# Decadimenti $b \to s\gamma$

## Risultati più recenti da BaBar

F. Bucci
Università di Pisa

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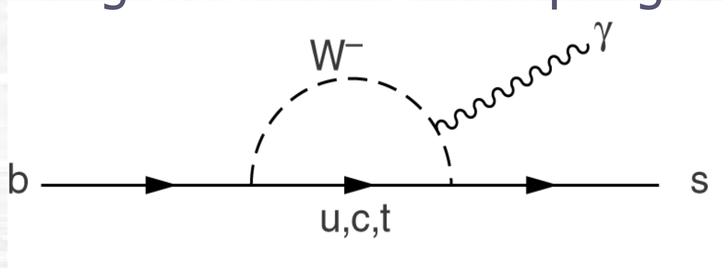
# $b \to s\gamma$ decays

Proceed through an electroweak penguin diagram




- Do not occur at tree level, so branching fractions ($\mathcal{B}$) tend to be small
  **rare decays**
- Relatively low SM uncertainty for $\mathcal{B}$ and CP asymmetry ($A_{CP}$)
  **good place to look for non-SM physics**

**New BaBar results:**

- $B \to X_s\ \gamma$ (two independent measurements)
- $B \to K^{*}\gamma$ (time-dependent $A_{CP}$ measurement)

# $B \to X_s\gamma$ Physics Interest

**Both the $B \to X_s \gamma$ branching fraction and the direct CP asymmetry are sensitive to new physics**

- The branching fraction in the SM has been computed with ~8% precision:

$$\mathcal{B}(B \to X_s\gamma)[E_\gamma > 1.6 \text{ GeV}] = (3.57 \pm 0.30) \times 10^{-4}$$

P. Gambino and M. Misiak, Nucl. Phys. B 611, 338 (2001)

- Direct CP asymmetry is expected to be small:

$$A_{CP}(b \to s\gamma) \equiv \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)} = 0.004^{+0.0024}_{-0.0014}$$

T. Hurth, E. Lunghi and W. Porod, hep-ph/0312260

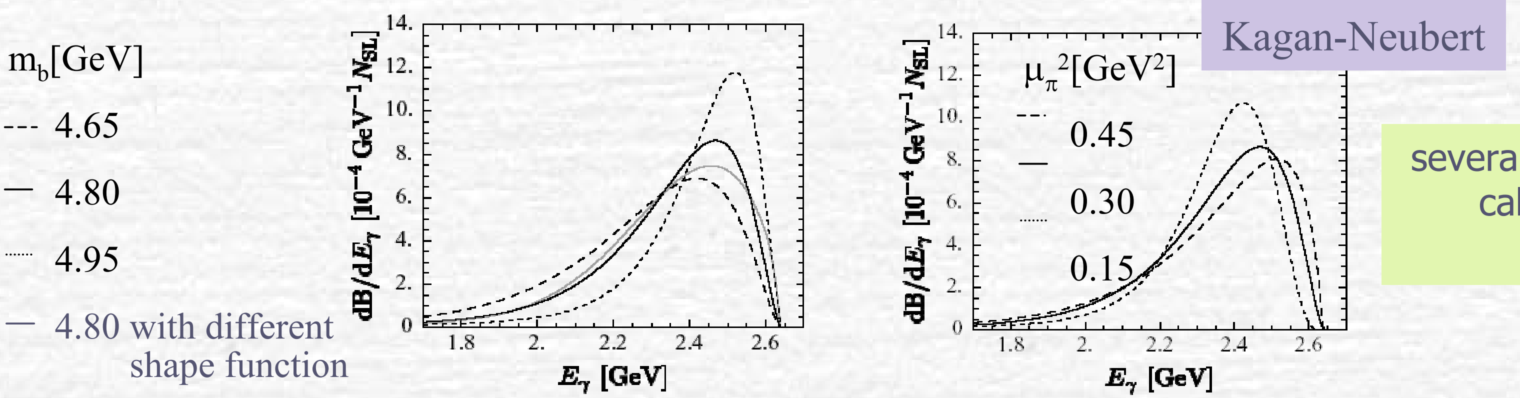
- If $b \to s\gamma$ and $b \to d\gamma$ are not distinguished, $A_{CP}$ predicted

$$A_{CP}(b \to s\gamma + b \to d\gamma) \approx 10^{-9}$$

T. Hurth and T. Mannel, hep-ph/0109041(2001)

# $B \to X_s \gamma$ Physics Interest

**The $E_\gamma$ spectrum measurement gives information on the Heavy Quark Expansion parameters $m_b$ and $\mu_\pi^2 = -\lambda_1$**




several parameterized calculations of the spectrum

- Reflects motion of the b quark inside the B meson
- Underlying **shape function** is needed to extract CKM element $|V_{ub}|$ from inclusive $B \to X_u l \nu$ measurements
- Not affected by new physiscs

Theorist now predict **truncated moments and partial branching fractions** (PBF) above various minimum $E_\gamma$ cuts, **as function of HQET parameters**

# $B \to K^{*0}\gamma$ ($K^{*0} \to K^0_s \pi^0$) Physics Interest

If both $B^0$ and $\bar{B}^0$ can decay to a final state f, difference in proper decay times of the signal B and the other (tag) B is distributed as:

$$f_{\pm}(\Delta t) = \frac{e^{-\frac{|\Delta t|}{\tau}}}{4\tau}[1 \mp C_f \cos(\Delta m_d \Delta t) \mp S_f \sin(\Delta m_d \Delta t)]$$

- In the limit of massless s the photons are completely polarised, with opposite helicities for $B^0$ and $\bar{B}^0$
- Thus, in the SM the CPV asymmetry due to the interference between decays with or without mixing is expected to be small:

$\Rightarrow S_{K^{*0}\gamma} \approx -2\ \mathbf{m_s/m_b} \sin 2\beta \approx -0.04,\ \ C_{K^{*0}\gamma} \approx 0$

**In SM extensions, new particles could appear in the loop, enhancing CP violation**

Recent theoretical developments predict that all contributions to $K^0_s\pi^0\gamma$ have same CP, so no need to resolve resonance structure

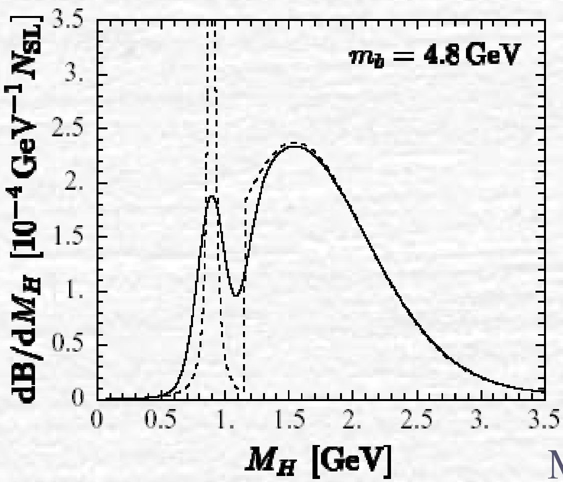
# $B \to X_s\gamma$ Signal Model

**The $B \to X_s\ \gamma$ calculations give smooth spectra, no resonances**

Need predicted spectra to estimate experimental efficiency, optimize selection cuts, fit the measured spectrum

Photon energy in the B rest fame is related to the mass of $X_s$: $E_\gamma^B = \dfrac{m_B^2 - m_{X_s}^2}{2m_B}$

Replace $m_{Xs}$ spectrum below some cutoff by $K^*(892)$ Breit-Wigner of same area.




$M_H$ is used for $M_{Xs}$

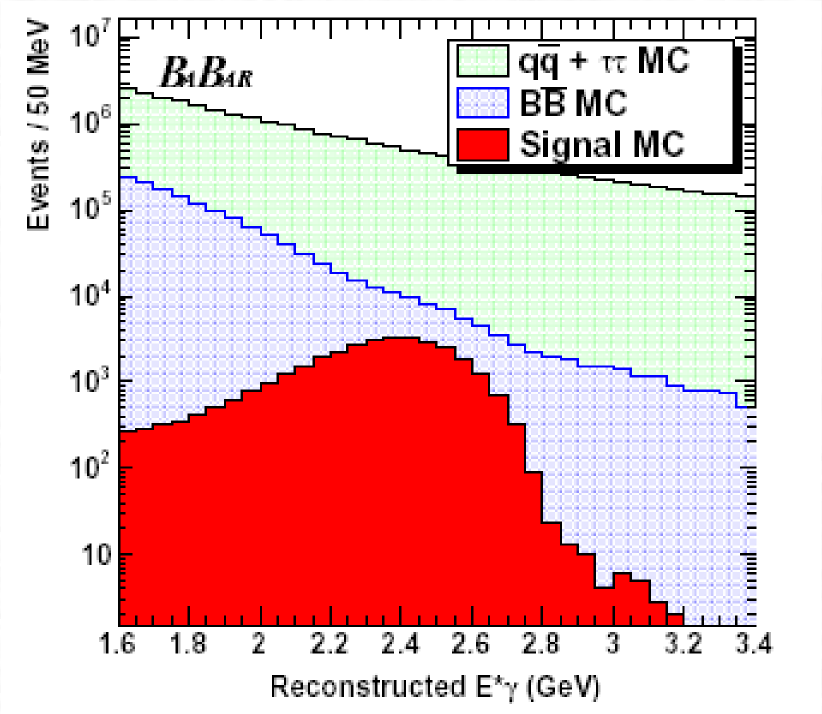
# Backgrounds to High-Energy Photon from $B \to X_s \gamma$

**Other $B\bar{B}$ States**

- Photon from meson decay, mostly $\pi^0$ or $\eta$
- Neutral hadron fakes $\gamma$
- Electron from $B \to X e \nu$ fakes $\gamma$

**Continuum**

- Photon from meson decay, mostly $\pi^0$ or $\eta$
- Neutral hadron fakes $\gamma$
- Initial state radiation




Photon energy spectra as predicted by MC before selection cuts

# Techniques

**Two independent BaBar measurements, both on ≈ $88 \cdot 10^6$ $B\bar{B}$ pairs**

**Sum of exclusive final states**

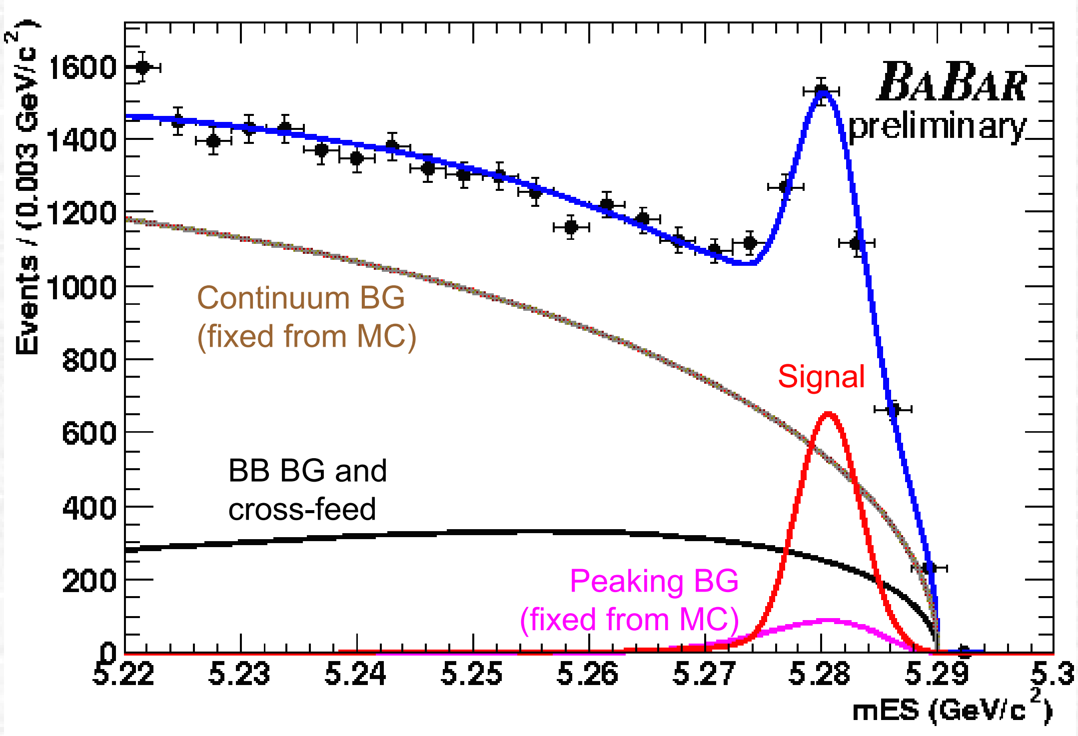
- 38 exclusive modes (~ 55 % of all final state) reconstructed
- Kinematic constraints suppress backgrounds significantly
- Efficiency and fraction of unmeasured modes sensitive to $X_s$ fragmentation
- Precise measurement of $E_\gamma$ in the B rest frame ($\sigma_E$ ~ 5 MeV)

**Fully inclusive**

- Reconstruct only photon
- High momentum lepton from other B to greatly reduce continuum background
- Little sensitivity to fragmentation details
- Photon energy spectrum in $\Upsilon(4S)$ rest of mass frame

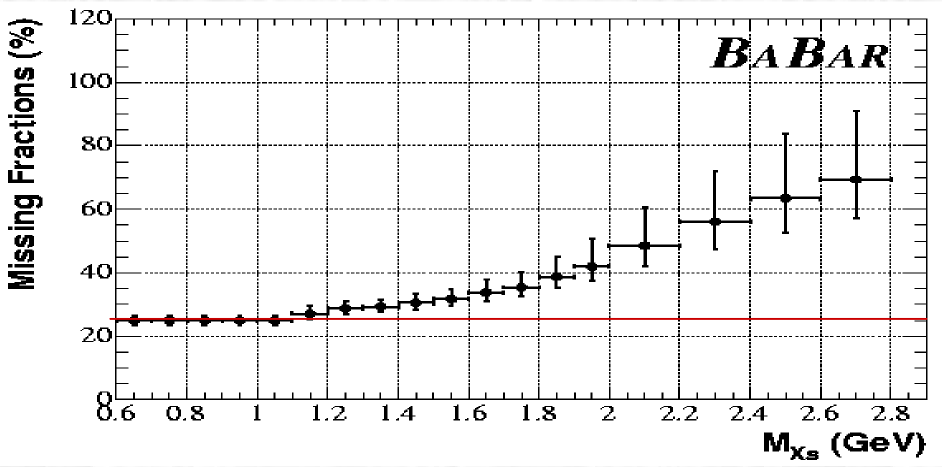
# $B \to X_s \gamma$ Sum of Exclusive Modes

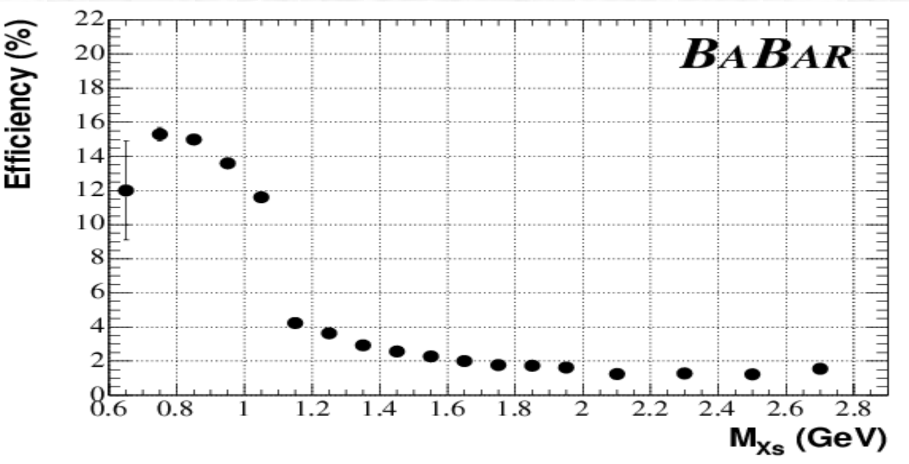
- Reconstruct $X_s$ in 38 states
- Use event shape to reduce continuum background
- Use $\Delta E \equiv E_B^* - \sqrt{s}/2$ and $m_{ES} \equiv \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$ to constrain exclusive states
- Fit $m_{ES}$ (for each $m_{Xs}$ bin) to extract signal yield
- Use observed yield in different modes to correct MC fragmentation




Fit to data for full $m_{Xs}$ range (0.6-2.8 GeV)

# $B \to X_s \gamma$ Sum of Exclusive Modes




**Missing States**

- Dominant syst. uncertainty at $m_{Xs}$>2.2 GeV
- The 25% component which is present at all $M_{Xs}$ masses comes from $K_L$, which is well understood because $B \to X_s \gamma$ decays are isospin symmetric

**Efficiency**

- Not including missing states
- Highest for low-multiplicity

# $B \to X_s \gamma$ Sum of Exclusive Modes

**Systematic Uncertainties for $0.6 < m_{X_s} < 2.8$ GeV**

| Systematic | Uncertainty |
|---|---|
| BB-count | 1.1% |
| Signal MC Stats | 1.1% |
| Peaking BG | 1.6% |
| Fragmentation | 5.9% |
| Detection | 6.1% |
| Fitting | +9.5 –2.9% |
| Missing states | +13.8 –7.6% |
| **Total experimental** | **+19.0 –12.0%** |
| Signal model-dependence | +2.1 –2.4% |

**Using fit to the** measured **spectrum, bootstrap the signal Monte Carlo** with the fitted parameters

Lines in red: significant improvement expected with more statistics

# $B \rightarrow X_s\gamma$ Fully Inclusive

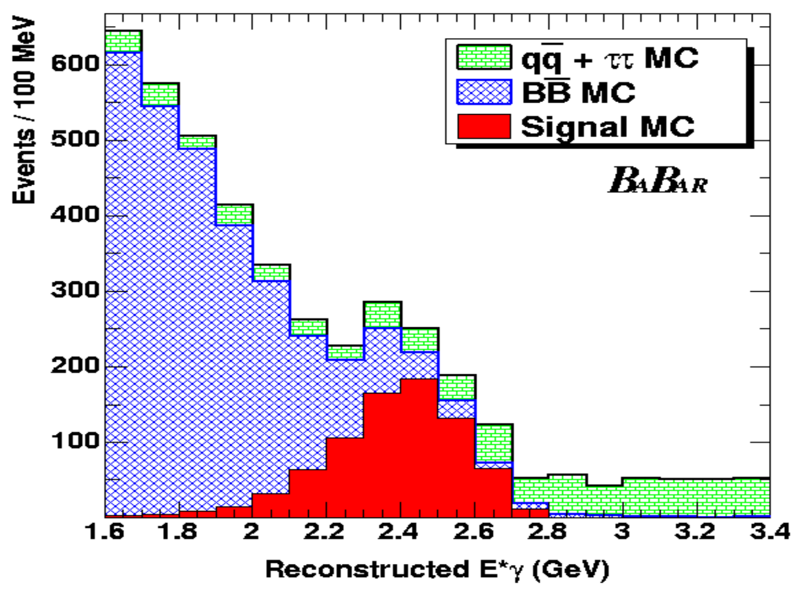
**Background reduction is the primary challenge**

**Continuum background**

- Reduced by event topology and high-momentum **lepton tag**.
- Remaining bkg subtracted using off-resonance data

**$B\bar{B}$ background**

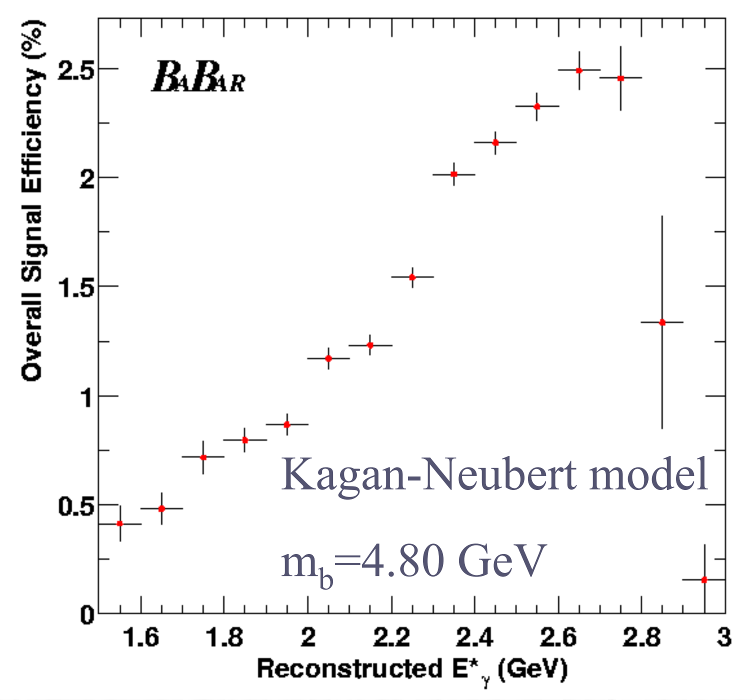
- Selection cuts reduce it 8 times more than signal
- Remaining bkg subtracted using MC
- 97% of $B\bar{B}$ background simulation corrected using data samples




Photon spectra from MC after selection cuts

# $B \to X_s \gamma$ Fully Inclusive

**Overall signal efficiency**




- Topological cuts, in particular, result in a strong energy-dependence to the efficiency
- But no significant dependence on fragmentation model

# $B \to X_s \gamma$ Fully Inclusive

**Systematic uncertainties on Branching Fraction for $2.0 < E^*_\gamma < 2.7$ GeV**

| Systematic | Uncertainty |
|---|---|
| Photon Detection and Quality | 3.3% |
| Topological Cuts | 3.0% |
| Fragmentation-Dependence | 1.4% |
| Lepton ID | 2.2% |
| Tag Efficiency | 3.0% |
| Miscellaneous | 1.7% |
| $B\bar{B}$ Subtraction | 6.5% |
| **Total experimental** | **8.4%** |
| Signal model-dependence | 4.8% |

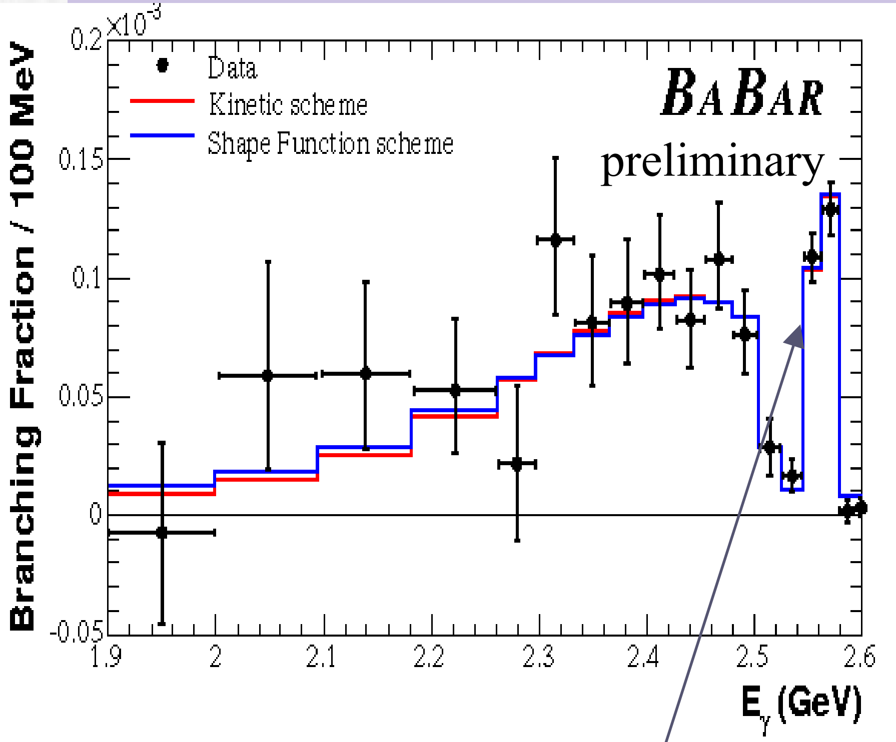
**Use the spectrum measurement**, in particular its mean **to reduce the signal model-dependence**

- Linear relation between predicted efficiency and $\langle E^*_\gamma \rangle$
- KN 460 matched measured mean, hence used for efficiency
- Uncertainty on efficiency translated from measured $\langle E^*_\gamma \rangle$ efficiency

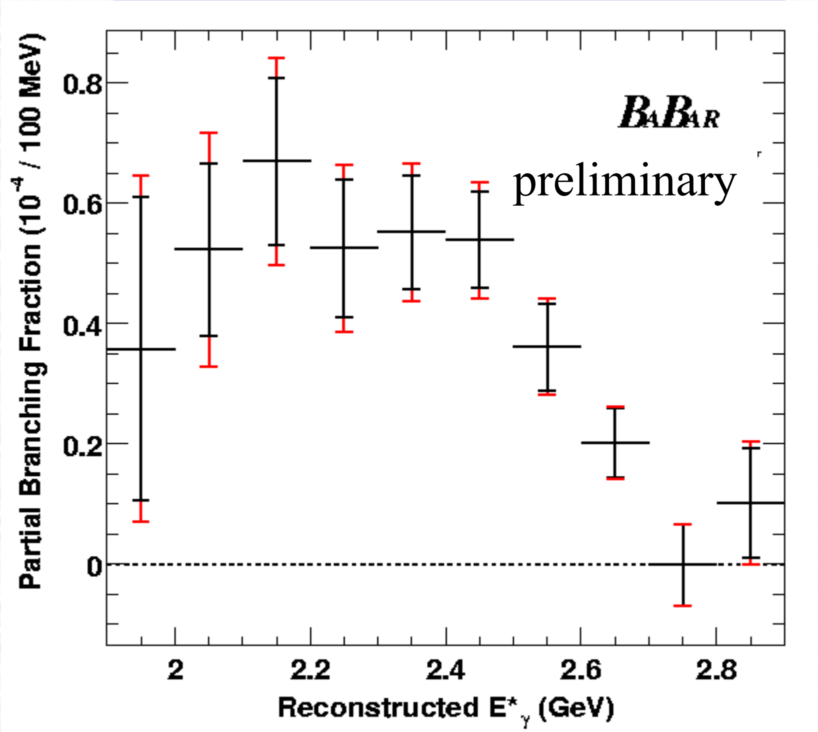
Lines in red: significant improvement expected with more statistics

# $B \to X_s \gamma$ Photon Spectrum

Sum of exclusive modes




Fully inclusive

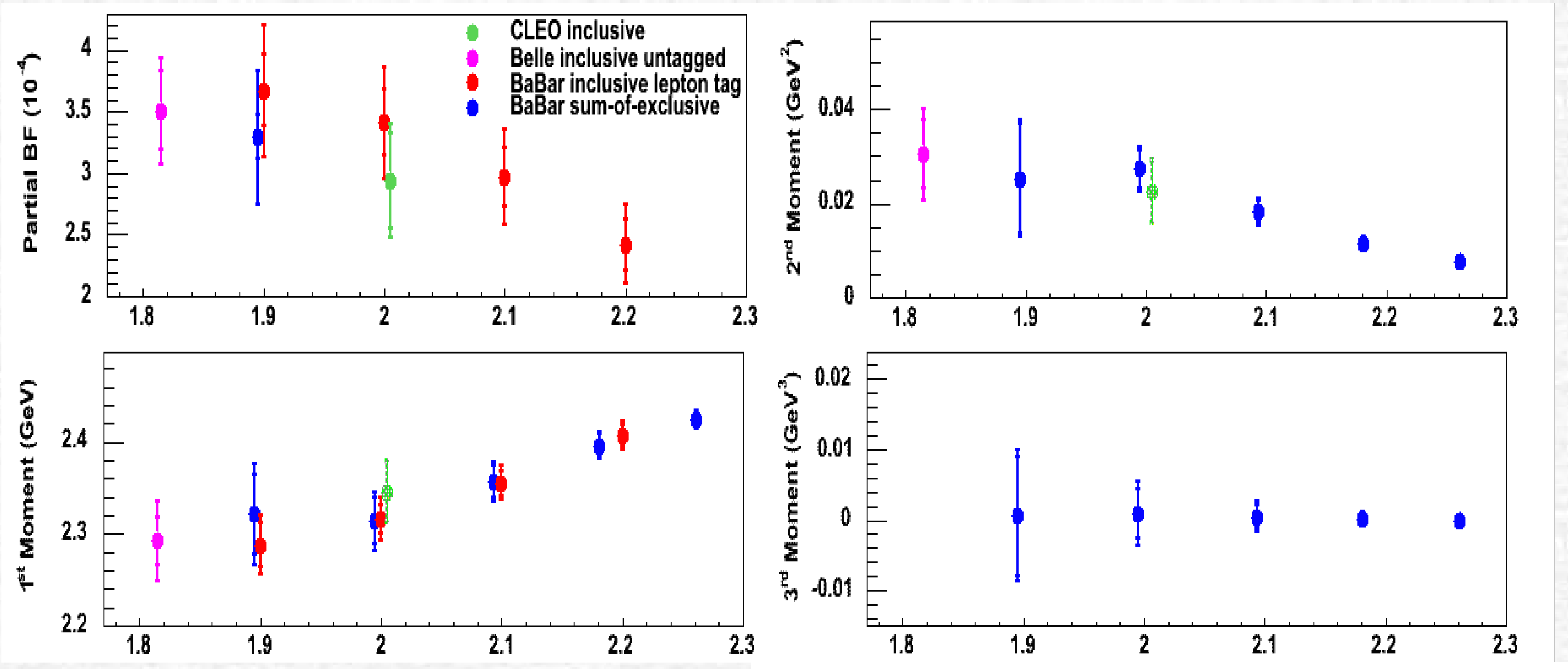



Very good photon energy resolution: note the $K^*_\gamma$ peak

Photon energy spectrum in $\Upsilon$(4S) frame

# $B \to X_s\gamma$ Moments

**$0^{th}$ to $3^{rd}$ moments of the photon energy spectrum as a function of minimum energy threshold in the B rest frame**




BaBar data preliminary

# $B \to X_s \gamma$ Branching Fraction

**No discrepancy with SM**

**Sum of exclusive modes**

| Scheme | **PBF($10^{-4}$)**, $E_\gamma$>1.9 GeV |
|---|---|
| "Kinetic" | $3.27 \pm 0.18 \ ^{+0.62}_{-0.39} \ ^{+0.12}_{-0.12}$ |
| "Shape Function" | $3.31 \pm 0.18 \ ^{+0.63}_{-0.40} \ ^{+0.02}_{-0.03}$ |

**Extrapolated BF ($E_\gamma$>1.6 GeV)**

$$\left(3.42 \pm 0.19 \ ^{+0.64}_{-0.41} \ ^{+0.07}_{-0.08}\right) \times 10^{-4}$$

Average from two schemes

**Fully Inclusive**

| Energy range (GeV) | **PBF (×$10^{-4}$)** true $E_\gamma$ range, B frame |
|---|---|
| 1.9-2.7 | 3.67±0.29±0.34±0.29 |
| 2.0-2.7 | 3.41±0.27±0.29±0.23 |
| 2.1-2.7 | 2.97±0.24±0.25±0.17 |
| 2.2-2.7 | 2.42±0.21±0.20±0.13 |

BF(PBF)±stat.±syst.±model-dep.

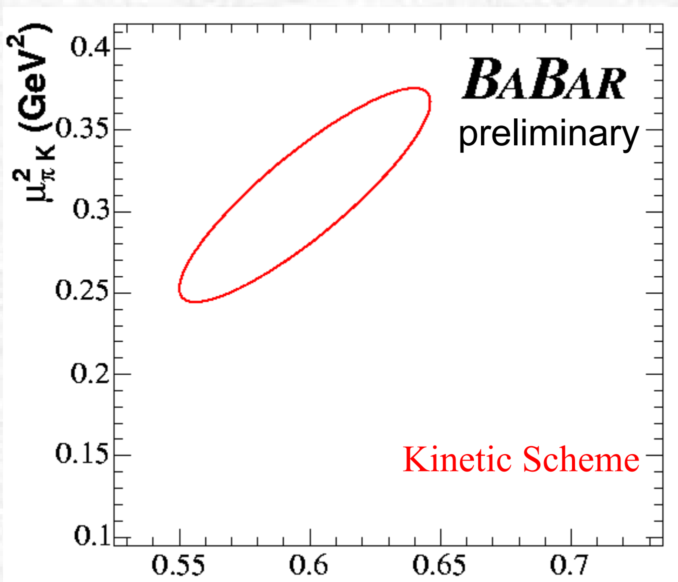
# $B \to X_s \gamma$ Spectrum Fits

**Fits from sum of exclusive method to**

$\overline{\Lambda} = m_B - m_b$

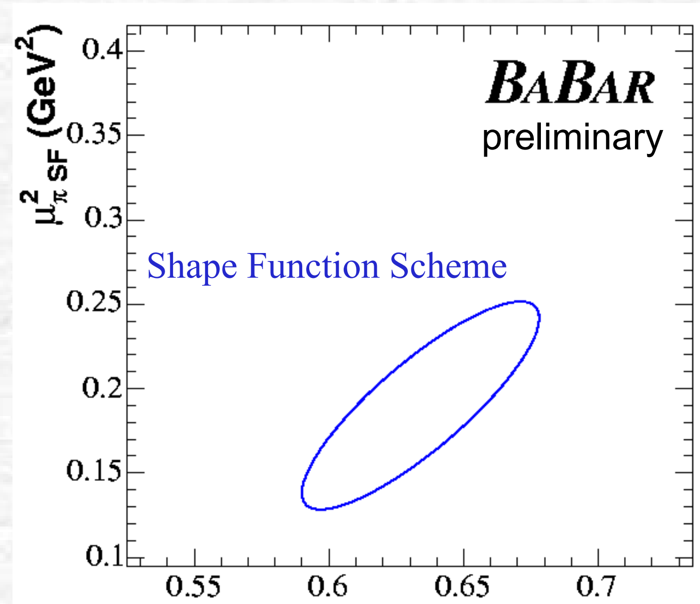
$\mu^2_\pi = -\lambda_1$

| Benson-Bigi-Uraltsev calculation | Neubert calculation |
|---|---|




$$\overline{\Lambda}_K = 0.59^{+0.05}_{-0.04}\,\mathrm{GeV}$$

$$\mu^2_{\pi K} = 0.30^{+0.07}_{-0.05}\,\mathrm{GeV}^2$$




$$\overline{\Lambda}_{SF} = 0.63^{+0.04}_{-0.04}\,\mathrm{GeV}$$

$$\mu^2_{\pi SF} = 0.19^{+0.06}_{-0.05}\,\mathrm{GeV}^2$$

# $B \to X_s \gamma$ CP Asymmetry

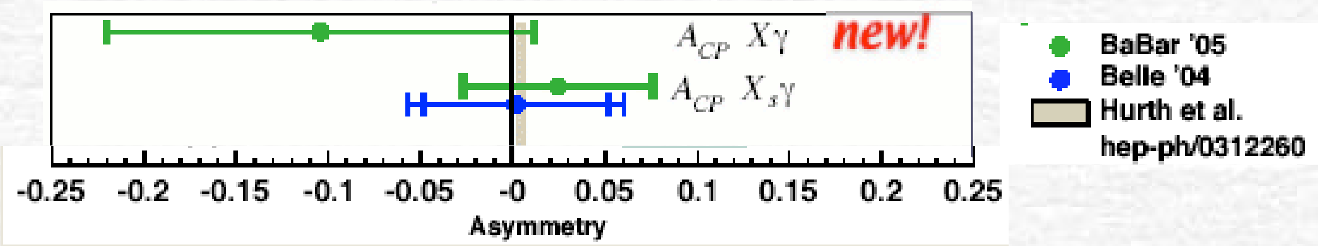
**Sum of exclusive modes**

Direct CP asymmetry for sum of 12 final states (published)

$A_{CP}$=0.025 ± 0.050(stat.) ± 0.015(syst.)

**Fully inclusive**

$A_{CP}(b \to s\gamma + b \to d\gamma)$= -0.110 ±0.115 (stat.) ± 0.017 (syst.)




No discrepancy with standard model. Both measurements are statistics-limited

# $B \to X_s \gamma$ Future

**Sum of exclusive modes**

- **Branching fraction:**
  - Dominant uncertainty systematics. Largest component due to missing states. 10% measurement might be possible with 500 $fb^{-1}$
- **Moments:**
  - Dominant uncertainty statistical. Could be halved with 500$fb^{-1}$

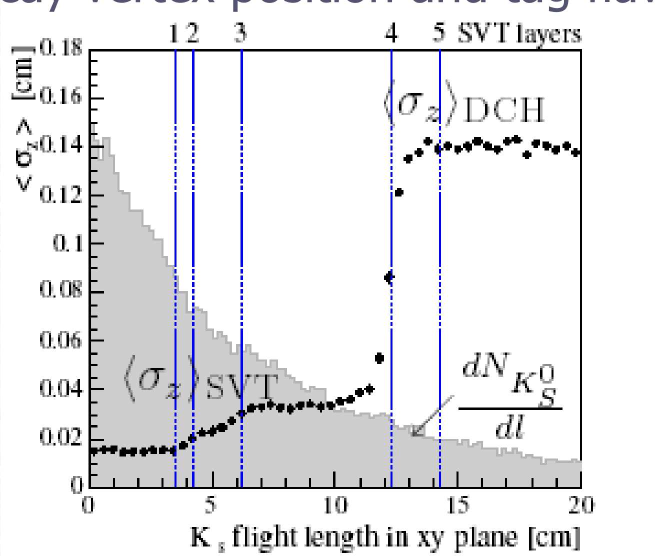
**Fully inclusive**

- **Branching fraction:**
  - Uncertainties have roughly equal size components. Large component of both systematic and signal model uncertainties depends on the size of the data sample. Uncertainty below 7% is expected with 500 $fb^{-1}$
- **Moments:**
  - Dominant uncertainty statistical. With 500 $fb^{-1}$, 0.8% precision expected

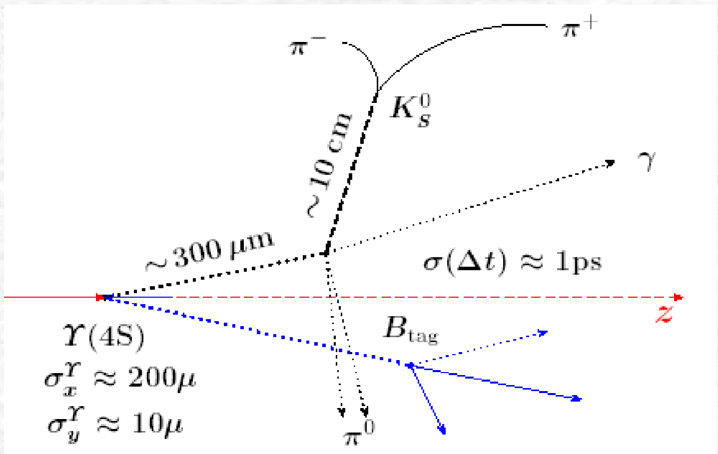
# $B \to K^{*0}\gamma$ ($K^{*0} \to K^0_s \pi^0$) Technique

Analysis performed on 232 million $B\bar{B}$ events

- Signal events selected using $m_{ES}$, $\Delta E$ and event shape cuts
- Remaining tracks assigned to the other B and used to determine its decay vertex position and tag flavor




Vertex precision depends on number of hits in SVT of $K^0_s$ decay daughters

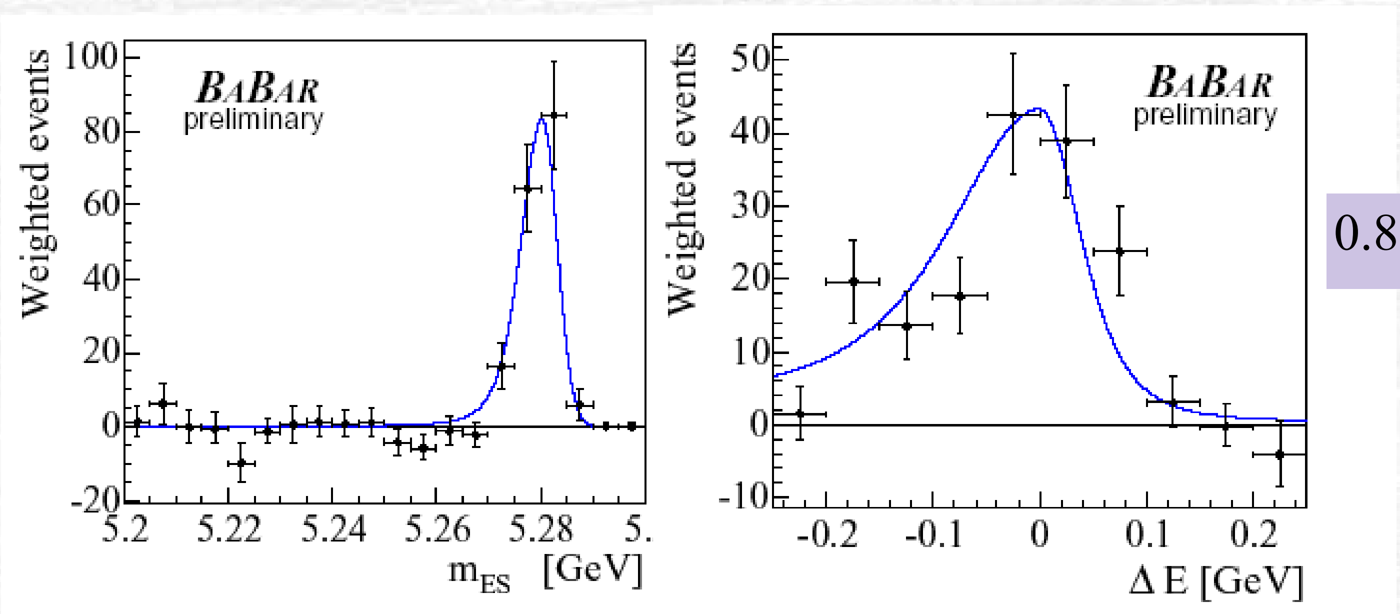



$B_{CP}$ decay vertex position reconstructed using

- $K^0_s$ reconstructed vertex and mometum
- Beam-line position and direction

# $B \to K^{*0}\gamma$ ($K^{*0} \to K^0_s\pi^0$) Results

**Measured $\Delta t$, $m_{ES}$, $\Delta E$, $m_{K^*}$ and event shape variables are inputs to an unbinned maximum-likelihood fit**




$0.8 < m_{K^0_s\pi^0} < 1.0\ GeV/c^2$

$N_{K^*\gamma} = 157 \pm 16$

Background-subtracted data for $m_{ES}$ and $\Delta E$ compared to the corresponding signal PDF

# $B \to K^{*0}\gamma$ ($K^{*0} \to K^0_s \pi^0$) Results

**preliminary**

$$0.8 < m_{K_s^0\pi^0} < 1.0 \ \ \mathrm{GeV/c^2}:$$
$$S_{K^{*0}\gamma} = -0.21 \pm 0.40 \pm 0.05$$
$$C_{K^{*0}\gamma} = -0.40 \pm 0.23 \pm 0.04$$

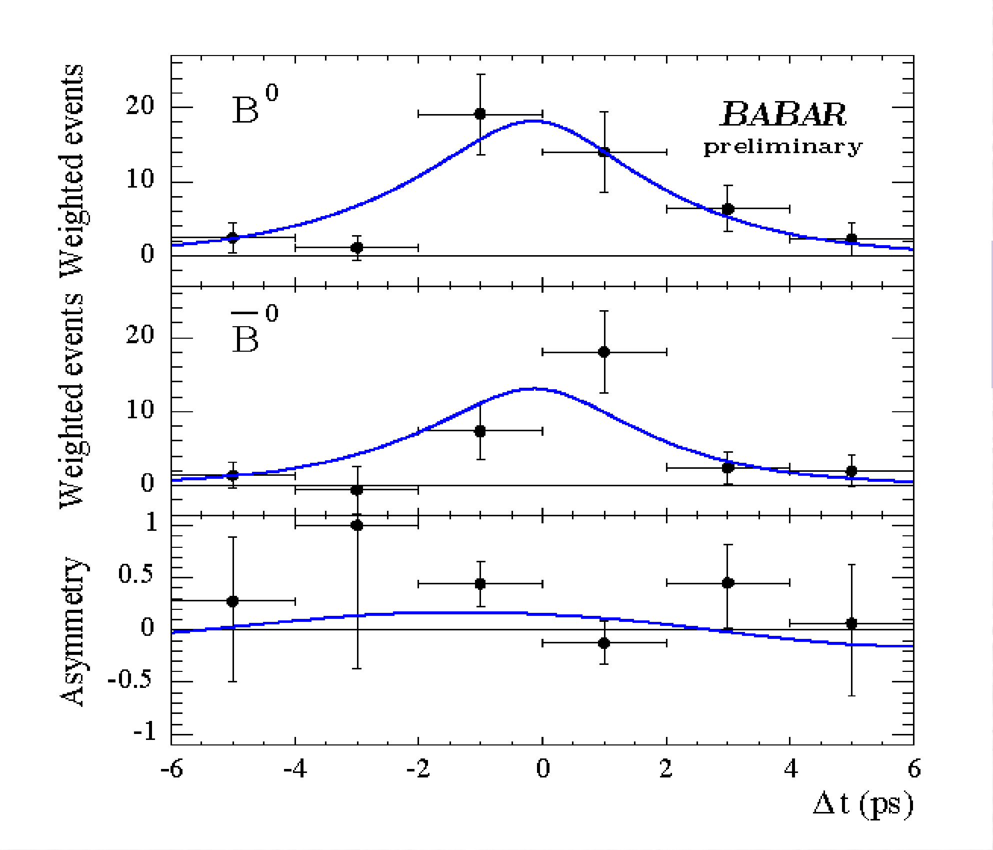
$$1.1 < m_{K_s^0\pi^0} < 1.8 \ \ \mathrm{GeV/c^2}:$$
$$S_{K_s^0\pi^0\gamma} = 0.9 \pm 1.0 \pm 0.2$$
$$C_{K_s^0\pi^0\gamma} = -1.0 \pm 0.5 \pm 0.3$$

Largest component of systematic uncertainty is from possible CP asymmetry in $B\bar{B}$ background

Consistent with the SM expectation of CP-violating asymmetry ≈ 0, statistics-limited results

# $B \to K^{*0}\gamma$ ($K^{*0} \to K^0{}_s\pi^0$) Results

**Background-subtracted $\Delta t$ distributions for $B \to K^{*0}\gamma$ ($K^{*0} \to K^0{}_s\pi^0$)**




No evidence of SM violation

# Conclusions

**Lots of preliminary new results from BaBar on radiative rare decays have been presented**

- Precision on $\mathcal{B}(B \to X_s \gamma)$ can be improved with higher statistics (at least in the fully inclusive analysis)
- Photon spectrum measurements (especially its moments) are becoming useful for determining HQET parameters
- Both time-dependent CP asymmetry in radiative penguin processes (211 $fb^{-1}$) and direct CP violation search in $B \to X_s \gamma (+B \to X_d \gamma)$ (81$fb^{-1}$) show no discrepancy with SM expectations. Statistics-limited

# Time-Dependent CPV Asymmetry

If both $B^0$ and $\overline{B}^0$ can decay to a final state f, difference in proper decay times of the signal B and the other (tag) B is distributed as:

$$f_{\pm}(\Delta t) = \frac{e^{-\frac{|\Delta t|}{\tau}}}{4\tau}[1 \mp C_f \cos(\Delta m_d \Delta t) \mp S_f \sin(\Delta m_d \Delta t)]$$

$C_f$ corresponds to "direct" CPV:

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

$S_f$ corresponds to CPV in interference between mixing and decay:

$$S_f = \frac{-2\,\mathrm{Im}\,\lambda_f}{1 + |\lambda_f|^2}$$

mixing phase

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

decay amplitude phase