Semileptonic B Decays at *BABAR*

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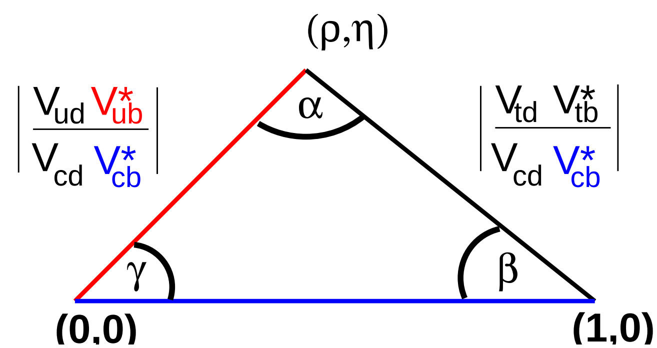
- Introduction
  - ▷ Motivation
  - ▷ PEP-II and detector
- $b \to c\ell\bar{\nu}$
  - ▷ $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ NEW
  - ▷ $\mathcal{B}(\bar{B} \to X\ell\bar{\nu})$
- Moments and OPE
  - ▷ Hadronic mass
  - ▷ Other methods
- $b \to u\ell\bar{\nu}$ and $|V_{ub}|$
  - ▷ $\bar{B} \to \rho e\bar{\nu}$
  - ▷ Endpoint spectrum
  - ▷ Hadronic recoil mass NEW

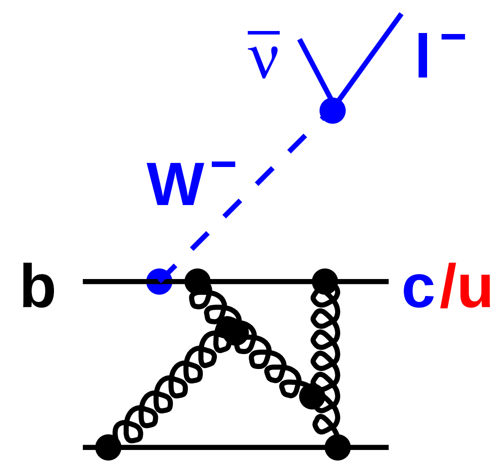
Motivation

- Test CKM description of quark mixing and CP violation
  - ▷ Complementary constraining measurements to angles ($e.g.\ \sin 2\beta$)
  - ▷ Quantitatively test underlying theory

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_W = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_M$$

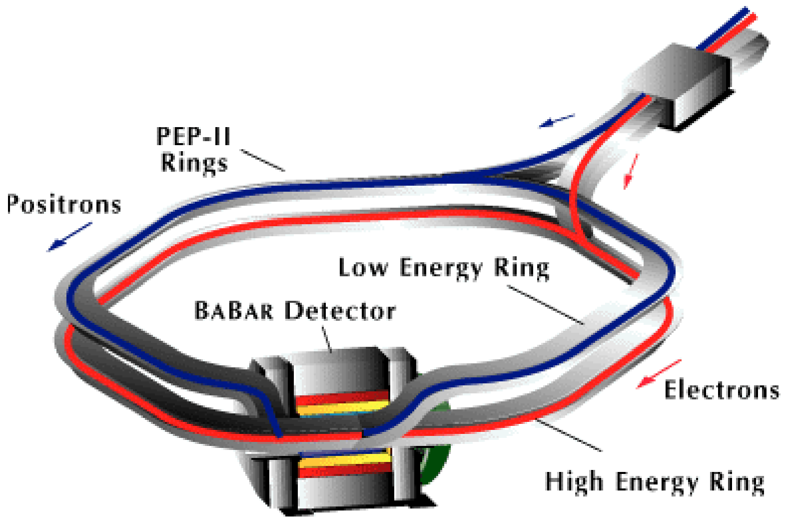


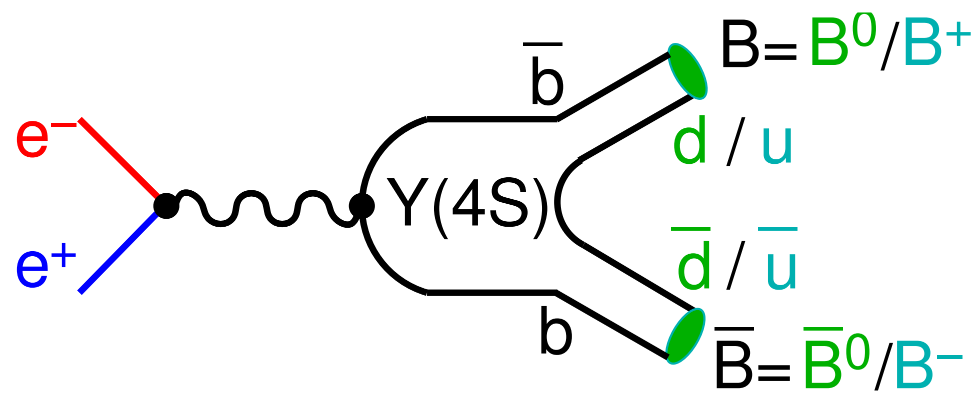
- Semileptonic B-decays give direct access to $|V_{cb}|$ and $|V_{ub}|$
  - ▷ Factorization of hadronic and leptonic currents
  - ▷ Inclusive
    - large rate $\Gamma_{sl} \propto \mathcal{B}/\tau \propto |V_{cb}|^2$
    - 'easy' to calculate $\longrightarrow$ OPE/HQE
  - ▷ Exclusive
    - 'easy' to measure
    - formfactors $\longrightarrow$ HQET, lattice
  - ▷ Separation of $b \to c\ell\bar{\nu}$ and $b \to u\ell\bar{\nu}$
    - $\mathcal{B}(\bar{B} \to X_c\ell\bar{\nu}) \sim 50 \cdot \mathcal{B}(\bar{B} \to X_u\ell\bar{\nu})$



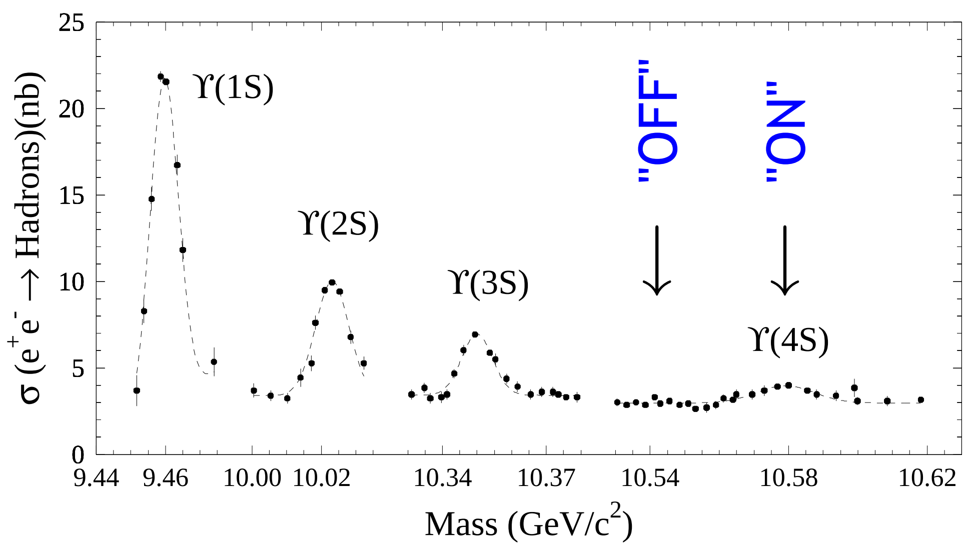
The PEP-II Collider on the $\Upsilon(4S)\ldots$

- Head-on collisions without crossing angle
  $e^-(9\,\mathrm{GeV}) \otimes e^+(3.1\,\mathrm{GeV}) \rightarrow \beta\gamma = 0.56$

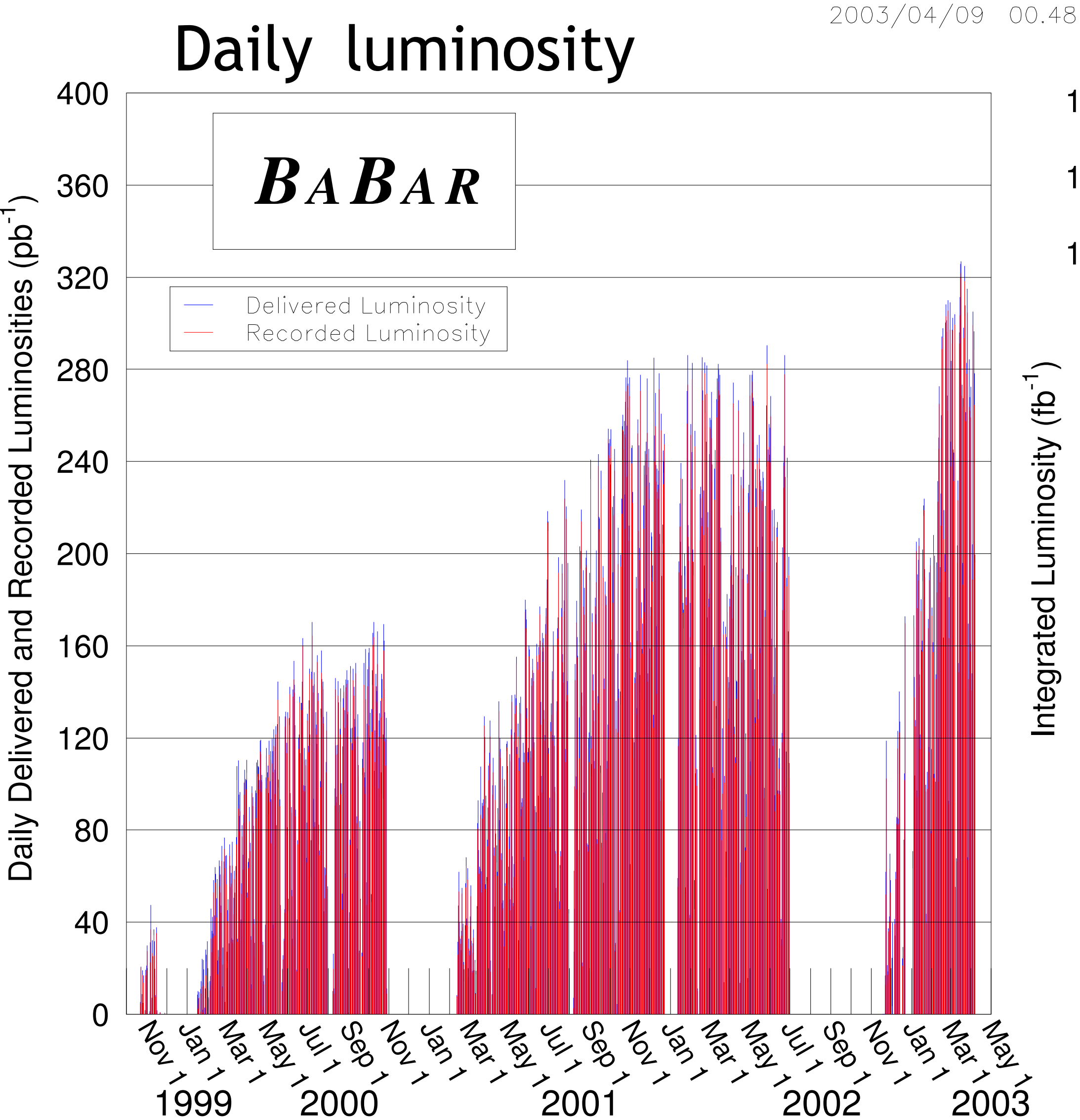


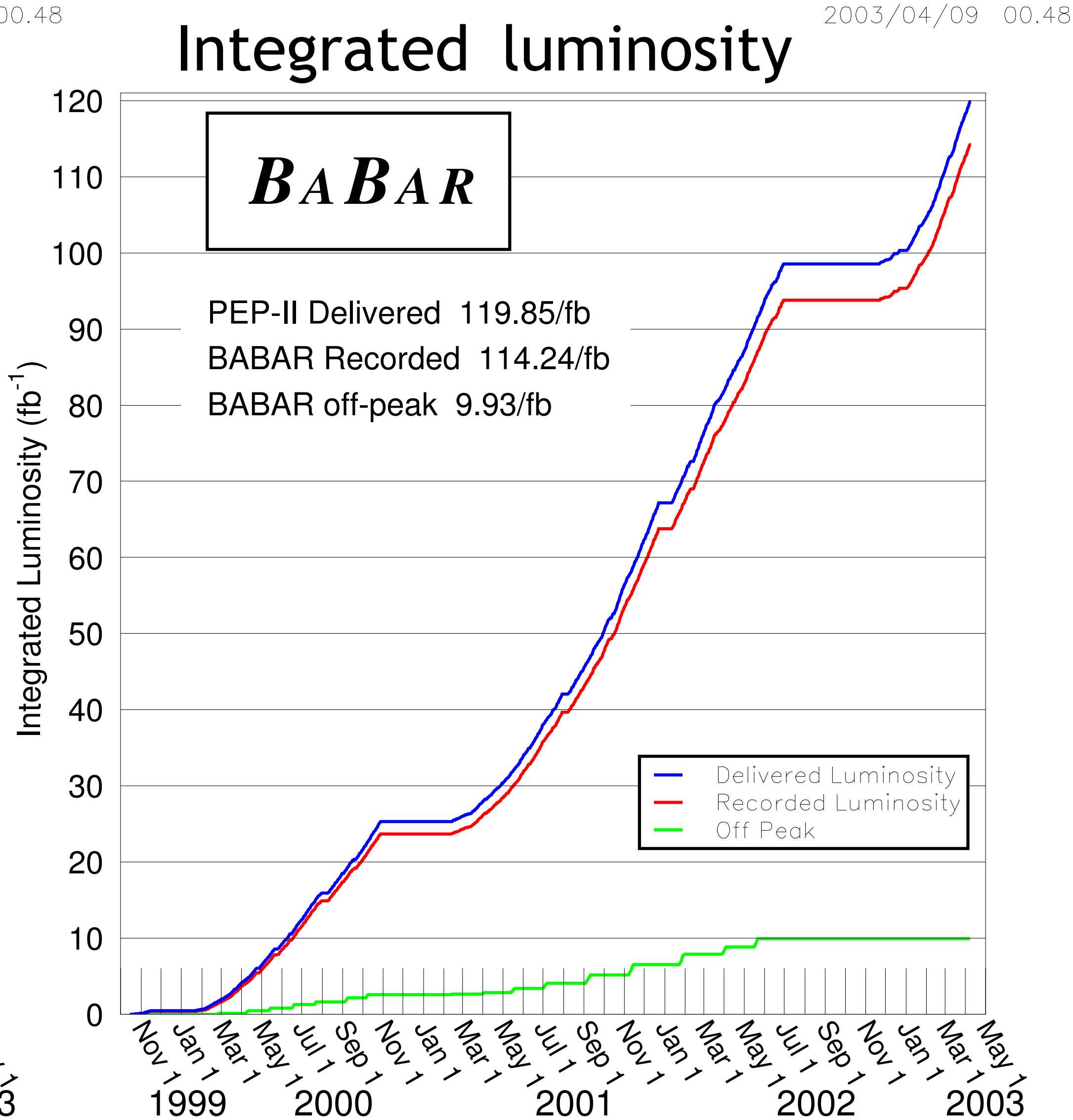


Parameter	design	achieved
$\mathcal{L}$ $[\times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	3.0	5.21
$\int \mathcal{L}\,dt/\mathrm{shift}$ $[\mathrm{pb}^{-1}]$	45	120
$\int \mathcal{L}\,dt/24\mathrm{h}$ $[\mathrm{pb}^{-1}]$	135	347
# bunches	1658	921
HER current $[A]$	0.75	1.05
LER current $[A]$	2.14	2.14



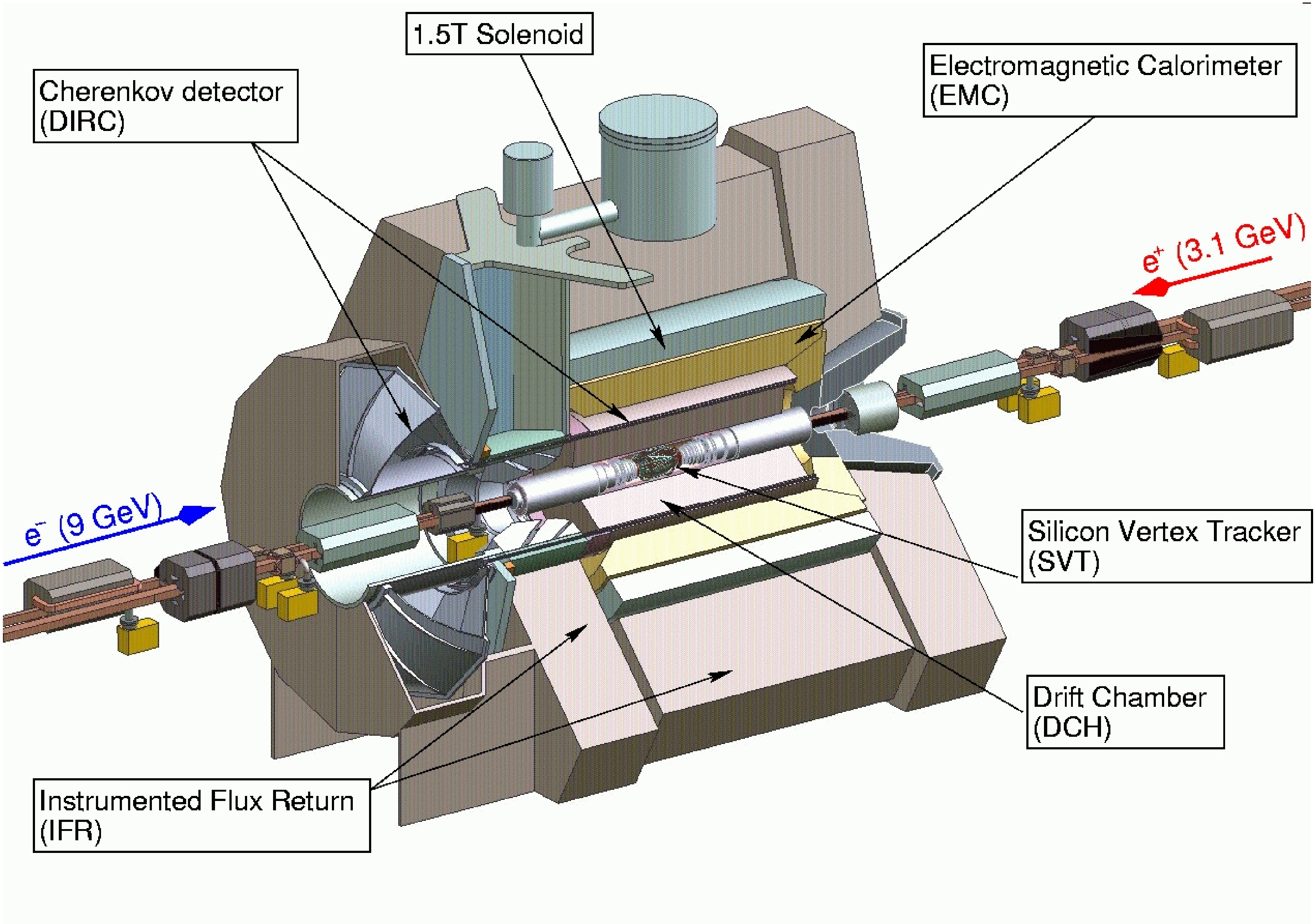
... a B Factory





- Operation efficiency $\langle\varepsilon\rangle \sim 97\%$. NB: $3-5$ $B\bar{B}$ events/s

The *BABAR* Detector



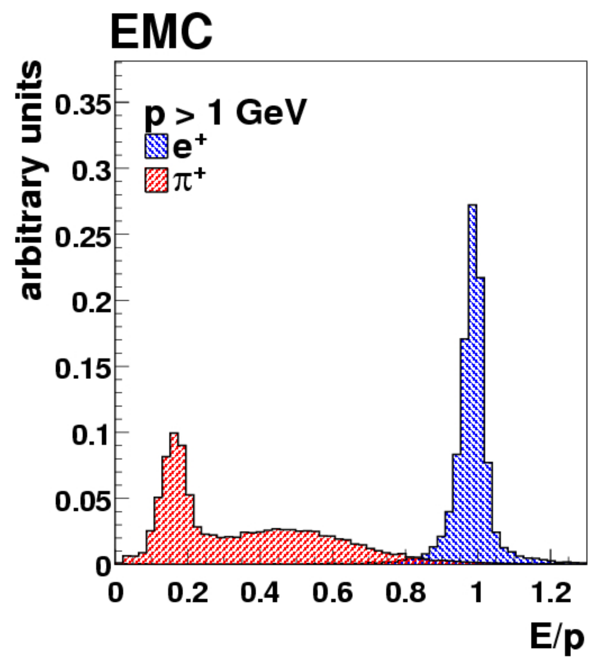
[1] Drescher *et al.*, NIM A237, 464
[2] Sinkus, Voss, NIM A391, 360

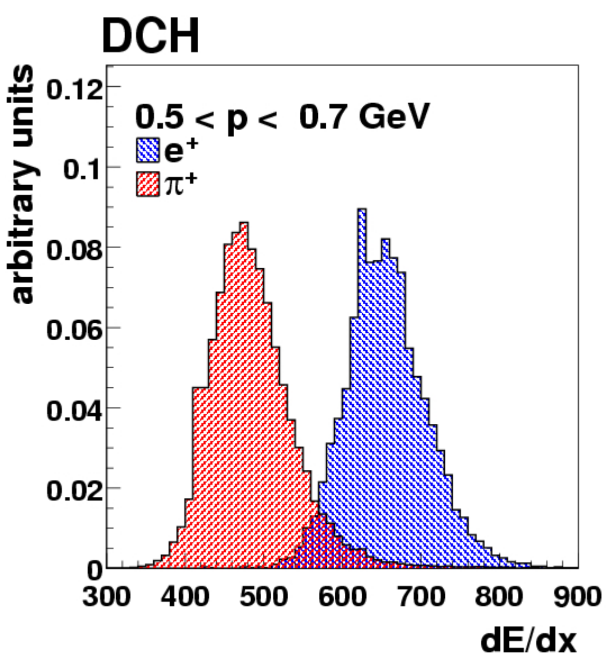
Electron Identification

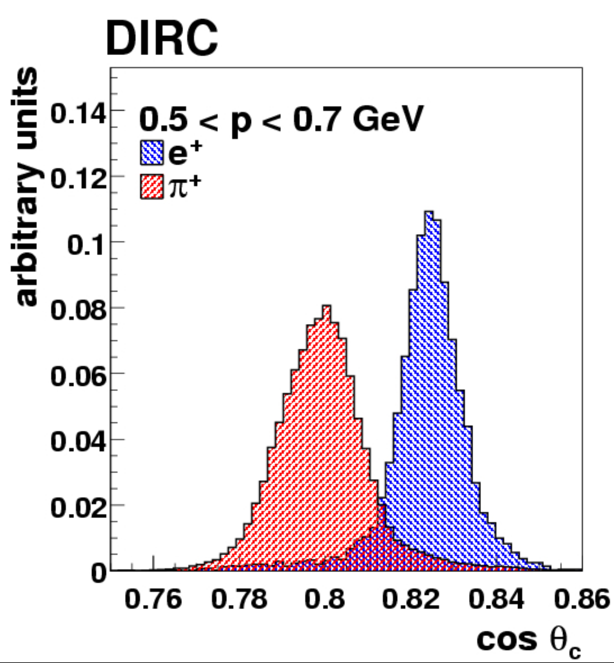
- Energy deposition E in EMC:
  - ▷ electrons $E/p \sim 1$, hadrons $E_{mip} \sim 200\,\mathrm{MeV}$
  - ▷ shower shapes, azimuthal[1] and lateral[2]:

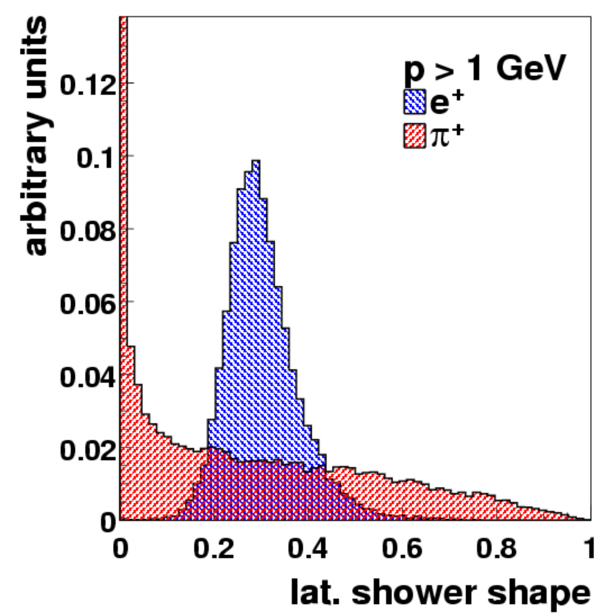
$$LAT = \frac{\sum_{i=3}^{n} E_i r_i^2}{\sum_{i=3}^{n} E_i r_i^2 + E_1 r_0^2 + E_2 r_0^2}$$

- Additional hadron rejection:
  - ▷ DCH: dE/dx (below Cherenkov threshold)
  - ▷ DIRC: $\cos\theta_C$ (above Cherenkov threshold)





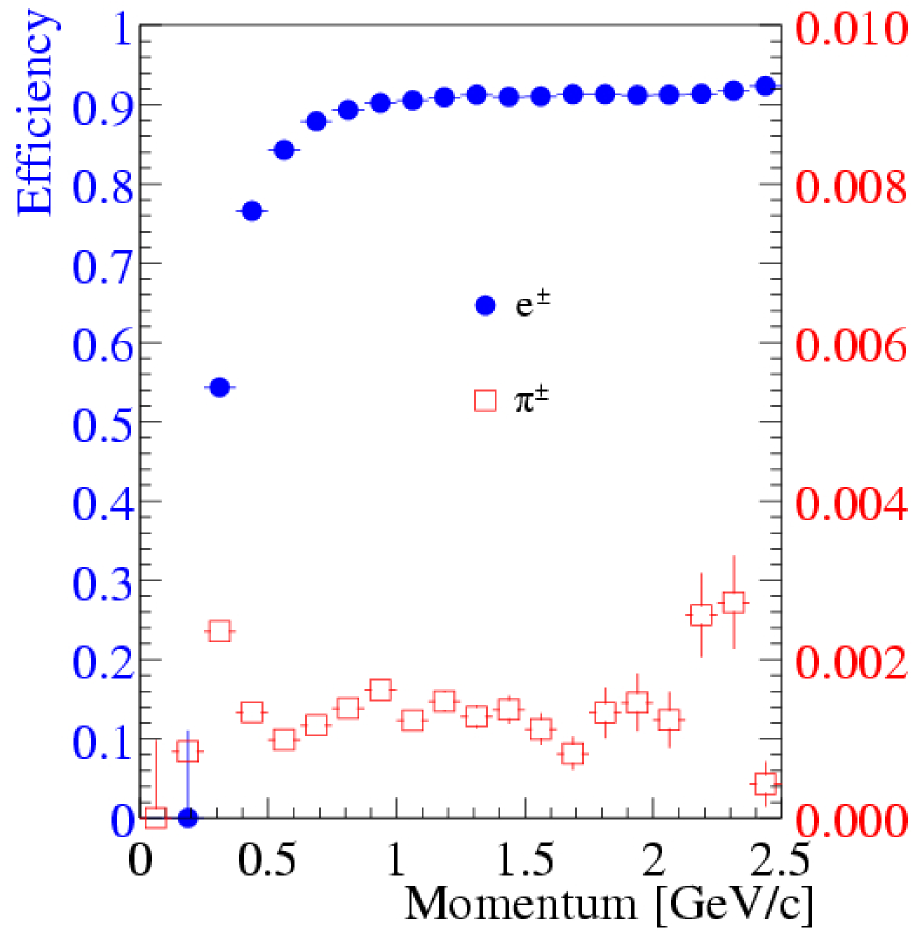




Electron Identification Performance

- Two selectors:
  - ▷ cut based $\langle\varepsilon\rangle \sim 91\%$
  - ▷ likelihood ratios $\langle\varepsilon\rangle \sim 92\%$
- Efficiency determination:
  - ▷ radiative Bhabha events in Data
- Hadron fakes
  - ▷ fractions from Monte Carlo
  - ▷ misidentification probability in Data
    - $K_S \to \pi^+\pi^-$, $\tau \to hhh$
    - $D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$
    - $\Lambda \to p\pi^-$

$$N_{\rm fake} = (f_\pi\eta_\pi + f_K\eta_K + f_p\eta_p) \cdot N_h$$
$$\langle\eta\rangle \sim 2.5 \cdot 10^{-3} \text{ (cut based)}$$
$$\langle\eta\rangle \sim 1.3 \cdot 10^{-3} \text{ (likelihood ratios)}$$

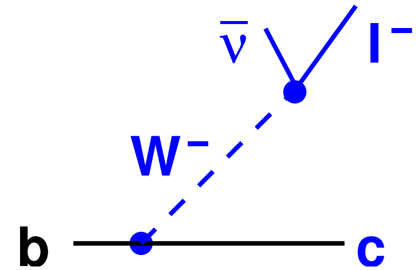


- MC-correction for shower overlaps in hadronic events

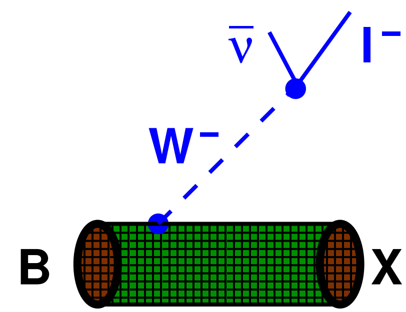
Semileptonic B Decays

- Weak decay of free quark

$$\Gamma(b \to c\ell\bar{\nu}) = \frac{G_F^2|V_{cb}|^2}{192\pi^3} m_b^5$$



- Improvements to free quark model
  - ▷ EW corrections
  - ▷ perturbative QCD corrections
- But: Quark mass m_b? Model for $b\bar{q}$ binding?
- For a model-independent test want

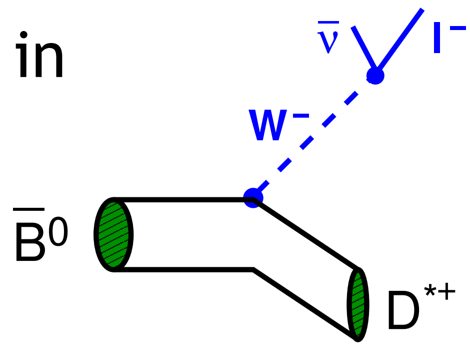


$$observable = (calc.\ factor) \times \left[1 + \sum_i (small\ parameter)^i\right]$$

- For $m_Q \gg \Lambda_{\rm QCD}$
  - ▷ Exclusive: Heavy Quark Effective Theory
  - ▷ Inclusive: Heavy Quark Expansion
- Separation of scales: Weak decay $\Leftrightarrow$ hadronization $\longrightarrow$ QCD

[1] Isgur, Wise, PLB232, 113
Isgur, Wise, PLB237, 527

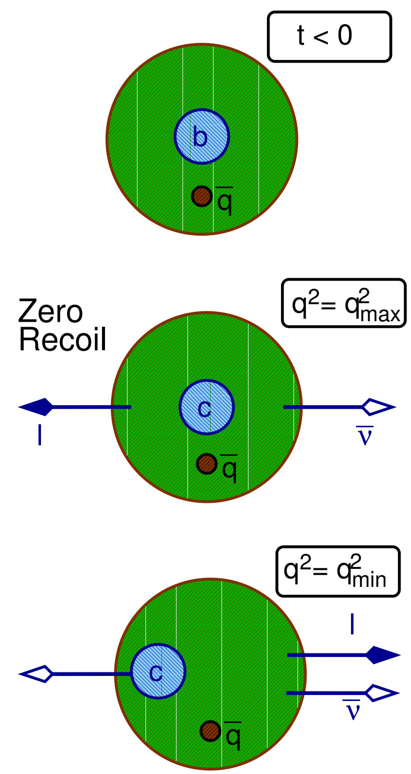
HQET: $\bar{B} \to D^* \ell \bar{\nu}$ at zero recoil



- Differential decay rate (schematically) given in Heavy-Quark Effective Theory[1] by

$$\frac{d\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}{dw} = \mathcal{K} \cdot |V_{cb}|^2 \begin{cases} (w^2-1)^{1/2} \cdot \mathcal{F}_*{}^2(w) \\ (w^2-1)^{3/2} \cdot \mathcal{F}^2(w) \end{cases}$$

where $w \equiv v_b \cdot v_c \to v_B \cdot v_{D^*} = E_{D^*}/m_{D^*}$



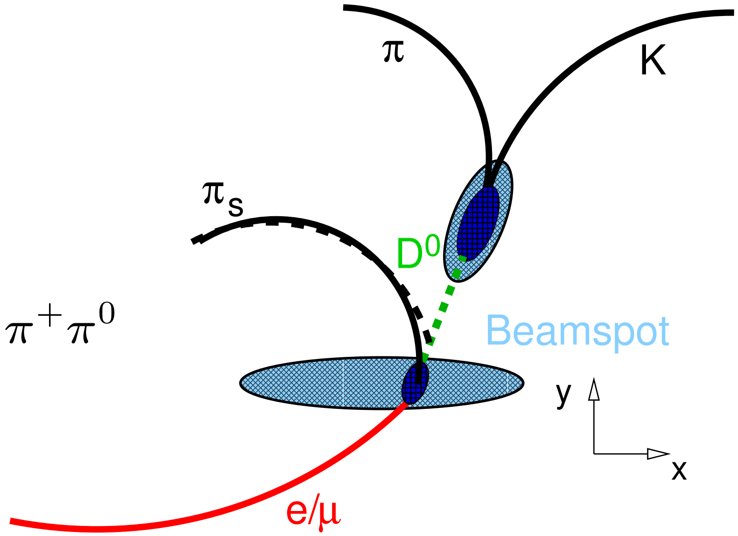
- Form factor $\mathcal{F}(w)$
  - ▷ HQET: reduction of number of form factors
  - ▷ HQS: normalization at zero recoil: $\mathcal{F}(1) \to 1$

valid in the limit $m_Q \to \infty$

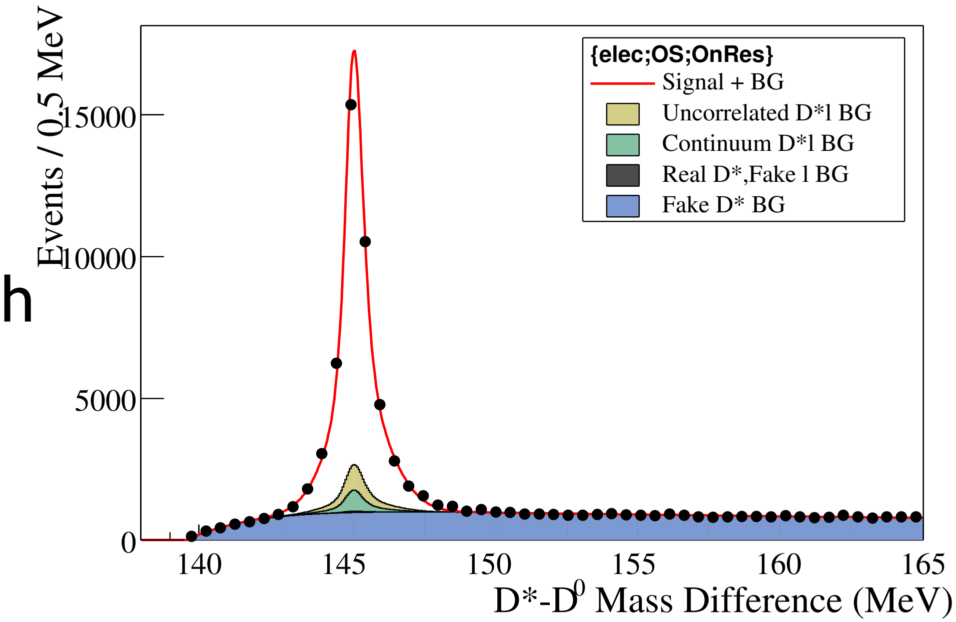
- Program for $|V_{cb}|$:
  - ▷ Measure rate at $w \to 1$
  - ▷ Compute corrections to $\mathcal{F}(1)$ for finite m_Q

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

- Event selection
  - ▷ lepton with $p^* > 1.2\,\mathrm{GeV}$
    - Electrons and muons
  - ▷ reconstructed $D^{*+} \to D^0\pi_s$
    - $D^0 \to K^-\pi^+, K^0_S\pi^+\pi^-, K^-\pi^+\pi^-\pi^+, K^-\pi^+\pi^0$
    - $\delta m = m_{D^0\pi_s} - m_{D^0}$



- Backgrounds:
  - ▷ Uncorrelated $B \to D^{*+}X,\ \bar{B} \to Y\ell \to \angle(D^{*+},\ell)$
  - ▷ Correlated $B \to D^{*+}X,\ X \to Y\ell \to$ MC
  - ▷ Continuum $\to$ off-resonance
  - ▷ Combinatorics $\to$ sideband
  - ▷ $B \to D^{*+}X\ell\bar{\nu}$



- Background characterization with
  - ▷ angle between D^{*+} and ℓ
  - ▷ angle between B^0 and $(D^{*+}\ell)$

both in $\Upsilon(4S)$ restframe

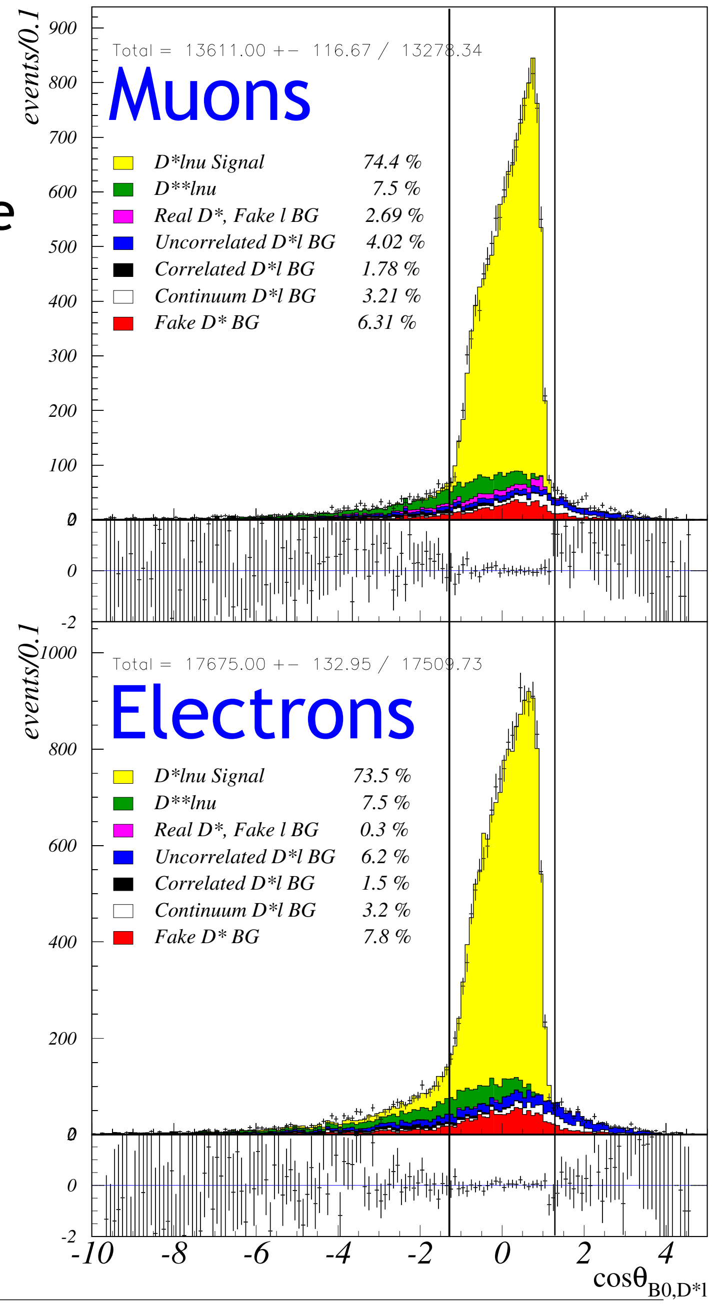
Signal extraction: $\cos\theta_{B^0,D^*\ell}$

- At $\Upsilon(4S)$, well known
  - ▷ beam parameters
  - ▷ B meson energy and momentum magnitude
- For signal decay $\bar{B} \to D^*\ell\bar{\nu}$

$$
\begin{aligned}
p_\nu^2 &= (p_B - p_{D^{*+}} - p_\ell)^2 \\
&= p_B^2 + p_{D^*\ell}^2 - 2p_B\,p_{D^*\ell} \\
&= m_B^2 + m_{D^*\ell}^2 - 2(E_B E_{D^*\ell} - \vec{p}_B \cdot \vec{p}_{D^*\ell})
\end{aligned}
$$

$$
\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}
$$

- If additional particle(s) missing
  - ▷ negative tail in $\cos\theta_{B,D^*\ell}$ distribution
  - ▷ Bremsstrahlung: electrons vs. muons



Preliminary Result: $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})$

- Full data set of
  - on resonance: $\mathcal{L} = 79.1\,\mathrm{fb}^{-1}$
  - off resonance: $\mathcal{L} = \;\; 9.6\,\mathrm{fb}^{-1}$

  giving $\sim 70'000$ signal events with purity of 70-80%
- Average $2(e/\mu) \times 4(D^0) \times 3(\mathrm{years})$ samples

$$\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu}) = \frac{N_{data} - N_{BG}}{\varepsilon \cdot N_{B^0} \cdot \mathcal{B}(D^{*-} \to \bar{D}^0\pi_s) \cdot \mathcal{B}(\bar{D}^0)}$$

- Preliminary result

$$\boxed{\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) = 4.92 \pm 0.03_{stat} \pm 0.02_{MC\ \ stat} \pm 0.30_{syst}\%}$$

- Completely systematics dominated
- Future work:
  - $|V_{cb}|$ to come soon . . .
  - Do the exclusive branching fractions add up?

[1] Belle, PLB 526,247
[2] CLEO, PRL 89,081803
[3] OPAL, PLB 482,15

Systematics

- Systematics (relative error in %) in comparison

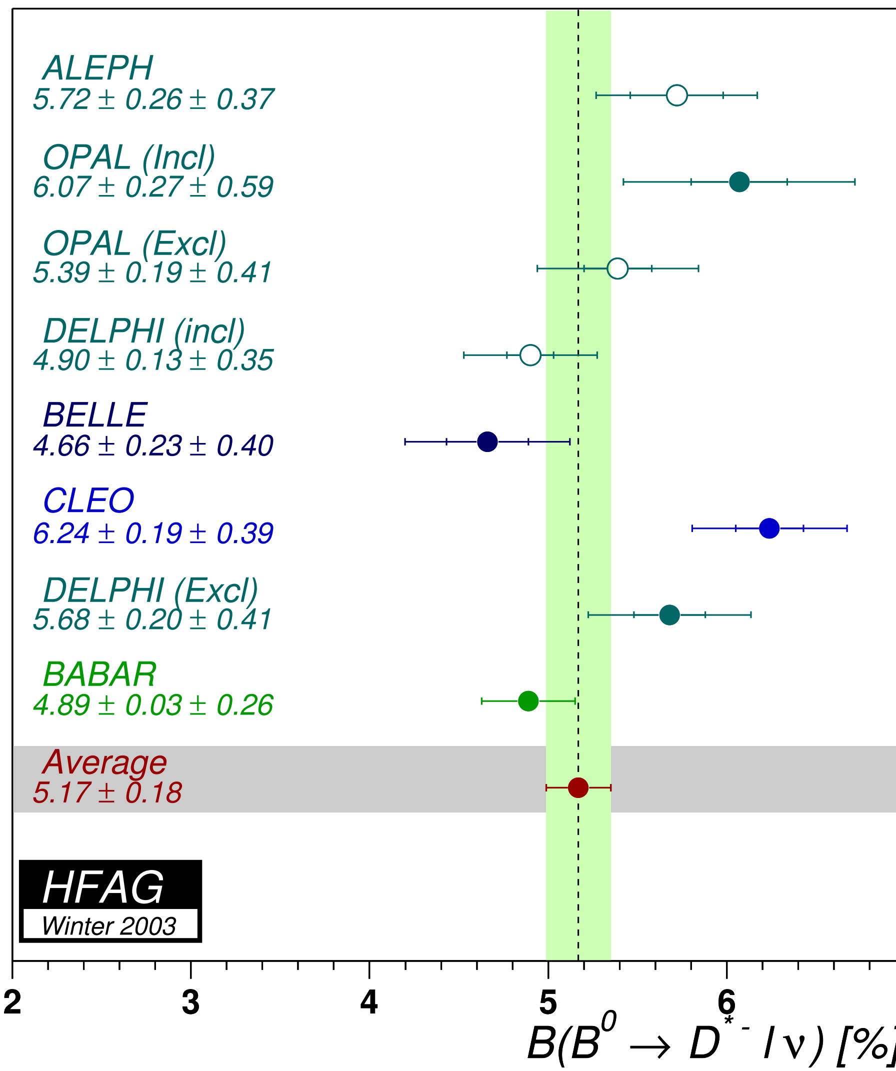
Source	BABAR	BELLE[1]	CLEO[2]	OPAL[3]
$\mathcal{B}$, τ_{B^0}	2.0	2.5	3.5	2.4
f_+/f_0, f_{B_d}	2.9	2.9	n/a	4.9
slow pion efficiency	1.9	5.0	2.8	n/a
Tracking/Vertexing	2.9	5.8	2.8	3.1
$D^{**}\ell\bar{\nu}$	2.0	0.5	0.9	5.4
Formfactors	1.8	0.3	1.8	1.1
Total	4.9	8.7	6.6	9.5

(Opal just as an example for an excl. LEP analysis)

- Differences between LEP and $\Upsilon(4S)$: $p_B \sim 30\,\mathrm{GeV} \Leftrightarrow 0.3\,\mathrm{GeV}$
  - ▷ background from $D^{**}\ell\bar{\nu}$ and $D^{*}X\ell\bar{\nu}$
  - ▷ slow charged pion (tracking)
  - ▷ dependence on formfactors (lepton spectrum)
  - ▷ slow neutral pion (calorimetry)

The World Average

- http://www.slac.stanford.edu/xorg/hfag/semi/ (or mirror at KEK)
- Scale results to set of common input parameters
- Correlated systematics
  - ▷ branching fractions
  - ▷ lifetimes
  - ▷ B production fractions
  - ▷ HQET parameters
  - ▷ D^{**} modeling
- Difference to PDG 2002!
  - ▷ Remove results obtained with different methods (2$\times$ ARGUS)
  - ▷ Remove superceeded results (CLEO)
- PDG will be updated

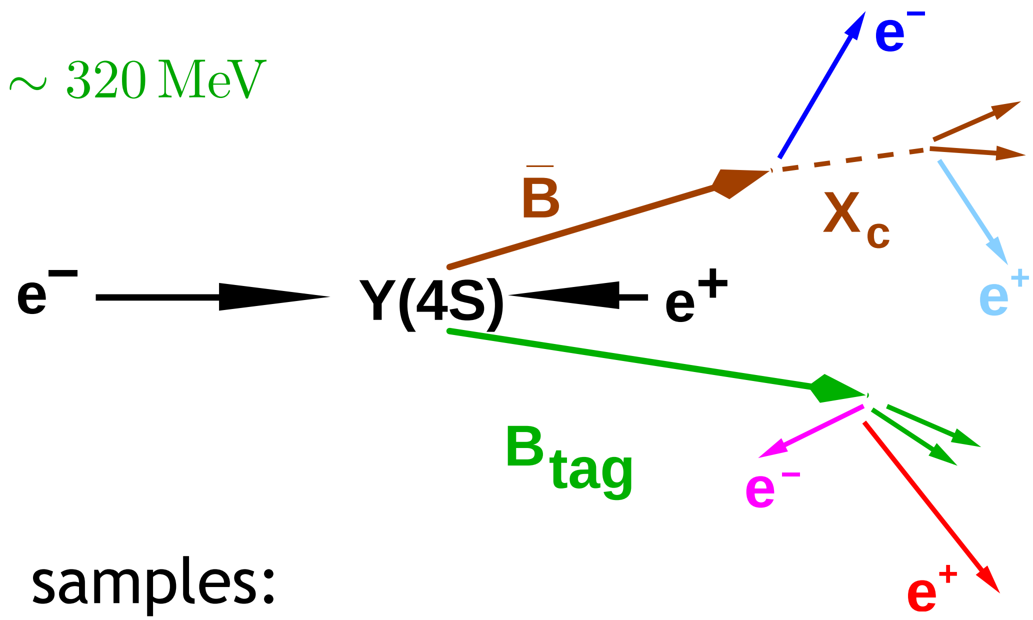


[1] ARGUS, PL B318, 397
[2] CLEO, PRL 76, 1570

$\mathcal{B}(\bar{B} \to X e^- \nu)$ with Electron Tags

- Charge correlation pioneered by ARGUS[1] and CLEO[2]
  - ▷ Select events with two electrons: tag and signal electron
  - ▷ Model-independent separation of prompt and cascade electrons

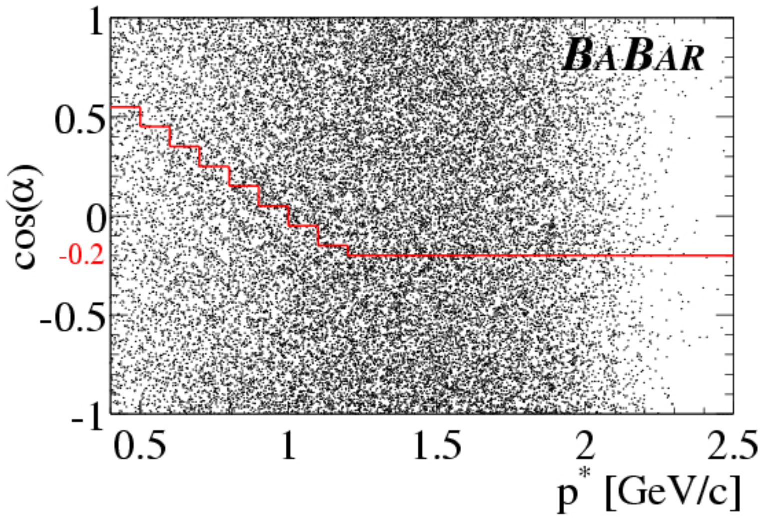
In $\Upsilon(4S)$ c.m.s.: $p_B^* \sim 320\,\mathrm{MeV}$

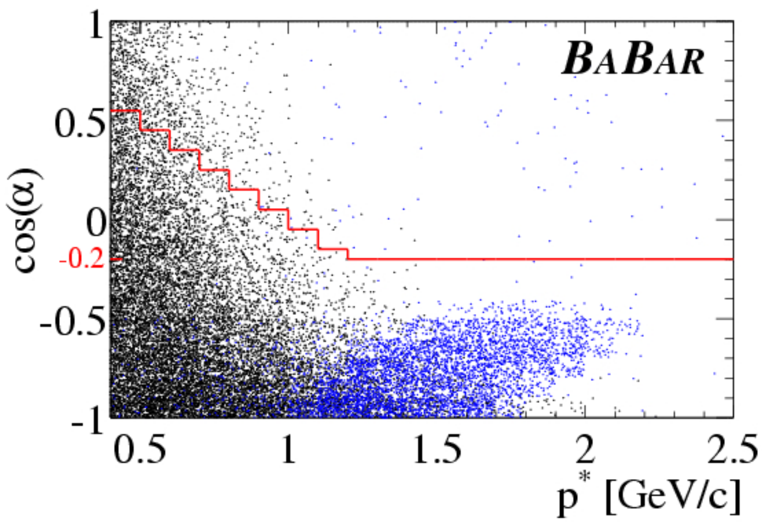


- Three electron samples:
  - ▷ Normalization with tag electron $(1.4 < p^* < 2.3\,\mathrm{GeV}/c)$
  - ▷ e^+e^-, mostly signal
    - tag and prompt signal from different B
    - tag and cascade signal from same B
    - tag and cascade signal from mixed B
  - ▷ e^+e^+, mostly background
    - tag and cascade signal from different B
    - tag and prompt signal from mixed B

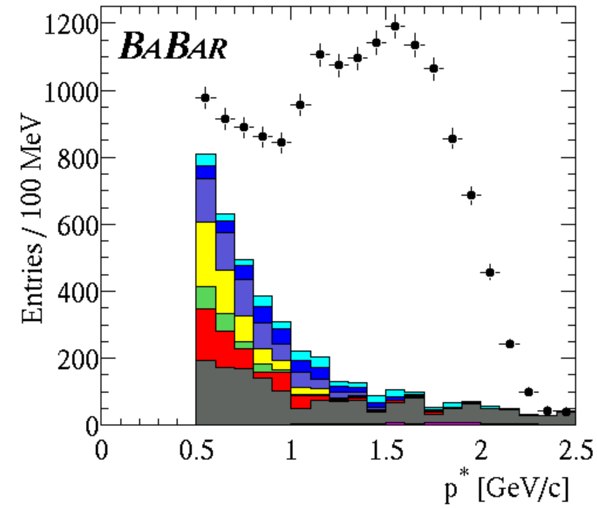
Determination of Electron Spectra

- Reduce same-B cascades:
  Angle between e^+ and e^-

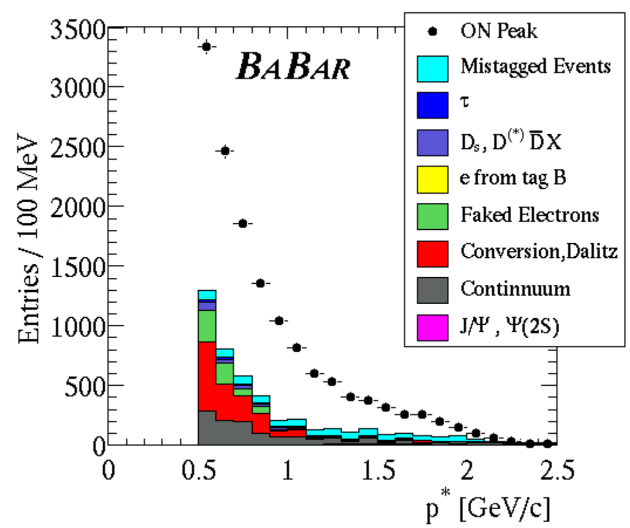




- Resulting Spectra:



$e^{\pm}e^{\mp}$

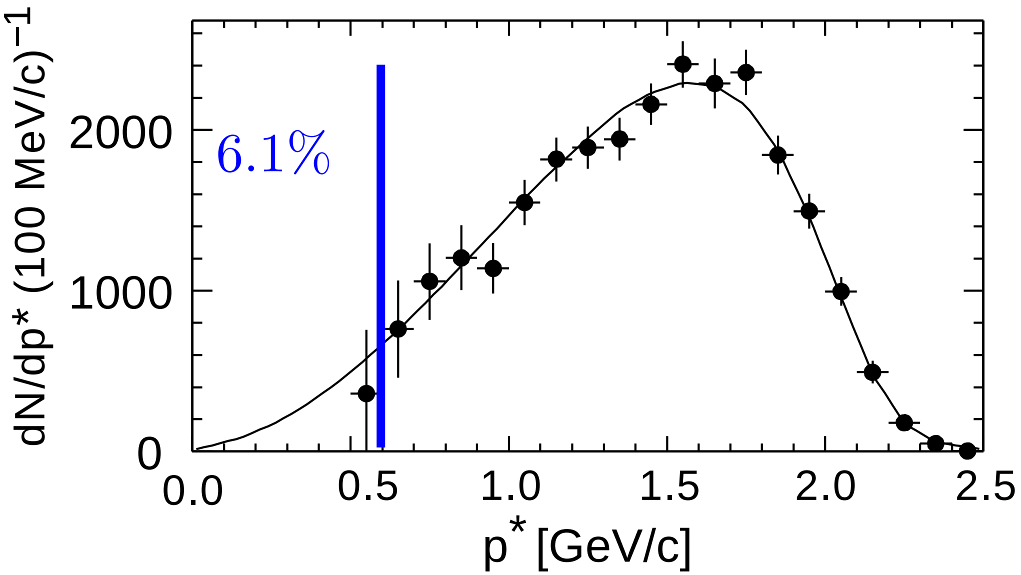


$e^{\pm}e^{\pm}$

The result: $\mathcal{B}(\bar{B} \to X e^- \nu)$

- Unfold $B^0\bar{B}^0$ mixing:

$$\frac{dN_{\pm\mp}}{dp^*} = \frac{dN_{prompt}}{dp^*} \cdot (1-\chi) + \frac{dN_{casc}}{dp^*} \cdot \chi$$
$$\frac{dN_{\pm\pm}}{dp^*} = \frac{dN_{prompt}}{dp^*} \cdot \chi + \frac{dN_{casc}}{dp^*} \cdot (1-\chi)$$



where N_{prompt} is corrected for opening angle efficiency

- Only small corrections:
  - ▷ Bremsstrahlung: $2.20 \pm 0.35\%$
  - ▷ Geometric acceptance: 16%
  - ▷ ε_ℓ vs. $\varepsilon_{\ell\ell}$: $2.0 \pm 0.5\%$
  - ▷ Extrapolation to $p^* = 0$: $6.1 \pm 0.9\%$

- Result on $4\,\text{fb}^{-1}$:

$$N_{prompt} = 25070 \pm 410_{stat}$$
$$N_{tag} = 304048 \pm 880_{stat}$$

$$\mathcal{B}(\bar{B} \to X e^- \nu) = 10.87 \pm 0.18 \pm 0.30\%$$

Determination of $|V_{cb}|$

- Instead of inclusive/exclusive models, use $\Upsilon(1S)$ expansion[1]

$$|V_{cb}| = 0.0419 \cdot \sqrt{\frac{\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu})}{0.105} \frac{1.60\,\mathrm{ps}}{\tau_b}} \times (1.0 \pm 0.019_{pert} \pm 0.017_{\lambda_1} \pm 0.012_{m_b})$$

- Other input parameters:

$$m_b^{1S} = 4.73 \pm 0.05\,\mathrm{GeV}$$
$$\lambda_1 = -0.25 \pm 0.25\,\mathrm{GeV}$$
$$\tau_B = 1.601 \pm 0.022\,\mathrm{ps}$$
$$\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}) = 0.17 \pm 0.05\%$$

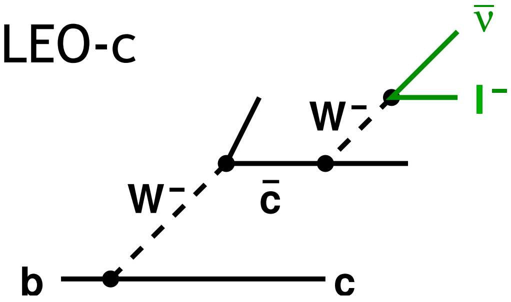
- Published result (theory errors added linearly):

$$|V_{cb}| = 0.0423 \pm 0.0007_{exp} \pm 0.0020_{theo}$$

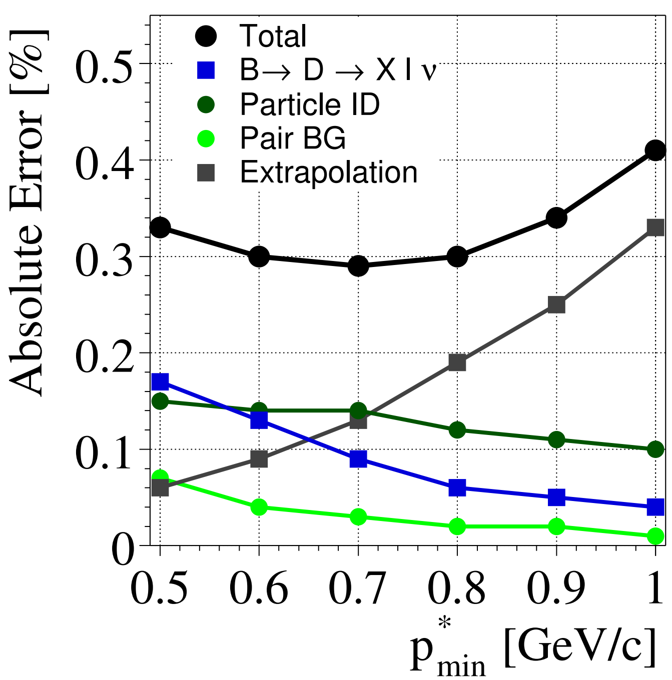
- Reduce theoretical errors by measuring parameters

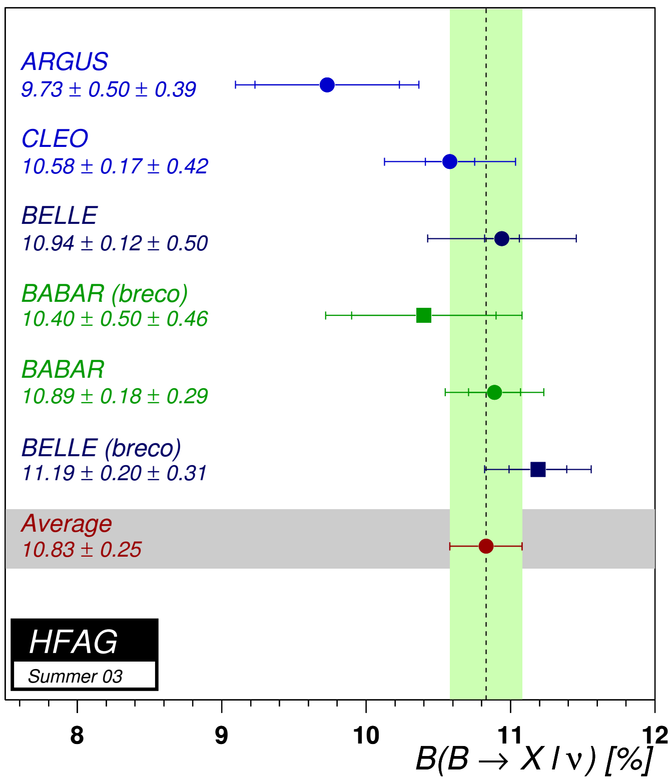
Systematics and Context

- Dominating systematics:
  - ▷ Upper vertex decays $\Delta\mathcal{B}(D_s \to \phi\pi) \sim 25\%$ $\longrightarrow$CLEO-c
  - ▷ Upper vertex decays $\mathcal{B}(B \to D^{(*)}D^{(*)}K)$
  - ▷ $\Upsilon(4S) \to B^0\bar{B}^0 \quad \Leftrightarrow \quad \Upsilon(4S) \to B^+B^-$
  - ▷ B^0 and B^+ lifetimes



$\longrightarrow$ B factories





Chay *et al.*, PL B247, 399
Bigi and Uraltsev, PL B293, 430

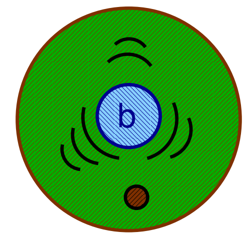
QCD in the Heavy Quark Limit

- Operator Product Expansion gives (schematically) decay rate:

$$\Gamma(b \to c\ell\bar{\nu}) \propto \frac{G_F^2|V_{cb}|^2}{192\pi^3} m_b^5 \left[1 + \frac{0}{m_b} + \frac{f(\lambda_1, \lambda_2)}{m_b^2} + \ldots + \frac{\alpha_S}{\pi}(\ldots) + \ldots \quad \right]$$

- Non-perturbative parameters
  - ▷ $\overline{\Lambda}$: interactions of light degrees of freedom with

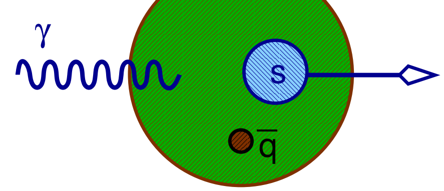
    b-quark : $m_B = m_b + \overline{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_b} + \ldots$



  - ▷ λ_1 : $(-)$ kinetic energy squared of b-quark in B-meson
  - ▷ λ_2 : chromo-magnetic coupling of b-quark spin to ''brown muck''

- Similar expansions for other observables $\mathcal{O} = f(\overline{\Lambda}, \lambda_1; \lambda_2)$, *e.g.* moments of lepton energy and hadronic mass distributions

- Determinations of $\overline{\Lambda}$ and λ_2:
  - ▷ $b \to s\gamma \to \langle E_\gamma \rangle = \frac{m_B - \overline{\Lambda}}{2} + \ldots$
  - ▷ Mass difference of B-B^* $\to$ $\lambda_2 \sim 0.12\,\mathrm{GeV}^2$

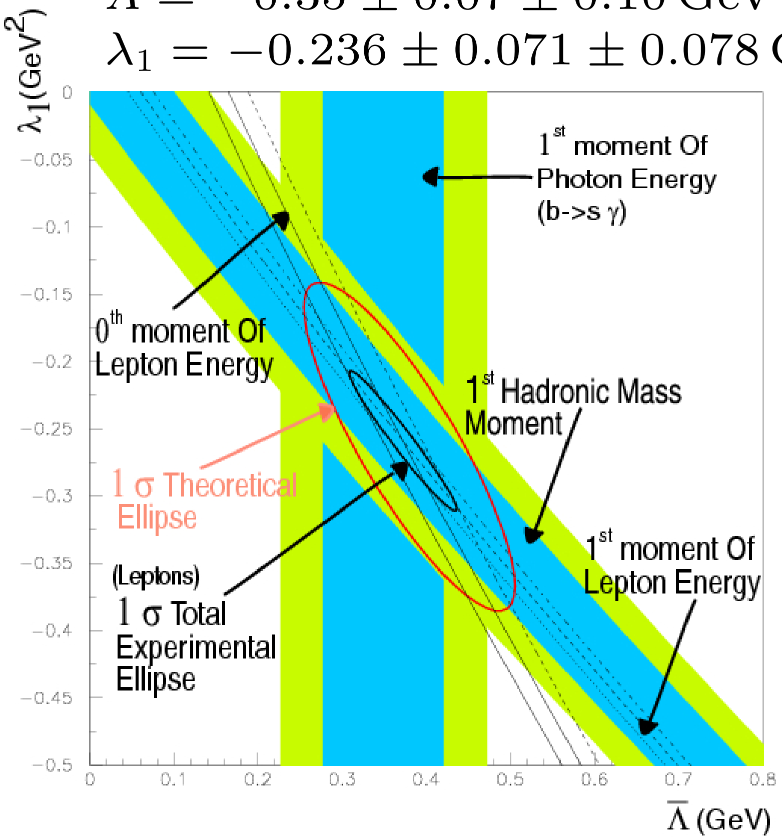


Spectral Moments Measurements

[1] CLEO, PRL 87, 251807
[2] CLEO, PRL 87, 251808
[3] Falk, Luke, PRD 57, 424
[4] DELPHI, hep-ex/0210046

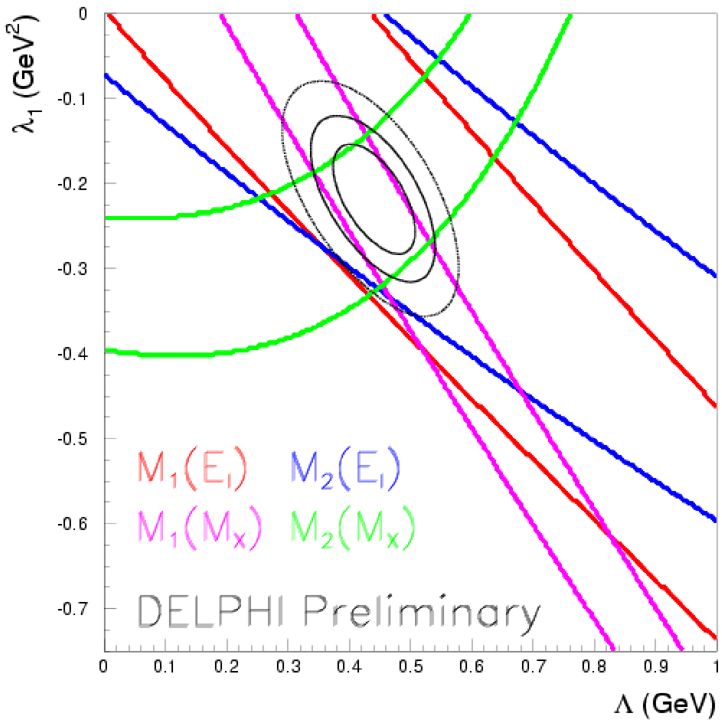
- CLEO[1,2] [3]

$$\overline{\Lambda} = 0.35 \pm 0.07 \pm 0.10\,\mathrm{GeV}$$
$$\lambda_1 = -0.236 \pm 0.071 \pm 0.078\,\mathrm{GeV}^2$$

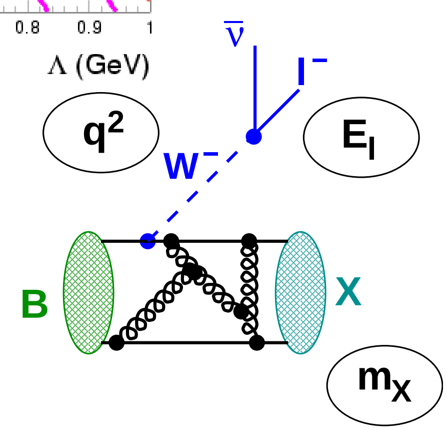


DELPHI[4]

$$\overline{\Lambda} = 0.44 \pm 0.04 \pm 0.05 \pm 0.07\,\mathrm{GeV}$$
$$\lambda_1 = -0.23 \pm 0.04 \pm 0.05 \pm 0.08\,\mathrm{GeV}^2$$



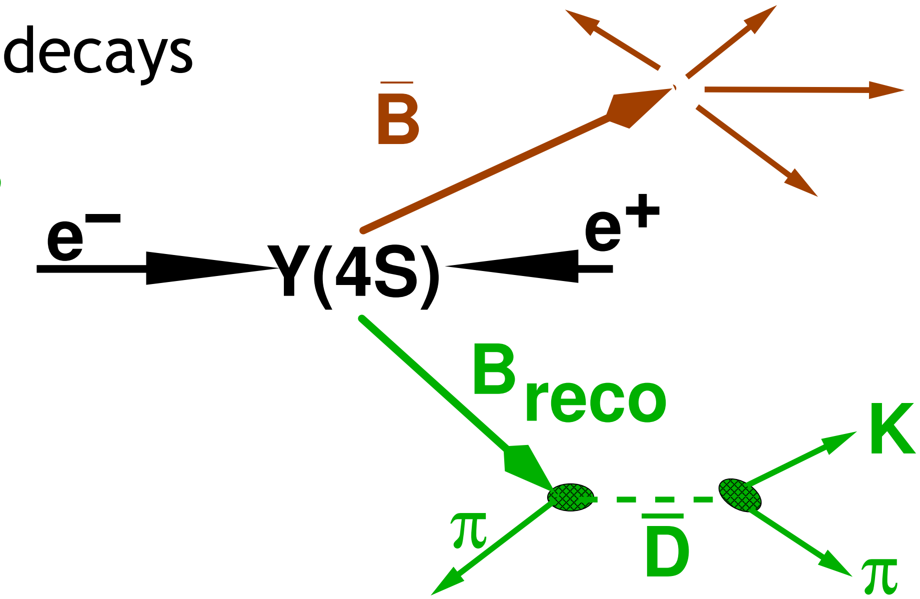
- Caveats
  - ▷ CLEO: Restricted phase space, as $p_\ell > 1.5\,\mathrm{GeV}/c$
  - ▷ DELPHI: Only high-mass charm states



'Recoil' Physics

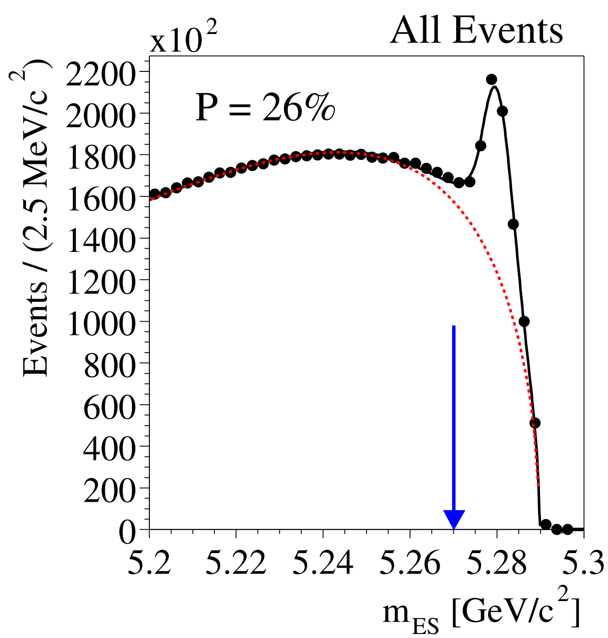
- Fully reconstructed hadronic B-decays

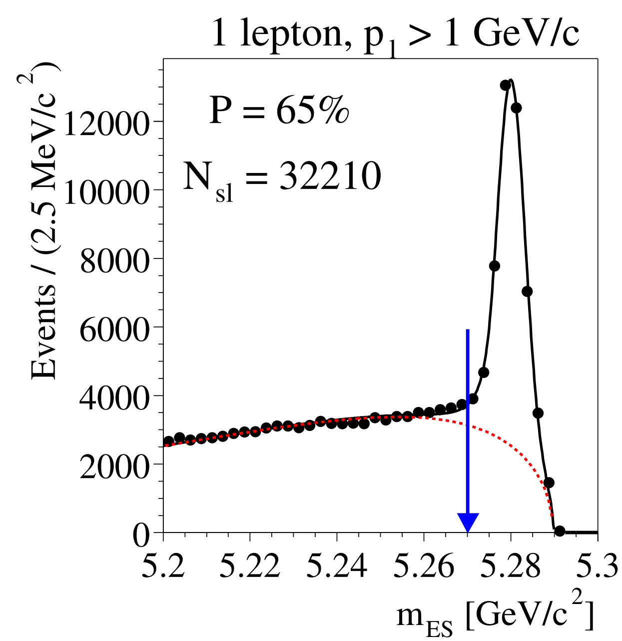
$$B \rightarrow D^{(*)}(n_1\pi^{\pm} + n_2K^{\pm} + n_3K^0_S + n_4\pi^0),$$
$$n_1 + n_2 < 6, n_3 < 3, n_4 < 3$$



- Knowledge of beam energies at the $\Upsilon(4S)$:

$$m_{ES} = \sqrt{E^2_{beam} - \vec{p}^{\,2}_B}$$
$$\Delta E = E_B - E_{beam}$$



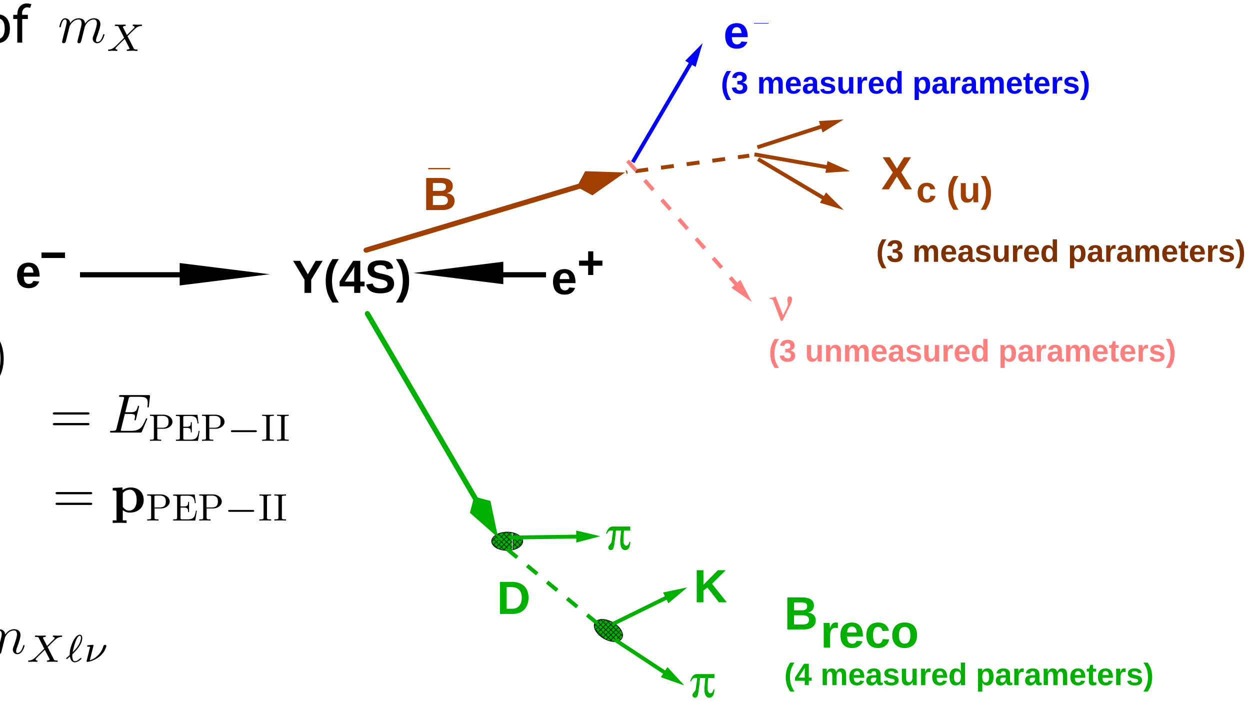


- Efficiency:
  - ▷ $B^0 \sim 0.3\%$
  - ▷ $B^+ \sim 0.5\%$

  $\rightarrow \sim 4000 B/\,\mathrm{fb}^{-1}$

Hadronic Mass Moments at *BABAR*

- Goal: Measure m_{X_c} distribution for different (low) p_ℓ cuts
  - ▷ Access to different phase space compared to CLEO
  - ▷ Direct measurement of m_X



- Kinematic Fit
  - ▷ Conservation of $(E, \vec{p})$

$$E_{B_{reco}} + E_X + E_\ell + E_\nu = E_{\mathrm{PEP-II}}$$

$$\mathbf{p}_{B_{reco}} + \mathbf{p}_X + \mathbf{p}_\ell + \mathbf{p}_\nu = \mathbf{p}_{\mathrm{PEP-II}}$$

  - ▷ Mass constraint

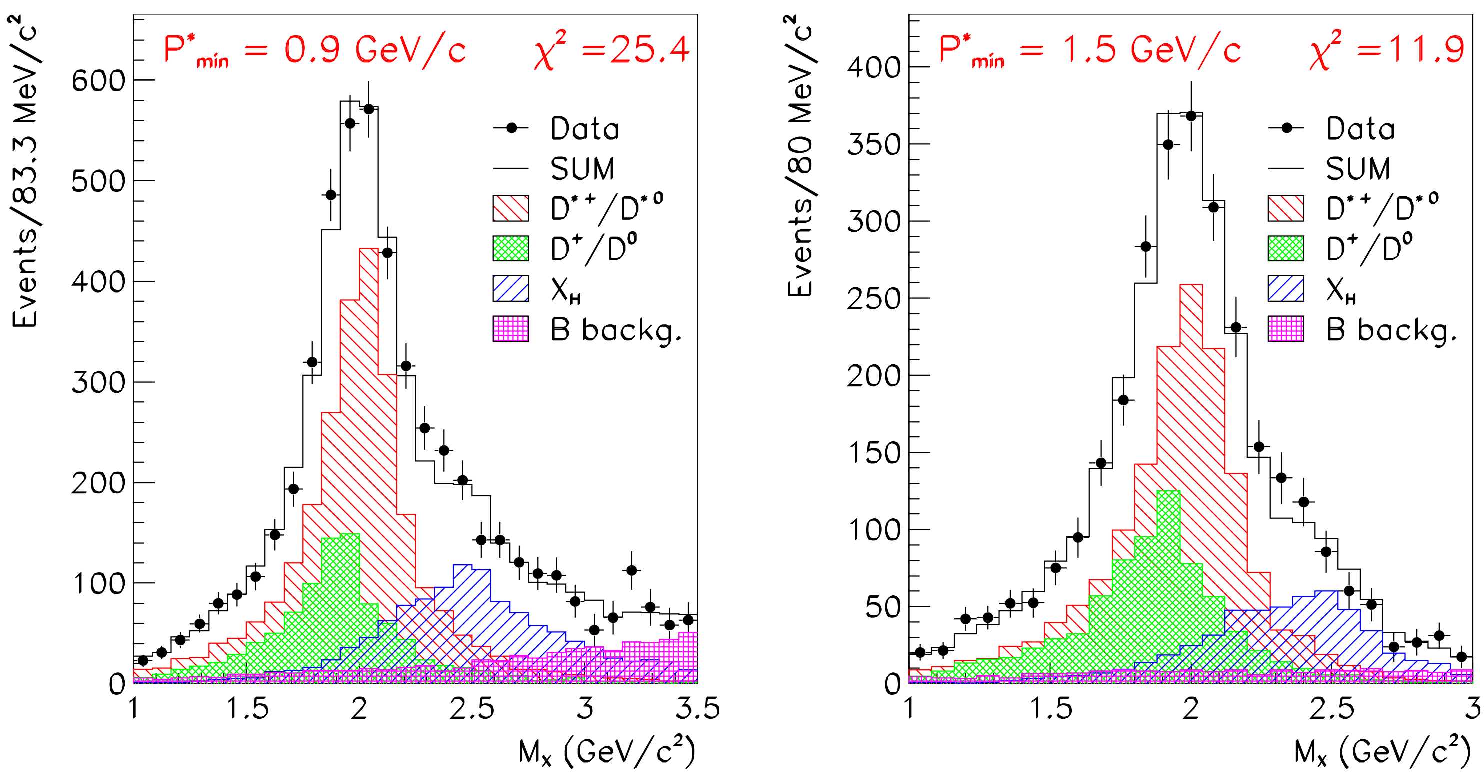
$$m_{B_{reco}} = m_{X\ell\nu}$$

- Event selection:
  - ▷ One lepton with $p^* > 0.9\,\mathrm{GeV}$
  - ▷ $Q_\ell = Q_B$ for B^+_{reco}
  - ▷ $|Q| \leq 1$
  - ▷ $m^2_{miss} \leq 1\,\mathrm{GeV}^2$

- Preliminary analysis on $50\,\mathrm{fb}^{-1}$

Fit to m_X Distribution

- Measure m_X with as a function of p^*_{min} of lepton in recoil
- Binned χ^2 fit to m_X distribution with 3 floating contributions:
  - ▷ $D^{+/0}$, $D^{*+/0}$, X_H(resonant and non-resonant components)
  - ▷ Background component fixed
  - ▷ Non-resonant X_H contribution p^*_{min}-dependent



[1] Scora *et al.*, PRD 52, 2783
[2] CLEO, PRL 76, 3898
[3] Goity, Roberts, PRD 51, 3459

Determination of Moment

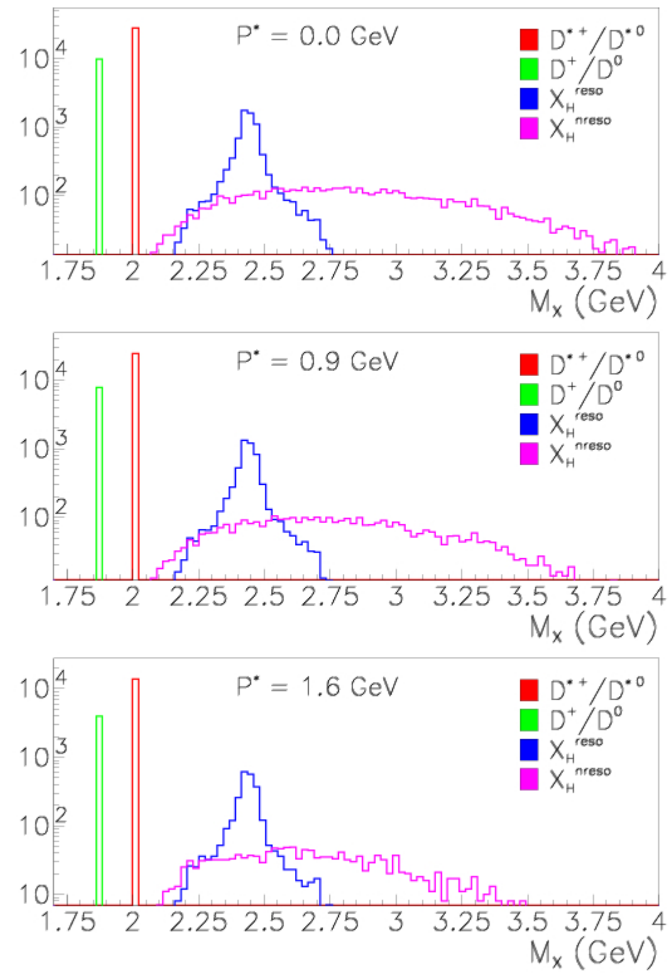
- Use underlying true values for experimental determination

$$\langle m_X^2 - \overline{m}_D^2\rangle = R_{D^*}(M_{D^*}^2 - \overline{m}_D^2) + R_D(M_D^2 - \overline{m}_D^2) + R_{X_H}\langle M_{X_H}^2 - \overline{m}_D^2\rangle$$

▷ $\overline{m}_D^2 = \frac{m_D + 3m_{D^*}}{4} = 1.975\,\mathrm{GeV}/c^2$

- Input parameters:

Channel	$\langle M_y^{gen}\rangle$	$\mathcal{B}$	Model
$D\ell\nu$	1.867	~ 0.2	ISGW2[1]
$D^*\ell\nu$	2.009	~ 0.5	HQET, FF[2]
$X_H^{res}\ell\nu$	~ 2.4	~ 0.2	ISGW2[1]
$X_H^{nres}\ell\nu$	~ 2.86	~ 0.1	GR[3]

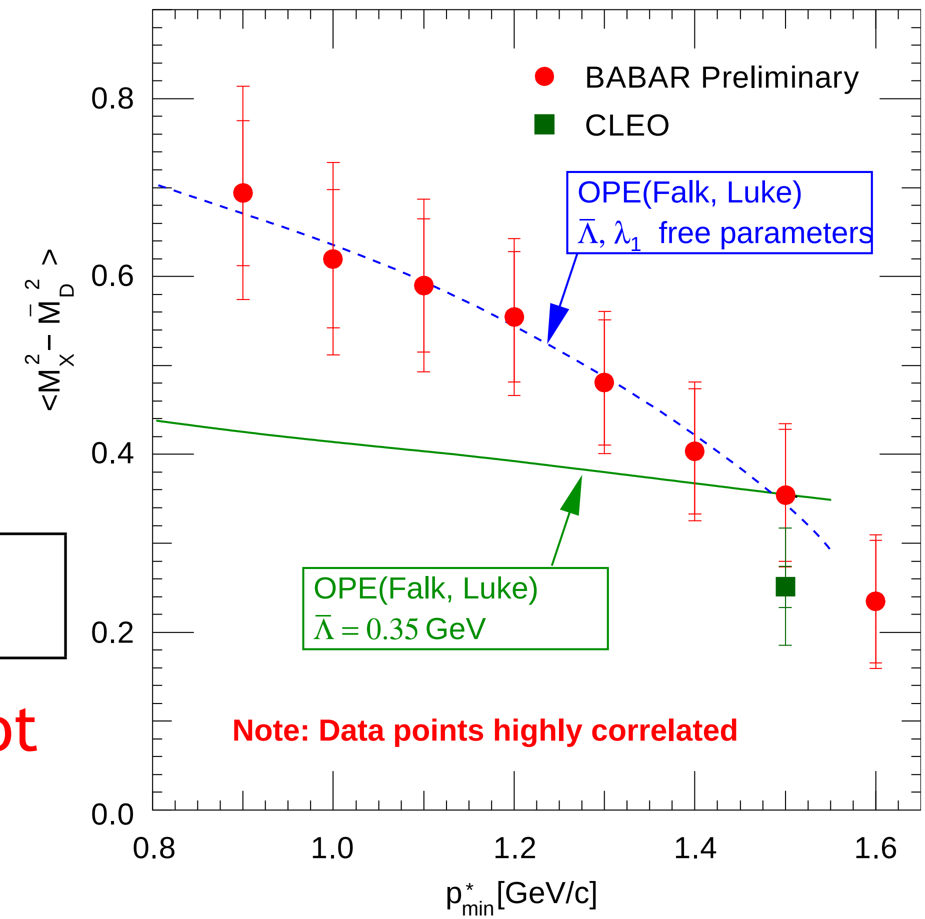


- Parameters of non-resonant X_H not precisely known

Preliminary Results

- Strong p^*_{min} dependence of moments
- Statistics limited,
  largest systematics:
  X_H model and background
- For $p^*_{min} = 1.5\,\mathrm{GeV}/c$ and
  with $\bar{\Lambda} = 0.35 \pm 0.13\,\mathrm{GeV}$
  (from $b \to s\gamma$, CLEO[1]):

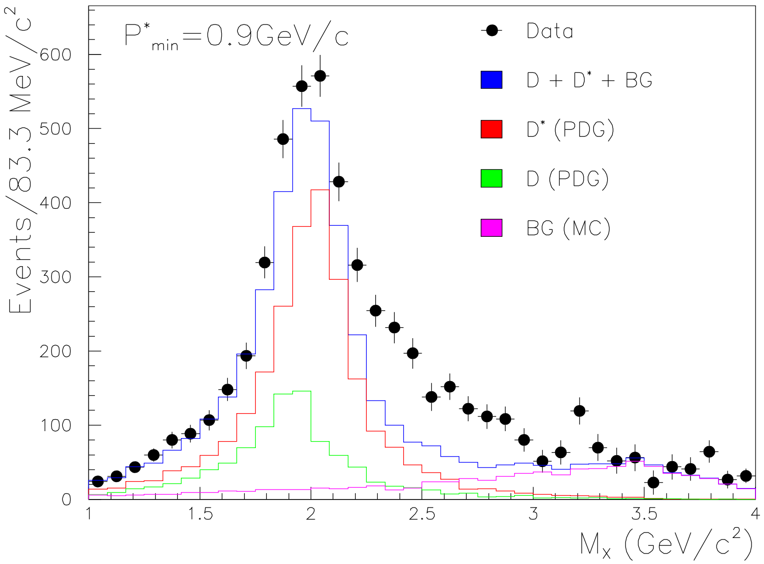
$$\lambda_1 = -0.17 \pm 0.06 \pm 0.07\,\mathrm{GeV}^2$$



- BUT: These parameters do not describe p^*_{min} dependence of moments
- Rise of moment driven by high-mass charm states
  - ▷ phase-space suppressed at $p^*_{min} > 1.5\,\mathrm{GeV}$
  - ▷ largest contribution from non-resonant X_h

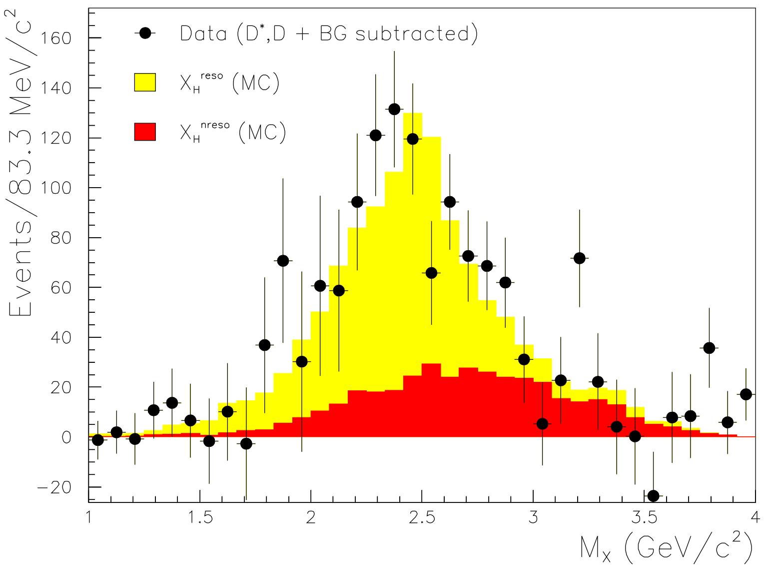
X_H Mass Distribution

- Largest contribution to systematic error at low p^*_{min}



- Estimate contribution from data:
  - ▷ Assume PDG $\mathcal{B}$ for D^* and D
  - ▷ Fix background BG
  - ▷ Subtract D^*, D, and BG from data

- Resulting distribution is fully compatible with MC



$\Rightarrow$ $\langle m_{X_H} \rangle$ consistent with value used in determination of first mass moment

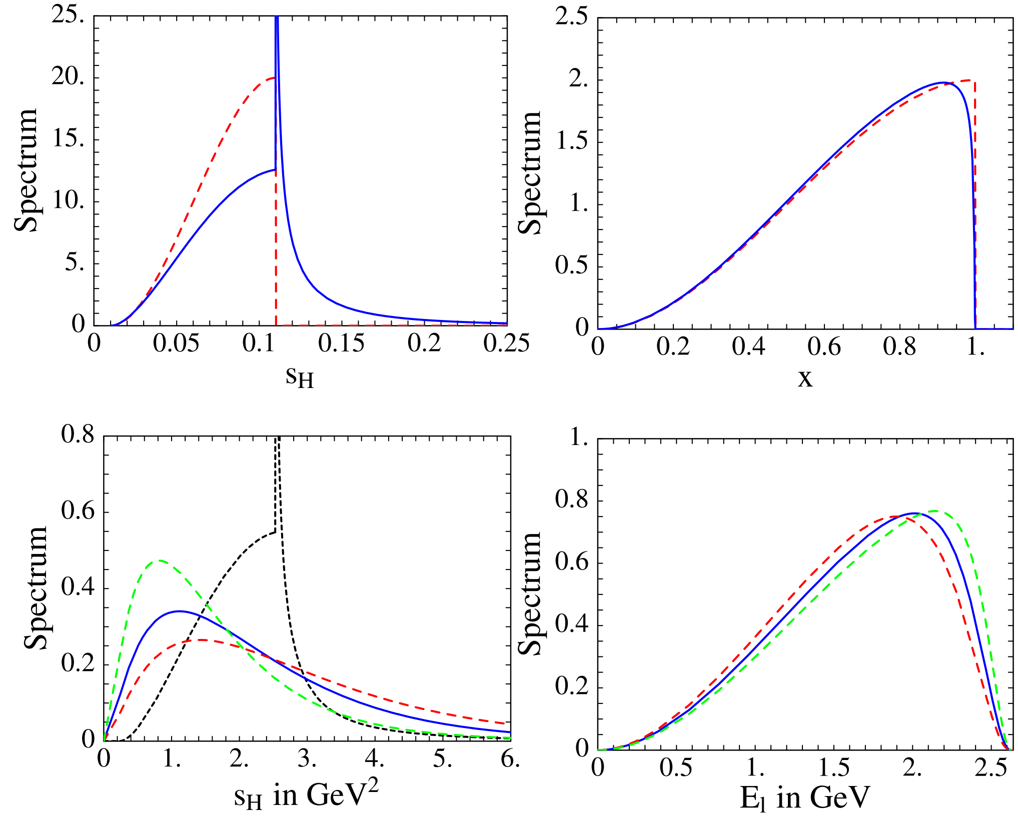
[1] Gremm, *et al.*, PRL 77, 20
[2] CLEO, hep-ex/0209024

Lepton Energy Moments (Prospects)

- Parton-level corrections different for
  - ▷ hadronic mass $(s_H = {m_X}^2)$
  - ▷ lepton energy
- Previous analyses
  - ▷ Gremm *et al.*[1]
  - ▷ CLEO[2]

  Single lepton sample
  - ▷ Lepton with $p^* > 1.5\,\mathrm{GeV}$ to reject cascade leptons and background
    $\longrightarrow$ limited phase space

hadronic mass   lepton energy

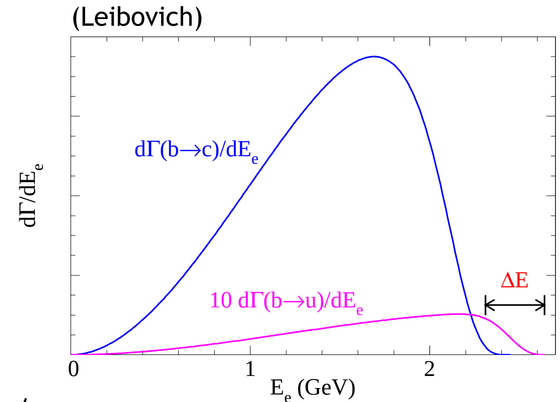


- At B factories, use lepton-tagged lepton sample
  - ▷ (Nearly) full phase space of prompt leptons
  - ▷ Generalized and higher moments
    $\longrightarrow$ bands with different inclinations in $(\overline{\Lambda}, \lambda_1)$ plane
  - ▷ Systematics limited by bremsstrahlung and absence of muons

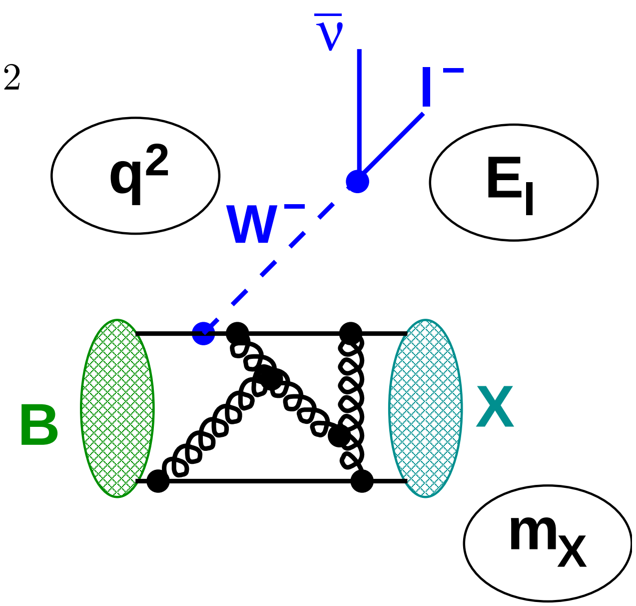
[1] Neubert, PR D49, 3392
Bigi *et al.*, IJMP A9,2467
[2] Barger *et al.*, PL B251, 629
[3] Bauer *et al.*, PL B479, 395
[4] Greub *et al.*, PR D56, 4250
[5] Bauer *et al.*, PR D64, 113004

Analysis Strategies for $\bar{B} \to X_u \ell \bar{\nu}$

- The problem: $\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}) \sim 50 \cdot \mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$
- Exclusive $|V_{ub}|$ measurements:
  - ▷ Experimentally: $\bar{B} \to \rho \ell \bar{\nu}$, $\bar{B} \to \pi \ell \bar{\nu}$
  - ▷ Form factors: Lattice QCD, quark models, sum rules, . . .



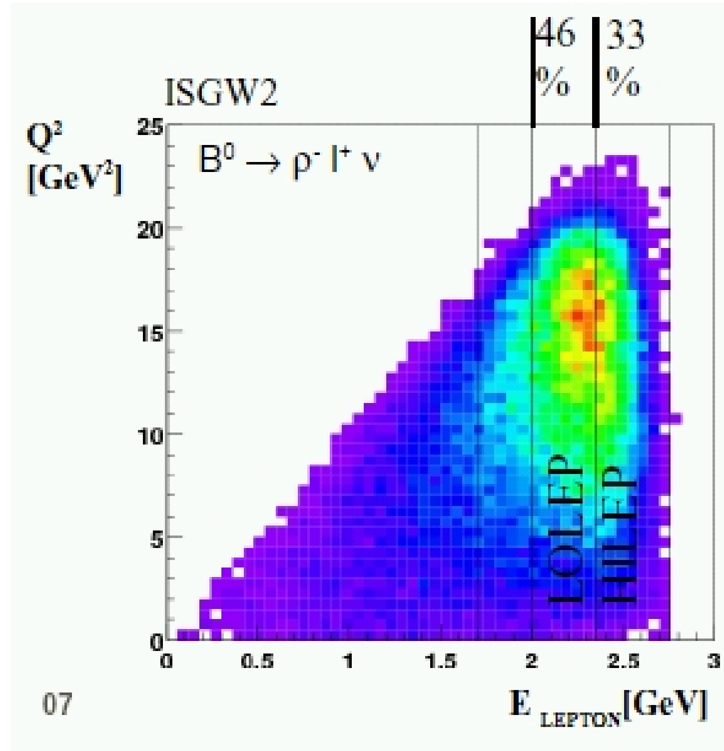
- Inclusive $|V_{ub}|$ measurements:
  - ▷ Lepton energy spectrum[1]: $E_\ell > (m_B^2 - m_D^2)/2m_B$
  - ▷ Hadronic mass spectrum[2]: $m_X < m_D$
  - ▷ Dilepton mass spectrum[3]: $q^2 > (m_B - m_D)^2$
  - ▷ Hadronic energy spectrum[4]: $E_X < m_D$
  - ▷ Combinations of the above[5]: (m_X, q^2)



- Restricted phase space
  - ▷ Extrapolation:
    $$f_u(E_\ell > 2.3\,\text{GeV}) \sim 10\%$$
    $$f_u(m_X < 1.55\,\text{GeV}) \sim 70\%$$
  - ▷ Convergence of calculation

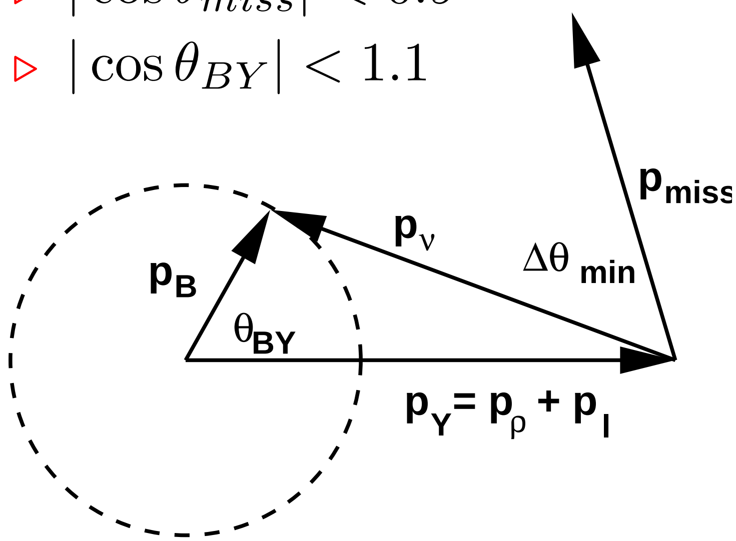
Exclusive $\bar{B} \to \rho e \bar{\nu}$ Analysis Strategy

- Analysis based on $50\,\text{fb}^{-1}$
- Two energy ranges for lepton
  - ▷ LOLEP: $2.0 < E_e < 2.3\,\text{GeV}$ $(b \to c\ell\bar{\nu})$
  - ▷ HILEP: $2.3 < E_e < 2.7\,\text{GeV}$ (signal) (+ continuum)



LOLEP
HILEP

- ν reconstruction
  - ▷ $0.8 < \cos\Delta\theta_{min} < 1.0$
  - ▷ $|\cos\theta_{miss}| < 0.9$
  - ▷ $|\cos\theta_{BY}| < 1.1$



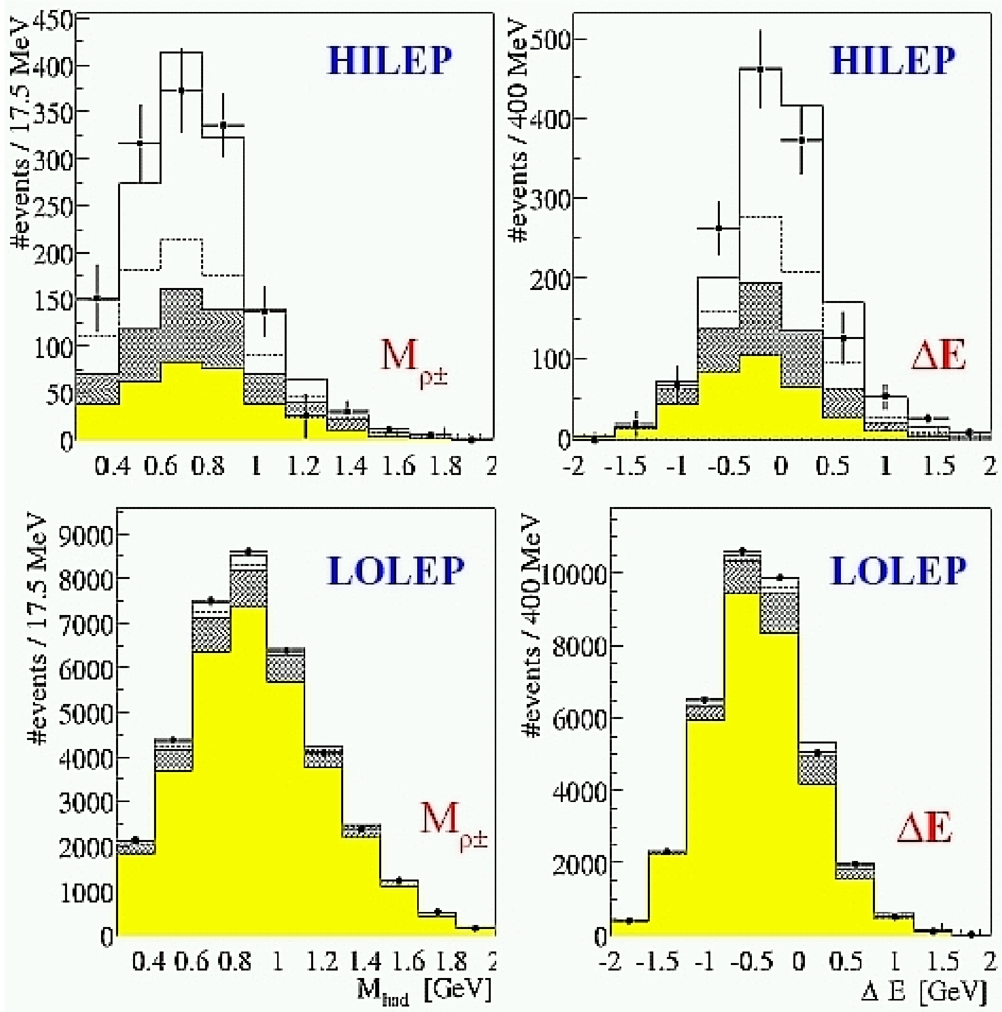
- Continuum suppression
  - ▷ Event shape $R_2 < 0.4$
  - ▷ Neural net with 14 variables

Fit for $B^0 \to \rho^- e^+ \bar{\nu}$

- Binned max. likelihood fit:

$$\Delta E^* = E_{had} + E_e + |p_\nu| - E_{beam}$$
$$m_{had} = m_{\pi\pi(\pi)}$$

with
- $|p_\nu|$ from missing momentum
- continuum shape from off-peak data, other shapes from MC



(Projections for $B^0 \to \rho^- e^+ \nu$)

- Isospin and quark model relations used in fit:

$$\Gamma(B^0 \to \rho^- e^+ \nu) = 2\Gamma(B^+ \to \rho^0 e^+ \nu)$$
$$\Gamma(B^0 \to \pi^- e^+ \nu) = 2\Gamma(B^+ \to \pi^0 e^+ \nu)$$
$$\Gamma(B^+ \to \rho^0 e^+ \nu) = 2\Gamma(B^+ \to \omega e^+ \nu)$$

$$\mathcal{B}(B^0 \to \rho^- e^+ \bar{\nu}) = (3.29 \pm 0.42 \pm 0.47 \pm 0.60) \times 10^{-4}$$

$$B^+ \to \rho^0 e^+ \nu \; : \; 321 \pm 40$$
$$B^0 \to \rho^+ e^+ \nu \; : \; 505 \pm 63$$

[1] Scora *et al.*, PR D52, 2783
[2] Beyer, Melikhov, PL B436, 344
[3] Del Debbio, *et al.*, PL B416, 392
[4] Ball, Braun, PR D58, 094016
[5] Ligeti, Wise, PR D53, 4937

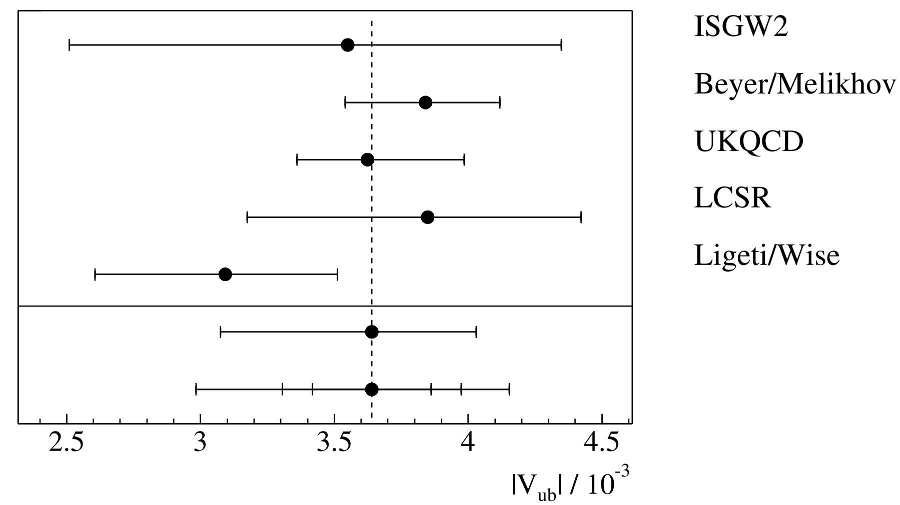
Exclusive $|V_{ub}|$ Result

- Systematic error:
  - ▷ Detector simulation: $\pm 8\%$
  - ▷ Background modeling: $\pm^{11}_{10}\%$
  - ▷ Method, analysis, *etc.*: $\pm 9\%$

- $$|V_{ub}| = \sqrt{\frac{\mathcal{B}(B^0 \to \rho^- e^+ \bar{\nu})}{\Gamma_{theo} \cdot \tau_{B^0}}}$$

$$\tau_{B^0} = 1.542 \pm 0.016\,\text{ps}$$

- Models used for Γ_{theo}
  - ▷ ISGW2[1] HQET constituent quark model
  - ▷ UKQCD[2] Lattice QCD
  - ▷ LCSR[3] Light cone sum rules
  - ▷ Beyer/Melikhov[4] fully relativistic quark model
  - ▷ Ligeti/Wise[5] HQET model, SU(3) flavor and SU(4) spin-flavor symmetry



$$|V_{ub}| = (3.64 \pm 0.22 \pm 0.25^{+0.39}_{-0.56}) \times 10^{-3}$$

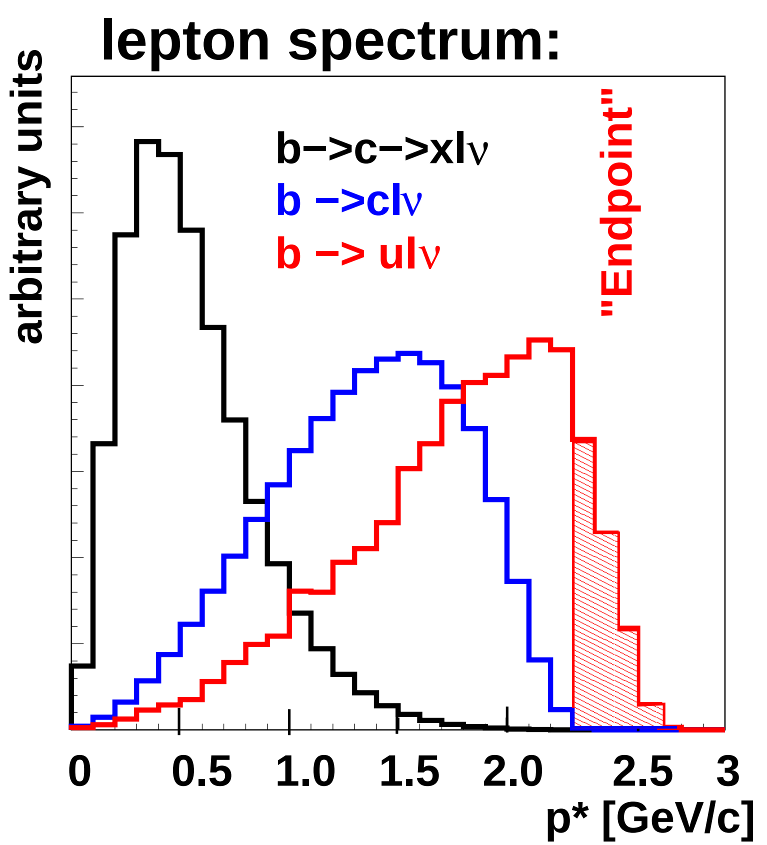
- Result and error:
  - ▷ Central value: weighted average of the five FF results
  - ▷ Error: half of the full spread of all theoretical uncertainties

[1] Neubert, PR D49, 3392
Bigi *et al.*, IJMP A9,2467
[2] Voloshin, PL B515, 74
Bauer *et al.*, hep-ph/0205150
Neubert, hep-ph/0207002

$\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$: 'Endpoint'

- Original method to measure charmless semileptonic B-decays
  - ▷ Best experimental rejection of $\bar{B} \to X_c \ell \bar{\nu}$
- Problems:
  - ▷ Sample $\sim 10\%$ of phase space
  - ▷ Large model-dependence in extrapolation
- Solution at $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ [1]
  - ▷ Fermi motion of b-quark parametrized by shape function
  - ▷ Use photon energy spectrum in $b \to s\gamma$ to constrain it

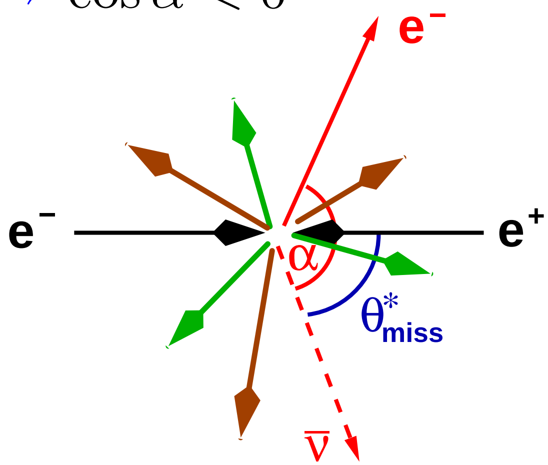
  $\longrightarrow$ Remove (to some extent) model-dependence from fraction $f_u(\Delta p^*)$

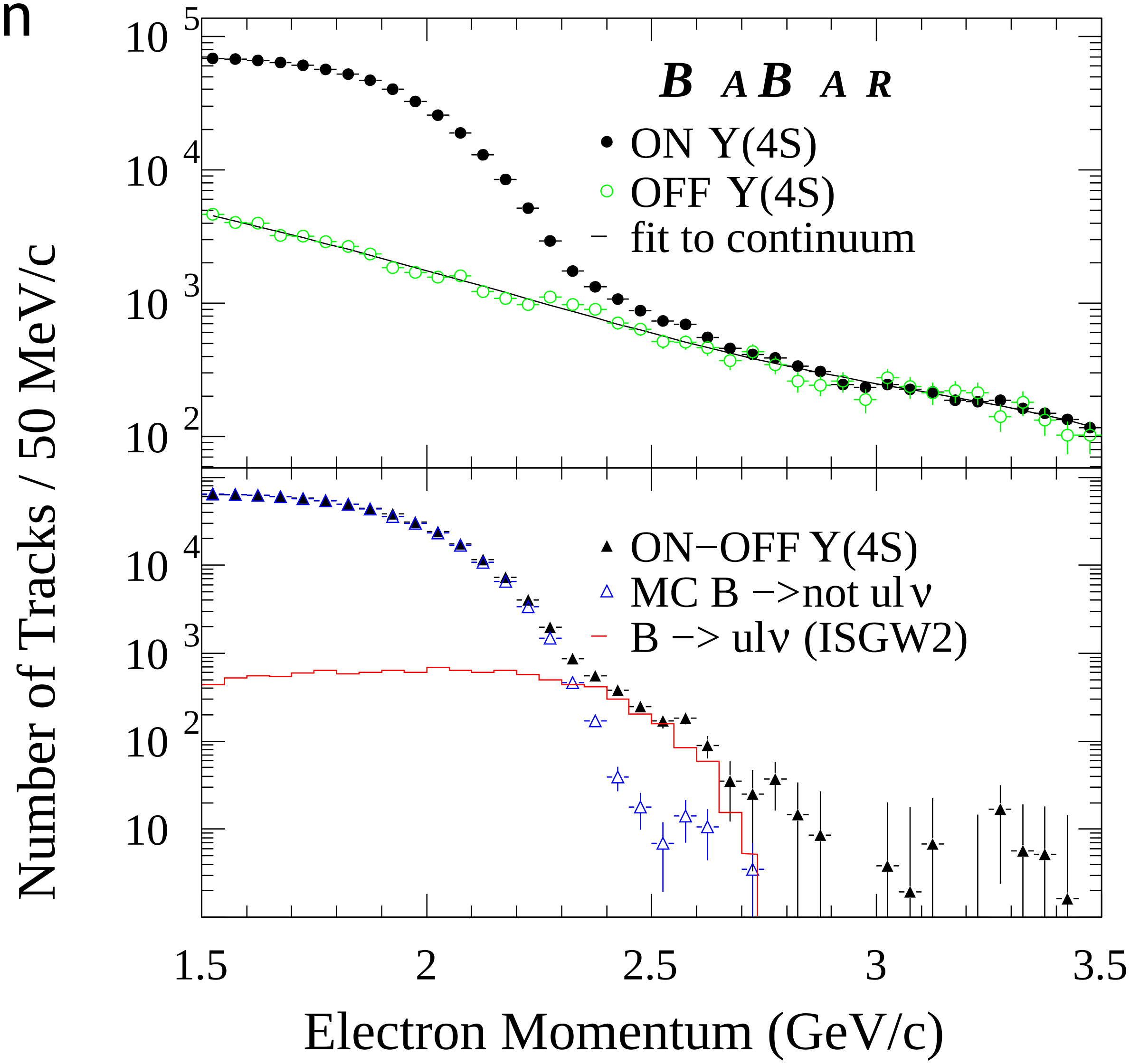


- Importance of sub-leading effects[2]?
  - ▷ These results not corrected with recent calculations

Event Selection

- Analysis based on $20\,\text{fb}^{-1}$
- Event selection based on
  - ▷ $R_2 < 0.4$
  - ▷ high-momentum electron
    - $\longrightarrow$ $p^* > 2.0\,\text{GeV}$
  - ▷ and ν signature
    - $\longrightarrow$ $p_{miss} > 1\,\text{GeV}$
    - $\longrightarrow$ $-0.9 < \cos\theta^*_{miss} < 0.8$
    - $\longrightarrow$ $\cos\alpha < 0$

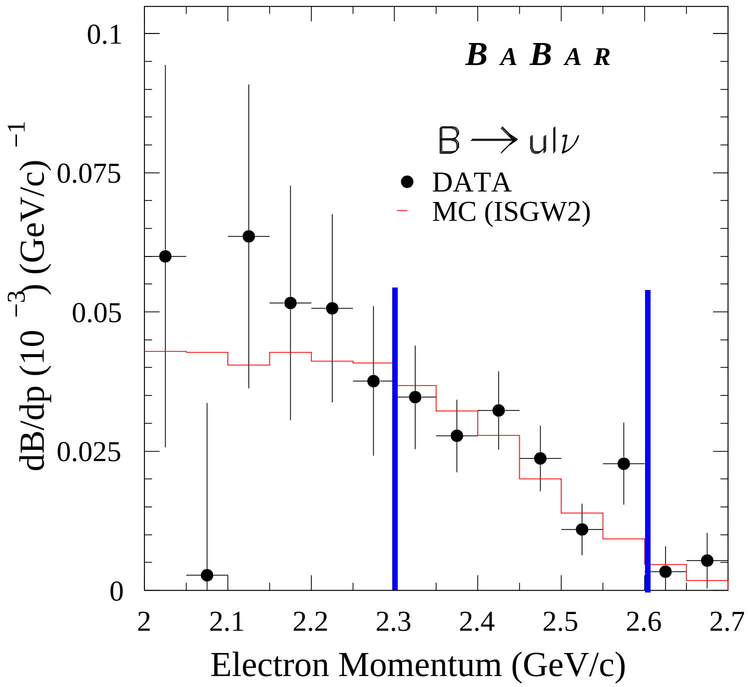




Preliminary Results

- Electron yields

p^* [GeV]	2.0 - 2.3	2.3 - 2.6
N_{on}	74140 ± 272	6455 ± 80
N_{off}	7749 ± 165	4051 ± 93
$N_{b\to c\ell\bar{\nu}}$	61158 ± 470	470 ± 41
N_{BG}	1377 ± 71	238 ± 31
$N_{b\to u\ell\bar{\nu}}$	3857 ± 572	1696 ± 133



- Partial branching fraction for $2.3 < p^* < 2.6\,\mathrm{GeV}$:

$$\Delta\mathcal{B}(\bar{B} \to X_u e\bar{\nu}) = (0.152 \pm 0.014_{stat} \pm 0.014_{syst}) \times 10^{-3}$$

- With $f_u(2.3 < p^* < 2.6) = 0.074 \pm 0.014 \pm 0.009$ from CLEO[1]

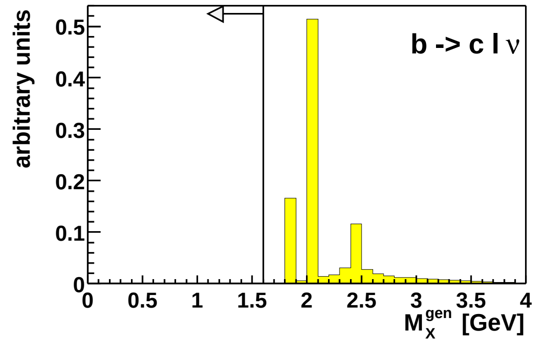
$$\mathcal{B}(\bar{B} \to X_u \ell\bar{\nu}) = (2.05 \pm 0.27_{exp} \pm 0.46_{f_u}) \times 10^{-3}$$

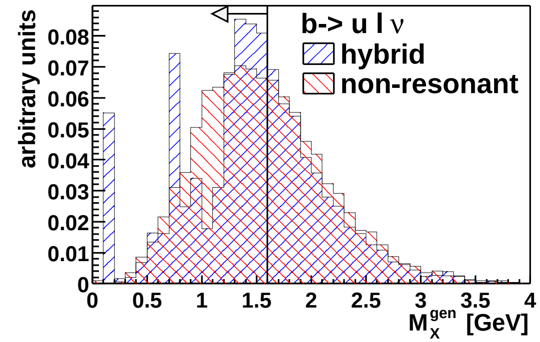
$$|V_{ub}| = (4.43 \pm 0.29_{exp} \pm 0.25_{OPE} \pm 0.50_{f_u} \pm 0.35_{s\gamma}) \times 10^{-3}$$

Barger *et al.*, PL B251, 629
Dikeman *et al.*, NP B509, 378
Bigi *et al.*, EPJ C4, 453
Falk *et al.*, PL B406, 225

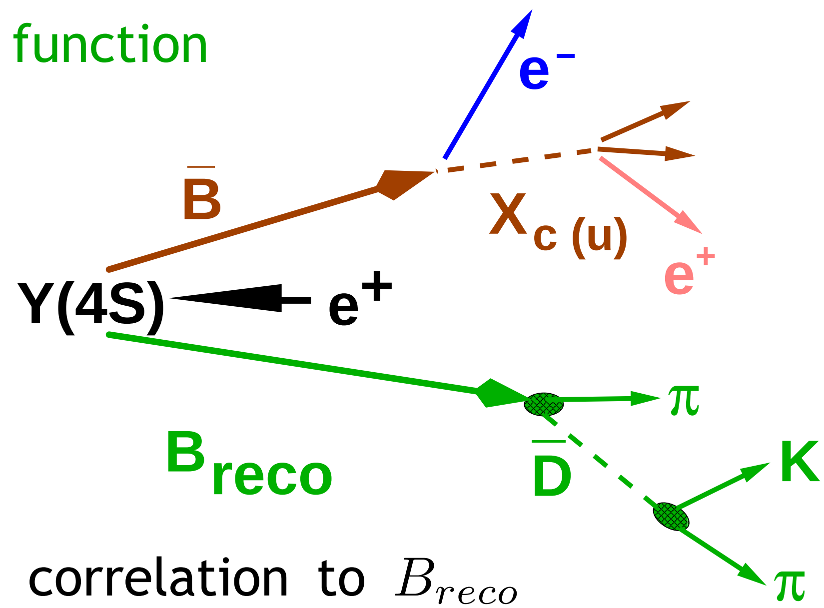
$\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$: hadronic recoil mass

- Advantages
  - Large acceptance
  - Good $b \to c\ell\bar{\nu}$ rejection
  - Good resolution with direct measurement





- Disadvantages
  - Leading order dependence on shape function
  - Low statistics of B_{reco} sample

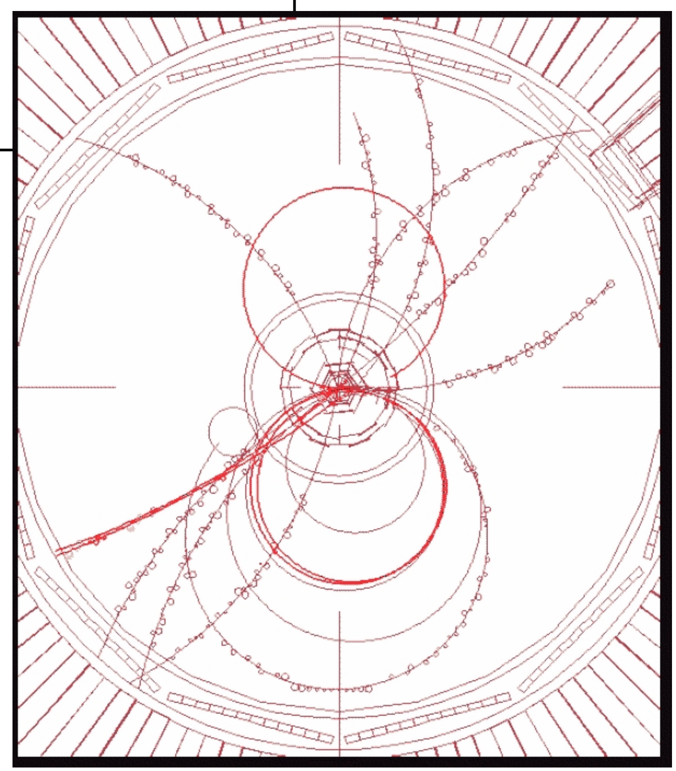


- Experimentally
  - separate the two B mesons
  - veto on K^+ and K^0_S
    $\to$ data control sample
  - lepton with $p^* > 1\,\mathrm{GeV}/c$ and charge correlation to B_{reco}
  - well reconstructed event: m^2_{miss}, Q_{tot}
  - measure $\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}) / \mathcal{B}(\bar{B} \to X \ell \bar{\nu})$ to reduce expt'l systematics

Event Selection

- Determination of signal and normalization samples

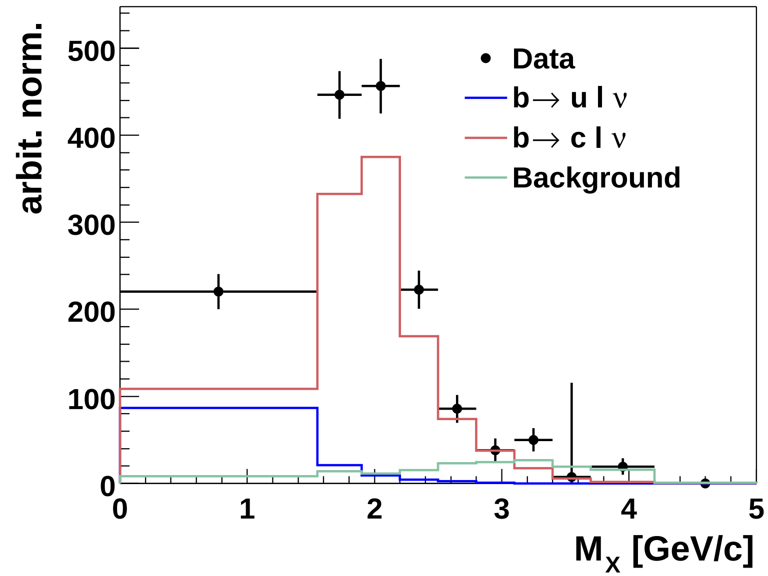
Selection	Signal	Normalization
B_{reco} purity	0.08 - 0.24	0.08 - 0.24
lepton momentum p^*	$> 1\,\mathrm{GeV}$	$> 1\,\mathrm{GeV}$
number of leptons	$= 1$	≥ 1
charge correlation lepton-B_{reco}	yes	-
missing mass m^2_{miss}	< 0.5	-
total charge of event Q_{tot}	$= 0$	-
K^+ and $K^0_S(\to \pi^+\pi^-)$ veto	yes	-
Partial reco'ed $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ veto	yes	-



- $b \to c\ell\bar{\nu}$ background in $m_X < 1.55\,\mathrm{GeV}$:
  - ▷ $\sim 25\%$ undetected K_L
  - ▷ $\sim 30\%$ $K^0_S \to \pi^0\pi^0$
  - ▷ $\sim 15\%$ missed K^+
- Specific cuts against
  - ▷ curlers, clone, and other bad tracks
  - ▷ hadronic split-offs, neutral hadrons

Fit Method

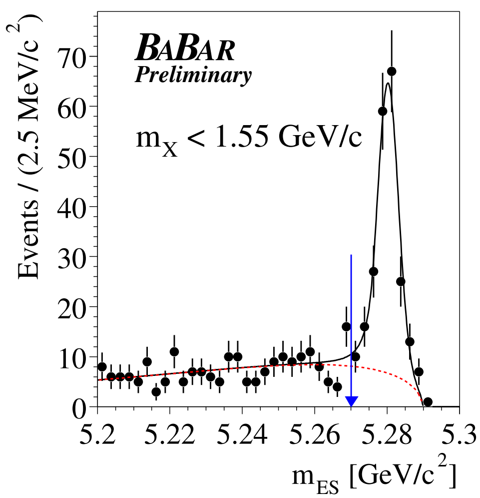
- Extract # signal events with fit of 3 shapes to m_X distribution:

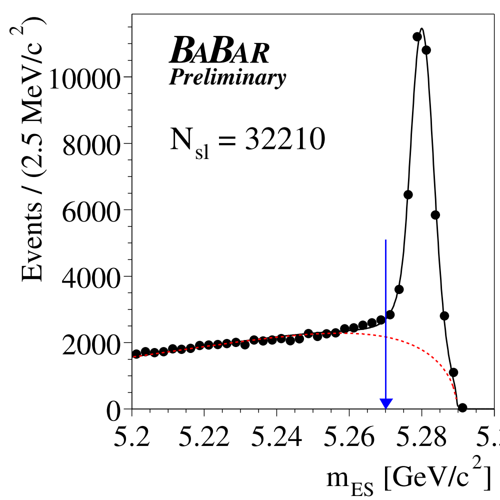


$$\frac{\mathcal{B}(B \to X_u \ell \nu)}{\mathcal{B}(B \to X \ell \nu)} = \frac{(N_{data} - N_{bg})/(\varepsilon^u_{sel} f_u)}{N_{sl}} \times \frac{\varepsilon^{sl}_l \varepsilon^{sl}_t}{\varepsilon^u_l \varepsilon^u_t}$$

- ▷ ε^u_{sel} : signal efficiency
  - ▷ f_u : signal fraction with $m_X < 1.55\,\mathrm{GeV}$
  - ▷ $\varepsilon^{sl}_t / \varepsilon^u_t$: B_{reco} bias
  - ▷ $\varepsilon^{sl}_l / \varepsilon^u_l$: lepton spectrum

- Apply corrections for
  - ▷ background in N_{sl} (6.8%)
    - fake leptons
    - cascade charm decays
    - τ decays
  - ▷ sideband subtraction
  - ▷ mixing of B^0 mesons



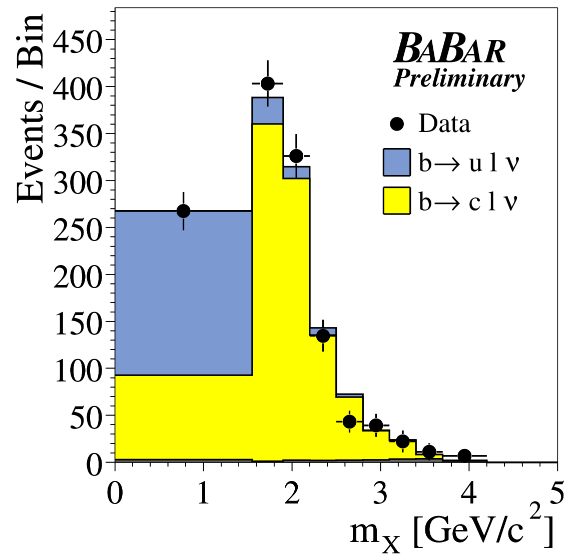


Preliminary Result

- Preliminary result

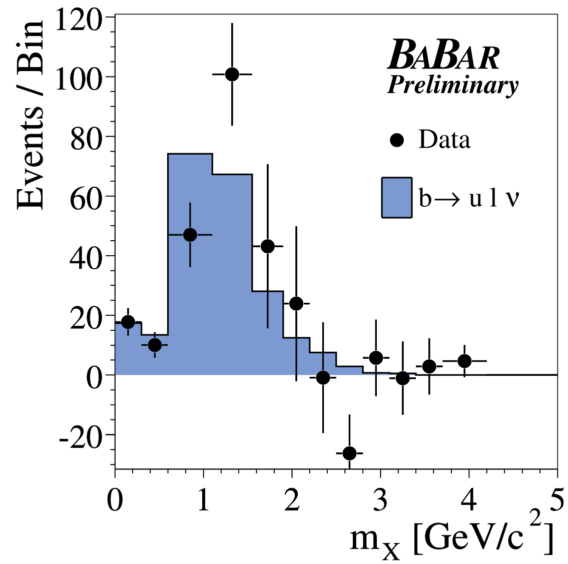
$$\frac{\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})}{\mathcal{B}(\bar{B} \to X \ell \bar{\nu})} = 0.0197 \pm 0.0025_{stat} \pm 0.0010_{MCstat}$$

$$(\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}) = (2.14 \pm 0.29_{stat} \pm 0.25_{syst} \pm 0.37_{\overline{\Lambda},\lambda_1}) \times 10^{-3})$$



- Good consistency in subsamples

Subset	N_u	S/B	$R_{u/sl}[10^{-4}]$
$m_X < 1.55$ GeV	167 ± 21	1.7	197 ± 25
$m_X < 1.40$ GeV	134 ± 19	2.1	177 ± 25
$m_X < 1.70$ GeV	191 ± 26	1.1	211 ± 29
B^0 tags	76 ± 13	3.6	246 ± 43
B^+ tags	91 ± 16	1.2	168 ± 30
electrons	99 ± 15	2.1	226 ± 35
muons	67 ± 14	1.4	166 ± 36



- S/B comparable to exclusive analyses

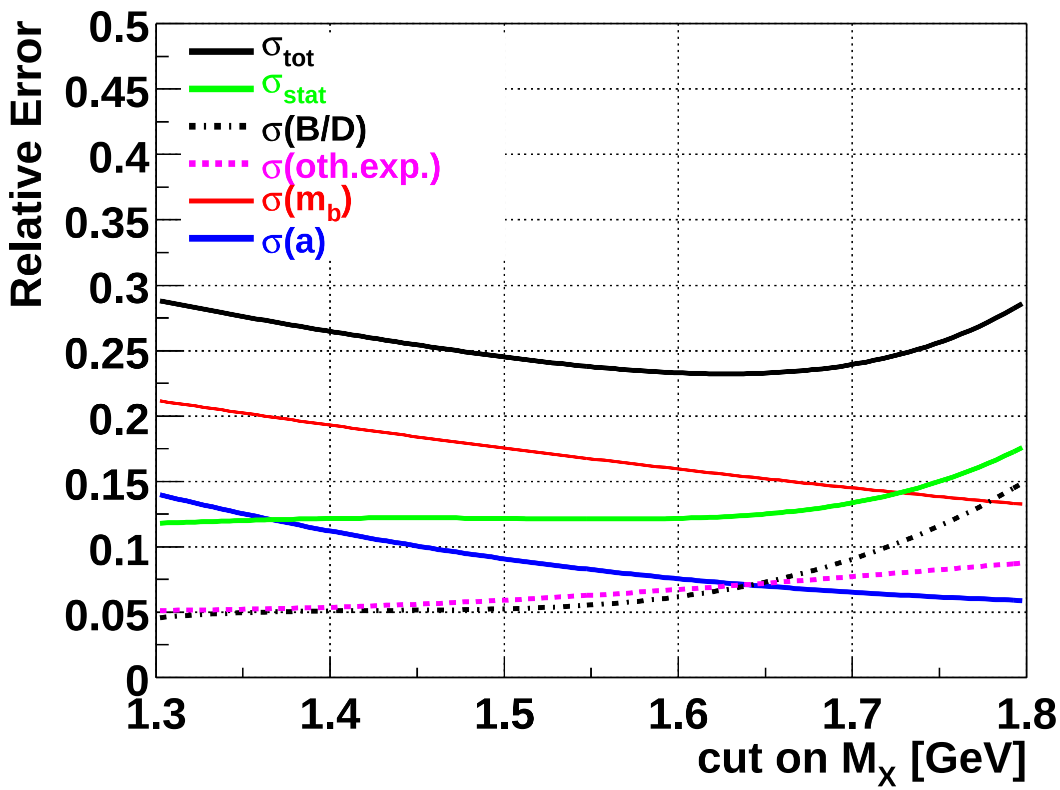
Systematics

- Detector and fitting

Source	Δ
Electron ID	1.0%
Kaon ID	2.3%
Tracking	1.0%
Photons	4.7%
K_L	1.0%
B_{reco}, m_{ES}	3.8%
B_{reco}, tagging	4.0%
Binning	2.9%
Total	9.8%

- Modeling of signal and background

Source	Δ
B and D decays	4.4%
$b \to u\ell\bar{\nu}$ decays	2.8%
Hadronization	3.0%
Total	6.0%

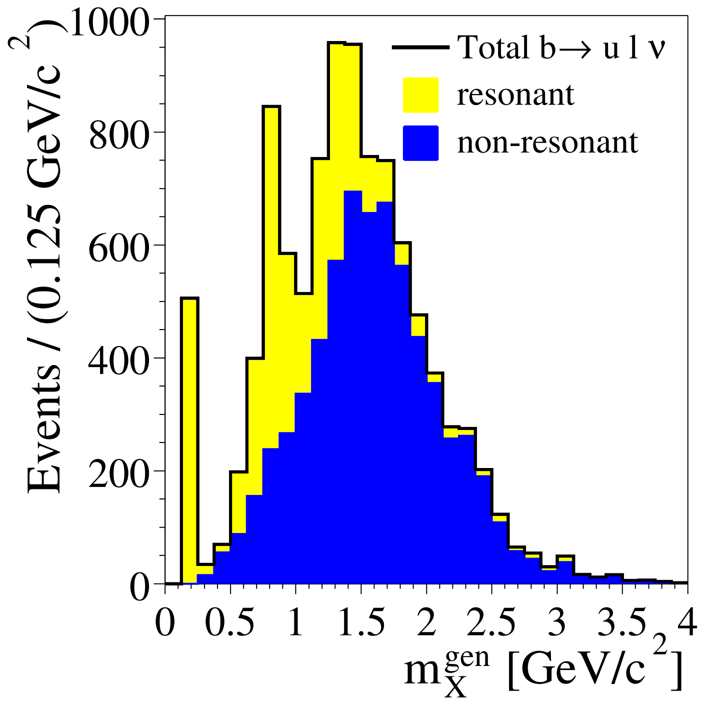


- Hadronization error evaluation:
  - ▷ multiplicity-dependent fit
  - ▷ non-resonant vs. hybrid signal MC
  - ▷ $s\bar{s}$ popping
- All systematics reducible

[1] Scora *et al.*, PRD 52, 2783
[2] deFazio *et al.*, JHEP 9906, 017

Signal Simulation

- Hybrid MC simulation
  - ▷ ISGW2[1] for (low-mass) resonances ($m_X < 1.5\,\mathrm{GeV}$)
  - ▷ Nonresonant HQE calculation by de Fazio/Neubert[2]
  - ▷ cumulative distribution function like HQE calculation (above lowest resonances)

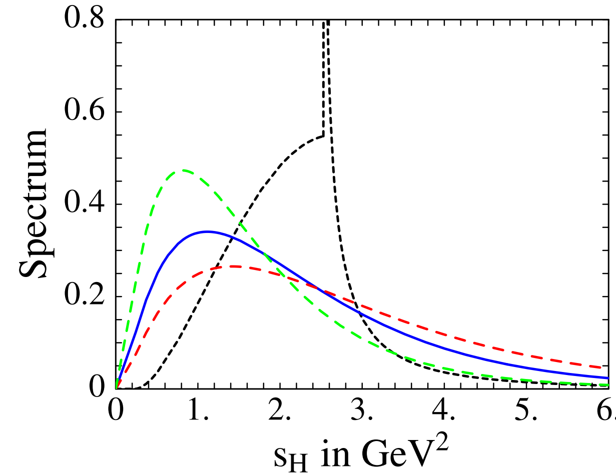


- Fermi motion of b quark in B meson parametrized with a model

$$f(k_+) = N(1-x)^a \cdot e^{(1+a)x}$$

where $x = k_+/\overline{\Lambda}$

$\overline{\Lambda} \equiv m_B - m_b$ and $\lambda_1 = -3\overline{\Lambda}^2/(1+a)$

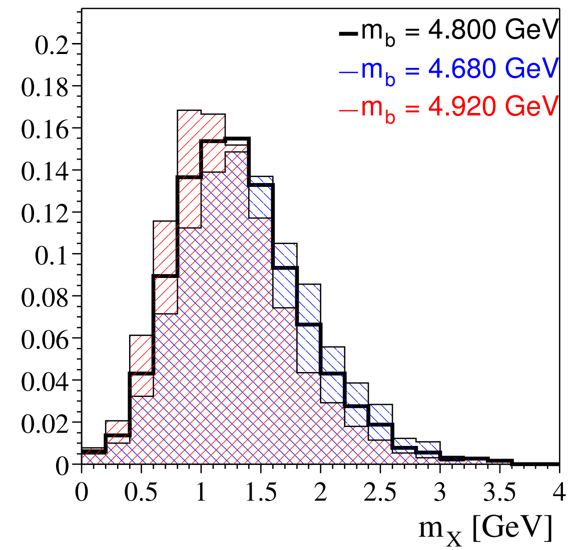


- This parametrization is not unique, but motivated by constraints on the first few moments

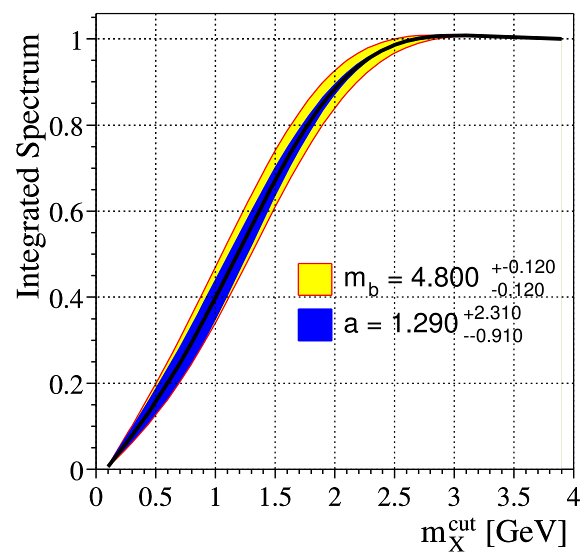
Theoretical Uncertainty

- Hadronic recoil mass m_X depends on
  - ▷ mass of b quark (pole mass)
  - ▷ kinetic energy of b quark
- Reweighting of MC events to study
  - ▷ extrapolation factor $f_u(m_X^{cut})$
  - ▷ efficiency $\varepsilon^u_{sel}(m_X)$

$$m_b = 4.800 \pm 0.120\,\mathrm{GeV} \qquad a = 1.29^{+2.31}_{-0.91}\,\mathrm{GeV}^2$$
$$\overline{\Lambda} = 0.480 \pm 0.120\,\mathrm{GeV} \qquad \lambda_1 = -0.300^{+0.150}_{-0.200}\,\mathrm{GeV}^2$$



- Equivalent to CLEO's published values[1]
  - ▷ without terms $\propto \mathcal{O}(1/m_B^3)$ and $\propto \mathcal{O}(\beta_0 \alpha_S^2)$
- Shape function parametrization not unique
  - ▷ no error included for unknown shape
  - ▷ $\Delta(m_b) = 120\,\mathrm{MeV}$ instead of "canonical" $\Delta(m_b) = 90\,\mathrm{MeV}$ (PDG2002/CKM workshop)
- Combined theoretical error: 17.5%



[1] Uraltsev *et al.*, IJMP A14, 4641
[2] Hoang *et al.*, PRL 82, 277

Extraction of $|V_{ub}|$

- With PDG (CKM 2002 workshop) formula

$$|V_{ub}| = 0.00445 \cdot \left(\frac{\mathcal{B}(b\to u\ell\bar{\nu})}{0.002} \cdot \frac{1.55\,\mathrm{ps}}{\tau_b}\right)^{1/2} \times (1.0 \pm 0.020_{pert} \pm 0.052_{1/m_b^3})$$

$$|V_{ub}| = (4.52 \pm 0.29_{stat} \pm 0.33_{syst} \pm 0.40_{\overline{\Lambda},\lambda_1} \pm 0.25_{theo}) \times 10^{-3}$$

  - ▷ $\mathcal{B}(\bar{B} \to Xe^-\nu) = 10.87 \pm 0.18 \pm 0.30\%$
  - ▷ $\tau_B = 1.608 \pm 0.016\,\mathrm{s}$, average of B^0 and B^+
  - ▷ Negligible dependence on "f_+/f_0"

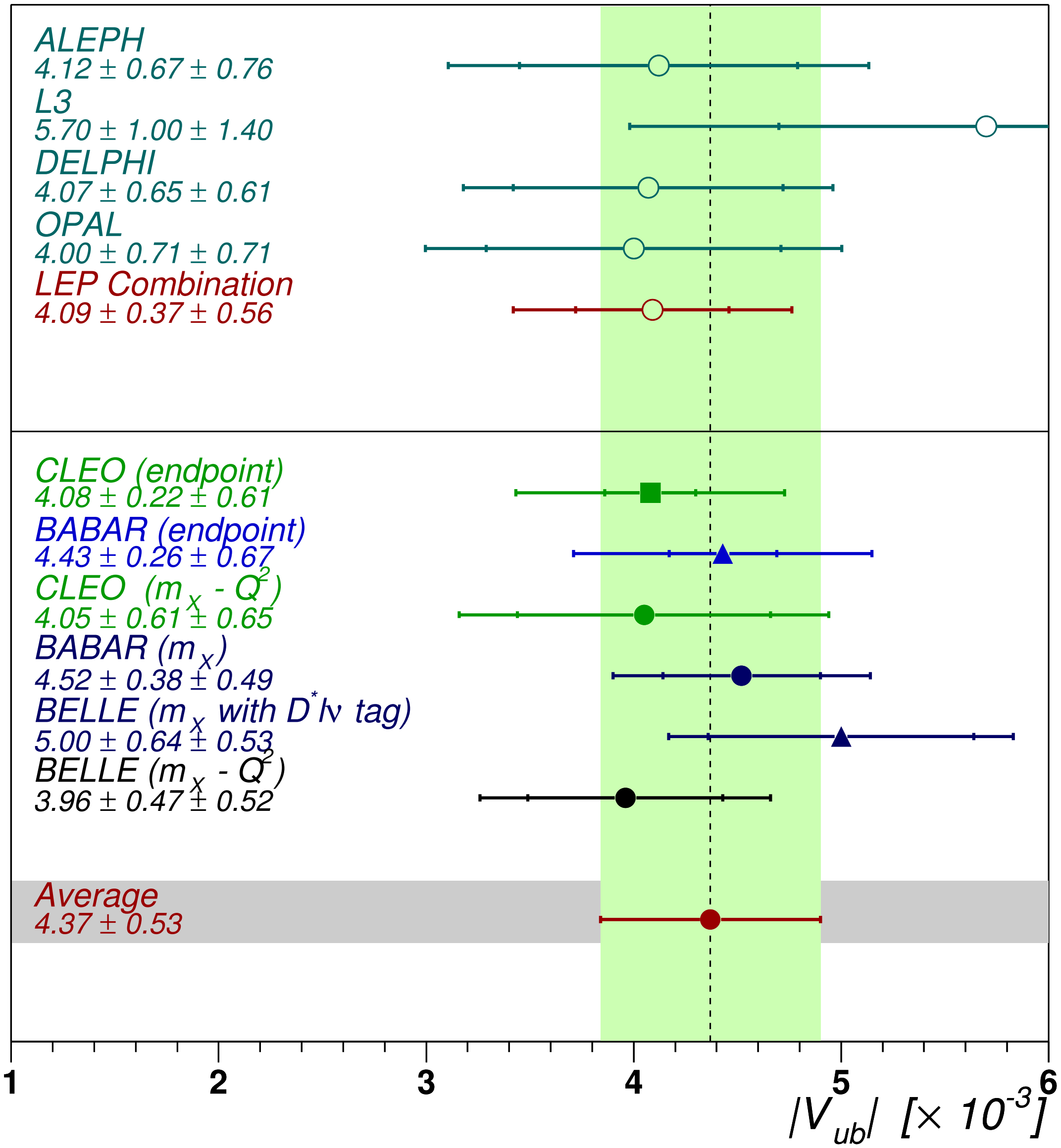
- Last two errors indicate uncertainties due to
  - ▷ $\overline{\Lambda}, \lambda_1$: extrapolation to full phase space
  - ▷ *theo*: $\Gamma(b \to u\ell\bar{\nu}) \to |V_{ub}|$

- Combination of assessment of theoretical errors by
  - ▷ Uraltsev [1] and Hoang, *et al.* [2]
  - ▷ with increased error on b quark mass of $\Delta(m_b) = 90\,\mathrm{MeV}$

- The total relative error on $|V_{ub}|$ amounts to 13.8%

In Context

- This is NOT an official world average. Average of $\Upsilon(4S)$ measurements only.
- No scaling to common
  - ▷ exp'l input parameters
  - ▷ theoretical parameters
- Error bars show
  - ▷ stat$\oplus$det (''uncorrelated'')
  - ▷ total
- Correlated errors
  - ▷ $b \to c\ell\bar{\nu}$ modeling
  - ▷ $b \to u\ell\bar{\nu}$ modeling
  - ▷ extrapolation
  - ▷ $b \to s\gamma$ vs. $b \to u\ell\bar{\nu}$
  - ▷ $\Gamma(b \to u\ell\bar{\nu}) \to |V_{ub}|$
- Relative error: $\sim 12\%$



The Future of $|V_{ub}|$

[1] Bauer *et al.*, PL B479, 395
[2] Bauer *et al.*, PR D64, 113004
[3] Leibovich *et al.*, PR D61, 053006
Aglietti *et al.*, ph/0204140

- Inclusive analyses with HQE
  - ▷ measure $|V_{ub}|$ with more methods
  - ▷ avoid shape function dependence with
    - high Q^2 region[1] – subleading effects?
    - combination m_X-Q^2[2]
    - direct combinations with $b \to s\gamma$[3]
  - ▷ better determinations of m_b and $\overline{\Lambda}$, λ_1, ...

$\longrightarrow$ projected error on $|V_{ub}|$ of 5-10% (theory limited); next updates of inclusive analyses this summer

- Exclusive decays $\bar{B} \to \pi\ell\bar{\nu}$ (on the recoil) with lattice QCD
  - ▷ recoil: no background (and no statistics: $\mathcal{O}(20)$ events $/100\,\text{fb}^{-1}$) apart from recoil, statistics not a problem (but background ...)
  - ▷ coverage of full phase space
  - ▷ want/need improved and unquenched Lattice calculations

$\longrightarrow$ projected error on $|V_{ub}|$ of (maybe) 1-2% to 5%; unquenched calculations by the end of this year? (JLC?)

Conclusions

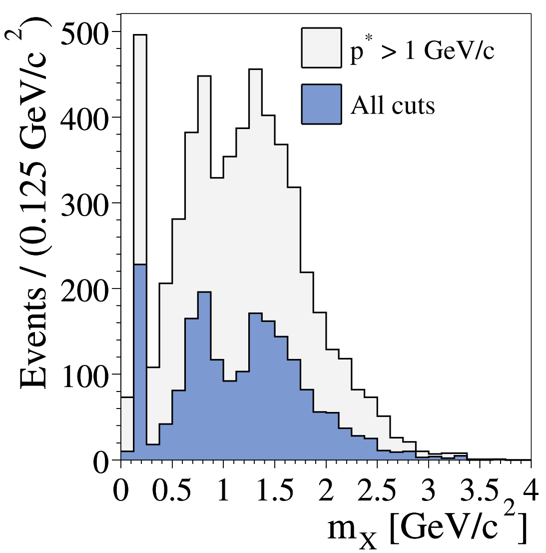
- PEP-II and *BABAR* are running very fine:
  - ▷ $99\,\text{fb}^{-1}$ delivered in Run 1+2, $20\,\text{fb}^{-1}$ now in Run 3
  - ▷ Precise measurements of $\mathcal{B}(\bar{B} \to D^* \ell \bar{\nu})$ and $|V_{ub}|$
- 'Physics on the recoil'
  - ▷ ca. $4000\,B/\,\text{fb}^{-1}$: statistics limited $\longrightarrow$ complementary systematics
  - ▷ Now: Inclusive analyses of $b \to c\ell\bar{\nu}$ and $b \to u\ell\bar{\nu}$ + OPE
  - ▷ Future: Exclusive $b \to u\ell\bar{\nu}$ + Lattice
- Starting to take OPE/HQET a step further:
  - ▷ $b \to c\ell\bar{\nu}$

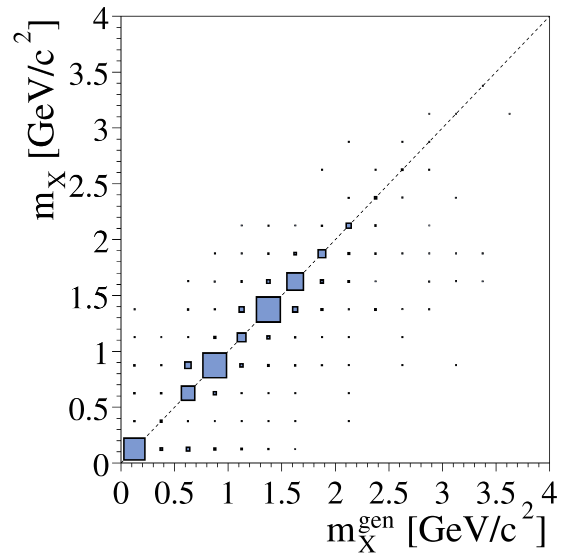
    Precision measurements of parameters $\overline{\Lambda}(= m_b)$, λ_1, . . .
    Testing the consistency of theory $\longrightarrow$ hadronic mass moments, . . .
    $\longrightarrow$ Critical for (inclusive) precision determination of $|V_{ub}|$
  - ▷ $b \to u\ell\bar{\nu}$

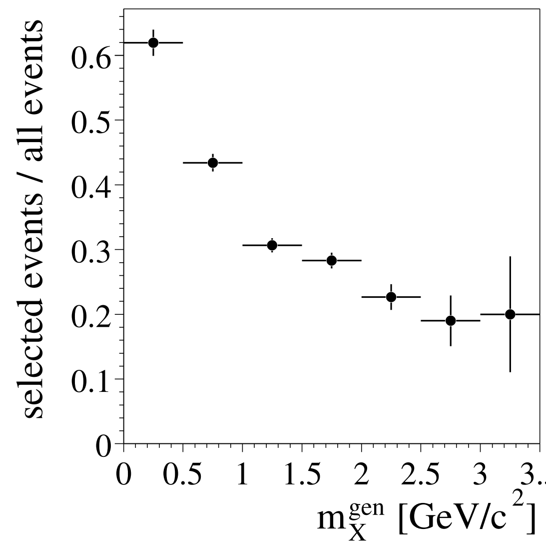
    Error on $|V_{ub}|$ approaching 10%
    Constraints on the Unitarity Triangle

Reconstruction of hadronic mass

- Use kinematic fit to measure m_X
  - ▷ improve resolution
  - ▷ reduce bias due to lost particles
- Rms of hadronic mass about $300\,\mathrm{MeV}$
- Good reconstruction and efficiency over entire phase space:







Determination of $|V_{ub}|$

- For $|V_{ub}|$ determination, need extrapolation to full branching fraction:

$$|V_{ub}| = 0.00445 \cdot \sqrt{\frac{\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})}{0.002} \cdot \frac{1.55\,\mathrm{ps}}{\tau_b}} \times (1.0 \pm 0.020_{OPE} \pm 0.052_{m_b})$$

- With $f_u(2.3 < p^* < 2.6) = 0.074 \pm 0.014 \pm 0.009$ from CLEO [1]

$$\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu}) = (2.05 \pm 0.27_{exp} \pm 0.46_{f_u}) \times 10^{-3}$$

$$|V_{ub}| = (4.43 \pm 0.29_{exp} \pm 0.25_{OPE} \pm 0.50_{f_u} \pm 0.35_{s\gamma}) \times 10^{-3}$$

- Errors are
  - ▷ exp: Combined statistical and (detector) systematic
  - ▷ OPE: Translation of rate into $|V_{ub}|$ (from PDG 2002/CKM 2002)
  - ▷ f_u: Combined error of f_u from $b \to s\gamma$ (from CLEO)
  - ▷ $s\gamma$: Validity of combination of $b \to s\gamma$ and $b \to u\ell\bar{\nu}$ (à la CLEO)