2.23 \pm 0.19(stat.) \pm 0.23(syst.)\ \%$

$BR(B^- \to D^{*0} l\nu) = 6.81 \pm 0.23(stat.) \pm 0.30(syst.)\ \%$

$BR(B^- \to D^{**0} l\nu) = 1.93 \pm 0.19(stat.) \pm 0.23(syst.)\ \%$

Belle PRD72 051109

$BR(B^- \to D^0 l\nu) = 2.37 \pm 0.10(stat.)\ \%$

$BR(B^- \to D^{*0} l\nu) = 6.06 \pm 0.25(stat.)\%$

$BR(B^- \to D^{**0} l\nu) = 1.81 \pm 0.20(stat.) \pm 0.20(syst.)\ \%$

→ BABAR and Belle results are nicely consistent

A Remaining Puzzle

- Compare measurements of $B^0 \to D^{*+} l \nu$ and $B^+ \to D^{*0} l \nu$:

B factories measure

LEP values somewhat larger
CLEO value much larger

$BR(B^0 \to D^{*-} l\nu)$	$= 4.77 \pm 0.39^{\text{total}}$ %	(Babar Untagged)
$BR(B^0 \to D^{*-} l\nu)$	$= 4.74 \pm 0.48^{\text{total}}$ %	(Belle Untagged)
$BR(B^0 \to D^{*-} l\nu)$	$= 4.70 \pm 0.24^{\text{stat}}$ %	(Belle Tagged)

$BR(B^- \to D^{*0} l\nu)$	$= 6.81 \pm 0.39^{\text{total}}$ %	(Babar Tagged)
$BR(B^- \to D^{*0} l\nu)$	$= 6.06 \pm 0.25^{\text{stat}}$ %	(Belle Tagged)

- Charged-over-neutral BF ratio does not match lifetime ratio (& isospin):

$$R = \frac{Br(B^+)}{Br(B^0)} = 1.32 \pm 0.07 \neq \frac{\tau(B^+)}{\tau(B^0)} = 1.07 \pm 0.02$$

B factories average from
D. Lopez Pegna, DPF.06

Exclusive $B \to X_u l \nu$

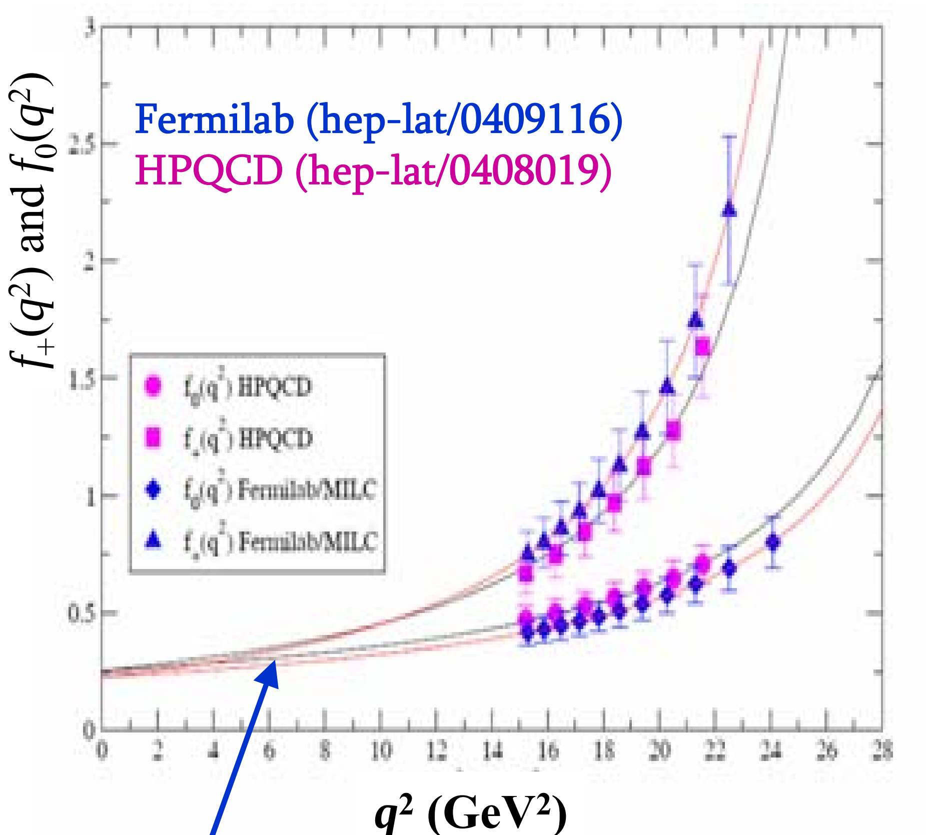
- Branching fractions are $O(10^{-4})$ → in general statistics limited
- $B \to \pi l \nu$ most promising, both experimentally and theoretically
- For $B \to \pi l \nu$, one form factor needed to extract $|V_{ub}|$

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

- $f_+(q^2)$ has been calculated using:
  - Lattice QCD ($q^2 > 16$ GeV^2) → 11% uncertainty
  - Light Cone Sum Rules ($q^2 < 14$ GeV^2) → 11% uncertainty
  - quark models (ISGW2), …

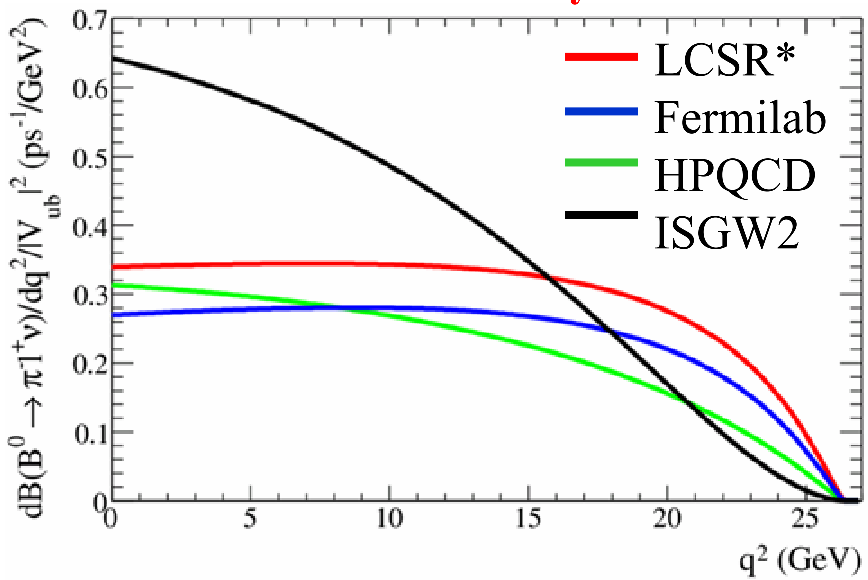
Form-Factor Calculations for $B \to \pi l \nu$

- Unquenched LQCD calculations appeared in 2004
- New light-cone sum rule calculation appeared in 2004



Extrapolation to low q^2 $\rightarrow$ additional uncertainty

*Ball-Zwicky PRD71:014015

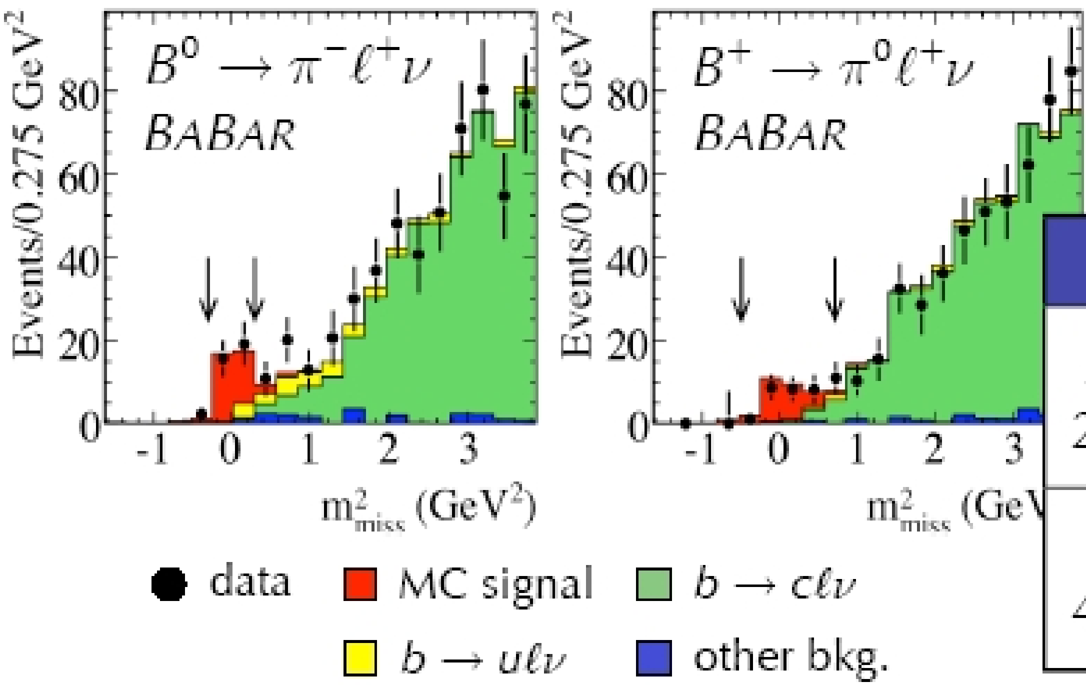


Becirevic-Kaidalov

$$f_+(q^2) = \frac{1}{\left(1 - q^2/m_{B^*}^2\right)\left(1 - \alpha q^2/m_{B^*}^2\right)}$$

$B \to \pi l \nu$ with Hadronic Tags

- Hadronic tags have high purity, but low efficiency
  - Event kinematics is known by a 2-C fit
  - Use m_B and m_{miss} distributions to extract the signal yield

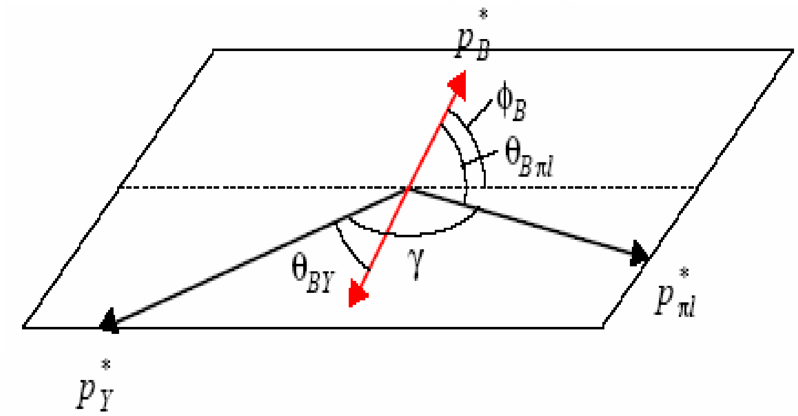


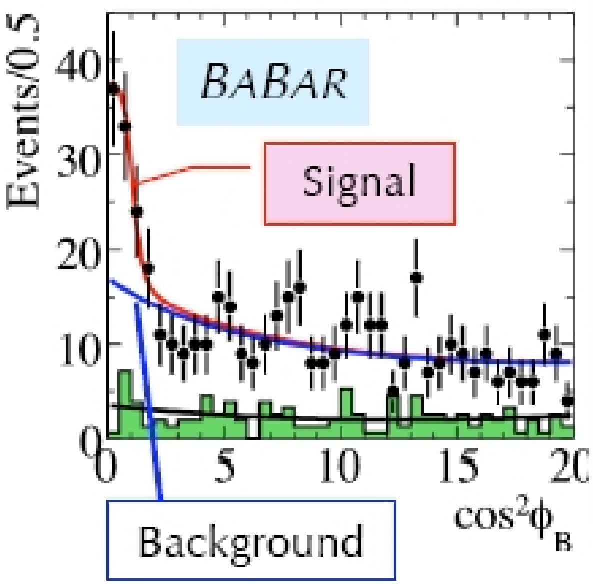
	Mode	BF (10^{-4})
BABAR 211 fb^{-1}	$\pi^-\ell\nu$	1.07 ± 0.33
	$\pi^0\ell\nu$	0.82 ± 0.25
Belle 497 fb^{-1}	$\pi^-\ell\nu$	1.49 ± 0.27
	$\pi^0\ell\nu$	0.86 ± 0.18

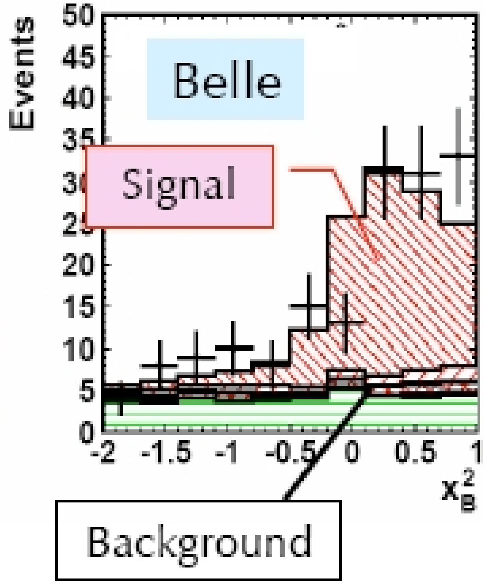
Prelim.

$B \to \pi l \nu$ with Semileptonic Tags

- Tag one B in $D^{(*)}\ell\nu$ and look for $B \to \pi\ell\nu$ in the recoil
  - Pro: $B \to D^*\ell\nu$ BF large
  - Con: Two neutrinos in the event
- Event kinematics determined assuming known m_B and m_ν



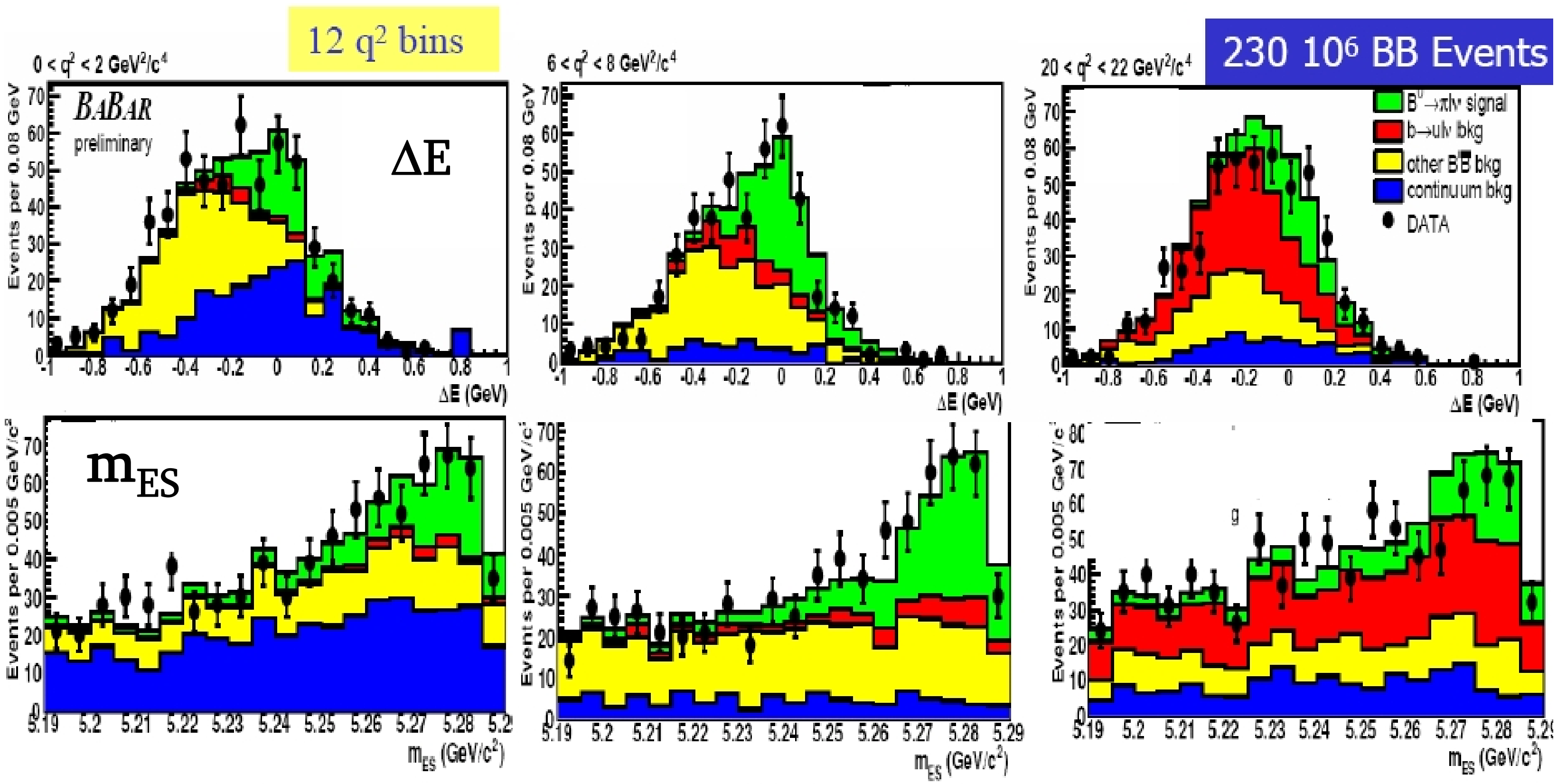




	Mode	BF (10^{-4})
BABAR 211 fb^{-1}	$\pi^-\ell\nu$	1.12 ± 0.27
	$\pi^0\ell\nu$	0.73 ± 0.21
Belle 253 fb^{-1}	$\pi^-\ell\nu$	1.38 ± 0.24
	$\pi^0\ell\nu$	0.77 ± 0.16

Untagged $B \to \pi l \nu$: “Loose” ν Cuts

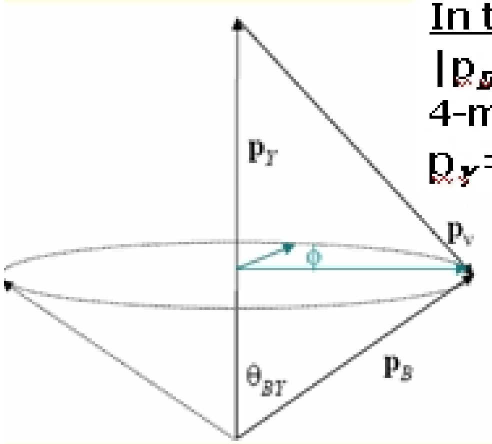
- Missing 4-momentum = p_ν ➔ Reconstruct $B \to \pi \ell \nu$
  - Calculate m_B and ΔE, and perform 2-D fit for signal yields
- *BABAR*'s new result (206 fb^{-1}, preliminary) uses 12 q^2 bins



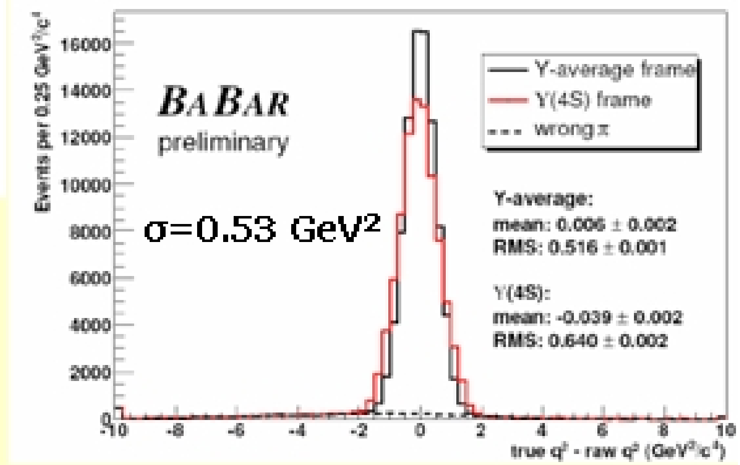
“Loose” ν Cuts – New Features

1. $q^2=(p_B-p_\pi)^2$ with the "Υ-average frame" method

average over arbitrary azimuth Φ, Φ+90°, Φ+180°, Φ+270°



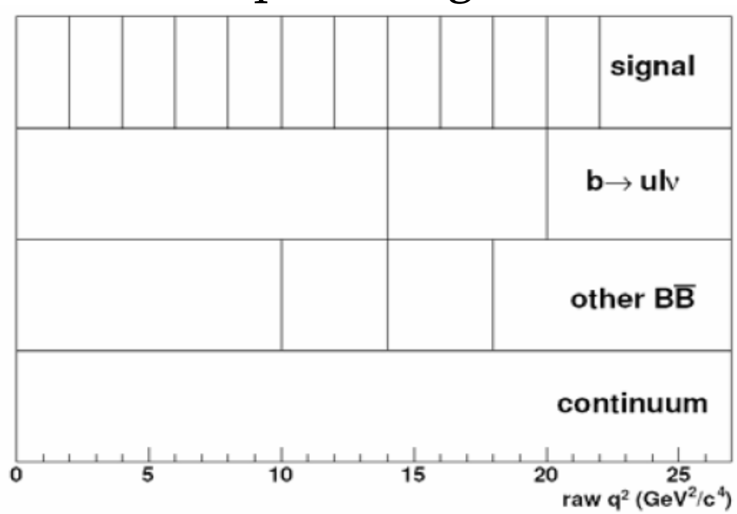
In the Υ(4S) frame:
$|p_B|$ = nominal from 4-mom. conservation
$p_\Upsilon = p_\pi + p_l$



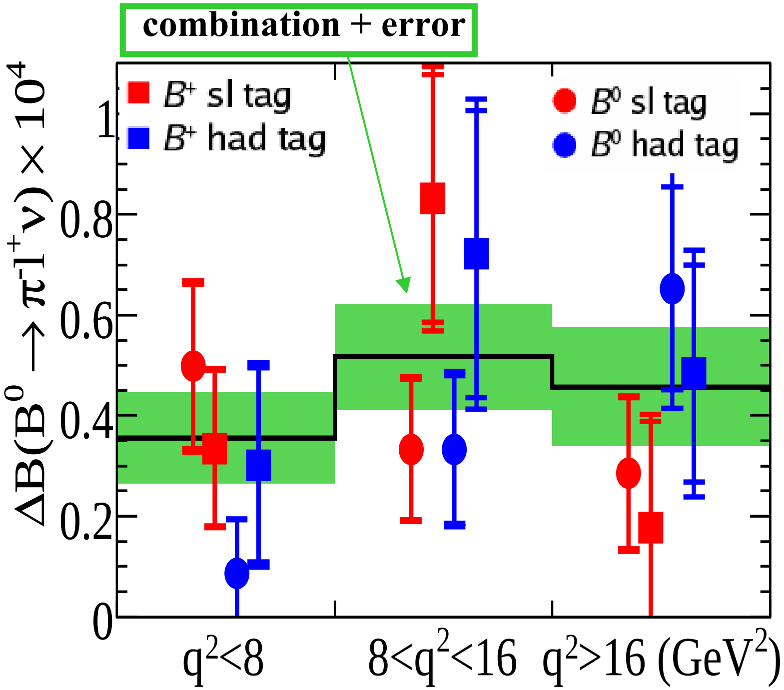
2. Fit backgrounds in bins of q^2

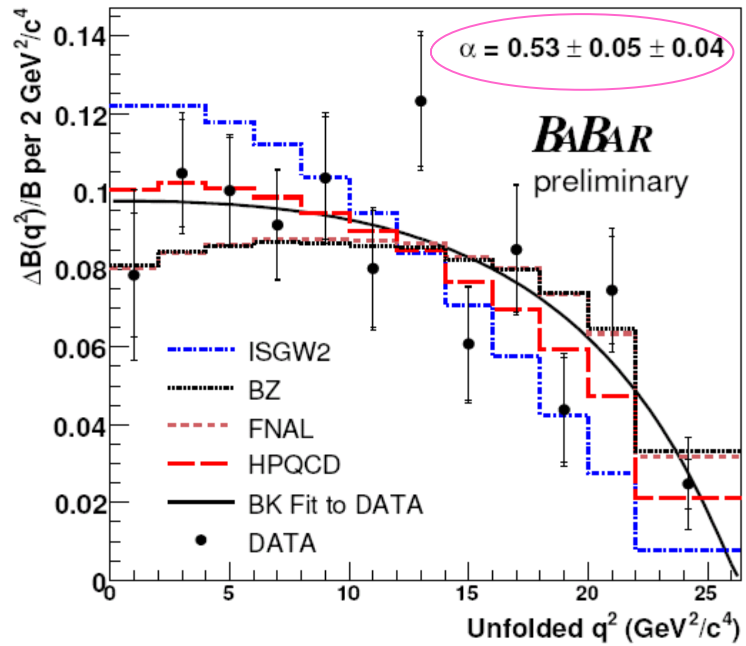
→ reduces syt. uncertainties due to background modeling

q² binning



$B \to \pi l \nu$ Results : Form Factor and $|V_{ub}|$





$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.33 \pm 0.17_{\rm stat} \pm 0.11_{\rm syst}) \times 10^{-4}$$

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

compare shape with theo. predictions

	q^2 (GeV^2/c^4)	$\lvert V_{ub}\rvert$ (10^{-3})	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky [6]	<16	$3.2 \pm 0.2 \pm 0.1^{+0.5}_{-0.4}$	$3.6 \pm 0.1 \pm 0.1^{+0.6}_{-0.4}$
HPQCD [3]	>16	$4.5 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$	$4.1 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}$
FNAL [4]	>16	$4.0 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$	$3.6 \pm 0.2 \pm 0.2^{+0.6}_{-0.4}$
APE [5]	>16	$4.1 \pm 0.5 \pm 0.3^{+1.6}_{-0.7}$	$3.7 \pm 0.2 \pm 0.2^{+1.4}_{-0.7}$

tagged **untagged**

QCD calculation	stat+syst errors χ^2	$Prob(\chi^2)$ (%)	
ISGW2 [7]	34.1	0.07	**incomp.**
Ball-Zwicky [6]	13.0	37.2	**fits well**
FNAL [4]	12.5	41.0	
HPQCD [3]	10.2	60.2	

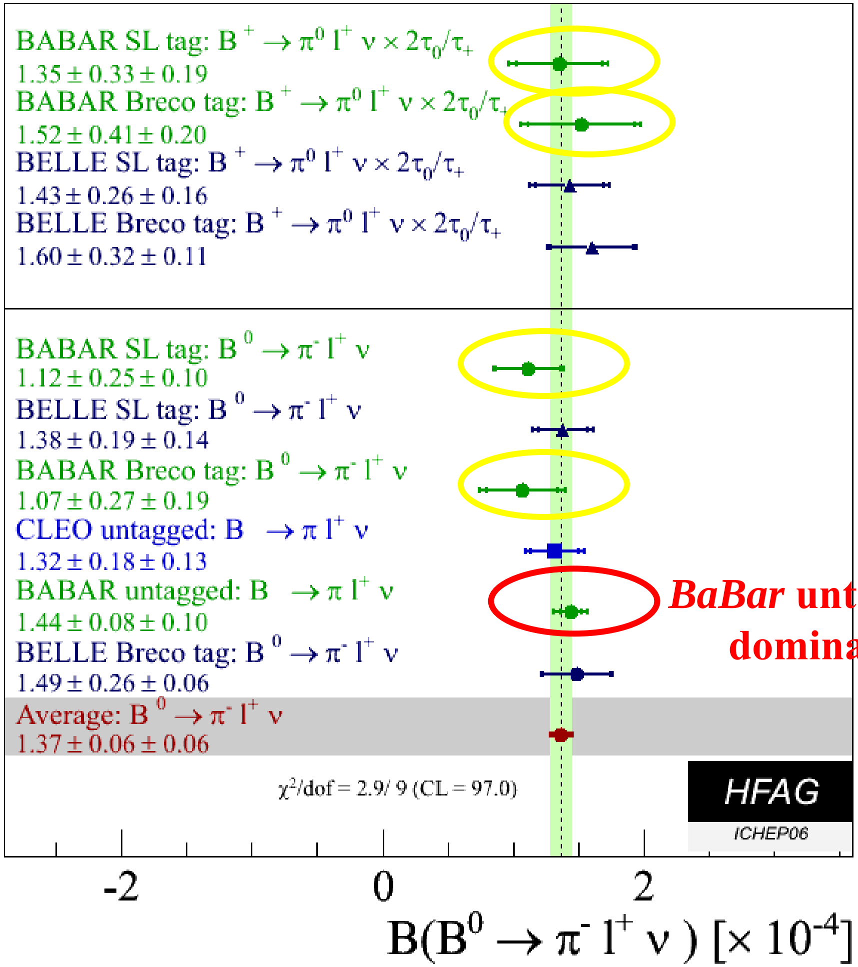
$B \to \pi l \nu$: Systematic Uncertainties

Error Source	$q^2 < 8$	8 - 16	$q^2 > 16$	All q^2
Signal reconstruction	2.3%	1.7%	1.7%	1.5%
Neutrino reconstruction	6.5%	5.4%	2.2%	4.8%
KL Contribution	5.9%	3.3%	4.8%	4.0%
$b \to c l \nu$ background	2.5%	3.0%	1.5%	1.5%
$b \to u l \nu$	2.7%	1.8%	3.7%	1.7%
Non-BB Background	4.8%	1.5%	4.4%	1.6%
Others	3.4%	2.2%	2.1%	2.0%
Total Systematic Error	11.4%	7.9%	8.4%	7.3%

Largest syst. uncertainties:

- ν reconstruction (track, photon efficiencies), K_L reco./production
- $X_u\, l\, \nu$ background (high q^2)
- continuum background (high and low q^2)

Exclusive $|V_{ub}|$: Summary



BaBar **untagged dominant**

Exclusive $|V_{ub}|$ averages from HFAG:

HPQCD , $q^2 > 16$ GeV^2

$$|V_{ub}| = (3.93 \pm 0.26_{exp}{}^{+0.59}_{-0.41 theo(FF)}) \times 10^{-3}$$

Ball-Zwicky , $q^2 < 16$ GeV^2

$$|V_{ub}| = (3.38 \pm 0.12_{exp}{}^{+0.56}_{-0.37 theo(FF)}) \times 10^{-3}$$

Errors of exclusive $|V_{ub}|$ dominated by form-factor uncertainty

HFAG branching fraction average:

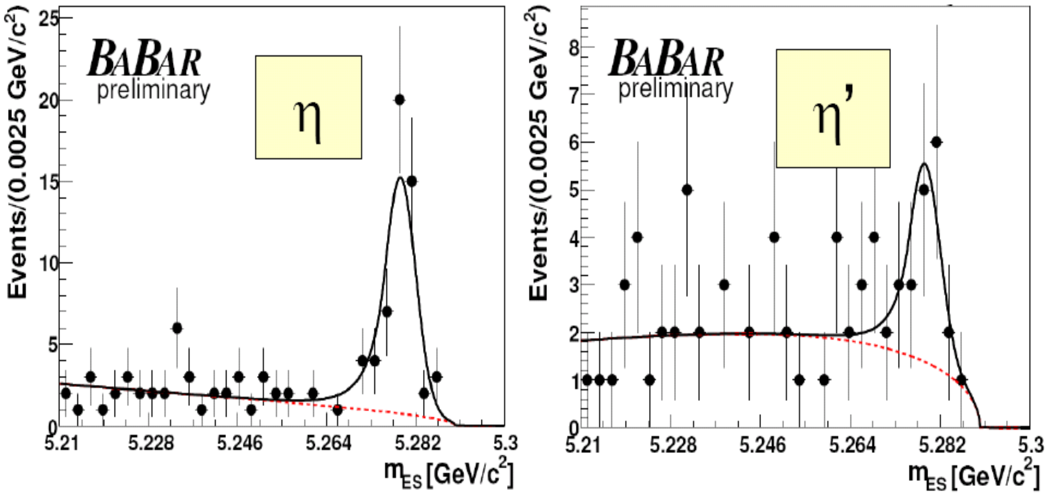
$$BR(B^0 \to \pi^- \lambda^+ \nu) = (1.37 \pm 0.06 \ \pm 0.06\ ) \times 10^{-4}$$

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

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

315 fb^{-1}

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



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

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

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

- fit to m_B distributions to extract signal yields

Need more data!

Prospects for 1/ab (end of 2008)

Syst. Errors will be reduced:

→ Improved track and neutral reconstruction
→ Better measurements of $B \to X_u l\nu$ background

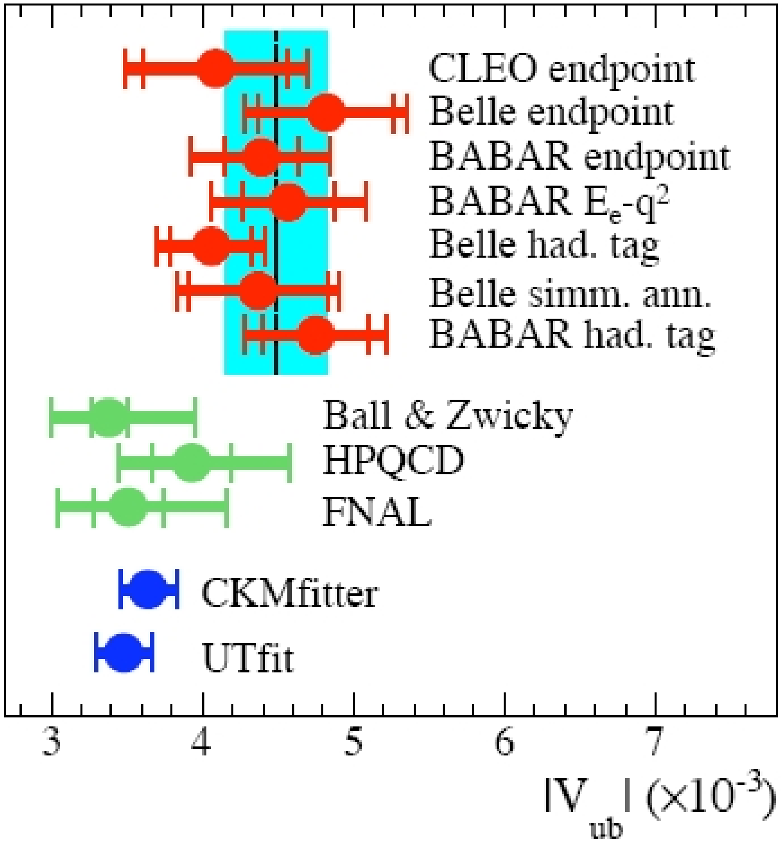
Event Selection	Yield [Evt/10^9BB]	S/B	σ_{stat}	σ_{syst}	σ_{exp}
hadronic tags	130	8	11 %	6%	13%
$D^{(*)} \ell \nu$ tags	600	2.5	7 %	6%	9%
No tags	15,000	0.5	2.5 %	4%	5%

Theoretical input to translate Bf to $|V_{ub}|$:

→ Need improved FF calculations with reliable error estimate (if possible over full q^2 range)

Untagged measurements will still dominate in the near future!

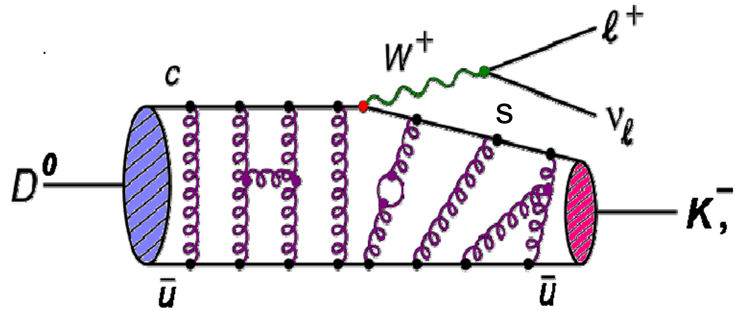
$|V_{ub}|$ - Inclusive vs. Exclusive



Tension between global CKM fit and inclusive $|V_{ub}|$: ~ 2.5-3 σ

Are inclusive or exclusive theory correct?
Good that we have a cross-check inclusive vs. exclusive

Charm Semileptonic Decays



- Motivation: Study QCD effects (form factors) in semileptonic decays and test LQCD with high precision!
- D-meson sample from $e^+ e^- \to c\underline{c}$ → fragmentation ($D/D_s/\Lambda$, ...)
- Large cross-section: σ_{cc} ~1.3 nb → typically several k events

Pseudoscalar	Vector
$D^0 \to K^- e^+ \nu$	$D_s^+ \to \varphi e^+ \nu$
$D_s \to \eta/\eta' e\nu$	$D \to K\pi e\nu$
$D^0 \to \pi^- e^+ \nu$	

Differ only in spectator q

Helpful for V_{ub}?

Study $K\pi$ vs K^*

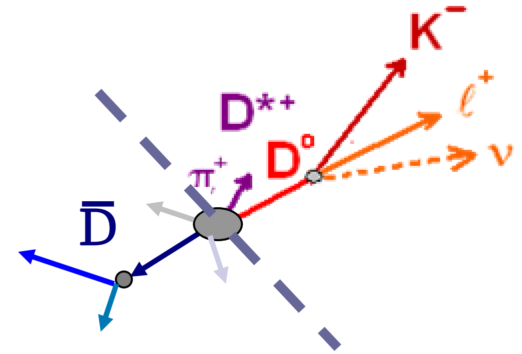
How to Determine the Decay Kinematics

- Define two hemispheres:
  - take soft π^+, K^- and ℓ^+ in the same hemisphere

Cuts $\begin{cases} p^*_\ell\,,\ p_\ell > 0.5\ \text{GeV} \\ p^*_{\pi+} < 0.4\ \text{GeV} \\ \cos\theta_{thrust} < 0.6 \end{cases}$

$\Upsilon(4S)$ rest frame : *jet-like events*

$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\ell^+\nu$



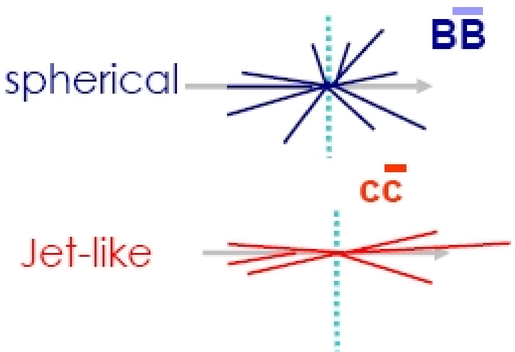
- Compute D direction $(-\ p_{\text{all particles} \neq K,\ell})$
- Compute the missing energy in the ℓ hemisphere
- Fit $p_D = p_K + p_\ell + p_\nu$
  - From p_K, p_ℓ, computed E_{miss} and D^0 direction
  - Constraints using m_D and m_{D^*} (1c or 2c fit)

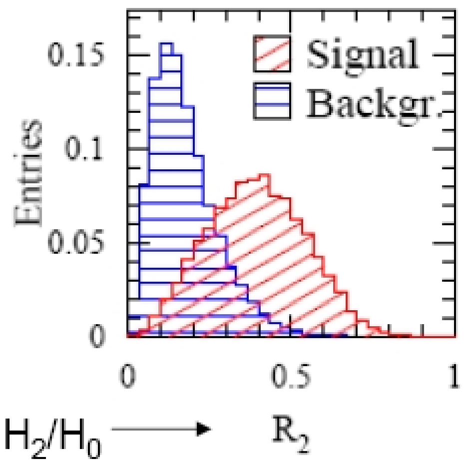
- Compute $q^2 = (p_D - p_K)^2$

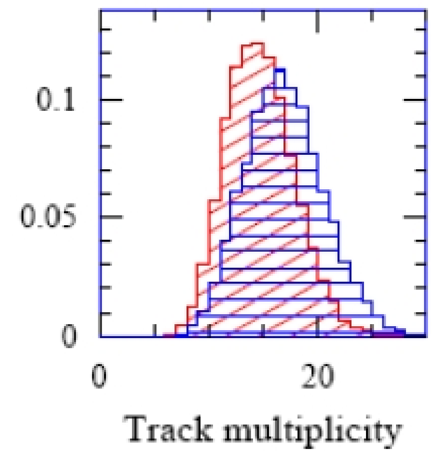
Background Suppression

Use linear combinations of variables to suppress bkg (→ 2 Fisher discriminants)

(1) $B\underline{B}$ background : 2 event-shape variables



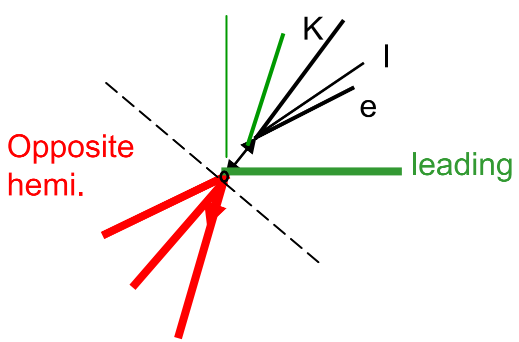


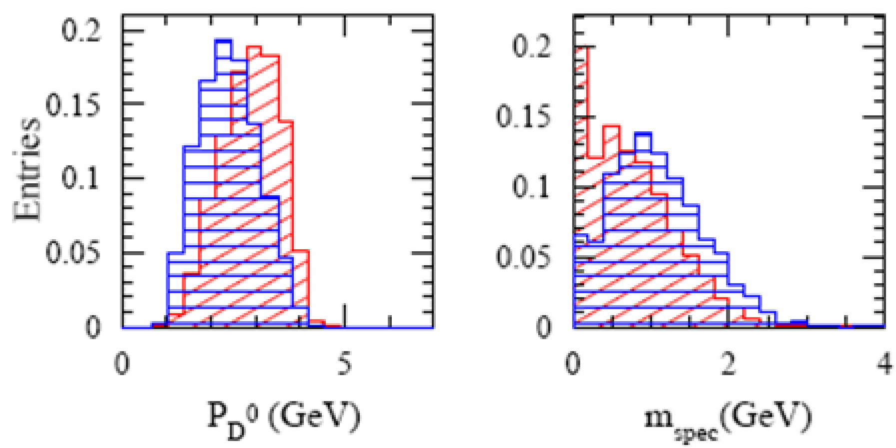


Fox-Wolfram moment H_2/H_0 ⟶

(2) Background from other $c\underline{c}$: 8 kinematic and spectator-system variables

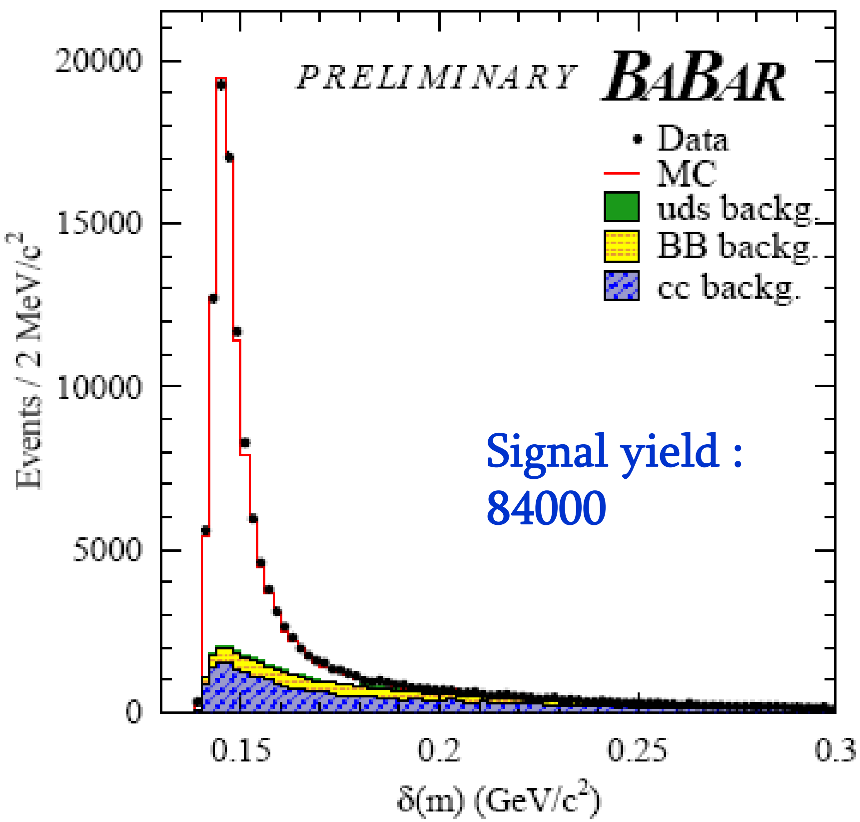
(e.g. from $D^0 \to K\pi e\nu$)



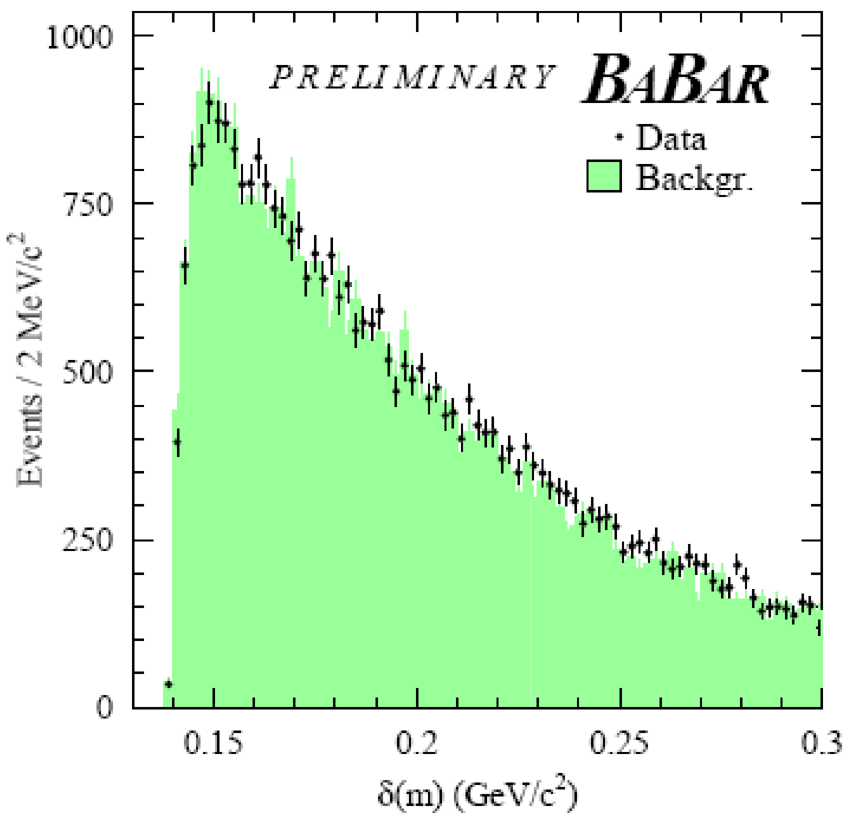


$D^0 \to K^- e^+ \nu$: Data-MC Agreement

D*-D Mass difference

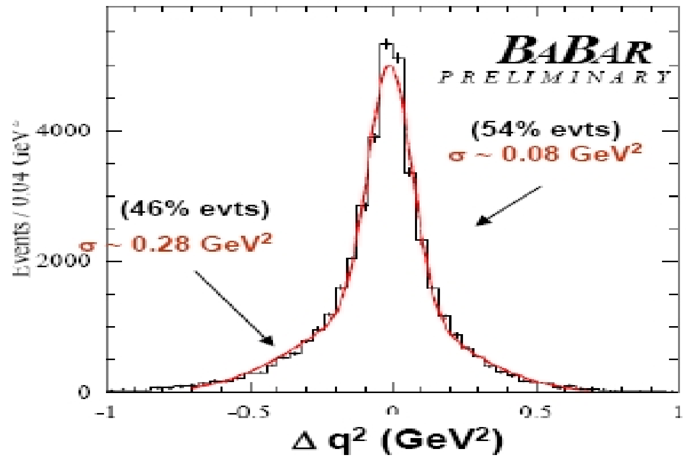


Check data-MC agreement for bkg with wrong-charge control sample

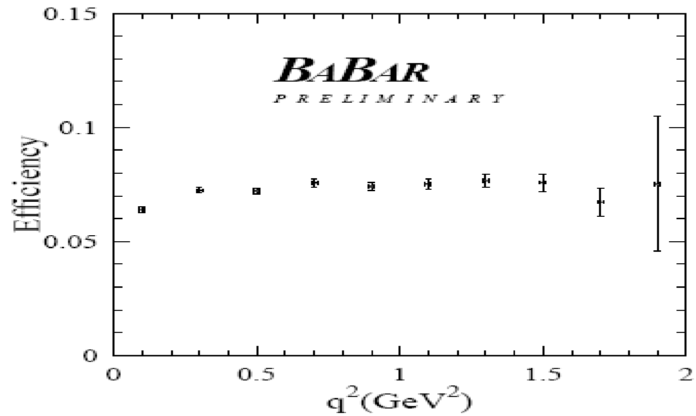


q^2 Spectrum

q^2 resolution



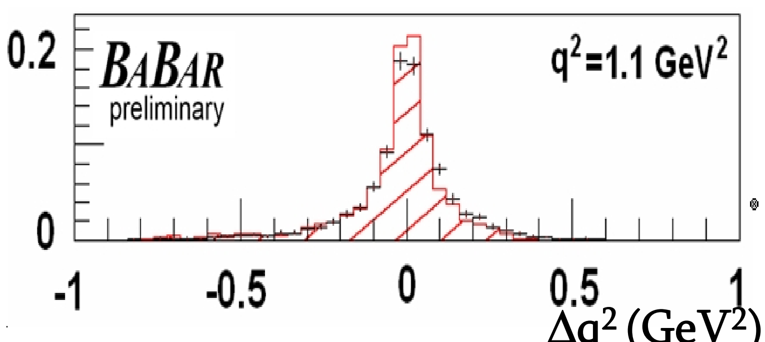
Efficiency vs. q^2

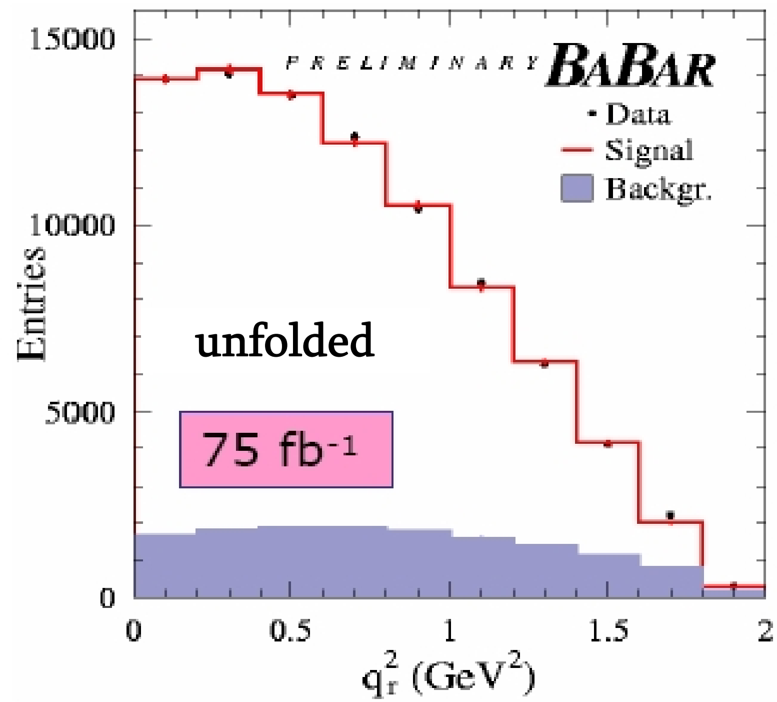


Use control samples to check reconstruction:

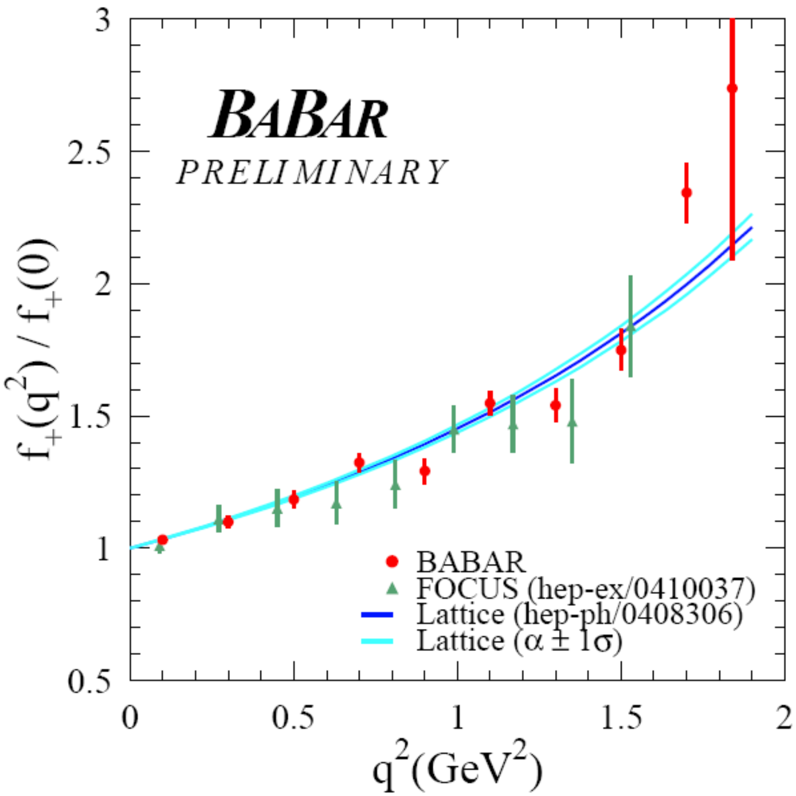
$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^0$ $(\pi^0 \to \gamma\gamma)$

Apply same selection criteria,
Treat π as e and π^0 as ν
→ q^2 resolution from data





$D^0 \to K^- e^+ \nu$: Form-Factor Results



- Fit 2 parameterizations to data :

$$\left|f_+(q^2)\right| = \frac{f_+(0)}{1 - \frac{q^2}{m^2_{pole}}}$$

$$\left|f_+(q^2)\right| = \frac{f_+(0)}{\left(1 - \frac{q^2}{m^2_{D_s^*}}\right)\left(1 - \frac{\alpha_{pole} q^2}{m^2_{D_s^*}}\right)}$$

- Pole mass below $m(D_S^*)$= 2.112 GeV
- α agrees well with LQCD hep-ph/0408306

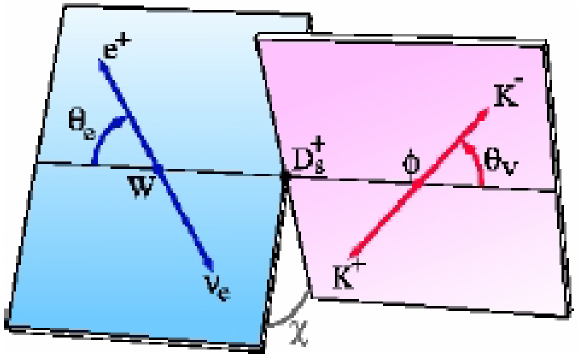
  α = 0.50 +- 0.04
- Discrepancy with CLEO-c value !

experiment	stat	$m_{pole}(\mathrm{GeV}/c^2)$	α_{pole}
CLEO-c	281 pb^{-1}	$1.98 \pm 0.03 \pm 0.02$	$0.19 \pm 0.05 \pm 0.03$
FOCUS	13k evts	$1.93 \pm 0.05 \pm 0.03$	$0.28 \pm 0.08 \pm 0.07$
Belle	282 fb^{-1}	$1.82 \pm 0.04 \pm 0.03$	$0.52 \pm 0.08 \pm 0.06$
BaBar	75 fb^{-1}	$1.854 \pm 0.016 \pm 0.020$	$0.43 \pm 0.03 \pm 0.04$

$D_s \to \phi\, e\, \nu$

$D_s \to \varphi e \nu$
$\quad \hookrightarrow K^+K^-$

4 kinematic variables :
q^2 , θ_v, θ_l, χ

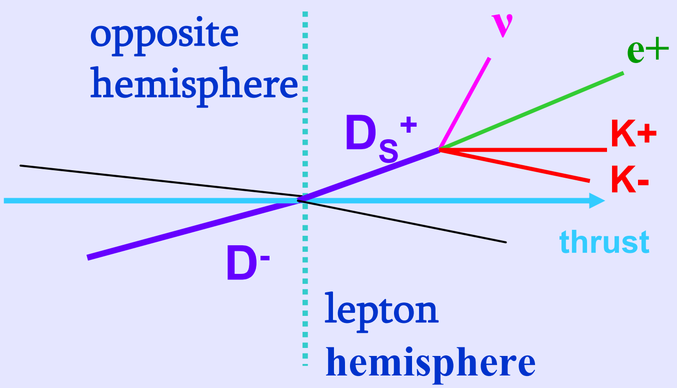


- Use pole dominance parameterization for the three form factors A_1, A_2, V :

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

- Measure form-factor ratios at $q^2 = 0$:

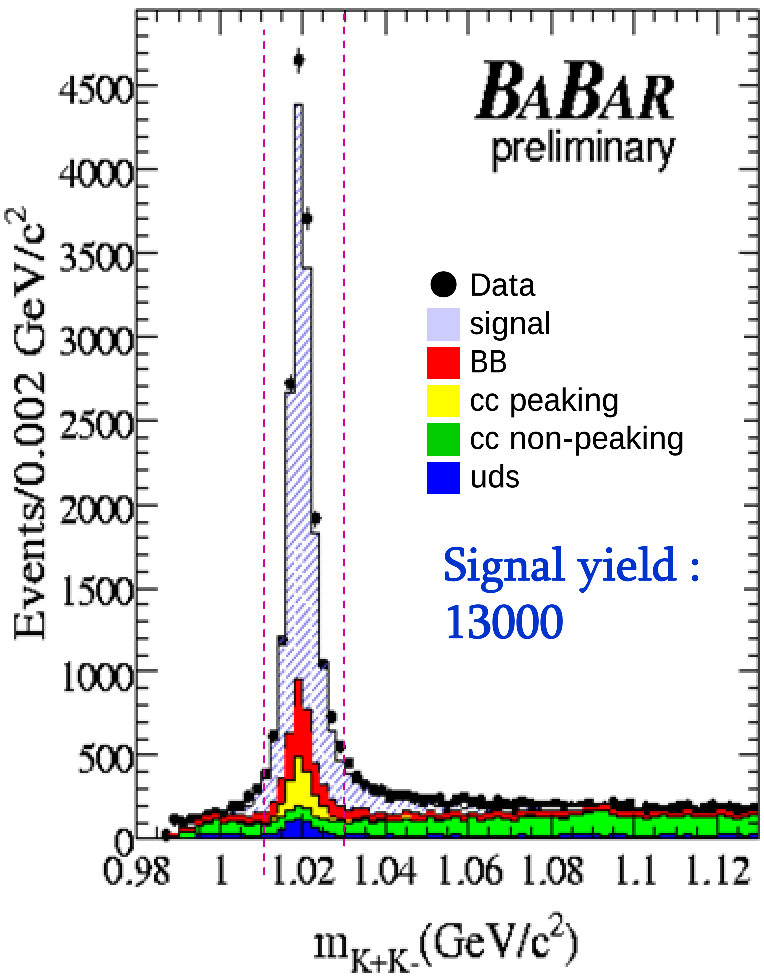
$$r_V = V(0)/A_1(0) \qquad r_2 = A_2(0)/A_1(0)$$

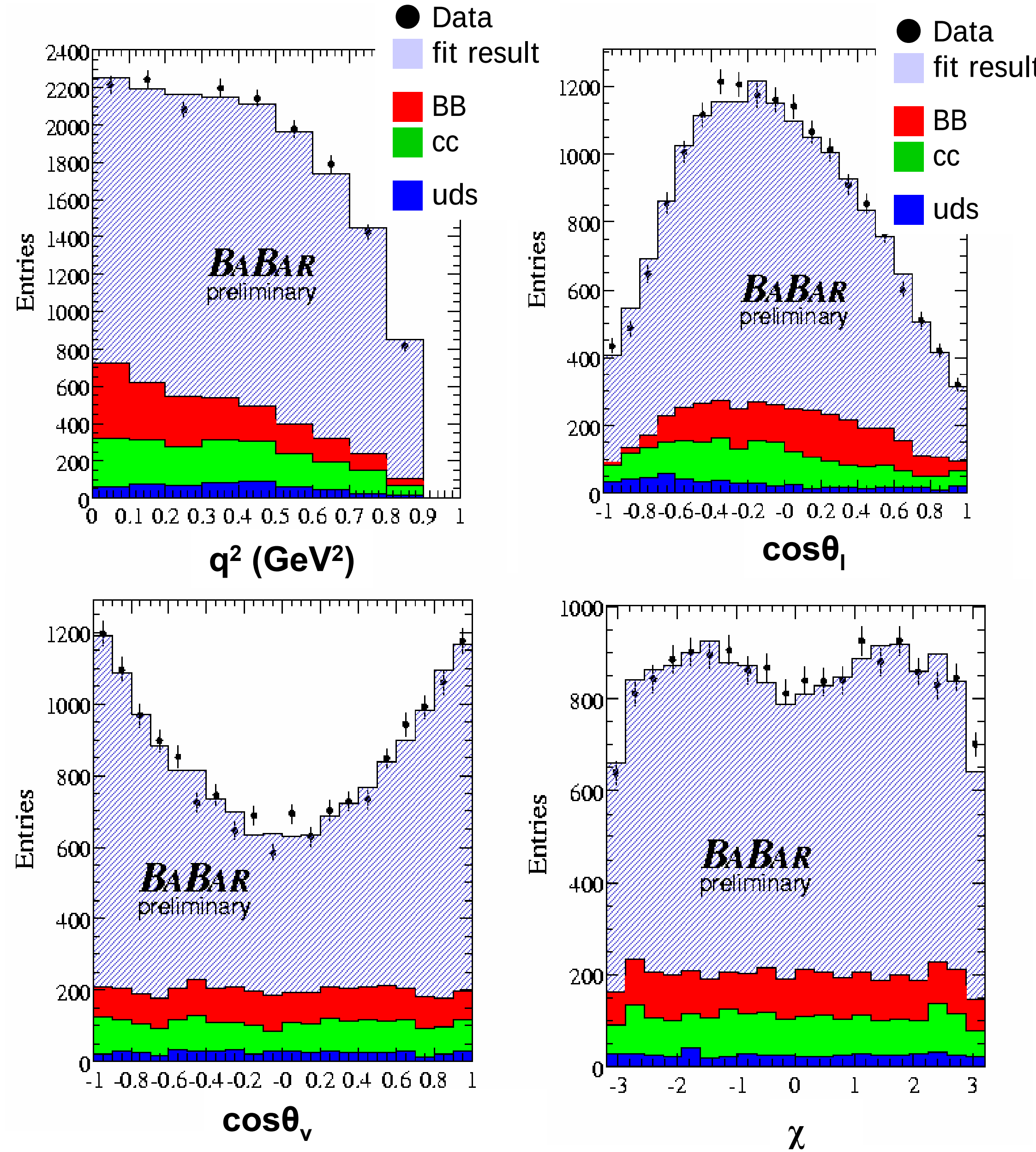


$D_s \to \phi\, l\, \nu$, $\phi \to K^+K^-$

- Same Method as for $D \to Kl\nu$, but without D^*
- Fit $p_{Ds} = p_{K+} + p_{K-} + p_l + p_\nu$ (m_{Ds} mass constraint)
- Compute kinematic variables : q^2 , θ_V, θ_l, χ

$D_s \to \phi\, e\, \nu$: Fit Results



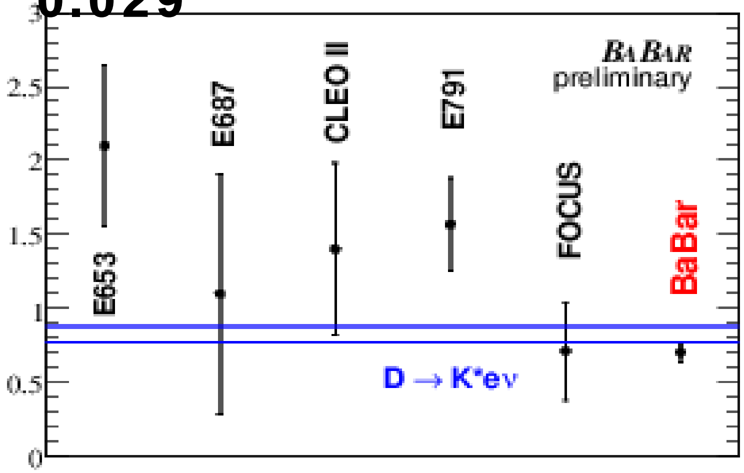


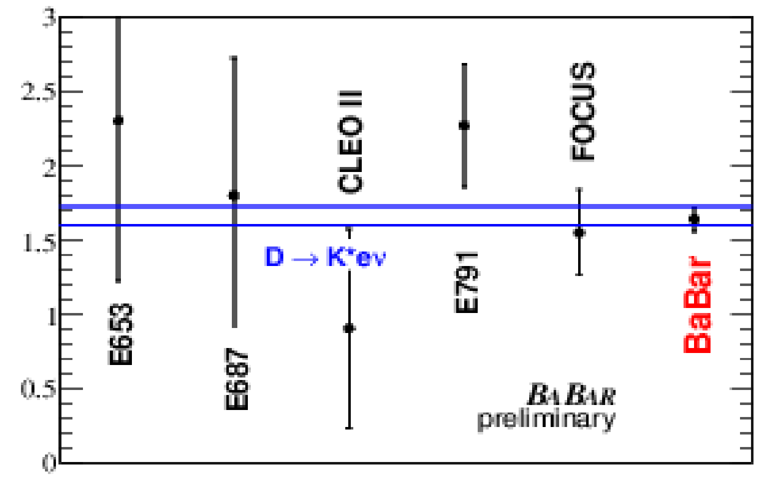
$D_s \to \phi \, l \, \nu$: Form-Factor Results

- Form factor ratios at $q^2=0$ (fixing $m_A = 2.5$ GeV and $m_V = 2.1$GeV) :

r_2 = 0.705 ± 0.056 ± 0.029

r_V = 1.636 ± 0.067 ± 0.038





→ Same accuracy as $D \to K^* e\nu$ (FPCP 2006, J.Wiss)

- Fixing only the vector pole mass :

r_2 = 0.711 ± 0.111 ± 0.096

r_V = 1.633 ± 0.081 ± 0.068

$m_A = 2.53^{+0.54}_{-0.35} \pm 0.054$ GeV

Charm Semileptonic Decays - Summary

- $D \to K e\nu$ form factor : First study of the BABAR potential in charm sl decays
  Very successful, same precision as lattice reached

- Opens a large perspective for form-factors measurements in BABAR …

  - $D_s \to \phi e\nu$ form factors

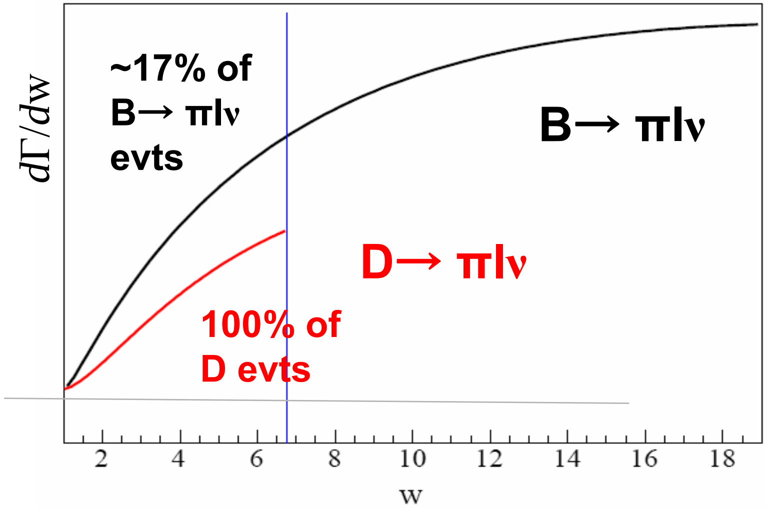
- Still a lot of interesting measurements we can do :

  - Form factors in $D \to \pi l\nu$ and $D \to K\pi l\nu$
  - More detailed study of FF in $D_s \to X e\nu$
  - Comparison between different channels
  - Charm baryons, ….

- In the future: Derive $|V_{ub}|$ using ratio of
  $D \to \pi l\nu$ and $B \to \pi l\nu$

$$\frac{d\Gamma(B \to \pi\lambda\nu)/dw}{d\Gamma(D \to \pi\lambda\nu)/dw} = \left|\frac{V_{ub}}{V_{cd}}\right|^2 \left(\frac{M_B}{M_D}\right) \left|\frac{f_+^{B\to\pi}}{f_+^{D\to\pi}}\right|^2$$

$q^2_D \in [0; 2.975]$ GeV^2
$q^2_B \in [18; 26.4]$ GeV^2

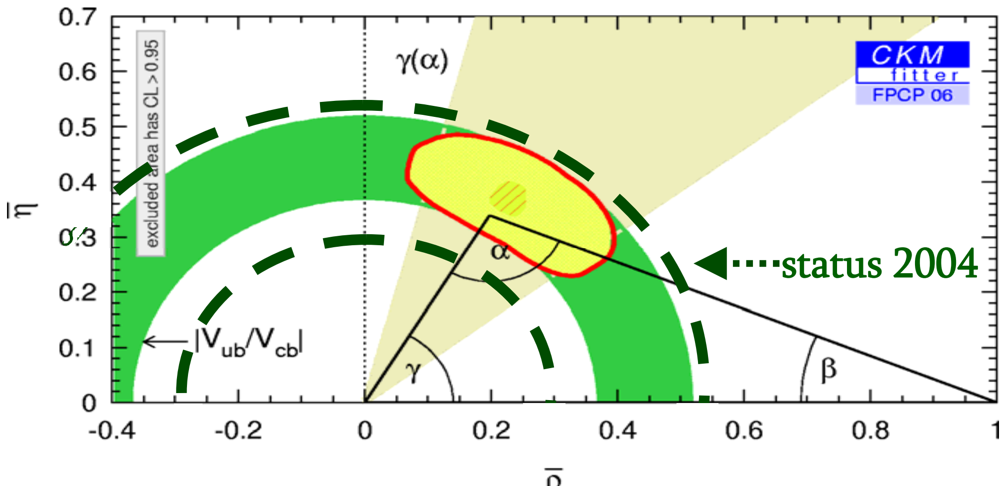


Conclusions

- BABAR has a number of new and precise measurements in the $B \rightarrow D/D^*/D^{**}$ sector.
  A number of problems remain: $D^*l\nu$ puzzle, sum of exclusive, …

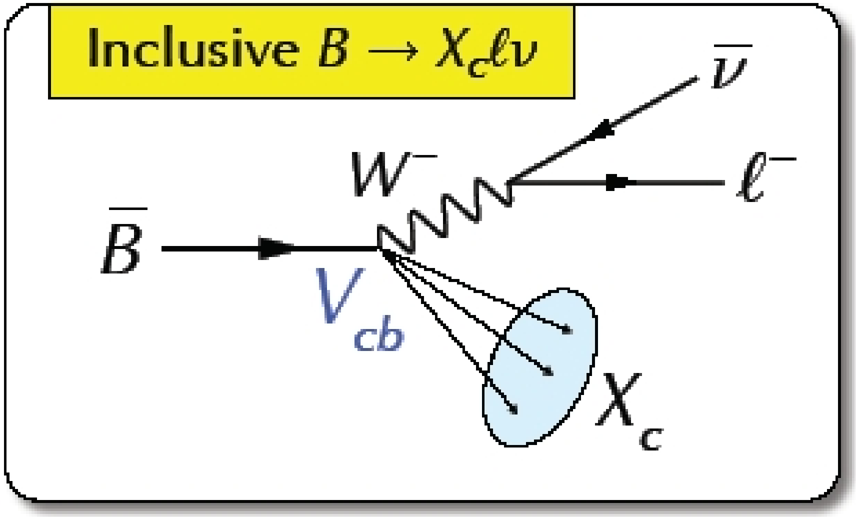
- A lot of progress in exclusive $|V_{ub}|$ (esp. $\pi l\nu$) in the last two years.
  Need improved FF calculations from theory !
  Important cross-check of this most precise inclusive $|V_{ub}|$.

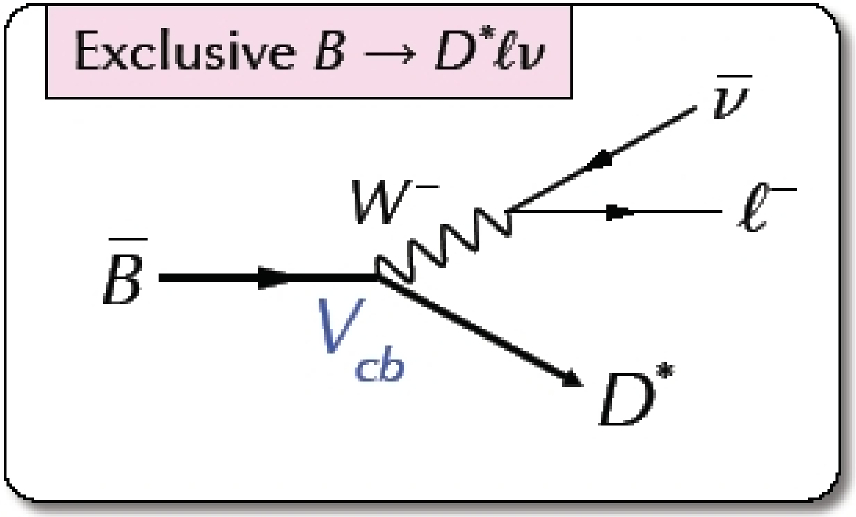
- Charm SL decays provide high-quality lattice calibration.
  Techniques can be applied to B decays !

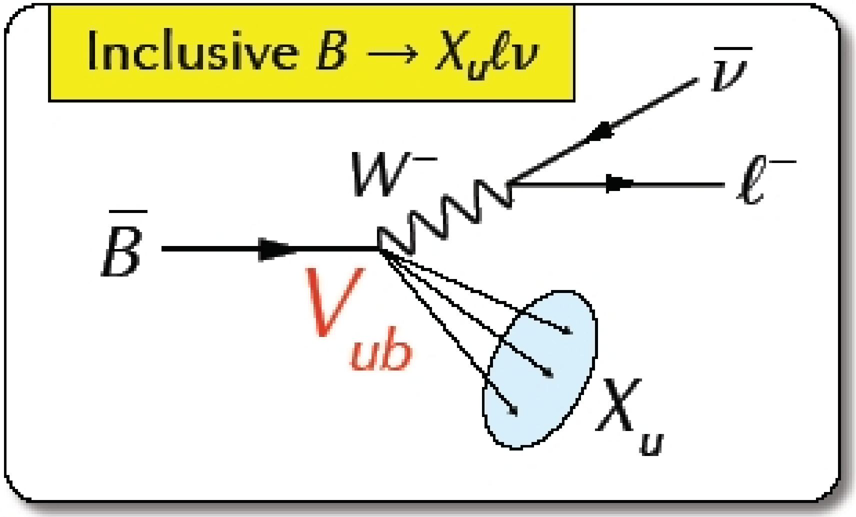


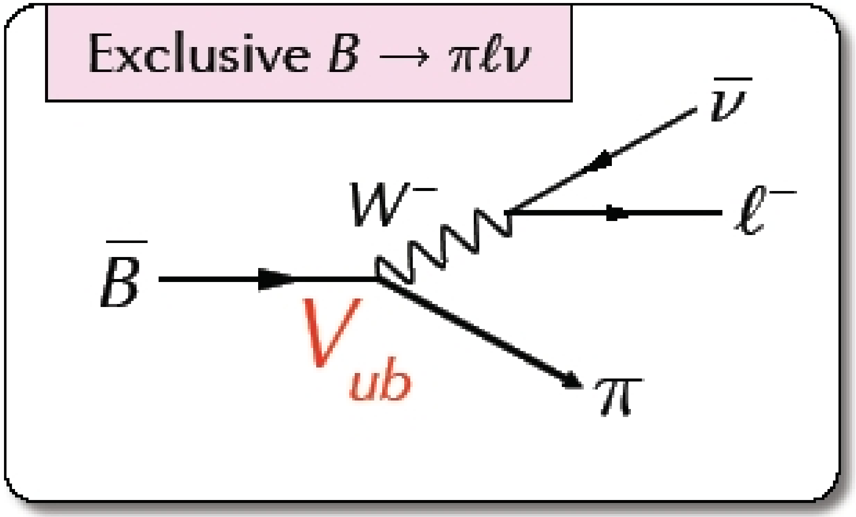
Backup Slides

Inclusive vs. Exclusive

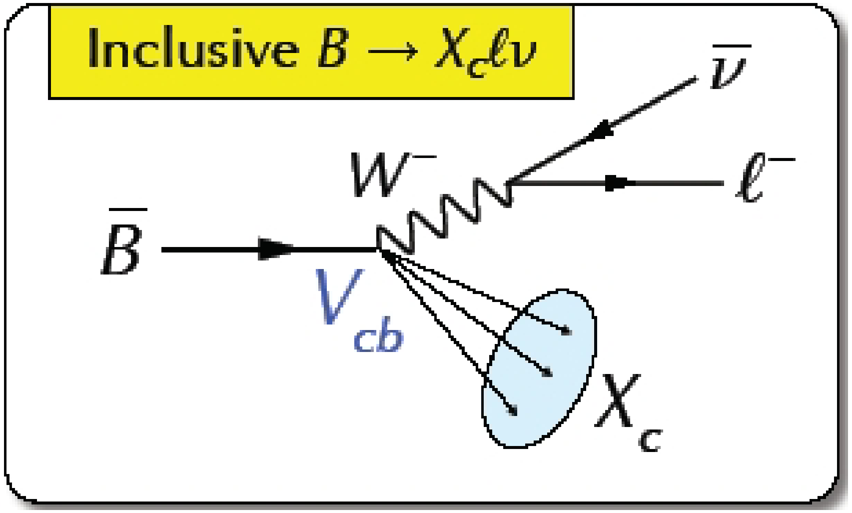








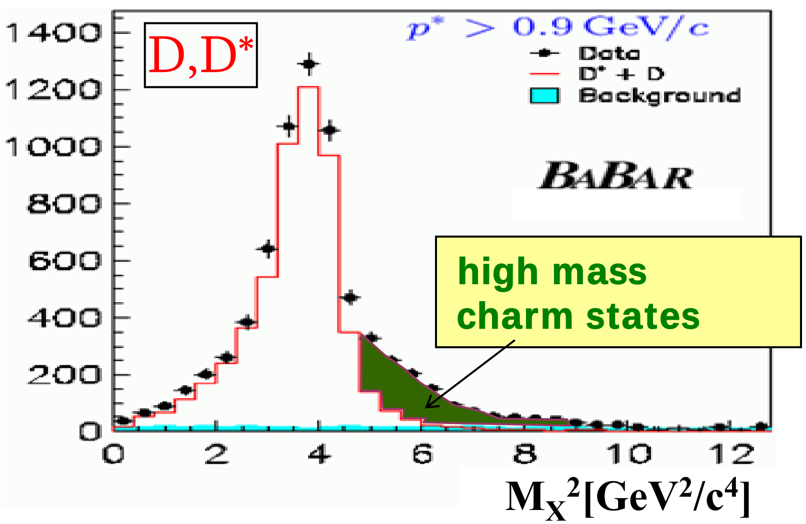
Inclusive Determination of $|V_{cb}|$

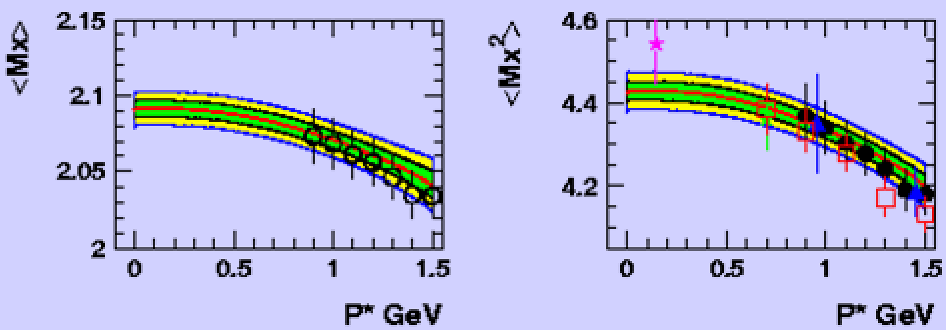


- Energy(lep), Mass(X_c) spectra
- $\Gamma_{cl\nu} \sim |V_{cb}|^2 f_{OPE}(m_b,m_c,a_i)$
- OPE calculation of moments :

  $<M_X^n> = f_{OPE}'(m_b,m_c,a_i)$

- Measure E_l , m_X moments
- Perform global OPE fit to data:





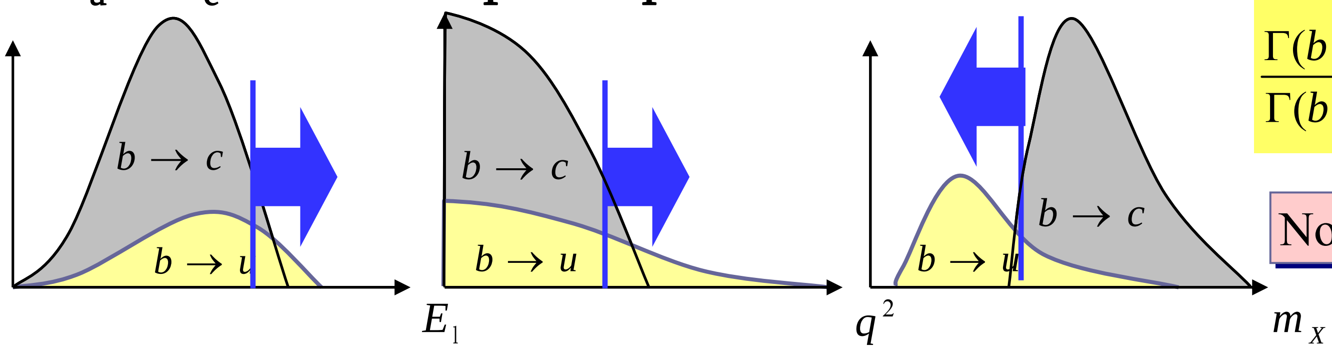
$|V_{cb}|$ with 2% error

Inclusive Determination of $|V_{ub}|$

- Inclusive rate from HQE in α_s (perturbativ) und $1/m_b$ (non -perturbativ)

$$\Gamma(B \to X_u l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2 \times \left\{ 1 + O(\alpha_S) + O\left(\frac{1}{m_b^3}\right) \right\}$$

- Problem (exp.): Separation of $B \to X_u l\nu$ signal from $B \to X_c l\nu$ background
  - $m_u < m_c$ → restrict phase space



$$\frac{\Gamma(b \to u l \bar{\nu})}{\Gamma(b \to c l \bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$

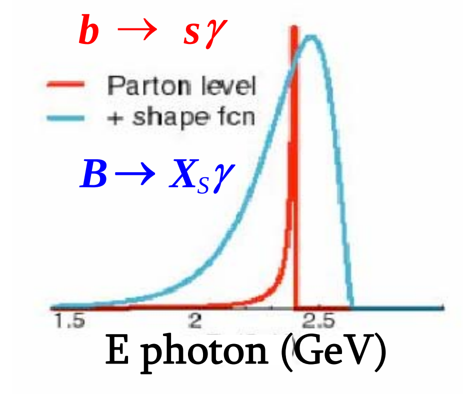
Not to scale!

← Smeared due to e.g. exp. resolution →

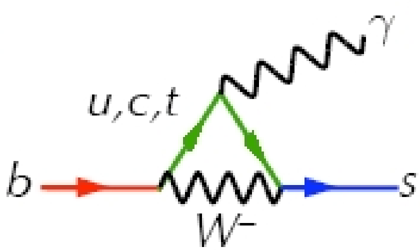
- Problem (theo.): Poor convergence of HQE in regions where $B \to X_c l\nu$ kinematically forbidden
  → Need non-perturbative Shape Function (SF) to determine partial rates
  → Use SF together with calculation of triple-differential decay rate Bosch, Lange, Neubert, Paz (BLNP) to get $|V_{ub}|$

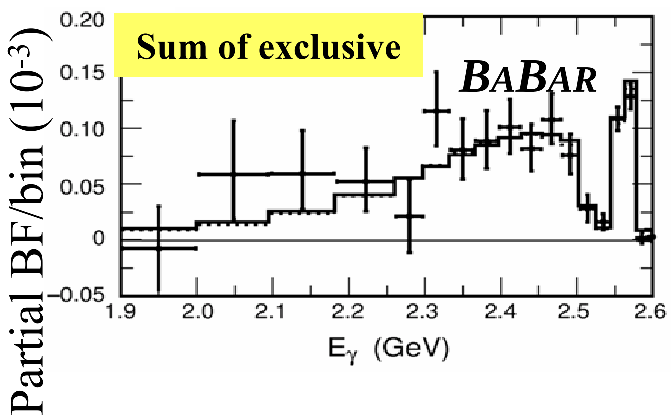
Shape Function – What Is It ?

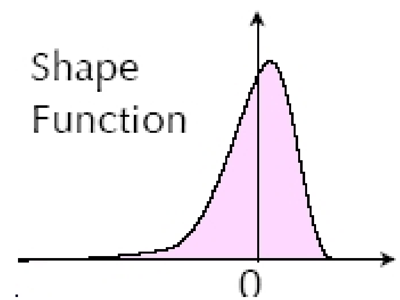
- The Shape Function (SF) describes Fermi motion of b quark inside B meson
  → smears kinematic spectra



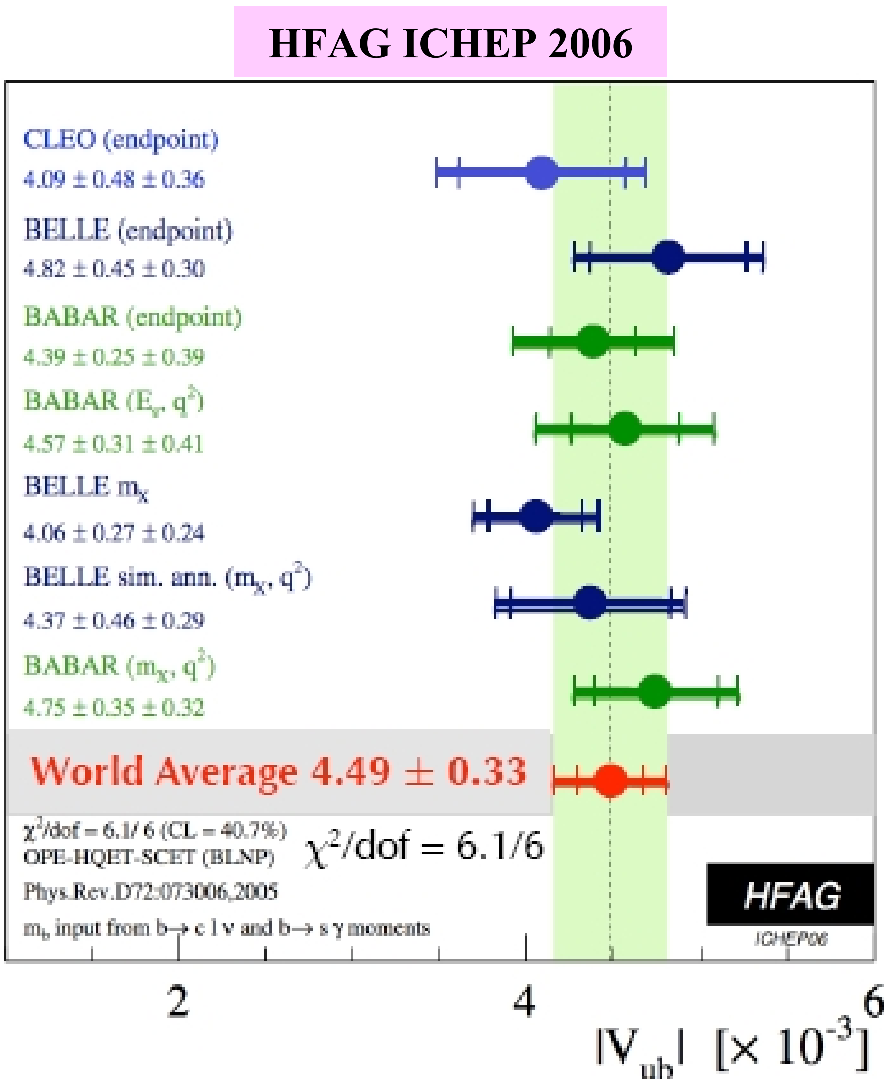
- cannot be calculated & shape is unknown
- Universal property of B meson (leading order 1/mb)
- Determine moments of SF e.g. with b → sg decays







Status of Inclusive $|V_{ub}|$

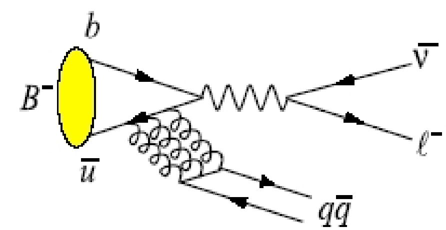


$|V_{ub}|$ with error of 7%

Statistical	± 2.2%
Exp. systematic	± 3.8%
SF param. (m_b, μ_π^2)	± 4.2%
Theory	± 4.2%

- Exp. and SF param. error will decrease with more data

- Theo. Errors:
  (1) Weak annihilation: 1.9%



(2) Subleading SF: 3.8%
higher order non-pert. corrections cannot be constrained with $b \to s\gamma$

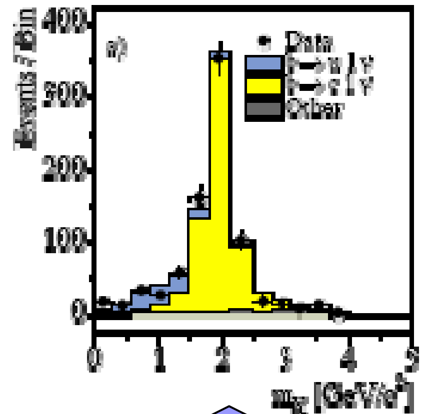
$|V_{ub}|$ "without" Shape Function

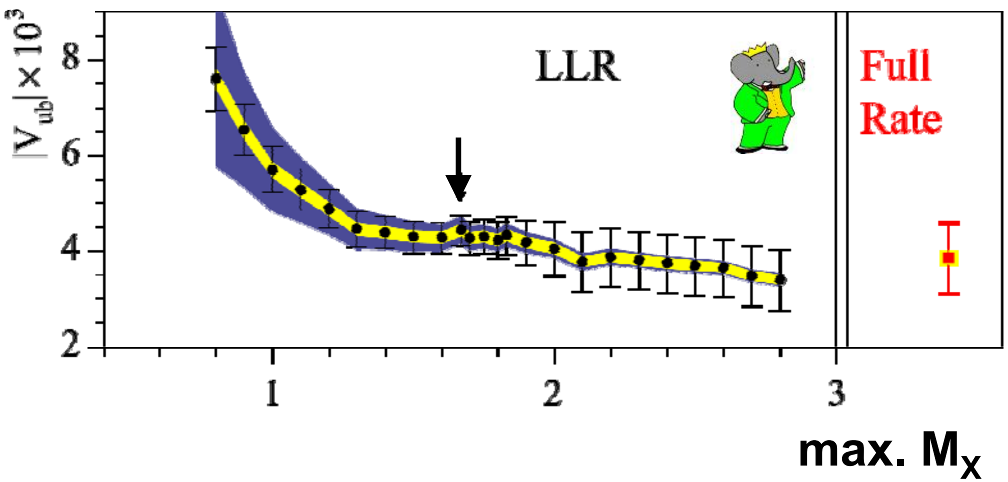
(1) Extract $|V_{ub}|$ from full M_X spectrum

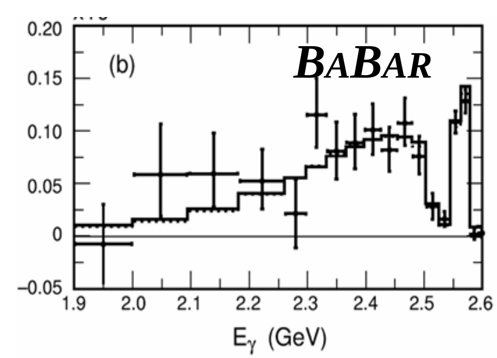
(2) Relate $b \to ul\nu$ to $b \to s\gamma$ through weight function

$$\Gamma(B \to X_u l\,\nu) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \int W(E_\gamma) \frac{d\Gamma(B \to X_s \gamma)}{dE_\gamma} dE_\gamma$$

LLR (Leibovich, Low, Rothstein) hep-ph/0005124







LLR (M_X < 1.67 GeV): $|V_{ub}| = (4.43 \pm 0.45_{exp} \pm 0.29_{theo})\ 10^{-3}$

OPE (M_X < 2.50 GeV): $|V_{ub}| = (3.84 \pm 0.76_{exp} \pm 0.10_{theo})\ 10^{-3}$