Experimental Aspects of $B \rightarrow X_s\gamma$

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Motivation

- Search for New Physics
  - branching fraction
  - CP asymmetry
  - isospin asymmetry
- Measure b-quark mass and other HQE parameters
  - helpful in reducing systematic errors on Vub

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):

$$B(B \to X_s \gamma, E > 1.6 GeV) = (3.55 \pm 0.26) \times 10^{-4}$$

  - Theory:

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

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

Inclusive vs. Exclusive Measurements

- **Theory**: inclusive processes are easier to calculate.
  - Larger uncertainties occur for calculations of exclusive modes.
- **Experiment**: in many cases, including $b \rightarrow s\gamma$, inclusive measurements are more difficult.
  - fewer kinematic handles to suppress backgrounds
  - in some cases, rest from of B meson not determined
- Lots of work going on in both inclusive and exclusive decays, both theoretically and experimentally
- This talk: inclusive $b \rightarrow s\gamma$ measurements

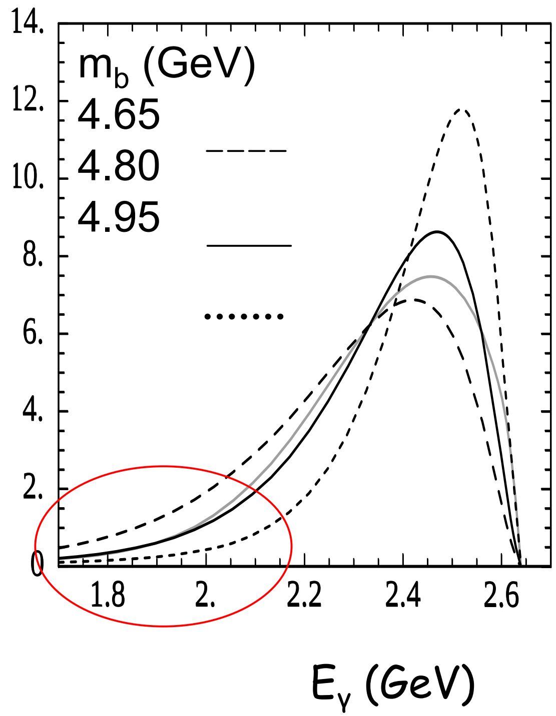
Inclusive measurements

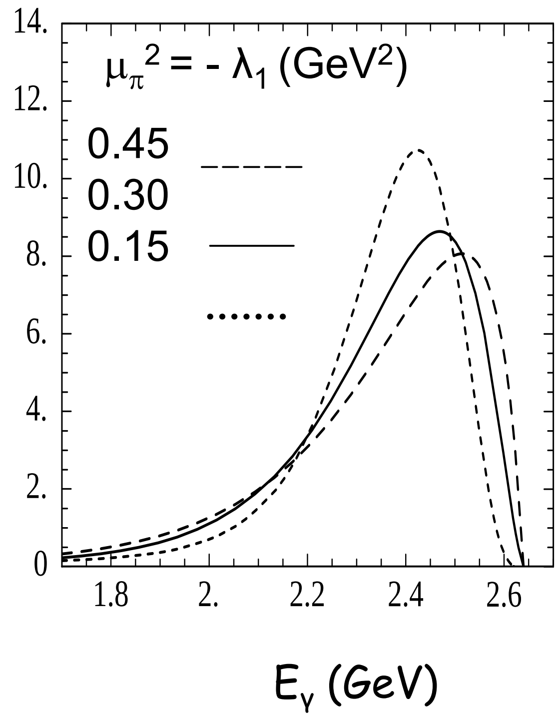
- Ideally, you'd like to make a fully inclusive measurement
  1. no requirement on the X_s hadronic system
  2. no cut on photon energy
- X_s hadronic system
  - "fully inclusive" makes no requirement, but tags other B in event
  - "semi inclusive" reconstructs as many exclusive decay modes as possible. 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

"Traditionally" theorists have requested going to lowest possible photon energy

- E_{min} = 1.9 GeV is now pretty much "standard"
- Can we do better?
- Do we need to?





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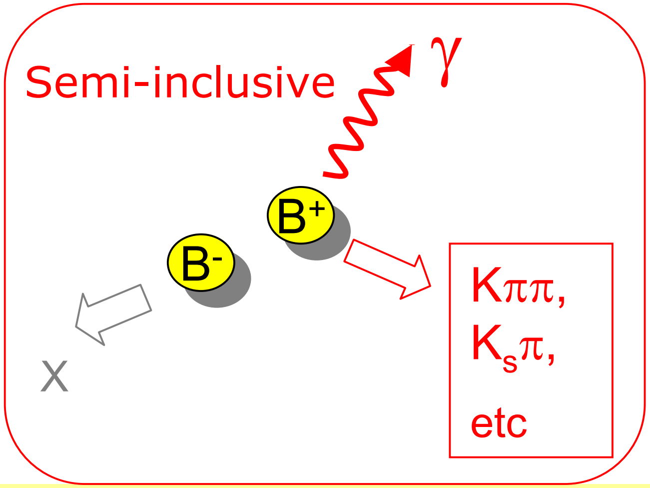
Experimental Approaches: semi-inclusive

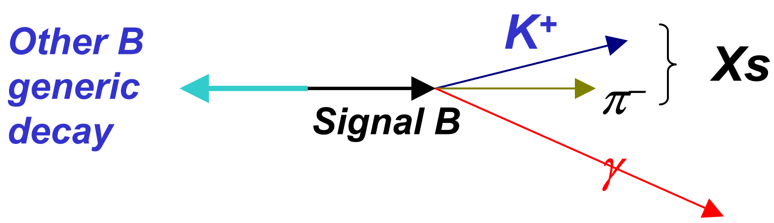


- Sum up many (up to 30 or so) individual modes
- Rely on simulation to estimate the missing fraction

- Advantages:
  - good background rejection
  - photon energy measured in B rest frame (matches with theoretical calculations)
  - good photon resolution through measurement of hadronic mass
  - charge and flavor of B parent known → asymmetries

- Disadvantages:
  - only about half of rate is actually measured
  - Monte Carlo does not do a great job of simulating X_s fragmention
  - missing modes fraction is even greater at higher mass (low photon energy)
  - BF is systematics limited

Semi-inclusive modes



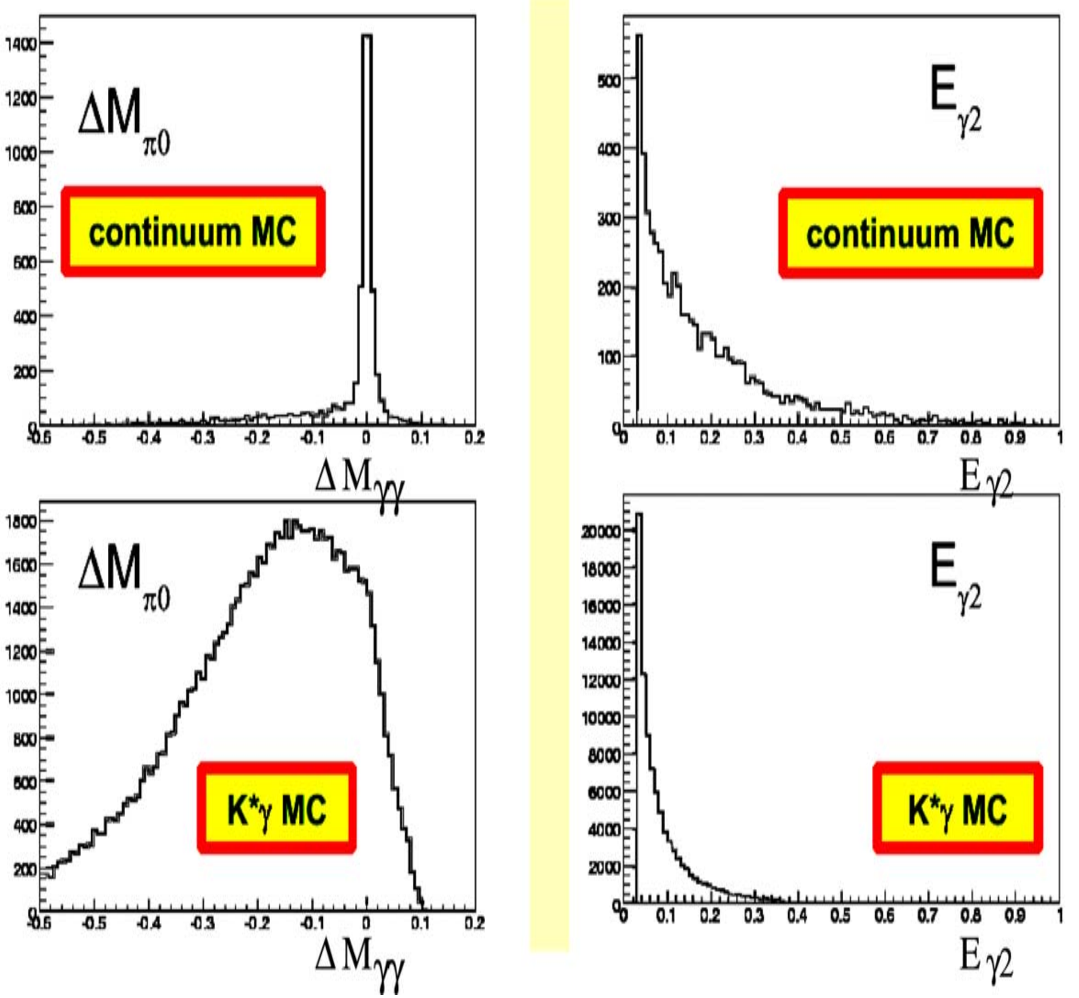
- A Sum-of-Exclusive Modes Approach:
  - B->Xsγ
  - Fully reconstruct the signal B using 38 final decay modes.
  - M_{Xs} [0.6,2.8] GeV, Eγ [1.9, 2.6] GeV
  - E*γ>1.6 GeV
  - Flavor blind modes are not used for A_{CP} calculation

Final states of the X_s used in B reconstruction.

[illegible]e	Final State	Type	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	$K^+K^-K^0_S\pi^0$

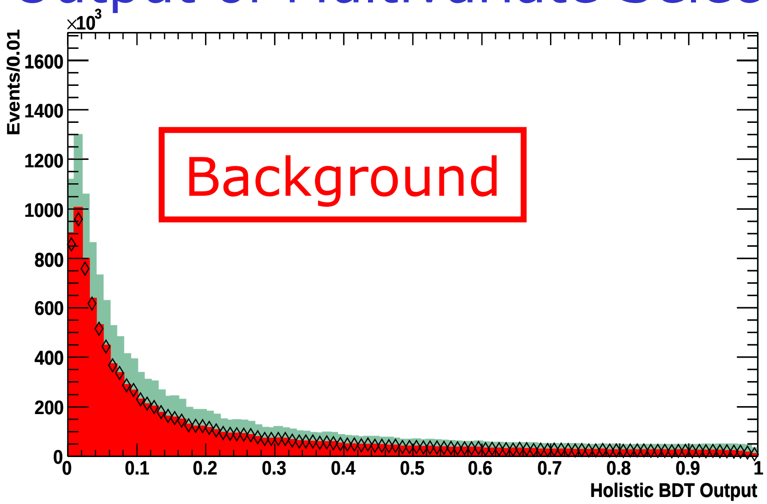
Semi-inclusive: BB background suppression

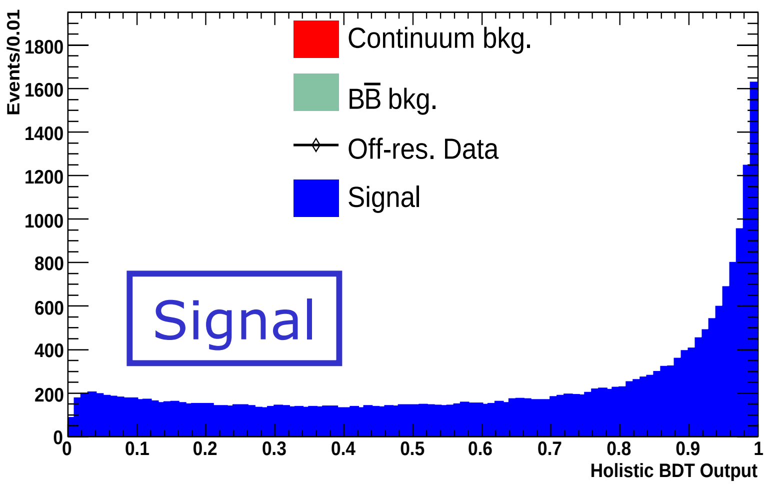
- About 70% of high-energy photons in BB background events come from π^0 and η decay
- Construct veto by pairing high-energy photon with all other photon candidates in event. $\gamma\gamma$ invariant mass and energy of second photon are discriminating variables



Semi-inclusive: Continuum background suppression

Output of Multivariate Selector





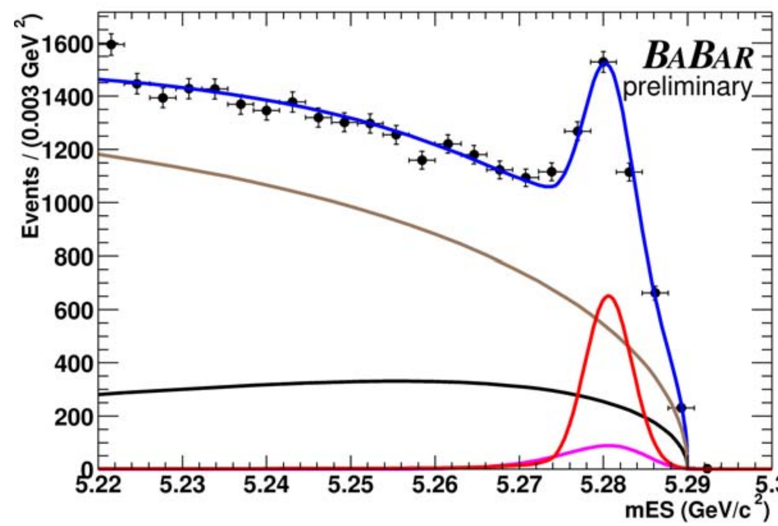
- Event shape variables exploited to reduce continuum background
  - jettier than signal (and BB) events
- Boosted DecisionTree (BDT) to combine the information of 17 ROE variables
  - 7 Event shape variables, 2 B kinematic variables and 8 flavor tagging variables

Semi-inclusive: Fit to B mass, photon spectrum

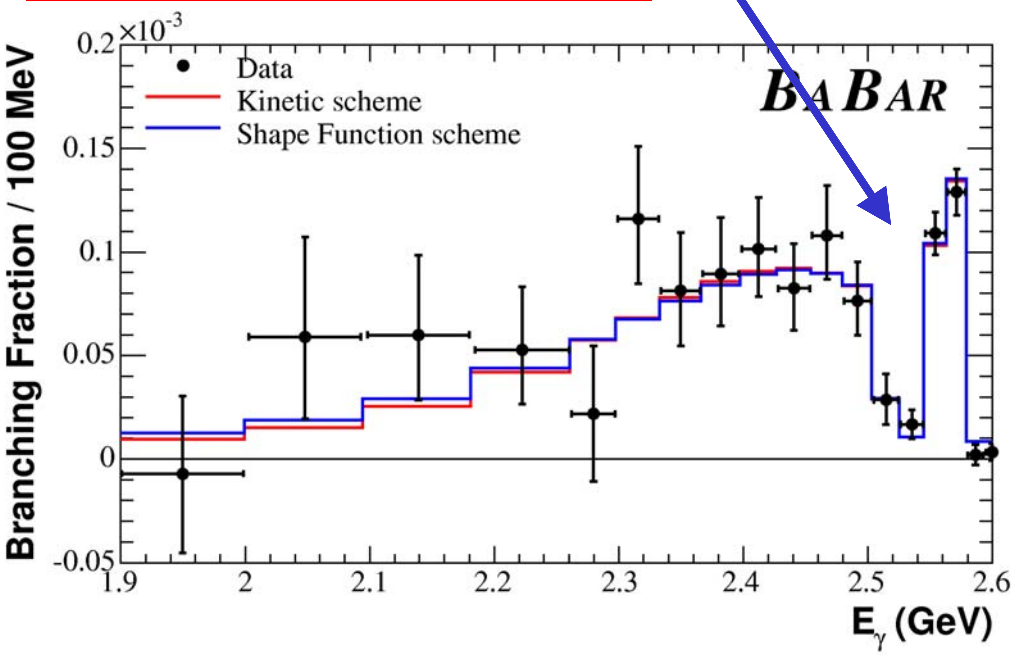
- Usual B decay kinematic variables to extract signal: ΔE and m_{ES}
- Very good photon energy resolution: note the $K^*\gamma$ peak

90 million B$\underline{\text{B}}$ pairs

Energy-substituted Mass



Photon Energy Spectrum



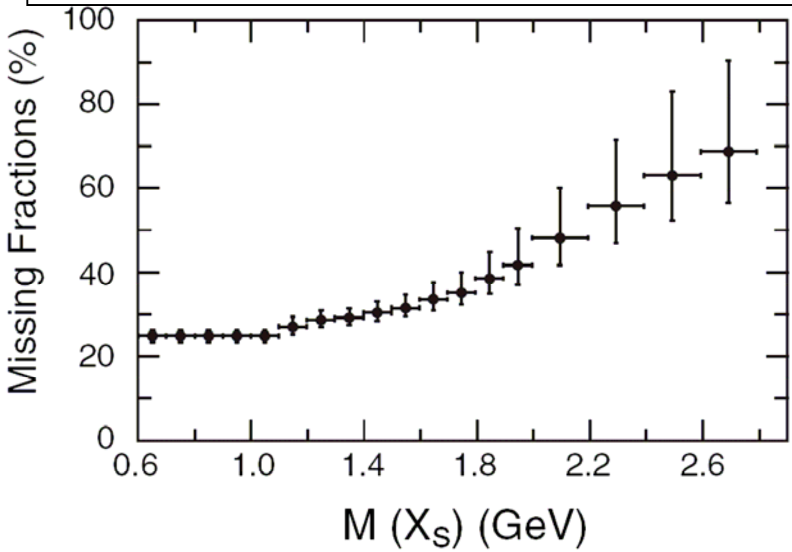
$$E_\gamma = \frac{M_B^2 - M(X_s)^2}{2M_B}.$$

Semi-inclusive: Systematics

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

Check MC fragmentation on reconstructed modes: not very good agreement

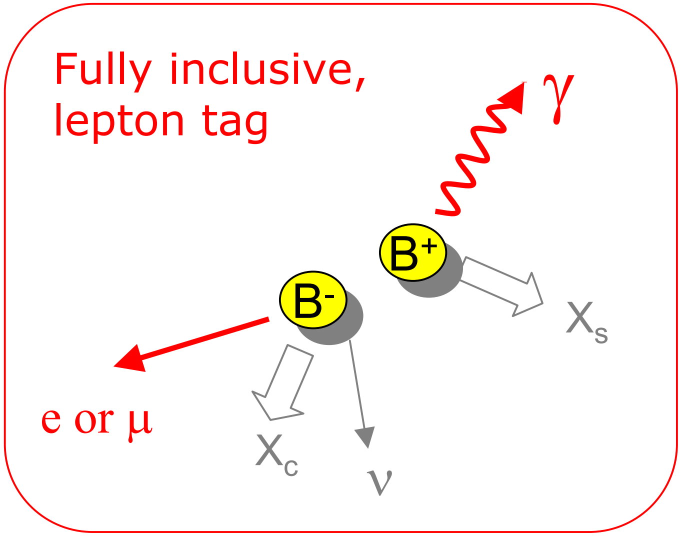
Missing fraction as function of M(Xs)



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

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
$K^-\pi^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-\pi^+\pi^-$ $K^-\pi^+\pi^-\pi^+\pi^0$, $K_S^0\pi^+\pi^-\pi^-\pi^0$ $K^-\pi^+\pi^-\pi^0\pi^0$, $K_S^0\pi^+\pi^-\pi^0\pi^0$	$1.32^{+1.55}_{-1.32}$
$K^-\eta$, $K_S^0\eta$, $K^-\eta\pi^+$ $K_S^0\eta\pi^-$, $K^-\eta\pi^0$, $K_S^0\eta\pi^0$ $K^-\eta\pi^+\pi^-$, $K_S^0\eta\pi^+\pi^-$ $K^-\eta\pi^+\pi^0$, $K_S^0\eta\pi^-\pi^0$	$0.83^{+1.00}_{-0.83}$
$K^-K^+K^-$, $K^-K^+K_S^0$ $K^-K^+K^-\pi^+$, $K^-K^+K_S^0\pi^-$ $K^-K^+K^-\pi^0$, $K^-K^+K_S^0\pi^0$	$0.27^{+0.54}_{-0.27}$

Experimental Approaches: fully inclusive with lepton tag



- Inclusive selection of high-energy photons
- Lepton tag on other side reduces continuum background
- Careful studies on data + MC for B$\underline{\text{B}}$ background

- Advantages:
  - more inclusive → no assumptions on Xs fragmentation
  - higher statistics
  - potential to provide best BF measurement at B-factories

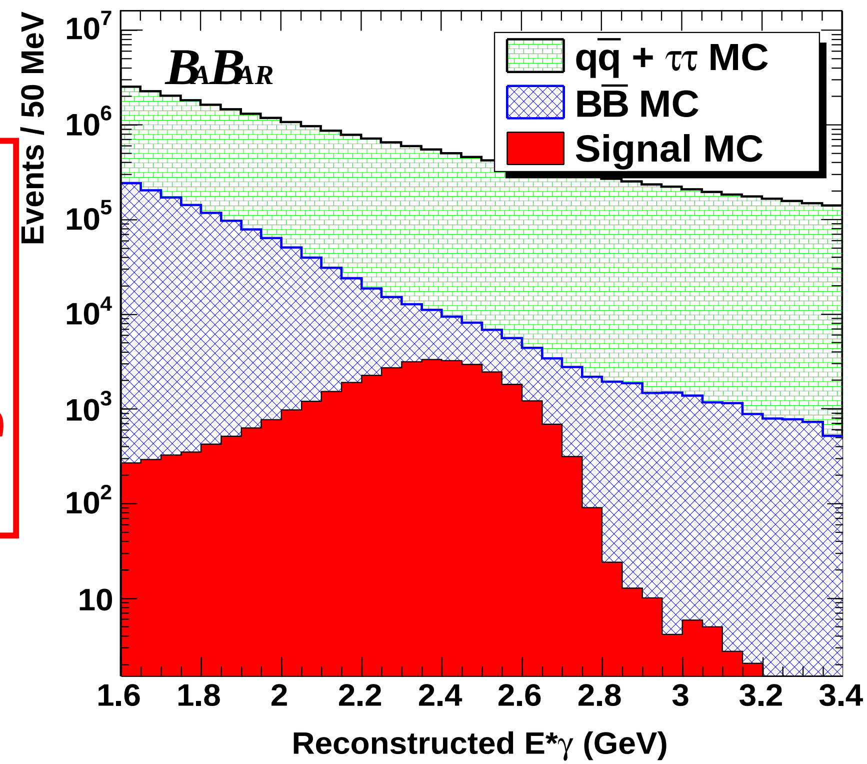
- Disadvantages:
  - photon energy measured in Y(4S) rest frame
  - calorimeter resolution for photon energy
  - many sources of B$\underline{\text{B}}$ background need to be estimated
  - b→dg not detected: CP asymmetry is b→(s/d)g

Inclusive: very large backgrounds

- Very large background to inclusive high-energy photons
  - mostly from π^0 and η decays
  - initial state radiation in $q\bar{q}$ events
- Lepton tag on other side achieves large reduction in continuum background
- Use also missing energy to select semi-leptonic B decays
- Event shape variables also exploited using multivariate techniques

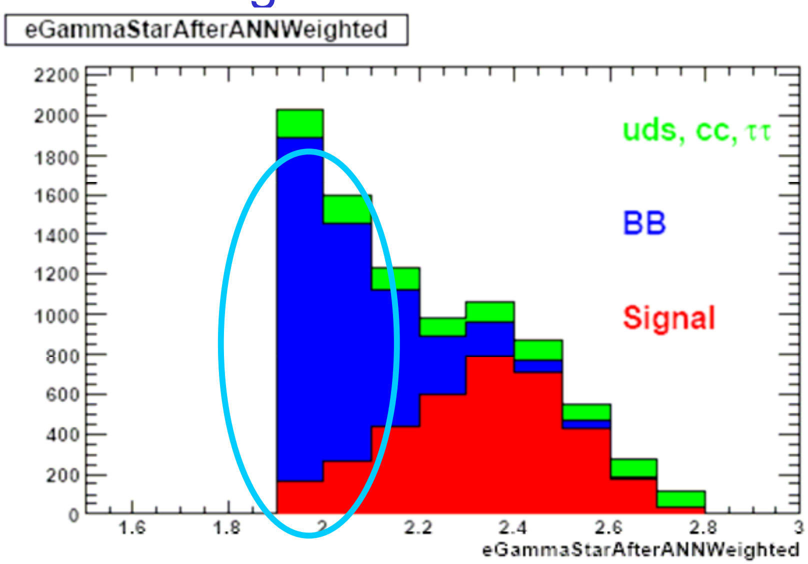
Inclusive Photons
$E\gamma > 1.6$ GeV

Log scale →

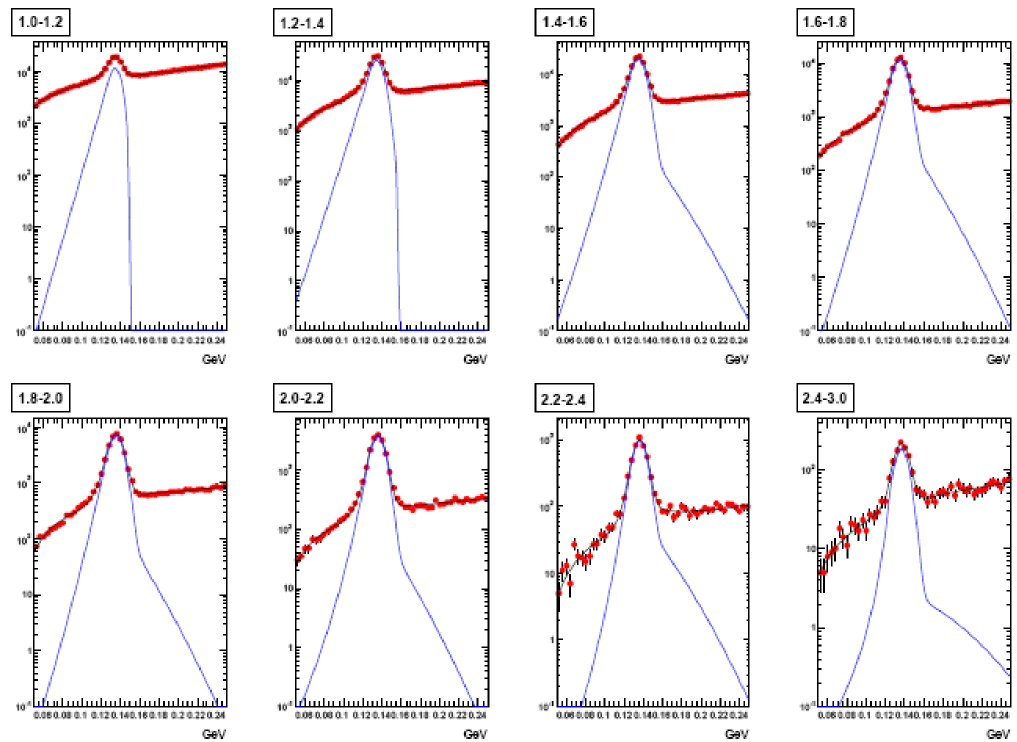


Inclusive, lepton tag: after selection

- BB background reduced with π^0 and η veto
- Still significant background remains at low $E\gamma$
- Study inclusive π^0 and η production to tune MC of BB background



$\gamma\gamma$ invariant mass in bins of π^0 energy

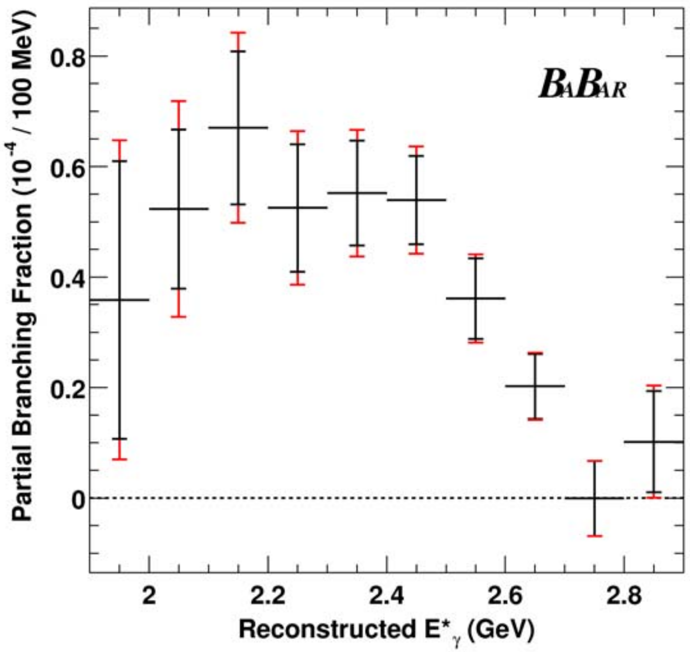


Fits to data and MC

Inclusive, lepton tag: Photon Spectrum

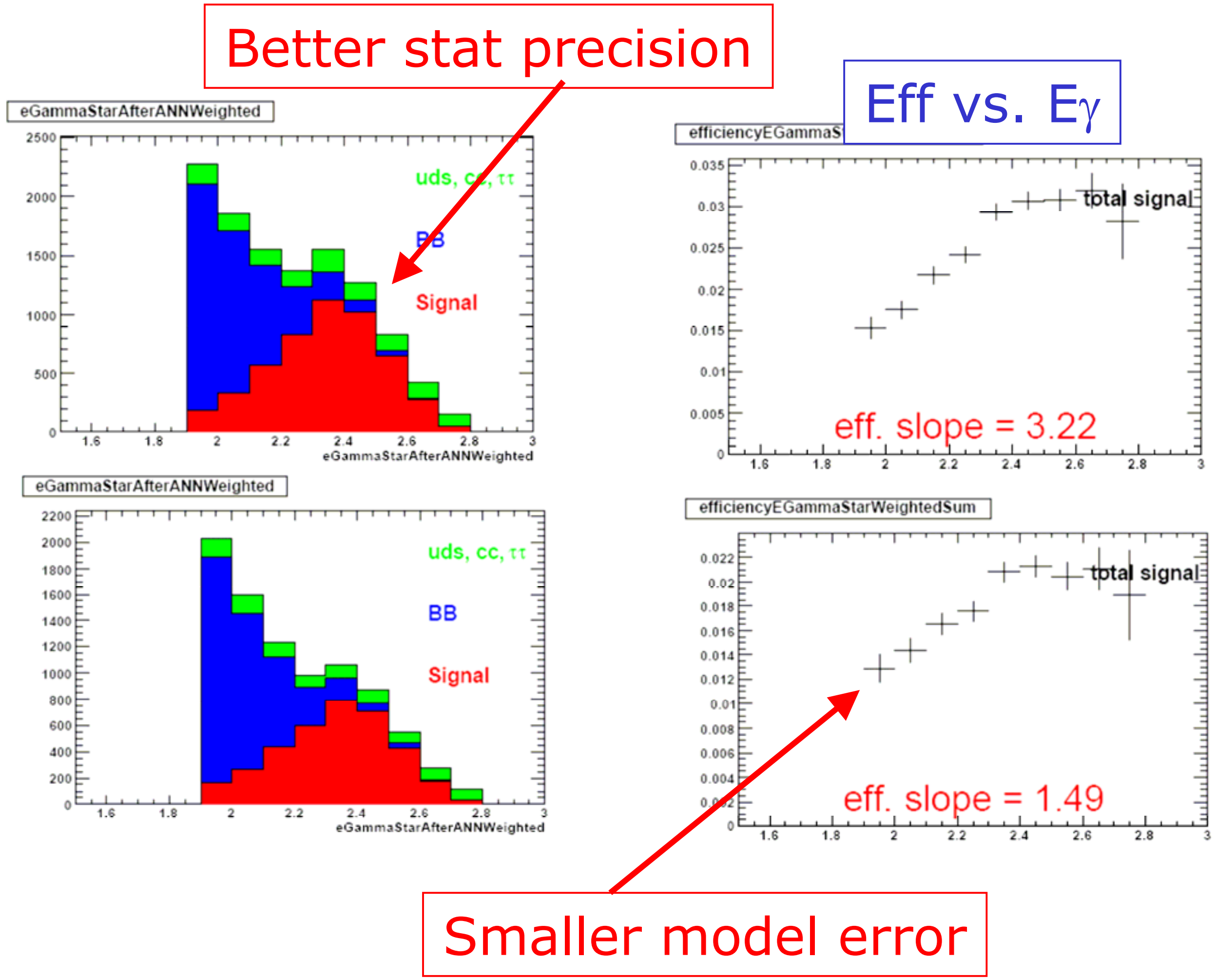
90 million BB pairs

- Note worse resolution compared to semi-inclusive
- Large error bars on lowest energy bin 1.9-2.0 GeV

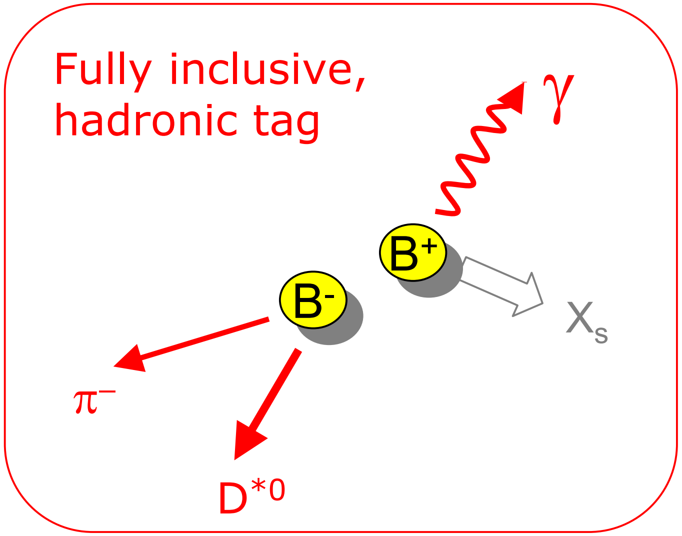


Inclusive, lepton tag: Systematics/Model Uncertainties

- Energy-dependent efficiency → large extrapolation errors
- BB background subtraction



Experimental Approaches: fully inclusive with hadronic tag



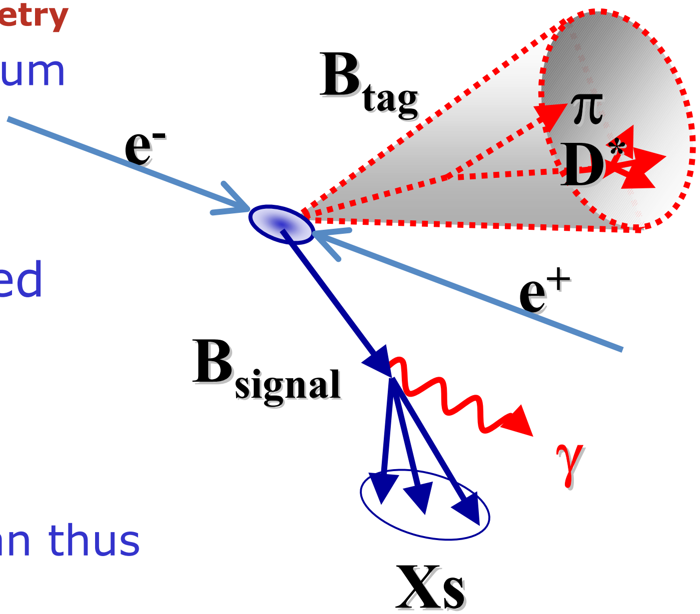
- Start with a fully-reconstructed hadronic B decay
- Search for high-energy photon in rest of event
- Fits to m_{ES} spectrum of hadronic B yields photon spectrum

- Advantages:
  - more inclusive → no assumptions on Xs fragmentation
  - photon energy in B rest frame
  - charge of parent B known → isospin asymmetry

- Disadvantages:
  - low efficiency for hadronic reconstruction

Inclusive, hadronic tag: A New Approach

- 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 Y(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

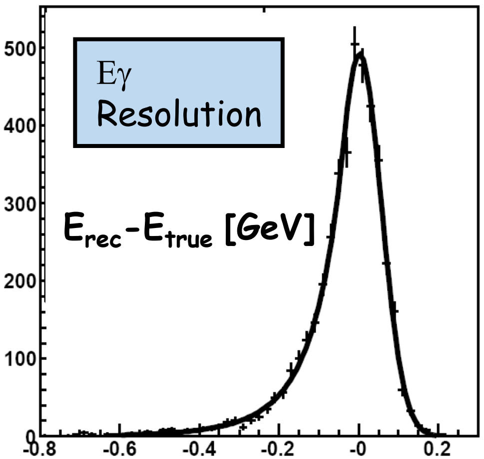
$$m_{ES} = \sqrt{(E^*_{beam})^2 - P^2_{B_{reco}}}$$

  - 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

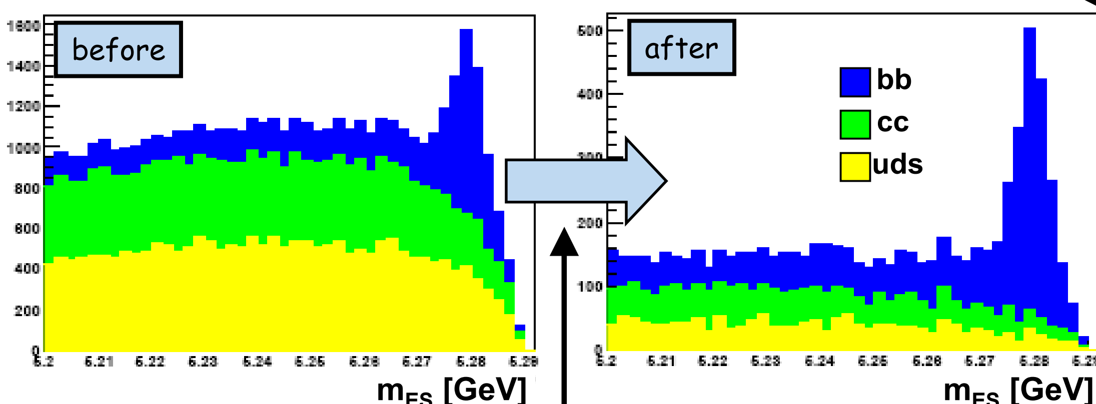
- Disadvantage: small B reconstruction efficiency of ~0.3%

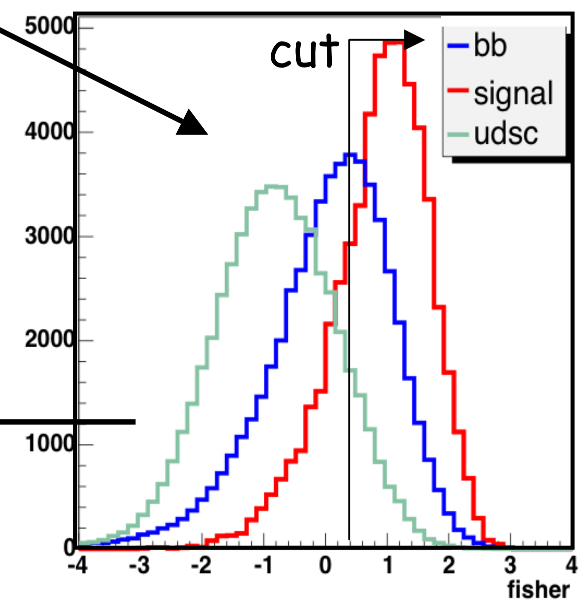
Inclusive, hadronic tag: Event Selection

- B_{reco} sample: well-measured $B \rightarrow D^{(*)}X$ decays
  (X: relevant combinations of $\pi^{\pm}, \pi^0, K^{\pm}, K_S^0$ with $|\Sigma q|=1$)
- Select well-reconstructed high-energy photons
  (E_{γ}>1.3GeV in the B_{signal} rest frame)
- Veto photons compatible with π^0, η, ρ decays
- Suppress continuum using Fisher discriminant
  (12 inputs, mostly based on event shape)



m_{ES} distribution (from MC simulation)





- Selection optimized to maximize $S^2/(S+B)$
- Remaining background mainly from π^0 and η

Inclusive, hadronic tags: m_{ES} Fits

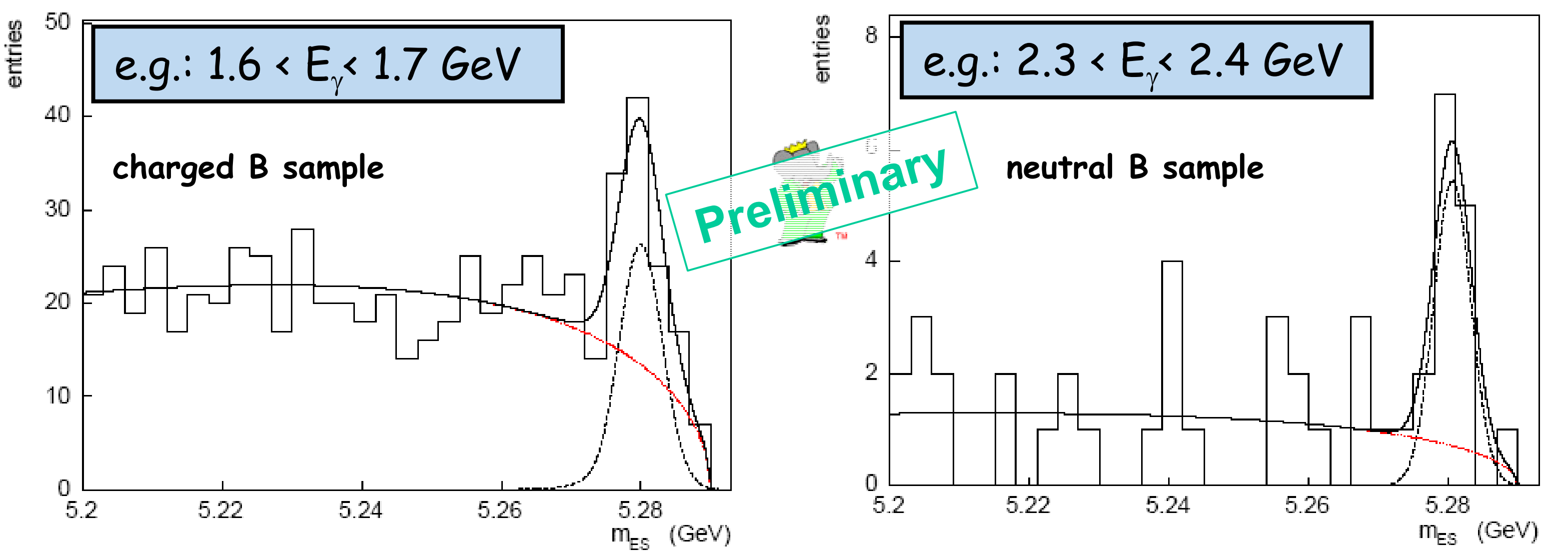
- Determine Partial Branching Fraction in bins of photon energy:

$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma} = \frac{N_i^{Data} - N_i^{BG}}{\varepsilon_i^{sig} \cdot c^{\mathrm{tag}} \cdot N^{B_{reco}}}$$

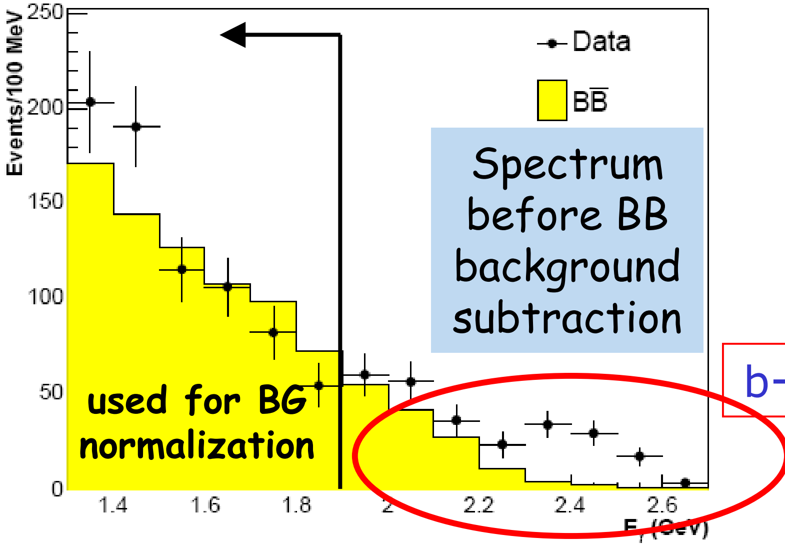
Selection efficiency, also correcting for resolution

Correction factor accounting for $B \to X_s\gamma$ final state affecting the probability to find a tag B.

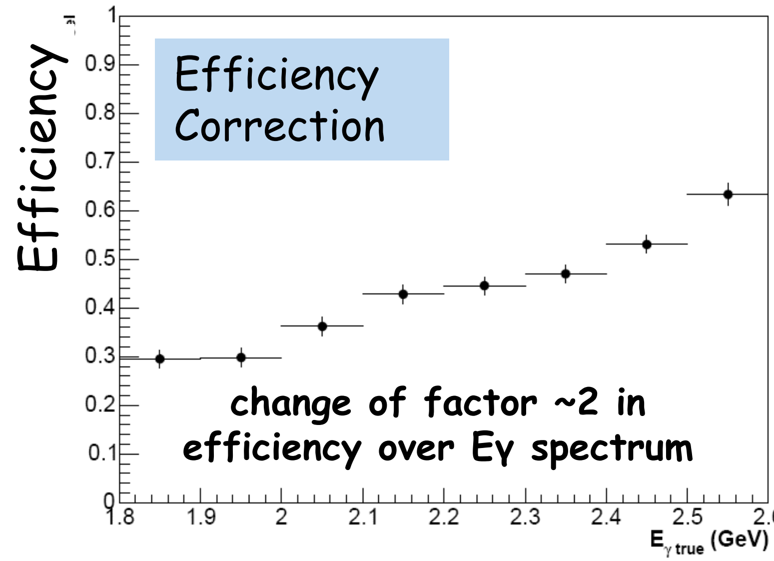
- All numbers determined from fits to m_{ES}

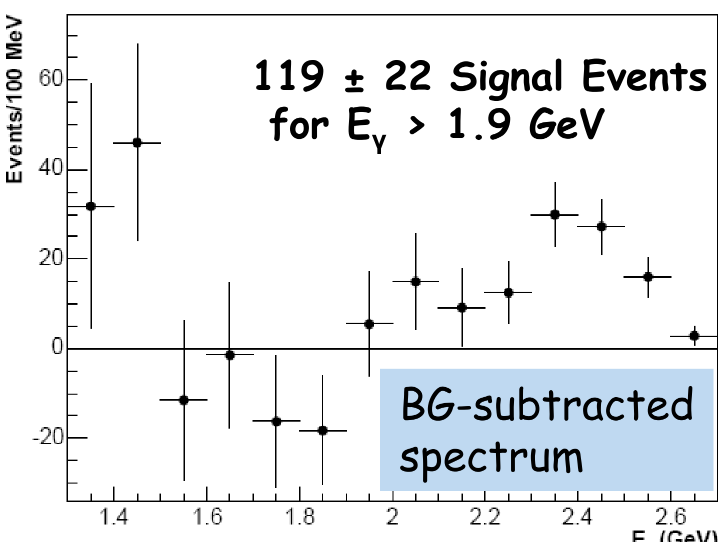


Inclusive, hadronic tags: E_γ Spectrum



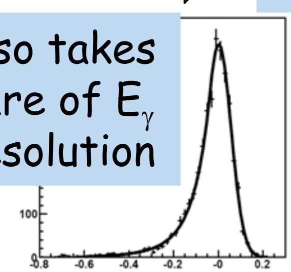
b→sγ signal

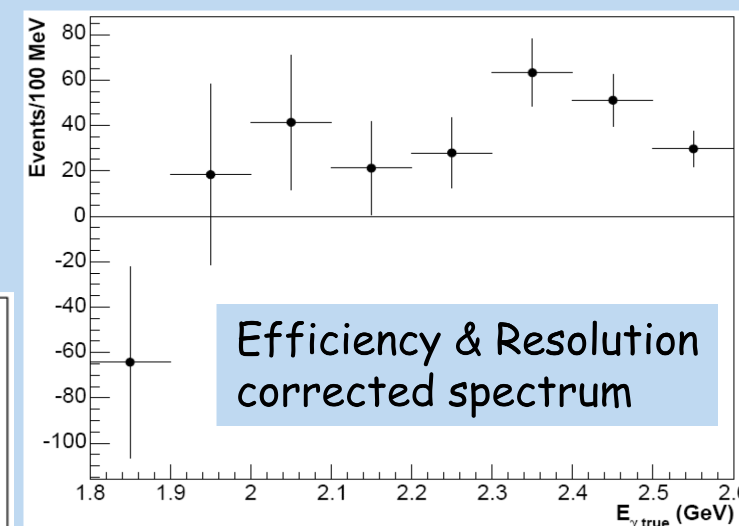




efficiency correction

also takes care of E_γ resolution

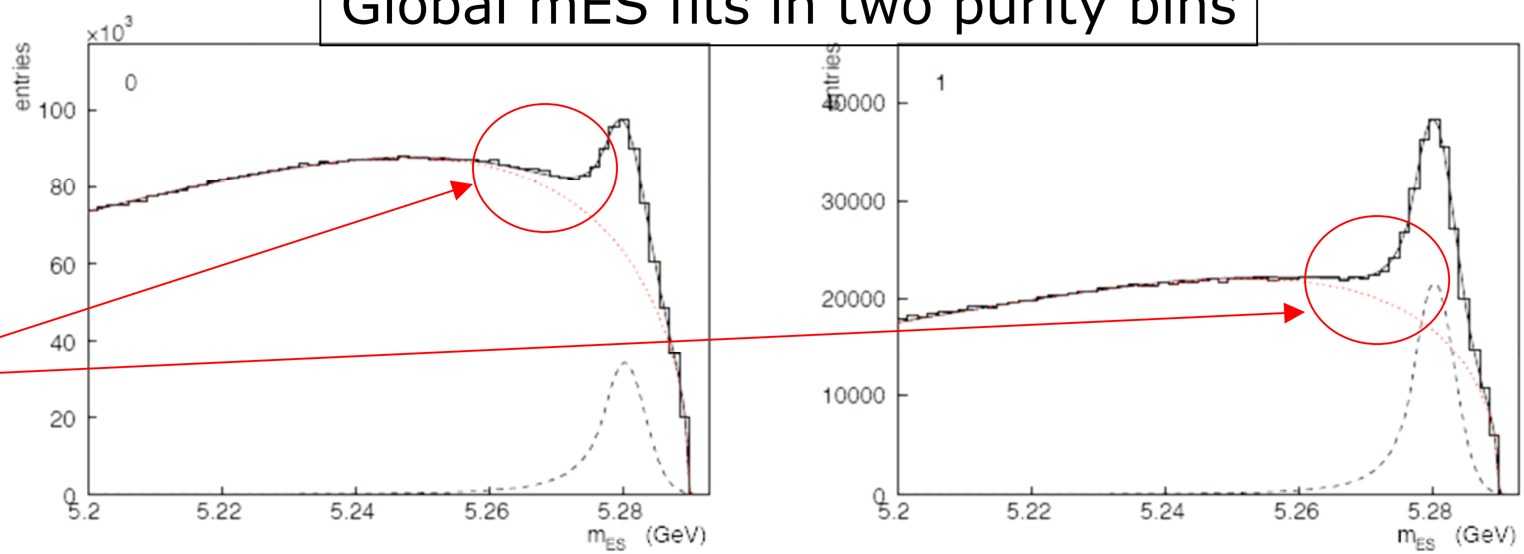




Inclusive, hadronic tags: Systematics

- Expected low systematics due to fully reconstructed hadronic tags, however:
  - 12% (of BF) due to extraction of yields from mES fits
  - 10% due to $B\bar{B}$ background modeling

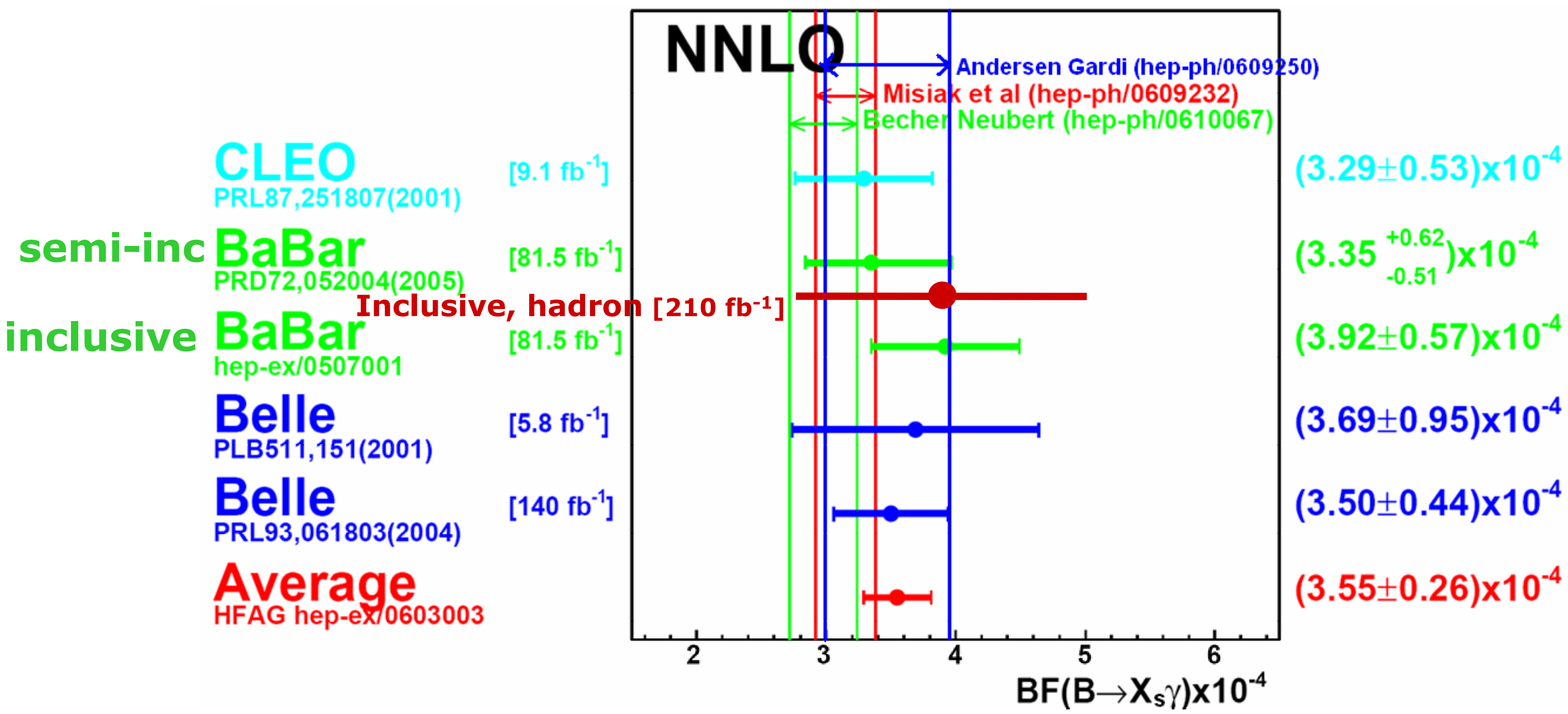
Global mES fits in two purity bins



Challenge: model these low-energy tails correctly

$B \rightarrow X_s\gamma$ BF Results

- Measurements are in good agreement
  - with each other
  - with theoretical calculations



Uncertainties for 3 Approaches

Approach	Lumi (fb^{-1})	E_{min} (GeV)	Partial BF (10^{-6})	Stat %	Syst %	Model %
Semi-inclusive	80	1.9	327	6	**15**	2
Inclusive, lepton	80	1.9	367	8	9	8
Inclusive, hadron	210	1.9	366	23	**16**	-

Large stat component: will be smaller with increased statistics

- Semi-inclusve syst error limits usefulness for BF measurements
  - largely absent in asymmetry measurements, though
- Inclusive, lepton – can expect improvement in syst and model errors as well
- Inclusive, hadron – new analysis, can expect improvements going forward, although 16% syst. looks worriesome

Another "use" of $B \rightarrow X_s\gamma$: measuring m_b

- One of the "uses" of the $B \rightarrow X_s\gamma$ measurement has been its ability to determine the HQE parameters m_b and μ_π^2 via spectrum moments
- This is important because reducing the error on m_b leads to large improvements in the determination of V_{ub} using inclusive measurements

Inclusive V_{ub} and m_b

- V_{ub} extracted from partial $b \to u l \nu$ BF:

$$|V_{ub}| = \left[\Delta B / (\Delta\zeta\tau_B)\right]^{\frac{1}{2}}$$

from theory

- m_b dependence is large:

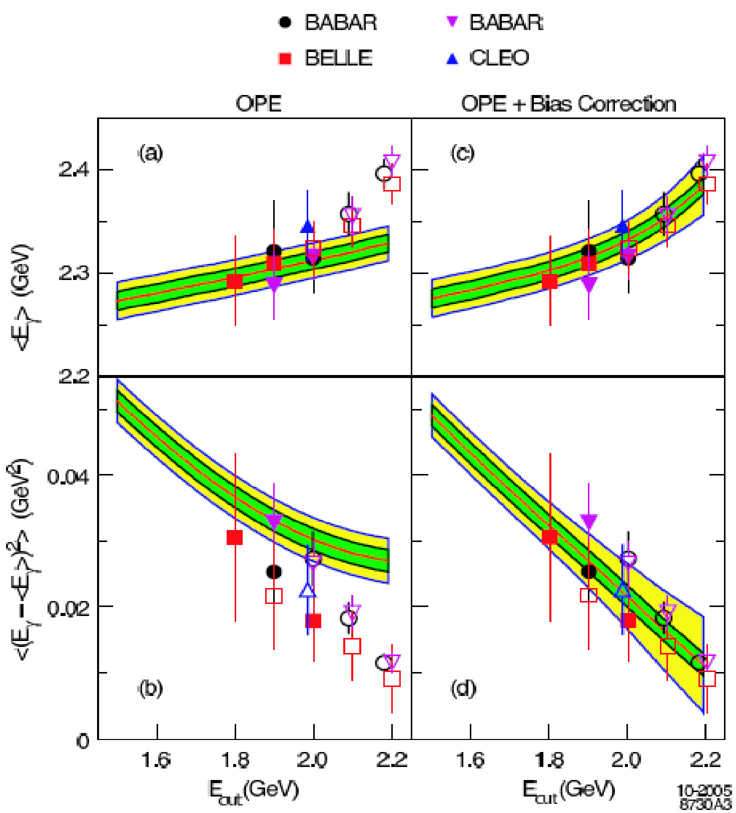
$$\left(\frac{\Delta\Gamma_u}{\Gamma_u}\right) \approx (7-20) \times \left(\frac{\Delta m_b}{m_b}\right)$$

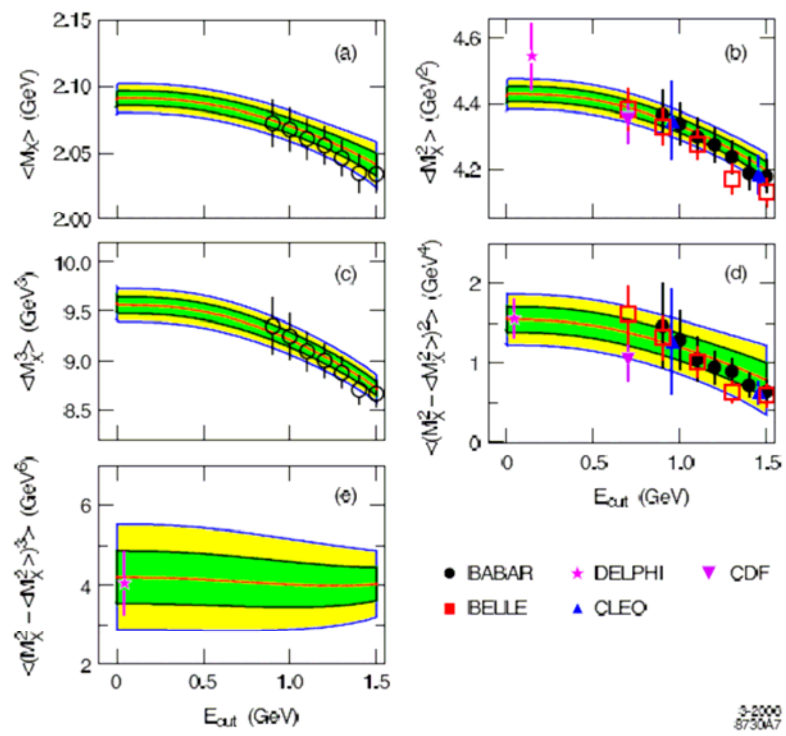
factor depends on experimental cuts

Best measurement of m_b important!

Determining m_b

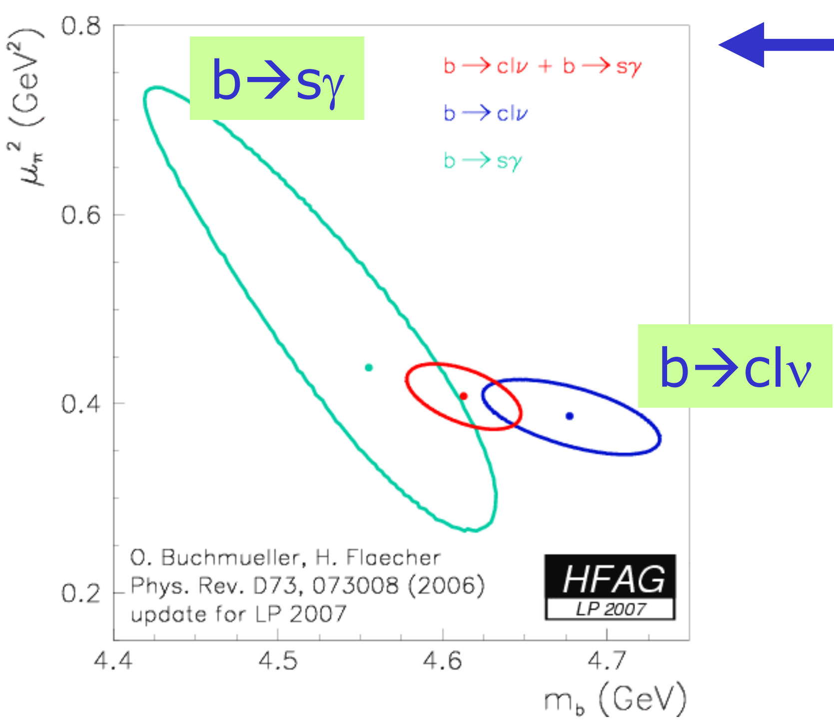
- Hadronic and leptonic moments in $b \to c l \nu$
- Photon spectrum in $b \to s\gamma$





- HFAG uses the Flächer/Buchmüller analysis for m_b and μ_π^2
- The m_b Bible:
  - hep-ph/0507253

m_b results



LP2007 update

m_b = 4.613 +/- 0.022 +/- 0.027
μ_π^2 = 0.408 +/- 0.017 +/- 0.031

- Improvements in m_b will lead to improvements in V_{ub}, which is already theory error-limited
- From HFAG (2007):

|Vub| = 4.31 +/- 0.17 (exp.) +/- 0.35 (theory)

On 8.9% total error, 6.9% is due to uncertainty in HQE parameters, mostly m_b

Expectations for SuperB

- No real work done on this yet, but we can make rough estimates based on B-factory analyses
- Of the 3 approaches, best best is inclusive, lepton tag analysis
- Look in more detail at errors for that analysis

Example Systematics: Inclusive, lepton

- These numbers for 80 fb^{-1} analysis
- Largest component will almost scale with lumi
- Others can be improved with judicious event selection

Effect	Uncertainty (%)
BB background	5.5
Photon selection	3.3
Efficiency event shape cuts	3
Lepton ID	2
Total Syst.	**8.5**
Stat.	**8**

statistics-dependent (BB background)

room for improvement, if needed (Photon selection; Efficiency event shape cuts)

Need to study carefully, but we can certainly reduce the systematic uncertainty significantly at SuperB ➔ perhaps we can achieve 5% experimental error

Asymmetry Measurements

- Asymmetry measurements become very interesting at SuperB
- Lower systematics due to cancellations in ratio
- Current uncertainties very statistics-dominated
- The different approaches previously presented are able to measure different asymmetries…

Asymmetry Measurements (2)

Direct CP Asymmetry

$$A_{CP} = \frac{B(B \to X_s\gamma) - B(\overline{B} \to X_s\gamma)}{B(B \to X_s\gamma) + B(\overline{B} \to X_s\gamma)}$$

- SM: $A_{CP} = 0.0044^{+0.0024}_{-0.0014}$
- BaBar Semi-inclusive result (80 fb-1):
  - A_{CP} = 0.025 +- 0.050 (stat) +- 0.015 (syst.)

Direct CP Asymmetry (s+d)

$$A_{CP}(s+d) = \frac{B(B \to X_{s.d}\gamma) - B(\overline{B} \to X_{s,d}\gamma)}{B(B \to X_{s,d}\gamma) + B(\overline{B} \to X_{s,d}\gamma)}$$

- SM: A_{CP}(s+d) almost identically zero
- Inclusive measurements include $B \to X_d\gamma$
- A_{CP}(s+d) = -0.110 +- 0.115 (stat) +- 0.017 (syst.) (lepton)
- A_{CP}(s+d) = 0.10 +- 0.18 (stat) +- 0.05 (syst.) (hadron)

Isospin Asymmetry

$$\Delta_{-0} = \frac{B(\overline{B}^0 \to X_s\gamma) - B(B^- \to X_s\gamma)}{B(\overline{B}^0 \to X_s\gamma) + B(B^- \to X_s\gamma)}$$

- SM: 5-10% in exclusive $K^*\gamma$ channel
- $\Delta_{-0} = -0.006 \pm 0.058_{stat} \pm 0.009_{syst} \pm 0.024_{(B0/B+)}$ (semi)
- $\Delta_{-0} = -0.06 \pm 0.15_{stat} \pm 0.07_{syst}$ (hadron)

Summary

- Currently BF($b \rightarrow s\gamma$) measured to about 7%, while theoretical error is around the same
- Real studies not performed yet, but we can see that BF($b \rightarrow s\gamma$) will likely be measured with perhaps 5% experimental error, perhaps better

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

- Also expect improvements in measurements of photon spectrum moments ➔ lead to improvements in $|V_{ub}|$
  - current moment measurements are stats-limited
  - complicated relationship between moments and $m_b \rightarrow$ not easy to estimate m_b improvement without dedicated study