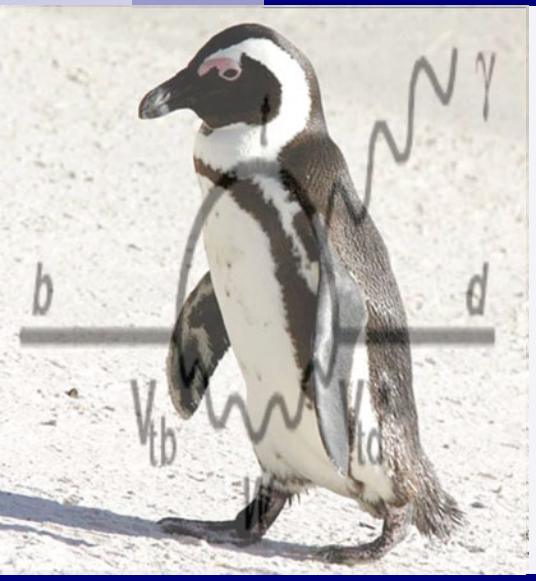
FPCP 2007: 5th Flavor Physics and CP Violation Conference
Bled/Slovenia, May 12-16, 2007

Radiative Penguin Decays



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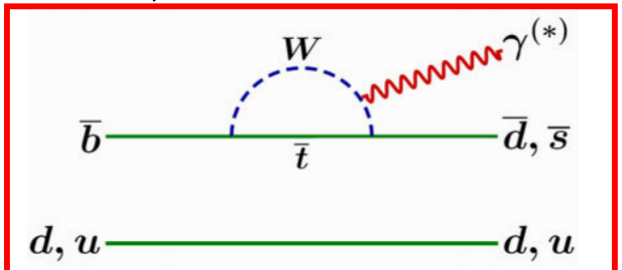
for the BaBar and Belle Collaborations

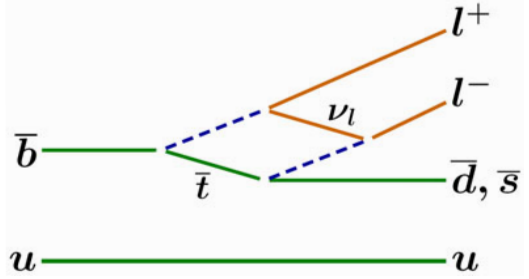
BaBar TALK-07/036

Radiative B Decays

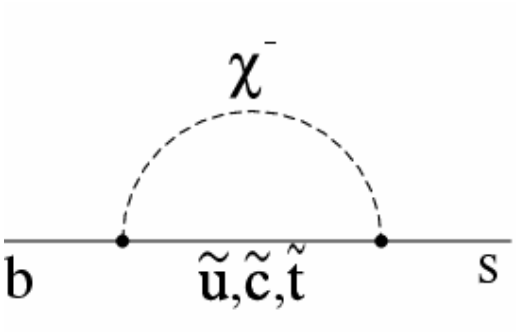
- b→s,d transitions with a final-state high-energy γ or lepton pair



`radiative penguin'



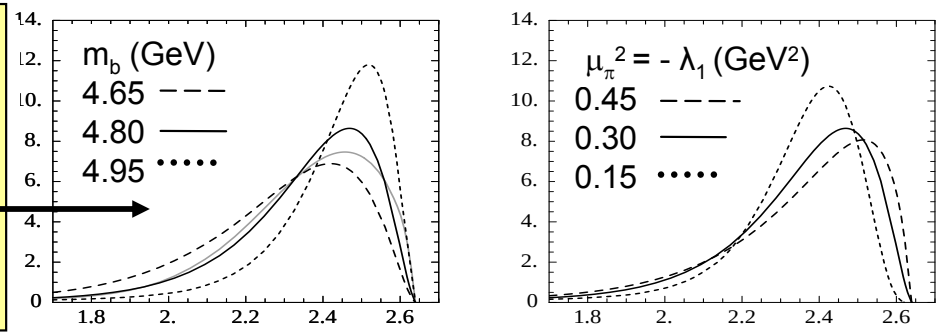
`WW box'



e.g.

- Flavor-Changing Neutral Current
  - absent in the SM at tree-level; dominated by W-top loop
  - additional helicity suppression for photon penguin
- Sensitive to New Physics at leading order
  - provides powerful NP constraints; window to the TeV scale
  - theoretically relatively clean (only one hadronic current)

- E_γ spectrum sensitive to b quark mass and Fermi motion
  - $m_b \sim E_\gamma/2$, $\mu_\pi^2 \sim \langle E_\gamma^2 - \langle E_\gamma \rangle^2 \rangle$
  - important for, e.g., V_{ub} extraction



In This Talk:

- $b \to s\gamma$ with hadronic B tag

  hot off the press! **[210 fb^{-1}]**

- $B \to p\bar{\Lambda}\gamma$

  KEK 2007-6, submitted to PRD-RC ; [414 fb^{-1}]

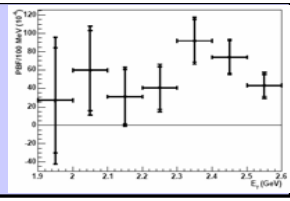
- $B \to (\rho,\omega)\gamma$

  Phys. Rev. Lett. 98, 151802 (2007) ; [316 fb^{-1}]

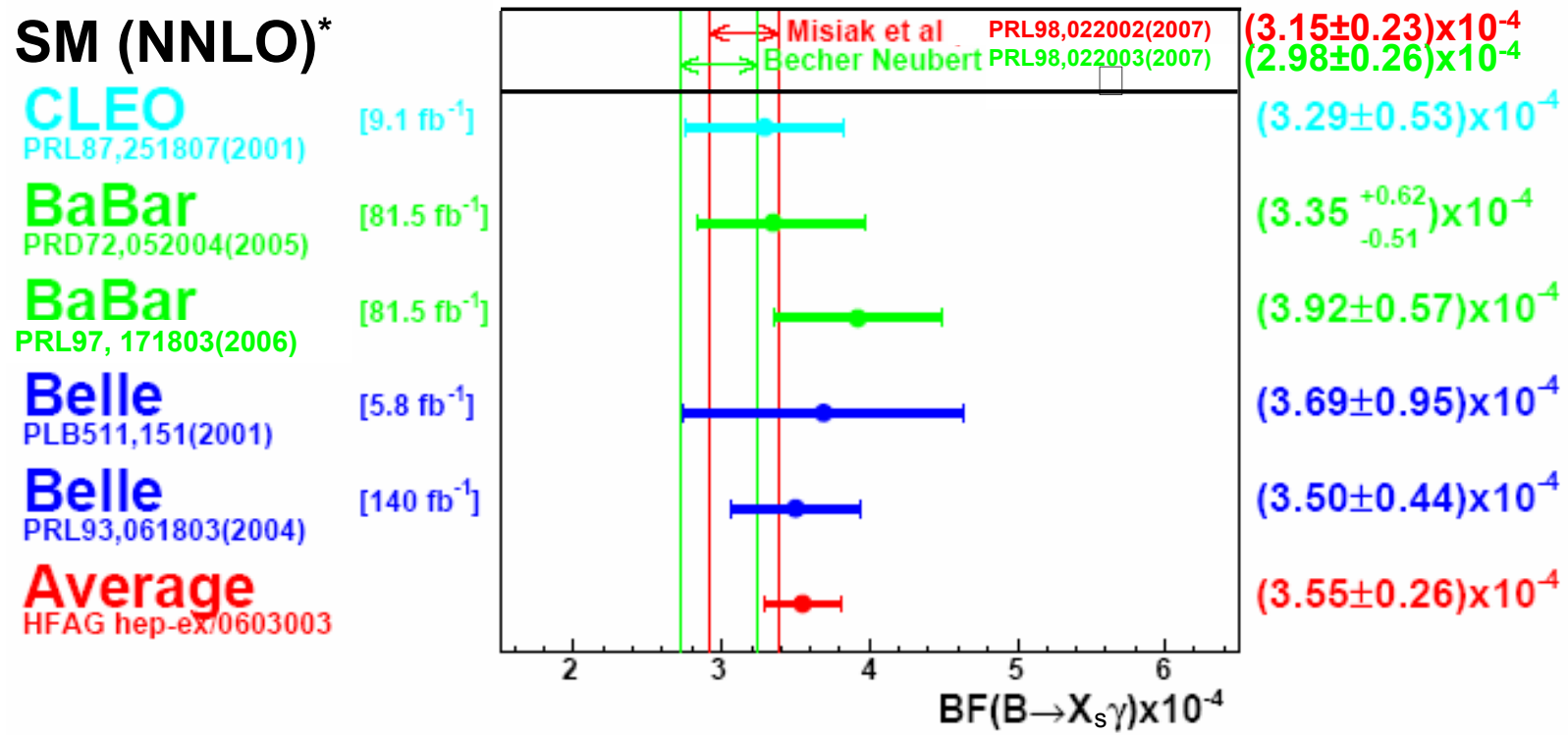
and

- other news since FPCP06

Inclusive b→sγ Decays



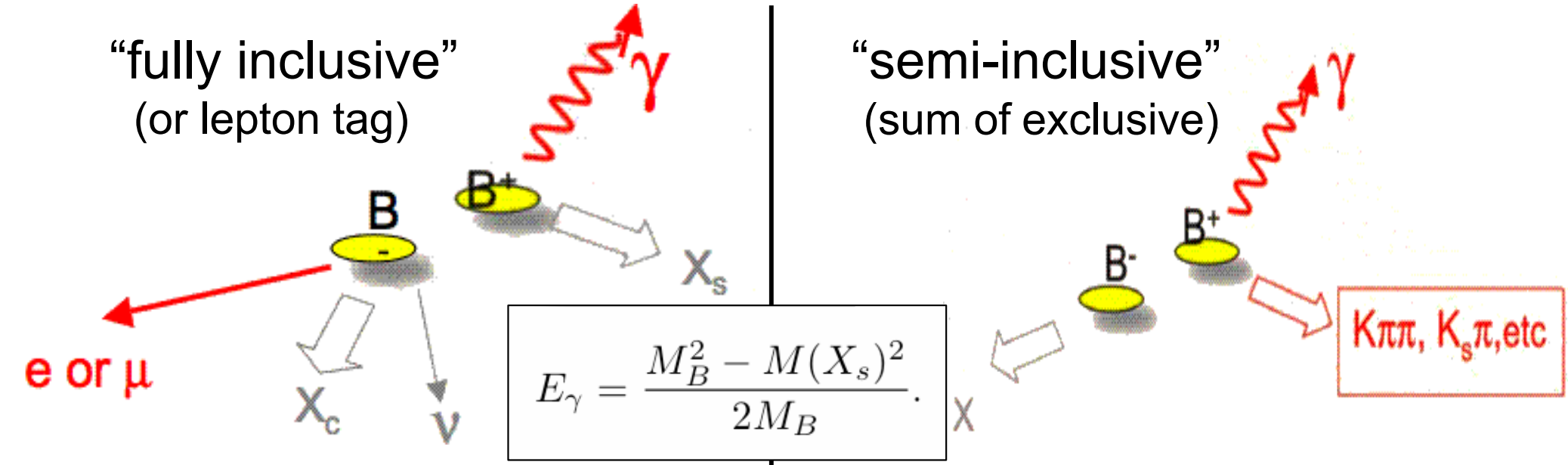
Status of branching fraction measurements
(note recent theory breakthrough; can now compare to NNLO!):



- Experimental BF results extrapolated down to $E_\gamma^* > 1.6$ GeV (based on HQE fits to b→clν and b→sγ moments)
- Additional observables: CP and isospin asymmetries

*also: Andersen, Gardi [hep-ph/0609250]: (3.47 ± 0.48) x 10^{-4})

Inclusive b → sγ : Experimental Methods



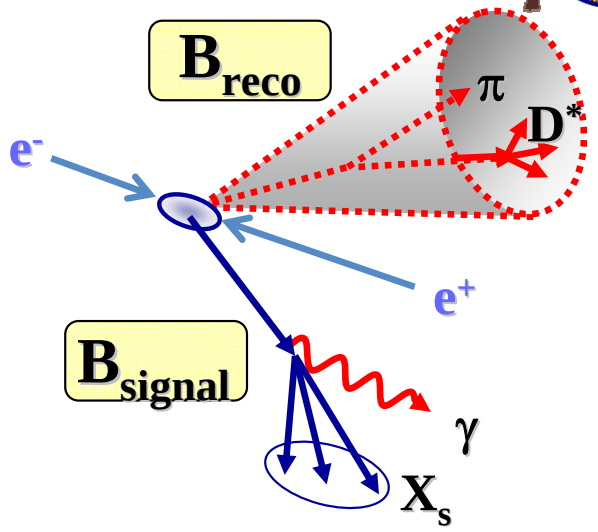
- Measure only the γ (and tag lepton)
- Pros
  - no X_s fragmentation sensitivity
  - theoretically clean
- Cons
  - high background
  - measure E_γ in $\Upsilon(4s)$ frame

- Fully reconstruct X_s final states
- Pros
  - lower background
  - good E_γ resolution in B-frame
- Cons
  - missing X_s decay modes
  - X_s fragmentation systematic

Inclusive b → sγ : A New Approach

- Measure high-energy γ recoiling against a fully reconstructed hadronic B decay
- Photon energy spectrum is extracted from fits to m_{ES} in bins of E_γ

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

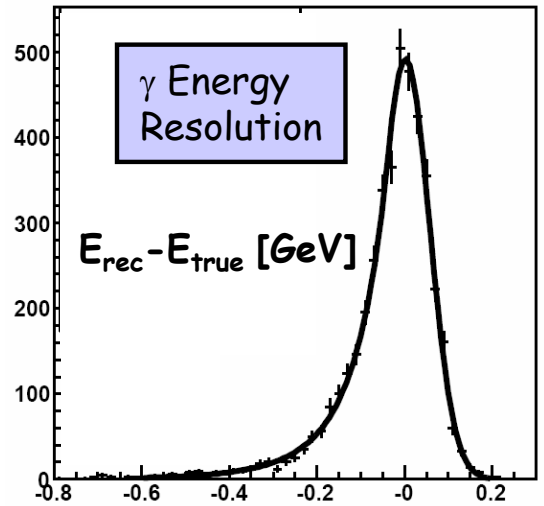


- Through full reconstruction of B_{reco} [and Y(4S) momentum], flavor, charge and four-momentum of signal B are known
  - can measure photon energy in the signal B rest frame and CP asymmetry
- Fits to m_{ES} provide information on
  - total number of BB pairs → BF normalization
  - non-peaking background → continuum subtraction
- Independent of lepton-tagged sample used in previous analysis

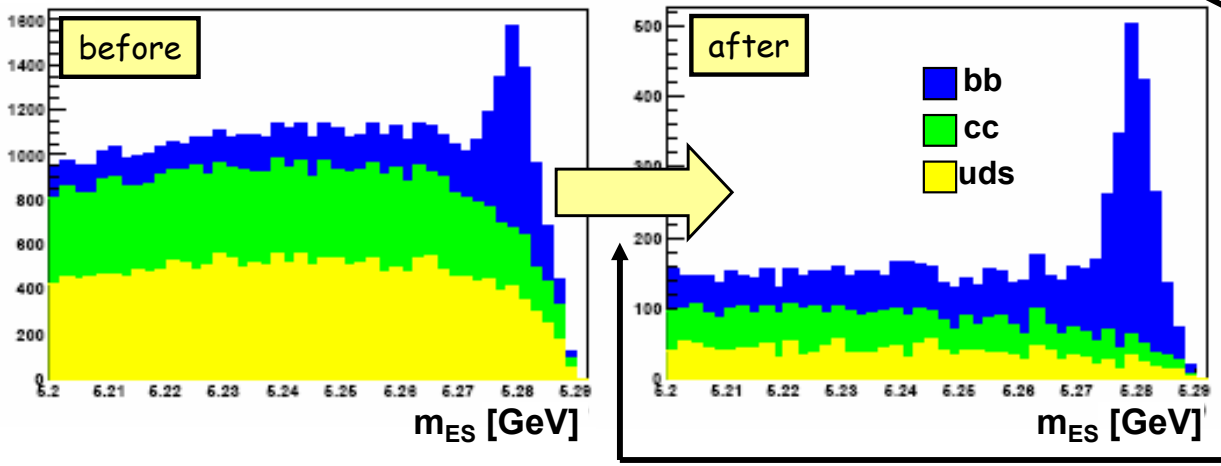
- Downside: small efficiency of B_{reco} tag (about 0.3%)

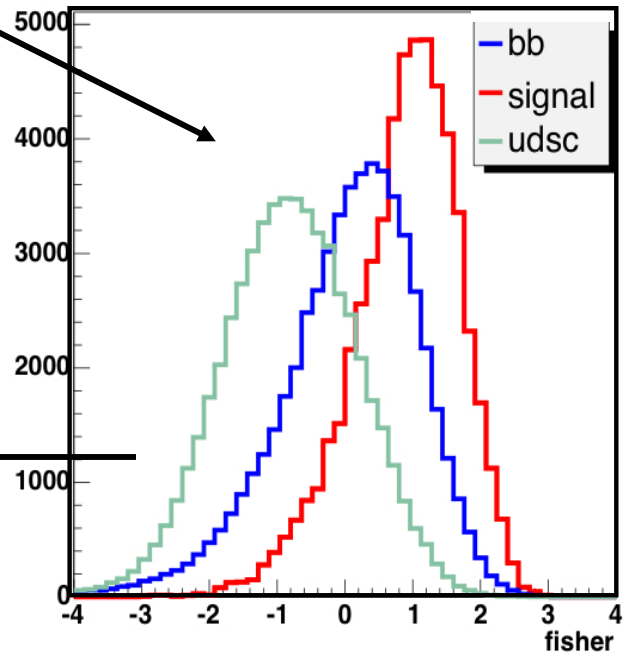
Inclusive b → sγ : Event Selection [210 fb^{-1}]

- B_{reco} sample: well-measured B→DX decays
  (X: relevant combinations of $\pi^{\pm}$,π^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)





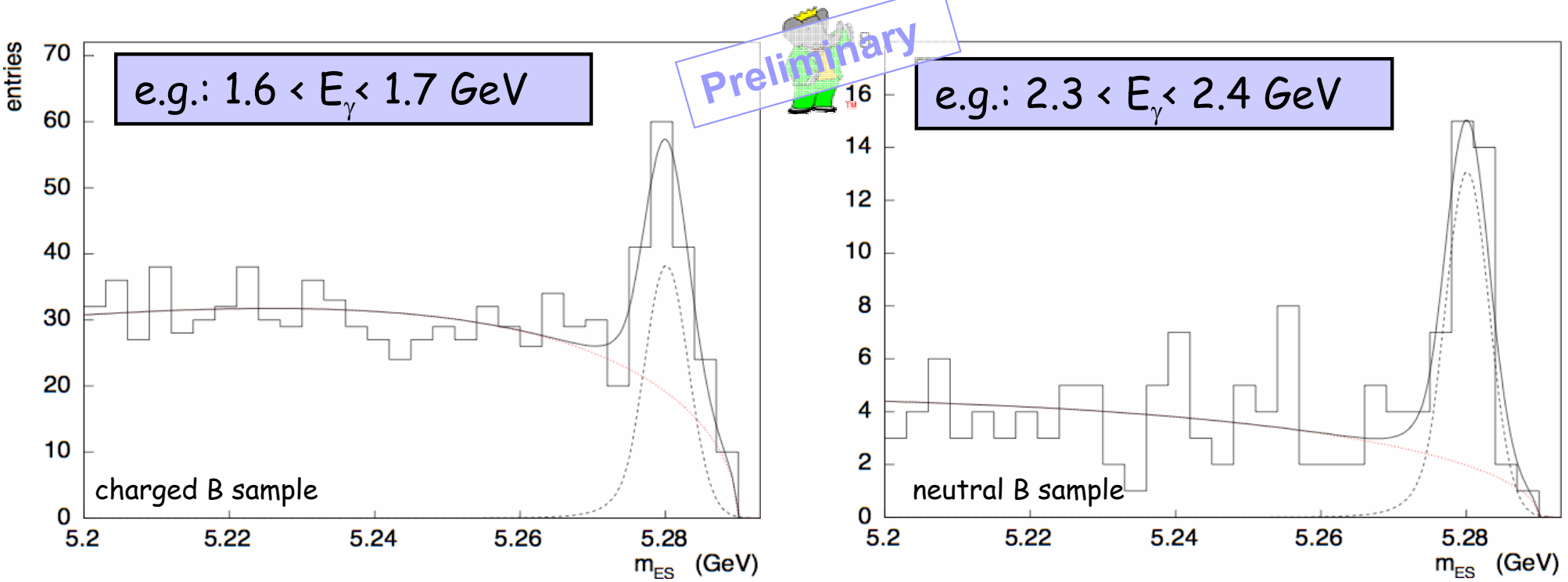
- Selection optimized to maximize $S^2/(S+B)$
- Remaining background mainly from π^0 and η

Inclusive $b \to s\gamma$: m_{ES} Fits

- For each E_γ bin i:

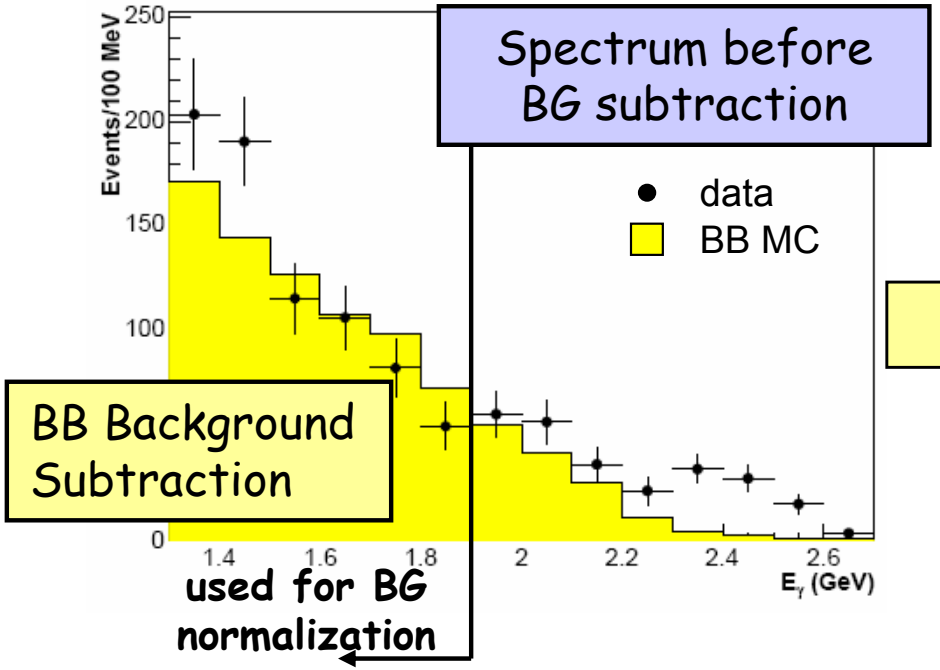
$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma} = \frac{N_i^{Data} - N_i^{BG}}{\varepsilon_i^{sig} \cdot C^{tag} \cdot N^{B_{reco}}}$$

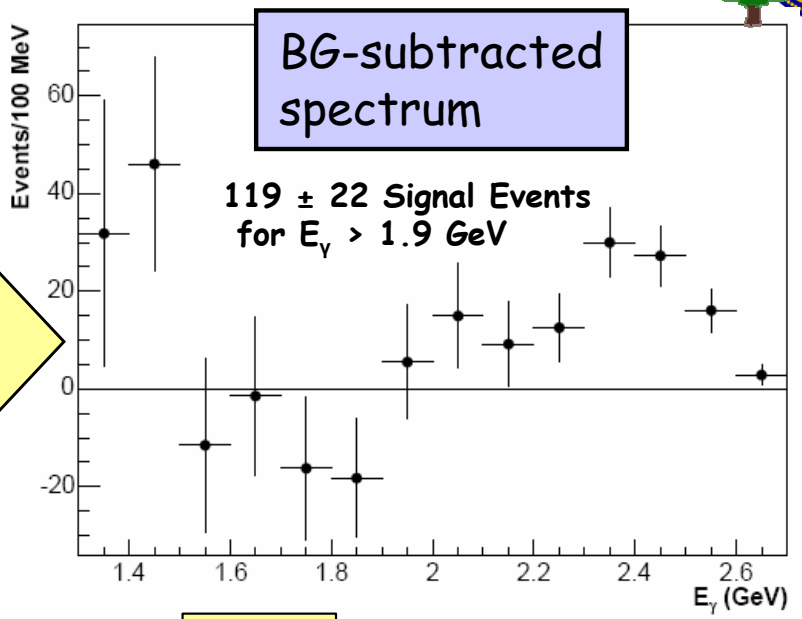
- All numbers determined from fits to m_{ES}

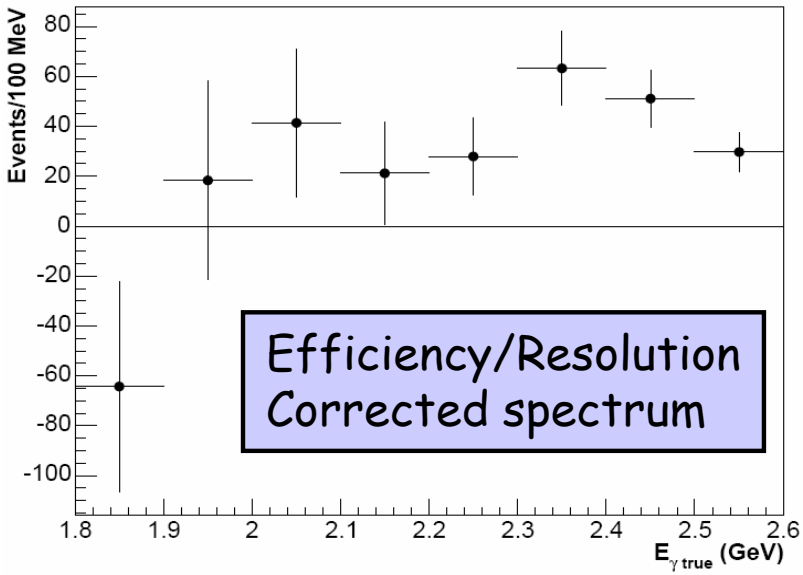


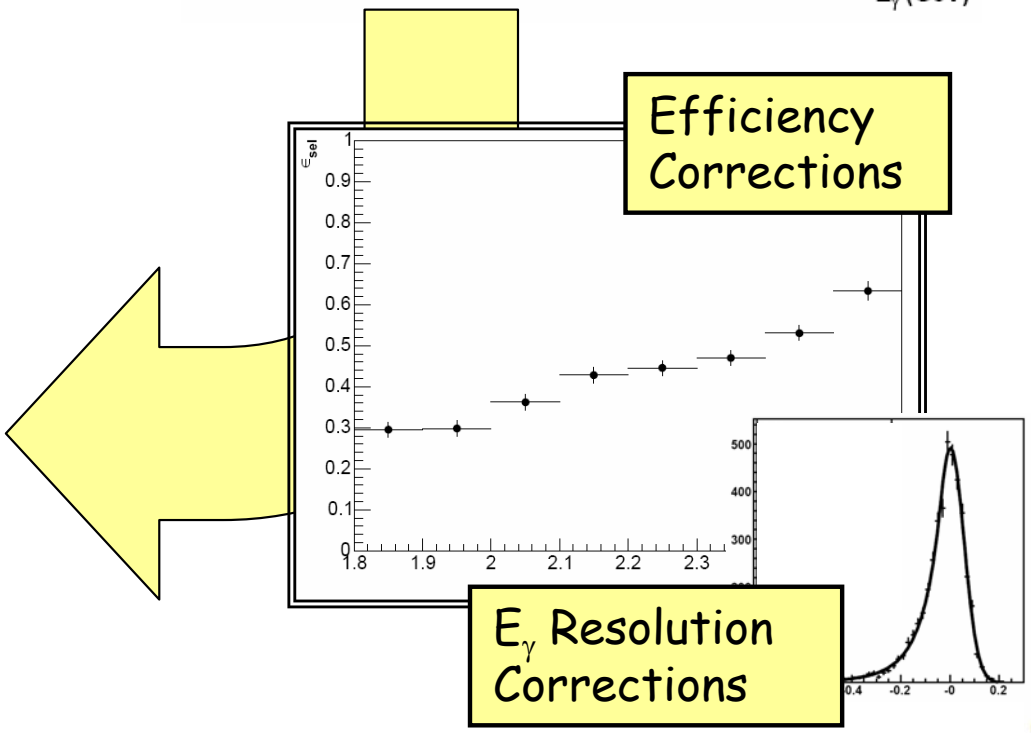
Inclusive b → sγ : E_γ Spectrum

Preliminary



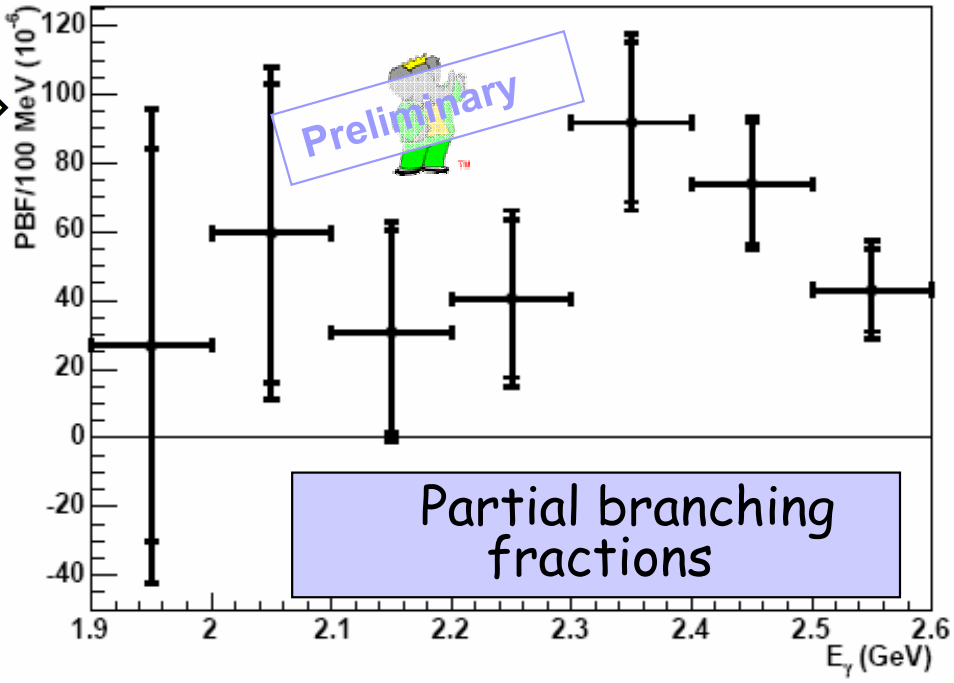






Inclusive b → sγ : Partial Branching Fractions

- Normalize from m_{ES} fit to entire B_{reco} sample
- No extrapolation to full dataset necessary



Integrate for different minimum photon energies

Preliminary

$BF[E_\gamma > E_{cut}]/10^{-6}$				contributions to systematic uncertainties				
$E_{\rm cut}$(GeV)	Value	$\sigma_{\rm stat}$	$\sigma_{\rm syst}$	Background Modelling	M_{ES} fit Parameterisation	Detector Response	$B \to X_s\gamma$ Model	$b \to d\gamma$ Subtraction
1.9	366	± 85	± 59	35	44	16	8	2
2.0	339	± 64	± 47	31	34	4	6	1
2.1	278	± 48	± 34	22	24	6	5	1
2.2	248	± 38	± 26	14	18	8	5	1
2.3	207	± 30	± 19	10	14	1	5	1

statistical uncertainties dominate

(systematic uncertainties will be reduced with larger data sample!)

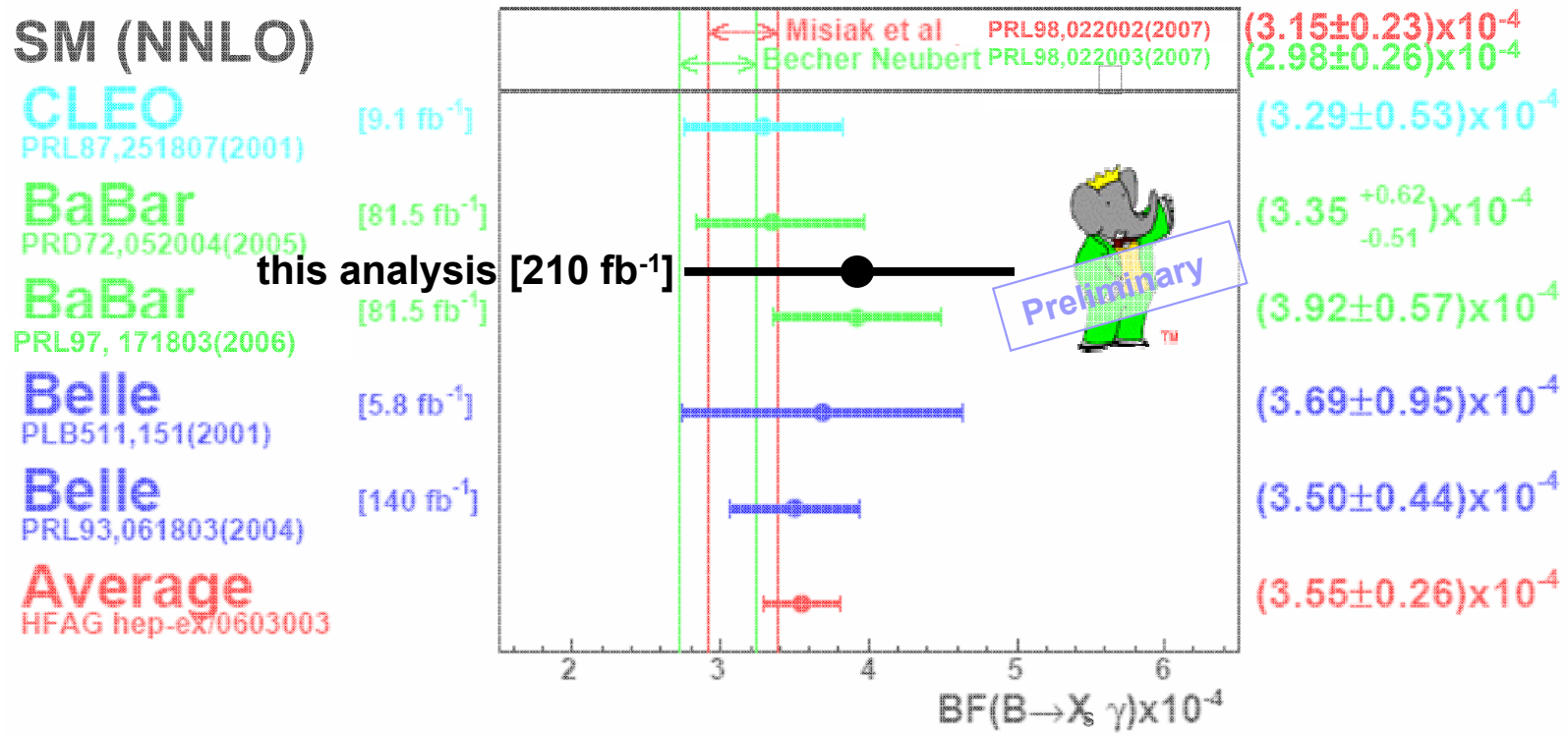
Inclusive b → sγ : Branching Fractions

$BF(b\to s\gamma)\ [E_\gamma > 1.9\ GeV] = (3.66 \pm 0.85 \pm 0.59) \times 10^{-4}$ ← measured

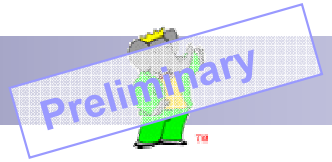
extrapolated

Extrapolate (using hep-ph/0507253)

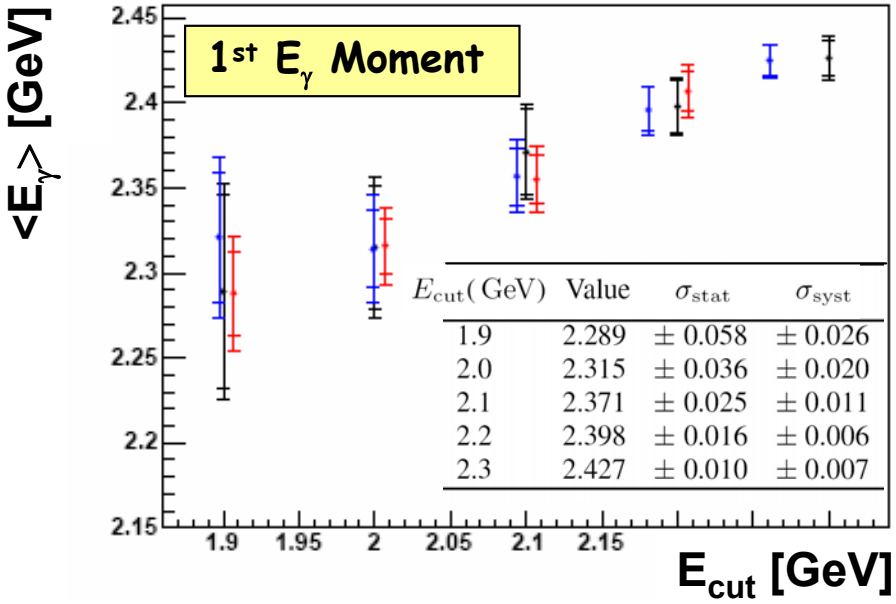
$BF(b\to s\gamma)\ [E_\gamma > 1.6\ GeV] = (3.91 \pm 0.91 \pm 0.63) \times 10^{-4}$

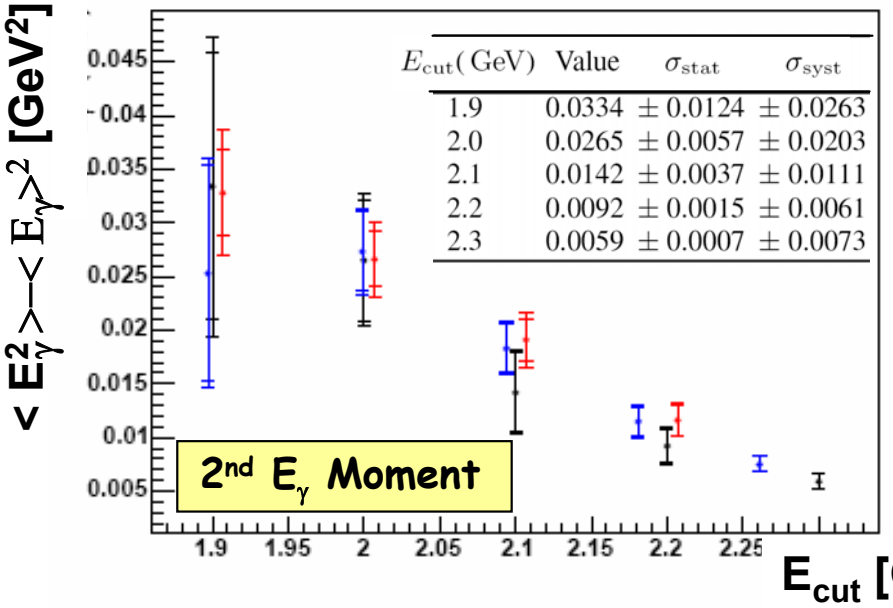


Inclusive b → sγ : E_γ Moments



- Measurement photon energy moments as a function of minimum energy
- Good agreement with previous results based on different methods and independent data samples





this analysis

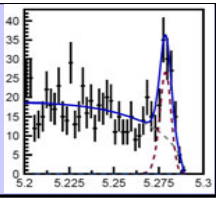
lepton tag

sum of exclusive modes

Next steps:

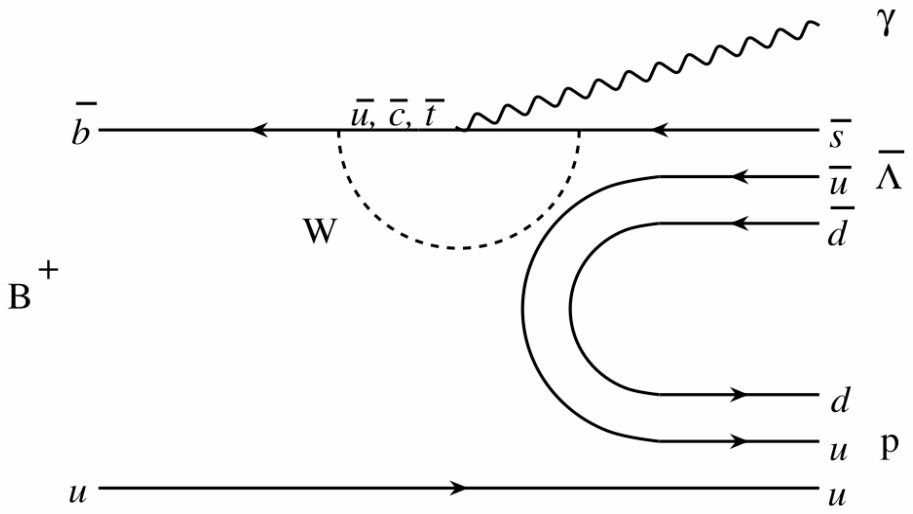
- Measure asymmetries
- Use as input for HQE parameter extraction / combine with other measurements
- Extend to full data set

Baryonic b→sγ Decays



$B^+ \to p\bar{\Lambda}\gamma$

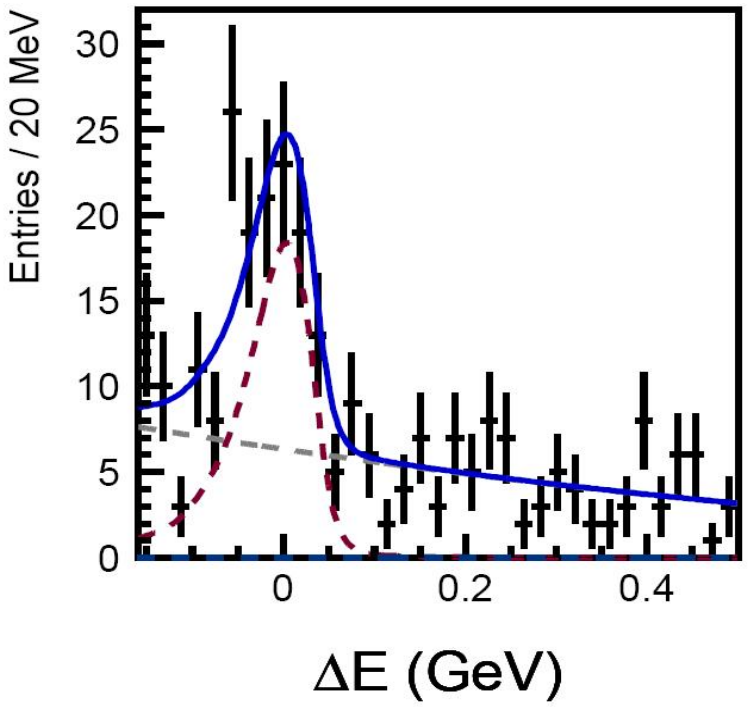
First observed by Belle in 2005 using 140/fb; **now updated with 414/fb**

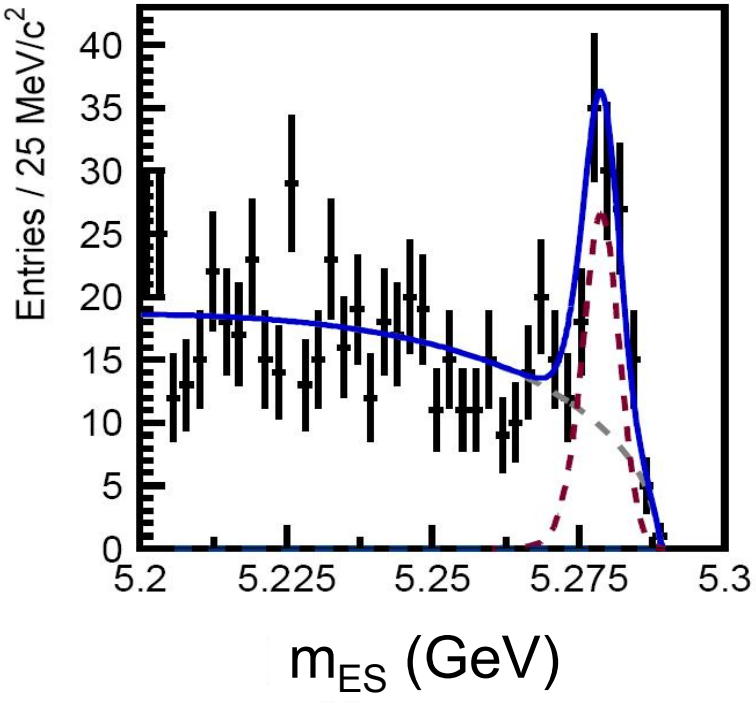


- Rare: SM predicts BF of $O(10^{-6})$
- Baryon restricts phase space
  → access to low photon momentum
- Provides information on the baryon production mechanism
- Helicity probes spin of s quark; large (>>5%) "wrong"-helicity contribution would indicate NP

$B \to p\bar{\Lambda}\gamma$: Branching Fraction

Preliminary





98 $^{+13}_{-12}$ signal events for $m_{p\Lambda} < 2.8$ GeV ;
stat. significance: 14.3σ

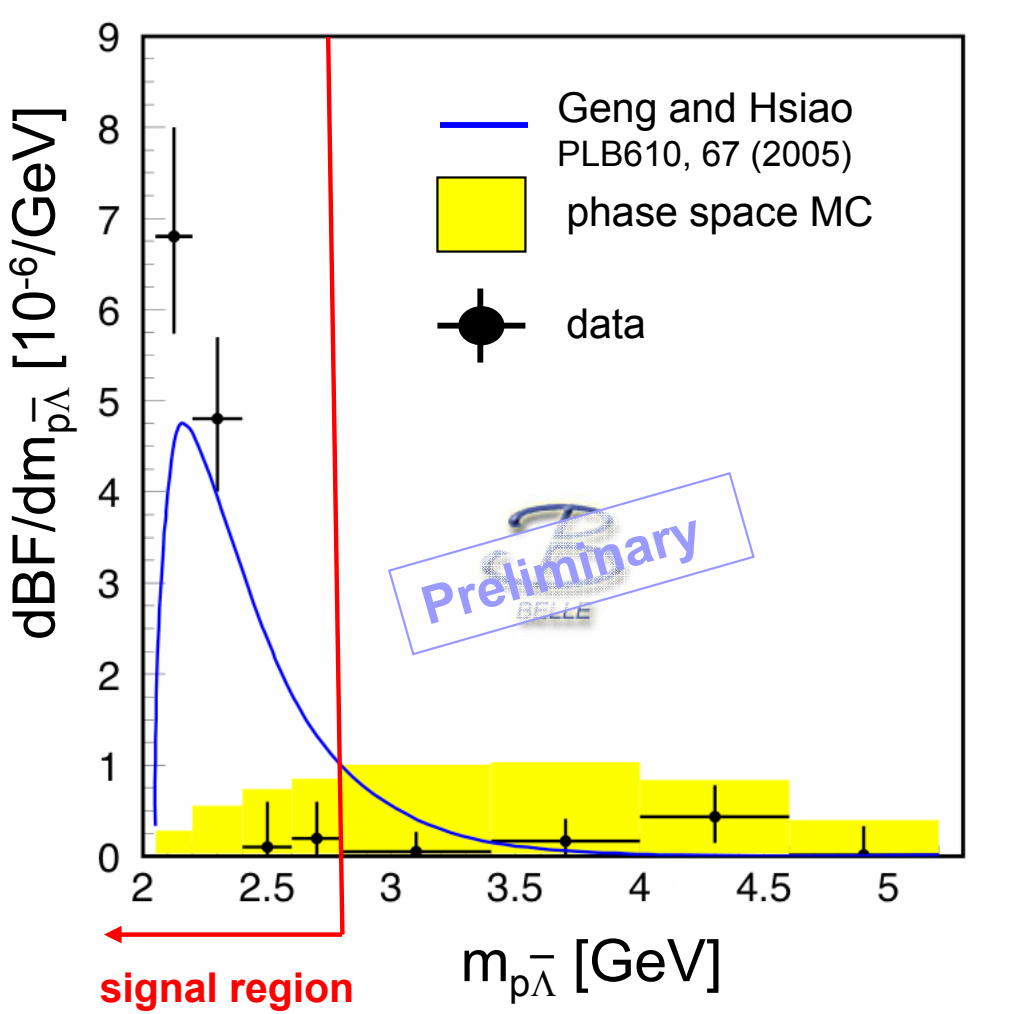
Full mass range: $BF(B \to p\bar{\Lambda}\gamma) = (2.45\ ^{+0.44}_{-0.38}\ \pm 0.22) \times 10^{-6}$

Compare to theory:

- **Pole Model** [Cheng and Yang, Phys.Lett. B533, 271 (2002)] : **~ 1.2 x 10^{-6}**
- **QCD counting rules** [Geng and Hsiao, Phys.Lett. B610, 67 (2005)] : **~ 1.0 x 10^{-6}**

$B \to p\bar{\Lambda}\gamma$: Di-Baryon Mass

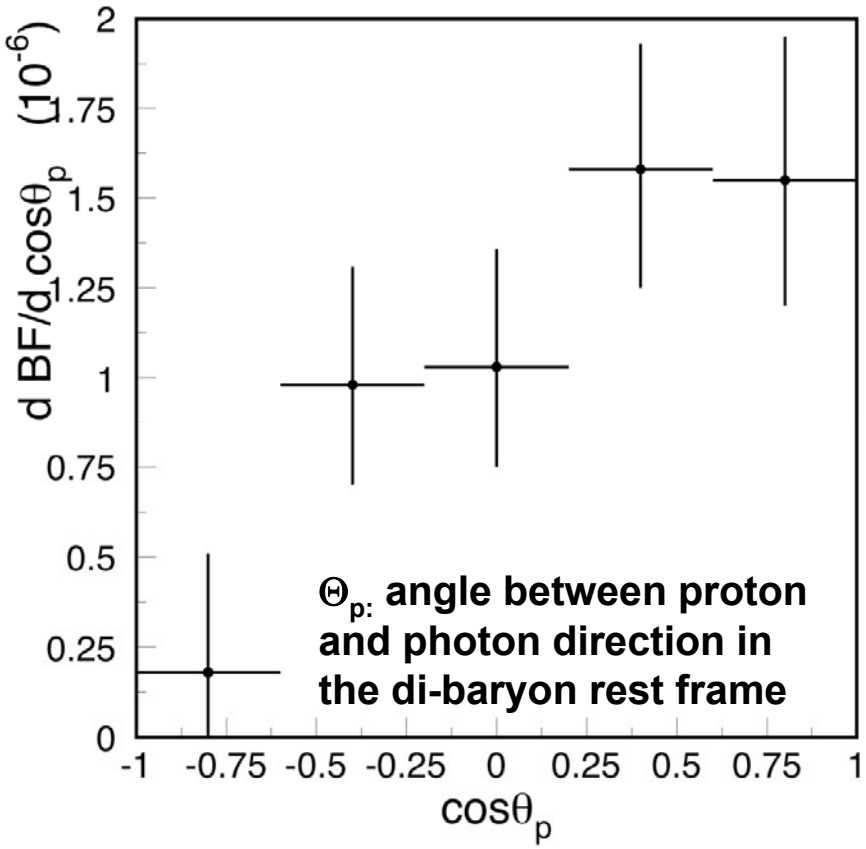
Near-threshold enhancement (as observed in other baryonic B decays):



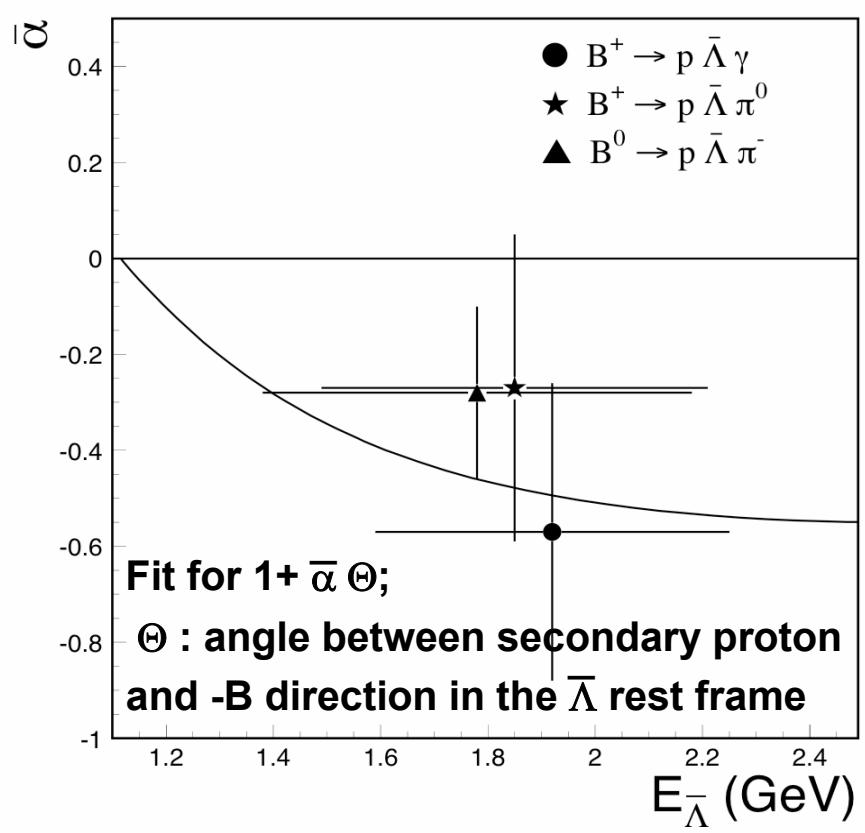
$B \to p\bar{\Lambda}\gamma$: Angular Analysis

Preliminary

- **Helicity angle**



- **Anisotropy vs. Λ energy**



consistent with short-distance $b \to s\gamma$ picture

consistent with left-handedness of $b \to s$ weak decays

Aside: B → pΛ̄π

Preliminary

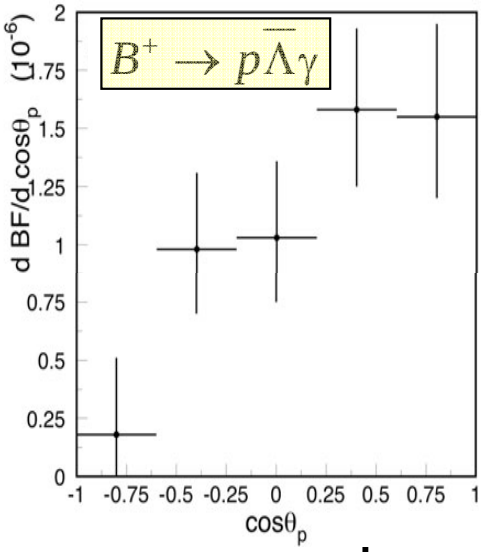
Mode	Y	σ	$\mathcal{B}$ (10^{-6})	A_θ	A_{CP}
$B^+ \to p\bar{\Lambda}\gamma$	114^{+18}_{-16}	14.5	$2.45^{+0.44}_{-0.38} \pm 0.22$	$0.29 \pm 0.14 \pm 0.03$	$0.17 \pm 0.16 \pm 0.05$
$B^+ \to p\bar{\Lambda}\pi^0$	89^{+19}_{-17}	10.2	$3.00^{+0.61}_{-0.53} \pm 0.33$	$-0.16 \pm 0.18 \pm 0.03$	$0.01 \pm 0.17 \pm 0.04$
$B^0 \to p\bar{\Lambda}\pi^-$	178^{+18}_{-16}	20.0	$3.23^{+0.33}_{-0.29} \pm 0.29$	$-0.41 \pm 0.11 \pm 0.03$	$-0.02 \pm 0.10 \pm 0.03$

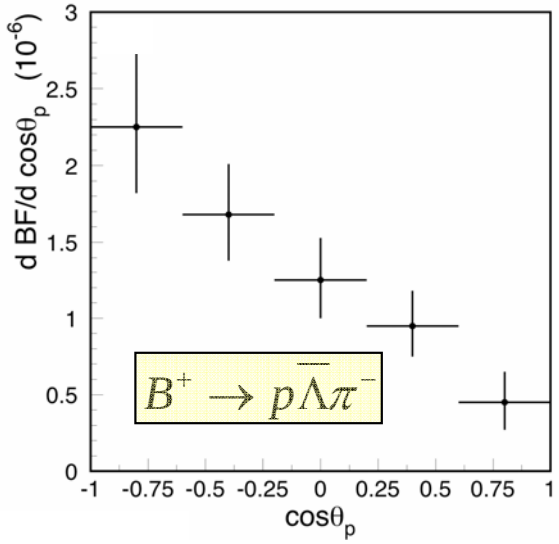
Summary of preliminary results: Y is the fitted signal or upper limit at 90% confidence, σ is the statistical significance, $\mathcal{B}$ is the branching fraction, A_θ is the angular asymmetry and A_{CP} is the charge asymmetry.

First observation

$$\frac{BF(B^+ \to p\bar{\Lambda}\pi^0)}{BF(B^+ \to p\bar{\Lambda}\pi^-)} = 0.93^{+0.21}_{-0.19} \pm 0.09$$

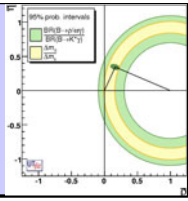
(naïve factorization: 0.5)





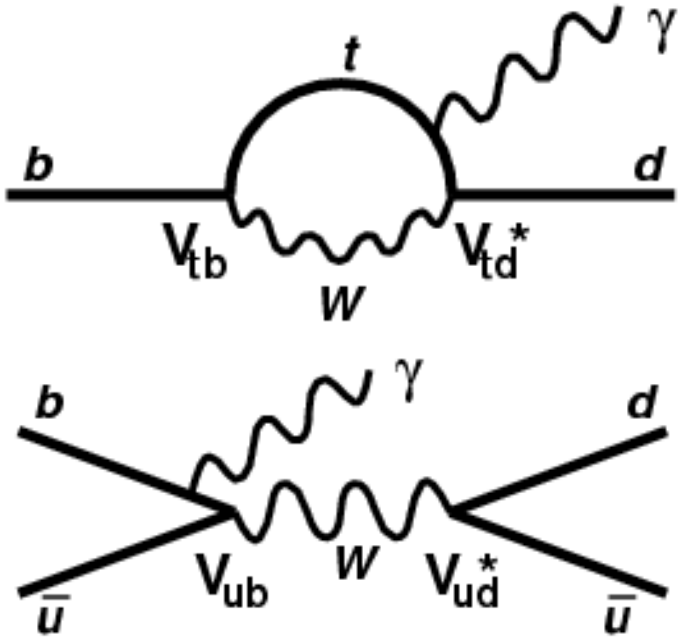
- Some indication of differences in decay dynamics
- Long-distance effects in B → pΛ̄π⁻ ?

Exclusive b→dγ Decays

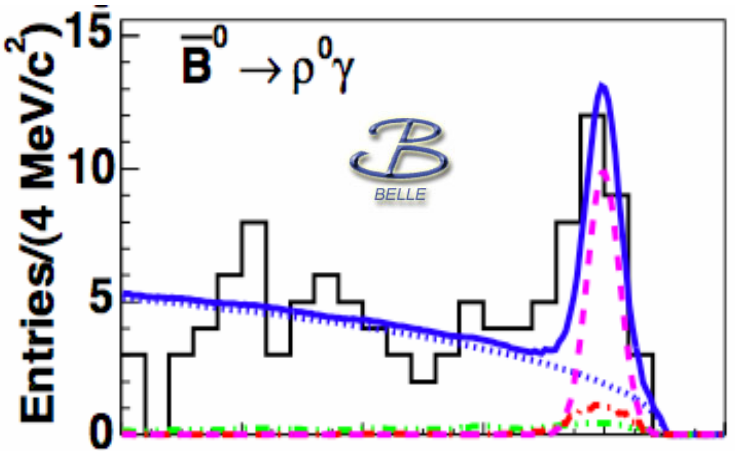


i.e. $B \to \rho^{\pm}\gamma$, $B \to \rho^{0}\gamma$, $B \to \omega\gamma$

- SM branching fraction suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ w.r.t. b→sγ
- Second sizable SM diagram
  - expect significant (~10%) SM A_{CP}
- BF constrains $|V_{td}/V_{ts}|$ within SM
  - comparison with B_s mixing provides window on NP



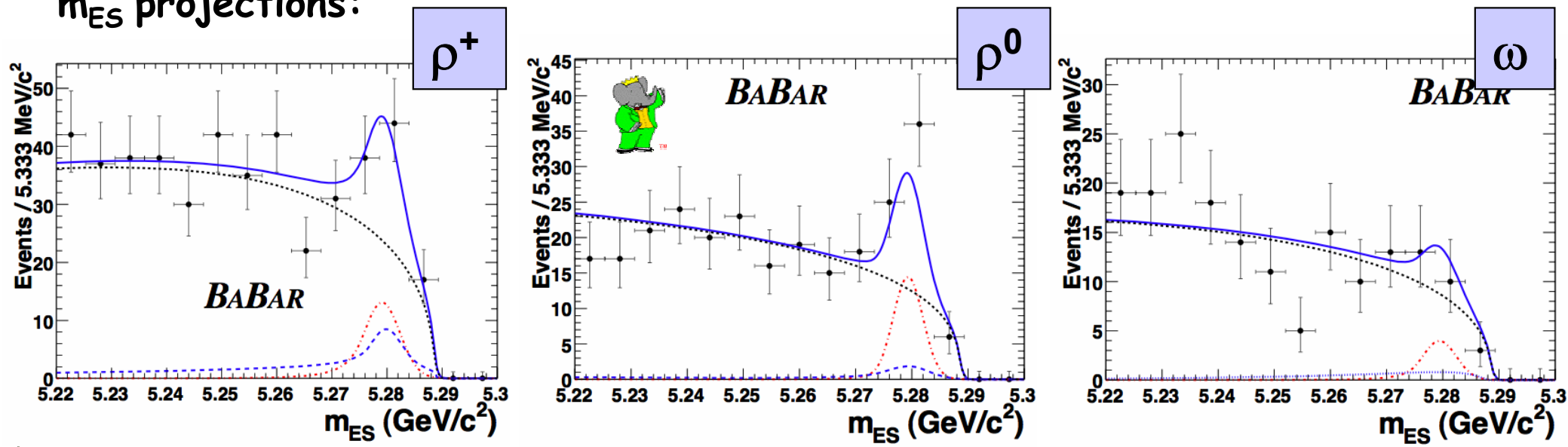
- First observed by Belle ($B \to \rho^0\gamma$)
  PRL 96, 221601 (2006)
- Here: recent BaBar measurement
  PRL 98, 151802 (2007)



$B \to (\rho,\omega)\gamma$: BaBar Analysis [316 fb^{-1}]

- Reconstruct $\rho^{+/0} \to \pi^+\pi^{0/-}$, $\omega \to \pi^+\pi^-\pi^0$
- Background suppression/discrimination is key:
  - continuum [Neural Net with event shape, B tagging information, …]
  - $B \to K^*\gamma$ [particle ID]
  - $B \to (\rho^{\pm,0},\omega)(\pi^0,\eta)$ [veto and helicity angle]
- Perform 4D (5D) likelihood fits for ρ (ω) channels
  - [m_{ES}, ΔE, NN output, decay angles]

m_{ES} projections:



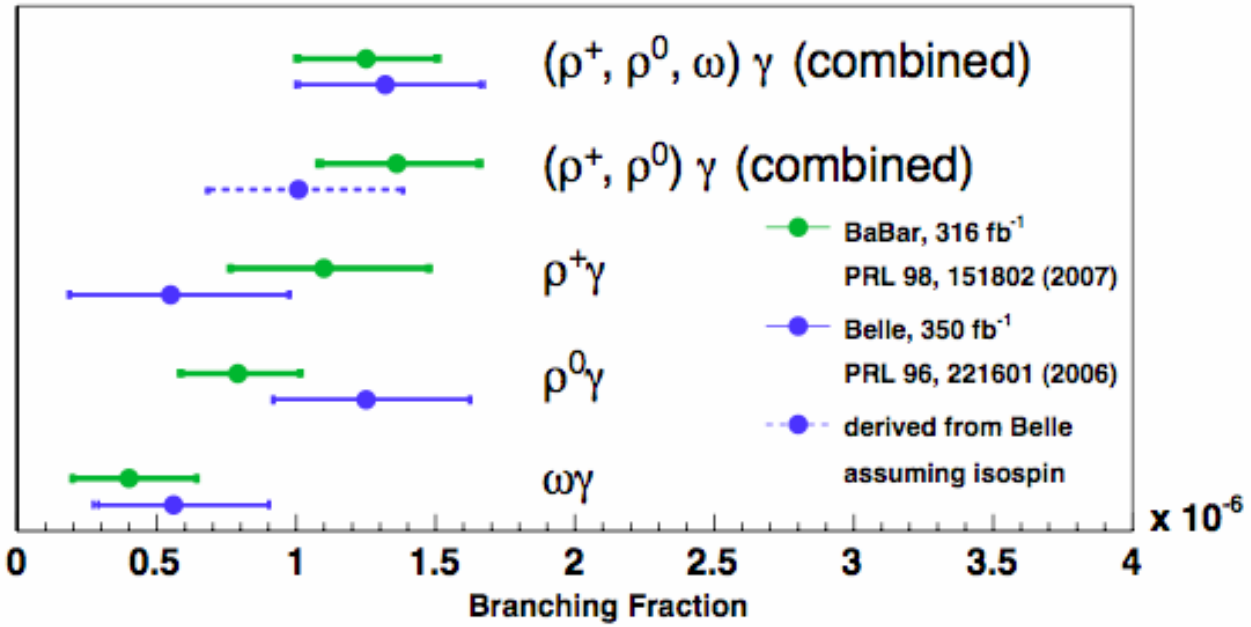
B → (ρ,ω)γ : Branching Fractions

PRL 98, 151802 (2007)

PRL 96, 221601 (2006)

Mode	N_{signal}	Significance	$BF(10^{-6})$	N_{signal}	Significance	$BF(10^{-6})$
$B^+ \to \rho^+\gamma$	$42.0^{+14.0}_{-12.7}$	3.8σ	$1.10^{+0.37}_{-0.33} \pm 0.09$	8.5	1.6σ	$0.55^{+0.42+0.09}_{-0.36-0.08}$
$B^0 \to \rho^0\gamma$	$38.7^{+10.6}_{-9.8}$	4.9σ	$0.79^{+0.22}_{-0.20} \pm 0.06$	20.7	5.2σ	$1.25^{+0.37+0.07}_{-0.33-0.06}$
$B^0 \to \omega\gamma$	$11.0^{+6.7}_{-5.6}$	2.2σ	$0.40^{+0.24}_{-0.20} \pm 0.05$	5.7	2.3σ	$0.56^{+0.34+0.05}_{-0.27-0.10}$
Combined	**simultaneous fit**	6.4σ	$1.25^{+0.25}_{-0.24} \pm 0.09$	36.9	5.1σ	$1.32^{+0.34+0.10}_{-0.31-0.09}$

- First evidence of $B^+ \to \rho^+\gamma$
- First BaBar observation of $B \to (\rho/\omega)\,\gamma$
- Consolidated experimental picture; BaBar and Belle results agree well



$B \to (\rho,\omega)\gamma$: CKM Constraint

- Together with $B \to K^*\gamma$, measures $|V_{td}/V_{ts}|$ within SM
- Hadronic uncertainties partially cancel in ratio

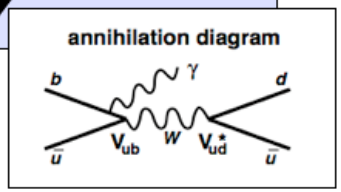
isopin factor: 1(.5) for $\rho^{\pm}(\rho^0)$

form factor ratio

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

well measured

annihilation amplitude corrections



[see Ali, Lunghi, Parkhomenko (2001), update: PLB 595, 323 (2004)]

Experiment	$\mathcal{B}(10^{-6})$
Babar	$1.25^{+0.25}_{-0.24} \pm 0.08$
Belle	$1.32^{+0.34+0.10}_{-0.31-0.09}$
Average	$1.28^{+0.20}_{-0.19} \pm 0.06$

stat. syst.

using **Ball, Jones, Zwicky, PRD 75 054004 (2007)**

B factories average:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.202^{+0.017}_{-0.016} \pm 0.015$$

exp. theor.

$B \to (\rho,\omega)\gamma$: Comparison with B_s Mixing

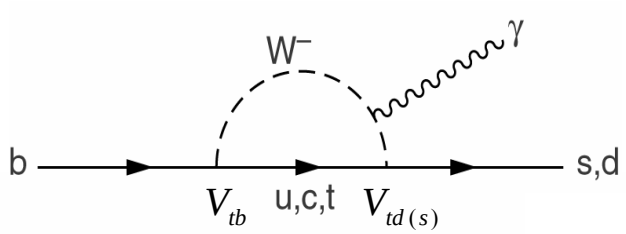
B factories:

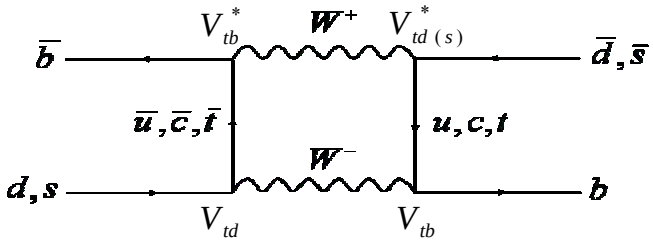
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.202^{+0.017}_{-0.016} \pm 0.015$$

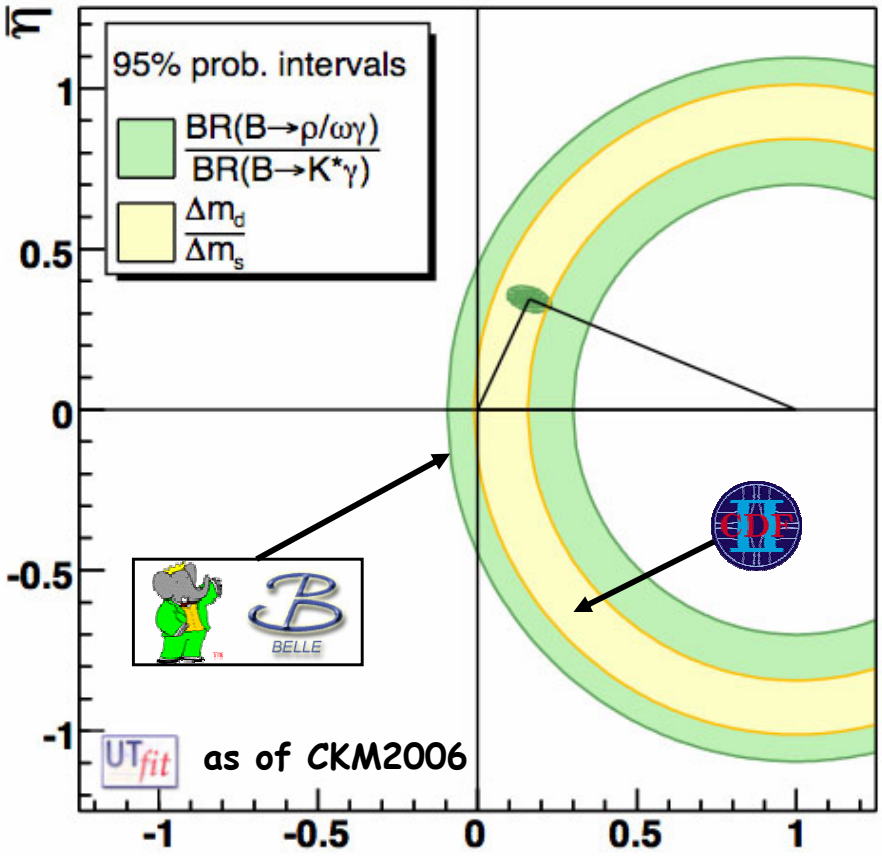
Experiment | Theory

CDF: PRL 97, 242003 (2006)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$







- Independent physics providing same constraint within the SM
- New Physics could enter these two processes differently
- Excellent agreement but within still sizeable uncertainties

- Significant improvement will take effort from experiment and theory
- Asymmetry measurements?

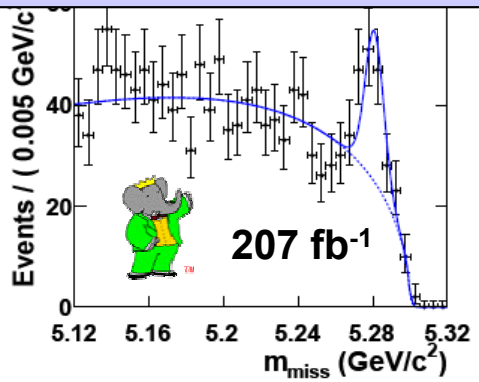
More Results Since FPCP 2006

BF($B^+ \to K^+\phi\gamma$) =
$(3.5\pm0.6\pm0.4)\times10^{-6}$

BF($B^0 \to K^0\phi\gamma$)
$< 2.7\times10^{-6}$ 90% C.L.

$A_{CP}(B^+ \to K^+\phi\gamma)$
$= (-26\pm14\pm5)\%$.

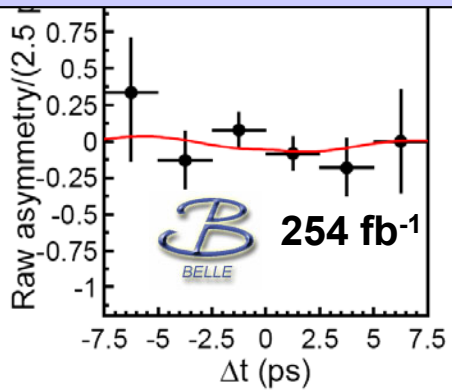
$B \to K\phi\gamma$ (BF and A_{CP})



Phys.Rev. D75, 051102 (2007)

$S(K_S\pi^0\gamma)$ =
$(-0.10\pm0.31\pm0.07)$
$A(K_S\pi^0\gamma)$ =
$(-0.20\pm0.20\pm0.06)$
$S(K^*\gamma)$ =
$(-0.32\pm0.36\pm0.05)$
$A(K^*\gamma)$ =
$(-0.20\pm0.24\pm0.05)$

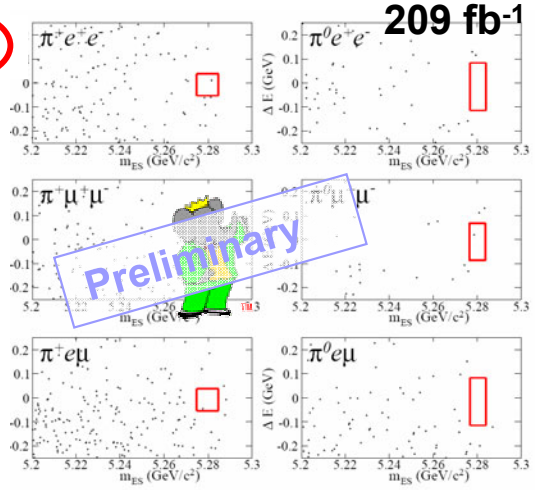
TDCPV in $B \to K_S\pi^0\gamma$



Phys.Rev. D74, 111104 (2006)

$B \to \pi l^+ l^-$

	BF U.L.×10^{-7}
$B^+ \to \pi^+ e^+ e^-$	1.8
$B^0 \to \pi^0 e^+ e^-$	1.4
$B^+ \to \pi^+ \mu^+ \mu^-$	2.8
$B^0 \to \pi^0 \mu^+ \mu^-$	5.1
$B^+ \to \pi^+ e^\pm \mu^\mp$	1.7
$B^0 \to \pi^0 e^\pm \mu^\mp$	1.4
$B^+ \to \pi^+ \ell^+ \ell^-$	1.2
$B^0 \to \pi^0 \ell^+ \ell^-$	1.2
$B \to \pi \ell^+ \ell^-$	0.91
$B \to \pi e^\pm \mu^\mp$	0.92



hep-ex/0703018, subm. to PRL

$B \to K^{(*)}\nu\bar{\nu}$

see

Summary and Conclusions

- **Radiative Penguin decays of B Mesons**
  - continue to generate a lot of activity (both experiment and theory)
- **Measurement of b→sγ with hadronic B tag**
  - new tool to cover this essential part of the B factory program
  - complementary to previous experimental approaches
  - importance will increase with growing data sets
- **Experimental study of B →pΛ̄γ/π decays**
  - provides interesting information on underlying dynamics
- **Exclusive b →dγ decays** (B →ρ/ωγ)
  - continue to move from limits to signals
  - B_s mixing provides excellent SM reference
  - no hint of NP yet; need to reduce uncertainties + add observables

- **More to come…**
  - much more data available and being taken
  - continue to improve experimental methods