CLEO CKM Results

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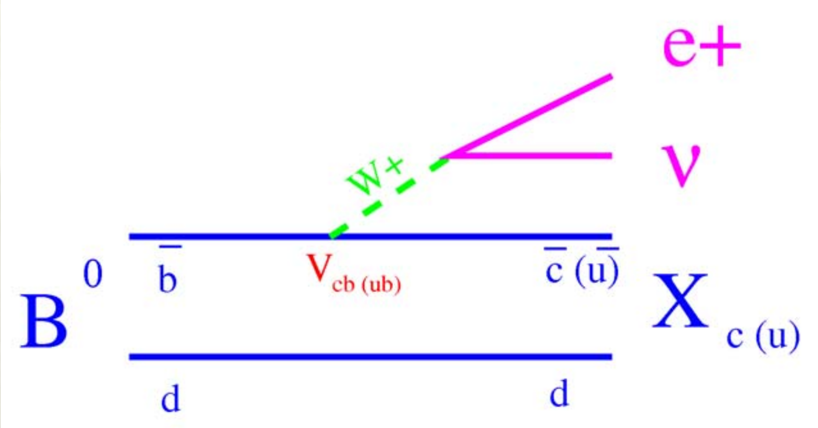
CKM Measurements in Semileptonic B Decays

In naïve spectator picture
analogous to μ decay

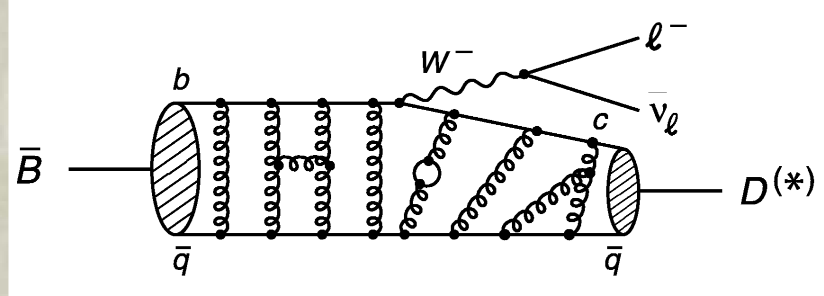
$$\Gamma(b \to u\ell\nu) = \frac{\mathcal{B}(b \to u\ell\nu)}{\tau_b} \approx \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2$$



Rate is proportional to $|V_{ckm}|^2$

Complication!

- Quarks are found in hadrons.
- QCD corrections are needed to extract weak decay physics.



Both perturbative and non-perturbative QCD corrections:

Directly calculate or measure via symmetry-related processes

Use many techniques and compare results to gain confidence in hadronic corrections.

Recent CLEO CKM Measurements

- Exclusive $|V_{ub}|$
  - $B \to \pi \ell \nu$; $B \to \eta \ell \nu$; $B \to \rho \ell \nu$; $B \to \omega \ell \nu$
    neutrino reconstruction PRD 68, 072003 (2003)
- Inclusive $|V_{ub}|$
  - From lepton energy endpoint PRL 88, 231803 (2002)
  - With help from $b \to s \gamma$ PRL 87, 251807 (2001)
- Exclusive $|V_{cb}|$
  - $B \to D^* \ell \nu$ PRL 89 081803 (2002) & PRD 67 032001 (2003)
- Inclusive $|V_{cb}|$
  - Hadronic Mass spectrum with neutrino reconstruction
    - $E_\ell > 1.5$ GeV PRL 87 251808 (2001)
    - $E_\ell > 1.0$ GeV hep-ex/0403052
  - Lepton spectrum
    - $E_\ell > 1.5$ GeV PRD 67 072001(2003)
    - $E_\ell > 0.6$ GeV using lepton tags hep-ex/0403053

I will focus solely on new inclusive $B \to X_c \ell \nu$ results

Heavy Quark Effective Theory

- Semileptonic rate expressed as a double expansion in α_s and $1/m_b$
- Introduce expansion parameters as matrix elements of non-perturbative operators
  - Use "kinetic mass" formulation of Gambino & Uraltsev EPJ C 34, 181 (2004)

$$\Gamma(b \to c\ell\nu) = \frac{G_F^2 m_b^5 |V_{cb}|^2}{192\pi^3}\left[1 + P\left(\alpha_s, \mu, \tfrac{m_b}{m_c}\right) + N\left(m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3\right)\right]$$

$$\begin{aligned}
&: \; m_c \Rightarrow c \text{ quark mass} \\
O(1/m_b) &: \; m_b \Rightarrow b \text{ quark mass } (\Leftrightarrow \overline{\Lambda}) \\
O(1/m_b^2) &: \; \mu_\pi^2 \Rightarrow \text{Fermi momentum of } b \text{ quark } (\Leftrightarrow \lambda_1) \\
&: \; \mu_G^2 \Rightarrow \text{Hyperfine splitting } (\Leftrightarrow \lambda_2) \\
O(1/m_b^3) &: \; \rho_D^3 \Rightarrow \text{Darwin Term} \\
&: \; \rho_{LS}^3 \Rightarrow \text{Spin-orbit coupling}
\end{aligned}$$

Moments of Observable Spectra

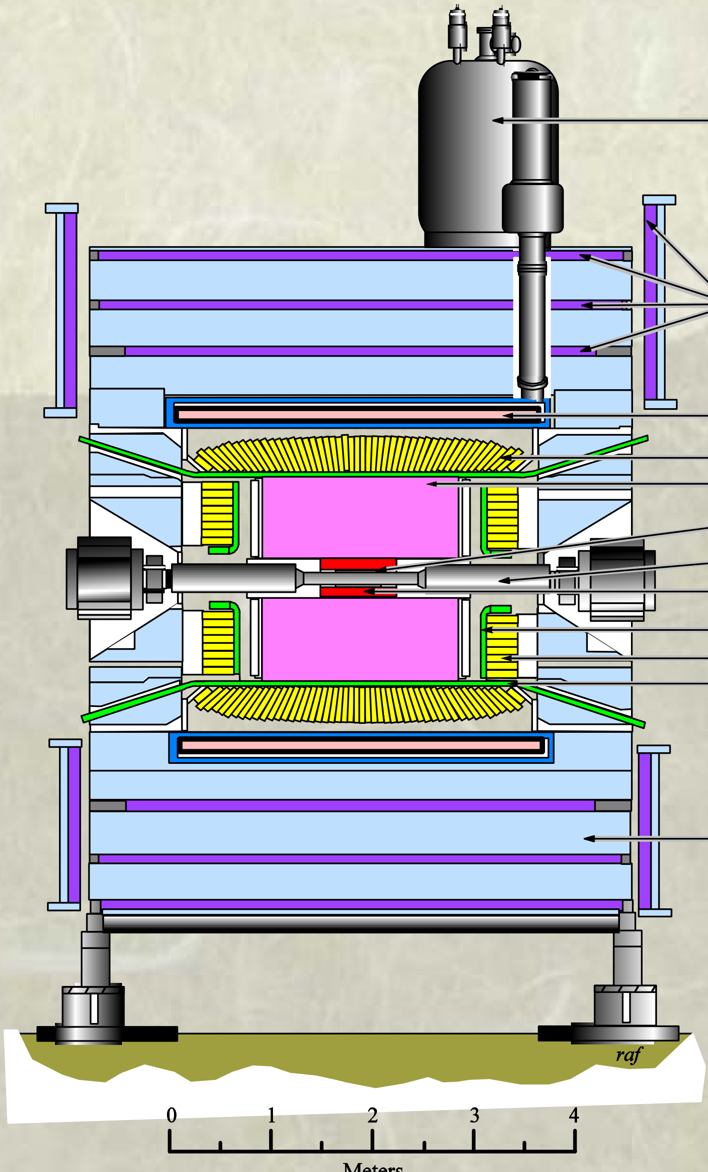
- Moment of distribution defined in usual way:

eg., lepton energy moment:
including experimental cuts

$$E_\ell^{(n)}(E_{cut}) = \frac{\int_{E_{cut}} E_\ell^n \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{E_{cut}} \frac{d\Gamma}{dE_\ell} dE_\ell}$$

- A commom set of HQET parameters appear in expressions for
  - Lepton energy moments in $B \rightarrow X_c l \nu$
  - Hadronic mass-squared moments in $B \rightarrow X_c l \nu$
  - q^2 moments in $B \rightarrow X_c l \nu$
  - Photon energy moments in $B \rightarrow X_s \gamma$
  - Semileptonic width
- Simultaneously fit these measurements to determine HQET parameters and extract $|V_{cb}|$ from observed decay rate

The CLEO II Detector

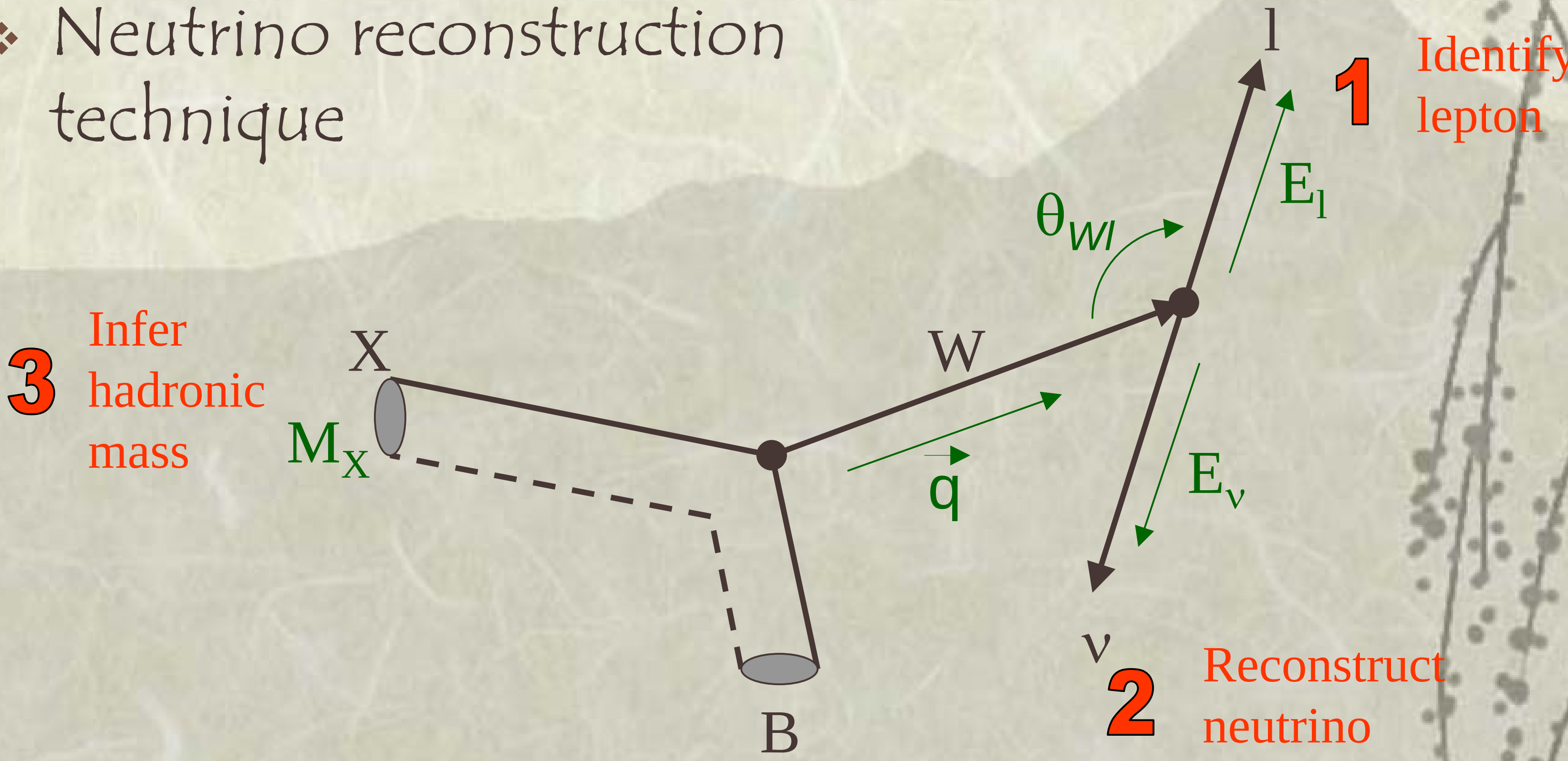


- CESR symmetric e^+e^- collider
  - Energy near Υ(4S)
- Most relevant features of detector:
  - Hermeticity of detector ⇔neutrino reconstruction
  - Excellent shower resolution of CsI calorimeter ⇔photons, electrons
  - Good charged particle resolution and *dE/dx* of drift chamber ⇔leptons

Hadronic Mass and q^2 in $B \rightarrow X_c l \nu$

hep-ex/0403052 to appear in PRD

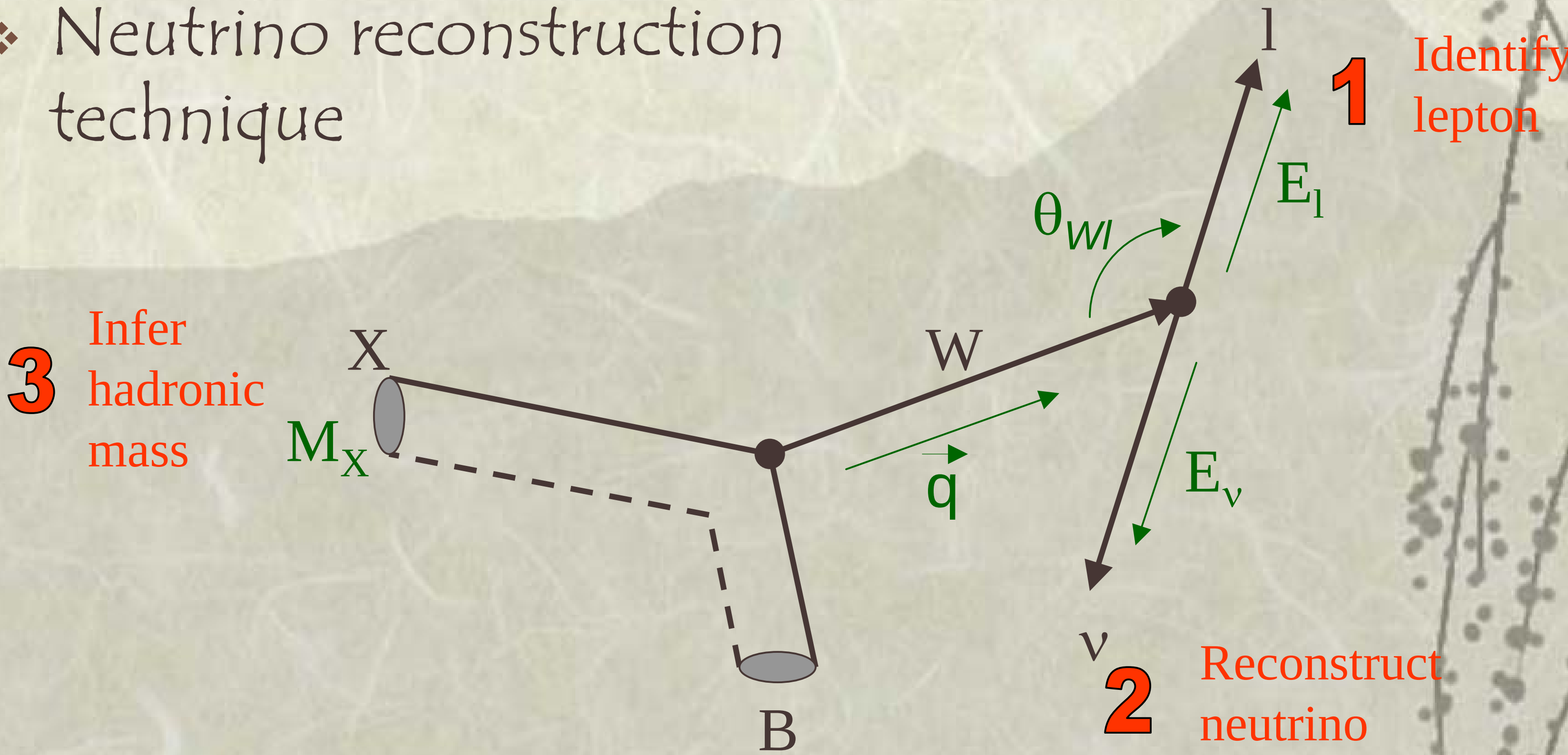
- Neutrino reconstruction technique



$$M_X^2 = M_B^2 + q^2 - 2E_{\text{beam}}\left(E_\ell + E_\nu\right) + 2\underbrace{\left|\vec{p}_B\right|}_{\text{Small}}\left|\vec{p}_\ell + \vec{p}_\nu\right|\underbrace{\cos\theta_{B-\ell\nu}}_{\text{Unknown}}$$

Hadronic Mass and q^2 in $B \rightarrow X_c l \nu$

- Neutrino reconstruction technique



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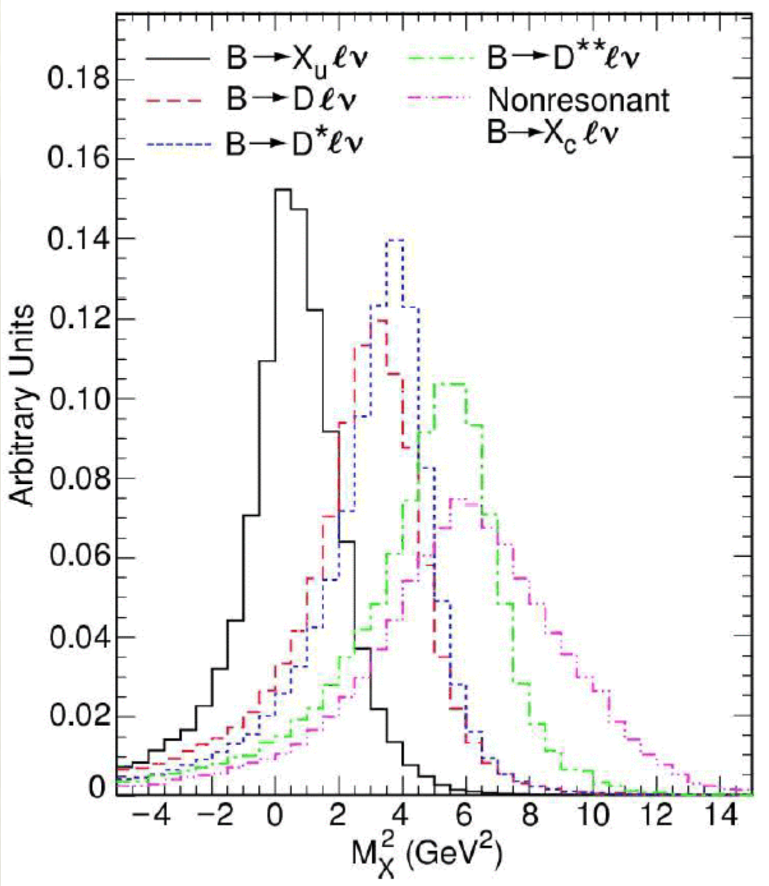
Hadronic Mass and q^2 in $B \to X_c l\nu$

- Selection criteria applied to suppress continuum and enhance neutrino reconstruction
- Fit differential decay rate in three dimensions:
  - q^2
  - M_X^2
  - $\cos\theta_{Wl}$
- Fit Components and models:
  - $B \to Dl\nu$ HQET+measured FF's
  - $B \to D^* l\nu$ HQET+measured FF's
  - $B \to D^{**} l\nu$ ISGW2
  - $B \to (X_c)_{non\text{-}res} l\nu$ Goity-Roberts
  - $B \to X_u l\nu$ ISGW2+NR
  - Secondary leptons CLEO MC
  - Continuum and fakes data

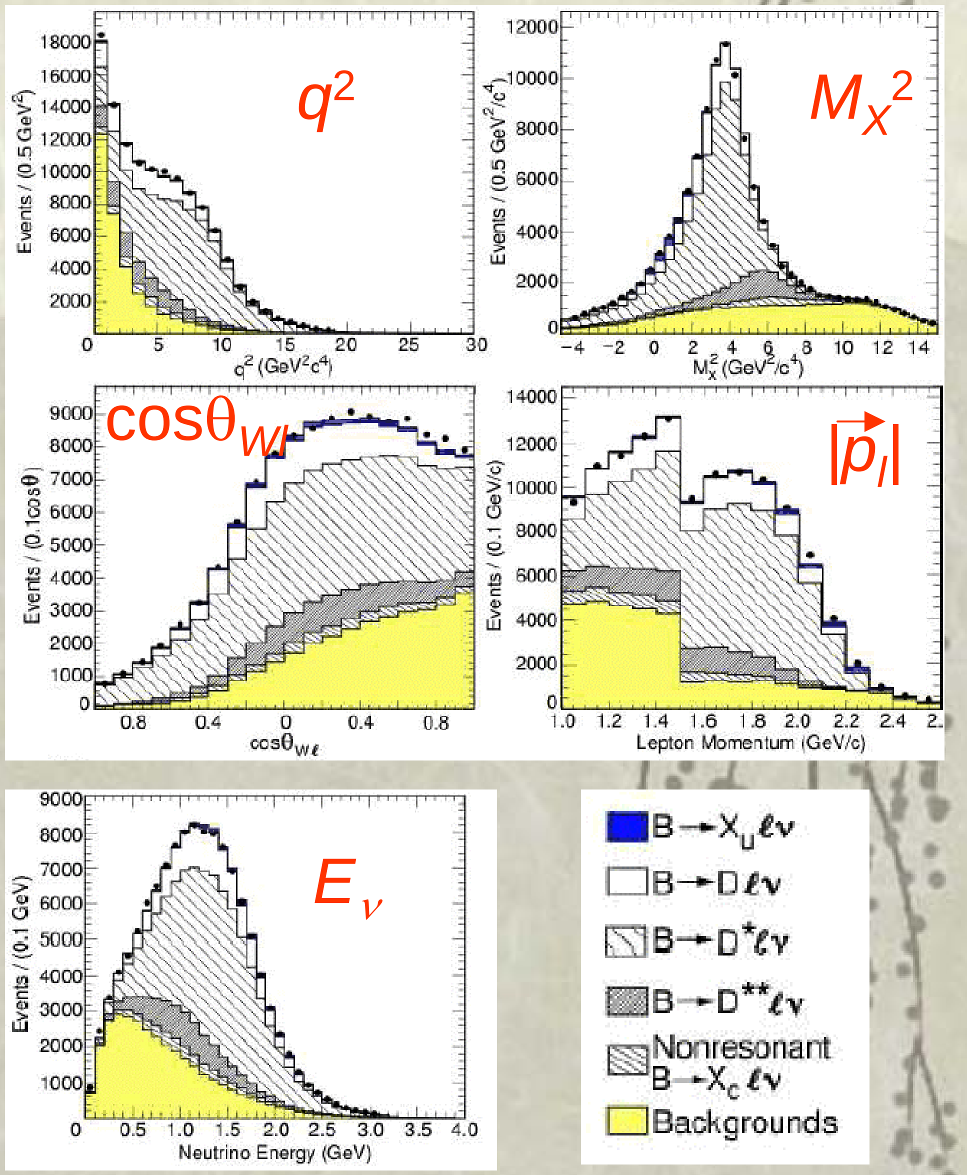
Fit Components



Note: histograms normalized to same area

Hadronic Mass and q^2 *in* $B \to X_c l\nu$

- Fit projections
  - Fit provides reasonable description of the data
- Branching fractions of individual modes are very model-dependent
- Inclusive differential decay rate much less model-dependent



Hadronic Mass and q^2 Moments

Moment	$E_\ell > 1.0$ GeV	$E_\ell > 1.5$ GeV
$\langle M_X^2 - \overline{M}_D^2 \rangle$ (GeV$^2/c^4$)	$0.456 \pm 0.014 \pm 0.045 \pm 0.109$	$0.293 \pm 0.012 \pm 0.033 \pm 0.048$
$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$ (GeV$^4/c^8$)	$1.266 \pm 0.065 \pm 0.222 \pm 0.631$	$0.629 \pm 0.031 \pm 0.088 \pm 0.113$
$\langle q^2 \rangle$ (GeV^2)	$4.892 \pm 0.015 \pm 0.094 \pm 0.100$	$5.287 \pm 0.020 \pm 0.073 \pm 0.095$
$\langle (q^2 - \langle q^2 \rangle)^2 \rangle$ (GeV^4)	$2.852 \pm 0.002 \pm 0.003 \pm 0.047$	$2.879 \pm 0.006 \pm 0.007 \pm 0.049$

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- Results are consistent with previous CLEO measurements PRL 87 251808 (2001)
- Uncertainties and results comparable to BaBar measurements (statistics vs systematics)
- q^2 moments expected to be somewhat complementary to M_X moments
  - Only measured by CLEO

Lepton Energy Moments in $B \to X_c l\nu$

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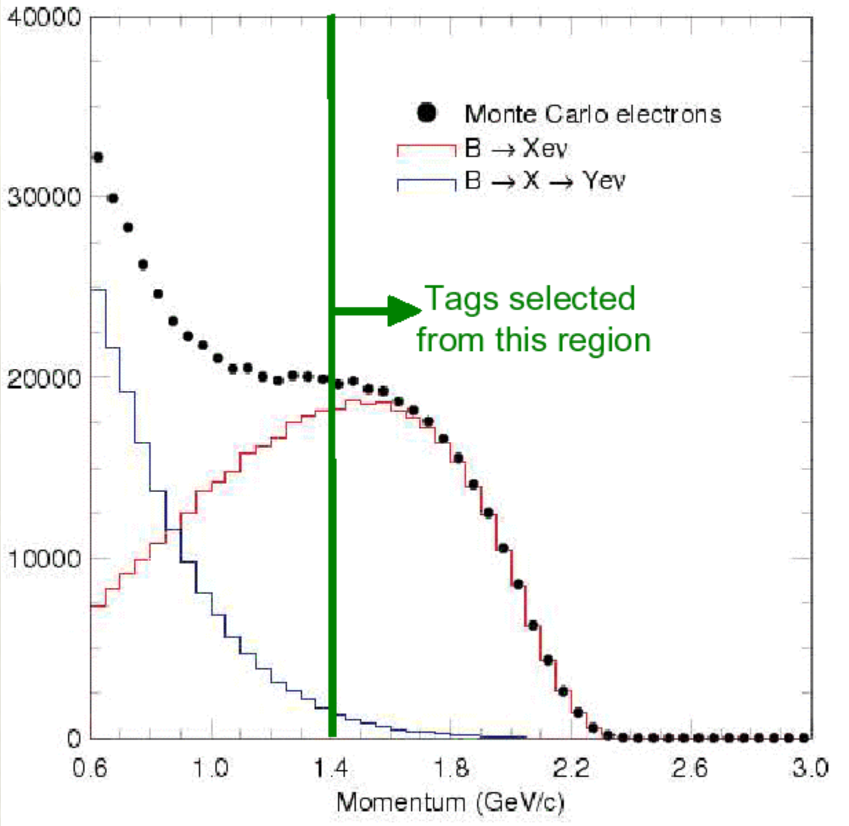

Monte Carlo simulation of electron daughters from B decay

- Di-lepton event sample
- Use one lepton as the "tag":
  - $p_l > 1.4$ GeV/c, e or μ
  - ~97% of sample is primary $B \to Xl\nu$
  - Lepton charge tags flavor of parent B meson
- Look for signal electron in "tagged" events
  - $p_e > 0.6$ GeV/c
  - Correct for backgrounds and efficiencies
  - Use charge and kinematic correlations to separate the spectra from primary and secondary leptons
    - Primary leptons are the signal

Lepton Energy Moments in B → $X_c l\nu$

	Unmixed B^0	Mixed B^0
Primary Events	$\ell^+ \leftarrow \bar{b} \quad b \rightarrow e^-$	$\ell^+ \leftarrow \bar{b} \quad \bar{b} \rightarrow e^+$
Opposite B Secondaries	$\ell^+ \leftarrow \bar{b} \quad b \rightarrow c \rightarrow e^+$	$\ell^+ \leftarrow \bar{b} \quad \bar{b} \rightarrow \bar{c} \rightarrow e^-$
Same B Secondaries	$\bar{b} \rightarrow \bar{c}\ell^+ \rightarrow e^-$	

Lepton Energy Moments in $B \rightarrow X_c l \nu$

	Unmixed B^0	Mixed B^0
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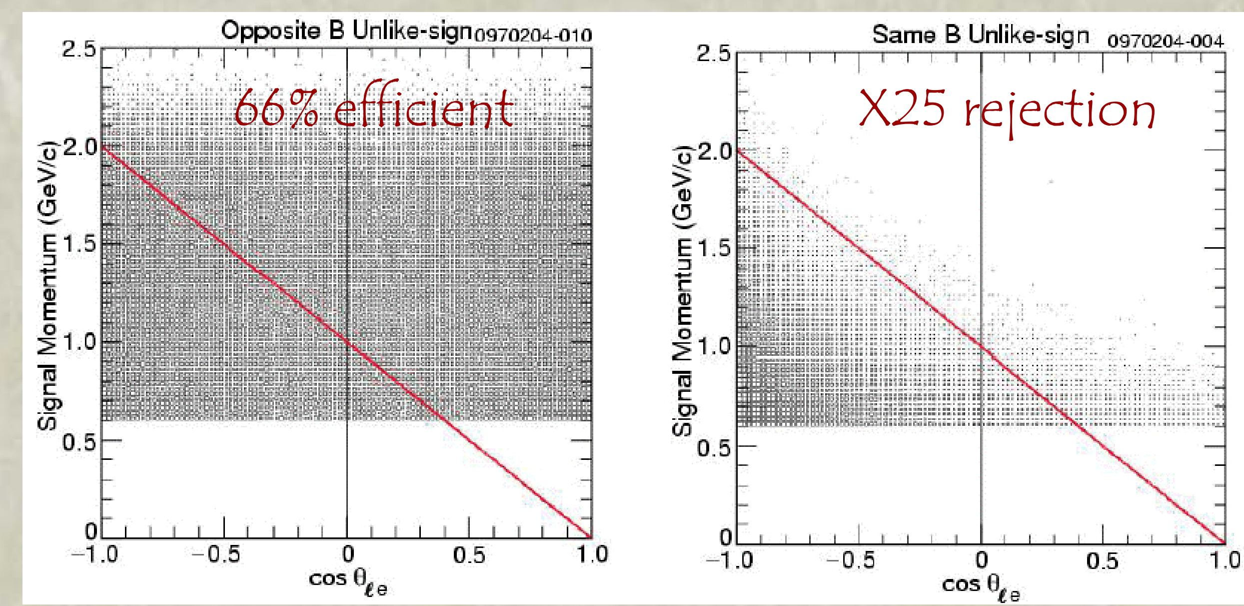
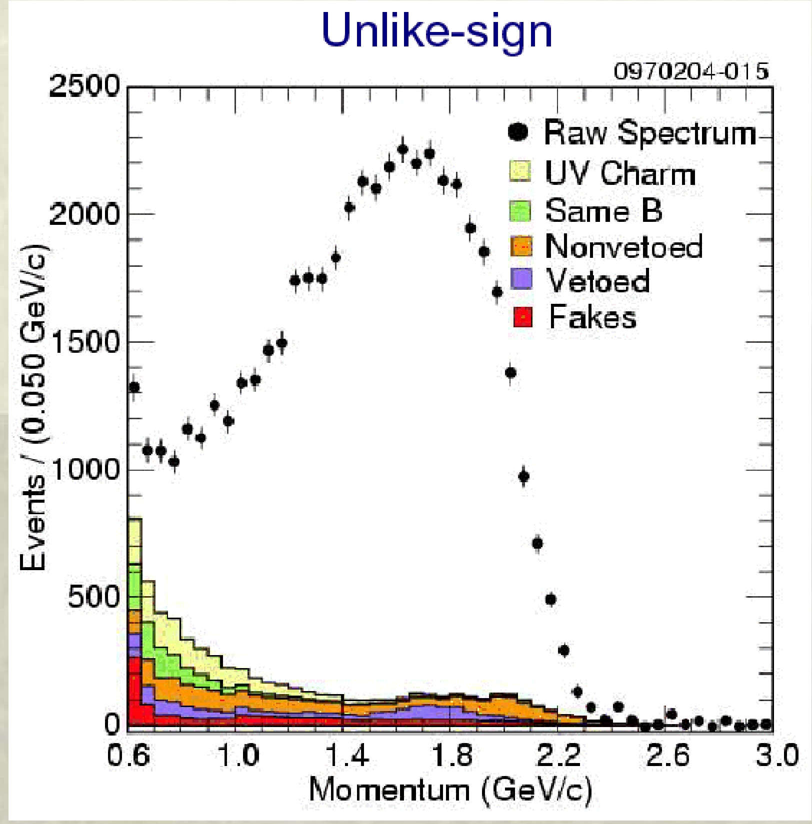
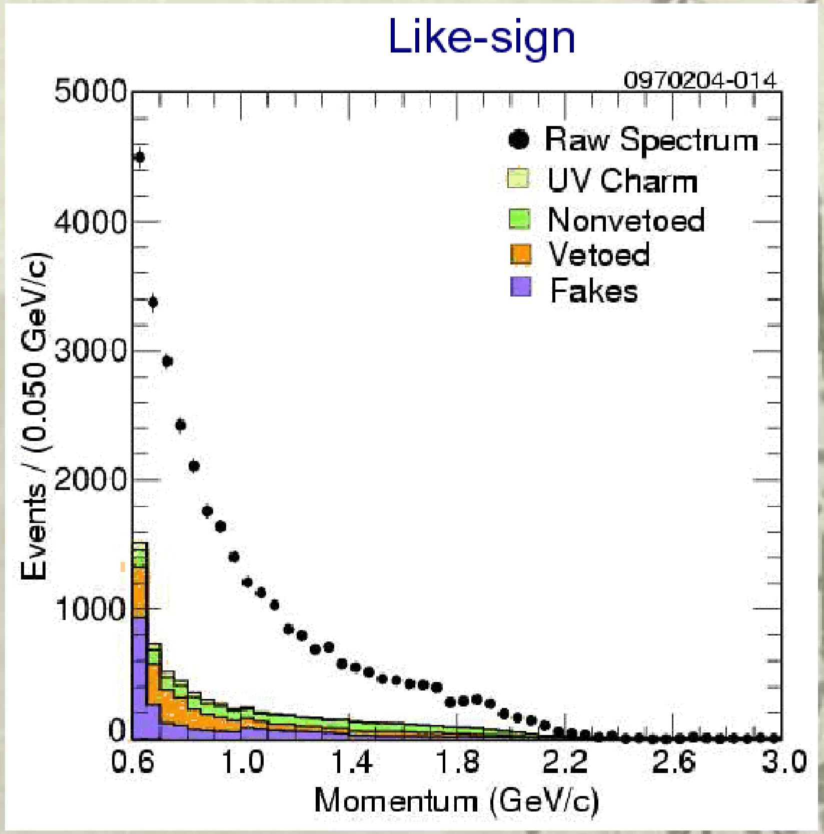
~~Same B Secondaries~~	$\bar{b} \rightarrow \bar{c}\ell^+ \rightarrow e^-$	

Easily vetoed with kinematic cut



Lepton Energy Moments in B →$X_c l\nu$



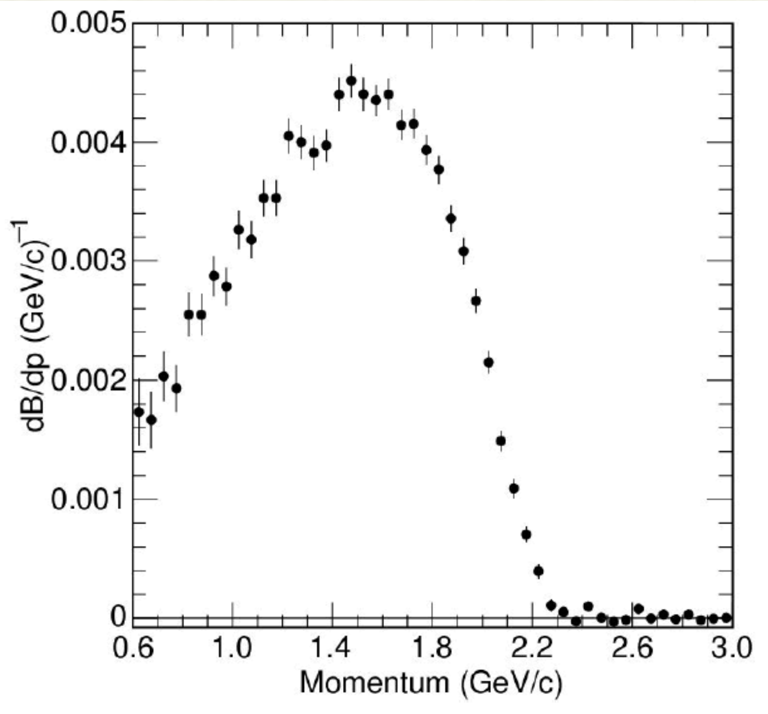


- Subtract backgrounds
- Correct for efficiencies
- Algebraically solve for primary spectrum

$$\frac{dN\left(\ell^{\pm}e^{\mp}\right)}{dp}=\left[\frac{dB(b)}{dp}(1-\chi)+\frac{dB(c)^{\text{opp b}}}{dp}\chi+\frac{dB(c)^{\text{same b}}}{dp}\right]$$

$$\frac{dN\left(\ell^{\pm}e^{\pm}\right)}{dp}=\left[\frac{dB(b)}{dp}\chi+\frac{dB(c)^{\text{opp b}}}{dp}(1-\chi)\right]$$

Lepton Energy Moments in $B \rightarrow X_c l\nu$



E_{min}	$\langle E_\ell \rangle$ (GeV)	$\langle E_\ell^2 \rangle$ (GeV^2)	$\langle E_\ell^2 - \langle E_\ell \rangle^2 \rangle$ (GeV^2)
0.6	$1.4261 \pm 0.0043 \pm 0.0105$	$2.1856 \pm 0.0112 \pm 0.0271$	$0.1526 \pm 0.0021 \pm 0.0031$
0.7	$1.4509 \pm 0.0035 \pm 0.0079$	$2.2419 \pm 0.0097 \pm 0.0216$	$0.1374 \pm 0.0015 \pm 0.0018$
0.8	$1.4779 \pm 0.0031 \pm 0.0061$	$2.3066 \pm 0.0090 \pm 0.0177$	$0.1228 \pm 0.0013 \pm 0.0012$
0.9	$1.5119 \pm 0.0028 \pm 0.0047$	$2.3923 \pm 0.0085 \pm 0.0144$	$0.1068 \pm 0.0011 \pm 0.0010$
1.0	$1.5483 \pm 0.0026 \pm 0.0039$	$2.4890 \pm 0.0082 \pm 0.0127$	$0.0918 \pm 0.0010 \pm 0.0011$
1.1	$1.5884 \pm 0.0024 \pm 0.0033$	$2.6003 \pm 0.0080 \pm 0.0111$	$0.0775 \pm 0.0009 \pm 0.0012$
1.2	$1.6315 \pm 0.0023 \pm 0.0031$	$2.7259 \pm 0.0078 \pm 0.0109$	$0.0642 \pm 0.0009 \pm 0.0012$
1.3	$1.6794 \pm 0.0022 \pm 0.0029$	$2.8720 \pm 0.0078 \pm 0.0106$	$0.0516 \pm 0.0008 \pm 0.0011$
1.4	$1.7256 \pm 0.0021 \pm 0.0030$	$3.0192 \pm 0.0079 \pm 0.0112$	$0.0413 \pm 0.0008 \pm 0.0010$
1.5	$1.7792 \pm 0.0021 \pm 0.0027$	$3.1972 \pm 0.0081 \pm 0.0107$	$0.0316 \pm 0.0008 \pm 0.0010$

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- Correct for
  - EW radiation (FSR and detector bremsstrahlung)
  - B boost
- Results consistent with previous CLEO measurements
- Systematics-limited--- Uncertainty on moments comparable to BaBar
- Integrate measured spectrum

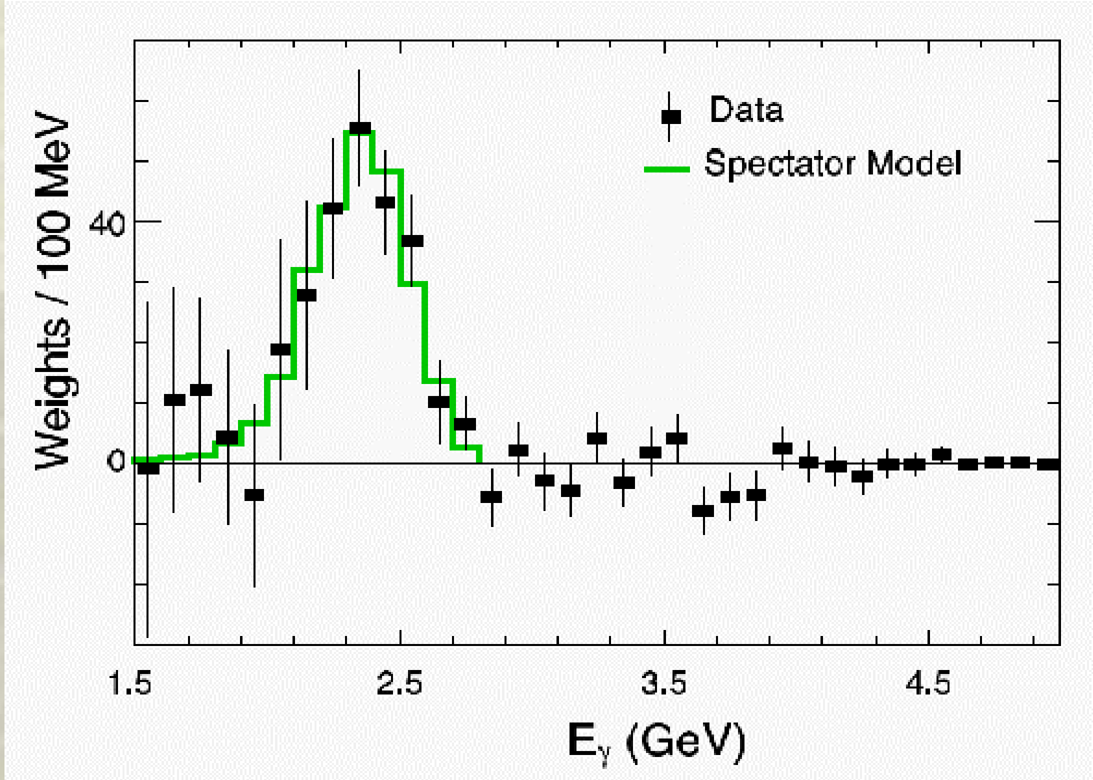
$$BR(B \rightarrow Xe\nu) = (10.91 \pm 0.09 \pm 0.24)\%$$

Photon Energy Moments in $B \rightarrow X_s \gamma$

- $b \rightarrow s\gamma$ measurement is key to extracting HQET parameters
  - Sensitive to m_b
    - 2-body decay:

$$\langle E_\gamma \rangle \approx \frac{m_b}{2}$$

  - Independent of m_c
  - New Physics in loop would not change spectrum



$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011 \text{ GeV}$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020 \text{ GeV}^2$$

PRL 87, 251807 (2001)
hep-ex/0108032

Combined Fit to Determine $|V_{cb}|$

Work in progress: Alex Smith (UMN) @ Beach 2004

Measurements included in fit:

- 1st and 2nd photon energy moments : $E_\gamma > 2.0$ GeV
- 1st and 2nd lepton energy moments : $E_e > 0.7, 1.2, 1.5$ GeV
- 1st and 2nd hadronic mass moments : $E_e > 1.0, 1.5$ GeV
- 1st q^2 moment : $E_e > 1.0, 1.5$ GeV

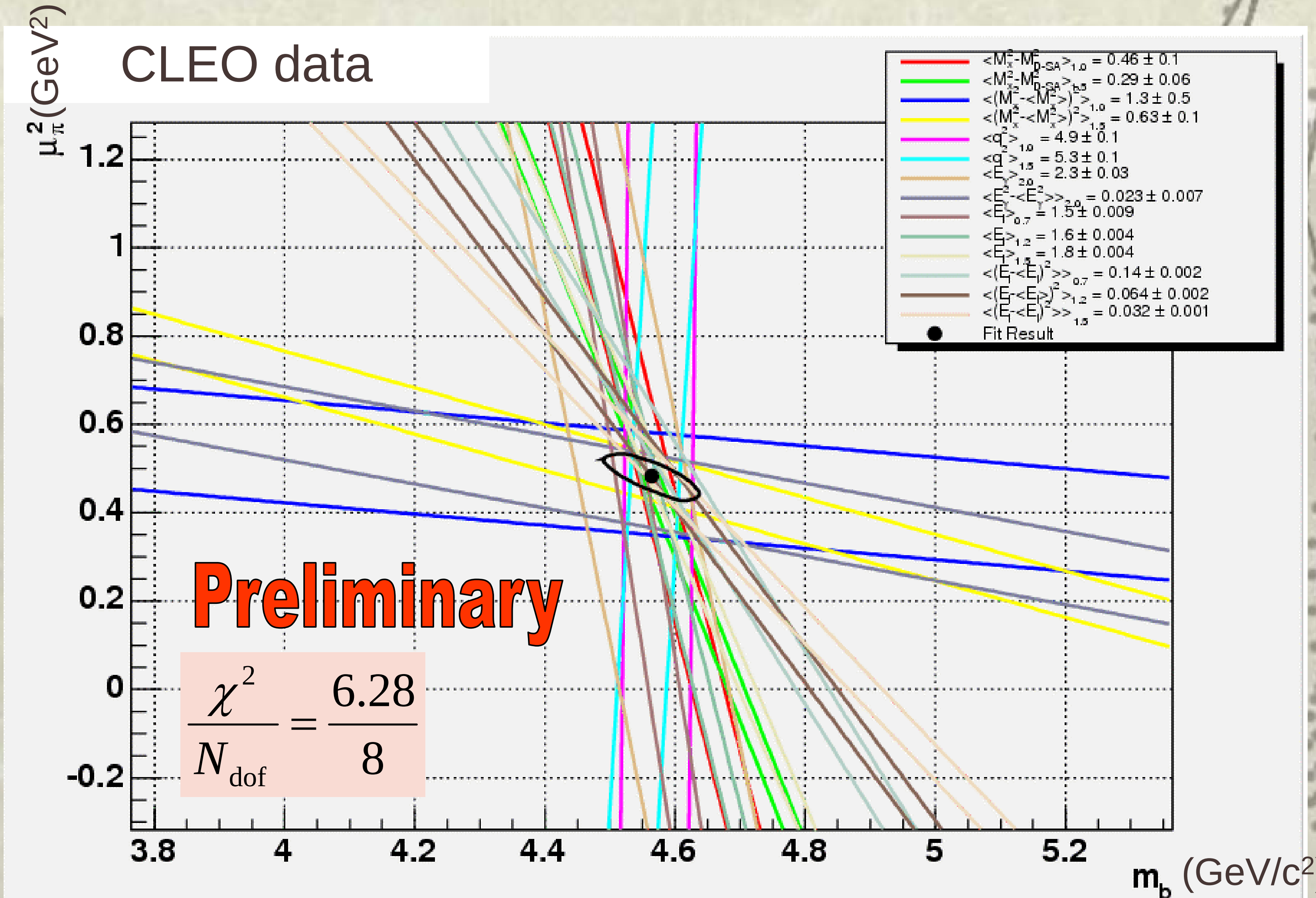
❖ Chi-squared fit including full correlation matrix of measurements

❖ Uses $\mathcal{O}(1/m^3)$ formulation and code from Gambino and Uraltsev [EPJ C 34, 181 (2004) hep-ph/0401063]

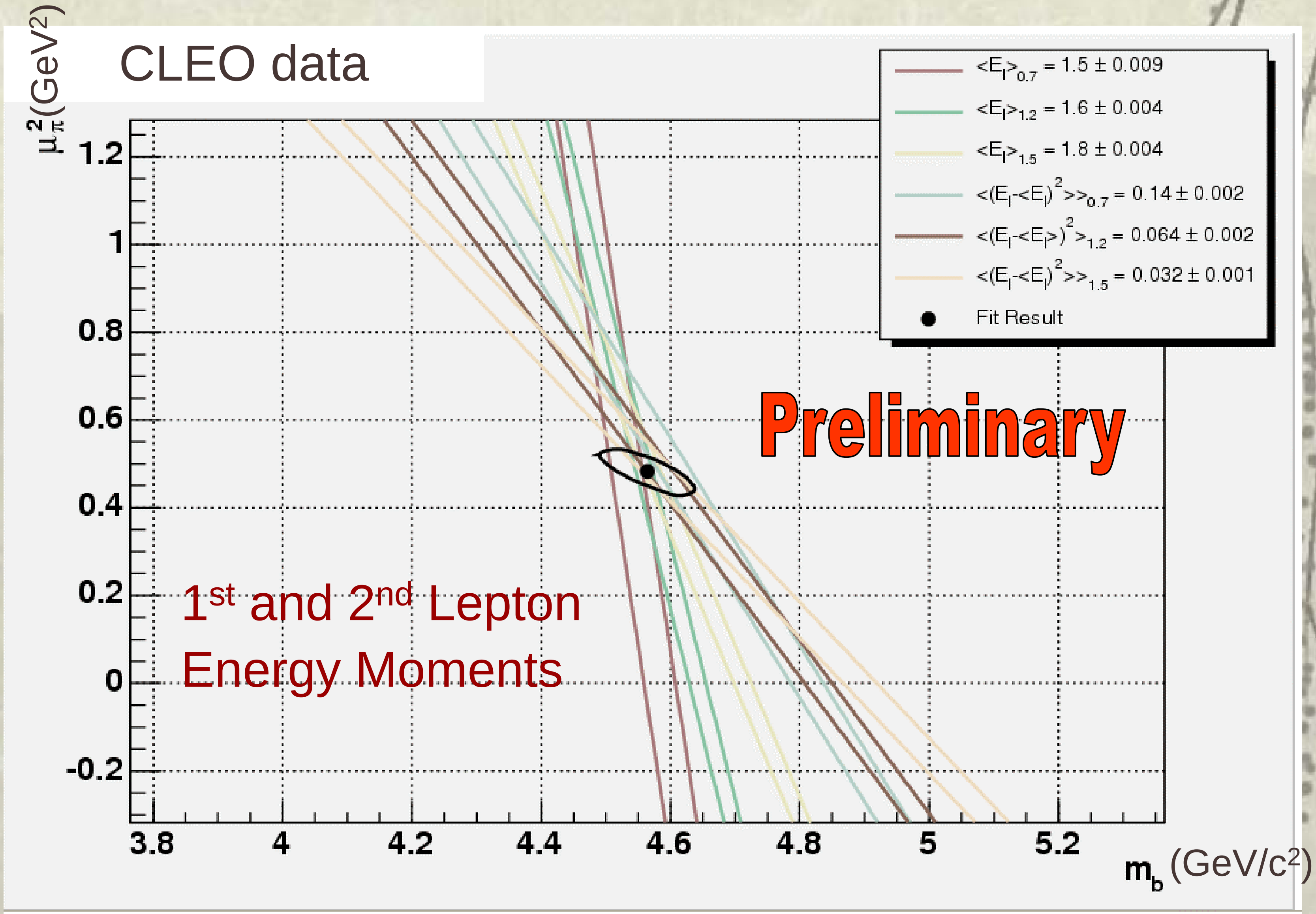
- Includes perturbative corrections to account for lepton/photon energy cuts

❖ Will also use approach of Bauer, Ligeti, *et al* before finalizing results [PRD 67 054012 (2003) hep-ph/0210027]

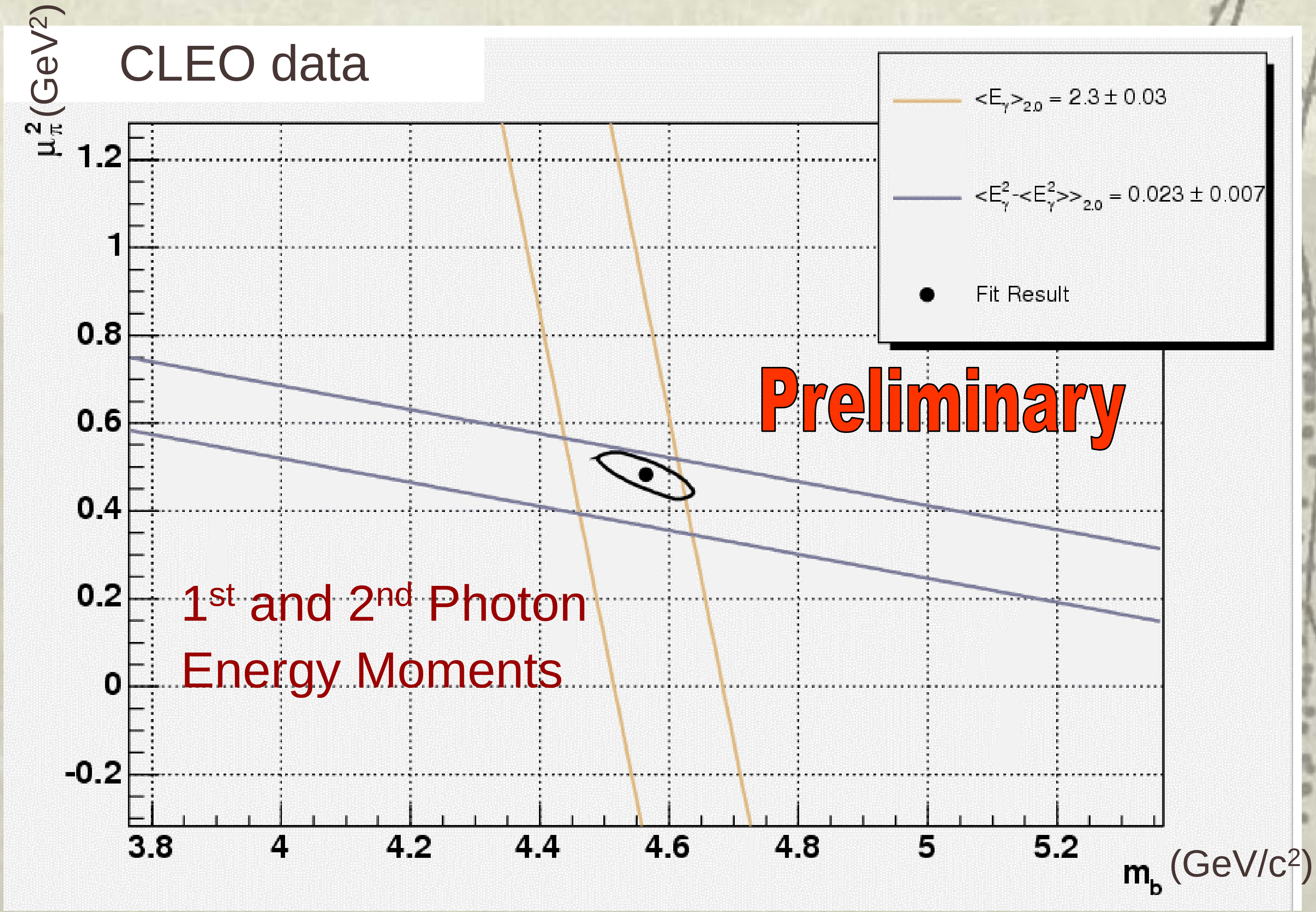
Combined Fit to Determine $|V_{cb}|$



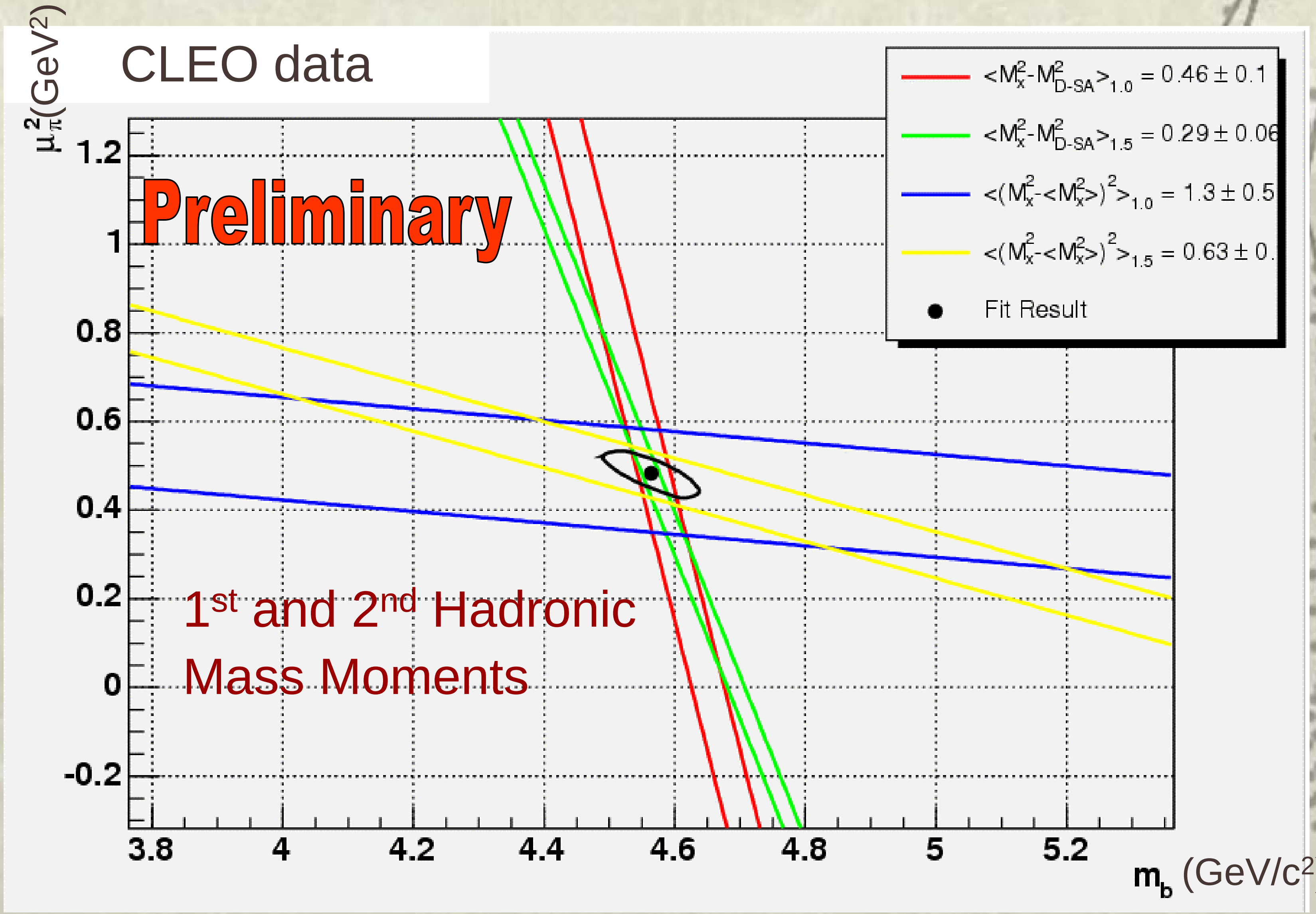
Constraints from Lepton Energy



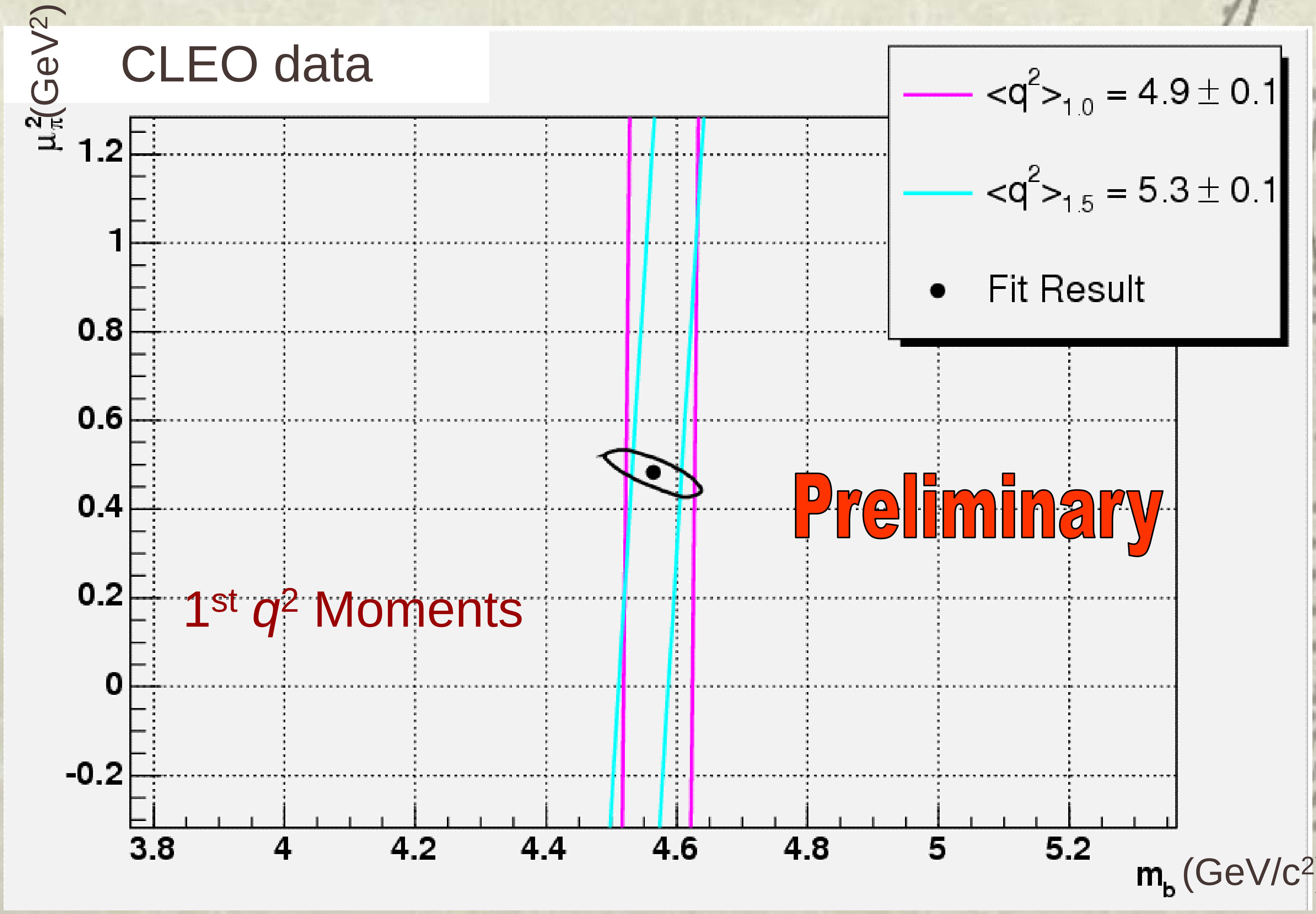
Constraints from Photon Energy



Constraints from Hadronic Mass



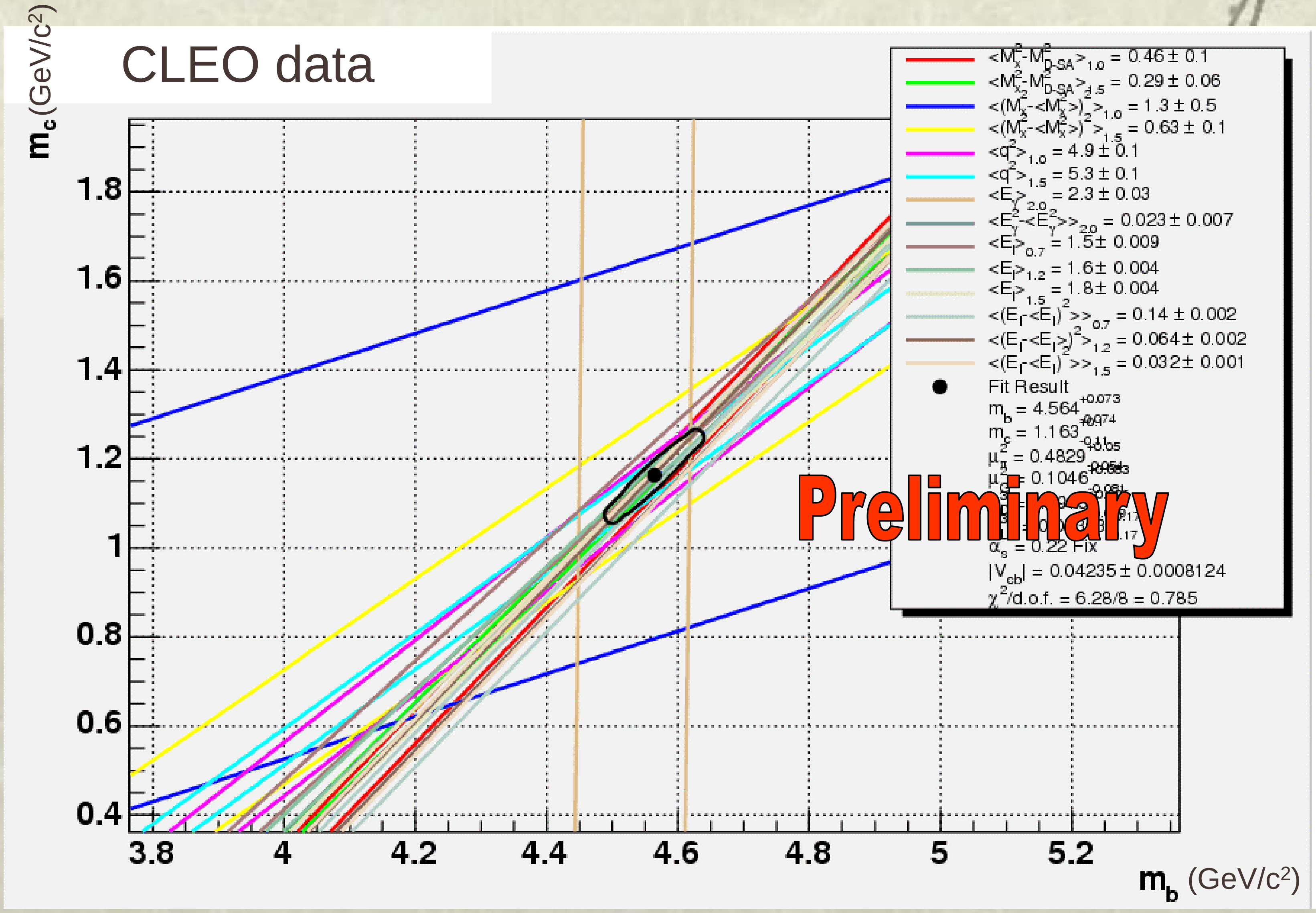
Constraint from q^2



Combined Fit to Determine $|V_{cb}|$

- Only CLEO has measured photon energy, q^2, hadronic mass, and lepton energy in a single experiment
  - A solution consistent with all measurements is found
  - Without $B \rightarrow X_s\gamma$, m_b and m_c almost completely correlated in fit
  - Most of the sensitivity to m_b comes from $B \rightarrow X_s\gamma$ measurement
    - First moment ⇔ mean photon energy ⇔ $m_b/2$ (approx.)
    - Other measurements primarily constrain $m_b - Cm_c$, $C \sim 0.6$ (next slide illustrates)
  - q^2 moment gives some complementary information
    - Nearly independent of μ_π^2

Combined Fit to Determine $|V_{cb}|$



Combined Fit to Determine $|V_{cb}|$

$$\left|V_{cb}\right| = \left(42.4 \pm 0.8\right) \times 10^{-3}$$

N.B. Only expt. uncertainty

Preliminary

- Measurement of $|V_{cb}|$ and HQET parameters, including $m_b(\mu)$, $m_c(\mu)$, $\mu_\pi^2(\mu)$ at μ=1 GeV
- Expect to reduce experimental errors significantly with additional measurements
- Theory errors under study and not shown or included in fit
  - Expected to be >= experimental errors

$$m_b = 4.564^{+0.073}_{-0.074}\ \text{GeV}/c^2$$

$$m_c = 1.16^{+0.10}_{-0.11}\ \text{GeV}/c^2$$

$$\mu_\pi^2 = 0.483^{+0.050}_{-0.054}\ \text{GeV}^2$$

$$\mu_G^2 = 0.10^{+0.083}_{-0.081}\ \text{GeV}^2$$

$$\tilde{\rho}_D^3 = 0.091^{+0.026}_{-0.029}\ \text{GeV}^3$$

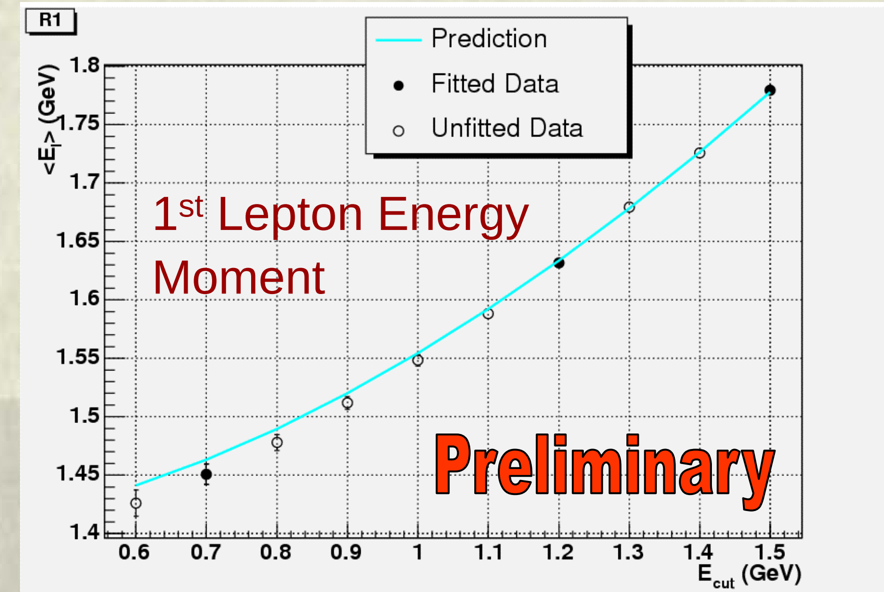
$$\rho_{LS}^3 = 0.05 \pm 0.17\ \text{GeV}^3$$

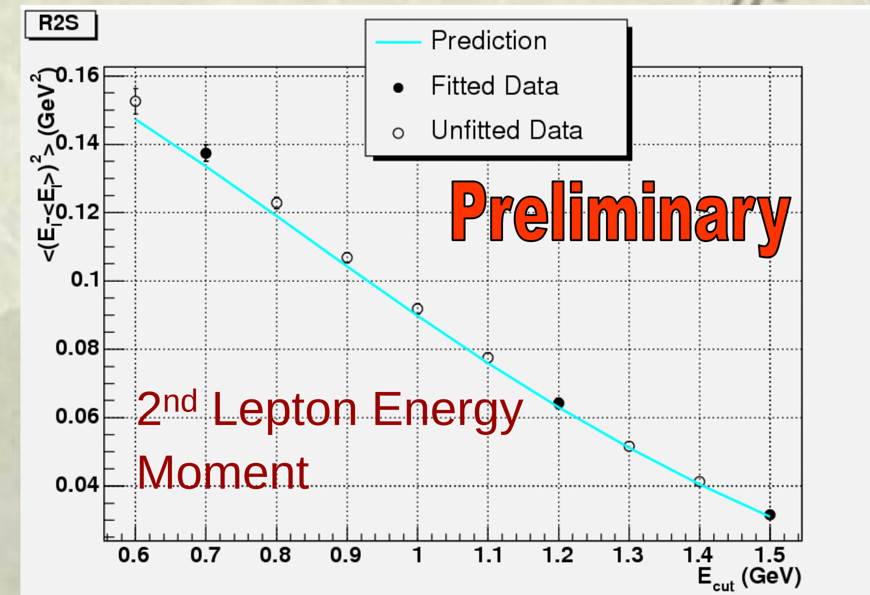
Summary and Outlook

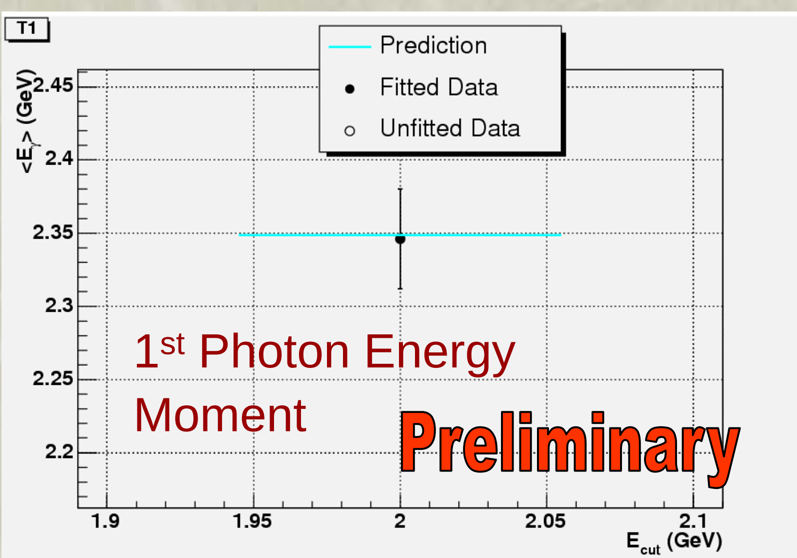
- Potential to significantly improve measurement of $|V_{cb}|$ *or test framework of heavy quark expansion*
  - Experimental errors expected to be less than 2%
  - Theoretical errors expected to be comparable to expt. errors
  - Theoretical models will benefit from experimental constraints on higher order parameters
- Many improvements to analysis in progress:
  - 3rd lepton energy moments
  - Include more 1st and 2nd lepton energy moments
  - 2nd q^2 moments –Complementary sensitivity to parameters
  - Improved $B \rightarrow X_s \gamma$ moments: Critical constraint on m_b
  - Include theoretical uncertainties in fit
- CLEO has measured many *different* moments in a single experiment
  - Complementary to and of comparable precision to public BaBar measurements

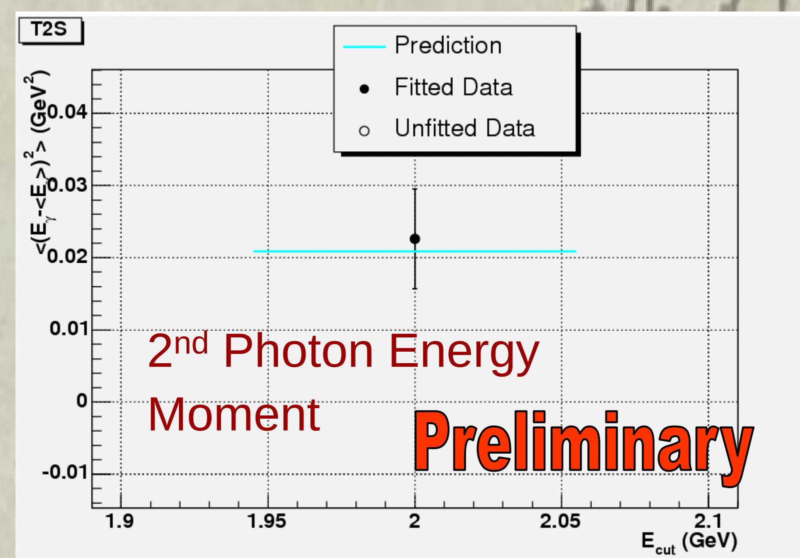
Supplementary Slides

Variation with Energy Cuts

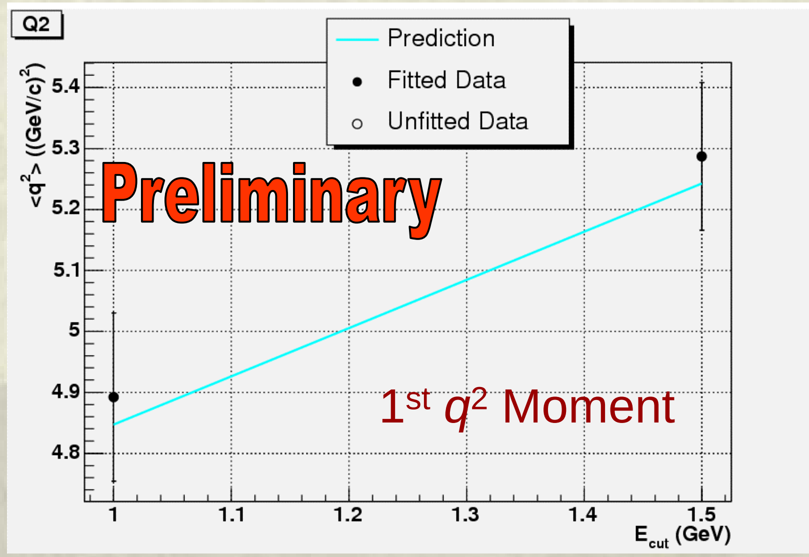


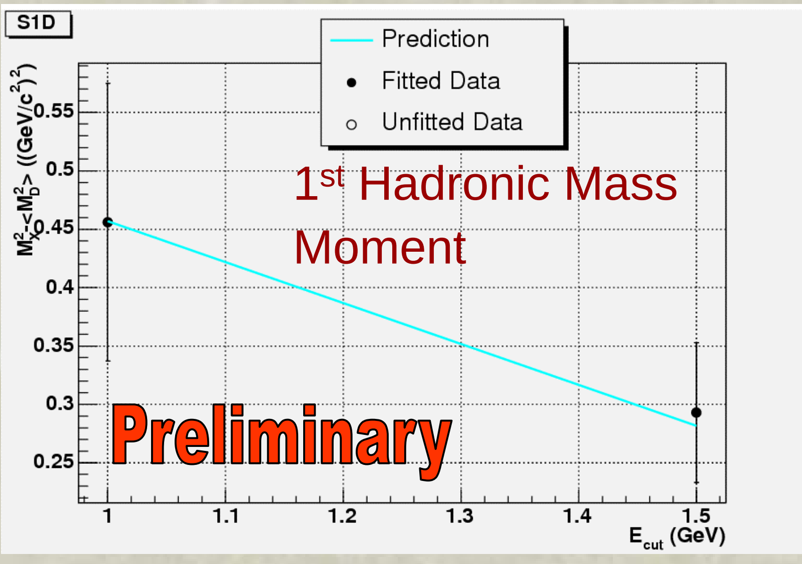


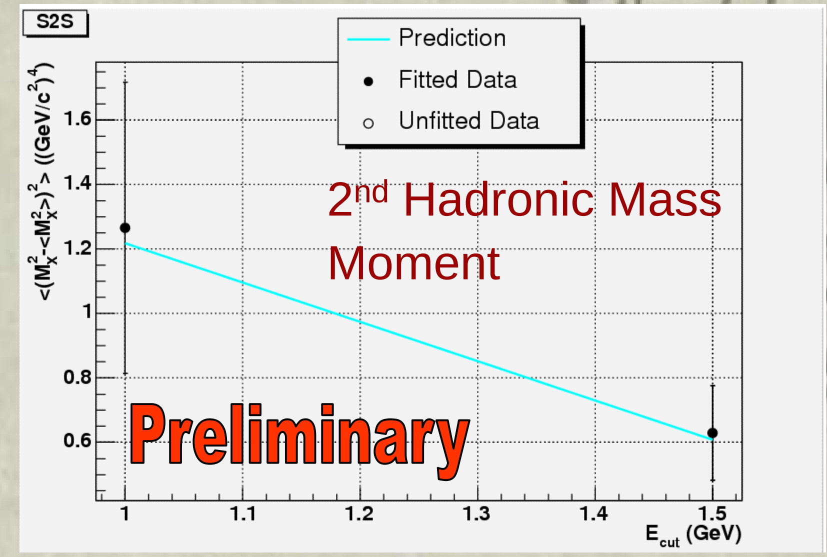




Variation with Energy Cuts







Combined Fit Pulls