Radiative penguin decays

Borys Knysh
after
Al Eisner, Stephen Playfer (BABAR)
Mikihiko Nakao (Belle)
Tobias Hurth (theory)

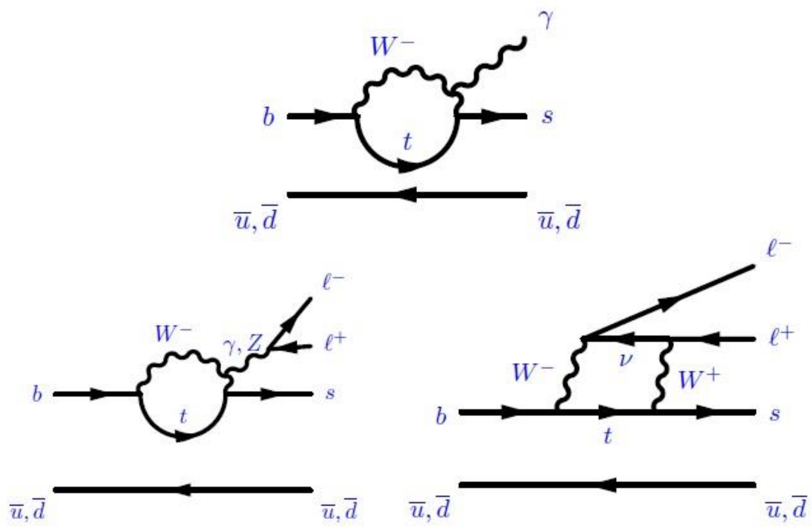
Decay modes

Radiative penguins

- $b \to s\gamma$
- $b \to d\gamma$

Electroweak penguins

- $b \to s l^+ l^-$
- $b \to d l^+ l^-$
- $b \to s \nu \bar{\nu}$



These B decay modes are considered

to be among the most sensitive probes for physics beyond

the SM!

Effective electroweak Hamiltonian

- Rare B decays are governed by an interplay between the weak and strong interactions.
- short-distance QCD effects are very important
- Hard gluon exchange $\alpha^n(m_b)\log^m(m_b/M)$, $m \le n, n = 0,1,2, \ldots$
- To obtain a reasonable result, one must re-sum at least all the leading-log (LL) terms…

Effective low-energy theory with five quarks

- obtained by integrating out the heavy particles (electroweak bosons, top-quark)
- theoretical framework for both inclusive and exclusive modes allows for a separation of the B meson decay:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_{i}^{N} \lambda_{CKM} C_i(\mu, M) O_i(\mu)$$

- The effective electroweak Hamiltonian
- $H_{eff} = -\frac{4G_F}{\sqrt{2}} \lambda_q^t \sum_{i=1}^{10} C_i O_i + \lambda_q^u \sum_{i=1}^{2} C_i (O_i - O_i^u)$, $\lambda_q^t = \mathrm{V_{tb} V_{tq}^*}, \lambda_q^u = V_{ub} V_{uq}^*$

Effective field theory approach

- At the scale $\mu = M_W$ the full SM theory is matched with the effective theory, Wilson coefficients are obtained by comparison and have very small QCD corrections;
- The evolution of these Wilson coefficients from $\mu = M_W$ down to $\mu = m_b$ must then be performed with the help of the renormalization group;
- Calculate corrections to the order of α_s^2
- **For inclusive processes** (use quark-hadron duality):

$$\Gamma(B \to X_s\gamma) = \Gamma(b \to s\gamma) + O(\Lambda_{QCD}/m_b)$$

- **For exclusive processes** use QCD-improved factorization ($\mathrm{m}_b \to \infty$) – allows for perturbative calculation of QCD corrections, however has the drawback – important corrections of the type $1/\mathrm{m}_b$ are missing

Power corrections to inclusive decays $B \to X_s\gamma$ + ugly formulas

- The inclusive decay rate is defined as:

$$\Gamma = \frac{1}{2m_{H_b}} \sum_X (2\pi)^4 \delta^4(p_i - p_f) \left| \langle X | H_{eff} | H_b \rangle \right|^2$$

- Optical theorem:

$$\Gamma = \frac{1}{2m_{H_b}} Im\langle X|\boldsymbol{T}|H_b\rangle; \boldsymbol{T} = i \int d^4x\, T[H_{eff}(x) H_{eff}(0)]$$

- OPE: $T\left[H_{eff}H_{eff}\right] = \frac{1}{m_b}\sum_{i,j=0} \frac{c_i^j P_i^j}{m_b^j} \sim \Lambda_{QCD}$
- $\Gamma_{B\to X_s\gamma}^{O_7,O_7} = \alpha_{EM} G_F^2 m_b^5 / 32\pi^4 |V_{tb}V_{ts}|^2 C_7^2(m_b)(1 - \frac{1}{m_b^2}[\frac{1}{2}\mu_\pi^2 + \frac{3}{2}\mu_G^2])$
- However due to O_2 contribution , cut on photon energy is required (<1.6 GeV) and irreducible theoretical uncertainty becomes 4-5%

Power corrections to inclusive decays $B \to X_d \gamma$

- The same as $B \to X_s \gamma$
- But the long-distance contributions from the intermediate u quark in the penguin loops are critical (O_1^u)
- However it vanishes at order $\frac{\Lambda_{QCD}}{m_b}$;
- But appears again at $(\frac{\Lambda_{QCD}}{m_b})^2$ due to interference with O_8

Power corrections to inclusive decays $B \to X_s l^+ l^-$

- O_9 corrections appear at $\frac{1}{m_b^2}, \frac{1}{m_b^3}, \frac{1}{m_c^2}$,;
- However, a systematic analysis of hadronic power corrections including all relevant operators has yet to be performed. Thus, an additional uncertainty of 5% should be added to all theoretical predictions for this mode on the basis of a simple dimensional estimate.

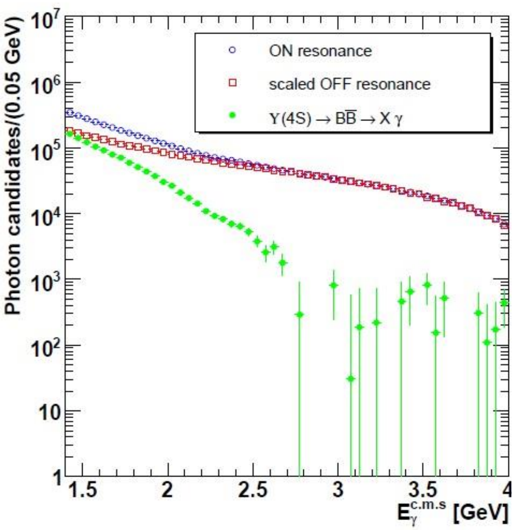
Inclusive $b \to s\gamma$

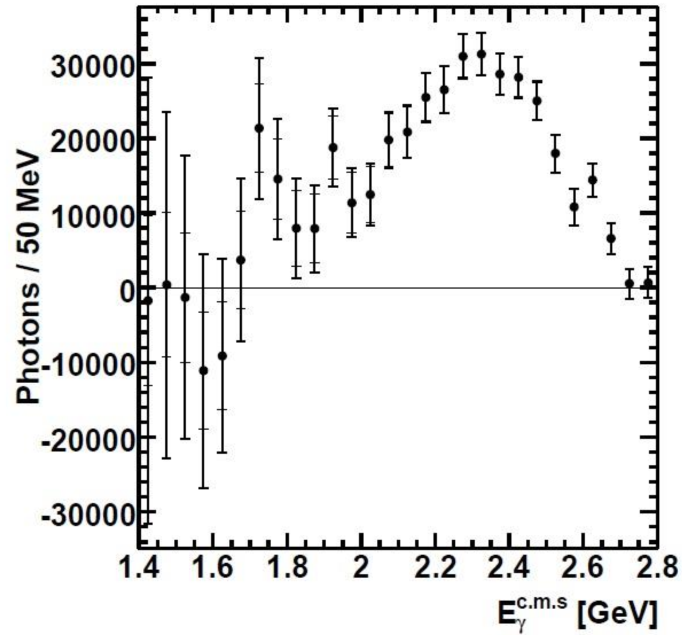
- $b \to s\gamma$ was first observed by CLEO II in exclusive $\mathrm{B} \to K^*\gamma$
- using a combination of a fully inclusive photon spectrum, and a “pseudoreconstruction” of a sum of exclusive final states
- $Br(B \to X_s\gamma)_{NNLL} = \left(3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}\right) 10^{-4}$ (stat, syst, model-dependent)
- Cut on photon spectrum at 2 GEV rather than theoretical at 1.6 GeV
- At B-factories threshold was decreased to 1.7 GeV
- The hallmark of a fully inclusive measurement is that for a signal B it requires only the detection of a high-energy photon with E close to half the b-quark mass;
- The processes $B \to X_s\gamma$ and $B \to X_d\gamma$ are not separated
- However for $B \to X_d\gamma$ is easily subtracted $\frac{Br(B\to X_d\gamma)}{Br(B\to X_s\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 = 0.044 \pm 0.003$;
- electromagnetic-calorimeter resolution

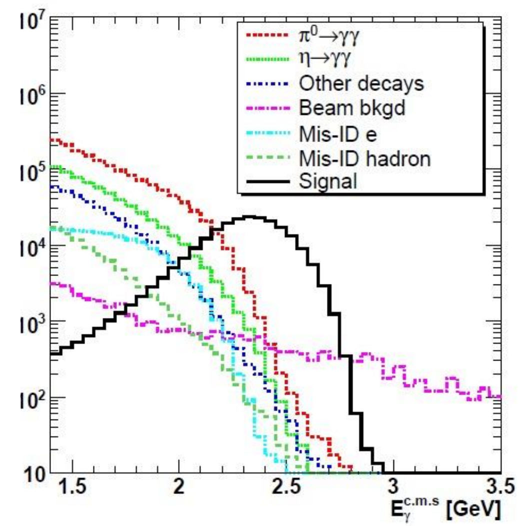
Belle fully inclusive

- $605\ fb^{-1}$ of $\Upsilon(4S)$ data & $68\ fb^{-1}$ on 60MeV below upsilon
- Event shape information is used to suppress a large fraction of the background
- off-resonance data, which is free from B-meson decays is subtracted from spectra
- Once the non-B backgrounds are subtracted, the dominant background sources are the B decay modes that produce photons through secondary meson decays
- Photons were checked to form π^0/η, if yes ->rejected -> 3% systematic errors which mainly came from the isolation requirement and the understanding vertices.
- Other sources of photons in B decays then dominate the uncertainty on the background, giving a systematic error of 2-7% (ω, η', charmonium decays, fake from electrons, anti-neutrons, …)

Belle: Photon energy spectrum (inclusive)







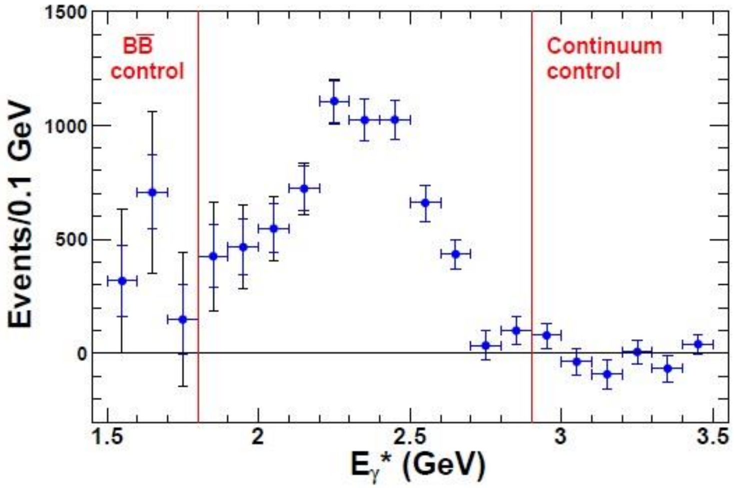
$$Br(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40)10^{-4}\ (Belle, E_\gamma > 1.7\ GeV)$$

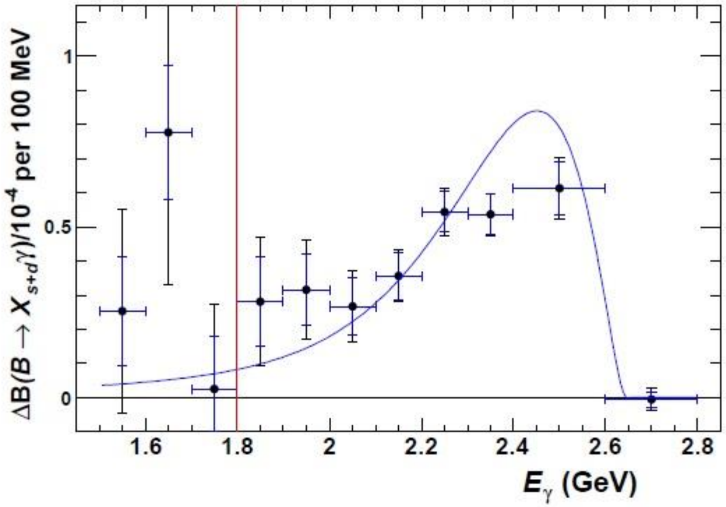
BABAR fully inclusive with lepton tagging

- Initially $347\ fb^{-1}$ of $\Upsilon(4S)$ data & $36\ fb^{-1}$ on 40MeV below upsilon;
- For the signal it relies on the detection of high energy photons - with photon-quality requirements analogous to those used by Belle including isolation, and a veto
- The lepton momentum threshold is $p^* > 1.05\ GeV$ for both electrons and muons → 98% of continuum events are removed and 12% of signal events;
- Statistical uncertainties less than in untagged analysis
- However lepton tagging introduces an additional small systematic error of up to 2.4% due to lepton identication and uncertainties in $b \to clv$ branching fractions;

BABAr: Photon energy spectrum (inclusive)

$Br(B \to X_s\gamma) = (3.21 \pm 0.15 \pm 0.29 \pm 0.08)10^{-4}\ (BABAr, E_\gamma > 1.8\ GeV)$





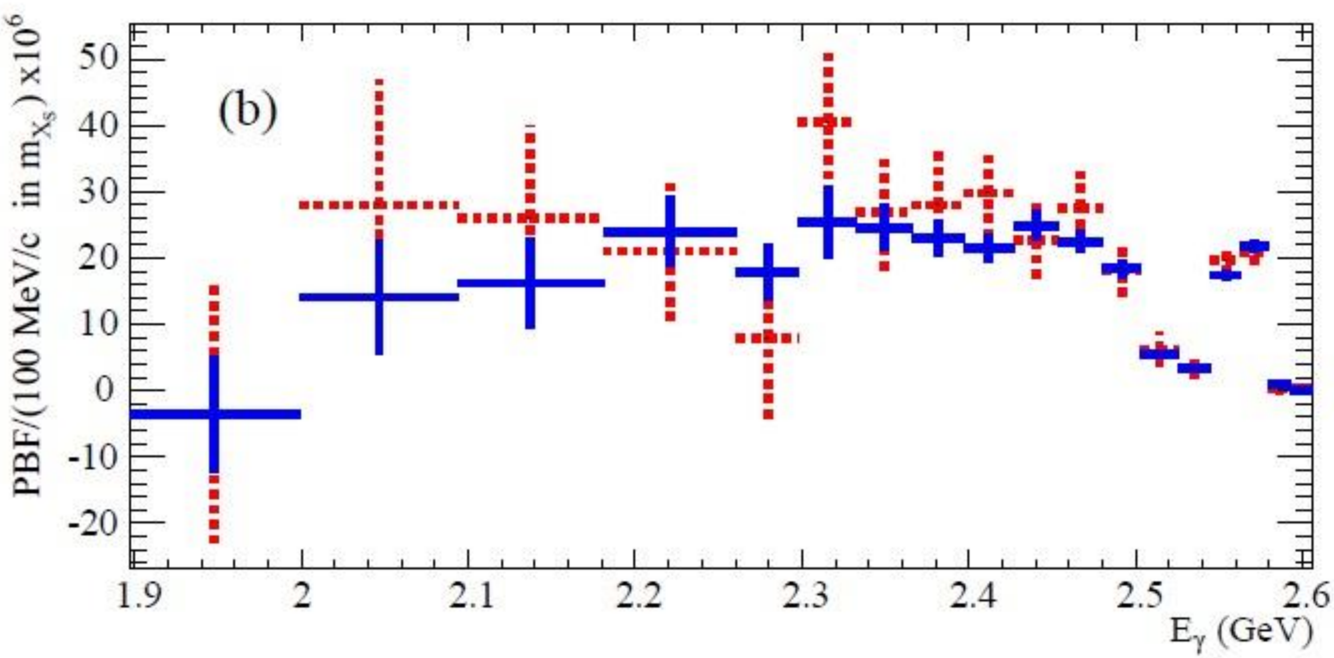
BABAR fully inclusive with reconstructed-B tagging

- $210 fb^{-1}$ of $\Upsilon(4S)$ data, more than 1000 different hadronic final states were reconstructed, representing 5% of the decay width of the B meson;
- recoil-B technique;
- signal B meson is tagged by fully reconstructing the non-signal B meson in a hadronic decay mode;
- π^0 veto, B candidates with $\Delta E = 60\ MeV$;
- Measures the momentum of the tag B,
- identifies both the flavor and the charge of the B
- Type equation here.
- $Br(B \rightarrow X_s \gamma) = (3.66 \pm 0.85 \pm 0.60) 10^{-4}\ (BABAr, E_\gamma > 1.9\ GeV)$

Sum of exclusive modes

- Belle: $6fb^{-1}, E_{\gamma} > 2.24GeV$
- $Br(B \rightarrow X_s\gamma) = (3.66 \pm 0.53 \pm 0.42)10^{-4}$ $(Belle, E_{\gamma} > 2.24\ GeV;$
- BABAr: a set of 38 exclusive final states is explicitly reconstructed;
- The photon energy in the B rest frame is precisely deduced from the measured X_s mass;
- The main limitation of this analysis is the understanding of the hadronization of the s quark into different X_s final states, and the estimation of the fraction of missing final states that have not been included in the analysis.
- 50% - $B \rightarrow Kn(\pi)\gamma, B \rightarrow Kn(\pi)\eta\gamma$, 25% - due to K_L^0 modes, 25% - high multiplicity final states

Sum of exclusive modes



$$Br(B \to X_s\gamma) = (3.29 \pm 0.19 \pm 0.48)10^{-4}\ (BABAr, E_\gamma > 1.9\ GeV)$$

Constraints on new physics from $B \to X_s\gamma$

- Charged Higgs mass $m_{H^+} > 380GeV$ at C.L. = 95%
- inverse compactification radius $\frac{1}{R} > 600GeV$ at C.L = 95%

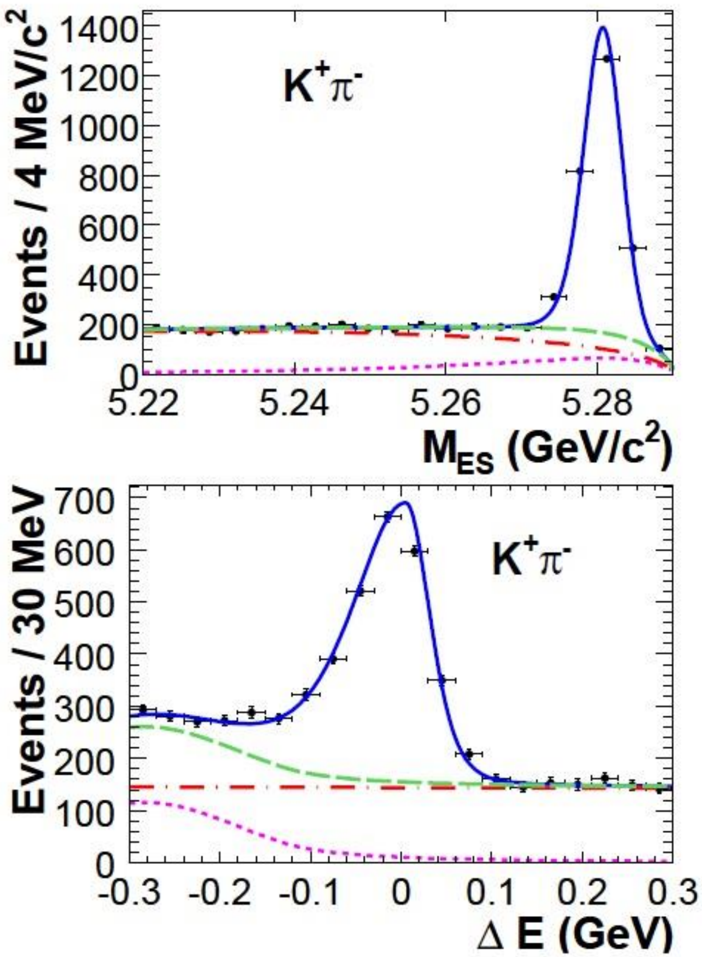
In both cases, the bounds are much stronger than those previously derived from other measurements

Exclusive $b \to s\gamma$

$B \to K^*\gamma$

- K^* reconstructed in the 4 final states: $K^+\pi^-, K_S^0\pi^0, K^+\pi^0, K_S^0\pi^+$
- Combinatorial background;
- $B \to K\pi\pi\gamma, B \to K\pi^0$;

Mode	Belle	BaBar	Average
$K^*(892)^0\gamma$	$40.1 \pm 2.1 \pm 1.7$	$43.3 \pm 1.0 \pm 1.6$	42.4 ± 1.5
$K^*(892)^+\gamma$	$42.5 \pm 3.1 \pm 2.4$	$43.6 \pm 1.4 \pm 1.6$	43.1 ± 1.8
$K_2^*(1430)^0\gamma$	$13.0 \pm 5.0 \pm 1.0$	$12.2 \pm 2.5 \pm 1.0$	12.4 ± 2.4
$K_2^*(1430)^+\gamma$		$14.5 \pm 4.0 \pm 1.5$	14.5 ± 4.3
$K_1(1270)^+\gamma$	$43.0 \pm 9.0 \pm 9.0$		43.0 ± 13.0
$K^+\pi^-\pi^+\gamma$	$25.0 \pm 1.8 \pm 2.2$	$29.5 \pm 1.3 \pm 1.9$	27.6 ± 2.2
$K^0\pi^+\pi^-\gamma$	$24.0 \pm 4.0 \pm 3.0$	$18.5 \pm 2.1 \pm 1.2$	19.5 ± 2.2
$K^+\pi^-\pi^0\gamma$		$40.7 \pm 2.2 \pm 3.1$	40.7 ± 3.9
$K^0\pi^+\pi^0\gamma$		$45.6 \pm 4.2 \pm 3.0$	45.6 ± 5.1
$K^+\phi\gamma$	$2.5 \pm 0.3 \pm 0.2$	$3.5 \pm 0.6 \pm 0.4$	2.8 ± 0.3
$K^0\phi\gamma$	$2.7 \pm 0.6 \pm 0.3$		2.7 ± 0.7
$K^+\eta\gamma$	$8.4 \pm 1.5 \pm 1.1$	$7.7 \pm 1.0 \pm 0.4$	7.9 ± 0.9
$K^0\eta\gamma$	$8.7 \pm 2.9 \pm 1.8$	$7.1 \pm 2.1 \pm 0.4$	7.6 ± 1.8
$K^+\eta'\gamma$	$3.6 \pm 1.2 \pm 0.4$	$1.9 \pm 1.4 \pm 0.1$	2.9 ± 1.0
$\overline{\Lambda}p\gamma$	$2.5 \pm 0.4 \pm 0.2$		2.5 ± 0.5
$B_s^0 \to \phi\gamma$	$57 \pm 17 \pm 12$		57 ± 21



Other exclusive $b \to s\gamma$ modes

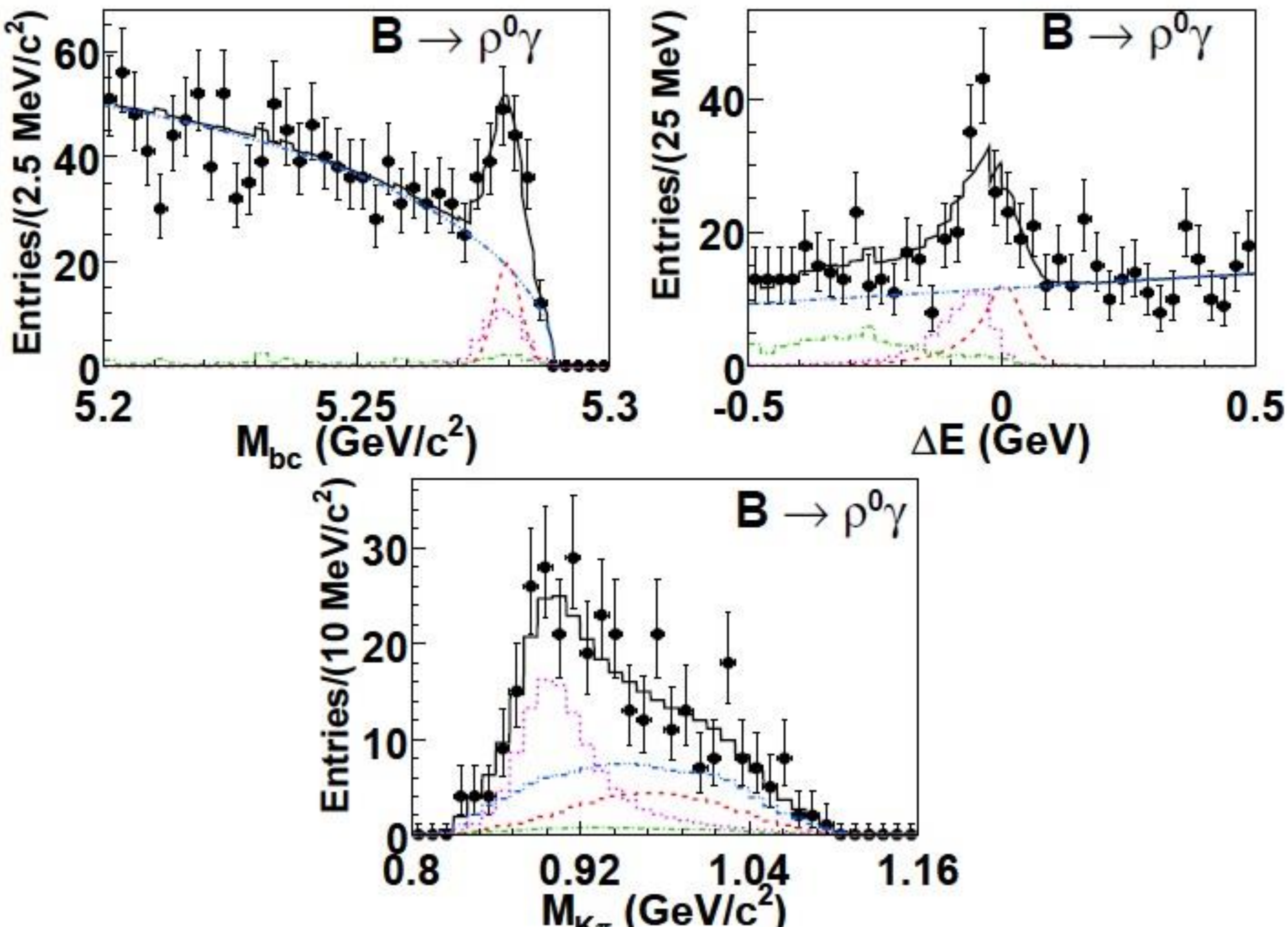
- $B \to K\pi\pi\gamma$ – measurements of the photon polarization (full Dalitz plot analysis is required)
- Upper limits on $K^*(1410), K_1(1400), K_3^*(1780)$
- X_s final states $K\eta, K\eta', K\phi$ for the first time have been measured – primary interest (time-dependent CP assymetry can be measured)
- Baryonic radiative decay $B^+ \to \overline{\Lambda} p\gamma$ has been measured
- First $B_s^0 \to \phi\gamma$ radiative decay was observed;
- Large hadronic uncertainties are due to the nonperturbative input of the QCDF approach
- These uncertainties do not allow precise predictions of the branching fractions of exclusive modes
- $Br(B \to K^*\gamma) \sim F(q^2 = 0)$→ QCD sum rules → 20% theoretical uncertainties

Exclusive and inclusive $b \rightarrow d\gamma$

- Proceed through penguin diagram
- Suppressed due to $\left|\frac{V_{td}}{V_{ts}}\right|^2$
- U-quark contribution is not negligible anymore
- $b \rightarrow s\gamma$ events are large background for $b \rightarrow d\gamma$
- However they are also good control sample;

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

Exclusive $b \to d\gamma$



Rate asymmetries

The direct CP asymmetry

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}) - \Gamma(B \to X)}{\Gamma(\bar{B} \to \bar{X}) + \Gamma(B \to X)}$$

$A_{CP}(B \to X_s\gamma) = -0.011 \pm 0.030 \pm 0.014$- BABAR results

$A_{CP}(B \to X_s\gamma) = 0.002 \pm 0.050 \pm 0.030$- Belle results