Exclusive Radiative *B* Decays at BaBar

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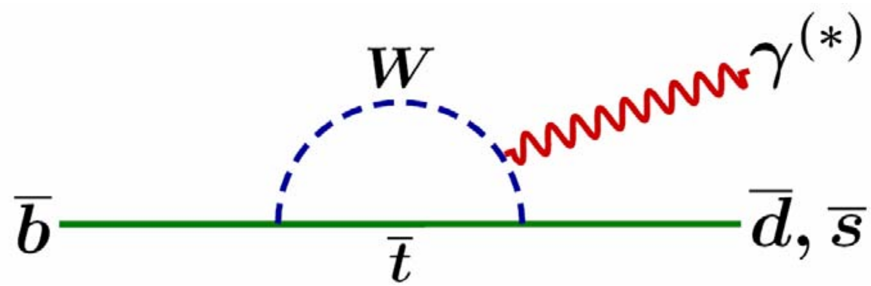
on behalf of the BaBar collaboration

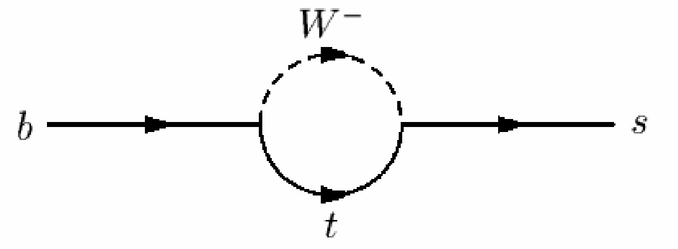
Outline

- **motivation**
- **BaBar measurements of**
  - $B \to (\rho,\omega)\gamma$
  - $B \to K^{(*)} l^+ l^-$
  - $B \to K_s^0 \pi^0 \gamma$ (TD CPV)
  - $B \to K\pi\pi\gamma$
  - $B \to D^{*0}\gamma$



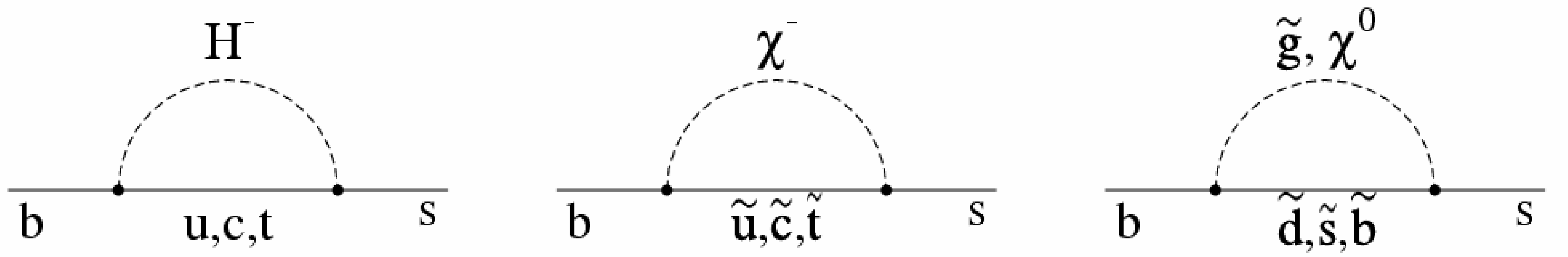
b → s,d transitions

- b → s,d transitions are a Flavor Changing Neutral Current
  - absent in the standard model at tree-level
  - exist only at loop level



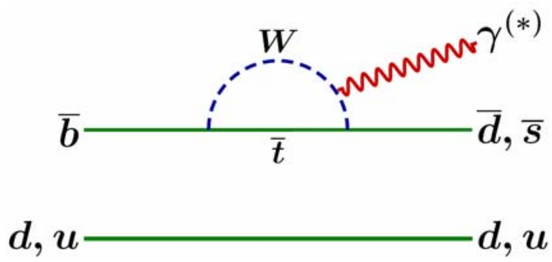
- heavy particles dominate in loop
  - in SM: sensitive to 'top' CKM parameters: $A \to V_{tb}V^*_{tq}$
  - sensitive to high virtual mass scale:

    → e.g. from new physics

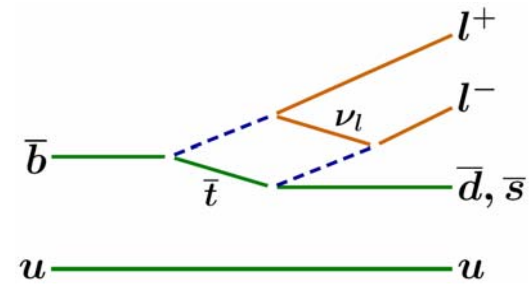


Radiative decays: B $\to X\gamma$ and B $\to Xl^+l^-$

- topologies:



`radiative penguin'



`WW box'

- theoretical framework: Operator Product Expansion
  - ➢ separate weak scale from *B*-mass scale

- firm theoretical predictions for ***inclusive*** branching fractions

quark-hadron duality: $\Gamma(b \to s\gamma) \approx \Gamma(B \to X_s\gamma)$

$BF(b \to s\gamma)_{TH}$ = (3.57 ± 0.30) x 10^{-4} (SM NLO, Buras et al 2002)

$BF(b \to s\gamma)_{EXP}$ = (3.54 ± 0.30) x 10^{-4} (HFAG, 2004)

See talk by Colin Jessop

➢ agreement highly constrains new physics at the electroweak scale!

Exclusive Radiative Decays

- ***exclusive*** **decays are experimentally easier**

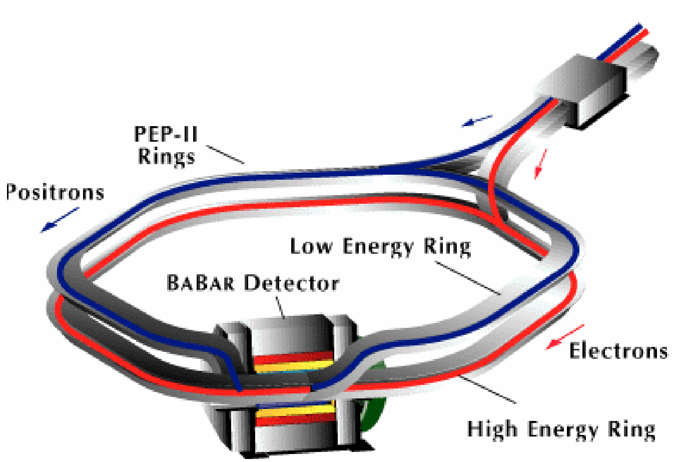
  $B \to K^*\gamma$, $B \to \rho\gamma$, $B \to K^{(*)} l^+l^-$, …

- **theoretical predictions more complicated**
  - **hadrons ≠ quarks → need Form Factors**
  - **different approaches: LCSR,CLFQM, lattice,…**

- **reasonably clean predictions for**
  - **ratios of branching fractions**
  - **CP asymmetries**
  - **photon polarization: angular distributions, mixing-induced CPV**
  - **forward-backward asymmetry in $X_s l^+l^-$**

➢ **several new physics models allow for observable differences with SM even if inclusive branching fraction is close to SM**

PEP-II and Babar



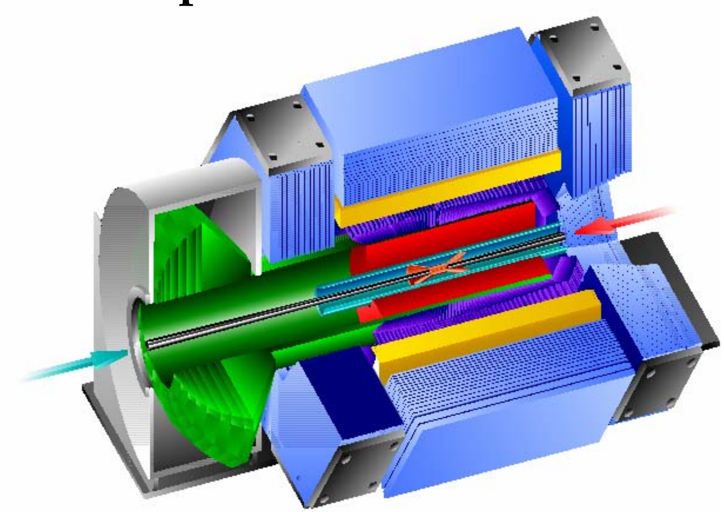
PEP-II: asymmetric-energy e+e- collider

- operating at Y(4S) resonance (10.580 GeV)
- asymmetric energy: 9.0 GeV e^- vs 3.1 GeV e^+
- hadronic cross-sections:

  uds / cc / bb = 2.1 / 1.3 / 1.1 nb
- integrated lumi (July 2005): 255 fb^{-1}
  - ➢ over 250M BB pairs!

BaBar

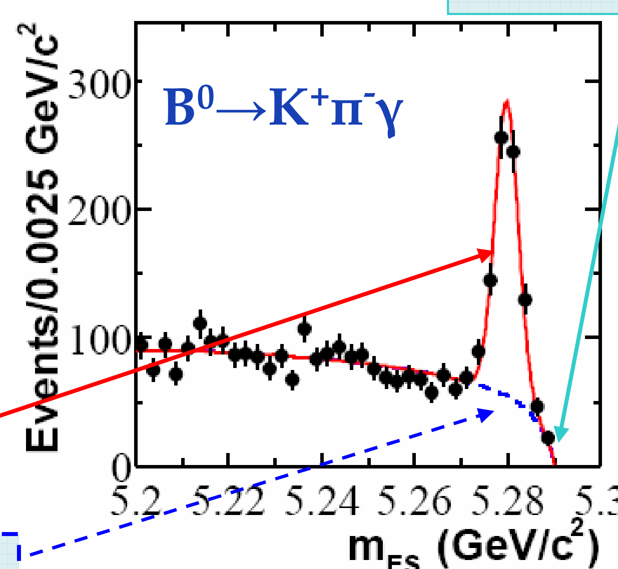
- 1.5 T superconducting coil
- 40 layer wire drift chamber
- 5 layer double sided silicon vertex detector
- CsI electromagnetic calorimeter (γ,$e^{\pm}$)
- cherenkov detector ($\pi/K/p$)
- muon detector (μ,K_L)



results presented here based on between 80 fb^{-1} and 210 fb^{-1}

Experimental issues

- main challenge: rare decays → large backgrounds
- common strategy
  - select high energy photons / clean lepton pairs
  - suppress background with event topology, vertex separation, tag on opposite B, π^0/η vetos, …
  - estimate 'peaking' background from other *B* decays from MC
  - extract signal with <u>multivariate maximum likelihood fit</u> m_{ES}, ΔE, `event shape', …
- for illustrations in this talk: <u>m_{ES} distribution</u>
  - use initial Υ(4S) four-momentum and the fact that 2nd particle is also a B



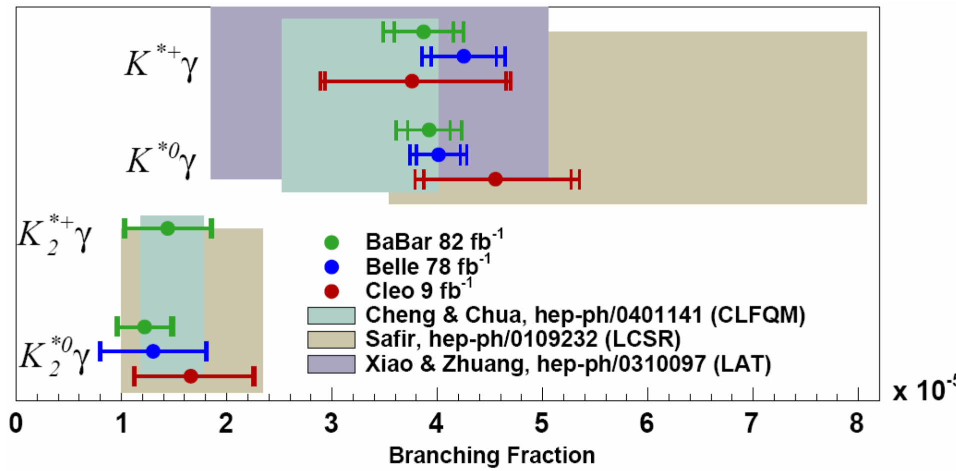
PRD 70, 112006 (2004)

Most easily accessible: $B \to K^*\gamma$

BF measurements on 82 fb^{-1} :

$\mathrm{B}(B^0 \to K^{*0}\gamma) = (38.7 \pm 2.8 \pm 2.6) \times 10^{-6}$

$\mathrm{B}(B^+ \to K^{*+}\gamma) = (39.2 \pm 2.0 \pm 2.4) \times 10^{-6}$



- almost systematics limited !
- data more accurate than theory
  - ➔ important calibration for Form Factor calculations
- asymmetries also measured precisely:

	BaBar	theory
A_{CP}	$-0.013 \pm 0.036 \pm 0.010$	$\lvert A_{CP} \rvert < 0.01$ (Kagan and Neubert, 1998)
$\Delta_{0-} = \dfrac{\Gamma(K^{*0}\gamma) - \Gamma(K^{*-}\gamma)}{\Gamma(K^{*0}\gamma) + \Gamma(K^{*-}\gamma)}$	$0.050 \pm 0.045 \pm 0.028 \pm 0.024$	0.05-0.1 (Kagan and Neubert, 2002)

from B^+B^- / B^0B^0

PRL 92, 111801 (2004)

$B \to \rho\gamma$ and $B \to \omega\gamma$

Motivation:

- $b \to d\gamma$ transition, BF $\propto |V_{td} V_{tb}|^2$
- SM prediction: 0.9 - 1.8 x 10^{-6}
- clean SM prediction for ratio of $B \to \rho/\omega\gamma$ and $B \to K^*\gamma$:

Ali and Parkhomenko, Eur.Phys.JC 23,89 (2002)
Ali et al, PLB 595,323 (2004)

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

difference in dynamics (such as W-annihilation) $\Delta R \approx 0.1 \pm 0.1$

form factor ratio $\zeta^2 \approx 0.85 \pm 0.1$ (largest uncertainty)

with average BF:

$$\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma] = \frac{1}{2}\left\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}\left[\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma)\right]\right\}$$

Experimental difficulties

- large continuum background ➔ reject with event shape, ΔZ
- background from $B \to K^*\gamma$ ➔ reject with PID, ΔE
- background from $B \to \rho\pi^0, \rho\eta, \omega\pi^0, \omega\eta$ ➔ reject with helicity angles, π^0/η vetos

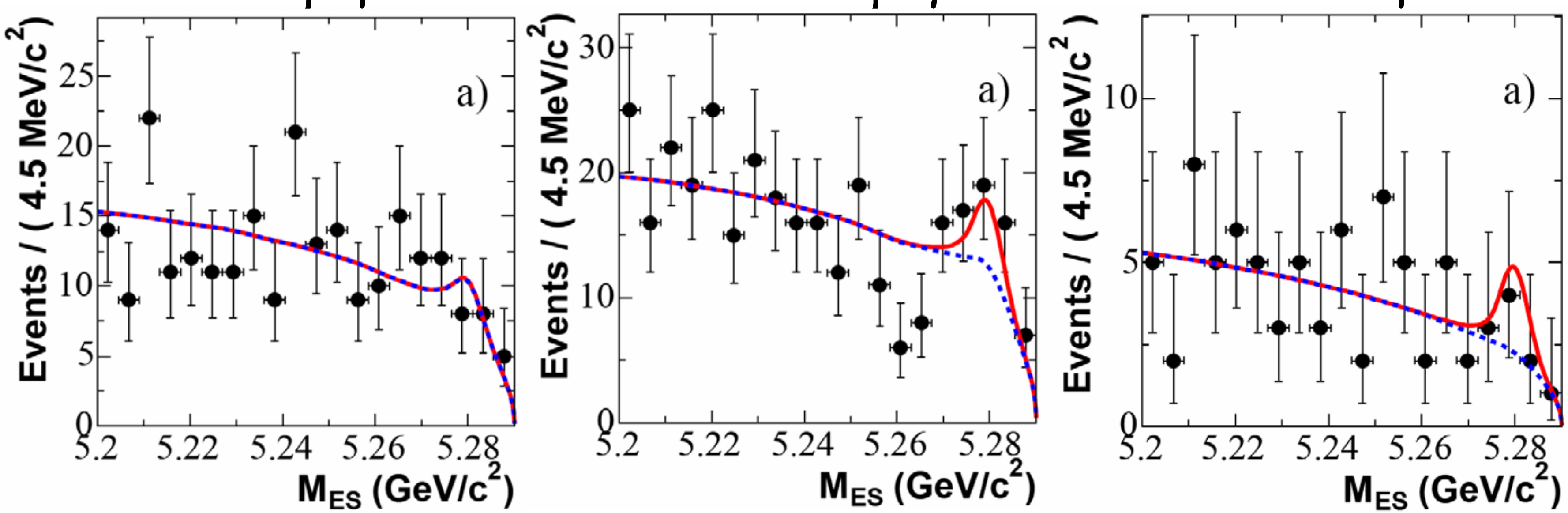
$B \to \rho\gamma$ and $B^0 \to \omega\gamma$

Yield and BF in 211M BBar

Mode	Signal Yield	$\epsilon(\%)$	$\mathcal{B}(10^{-6})$	$\mathcal{B}(10^{-6})$ 90% C.L.
$B^+ \to \rho^+\gamma$	$26\,^{+15}_{-14}\,^{+2}_{-2}$	13.2 ± 1.4	$0.9\,^{+0.6}_{-0.5} \pm 0.1$	< 1.8
$B^0 \to \rho^0\gamma$	$0.3^{+7.2+1.7}_{-5.4-1.6}$	15.8 ± 1.9	$0.0 \pm 0.2 \pm 0.1$	< 0.4
$B^0 \to \omega\gamma$	$8.3^{+5.7+1.3}_{-4.5-1.9}$	8.6 ± 0.9	$0.5 \pm 0.3 \pm 0.1$	< 1.0
Combined	—		$0.6 \pm 0.3 \pm 0.1$	< 1.2

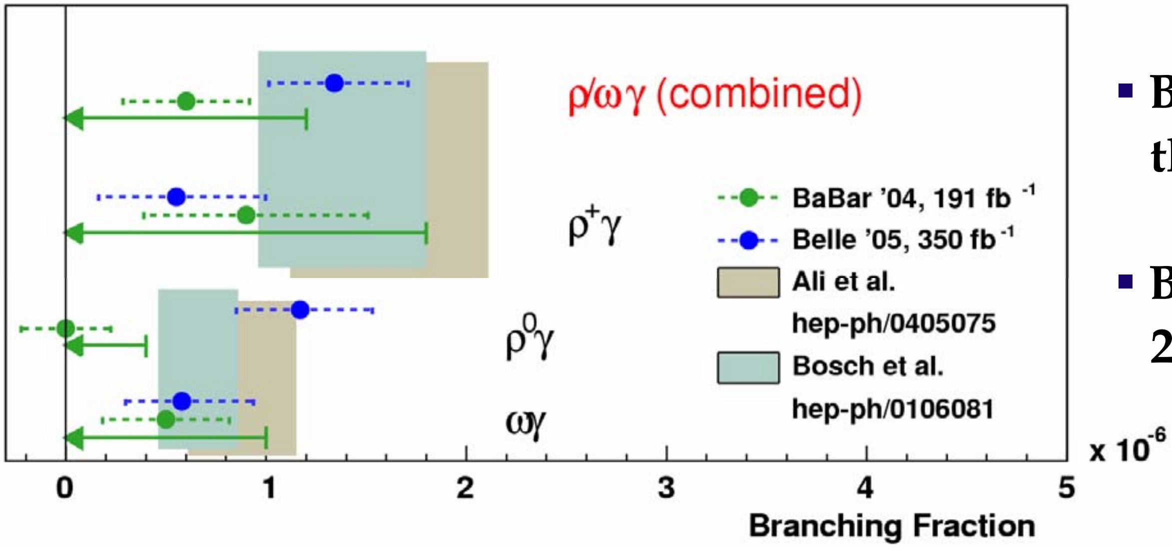
m_{ES} distributions for ***subselection*** **(efficiency ≈ 45%)**

$B^0 \to \rho^0\gamma$ $\qquad$ $B^+ \to \rho^+\gamma$ $\qquad$ $B^0 \to \omega\gamma$



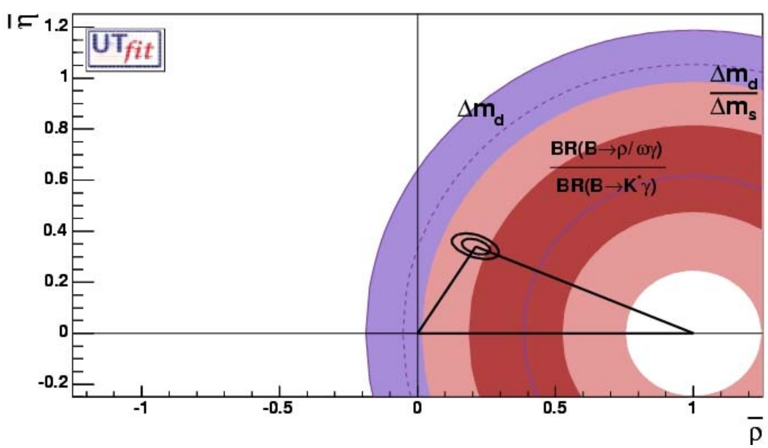
PRL 92, 111801 (2004)

$B \to \rho\gamma$ and $B^0 \to \omega\gamma$



- BaBar low compared to theory prediction
- BaBar and Belle are 2.7σ apart in $B^0 \to \rho^0\gamma$

BaBar $B \to \rho\gamma$ constraint in the Unitary Triangle



Turning things around:

- penguins are starting to provide meaningful CKM constraint!
  - ➢ no need to wait for B_s mixing ☺
- BaBar data favor a low value of V_{td}
- theory errors not negligible!

$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$

hep-ex/0507005, preliminary

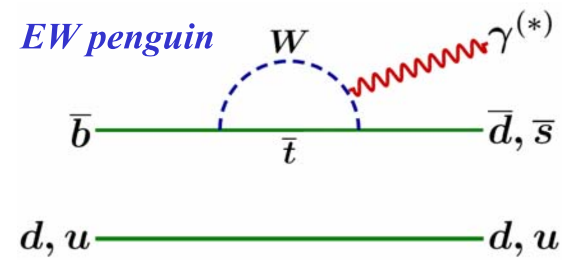
Motivation

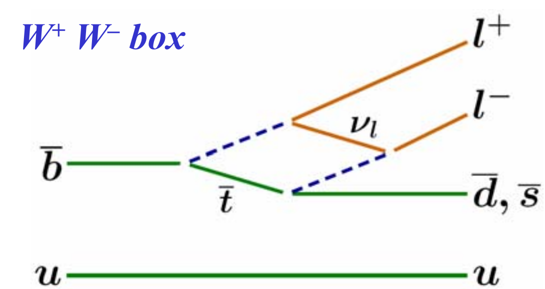
- SM predictions:
  - BF ~ 10^{-6}
  - negligible direct CP asymmetry
  - $R_K = B(B \to K\mu^+\mu^-) / B(B \to Ke^+e^-) \approx 1$
  - $R_{K^*} = B(B \to K^*\mu^+\mu^-) / B(B \to K^*e^+e^-) \approx 0.75$
  - q^2 -distribution sensitive to relative contribution of γ-, Z-penguin and box diagram
- new physics can show up in any of these

Experimental issues

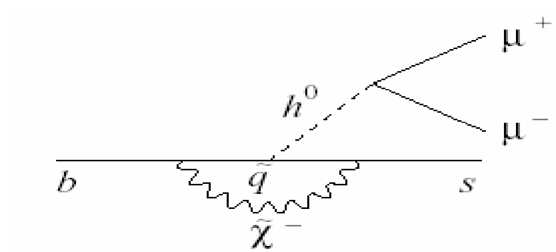
- clean signature but very small BF
- large background from $B \to K^{(*)} \psi$:
  - ➢ apply veto and use as control sample

SM diagrams





SUSY diagram

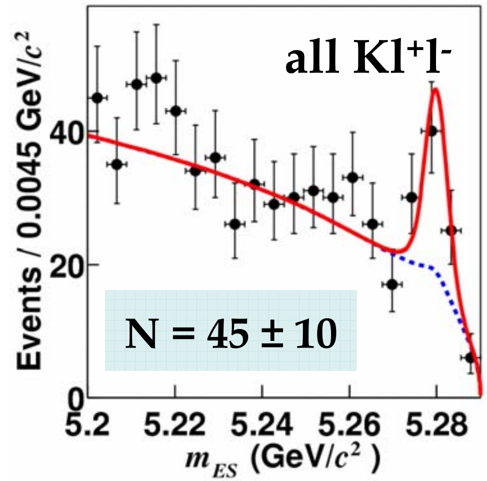


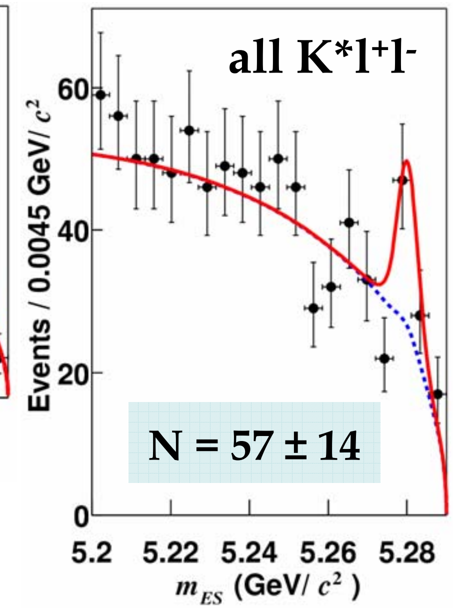
hep-ex/0507005, preliminary

$B \to K l^+ l^-$ and $B \to K^* l^+ l^-$

Event yields in 229M BBbar

	Signal yield	$\mathcal{B} \times 10^6$	signfic.
$B^+ \to K^+ e^+ e^-$	$25.9^{+7.4}_{-6.5}$	$0.43^{+0.12}_{-0.11} \pm 0.03$	5.3
$B^+ \to K^+ \mu^+ \mu^-$	$10.9^{+5.1}_{-4.3}$	$0.31^{+0.15}_{-0.12} \pm 0.04$	3.0
$B^0 \to K^0 e^+ e^-$	$2.4^{+2.8}_{-2.0}$	$0.14^{+0.16}_{-0.11} \pm 0.02$	1.2
$B^0 \to K^0 \mu^+ \mu^-$	$6.3^{+3.6}_{-2.8}$	$0.60^{+0.34}_{-0.27} \pm 0.05$	2.8
$B^0 \to K^{*0} e^+ e^-$	$29.4^{+9.5}_{-8.4}$	$1.03^{+0.33}_{-0.29} \pm 0.12$	4.4
$B^0 \to K^{*0} \mu^+ \mu^-$	$15.9^{+7.0}_{-5.9}$	$0.89^{+0.39}_{-0.33} \pm 0.14$	3.3
$B^+ \to K^{*+} e^+ e^-$	$6.2^{+7.0}_{-5.6}$	$0.77^{+0.87}_{-0.70} \pm 0.60$	1.0
$B^+ \to K^{*+} \mu^+ \mu^-$	$4.7^{+4.6}_{-3.4}$	$1.00^{+0.96}_{-0.71} \pm 0.16$	1.6





Results

$B(B \to K l^+ l^-) = (0.34 \pm 0.07 \pm 0.03) \times 10^{-6}$

$B(B \to K^* l^+ l^-) = (0.78\ ^{+0.19}_{-0.17} \pm 0.12) \times 10^{-6}$

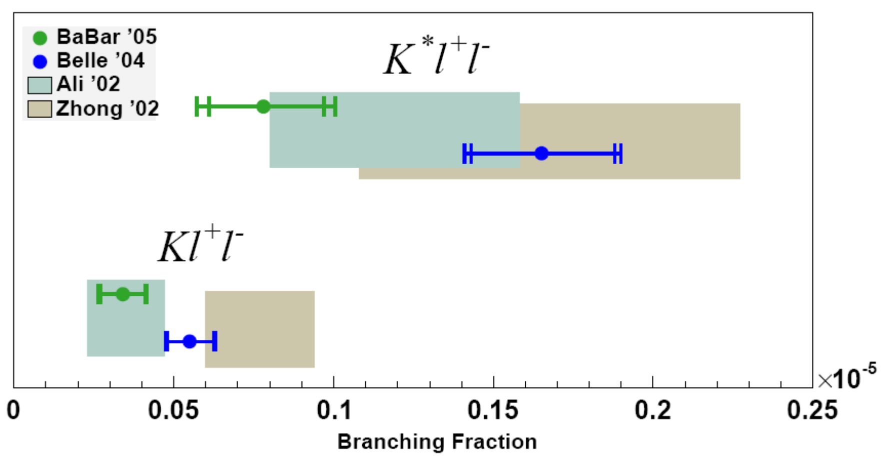
$R_K = 1.06 \pm 0.48 \pm 0.05$

$R_{K^*} = 0.93 \pm 0.46 \pm 0.12$

$A_{CP}(B^+ \to K^+ l^+ l^-) = -0.08 \pm 0.22 \pm \pm 0.11$

$A_{CP}(B^+ \to K^{*+} l^+ l^-) = 0.03 \pm 0.\ 23 \pm \pm 0.12$

comparison to SM prediction for BF



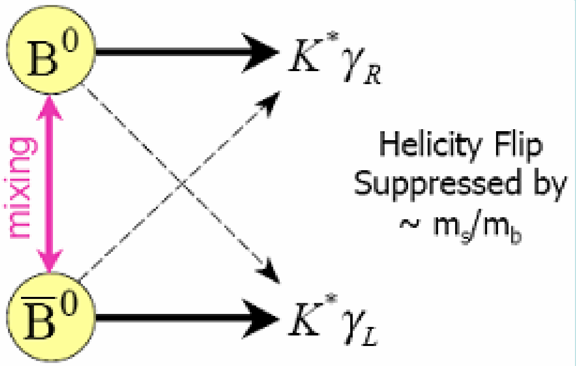
soon to come: forward-backward asymmetry

Mixing induced CP violation in $B \to K_s \pi^0 \gamma$

hep-ex/0507038, submitted to PRL

Motivation

- time-dependent CPV: interference between amplitudes for direct and 'mixed' decay
  - in $B^0 \to K^{*0}\gamma$ phase between mixed and unmixed decay is 2β
- Atwood,Gronau,Soni (1997)
  - W couples only to left-handed quark: $b \to s\,\gamma_L$
  - interference suppressed in SM: $S_{mix} \approx -0.04 \sin(2\beta)$
  - possibly large enhancement from NP
- recent theoretical development:
  - Atwood et al (2004): can use $K_s\pi^0$ even if not from resonance
  - Grinstein at al (2005): final state effects $O(\Lambda/m_B)$ depend on $m_{K\pi}$



Analysis

- split sample in K* (0.8 < m(Kπ)< 1.0 GeV) and 'non-K*' (1.1 < m(Kπ) <1.8 GeV)
- max likelihood fit to m_{ES}, ΔE, Δt, and event shape

Main complications

- measure B vertex with one trajectory (like in $K_s\pi^0$, well established by now)
- large background from other B decays: assign systematic uncertainty

hep-ex/0507038, submitted to PRL

Mixing induced CP violation in $B \to K_s \pi^0 \gamma$

Results:

0.8 < $m_{K\pi}$ < 1.0 GeV:

N = 156 ± 16

S = −0.21 ± 0.40 ± 0.05

C = −0.40 ± 0.23 ± 0.04

1.1 < $m_{K\pi}$ < 1.8 GeV:

N = 59 ± 13

S = 0.9 ± 1.0 ± 0.2

C = −1.0 ± 0.5 ± 0.2

K*(890) γ :

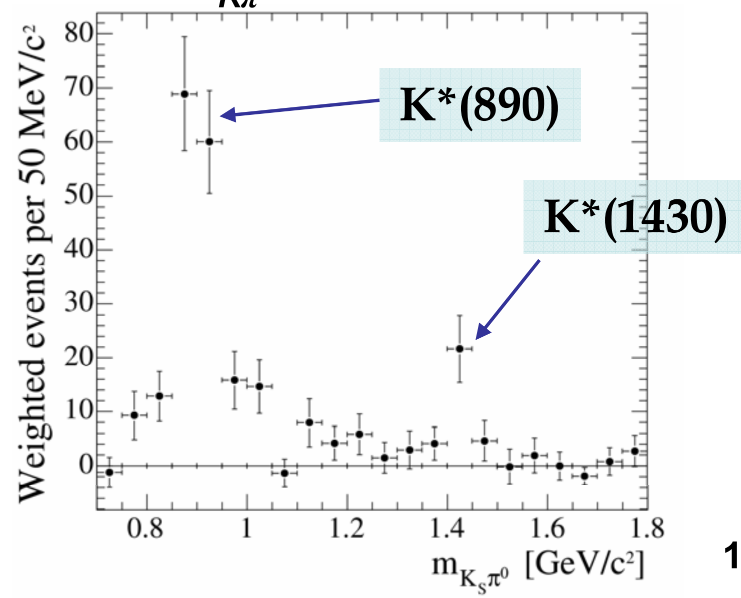
- in agreement with SM

  but statistical errors still large

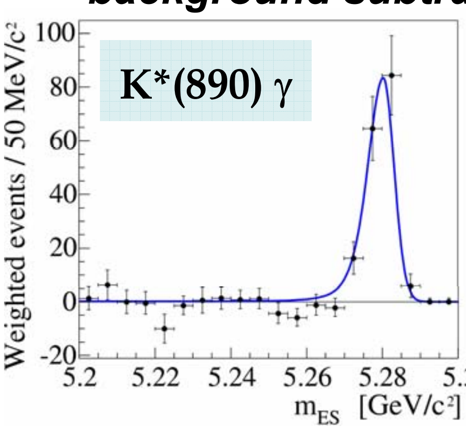
other $K_s \pi^0 \gamma$:

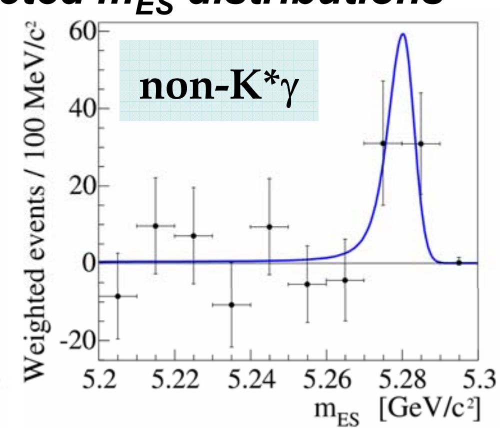
- only small contribution to total precision
- large syst. uncertainty due to other B decays

$m_{K\pi}$ distribution



background subtracted m_{ES} distributions





hep-ex/0507031, preliminary

$B \rightarrow K\pi\pi\gamma$

Motivation (Gronau et al (2002))

- photon polarization can be probed via up-down asymmetry
- requires interference through resonances $(K\pi^+)\,\pi^0 \;\leftrightarrow\; (K\pi^0)\,\pi^+$

Analysis strategy

- select candidates in four decay modes:

  $K^+\pi^-\pi^+\gamma,\; K^+\pi^-\pi^0\gamma,\; K^0\pi^+\pi^-\gamma,\; K^0\pi^+\pi^0\gamma$

  (modes with 2 pi0 have too much background)
- maximum likelihood fit to ΔE, m_{ES}

Experimental challenges

- large continuum background
  - ➔ reject with cut on event-shape Fisher
- background from other $B\rightarrow X_s\gamma$ ('feed-up' and 'feed-down')
  - ➔ estimate impact with MC
- cross-feed between modes
  - ➔ fit all modes simultaneously using cross-feed matrix

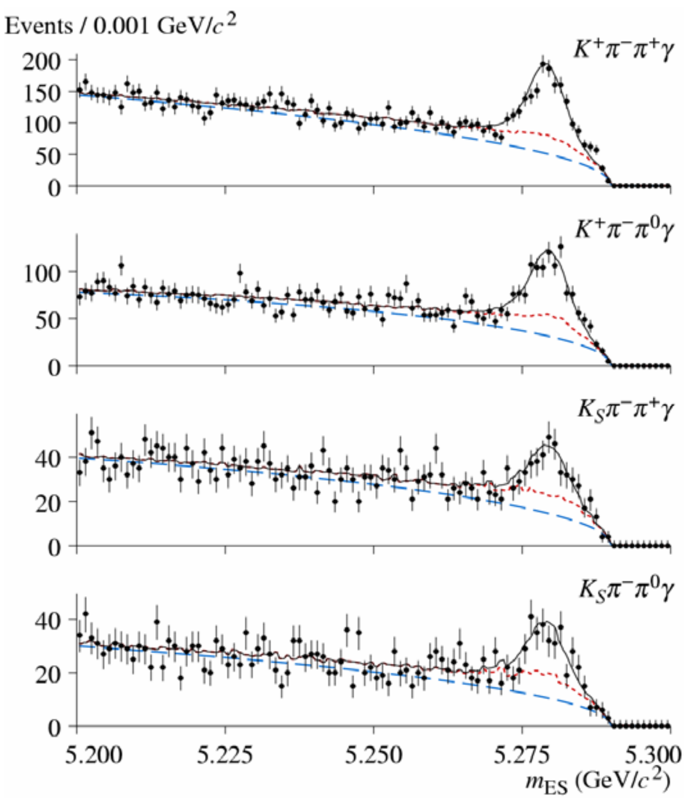
hep-ex/0507031, preliminary

Branching fraction of $B \to K\pi\pi\gamma$

Yields and branching fractions in 230M BB decays

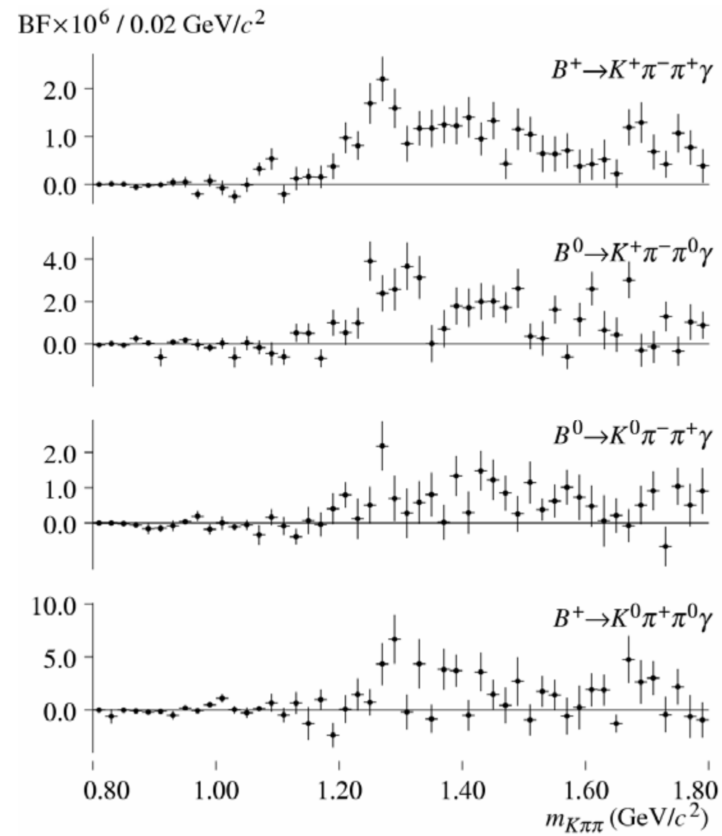
Channel	Yield	Branching Fraction (10^{-5})
$K^+\pi^-\pi^+\gamma$	899 ± 38	$2.95 \pm 0.13 \pm 0.19$
$K^+\pi^-\pi^0\gamma$	572 ± 31	$4.07 \pm 0.22 \pm 0.31$
$K^0\pi^+\pi^-\gamma$	176 ± 20	$1.85 \pm 0.21 \pm 0.12$
$K^0\pi^+\pi^0\gamma$	164 ± 15	$4.56 \pm 0.42 \pm 0.30$

first observation! (for $K^+\pi^-\pi^0\gamma$ and $K^0\pi^+\pi^0\gamma$)



$K\pi\pi$ invariant mass

(background subtracted)



Branching fraction of $B \to K\pi\pi\gamma$

hep-ex/0507031, preliminary

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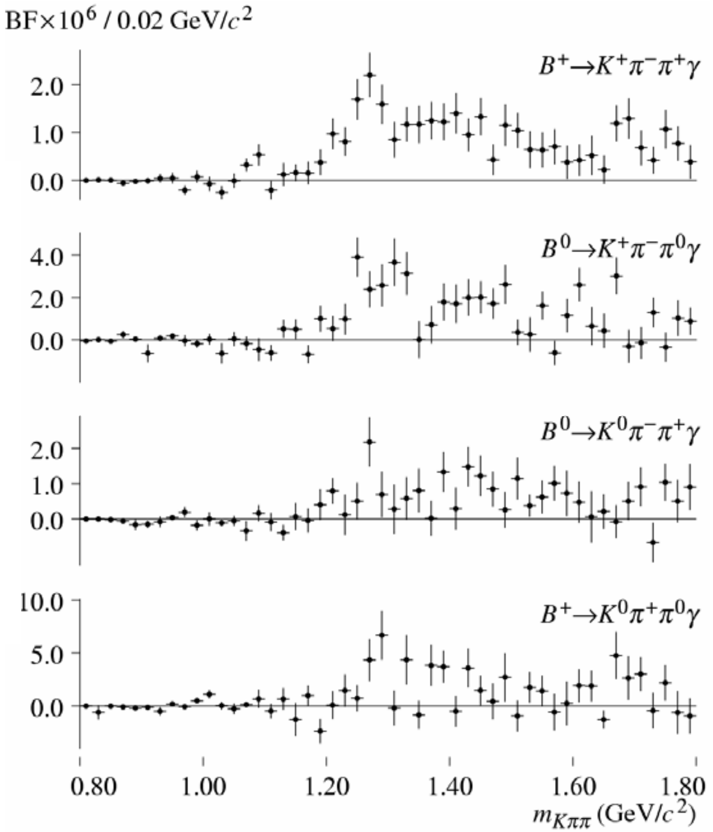
first observation!

$K\pi\pi$ invariant mass (background subtracted)



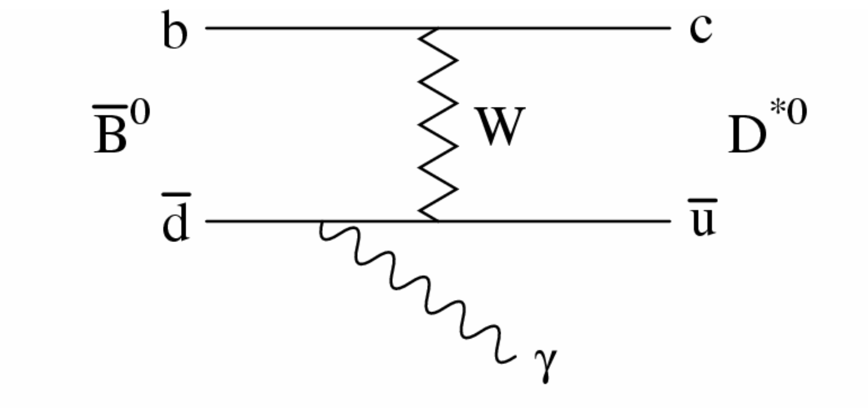
- study of resonance structure in progress
- $K_1(1270)$ most striking
- polarization analysis requires

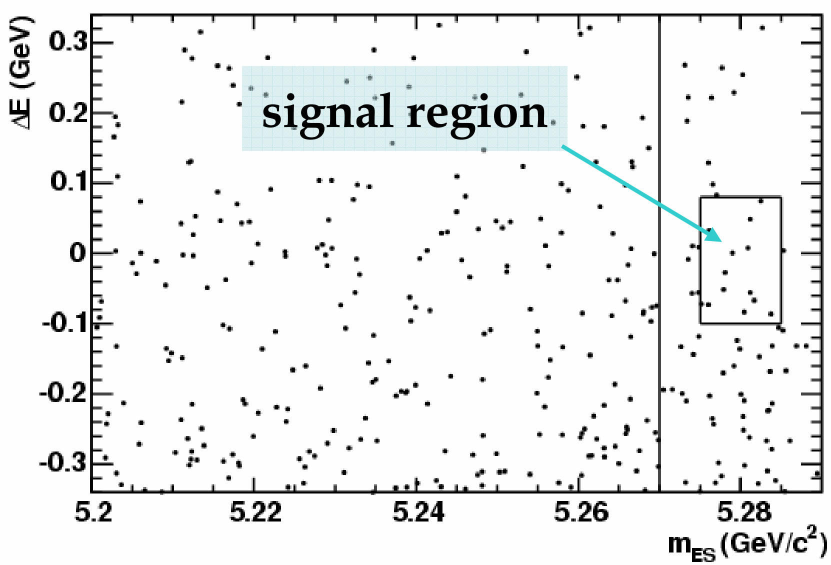
  'clean' $K_1(1400)$ in $K\pi^+\pi^0$ modes

➔ probably needs super-B factory statistics

hep-ex/0506070, submitted to PRL

$\overline{B}^0 \rightarrow D^{*0}\,\gamma$





Motivation

- weak annihilation diagram
  - understanding important for $b \rightarrow d\gamma$
- SM expectation: 1 x 10^{-6} (Cheng, '94)

Analysis strategy

- cut-and-count analysis
- 6 decay modes:

  $D^* \rightarrow D^0\,\gamma,\ D^0\,\pi^0$

  $D^0 \rightarrow K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^+\pi^-$
- total efficiency = 1.8 ± 0.3 %

Results

- event yield in 80/fb:

  expected background: 9.4 ± 1.7

  observed: 13
- BF($B^0 \rightarrow D^{*0}\,\gamma$) < 2.5 10^{-5} at 90% CL

Summary

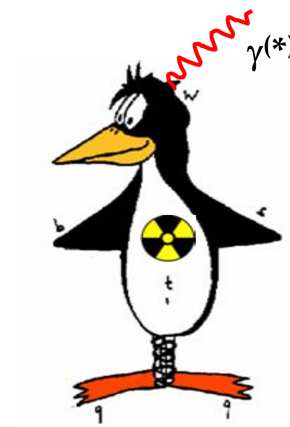
Exclusive radiative B decays

- **are a sensitive probe for new physics in FCNC**
- **well experimentally accessible with samples of 10^8 BB**

BaBar measurements

- **$B \rightarrow X_s\gamma$ BFs and CP-asymmetries become precision measurements**
- **no significant signal for $b \rightarrow d\gamma$**
  - ➔ **our results favor a low value of V_{td}**
- **$B \rightarrow K l^+ l^-$, $B \rightarrow K^* l^+ l^-$ and TDCPV in $B \rightarrow K_s \pi^0 \gamma$ still statistics limited, but ...**

we are looking forward to much more statistics!



`radiative penguin'