Recent Results on Radiative and Electroweak Penguin Decays of B Mesons at *BABAR*

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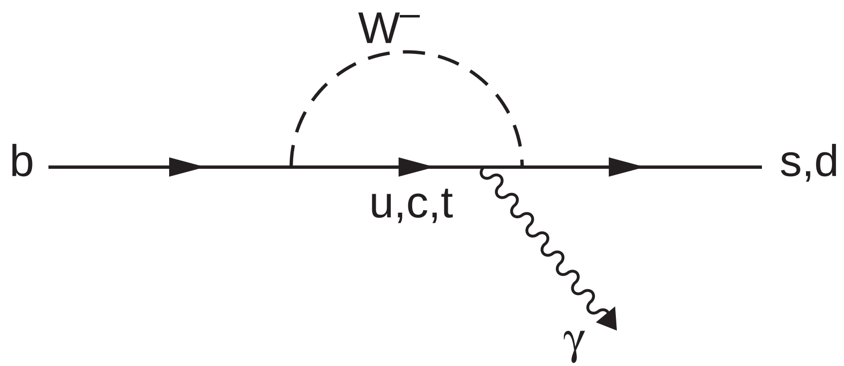
Radiative and Electroweak Decays of B Mesons

- **Flavor-changing neutral current processes:** $b \to s(d)\gamma$ **and** $b \to s(d)\ell^+\ell^-$.
- **At hadron level:** $B \to X_{s(d)}\gamma$ **and** $B \to X_{s(d)}\ell^+\ell^-$
- **These do not occur at tree level (unlike dominant B decays), but rather via one-loop (Penguin) diagrams.**
- **Thus branching fractions (BFs) are small – these are rare decays.**
- **Standard Model (SM): the loops in the leading diagrams involve heavy quarks and W bosons.**
- **Beyond the SM: new particles (*e.g.*, charged Higgs or chargino) can show up virtually in the loops.**
- **Extensive theoretical effort has yielded low SM uncertainties for BFs and CP asymmetries (A_{CP}) for inclusive processes $\Longrightarrow$**

Good place to look for new physics (NP).

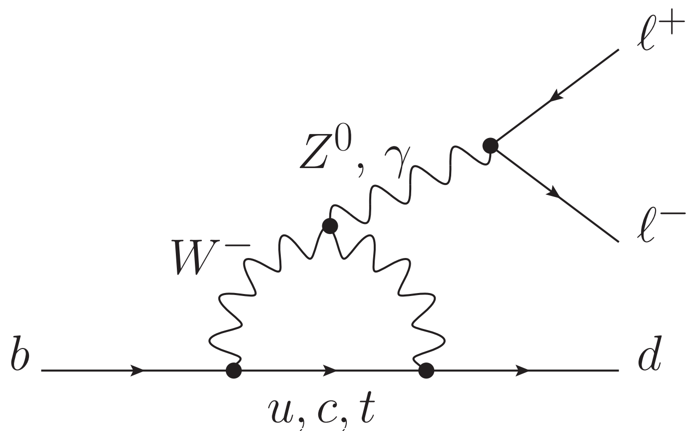
- **Exclusive-state predictions are less precise.**

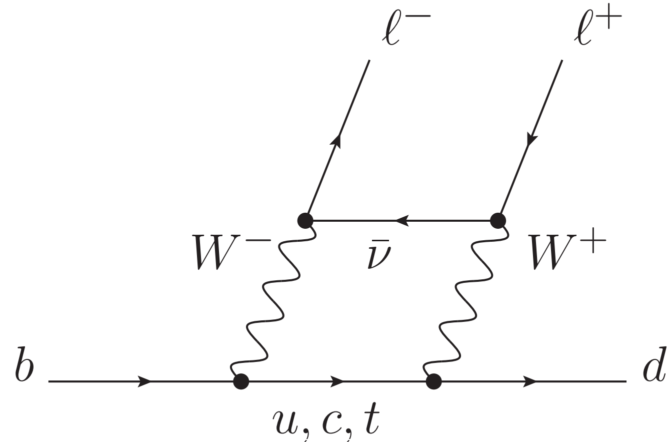
SM Diagrams for Radiative and Electroweak Decays of B Mesons



(plus diagram with γ attached to W line)

Amplitude dominated by t quark in loop





(plus diagram with γ (Z^0) attached to quark line; similar for final-state s)

BABAR Analyses in this Talk

- **Fully-inclusive measurement of $B \to X_s\gamma$ (J.P. Lees *et al.*, Phys. Rev. Lett. 109, 191801 (2012), J.P. Lees *et al.*, Phys. Rev. D 86, 112008 (2013))**
  - $\mathcal{B}(B \to X_s\gamma)$ – **sensitive to NP**
  - **Direct *CP* asymmetry (A_{CP}) in $B \to X_{s+d}\gamma$ – sensitive to NP**
  - **Photon energy spectrum in $B \to X_s\gamma$ – not sensitive to NP (rather, reflects motion of *b* quark inside *B*, *i.e.*, the shape function)**
- **Direct A_{CP} in $B \to X_s\gamma$ via sum of exclusive modes – sensistive to NP (preliminary results)**
- **Search for $B \to X_d\ell^+\ell^-$ decays in exclusive modes – SM predictions for BF to π, η: $\mathcal{O}(1 \text{ to } 4 \times 10^{-8})$ (J.P. Lees *et al.*, arXiv:1303.6010, to be published in Phys. Rev. D)**
- **Not included: Search for $B \to K^{(*)}\nu\bar{\nu}$ with hadronic recoil – SM BFs $\approx 4.5(6.8) \times 10^{-6}$ for K (K^*), New *BABAR* 90% CL isospin-averaged limits: $\approx 32(79) \times 10^{-6}$ (J.P. Lees *et al.*, Phys. Rev. D 87, 112005 (2013))**

Theory

Effective Hamiltonian: sum of operators $\mathcal{O}_i$ times Wilson coefficients, C_i.

- **For $B \to X_{s(d)}\gamma$ in the SM, the important terms involve C_7 and C_8.**
- **Coefficients in the SM are real; NP may introduce non-zero phases.**
- **For $B \to X_{s(d)}\ell^+\ell^-$ there are two additional operators, $\mathcal{O}_9$ and $\mathcal{O}_{10}$, both significant in SM.**

Radiative Decays

- **After a computation involving thousands of diagrams and many contributors, SM prediction at NNLO (next-to-next-leading-order) is**

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

(M. Misiak *et al.*, Phys. Rev. Lett. 98, 022002 (2007))
where E_γ is the photon energy in the B rest frame.

- **Since t quark dominates loops,**

$$\boxed{\mathcal{B}(B \to X_d\gamma)/\mathcal{B}(B \to X_s\gamma) \approx (|V_{td}|/|V_{ts}|)^2 = 0.044 \pm 0.003}$$

Theory: Direct A_{CP} in $B \to X_{s(d)}\gamma$

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

- **Older SM computations** (*e.g.*, T. Hurth *et al.*, Nucl. Phys. B 704, 56 (2005)):
  - $A_{CP}(X_s) = 0.0044^{+0.0024}_{-0.0014}$ and $A_{CP}(X_d) = -0.102^{+0.033}_{-0.058}$
  - If X_s and X_d are not separated, the combined

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

    is zero to order 10^{-6}, a very sensitive test for NP.
- **Recently**, M. Benzke *et al.* (Phys. Rev. Lett. 106, 141801 (2011)) found
  - Long-distance ("resolved photon") effects increase the uncertainty:

    $$\boxed{-0.006 < A_{CP}(X_s) < 0.028} \quad \text{SM prediction}$$

  - These effects cancel for a a new proposed measurement:

    $$\boxed{\Delta A_{CP}(X_s) \equiv A_{CP}(X_s^-) - A_{CP}(X_s^0) \propto \tilde{\Lambda}_{78}\mathrm{Im}(C_8/C_7)}$$

    which is zero in SM. (Hadronic factor is uncertain: $17 < \tilde{\Lambda}_{78} < 190\,\mathrm{MeV}$.)
  - The precise prediction $\boxed{A_{CP}(X_s + X_d) = 0}$ is preserved.

BABAR Fully-inclusive $B \to X_s\gamma$: Analysis Ingredients

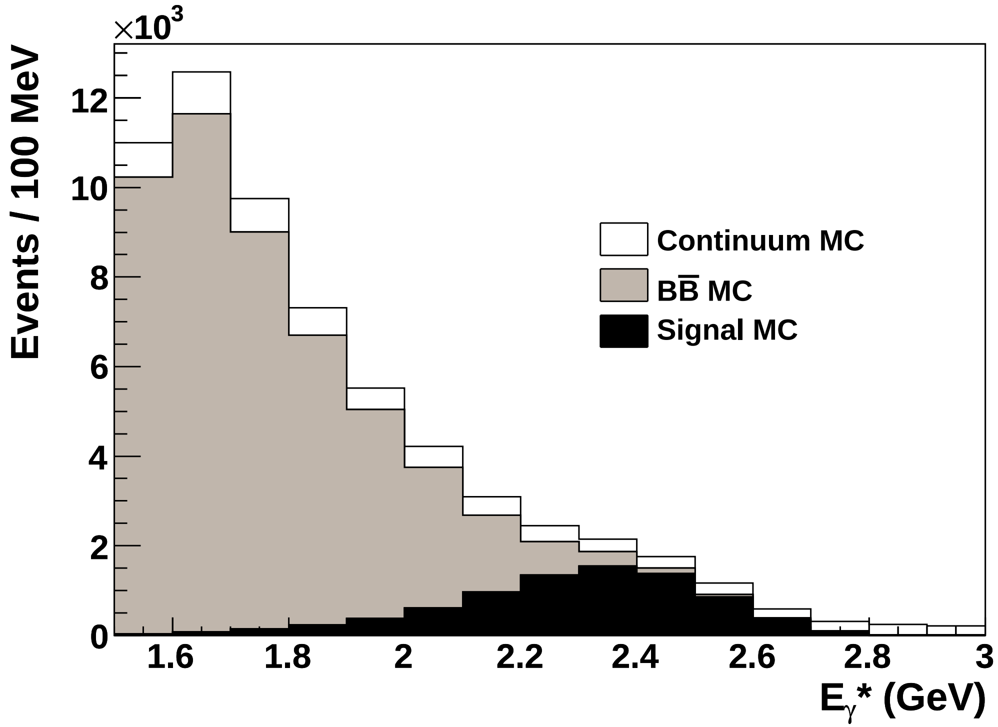
Notation: E_γ is true γ energy in B rest frame,
E^*_γ is measured energy in CM ($\Upsilon(4S)$) frame.

- Inclusivity: from B decay require only a γ with $E^*_\gamma > 1.53\,\text{GeV}$ (CM).
- The B rest frame is not known. E^*_γ differs from E_γ by Doppler smearing (motion of B in CM frame) and calorimeter energy resolution.
- Backgrounds: Continuum ($e^+e^- \to q\overline{q}$ ($q \neq b$) or $\tau^+\tau^-$) and other $B\overline{B}$.
- Suppress Continuum using:
  - Full-event topology
  - High-p Lepton Tag (e or μ): in signal and other $B\overline{B}$ events, lepton is from semileptonic decay of other B; far less likely for Continuum.
    Bonus: lepton also provide CP tag
- Veto candidate high-energy γ when partner from π^0 or η decay is found.

BABAR Fully-inclusive $B \to X_s\gamma$: Analysis Ingredients

Photon Spectrum
after event selection

(GEANT4/EVTGEN-based Monte Carlo (MC) estimates, scaled to data luminosity)



- Subtract Continuum by scaling the data (10%) collected off-resonance – dominates statistical error
- Subtact $B\overline{B}$ using data-corrected MC – dominates systematic error
- Large $B\overline{B}$ background implies no useful signal measurement below 1.8 GeV
- Signal Region ("blind") above 1.8 GeV; Control Region 1.53 to 1.8 GeV.
- For A_{CP}, count events by lepton charge for $E^*_\gamma > 2.1$ GeV (optimized blind).

Inclusive $B \to X_s\gamma$: Monte Carlo Composition of B Background

MC Category		1.53 to 1.8 GeV		1.8 to 2.8 GeV	
Particle	Parent	Fraction	Corr. Factor	Fraction	Corr. Factor
Photon	π^0	0.5390	1.05	0.6127	1.09
	η	0.2062	0.79	0.1919	0.75
	ω	0.0386	0.80	0.0270	0.80
	η'	0.0112	0.52	0.0082	1.13
	B	0.0362	1.00	0.0194	1.00
	J/ψ	0.0061	1.00	0.0071	1.00
	$e^\pm$	0.0967	1.07	0.0619	1.07
	Other	0.0035	1.00	0.0032	1.00
	Total	0.9375	—	0.9315	—
$e^\pm$	Any	0.0411	1.65	0.0333	1.68
$\overline{n}$	Any	0.0170	0.35	0.0243	0.15
Other	Any	0.0029	1.00	0.0028	1.00
None		0.0015	1.00	0.0079	1.00

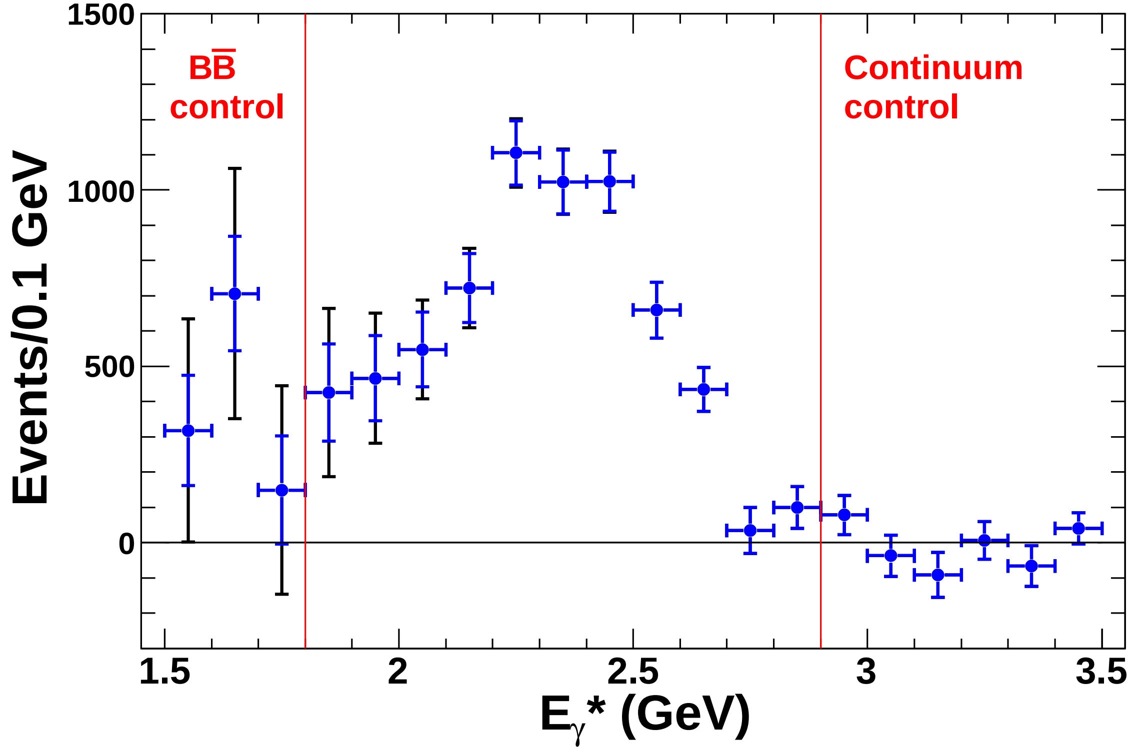
Most components corrected using studies of Data *vs.* MC control samples.

BABAR Fully-inclusive $B \to X_s\gamma$: Results

BABAR Photon Spectrum ($347.1\,\mathrm{fb}^{-1}$) after background subtraction

Inner errors: stat only
Outer errors: stat $\oplus$ syst

(Systematic errors are highly correlated)



After correcting for efficiency, making small adjustment from E^*_γ to E_γ, including the additional systematics (allowing for correlations), and scaling by 0.958 to account for $X_d\gamma$ contribution:

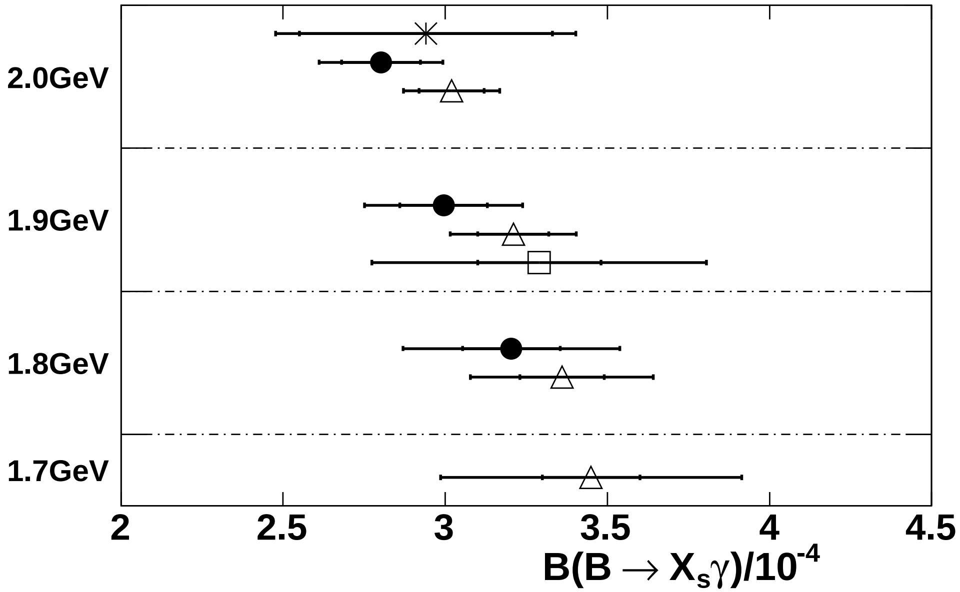
$$\boxed{\mathcal{B}(B \to X_s\gamma) = (3.21 \pm 0.15 \pm 0.29 \pm 0.08) \times 10^{-4} \quad (E_\gamma > 1.8\,\mathrm{GeV})}$$

Errors: statistical, systematic and model-dependence.

BABAR Fully-inclusive $B \to X_s\gamma$: Results

Compare Branching Fraction to earlier measurements (vs. min. E_γ)

- ● This BABAR
- $*$ CLEO
- △ Belle
- □ BABAR Sum-of-exclusive



Measurements with different thresholds from a single experiment are strongly correlated. Uncertainties increase toward lower thresholds due to increasing $B\overline{B}$ backgrounds – *c.f.* Belle's 1.7-GeV result.

To compare to theory, one must extrapolate down to 1.6 GeV

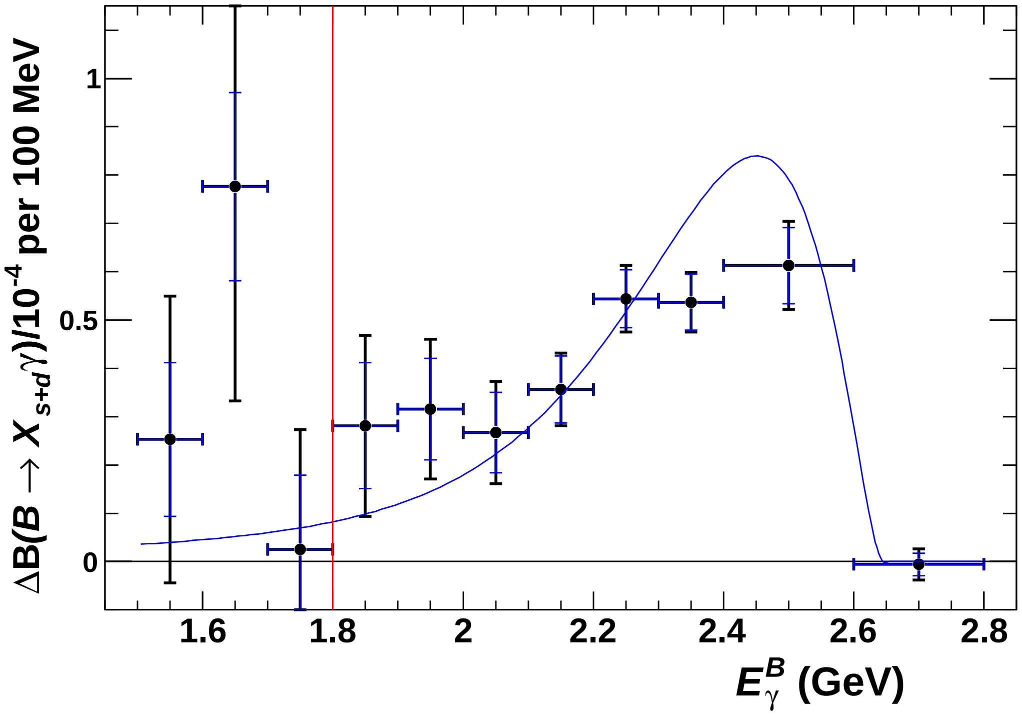
BABAR Fully-inclusive $B \to X_s\gamma$: Results

Unfold measured BABAR photon spectrum in E^*_γ to true spectrum in E_γ

Method adapted from Bogdan Malaescu

Vertical line separates control region from signal region

Curve: shape for kinetic scheme with HFAG world-average HQET parameters



- **Heavy Quark Effective Theory can compute spectral shape in the "kinetic scheme" or "shape function scheme" for any set of HQET parameters.**
- **Heavy Flavor Averaging Group (HFAG) has computed world-average values of HQET parameters using measurements of $B \to X_c\ell\nu$ and $B \to X_s\gamma$.**

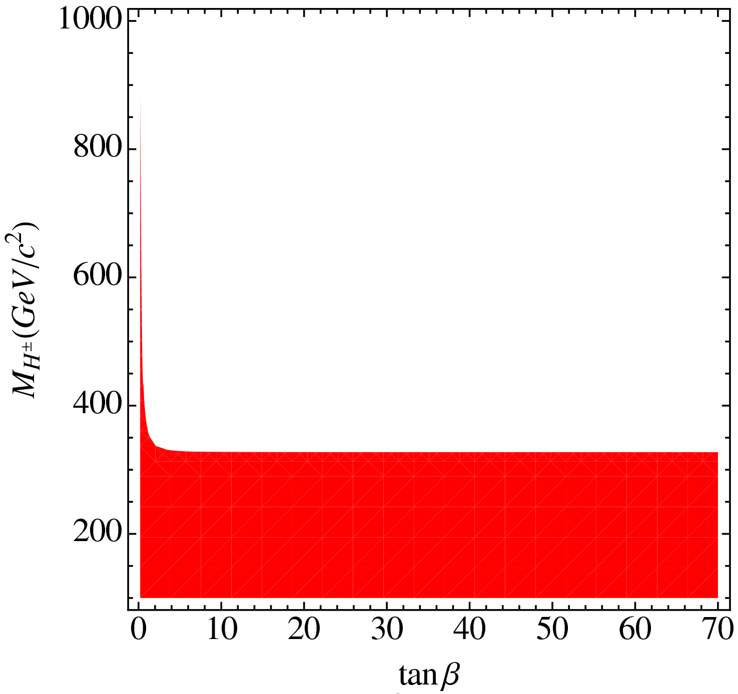
BABAR Fully-inclusive $B \to X_s\gamma$: Illustration of NP Constraint

Extrapolate BABAR 1.8-GeV result down, using HFAG-provided factor:

$$\text{Extrapolated} \quad \mathcal{B}(B \to X_s\gamma) = (3.31 \pm 0.35) \times 10^{-4} \quad (E_\gamma > 1.6\,\text{GeV})$$

Consistent with SM prediction of $(3.15 \pm 0.23) \times 10^{-4}$.

- Comparison can constrain New Physics.
- Example: type-II two-Higgs doublet model (M. Misiak *et al.*, *ibid*, and U. Haisch, arXiv:0805.2141v2)
  - The red region is excluded at 95% CL ($m_{H^\pm} < 327\,\text{GeV}/c^2$ for most $\tan\beta$)
  - Recent THDM update strengthens limit (T. Hermann *et al.*, JHEP 1211, 036 (2012))



$m_{H^\pm}$ (GeV/c^2) vs. $\tan\beta$

BABAR Fully-inclusive $B \to X_s\gamma$: A_{CP} Results

In contrast to the branching fraction, for A_{CP} $B \to X_s\gamma$ and $B \to X_d\gamma$ behave very differently. Thus only sum of X_s and X_d events is measured.

Tag B vs. $\overline{B}$ by lepton charge, correct for mistags.

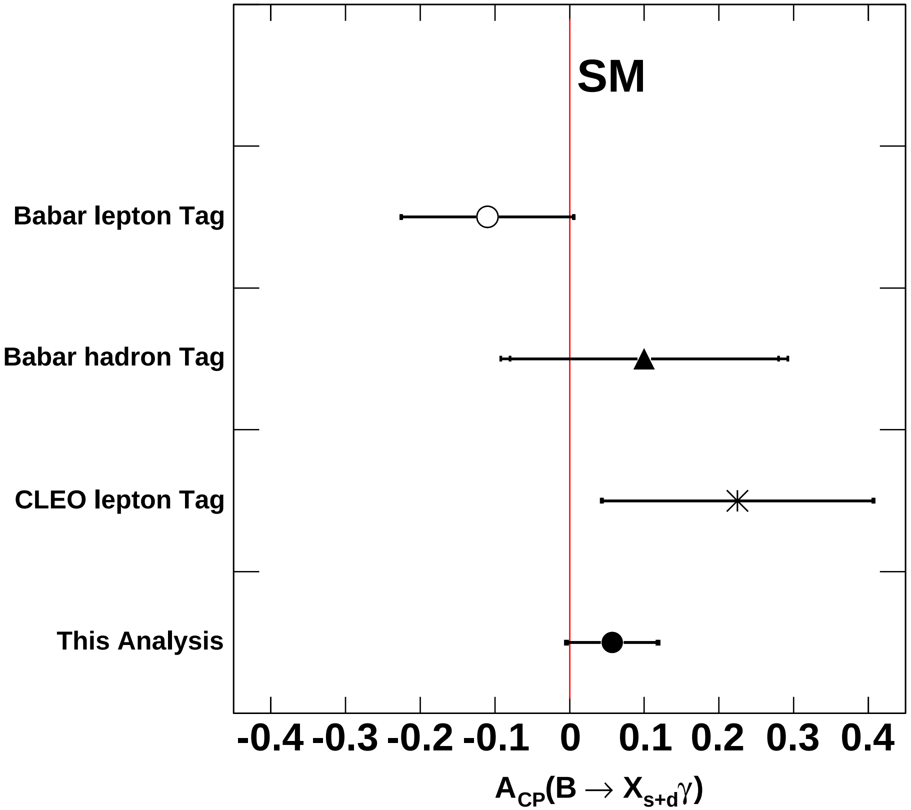
$$\boxed{A_{CP}(B \to X_{s+d}\gamma) = 0.057 \pm 0.060(\text{stat}) \pm 0.018(\text{syst})}$$

Consistent with SM prediction of 0.

Compare to previous measurements

"BABAR lepton tag" superceded by present measurement

Most precise measurement to date



BABAR Direct $A_{CP}(B \to X_s\gamma)$ by Sum of Exclusive Decays

Using exclusive final states (Data sample: $420\,\mathrm{fb}^{-1}$)

- Distinguish X_s from X_d by kaon ($K^\pm$ or K^0_S) in reconstructed final state.
- Assign CP charge by B^+ vs. B^-, or for B^0 by K^+ vs. K^- in final state.
- **Inclusiveness**: as many final states as feasible. (Only $K^0_S \to \pi^+\pi^-$ used.)

These 16 modes are used for A_{CP} measurement:

Charged Modes	Neutral Modes
$K^0_S\ \pi^+\ \gamma$	$K^+\ \pi^-\ \gamma$
$K^+\ \pi^0\ \gamma$	$K^+\ \pi^-\ \pi^0\ \gamma$
$K^+\ \pi^+\ \pi^-\ \gamma$	$K^+\ \pi^+\ \pi^-\ \pi^-\ \gamma$
$K^0_S\ \pi^+\ \pi^0\ \gamma$	$K^+\ \pi^-\ \pi^0\ \pi^0\ \gamma$
$K^+\ \pi^0\ \pi^0\ \gamma$	$K^+\ \eta\ \pi^-\ \gamma$
$K^0_S\ \pi^+\ \pi^-\ \pi^+\ \gamma$	$K^+\ K^-\ K^+\ \pi^-\ \gamma$
$K^+\ \pi^+\ \pi^-\ \pi^0\ \gamma$	
$K^0_S\ \pi^+\ \pi^0\ \pi^0\ \gamma$	
$K^+\ \eta\ \gamma$	
$K^+\ K^-\ K^+\ \gamma$	

BABAR Direct $A_{CP}(B \to X_s\gamma)$: Analysis Ingredients

- Standard B reconstruction variables: m_{ES} (energy-substituted mass) and ΔE (beam energy minus candidate energy in CM frame).
- After event selection, signal yield and A_{CP} extracted by fits to m_{ES} spectra.
- Largest background is Continuum events (no peak in m_{ES}).
- Background suppression uses event topology (reduces Continuum) and photon-pair masses.
- Peaking background: signal-crossfeed and a fraction of non-signal $B\overline{B}$ events. The fit-extracted A_{CP} includes a contribution from peaking background.

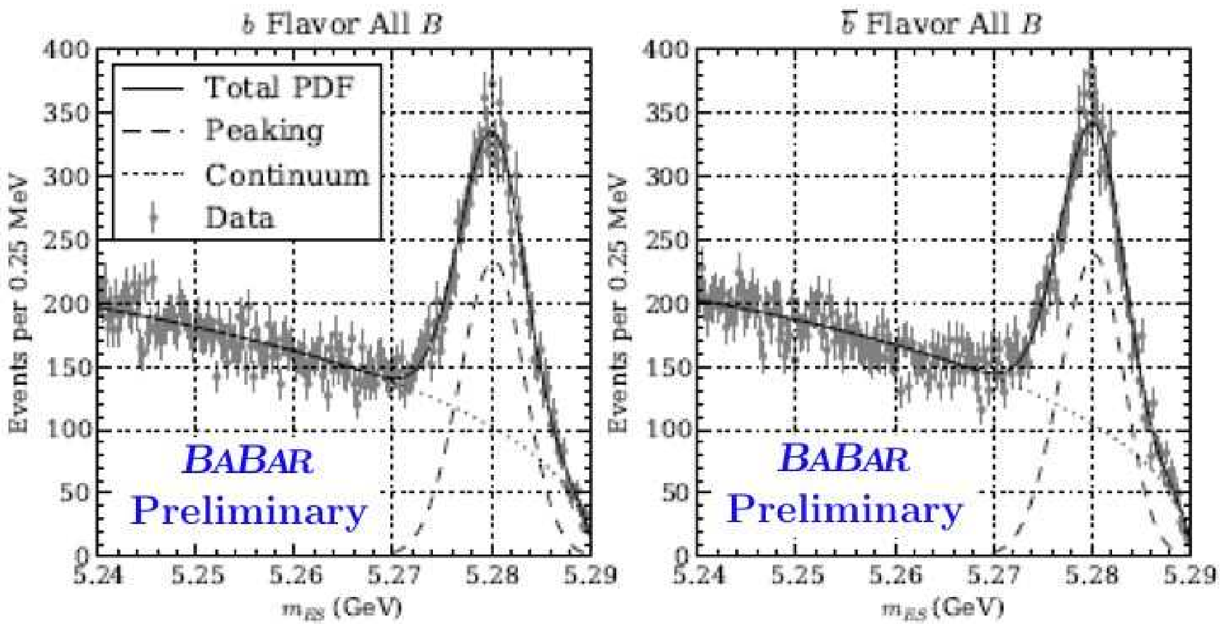
The selected sample represents E_γ (computed most precisely from m_{X_s}) above $\sim 2.2\,\mathrm{GeV}$, not a sharp cutoff. $B\overline{B}$ background is small in this region.

BABAR Direct $A_{CP}(B \to X_s\gamma)$: Preliminary Results

m_{ES} Spectra for sum of all A_{CP} modes

Fit spectra to peaking plus non-peaking components

Similar fits done for separate charged and neutral B's



B $\overline{B}$

Fitting the spectra yields A_{CP} for peak events. Correct for detector asymmetry and assign systematic error (0.009) for asymmetry in peaking backgrounds.

BABAR Preliminary Results (both consistent with SM)

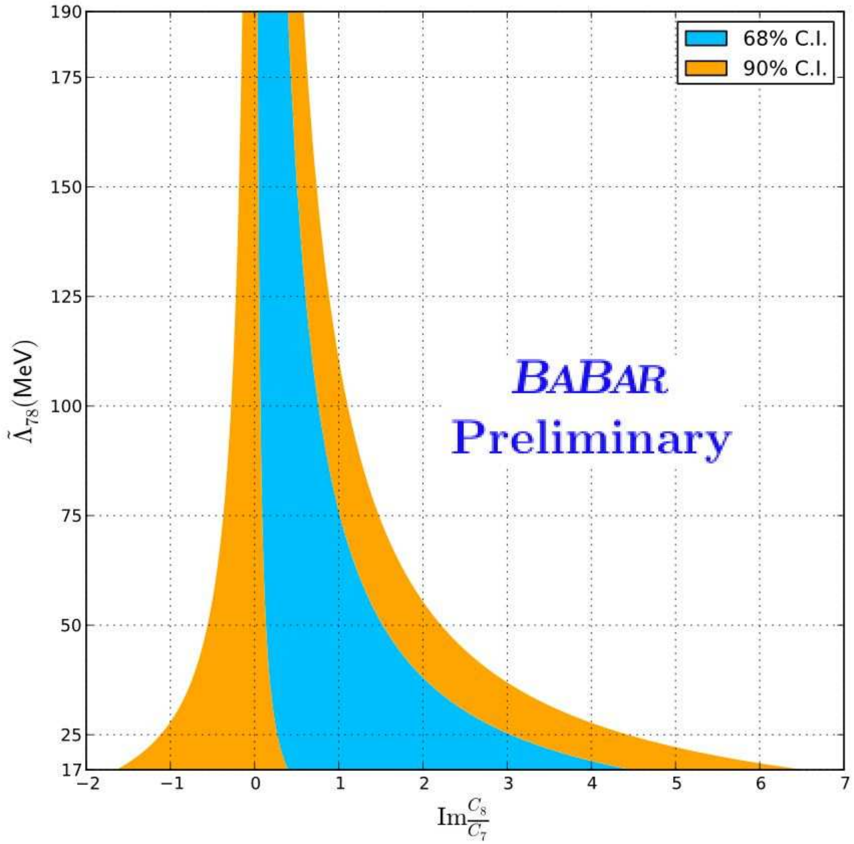
$$\boxed{A_{CP}(X_s) = 0.017 \pm 0.019(\text{stat}) \pm 0.010(\text{syst})}$$

$$\boxed{\Delta A_{CP}(X_s) = 0.050 \pm 0.039(\text{stat}) \pm 0.015(\text{syst}) \quad (\text{first measurement})}$$

BABAR Direct $A_{CP}(B \to X_s\gamma)$: Preliminary Results

Limits on $\mathrm{Im}(C_8/C_7)$ (non-zero only with NP)

- Allow for full range of coefficient $\tilde{\Lambda}_{78}$
- For each value of $\tilde{\Lambda}_{78}$ *vs.* $\mathrm{Im}(C_8/C_7)$:
  - compute theory $\Delta A_{CP}(X_s)$ and
  - compare it to measured value (Gaussian errors)
- Plot shows 68% and 90% confidence regions
- Conservative limits on $\mathrm{Im}(C_8/C_7)$: horizontal extremes of shaded areas



$$0.07 \le \mathrm{Im}(C_8/C_7) \le 4.48 \quad (68\%\ \mathrm{CL})$$
$$-1.64 \le \mathrm{Im}(C_8/C_7) \le 6.52 \quad (90\%\ \mathrm{CL})$$

BABAR Preliminary

$B \to X_{s(d)}\ell^+\ell^-$ Measurements

- Branching fractions $\mathcal{O}(\alpha)$ smaller than for $B \to X_{s(d)}\gamma$. Thus:
- Most measurements to date are of exclusive modes (much less precise BF predictions, but more easily measured, than inclusive process).
- Most publications have been for $B \to K^{(*)}\ell^+\ell^-$ (See Backup.) PDG averages: $\mathcal{B}(B \to K\ell^+\ell^-) = (0.48 \pm 0.04) \times 10^{-6}$, $\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.05 \pm 0.10) \times 10^{-6}$
- Additional degrees of freedom *vs.* $B \to X_{s(d)}\gamma$: $m_{\ell^+\ell^-}$ and lepton angles – may provide sensitive NP tests, *e.g.*, angular asymmetries as function of $m_{\ell^+\ell^-}$
- $B \to X_d\ell^+\ell^-$ is suppressed by additional CKM factor of ≈ 23.
- SM BF predictions in ranges $(1.4 - 3.3) \times 10^{-8}$ for $\pi\ \ell^+\ell^-$ modes, $(2.5 - 3.7) \times 10^{-8}$ for $\eta\ \ell^+\ell^-$ (largest uncertainties are in form factors). NP could significantly increase these BFs.

Here: recent *BABAR* searches for $B^\pm \to \pi^\pm\ell^+\ell^-$, $B^0 \to \pi^0\ell^+\ell^-$, $B^0 \to \eta\ell^+\ell^-$

BABAR Search for $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ Decays

Analysis of 428 fb^{-1} of data

- Reconstruct B candidates from: high-energy γ; $\pi^\pm$ or π^0 (to $\gamma\ \gamma$) or η (to $\gamma\ \gamma$ or $\pi^+\ \pi^-\ \pi^0$); $\ell^+\ell^-$ ($e^+\ e^-$ or $\mu^+\ \mu^-$)
- Largest backgrounds (there are others)
  - $B \to J/\psi(\to \ell^+\ell^-)X$ (likewise $\psi(2S)$) – veto using $m_{\ell^+\ell^-}$
  - Random combinations of particles – suppress based on event topology and missing energy/momentum
  - $B \to K^{(*)}\ell^+\ell^-$ – ΔE spectra differ from signal, include in fits (*e.g.*, $K^\pm \to \pi^\pm$ misidentification or lost π from K^0_S decay)
- Unbinned maximum likelihood fits in m_{ES} and ΔE, including:
  - Signal (shapes from MC, yield free)
  - Combinatoric background ("ARGUS" shape and yield free)
  - Peaking background, mostly from $B \to K^{(*)}\ell^+\ell^-$ (compute yields from known BFs or control samples, shapes from MC)

BABAR Search for $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ Decays

Examples of fits

Components:

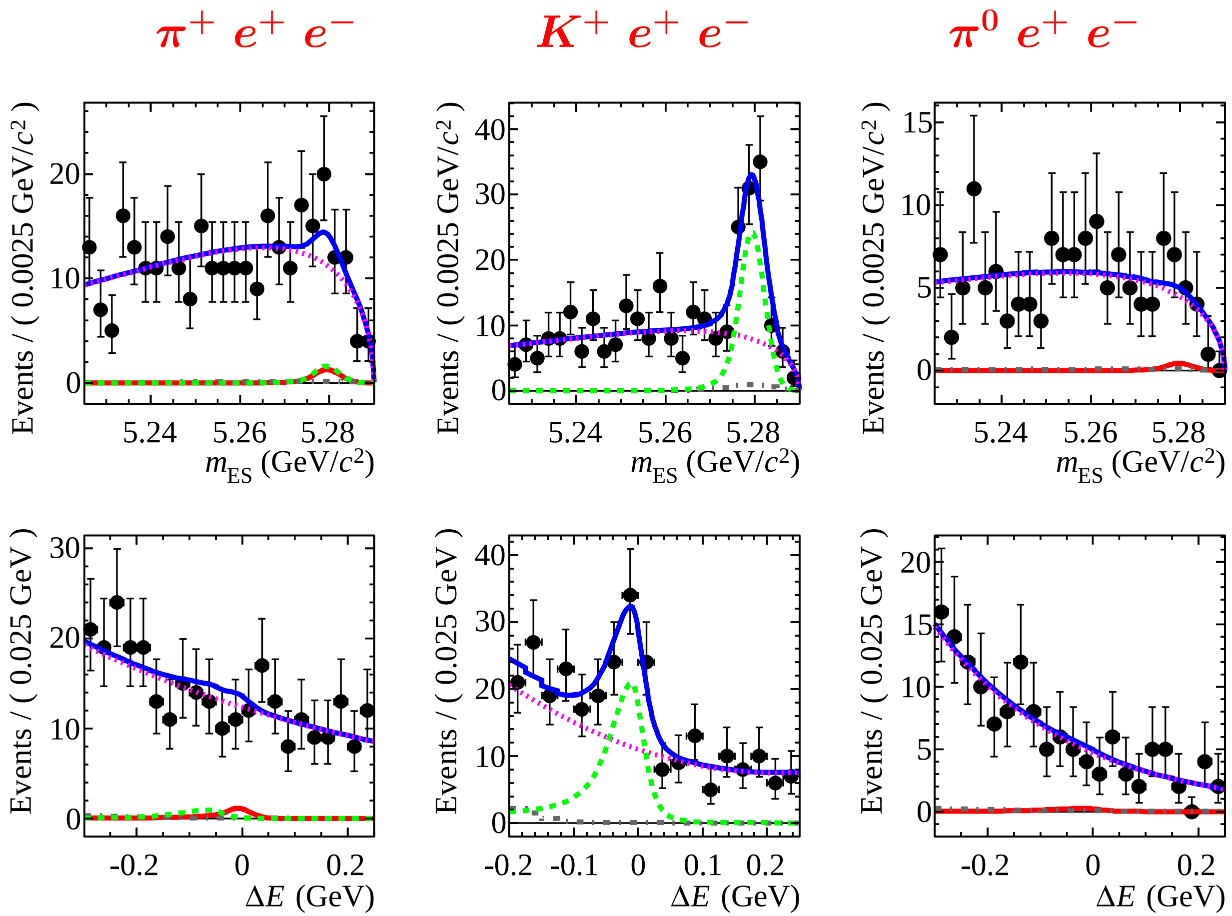
Cominatoric: dotted

K^* and K^0_S: dot-dash

$K^+ e^+ e^-$: dashed

$\pi\ e^+ e^-$: solid red

Total fit: solid blue



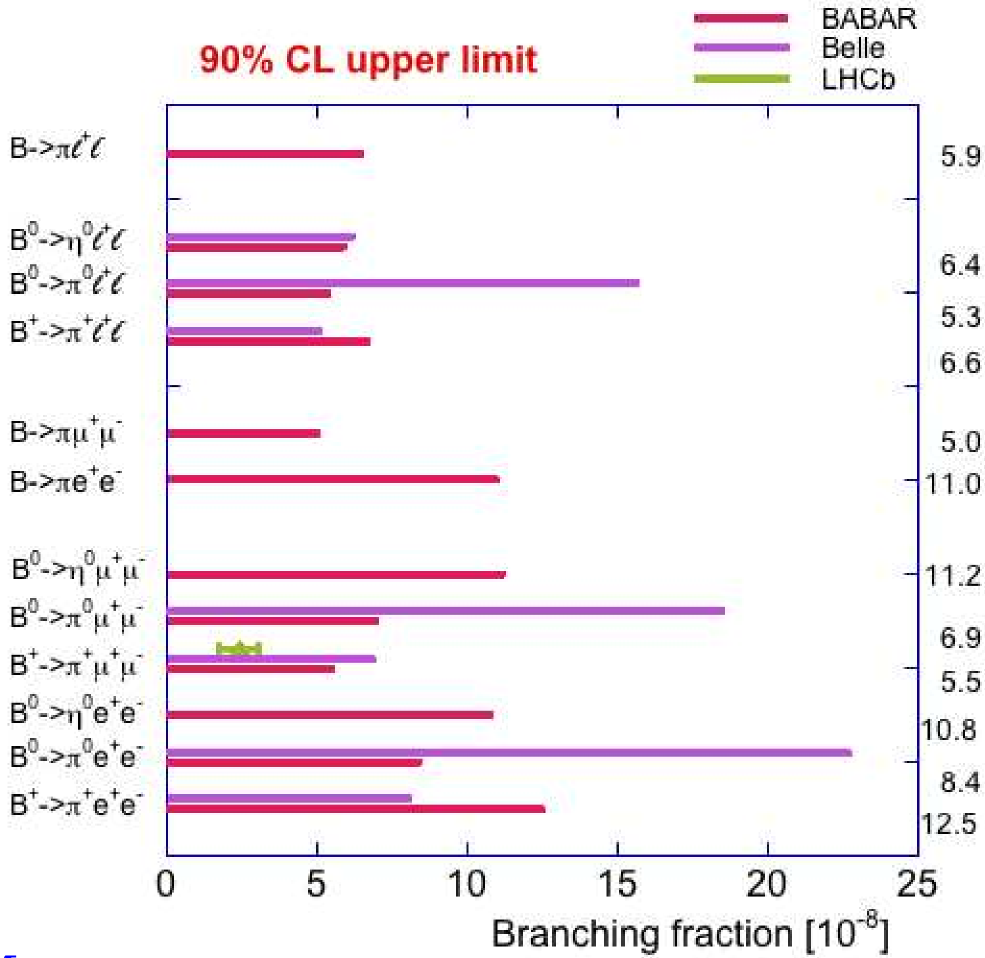
($K^+ e^+ e^-$ is fit simultaneously with $\pi^+ e^+ e^-$, to which it is a background; $K^+ e^+ e^-$ yield ratio is fixed, based on known K-misID probability.)

BABAR Search for $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ Decays

BABAR: No signals found

90% CL BABAR upper limits shown to right of plot (BF in 10^{-8})

(including averages over lepton flavor and π isospin)



LHCB: confirmed $\pi^+ \mu^+ \mu^-$ signal, significance 5.2σ

So far: no disagreement with SM

Summary

Several recent *BABAR* measurements have the potential for finding or constraining new physics (NP) beyond the SM

- $\mathcal{B}(B \to X_s\gamma)$
- $A_{CP}(B \to X_{s+d}\gamma)$
- $A_{CP}(B \to X_s\gamma)$ and $\Delta A_{CP}(X_s)$
- Search for ultra-rare decays $B \to (\pi, \eta)\ell^+\ell^-$

No evidence for NP found, but current results can be used to constrain specific NP models.

These measurements can be fruitfully pursued at a future high-intensity *B*-factory (Belle-II). Their power depends on the precision of the SM predictions and (especially for $\mathcal{B}(B \to X_s\gamma)$) the ability to reduce systematic uncertainties.

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

$B \to K^{(*)}\ell^+\ell^-$ branching fractions (in 10^{-6})