Inclusive Measurements of $B \rightarrow X_c l \nu$ and $B \rightarrow X_s \gamma$ Decays

Mini-review

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On behalf of the *BABAR* Collaboration

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Inclusive *vs.* Exclusive Measurements

- **Exclusive *B* decays:** $B \rightarrow D^* l \nu$, $B \rightarrow K^*\gamma$
  - Experimentally clean signatures
  - Presence of hadronic form factor can preclude definitive statements regarding agreement between theory and experiment

- **Inclusive *B* decays:** $B \rightarrow X_c l \nu$, $B \rightarrow X_s \gamma$
  - Non-perturbative effects are suppressed in the Heavy Quark Expansion (lowest-order contribution: Λ^2/m_b^2)
  - Precise SM predictions (less than 10% uncertainty)
  - Experimentally very difficult! Inclusive signal → minimal event selection requirements → large backgrounds.

Hadronic Mass, Lepton, and Photon Spectra

- **Heavy Quark Expansion breaks down at end points → cannot use HQE to predict spectral shape**
- **Integrated quantities (moments) of spectra are well-defined in theory and experiment**
  - **Lepton Momentum and Hadronic Mass Spectra from $B \rightarrow X_c l \nu$ decays**
  - **Photon Spectrum from $B \rightarrow X_s \gamma$ decays**
- **Non-perturbative terms collected into a shape function – similar to parton distribution function**
- **Same shape function universal to all *B* decays**
- **Measurements of spectral moments constrain shape function parameters**

$B \to X_c l \nu$ Decays

- Dominant *B* decay process ~ 20%
- Discrepancy between branching fractions of inclusive measurements and sum-of-exclusive measurements—not discussed here
- Moments used to extract:
  - CKM matrix element V_{cb}
  - *b*- and *c*-quark masses
  - Total $B \to X_c l \nu$ branching fraction
  - Heavy Quark Effective Theory (HQET) parameters

μ_π^2	μ_G^2	ρ_D^3	ρ_{LS}^3
Kinetic Exp. Value	Chromomagnetic Exp. Value	Darwin-term Exp. Value	Spin-orbit coupling Exp. Value

$B \rightarrow X_c \, l \, \nu$ Measurements

- **Hadronic X_c mass moments (k = 1 – 6)**

$$\langle M_X^k \rangle = \frac{\sum_i (M_X^k)_i N_i}{\sum_i N_i} \qquad \sigma^2 \left[\langle M_X^k \rangle \right] = \frac{\sum_{i,j} (M_X^k)_i X_{ij} (M_X^k)_j}{\left(\sum_i N_i\right)^2}$$

$$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$$

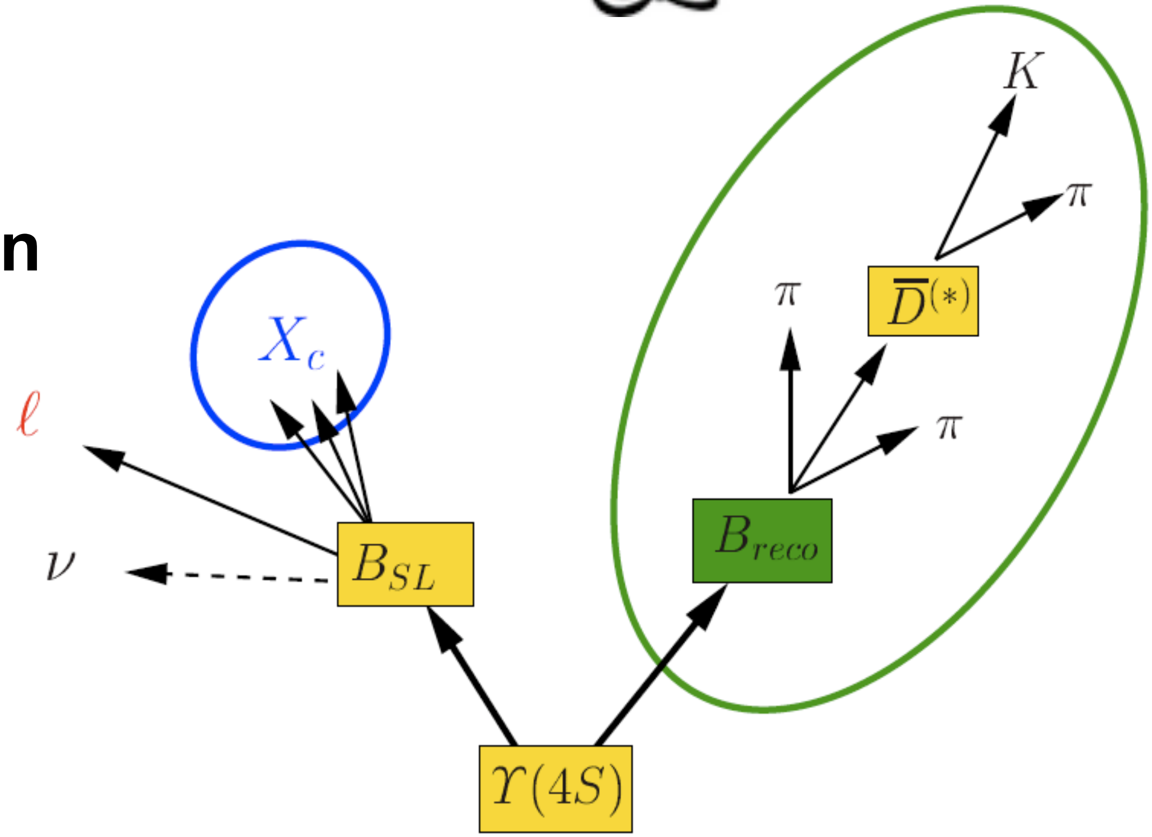
- **Mixed mass/energy moments (k = 2, 4, 6)**
  - **Gambino & Uraltsev:** Eur. Phys. J. C **34**, 181 (2004)

$$n_X^2 = M_X^2 c^4 - 2\tilde{\Lambda} E_X + \tilde{\Lambda}^2$$

- **Fitting method to extract SM & QCD parameters:**
  - **Buchmüller & Flächer:** PRD **73**, 073008 (2006)
  - **B. Aubert *et al.***: PRL **93**, 011803 (2004)

$B \to X_c \, l \, \nu$ Event Selection

- An Υ(4S) event is tagged by hadronic reconstruction of B_{reco}
- High-momentum lepton used to select signal B_{SL}
  - Belle: $p_l > 0.7$ GeV/c
  - BaBar: $p_l > 0.8$ GeV/c
- Remaining tracks and neutral deposits used for X_c reconstruction.



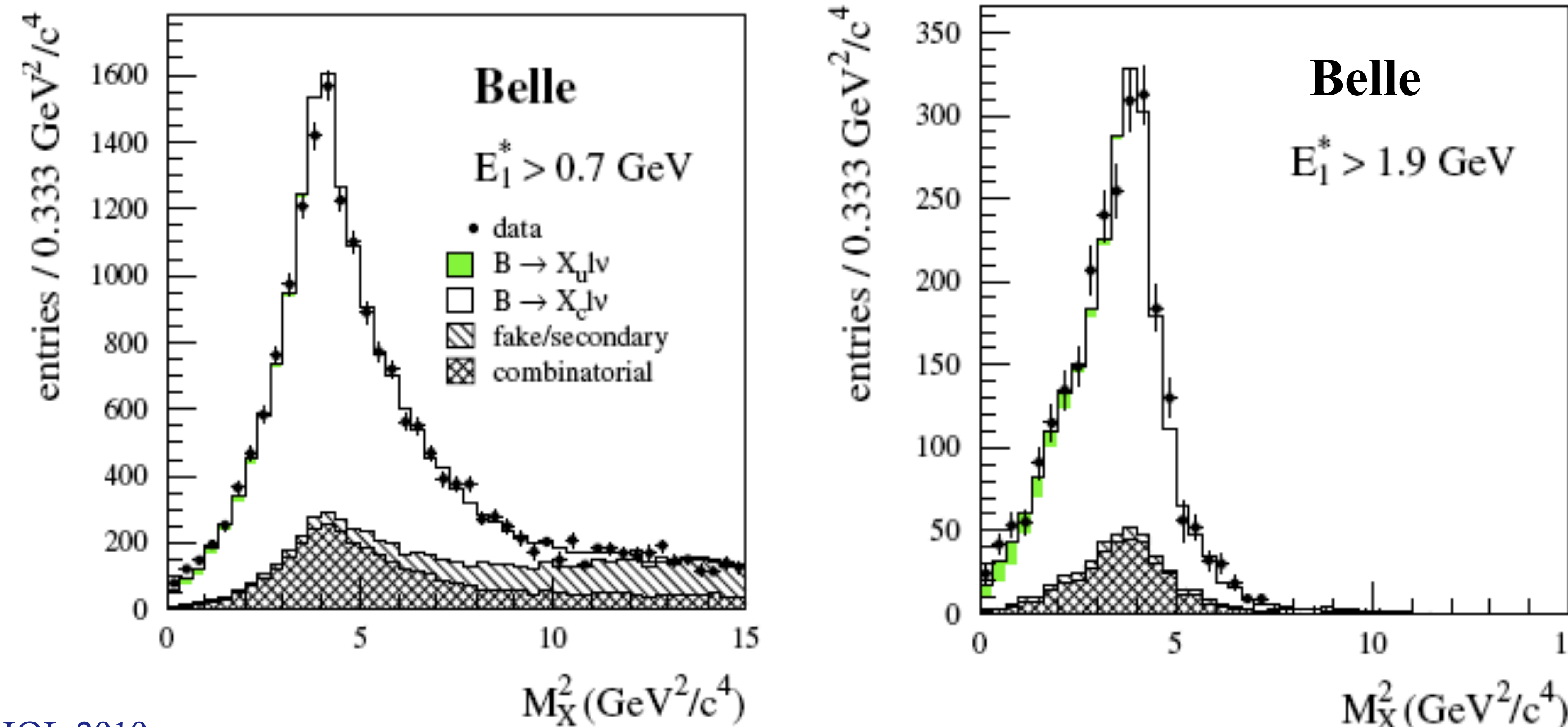
- Can improve 4-momentum resolution of X_c system
  - Belle: $p_X' = (p_{e+} + p_{e-}) - p_{Breco} - p_l - p_\nu$
  - BaBar: Kinematic fit with constraint $p_\nu^2 = 0$.

$B \rightarrow X_c\, l\, \nu$ Backgrounds

- **Combinatorial Backgrounds**
  - B_{reco} mis-reconstructed with particles from B_{SL}
- **Continuum Backgrounds**
  - $e^+e^- \rightarrow q\bar{q}$ (q = u, d, s, c)
- **Residual Backgrounds**
  - B_{reco} correctly reconstructed, B_{SL} reconstructed with non-signal decays
    - $B \rightarrow X_u\, l\, \nu$ Decays
    - Leptons mis-identified by hadrons
    - Tagged lepton from secondary decay

X_c Mass Spectrum

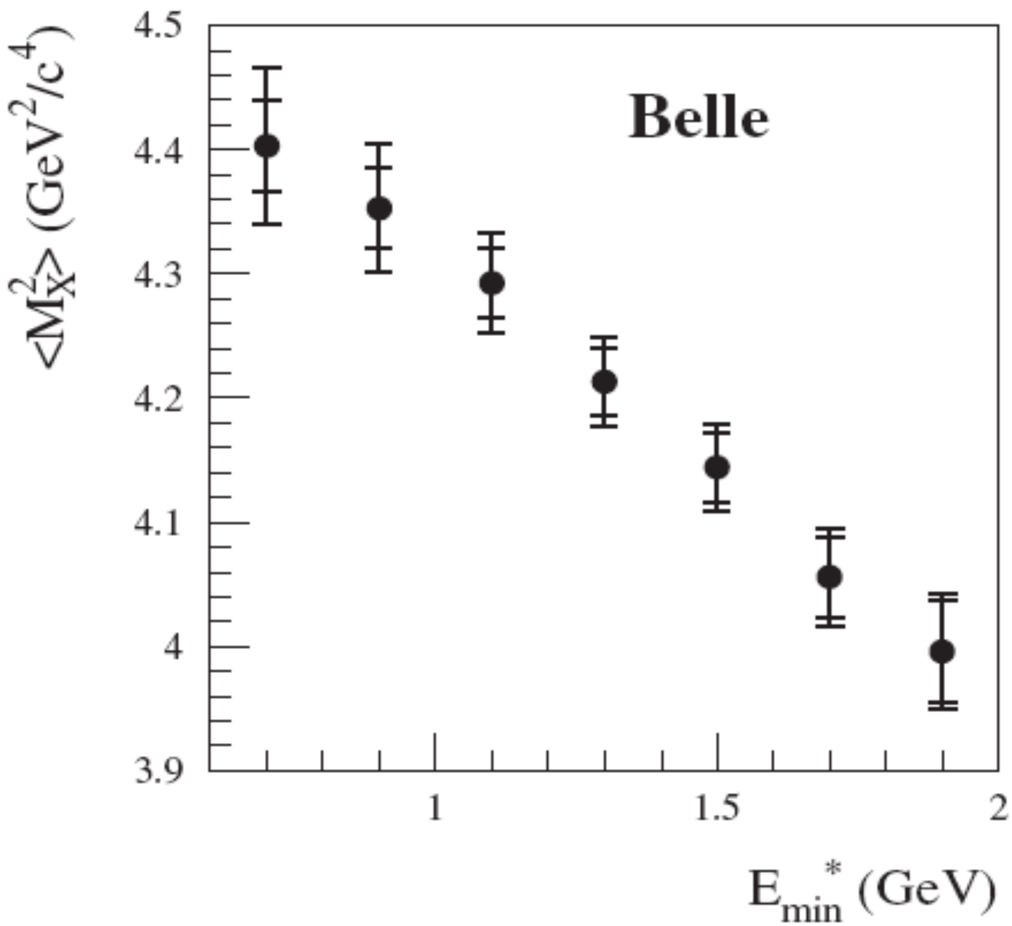
- Uses 152×10^6 $B\bar{B}$ events
- Continuum background subtracted with off-peak data
- Signal and remaining background shapes modeled with MC samples
- Use Singular Value Decomposition (SVD) algorithm to unfold detector resolution effects from mass spectrum.



Systematic Uncertainties

- Secondary/fake leptons
- Branching fraction normalizations
  - Signal modes: $B \to D^{(*)} l\nu$, $B \to D^{**} l\nu$, $B \to (D^{(*)}\pi)_{nonres} l\nu$
  - Background components
- Form Factor Shapes
  - HQET-based $B \to D^{(*)} l\nu$ model
- SVD Algorithm
  - Effects from unfolding parameter
  - Changes in binning
  - Bin-to-bin efficiency corrections

X_c Mass Moments

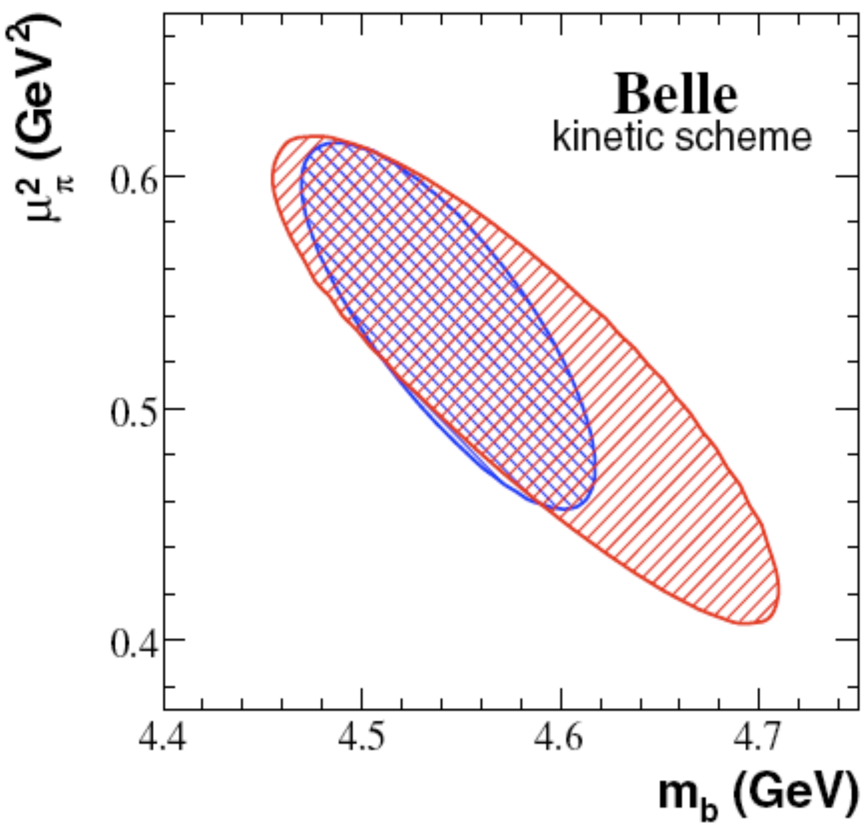


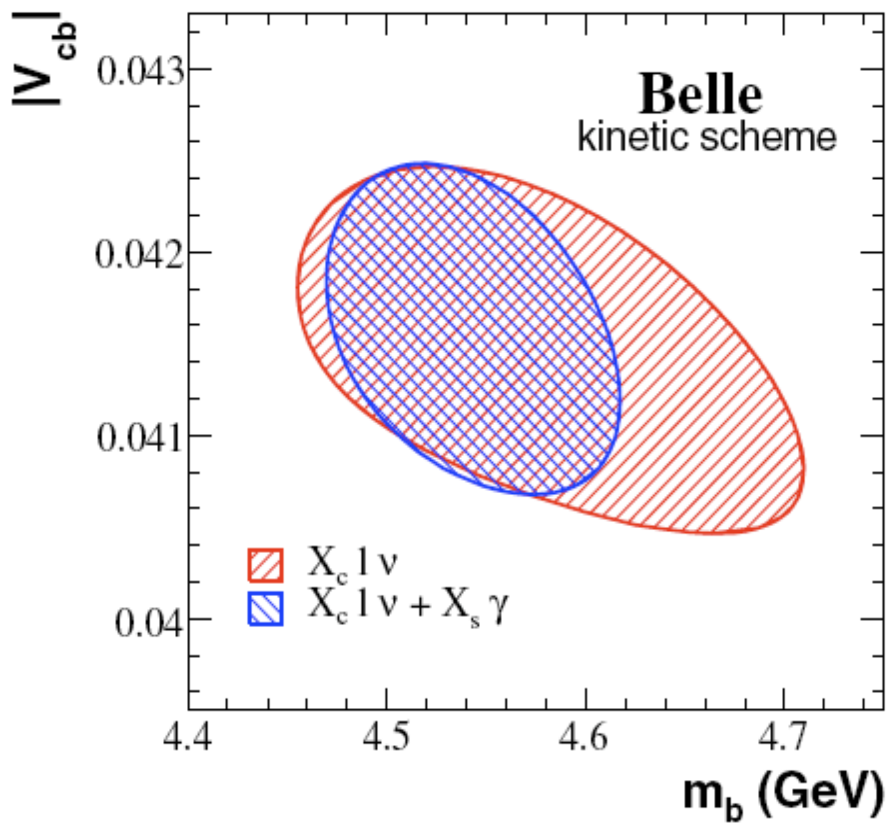
E^*_{min} (GeV)	$\langle M_X^2 \rangle$ (GeV$^2/c^4$)
0.7	4.403 ± 0.036 ± 0.052
0.9	4.353 ± 0.032 ± 0.041
1.1	4.293 ± 0.028 ± 0.029
1.3	4.213 ± 0.027 ± 0.024
1.5	4.144 ± 0.028 ± 0.022
1.7	4.056 ± 0.033 ± 0.022
1.9	3.996 ± 0.041 ± 0.021

- **Mass moments computed for multiple lepton energy requirements**
  - **E_{min}* > [0.7, 0.9, … , 1.9] GeV/c**
- **All measurements correlated (overlapping events)**
- **Correlation matrix required for extracting V_{cb} and *b*- and *c*-quark masses**

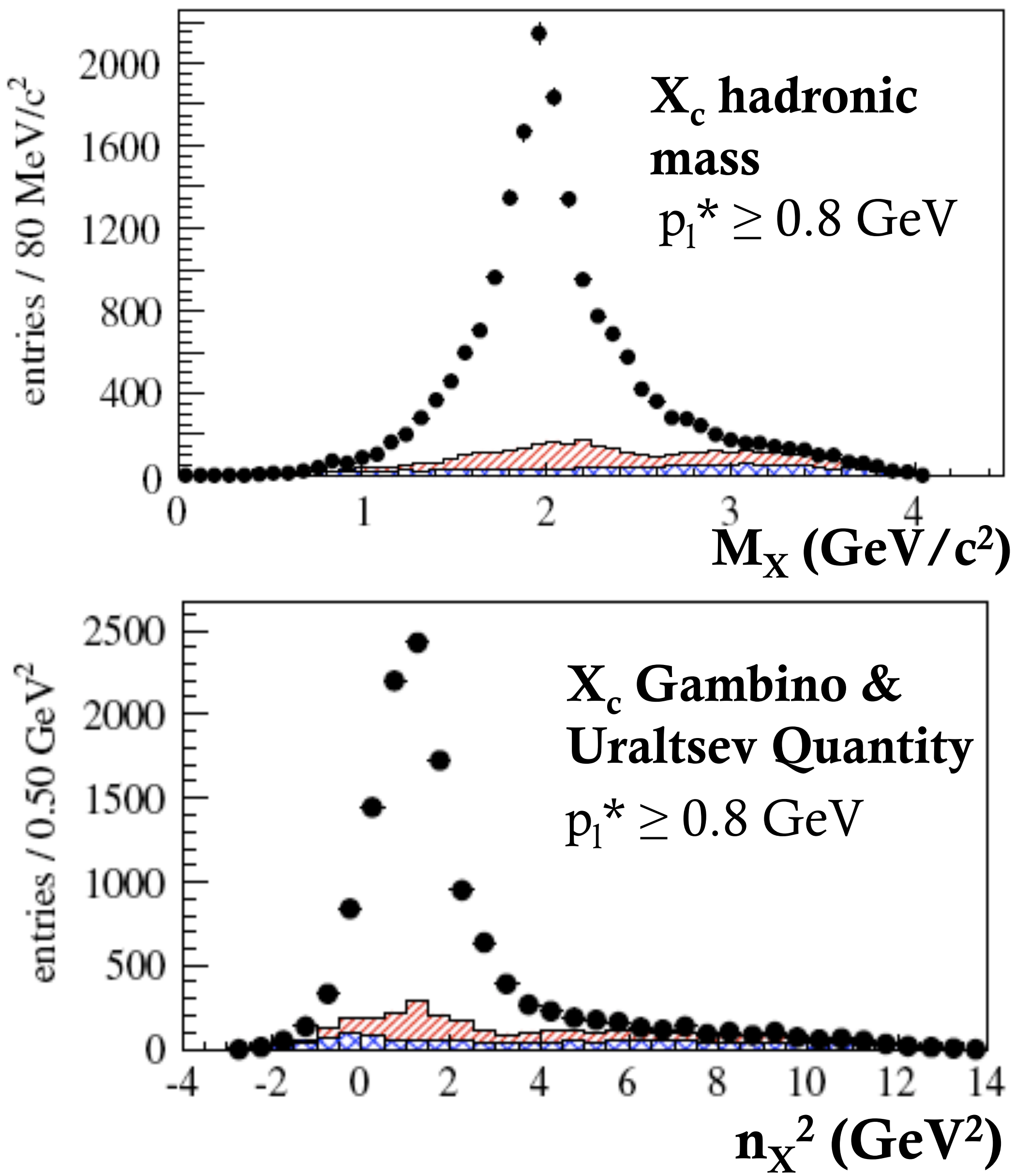
Extracting SM/QCD Parameters

- Constraints on V_{cb}, m_b, and $\mu_\pi{}^2$ obtained by incorporating various spectra into fits, based on phenomenological calculations





X_c Mass / Mixed Energy Moments



- Uses 232×10^6 $B\bar{B}$ events
- Continuum and combinatorial background parameterized with an empirical threshold function
- Residual background and signal modeled with MC samples

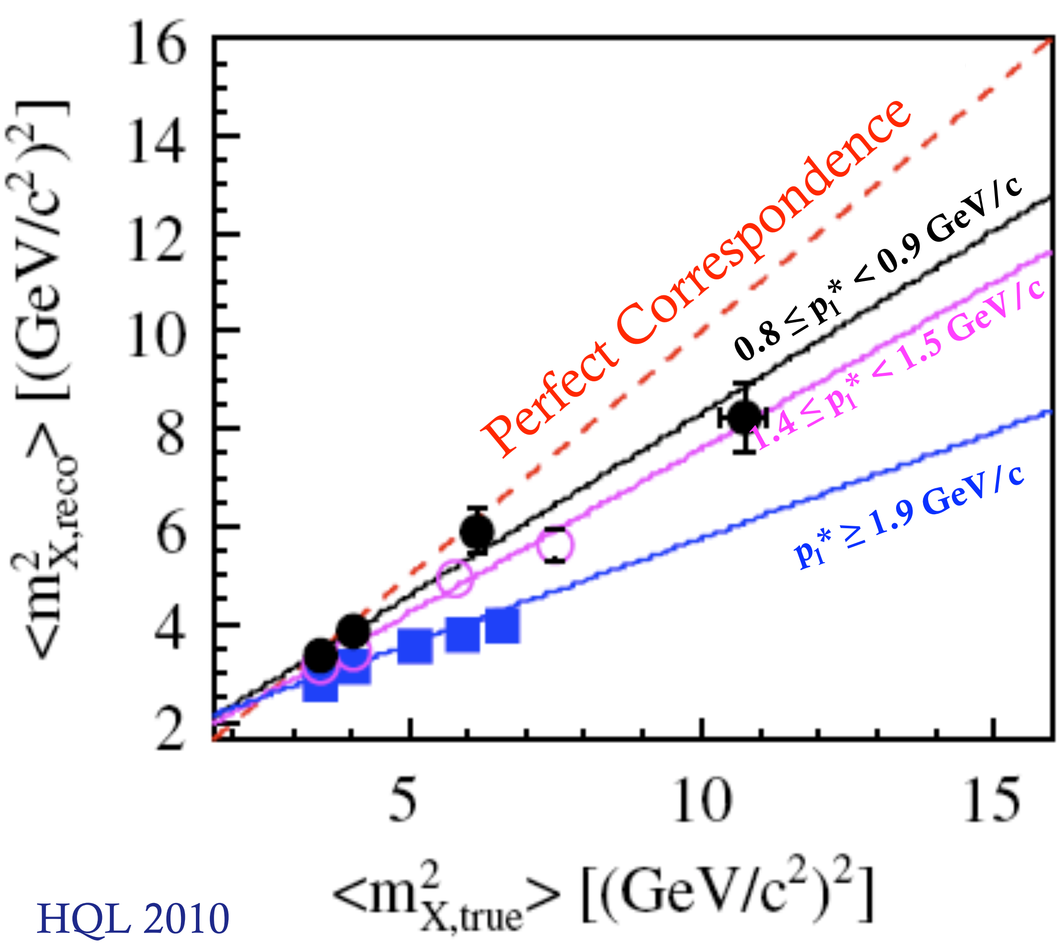
● Data

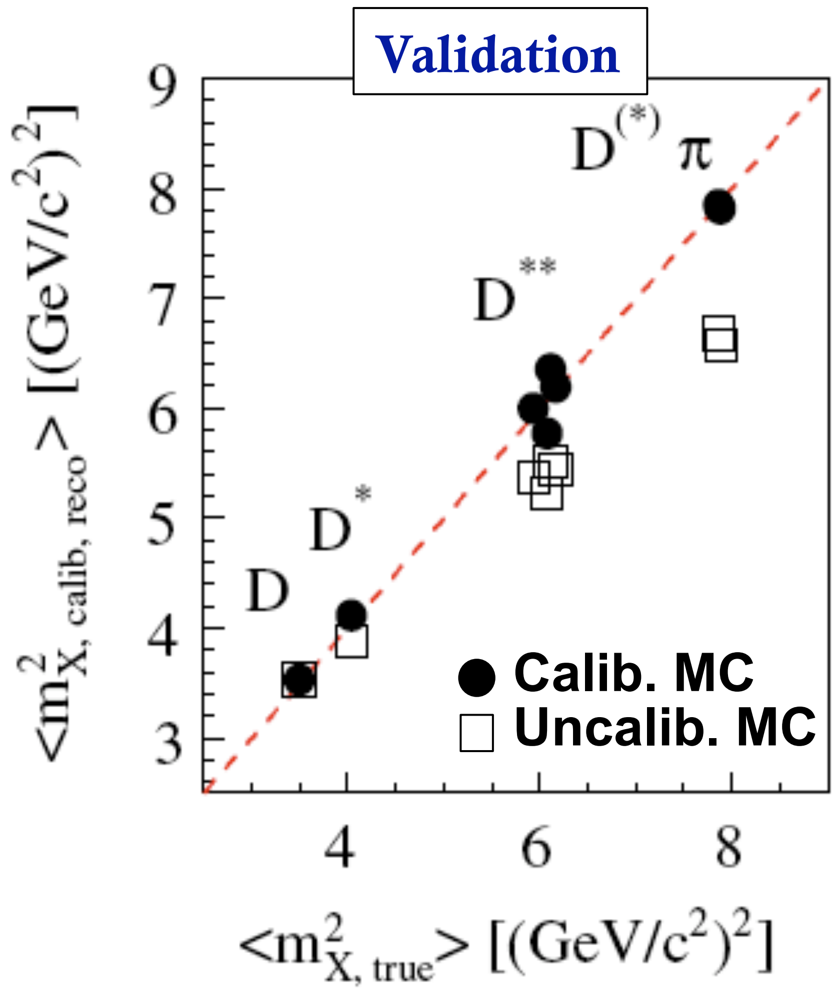
Combinatorial/ Continuum Background

Residual Background

Correcting for Detector Resolution

- **Instead of unfolding the spectrum, resolution effects are taken into account through corrections to the moments.**
  - **Parameterized by linear calibration between "true" and "reconstructed" quantities in MC**



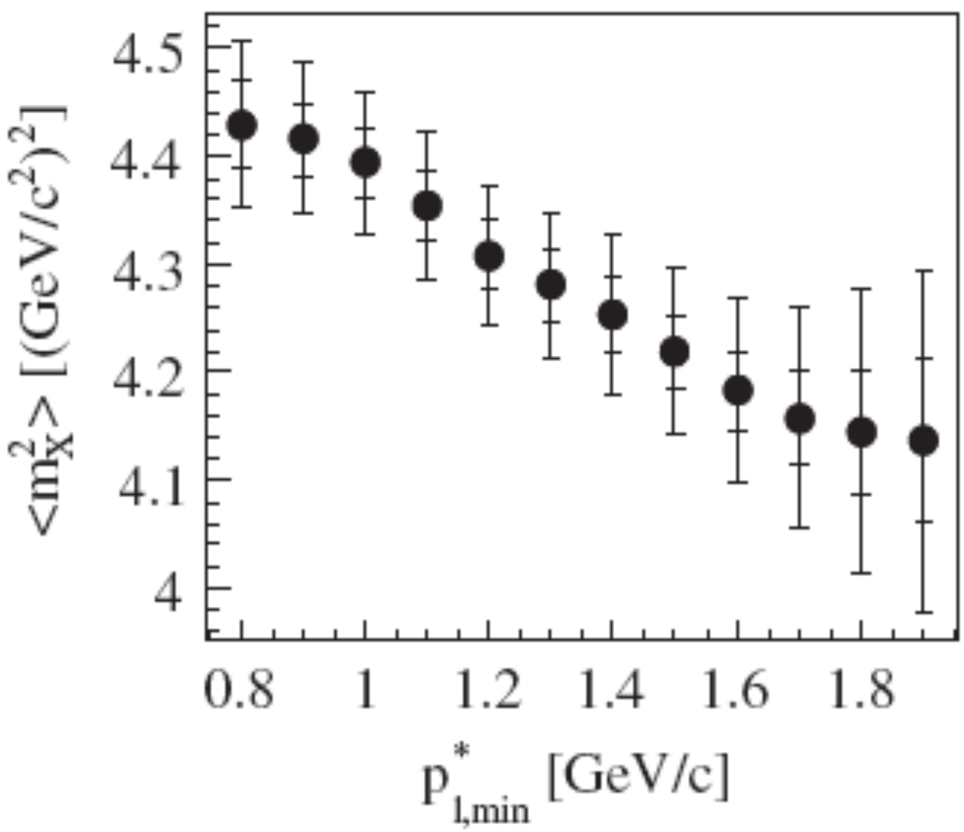


Systematic Uncertainties

- Limited MC statistics
- Simulation-related effects
  - Selecting charged tracks and photons
  - Particle (mis-)identification
  - Final State Radiation
- Detector calibration/resolution
- Branching fractions of backgrounds
  - $B \rightarrow X_u l \nu$ Decays
  - Secondary/fake leptons
- Signal Models
  - Effect of varying signal components

PRD **81**, 032003 (2010)

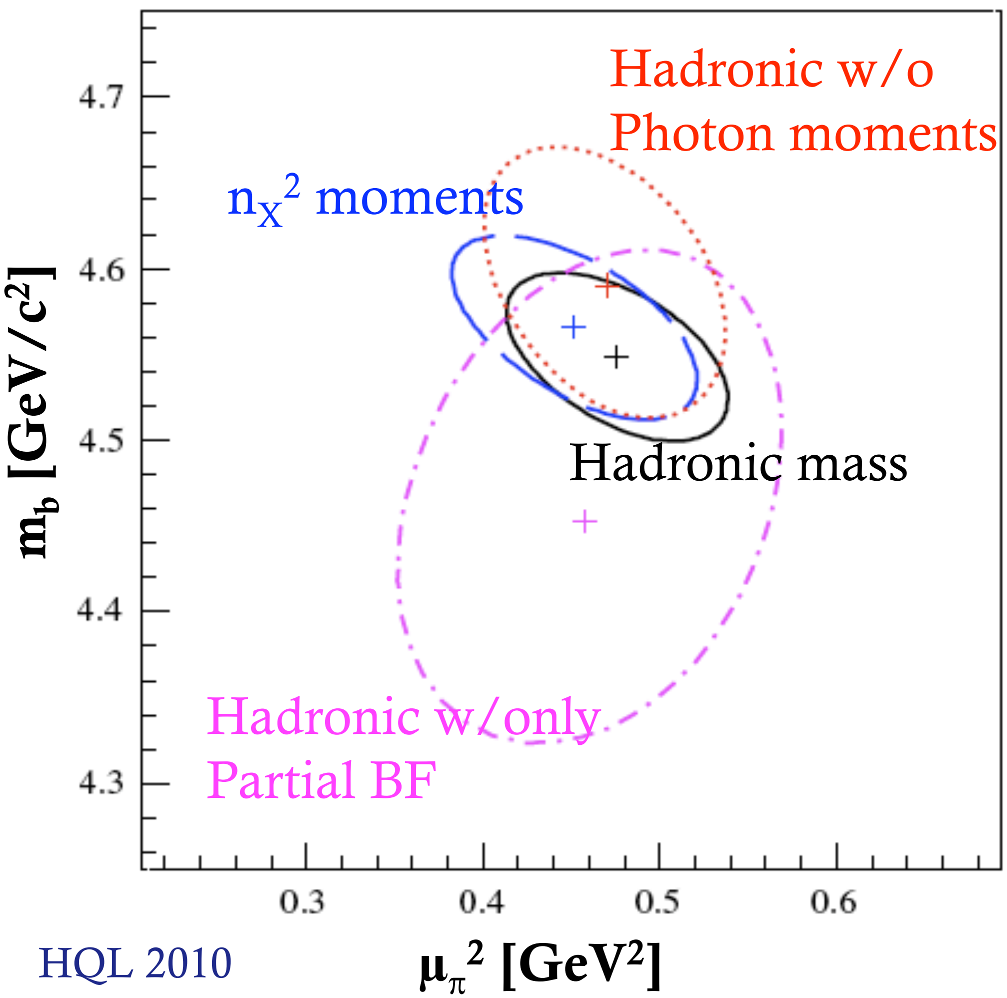
X_c Mass Moments

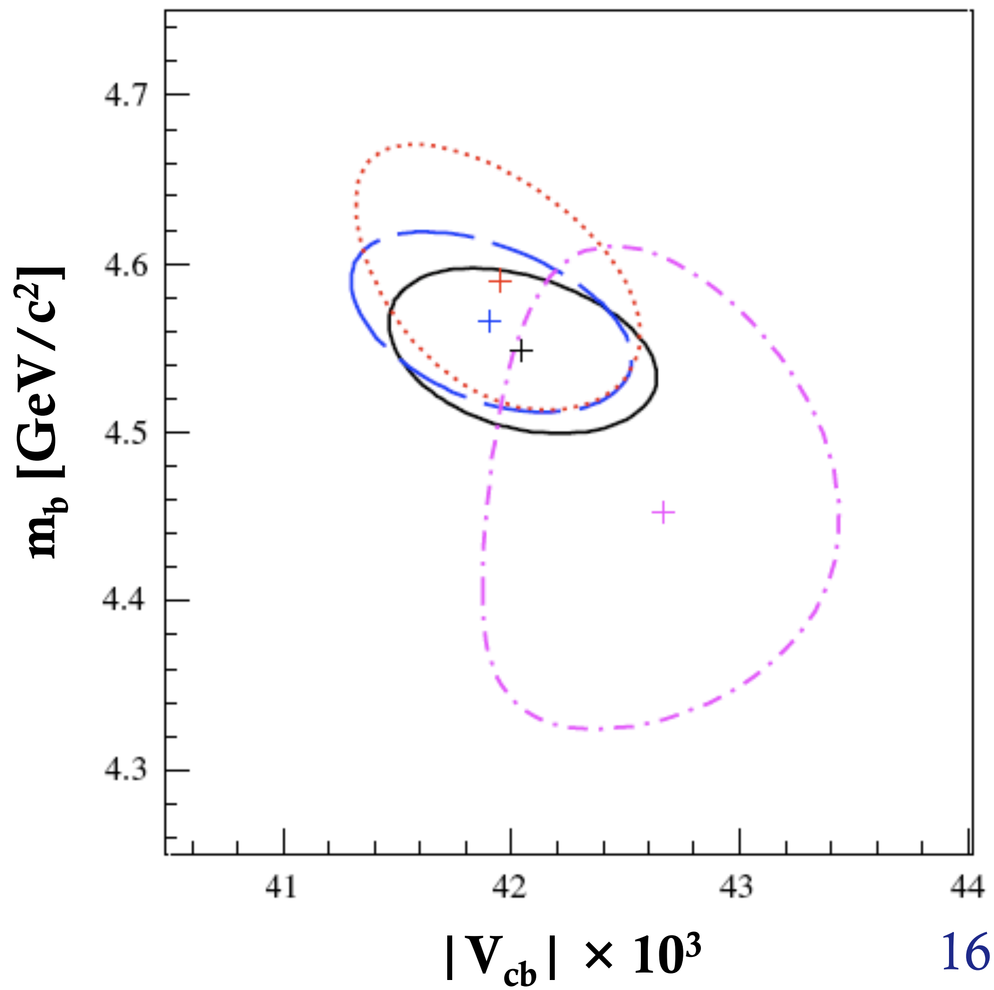


k	$p^*_{\ell,min}$ [GeV/c]	$\langle m_X^k \rangle$	σ_{stat}	σ_{sys}
2	0.8	4.429	±0.029	±0.070
	0.9	4.416	±0.027	±0.063
	1.0	4.394	±0.026	±0.058
	1.1	4.354	±0.026	±0.063
	1.2	4.308	±0.026	±0.058
	1.3	4.281	±0.027	±0.061
	1.4	4.253	±0.028	±0.066
	1.5	4.220	±0.031	±0.070
	1.6	4.183	±0.034	±0.078
	1.7	4.158	±0.040	±0.094
	1.8	4.145	±0.051	±0.120
	1.9	4.136	±0.069	±0.142

Extracting SM/QCD Parameters

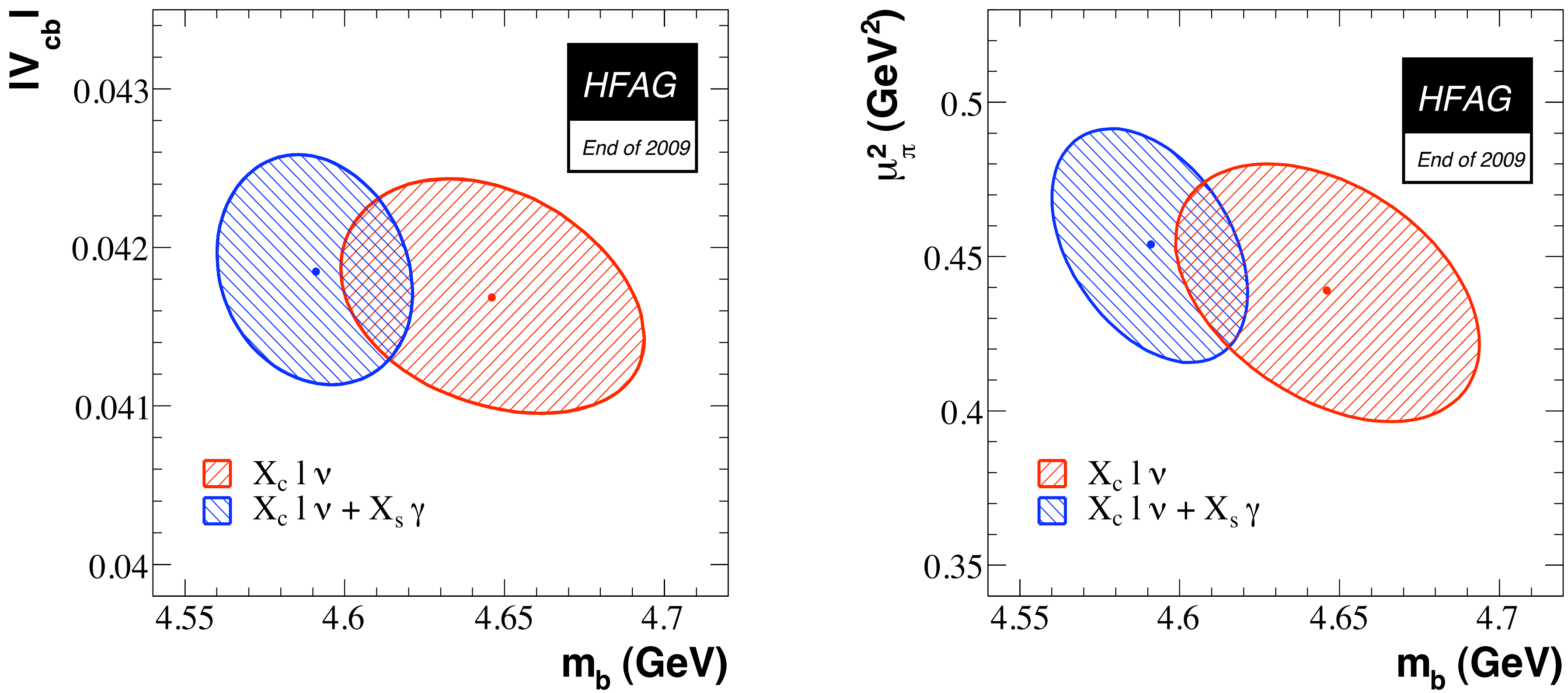
- **Use experimental inputs—moments from hadronic mass, lepton momentum, and photon energy to constrain heavy quark parameters.**





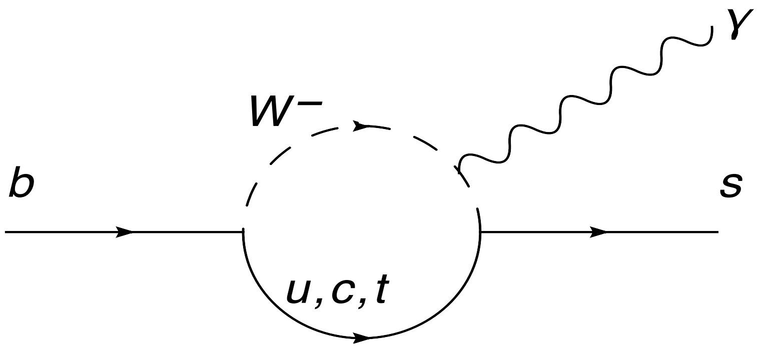
Heavy Flavor Averaging Group (HFAG) Fit

- **Measurements from multiple collaborations used to calculate V_{cb}, m_b and μ_π^2**

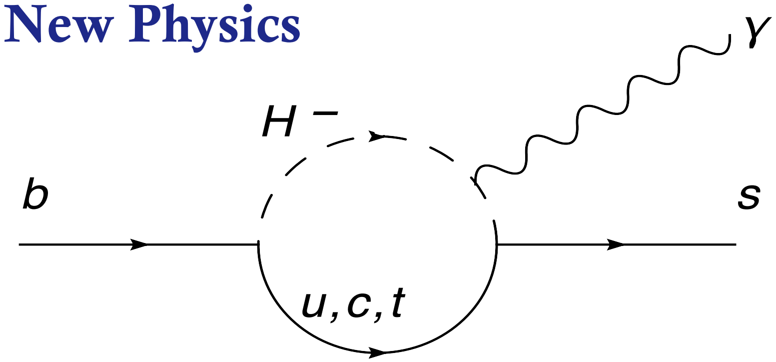


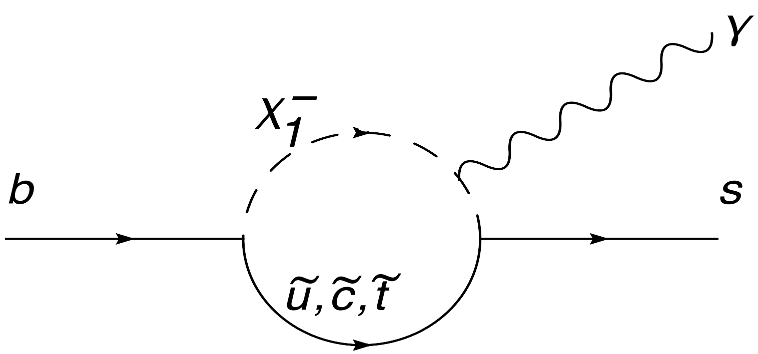
- **Tension between semi-leptonic results and SL+ radiative penguin results—source of much discussion**

$B \rightarrow X_s \gamma$ and New Physics



New Physics





- **Flavor-changing neutral currents forbidden at tree-level (SM)**
- **At least 1st-order ("Penguin") loops necessary**
  - **4-momentum conservation → radiated particle**
- **NP particles could propagate in loop**
- **If NP couplings ~ SM couplings, NP observable.**

$B \rightarrow X_s \gamma$ Measurements and New Physics

- **Branching Fraction – Belle, Dec 2009**
  - Theoretical precision at 7% level!

$$\mathcal{B}(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4} \qquad E_\gamma^B > 1.6 \text{ GeV}$$

  - Precision measurement required to make strong statement regarding new physics.

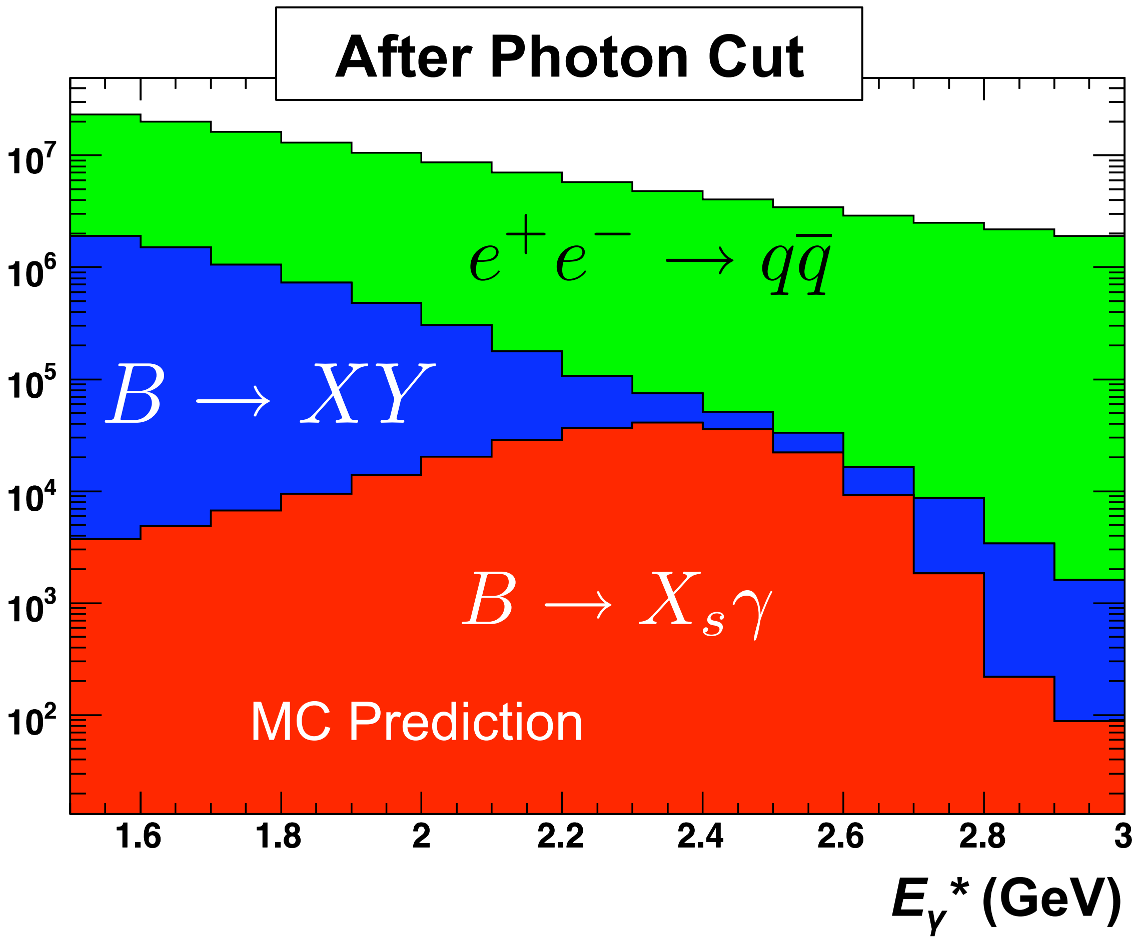
- **Direct *CP*-Asymmetry – New *BABAR* Result**

$$A_{CP}(B \to X_{s+d}\gamma) = \frac{\Gamma(\overline{B} \to \overline{X}_{s+d}\gamma) - \Gamma(B \to X_{s+d}\gamma)}{\Gamma(\overline{B} \to \overline{X}_{s+d}\gamma) + \Gamma(B \to X_{s+d}\gamma)}$$

$$A_{CP}^{SM}(B \to X_{s+d}\gamma) \sim 10^{-6}$$

Inclusive $B \rightarrow X_s \gamma$ Analysis Strategy (1)

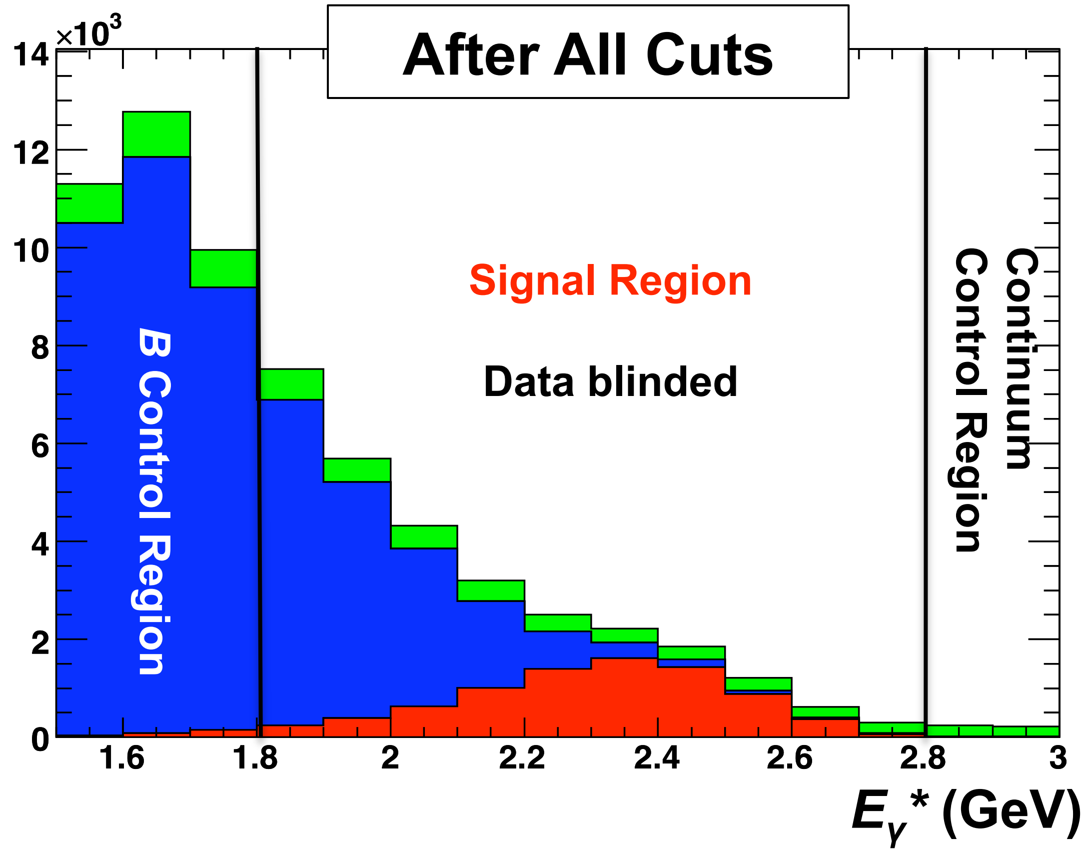
- **Apply photon energy cut to suppress continuum and** B$\bar{B}$ **backgrounds**



- **Vetoes: Remove photons consistent with π^0/η decays**

Inclusive $B \rightarrow X_s \gamma$ Analysis Strategy (2)

- **Lepton tagging:** Reduce continuum background by requiring high-momentum lepton from non-signal *B*
- **Discriminant:** Further continuum suppression achieved using multivariate discriminant with topological variables



- Remaining background ***subtracted*** using:
  - Off-resonance data for continuum background
  - Data-corrected Monte Carlo predictions of $B\bar{B}$ background

Remaining *B*-Backgrounds after Event Selection

Background Process	Belle $1.7 < E^*_\gamma < 2.8$ GeV	*BABAR* Preliminary $1.8 < E^*_\gamma < 2.8$ GeV
$B \to X\pi^0$	0.597	0.613
$B \to X\eta$	0.199	0.192
$B \to X + \text{other}$ $\omega, \eta', J/\psi, e(\gamma)$, FSR	0.111	0.123
Fake γ: $e^\pm$	0.041	0.033
Fake γ: K^0_L and $\overline{n}$	0.020	0.025
Other	0.032	0.014

- **Data-based MC corrections applied to events from $B\overline{B}$ background components**

Uses 657 × 10^6
$B\bar{B}$ events

BELLE

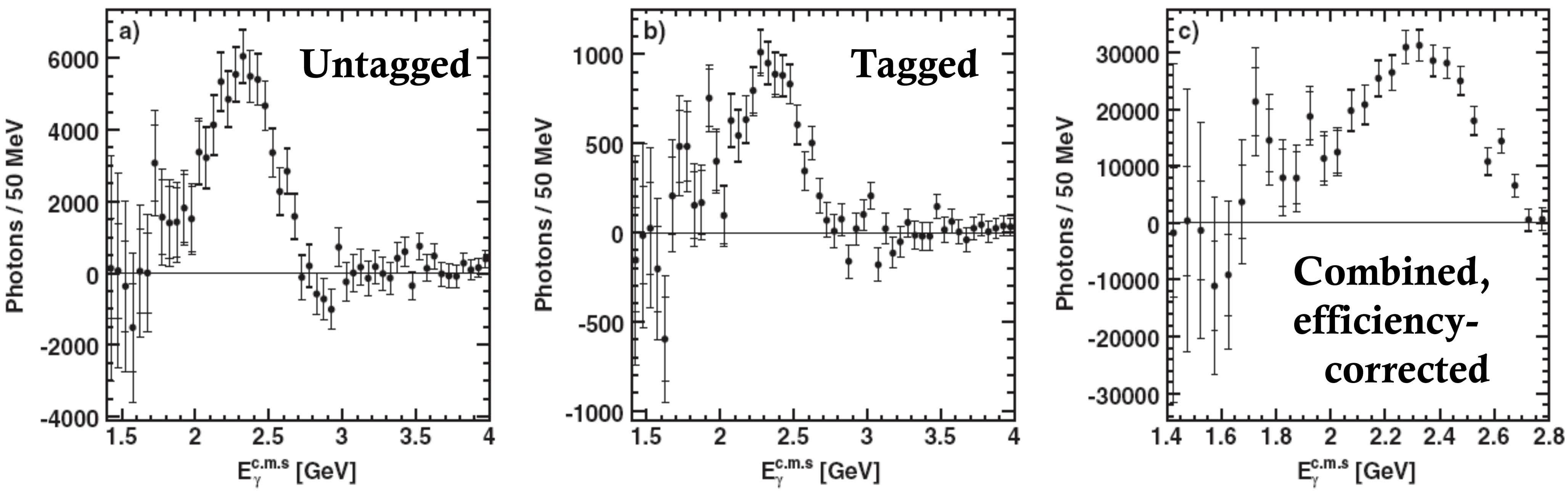
Corrected $B\bar{B}$ Components at Belle

Background Process	Belle $1.7 < E_\gamma^* < 2.8$ GeV	*BABAR* **Preliminary** $1.8 < E_\gamma^* < 2.8$ GeV
$B \to X\pi^0$	0.597	0.613
$B \to X\eta$	0.199	0.192
$B \to X + \text{other}$ $\omega, \eta', J/\psi, e(\gamma)$, FSR	0.111	0.123
Fake γ: $e^\pm$	0.041	0.033
Fake γ: K_L^0 and $\bar{n}$	0.020	0.025
Other	0.032	0.014

PRL **103**, 241801 (2009)

$B \rightarrow X_{s+d}\, \gamma$ Result

- **Admixture between lepton-tagged and untagged methods.**
- **Photon spectrum measured down to 1.7 GeV (97% of spectrum)**
- **Detector resolution effects unfolded with SVD algorithm**



$$\mathcal{B}(B \rightarrow X_s\gamma)_{E_\gamma > 1.7\ \mathrm{GeV}} = \left(3.45 \pm 0.15_{\mathrm{stat.}} \pm 0.40_{\mathrm{syst.}}\right) \times 10^{-4}$$

Uses 383 × 10⁶ $B\bar{B}$ events

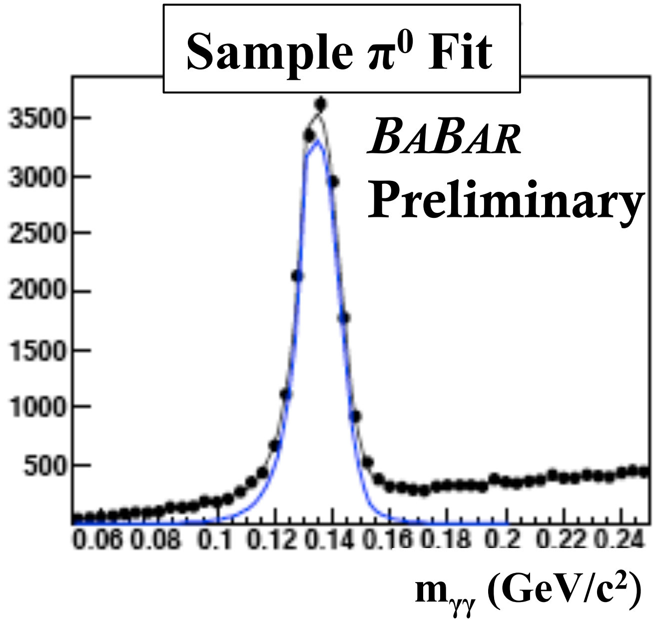
Corrected $B\bar{B}$ Components at *BABAR*

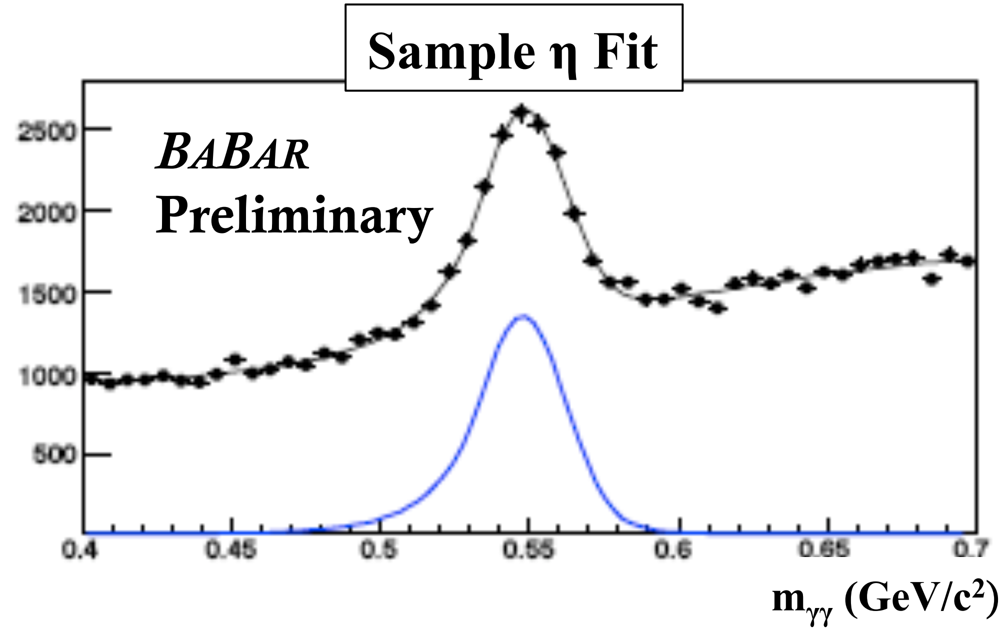
Background Process	Belle $1.7 < E^*_\gamma < 2.8$ GeV	*BABAR* Preliminary $1.8 < E^*_\gamma < 2.8$ GeV
$B \to X\pi^0$	0.597	0.613
$B \to X\eta$	0.199	0.192
$B \to X + \text{other}$ ($\omega, \eta', J/\psi, e(\gamma)$, FSR)	0.111	0.123
Fake γ: $e^\pm$	0.041	0.033
Fake γ: K^0_L and $\overline{n}$	0.020	0.025
Other	0.032	0.014

- **Additional corrections due to MC mismodeling of semi-leptonic decays (lepton tagging)**

Correcting π^0/η Backgrounds

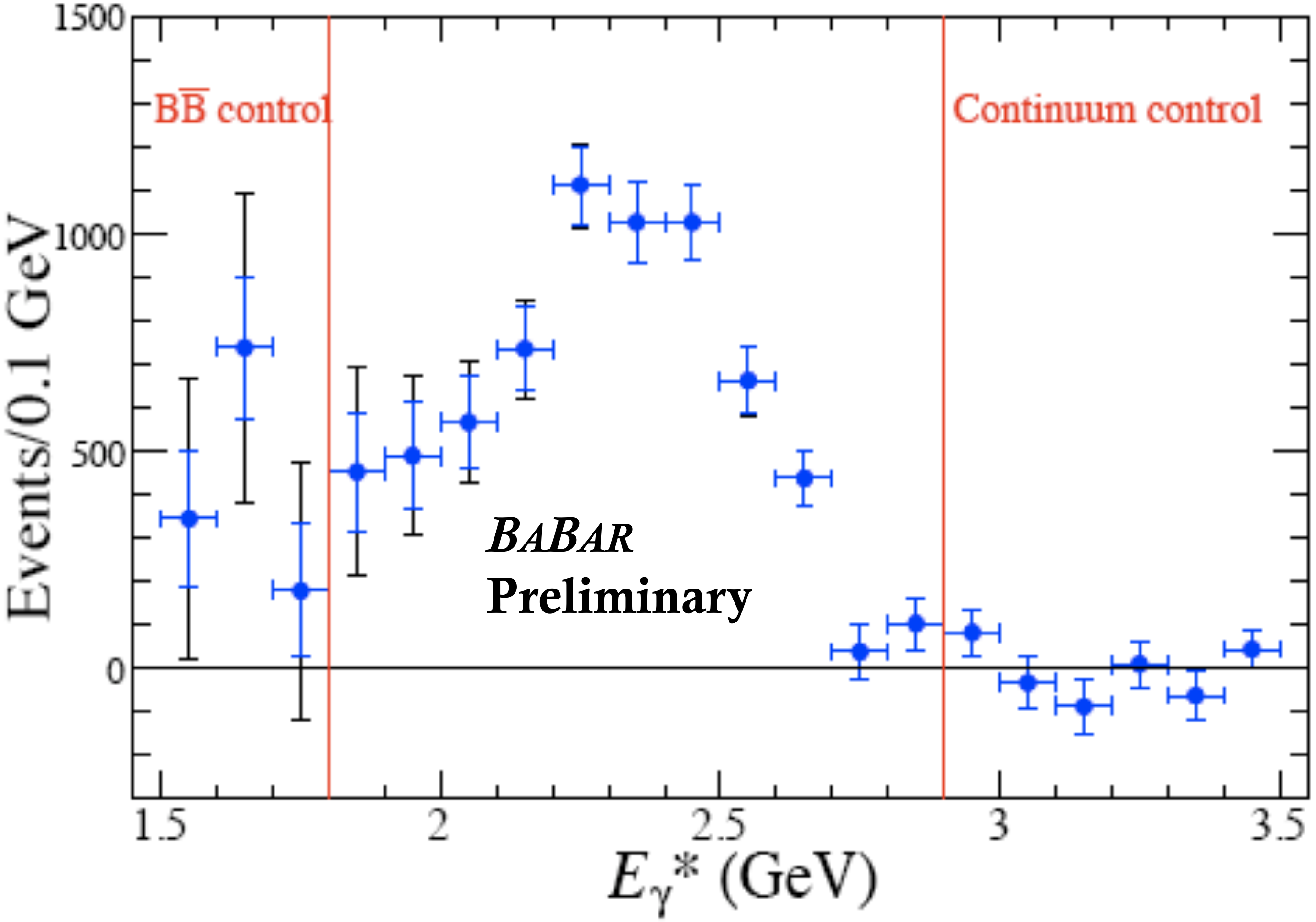
- **80% of backgrounds from $\pi^0/\eta \rightarrow \gamma\gamma$ decays.**
- **Use specific controls samples to compare data and MC, and apply appropriate correction to MC events.**





- **MC corrections are very sensitive to modeling of photon detection efficiencies—dominant systematic error.**

$B \rightarrow X_{s+d}\,\gamma$ Photon Spectrum



- **To extract A_{CP}, spectrum is separated according to charge of tagged lepton.**
  - **lepton$^{+(-)}$ tag → signal decay from B̄(B) meson**

Raw *CP*-Asymmetry

$$A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma) = 0.045 \pm 0.044_{\text{stat.}}$$

***BaBar* Preliminary**

- **Raw *CP*-Asymmetry is not the true quantity. Additional affects dilute measured asymmetry:**
  - **$B^0 - \bar{B}^0$ oscillations**
  - **B → D → lepton (cascade) decays**
  - **Wrong-sign misidentification**

$$A_{CP}(B \to X_{s+d}\gamma) = \frac{1}{1-2\omega} A_{CP}^{\text{meas}}(B \to X_{s+d}\gamma)$$

$$\omega = \frac{\chi_d}{2} + \omega_{\text{cascade}} + \omega_{\text{mis-ID}}$$

Systematic Uncertainties

- **Multiplicative Systematics**
  - Subdominant errors multiplied by the measured central value

Source	$\omega \pm \Delta\omega$	$\Delta A_{CP}/A_{CP}$
$B^0\overline{B}^0$ oscillation	$(0.1824 \pm 0.0024)/2$	
Fake lepton ID	0.0073 ± 0.0037	
non-direct-semileptonic	0.0328 ± 0.0035	
$B^0\overline{B}^0 : B^+B^- = 1:1$	± 0.0030	
Total ω	0.131 ± 0.0064	0.018
$B\overline{B}$ yield		0.022
Total mult. uncertainty		0.029

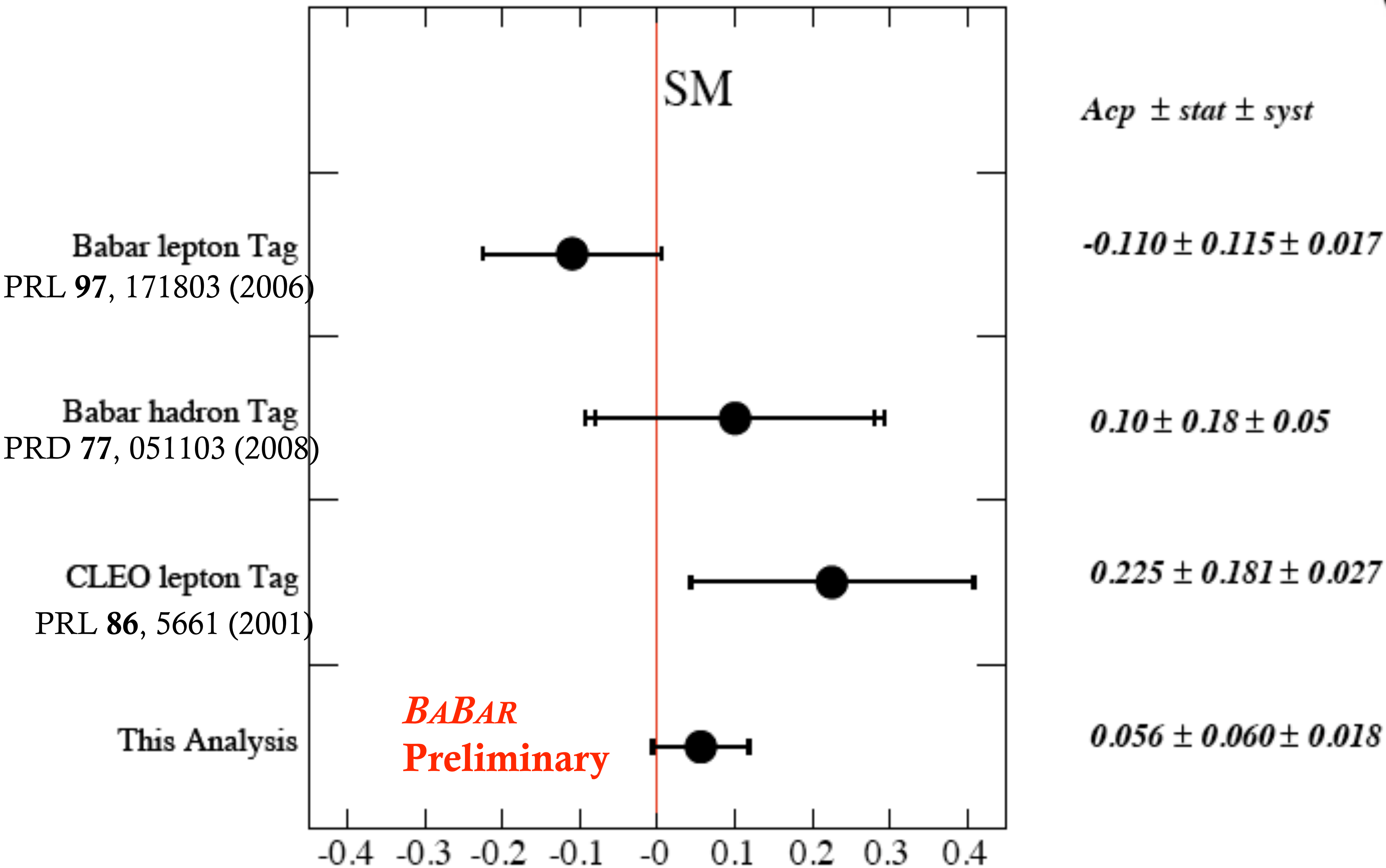
- **Additive Systematics**
  - Accounts for potential biases

Source	Correction (10^{-2})
$B\overline{B}$ background	-0.4 ± 0.6
Detection asymmetry	0.0 ± 1.1
Total	-0.4 ± 1.3

$$A_{CP} = \frac{(0.045 \pm 0.044(stat.)) - (0.004 \pm 0.013)}{0.738(1 \pm 0.029)}$$
$$= 0.056 \pm 0.060(stat.) \pm 0.018(syst.)$$

BABAR Preliminary

Comparison with Other Measurements



Summary

- Inclusive $B \to X_c l \nu$ and $B \to X_s \gamma$ decays are probes of the Standard Model:
  - Fundamental SM parameters: V_{cb}, m_b, m_c
  - QCD parameters: μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3
  - Extracted by using a fit with lepton momentum, hadronic mass, and photon energy spectra

- $B \to X_s \gamma$ decays are sensitive to new physics through new physics particles propagating in penguin diagram
  - Branching fraction result from Belle consistent with SM
  - New preliminary A_{CP} result from *BABAR* consistent with SM

Thank you.