Radiative B decays

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representing the BaBar collaboration

Heavy Quarks and Leptons
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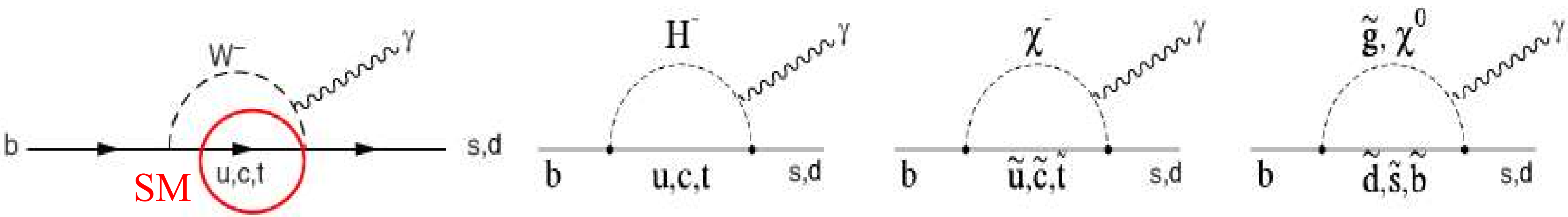
Overview

- Introduction and motivation.
- $b \to s\gamma$ results:
  - Branching fraction.
  - Photon energy spectrum.
  - CP asymmetries.
- $b \to d\gamma$ results:
  - Exclusive branching fractions.
  - CP asymmetries.
  - Inclusive branching fraction.

Radiative penguin decays

- Flavour changing neutral currents (FCNC) do not occur at tree level in the standard model (SM)
  - procede via one loop or higher order processes.
- SM dominated by top quark contribution.
- New physics (NP) can appear in the loop with size comparable to leading SM contributions.



- Studies of FCNC very active at B-factories:
  - I will cover recent results from both $b \to s\gamma$ and $b \to d\gamma$ in inclusive and exclusive analyses.

Observables

- Branching fraction (BF): NNLO calculation for $b \to s\gamma$:

Misiak et. al: $BF(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ [Phys. Rev. Lett. 98 022002].
Becher et. al: $BF(b \to s\gamma) = (2.98 \pm 0.26) \times 10^{-4}$ [Phys. Rev. Lett. 98 022003].

- $b \to d\gamma$ SM rate is CKM suppressed w.r.t. $b \to s\gamma$ by factor ~20.
- Use ratio of BFs to constrain SM via $|V_{td}/V_{ts}|$, e.g. for exclusive modes:

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

ξ ratio of the form factors for $B \to \rho\gamma$ and $B \to K^*\gamma$

ΔR differences in decay dynamics

$|V_{td}/V_{ts}|$ also obtained from the ratio of B_d and B_s mixing frequencies, but new physics affects them in different ways.

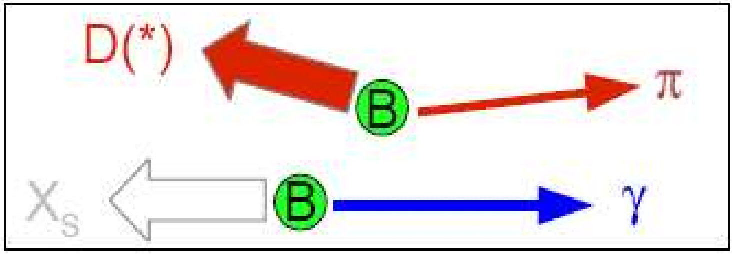
Observables

- Photon energy (E_γ) distribution depends on mass (m_b) and fermi motion (μ_π) of b quark – can be used to reduce model dependent error on $|V_{ub}|$ and $|V_{cb}|$.
- CP asymmetry A_{cp} <1% (SM). NP effects can enhance this to 15% [*Hurth, Lunghi & Porod, Nucl. Phys. B704, 56*].
- Isospin asymmetry Δ_{0-} B^0B^+ partial rate asymmetry - up to 10% in SM [*Kagan & Neubert, Phys. Lett. B539, 227*].

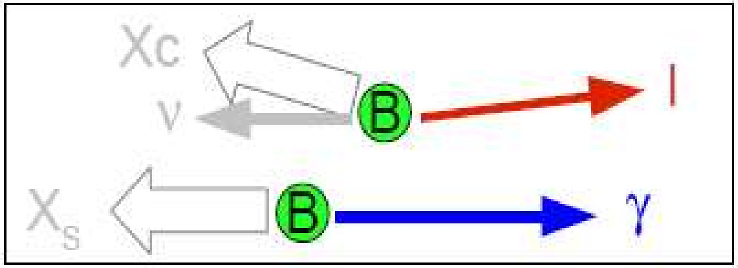
- Experimental quantities:
  - $m_{ES} \equiv M_{cb} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$, $\Delta E = E^*_B - E^*_{beam}$

Analysis methods

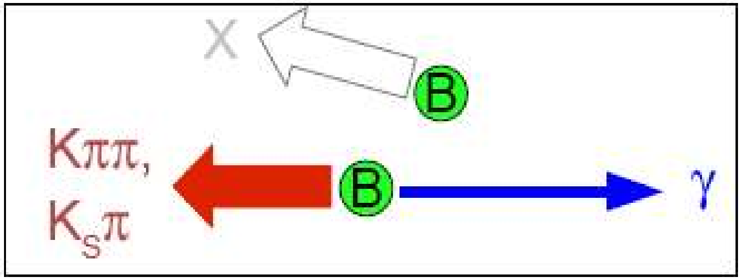
- B recoil $b \to s\gamma$
  - Fully reconstruct one B
  - Measure photon from other B



- Inclusive $b \to s\gamma$
  - Reconstruct only the photon
  - Reduce background with lepton tag



- Semi-inclusive $b \to s\gamma, b \to d\gamma$
  - Reconstruct many exclusive final states



- Exclusive $b \to s\gamma^{\blacklozenge}, b \to d\gamma$
  - reconstruct one final hadronic state

♦ *results not presented here*

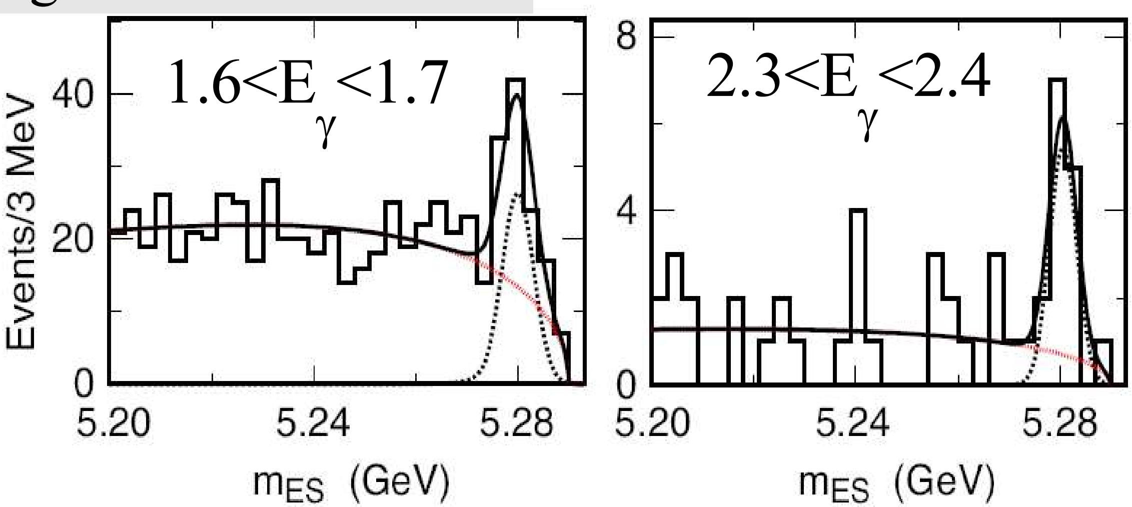
$b \to s\gamma$

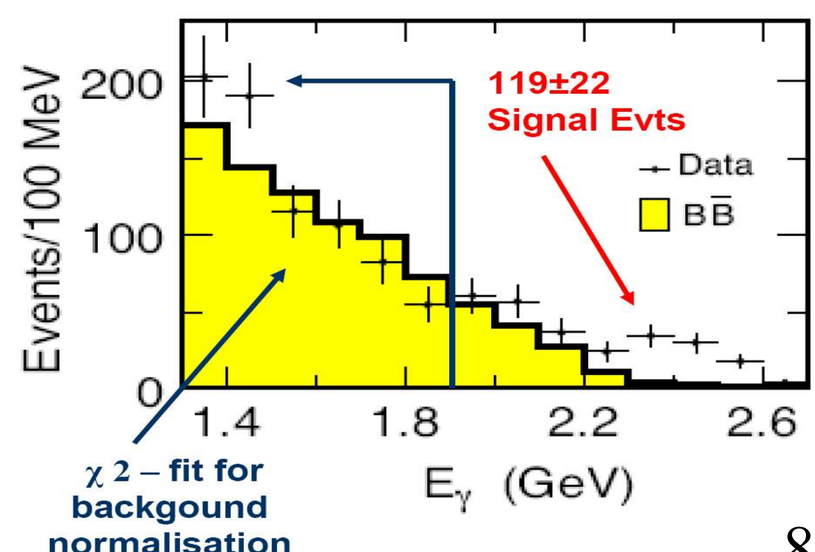
[BaBar, Phys.Rev.D77:051103,2008, 210fb^{-1}]

$B \to X_s \gamma$: B recoil method

- Fully reconstruct 'tagged' B in >1000 hadronic modes.
- Signal B from one high-energy photon, plus all non-tag tracks and neutrals.
- Photon spectrum can be measured in signal B rest frame
- Efficiency ~0.3% but excellent signal/background.

Tag-side B after all cuts





[BaBar, Phys.Rev.D77:051103,2008, 210fb^{-1}]

$B \to X_s \gamma$: B recoil method

- Extract BF, A_{CP}, Δ_{0-}, from E_γ>1.9 GeV region.

$BF(B \to X_s \gamma) = (3.65 \pm 0.85(stat.) \pm 0.60(syst.)) \times 10^{-4}$ *(E_γ>1.9GeV, $b \to d\gamma$ subtracted)*

$\mathbf{BF(B \to X_s \gamma) = (3.91 \pm 1.11) \times 10^{-4}}$ ***(E_γ>1.6GeV)***

$A_{CP} = 0.10 \pm 0.18(stat.) \pm 0.05(syst.)$ *(E_γ>2.2GeV)*

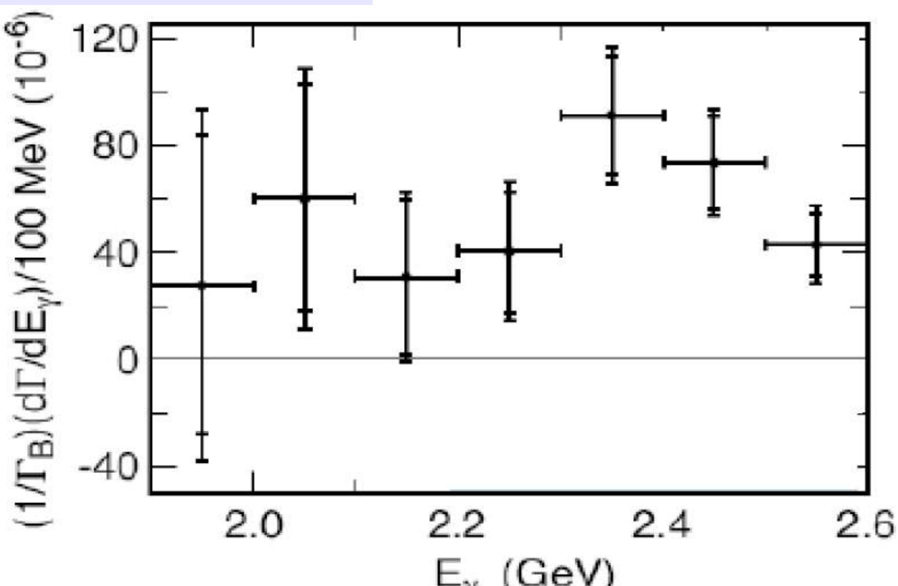
$\Delta_{0-} = -0.06 \pm 0.15(stat.) \pm 0.07(syst.)$ *(E_γ>2.2GeV)*

(untagged asymmetries: $b \to (s,d)\gamma$)

- Moments of photon spectrum:

$m_b = 4.46^{+0.21}_{-0.23}$ GeV

$\mu_\pi^2 = 0.64^{+0.39}_{-0.38}$ GeV^2



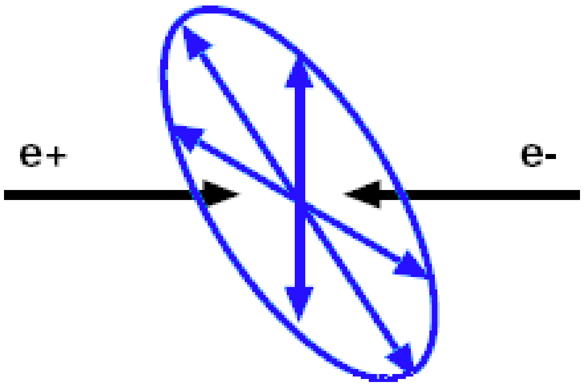
- *Method is statistics limited*

[Belle, arXiv:0803.2158 (hep-ex) 605fb^{-1}]

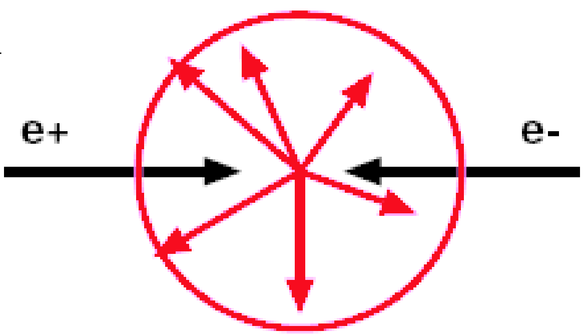
$b \to s\gamma$: Inclusive method

- First analysis to measure down to E_γ>1.7GeV.
- Find isolated clusters in calorimeter:
  - E_γ > 1.4GeV.
  - veto γs from π^0, η and BhaBha.
  - Use topological info to suppress continuum background.
- Background subtraction:
  - Estimate continuum using off-resonance data.
  - Estimate B decays using "corrected" MC.

Continuum: jet-like

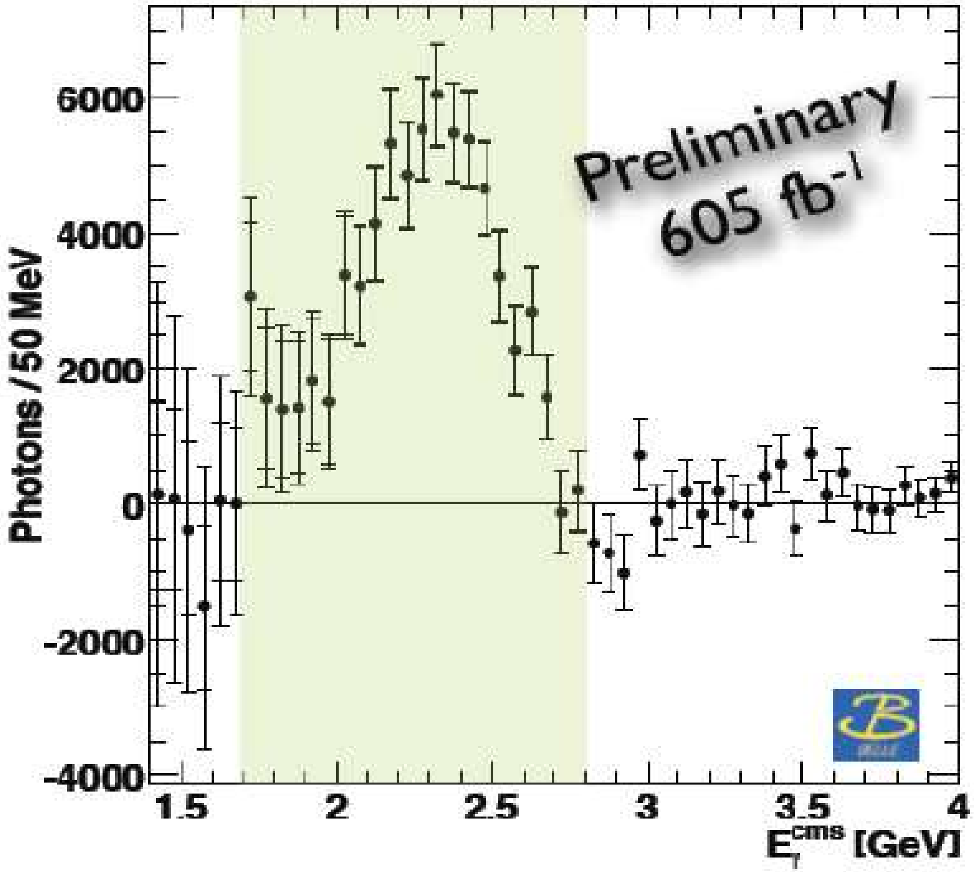


BB: spherical



[Belle, Moriond 2008, 605fb^{-1}]

b→sγ: Inclusive method



- Photon energy spectrum peaks at half the b-quark mass.
- Yield above E_γ endpoint (2.8GeV) is consistent with zero.

$$BF(B\to X_s\gamma) = (3.31 \pm 0.19(stat.) \pm 0.37(syst.) \pm 0.01(boost)) \times 10^{-4} \quad (E_\gamma > 1.7GeV)$$

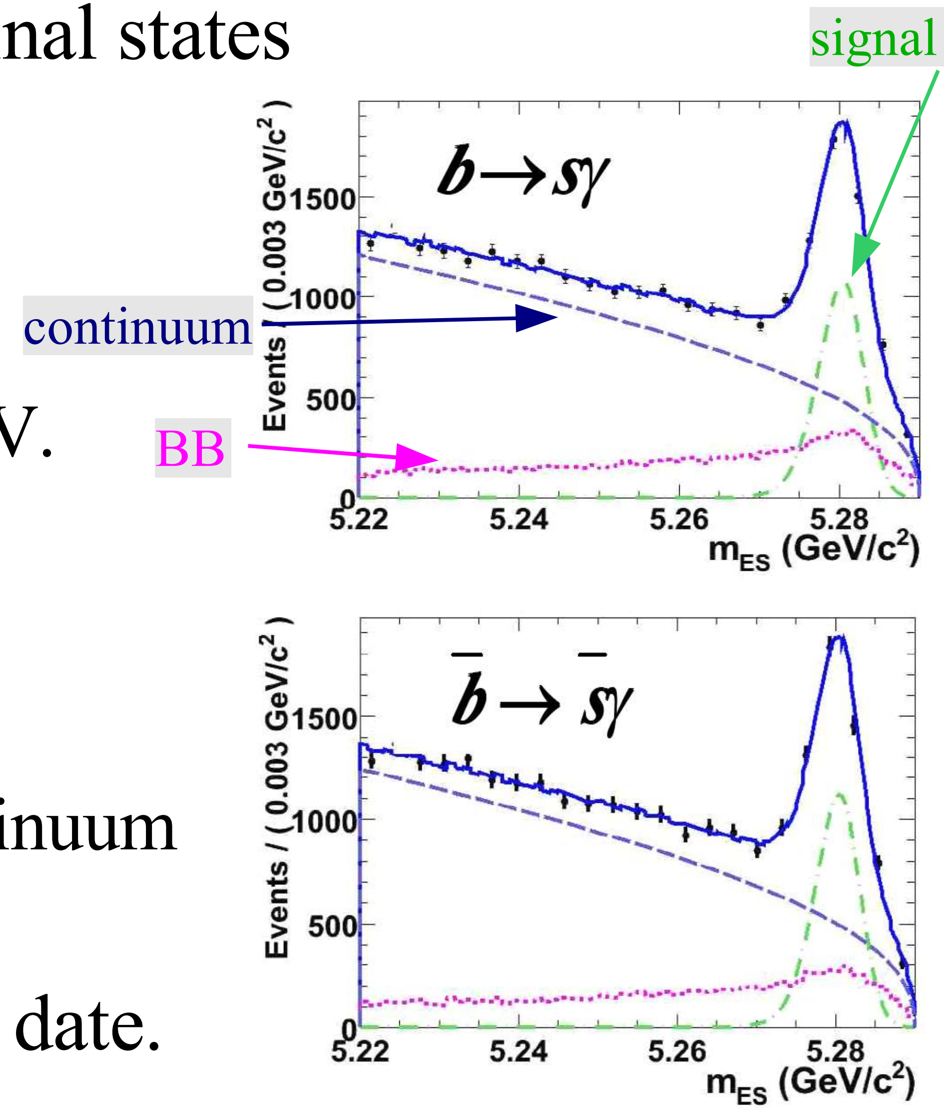
$$\mathbf{BF(B\to X_s\gamma) = (3.37 \pm 0.41) \times 10^{-4}} \quad (E_\gamma > 1.6GeV)$$

$$\langle E_\gamma \rangle = 2.281 \pm 0.032(stat.) \pm 0.053(syst.) \pm 0.001(boost)\ GeV$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0396 \pm 0.0156(stat.) \pm 0.0214(syst.) \pm 0.0012(boost)\ GeV^2$$

$B \to X_s \gamma$: Semi-inclusive

- Sum of 16 exclusive $B \to X_s \gamma$ final states
  - 50% of total width.
- Hadronic mass range
  - $0.6 - 2.8\ GeV/c^2$: $E_\gamma > 1.9 GeV$.
- Large backgrounds
  - veto photons from π^0/η.
  - boosted decision tree for continuum suppression .
- Most accurate measurement to date.



$$A_{CP}(b \to s\gamma) = -0.012 \pm 0.030(\mathit{stat.}) \pm 0.018(\mathit{syst.})$$

BF($B \to X_s \gamma$): Summary

CLEO Phys.Rev.Lett.87,251807(2001)
BR($B \to X_s\gamma$) = (3.29± 0.53) 10^{-4} (9.1 fb^{-1})

Belle Semi Phys.Lett.B511:151(2001)
BR($B \to X_s\gamma$) = (3.29± 0.53) 10^{-4} (5.8 fb^{-1})

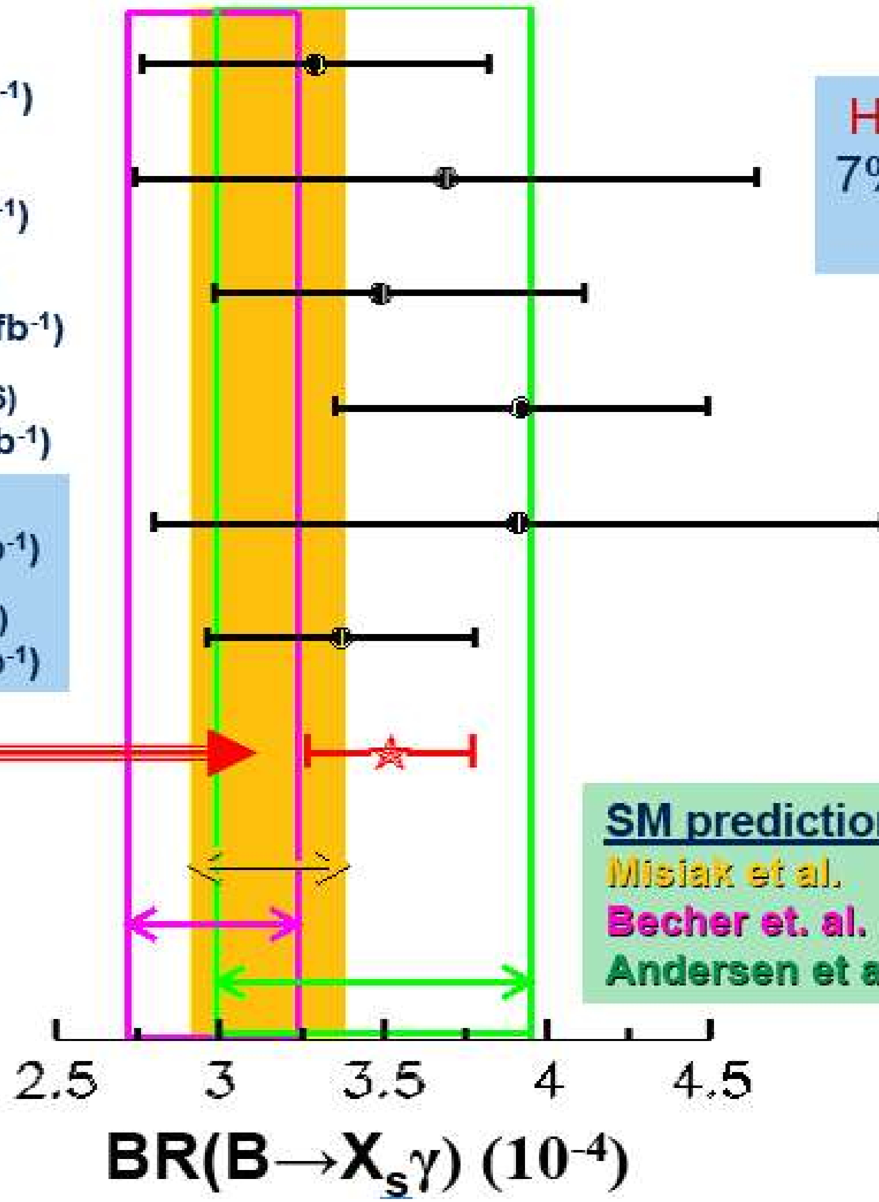
BaBar Semi Phys.Rev.D72:052004(2005)
BR($B \to X_s\gamma$) = ($3.29^{+0.62}_{-0.50}$) 10^{-4} (81.5 fb^{-1})

BaBar Incl Phys.Rev.Lett.97:171803(2006)
BR($B \to X_s\gamma$) = (3.92± 0.56) 10^{-4} (81.5 fb^{-1})

BaBar Full Phys.Rev.D77:051103(2008)
BR($B \to X_s\gamma$) = (3.91± 1.11) 10^{-4} (210 fb^{-1})

BELLE Incl (A. Limosani, Moriond EW08)
BR($B \to X_s\gamma$) = (3.37± 0.41) 10^{-4} (605 fb^{-1})

HFAG Average 08 (preliminary)
BR($B \to X_s\gamma$) = (3.52± 0.25) 10^{-4}



HFAG average:
7% experimental uncertainty

SM predictions:
Misiak et al. (hep-ph/0609232)
Becher et. al. (hep-ph/0610067)
Andersen et al. (hep-ph/0609250)

- Good agreement between theory and experiment!

$b \to d\gamma$

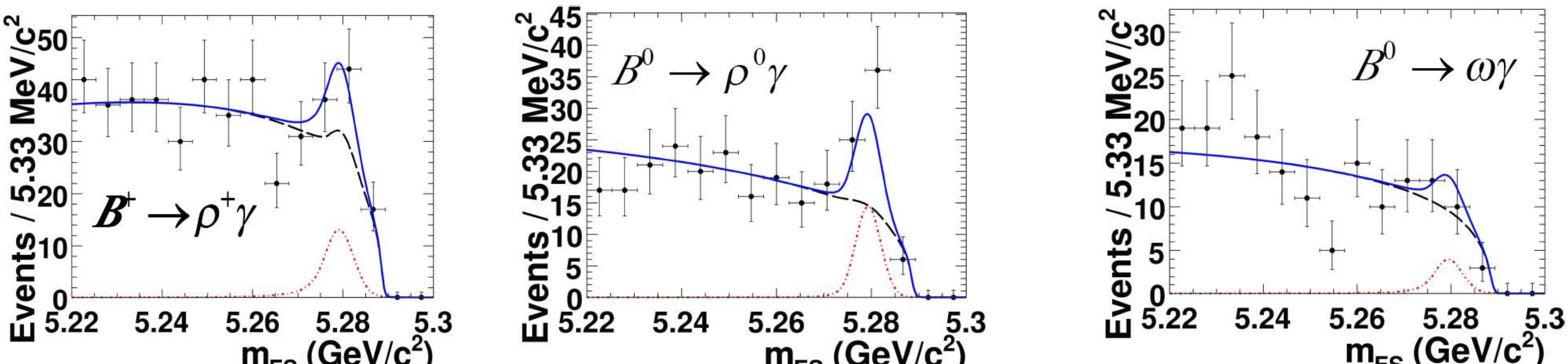
[BaBar, PRL98, 151802 (2007) 347M BB]

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

- Continuum background significant - novel use of information from lepton tags to suppress non-B backgrounds.
- 4D fit (5D in $\omega\gamma$) to extract signal
  - m_{ES}, ΔE, $\cos\theta_H$, NN_{out} ($\cos\theta_D$).

$\cos\theta_H$: helicity angle,
NN_{out}: neural net output
$\cos\theta_D$: Dalitz angle

$$BF(B\to\rho\gamma) = (1.36 \pm 0.28(stat.) \pm 0.10(syst.)\ ) \times 10^{-6}$$
$$BF(B\to(\rho\omega)\gamma) = (1.25 \pm 0.25(stat.) \pm 0.09(syst.)\ ) \times 10^{-6}$$

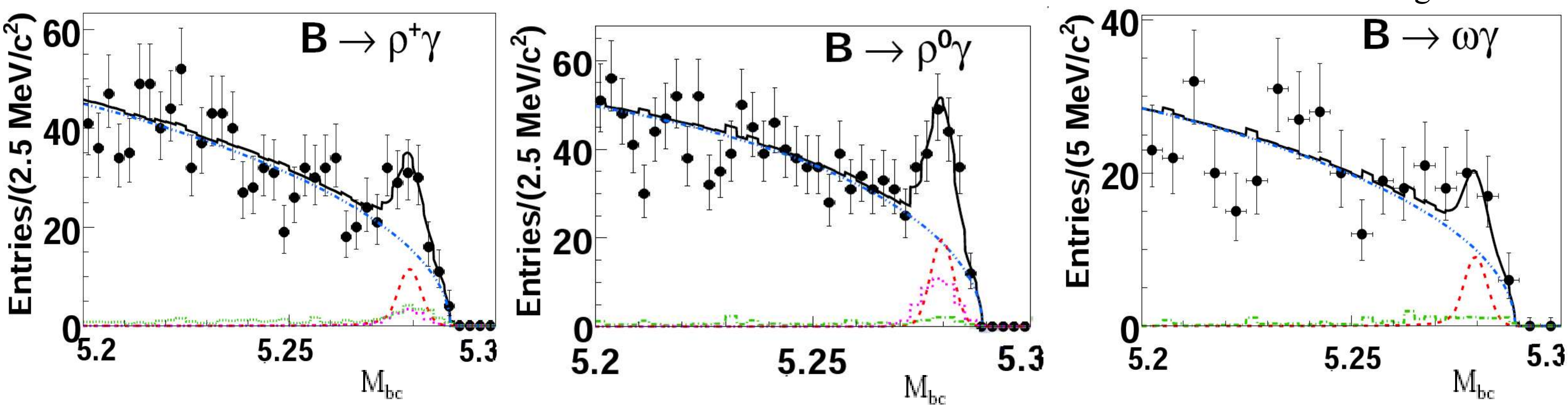


[Belle, arXiv:0804:4770 (submitted to PRL) 657M BB]

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

- $B\to K^*\gamma$ backgrounds also a problem.
- 2D fit (3D for $\rho^0\gamma$) to extract signal: M_{bc}, ΔE ($m_{K\pi}$).

$m_{K\pi}$: invariant mass of $\pi\pi$ pair with K mass assigned to one π.



$$BF(B\to\rho\gamma) = (1.21^{+0.24}_{-0.22}(stat.) \pm 0.12(syst.)\ ) \times 10^{-6}$$

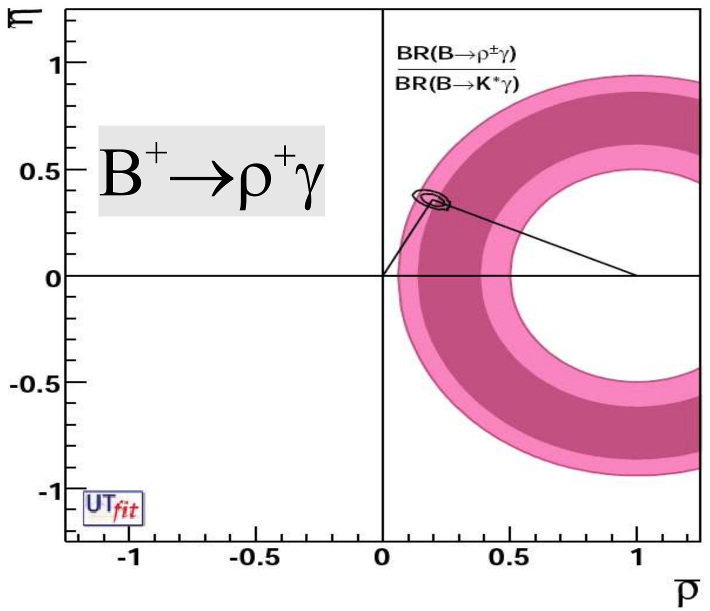
$$BF(B\to(\rho\omega)\gamma) = (1.14 \pm 0.20(stat.)^{+0.10}_{-0.12}(syst.)\ ) \times 10^{-6}$$

$B\to(\rho,\omega)\gamma$ and $|V_{td}/V_{ts}|$

- Reminder:

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

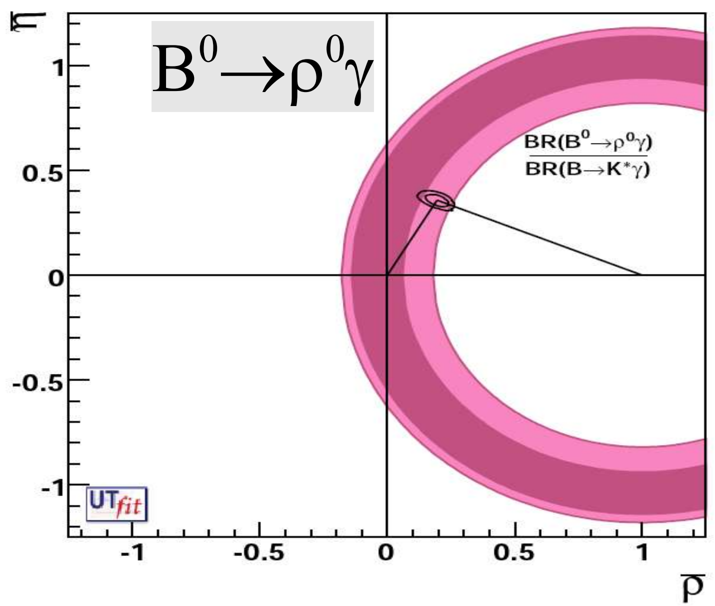
($\zeta\sim0.85$, $\Delta R\sim0.1$)



- Average $\frac{BF(B\to(\rho,\omega)\gamma)}{BF(B\to K^*\gamma)}$ gives:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.206\pm0.018$$

B_d/B_s mixing gives 0.211 ± 0.007.

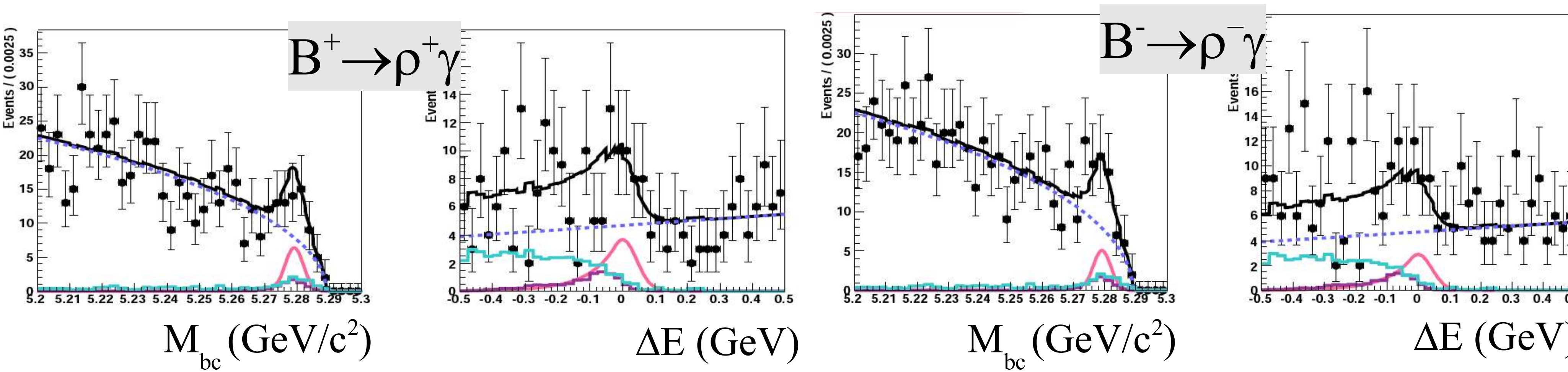


A_{CP} in $B \to \rho\gamma$

- Direct CP in $B^+ \to \rho^+\gamma$:

$$A_{CP}(B^+ \to \rho^+\gamma) = \frac{N(B^- \to \rho^-\gamma) - N(B^+ \to \rho^+\gamma)}{N(B^- \to \rho^-\gamma) + N(B^+ \to \rho^+\gamma)}$$

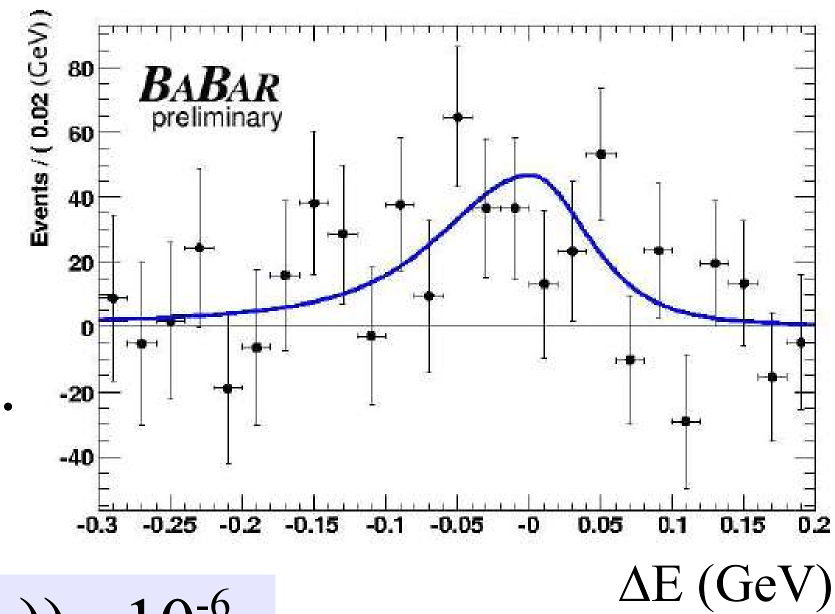
  - Simultaneous fit to M_{bc} and ΔE of $B^+ \to \rho^+\gamma$ and $B^- \to \rho^-\gamma$.
  - Asymmetries in background sources included in systematic error.
  - $B \to D\pi$ control sample used to understand detector bias.



$$A_{CP}(B^+ \to \rho^+\gamma) = -0.11 \pm 0.32(\text{stat.}) \pm 0.09(\text{syst.})$$

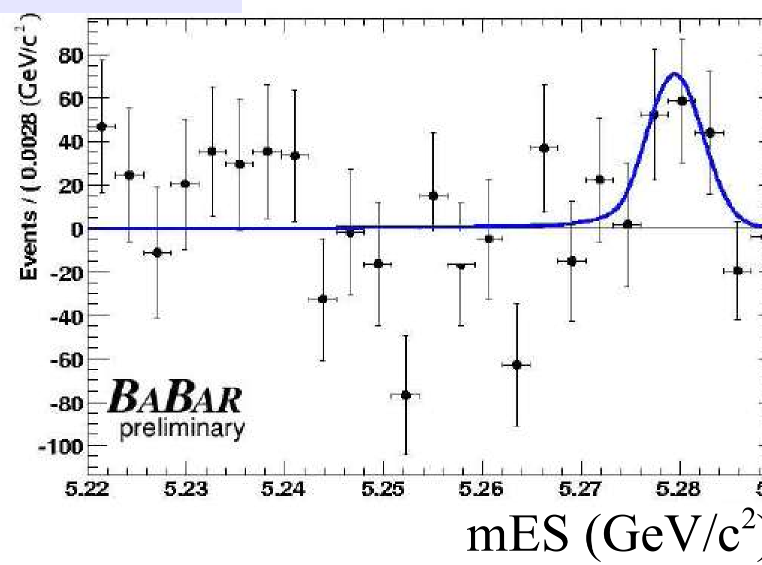
Semi-inclusive $b \to d\gamma$

- Sum of seven exclusive final states
  - Up to 4 πs, up to 1 π^0/η.
  - mass range $1.0 < M(X_d) < 1.8 GeV/c^2$. (excludes ρ/ω resonances)



$BF(B \to X_d\gamma) = (3.1 \pm 0.9(\textit{stat.}) \pm 0.7(\textit{syst.}))\ x10^{-6}$

  - Inclusive BF measurement plus inclusive $|V_{td}/V_{ts}|$ coming soon...

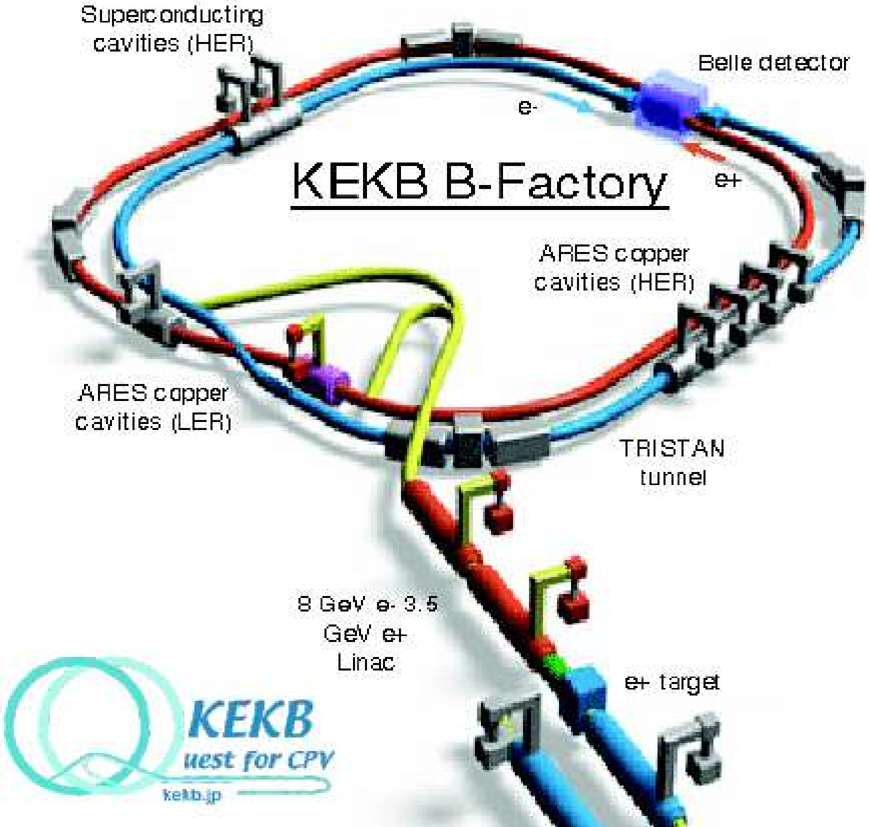


Summary

- Precise measurements of $b\to s\gamma$:
  - Branching fractions with $E_\gamma > 1.7$GeV and $E_\gamma > 1.9$GeV.
  - CP asymmetry with $0.6 < M(X_s) < 2.8 \mathrm{GeV}/c^2$.
- New measurements of $b\to d\gamma$:
  - Branching fractions.
  - First measurements of the CP asymmetry of $B\to\rho\gamma$.
  - First evidence for $B\to X_d\gamma$: with $1.0 < M(X_d) < 1.8 \mathrm{GeV}/c^2$.

Backup slides

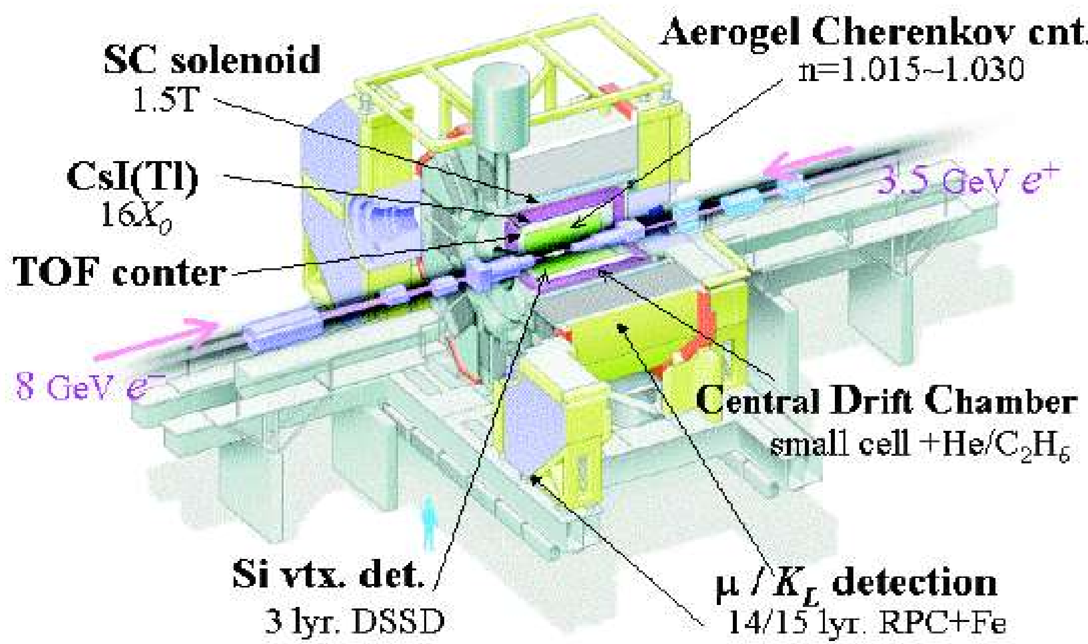
KEKB and Belle



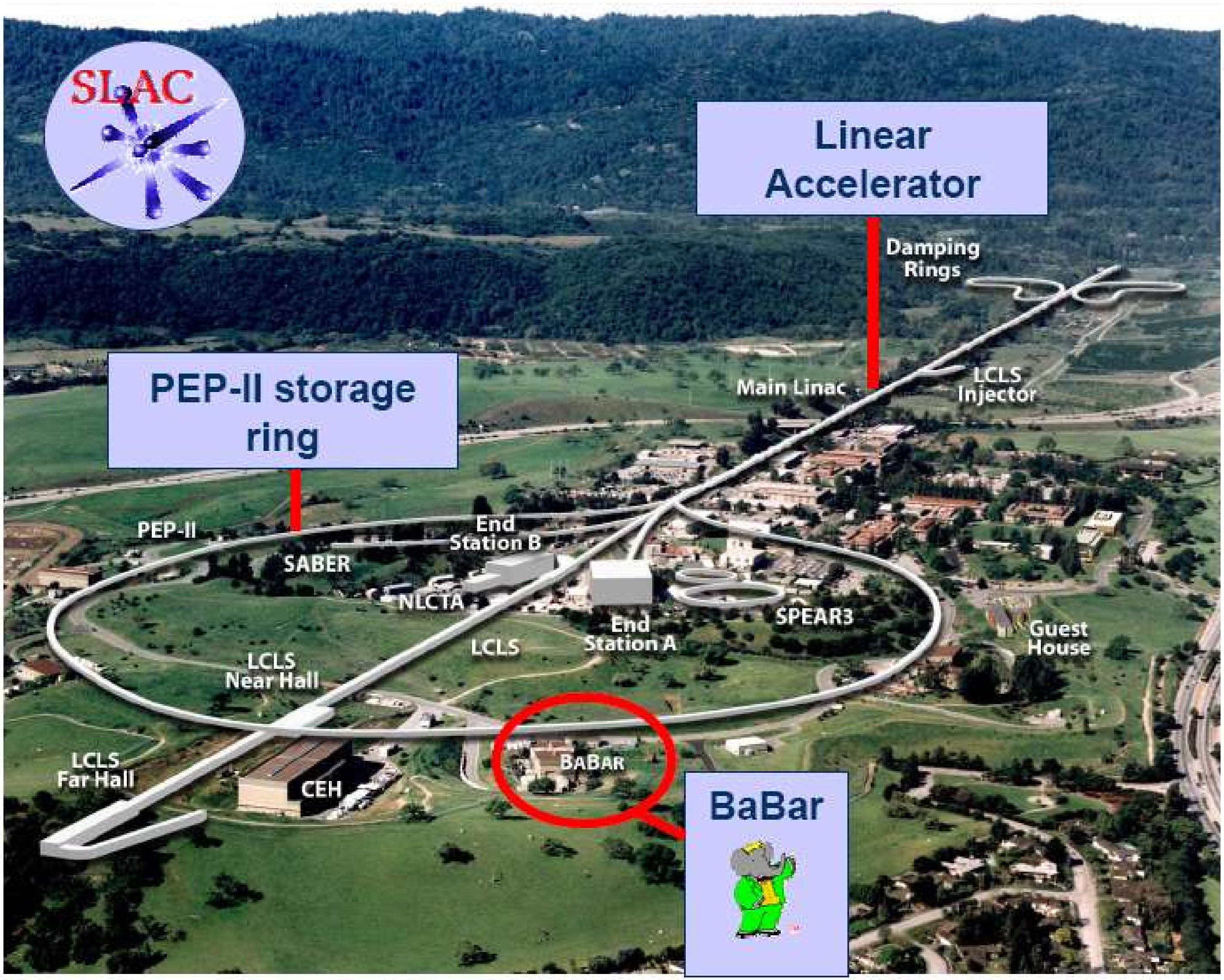
Luminosity	KEKB
Peak	>16.5x10^{33} /cm^2/s
Total Integrated	>700/fb

Solid angle coverage	~92%
Particle ID	e m p K p

Belle Detector



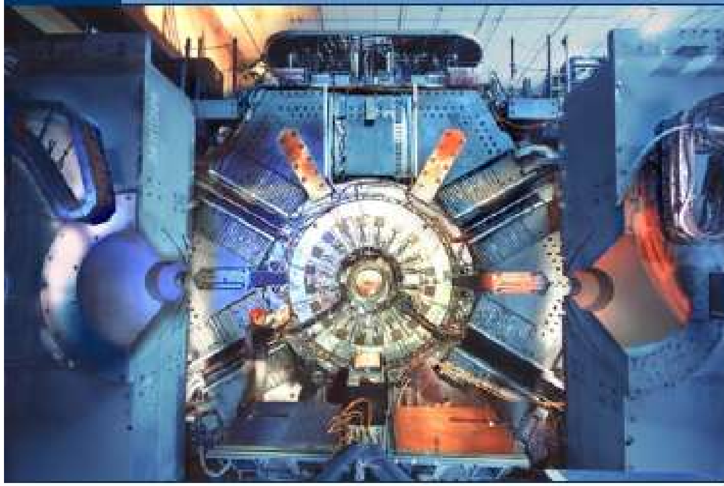
PEP-II and BaBar at SLAC

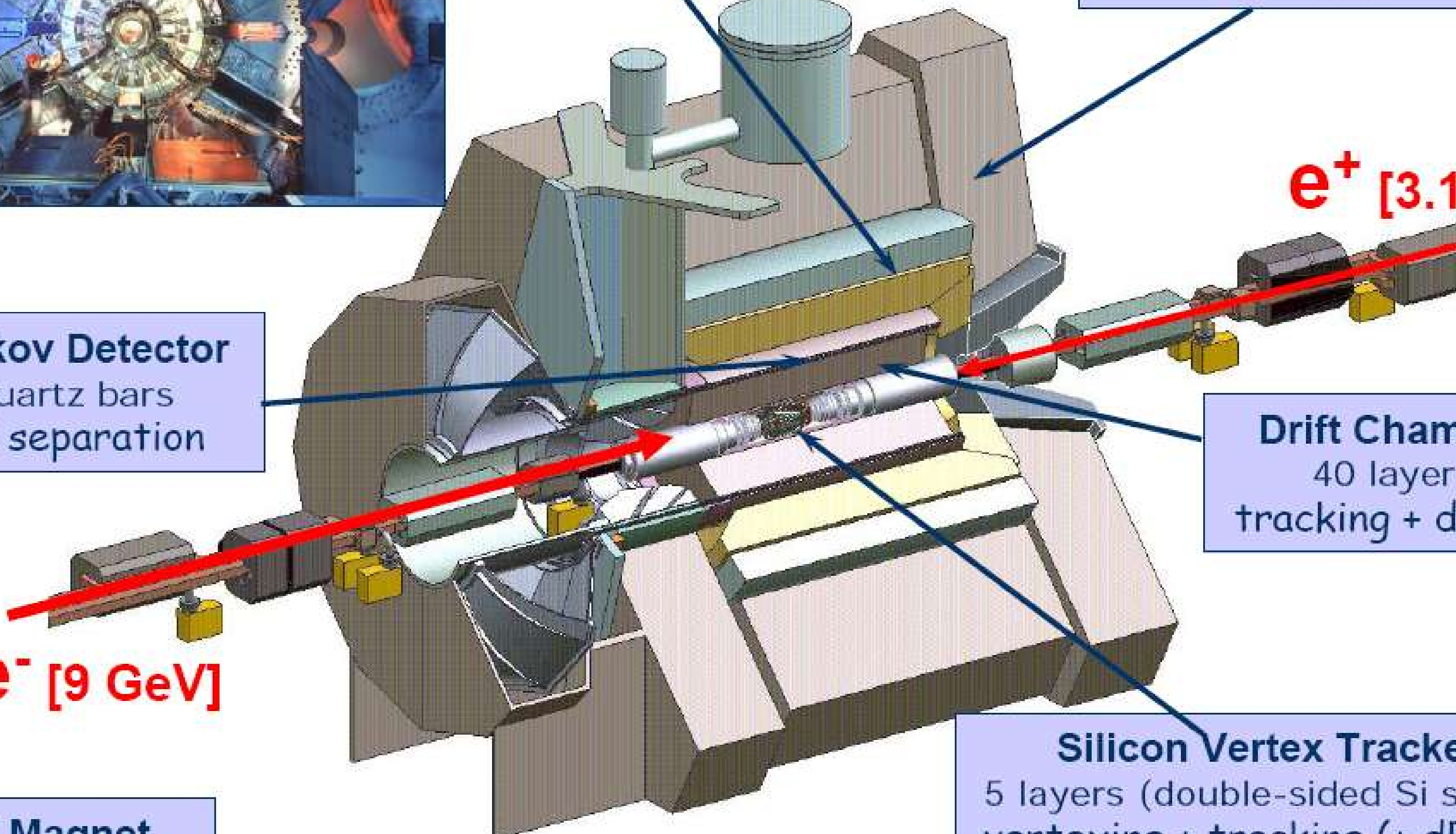


- asymmetric e^+-e^- storage ring
- 9 GeV e^- on 3.1 GeV e^+
- Y(4S) boost $\beta\gamma$~0.56

Peak luminosity of 1.2×10^{34} cm^{-2} s^{-1} (more than 3x design!)

BaBar Detector





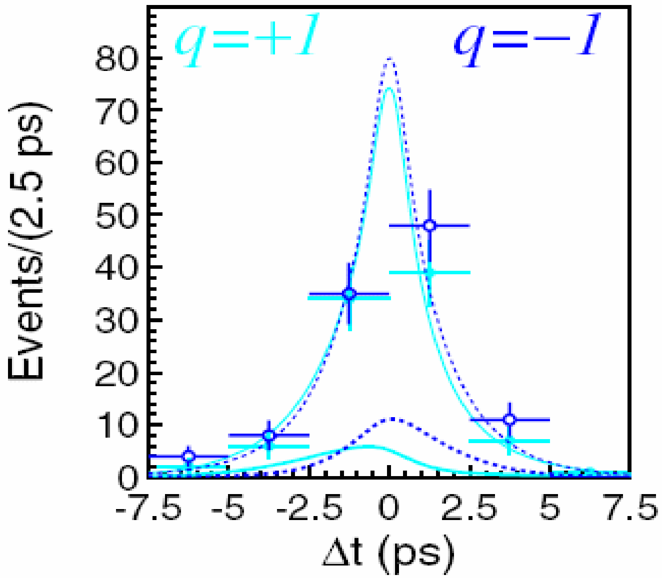
1.5T Magnet

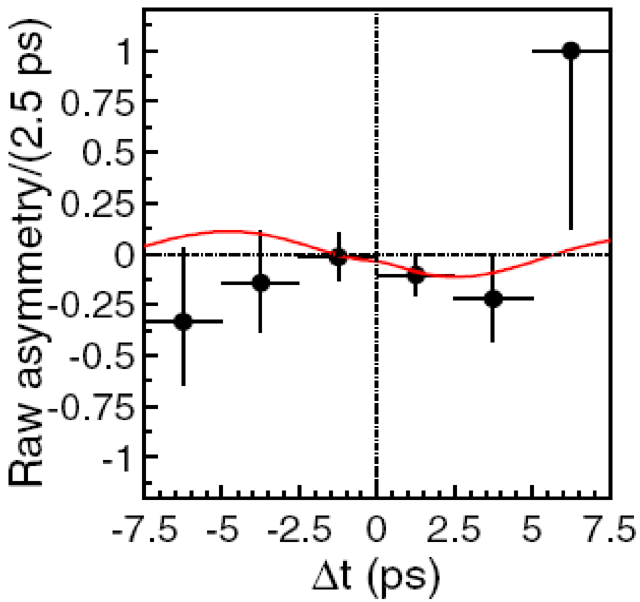
$B^0 \to \rho^0\gamma$

- Time-dependent CPV in $B^0 \to \rho^0\gamma$:

$$A_{CP}(\Delta t) = \boldsymbol{S}\sin\Delta m\Delta t + \boldsymbol{A}\cos\Delta m\Delta t$$

  - ***S*** ~zero in SM
  - ***A*** could be non-zero





S = -0.83 ±0.65(stat.) ±0.18(syst.)
A = -0.44 ±0.49(stat.) ±0.14(syst.)