Determination of the b-quark mass and nonperturbative parameters in semileptonic and radiative penguin decays at $BABAR$

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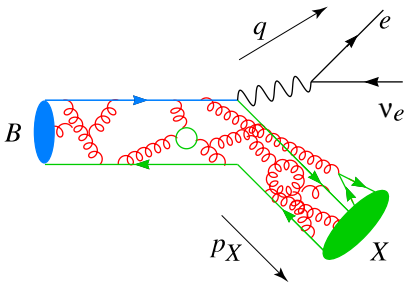
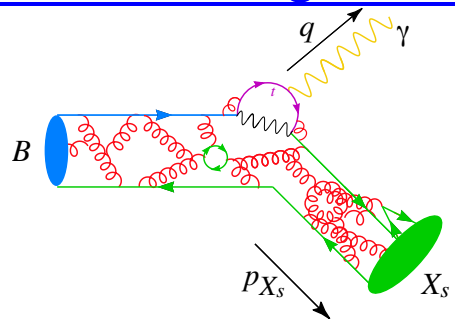
Semileptonic & Radiative Penguin Decays





Inclusive decay rate

$$\Gamma_{\rm sl,c} \propto |V_{cb}|^2 m_b^5 A^{\rm pert}[\Phi(\tfrac{m_c}{m_b})(1-\tfrac{\mu_\pi^2-\mu_G^2}{2m_b^2}) - 2(1-\tfrac{m_c^2}{m_b^2})^4\tfrac{\mu_G^2}{m_b^2} + \mathcal{O}(\tfrac{1}{m_b^3})]$$

- ⋆ Moments of differential decay distributions of $B \to X_{c,u}\ell\nu$, $B \to X_s\gamma$
  - ⋆ Only depend on m_b and same universal nonperturbative parameters ($\longrightarrow$ dynamics of b in B)
  - ⋆ "2-body" $B \to X_s\gamma$ directly sensitive to m_b, while "3-body" $B \to X_{c,u}\ell\nu$ indirectly sensitive to m_b
  - ⋆ No term at $\mathcal{O}(\frac{1}{m_b})$
  - ⋆ $\mu_\pi^2 \propto$ kinetic energy of b quark in B
  - ⋆ $\mu_G^2 \propto$ chromomagnetic moment of b in B ($B - B^*$ mass splitting)
- ⋆ New and recent results from $BABAR$ in all 3 decay modes

$|V_{qb}|$ from $B \to X_q \ell \nu$ Decays

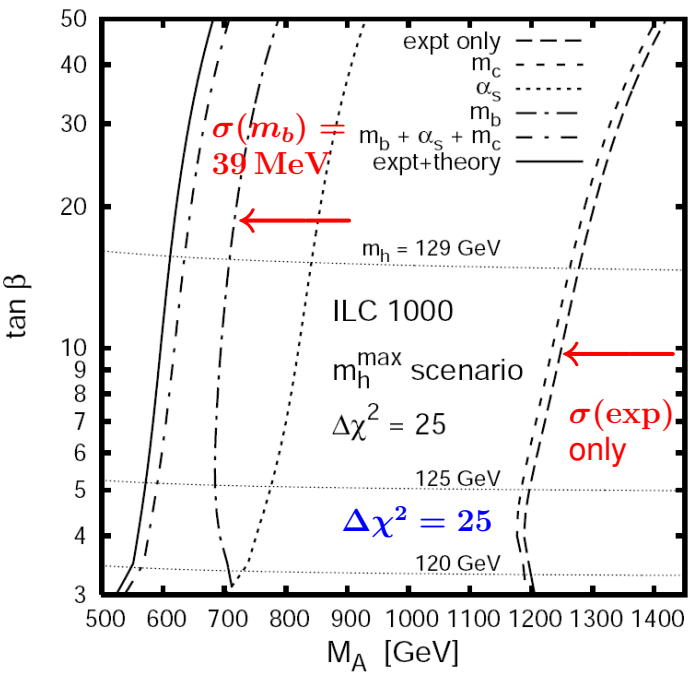
Two complementary approaches $\quad (\Gamma = G_F^2 |V_{qb}|^2 m_b^5 |L_\mu|^2 |\langle X | J_L^\mu | B \rangle|^2)$

Exclusive	Inclusive
Reconstruct specific final state ($X_q = D^{(*)}, \pi, \rho, ...$)	Sum over all X_q
Parametrize $\langle D^* | J_L^\mu | B \rangle$, $\langle \pi | J_L^\mu | B \rangle$, ...	Perform Operator Product Expansion (HQE) in $1/m_b$
Different form factors (FF) $f_i(q^2)$: Lattice QCD, QCD sum rules, Measurements	Universal nonpert. parameters: Measure in $B \to X_q \ell \nu$ and $B \to X_s \gamma$

- ⋆ Hint of tension ($\sim 2\sigma$) between $|V_{ub}|$ (tree-level, NP insensitive) and $\sin 2\beta$ (loop process, NP sensitive)
- ⋆ Exclusive determinations of $|V_{ub}|$ systematically lower than inclusive determinations and in better agreement with global CKM fit

The b-Quark Mass

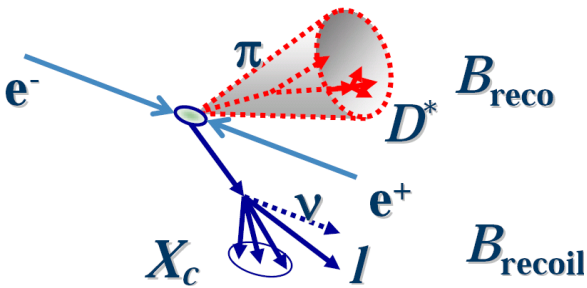
- Dependence of $|V_{ub}|$ measurements on m_b: $\sigma(m_b) = 40\,\mathrm{MeV}$
  - $\sigma(|V_{ub}|)/|V_{ub}| \approx 2\%$ without phase space cuts
  - $\sigma(|V_{ub}|)/|V_{ub}| \approx \mathcal{O}(5\%)$ with necessary phase space cuts
- Learn about dynamics of b quark in B meson through nonperturbative parameters
- Renormalization scheme: kinetic scheme ($\mu = 1\,\mathrm{GeV}$) (widely used in B physics)
- Good knowledge of m_b important when studying New Physics effects in Higgs sector
  - SM – MSSM Higgs separation



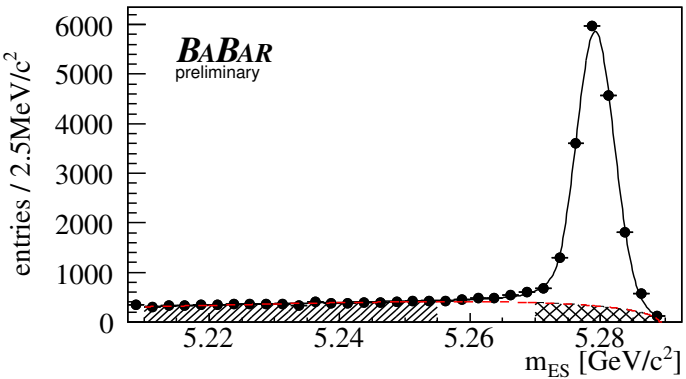
[Droll, Logan, Phys. Rev. D **76**:015001 (2007)]

Analyses on the Recoil

- Hadronic decay of one B fully reconstructed:
  $B_{\rm reco} \to D^{(*)}Y$, $Y = n_1 K^{\pm} + n_2 K_S + n_3 \pi^{\pm} + n_4 \pi^0$
  - Low efficiency, $\epsilon \approx 0.3\%$
  - Inclusive measurement of X system (with good resolution)
  - Measure kinematic quantities in B rest frame
  - Charge and flavor determined



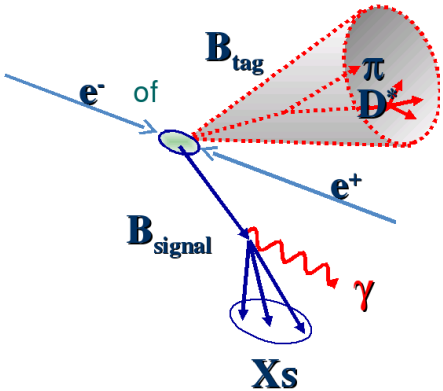
- Subtract combinatorial $B_{\rm reco}$ and continuum background by fitting $m_{\rm ES} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_B}$
- Modeling background with threshold function and signal with Gaussian with exponential tail

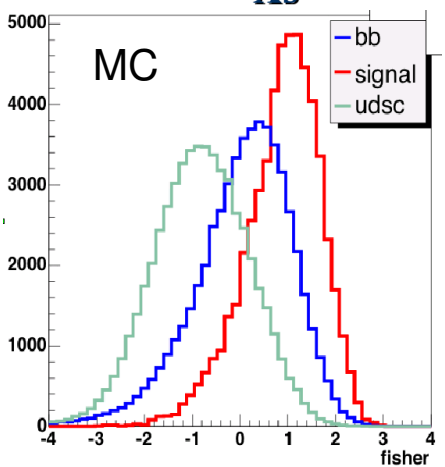


$B \to X_s\gamma$: Analysis

232M $B\bar{B}$

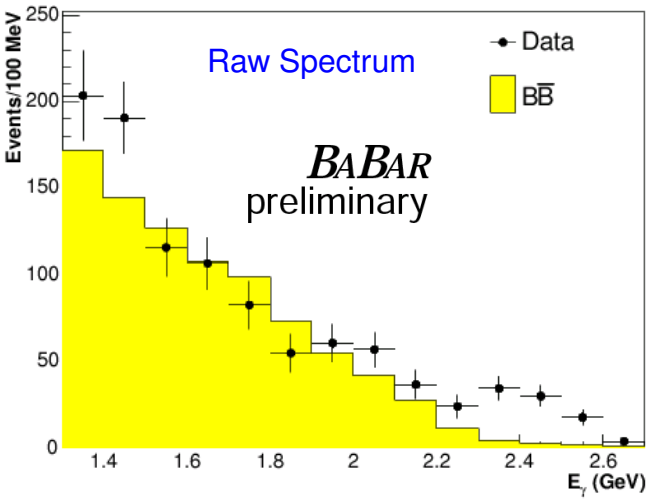
- ⋆ Events tagged by hadronic B decay
- ⋆ Well reconstructed high energy photon $E_\gamma > 1.3\,\mathrm{GeV}$
  - ⋆ Photon energy measured in B rest frame
- ⋆ Veto γ compatible with π^0, η, ρ decays
- ⋆ Suppress continuum with Fisher discriminant (mostly event shape variables)
  - ⋆ $B\bar{B}$ isotropic vs. light $q\bar{q}$ jetty
- ⋆ Subtract B_{reco} combinatoric and remaining continuum background in bins of E_γ



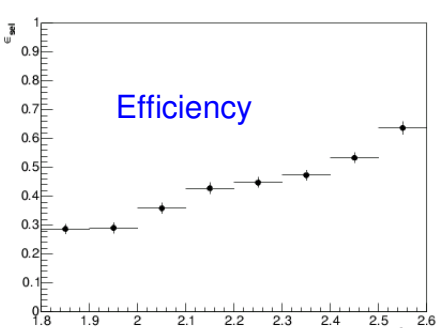


See Minghui Lu's talk for more details!

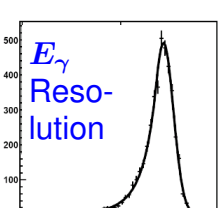
$B \to X_s\gamma$: The E_γ Spectrum

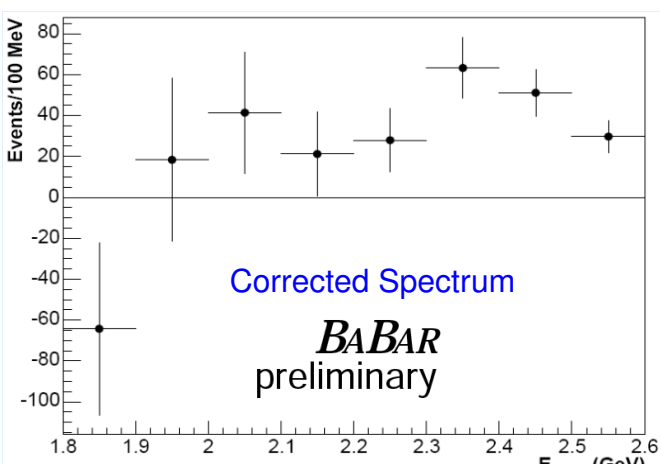


- $E_\gamma < 1.9\,\mathrm{GeV}$ for background control
- Main background γ from π^0 decays
- 119 ± 22 $B \to X\gamma$ signal decays for $E_\gamma > 1.9\,\mathrm{GeV}$

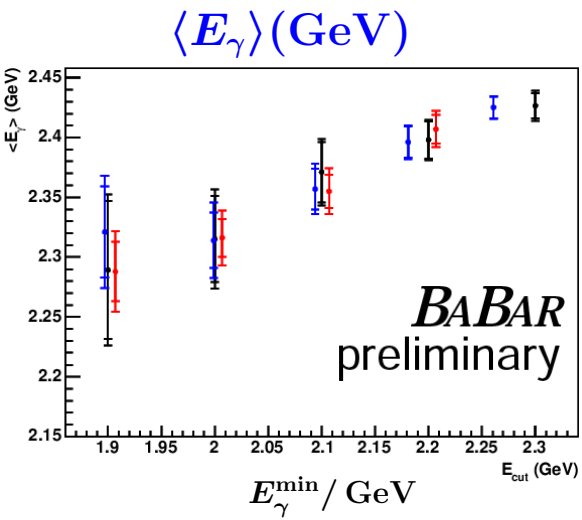


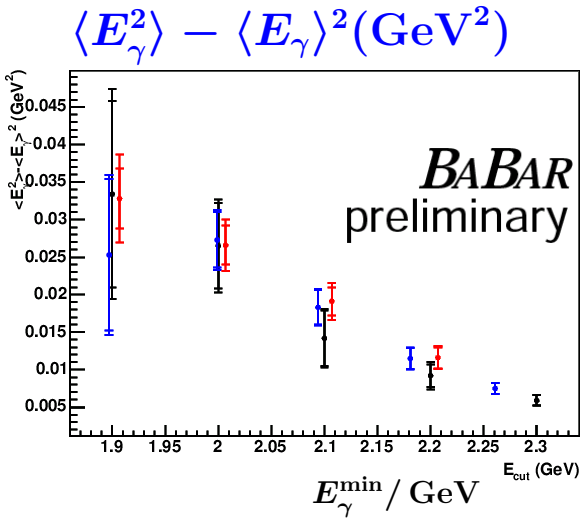
Efficiency and resolution Correction $\Longrightarrow$





$B \to X_s\gamma$: Moments and HQE Fits





this analysis

lepton tag

sum of exclusive modes

[BABAR, Phys. Rev. D **72**, 052004 (2005)]

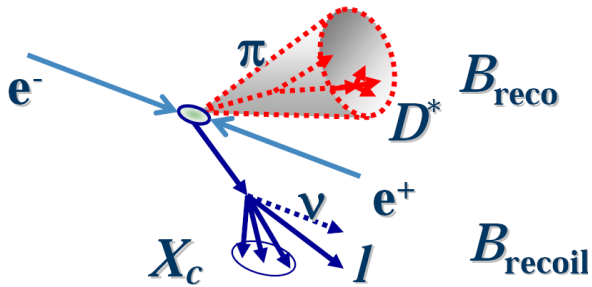
- ★ Consistency between measured moments in different analyses
- ★ This analysis limited by statistics
- ★ Much cleaner environment leads to potential for reduced systematics

HQE fits to moments from lepton tag analysis

$$m_b^{\mathrm{kin}} = (4.44^{+0.08+0.12}_{-0.07-0.14})\ \mathrm{GeV}$$
$$\mu_\pi^{2\mathrm{kin}} = (0.64^{+0.13+0.23}_{-0.12-0.24})\ \mathrm{GeV}^2$$
$$\rho = -0.93$$

[BABAR, Phys. Rev. Lett. **97** 171803 (2006)]

$B \to X_c \ell \nu$: Analysis

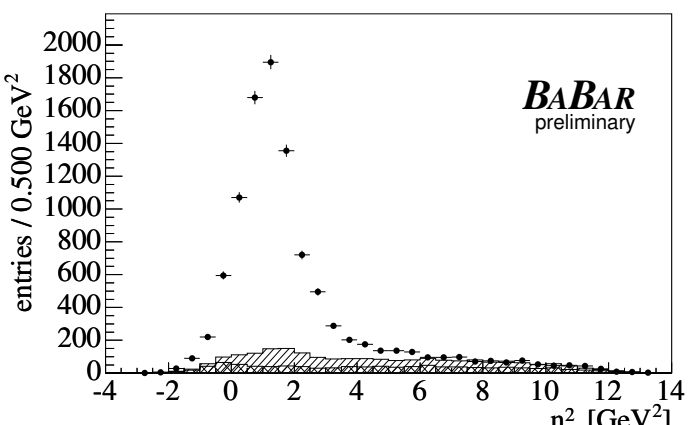


[hep-ex/0707.2670]

232M $B\bar{B}$

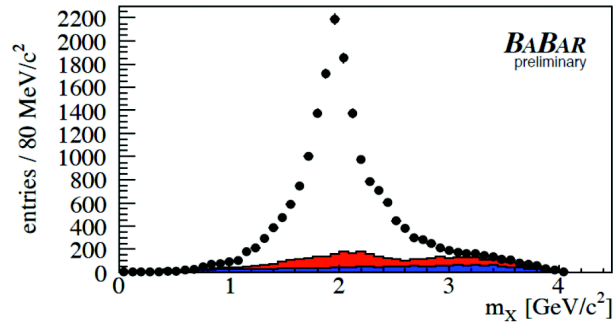
- ⋆ Events tagged by hadronic B decay
- ⋆ Combinatorial and continuum background from $m_{\rm ES}$ sideband
- ⋆ Require exactly 1 lepton (e, μ) in recoil with energy $E_\ell > 0.8\,\mathrm{GeV}$ in B rest frame

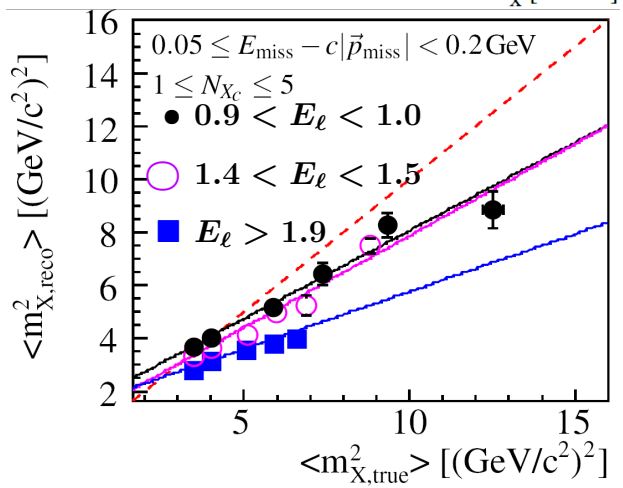
- ⋆ Remaining charged and neutral particles form inclusive X_c system
- ⋆ Measure moments of hadronic mass m_X and mixed mass-and-energy moments
  $n_X = m_X^2 c^4 - 2\bar{\Lambda} E_X + \bar{\Lambda}^2$
  - ⋆ $\bar{\Lambda} = 0.65\,\mathrm{GeV}$
- ⋆ Improve resolution with kinematic fit
  - ⋆ Energy-momentum conservation
  - ⋆ $E_{\rm miss}$, $p_{\rm miss}$ consistent with ν



$B \to X_c \ell \nu$: Measurement of Moments

- Background $\approx 20\%$
  - B_{reco} combinatorial bkgd
  - Not $B \to X_c \ell \nu$ on signal side
- m_X, n_X distorted due to unmeasured particles
- Linear correction functions for moments (event-by-event)
  $\langle m_X, \text{reco}^k \rangle \to \langle m_X, \text{true}^k \rangle$
  $\langle n_X, \text{reco}^k \rangle \to \langle n_X, \text{true}^k \rangle$
  - Determined and tested on simulation
- Determine $\langle m_X^k \rangle, \langle n_X^k \rangle$ as function of cut on $E_{\ell \text{min}}$

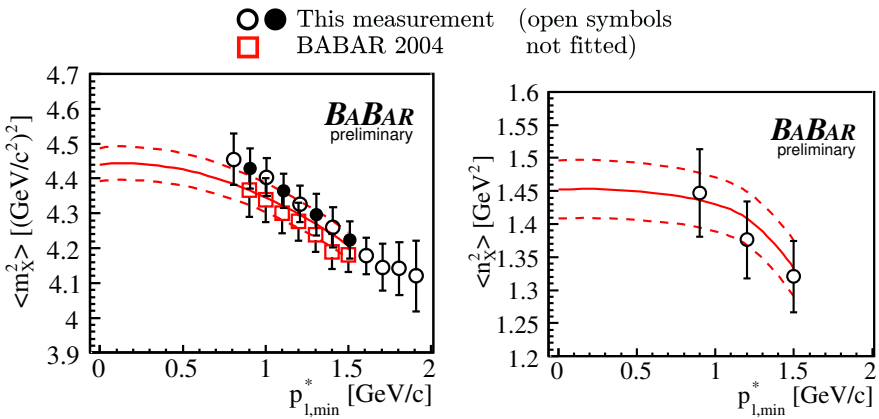


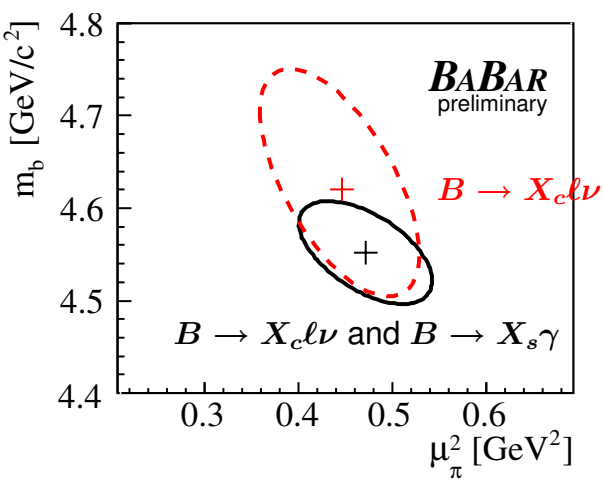


- Dominant systematic uncertainty: Impact of reconstruction efficiency on inclusive event reconstruction

$B \to X_c \ell \nu$: Moments and HQE Fit

- ★ Input to HQE fit
  - ★ $\langle m_X^2 \rangle$ and $\langle m_X^4 \rangle$
  - ★ E_ℓ moments
    [BABAR, Phys. Rev. D **69**, 111104 (2004)]
  - ★ E_γ moments
    [BABAR, Phys. Rev. D **72**, 052004 (2005), Phys. Rev. Lett. **97** 171803 (2006)]
  - ★ B lifetime





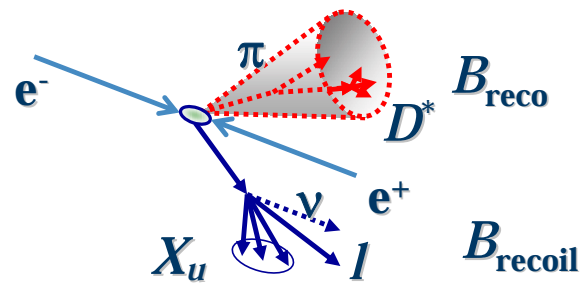
[Benson, Bigi, Mannel, Uraltsev, Nucl. Phys. B **665**:367
Gambino, Uraltsev, hep-ph/0401063, hep-ph/0403166]

	m_b/GeV	m_c/GeV	μ_π^2/GeV^2
	4.552	1.070	0.471
σ(exp)	0.038	0.055	0.034
σ(theo)	0.040	0.065	0.062
σ(tot)	0.055	0.085	0.070

$$|V_{cb}| = (41.88 \pm 0.81) \times 10^{-3}$$

[hep-ex/0707.2670]

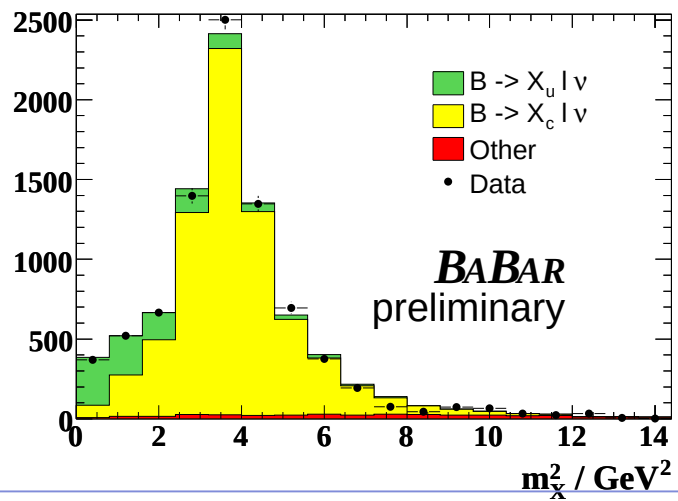
$B \to X_u \ell \nu$: The Mass Spectrum New!



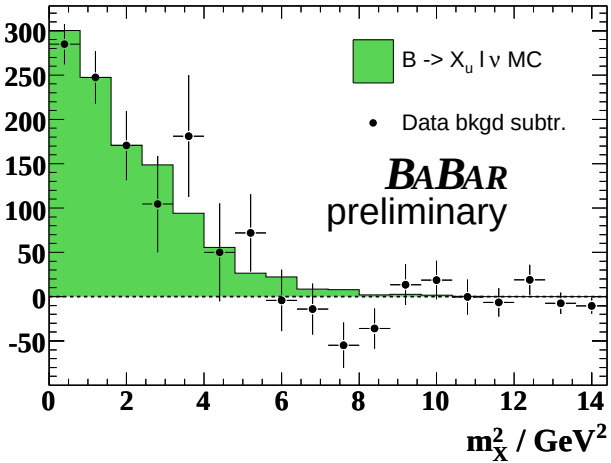
383M $B\bar{B}$

- ⋆ $B \to X_u \ell \nu$ sensitive to m_b
  - ⋆ $B \to X_c \ell \nu$ sensitive to $m_b - m_c$
- ⋆ Study m_b, μ_π^2, ..., HQE in the same mode in which we measure $|V_{ub}|$
- ⋆ Hadronic tag analysis, require exactly 1 lepton (e, μ) in recoil with $E_\ell > 1\,\mathrm{GeV}$

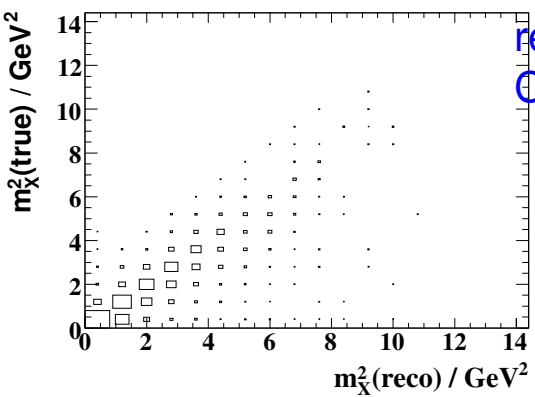
- ⋆ Remaining charged and neutral particles form inclusive X system
- ⋆ Measure hadronic mass m_X
- ⋆ Large background from $B \to X_c \ell \nu$ decays
- ⋆ Veto events with $K^\pm$, K_S and partially reconstructed $D^{*\pm}$
- ⋆ Subtract remaining $B \to X_c \ell \nu$ and non-semileptonic backgrounds by fit



$B \to X_u \ell \nu$: Unfolding the Spectrum

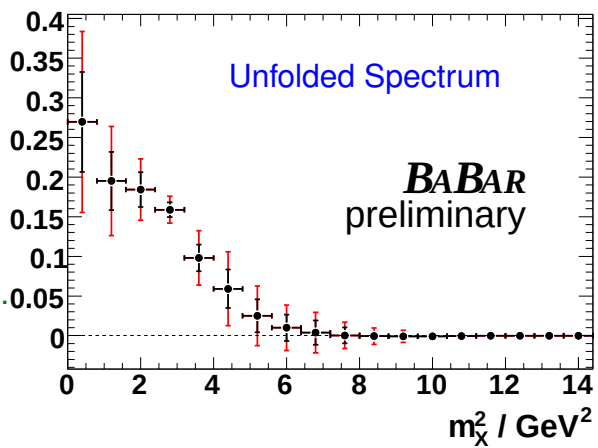


- ★ 1027 ± 176 signal events
- ★ Unfold spectrum for detector acceptance, efficiency and resolution
- ★ Significant bin-by-bin correlations due to unfolding



Efficiency and resolution Correction $\Longrightarrow$

[A. Höcker, V. Kartvelishvili, Nucl.Instrum.Meth. A **372**, 469-481 (1996)]



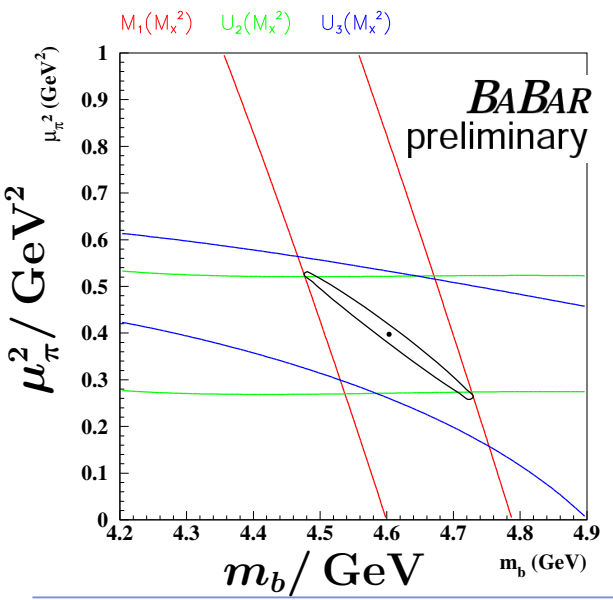
$B \to X_u \ell \nu$: Moments and HQE Fit

★ Extract mass moments with upper cut: $m_X^2 < 6.4\,\mathrm{GeV}^2$

Central Moments

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

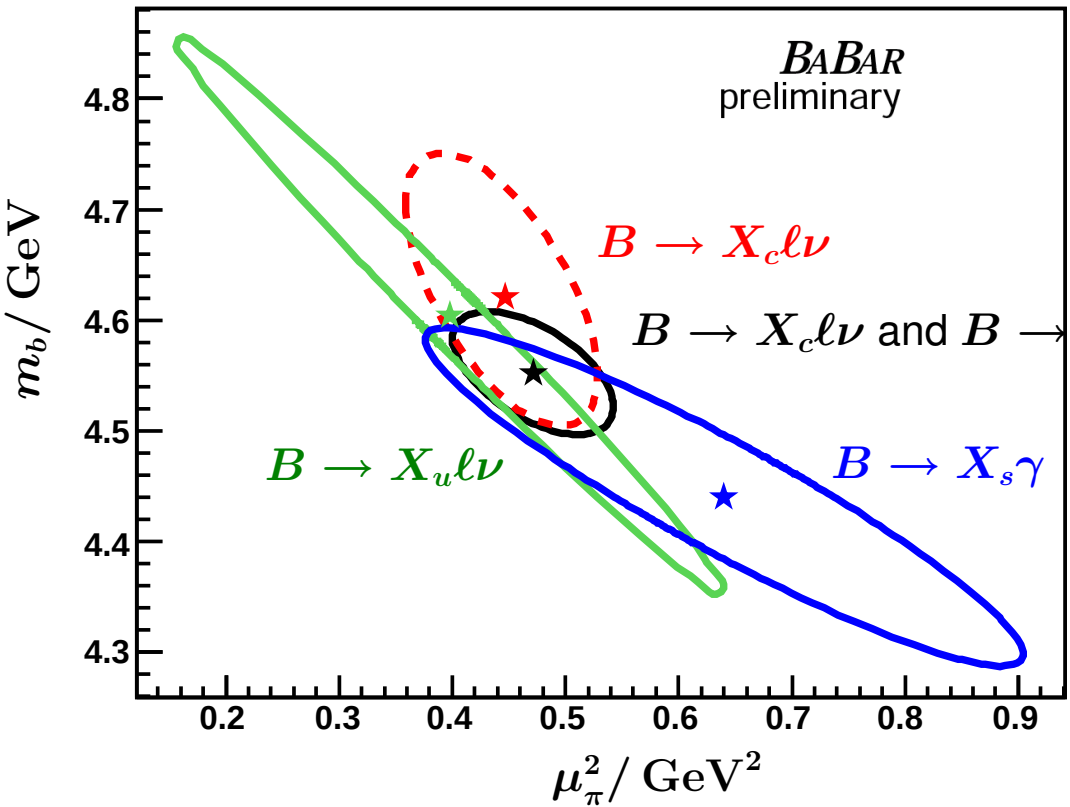
Highly correlated: $\rho_{12} = 0.99$, $\rho_{23} = 0.94$ and $\rho_{13} = 0.88$



[P. Gambino, G. Ossola, N. Uraltsev, JHEP **0509**, 010 (2005)]

	m_b/GeV	μ_π^2/GeV^2
	4.604	0.398
$\sigma(\mathrm{stat})$	0.125	0.135
$\sigma(\mathrm{syst})$	0.193	0.195
$\sigma(\mathrm{theo})$	0.097	0.036
$\sigma(\mathrm{tot})$	0.250	0.240

Compare Results in Different Modes



[hep-ex/0707.2670]

[Phys. Rev. D **69**, 111104 (2004)]

[Phys. Rev. D **72**, 052004 (2005), Phys. Rev. Lett. **97** 171803 (2006)]

[Phys. Rev. Lett. **97** 171803 (2006)]

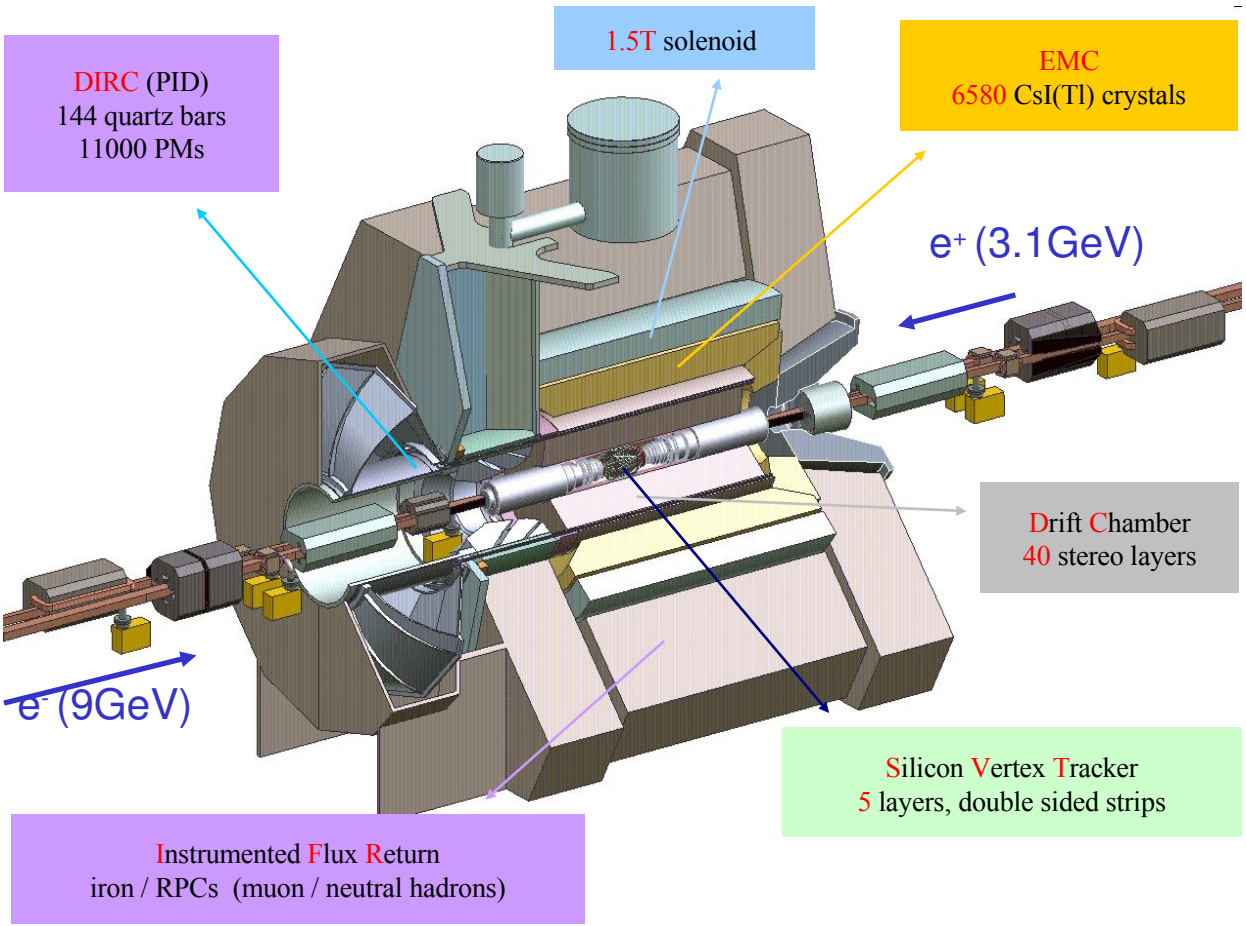
★ m_b and μ_π^2 extracted in different decay modes compatible

Summary

- ⋆ New preliminary results from $BABAR$ on m_b and nonperturbative parameters in $B \to X_s\gamma$ and $B \to X_{c,u}\ell\nu$
- ⋆ First $B \to X_s\gamma$ with hadronic tag from $BABAR$
  - ⋆ Cleaner environment reduces systematic uncertainties
- ⋆ Hadronic mass moments in $B \to X_c\ell\nu$ with larger statistics and first measurement of mixed mass-and-energy moments in $B \to X_c\ell\nu$
  - ⋆ Mixed moments expected to yield more reliable extraction of higher-order nonperturbative parameters
- ⋆ New: First determination of m_b in $B \to X_u\ell\nu$
  - ⋆ Consistent with determination in the other decay modes
  - ⋆ Good constraint on combination of m_b and μ_π^2

Backup Slides

The *BABAR* Detector



$BABAR$ and PEP-II

- PEP-II is "asymmetric B-factory":
  - $e^-(9\,\mathrm{GeV})e^+(3.1\,\mathrm{GeV}) \to \Upsilon(4S) \to B\bar{B}$
  - Collected $\sim 477\,\mathrm{fb}^{-1}$ (525 million $B\bar{B}$) between 1999 and now