B Physics and Quarkonia

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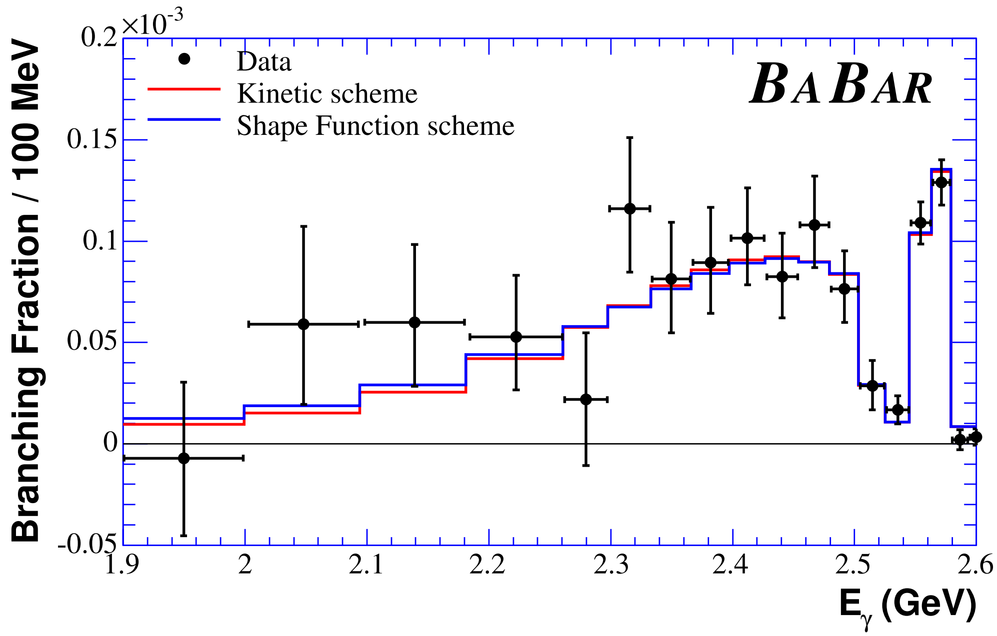
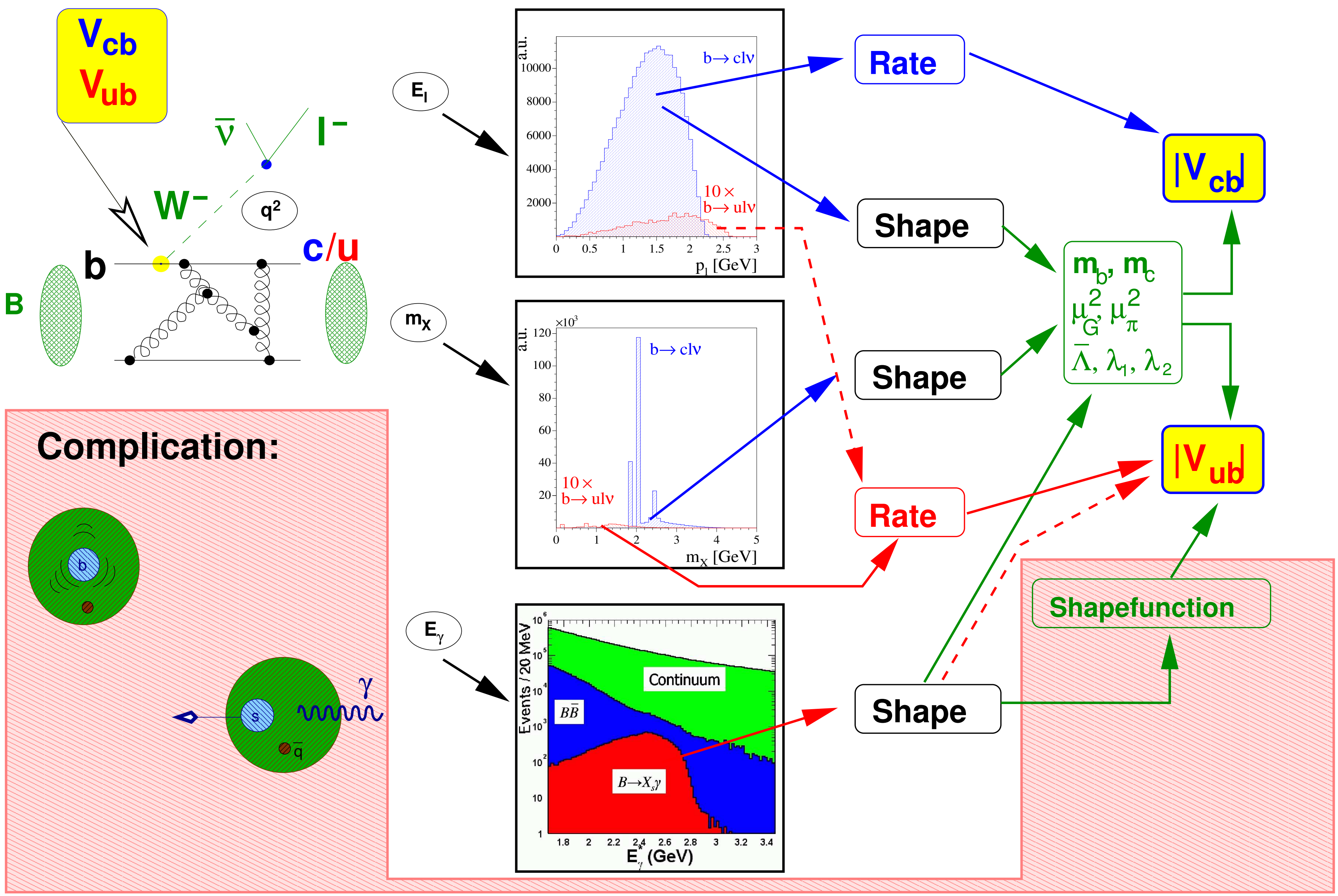
2006/07/21

- Part I
  - ▷ Introduction
  - ▷ B-factories: CP violation
  - ▷ Tevatron: B_s mixing
- Part II
  - ▷ Semileptonic Decays
  - ▷ Radiative and Some Rare Decays
  - ▷ Heavy Quarkonia



UT Sides: Semileptonic B Decays



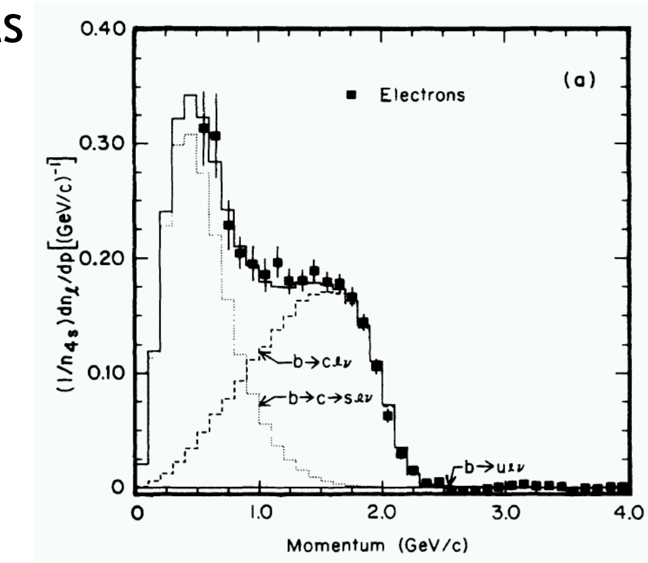
Semileptonic B decays

- Semileptonic B-decays give direct access to $|V_{cb}|$ and $|V_{ub}|$
  - ▷ Factorization of hadronic and leptonic currents
  - ▷ Issue: Separation $b \to c\ell\bar{\nu}$ vs. $b \to u\ell\bar{\nu}$

$$\mathcal{B}(\bar{B} \to X_c\ell\bar{\nu}) \sim 10.61 \pm 0.17\%$$

$$\mathcal{B}(\bar{B} \to X_u\ell\bar{\nu}) \sim 0.20 \pm 0.05\%$$

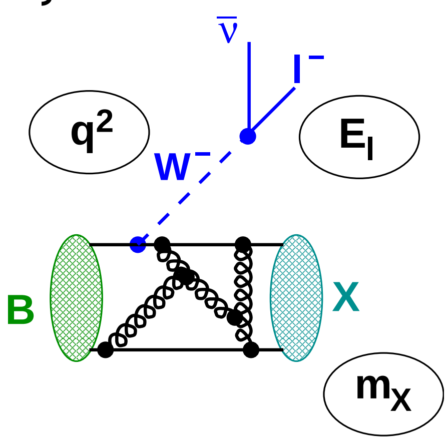
  - ▷ Issue: Model-independence!



▷ Inclusive

large rate $\Gamma_{sl} \propto \mathcal{B}/\tau \propto \gamma_x |V_{xb}|^2$

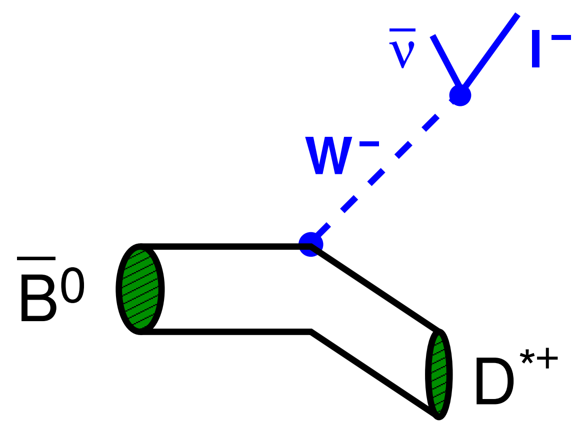
'easy' to calculate $\longrightarrow$ OPE/HQE



▷ Exclusive

'easy' to measure

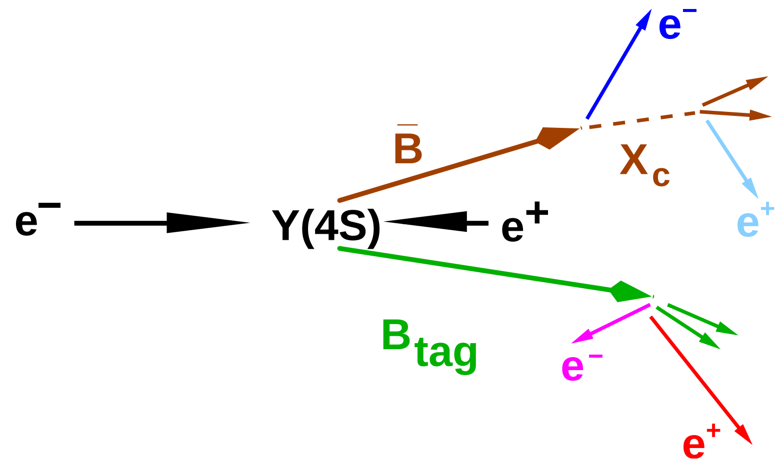
formfactors $\longrightarrow$ HQET, lattice

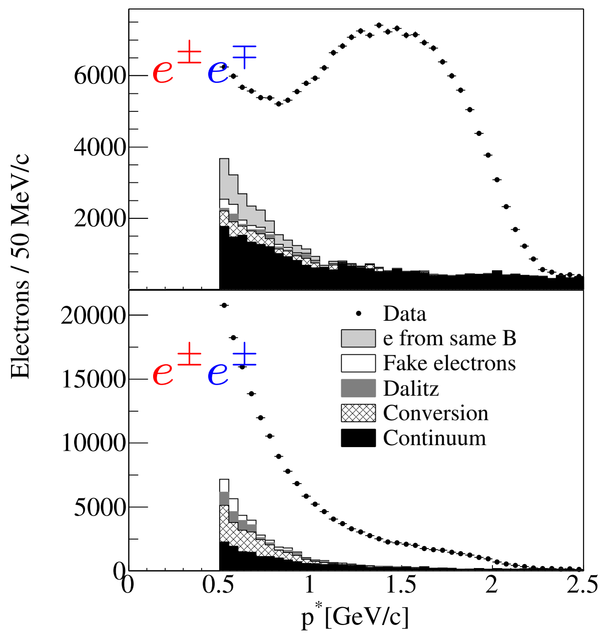


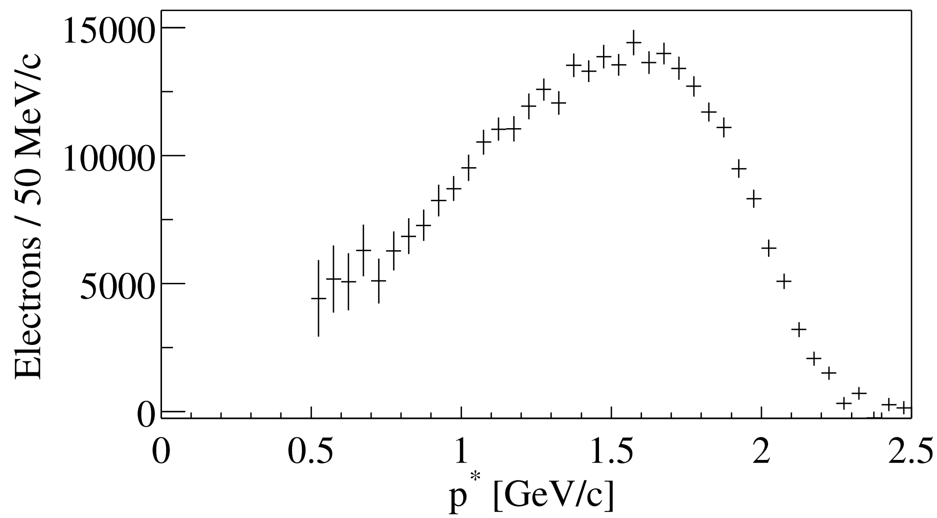
Phys.Rev.D69:111104,2004

Electron Spectrum

- Events with two electrons
  - ▷ tag electron, $p^* > 1.4\,$GeV
  - ▷ signal electron, $p^* > 0.5\,$GeV
- Very large statistics
  - ▷ Unlike-sign sample
  - ▷ like-sign sample





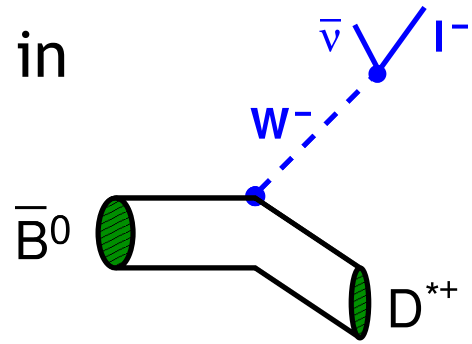


unfold $B^0\bar{B}^0$ mixing

$$\mathcal{B}(B \to Xe\nu) = (10.36 \pm 0.06_{stat} \pm 0.23_{syst})\%$$
$$(\text{for } p^* > 0.6\,\text{GeV})$$

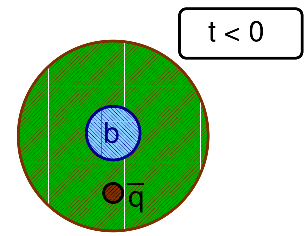
Exlusive Semileptonic B decays

- Differential decay rate (schematically) given in HQET by $(w = v_B \cdot v_D^{(*)} = E_D^{(*)}/m_D^{(*)})$

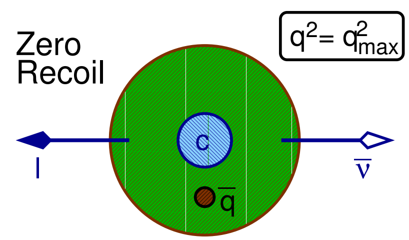


$$\frac{d\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}{dw} = \mathcal{K} \cdot |V_{cb}|^2 \begin{cases} (w^2-1)^{1/2} \cdot \mathcal{F}_*{}^2(w) \\ (w^2-1)^{3/2} \cdot \mathcal{F}^2(w) \end{cases}$$

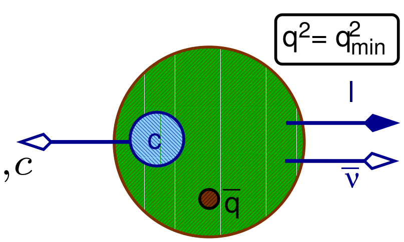
- At zero recoil:
  - ▷ HQET: One form factor $\mathcal{F}_{(*)}(w)$
  - ▷ HQS: Normalization $\mathcal{F}(1) = \xi(1) = 1$



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

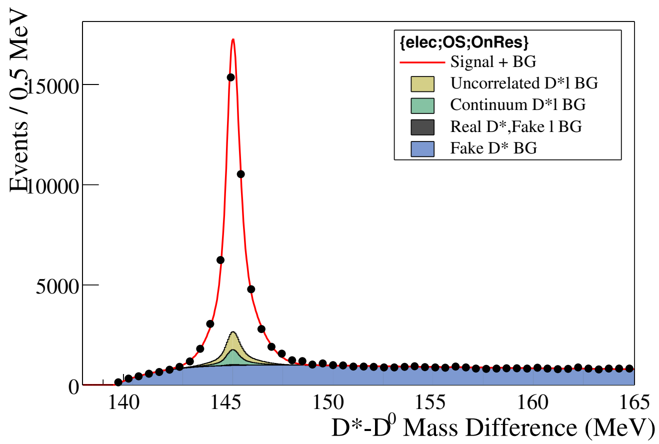


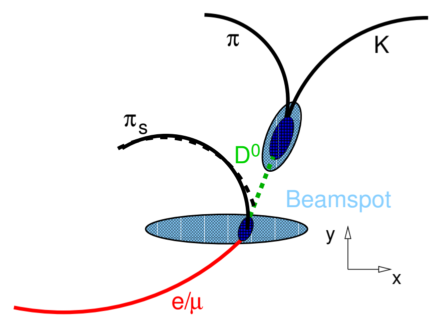
- Preference for $\bar{B} \to D^*\ell\bar{\nu}$ over $\bar{B} \to D\ell\bar{\nu}$:
  - ▷ Less kinematic suppression towards $w = 1$
  - ▷ Luke's theorem: no corrections to $\mathcal{F}_*(w)$ at $1/m_{b,c}$
  - ▷ Better experimental conditions!

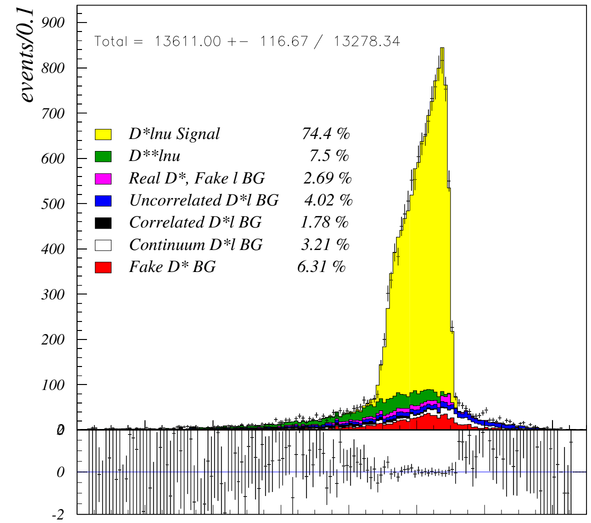


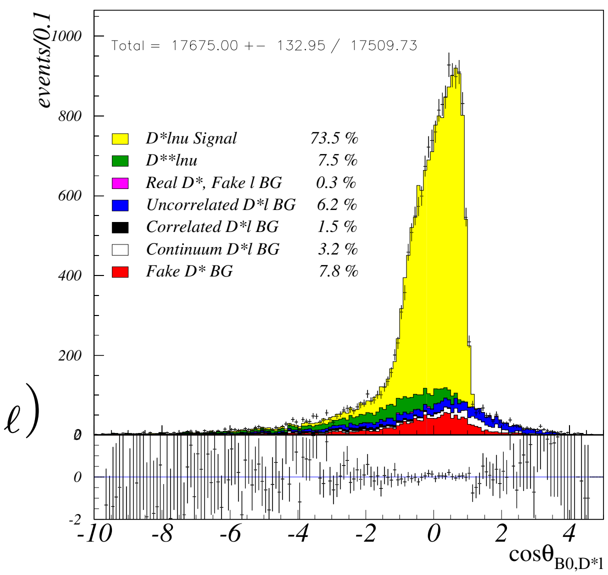
Reconstruction of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$

- Charged lepton with $p^* > 1\,\text{GeV}$
- Reconstruct $D^{*+} \to D^0\pi_s^+$
  - ▷ Use mass difference $m_{D^{*-}} - m_{D^0}$









- Check against missing particles

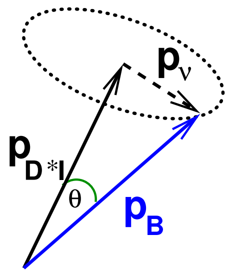
$$
\begin{aligned}
p_\nu^2 &= (p_B - p_{D^{*+}} - p_\ell)^2 \\
&= p_B^2 + p_{D^*\ell}^2 - 2p_B\,p_{D^*\ell} \\
&= m_B^2 + m_{D^*\ell}^2 - 2(E_B E_{D^*\ell} - \vec{p}_B \cdot \vec{p}_{D^*\ell}) \\
\to \quad \cos\theta_{B,D^*\ell} &= \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}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

Measurement of $d\Gamma/dw$ and $|V_{cb}|$

- $\vec{p}_B$ up to azimuthal ambiguity

$\Rightarrow$ Estimate w from

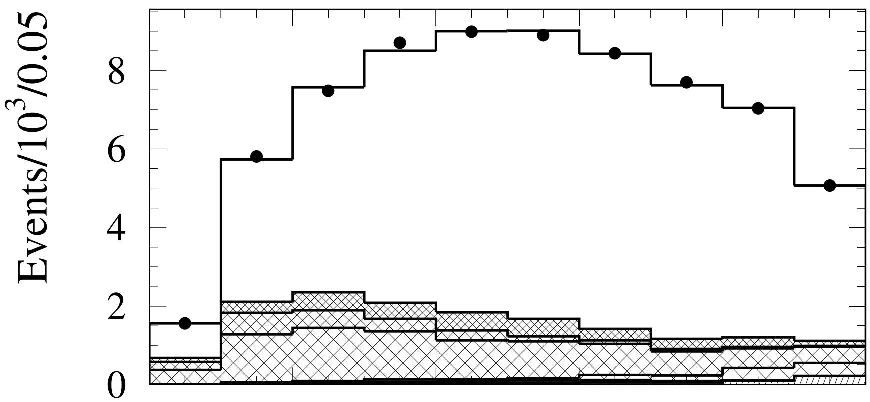
$$w = \frac{m^2_{B^0} + m^2_{D^*} - q^2}{2 m_{B^0} m_{D^*}}$$



where $q^2 = (p_{B^0} - p_{D^*})^2$

▷ Average of min. and max. w

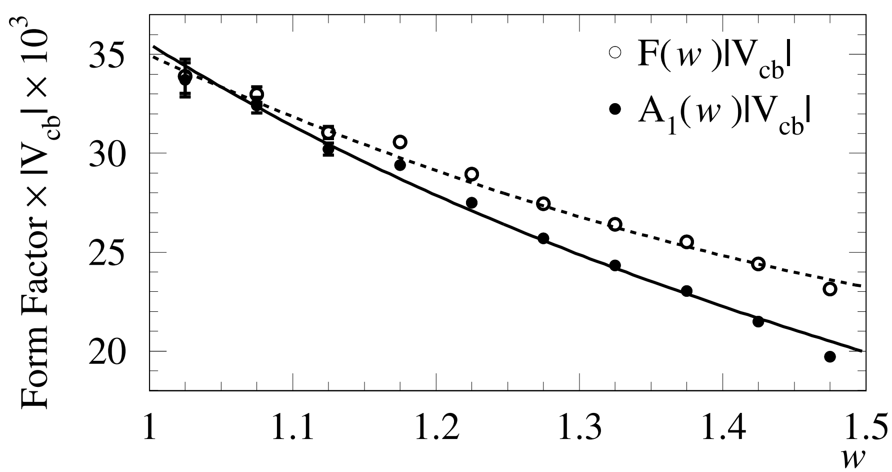
$\rightarrow \sigma(w) \sim 0.04$



$\downarrow \varepsilon$ corrections!

- Results

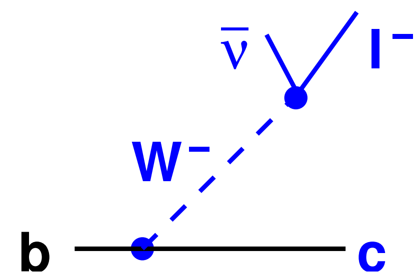
$$\mathcal{B} = (4.90 \pm 0.07 \pm 0.36)\%$$
$$|V_{cb}|F(1) = (35.5 \pm 0.3 \pm 1.6) \times 10^{-3}$$
$$|V_{cb}| = (38.7 \pm 0.3 \pm 1.7 \pm 1.4) \times 10^{-3}$$



$F(1) = 0.919 \pm 0.033$ from (un)quenched lattice QCD

Inclusive Semileptonic B Decays

- Quark-hadron duality $\Gamma(b \to x\ell\nu) = \sum_i \Gamma_i(B \to X_i \ell\nu)$
- Weak decay of free quark



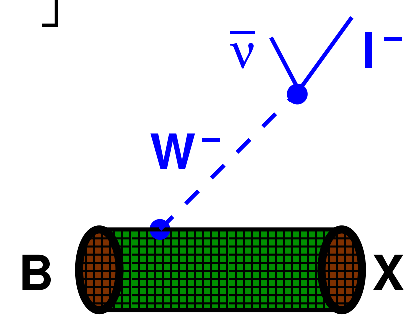
$$\Gamma(b \to c\ell\bar{\nu}) \quad = \quad \frac{G_F^2 |V_{cb}|^2}{192\pi^3} m_b^5$$

- For a model-independent test

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

Need a real theory $\longrightarrow$ expansion

- Separation of scales $\longrightarrow$ OPE



$$\mathcal{H}_{\text{eff}} \quad = \quad \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} C_i(\mu, M) \times \mathcal{O}_i(\mu)$$

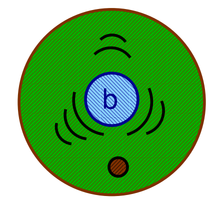
- ▷ Wilson coefficients $C_i(\mu, M)$ short distance, perturbative calc.
- ▷ Matrix elements $\mathcal{O}_i(\mu)$ long distance, nonperturbative/meas.

QCD in the Heavy Quark Limit

- Operator Product Expansion gives decay rate $(r = m_c^2/m_b^2)$:

$$
\begin{aligned}
\Gamma(b \to c\ell\bar{\nu}) &= \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3}(1 + A_{ew})A_{\text{pert}}(r,\mu) \times \\
&\left[z_0(r)\left(1 - \frac{\mu_\pi^2 - \mu_G^2 + \frac{\rho_D^3 + \rho_{LS}^3}{m_b}}{2m_b^2}\right) - 2(1-r)^4 \frac{\mu_G^2 + \frac{\rho_D^3 + \rho_{LS}^3}{m_b}}{m_b^2} + d(r)\frac{\rho_D^3}{m_b^3} + \mathcal{O}(1/m_b^4) \right]
\end{aligned}
$$

where
  - ▷ $\mu \sim 1\,$GeV is the separation scale
  - ▷ $z_0(r)$ and $d(r)$ are phase-space functions
  - ▷ μ_π^2, μ_G^2 : exp. value of kinetic, chromomagnetic 5d operator
  - ▷ ρ_D^3, ρ_{LS}^3 : exp. value of Darwin, spin-orbit 6d operator



- Expansions with the same parameters for moments of
  - ▷ hadronic mass, lepton energy, . . .
  - ▷ photon energy in $b \to s\gamma$

including cut on E_ℓ:

$X \in \{m_X, E_\ell, E_\gamma, \ldots\}$

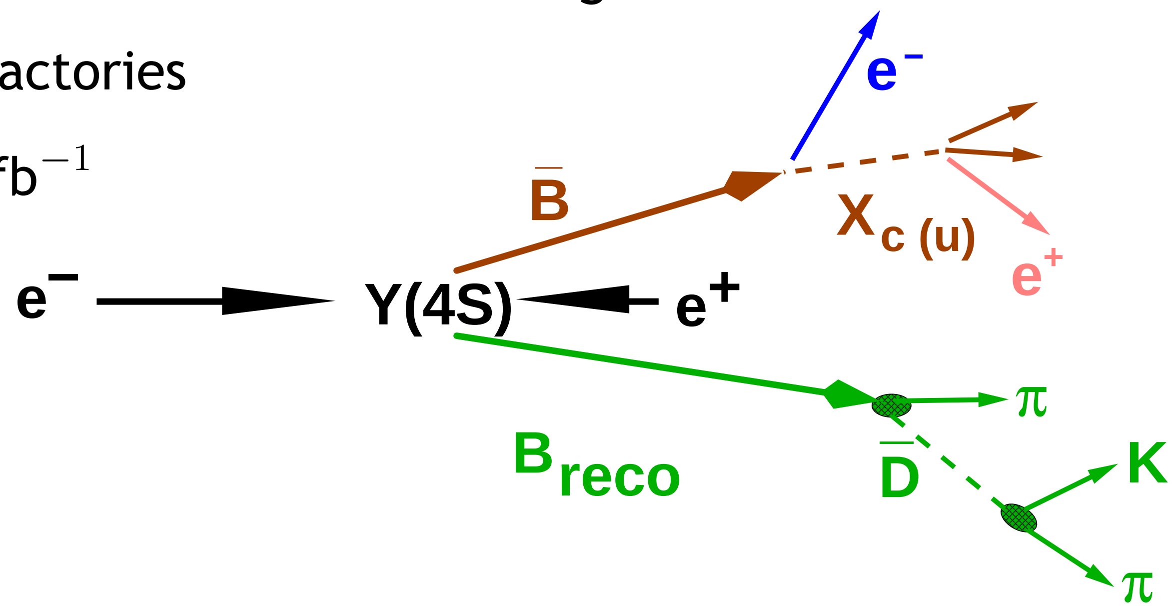
$$
\begin{aligned}
\langle X^n \rangle (E_{\text{cut}}) &= \left.\frac{\int dX (X - X_0)^n \frac{d\Gamma}{dX}}{\int dX \frac{d\Gamma}{dX}}\right|_{E_\ell > E_{\text{cut}}} \\
&= f(E_{\text{cut}}, m_b, r, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)
\end{aligned}
$$

Recoil Physics – B meson beam

- Fully reconstructed hadronic B decay
  - ▷ Like time-dependent CP measurements
  - ▷ BUT: fully reconstructed B is the tag!

  $\longrightarrow$ Only at B factories

  $\longrightarrow$ ca. $4000 B/\text{fb}^{-1}$



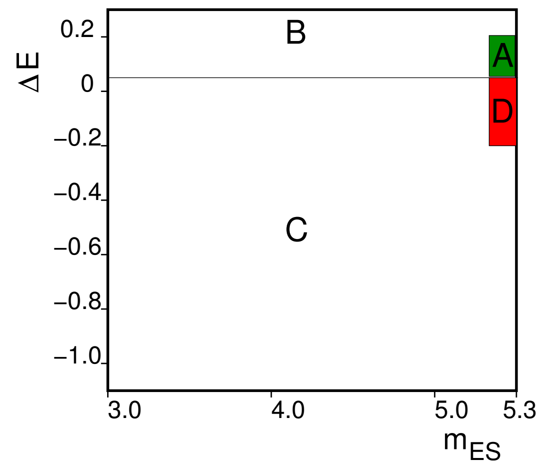
- Advantages:
  - ▷ $\vec{p}_B$, charge and $b/\bar{b}$ contents
  - ▷ background studies: m_{ES} sidebands
  - ▷ neutrino reconstruction!

- Disadvantages:
  - ▷ $\varepsilon_{B^+} = 0.5\%$
  - ▷ $\varepsilon_{B^0} = 0.3\%$
  - ▷ (small) bias of recoil on $\varepsilon_{B_{reco}}$

Maximizing the yield

- Reconstruct as many hadronic B decay modes as possible
- Start with 'seeds' for $B^0 \to D^{(*)+}Y^-$ and $B^+ \to D^{(*)0}Y^0$

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

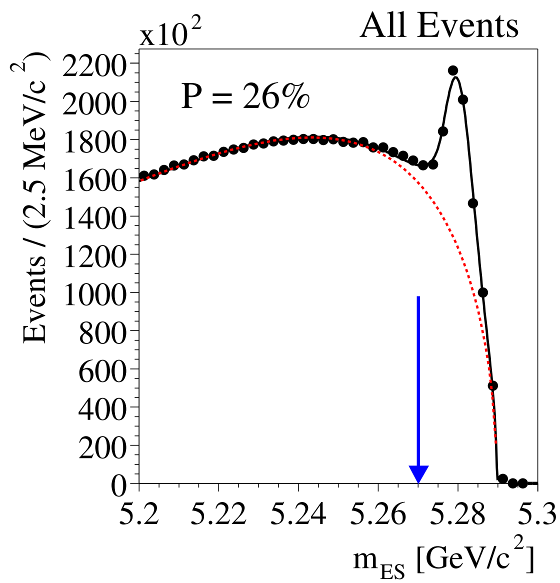


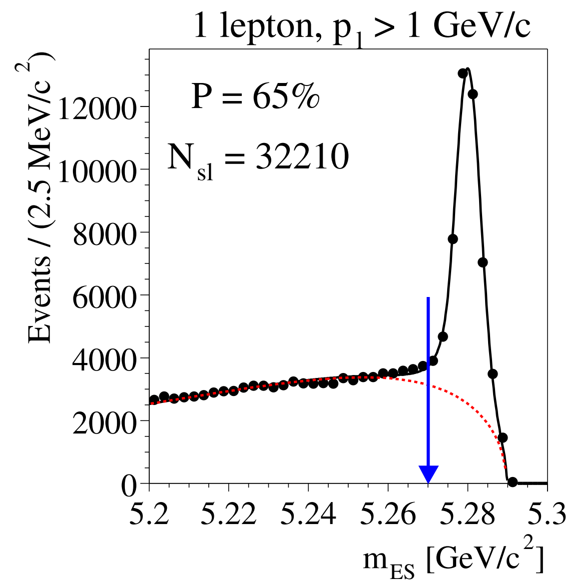
$\longrightarrow$ Loss of ΔE for sidebands

▷ More than 1000 modes!

▷ Ordered selection according to 'purity' $S/(S+B)$

- Balance between
  - ▷ statistics vs. purity
  - $\longrightarrow$ less modes
  - $\longrightarrow$ lepton energy cut

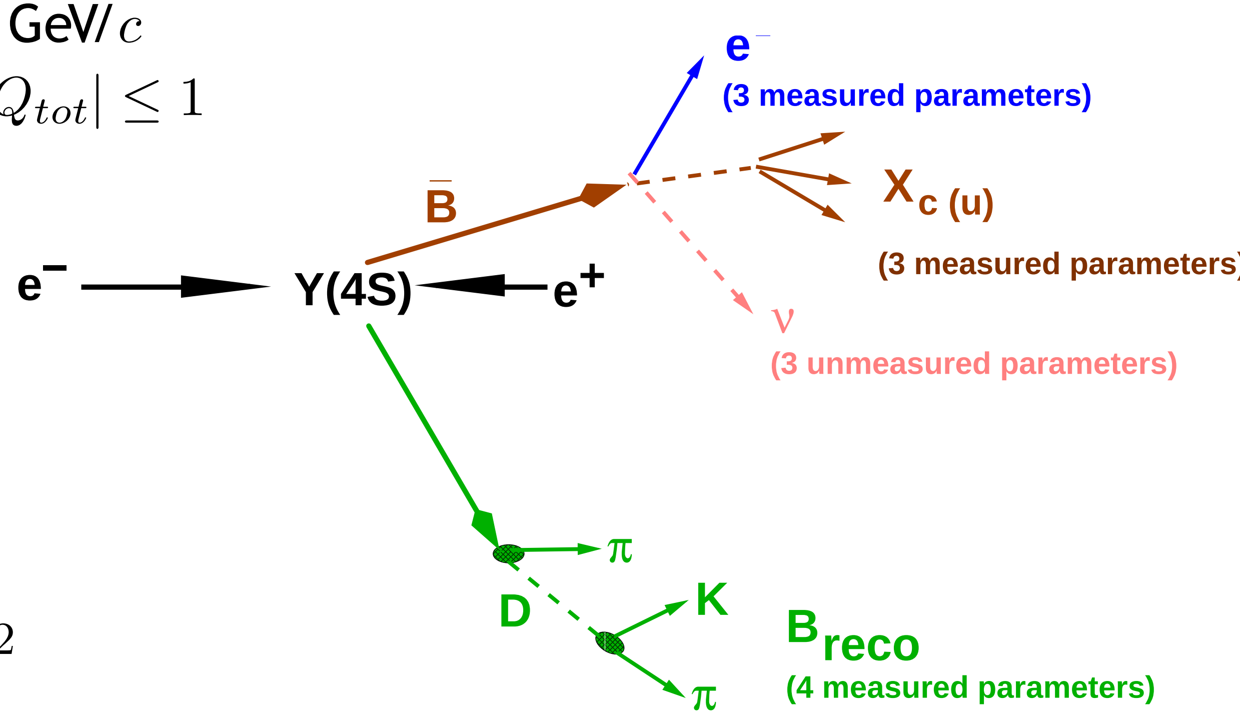




Event Reconstruction

- Measure m_{X_c} distribution for different p^*_{min} cuts
- Tag events with B_{reco} and
  - ▷ Lepton ℓ with $p^* > 0.9$ GeV/c
  - ▷ $Q_\ell \cdot Q_{b(B_{reco})} < 0$ and $|Q_{tot}| \leq 1$

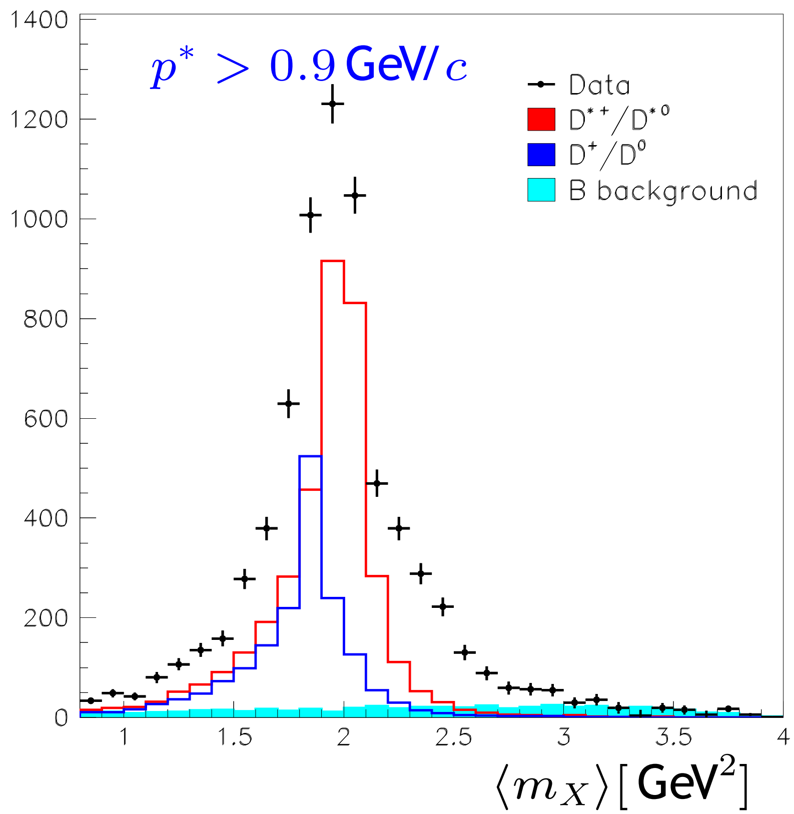
  $\rightarrow$ 7100 signal events



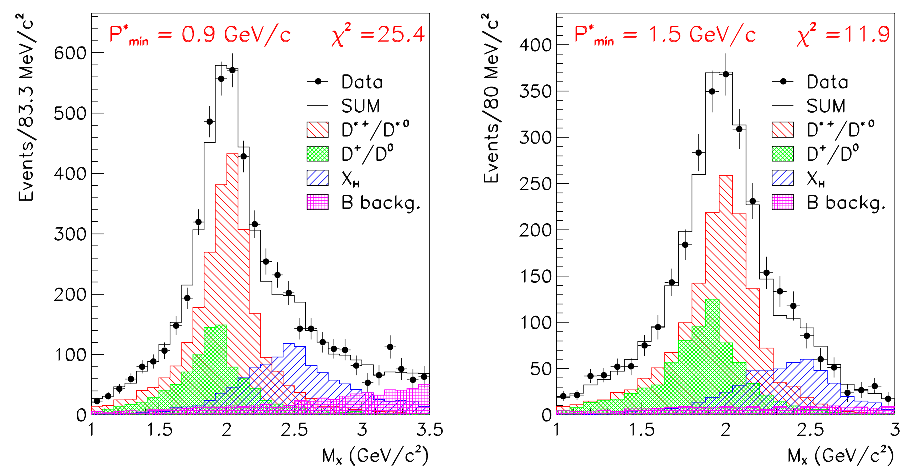
- Hadronic system X_c:
  - ▷ Tracks
  - ▷ Neutrals
- 2C kinematic fit
  $\rightarrow \sigma(m_X) \sim 350$ MeV/c^2
- Neutrino reconstruction via
  $p_{miss} = p_{\Upsilon(4S)} - p_{B_{reco}} - p_X - p_\ell$
  - ▷ $E_{miss} > 0.5$ GeV, $|\vec{p}_{miss}| > 0.5$ GeV
  - ▷ $\left|E_{miss} - |\vec{p}_{miss}|\right| < 0.5$ GeV

Determination of $\langle m_X{}^n \rangle$

- Resulting mass distribution:



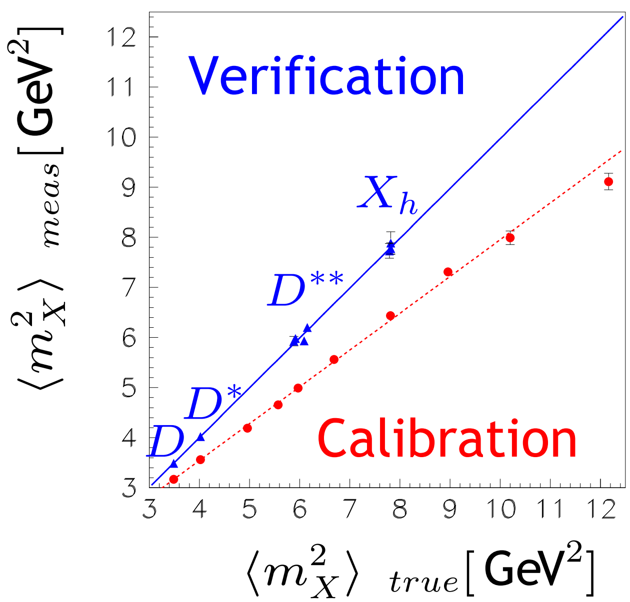
- Method 1:
  Fit data with MC shapes
  plus true generated values
  $\longrightarrow$ moments



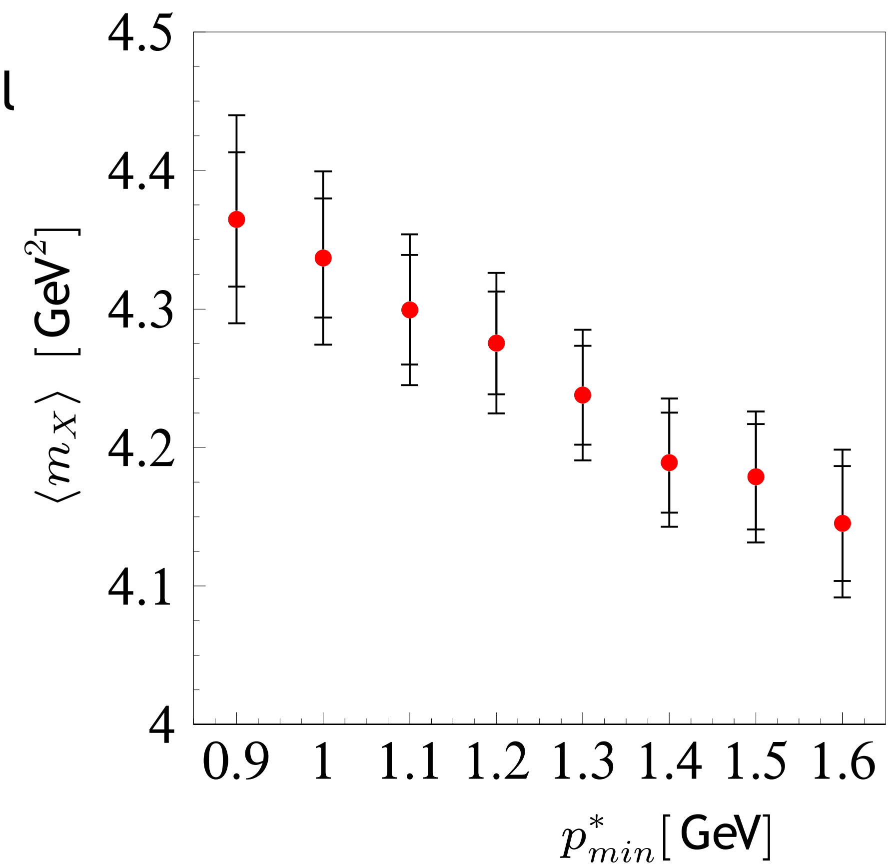
- Method 2:
  Direct determination,
  if corrections not too large
  - ▷ background subtraction
  - ▷ efficiency correction
  - ▷ calibration

Direct Determination of $\langle m_X^2 \rangle$

- Calibration for $\langle m_X^2 \rangle$
  - in bins of $m^2_{X(true)}$
  - dependent on
    - multiplicity of X system
    - $E_{miss} - |\vec{p}_{miss}|$
  - event-by-event
  - no dependence on decay model
  - verified per decay mode

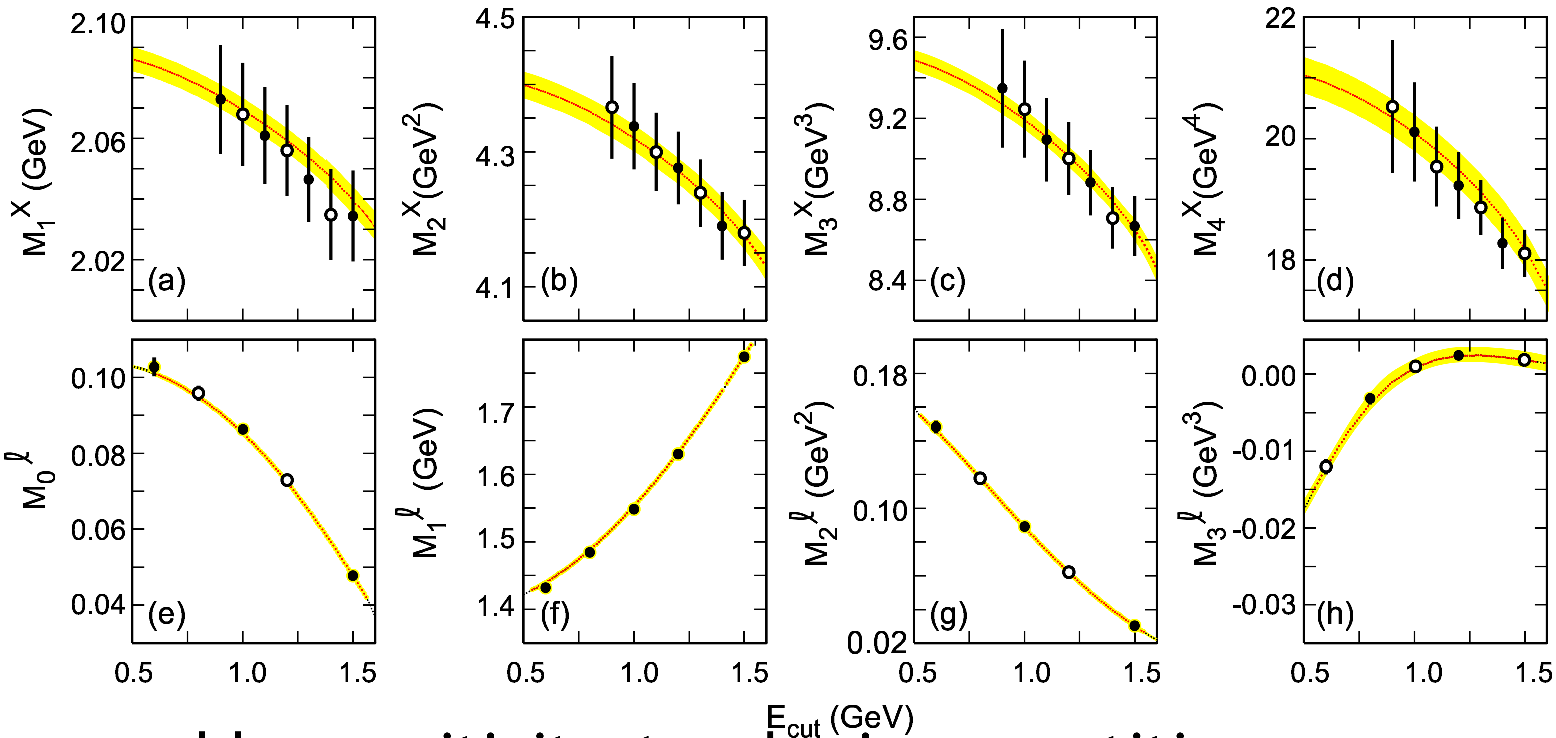


- Result
  - substantial rise towards lower p^*_{min} from high-mass charm states
  - large correlation between bins



'Global' Fit

- Excellent fit ($\chi^2/dof = 15/20$) in kinetic scheme
  - ▷ Take into account varying e threshold momentum
  - ▷ $\Gamma(b \to c\ell\bar{\nu}), |V_{cb}|,\ m_b,\ m_c$ and including $1/\,\mathrm{m}_b^3$ parameters
  - ▷ Accounting for all correlations



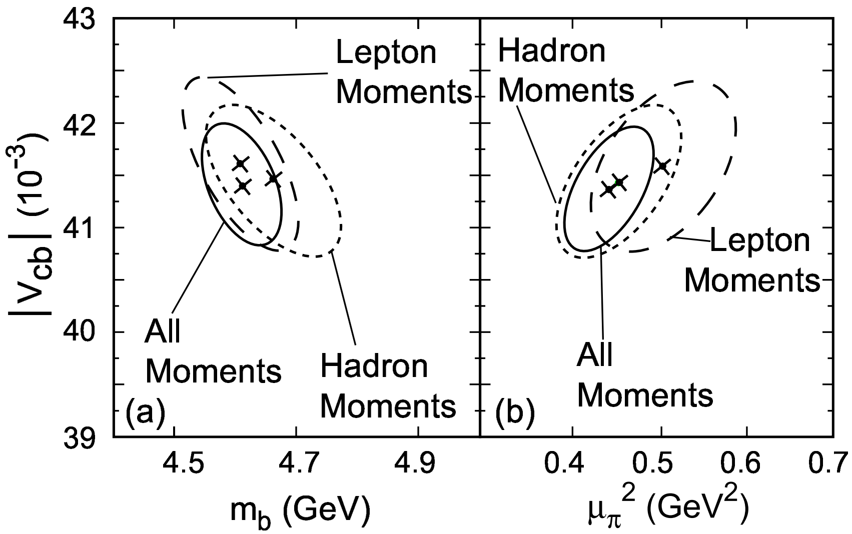
- Comparable sensitivity to physics quantities:
  - ▷ mass moments have higher sensitivity to OPE parameters
  - ▷ lepton moments with much better experimental precision

Precision QCD

- Precise and consistent picture

$$\begin{aligned}
\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}) &= (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\% \\
|V_{cb}| &= (41.4 \pm 0.4_{exp} \pm 0.4_{HQE} \pm 0.2_{\alpha_S} \pm 0.6_{\Gamma_{SL}}) \times 10^{-3} \\
m_b(1\,\text{GeV}) &= (4.61 \pm 0.05_{exp} \pm 0.04_{HQE} \pm 0.02_{\alpha_S})\,\text{GeV} \\
m_c(1\,\text{GeV}) &= (1.18 \pm 0.07_{exp} \pm 0.06_{HQE} \pm 0.02_{\alpha_S})\,\text{GeV} \\
\mu_\pi^2 &= (0.45 \pm 0.04_{exp} \pm 0.04_{HQE} \pm 0.01_{\alpha_S})\,\text{GeV}^2
\end{aligned}$$

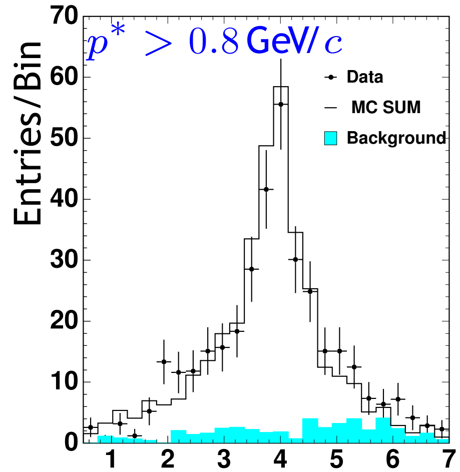
- Note:
  - ▷ SL OPE fit w/o external constraints
  - ▷ 2.0% Determination of $|V_{cb}|$
  - ▷ 1.5% Determination of m_b
  - ▷ 8.0% Determination of m_c

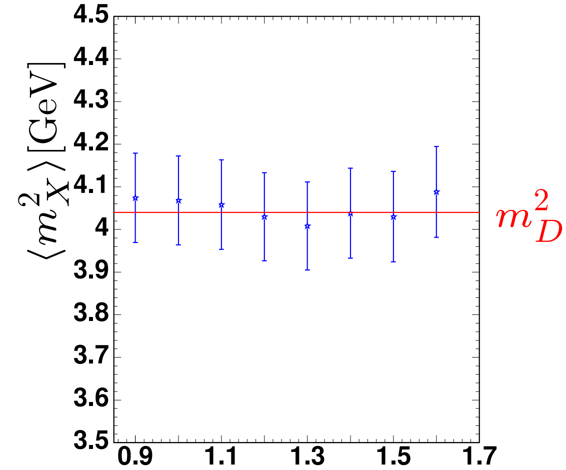


- Improvements
  - ▷ $b \to s\gamma$ photon energy spectrum
  - ▷ Followups: hep-ph/0507253

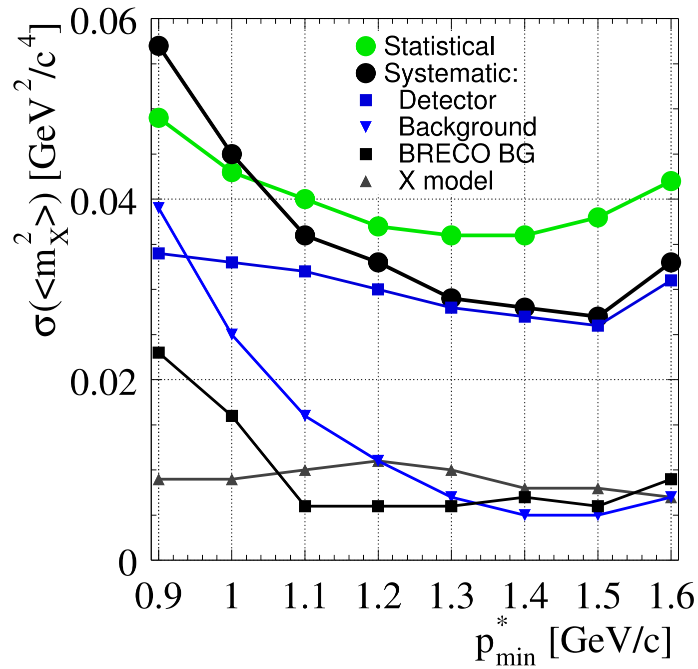
Cross Checks and Systematics

- Cross-check with partially reconstructed $\bar{B} \to D^* \ell \bar{\nu}$ in data
  - ▷ $D^{*+} \to D^0 \pi_s^+$
  - ▷ reconstruct only π_s^+
  - ▷ approximate D^{*+} momentum with information from π_s^+



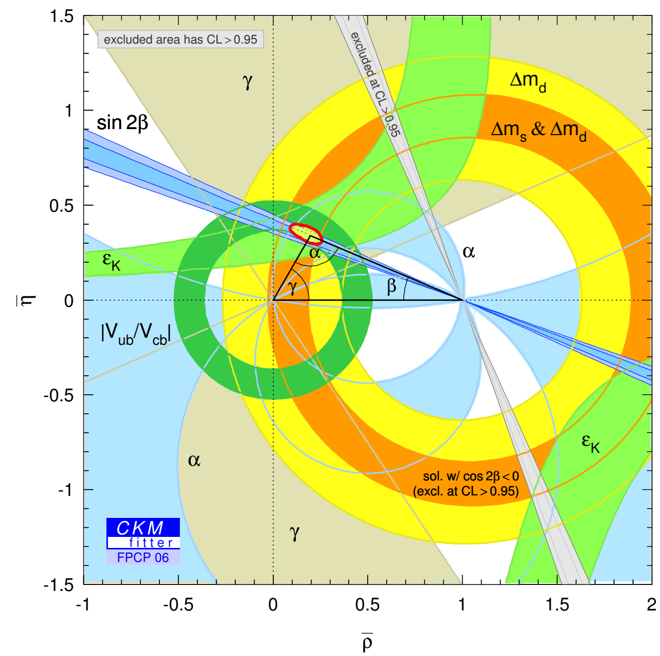


- Consistent measurements in independent data sets
- Systematic errors:
  - ▷ small contribution from decay model
  - ▷ well balanced to statistical error



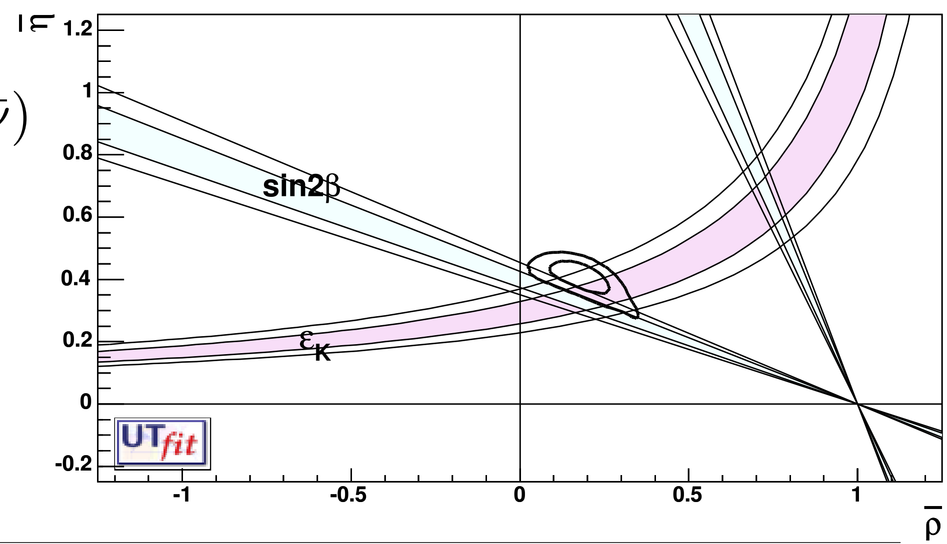
$|V_{ub}|$ is a small critical number

- Tension between $\sin 2\beta$ and $|V_{ub}|$?
  - ▷ Mostly driven by inclusive $|V_{ub}|$
- Significance of (dis)agreement
  - ▷ need errors with sound statistical interpretation
  - ▷ Error hierarchy
    statistical
    systematic
    theoretical
    model



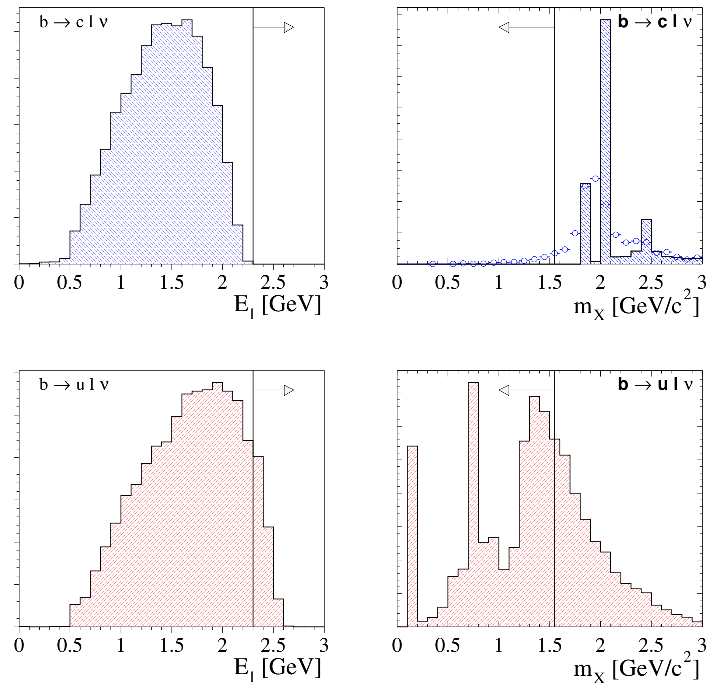
- The main problem in $|V_{ub}|$:
  - ▷ $\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}) \sim 50 \cdot \mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$
  - ▷ 'You have to apply cuts to reduce charm.'
  - ▷ 'Large extrapolation induces large theoretical uncertainty.'

  $\longrightarrow$ Wrong!



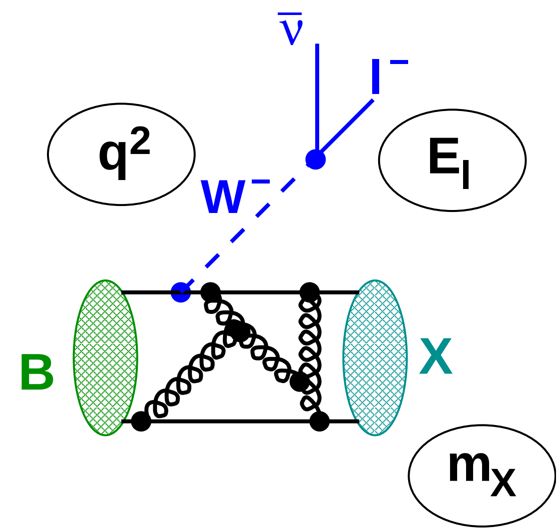
Charmless Semileptonic Decays

- Exclusive $|V_{ub}|$ measurements
  - ▷ Experimentally: $\bar{B} \to \pi \ell \bar{\nu}$, . . .
  - ▷ Form factors: Lattice QCD (eventually)



- Inclusive $|V_{ub}|$ measurements

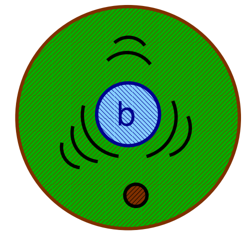
Method	Cut	$\mathcal{A}[\%]$
Lepton energy	$E_\ell > (m_B^2 - m_D^2)/2m_B$	10
Hadron mass	$m_X < m_D$	70
Dilepton mass	$q^2 > (m_B - m_D)^2$	20
Hadronic energy	$E_X < m_D$	70
Combinations	(m_X, Q^2)	30
Had. light-cone var.	$P_X^+ \equiv E_X - \lvert\vec{p_X}\rvert < m_D^2/m_B$	70
Combinations	(E_ℓ, Q^2)	30
Ratios	$(\int dx \frac{d\Gamma^{b\to u\ell\bar{\nu}}}{dx} / \int dy \frac{d\Gamma^{b\to s\gamma}}{dy})$	30-70
Full rate	None	100

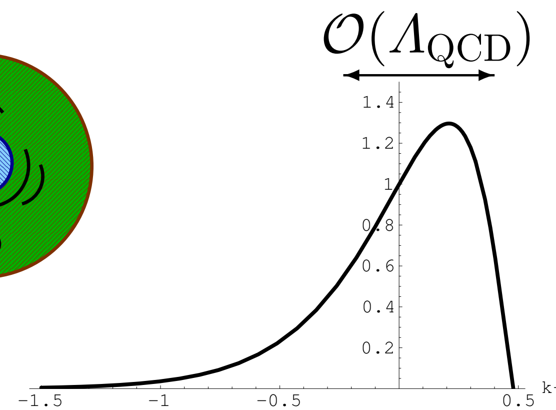


- But: Experimental complications
  - ▷ How to measure
    hadronic system X (disentangle second B)?
    neutrino (missing momentum)?

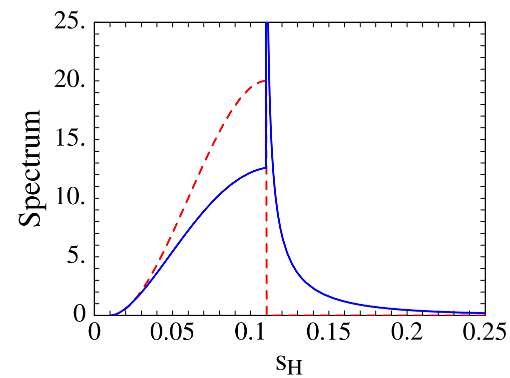
$|V_{ub}|$: Complicated QCD

- Nonperturbative 'shape function'
  - ▷ convolving parton-level distributions with (B meson) universal structure function $f(k_+)$, *e.g.*

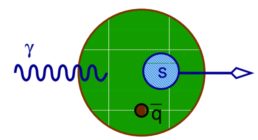




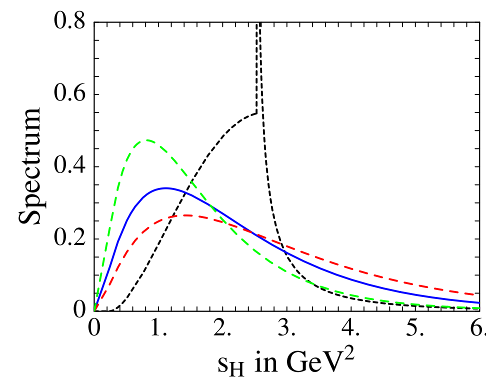
$$\frac{d\Gamma}{dE_\ell} = \int dk_+ f(k_+) \frac{\Gamma_{pert}(m_b \to m_b + k_+)}{dE}$$



  - ▷ Impact varies over phase space
  - ▷ $b \to s\gamma$ photon energy spectrum directly sensitive to $f(k_+)$
    - But: $\mathcal{B}(b \to s\gamma) \sim 3 \times 10^{-4}$; experimentally very difficult
    - modeling of $f(k_+)$

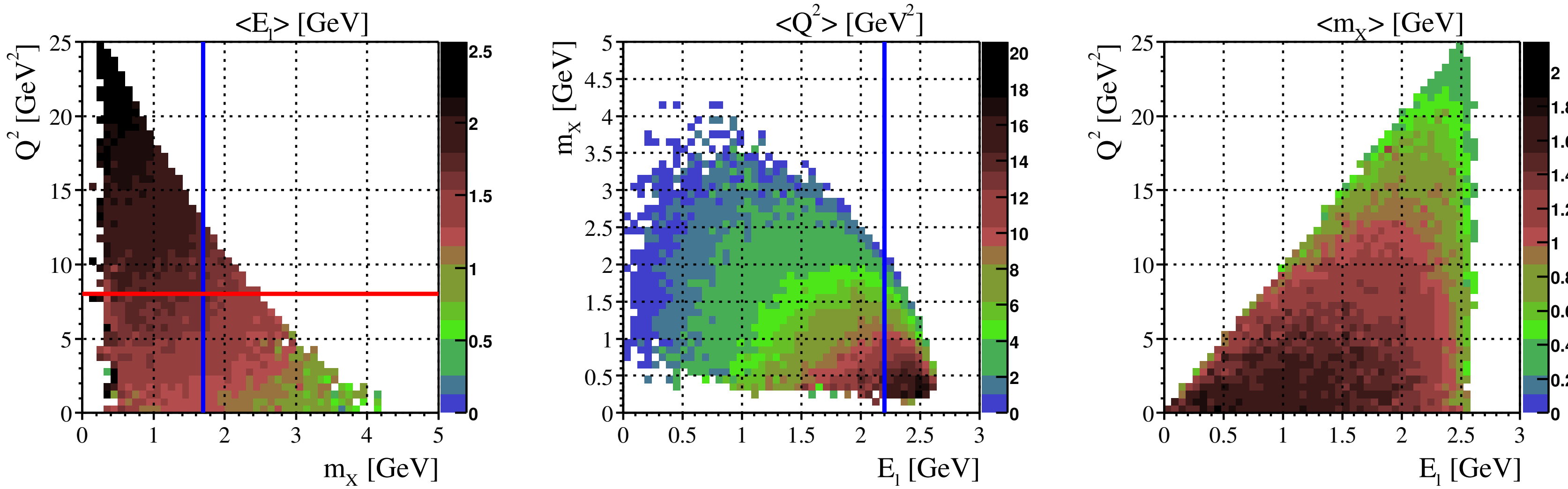


  - ▷ 'Theoretically' also $b \to c\ell\bar{\nu}$ and OPE parameters

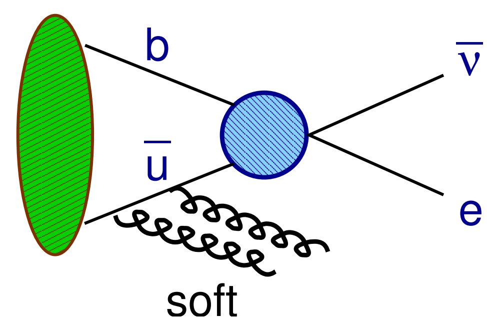


- Complications to this naive picture
  - ▷ Subleading effects
  - ▷ Perturbative corrections

More Complications



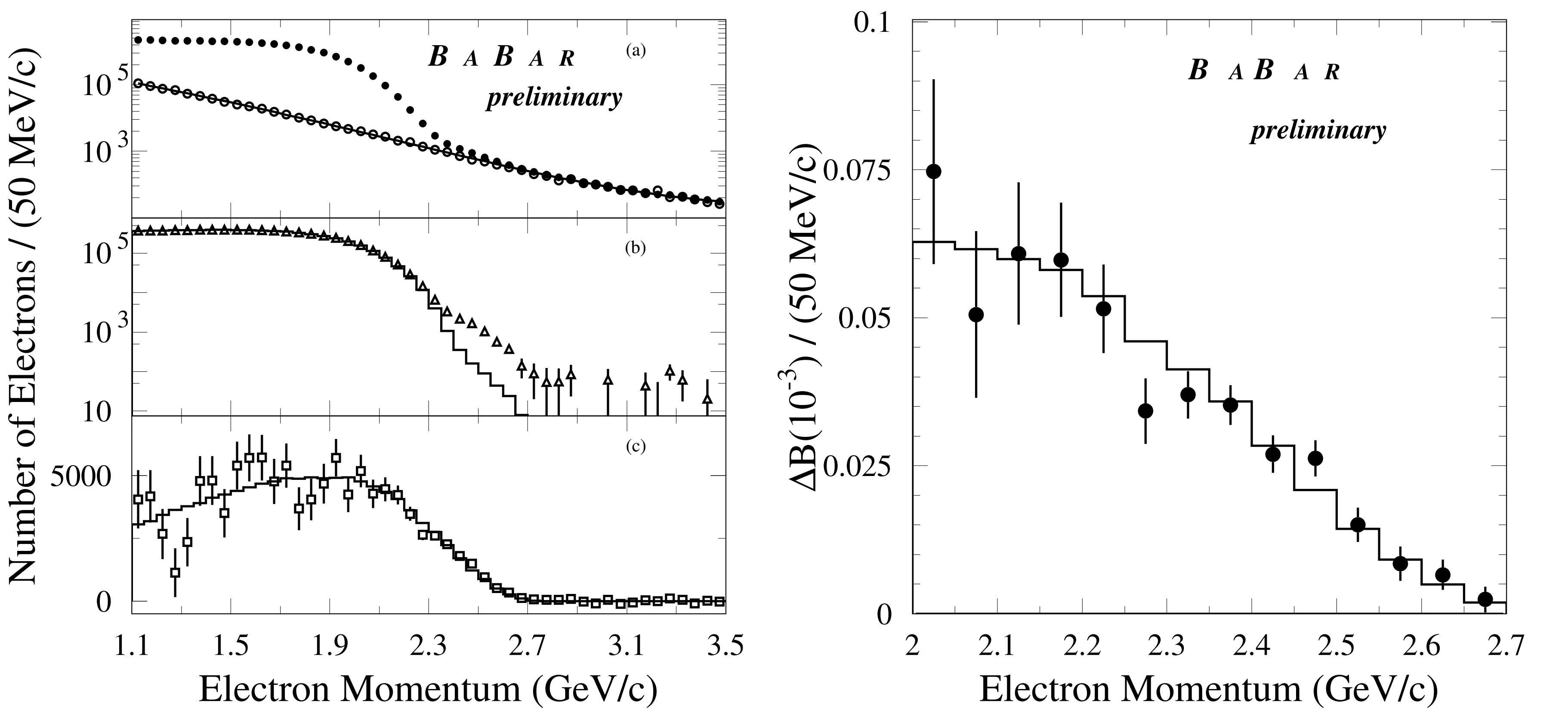
- Nonperturbative (unknown and large?) uncertainties
  - factorization violation
  - Measure B^+ and B^0 separately
- Weak annihilation/Pauli interference
  - Concentrated at highest Q^2



- Quark hadron duality
  - In 'resonance region' $m_X \sim \Lambda_{\rm QCD}$
- Roughly inversely proportional to fraction of events included

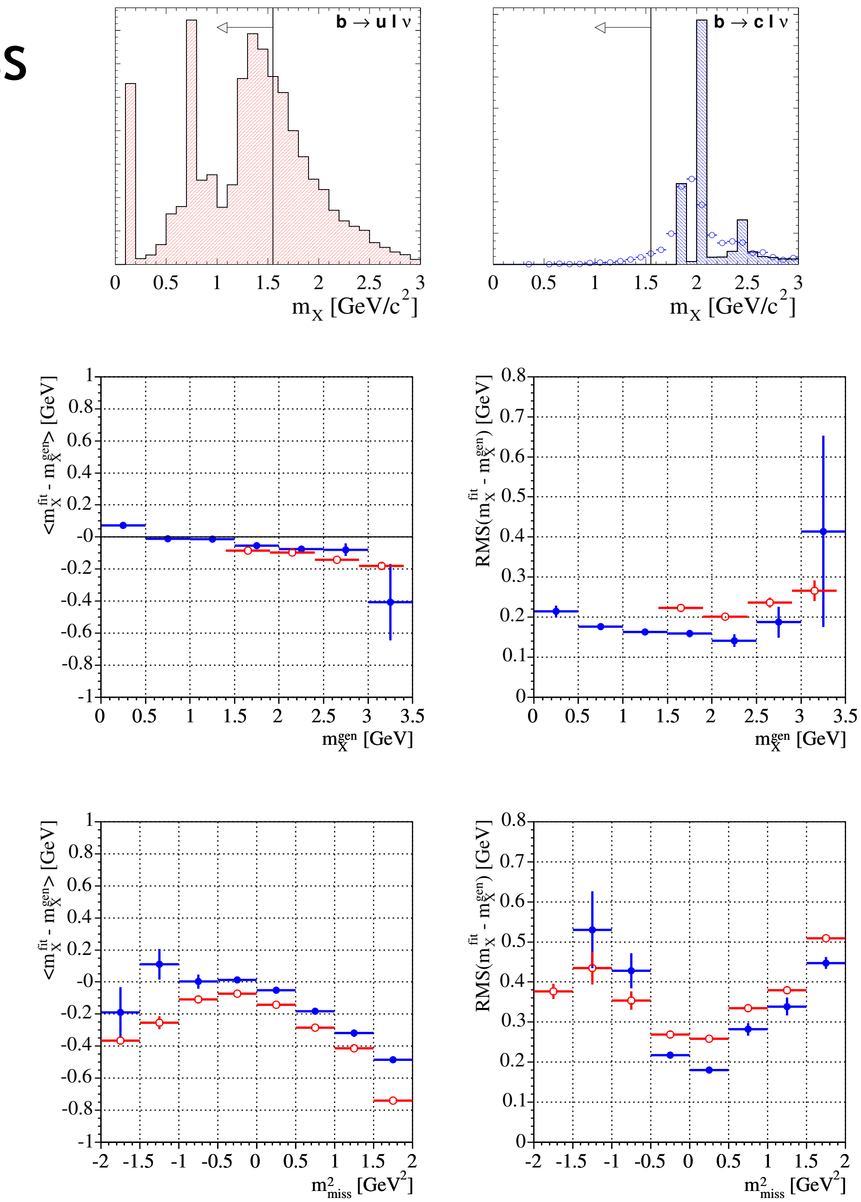
Take 1: 'Endpoint' Spectrum

- The 'easiest' measurement
- Need accurate model of $b \to c\ell\bar{\nu}$ background
  - ▷ Improved formfactor measurements by *BABAR for* $\bar{B} \to D^*\ell\bar{\nu}$
  - ▷ Tour de force: Measured $b \to u\ell\bar{\nu}$ spectrum to $p > 2.0$ GeV (not an 'endpoint' spectrum any more)



Take 2: Hadronic mass in recoil

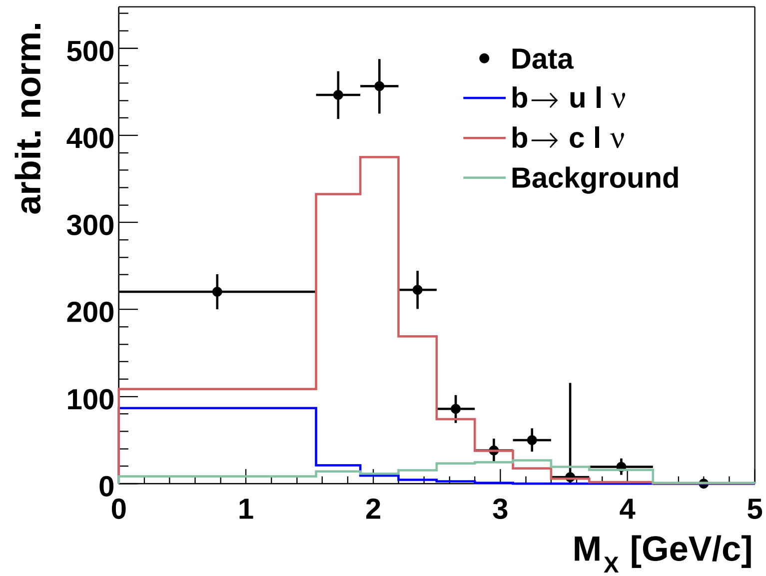
- Advantages of hadronic recoil mass
  - ▷ Large acceptance (50 - 80%)
  - ▷ Decent $b \to c\ell\bar{\nu}$ rejection
- Disadvantages
  - ▷ Dependence on shape function
  - ▷ Low statistics of B_{reco} sample
- Experimental strategy
  - ▷ like moments analysis
  - ▷ Normalization:
    B_{reco}, lepton, well-measured event
  - ▷ Signal: veto on
    events with K^+, K^0_S
    partially reco'ed $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$
  - ▷ Reduce experimental systematics:
    $\mathcal{B}(\bar{B} \to X_u\ell\bar{\nu})/\mathcal{B}(\bar{B} \to X\ell\bar{\nu})$



Signal Extraction

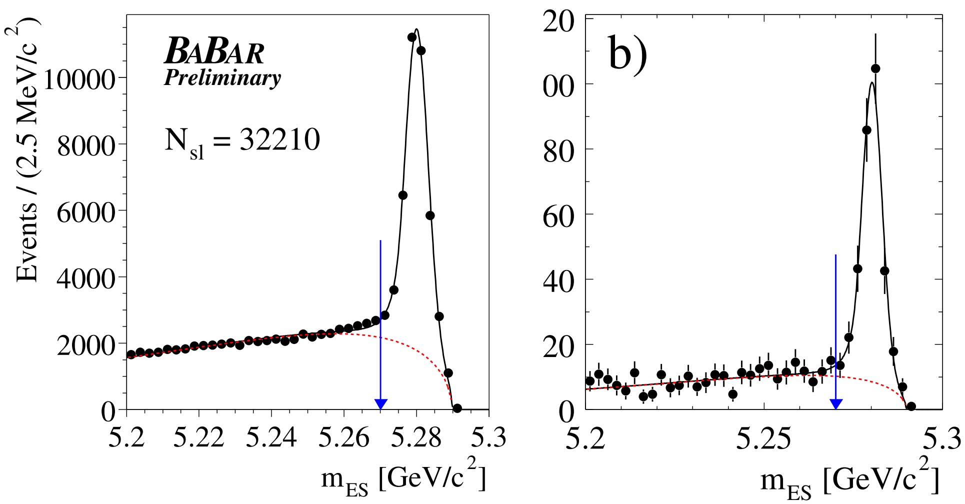
- Extract # signal events with fit of 3 shapes to m_X distribution:

$$\boxed{\frac{\mathcal{B}(B \to X_u \ell\nu)}{\mathcal{B}(B \to X\ell\nu)} \propto \frac{(N_{data} - N_{bg})/(\varepsilon^u_{sel} f_u)}{N_{sl}}}$$



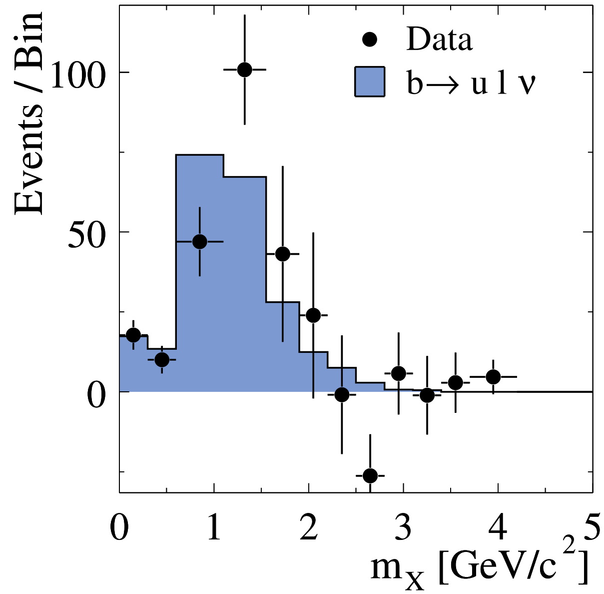
- ▷ ε^u_{sel} : signal efficiency
  ▷ f_u : signal fraction with $m_X < 1.55$ GeV

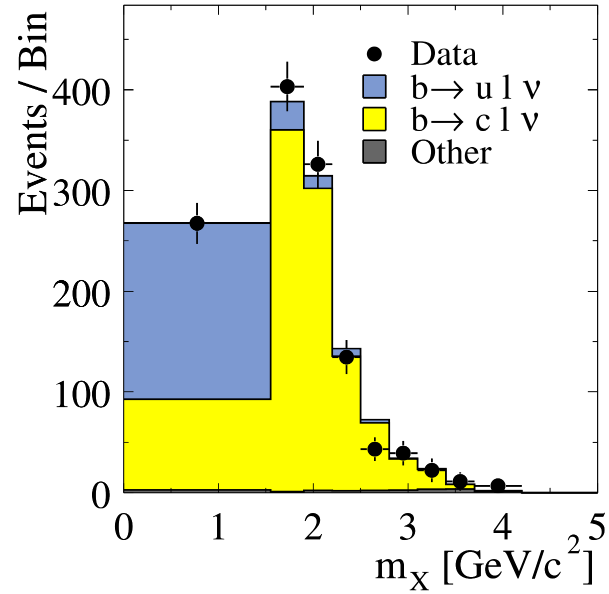
- Apply corrections for
  - ▷ sideband subtraction
  - ▷ mixing of B^0 mesons
  - ▷ background in N_{sl}
    - fake leptons
    - cascade charm decays
    - τ decays



Hadronic mass results

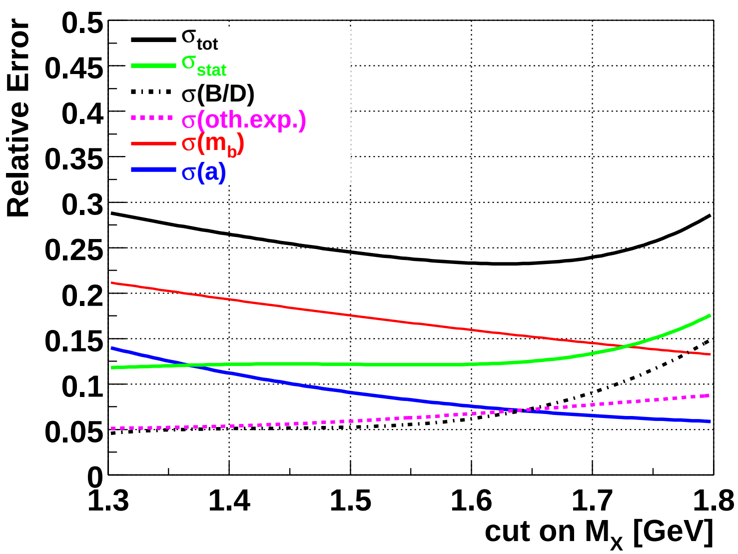
- Measure $b \to u\ell\bar{\nu}$ up to some cut-off
  BABAR: $m_X < 1.55$ GeV
  BELLE: $m_X < 1.70$ GeV





- S/B comparable to exclusive analyses
  - ▷ B^0: $S/B \sim 3.6$
  - ▷ B^+: $S/B \sim 1.2$

- Reducing shape function sensitivity
  - ▷ add Q^2 requirements



PL B486, 86-91(2000)

Take 3: Avoid the shape function

- Shape function in $b \to u \ell \bar{\nu}$ decays = shape function in $b \to s\gamma$

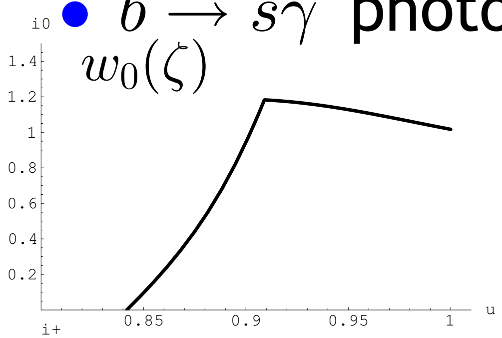
$(\zeta = m_X^{\max},\ |V_{ts}| = |V_{cb}|)$

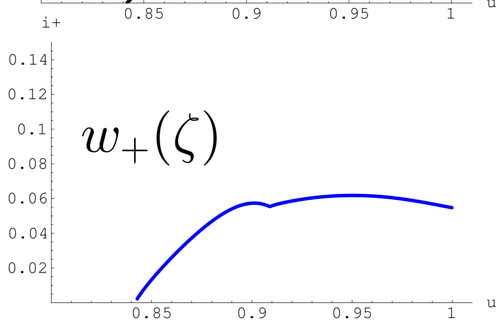
$$\frac{|V_{ub}|}{|V_{ts}|} = \left\{ \frac{6\alpha(1+H^{\gamma}_{mix})C_7(m_b)^2}{\pi} \times \frac{\delta\Gamma(\zeta)}{[I_0(\zeta)+I_+(\zeta)]} \right\}^{\frac{1}{2}}$$

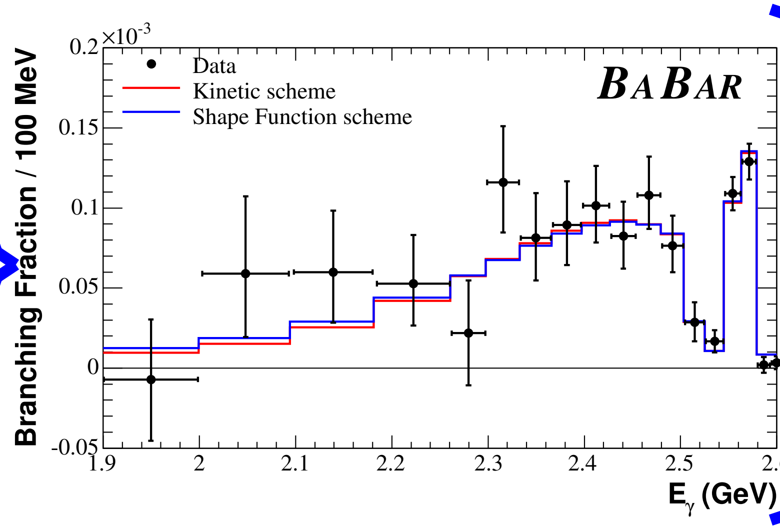
$$= \left\{ \frac{6\alpha(1+H^{\gamma}_{mix})C_7(m_b)^2}{\pi[I_0(\zeta)+I_+(\zeta)]} \right\}^{\frac{1}{2}} \times \left\{ \frac{N_u(\zeta)}{\varepsilon_u} \times \frac{f_{\bar{B}\to X\ell\bar{\nu}}}{N_{SL}} \times \frac{\varepsilon_l^{sl}}{\varepsilon_l^{u}} \times \frac{\varepsilon_{reco}^{sl}}{\varepsilon_{reco}^{u}} \right\}^{\frac{1}{2}}$$

- $b \to s\gamma$ photon energy spectrum

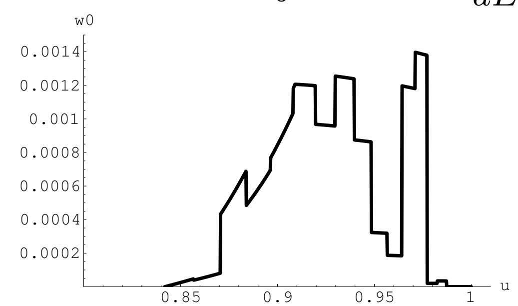
$I_0(\zeta) = \int du\, w_0(\zeta) \frac{d\Gamma}{dE_u}$

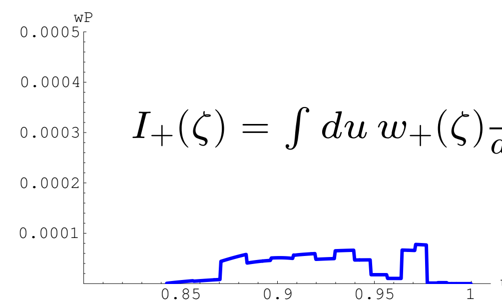






$u = 2E_\gamma/m_B$

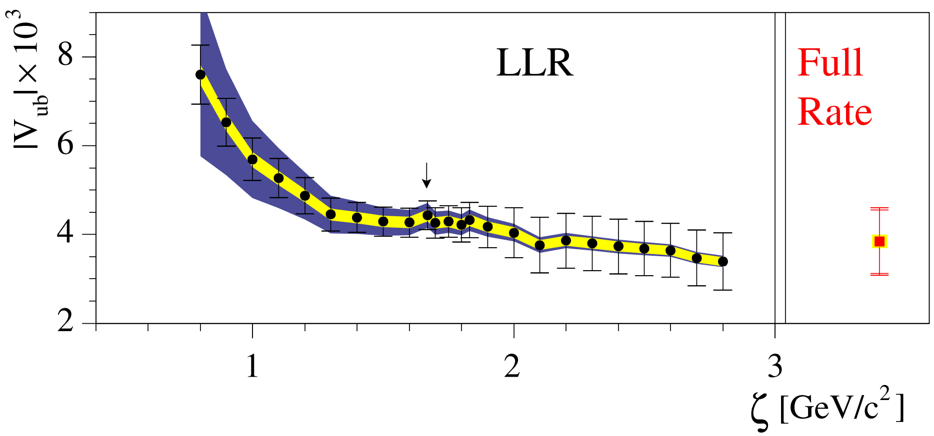


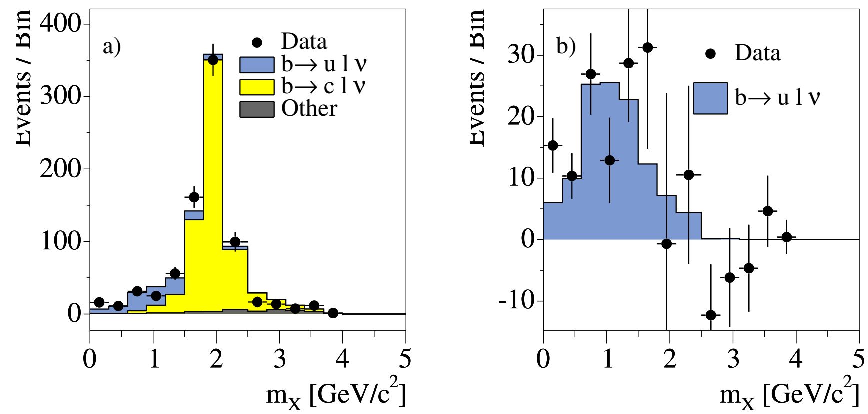


$I_+(\zeta) = \int du\, w_+(\zeta) \frac{d\Gamma}{dE_u}$

Most recent incl. $|V_{ub}|$ determinations

- Leibovich, Low, Rothstein:
  - ▷ no extrapolation using $b \to s\gamma$ spectrum





- Full Rate $m_X < 2.5\,$GeV
  - ▷ no dynamics in bg mass distribution, only detector resolution (plus small non-resonant contributions)
  - ▷ no extrapolation
  - ▷ Determine $|V_{ub}|$ directly from

$$|V_{ub}| = 0.00445 \cdot \left(\frac{\mathcal{B}(b \to u\ell\bar{\nu})}{0.002} \cdot \frac{1.55\,\mathrm{ps}}{\tau_b}\right)^{1/2} \times (1.0 \pm 0.028_{pert} \pm 0.039_{1/m_b^3})$$

Comparison to other BABAR results

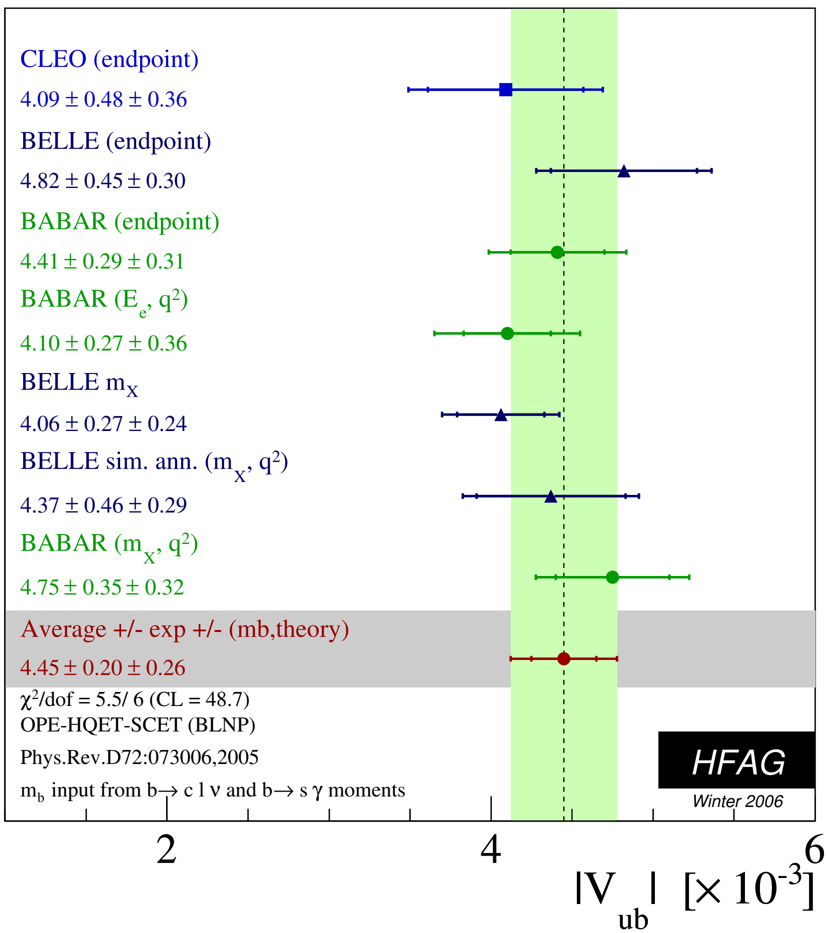
- Transfer of errors
  - away from model-dependent shape function

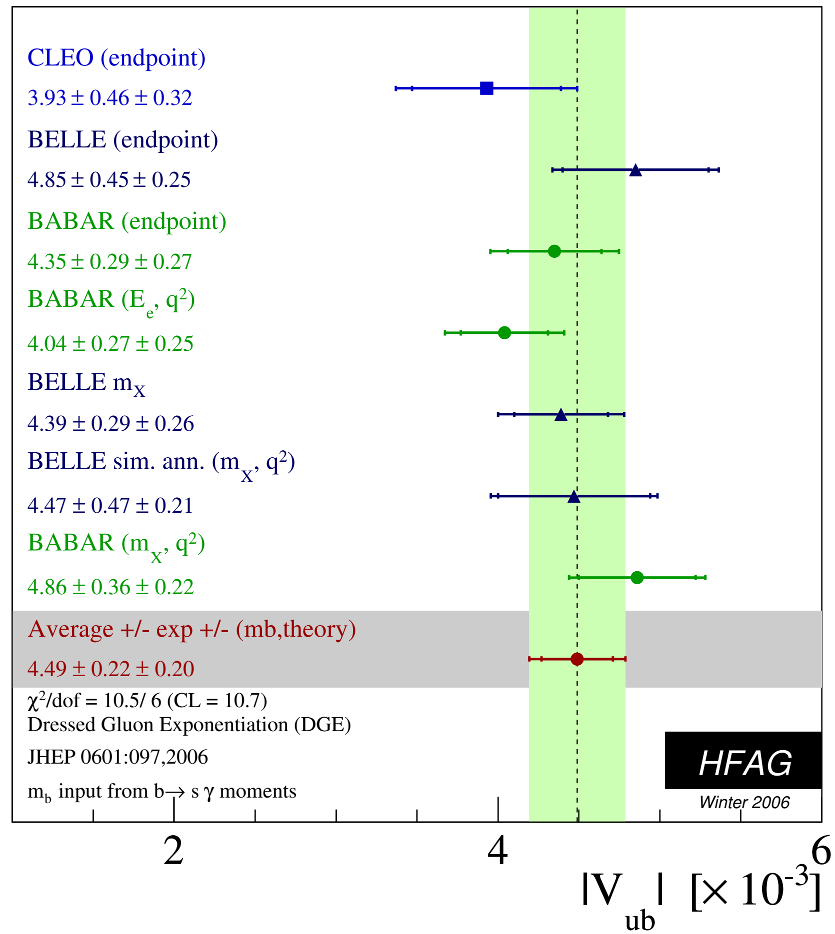
Method	$\lvert V_{ub}\rvert$ $\times 10^3$	stat %	syst %	SF %	theo %	total %
hadronic mass	4.87	3.7	5.3	8.9	4.8	12.6
(m_X, q^2)	4.65	5.2	5.2	9.2	4.8	13.1
(E_ℓ, q^2)	3.95	4.7	4.8	12.6	5.6	15.6
endpoint	4.44	3.6	5.7	9.0	4.8	12.3
with $b \to s\gamma$	4.43	8.4	4.3	3.9	6.4	12.1
full rate	3.84	18.2	5.4	5.6	4.8	20.3

- Full rate: decrease statistical error
  - better fits including $b \to c\ell\bar{\nu}$ 'control samples'
  - . . .
- Combinations methods
  - more will appear in future

World Averages for $|V_{ub}|$

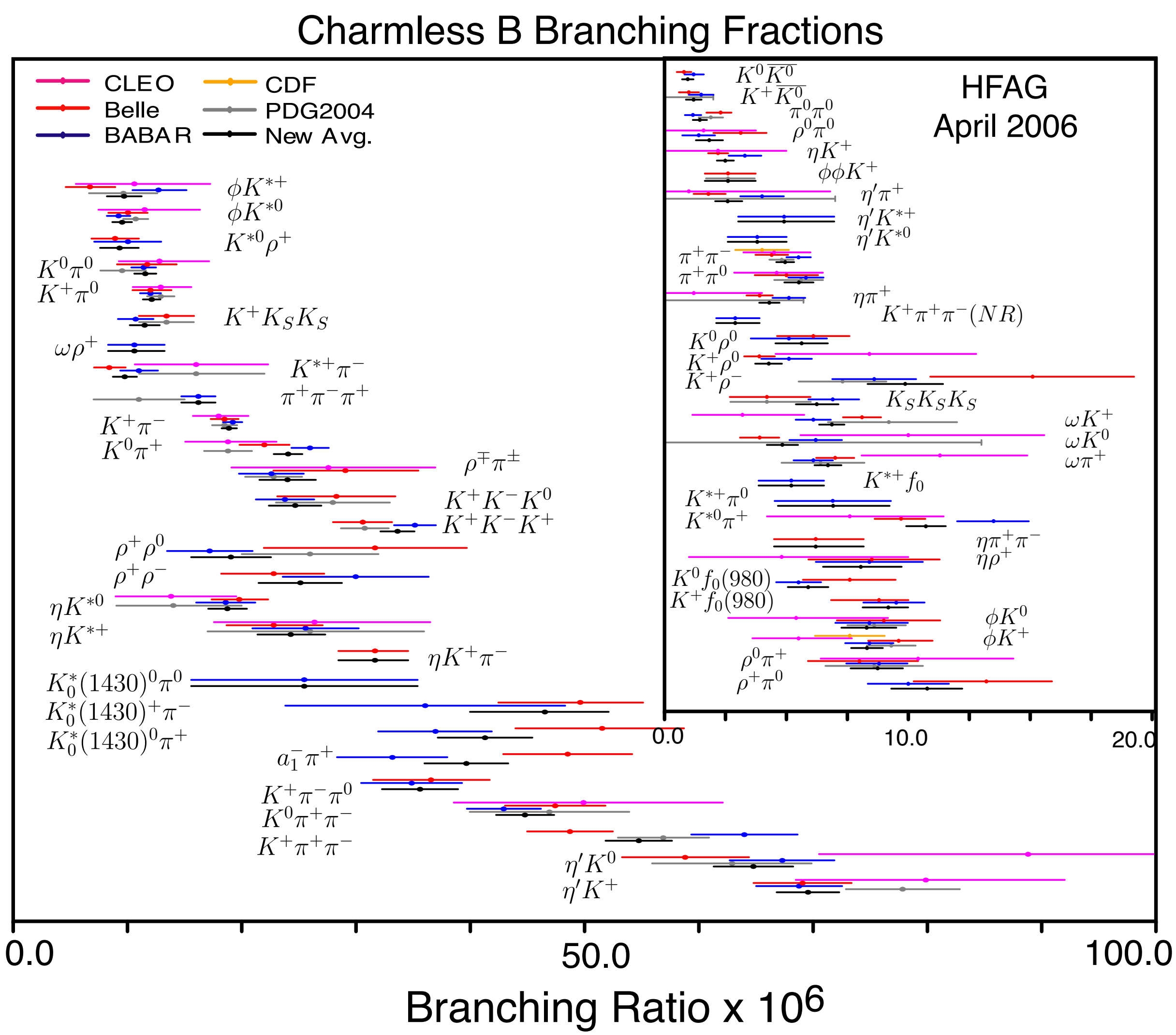
- HFAG averages of $|V_{ub}|$
  - ▷ variety of shape function schemes (BLNP vs DGE)
  - ▷ variety of mass determinations
  - ▷ less than 10% error!





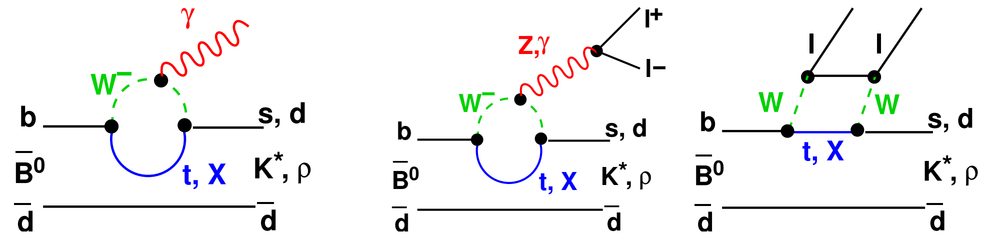
'Charmless': too much to cover

- 59 modes with significant branching fractions
  - Tests of theoretical approaches



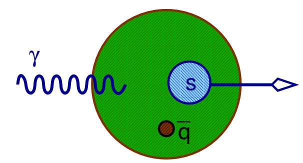
Rare (Radiative) Decays

- Sensitive probe to new physics
  - ▷ Branching fraction
  - ▷ CP asymmetries
  - ▷ forward-backward asymmetries

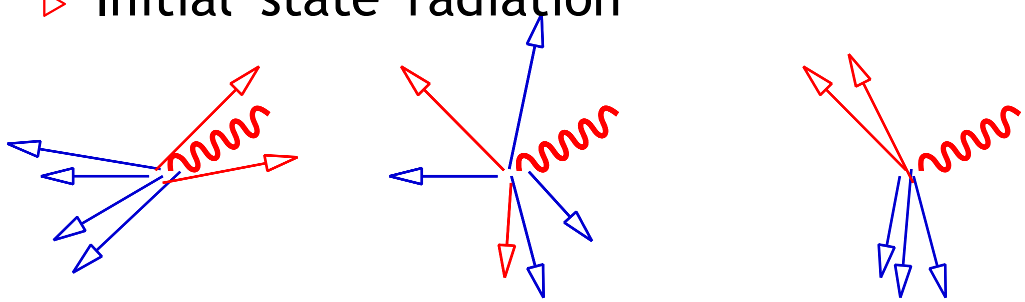


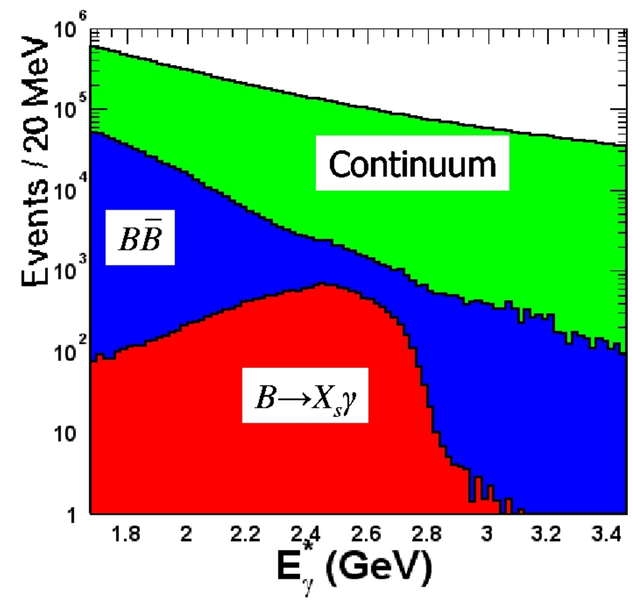
- $b \to s\gamma$ is a direct probe to the b dynamics inside B-meson
  - ▷ two-body decay, e.g. $B \to K^*\gamma$
  - ▷ sensitive to the mass and kinetic energy of b quark

  $\to$ 'shape function'



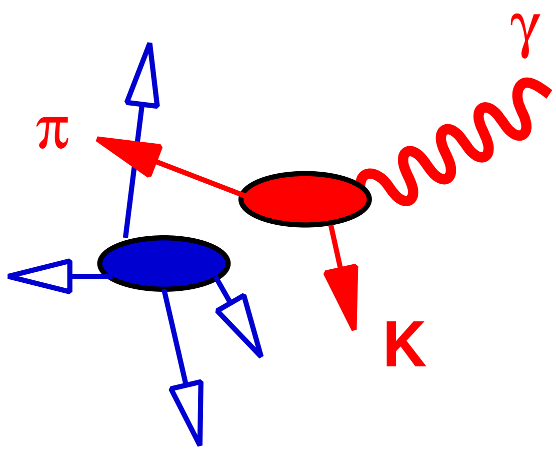
- Difficult measurement
  - ▷ merged π^0 from continuum events
  - ▷ (merged) π^0 from $B\bar{B}$ events
  - ▷ Initial state radiation





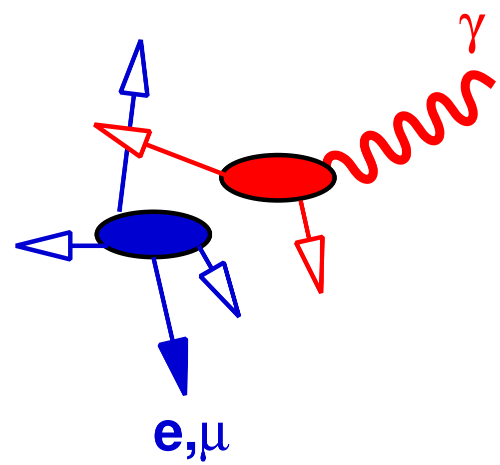
Experimental Methodologies for $b \to s\gamma$

- Sum of exclusive modes 'semi-inclusive'



- Sum of ca. 40 modes
- Full reconstruction of B
  - ▷ m_{ES} and ΔE
  - ▷ Photon measured in B restframe (better resolution!)
- Dominant systematics
  - ▷ missing final states

- (fully) inclusive

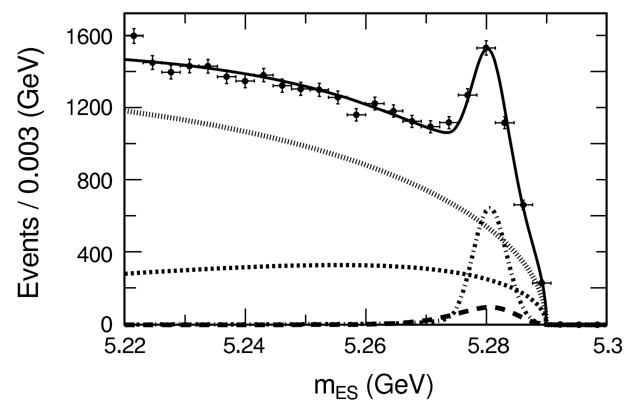


- High-energy photon
  - ▷ $E^*_\gamma > 1.5$ GeV
- Background reduction
  - ▷ lepton tag
- Dominant systematics
  - ▷ B background subtraction

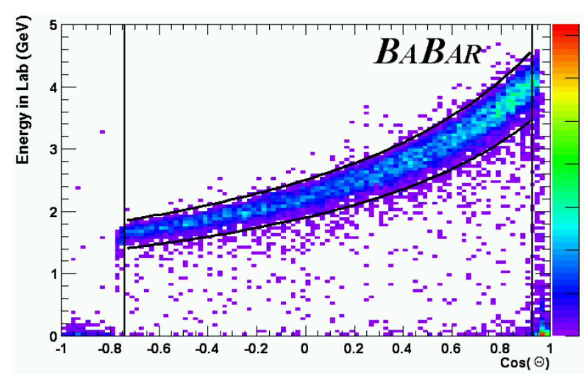
PRD 72, 052004 (2005)
hep-ex/0507001

Reconstruction Techniques

- Semi-inclusive method
  - ▷ Select events with photons $E^*_\gamma > 1.8$ GeV
  - ▷ Reconstruct hadonic system in many decay modes (55% of $\Gamma_{b\to s\gamma}$)
  - ▷ one big complex neural network
  - ▷ Select B candidates with m_{ES} and ΔE for m_{ES}: scale E_γ so that $\Delta E = 0$
  - ▷ For photon energy use $E_\gamma = (m_B^2 - m_X^2)/2$

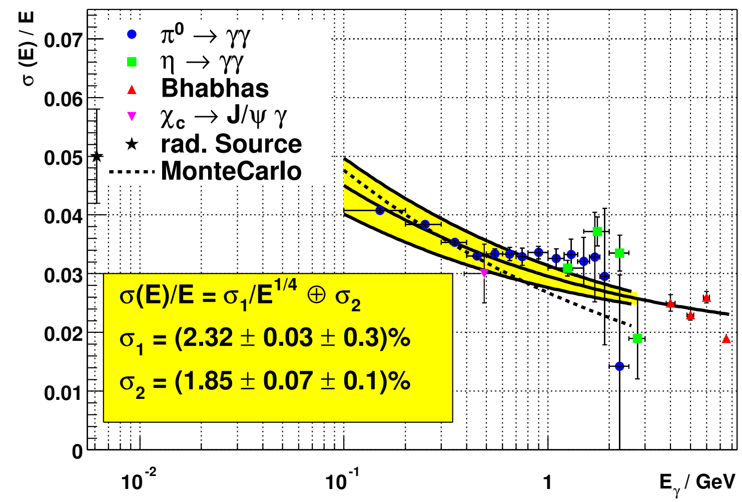


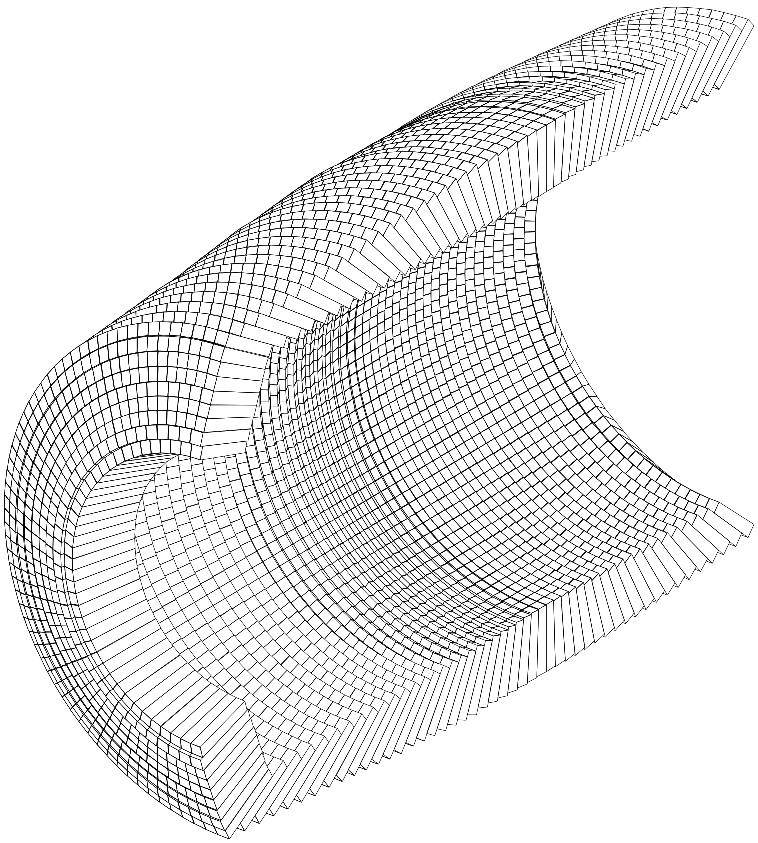
- Fully inclusive method
  - ▷ Lepton $p^* > 1.4$ GeV
  - ▷ Photon $E^*_\gamma > 1.5$ GeV
  - ▷ one big complex neural network
  - ▷ tune MC simulation so that BG described (this step can take very long!)
  - ▷ determine π^0 background yield bin-by-bin and subtract
  - ▷ Assume something about $b \to d\gamma$ and subtract



Energy resolution

- Energy resolution of BABAR calorimeter
  - ▷ Photons have energy in range 1.5-4.5 GeV
  - ▷ Resolution affected by
    - scintillation photon statistics
    - leakage, non-uniformity



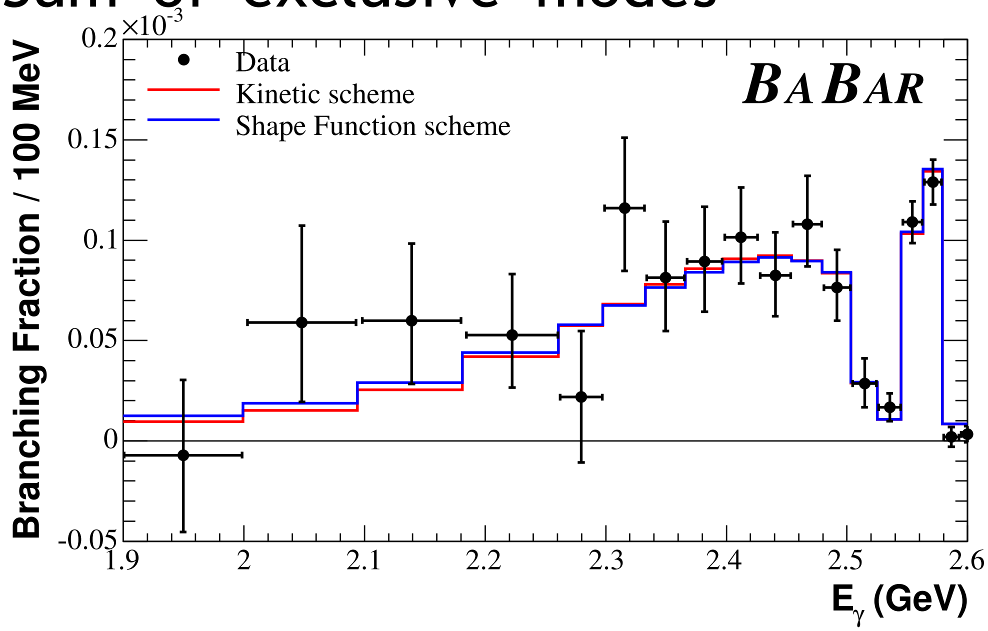


- BABAR electromagnetic calorimeter
  - ▷ 6580 CsI(Tl) doped crystals
  - ▷ 16-17 X_0 thick
- Belle similar detector
  - ▷ better resolution (calibration)

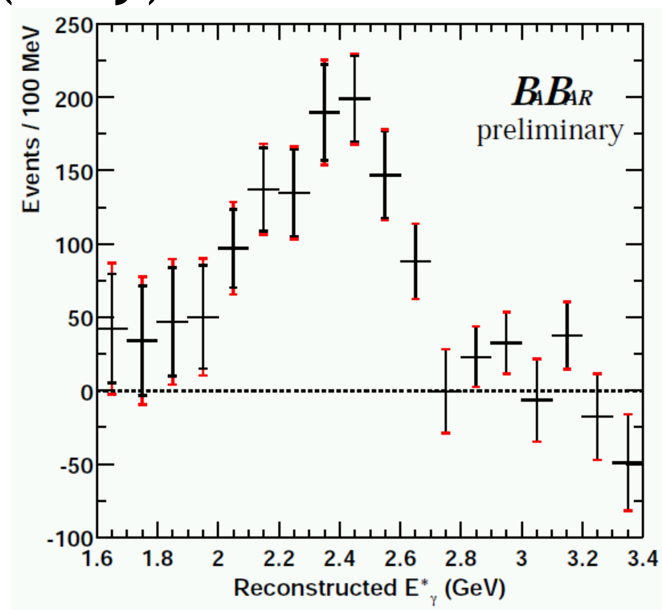
PRD 72, 052004 (2005)
hep-ex/0507001

Photon energy spectrum from $b \to s\gamma$

- Sum of exclusive modes



- (fully) inclusive



- Differences in resolution: Photons from $B \to K^*\gamma$!
- Partial branching fractions $E_\gamma > 1.6$ GeV

$$\begin{aligned} \mathcal{B}_{\rm semi} &= (3.57 \pm 0.20 \pm 0.52 \pm 0.04) \times 10^{-4} \\ \mathcal{B}_{\rm incl} &= (3.91 \pm 0.31 \pm 0.36 \pm 0.30) \times 10^{-4} \end{aligned}$$

- For parameters of HQE: moments of spectrum!

PRL 93, 021804 (2004)
hep-ex/0507001

CP Asymmetry in $b \to s\gamma$

- In SM, asymmetry expected to be very small

$$A_{CP} = \frac{\Gamma(b \to s\gamma + b \to d\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma + \bar{b} \to \bar{d}\gamma)}{\Gamma(b \to s\gamma + b \to d\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma + \bar{b} \to \bar{d}\gamma)}$$

- How to discriminate between b and $\bar{b}$ decays with photons?
- Semi-exclusive: Self-tagging final states (K charge)
  - ▷ $B^0 \to K^*\gamma \to (K^+\pi^-)\gamma$
- Inclusive: Charge of lepton tag

$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}\frac{1}{1-2w}$$

$w = (11.9 \pm 0.4)\%$, mostly from $B^0\bar{B}^0$ oscillations (50%)

- Results consistent (with zero)

$$\boxed{\begin{aligned} A_{\rm semi} &= 0.025 \pm 0.050 \pm 0.015 \\ A_{\rm incl} &= 0.110 \pm 0.115 \pm 0.017 \end{aligned}}$$

$B \to (\rho, \omega)\gamma$ Penguins

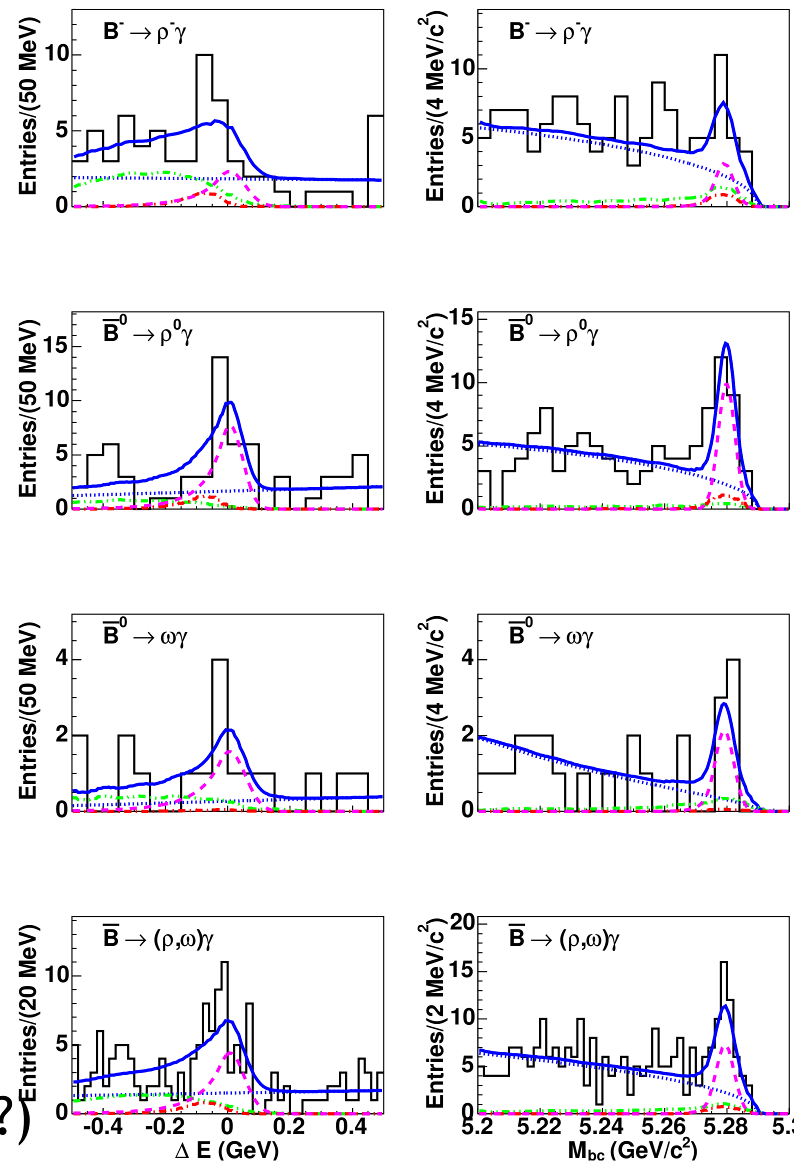
- In SM, suppressed by $|V_{td}|^2/|V_{ts}|^2$
- Excl. reconstruction in ca. $360\,\mathrm{fb}^{-1}$

$$B^- \to \rho^-\gamma$$
$$\bar{B}^0 \to (\rho^0, \omega)\gamma$$

- Veto
  - ▷ charged kaons
  - ▷ tracks possibly forming K_S^0
  - ▷ $B \to K^*\gamma$ (!)
- Belle results consistent with SM

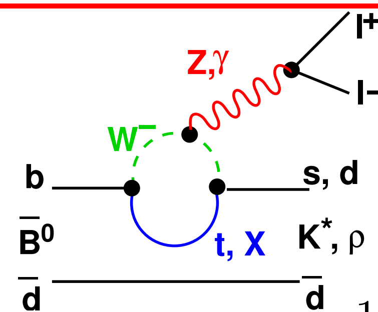
$$\mathcal{B}(\bar{B} \to (\rho,\omega)\gamma) = (1.32\,^{+0.34}_{-0.31}\,^{+0.10}_{-0.09}) \times 10^{-6}$$
$$|V_{td}|/|V_{ts}| = 0.199\,^{+0.026}_{-0.025}\mathrm{exp}\,^{+0.018}_{-0.015}\mathrm{theo}$$

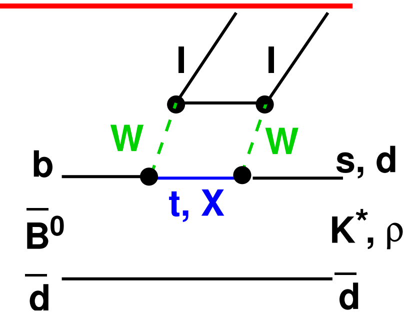
BABAR sees nothing yet (deja vu . . . ?)



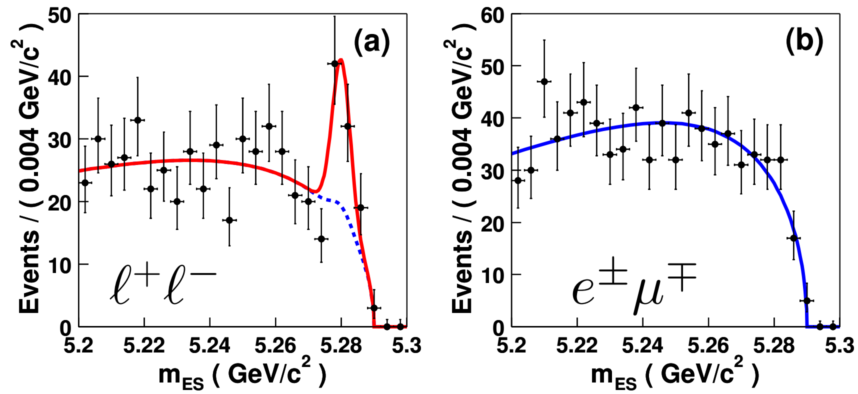
PRL 93, 081802 (2004)

Reconstructing $b \to s\ell^+\ell^-$





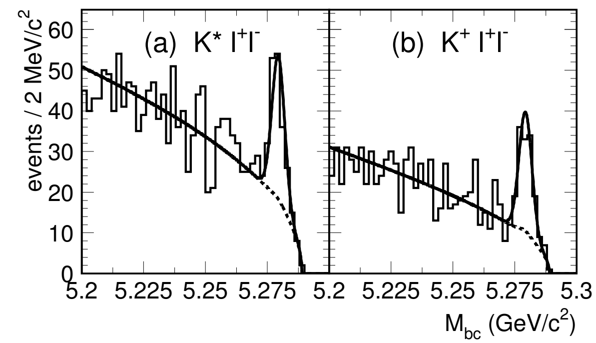
- Physics interest
  - ▷ Rate
  - ▷ Charge asymmetry
- Semi-inclusive reconstruction in $\mathcal{L} = 80\,\mathrm{fb}^{-1}$
  - ▷ X_s consists of one K^0_S, $K^{\pm}$ plus 1-2 pions (at most one π^0)
  - ▷ about 50% of the total rate reconstructed or 30% missing (is $K^0_L \sim K^0_S$)
- Vetos
  - ▷ $J/\psi \to \ell^+\ell^-$
  - ▷ $K^*\gamma$ with $\gamma \to e^+e^-$
- Results consistent with SM



$$
\begin{aligned}
\mathcal{B}(m_{\ell\ell} > 0.2\,\mathrm{GeV}) &= (5.6 \pm 1.5 \pm 0.6 \pm 1.1) \times 10^{-6} \\
&= (4.2 \pm 0.7) \times 10^{-6} \quad (SM) \\
A_{CP} &= -0.22 \pm 0.26 \pm 0.02
\end{aligned}
$$

$B \to K^{(*)}\ell^+\ell^-$ Asymmetry

- New physics can alter Wilson coefficients
  - ▷ $\overline{C}_7^{eff}$, $\overline{C}_9^{eff}$, $\overline{C}_{10}^{eff}$
  - ▷ magnitude of $\overline{C}_7^{eff}$ constrained by $b \to s\gamma$ rate
  - ▷ sign of $\overline{C}_7^{eff}$ accessible via
    FB asymmetry or rate differential in Q^2 and θ



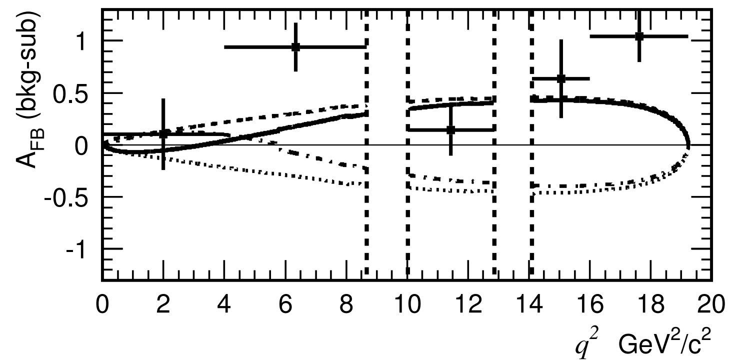
- FB asymmetry defined as

$$A_{FB} = \frac{\int_{-1}^{1} \mathrm{sgn}(\cos\theta) g(q^2,\theta) d\cos\theta}{\int_{-1}^{1} g(q^2,\theta) d\cos\theta}$$

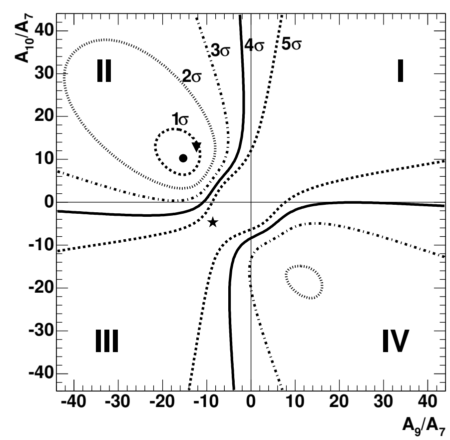
$$g(q^2,\theta) = \frac{d^2\Gamma}{dq^2 d\cos\theta}$$

$$\theta = \angle(\ell^-, B)$$

θ is measured in the dilepton rest frame



- Belle result, 386M$B\bar{B}$
  (A_i leading order terms of W.C.)



hep-ex/0604018

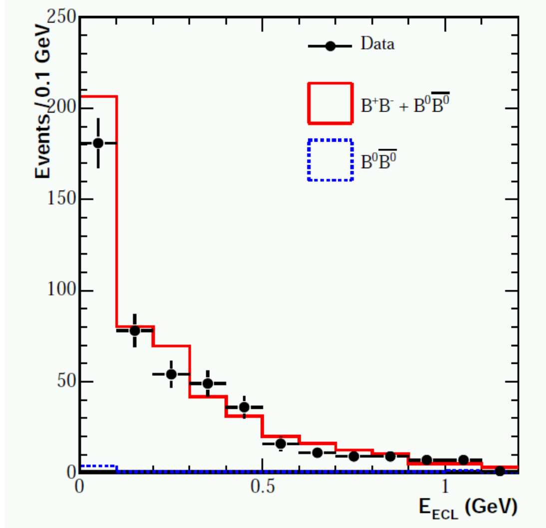
Evidence for $B^+ \to \tau^+ \nu$

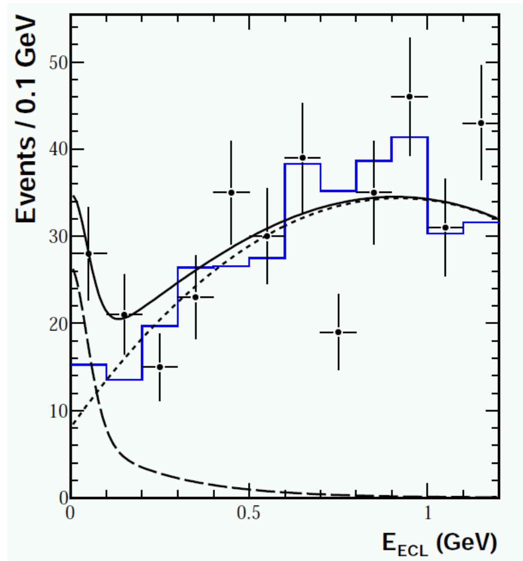
- New Belle result, $\mathcal{L} = 414\,\mathrm{fb}^{-1}$
  - ▷ Hadronic Recoil physics
- Signal event signature
  - ▷ τ decays: $\ell\nu\bar{\nu}$, $h(\pi^0)\nu$, $hhh\nu$
  - ▷ E_{ECL}: unassigned energy in ECAL
    extensive validation with sidebands
- Spurious energy deposits
  - ▷ soft π^0 from B_{reco}
  - ▷ hadronic showers (split-offs)
- Result

$$
\begin{aligned}
n_{\mathrm{Sig}} &= 21.2\,^{+6.7}_{-5.7} \\
\mathcal{B}(B^+ \to \tau^+\nu) &= (1.06\,^{+0.34}_{-0.28}\,^{+0.18}_{-0.16}) \times 10^{-4} \\
f_B &= 0.176\,^{+0.028}_{-0.023}\,^{+0.020}_{-0.019}\ \mathrm{GeV}
\end{aligned}
$$

  - ▷ 4.2σ Significance

Double tag control sample





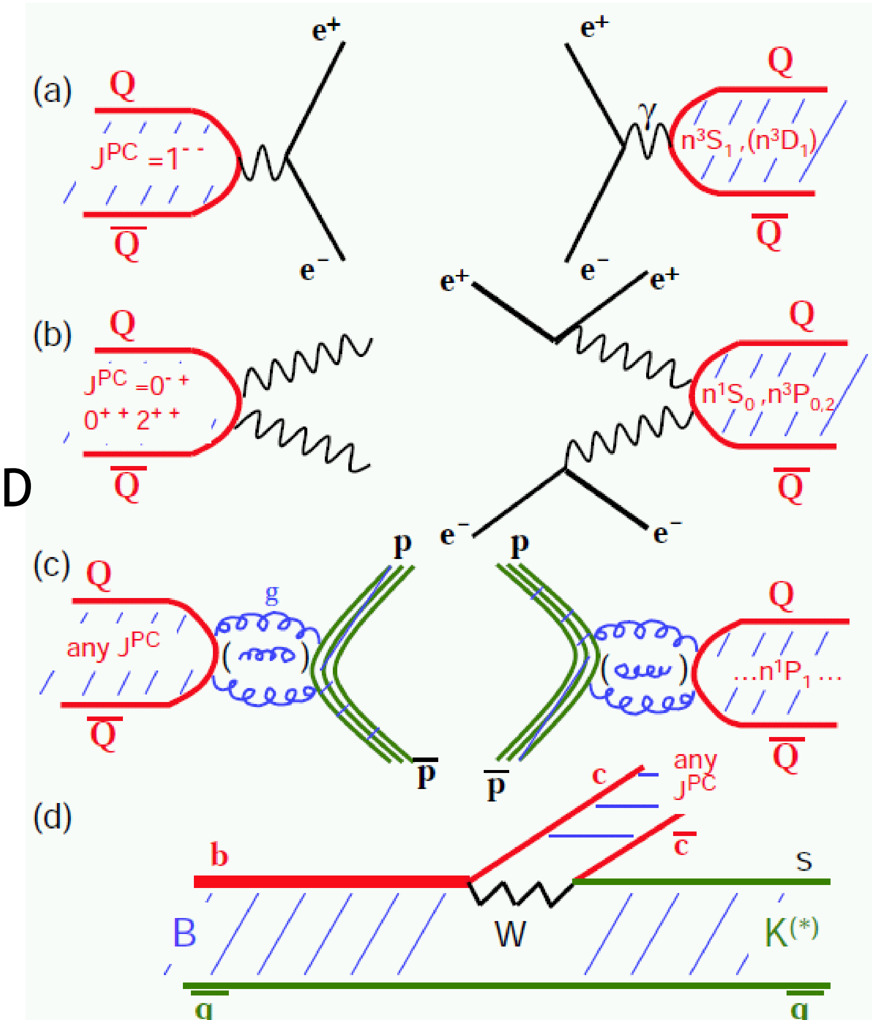
Introduction

- Heavy quarkonia are bound states
  - ▷ $b\bar{b}$ and $c\bar{c}$
- Large m_Q
  - ▷ small velocities of constituents
  - ▷ α_S is small in production and decay

$\Rightarrow$ Testing ground for
  - ▷ NRQCD and lattice QCD
  - ▷ perturbative and non-perturbative QCD
  - ▷ potential models

- Production of onium
  - ▷ color singlet state
  - ▷ color octet state
  - ▷ Color evaporation model

Decay: Production:



In B decays

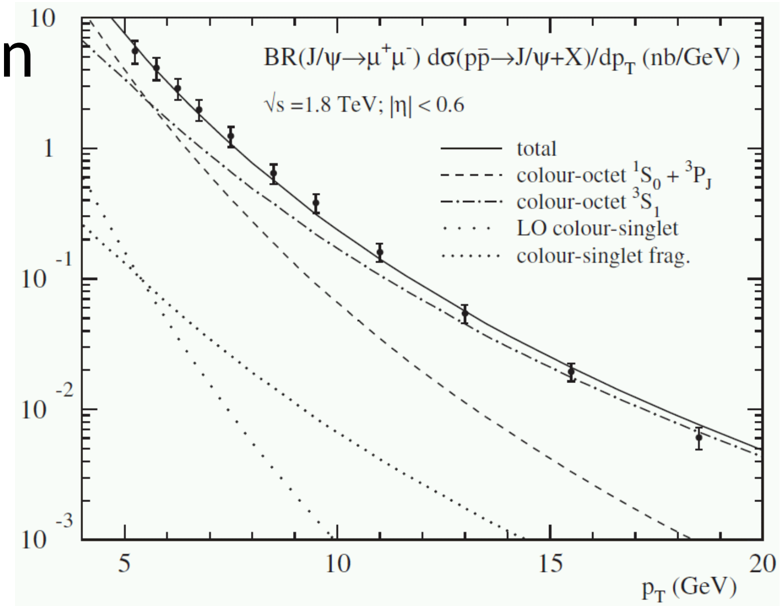
Hadroproduction

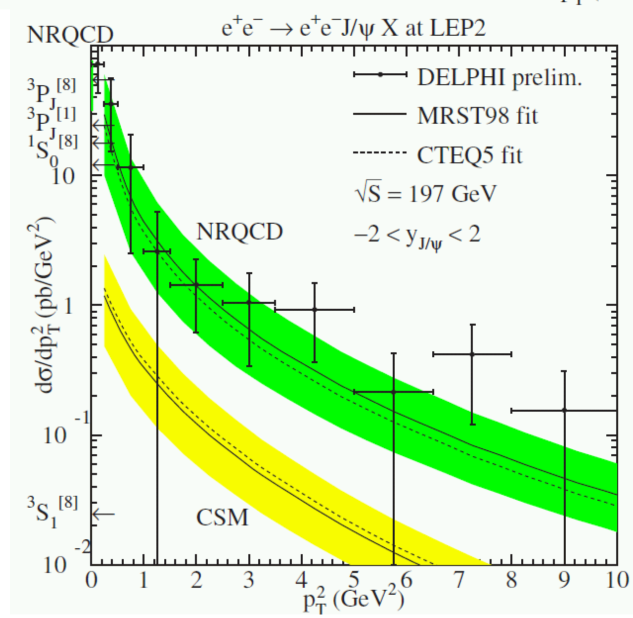
- Charmonium production at Tevatron
- Color-singlet model
  - ▷ falls short in describing production

  NRQCD approach: factorization
  - ▷ 'universal' matrix elements
  - ▷ process dependent hard coefficients
- Including color-octet contributions
  - ▷ decent agreement
  - ▷ ME from fits to data

  'accomodating' the cross section
- Works also at LEP2
  - ▷ ME from Tevatron
  - ▷ Different linear combination

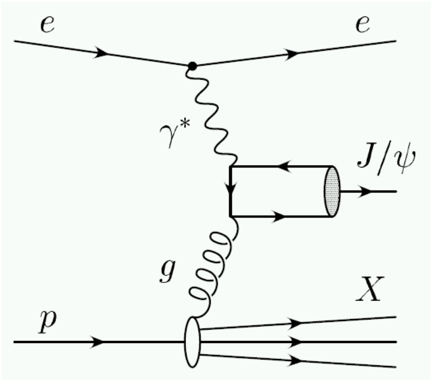
  'kind of'





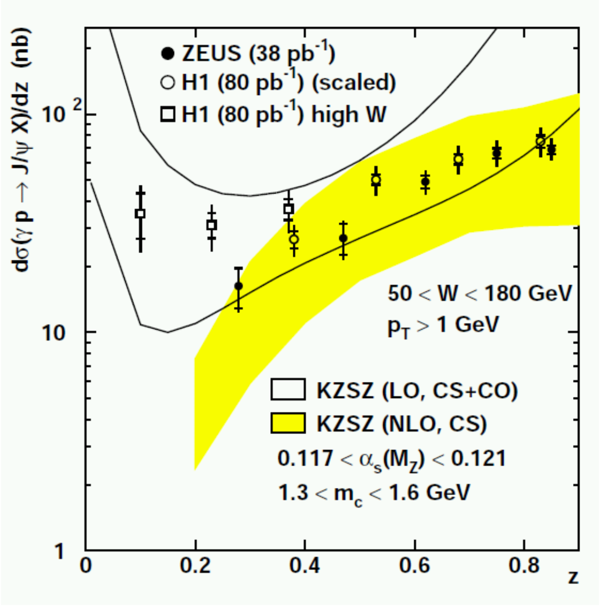
HERA: Photoproduction

- Quasi-real photon $(Q^2 \sim 0)$

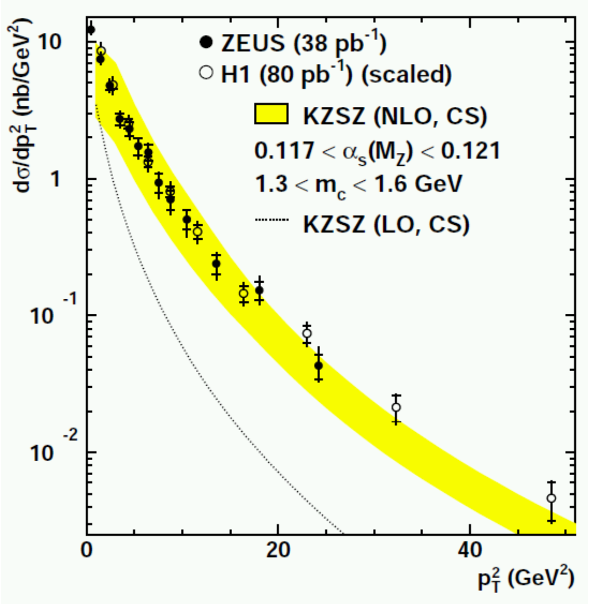


Elasticity

$$z = \frac{(E-p_z)_{J/\psi}}{(E-p_z)_X}$$

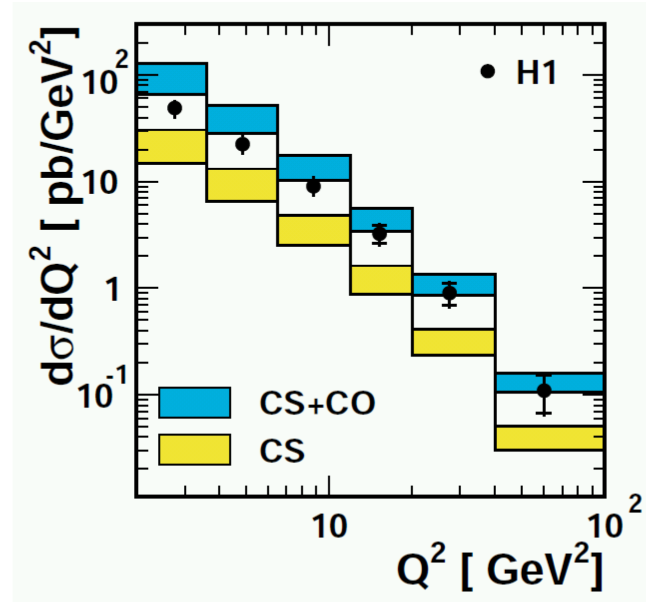


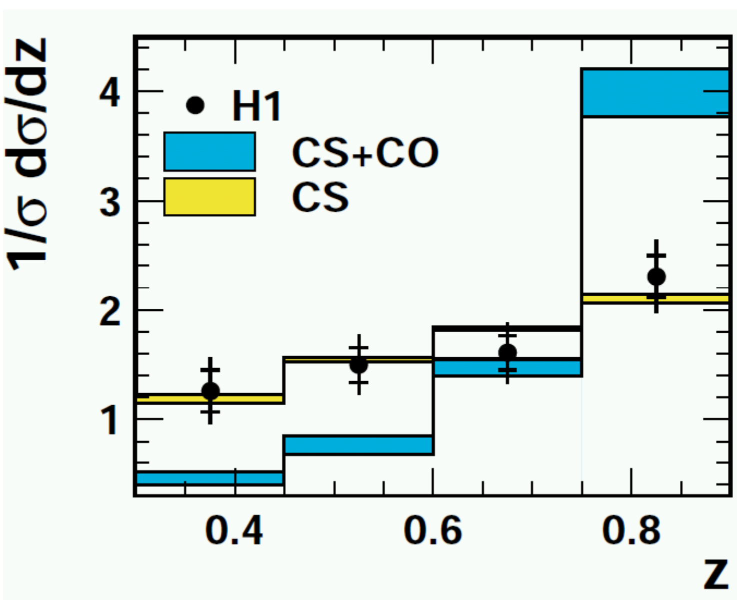
- Inelastic J/ψ production
  - ▷ Little room for COM ($p_\perp$ cut OK?)
- Differential spectrum with CSM
  - ▷ Large uncertainties due to m_c
- COM only at leading order
  - ▷ multiple soft-gluon emission near $z = 1$
  - ▷ v expansion breaks down near $z = 1$ $\longrightarrow$SF

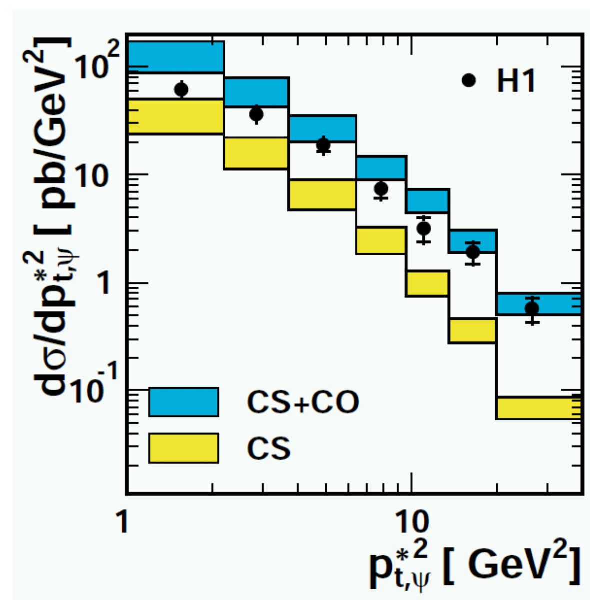


HERA Deep-inelastic Scattering

- NRQCD prediction
  - ▷ ME from Tevatron
  - ▷ different LC of ME than at Tevatron
- Situation looks somewhat better
  - ▷ Results from ZEUS somewhat worse
- Inelasticity?





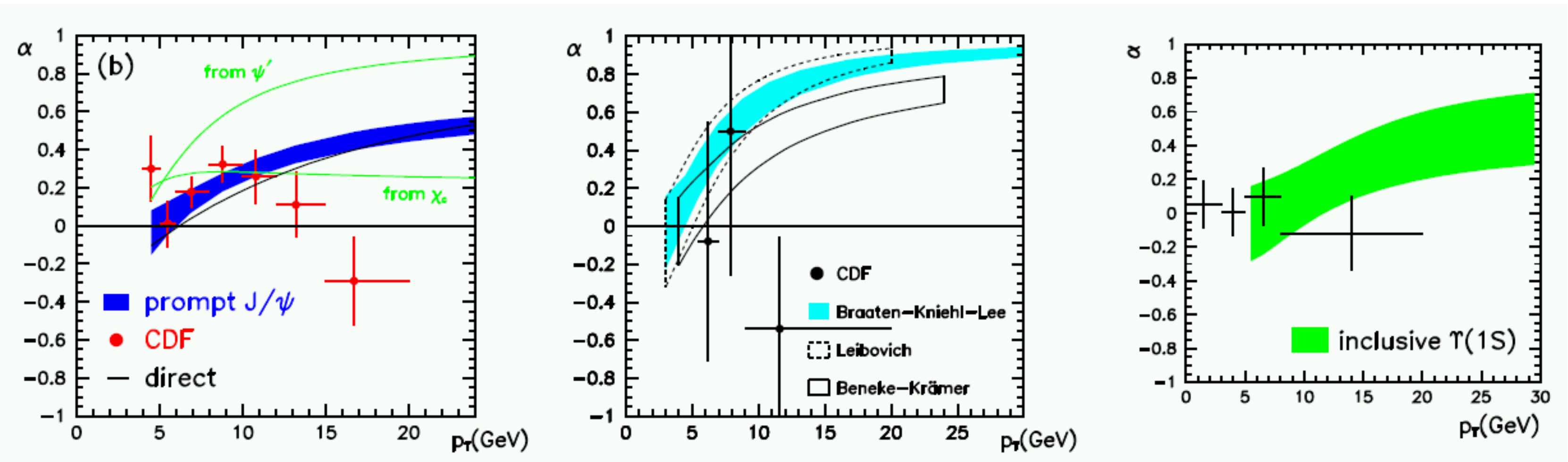


Quarkonium Polarization

- At large $p_\perp$, gluon is nearly on mass shell
  - ▷ transversely polarized
  - ▷ gluon's polarization transferred to J/ψ
  - ▷ Dilution by radiative corrections and color-singlet production
- Measurement of lepton angular distribution

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha(p_\perp)\cos^2\theta,$$

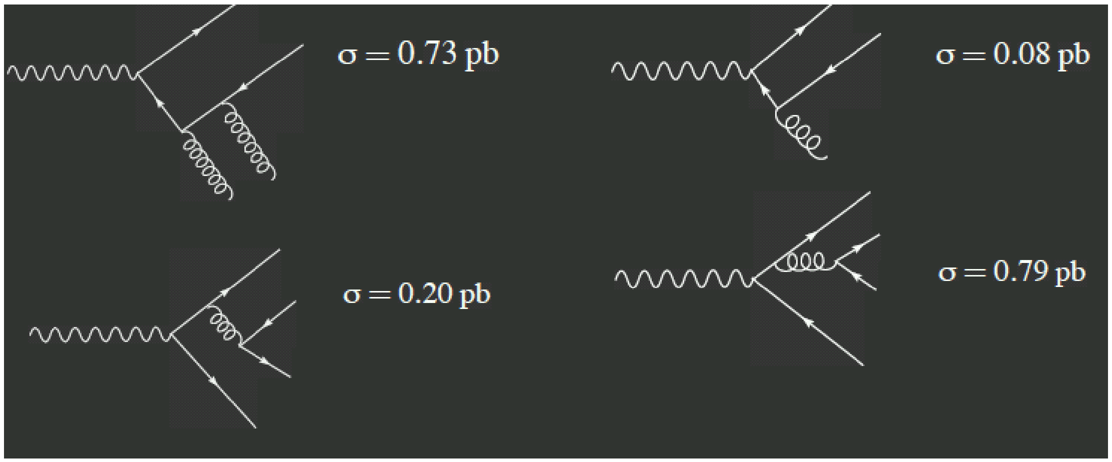
where $\alpha = 1$ corresponds to 100% transversely polarized



- New data not yet/conclusive

Charmonium Production at *B*-factories

- NRQCD predictions



CO: 0.93 pb CS: 0.87 pb

BABAR

$\sigma_{tot} = 2.52 \pm 0.21 \pm 0.21$ pb

Belle

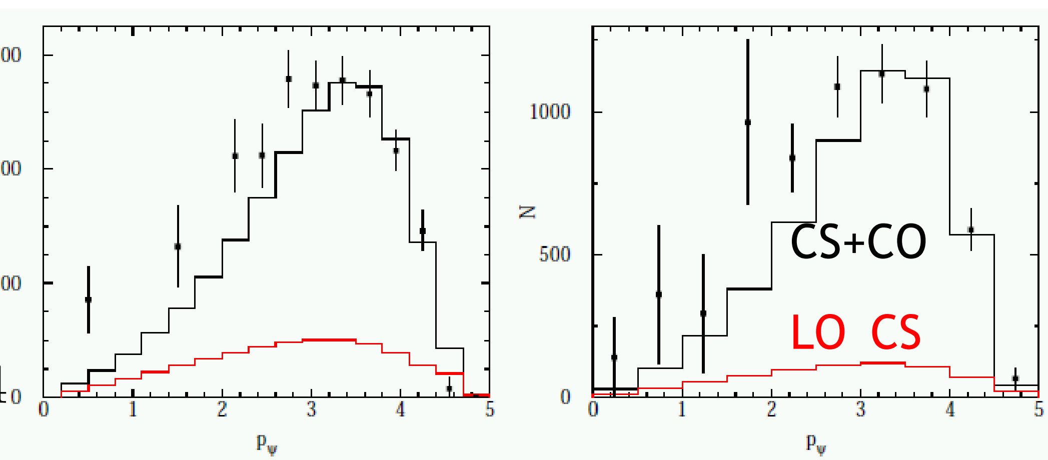
$\sigma_{tot} = 1.47 \pm 0.10 \pm 0.13$ pb

- Experiment vs. theory
  - ▷ resummed endpoint logs
  - ▷ disagreement in

    $R = \sigma(J/\psi\, c\bar{c})/\sigma(J/\psi\, X)$

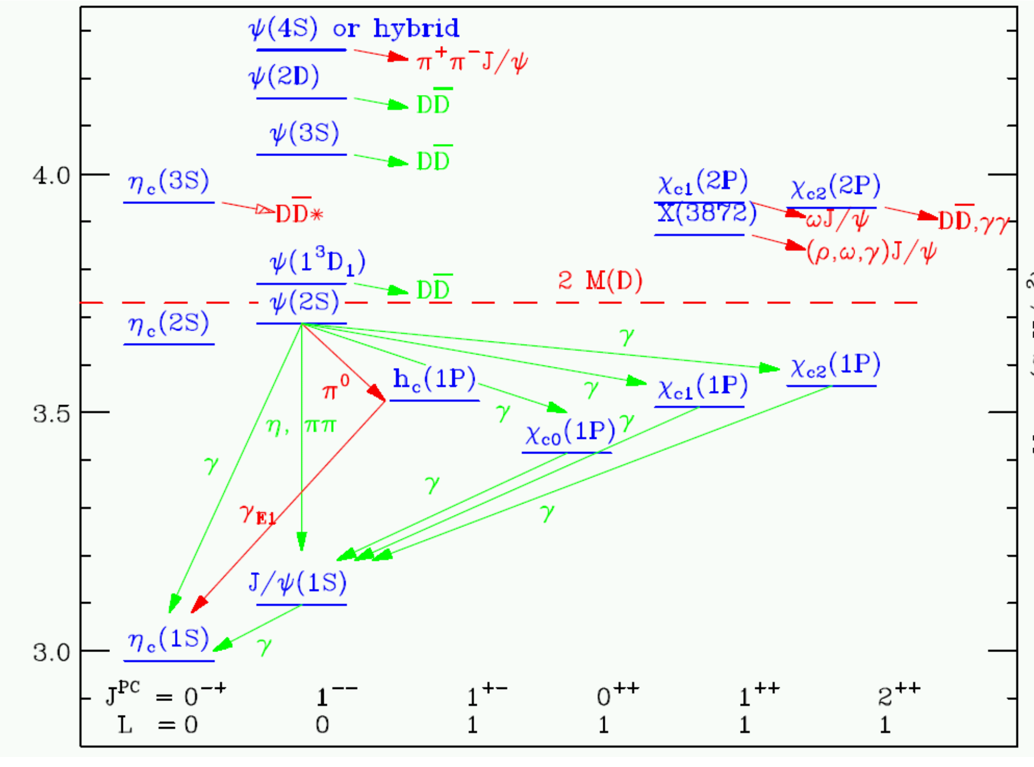
    NRQCD: $R \approx 0.1$

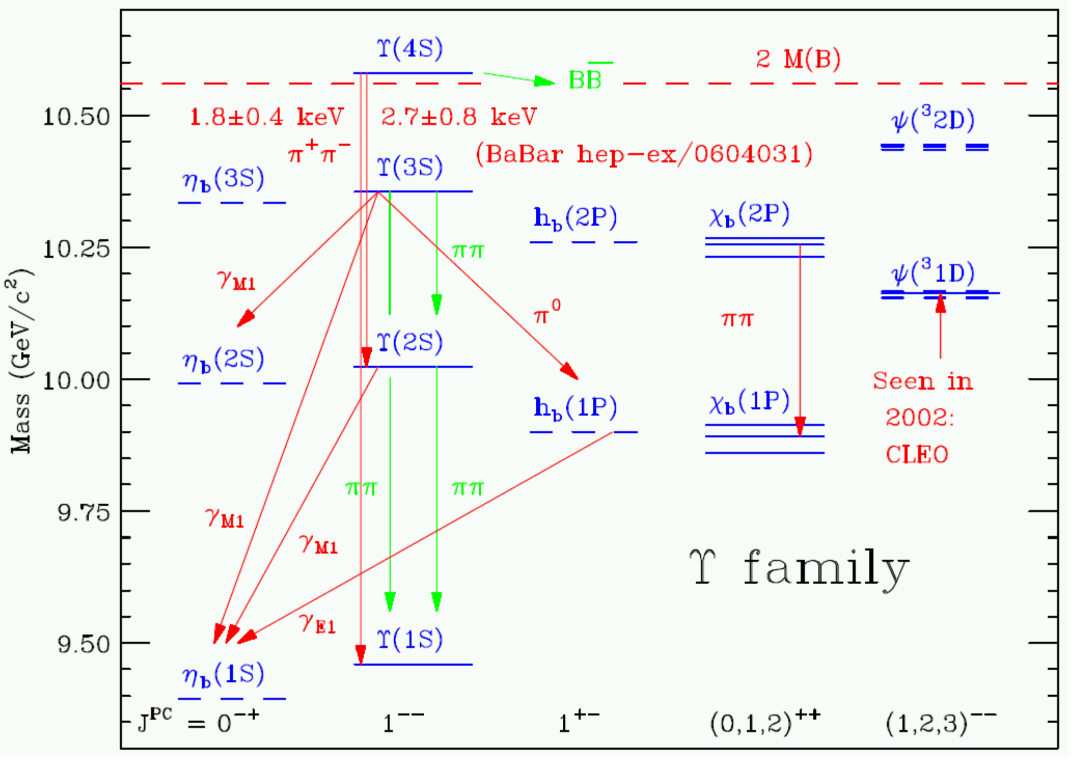
    Belle: $R = 0.82 \pm 0.15 \pm 0.14$



Spectroscopy

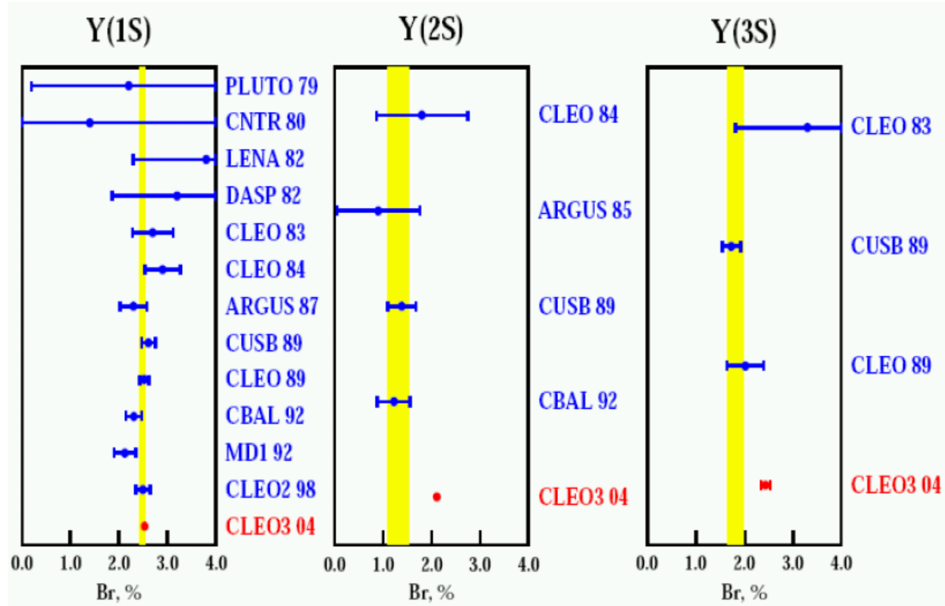
- To measure and understand the states and transitions
  - ▷ lattice
  - ▷ relativistic potential models

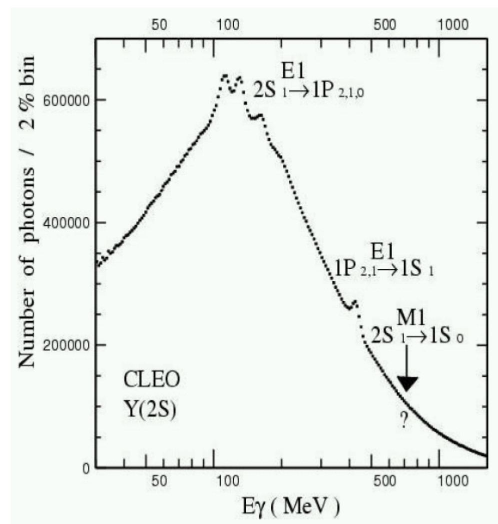




Physics at the $\Upsilon(nS)$

- Masses
  - ▷ Test of (unquenched) lattice QCD
- Total and leptonic width
  - ▷ Enter in many pQCD calculations
  - ▷ Significant changes wrt PDG
- J/ψ production in $\Upsilon(1S)$ decays
  - ▷ Test (successful) of CO model
- Di-pion transitions from $\Upsilon(nS)$
  - ▷ Searches for h_b
- Radiative transitions from $\Upsilon(nS)$
  - ▷ Test of relativistic corrections
  - ▷ Search for $\eta_b(1S)$ and $\eta_b(2S)$





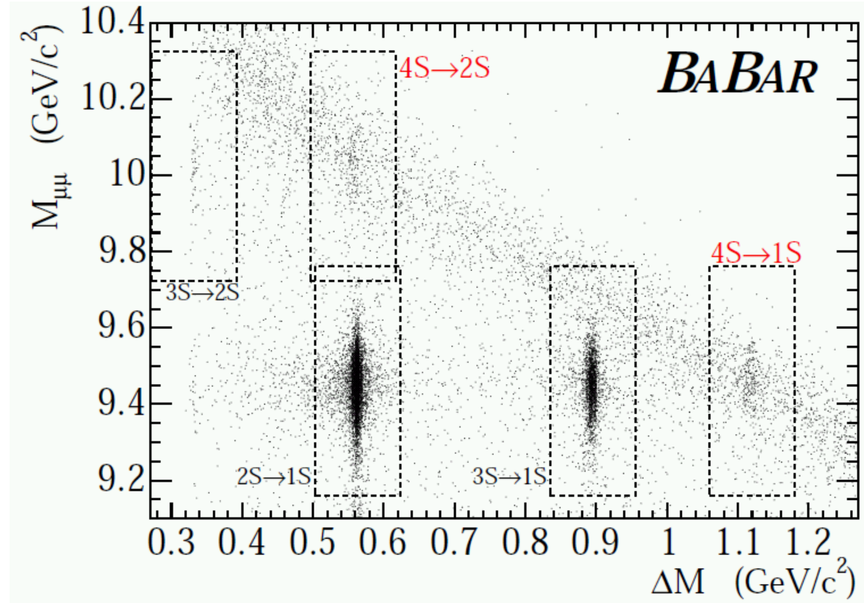
Hadronic $\Upsilon(mS) \to \Upsilon(nS)$ Transitions

- Measurements at the B-factories
  - $\Delta m = m_{\pi\pi\mu\mu} - m_{\mu\mu} \sim m_{nS} - m_{mS}$
  - Study dipion mass and rates

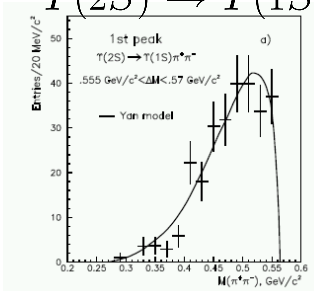
$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)\right) = (0.90 \pm 0.15) \times 10^{-4},$$
$$\mathcal{B}\left(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)\right) = (1.29 \pm 0.32) \times 10^{-4},$$
$$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)) = (1.8 \pm 0.4)\ \mathrm{keV},$$

and

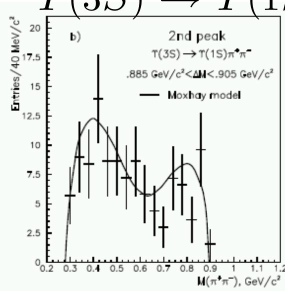
$$\Gamma(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)) = (2.7 \pm 0.8)\ \mathrm{keV}.$$



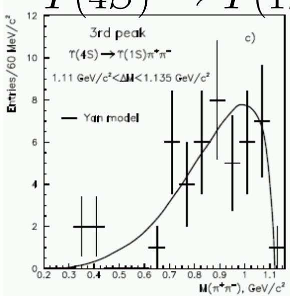
$\Upsilon(2S) \to \Upsilon(1S)$



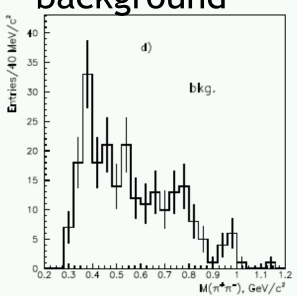
$\Upsilon(3S) \to \Upsilon(1S)$

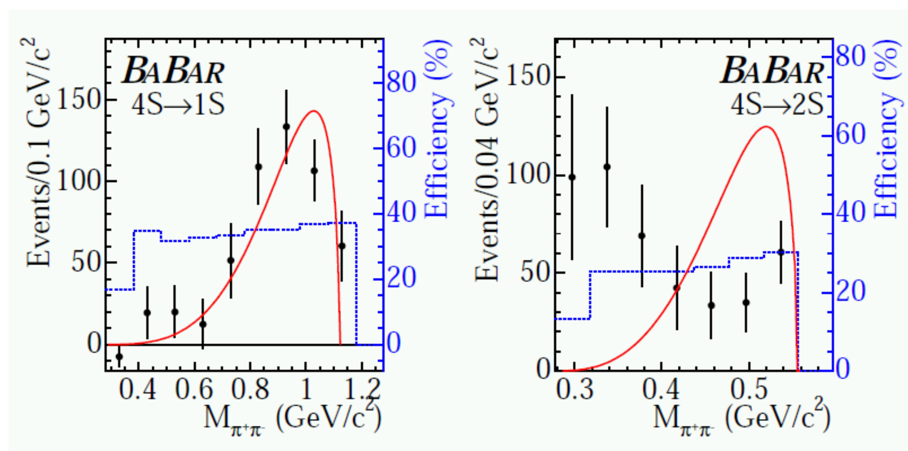


$\Upsilon(4S) \to \Upsilon(1S)$



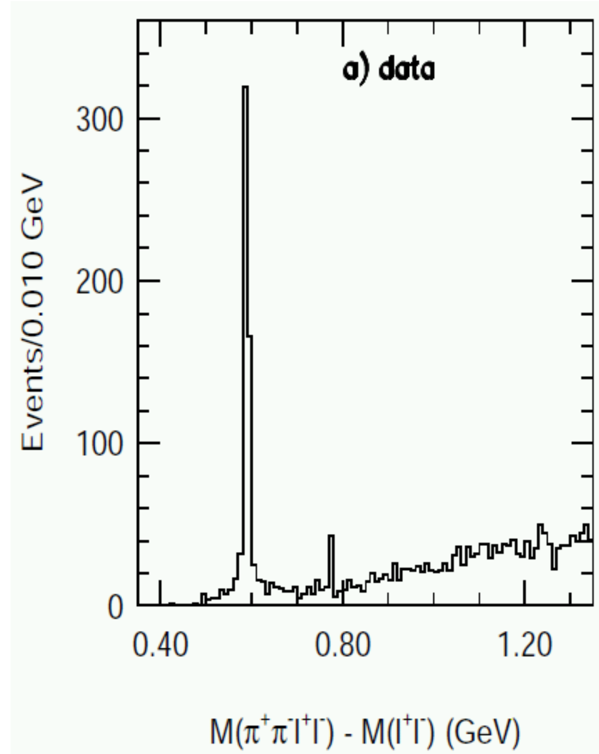
background

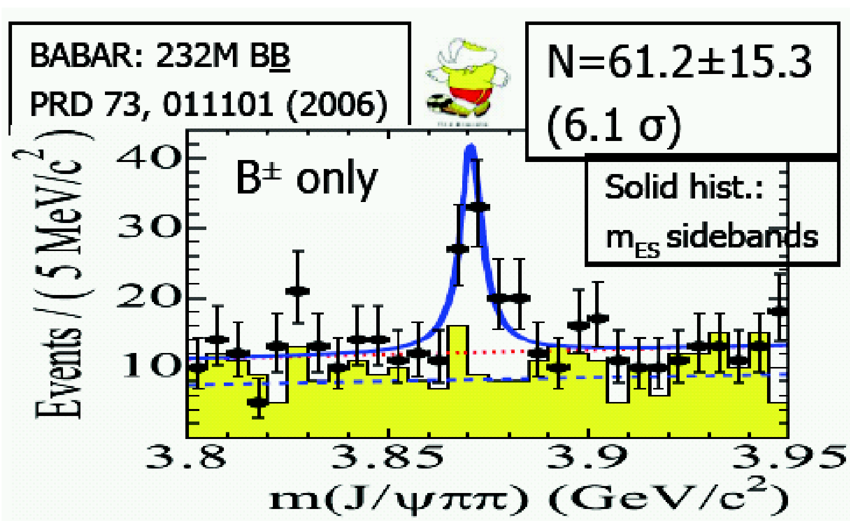


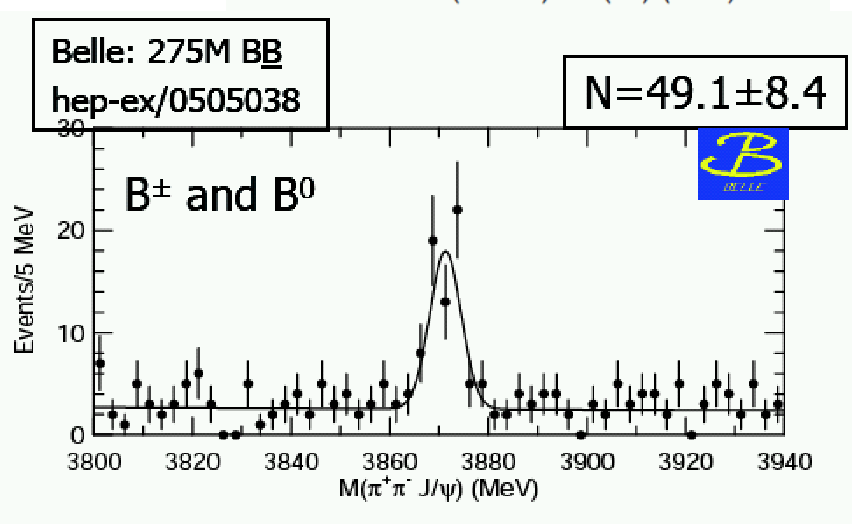


$X(3872)$

- $B \to K X(3872), X(3872) \to \pi^+\pi^- J/\psi$
  - ▷ The first of a series of new states
  - ▷ Belle, CDF, DO, BABAR
  - ▷ Molecule $(D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2}$?
- Probably $I = 0, J^{PC} = 1^{++}$
  - ▷ $X(3872) \to J/\psi\,\gamma$
  - ▷ $m_{\pi^+\pi^-}$ distribution
  - ▷ decay angular distributions
  - ▷ decays near threshold







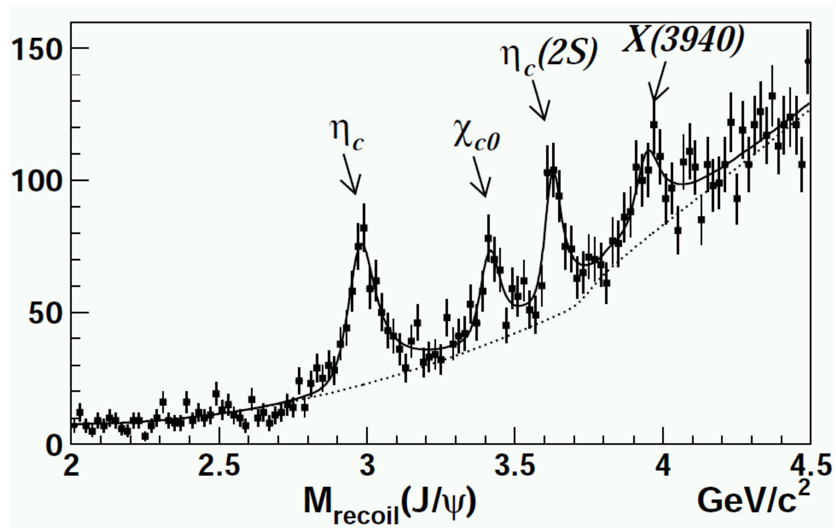
States around 3940 MeV

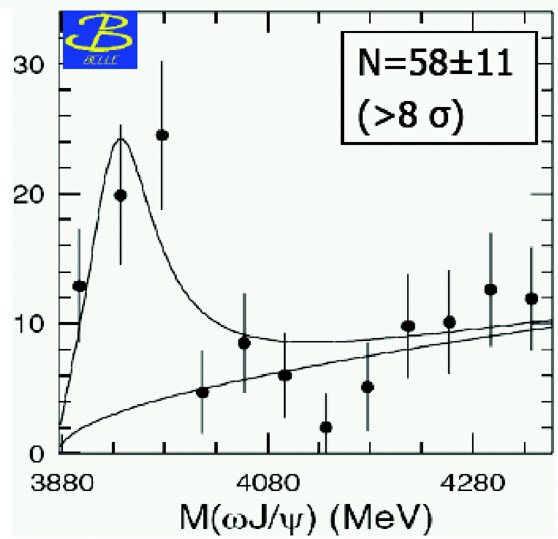
- Belle discovery in recoil against J/ψ with 3 known $c\bar{c}$ states
  - ▷ X(3940)
  - ▷ Possible interpretation: $\eta_c(3S)$

    $\rightarrow$ $J^{PC} = 0^{-+}$?
- Above threshold $D^{(*)}\bar{D}$
  - ▷ seen $X \rightarrow D^*\bar{D}$
  - ▷ only UL for $X \rightarrow D\bar{D}$
- $Y(3940)$ – same as $X(3940)$?
  - ▷ Observed in $Bp \rightarrow K^+Y$
  - ▷ $Y(3940) \rightarrow \omega J/\psi$

    $\rightarrow$ $C(Y) = +1$
- $Z(3940) \rightarrow D\bar{D}$ in $\gamma\gamma$ collisions
  - ▷ Likely 2^3P $c\bar{c}$ state

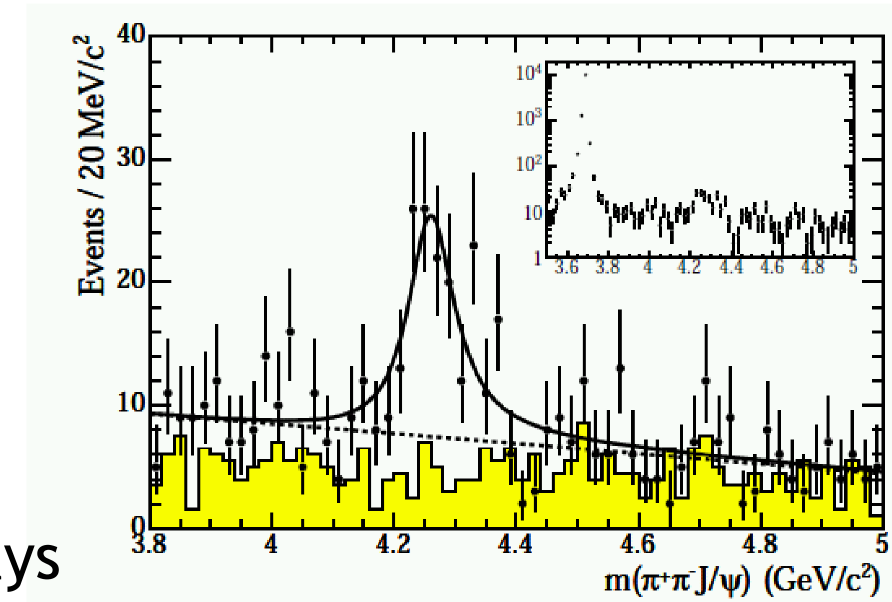
    $\rightarrow$ χ'_{c2}

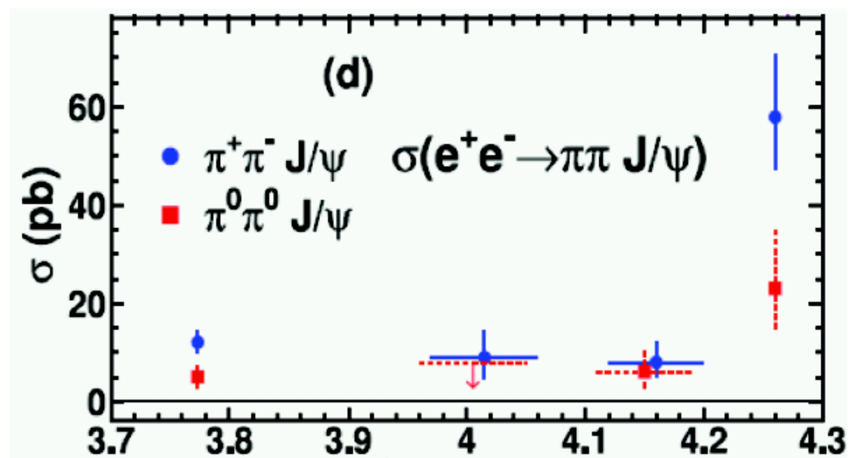




Y(4260)

- BABAR discovery
  - ▷ Initial state radiation
  - ▷ $Y(4260) \to J/\psi\, \pi^+\pi^-$
  - ▷ $J^{PC} = 1^{--}$
- Confirmations
  - ▷ CLEO-c scan
  - ▷ CLEO-III ISR
- Indications that seen in B decays
- Interpretation not clear
  - ▷ 4S state?
  - ▷ $cs\overline{cs}$ tetraquark?
  - ▷ $c\bar{c}g$ hybrid?





Conclusions

- Heavy quarkonium
  - ▷ Large experimental activity
  - ▷ CLEO-c and BESII
  - ▷ B-factories and also Tevatron experiments
- Time-dependent B_s oscillations measured at CDF (and D0)
  - ▷ Consistent with SM
- CP-violation in B decays
  - ▷ time-dependent and direct
  - ▷ consistent with SM
    Some hopes for new physics
- Complementary B physics
  - ▷ Rare and radiative decays
    Searching for new physics
  - ▷ $|V_{ub}|$ and $|V_{cb}|$
    Reducing theory/model errors
  - ▷ $B^+ \to \tau^+\nu$ and $b \to d$ penguins