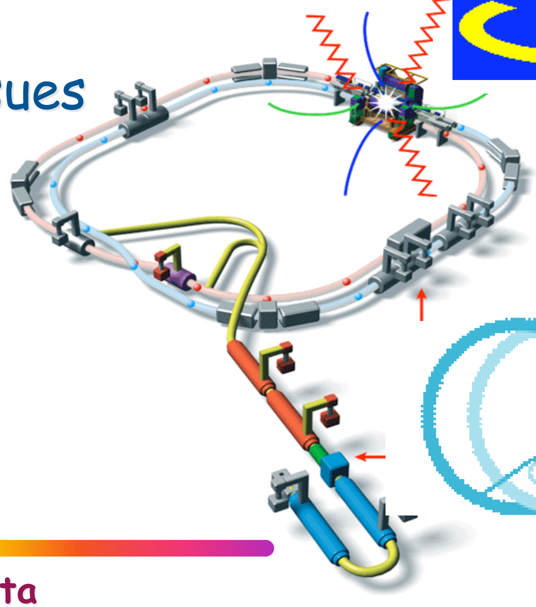
APS-DPF 2006 + JPS 2006

$B \to X_c \ell \nu$ spectrum at Belle and determination of $|V_{cb}|$

- Motivation and theoretical issues
- Belle measurements
- Global fit for Heavy Quark parameters, $|V_{cb}|$



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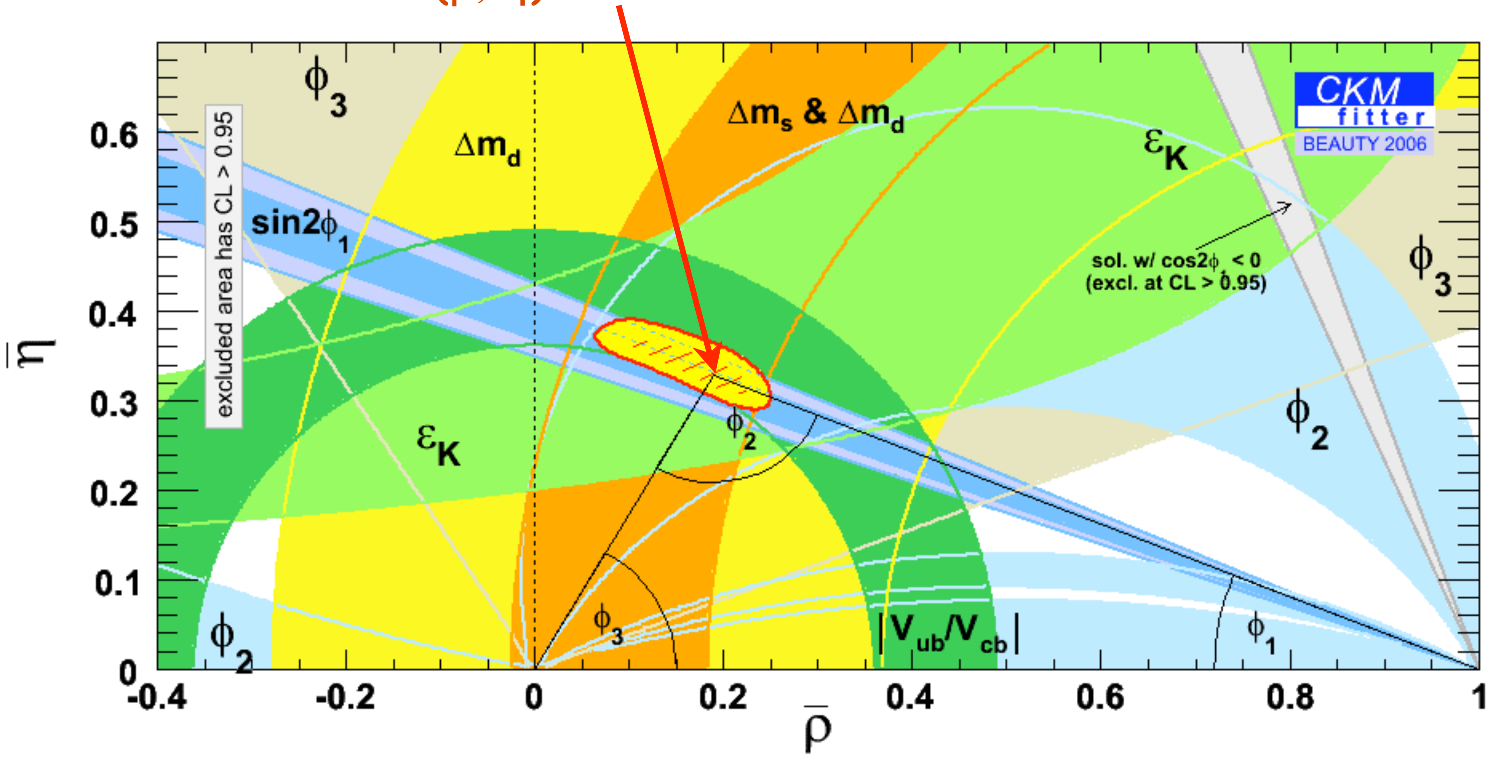
measurement of $|V_{cb}|$ via semileptonic B decay

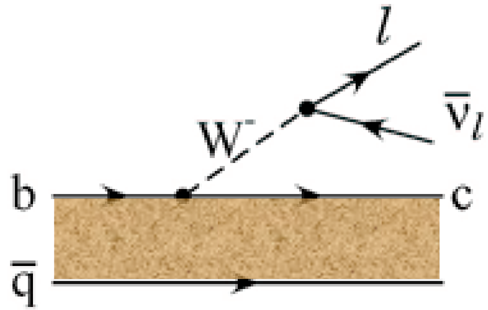
- $|V_{cb}|$ ~ "side" of the Unitarity Triangle; tests Standard Model by alternative route to (ρ, η)



- measurement precision limited by understanding of hadronic components
- inclusive semileptonic B decay:
  - Theoretically attractive: minimal hadronics, small uncertainty
  - Experimentally: high rate -> amenable to detailed dissection

Theory of inclusive semileptonic B decay

- Well understood at tree level
- Treatment in 2 regimes:
  "short distance": perturbative approach
  "long distance" - nonperturbative



- Degrees of freedom: hadronic recoil (X) 4-vector/polarization -> M_X, momentum
- well-separated "small" corrections, described by Heavy Quark Expansion (HQE):

$$\Gamma_{sl}(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 |(1 + A_{ew}) A_{nonpert} A_{pert}|$$

$A_{nonpert}$: in $1/m_b$ to $O(1/m_b^3)$

A_{pert}: in α_s to $O(\alpha_s^2)$

K. Kinoshita
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Nonperturbative parameters of HQE

- $A_{nonpert}$ expressed in terms of OPE, to $1/m_b^3$
- Coefficients at each order depend on definition of m_b: several schemes; we use
  - Kinetic running mass

    (P. Gambino, N. Uraltsev, Eur. Phys. J C34, 181 (2004))

    parameters: (7 dof) $m_b,\ m_c,\ \mu_\pi^2,\ \mu_G^2,\ \tilde{\rho}_D^3,\ \rho_{LS}^3, |V_{cb}|$
  - 1S mass

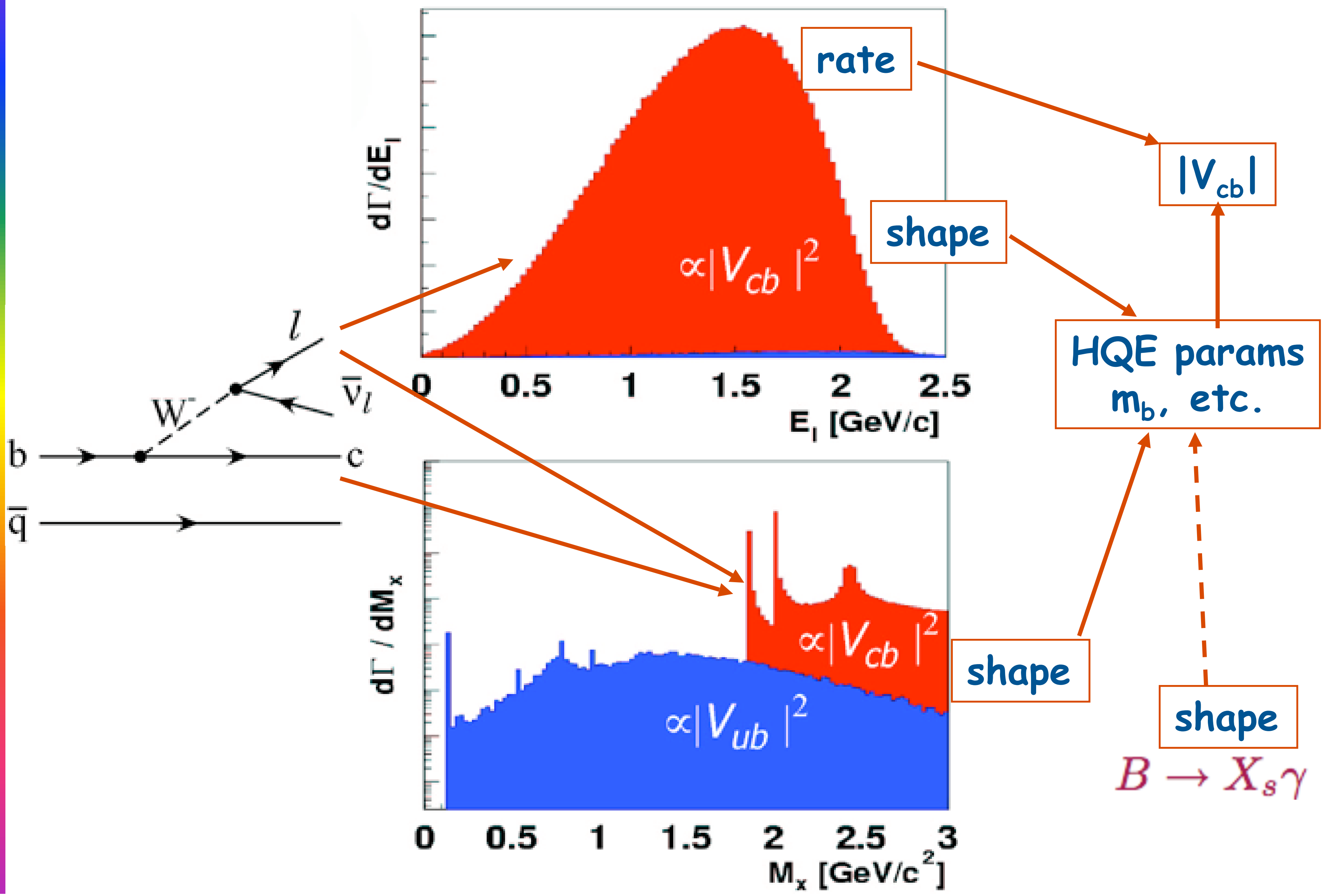
    (C. Bauer, Z. Ligeti, M. Luke,A. Manohar, M. Trott, PRD70, 094017)

    parameters: (7 dof) $\Lambda(m_b),\ \lambda_1,\ \rho_1,\ \mathcal{T}_{1-3},\ |V_{cb}|$

Nonperturbative parameters of HQE

- params at each order in m_b, may be extracted from spectral moments (data):
  - in lepton energy E_l (various cuts $E_l > E_{cut}$) to 4^{th} order
  - in $M_X{}^2$ (various cuts on E_l) to 2^{nd} order
  - (in photon energy from $B \to X_s \gamma$)
- measure moments with many different cuts; depend on params in different ways
- fit: corresponding theoretical calcs, 2 schemes
- global fit --> parameters --> $|V_{cb}|$

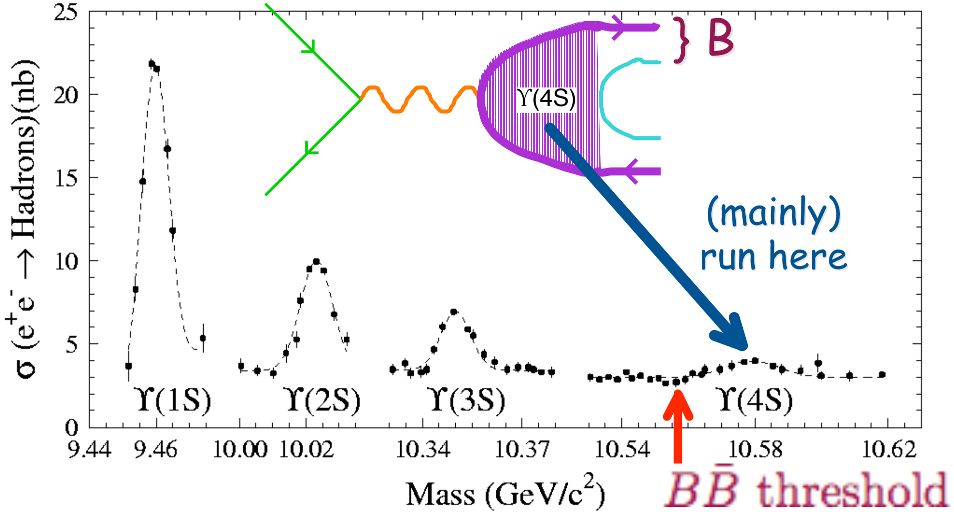
Strategy

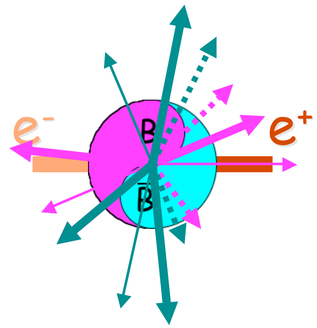


l
$\bar{\nu}_l$
W⁻
b
c
$\bar{q}$
dΓ/dE_l
0 0.5 1 1.5 2 2.5
E_l [GeV/c]
$\propto |V_{cb}|^2$
rate
shape
$|V_{cb}|$
HQE params
m_b, etc.
dΓ / dM_x
0 0.5 1 1.5 2 2.5 3
M_x [GeV/c²]
$\propto |V_{cb}|^2$
$\propto |V_{ub}|^2$
shape
shape
$B \to X_s \gamma$

Event/flavor/momentum tag: full B reconstruction

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$



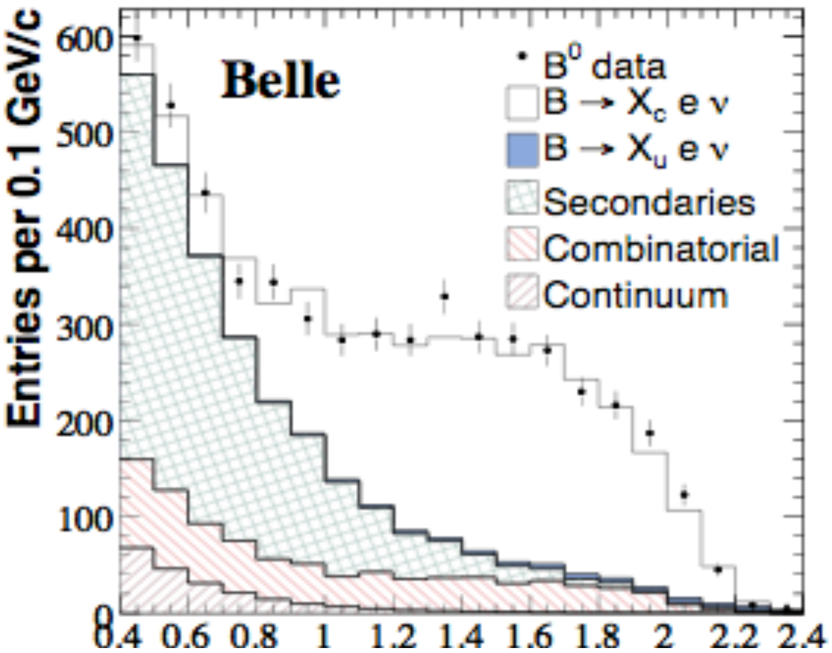


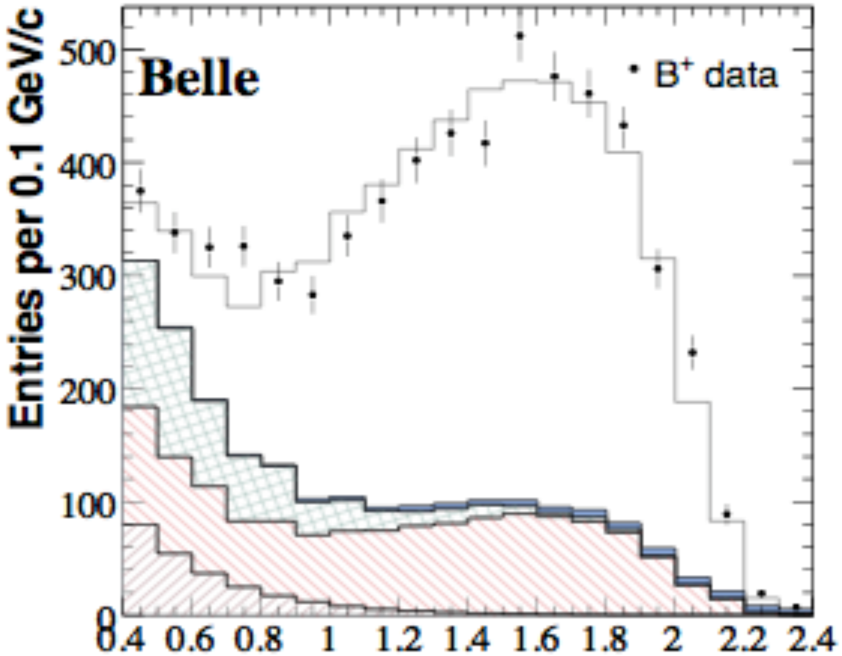
- Fully reconstruct one B ("tag")
  - High purity of correct tags
  - identify flavor of tag -> opp to other B
  - Reconstruct momentum -> know CMS of recoil
  - Low efficiency, but plenty of data at Belle!
- "signal" B = remainder of event
  - E_l in rest frame of signal B
  - E_l moments: electrons, p^{*B}>0.4 GeV/c
  - M_X: electrons+muons, all remaining particles (X), missing 4-momentum consistent with neutrino (m_{miss}^2<3 GeV²/c⁴)

Observed electron energy spectrum

- B^+, B^0 analyzed separately, tag in modes $D^{(*)}\{\pi/\rho/a_1\}$
  - N_{tag} B^+: 63,185±621, B^0: 39,504±392
- recover photons from FSR/bremsstrahlung (E<1 GeV, angle w. e < 0.05)
  $B^\pm$: require e charge consistent with flavor

140 fb^{-1}

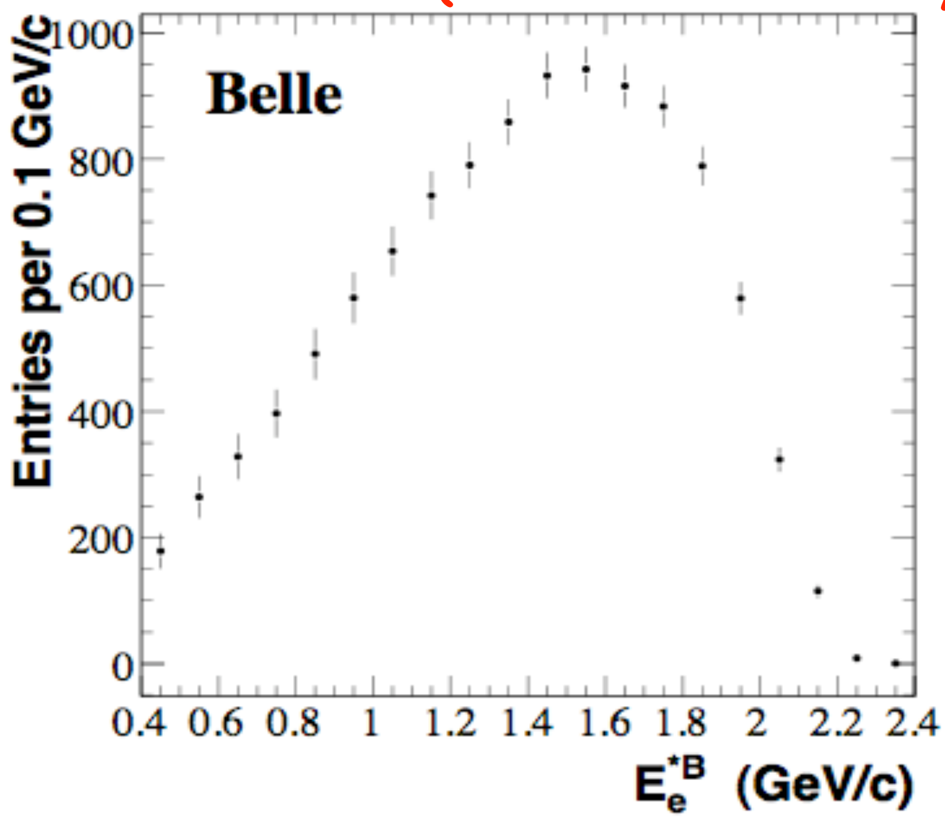




Back to the source

- Derive "root" spectrum, to compare with theory:
  - Subtract backgrounds including b->u
  - Unfold detector resolution/effects
  - Correct for final state radiation (PHOTOS)
- Combine $B^{\pm}$, B^0

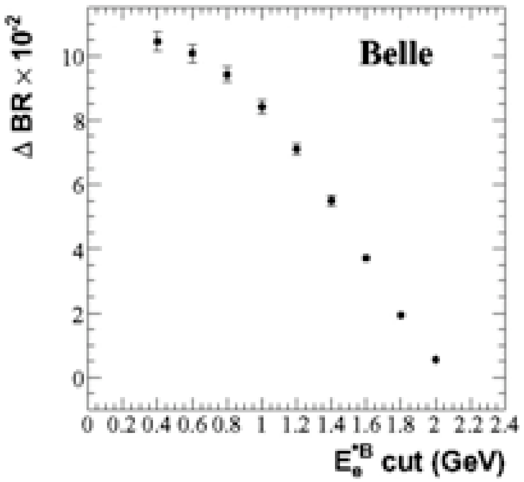
(statistical errors only)



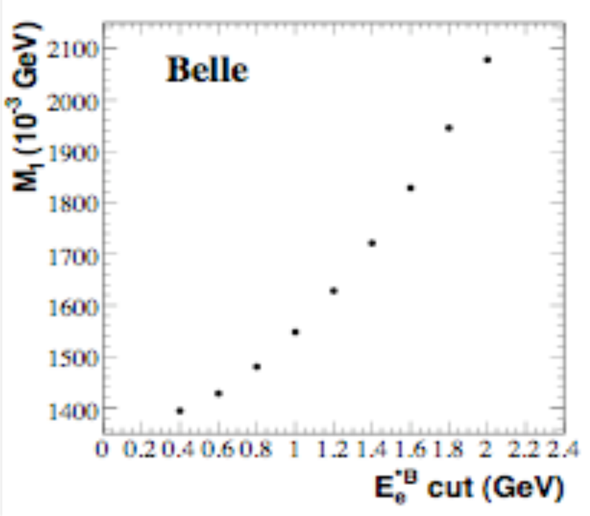
Moments of electron spectrum

- Moments (0-4) for many cuts:
  E_l>0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 GeV

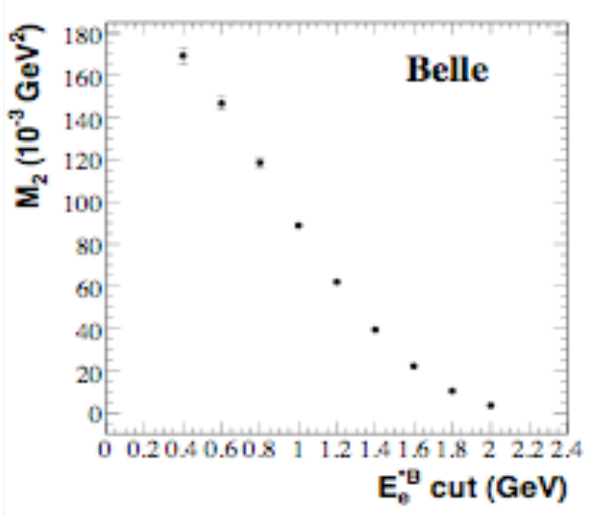
$\Delta\mathcal{B}$



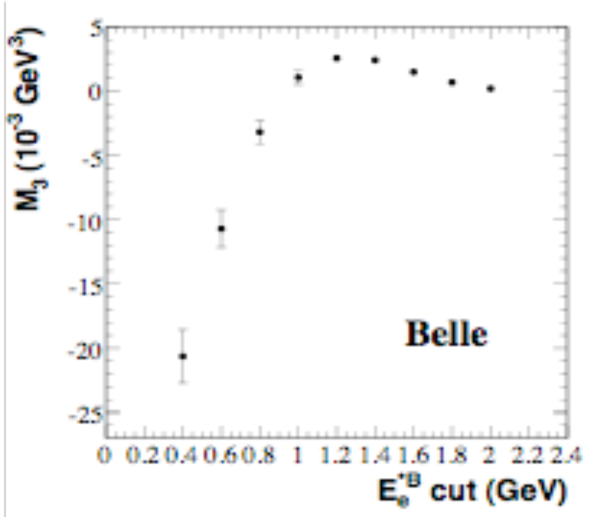
$\langle E_e^{*B} \rangle$



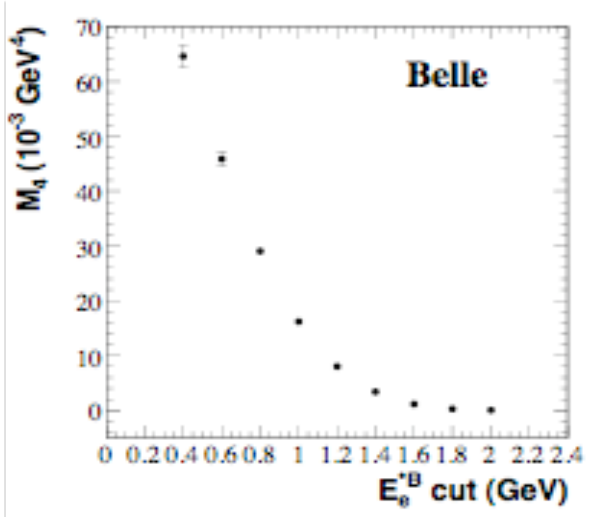
$\langle (E_e^{*B} - \langle E_e^{*B} \rangle)^2 \rangle$



$\langle (E_e^{*B} - \langle E_e^{*B} \rangle)^3 \rangle$

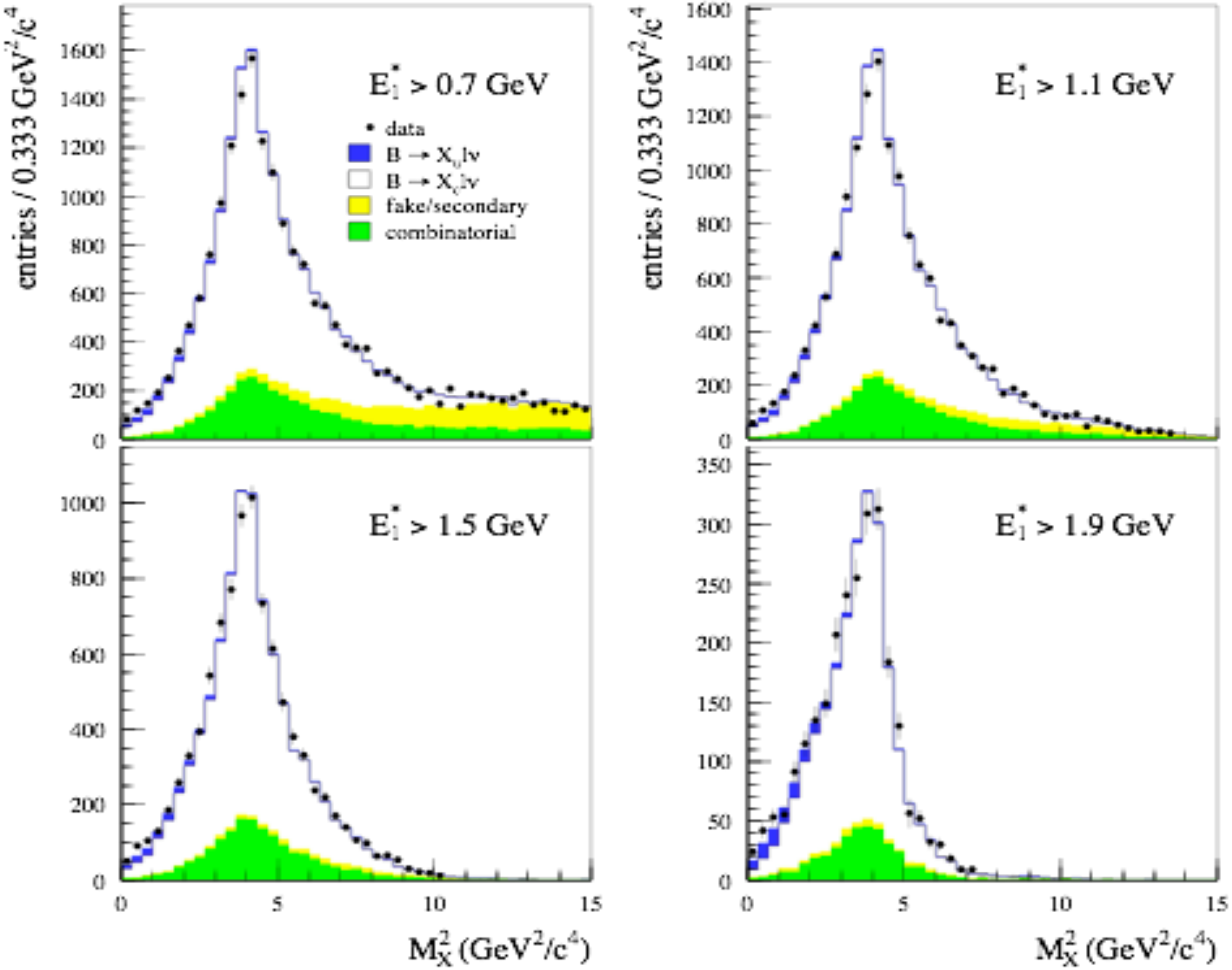


$\langle (E_e^{*B} - \langle E_e^{*B} \rangle)^4 \rangle$



Hadronic mass spectrum M_X

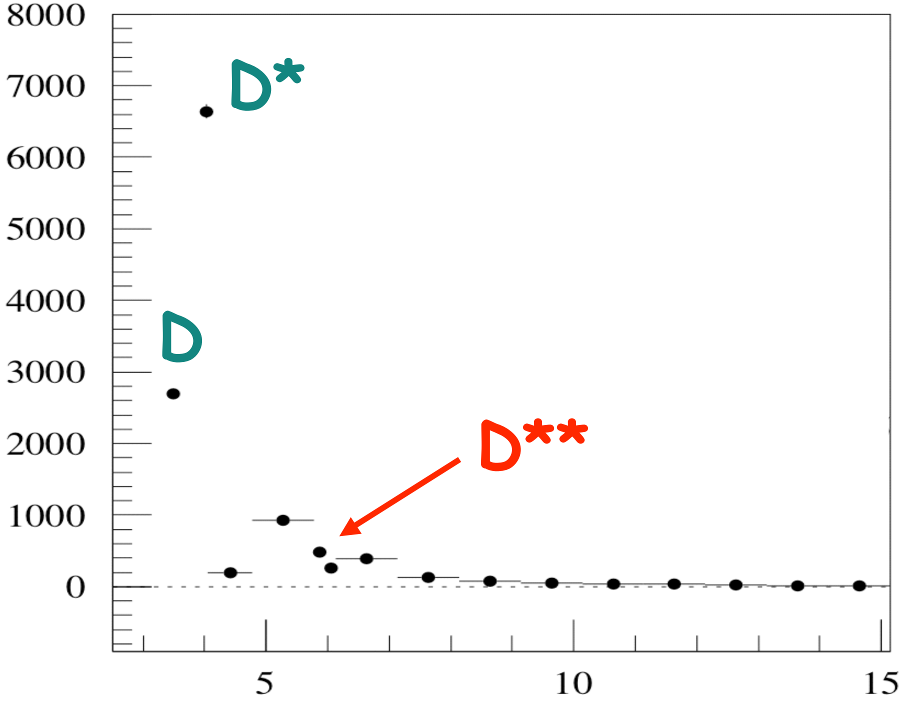
- distribution for several different E_l cuts

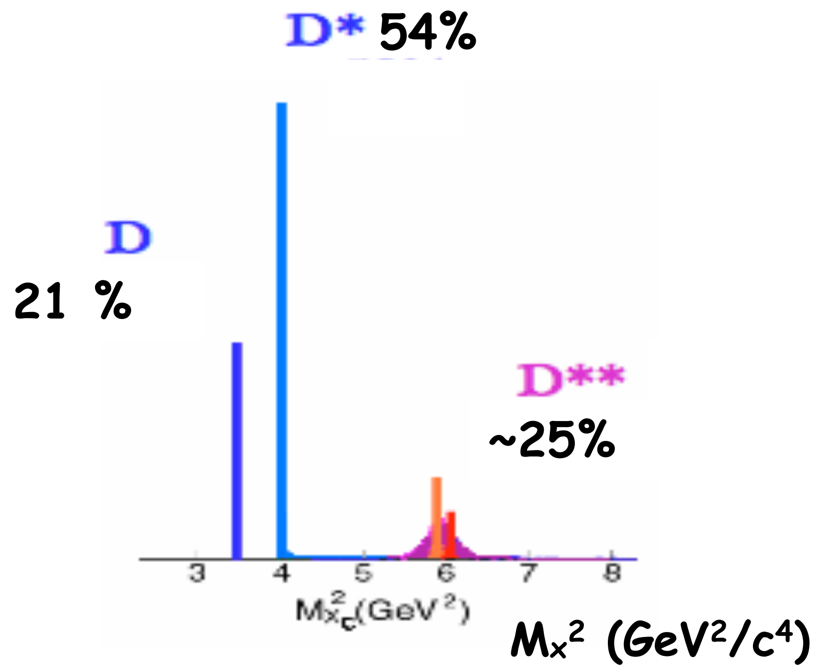


- Unfold mass resolution -> D, D*, D** contributions

Hadronic mass spectrum

- Unfolded spectrum





- Calculated 3 moments for 2 cuts: E_l>0.7, 1.5 GeV

PRELIMINARY

$\langle M_X^2 \rangle$ (GeV$^2/c^4$)	$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$ (GeV$^4/c^8$)	$\langle M_X^4 \rangle$ (GeV$^4/c^8$)
$4.403 \pm 0.036 \pm 0.052$	$1.494 \pm 0.173 \pm 0.327$	$20.88 \pm 0.48 \pm 0.77$
$4.144 \pm 0.028 \pm 0.022$	$0.515 \pm 0.061 \pm 0.064$	$17.69 \pm 0.28 \pm 0.23$

Global fits

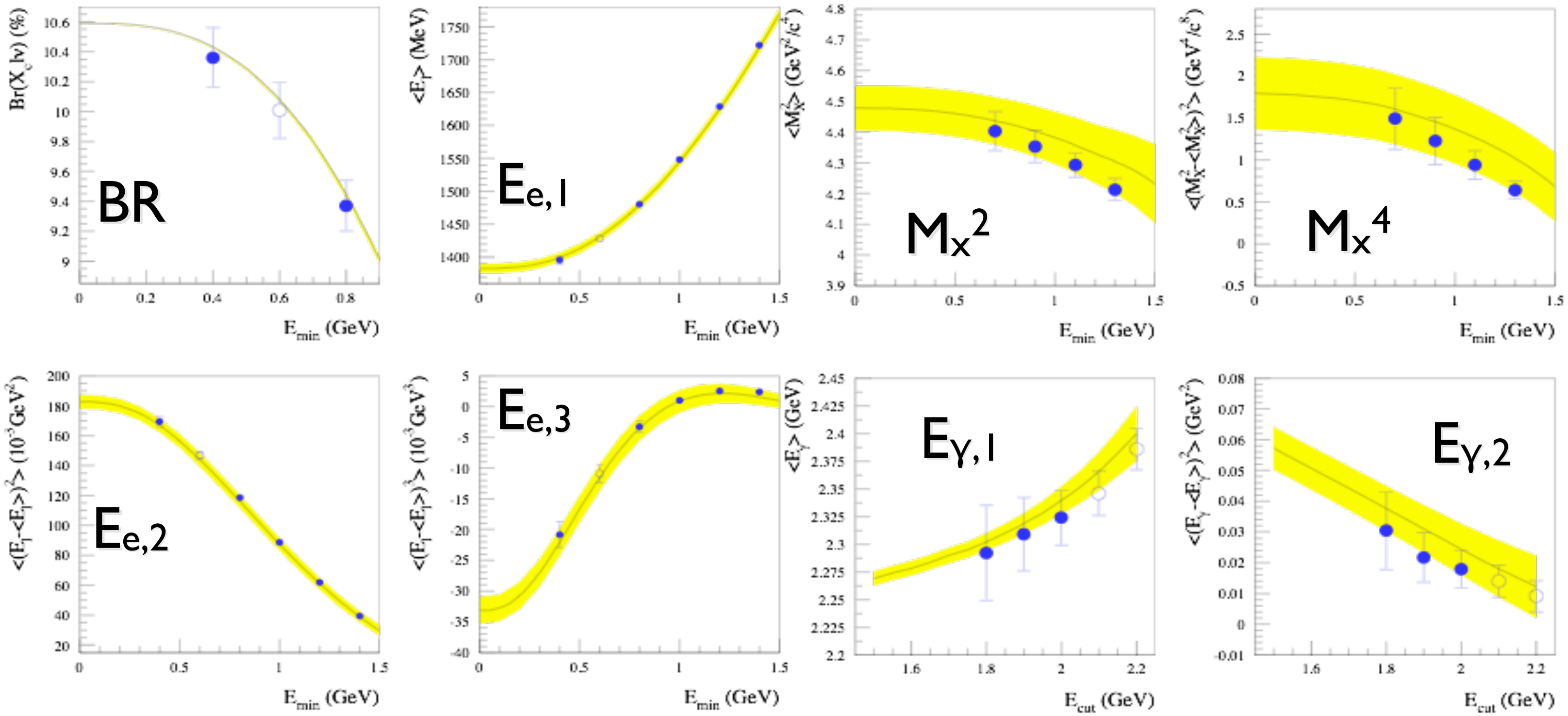
- Use lepton, M_X^2 moments, + moments of photon from $B \to X_s \gamma$
- χ^2 minimization, including correlations (remove points: highly correlated or w no theoretical prediction as yet)

	1S scheme	kinetic scheme
Lepton moments $\langle E_\ell^n \rangle_{E_{\rm min}}$	$n = 0$ $E_{\rm min} = 0.6, 1.0, 1.4$	$n = 0$ $E_{\rm min} = 0.4, 0.8$
	$n = 1$ $E_{\rm min} = 0.6, 0.8, 1.0, 1.2, 1.4$	$n = 1$ $E_{\rm min} = 0.4, 0.8, 1.0, 1.2$ 1.4
	$n = 2$ $E_{\rm min} = 0.6, 1.0, 1.4$	$n = 2$ $E_{\rm min} = 0.4, 0.8, 1.0, 1.2$ 1.4
	$n = 3$ $E_{\rm min} = 0.8, 1.2$	$n = 3$ $E_{\rm min} = 0.4, 0.8, 1.0, 1.2$ 1.4
Hadron moments $\langle M_X^{2n} \rangle_{E_{\rm min}}$	$n = 1$ $E_{\rm min} = 0.7, 1.1, 1.3, 1.5$	$n = 1$ $E_{\rm min} = 0.7, 0.9, 1.1, 1.3$
	$n = 2$ $E_{\rm min} = 0.7, 0.9, 1.3$	$n = 2$ $E_{\rm min} = 0.7, 0.9, 1.1, 1.3$
Photon moments $\langle E_\gamma^n \rangle_{E_{\rm min}}$	$n = 1$ $E_{\rm min} = 1.8, 2.0$	$n = 1$ $E_{\rm min} = 1.8, 1.9, 2.0$
	$n = 2$ $E_{\rm min} = 1.8, 2.0$	$n = 2$ $E_{\rm min} = 1.8, 1.9, 2.0$

Global fit - kinetic scheme

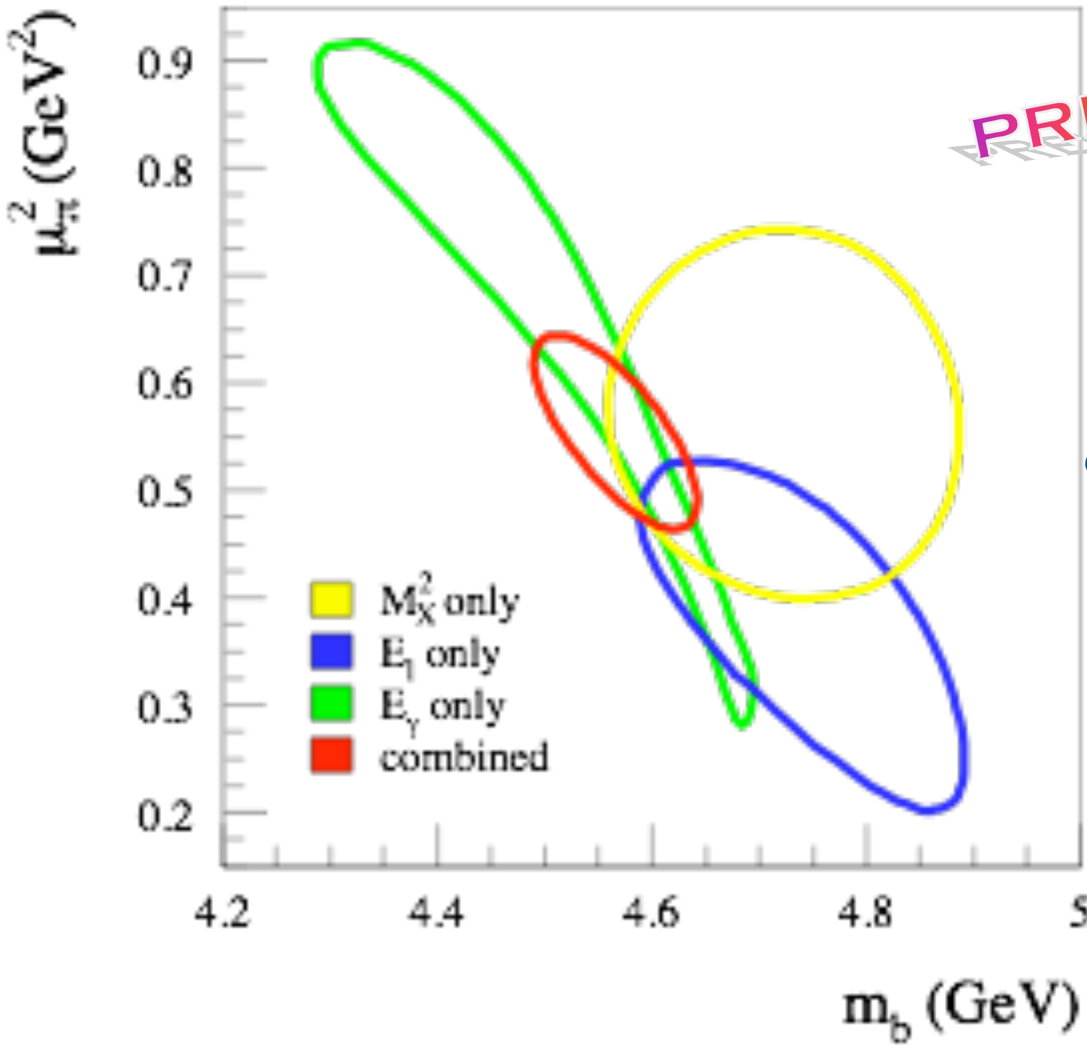
Filled circles: used in fit

Yellow band: theory error



χ^2 /dof =17.8/24

Global fit - kinetic scheme



PRELIMINARY

Contours $\Delta\chi^2 = 1$

Correlations illustrate power of combining different moments

Result of fit

Fit to all published values

(Buchmuller, Flacher PRD73:073008 (2006))

parameter	Belle (preliminary)	Buchmüller & Flächer
m_b (GeV/c^2)	4.564 ± 0.076	$4.590 \pm 0.025 \pm 0.030$
m_c (GeV/c^2)	1.105 ± 0.116	$1.142 \pm 0.037 \pm 0.045$
μ_π^2 (GeV^2)	0.557 ± 0.091	$0.401 \pm 0.019 \pm 0.035$
μ_G^2 (GeV^2)	0.358 ± 0.060	$0.297 \pm 0.024 \pm 0.046$
$\tilde{\rho}_D^3$ (GeV^3)	0.162 ± 0.053	$0.174 \pm 0.009 \pm 0.022$
ρ_{LS}^2 (GeV^3)	-0.174 ± 0.098	$-0.183 \pm 0.054 \pm 0.071$
$\mathcal{B}(B \to X_c \ell \nu)$ (%)	10.59 ± 0.16	$10.71 \pm 0.10 \pm 0.08$
$\|V_{cb}\| \times 10^3$	$41.93 \pm 0.65 \pm 0.48 \pm 0.63$	$41.96 \pm 0.23 \pm 0.35 \pm 0.59$

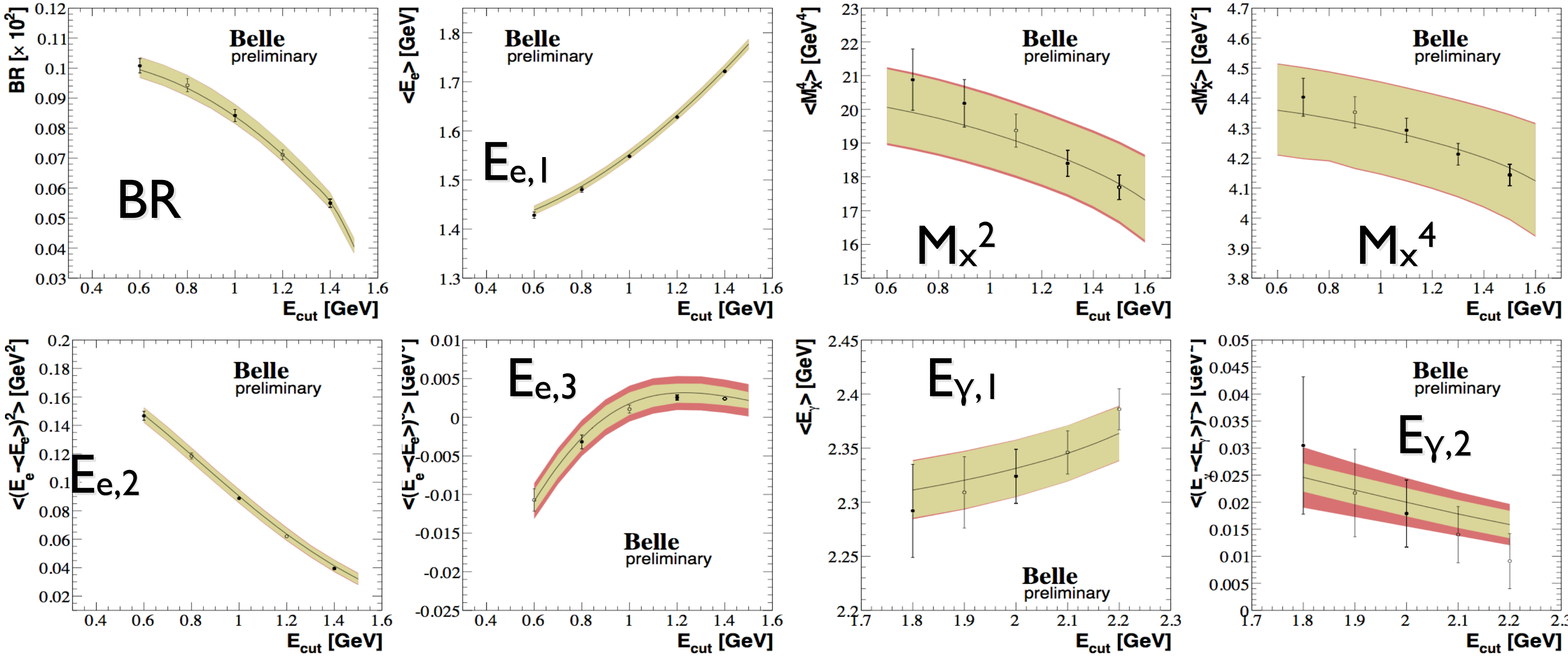
α_s Γ_{SL} HQE Γ_{SL}

Global fit - 1S scheme

Yellow band: fit error

Red band: Theory + Fit

Filled circles: used in fit



$|V_{cb}| = (41.5 \pm 0.5_{fit} \pm 0.2_{\tau})\times 10^{-3}$

$\chi^2/dof = 6/17$

PRELIMINARY

$m_b^{1s} = 4.73 \pm 0.05$ GeV

$\lambda_1 = -0.30 \pm 0.04$ GeV

(Bauer et al., PRD70, 094017(2004)): $|V_{cb}| = (41.5 \pm 0.4_{fit} \pm 0.1_{\tau})\times 10^{-3}$

Summary

- $|V_{cb}|$: currently, best precision via inclusive semileptonic B decays
  - Full reconstruction tag allows study w very low bg, in cms of B
  - HQE parametrizes nonperturbative effects to $O(1/m_b^3)$ via shape of E_l, M_X distributions
  - Mature experiment; well understood bg subtraction, unfolding
  - Shapes represented by moments w varying E_l cuts
  - global fit of parametrized HQE to measured moments
    - good consistency between 2 schemes
    - Constrain HQE parameters
    - -> lower theory uncertainty on $|V_{ub}|$ as well as $|V_{cb}|$
  - Belle: $|V_{cb}|=(41.93\pm0.65\pm0.48\pm0.63)\times10^{-3}$ (kinetic scheme)
    - <2% uncertainty, agrees w fit to published results
- References
  - Electron moments hep-ex/0610012
  - $M_X{}^2$ moments Belle-CONF-0668 (available soon at http://belle.kek.jp/conferences/ICHEP2006/)
  - B-> sγ moments hep-ex/0508005
  - Global fits Belle-CONF-0669