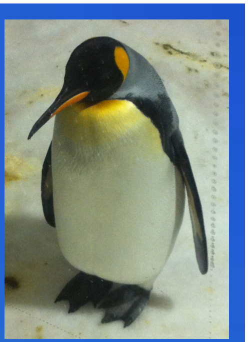


$B \to X_s \gamma$ and $B \to X_s \ell^+\ell^-$ at BABAR

G. Eigen, University of Bergen

representing the BABAR collaboration

New BABAR Results in 2012

- Study of $B \to X_{s+d}\gamma$ with 347 fb^{-1} using a fully inclusive method
  - γ energy spectrum and γ energy moments
  - CP asymmetry

- Study of $B \to X_s\gamma$ with 424 fb^{-1} using a sum of exclusive modes
  - γ energy spectrum

- Rate analysis of $B \to K \ell^+\ell^-$ and $B \to K^* \ell^+\ell^-$ modes with 424 fb^{-1}
  - Branching fractions
  - Isospin asymmetries
  - CP asymmetries and Lepton flavor ratios

BABAR: arXiv:1204.3933 (2012)

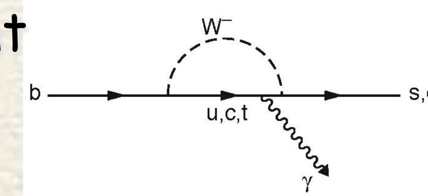
- Angular analyses of $B \to K^* \ell^+\ell^-$ with 424 fb^{-1}
  - K^* longitudinal polarization
  - Lepton forward-backward asymmetries

- Search for lepton-number violating processes in $B^+ \to K^+ \ell^-\ell^-$ (S. Robertsen)

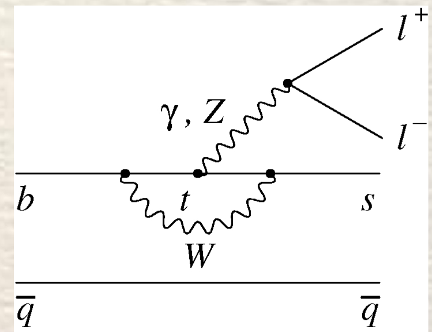
BABAR: arXiv:1202.3650 (2012)

Introduction

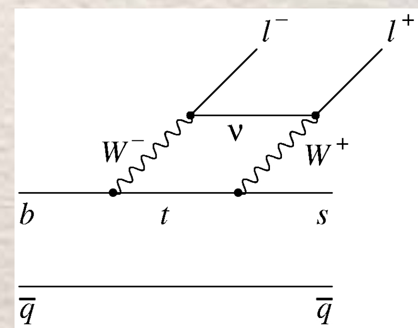
- $B \to X_s\gamma$ & $B \to K^{(*)} \ell^+\ell^-$ are flavor-changing neutral current (FCNC) processes, forbidden in SM at tree level



- Effective Hamiltonian factorizes short-distance from long-distance effects [$\mathcal{O}(\alpha_s)$]

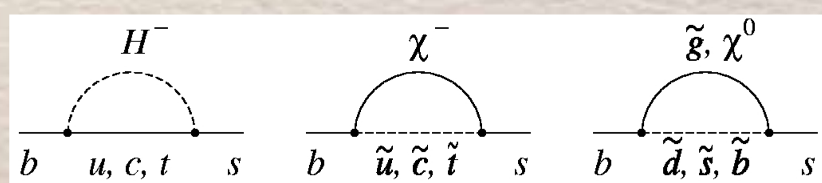


- 3 effective Wilson coefficients contribute
  - C_7^{eff} from EM penguin diagram
    $|C_7^{eff}| \approx 0.33$ from $\mathcal{B}(B \to X_s\gamma)$
  - C_9^{eff} from vector part of electroweak diagrams
  - C_{10}^{eff} from axial-vector part of EW diagrams



- New Physics adds new loops with new particles
  ➔ modifies SM values values of C_7^{eff}, C_9^{eff}, C_{10}^{eff}
  ➔ introduces new coefficients C_S and C_P

- Need to measure many observables to extract complex Wilson coefficients

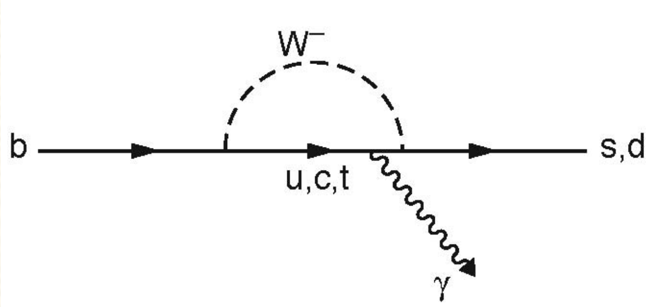


- Probe here New Physics at a scale of a few TeV

$B \rightarrow X_s\gamma$ Analyses

- $B \rightarrow X_s\gamma$ is largest EM FCNC loop process
- The SM prediction at NNLL (4 loop) is

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



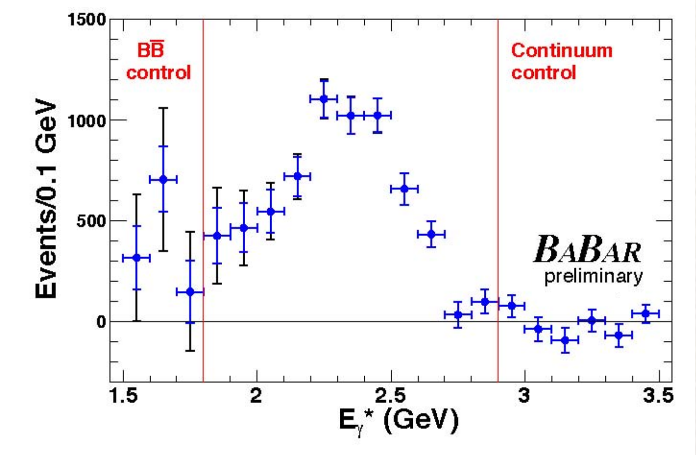
Misiak *et al.*, PRL98, 022002 (2007)

- The shape of the photon energy spectrum is important for determining the b quark momentum distribution
- The shape function is similar to that in $B \rightarrow X_u \ell \nu$ and thus helps in determining $|V_{ub}|$
- In the kinetic scheme, measure m_b, energy moments, and HQET parameter μ_π^2 (kinetic energy of b quark)
- The $B \rightarrow X_{s+d}\gamma$ CP asymmetry is sensitive for new physics processes
- BABAR updates results on
  - fully inclusive analysis $(383 \pm 4) \times 10^6$ $B\bar{B}$ events
  - semi inclusive modes $(471 \pm 1) \times 10^6$ $B\bar{B}$ events

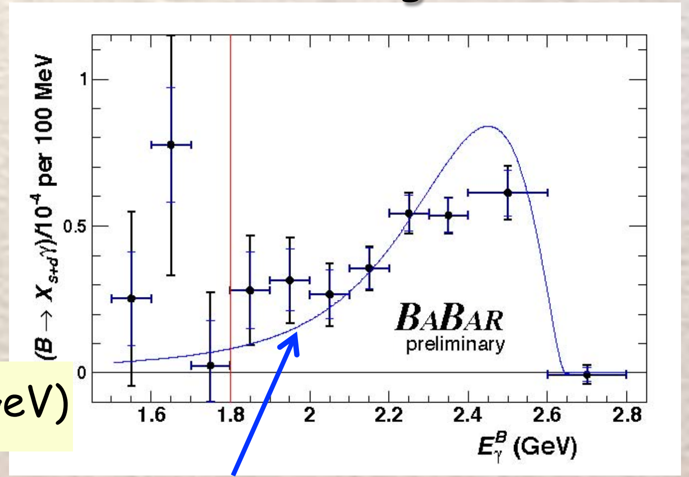
Inclusive $B \to X_s\gamma$: E_γ Spectrum

- Tag recoiling B via $Xe^{\pm}\nu$ or $X\mu^{\pm}\nu$ decay to suppress continuum background
- Use optimized π^0 and η vetoes, E_{miss}, and 2 neural networks (for e, μ each) based on event shape variables
- Signal efficiency is ε_s ~2.5% compared to $\varepsilon_{continuum}$=0.0005% and $\varepsilon_{B\bar{B}}$=0.013%
- Estimate remaining continuum background from $q\bar{q}$ continuum sample
- From measured E_γ spectrum yield branching fraction after correcting for calorimeter resolution, Doppler smearing and ε_{signal}

Measured background subtracted E_γ spectrum



Partial branching fraction



$$\mathcal{B}(B \to X_s\gamma) = \left(3.21 \pm 0.15_{stat} \pm 0.29_{sys} \pm 0.08_{mod}\right) \times 10^{-4}\ (E_\gamma > 1.8\ \text{GeV})$$

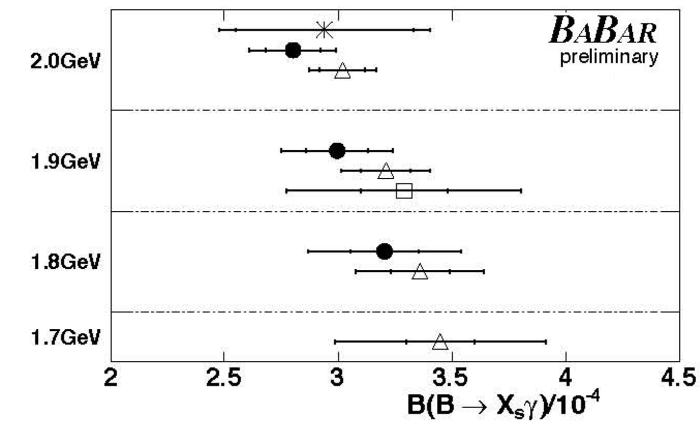
HFAG $\mathcal{B}(B \to X_s\gamma) = \left(3.55 \pm 0.24 \pm 0.09\right) \times 10^{-4}$

Kinetic model with HFAG averages

HFAG: arXiv:1010.1589v3 (2011)

Inclusive $B\to X_s\gamma$: Energy Moments

- Total branching fraction from BABAR, Belle and CLEO for different E_γ selection are in good agreement



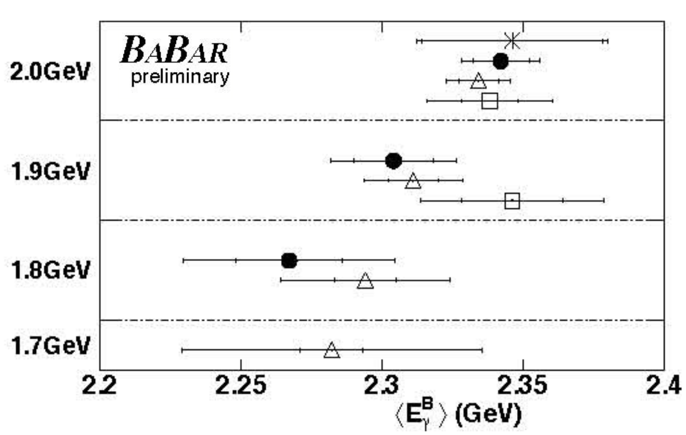
- Measure energy moments

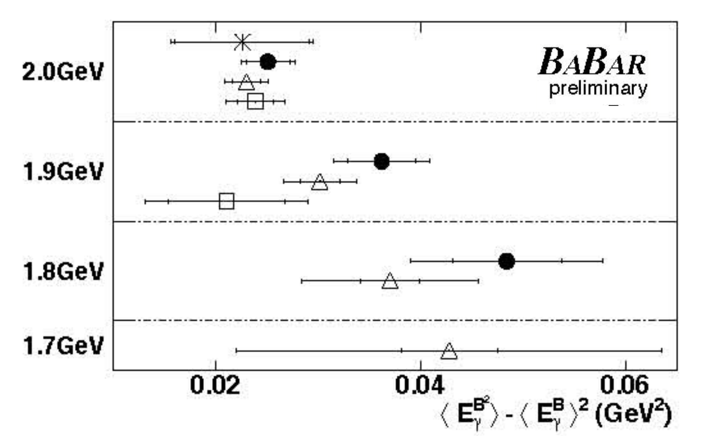
$$\langle E_\gamma\rangle = \left(2.267 \pm 0.019_{stat} \pm 0.032_{sys} \pm 0.003_{mod}\right)\text{GeV}\ (E_\gamma > 1.8\ \text{GeV})$$

$$\left\langle \left(E_\gamma - \langle E_\gamma\rangle\right)^2\right\rangle = \left(0.0484 \pm 0.0053_{stat} \pm 0.0077_{sys} \pm 0.0005_{mod}\right)\text{GeV}^2\ (E_\gamma > 1.8\ \text{GeV})$$

CLEO: PRL 87, 251807 (2001)
Belle: PRL 103, 241801 (2009)
BABAR: PRD 72, 052004 (2005)

- Energy moments from BABAR, Belle and CLEO for different E_γ selection are consistent





● this analysis
□ BABAR semi-inclusive
△ Belle
∗ CLEO

Inclusive $B \to X_s\gamma$: $\mathcal{A}_{CP}$ and New Physics

- Determine $B/\bar{B}$ from the tag charge
- Define *CP* asymmetry

$$\mathcal{A}_{CP}(\bar{B} \to X_{s+d}\gamma) \equiv \frac{\mathcal{B}(\bar{B} \to X_{s+d}\gamma) - \mathcal{B}(B \to X_{s+d}\gamma)}{\mathcal{B}(\bar{B} \to X_{s+d}\gamma) + \mathcal{B}(B \to X_{s+d}\gamma)}$$

- Measure A_{CP} after correcting for charge bias and mistagging

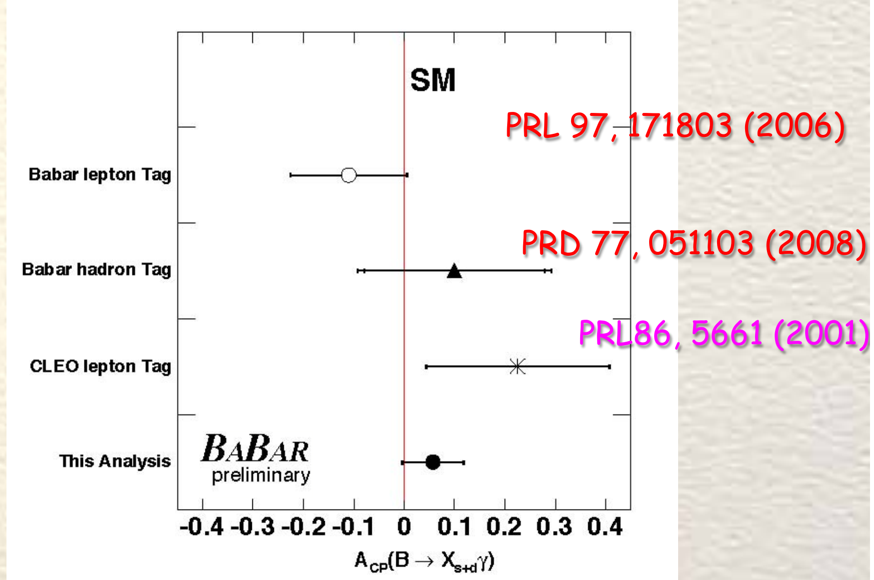
$$\mathcal{A}_{CP}(\bar{B} \to X_{s+d}\gamma) = 0.057 \pm 0.06_{stat} \pm 0.018_{sys}$$

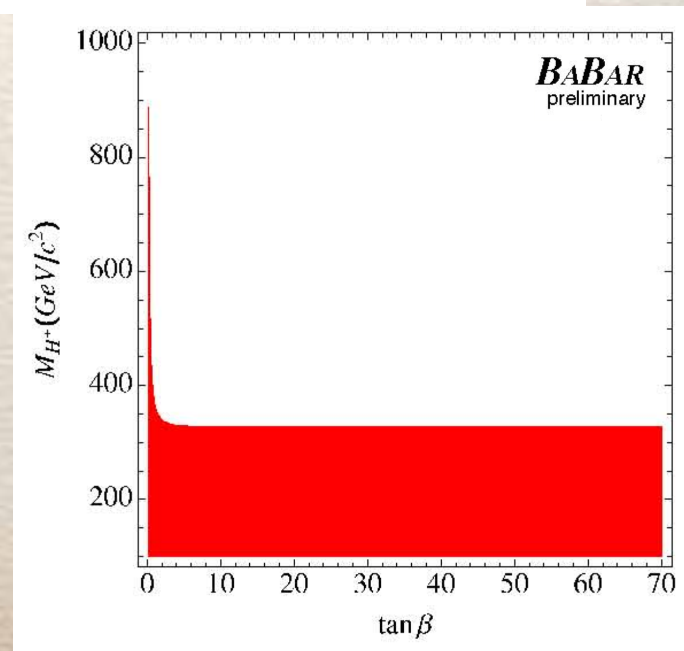
- Extrapolate corrected $\mathcal{B}(B \to X\gamma)$ from $E_\gamma > 1.8$ GeV to $E_\gamma > 1.6$ GeV (1.033±0.006)

$$\mathcal{B}(B \to X_s\gamma) = \left(3.31 \pm 0.16 \pm 0.30 \pm 0.09\right) \times 10^{-4}$$

HFAG: arXiv:1010.1589v3 (2011)

- Use this result to constrain new physics in type II two-higgs doublet model $m_{H\pm} < 327$ GeV is excluded at 95% CL independent of tan β





Haisch: arXiv:0805.2141 (2008)

$B \to X_s\gamma$ Semi-Inclusive Analysis

- Use sum of 38 exclusive $X_s\gamma$ modes with $\lesssim 4\pi$ ($\lesssim 2\pi^0$), 1(3)K ($\lesssim 1K^0_s$), $\lesssim 1\eta$
- Measured m_{X_s} is fitted to kinetic and shape function models

BABAR	kinetic model	shape function model
m_b [GeV/c^2]	$4.568^{+0.038}_{-0.036}$	$4.579^{+0.032}_{-0.029}$
μ_π^2 [GeV/c^2]	$0.450^{+0.054}_{-0.054}$	$0.257^{+0.034}_{-0.039}$

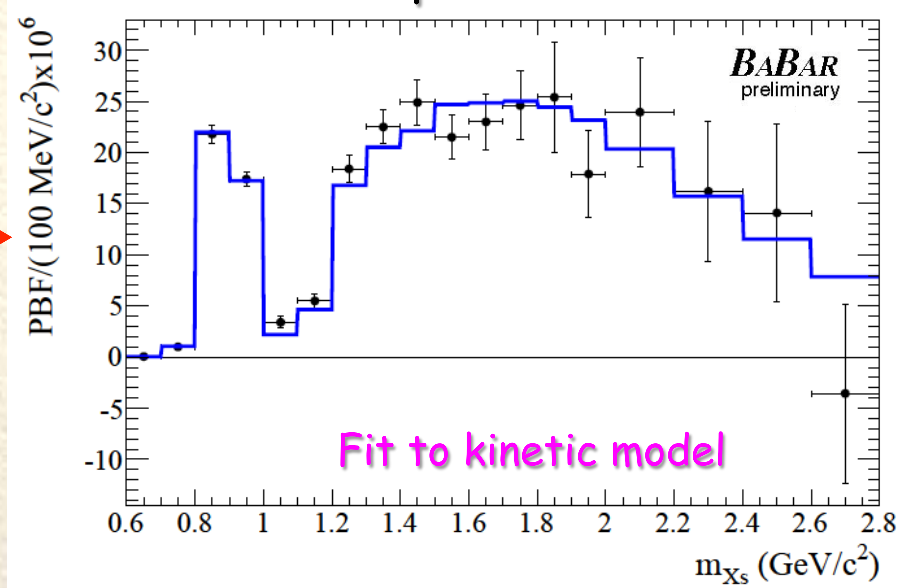
Benson *et al.*, Nucl.Phys B710, 371 (2005)
Lange *et al.*, Phys Rev D72, 073006 (2005)

World average	kinetic model	shape function model
m_b [GeV/c^2]	4.591 ± 0.031	$4.620^{+0.039}_{-0.032}$
μ_π^2 [GeV/c^2]	0.454 ± 0.038	$0.288^{+0.054}_{-0.074}$

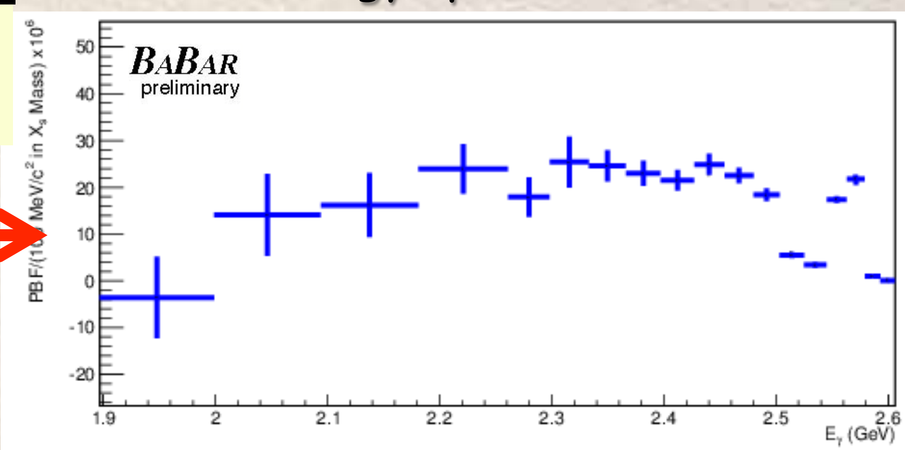
HFAG: arXiv:1010.1589v3 (2011)

- Reconstruct X_s ➔ $E_\gamma = \dfrac{m_B^2 - m_{X_s}^2}{2m_B}$
- Sum of partial branching fractions in each m_{X_s} bin is summed to to yield total branching fraction

Hadronic mass spectrum



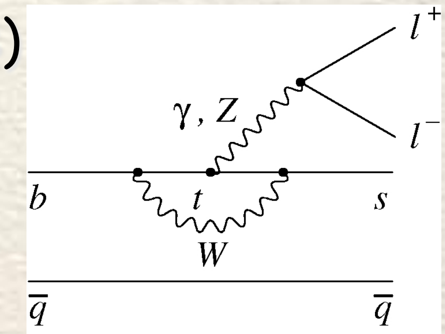
Photon energy spectrum



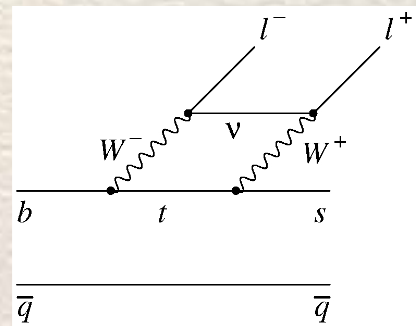
$$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.29 \pm 0.19_{stat} \pm 0.48_{sys}) \times 10^{-4}$$

Analysis Methodology for $B\to K^{(*)}\ell^+\ell^-$

- Fully reconstruct 8 $B\to K^{(*)}\ell^+\ell^-$ final states (471×10^6 $B\bar{B}$)
  - K, K^0_S, $K^\pm\pi^\mp$, or $K^0_S\,\pi^\pm$ recoiling against e^+e^- or $\mu^+\mu^-$
  - Select $e^\pm$ with $p>0.3$ GeV/c; $\mu^\pm$ with $p > 0.7$ GeV/c
  - Require good particle ID for e, μ, K, π; select $K^0_S \to\pi^+\pi^-$



- Utilize kinematic variables $m_{ES}=\sqrt{\left(\frac{E^2_{CM}}{4}-p^{*2}_B\right)}$ and $\Delta E = E^*_B - \frac{E_{CM}}{2}$



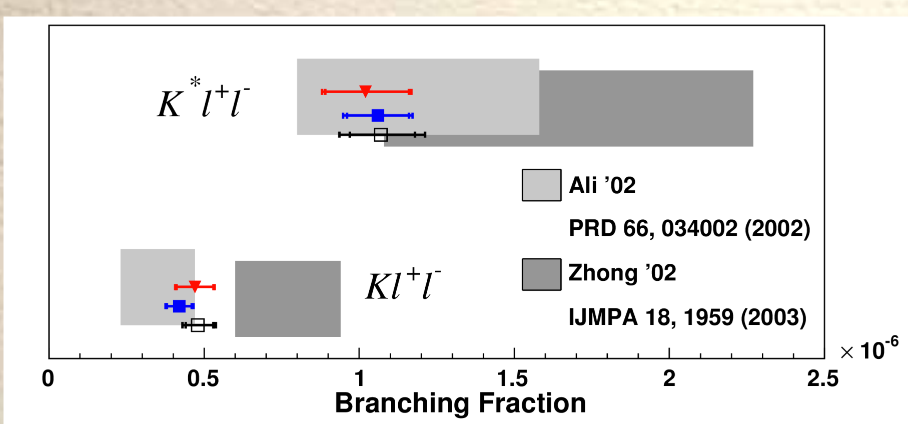
- Suppress combinatorial $B\bar{B}$ & $q\bar{q}$ backgrounds with 8 boosted decision trees
- Veto J/ψ and $\psi(2S)$ mass regions and use vetoed samples as controls samples for various checks
- For rate asymmetries do 1D (2D) fits in m_{ES} (m_{K^*}) for $B\to K^{(*)}\ell^+\ell^-$, for angular analyses fit m_{ES} and 1D angular distributions
- Use pseudo experiments to study performance
- *All analyses are blinded*

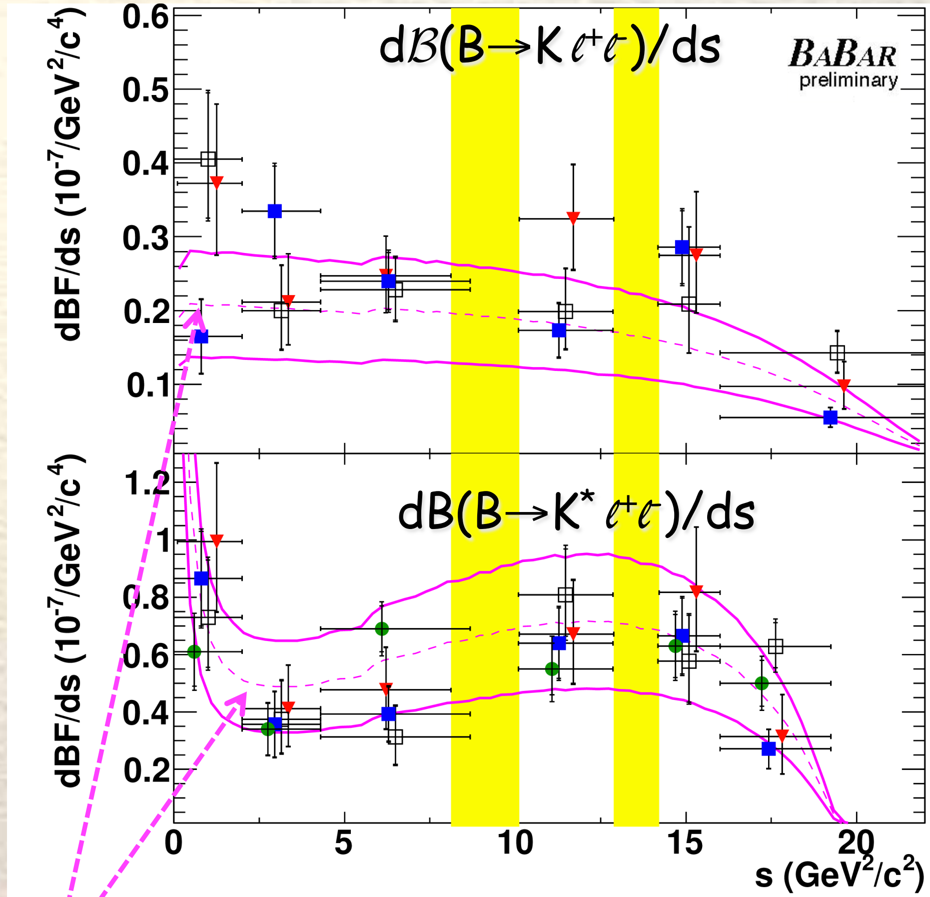
B→K^(*) ℓ⁺ℓ⁻ Branching Fractions

- BABAR $\mathcal{B}_{tot}$ measurements

$$\mathcal{B}(B \to K\ell^+\ell^-) = \left(4.7 \pm 0.6 \pm 0.2\right) \times 10^{-7}$$

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = \left(10.2^{+1.4}_{-1.3} \pm 0.5\right) \times 10^{-7}$$





- BABAR total and partial branching fraction measurements are in good agreement with results from Belle, CDF, LHCb, and the SM predictions

SM based prediction plus uncertainties (solid line) from Form factor models *

▼ *BABAR 471 M $B\bar{B}$*
■ CDF 6.8 fb^{-1} ($\mu^+\mu^-$ only) PRL 107, 201802 (2011)
□ Belle 657 *M $B\bar{B}$* PRL 103, 171801 (2009)
● LHCb 0.37 fb^{-1}($\mu^+\mu^-$ only) arXiv:1112.3515 (2012)

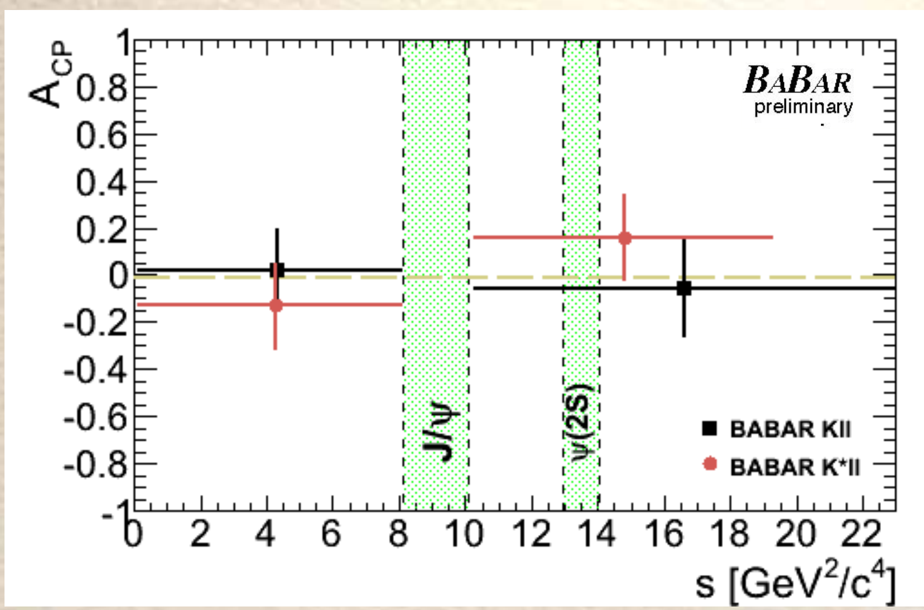
Ali *et al* PRD 66, 034002 (2002)
* Ball and Zwicky, PRD 71, 014015 (2005); ibid 014029 (2005)

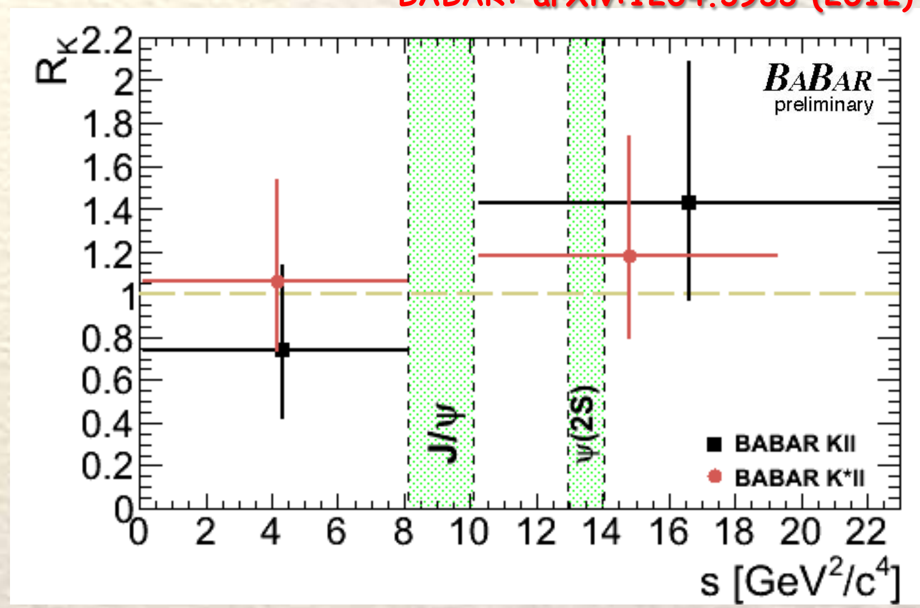
$B \to K^{(*)} \ell^+ \ell^-$ Rate Asymmetries

- $$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to \bar{K}^{(*)} \ell^+ \ell^-) - \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}{\mathcal{B}(\bar{B} \to K^{(*)} \ell^+ \ell^-) + \mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)}$$

- $$\mathcal{R}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$ $s \geq (2^* m_\mu)^2$

BABAR: arXiv:1204.3933 (2012)





- All A_{CP} results are consistent with zero ➔agree with small SM value
  Krüger *et al.*, PRD 61, 114028 (2000)
  Bobeth *et al.*, JHEP 807,106, (2008)
- All $R_{K(*)}$ results are consistent with unity ➔agree with SM
  Ali *et al.*, PRD 61, 074024 (2000)
- All s
  $$\mathcal{A}_{CP}(B \to K \ell^+ \ell^-) = -0.03 \pm 0.14 \pm 0.01$$
  $$\mathcal{A}_{CP}(B \to K^* \ell^+ \ell^-) = 0.03 \pm 0.13 \pm 0.01$$
- All s
  $$\mathcal{R}_K(B \to K \ell^+ \ell^-) = 1.00^{+0.31}_{-0.25} \pm 0.07$$
  $$\mathcal{R}_{K^*}(B \to K^* \ell^+ \ell^-) = 1.13^{+0.34}_{-0.26} \pm 0.10$$

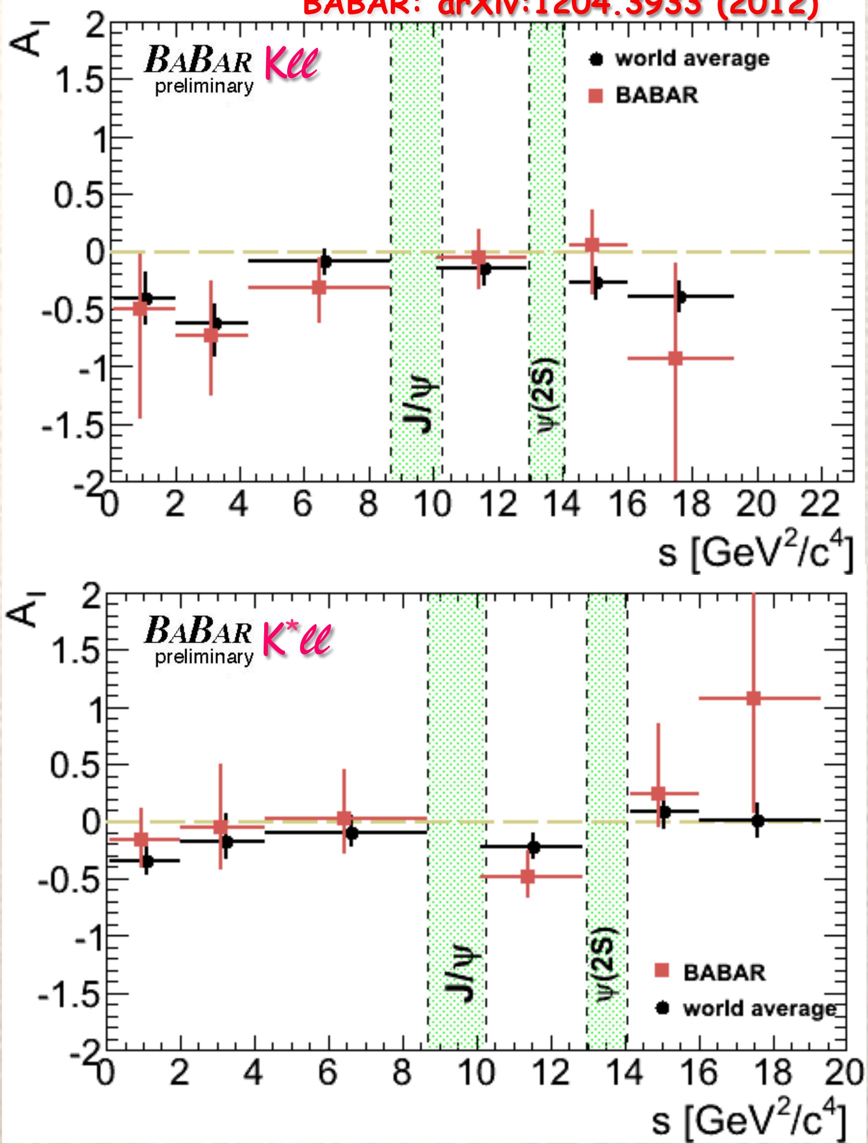
BABAR: arXiv:1204.3933 (2012)
c/f Belle: PRL 103, 171801 (2009)

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

- $$\mathcal{A}_I \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - r_\tau \mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + r_\tau \mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}$$
  $$r_\tau = \tau_{B^0} / \tau_{B^+} = 1/(1.071 \pm 0.09)$$
- In the SM, $\mathcal{A}_I$ is expected at $\mathcal{O}(+1\%)$
  Feldmann & Matias JHEP 0301, 074 (2003)
- Below $J/\psi(0.1<s<8.12\ \mathrm{GeV}^2/c^4)$ BABAR measures:
  $$\mathcal{A}_I^{low}(B \to K\ell^+\ell^-) = -0.58^{+0.29}_{-0.37} \pm 0.02$$
  $$\mathcal{A}_I^{low}(B \to K^*\ell^+\ell^-) = -0.25^{+0.17}_{-0.20} \pm 0.03$$
- This is consistent with the SM at the 2.1σ and 1.2σ levels
- WA confirms low $\mathcal{A}_I$ at low s
- BABAR results agree with those from Belle and LHCb

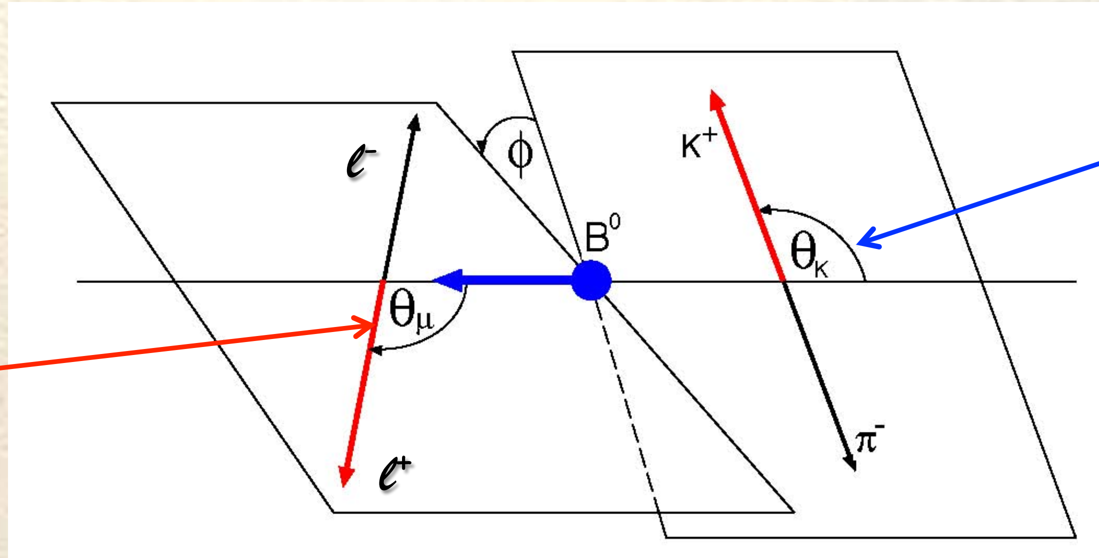
➔ WA: new BABAR, Belle, LHCb

BABAR: arXiv:1204.3933 (2012)



BABAR: arXiv::1204.3933 (2012)
Belle: PRL 103, 171801 (2009)
LHCb: arXiv::1205.3422 (2012)

Angular Observables in $B \to K^* \ell^+\ell^-$



θ_K: angle of K^+ and B in K^* rest frame

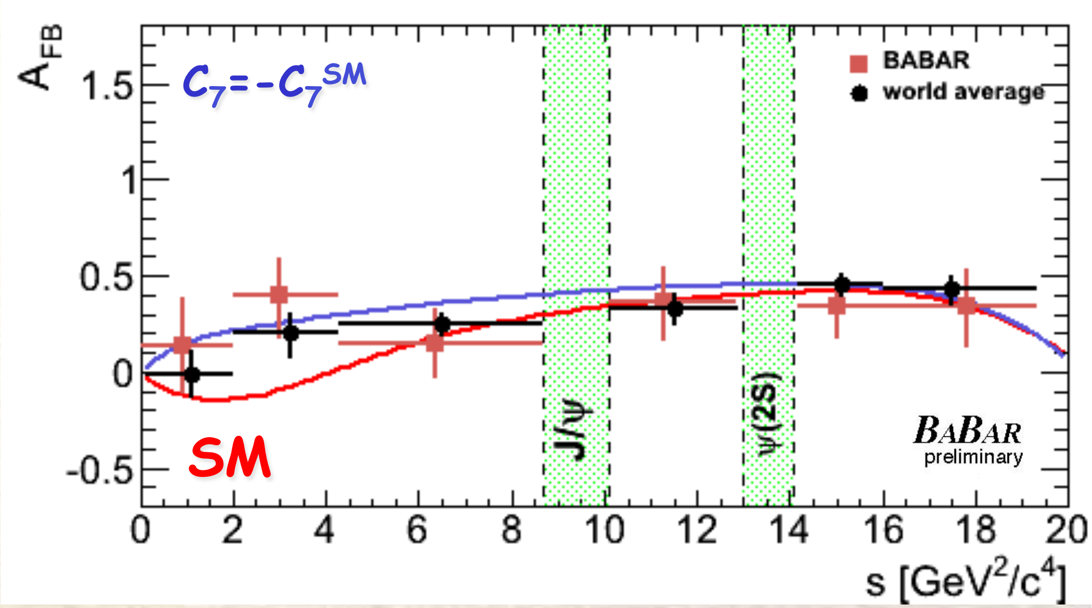
θ_ℓ: angle of ℓ^+ and B in $\ell^+\ell^-$ rest frame

- Fit to lepton and K angular distributions to extract K^* longitudinal polarization fraction $\mathcal{F}_L$ and lepton forward-backward asymmetry $\mathcal{A}_{FB}$
- $\mathcal{F}_L$: $$W(\cos\theta_K) = \tfrac{3}{2}\mathcal{F}_L \cos^2\theta_K + \tfrac{3}{4}(1-\mathcal{F}_L)\sin^2\theta_K$$
- $\mathcal{A}_{FB}$ $$W(\cos\theta_\ell) = \tfrac{3}{4}\mathcal{F}_L \sin^2\theta_\ell + \tfrac{3}{8}(1-\mathcal{F}_L)(1+\cos^2\theta_\ell) + \mathcal{A}_{FB}\cos\theta_\ell$$

Ali *et al.*, PRD 61, 074024 (2000)
Bobeth *et al.*, JHEP 0712, 040 (2007)

$B \to K^* \ell^+ \ell^-$ Forward-Backward Asymmetry $\mathcal{A}_{FB}$

- BABAR $\mathcal{A}_{FB}$ measurements in $B \to K^* \ell^+ \ell^-$ are the most precise except for LHCb results ($K^{*0}\mu^+\mu^-$)



- Results from BABAR, Belle, CDF and LHCb are in good agreement

- Results are consistent with the SM, but do not rule out the $C_7 = -C_7^{SM}$ model

➔WA: new BABAR, Belle, CDF, LHCb

CDF: Note 10047 (2010)
Belle: PRL 103, 171801 (2009)
LHCb: arXiv:1112.3515 (2012)

- In low mass region ($1 < s < 6$ GeV^2/c^2) measure

BABAR: $\mathcal{A}_{FB}(B \to K^* \ell^+ \ell^-) = 0.26^{+0.27}_{-0.30} \pm 0.07$

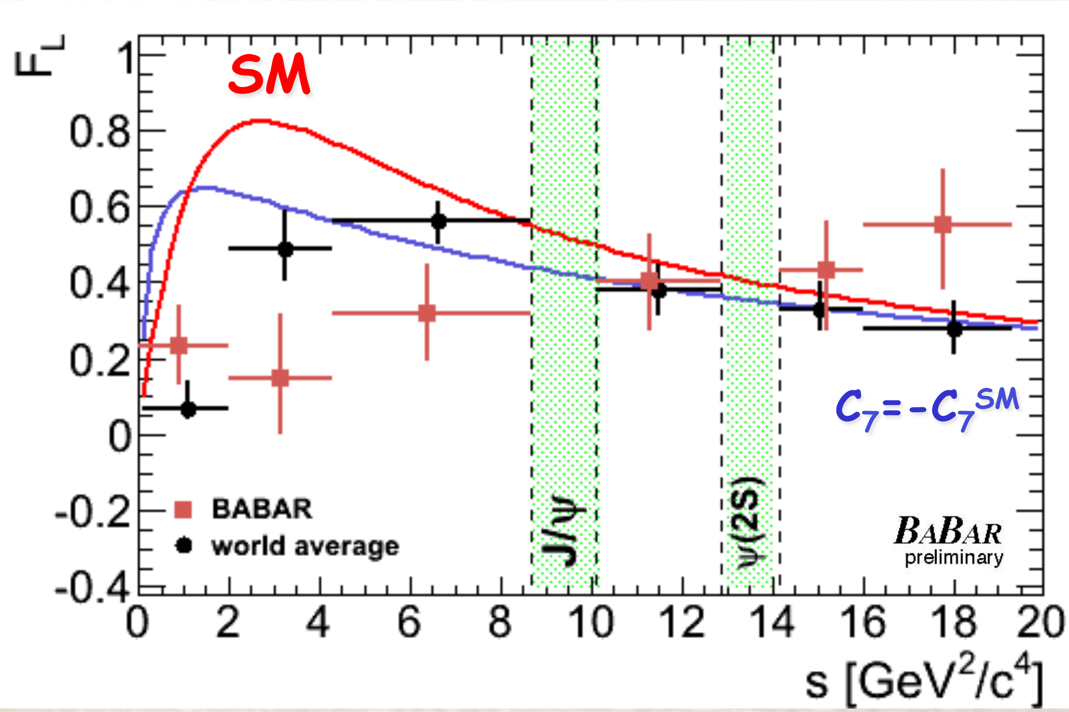
world average: $\mathcal{A}_{FB}^{WA}(K^* \ell\ell) = 0.11^{+0.08}_{-0.09}$

SM: $\mathcal{A}_{FB}^{SM} = -0.05^{+0.03}_{-0.04}$ $(1 < s < 6 \text{ GeV}^2/c^4)$

Ali et *al.* PRD 61, 074024 (2000)
Buchalla et *al.* PRD 63, 014015 (2000)
Ali et *al.* PRD 66, 034002 (2002)
Krüger et *al.* PRD 61, 114028 (2002)
Krüger & Matias PRD71, 094009 (2005)
C. Bobeth *et al.* JHEP 1007, 098 (2010)

K* Longitudinal Polarization $\mathcal{F}_L$ in $B\rightarrow K^*\ell^+\ell^-$

- BABAR $\mathcal{F}_L$ measurements in $B\rightarrow K^*\ell^+\ell^-$ are the most precise except for LHCb results ($K^{*0}\mu^+\mu^-$)
- Results from BABAR, Belle, CDF and LHCb are in good agreement
- Results are consistent with the SM, but do not rule out the C_7=-C_7^{SM} model



➔WA: new BABAR, Belle, CDF, LHCb

CDF: Note 10047 (2010)
Belle: PRL 103, 171801 (2009)
LHCb: arXiv:1112.3515 (2012)

- In low mass region ($1<s<6$ GeV^2/c^2) measure

BABAR: $\mathcal{F}_L = 0.25^{+0.09}_{-0.08} \pm 0.03$

world average: $\mathcal{F}_L = 0.41 \pm 0.06$

C. Bobeth *et al.* arXiv:1006.5013
Krüger & Matias PRD71, 094009 (2005)

SM: $\mathcal{F}_L^{SM} = 0.73^{+0.13}_{-0.23}$ **(1 < s < 6 GeV^2/c^4)**

Conclusion

- New BABAR $B \to X_s\gamma$ results
  - branching fractions from inclusive and semi-inclusive analyses are in good agreement with SM prediction
  - CP asymmetry is consistent with zero
  - New measurements on photon energy moments
  - New measurements on m_b and μ_π^2
  - Set limit on charged Higgs boson $m_{H\pm} > 327$ GeV @ 95% CL

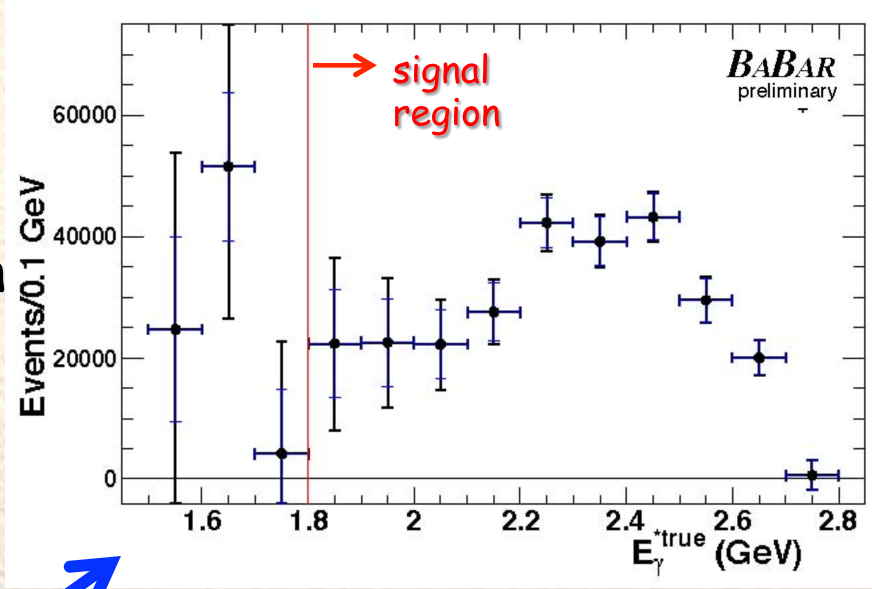
- New BABAR $B \to K(*)\ell^+\ell^-$ results
  - Partial and total branching fractions are in good agreement with SM
  - CP asymmetries and lepton-flavor ratios agree SM prediction
  - Isospin asymmetry is consistent with SM, but is lower at small s
  - $\mathcal{A}_{FB}$ and $\mathcal{F}_L$ are consistent with the SM prediction, but do not rule out flipped C_7 ($C_7=-C_7^{SM}$) model

- Significant progress will come from LHCb and the Super B-factories
  ➔idea: probe new angular observable that help in revealing small discrepancies wrt the SM

Backup Slides

$B \to X_s \gamma$: Corrected E_γ Spectrum

- First, correct measured E_γ spectrum for selection efficiency taking into account the additional correlated errors between the selection efficiency and background estimation
- Next, unfold the resolution smearing and correct resultant spectrum for detector acceptance
- Resulting E_γ spectrum still includes Doppler smearing
  ➔ this spectrum is used for comparison with theory
- Dominant uncertainty in the bins of the unfolded E_γ spectrum result from a shift of photon energy scale by ±0.3%



error bars: statistical and total (stat + sys+model added in quadrature)

Energy Range (GeV)	Change (events)	
	$E_\gamma^{*\,true}$ Bins	E_γ^B Bins
1.53 to 1.60	222.1	220.2
1.60 to 1.70	190.6	191.0
1.70 to 1.80	261.1	261.6
1.80 to 1.90	354.4	354.8
1.90 to 2.00	493.2	492.0
2.00 to 2.10	622.9	622.2
2.10 to 2.20	640.3	658.5
2.20 to 2.30	428.4	461.1
2.30 to 2.40	528.7	598.9
2.40 to 2.50	1184.2	1292.5
2.50 to 2.60	1080.6	967.6
2.60 to 2.70	490.8	475.7

Angular Distributions for $B \to K^{(*)}\ell^+\ell^-$

- $\mathcal{A}_{FB}$ results from interplay between $C_9(q^2)C_{10}$ and C_7C_{10}/q^2

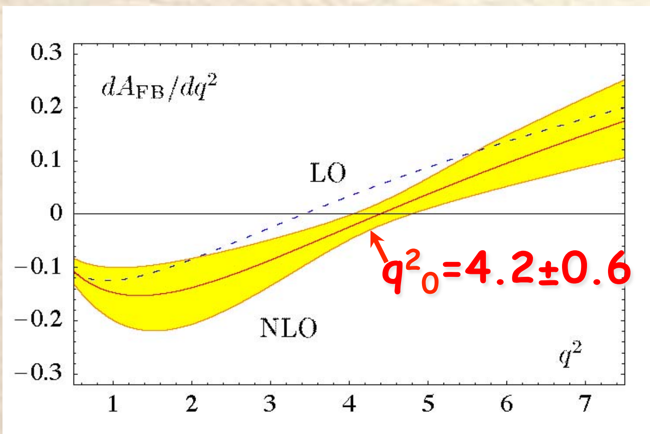
$$\frac{d\mathcal{A}_{FB}}{dq^2} \propto -\left\{ \mathrm{Re}\left[C_9^{eff}(q^2)C_{10}\right]VA_1 + \frac{m_b m_B}{q^2}\mathrm{Re}\left[C_7^{eff}C_{10}\right]\left[VT_2\left(1-\frac{m_{K^*}}{m_B}\right)+A_1T_1\left(1+\frac{m_{K^*}}{m_B}\right)\right]\right\} \quad K^*\ell^+\ell^-$$

form factors

- Recent SM calculations focus on low q^2-region

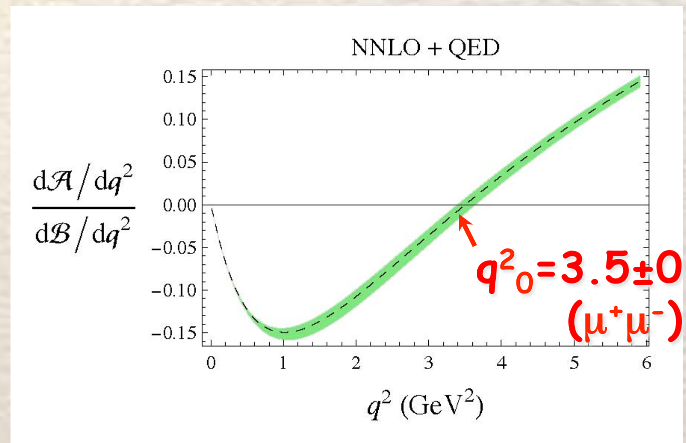
$K^*\ell^+\ell^-$

$\mathcal{O}(\alpha_s)$



$X_s\ell^+\ell^-$

$\mathcal{O}(\alpha_s^2)$



Feldmann & Matias JHEP 0301, 074 (2003)

Huber, Hurth & Lunghi, Nucl.Phys B802, 40 (2008)

- In the SM, $\mathcal{A}_{FB}$ crosses zero around q^2_0 =3.5-4.5 GeV^2