Radiative Penguin Decays at e^+e^- Colliders

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representing the BABAR collaboration

New BABAR Results since FPCP 2012

- Review on $b\rightarrow s,d\gamma$ and $b\rightarrow s/d\,\ell^+\ell^-$ analyses with focus on 3 new results since FPCP2012

- Study of $B\rightarrow X_s\gamma$ with 424 fb^{-1} using a sum of exclusive modes **new**
  - CP asymmetry

- Analysis of $B\rightarrow \pi/\eta\,\ell^+\ell^-$ modes with 424 fb^{-1} **new**
  - Branching fraction limits

BABAR: hep-ex/1303.6010 (2013)

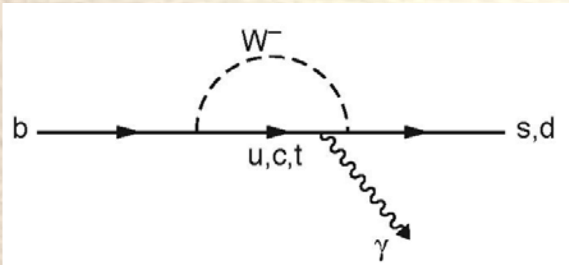
- Study of $B\rightarrow X_{s+d}\gamma$ with 347 fb^{-1} using a fully inclusive method **new**
  - γ energy spectrum and γ energy moments
  - CP asymmetry

BABAR: PRL109, 191801 (2012)
PRD86, 112008 (2012)

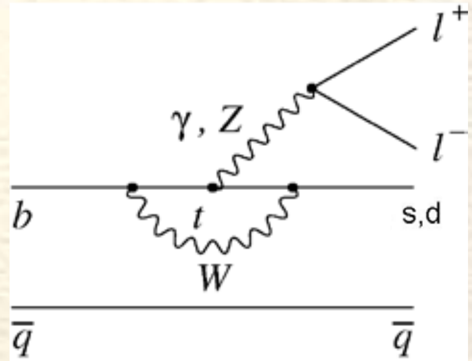
- All BABAR analyses are blinded

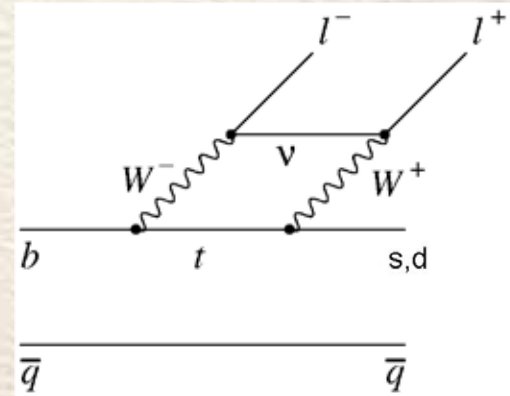
Introduction

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



C_7^{eff} (EM penguin)





C_9^{eff} & C_{10}^{eff} (V & A parts of weak penguin and box)

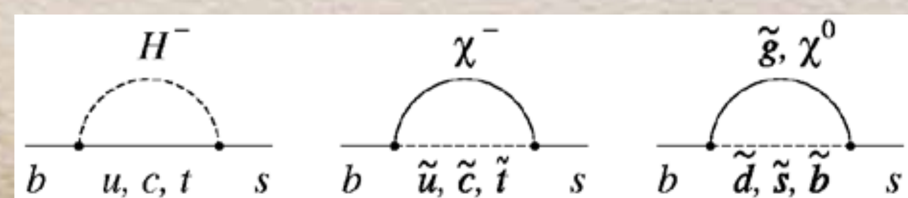
- Effective Hamiltonian factorizes short-distance from long-distance effects $[\mathcal{O}(\alpha_s)]$

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu)\mathcal{O}_i$$

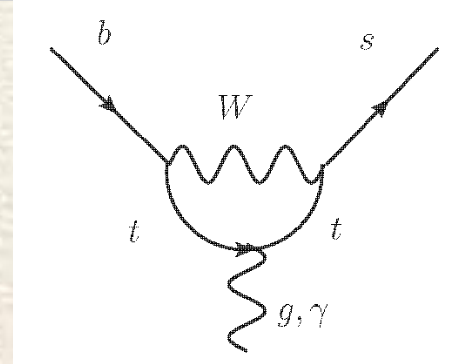
➔ 4 effective Wilson coefficient: C_7^{eff}, C_8^{eff}, C_9^{eff}, C_{10}^{eff}

- New physics adds new loops with new particles ➔ modifies SM values of Wilson coefficients and may introduce new terms, *e.g.* C_S and C_P

- Probe here new physics at a scale of a few TeV



$B \rightarrow X_s\gamma$ Studies



- In the Standard Model (SM) the $B \rightarrow X_s\gamma$, branching fraction is calculated at NNLL (4 loops)

$$\mathcal{B}(B \rightarrow X_s\gamma) = \left(3.14 \pm 0.22\right) \times 10^{-4} \; (E_\gamma > 1.6 \text{ GeV})$$

Misiak *et al.*, PRL98, 022002 (2007); Misiak FCPC 2013

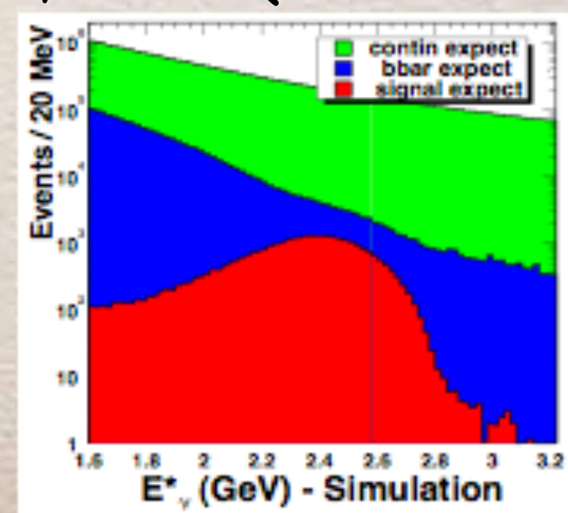
- The shape of the photon energy spectrum depends on b quark momentum inside the B meson (Fermi motion)

- Since the shape function is similar to that in $B \rightarrow X_u \ell \nu$, its measurement helps with determining $|V_{ub}|$

- In the kinetic scheme, measure m_b, energy moments, and HQET parameters, *e.g.* m_π^2 (kinetic energy of b quark)

- The *CP* asymmetry is sensitive to new physics

- Three strategies have been used:
  - Fully inclusive analysis with lepton tags ★
  - Semi inclusive analysis ★
  - Fully inclusive analysis with B-reconstruction

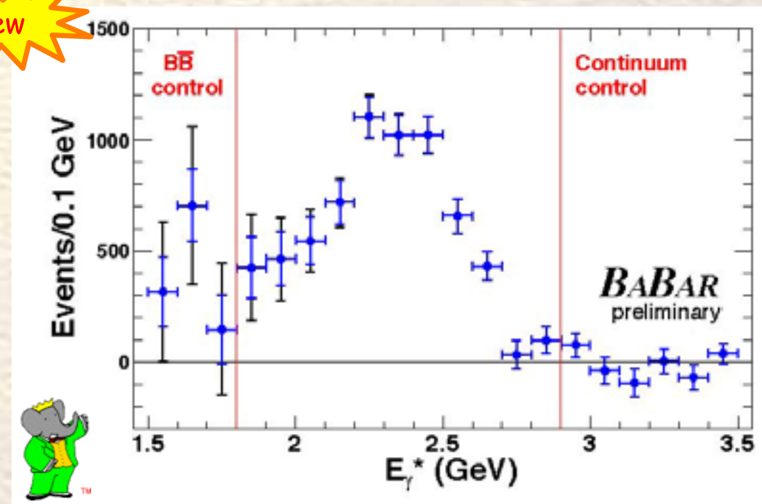


Inclusive $B \to X_s \gamma$: E_γ Spectrum

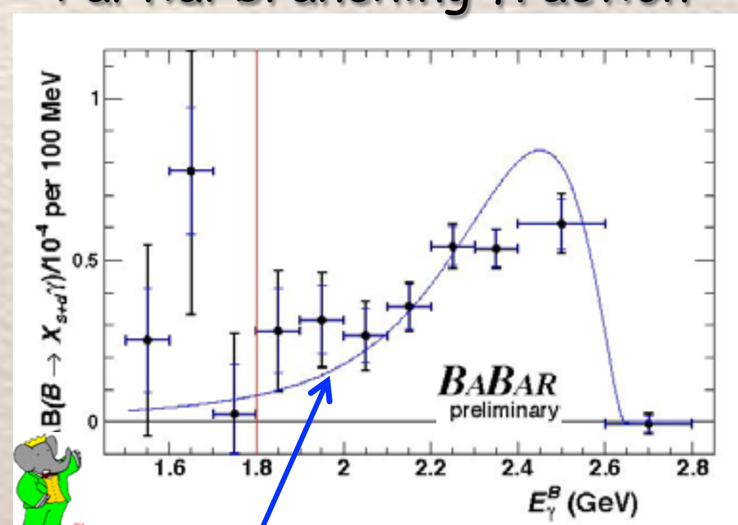
- Use BABAR sample of $(383 \pm 4) \times 10^6$ $B\bar{B}$ events
- new
- Tag recoiling B via $Xe^{\pm}\nu$ or $X\mu^{\pm}\nu$ decay to suppress continuum background
- Use optimized π^0 and η vetoes, E_{miss}, and 2 neural networks (for e, μ each) based on event shape variables
- Signal efficiency is 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}

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

Measured background subtracted E_ε spectrum



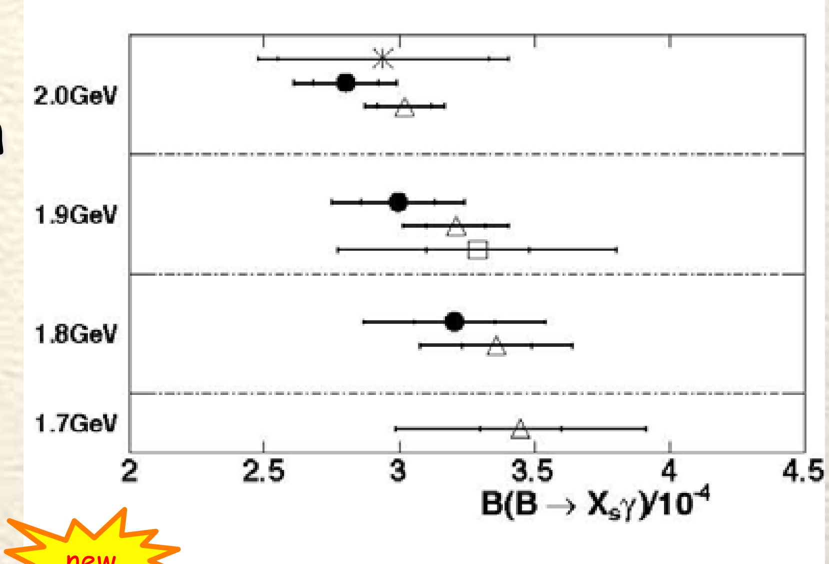
Partial branching fraction



Kinetic model with HFAG averages

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

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



- Measure energy moments for E_γ > 1.8 GeV

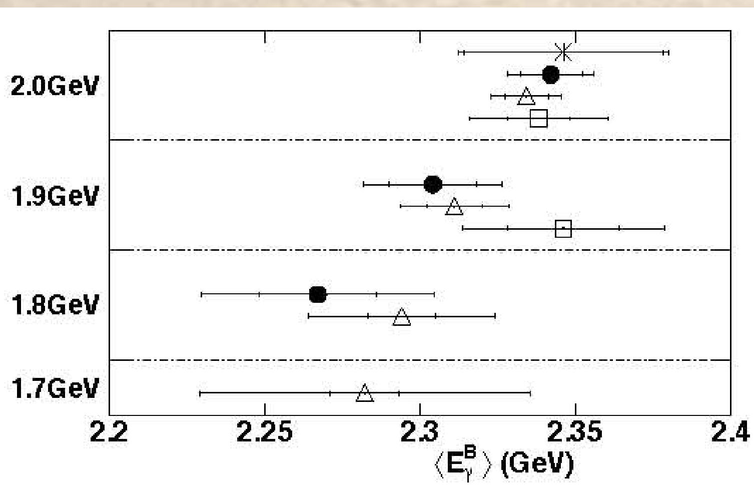
$$\langle E_\gamma \rangle = \left(2.267 \pm 0.019_{stat} \pm 0.032_{sys} \pm 0.003_{mod}\right) GeV$$

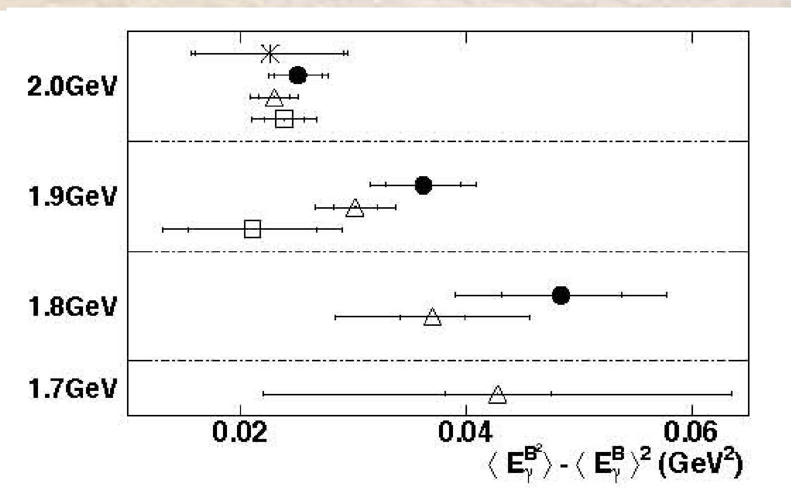
$$\left\langle \left(E_\gamma - \langle E_\gamma \rangle\right)^2 \right\rangle = \left(0.0484 \pm 0.0053_{stat} \pm 0.0077_{sys} \pm 0.0005_{mod}\right) GeV^2$$

new

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

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

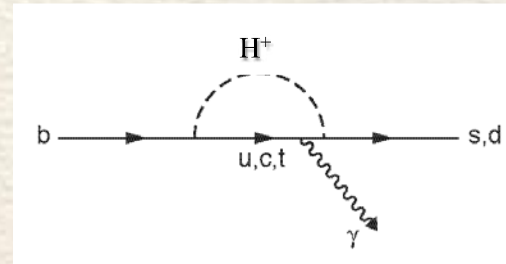




CLEO: PRL 87, 251807 (2001)
Belle: PRL 103, 241801 (2009)
BABAR: PRD 72, 052004 (2005)
BABAR: PRL.100, 191801 (2012)

Inclusive $B \to X_s\gamma$: New Physics Limits

- In 2Higgs Doublet Models, $B \to X\gamma$ may receive additional contributions from loop diagrams with a charged Higgs



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

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

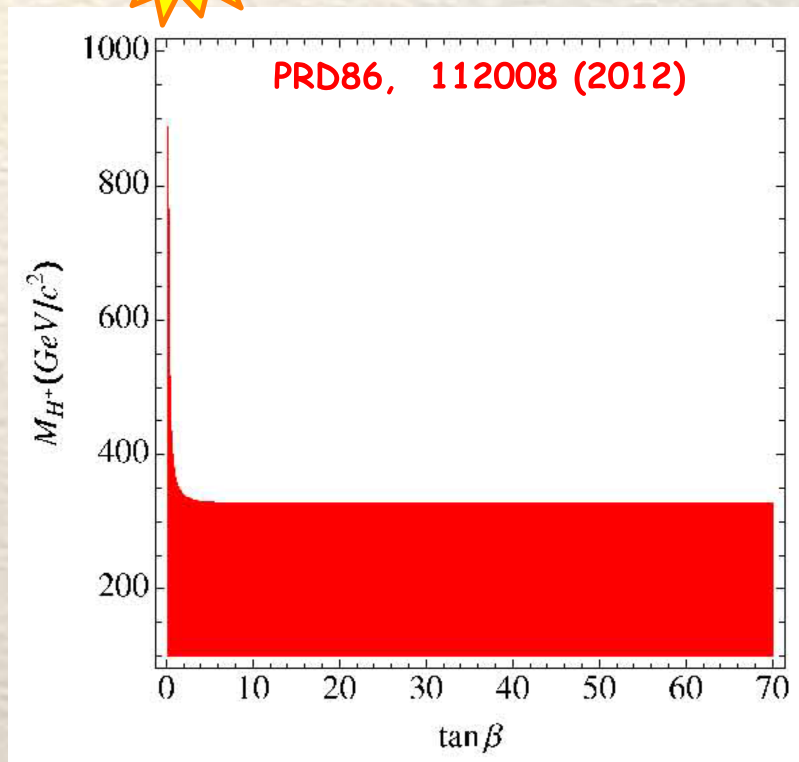
new

- In good agreement with SM prediction

$$\mathcal{B}(B \to X_s\gamma) = \left(3.14 \pm 0.22\right) \times 10^{-4}$$

- Use extrapolated result to constrain $m_{H\pm}$ in the type II two-higgs doublet model

- Exclude charged Higgs masses of $m_{H\pm} < 327$ GeV at 95% CL independent of $\tan\beta$



Haisch: arXiv:0805.2141 (2008)

- Recent BABAR $\mathcal{B}(B \to D^{(*)}\tau\nu)$ results exclude entire type II 2HDM

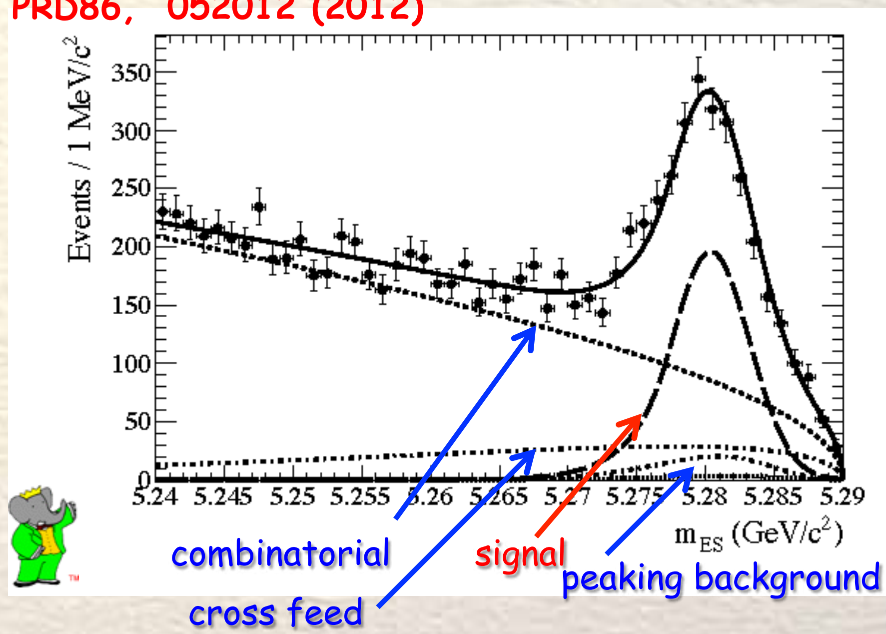
hep-ex/1303.0571 (2013)

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

- Use full BABAR sample of $(471\pm1)\times10^6$ $B\bar{B}$ events

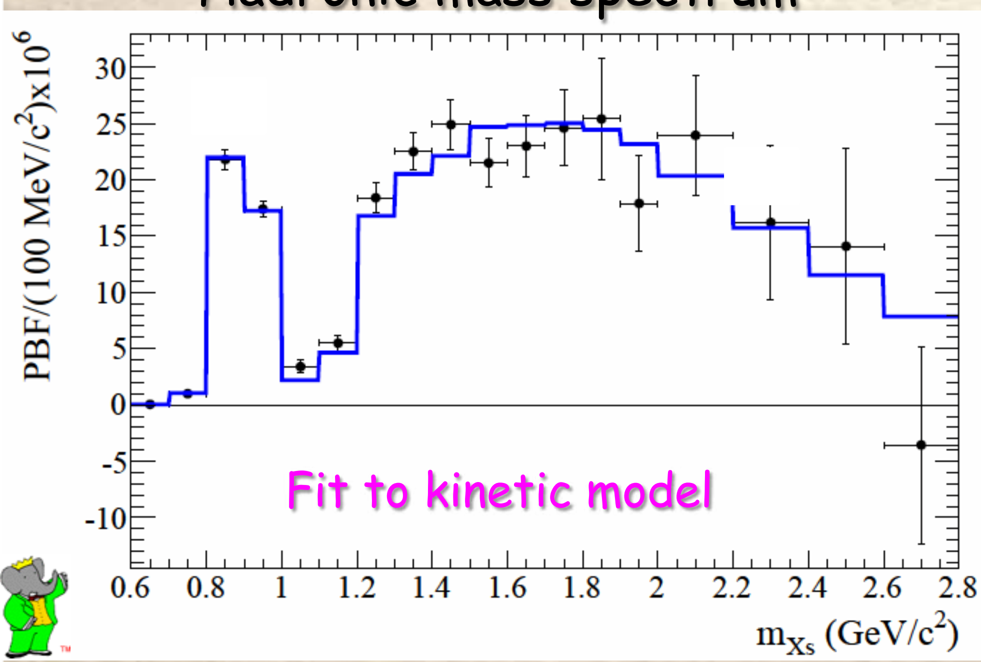
$$m_{ES} = \sqrt{\left(\tfrac{1}{4}E^2_{CM} - p^{*2}_B\right)}$$

PRD86, 052012 (2012)



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

Hadronic mass spectrum



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

- BABAR results agree well with WA

BABAR	kinetic model	shape function model
m_b [GeV/c²]	$4.568^{+0.038}_{-0.036}$	$4.579^{+0.032}_{-0.029}$
μ^2_π [GeV/c²]	$0.450^{+0.054}_{-0.054}$	$0.257^{+0.034}_{-0.039}$

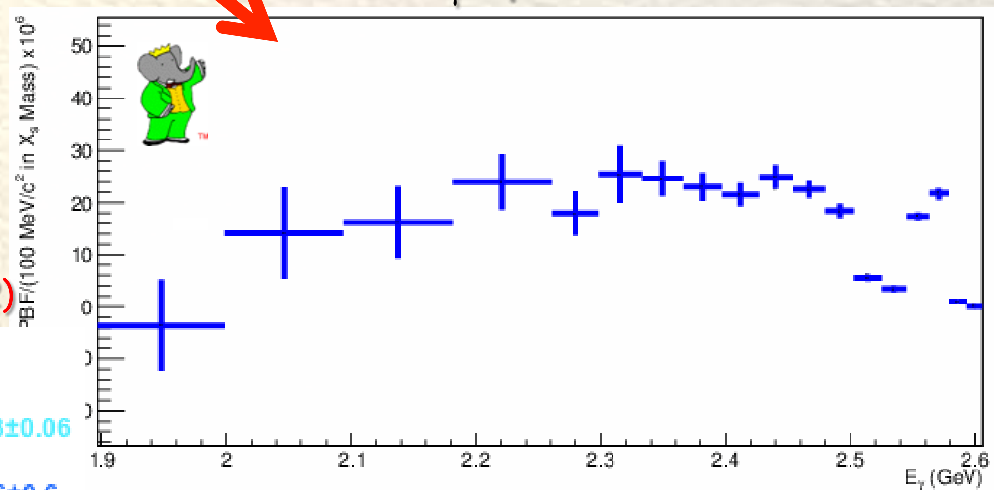
World average	kinetic model	shape function model
m_b [GeV/c²]	4.591 ± 0.031	$4.620^{+0.039}_{-0.032}$
μ^2_π [GeV/c²]	0.454 ± 0.038	$0.288^{+0.054}_{-0.074}$

HFAG: arXiv:1010.1589v3 (2011)

$B \to X_s \gamma$: Branching Fractions

- Reconstruct X_s ➔ Calculate E_γ by $E_\gamma = \left(m_B^2 - m_{X_s}^2\right)/2m_B$

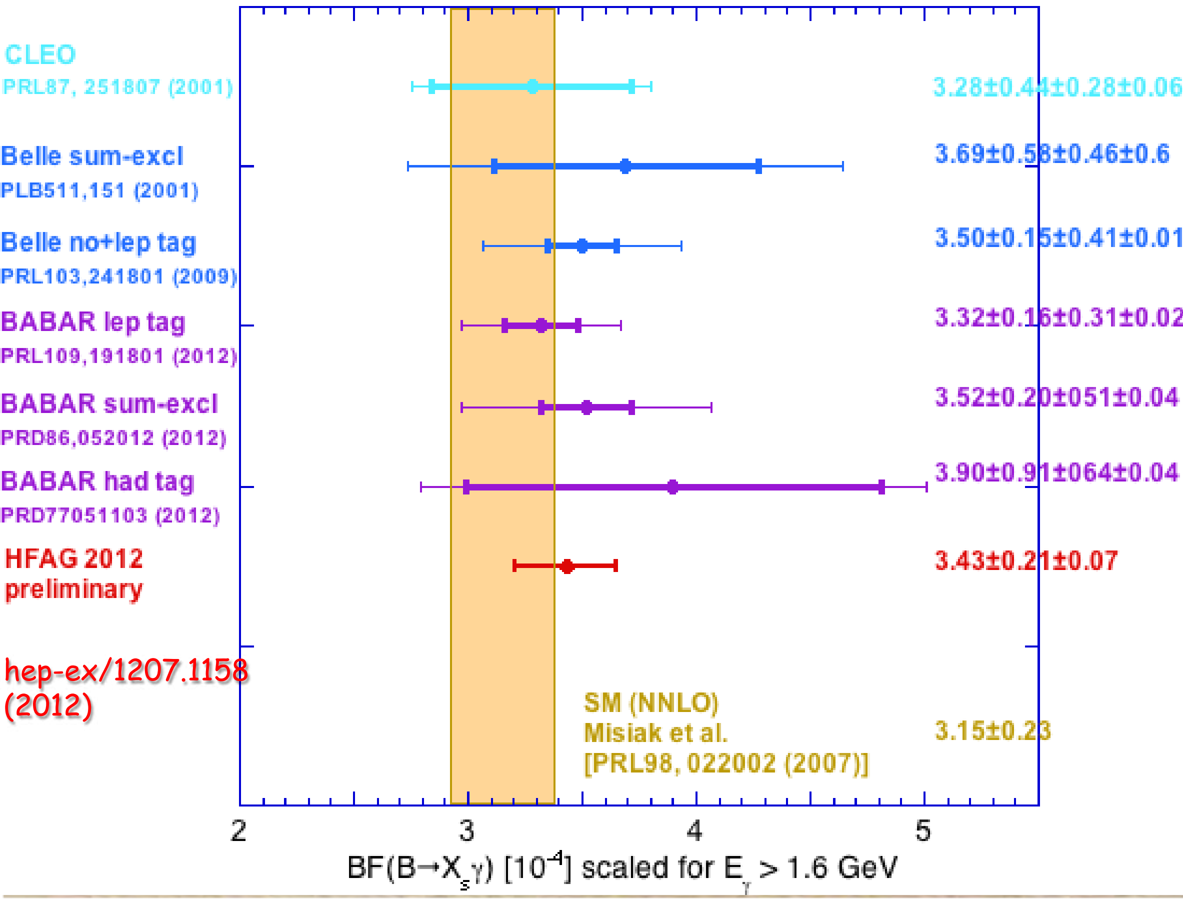
E_γ spectrum



- Sum partial branching fractions in each m_{Xs} bin to yield total branching fraction (E_γ>1.9 GeV)

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

Phys.Rev. D86, 052012 (2012)



- Compare all $B \to X\gamma$ total branching fractions after extrapolating measured values to E_γ >1.6 GeV

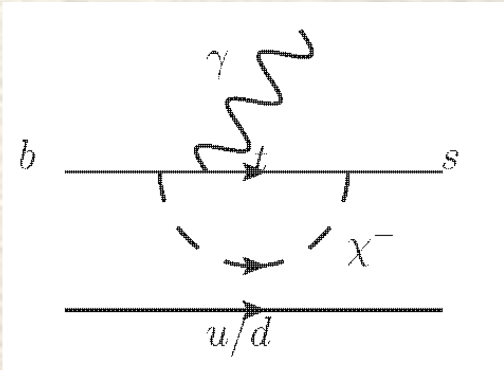
- All $B \to X\gamma$ branching fraction measurements are in good agreement with one another and with the SM prediction

$B \to X_s\gamma$: Direct $\mathcal{A}_{CP}$

- For the sum of exclusive decays, the CP asymmetry is measured by

$$\mathcal{A}_{CP}(X_s\gamma) \equiv \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- The SM predictions yield $-0.6\% < \mathcal{A}_{CP}(X_s\gamma) < 2.8\%$
- The present world average is $\mathcal{A}_{CP}(X_s\gamma) = -0.8 \pm 2.9$
- The difference for charged and neutral B decays is



New physics contribution to C_7^{eff}

$$\Delta\mathcal{A}_{CP}(X_s\gamma) = \mathcal{A}_{CP}(B^+ \to X_s^+\gamma) - \mathcal{A}_{CP}(B^0 \to X_s^0\gamma)$$

- $\Delta\mathcal{A}_{CP}(B \to X_s\gamma)$ depends on C_7^{eff} and C_8^{eff}:

$$\Delta\mathcal{A}_{CP}(X_s\gamma) \approx 4\pi^2\alpha_s \frac{\bar{\Lambda}_{78}}{m_b} \Im m \frac{C_8^{eff}}{C_7^{eff}} \approx 0.12 \frac{\bar{\Lambda}_{78}}{100\ \mathrm{MeV}} \Im m \frac{C_8^{eff}}{C_7^{eff}}$$

$$17\ \mathrm{MeV} < \bar{\Lambda}_{78} < 190\ \mathrm{MeV}$$

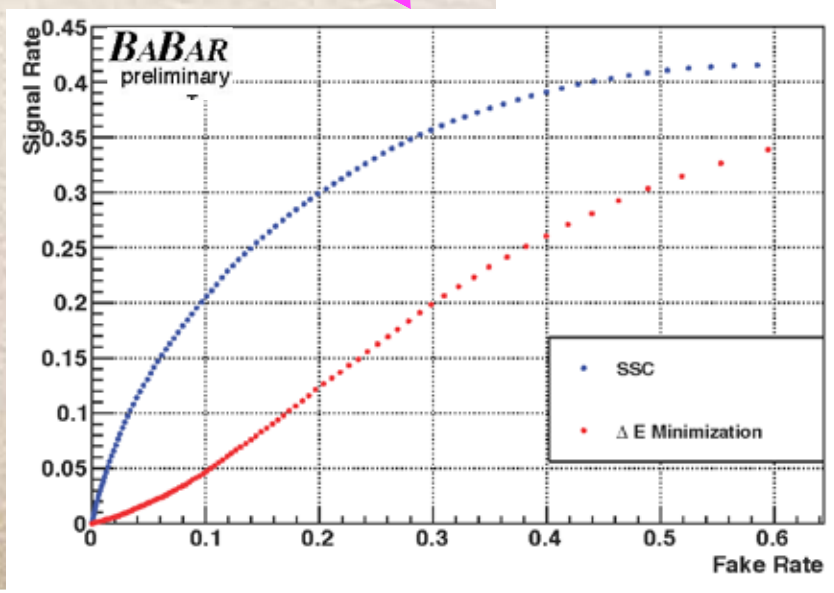
Benzke *et al.*, PRL106, 141801 (2011)

- In the SM, C_7^{eff} and C_8^{eff} are real ➔ $\Delta\mathcal{A}_{CP}(X_s\gamma)=0$
  - This may be modified by new physics contributions
- BABAR has performed a new semi-inclusive analysis with 471×10^6 $B\bar{B}$

$B \to X_s \gamma$: Event Selection for A_{CP}

- Use full BABAR sample of $(471\pm1)\times10^6$ $B\bar{B}$ events
- Reconstruct 16 exclusive modes to measure A_{CP} in semi-inclusive analysis
- Maximize signal extraction with Signal Selecting Classifier ➔bagged decision tree with 6 inputs
- Select candidate with maximum SSC
  ➔ improved efficiency compared to ΔE selection
- Train separate bagged decision tree to separate true primary γ from that of π^0 decay
- Use Background Rejection Classifier to remove continuum background based on bagged decision trees using event shape variables
- Use X_s mass-dependent optimization for $S/(S+B)^{1/2}$ & loose K, π IDs

Final State
$B^+ \to K_S\pi^+\gamma$
$B^+ \to K^+\pi^0\gamma$
$B^0 \to K^+\pi^-\gamma$
$B^+ \to K^+\pi^+\pi^-\gamma$
$B^+ \to K_S\pi^+\pi^0\gamma$
$B^+ \to K^+\pi^0\pi^0\gamma$
$B^0 \to K^+\pi^-\pi^0\gamma$
$B^+ \to K_S\pi^+\pi^-\pi^+\gamma$
$B^+ \to K^+\pi^+\pi^-\pi^0\gamma$
$B^+ \to K_S\pi^+\pi^0\pi^0\gamma$
$B^0 \to K^+\pi^+\pi^-\pi^-\gamma$
$B^0 \to K^+\pi^-\pi^0\pi^0\gamma$
$B^+ \to K^+\eta(\to\gamma\gamma)\gamma$
$B^0 \to K^+\eta(\to\gamma\gamma)\pi^-\gamma$
$B^+ \to K^+K^-K^+\gamma$
$B^0 \to K^+K^-K^+\pi^-\gamma$



$B \to X_s \gamma$: Semi-Inclusive $\mathcal{A}_{CP}$ Results

- Fit m_{ES} for $\bar{B}$ and B tagged samples simultaneously to extract $\mathcal{A}_{CP}$
- Correct raw asymmetry for detector bias determined from sidebands
- In full X_s mass region determine corrected $\mathcal{A}_{CP}$

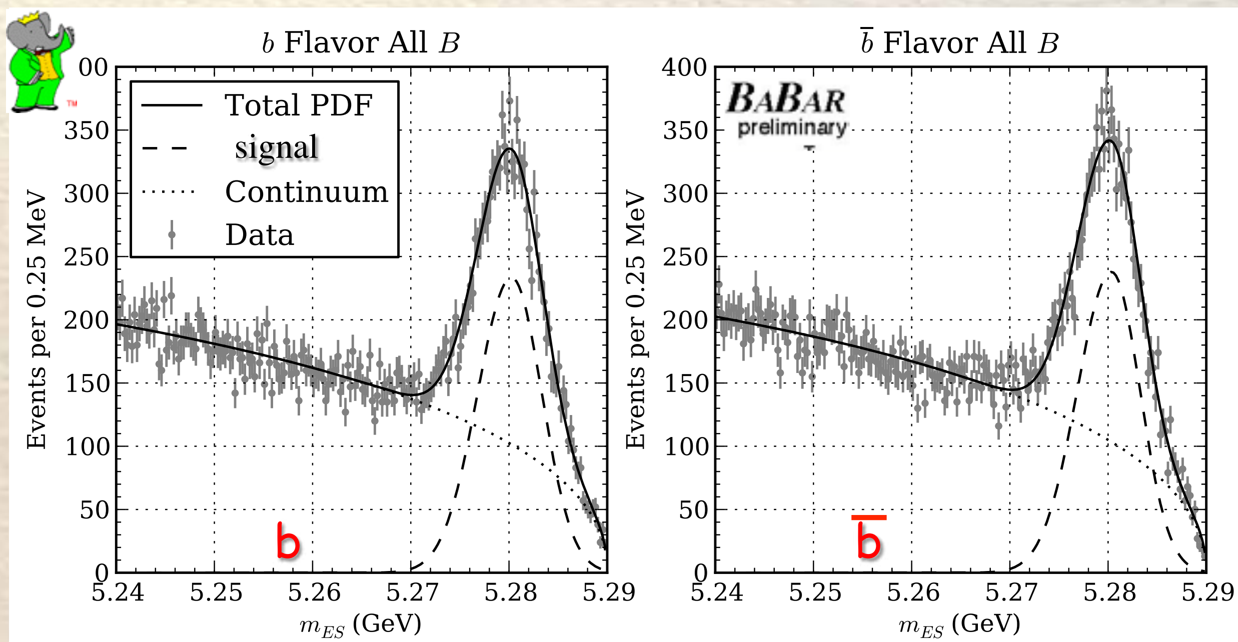
$$\mathcal{A}_{CP}(X_s\gamma) = \left(1.73 \pm 1.93_{stat} \pm 1.02_{sys}\right)\%$$

new

- This agrees well with the SM prediction

$$-0.6\% < \mathcal{A}_{CP}^{SM}(X_s\gamma) < 2.8\%$$

- These new results have the lowest uncertainties



$B \to X_s\gamma$: Implications on $Im(C_{8g}/C_{7\gamma})$

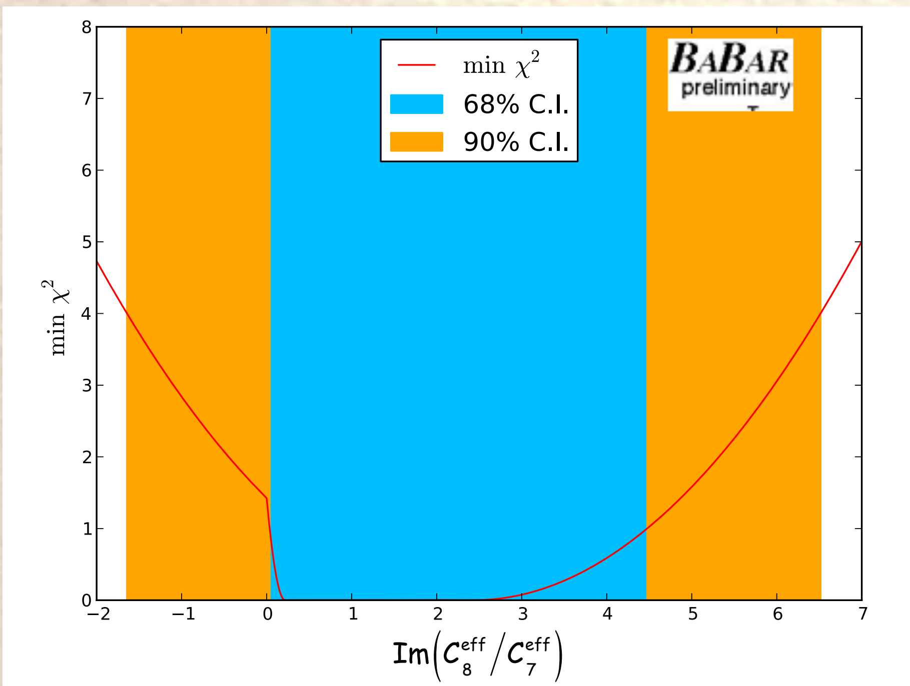
- From the simultaneous fits to charged and neutral B samples measure

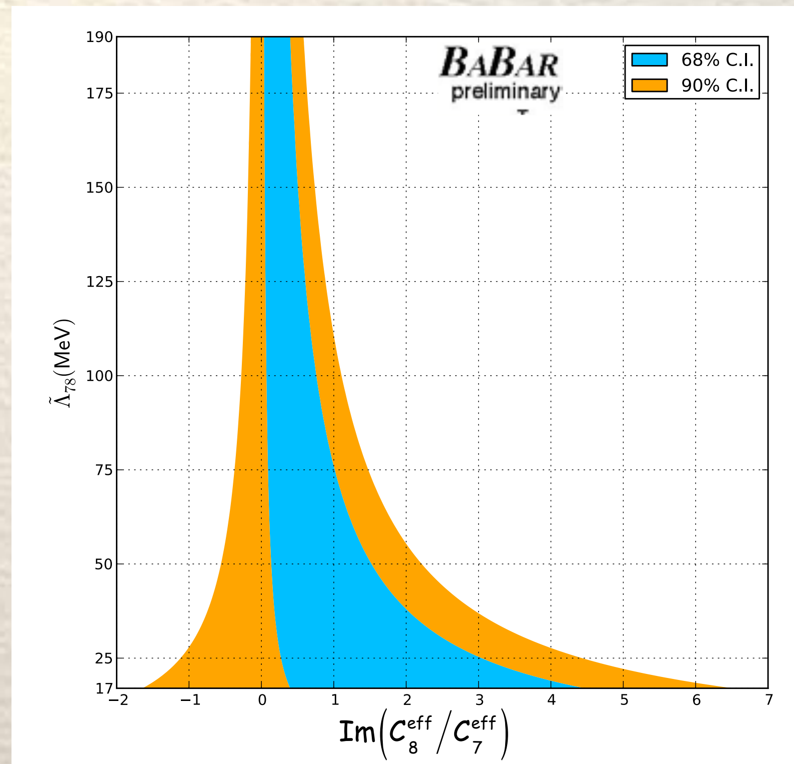
$$\Delta\mathcal{A}_{CP}(X_s\gamma) = \left(4.97 \pm 3.90_{stat} \pm 1.45_{sys}\right)\%$$

- Set 90% CL constraints on $\mathcal{I}m\,(C_8^{eff}/C_7^{eff})$

$$-1.64 < \mathrm{Im}\left(C_8^{eff}/C_7^{eff}\right) < 6.52 \text{ @90\% CL}$$

new





- This is the first $\Delta\mathcal{A}_{CP}(X_s\gamma)$ measurement and the first constraint on the ratio of Wilson coefficients C_8^{eff}/C_7^{eff} for new physics in this process

$B \rightarrow X_s\gamma$: $\mathcal{A}_{CP}$ from Inclusive Decays

- In the fully inclusive analysis, the *CP* asymmetry involves $b\rightarrow s\gamma$ & $b\rightarrow d\gamma$ contributions

new

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

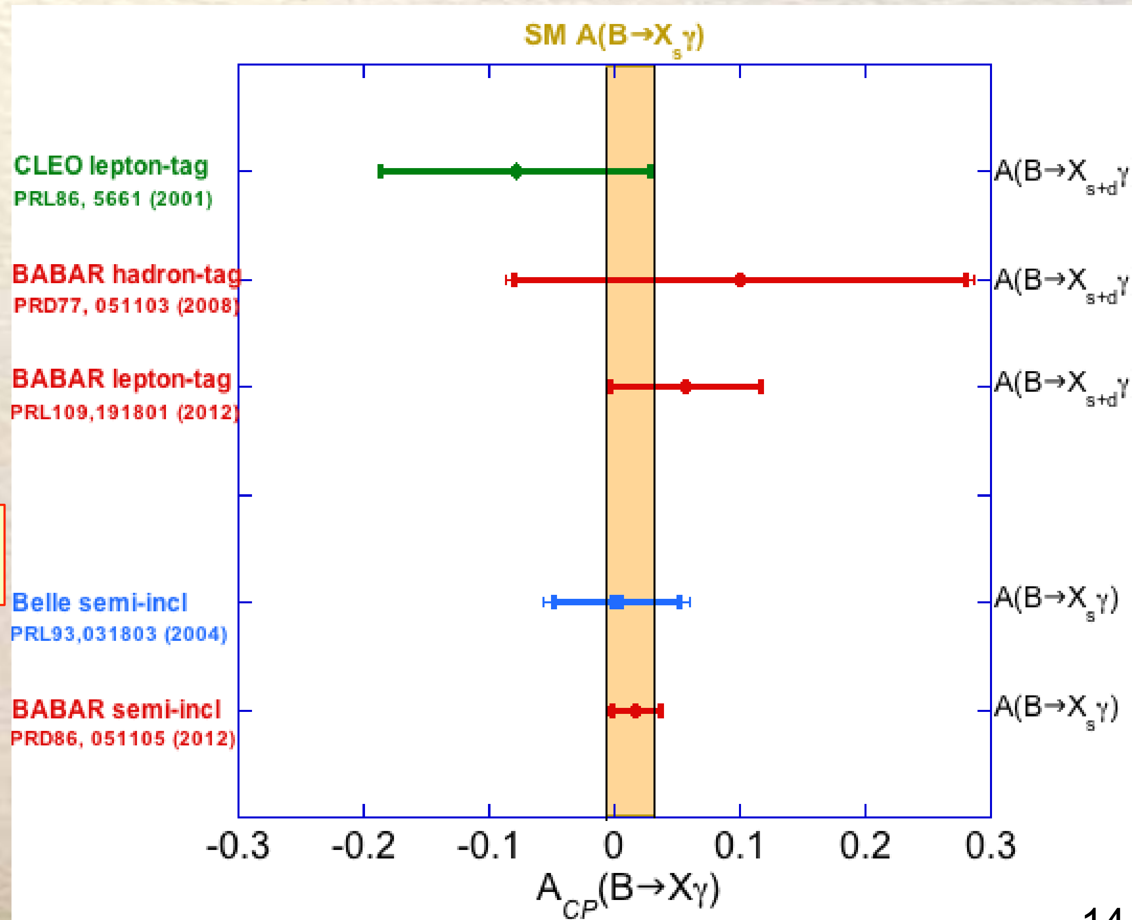
- Use BABAR sample of 383×10^6 $B\bar{B}$ events
- Determine $B/\bar{B}$ from the tag charge
- Correct $\mathcal{A}_{CP}$ for charge bias and mistagging

$$\mathcal{A}_{CP}(X_{s+d}\gamma) = 0.057 \pm 0.060_{stat} \pm 0.018_{sys}$$

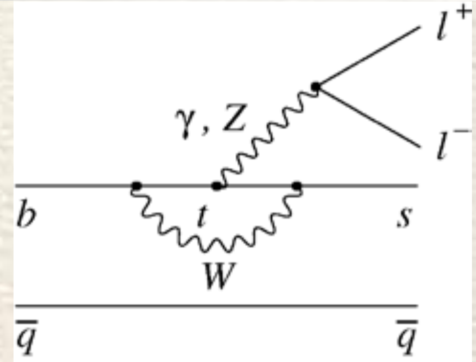
PRL109, 191801 (2012)

- All $\mathcal{A}_{CP}$ measurements are in good agreement with the SM prediction

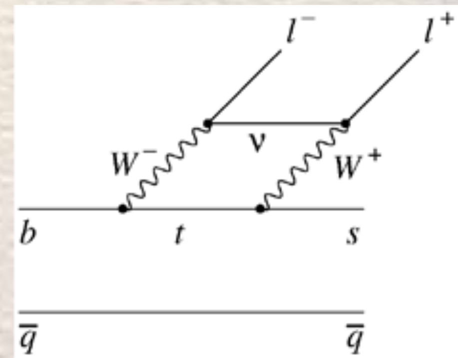
Comparison of A_{CP} Measurements



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



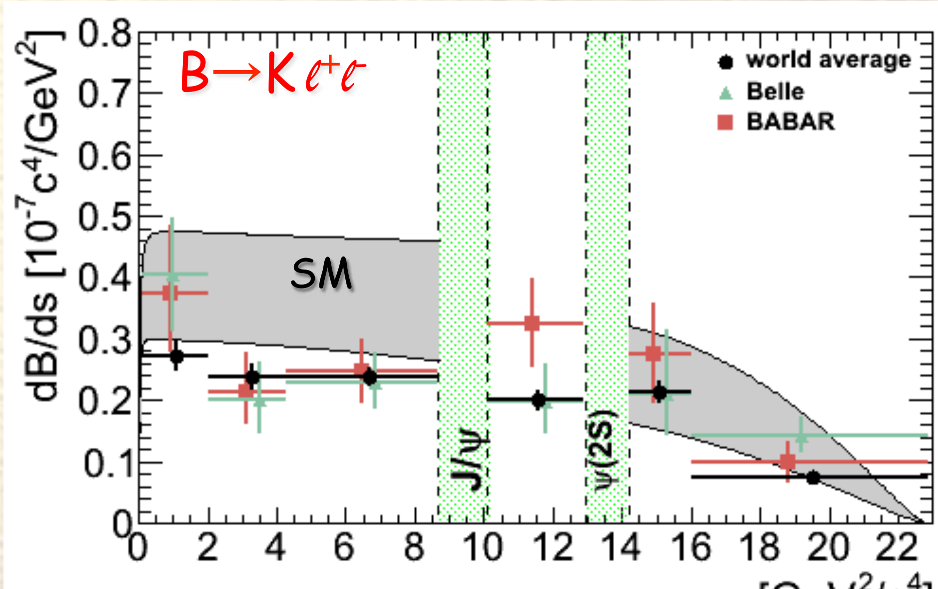
- Fully reconstruct $B \to K^{(*)} \ell^+ \ell^-$ final states
  - 8 in BABAR (471×10^6 $B\bar{B}$): K, K^0_S, $K^\pm\pi^\mp$ or $K^0_S\pi^\pm$
  - 10 in Belle (657×10^6 $B\bar{B}$): K, K^0_S, $K^\pm\pi^\mp$, $K^\pm\pi^0$ or $K^0_S\pi^\pm$
  - these hadrons recoil against e^+e^- or $\mu^+\mu^-$
  - Select $e^\pm$ with $p > 0.3$ (0.4) 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:
  BABAR defines 8 boosted decision trees, Belle uses likelihood
- Veto J/ψ and $\psi(2S)$ mass regions and use them as control samples
- Use pseudo-experiments to study performance
- Measure branching fractions, rate asymmetries and angular observables

B→K(*) ℓ+ℓ-: Partial Branching Fractions

- In the SM, partial branching fractions d$\mathcal{B}$/ds are calculated at
  - Low $s=q^2=m^2_{\ell\ell}$, large hadronic recoil $E_{K^*} \gg \Lambda$ ➔ use QCD factorization
  - High s ~$\mathcal{O}(m_b)$ small hadronic recoil $E_{K^*} \sim \Lambda$ ➔ use OPE in $1/m_b$
  - Large errors come from errors of form factors in hadronic MEs

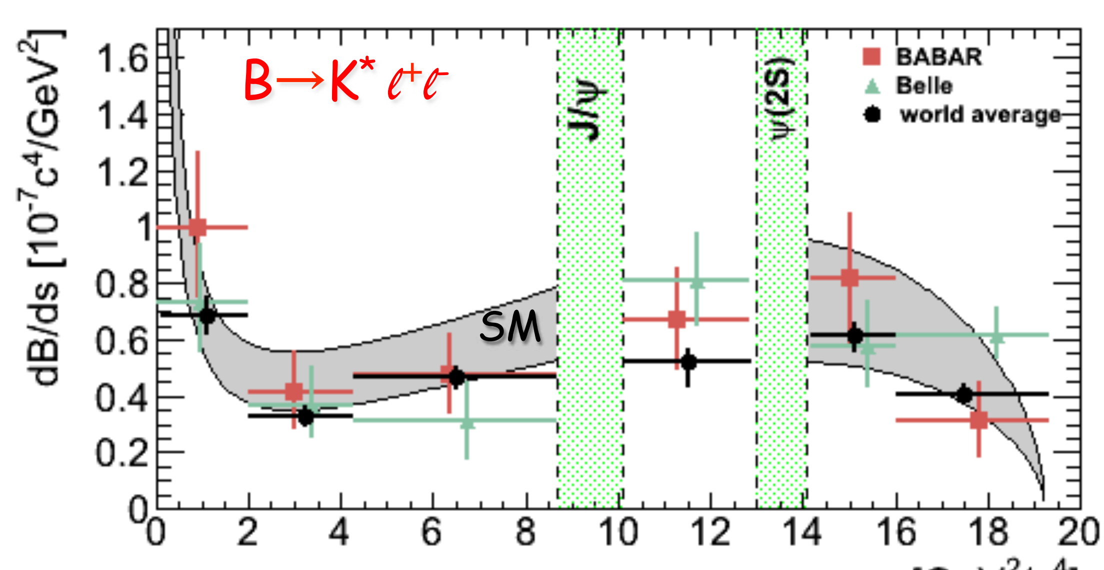


C. Bobeth *et al.* PRD87,034016 (2012)

- d$\mathcal{B}$/ds is measured in 6 s bins
  - BABAR, Belle: $B \to K^{(*)} \ell\ell$
  - CDF, LHCb: $B \to K^{(*)} \mu^+\mu^-$
  - CMS, ATLAS: $B \to K^{*0} \mu^+\mu^-$
  - Do naïve average (WA) (dominated by LHCb)

- All measurements agree well with the SM prediction

BABAR	PRD86, 052012 (2012)
Belle	PRL103, 171801 (2009)
CDF	CDF-note 10894 (2012)
CMS	CMS PAS BPH-11-009 (2013)
LHCb	hep-ex/1304.6325 (2013) JHEP1212,125 (2012)



C. Bobeth *et al.* PRD87,034016 (2012)

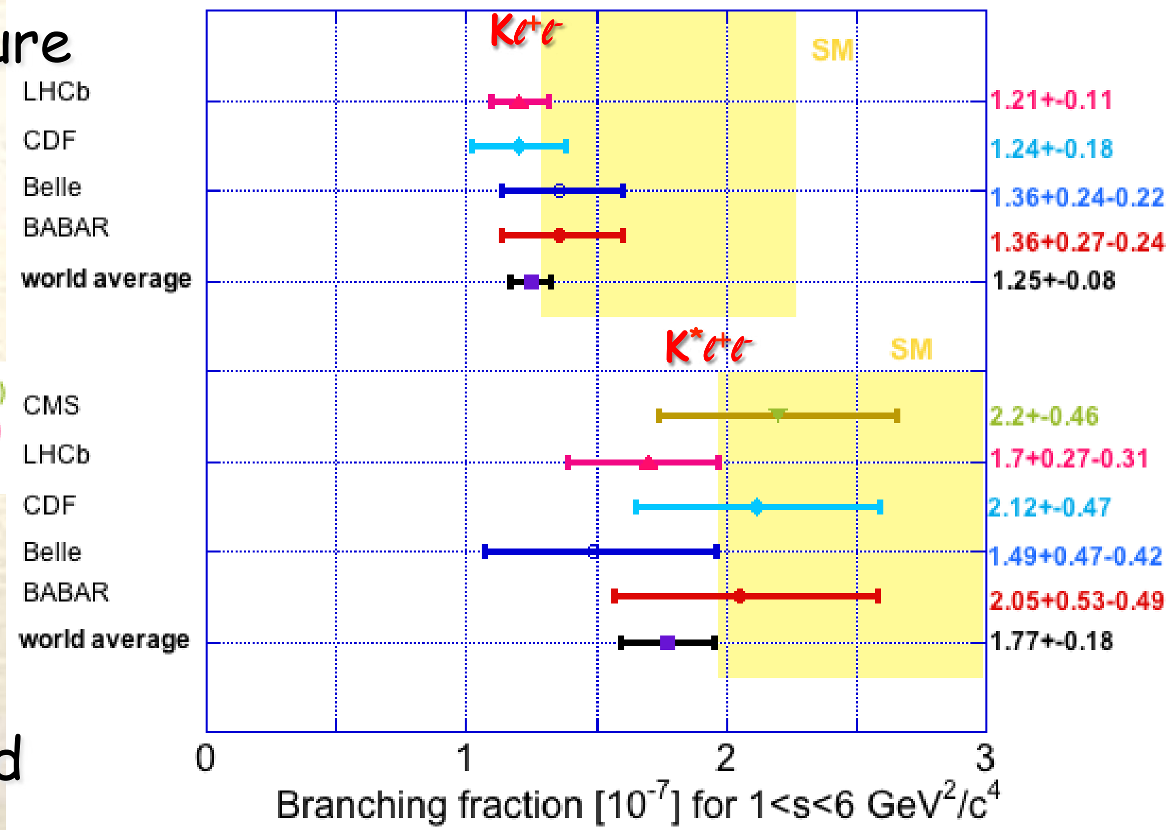
$B \to K^{(*)} \ell^+\ell^-$: Total Branching Fractions

- At low s ($1<s<6$ GeV^2/c^4) measure

WA $\mathcal{B}(B \to K\ell^+\ell^-) = (1.25 \pm 0.08) \times 10^{-7}$

$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.77 \pm 0.18) \times 10^{-7}$

BABAR	PRD86, 052012 (2012)	CMS	CMS PAS BPH-11-009 (2013)
Belle	PRL103, 171801 (2009)	LHCb	hep-ex/1304.6325 (2013) JHEP1212,125 (2012)
CDF	CDF-note 10894 (2012)		

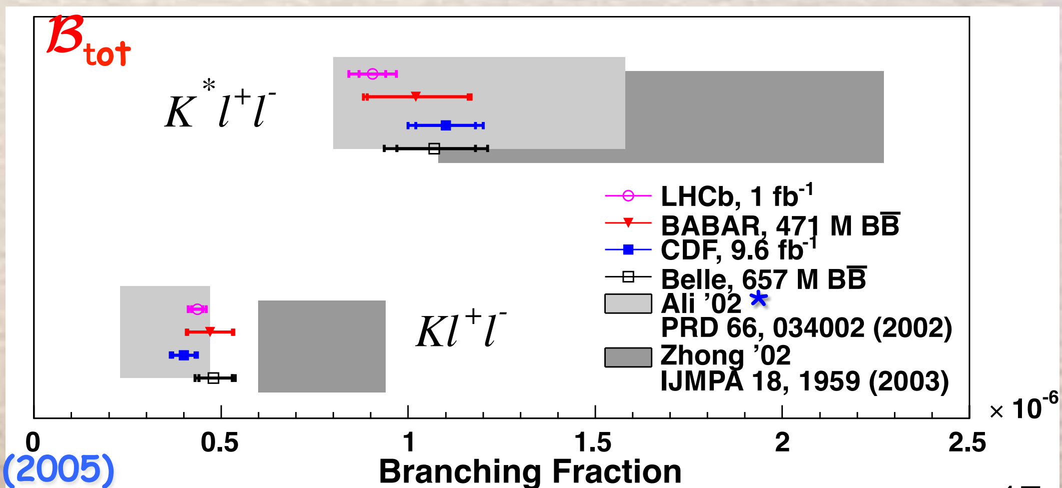


- Good agreement with the SM
  Bobeth et al: Phys.Rev. D87 (2013) 034016, JHEP 1201 (2012) 107

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

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

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



- BABAR $\mathcal{B}_{tot}$ results agree well with the SM prediction by Ali *et al.* & those of other experiments

Ball and Zwicky, PRD 71, 014015 (2005);ibid 014029 (2005)

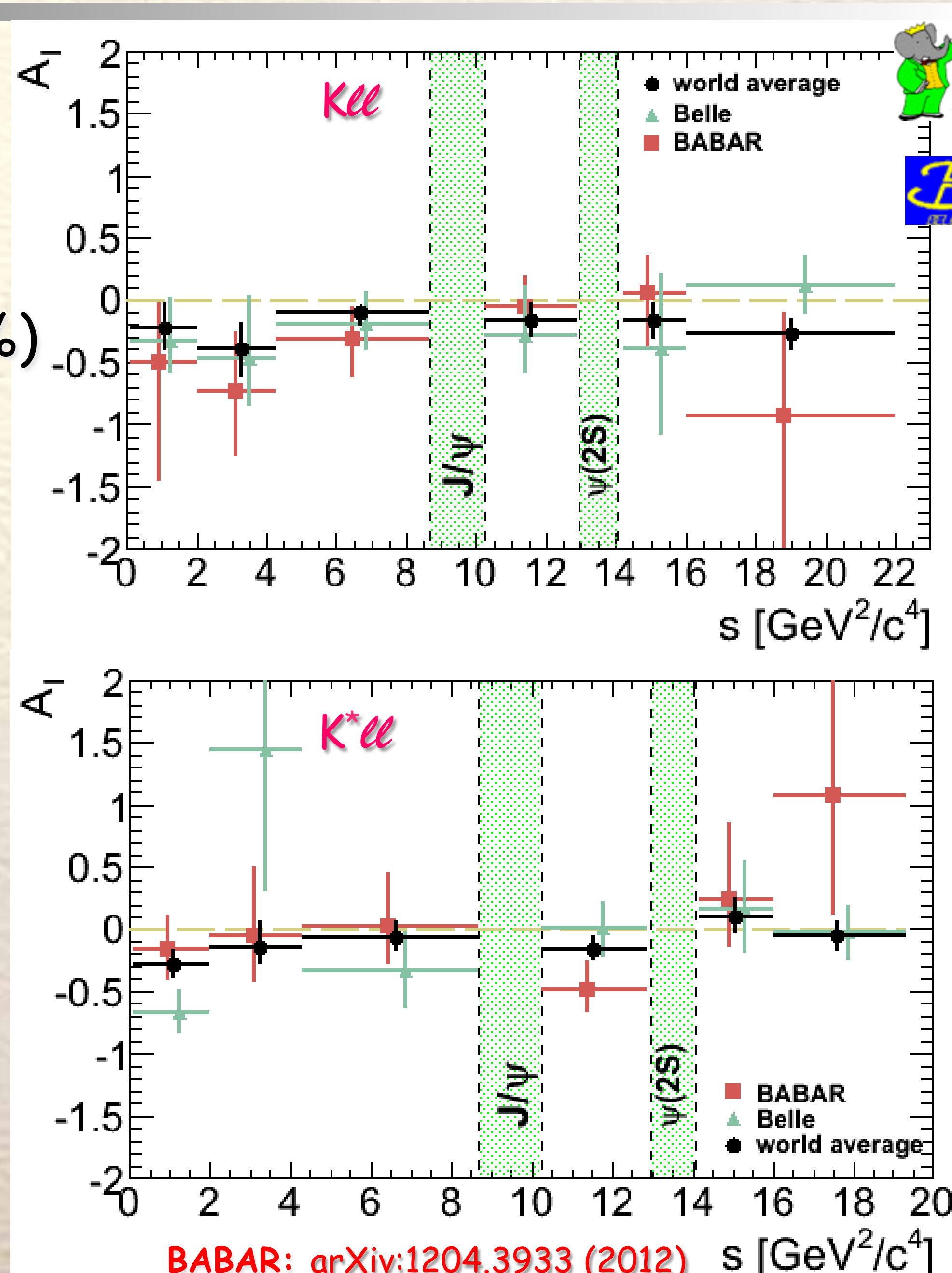
$B \to K^{(*)} \ell^+ \ell^-$: Isospin Asymmetry

- $$\mathcal{A}_I \equiv \frac{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) - r_\tau \mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}{\mathcal{B}(B^0 \to K^{(*)0}\ell^+\ell^-) + r_\tau \mathcal{B}(B^\pm \to K^{(*)\pm}\ell^+\ell^-)}$$
  $$r_\tau = \tau_{B^0} / \tau_{B^+} = 1/(1.071 \pm 0.09)$$
- In the SM, $\mathcal{A}_I$ is expected at $\mathcal{O}(+1\%)$
  Feldmann & Matias JHEP 0301, 074 (2003)
- Average $\mathcal{A}_I$ measurements from BABAR, Belle, CDF & LHCb at low s ($1<s<6$ GeV^2/c^4)

$$\mathcal{A}_I^{low}(B \to K\ell^+\ell^-) = -0.31 \pm 0.12$$

$$\mathcal{A}_I^{low}(B \to K^*\ell^+\ell^-) = -0.15 \pm 0.11$$

- At low s, $\mathcal{A}_I$ is below the SM, but consistent with the SM
- BABAR results agree with those from Belle and the WA dominated by LHCb



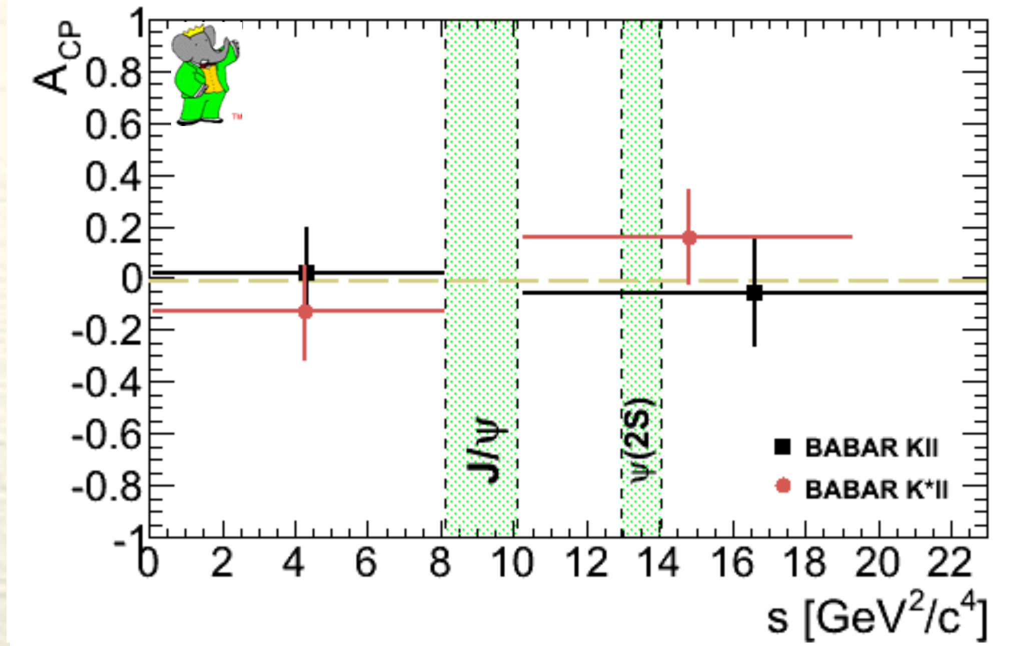
BABAR: arXiv:1204.3933 (2012)
Belle: PRL 103, 171801 (2009)
LHCb: arXiv:1205.3422 (2012)

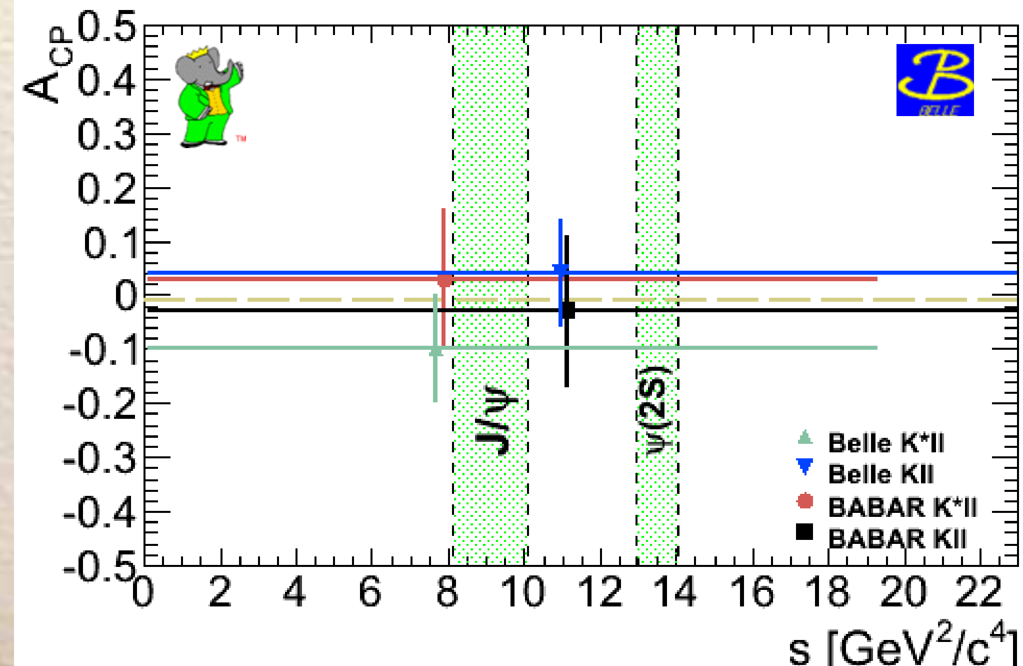
$B \to K^{(*)} \ell^+\ell^-$: CP Asymmetry

- $$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B} \to \bar{K}^{(*)}\ell^+\ell^-) - \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)}{\mathcal{B}(\bar{B} \to K^{(*)}\ell^+\ell^-) + \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)}$$
- In the SM, $\mathcal{A}_{CP}$=-0.01
  Krüger *et al.*, PRD 61, 114028 (2000)
  Bobeth *et al.*, JHEP 807,106, (2008)
- $\mathcal{A}_{CP}$ is measured by BABAR, Belle in $B \to K^{(*)} \ell^+\ell^-$
  - *e.g.* in all s, BABAR measured

$$\mathcal{A}_{CP}(B \to K\ell^+\ell^-) = -0.03 \pm 0.14 \pm 0.01$$
$$\mathcal{A}_{CP}(B \to K^*\ell^+\ell^-) = 0.03 \pm 0.13 \pm 0.01$$

- LHCb measured $\mathcal{A}_{CP}$ in $B \to K^*\mu^+\mu^-$
  LHCb: PRL 110, 031801 (2013)
- All $\mathcal{A}_{CP}$ results are consistent with zero ➔agree with small SM value
  BABAR: PRD86,032012 (2012)
  Belle: PRL 103, 171801 (2009)





$B \to K^{(*)} \ell^+ \ell^-$: Lepton Flavor Ratio

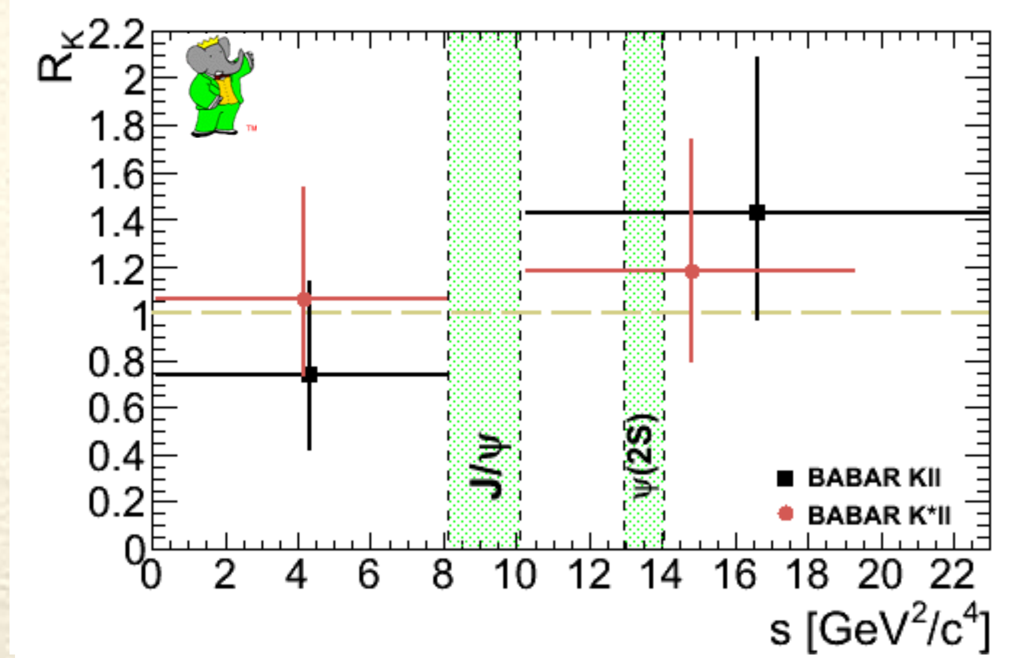
- $$\mathcal{R}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$ $s \geq (2^* m_\mu)^2$

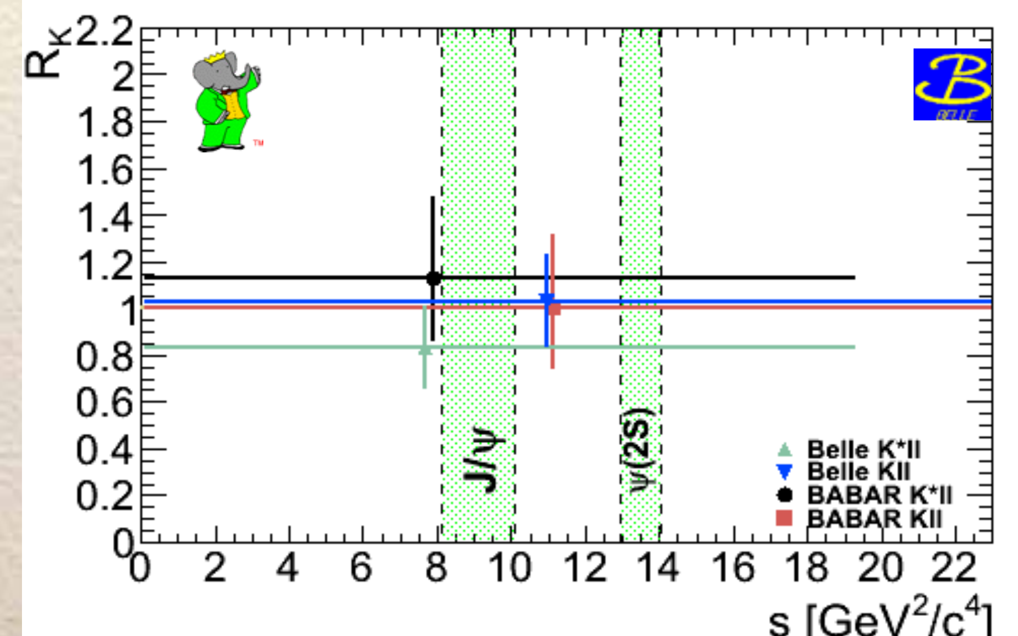
- In the SM, $\mathcal{R}_{K(*)}=1$ for $s \geq (2^* m_\mu)^2$

- $\mathcal{R}_{K(*)}$ is measured by BABAR, Belle in $B \to K^{(*)} \ell^+ \ell^-$
  - *e.g.* in all s, BABAR measured

$$\mathcal{R}_K(B \to K \ell^+ \ell^-) = 1.00^{+0.31}_{-0.25} \pm 0.07$$
$$\mathcal{R}_{K^*}(B \to K^* \ell^+ \ell^-) = 1.13^{+0.34}_{-0.26} \pm 0.10$$

- All $\mathcal{R}_{K(*)}$ results are consistent with unity ➔agree with SM

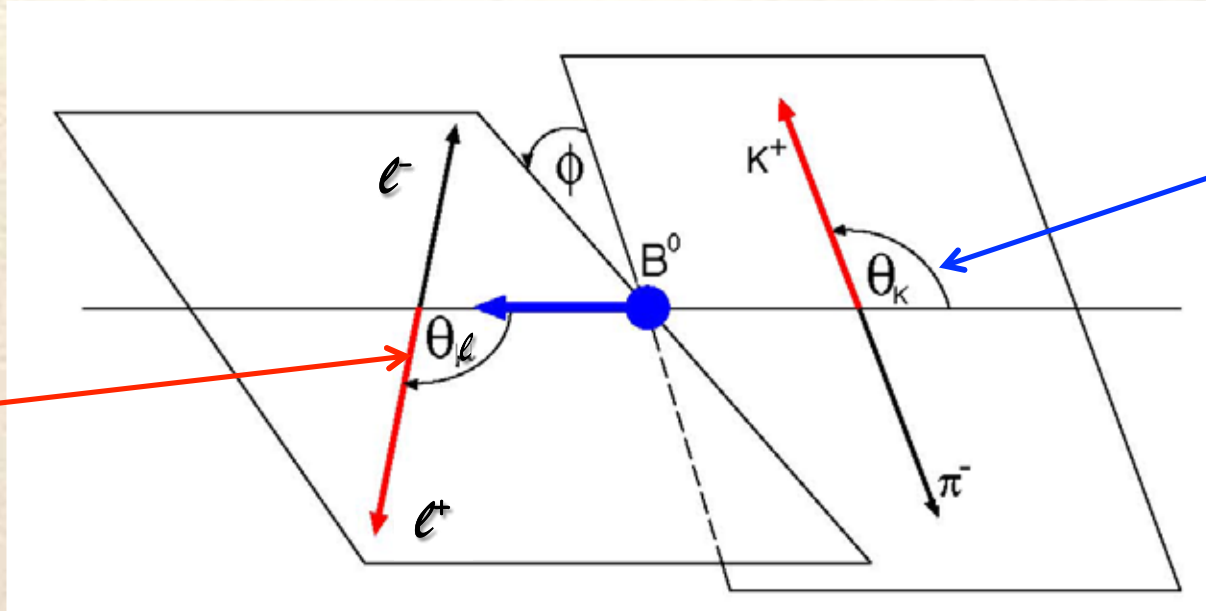




Ali *et al.*, PRD 61, 074024 (2000)
BABAR: PRD86,032012 (2012)
Belle: PRL 103, 171801 (2009)

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

- The $B \to K^* \ell^+ \ell^-$ angular distribution depends on 3 angles θ_K, θ_l, & ϕ



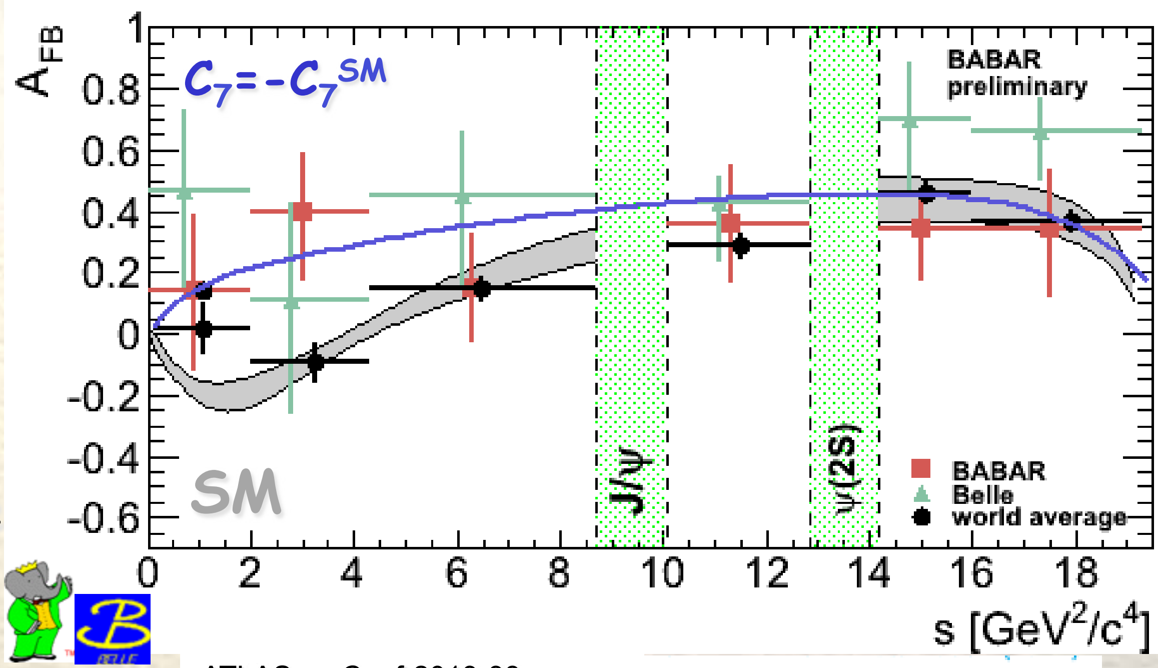
- The 1-d θ_K and θ_l projections depend on the K^* longitudinal polarization fraction $\mathcal{F}_L$ and lepton forward-backward asymmetry $\mathcal{A}_{FB}$
- $\mathcal{F}_L$: $$W(\cos\theta_K) = \tfrac{3}{2}\mathcal{F}_L \cos^2\theta_K + \tfrac{3}{4}(1-\mathcal{F}_L)\sin^2\theta_K$$

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

- $\mathcal{A}_{FB}$ $$W(\cos\theta_\ell) = \tfrac{3}{4}\mathcal{F}_L \sin^2\theta_\ell + \tfrac{3}{8}(1-\mathcal{F}_L)(1+\cos^2\theta_\ell) + \mathcal{A}_{FB}\cos\theta_\ell$$
- With limited statistics, we fit the 1-d projections to extract $\mathcal{F}_L$ and $\mathcal{A}_{FB}$

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

- $\mathcal{A}_{FB}$ is measured by
  - BABAR & Belle in $B \to K^* \ell\ell$
  - CDF in $K^* \mu^+ \mu^-$
  - LHCb, CMS and ATLAS in $K^{*0} \mu^+ \mu^-$



ATLAS	Conf-2013-38	CMS	CMS PAS BPH-11-009 (2013)
Belle	PRL103, 171801 (2009)	LHCb	hep-ex/1304.6325 (2013) JHEP1212,125 (2012)
CDF	CDF-note 10894 (2012)		

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

- All measurements are consistent

- Do naïve world average of all $\mathcal{A}_{FB}$ results
  ➔ WA (dominated by LHCb) agrees well with the SM

- In low mass region ($1<s<6$ GeV²/c⁴) measure

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

- world average: $\mathcal{A}^{WA}_{FB}(K^* \ell\ell) = -0.074^{+0.047}_{-0.048}$

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)
C. Bobeth *et al.* PRD87,034016 (2012)

$1<s<6$ GeV²/c⁴

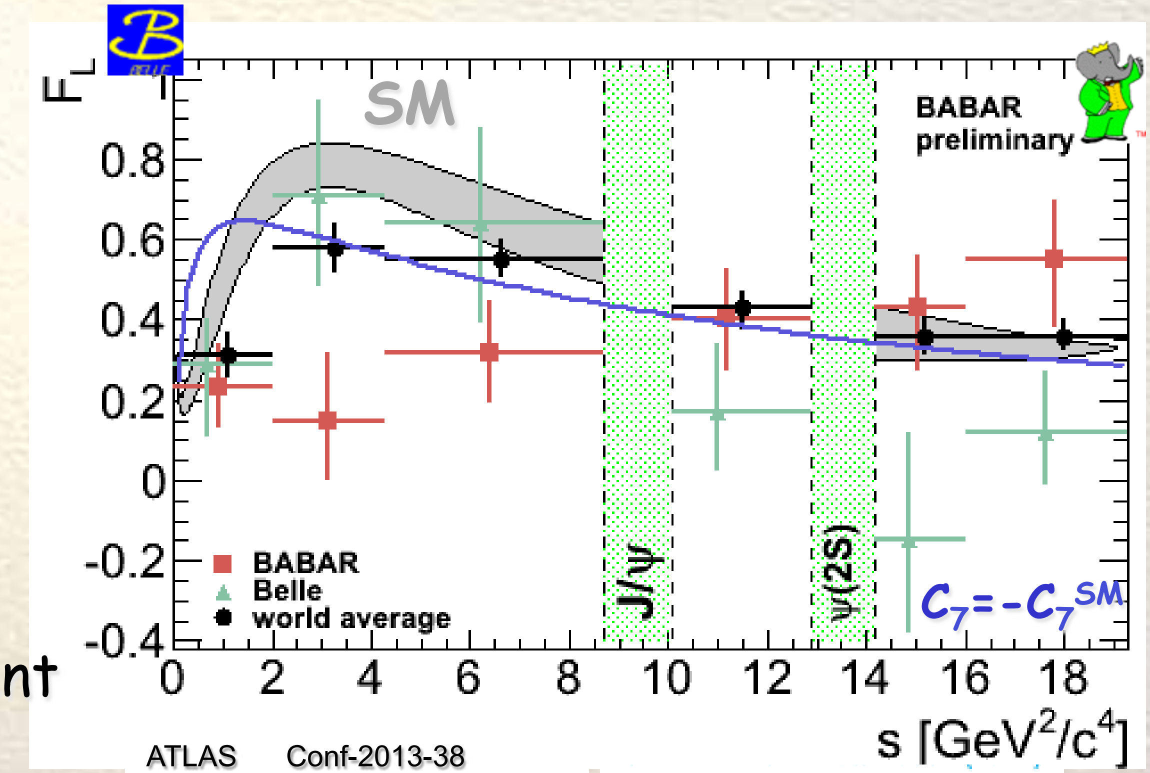
SM: $\mathcal{A}^{SM}_{FB} = -0.0494^{+0.0281}_{-0.0252} \quad (K^{*0} \ell^+ \ell^-)$

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

- $\mathcal{F}_L$ is measured by
  - BABAR & Belle in $B \to K^* \ell^+\ell^-$
  - CDF in $K^*\mu^+\mu^-$
  - LHCb, CMS and ATLAS in $K^{*0}\mu^+\mu^-$
- BABAR $\mathcal{F}_L$ measurement ($B \to K^* \ell^+\ell^-$) is the most precise except for LHCb ($K^{*0}\mu^+\mu^-$)
- All measurements are consistent
- Do naïve average of all $\mathcal{F}_L$ results (dominated by LHCb)
  ➔ are consistent with the SM & $C_7=-C_7^{SM}$ model
- In low mass region ($1<s<6$ GeV^2/c^4) measure

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

- world average: $\mathcal{F}_L = 0.523^{+0.047}_{-0.044}$



ATLAS	Conf-2013-38	CMS	CMS PAS BPH-11-009 (2013)
Belle	PRL103, 171801 (2009)	LHCb	hep-ex/1304.6325 (2013) JHEP1212,125 (2012)
CDF	CDF-note 10894 (2012)		

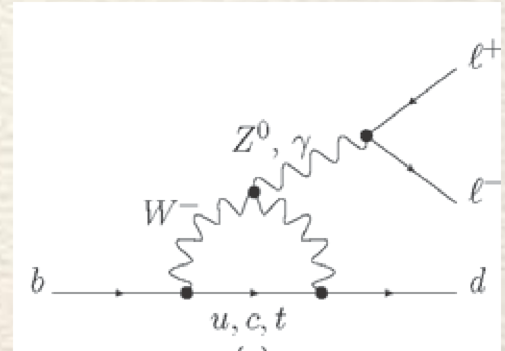
C. Bobeth *et al.* arXiv:1006.5013
Krüger & Matias PRD71, 094009 (2005)
C. Bobeth *et al.* PRD87,034016 (2012)

$1<s<6$ GeV^2/c^4

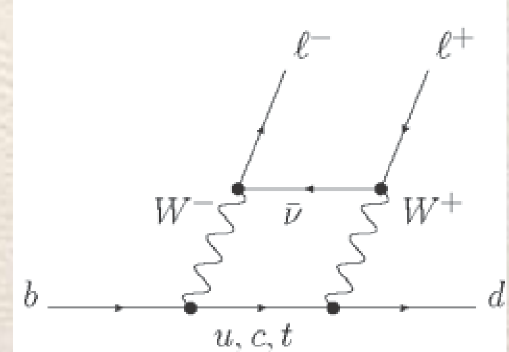
SM: $\mathcal{F}_L^{SM} = 0.735^{+0.06}_{-0.07} \quad (K^{*0}\ell^+\ell^-)$

Search for B→π/η ℓ⁺ℓ⁻ Decays

- In the SM, $B \to X_d \ell^+ \ell^-$ modes are also mediated in in lowest order by the photon penguin, Z-penguin and WW box diagrams



(a)

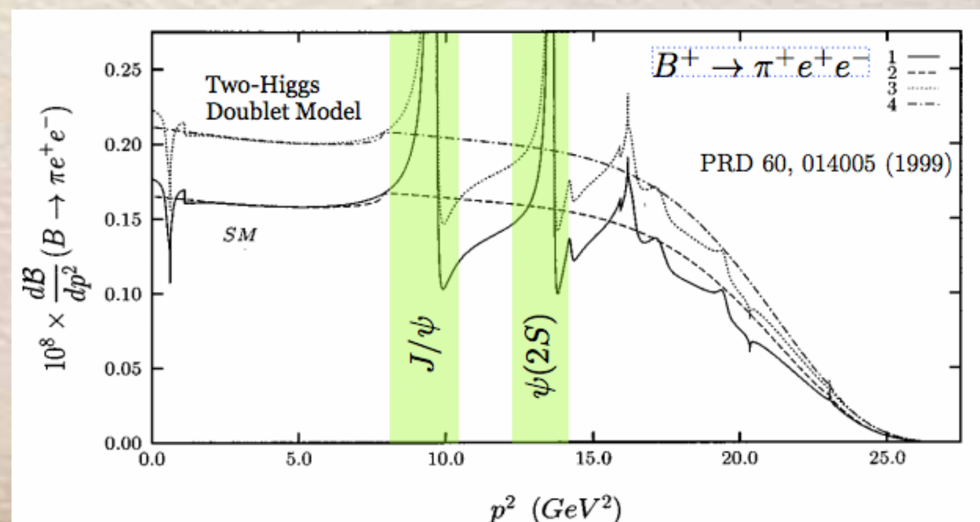


(b)

- The decays are suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ with respect to the related $b \to s\, \ell^+\ell^-$ modes

- In extensions of the SM, rates may increase significantly

- BABAR has updated the search for $B \to \pi \ell^+\ell^-$ modes and performed the first search for $B \to \eta \ell^+\ell^-$ modes using 471×10^6 $B\bar{B}$ events



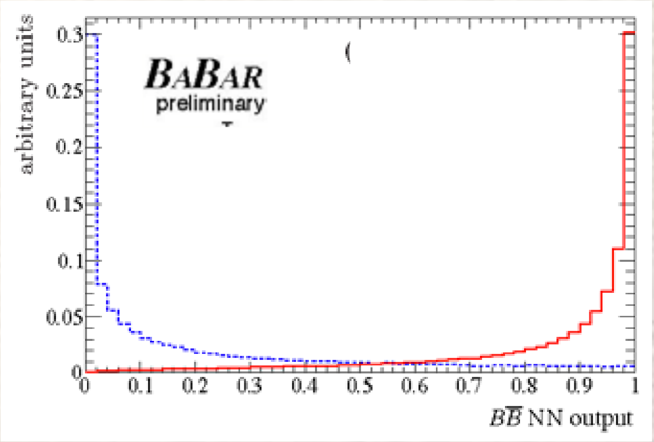
- SM predictions:

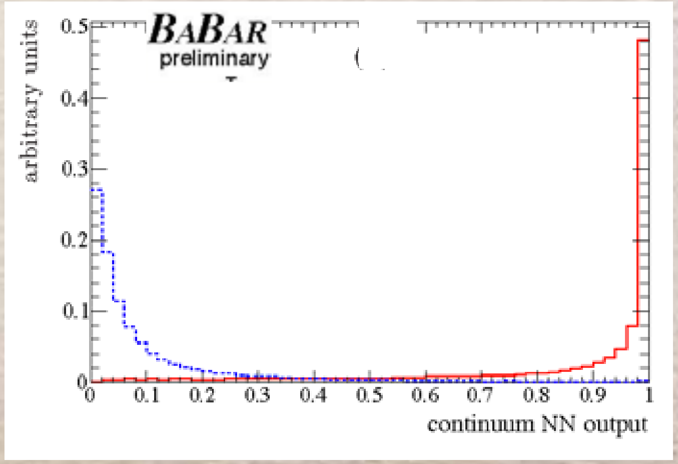
$$\mathcal{B}\left(B^\pm \to \pi^\pm \ell^+ \ell^-\right) = \left(1.96 - 3.30\right) \times 10^{-8}$$

$$\mathcal{B}\left(B^0 \to \eta \ell^+ \ell^-\right) = \left(2.5 - 3.7\right) \times 10^{-8}$$

$B \to \pi/\eta\, \ell^+\ell^-$: Analysis Methodology

- BABAR fully reconstructs 8 $B \to \pi/\eta\, \ell^+\ell^-$ final states (471×10^6 $B\bar{B}$)
  - Select $\pi^\pm$, π^0, $\eta \to \gamma\gamma$, or $\eta \to \pi^+\pi^-\pi^0$ recoiling against e^+e^- or $\mu^+\mu^-$
  - Select $p_\ell > 0.3$ GeV/c, recover $e^\pm$ bremsstrahlung losses, remove $\gamma \to ee$
  - Require good particle ID for e, μ, π; for γ require $E_\gamma > 50$ MeV
  - Select π^0: $115 < m_{\gamma\gamma} < 150$ MeV; η: $500 < m_{\gamma\gamma} < 575$ MeV, $535 < m_{3\pi} < 565$ MeV
  - Require $\mathcal{A}_\gamma^\eta = (E_{1,\gamma} - E_{2,\gamma})/(E_{1,\gamma} + E_{2,\gamma}) < 0.8$
- Veto J/ψ and ψ(2S) mass regions
- Suppress combinatorial $B\bar{B}$ & $q\bar{q}$ backgrounds by NNs, 2 each for e^+e^- & $\mu^+\mu^-$ modes using 12 and 14 input distributions
- Simultaneous fit to m_{ES} and ΔE distributions
- Use pseudo-experiments for validations





Search for $B \to \pi \ell^+ \ell^-$ Modes

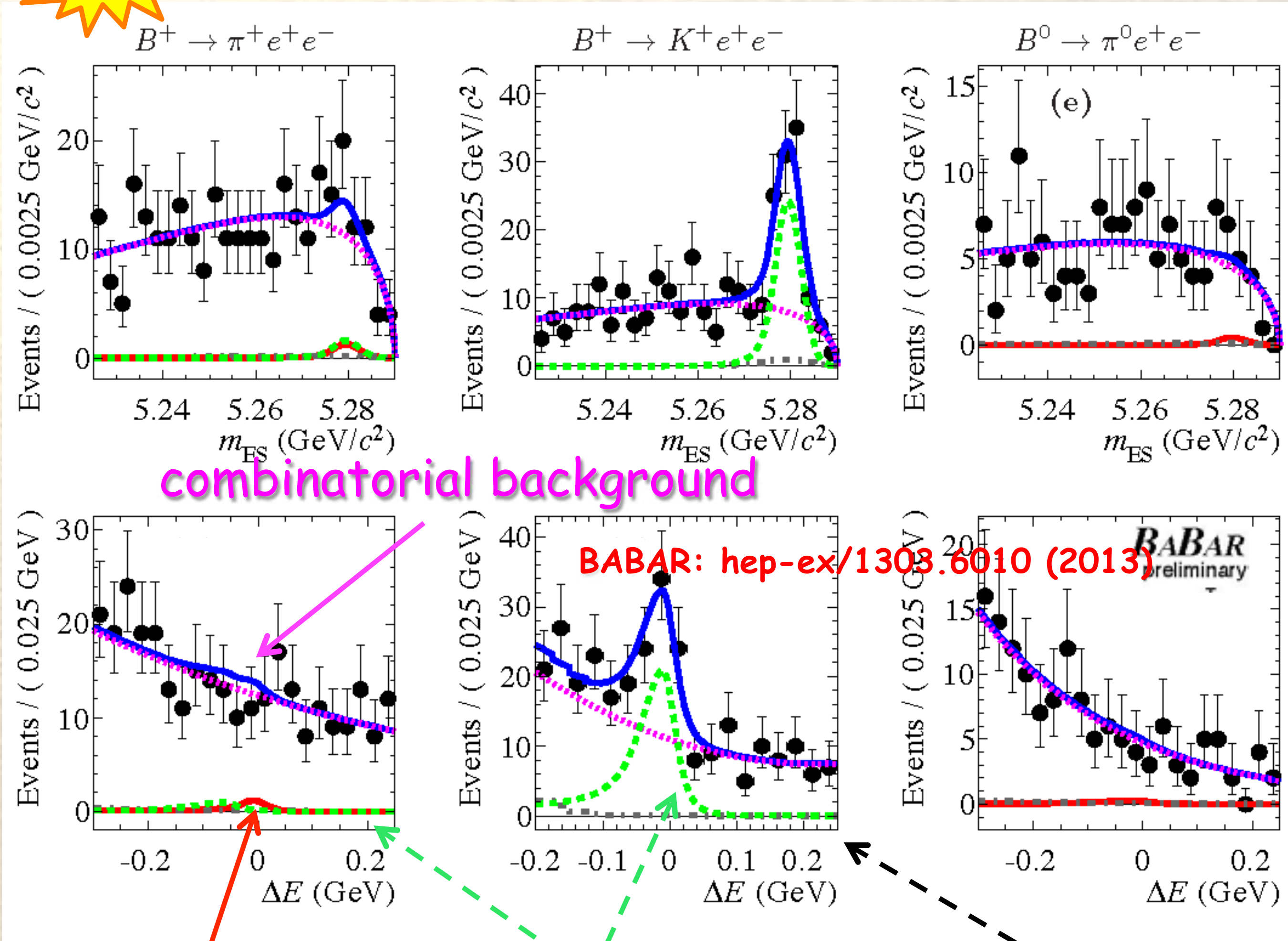
- Perform simultaneous unbinned maximum likelihood fit to the m_{ES} & ΔE distributions of $B \to \pi^\pm \ell^+ \ell^-$ & $B \to \pi^0 \ell^+ \ell^-$, separately for e^+e^- & $\mu^+\mu^-$ modes

- Add $B \to K^\pm \ell^+ \ell^-$ mode in the fit to extract peaking background

- Use vetoed J/ψ and $\psi(2S)$ samples to validate fit and evaluate $B \to K^\pm \ell^+ \ell^-$

new

Fit projections



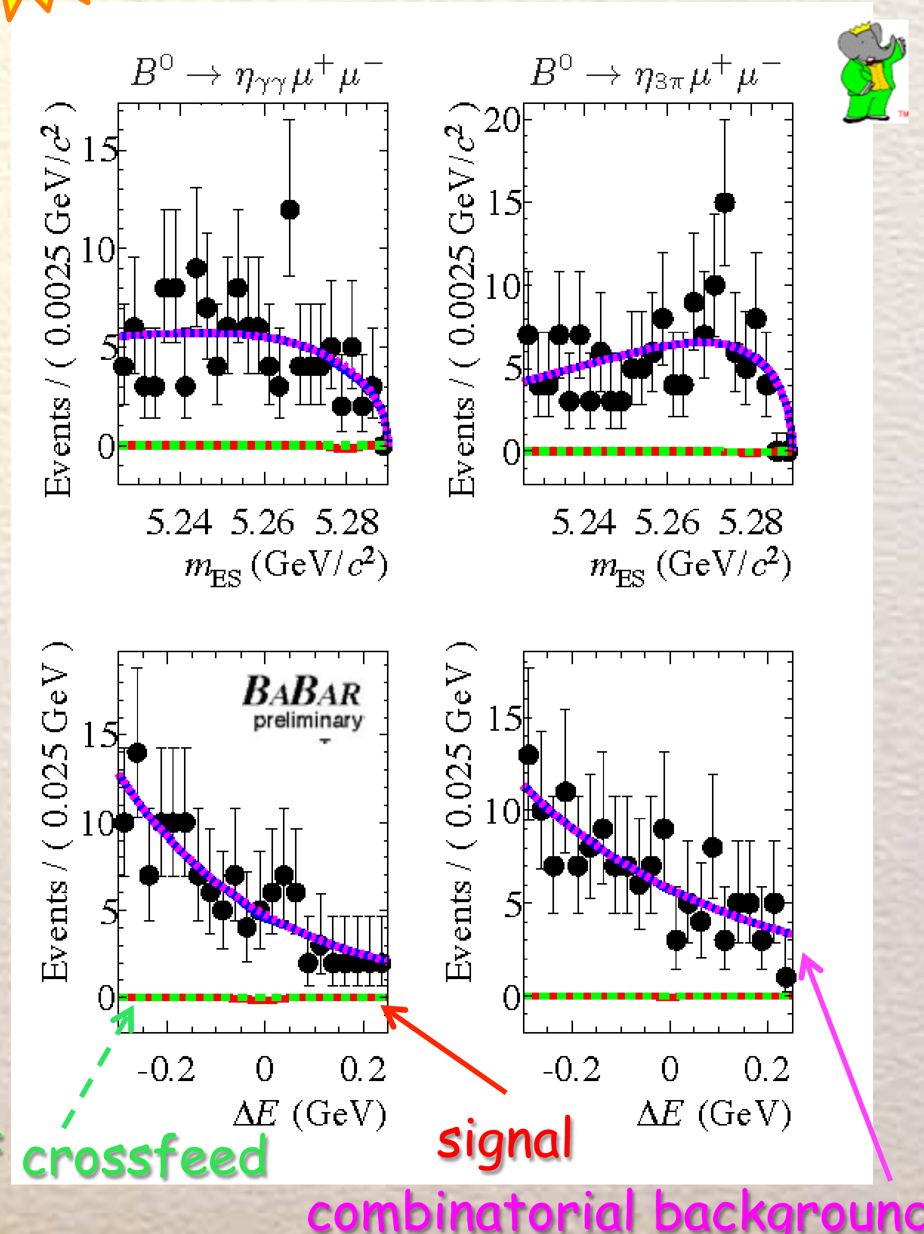
hep-ex/1303.6010 (2013)

Search for B→η ℓ⁺ℓ⁻ Modes

- Perform simultaneous unbinned maximum likelihood fit to the m_{ES} & ΔE distributions of B→η ℓ⁺ℓ⁻ separately for e⁺e⁻ & μ⁺μ⁻ modes
- Use vetoed J/ψ and ψ(2S) samples to validate fit
- In addition, perform fits for
  - Isospin averaged ⁻ modes B→π e⁺e⁻ and B→πμ⁺μ
  - Lepton-flavor averaged modes B→π± ℓ⁺ℓ⁻, B→π⁰ ℓ⁺ℓ⁻ and B→η ℓ⁺ℓ⁻
  - Isospins and lepton-flavor averaged modes B→π ℓ⁺ℓ⁻

new

Fit projections



hep-ex/1303.6010 (2013)

$B\to\pi/\eta\,\ell^+\ell^-$: Branching Fraction Upper Limits

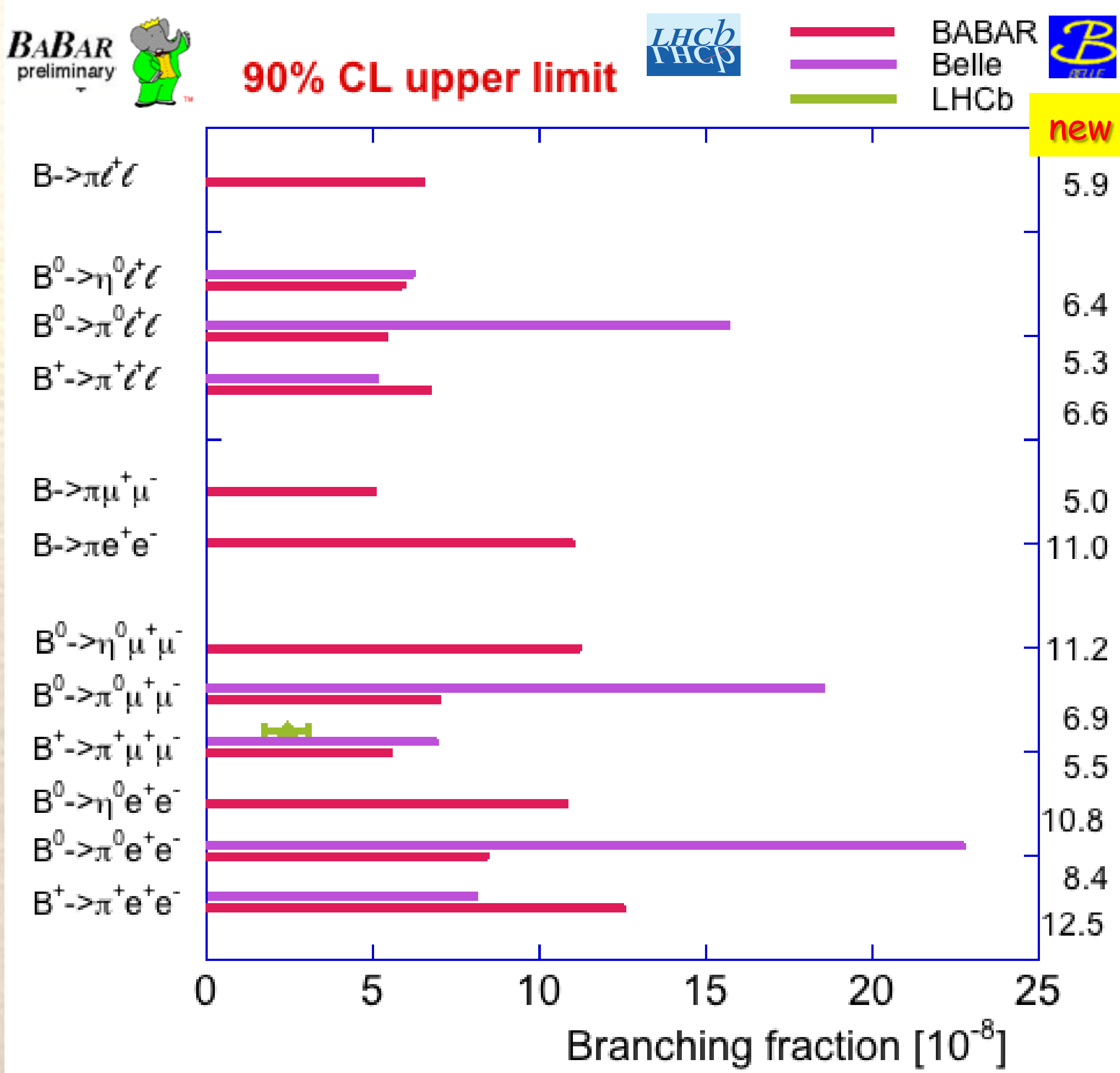
- See no signal in any of these modes (new)
- Set 90% CL branching fraction upper limits
- LHCb observed $B^\pm\to\pi^\pm\mu^+\mu^-$

$$\mathcal{B}(B^+\to\pi^+\ell^+\ell^-) = (2.4\pm0.6\pm0.1)\times10^{-8}$$

- Best limit for $B^0\to\pi^0\ell^+\ell^-$

$$\mathcal{B}(B^+\to\pi^0\ell^+\ell^-) < 5.3\times10^{-8}\ (90\%CL)$$

- First results for $B\to\eta\,\ell^+\ell^-$
- Limits are within a factor 2-3 of the SM predictions



Conclusions

- New BABAR $B \to X_s\gamma$ results
  - Branching fractions are in good agreement with the SM prediction
  - New $\mathcal{A}_{CP}$ is the most precise and consistent with the SM prediction
  - New measurements on photon energy moments
  - Set limit on charged Higgs boson $m_{H\pm} > 327$ GeV @ 95% CL
- New BABAR $B \to \pi/\eta\ell^+\ell^-$ results on branching fraction upper limits
- Present $B \to X\gamma$ and $B \to X\ell^+\ell^-$ results are in agreement with the SM
  - Largest deviations are $< 3\sigma$

  ➔ Need higher precision to probe the SM
- Significant progress will come from LHCb and Belle II
- High statistics samples allow for studying new observables

  ➔ probe new angular observables that help in revealing small discrepancies wrt the SM
- LHCb and Belle II will have the first shot at them

Backup Slides

B→$X_s\gamma$ Exclusive

- Various b→sγ and b→dγ exclusive modes have been measured by BABAR, Belle and CLEO
- B(B→ργ)/ B(B→K*γ) yield $|V_{td}/V_{ts}|$

$$\frac{\mathcal{B}(B\to\rho\gamma)}{\mathcal{B}(B\to K^*\gamma)} = S_\rho \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\left(m_B^2 - m_\rho^2\right)^3}{\left(m_B^2 - m_{K^*}^2\right)^3}\zeta^2\left[1+\Delta R(\rho/K^*)\right]$$

ζ=0.85±0.1 (ratio of form factors)

$\Delta R(\rho^0\gamma)$=0.092±0.073 (higher-order correct.)

S is isospin factor

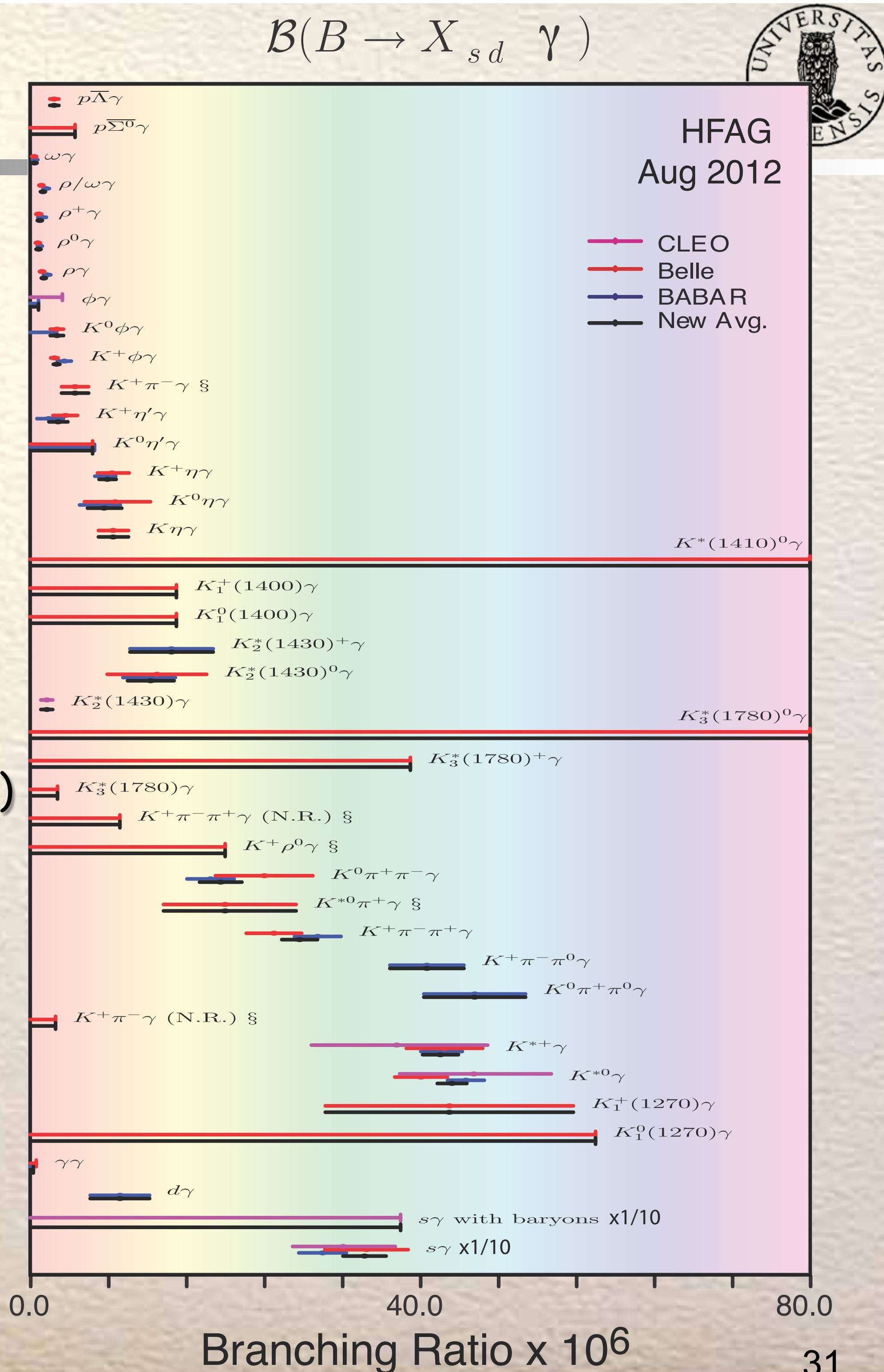
- BABAR/Belle average is

$$\mathcal{B}(B\to(\rho,\omega)\gamma) = (1.3 \pm 0.23)\times 10^{-6}$$

- Yield constraint on $|V_{td}/V_{ts}|$

B→(ρ/ω)γ

$$\left|\frac{V_{td}}{V_{ts}}\right|_{\rho/\omega\gamma} = 0.190^{+0.013}_{-0.014}(\mathrm{exp}) \pm 0.015(\mathrm{th})$$



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

- $\mathcal{A}_{FB}$ results from interplay between $C_9(q^2)C_{10}$ and $C_7 C_{10}/q^2$

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

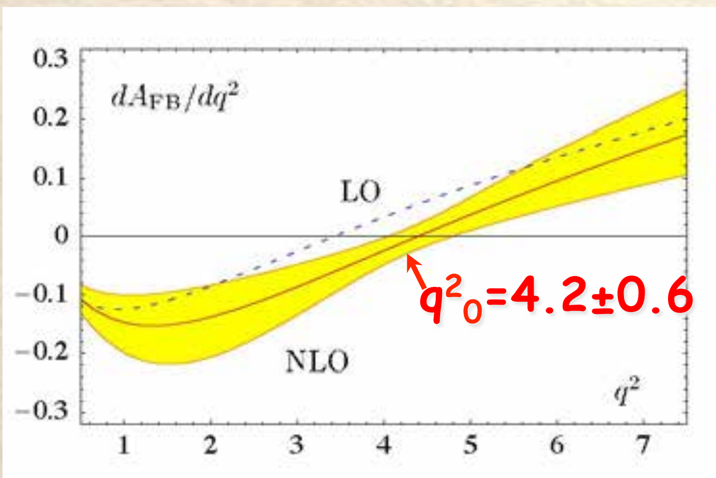
$K^* \ell^+\ell^-$

form factors

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

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

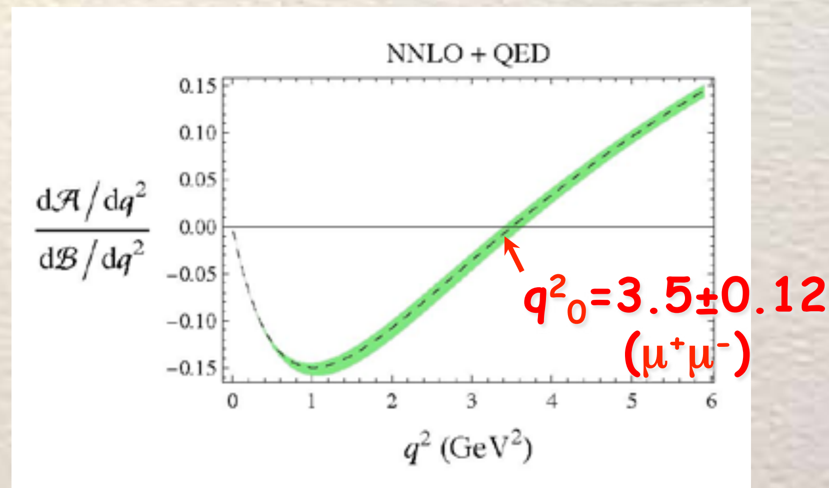
$\mathcal{O}(\alpha_s)$



Feldmann & Matias JHEP 0301, 074 (2003)

$X_s \ell^+\ell^-$

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



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

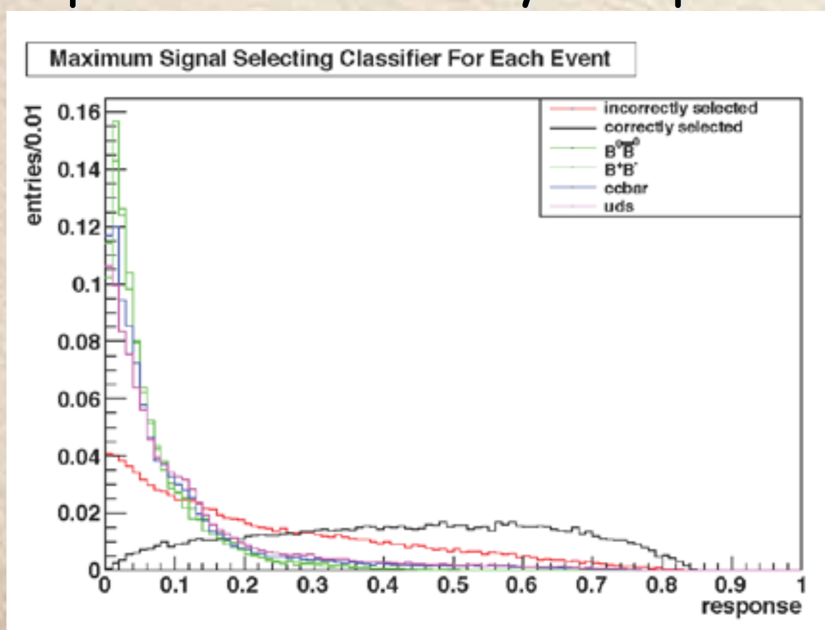
- In the SM, $\mathcal{A}_{FB}$ crosses zero around q^2_0 =3.5-4.5 GeV^2

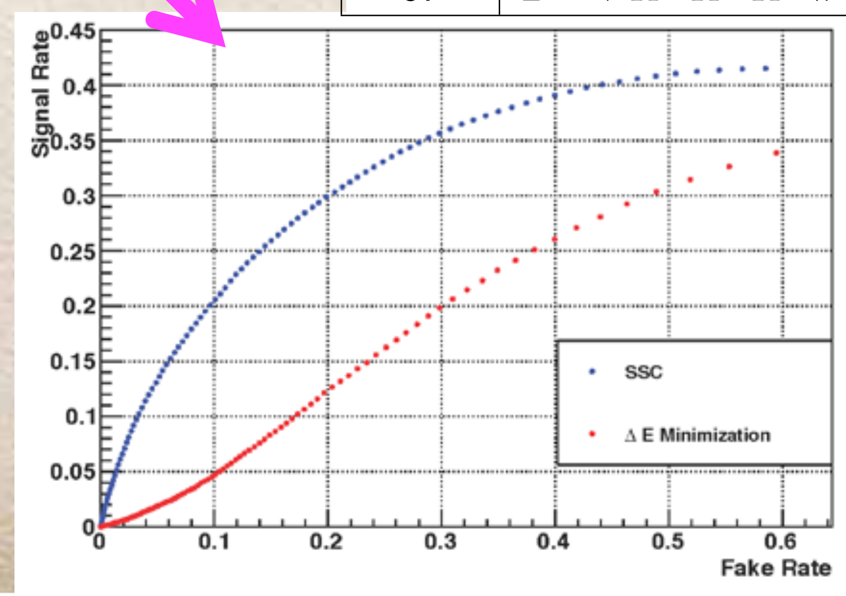
Semi-Inclusive A_{CP} Event Selection

- Use 16 modes for the A_{CP} measurements
- Maximize signal extraction with Signal Selecting Classifier ➔bagged decision tree with 6 inputs
  - $m(X_s)$, $p^{min}_{\pi 0}$, Thrust(B), $\Delta E/\sigma_E$, R_0, R_5
  - Trained on 5% signal MC with m_{ES}> 5.27 GeV
  - good PID for π,K; K_S^0, π^0, η selection
- Select candidate with maximum SSC

➔ improved efficiency compared to ΔE selection

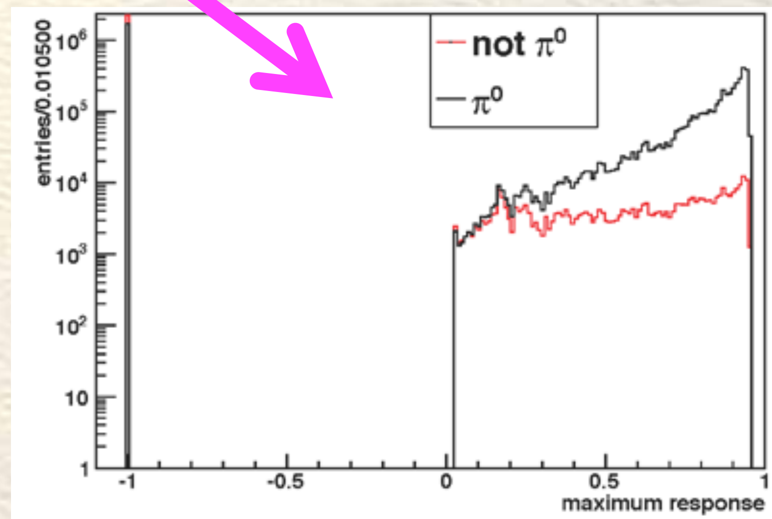
BiType	Final State
1	$B^+ \to K_S\pi^+\gamma$
2	$B^+ \to K^+\pi^0\gamma$
3	$B^0 \to K^+\pi^-\gamma$
5	$B^+ \to K^+\pi^+\pi^-\gamma$
6	$B^+ \to K_S\pi^+\pi^0\gamma$
7	$B^+ \to K^+\pi^0\pi^0\gamma$
9	$B^0 \to K^+\pi^-\pi^0\gamma$
11	$B^+ \to K_S\pi^+\pi^-\pi^+\gamma$
12	$B^+ \to K^+\pi^+\pi^-\pi^0\gamma$
13	$B^+ \to K_S\pi^+\pi^0\pi^0\gamma$
14	$B^0 \to K^+\pi^+\pi^-\pi^-\gamma$
16	$B^0 \to K^+\pi^-\pi^0\pi^0\gamma$
23	$B^+ \to K^+\eta(\to\gamma\gamma)\gamma$
27	$B^0 \to K^+\eta(\to\gamma\gamma)\pi^-\gamma$
33	$B^+ \to K^+K^-K^+\gamma$
37	$B^0 \to K^+K^-K^+\pi^-\gamma$



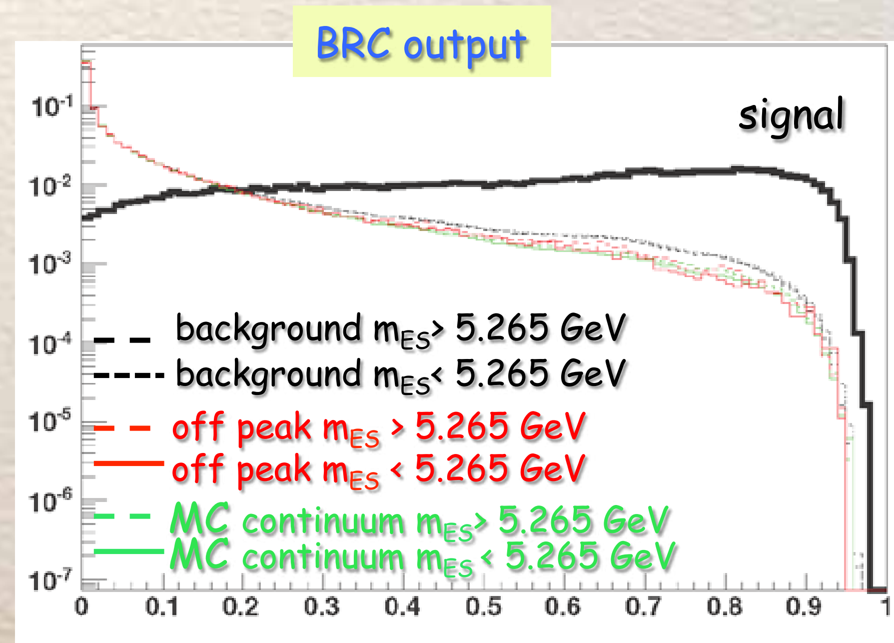


$B\to X_s\gamma$ Semi-Inclusive Analysis

- Train separate bagged decision tree to separate true π^0 from fake π^0



- Use Background Rejection Classifier to remove continuum background
- Train random forest with event-shape variables, *e.g.*
  - Cones of p-flow around B direction
  - L_0, L_1, L_2 of ROE along γ direction
  - L_2/L_0
  - $|\cos\theta^*_B|$, B flight direction (CM)
  - $|\cos\theta^*_T|$, $thrust_B$- $thrust_{ROE}$ (CM)
  - $|\cos\theta^*_{\gamma T}|$, $thrust_\gamma$- $thrust_{ROE}$ (CM)



- Use X_s mass-dependent optimization for $S/(S+B)^{1/2}$ & loose K,π IDs

X_s mass(GeV)	SSC	BRC
0.6-1.1	>0.14	>0.24
1.1-2.0	>0.22	>0.38
2.0-2.4	>0.39	>0.52
2.4-2.8	>0.48	>0.46

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

- Results on $\mathcal{F}_L$ and $\mathcal{A}_{FB}$

$\mathcal{F}_L$

s(GeV^2/c^4)	$B \to K^* \ell^+ \ell^-$	$B^0 \to K^{*0} \ell^+ \ell^-$	$B^+ \to K^{*+} \ell^+ \ell^-$
0.1 – 2.00	$0.23^{+0.10}_{-0.09} \pm 0.04$	$0.35^{+0.13}_{-0.12} \pm 0.04$	$-0.06^{+0.14}_{-0.12} \pm 0.06$
2.00 – 4.30	$0.15^{+0.17}_{-0.14} \pm 0.04$	$0.34^{+0.22}_{-0.22} \pm 0.08$	$-0.19^{+0.24}_{-0.24} \pm 0.04$
4.30 – 8.68	$0.32^{+0.12}_{-0.12} \pm 0.06$	$0.50^{+0.18}_{-0.15} \pm 0.05$	$0.14^{+0.15}_{-0.12} \pm 0.05$
10.09 – 12.86	$0.40^{+0.12}_{-0.12} \pm 0.06$	$0.48^{+0.13}_{-0.12} \pm 0.10$	$0.06^{+0.26}_{-0.25} \pm 0.05$
14.18 – 16.00	$0.43^{+0.10}_{-0.13} \pm 0.09$	$0.42^{+0.12}_{-0.16} \pm 0.11$	$0.58^{+0.34}_{-0.35} \pm 0.06$
$>$ 16.00	$0.55^{+0.15}_{-0.17} \pm 0.03$	$0.47^{+0.18}_{-0.20} \pm 0.13$	$0.71^{+0.30}_{-0.32} \pm 0.03$
1.00 – 6.00	$0.25^{+0.09}_{-0.08} \pm 0.03$	$0.47^{+0.13}_{-0.13} \pm 0.04$	$0.03^{+0.11}_{-0.10} \pm 0.03$

$\mathcal{A}_{FB}$

s(GeV^2/c^4)	$B \to K^* \ell^+ \ell^-$	$B^0 \to K^{*0} \ell^+ \ell^-$	$B^+ \to K^{*+} \ell^+ \ell^-$
0.1 – 2.00	$0.14^{+0.15}_{-0.16} \pm 0.20$	$-0.07^{+0.20}_{-0.20} \pm 0.19$	$0.45^{+0.18}_{-0.24} \pm 0.15$
2.00 – 4.30	$0.40^{+0.18}_{-0.22} \pm 0.07$	$0.21^{+0.23}_{-0.34} \pm 0.11$	$0.73^{+0.27}_{-0.42} \pm 0.07$
4.30 – 8.68	$0.15^{+0.16}_{-0.16} \pm 0.08$	$0.20^{+0.19}_{-0.20} \pm 0.08$	$0.06^{+0.27}_{-0.26} \pm 0.07$
10.09 – 12.86	$0.36^{+0.16}_{-0.17} \pm 0.10$	$0.35^{+0.16}_{-0.16} \pm 0.11$	$0.17^{+0.33}_{-0.33} \pm 0.16$
14.18 – 16.00	$0.34^{+0.08}_{-0.15} \pm 0.07$	$0.31^{+0.11}_{-0.19} \pm 0.13$	$0.42^{+0.35}_{-0.23} \pm 0.09$
$>$ 16.00	$0.34^{+0.19}_{-0.21} \pm 0.07$	$0.34^{+0.17}_{-0.26} \pm 0.08$	$0.17^{+0.38}_{-0.38} \pm 0.11$
1.00 – 6.00	$0.17^{+0.12}_{-0.14} \pm 0.07$	$0.02^{+0.16}_{-0.18} \pm 0.07$	$0.31^{+0.12}_{-0.14} \pm 0.07$