Inclusive Semileptonic B Decays at *BABAR*

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Overview

- Introduction: Heavy Quark Expansion (HQE) and moments of inclusive distributions

- Measurement of moments of the hadronic-mass distribution in inclusive decays $B \to X_c l \nu$
- Measurement of moments of the combined hadronic mass-and-energy spectrum:

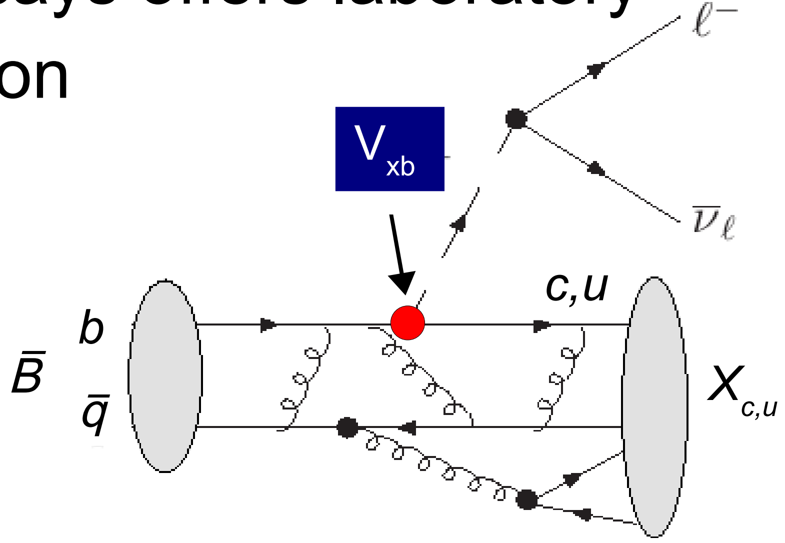
- Measurement of the unfolded hadronic mass spectrum and its moments in decays $B \to X_u l \nu$

SLAC-PUB-13036

- HQE-fit: Extraction of $|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \to X_c l \nu)$, and the leading non-perturbative HQE-parameters

Inclusive Semileptonic B Decays

- Study of semileptonic $B \rightarrow X_{c/u} l\nu$ decays offers laboratory for studying the b quark in the B meson
- Single hadronic current gives better control over theoretical uncertainties
- Γ_{sl} described by ***Heavy Quark Expansion*** (HQE) in $1/m_b^n$ and α_s
  - First non-pert. correction at $O(1/m_b^2)$
  - μ_π^2: kinetic energy of the b-quark, μ_G^2: chromomagnetic moment



$$\Gamma_{sl}(B \rightarrow X_{c,u} l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{xb}|^2 (1 + A_{ew}) A^{pert} A^{nonpert}$$

free quark decay | perturbative corr. | non-pert. corr.

Non-perturbative effects and quark masses need to be measured for a reliable extractions of $|V_{cb}|$ and $|V_{ub}|$

Moments of Inclusive Distributions

- Measure moments of inclusive distributions over wide range of phase space to avoid problems with quark-hadron duality
  - Moments depend only on quark masses and same set of universal non-perturbative parameters

$$\langle E_l^n \rangle = N_{norm} \int (E_l - \langle E_l \rangle)^n \left(\frac{\mathrm{d}\Gamma_{c,u}}{\mathrm{d}E_l} \right) \mathrm{d}E_l$$

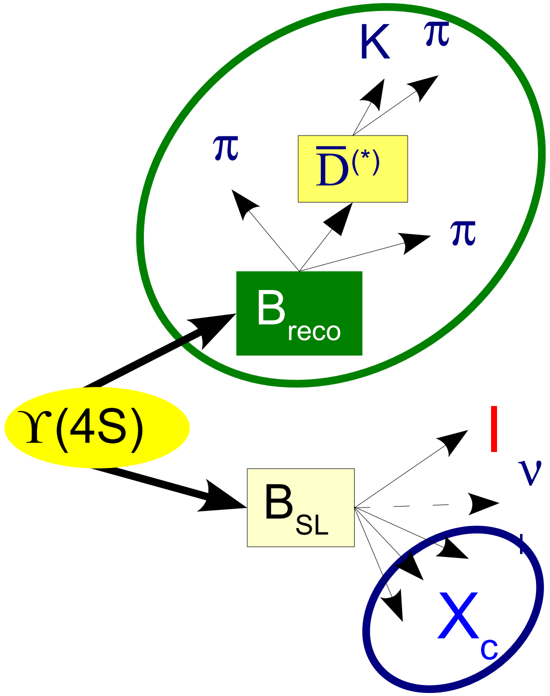
$$\langle m_X^n \rangle = N_{norm} \int m_X^n \left(\frac{\mathrm{d}\Gamma_{c,u}}{\mathrm{d}m_X} \right) \mathrm{d}m_X$$

  - Calculations available in *kinetic* [Benson et al., Nucl. Phys. B665:367] and *1S* scheme [Bauer et al., Phys. Rev. D70:094017]
  - *Combined fit:* experimental determination of quark masses and non-perturbatibe parameters
- Determination of $|V_{ub}|$ needs precise measurement of m_b
  - $b \to c l \nu$: sensitive to m_b-m_c, high statistics measurement
  - $b \to u l \nu$: sensitive to m_b, experimentally challenging, large $b \to c l \nu$ background, same mode in which $|V_{ub}|$ is extracted

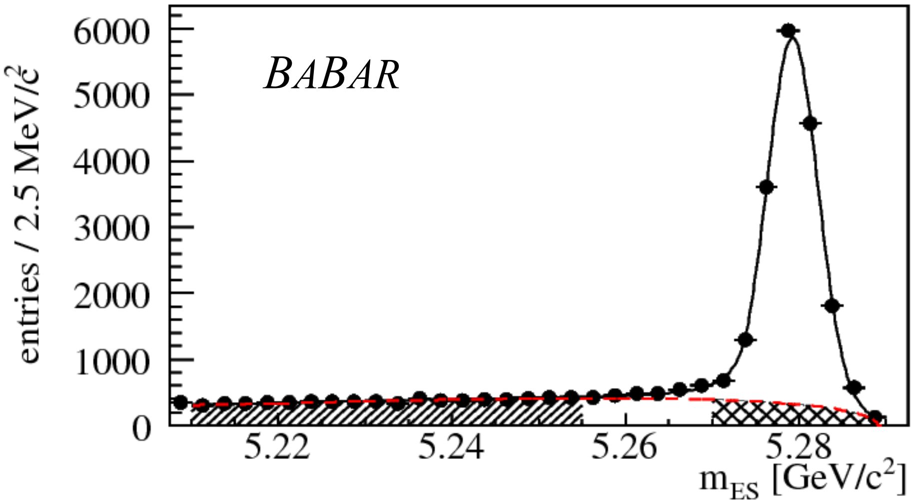
Moments of the *Hadronic Mass* and the Combined Hadronic Mass-and-Energy Distributions in Decays $B \to X_c l \nu$

Analysis Strategy

- Dataset: 230 million decays $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- On the “recoil” of fully-reconstructed B_{reco}
  - flavor and four-momentum of recoiling B_{SL} known
  - $m_{ES} = \sqrt{\frac{s}{4} - \vec{p}_B^{\,2}}$ used to subtract combinatorial background

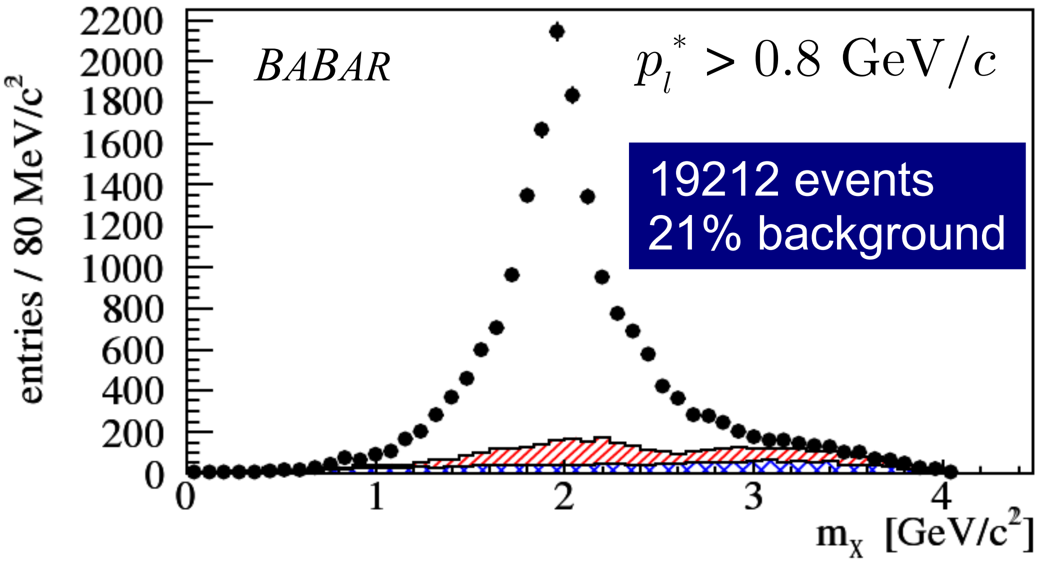


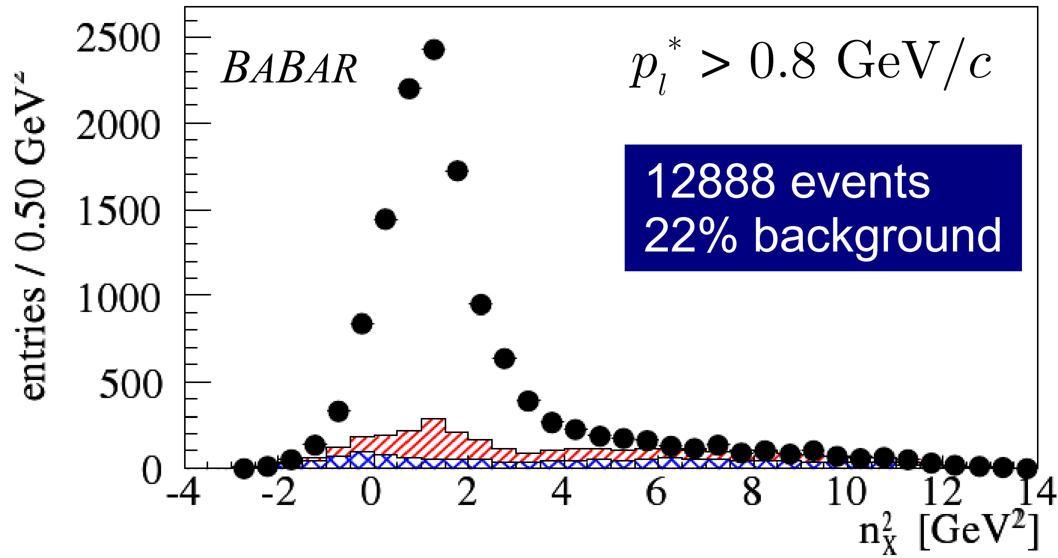
- Measure one recoiling lepton with $p^*_l > 0.8$GeV in the B_{SL} restframe
- Remaining particles form the inclusive hadronic X_c-system
- Missing mass and energy consistent with unmeasured neutrino
- Improve resolution with kinematic fit



Reconstructed Spectra

data   combinatorial/non-$B\bar{B}$ decays   residual background





- Background contributions:
  - mis-reconstructed B_{reco}-mesons (combinatorial background)
  - non-$B\bar{B}$ decays: $e^+e^- \to q\bar{q} \to$ „B_{reco}" + ℓ

determined from data

  - secondary decays: $B^{0,+} \to D^{(*)0,+}X \to Y\, l^+ \nu$, $B^{0,+} \to J/\psi$, $\psi(2S) \to l^+ l^-$, …
  - semileptonic decays to charmless hadronic final states: $B \to X_u\, l\, \nu$
  - $B\bar{B}$ oscillations

determined in simulations

Calibration Method

- Unmeasured/missing particles bias hadronic system: *5-16% effect for <m$_X$>*
  - Linear correction functions for moments (applied event-by-event):

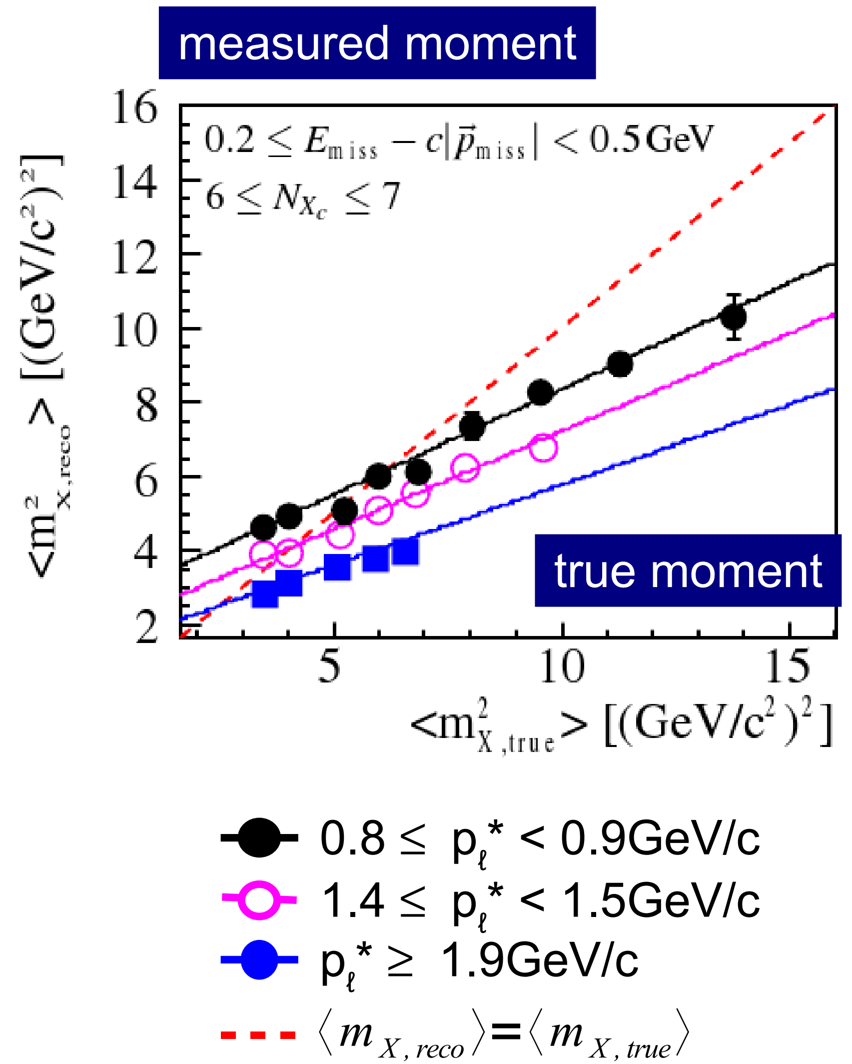
$$\langle m_{X,true}^{n}\rangle \leftrightarrow \langle m_{X,reco}^{n}\rangle,\ \ \langle n_{X,true}^{n}\rangle \leftrightarrow \langle n_{X,reco}^{n}\rangle$$

  - Determined and tested in simulation
- Measure moments $<m_X^n>$ and $<n_X^n>$ as function of minimum lepton momentum

$$n_X^2 = m_X^2 - 2\Lambda E_{XB} + \Lambda^2, \text{ with } \Lambda = 0.65 \text{ GeV}$$

[Gambino and Uraltsev, hep-ph/0401063]

- Systematic uncertainties:
  - Low dependence on simulation model
  - Main systematics: calibration method, photon selection efficiency, background subtraction



Measurement of the unfolded hadronic mass spectrum and its moments in decays $B \rightarrow X_u l \nu$

Mass Spectrum and Moments

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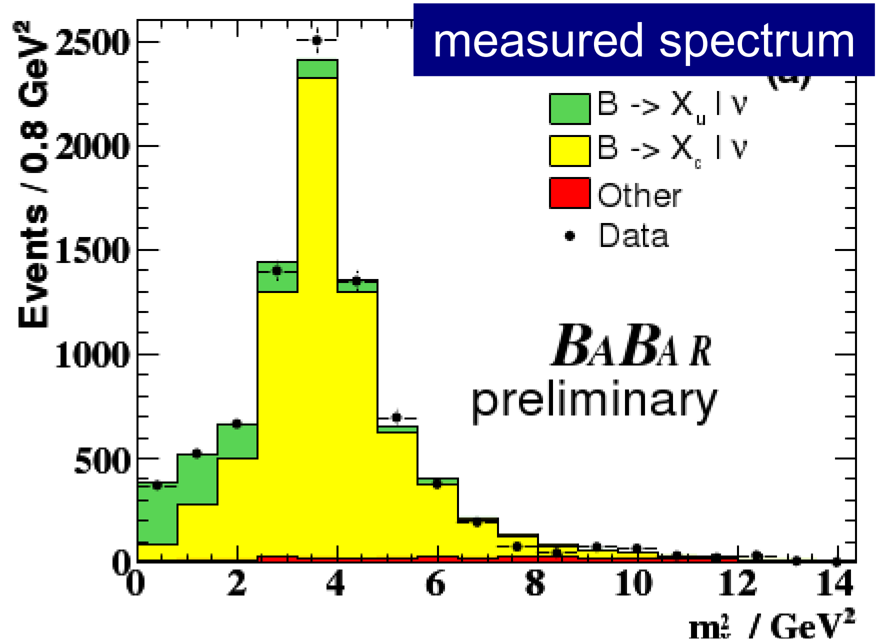
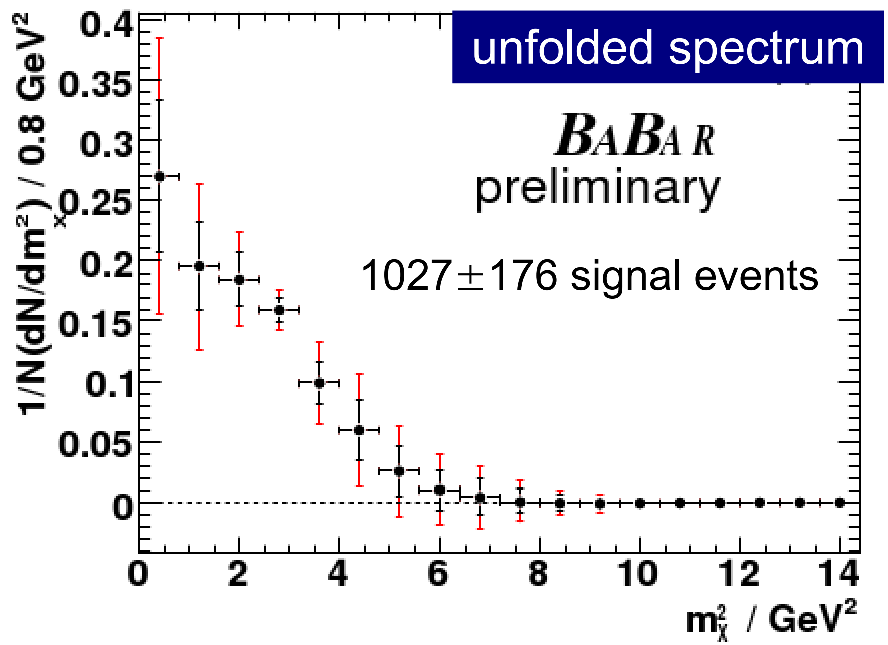
- 383 million decays Υ (4S)→$B\bar{B}$
- Measured on the recoil of fully reconstructed B mesons
- Select lepton with E_l > 1GeV
- Large background $B \rightarrow X_c l \nu$
- Veto events with $K^{\pm}$, K_S, and partially reconstructed $D^{*\pm}$
- Unfold spectrum for detector acceptance, efficiency, and resolution

measured spectrum



unfolded spectrum



Moments and Interpretation

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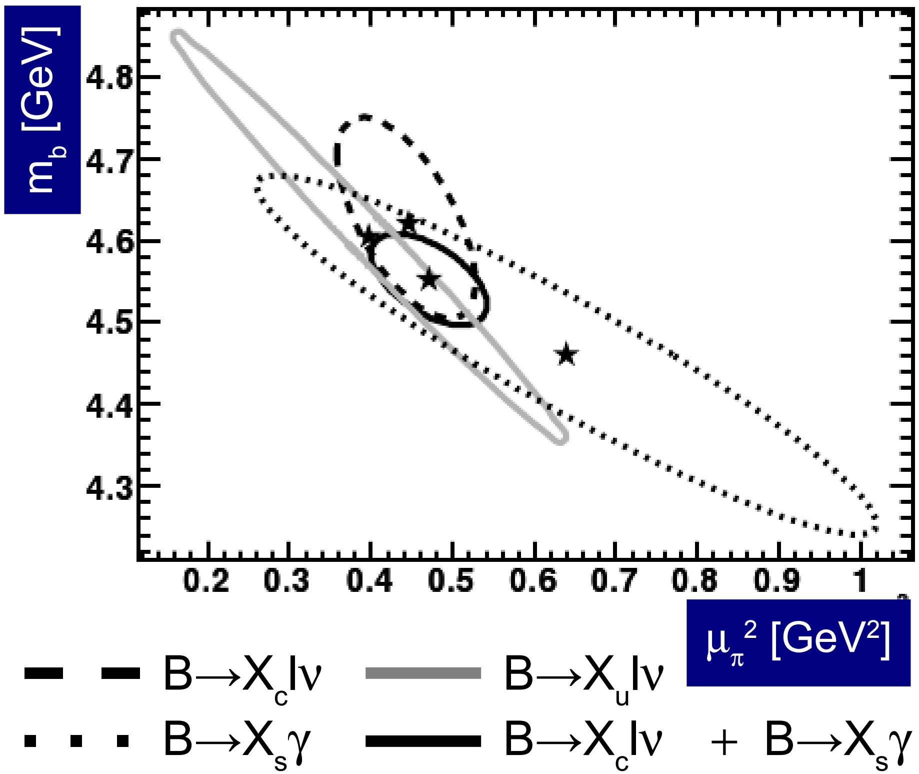
- Calculated moments from unfolded spectrum:
(highly correlated: ρ_{12}=0.99, ρ_{23}=0.94, ρ_{13}=0.88)

$$\langle m_X^2 \rangle = (1.96 \pm 0.34(\mathrm{stat}) \pm 0.53(\mathrm{syst}))\ \mathrm{GeV}^2$$
$$\langle (m_X^2)^2 - \langle m_X^2 \rangle^2 \rangle = (1.92 \pm 0.59(\mathrm{stat}) \pm 0.87(\mathrm{syst}))\ \mathrm{GeV}^4$$
$$\langle (m_X^2)^3 - \langle m_X^2 \rangle^3 \rangle = (1.79 \pm 0.62(\mathrm{stat}) \pm 0.78(\mathrm{syst}))\ \mathrm{GeV}^6$$

- HQE-fit to these moments in then *kinetic* scheme:

$$m_b = (4.604 \pm 0.250)\ \mathrm{GeV}$$
$$\mu_\pi^2 = (0.398 \pm 0.240)\ \mathrm{GeV}^2$$

[Gambino et al., JHEP 0509, 010 (2005)]



[hep-ex/0707.2670;
Phys. Rev. D69,111104;
Phys. Rev. D72,052004;
Phys. Rev. Lett. 97 171803]

HQE-fit: Extraction of $|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \rightarrow X_c l\nu)$, and the leading non-perturbative HQE-parameters

Combined HQE-Fits to *BABAR* Measurements

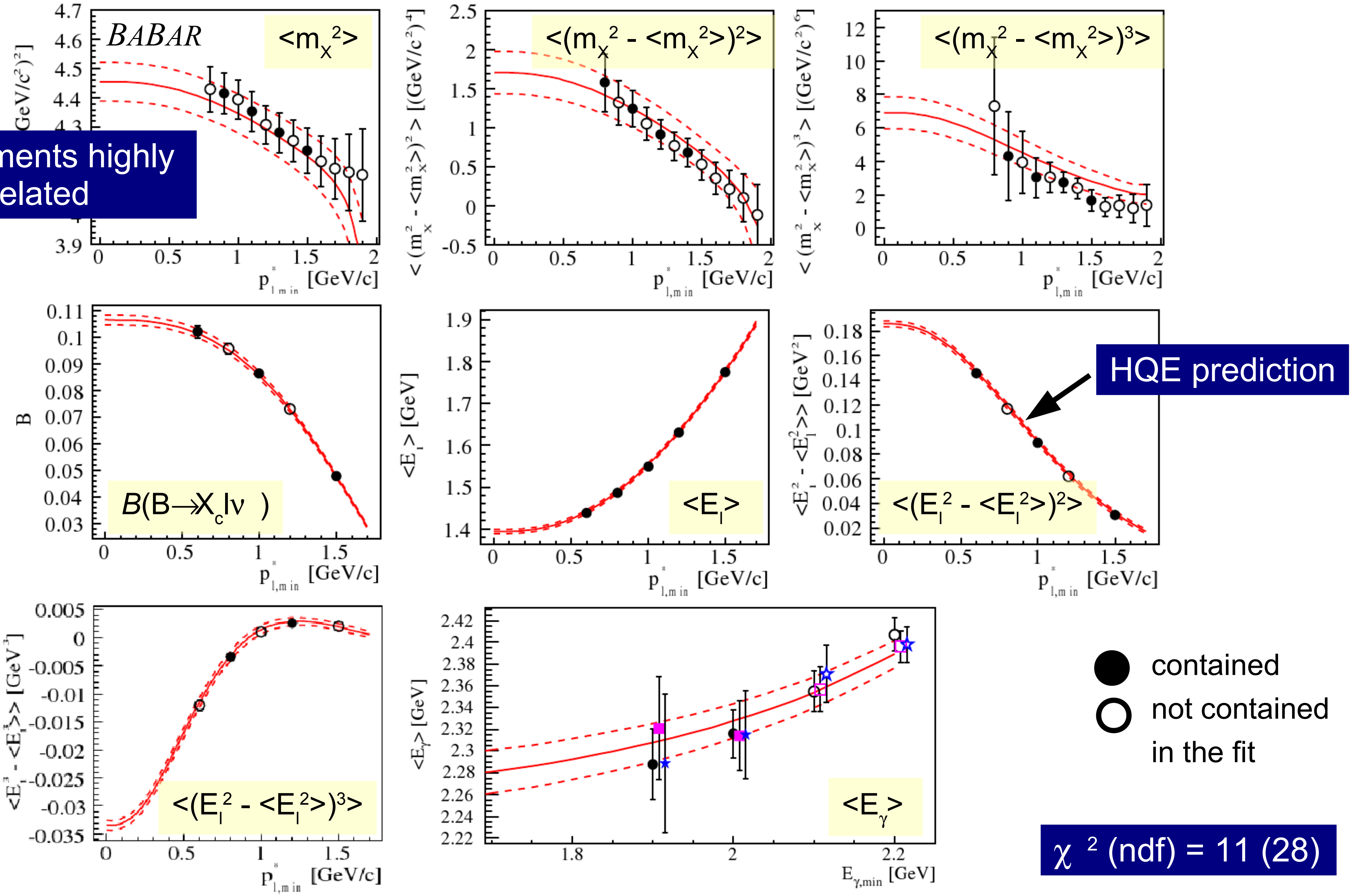
- Two combined χ^2-fits in the *kinetic* scheme:
  - Fit only subsets of measurements to reduce correlations
  - Uneven mass/mixed moments not used (reduced accuracy of the expansion)
  - 12 mass moments **or** 12 mixed moments measured in $B \to X_c l\nu$
  - 13 electron energy moments measured in $B \to X_c l\nu$ [Phys. Rev. D69, 111104 (with updated background BFs)]
  - 9 photon-energy moments measured in $B \to X_s\gamma$ [Phys.Rev. D72,052004, Phys.Rev.Lett. 97,171803, Phys.Rev. D77,051103]
- 8 fit parameters:

$$|V_{cb}|,\ \mathcal{B}(B \to X_c l\nu),\ m_b,\ m_c,\ \mu_\pi^2,\ \mu_G^2,\ \rho_{LS}^3,\ \rho_D^3$$

- Additional inputs:
  - B-meson lifetime: $\tau_B = (1.585 \pm 0.007)\,\mathrm{ps}$
  - Constraints: $\mu_G^2 = (0.35 \pm 0.07)\,\mathrm{GeV}^2$ — B-B* mass splitting
    $\rho_{LS}^3 = (-0.15 \pm 0.10)\,\mathrm{GeV}^3$ — sum rules

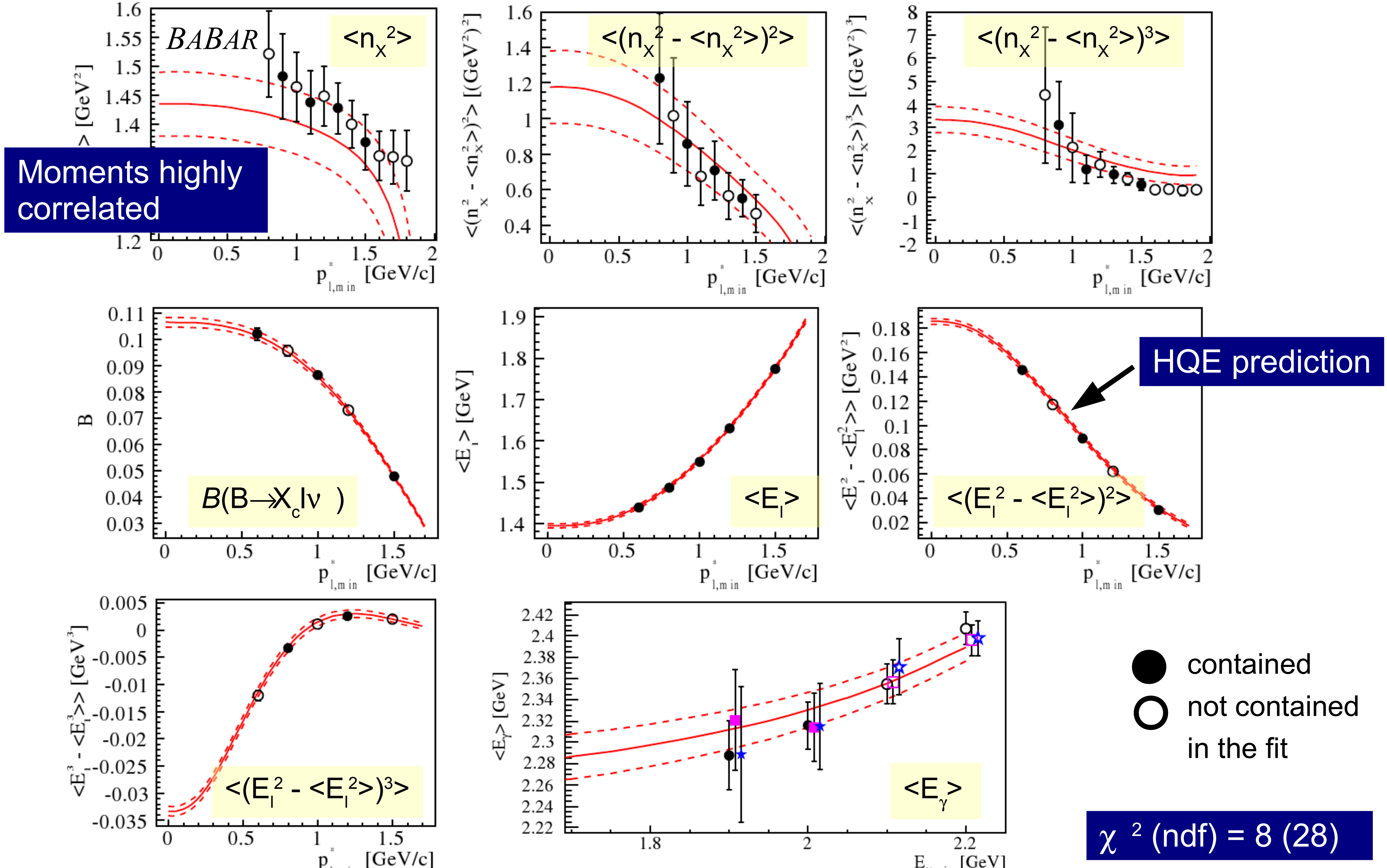
HQE Predictions (Mass Moments)

[Benson et al., Nucl.Phys.B665:367; Gambino and Uraltsev, hep-ph/0401063, hep-ph/0403166]



HQE Predictions (Mixed Moments)

[Benson et al., Nucl.Phys.B665:367; Gambino and Uraltsev, hep-ph/0401063, hep-ph/0403166]



Fit Results and Comparison

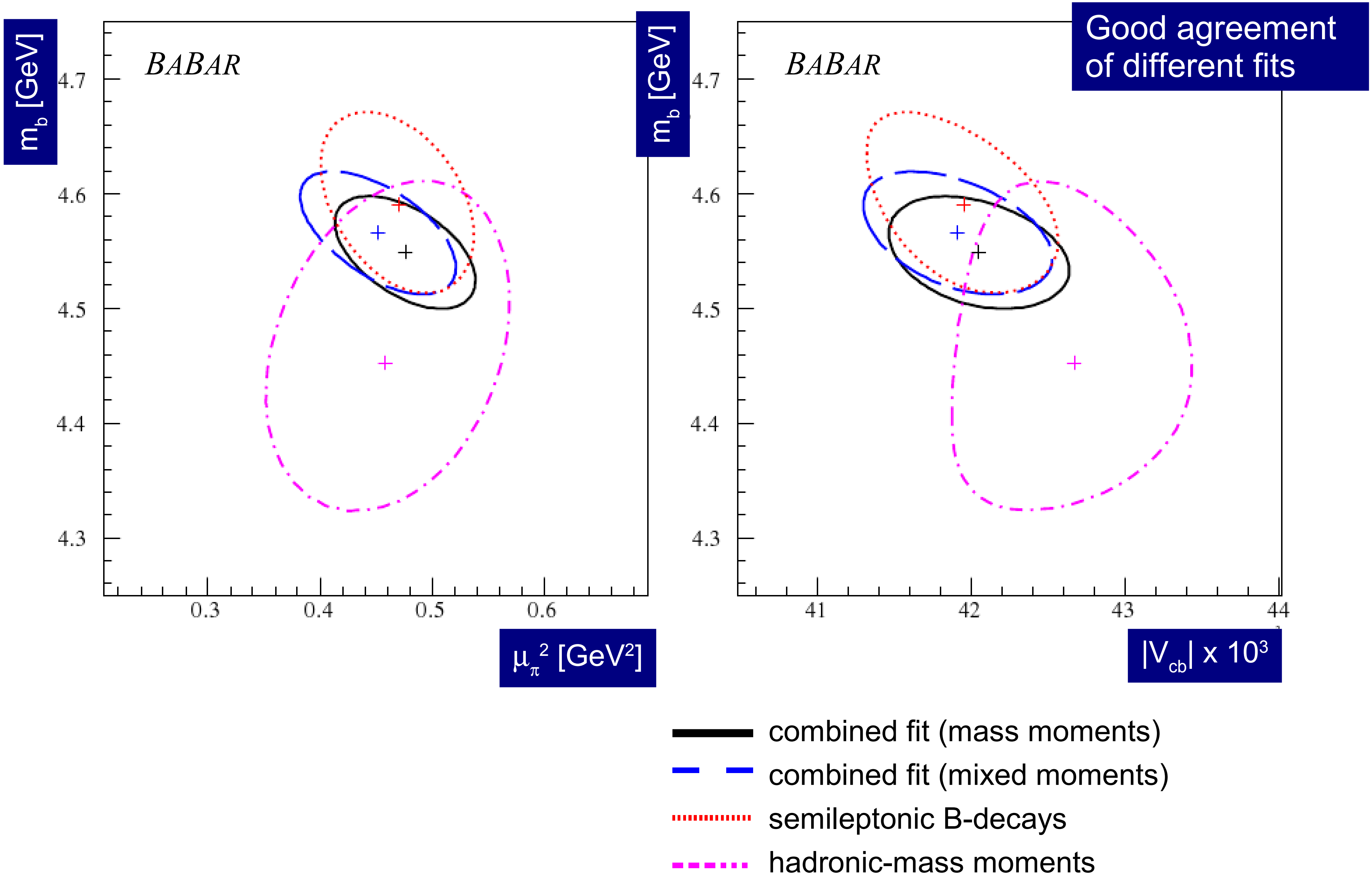
(kinetic scheme with μ=1)

	$\lvert V_{cb}\rvert \times 10^3$	m_b [GeV]	m_c [GeV]	μ_π^2 [GeV^2]
mass moments	42.05±0.83	4.549±0.049	1.077±0.074	0.476±0.063
mixed moments	41.91±0.85	4.566±0.053	1.101±0.078	0.452±0.069
$B\to X_u l\nu$ moments		4.604±0.250		0.398±0.240
HFAG (Winter 2009)*	41.54±0.73	4.620±0.035	1.190±0.052	0.424±0.042
BELLE 2008 [Phys.Rev. D78,032016]	41.58±0.90	4.543±0.075	1.055±0.118	0.539±0.079

(* combined result includes published moments $B\to X_c l\nu$ and $B\to X_s\gamma$ measured by BaBar, BELLE, CDF, CLEO, and DELPHI)

- Agreement with other measurements and combined HFAG results
- Good agreement of $B\to X_u l\nu$ and $B\to X_c l\nu$ results
  - m_b and μ_π^2 extracted in different decay modes compatible
- Good agreement of results of mixed and mass moments
  - Indicating that higher order corrections have been treated correctly for the calculation of the mass moments

Comparison of Fits



Good agreement of different fits

Summary

- Measurement of the first six moments of the hadronic mass spectrum in semileptonic B-meson decays $B \to X_c l\nu$
  - Good agreement with previous measurements
- First measurement of the mixed moments $\langle (n_X^2)^k \rangle$, k=1...3

- Measurement of the unfolded mass spectrum and its moments in $B \to X_u l\nu$

$m_b = (4.604 \pm 0.250)$ GeV
$\mu_\pi^2 = (0.398 \pm 0.240)$ GeV^2

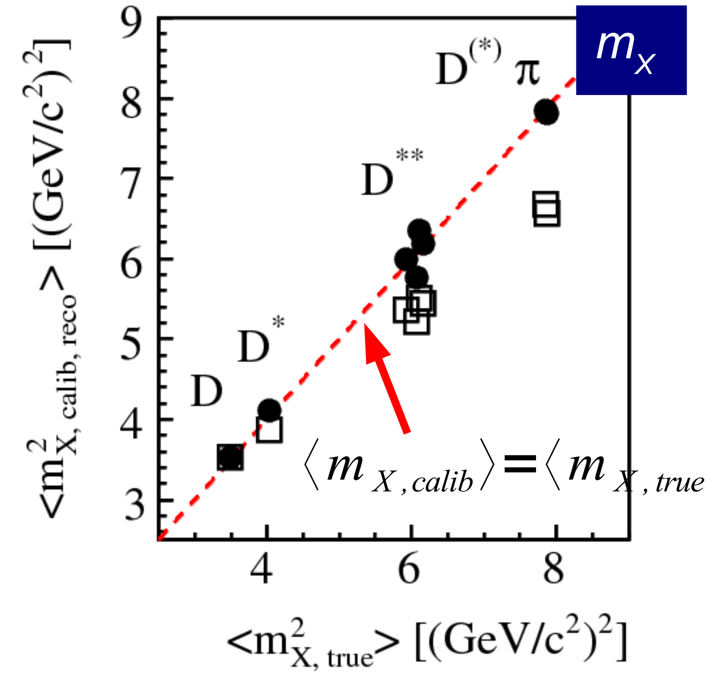
- Extraction of $|V_{cb}|$, m_b and m_c, semileptonic branching fraction $B(B \to X_c l\nu)$, and non-perturbative HQE-parameter in the *kinetic* scheme
  - In agreement with other measurements

$|V_{cb}| = (42.05 \pm 0.85)\ 10^{-3}$
$m_b = (4.549 \pm 0.049)$ GeV
$m_b - m_c = (3.472 \pm 0.032)$ GeV
$B(B \to X_c l\nu) = (10.64 \pm 0.18)\%$

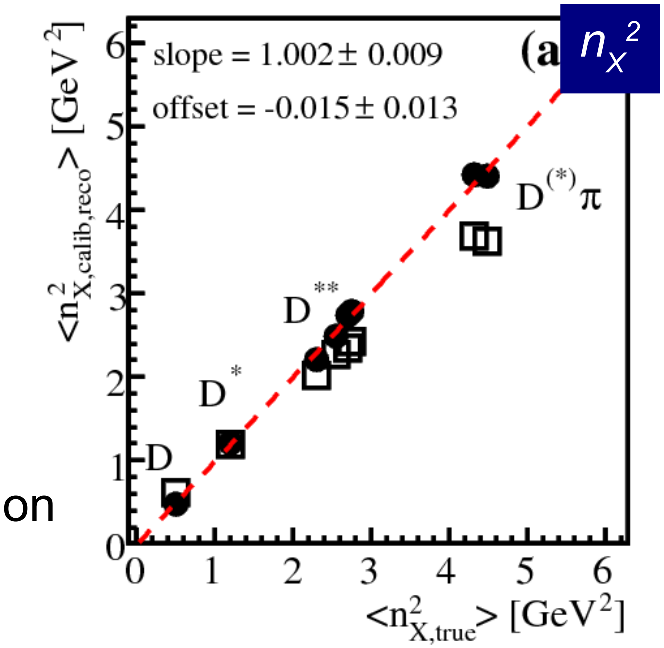
-- Backup Slides --

Verification with MC-Simulations of Exclusive Modes

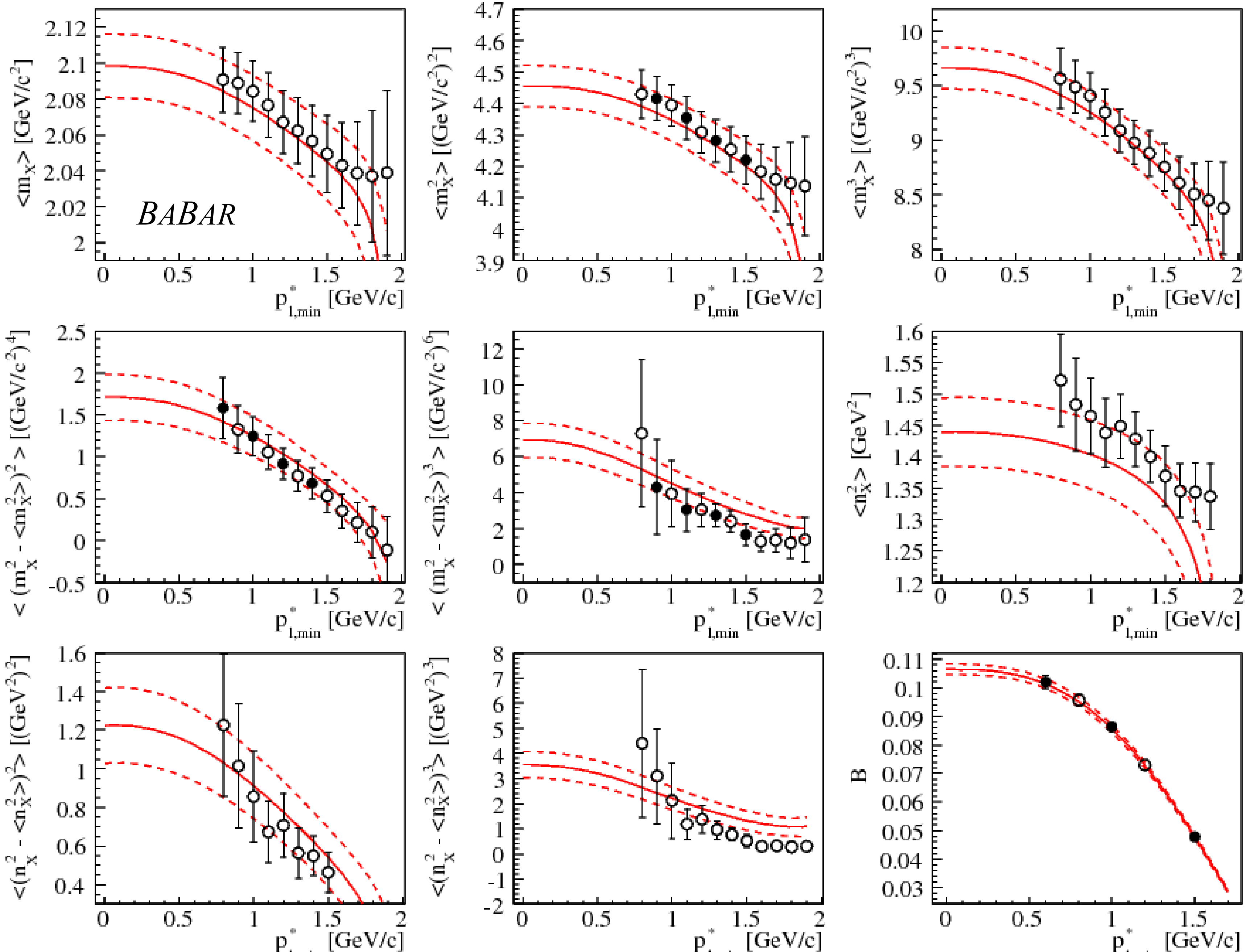
- Calibration curves constructed using a mixture of different exclusive hadronic final states
- Calibration applied to different simulated exclusive signal decays reproduces true underlying moments



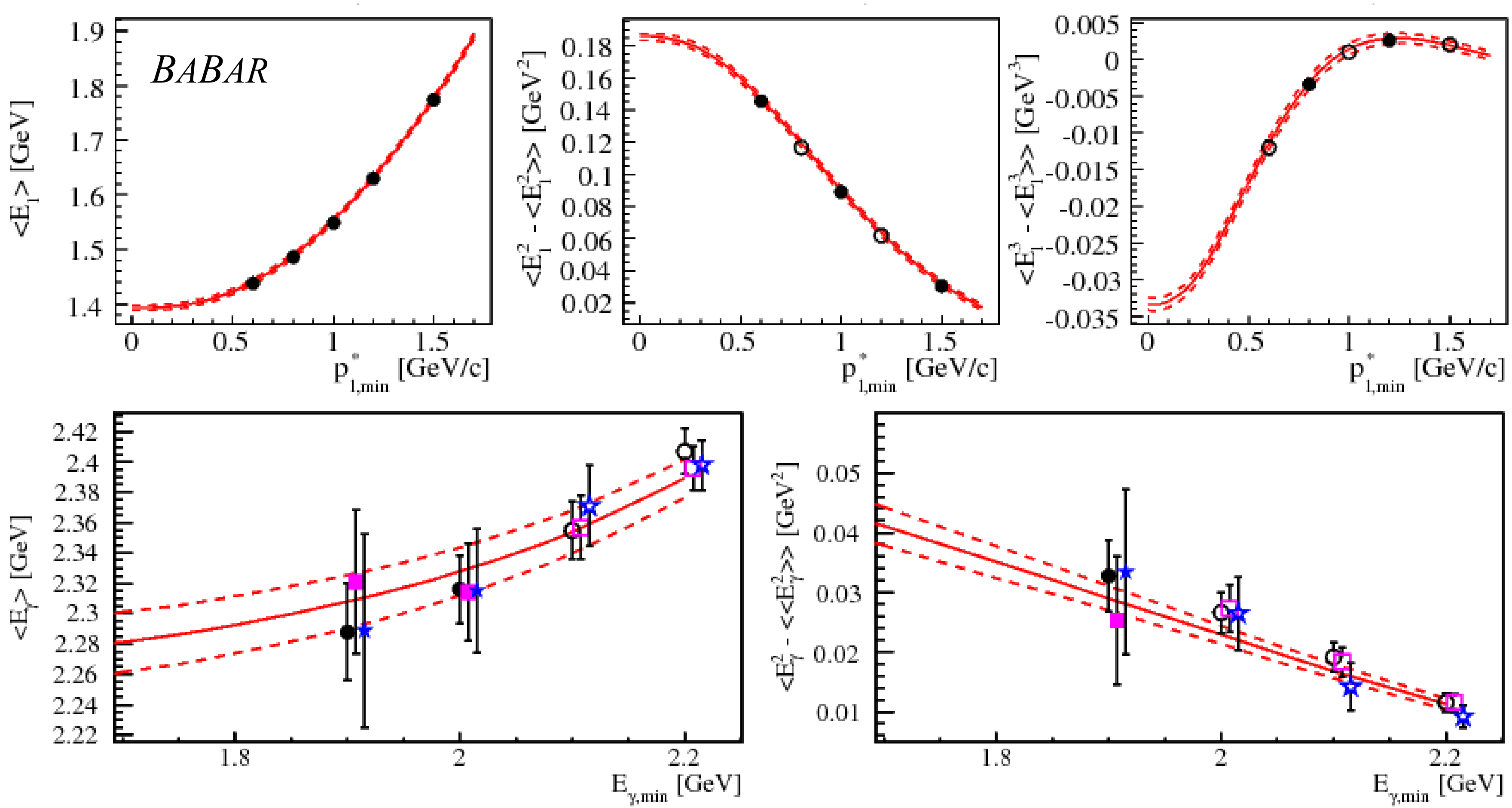
before
after calibration



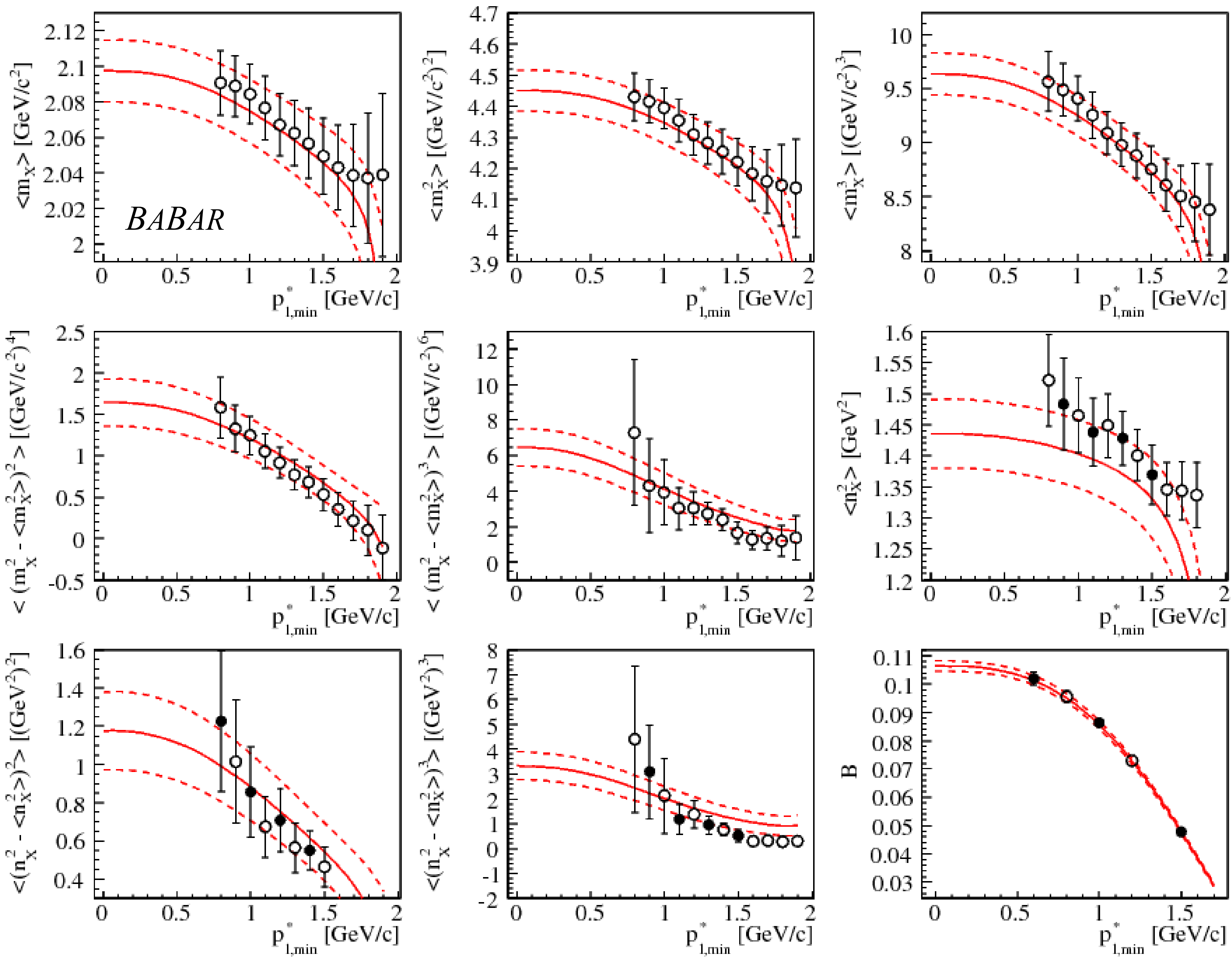
HQE Fit Predictions (Mass Moments)



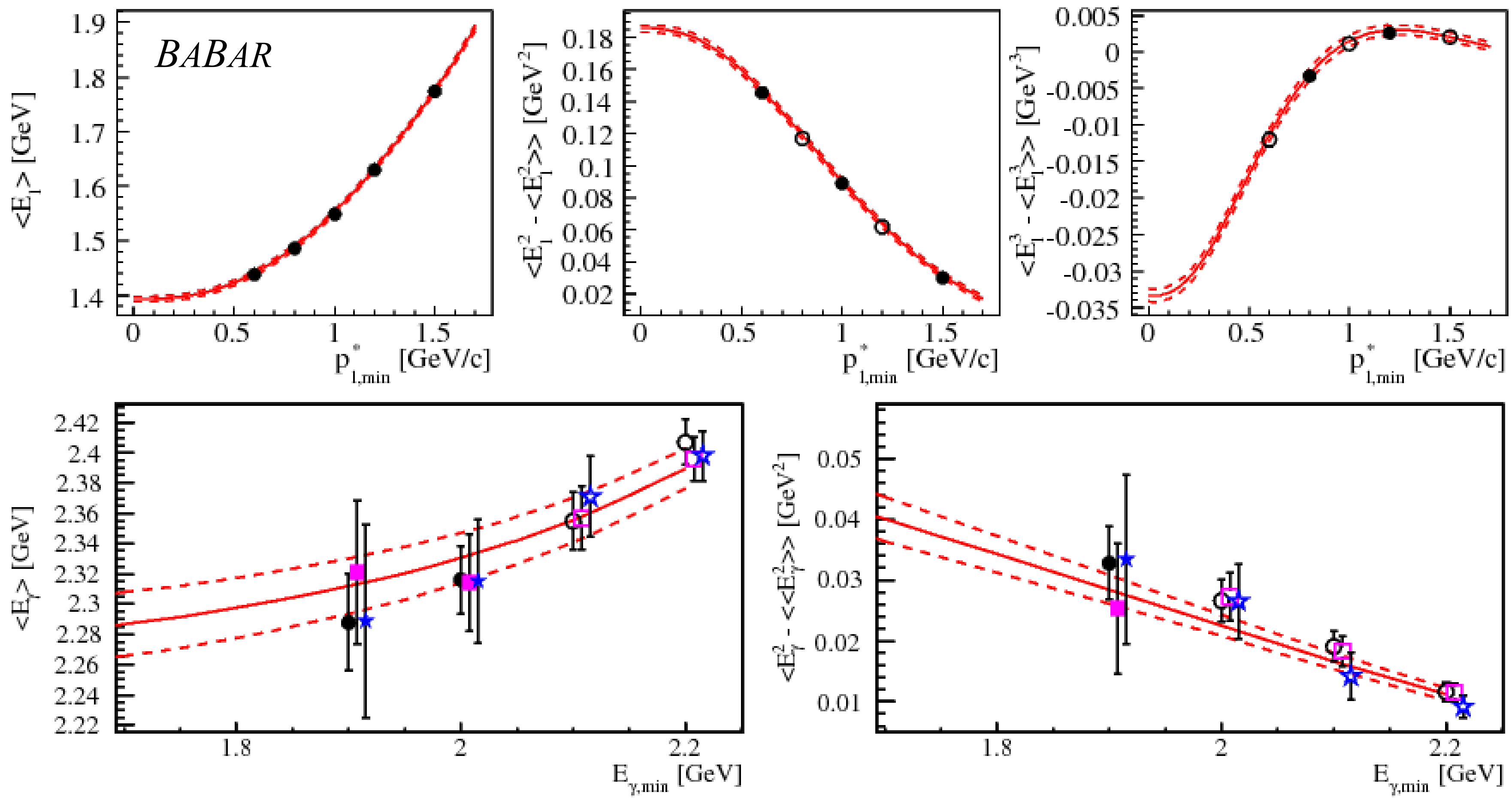
HQE Fit Predictions (Mass Moments)



HQE Fit Predictions (Mixed Moments)



HQE Fit Predictions (Mixed Moments)



HQE Fit Results

- Fits in good agreement with each other and previous measurements

Fit 1 (mass moments)

m_b-m_c = (3.472±0.032) GeV/c^2

	$\lvert V_{cb}\rvert \times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]
Results	42.05	4.549	1.077	10.642	0.476	0.300	0.203	-0.144
Δ_{exp}	0.45	0.031	0.041	0.165	0.021	0.044	0.017	0.075
Δ_{theo}	0.37	0.038	0.062	0.063	0.059	0.038	0.027	0.056
$\Delta_{\Gamma_{SL}}$	0.59							
Δ_{tot}	0.83	0.049	0.074	0.176	0.063	0.058	0.032	0.094

1.4% theoretical uncertainty on the semileptonic rate

Fit 2 (mixed hadronic moments)

m_b-m_c = (3.465±0.032) GeV/c^2

	$\lvert V_{cb}\rvert \times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]
Results	41.91	4.566	1.101	10.637	0.452	0.304	0.190	-0.156
Δ_{exp}	0.48	0.034	0.045	0.166	0.023	0.047	0.013	0.079
Δ_{theo}	0.38	0.041	0.064	0.061	0.065	0.039	0.031	0.052
$\Delta_{\Gamma_{SL}}$	0.59							
Δ_{tot}	0.85	0.053	0.078	0.176	0.069	0.061	0.034	0.095

2.0% 1.1% 6.5%

(kinetic scheme with μ =1GeV)