$B \rightarrow X_s\gamma$ at SuperB: the experimental viewpoint

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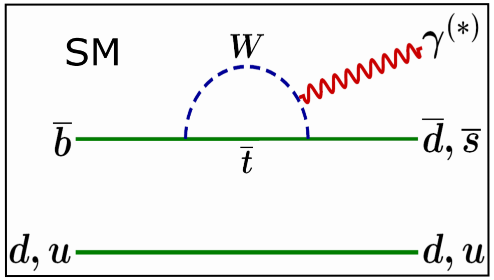
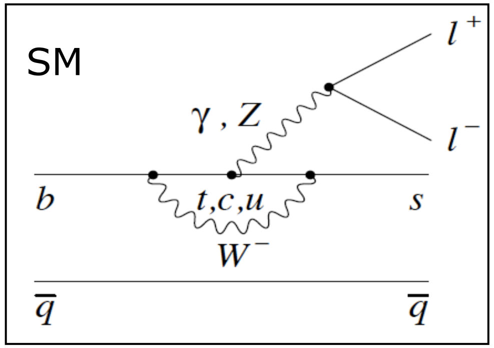
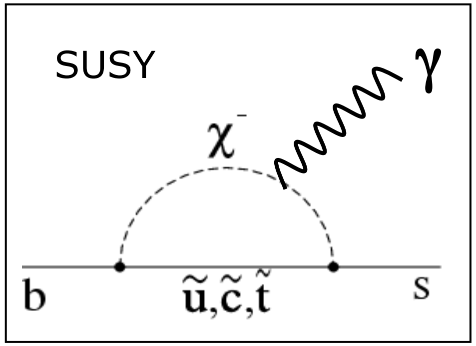
Outline

- Introduction
- BF($B \to X_s\ \gamma$)
- CP Asymmetries
- Open questions
- Summary

Radiative B decays







- Flavour-changing neutral current ($b \rightarrow s$ or $b \rightarrow d$)
  - forbidden at tree level in the SM
  - NP can contribute at the same order as the SM processes
  - **an excellent "laboratory" for NP searches**
- Observables:
  - **Branching fraction**; CP and isospin asymmetries; photon energy spectrum
- Inclusive measurements preferred: better theoretical predictions
- $B \rightarrow X_s \gamma$

- Measure b-quark mass and other HQE parameters from photon spectrum:
  helpful in reducing systematic errors on V_{ub}

not today

$b \rightarrow s\gamma$: Radiative Penguin Decay

- Flavor changing neutral current:
  - Not present at tree level in SM
- Loop diagram
  - measurements sensitive to new heavy particles in diagrams
- Current status of BF
  - Experiment (HFAG):

$$B(B \rightarrow X_s\gamma, E > 1.6GeV) = (3.55 \pm \overbrace{0.24_{stat+syst} \pm 0.09_{shpFcn}}^{\pm 0.26 \text{ (total error)}}) \times 10^{-4}$$

  - Theory:

$$B(B \rightarrow X_s\gamma, E > 1.6GeV) = (3.15 \pm 0.23) \times 10^{-4} \text{ (Misiak, et al)}$$

$$B(B \rightarrow X_s\gamma, E > 1.6GeV) = (2.98 \pm 0.26) \times 10^{-4} \text{ (Becher/Neubert)}$$

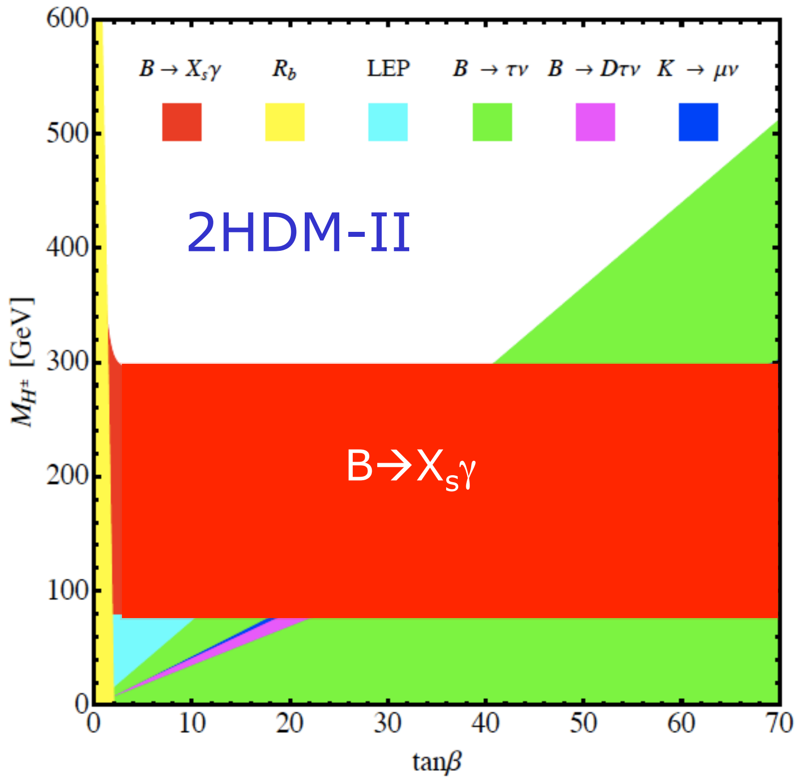
Strong constraints on NP

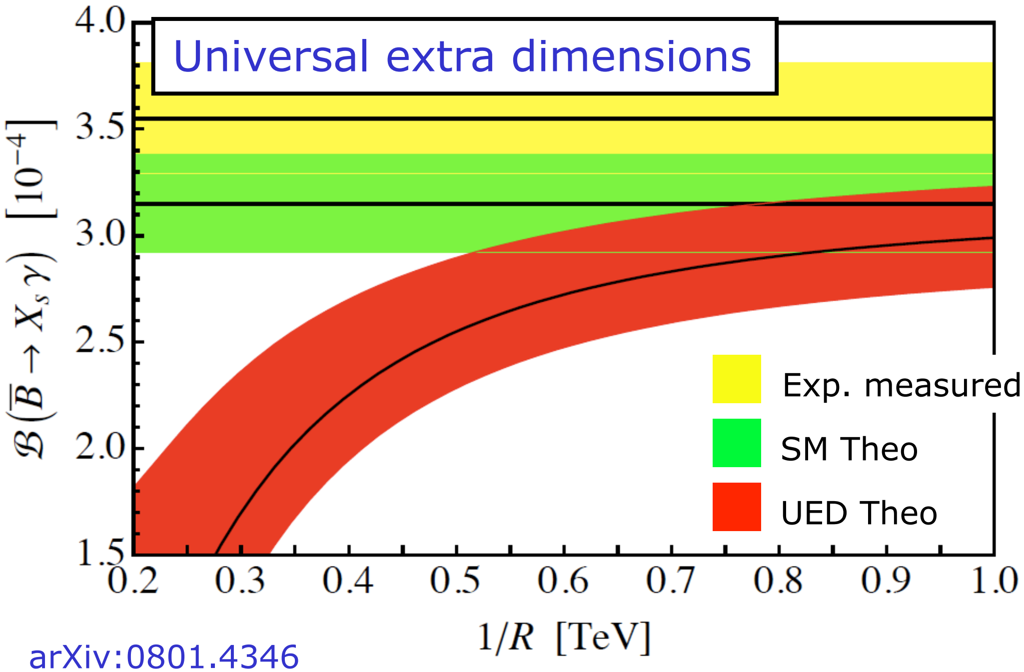
arXiv:0805.2141

- <u>2-Higgs doublet model, Type II</u>
  - B→$X_s\gamma$ gives strong constraint

$$m_{H^+} > 295\ \text{GeV}/c^2\ (95\%\ \text{CL})$$

  - even at low tan β





arXiv:0801.4346

- <u>Universal extra dimensions</u>
  - key parameter: "compactifcation radius" R
  - constraint from B→$X_s\gamma$

$$1/R > 650\ \text{GeV}\ (95\%\ \text{CL})$$

Experimental approaches to $B \to X_s \gamma$

- Fully-inclusive: no requirements on X_s system
  - potentially large backgrounds
  - few kinematic constraints on signal
  - Tagging of "other" B meson in event
    1. Untagged
    2. lepton-tagged
    3. hadron-tagged
- Semi-inclusive: reconstruct many (~10-50) exclusive channels
  - kinematic handles to reduce background
  - need to estimate contributions from missing channels
  - systematic errors large for BF, but maybe relevant for asymmetry measurements?

Towards a fully inclusive measurement of $b \to s\gamma$

- Ideally, you'd like to make a fully inclusive measurement
  1. no requirement on the X_s hadronic system
  2. no cut on photon energy
- X_s hadronic system
  - "fully inclusive" makes no requirement, but tags other B in event
  - "semi inclusive" reconstructs as many exclusive decay modes as possible. Estimate the amount of stuff that is missing.
- Photon energy: in practice, some cut on photon energy is unavoidable → make it as low as possible

Min photon energy cut

- Theorist: make cut as low as possible, inclusive calculation depends on this
- Experimentalist: ok, but it's going to give us a larger systematic

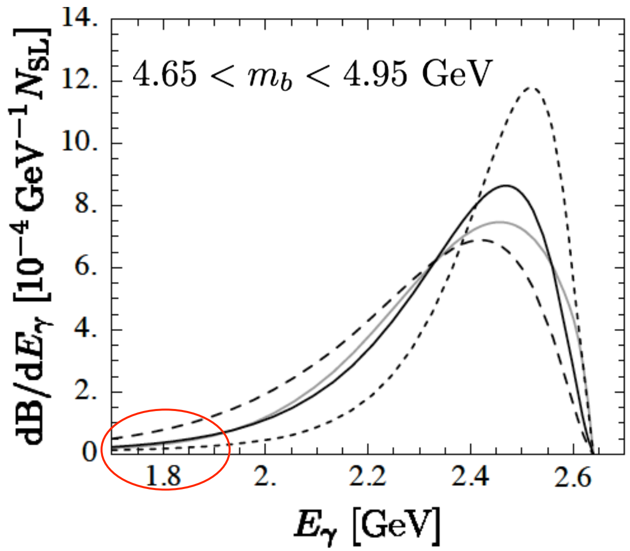
Belle inclusive measurement
PRL 103, 241801 (2009)

	$\mathrm{BF}(B \to X_s\gamma)$ (10^{-4})			
$E^{\mathrm{B}}_{\gamma-\mathrm{Low}}$ [GeV]	1.70	1.80	1.90	2.00
Value	3.45	3.36	3.21	3.02
$\pm$statistical	0.15	0.13	0.11	0.10
$\pm$systematic	0.40	0.25	0.16	0.11

- HFAG: partial BF measured by experiments extrapolated to Eγ > 1.6 GeV (the value used by theorists)
  - the syst. error in this extrapolation is determined by comparing extrapolation factor for 3 different models
  - resulting syst. error is small compared to increase in experimental systematic

Extrapolation factor

Scheme	$E_\gamma < 1.7$	$E_\gamma < 1.8$	$E_\gamma < 1.9$
Kinetic	0.986 ± 0.001	0.968 ± 0.002	0.939 ± 0.005
Neubert SF	0.982 ± 0.002	0.962 ± 0.004	0.930 ± 0.008
Kagan-Neubert	0.988 ± 0.002	0.970 ± 0.005	0.940 ± 0.009
Average	0.985 ± 0.004	0.967 ± 0.006	0.936 ± 0.010

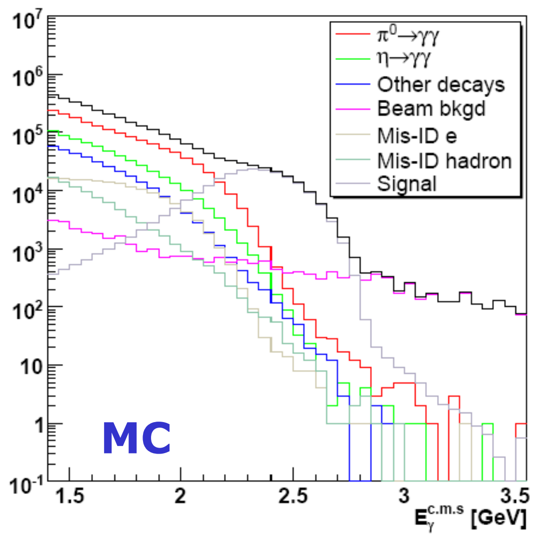


Untagged Inclusive $B \rightarrow X_s\gamma$ from Belle

$B\bar{B}$ Backgrounds:

- $B\bar{B}$ backgrounds remain after continuum subtraction
- Use MC + control samples where possible
  - inclusive π^0 and η rates measured on data
  - veto efficiencies measured with $D^0 \rightarrow K\pi\pi^0$ sample

Background contributions



Results, 1.7 < $E\gamma$ < 2.8 GeV (B-rest frame) :

most precise, lowest energy cut to date

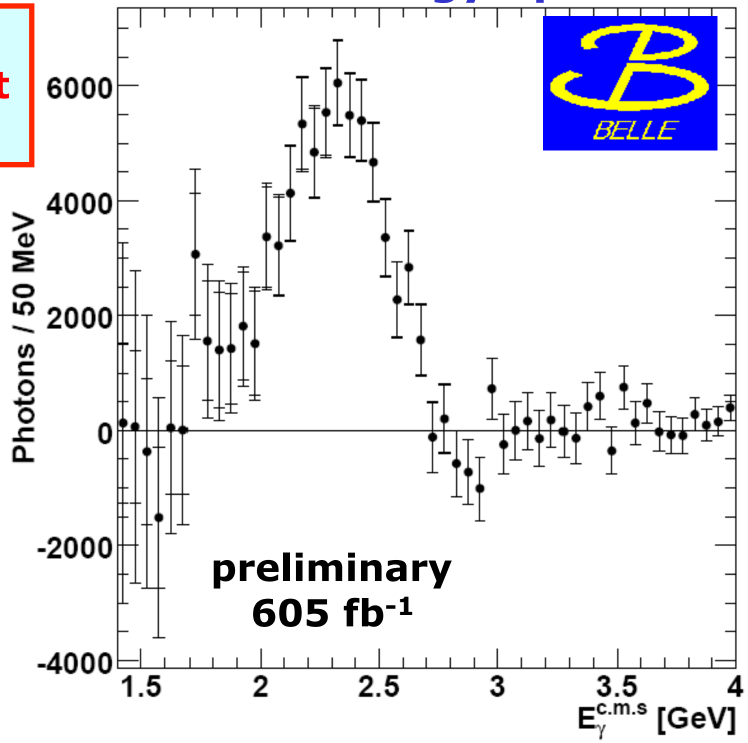
$$\mathcal{B}(B \rightarrow X_s\gamma) = (3.45 \pm \underset{\text{(stat)}}{0.15} \pm \underset{\text{(syst)}}{0.40}) \times 10^{-4}$$

1st and 2nd energy moments:

$$\langle E_\gamma \rangle = 2.282 \pm \underset{\text{(stat)}}{0.015} \pm \underset{\text{(syst)}}{0.051} \text{ GeV}$$

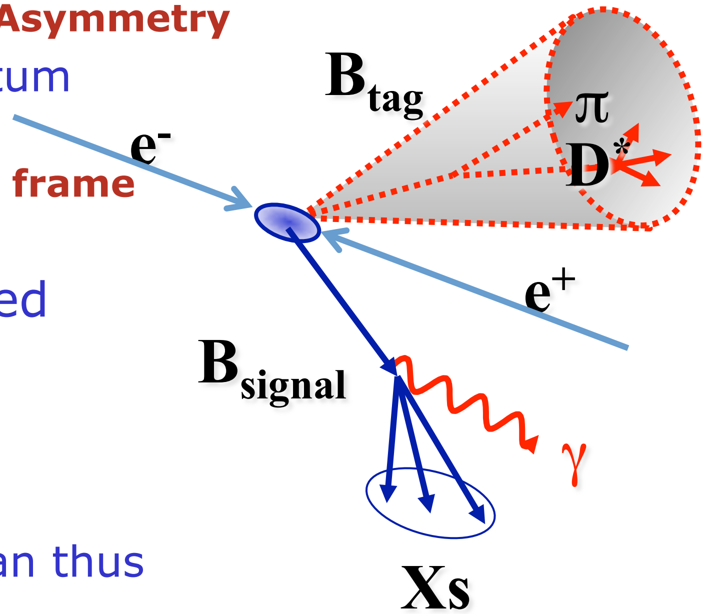
$$\langle E_\gamma^2 \rangle - \langle E\gamma \rangle^2 = 0.0428 \pm \underset{\text{(stat)}}{0.0047} \pm \underset{\text{(syst)}}{0.0202} \text{ GeV}^2$$

Photon Energy Spectrum



Hadron-tagged inclusive $B \rightarrow X_s\gamma$ from BaBar

- Hadronic decay of one B meson is fully reconstructed
  - 4-momentum, charge and flavour determined
    - **Enables measurement of Isospin and CP Asymmetry**
  - With 4-momentum of Υ(4S), also 4-momentum of decaying B is known
    - **Photon energy can be measured in B rest frame**



- Signal and BB background yields determined from fit to M_{ES} in bins of photon energy

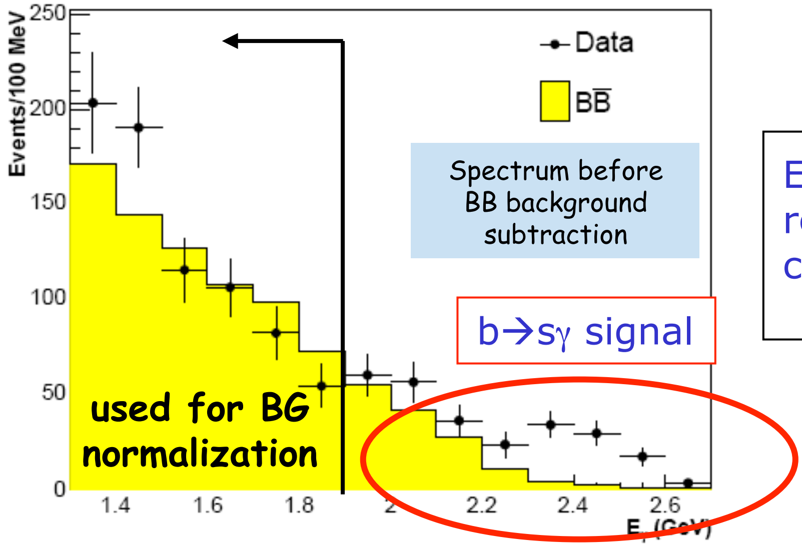
$$m_{ES} = \sqrt{(E^*_{beam})^2 - P^2_{B_{reco}}}$$

  - Continuum events do not peak in M_{ES} and can thus be subtracted
  - Normalization for branching fraction is determined from number of Bs in full reconstruction sample
  - Small efficiency extrapolation

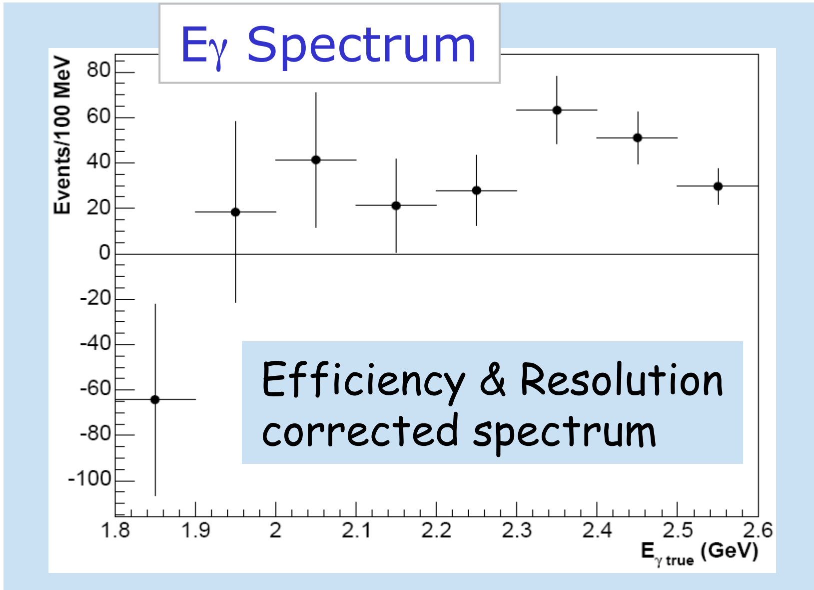
- Disadvantage: small B reconstruction efficiency of ~0.3%

Hadron-tagged inclusive $B \rightarrow X_s\gamma$ results

uses only ½ BaBar data sample



Efficiency, resolution corrections



BF Result:

$$B(B \rightarrow X_s\gamma; E_\gamma > 1.6 GeV) = (391 \pm 91 \pm 64 \pm 4) \times 10^{-6}$$

210 fb^{-1}

syst. error larger than expected

- Subsequent analyses (not $B \rightarrow X_s\gamma$) using hadronic tags have achieved smaller systematics
  - we expect improvement for $B \rightarrow X_s\gamma$ as well
- Babar currently working to update to full data set

$B \to X_s\gamma$ BF Results

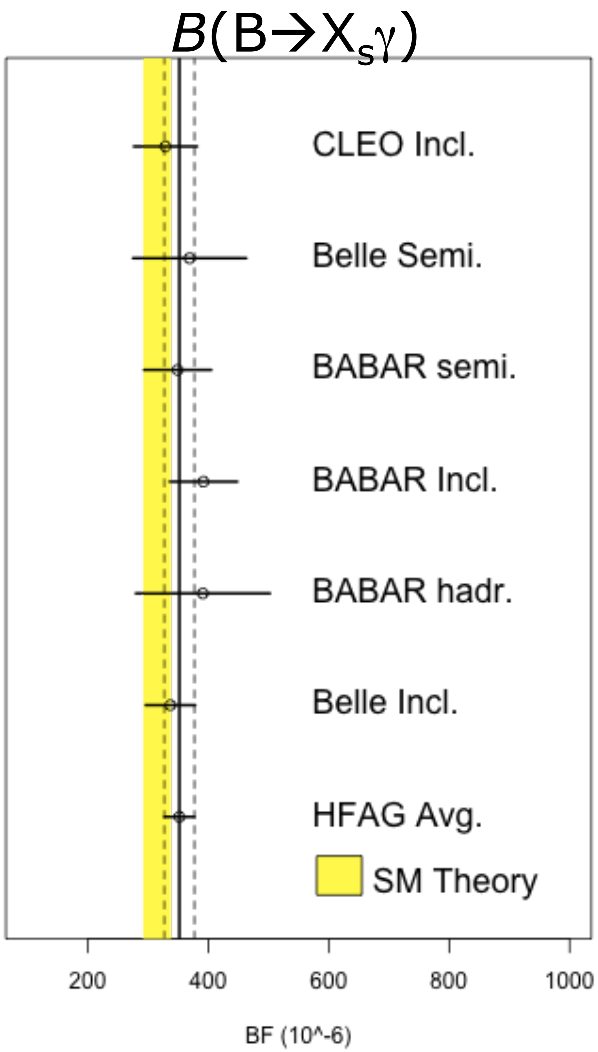
- Good agreement among experiments
- Good agreement with SM prediction

HFAG experimental average:

$$B(B \to X_s\gamma, E > 1.6GeV) = (3.55 \pm 0.24_{stat+syst} \pm 0.09_{shpFcn}) \times 10^{-4}$$

SM Theory (Misiak, et al):

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

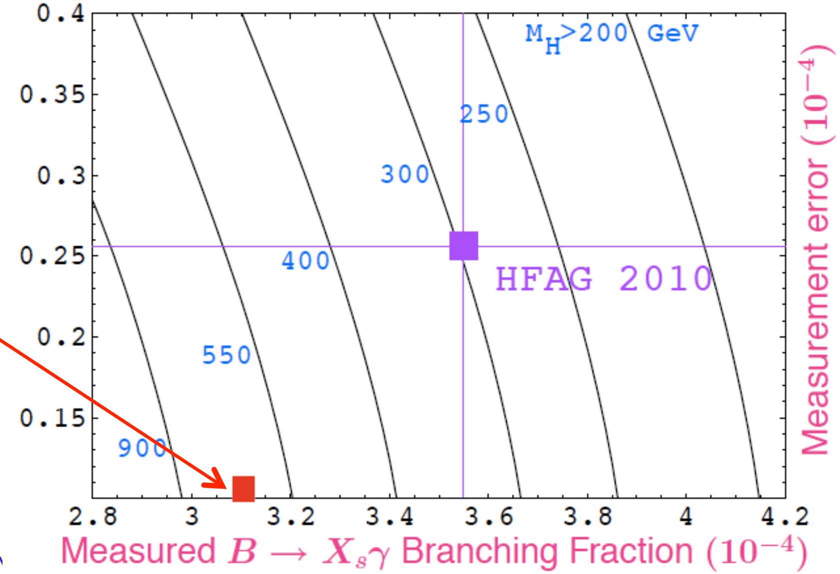


Expectations for SuperB: $\mathcal{B}(B \rightarrow X_s\gamma)$

- At SuperB, $\mathcal{B}(B \rightarrow X_s\gamma)$ will be completely systematics dominated
  - BaBar lepton tag sample: BF = ? ($\pm\, 5_{stat} \pm 9_{syst} \pm 3_{model}$)%, with SuperB lumi 200x greater
  - Recent estimate of syst. from current BaBar lepton tagged analysis (Wenfeng Wang) gives 3-4%
- Hadron- (and semileptonic-) tagged sample may reach similar systematic error, but this needs study
  - still be syst.-dominated (based on extrapolation from BaBar analysis)
- These methods will have mostly uncorrelated errors ➔ reduced overall BF uncertainty

New m_{H^+} limit if SM value is measured at SuperB (2HDM-II)

$$m_{H^+} > \simeq 650 \text{ GeV}$$



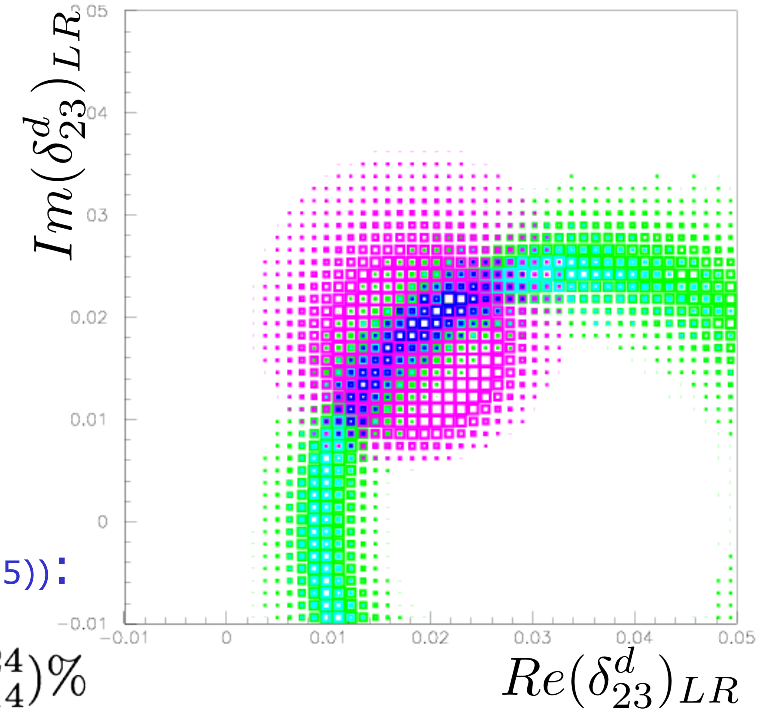
Direct CP Asymmetry – Promising for SuperB

- Large statistics leads to small stat uncertainty
- Many systematic uncertainties cancel
- Sensitivity to New Physics: SUSY, RH currents, etc.

$\mathcal{B}(B \to X_s \gamma)$

$\mathcal{B}(B \to X_s \ell^+ \ell^-)$

$\mathcal{A}_{CP}(B \to X_s \gamma)$



- SM (Hurth, et al (NPB 704,56 (2005)):

$$A_{CP}^{SM}(B \to X_s \gamma) = (0.44^{+0.24}_{-0.14})\%$$

  - Recent paper (Neubert, et al, PRL 106 (141801) 2011) finds significant long-range contribution to error ➔ $\sigma(A_{CP}^{SM}) \sim 5\%$

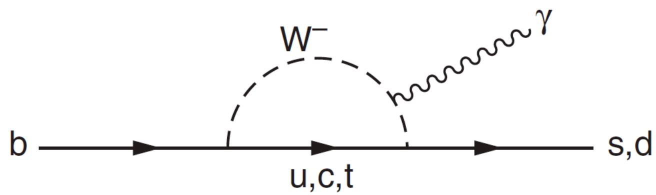
Know your asymmetry!

- Two different quantities measured experimentally

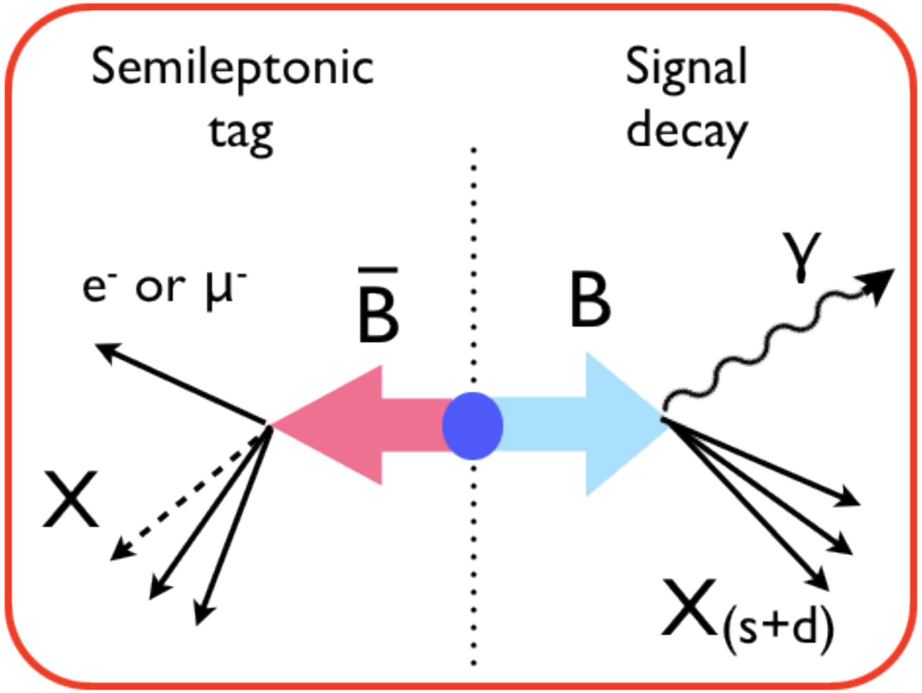
- $A_{CP}(B \rightarrow X_{(s+d)}\gamma)$: "untagged" asymmetry, from fully inclusive measurements, i.e. do not distinguish s/d
  - For BF, estimate and subtract $B \rightarrow X_d\gamma$ part
  - Not possible for A_{CP}, so we get $A_{CP}(B \rightarrow X_{(s+d)}\gamma)$

- $A_{CP}(B \rightarrow X_s\gamma)$: Existing measurements are NOT inclusive; sum-of-exclusive-states technique, includes ~50% of total inclusive rate
  - HFAG: $A_{CP}(B \to X_s\gamma) = (-1.2 \pm 2.8)\%$
  - Can we compare this to SM calculation? (I am told no.)
  - Can we measure $A_{CP}(B \rightarrow X_s\gamma)$ in an inclusive way?

$A_{CP}(B \rightarrow X_{(s+d)}\gamma)$ at BaBar



- Inclusive measurement:
  - no requirements on X_s
- High-energy photon: $E\gamma^*$>1.5 GeV
- Lepton tag: require electron or muon tag
  - semileptonic decay of "other" B
- BB background dominates
  - mostly π^0, $\eta \rightarrow \gamma\gamma$ that are explicitly vetoed
  - remaining BG estimated with MC + control sample



$A_{CP}(B \rightarrow X_{(s+d)}\gamma)$:

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

$A_{CP}(B \rightarrow X_{(s+d)}\gamma)$ at BaBar

- Control regions:
  - continuum: On-Off Peak Data = -100 ± 138 events
  - BB: 1252±272+841 ➔ 1.4σ (assumes not signal, where expect 100-400 signal events in low-energy tail)
- A_{CP} insensitive to photon energy cut: optimize ➔ (2.1–2.8) GeV
- Yields:
  - N(l+) = 2633 ± 158
  - N(l-) = 2397 ± 151
  - semileptonic decay of "other" B
- Account for mis-tag and bias:

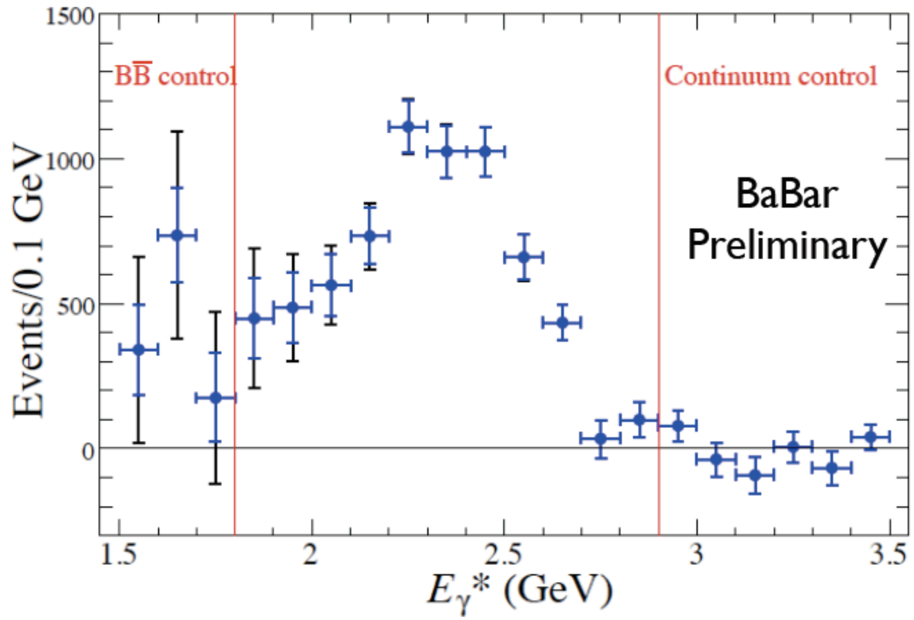
$$A_{CP} = \frac{A_{CP}^{\mathrm{meas}}}{1-2\omega} + \Delta A_{CP}$$

$$\omega = 0.131 \pm 0.0064$$

(B^0 mixing)

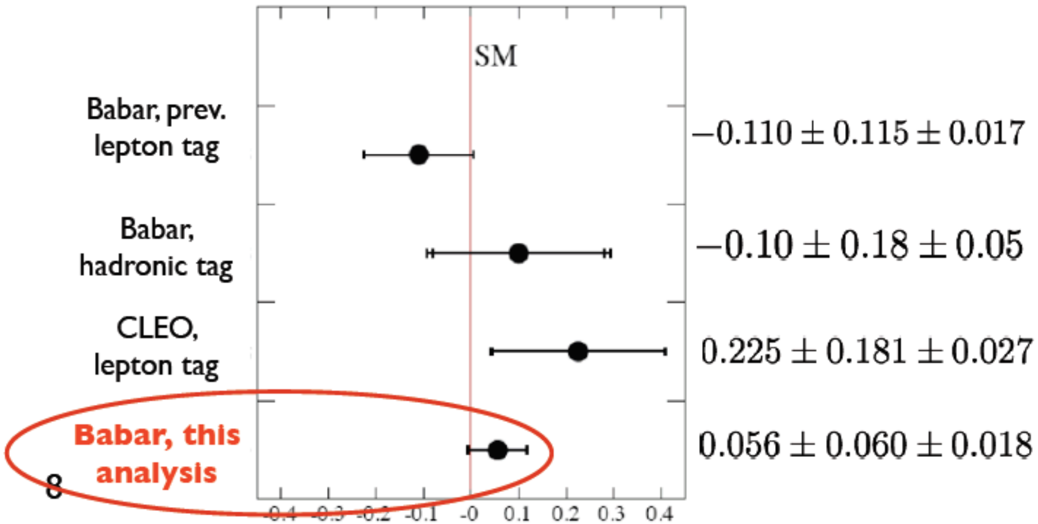
$$\Delta A_{CP} = -0.004 \pm 0.0013$$

(A_{CP} of background)



BaBar preliminary:

A_{CP} = 0.056 ± 0.060$_{stat}$ ± 0.018$_{syst}$



$A_{CP}(B \to X_s\gamma)$ at BaBar [PRL 101, 171804 (2008)]

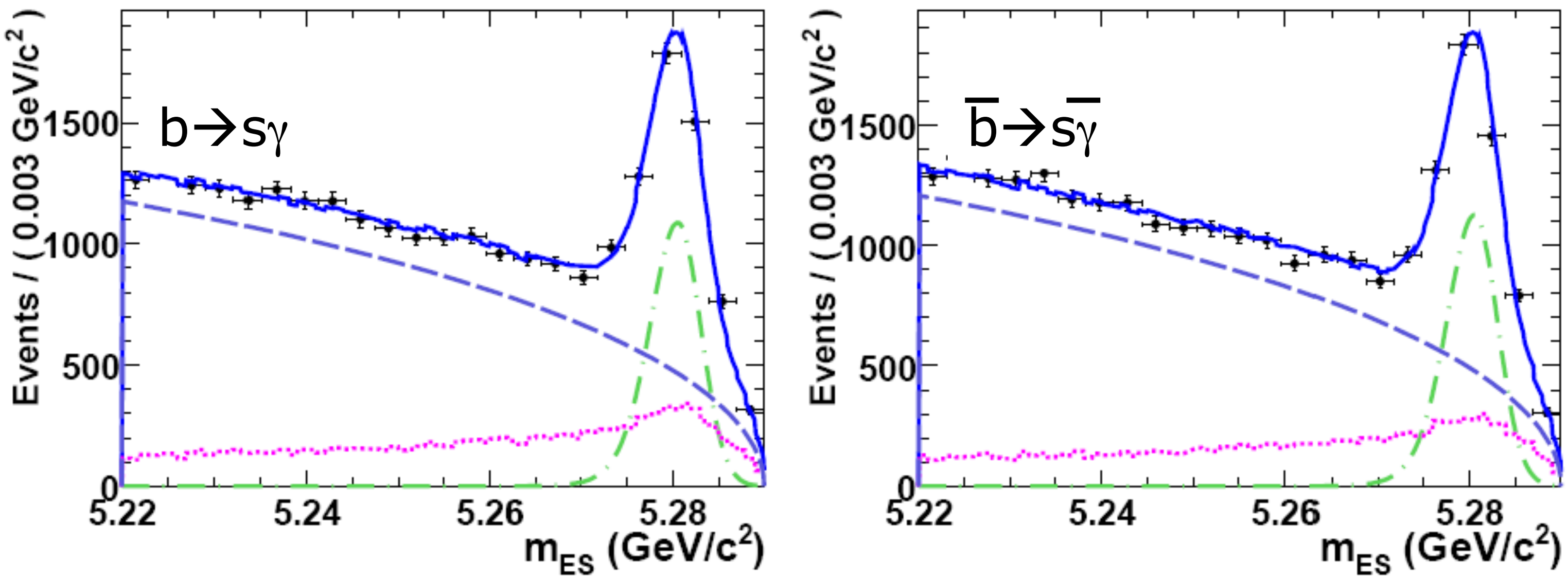
$$A_{CP} = \frac{B(b \to s\gamma) - B(\bar{b} \to \bar{s}\gamma)}{B(b \to s\gamma) + B(\bar{b} \to \bar{s}\gamma)}$$

- Sum of exclusive modes method
  - reconstruct $B \to X_s\gamma$ in 16 exclusive modes
  - **~50% of total rate**
- Extract yield from M_{ES} fit to signal region
- Control samples: sidebands and $B \to X_s\pi^0$ to evaluate:
  - inherent asymmetry in detector
  - uncertainties in background M_{ES} distributions

SM Calculation

$$A^{th}_{CP}(B \to X_s\gamma) = (0.44^{0.15}_{-0.10} \pm 0.03^{+0.19}_{0.09})\,\%$$

383 M $B\bar{B}$



Result: $A_{CP} = -0.011 \pm 0.030_{stat} \pm 0.014_{syst}$

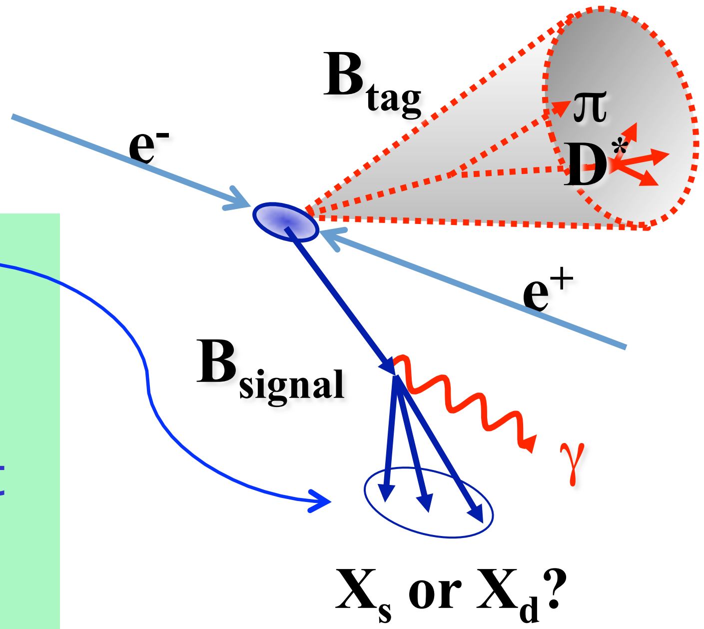
Expectations for SuperB: A_{CP}

- $A_{CP}(B \to X_{(s+d)}\gamma)$
  - Extrapolation from BaBar gives error of ~ $(\pm 1_{stat} \pm 1_{syst})\%$
  - SM prediction is very close to zero, but is significant A_{CP} predicted in NP models? Area for further study?

- $A_{CP}(B \to X_s\gamma)$
  - Semi-inclusive method (the only existing one currently) would yield total error of perhaps 1-1.5%, but is that useful (i.e. because it's not fully inclusive)?
  - Possibility to measure this inclusively using hadron-tagged method …

$A_{CP}(B \rightarrow X_s\gamma)$ with Hadronic Tags

- Potentially quite powerful because X_s (or X_d) system is fully isolated
- Possible to separate on event-by-event basis $B \rightarrow X_s\gamma$ from $B \rightarrow X_d\gamma$ decays (which has never been done inclusively)



- Truly inclusive measurements of:
  - $A_{CP}(B \rightarrow X_s\gamma)$ and $A_{CP}(B \rightarrow X_d\gamma)$
- Isospin asymmetry
- Neubert, et al. (PRL 106 (141801) 2011) although they find a larger-than-thought theoretical uncertainty on $A_{CP}(B \rightarrow X_s\gamma)$, they note an expected difference in A_{CP} for B^0 and B^+ decays
  - this joint CP/isospin asymmetry could be measured at SuperB using hadronic tags

Questions:

For theorists:

- E_{min} photon cut: motivations for reducing E_{min} at expense of experimental precision
- $A_{CP}(B \rightarrow X_s\gamma)$: how to use semi-inclusive result? Valid to compare to inclusive calculation?
- Is there general agreement on the finding of ~5% theoretical uncertainty on $A_{CP}(B \rightarrow X_s\gamma)$
- NP model predictions for $A_{CP}(B \rightarrow X_{(s+d)}\gamma)$?

For experimenters:

- Can hadron-tagged sample be used to separate $B \rightarrow X_s\gamma$ from $B \rightarrow X_d\gamma$?
- With what error can we measure $\mathcal{B}(B \rightarrow X_s\gamma)$ using hadronic tags? Semi-leptonic tags?

Conclusions

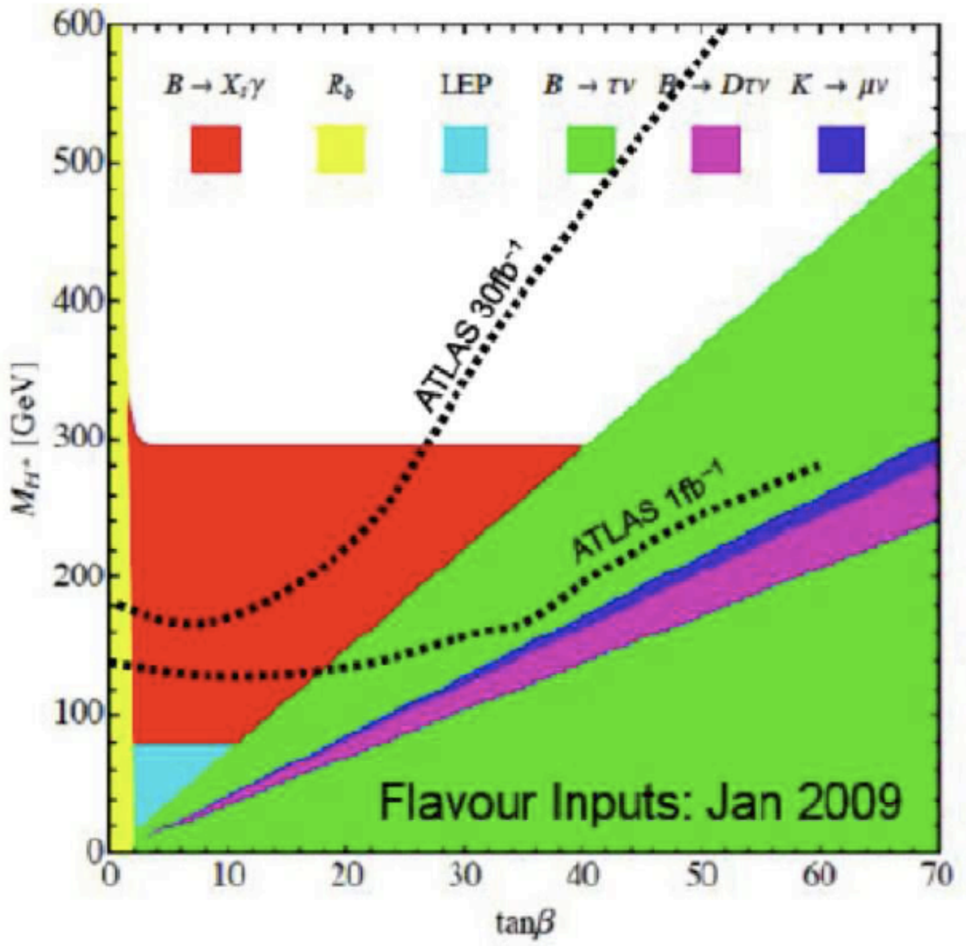
- $B \to X_s\gamma$ has been a key channel in searching for NP and constraining proposed models.
- It should continue to be a golden channel at SuperB.

- Currently $BF(B \to X_s\gamma)$ measured to about 7%, while theoretical error is around the same
- At SuperB this channel will be completely systematics-limited. Extrapolating from current B-factories, we can estimate that $BF(b \to s\gamma)$ will likely be measured with perhaps 3% experimental error
- Dedicated studies needed to confirm this estimate

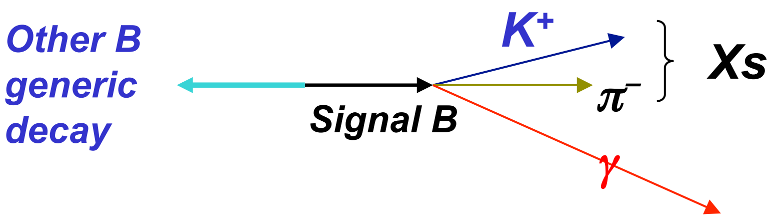
- Direct CP asymmetries have smaller systematic errors (maybe 1-2%?) and will give stringent tests at SuperB

backup slides

Latest Charged Higgs limit with ATLAS sensitivity



Semi-inclusive modes



- A Sum-of-Exclusive Modes Approach:
  - B->Xsγ
  - Fully reconstruct the signal B using 38 final decay modes.
  - M_{Xs} [0.6,2.8] GeV, Eγ [1.9, 2.6] GeV
  - E*γ>1.6 GeV
  - Flavor blind modes are not used for A_{CP} calculation

Final states of the X_s used in B reconstruction.

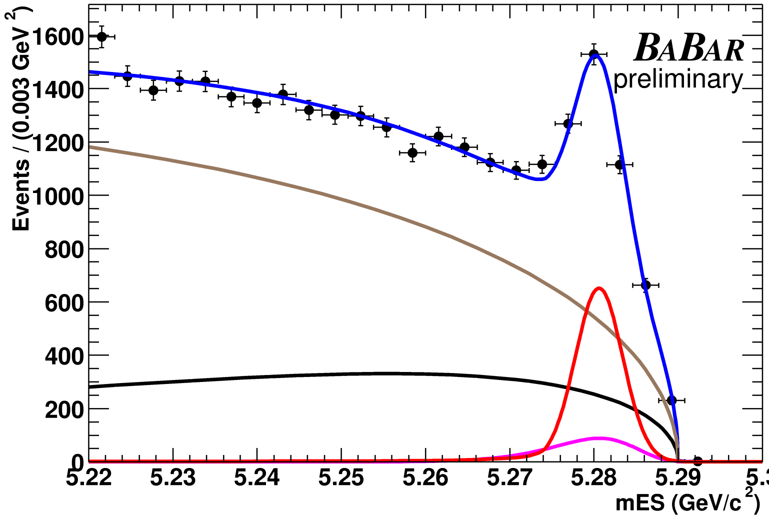
iType	Final State	iType	Final State
1	$K^0_s\pi^+$	20	$K^0_s\pi^+\pi^-\pi^+\pi^-$
2	$K^+\pi^0$	21	$K^0_s\pi^+\pi^-\pi^0$
3	$K^+\pi^-$	22	$K^0_s\pi^+\pi^-\pi^0\pi^0$
4	$K^0_s\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24	$K^0_s\eta$
6	$K^0_s\pi^+\pi^0$	25	$K^0_s\eta\pi^+$
7	$K^+\pi^0\pi^0$	26	$K^+\eta\pi^0$
8	$K^0_s\pi^+\pi^-$	27	$K^+\eta\pi^-$
9	$K^+\pi^-\pi^0$	28	$K^0_s\eta\pi^0$
10	$K^0_s\pi^0\pi^0$	29	$K^+\eta\pi^+\pi^-$
11	$K^0_s\pi^+\pi^-\pi^+$	30	$K^0_s\eta\pi^+\pi^0$
12	$K^+\pi^+\pi^-\pi^0$	31	$K^0_s\eta\pi^+\pi^-$
13	$K^0_s\pi^+\pi^0\pi^0$	32	$K^+\eta\pi^-\pi^0$
14	$K^+\pi^+\pi^-\pi^-$	33	$K^+K^-K^+$
15	$K^0_s\pi^0\pi^+\pi^-$	34	$K^+K^-K^0_s$
16	$K^+\pi^-\pi^0\pi^0$	35	$K^+K^-K^0_s\pi^+$
17	$K^+\pi^+\pi^-\pi^+\pi^-$	36	$K^+K^-K^+\pi^0$
18	$K^0_s\pi^+\pi^-\pi^+\pi^0$	37	$K^+K^-K^+\pi^-$
19	$K^+\pi^+\pi^-\pi^0\pi^0$	38	$K^+K^-K^0_s\pi^0$

Semi-inclusive: Fit to B mass, photon spectrum

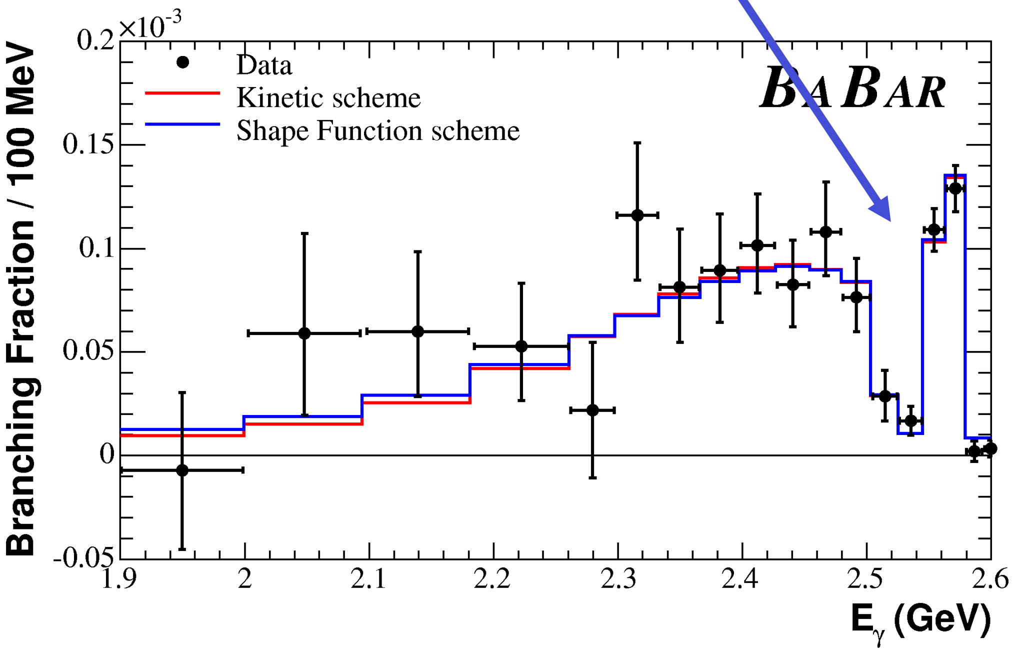
- Usual B decay kinematic variables to extract signal: ΔE and m_{ES}
- Very good photon energy resolution: note the $K^*\gamma$ peak

90 million $B\underline{B}$ pairs

Energy-substituted Mass



Photon Energy Spectrum

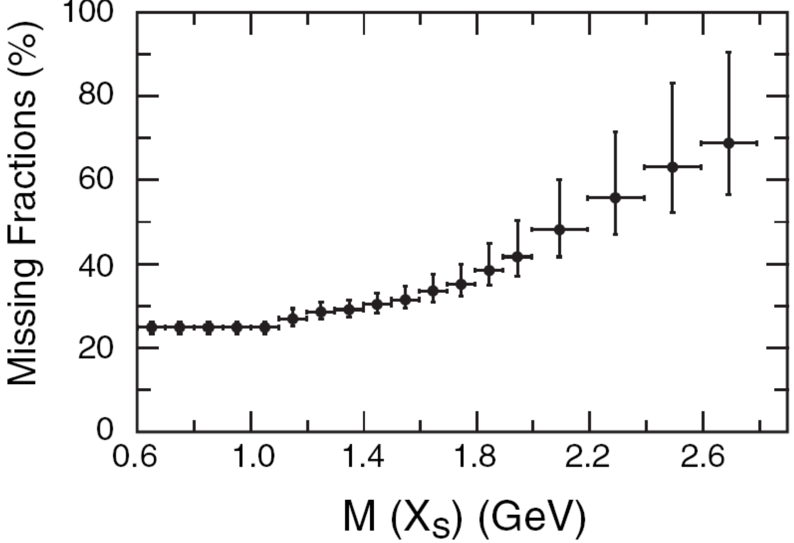


$$E_\gamma = \frac{M_B^2 - M(X_s)^2}{2M_B}.$$

Semi-inclusive: Systematics

The main difficulty with the semi-inclusive approach is accounting for the missing modes

Missing fraction as function of M(Xs)

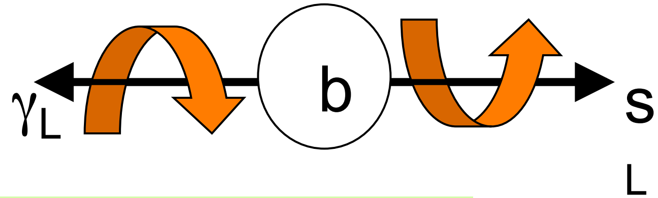


$$E_\gamma = \frac{M_B^2 - M(X_s)^2}{2M_B}.$$

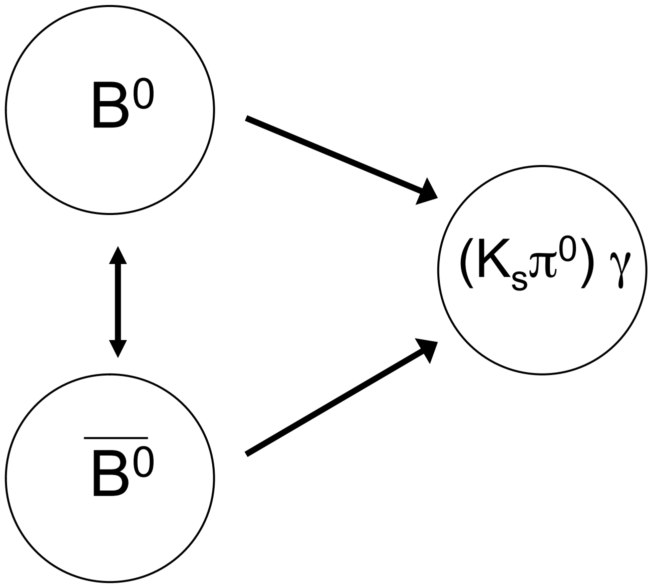
Check MC fragmentation on reconstructed modes: not very good agreement

Final states	Data/Monte Carlo
$K^-\pi^+$, $K_S^0\pi^-$	0.50 ± 0.07
$K^-\pi^0$, $K_S^0\pi^0$	0.19 ± 0.12
$K^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$	1.02 ± 0.14
$K^-\pi^+\pi^0$, $K_S^0\pi^-\pi^0$	1.34 ± 0.24
$K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-\pi^-$	2.67 ± 0.96
$K^-\pi^+\pi^-\pi^0$, $K_S^0\pi^+\pi^-\pi^0$	1.29 ± 0.61
$K^-\pi^0\pi^0$, $K_S^0\pi^0\pi^0$ $K^-\pi^+\pi^0\pi^0$, $K_S^0\pi^-\pi^0\pi^0$	1.89 ± 1.33
$K^-\pi^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-\pi^+\pi^-$ $K^-\pi^+\pi^-\pi^+\pi^0$, $K_S^0\pi^+\pi^-\pi^-\pi^0$ $K^-\pi^+\pi^-\pi^0\pi^0$, $K_S^0\pi^+\pi^-\pi^0\pi^0$	$1.32^{+1.55}_{-1.32}$
$K^-\eta$, $K_S^0\eta$, $K^-\eta\pi^+$ $K_S^0\eta\pi^-$, $K^-\eta\pi^0$, $K_S^0\eta\pi^0$ $K^-\eta\pi^+\pi^-$, $K_S^0\eta\pi^+\pi^-$ $K^-\eta\pi^+\pi^0$, $K_S^0\eta\pi^-\pi^0$	$0.83^{+1.00}_{-0.83}$
$K^-K^+K^-$, $K^-K^+K_S^0$ $K^-K^+K^-\pi^+$, $K^-K^+K_S^0\pi^-$ $K^-K^+K^-\pi^0$, $K^-K^+K_S^0\pi^0$	$0.27^{+0.54}_{-0.27}$

Time-dependent CP Violation in $B^0 \to K_S\pi^0\gamma$



- Standard model makes definite prediction of photon helicity
- $\underline{B} \to X_s\, \gamma_L$ and $B \to X_s\, \gamma_R$
  - D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. **79**, 185 (1997).
- If a helicity flip occurs, the photon will also flip its helicity, and one could find $B \to X_s\, \gamma_L$.
  - Rate $\sim m_s/m_b$



- Can produce interference between CP violation in B^0 mixing and decay for final states accessible to B^0 and $\underline{B}^0$
- Measure this through time-dependent CP violation (TDCPV)
- In SM: $\mathbf{S_{K^*\gamma} \sim 0.02}$
  - Atwood (ibid); P. Ball and R. Zwicky, Phys. Lett. B **642**, 478 (2006).
- Up to $\sim$ 0.1 with possible QCD corrections
  - B. Grinstein, Y. Grossman, Z. Ligeti and D. Pirjol, Phys. Rev. D **71**, 011504 (2005).
  - B. Grinstein and D. Pirjol, Phys. Rev. D **73**, 014013 (2006).

431 M BB

Time-dependent CPV in $B^0 \to K^*(K_S\pi^0)\gamma$

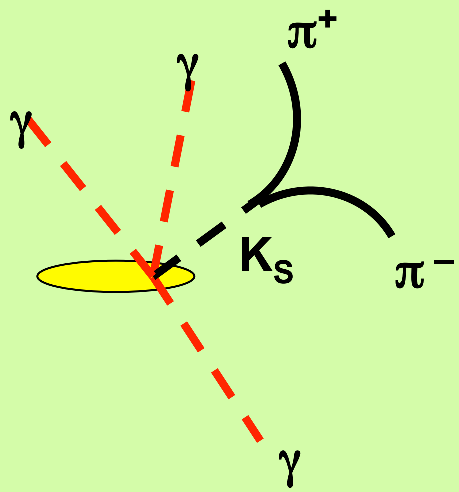
arXiv: 0708.1614 [hep-ex]

- Measure the proper time difference Δt in decays of neutral B mesons produced from $\Upsilon(4S) \to B^0\bar{B}^0$.
- The distribution of Δt follows

$$\mathcal{P}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times [1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)]$$

- The **S** parameter essentially measures the right-polarized to left-polarized photon ratio. **Large S ➔ New Physics**

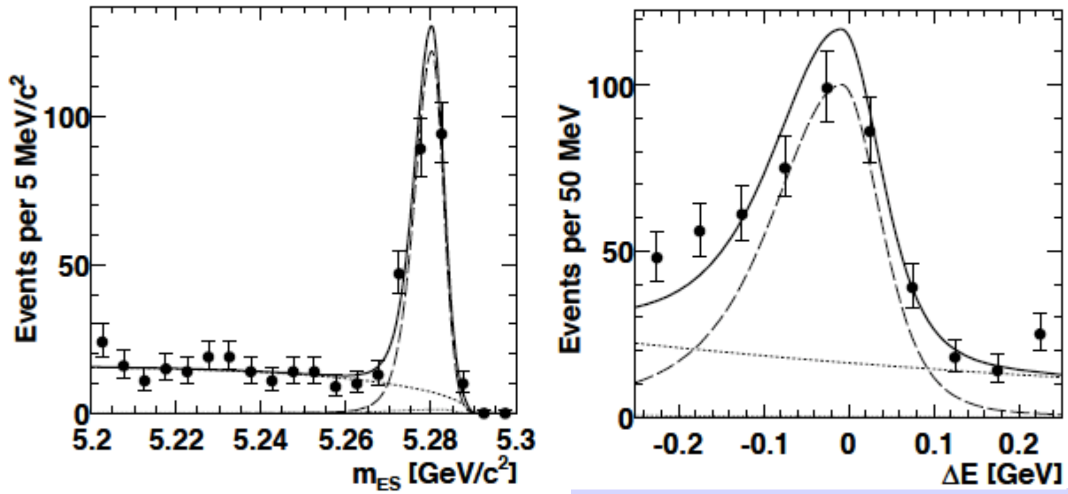
- A challenging aspect for $B^0 \to K^*(K_s\pi^0)\gamma$ decays is finding the signal B decay vertex.
- Constrain the K_s momentum to intersect with the beam spot (within errors).
- Also require the lifetime sum of both B^0's in the event to be $2\tau_B$.



TDCPV in $B^0 \rightarrow K^*(K_S\pi^0)\gamma$: Results

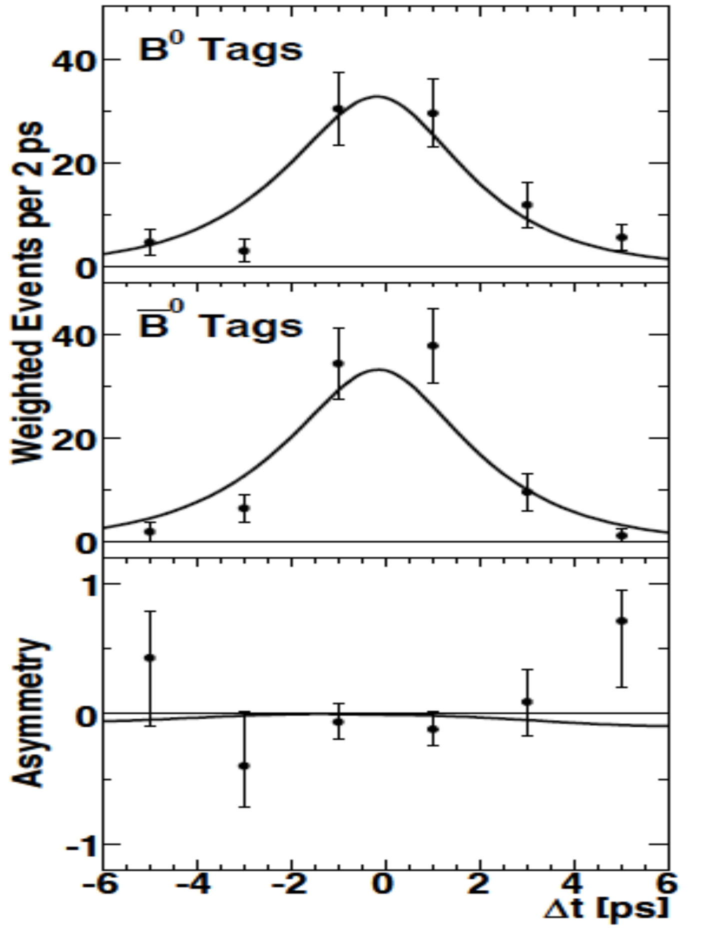
arXiv: 0708.1614 [hep-ex]

m_{ES} and ΔE - kinematics



467 M BB (full Babar data set)

Proper Time Distribution



- 339 ± 24 signal events
- S = −0.03 ± 0.29 ± 0.03
- C = −0.14 ± 0.16 ± 0.03

Note the small systematics, will do well at SuperB.

Inclusive, hadronic tags: Systematics

- Expected low systematics due to fully reconstructed hadronic tags, however:
  - 12% (of BF) due to extraction of yields from mES fits
  - 10% due to B$\underline{B}$ background modeling
- Other BABAR analyses have achieved lower systematics with hadronic tags ⇒ can be improved for SuperB

Global mES fits in two purity bins

<u>Challenge</u>: model these low-energy tails correctly