Radiative and electro-weak penguin decays at Belle

Li Jin (University of Hawaii)
Representing the Belle Collaboration

DPF2006 + JPS2006

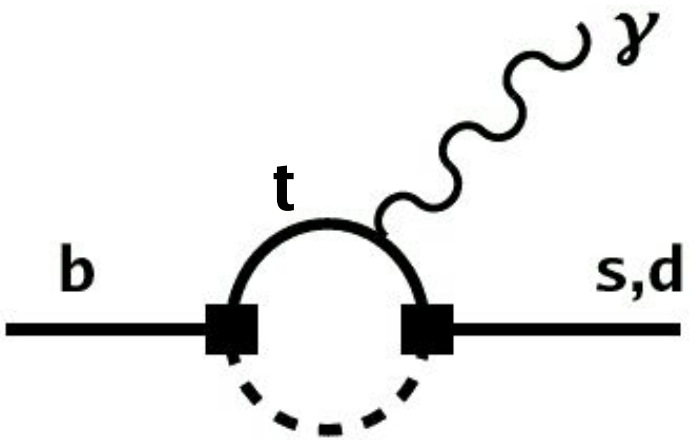
- $b \to d\gamma$
- $b \to s\gamma$ TCPV
- $b \to s\gamma$ inclusive
- $b \to s l^+ l^-$

What's missing:

$B \to l^+\nu$; $B \to l^+ l^-$; $B \to K(*)\nu\nu$; $B \to K\eta(')\gamma$; ... ...

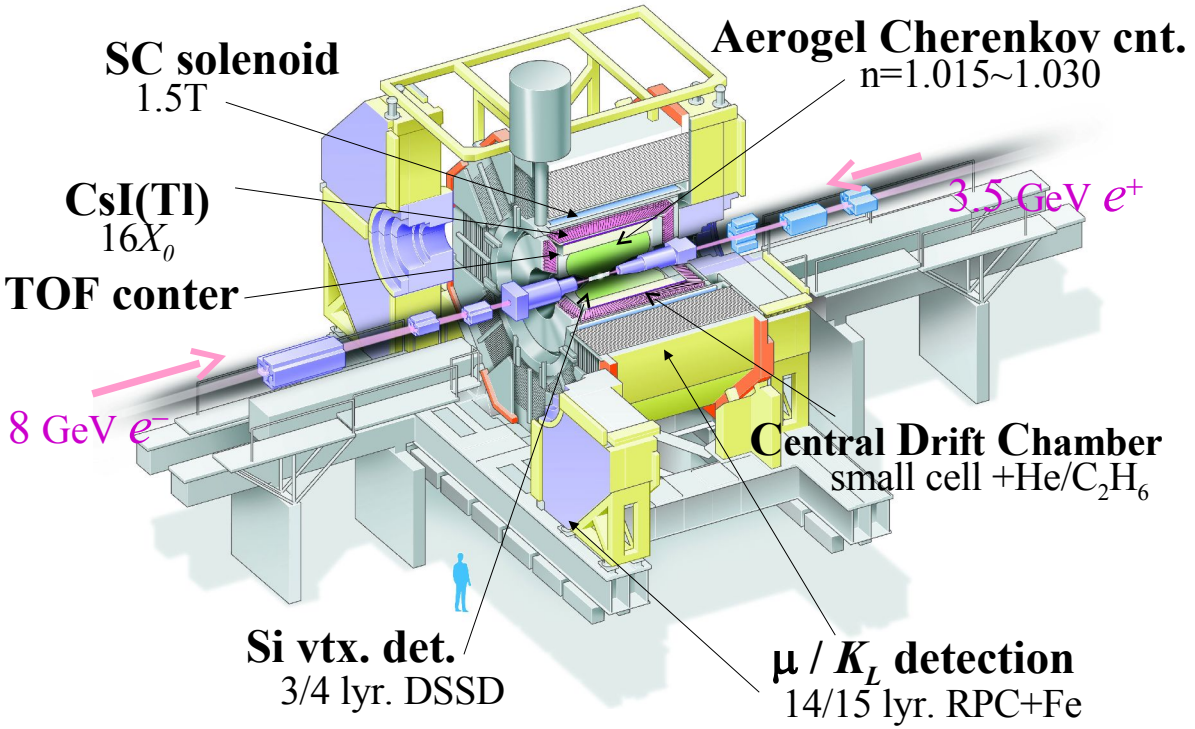
---To be discussed in Leo Piilonen's talk in the "Beyond the SM" session (Wed. 14:30)

Radiative Penguins

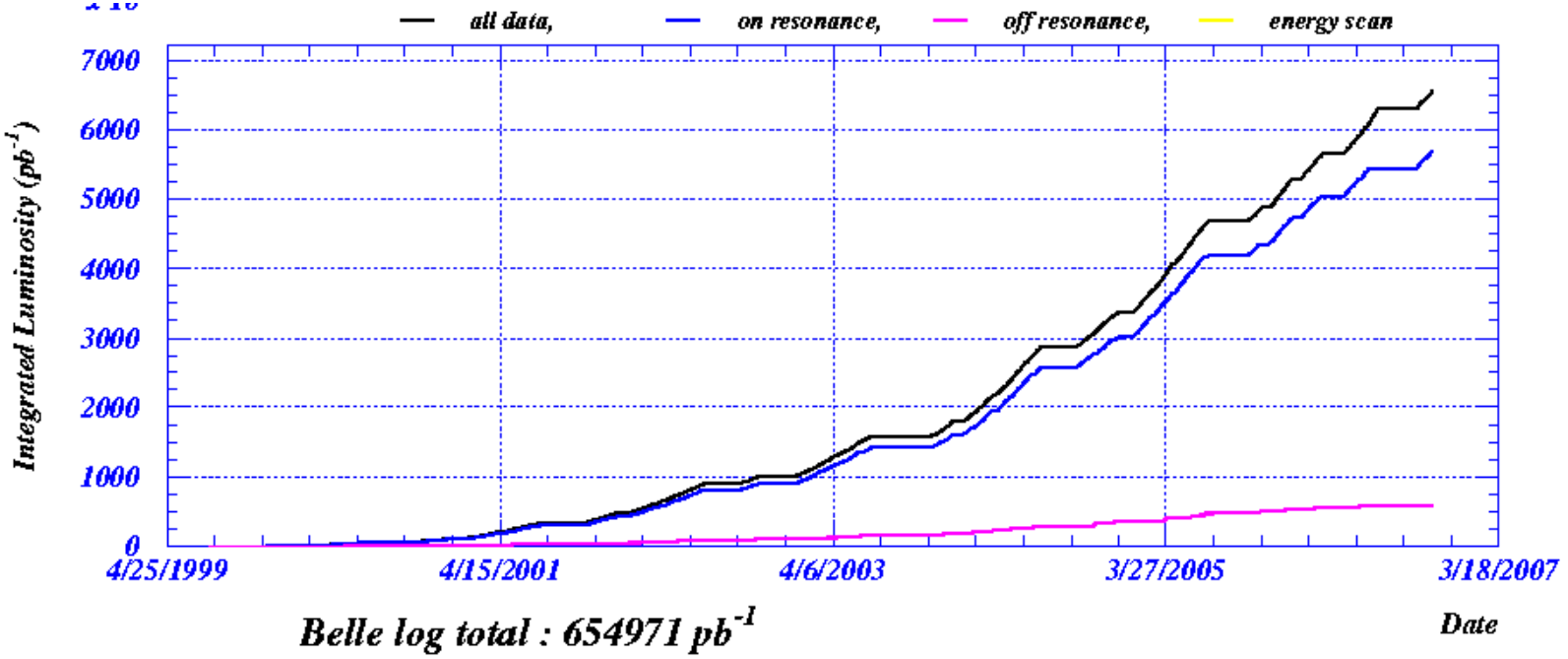


- Sensitive to New Physics in the Loop
- Theoretically clean (hadronic uncertainty small) : can be used to measure SM couplings $|V_{ts}|$,$|V_{td}|$

Belle Detector



Belle luminosity collected:
~ 600 fb^{-1}
386M or 535M BB used



Exclusive B mode techniques

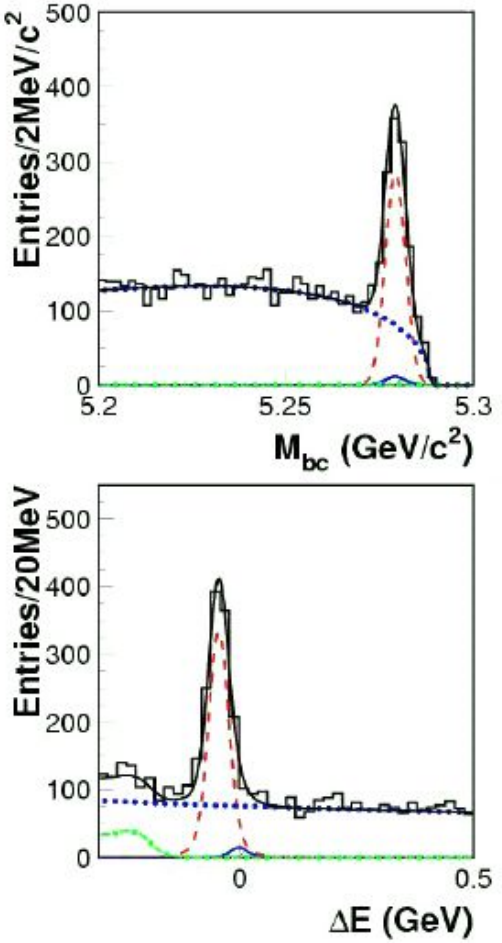
Two main variables:

Beam-constrained mass
(independent of particle id)

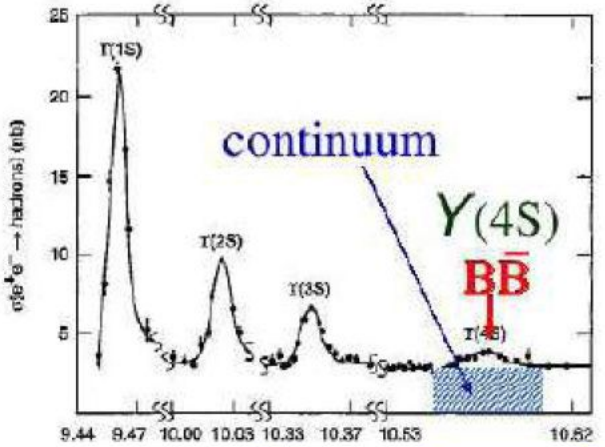
$$M_{bc} = \sqrt{E^{*2}_{\text{beam}} - |\vec{p}^{\,*}_B|^2}$$

Energy difference

$$\Delta E = E_B - E_{\text{beam}}$$

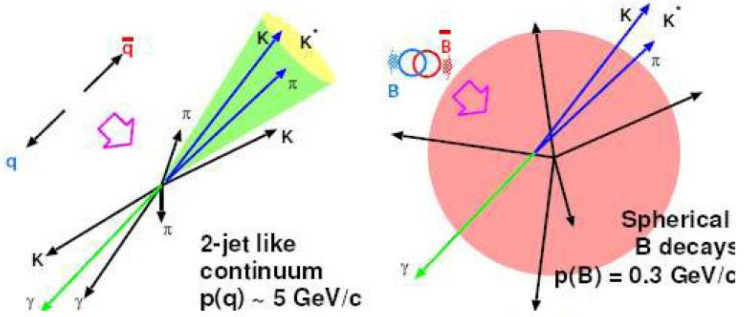


Continuum suppression:



Event Shape discrimination

continuum B B

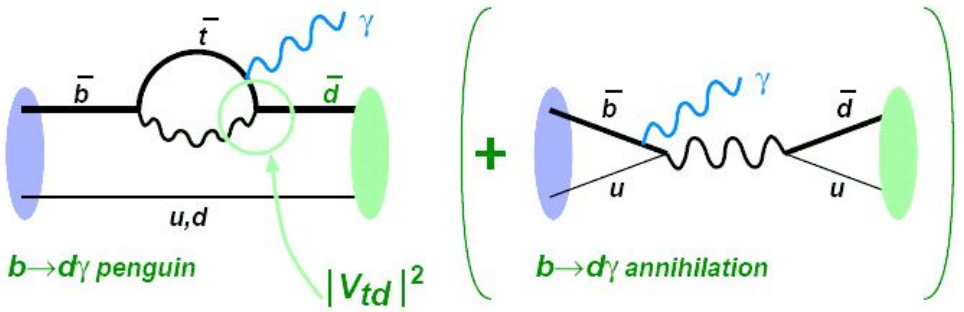


b → d γ in exclusive processes

b → dγ roles:

- Sensitive to $|V_{td}|$, or $|V_{td}/V_{ts}|$ w.r.t. b→sγ.
- Sensitive to New Physics emerging in the transition, since $|V_{td}|$ in SM is strongly suppressed.
- expect Large Direct CPV (penguin + annihilation)

-PRD72,094005(2005)-



Exclusive modes are straightforward experimentally:

$$B^- \to \rho^- \gamma\,,\ \bar{B}^0 \to \rho^0 \gamma\,,\ \bar{B}^0 \to \omega\,\gamma$$

(SU(3) breaking effect , annihilation contamination in the charged mode).
-PLB595,323(2004)-

B → ργ, B→ωγ backgrounds

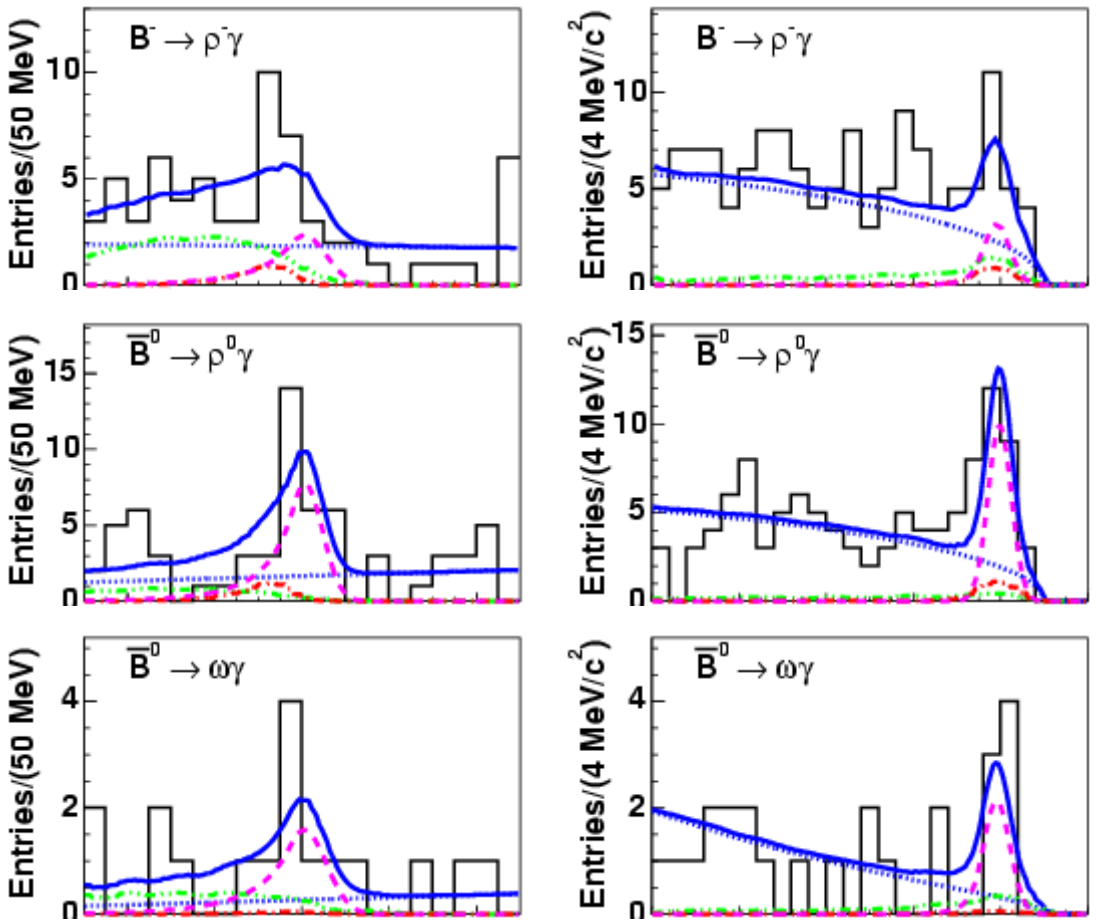
- B → K*γ backgrounds (x 30 signal size)
  - −ΔE distribution shifted low from mis-ID
  - −Particle ID requirements
  - −also is a good control sample for signal shape and cross-check
- Huge Continuum background
  - − Likelihood ratio from: Event Shape – Fisher discriminant from modified Fox-Wolfram moments, $\cos\theta_B^*$, and Δz
  - − Likelihood cut optimized for six individual flavour-tagging bins
- $B \to (\rho,\omega)\pi^0$ and $B \to (\rho,\omega)\eta$ BG

π^0,η veto based on π^0,η likelihoods; cut on decay helicity angle of (ρ,ω)

- Other $B \to X_s\gamma$
- Other rare B decays

Selection criteria optimized based by maximizing $N_S/\sqrt{N_B}$

$B \to \rho\gamma$ and $B \to \omega\gamma$ Signal in Belle



$B^- \to \rho^- \gamma\,(1.6\sigma)$

Yield = 8.5 events

$$BF = (0.55^{+0.42\,+0.09}_{-0.36\,-0.08}) \times 10^{-6}$$

$\bar{B}^0 \to \rho^0 \gamma\,(5.2\sigma)$

Yield = 20.7 events

$$BF = (1.25^{+0.37\,+0.07}_{-0.33\,-0.06}) \times 10^{-6}$$

$\bar{B}^0 \to \omega\gamma\,(2.3\sigma)$

Yield = 5.7 events

$$BF = (0.56^{+0.34\,+0.05}_{-0.27\,-0.10}) \times 10^{-6}$$

Signal, continuum, K*γ BG and other B

BELLE 386M BBbar
-PRL96,221601(2006)-

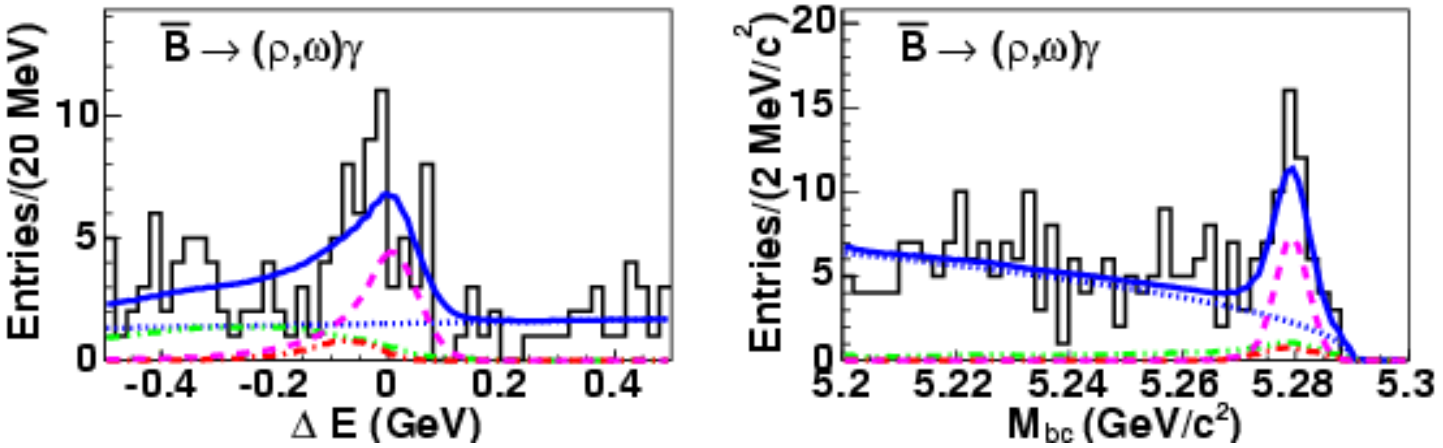
Combined $B \to (\rho, \omega)\gamma$

Assume isospin relationship: (expected violation less than 10%)

$$\Gamma(B \to (\rho, \omega)\gamma) \equiv \Gamma(B^- \to \rho^- \gamma) = 2\Gamma(\bar{B}^0 \to \rho^0 \gamma) = 2\Gamma(\bar{B}^0 \to \omega\gamma)$$

Simultaneous fit gives: (first observation)

$$BF(B \to (\rho, \omega)) = (1.32^{+0.34\,+0.10}_{-0.31\,-0.09}) \times 10^{-6} (5.1\sigma)$$



Toy MC study shows 4.9% of the times has a bigger isospin violation

Constraints on $|V_{td}/V_{ts}|$

Using the Relation:

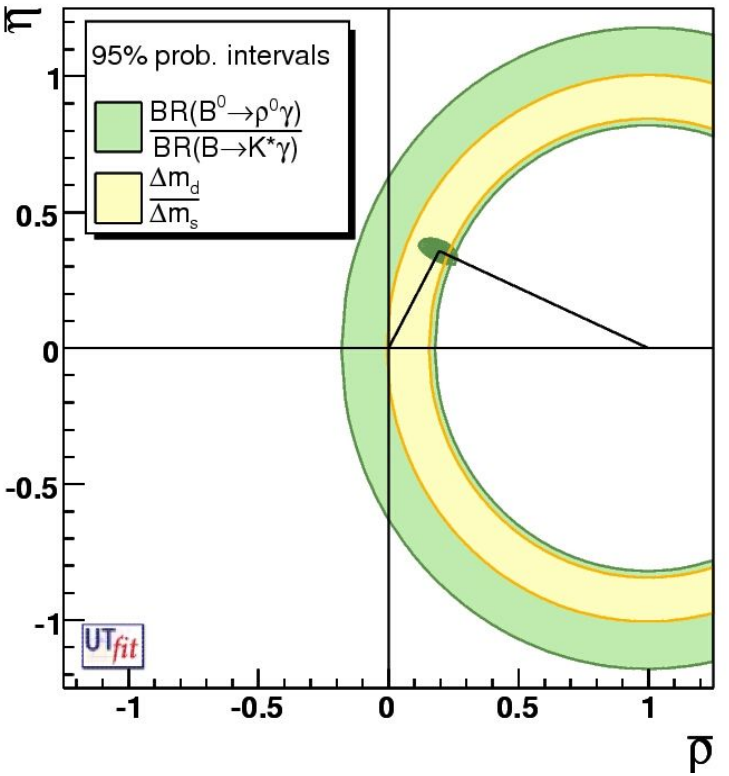
$$\frac{BF(\bar{B}\to(\rho,\omega)\gamma)}{BF(\bar{B}\to\bar{K}^*\gamma)}=\left|\frac{V_{td}}{V_{ts}}\right|^2\frac{(1-m^2_{(\rho,\omega)}/m^2_B)^3}{(1-m^2_{K^*}/m^2_B)^3}\zeta^2[1+\Delta R]$$

(form factor ratio $\zeta=0.85\pm0.10$ and SU(3) correction $\Delta R=0.1\pm0.1$)
Belle obtains:

$$|V_{td}/V_{ts}|=0.199^{+0.026}_{-0.025}(\text{exp})^{+0.018}_{-0.015}(\text{theor}).$$

$$0.142<|V_{td}/V_{ts}|<0.259 \quad (95\%\,\text{CL})$$

Conclusion:
- as expected in SM, no New Physics now.
- CPV study in future.
- quark level transition b→d observed and consistent with SM.



Time dependent CPV in $B^0 \to K_s \pi^0 \gamma$

In SM: Photons are mainly left-handed in $b \to s\gamma$ decay.

$$\frac{\Gamma[\bar{B}^0(t) \to f\gamma] - \Gamma[B^0(t) \to f\gamma]}{\Gamma[\bar{B}^0(t) \to f\gamma] + \Gamma[B^0(t) \to f\gamma]} = S\sin(\Delta mt) + C\cos(\Delta mt)$$

expected small S term in SM:

$$S = -2\underbrace{\left|\frac{A(\bar{B} \to f_s\gamma_R)}{A(\bar{B} \to f_s\gamma_L)}\right|}_{\ll 1}\cos\delta\sin 2\phi_1$$

- f = K^{*0} , |S| ~ 0.02 in SM. (-hep-ph/0609037-)
- f can be multibody states with pseudoscalar mesons. -PRD,71,076003-
- for f = Ksπ^0, |S| <0.08 in SM. (-PRD,73,014013)

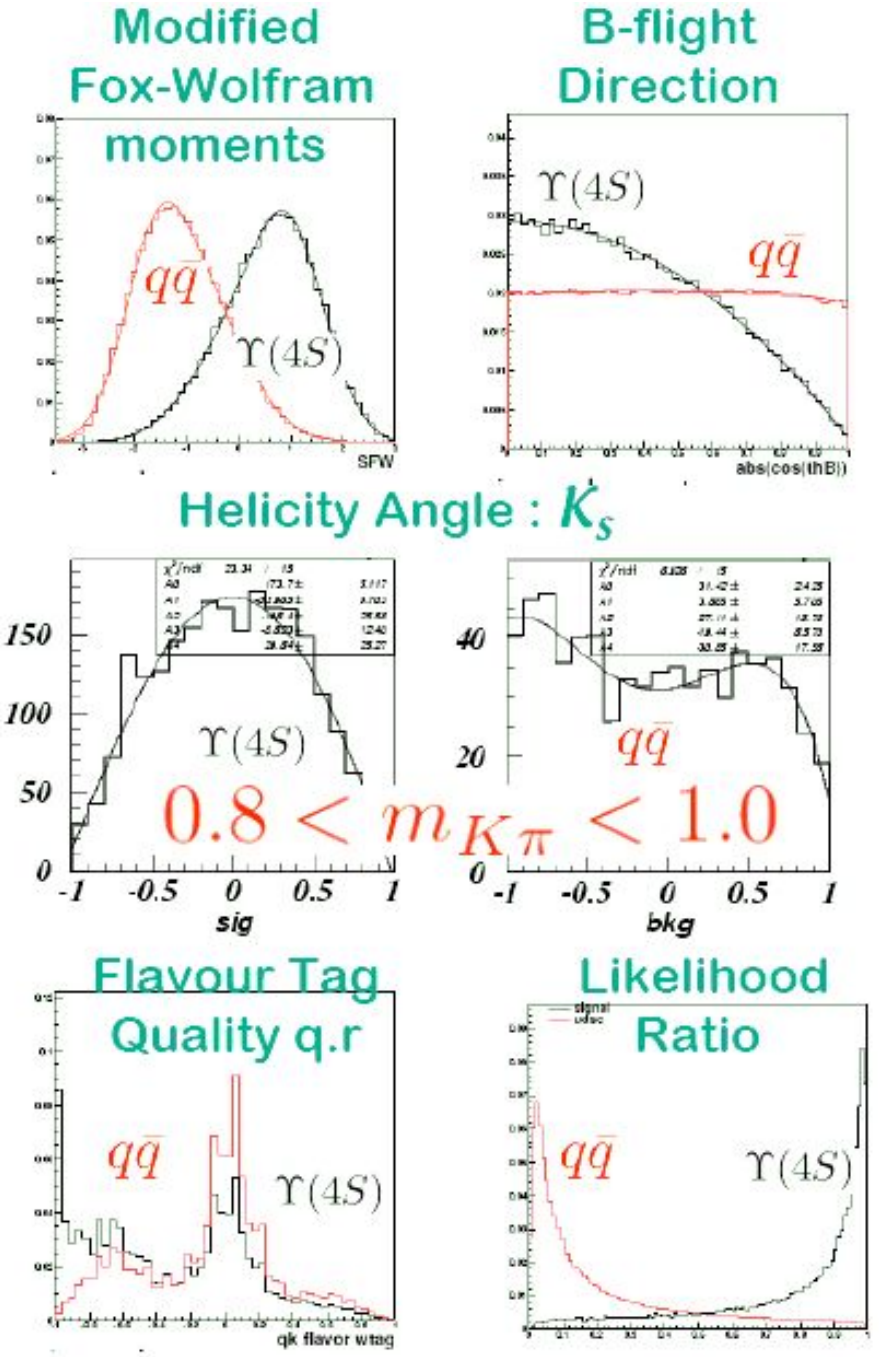
New Physics signal if |S| is larger than expected.

$B^0 \to K_s \pi^0 \gamma$ selection

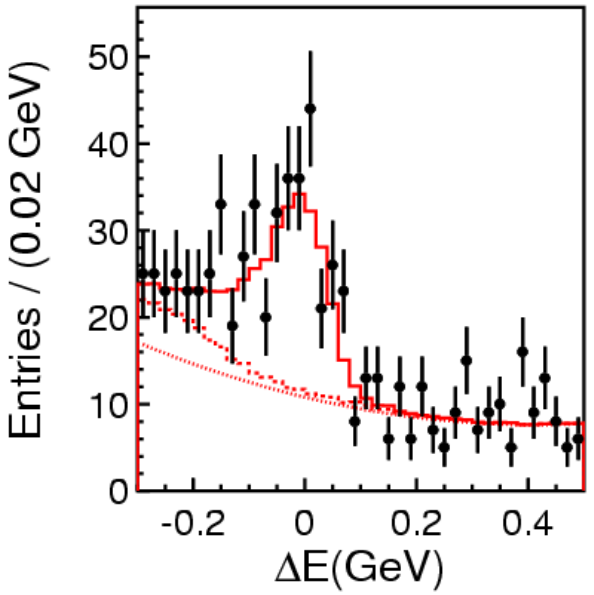
Use $M(K_s \pi^0) < 1.8$ GeV events

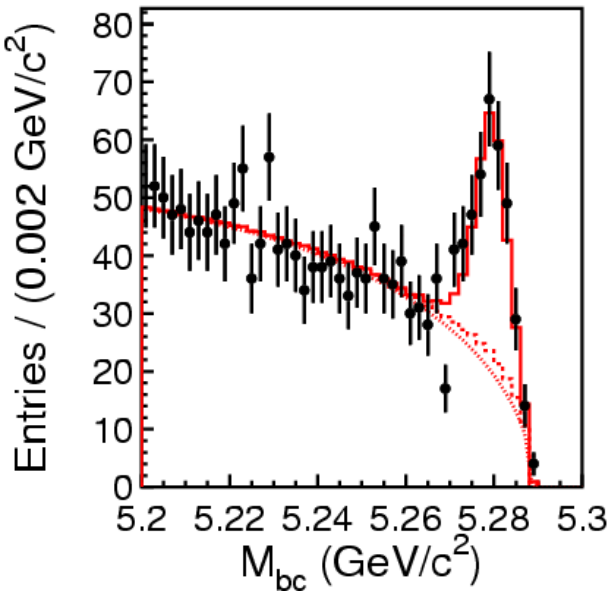
Continuum supression:
Likelihood constructed from
- Modified Fox-Wolfram moments (Event Shape)
- $\cos(\theta_B)$
- Helicity in $K_s \pi^0$ system for three different $M(K_s \pi^0)$ regions

Flavor tag quality dependent Likelihood cuts.



CP Asymmetry for $B^0 \to K_s \pi^0 \gamma$ in Belle

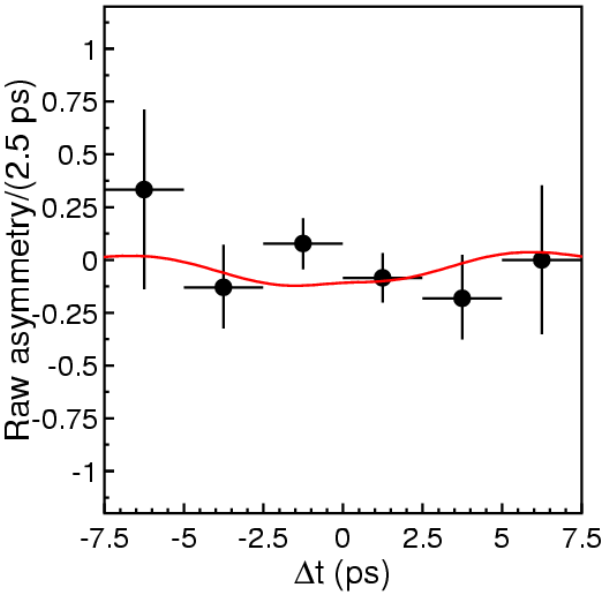




-hep-ex/0608017-

176.4±17 events in Signal Box

Asymmetry plot:



535 Million $B\bar{B}$

For $M(K_s\pi^0)<1.8$ GeV

$$S = -0.10 \pm 0.31 \pm 0.07$$

$$A = -0.20 \pm 0.20 \pm 0.06$$

For $K^{*0}(892)$ resonance region

$$S = -0.32^{+0.36}_{-0.33} \pm 0.05$$

$$A = -0.20 \pm 0.24 \pm 0.05$$

b → s γ inclusive

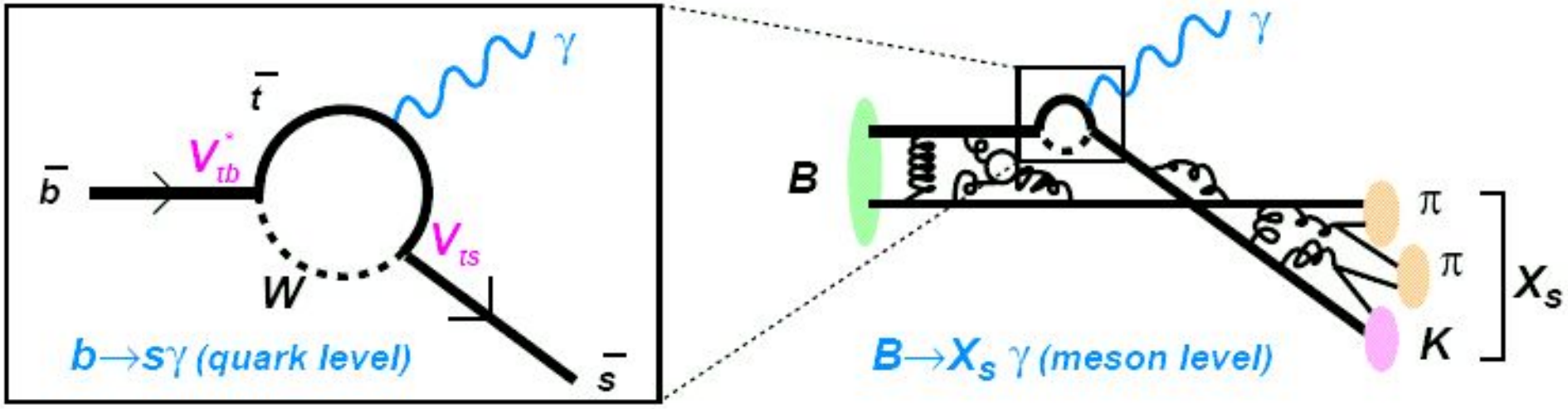
Inclusive b → sγ measurements.

- Inclusive branching fraction: measure Wilson coefficient C_7 .
- Inclusive photon energy spectrum: input to $|V_{ub}|$ and $|V_{cb}|$ extraction.

-hep-ph/0507253-

- Direct CPV is sensitive to NP in the loop.

electroweak penguin diagram



- Inclusive BR(B→ X_sγ) estimated at NNLO: (-hep-ph/0609232-)

$$BR(\bar{B}\to X_s\gamma)=(3.15\pm0.23)\times10^{-4}\ \text{for}\ E_\gamma>1.6\,\text{GeV}$$

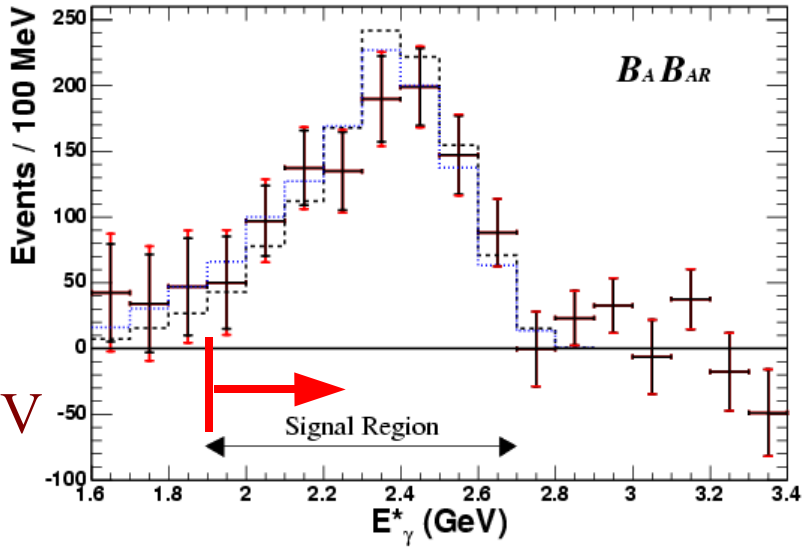
- First measurement by CLEO in 95, now precise measurements

Full inclusive b → X_s γ and E_γ spectrum

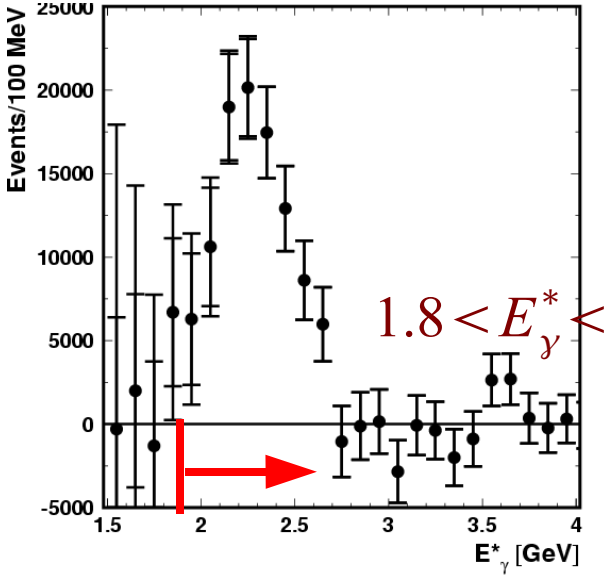
- γ cluster only.
- off-resonance continuum background rejection.
- subtraction of off-resonance and B → X(π^0,η) backgrounds.

BaBar 85.1fb^{-1},
9.6fb^{-1} off-resonance
-hep-ex/0607071-
Lepton-tag method
eff-uncorrected

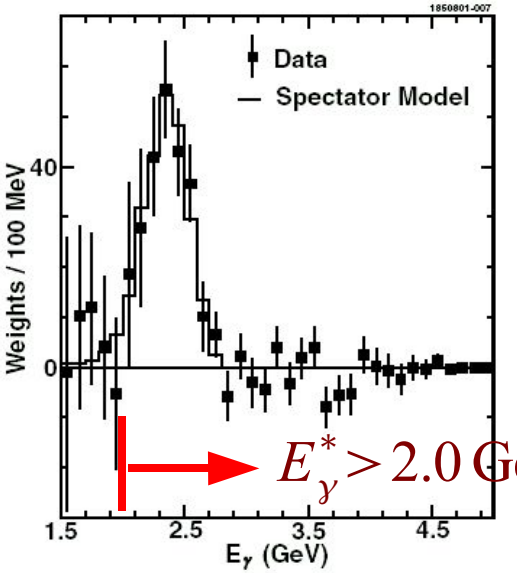
$1.9 < E^*_\gamma < 2.7$ GeV



Belle 140 fb^{-1},
15fb^{-1} off-resonance
-PRL93,061803(2004)-



$1.8 < E^*_\gamma < 2.8$ GeV



$E^*_\gamma > 2.0$ GeV

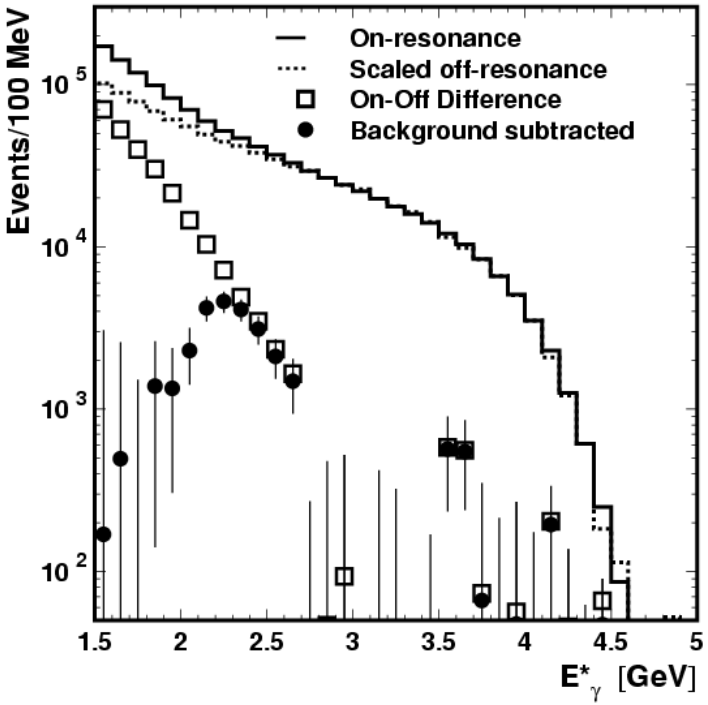
CLEO 9.1 fb^{-1},
4.4fb^{-1} off-resonance
-PRL87,251807(2001)-

Belle Inclusive b → s γ measurement

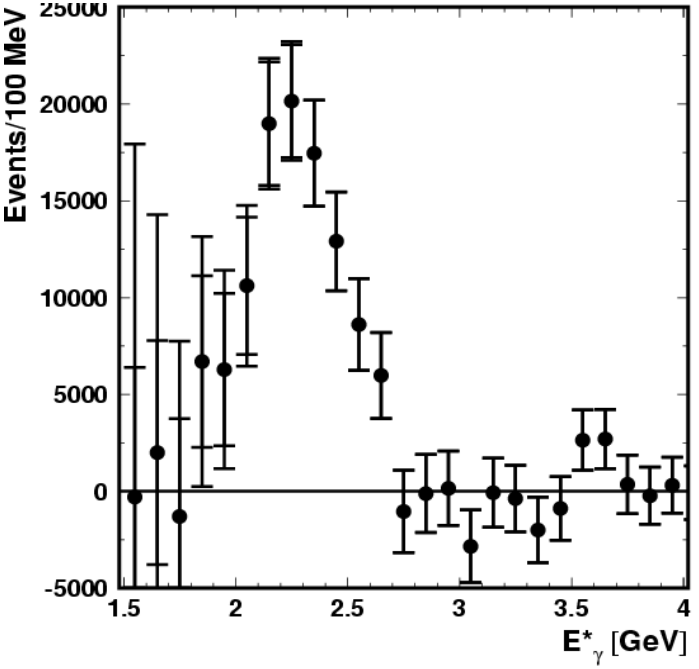
- collect high-energy γ
- continuum rejection by
  - Event Shape (Fox-Wolfram moments , thrust angle)
  - energy flows around the photon axis (3 regions)
- Subtract off-resonance data from on-resonance data spectrum
- Subtract B decay backgrounds(from π^0,η,η',ω and random clusters)

$$BF(b\to s\gamma)=(3.55\pm0.32^{+0.30+0.11}_{-0.31-0.07})\times10^{-4}$$

Belle 140 fb^{-1}



Subtracted and Eff-corrected

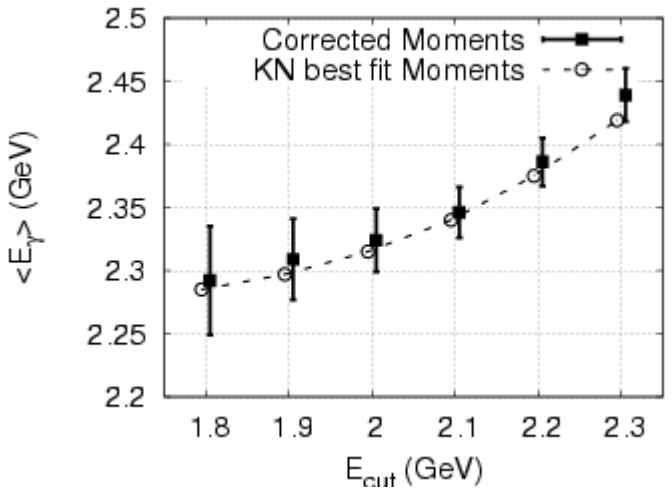


Belle Inclusive b → s γ measurement

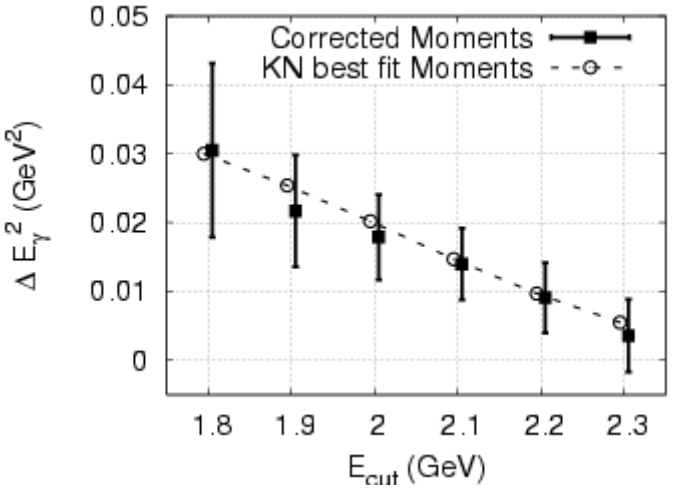
Photon energy spectrum moment measurement

1st moment $< E_\gamma >$, 2nd moment $<E_\gamma^2> - <E_\gamma>^2$ are related to mass and momentum of the b quark

- second momentum corrections:
  - B boost at Y(4S) frame.
  - detector resolution and binning.
- bias correction from low energy tail by studying $B \to K^{*\cdots} \gamma$ MC



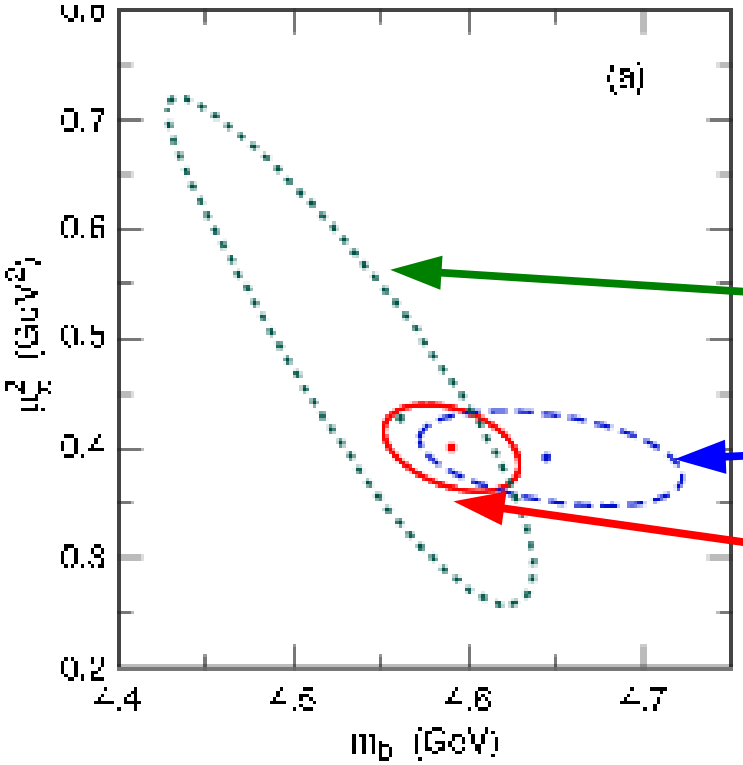
mean E_γ as with $E_\gamma > E_{cut}$



variance E_γ as with $E_\gamma > E_{cut}$

Compare with Kagan-Neubert (KN) Prescription -Eur.Phys.J.C7,5(1999)-

Fit to Heavy Quark Expansion



-hep-ph/0507253-

Parameters for the Heavy Quark Expansion:

- b-quark mass m_b
- kinetic expectation μ_π^2

fit to $B \to X_s\gamma$ moments

fit to $B \to X_c l\nu$ moments

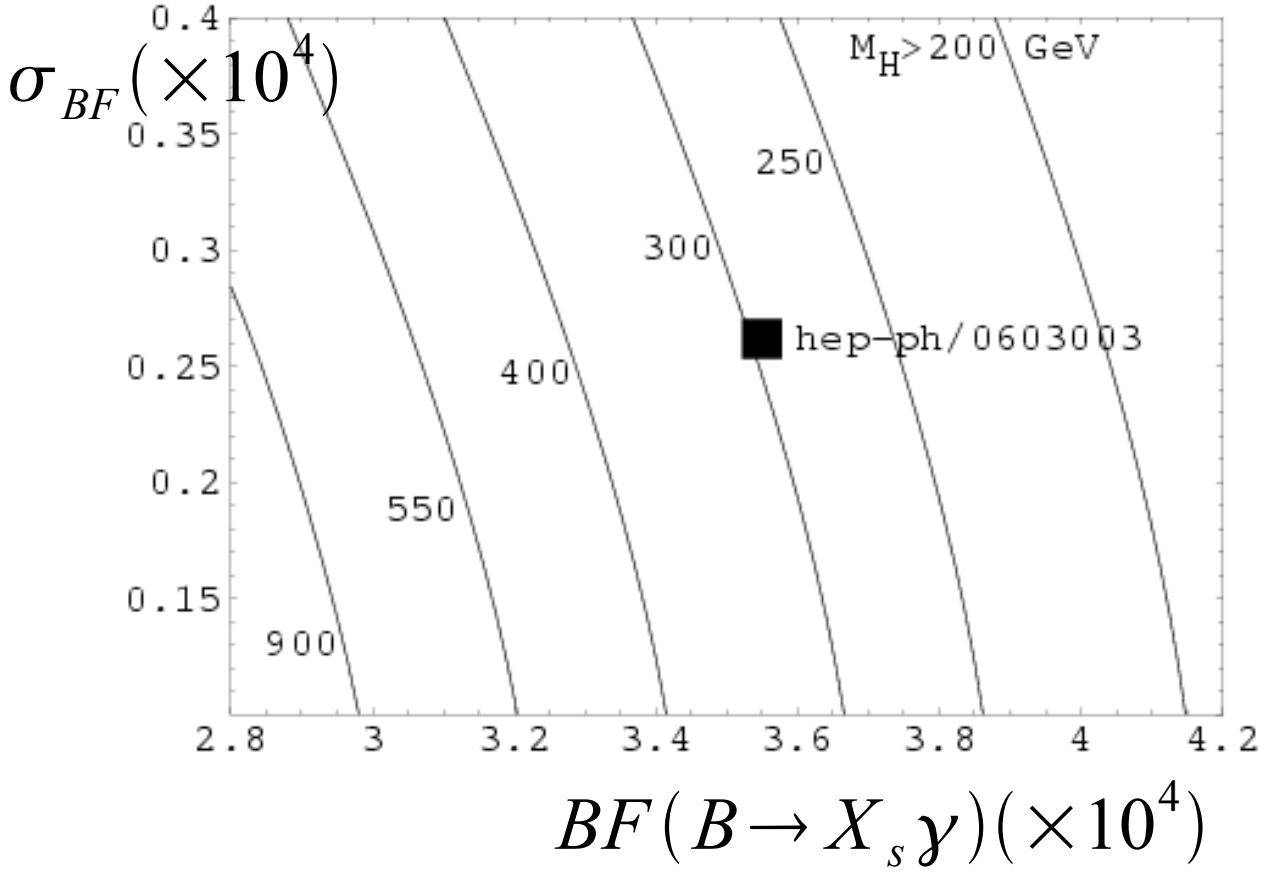
global fit (CLEO, Belle, BaBar data)

	m_b(GeV)	μ_π^2(GeV^2)
Kinetic	4.590±0.039	0.401±0.040
Shape Function	4.604±0.038	0.189±0.038

New Physics constraints from $B \to X_s \gamma$ BF

Heavor Flavor Averaging Group, -hep-ex/0603003-

$$BF(B \to X_s \gamma ; E_\gamma > 1.6\,\mathrm{GeV}) = (355 \pm 24^{+9}_{-10} \pm 3) \times 10^{-6}$$



-M.Misiak et al., hep-ph/0609232-

Example of a constraint on charged Higgs mass

- 95% CL lower limit on the Higgs mass 295 GeV, as a result of the new NNLO calculation
- Limit lower now

$$BR(\bar{B} \to X_s \gamma ; E_\gamma > 1.6\,\mathrm{GeV}) = (3.15 \pm 0.23) \times 10^{-4}$$

Direct CP asymmetry in b→sγ

$$A_{CP}=\frac{\Gamma(b\to s\gamma)-\Gamma(\bar{b}\to\bar{s}\gamma)}{\Gamma(b\to s\gamma)+\Gamma(\bar{b}\to\bar{s}\gamma)}$$

Very small in SM: -Nucl.Phys.B704,56(2005)-

$$A_{CP}^{SM}=(4.2^{+1.7}_{-1.2})\times10^{-3}$$

- Belle 140 fb^{-1}: $(2\pm50\pm30)\times10^{-3}$
- BaBar 82 fb^{-1}: $(25\pm50\pm15)\times10^{-3}$
- CLEo 9.1fb^{-1}: $(-79\pm108\pm22)\times10^{-3}$

HFAG: $A_{CP} = (4\pm37)\times10^{-3}$

- BaBar inclusive: $A_{CP}(B\to X_{(s+d)}\gamma)=-0.110\pm0.115\pm0.017$
- Note Possible cancellation of $A_{CP}(B\to X_s\gamma)$ and $A_{CP}(B\to X_d\gamma)$

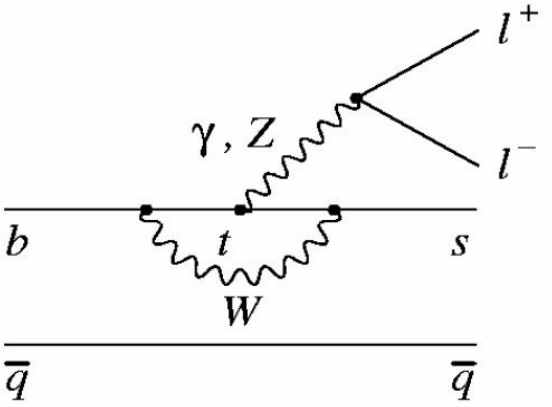
$b \to s l^+ l^-$

Effective Hamiltonian in SM:

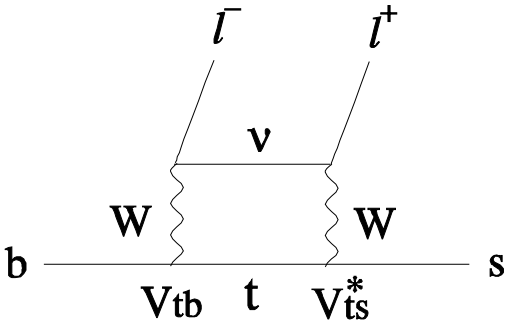
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

Wilson coefficient

operators at scale μ



b→sll penguin

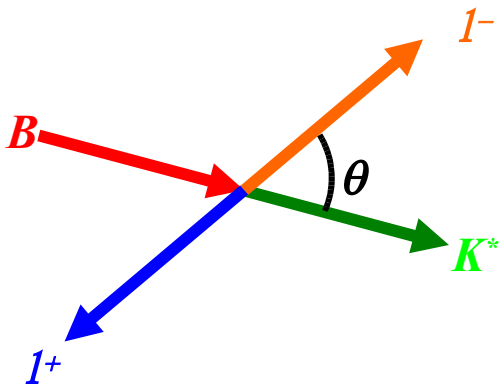


b→sll box

- O_7 : electromagnetic operator
- O_9 : semileptonic vector operator
- O_{10} : semileptonic axialvector operator

- At leading order, b → sll transition depends on O_7, O_9 and O_{10} only.
- At NNLO, $C_i^{\text{eff}} = A_i + \hat{s}$ dependent terms (i=7,9,10; $\hat{s} \equiv m_{ll}^2$)
- Inclusive b → sll branching fraction constrains C_9 and C_{10}.

Forward-Backward asymmetry in $B \to K^* l^+ l^-$



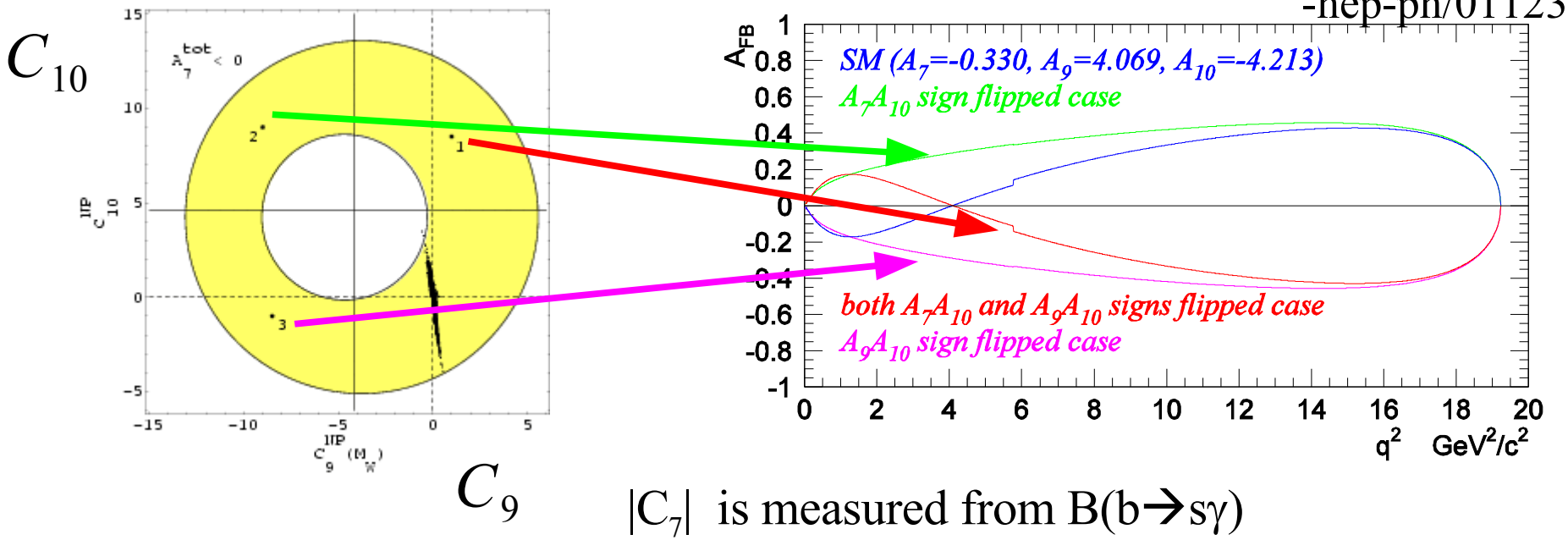
In $l^+ l^-$ CM frame:

- $\cos\theta_{l^- B} > 0$: Forward
- $\cos\theta_{l^- B} < 0$: Backward

$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_{l^- B} > 0) - \Gamma(q^2, \cos\theta_{l^- B} < 0)}{\Gamma(q^2, \cos\theta_{l^- B} > 0) + \Gamma(q^2, \cos\theta_{l^- B} < 0)}$$

A_{FB} from interference btw vector(C_7, C_9) and axial vector(C_{10}) couplings

-hep-ph/0112300-

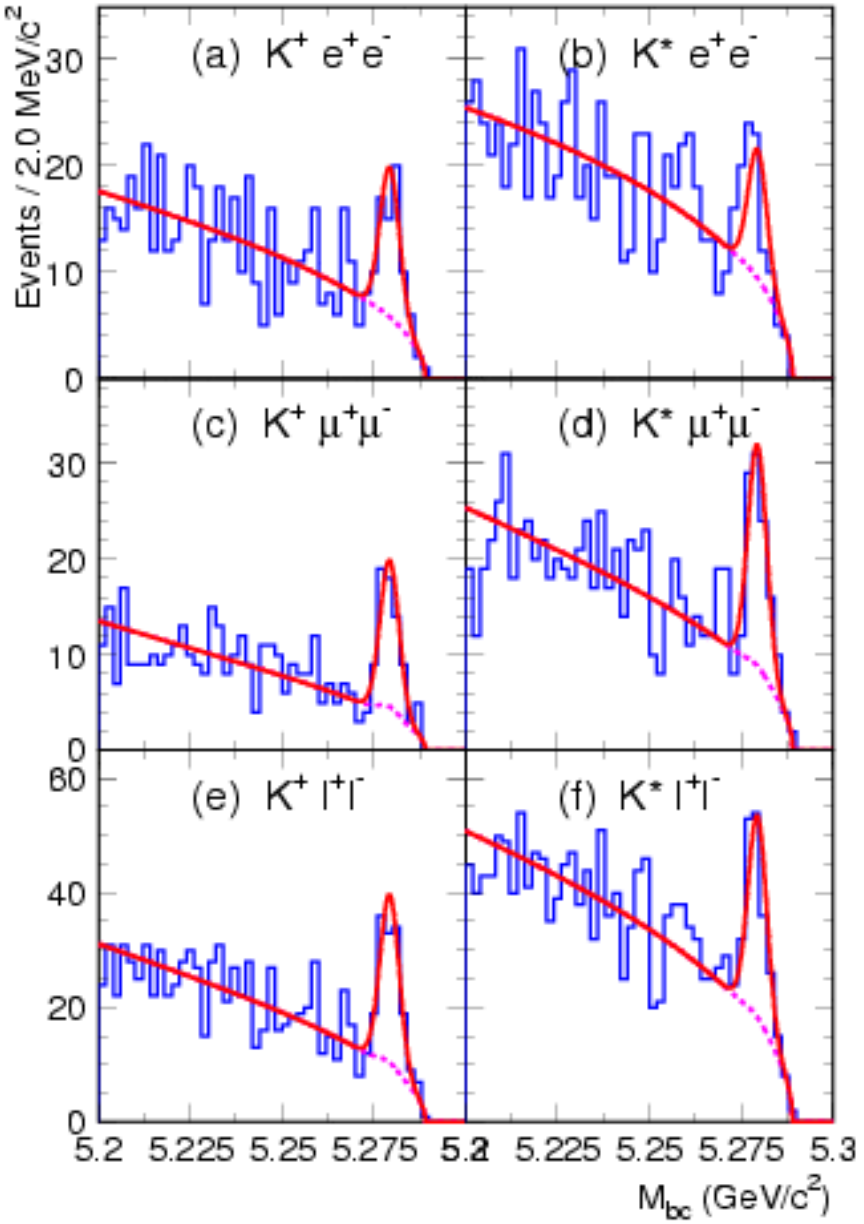


$|C_7|$ is measured from B(b→sγ)

$B \to K^* l^+ l^-$ Reconstruction in Belle

- Dataset: 357 fb^{-1} (386 M BBar pairs)
- Modes: $K^* \to K^+\pi^-, K^+\pi^0, K_s\pi^+$
- Dominant background: both B and Bbar decays semileptonically, suppressed with E_{miss} & $\cos\theta_B^*$ likelihood
- Charmonium (J/Ψ, $\Psi(2S)$) veto
- For $B \to K l^+ l^-$, $A_{FB} = 0$ in SM, used as a reference.

Singal Yield: $N_{sig} = 113.6 \pm 13.0$ for $B \to K^* l^+ l^-$, purity 44%



Extraction of A_{FB} and Wilson coeffs

Fix A to SM value (0.330) and extract A_9/A_7 and A_{10}/A_7 from an unbinned maximum likelihood fit , with double differential decay width $g(q^2,\theta) = d^2\Gamma/dq^2 d\cos\theta$ as PDF.

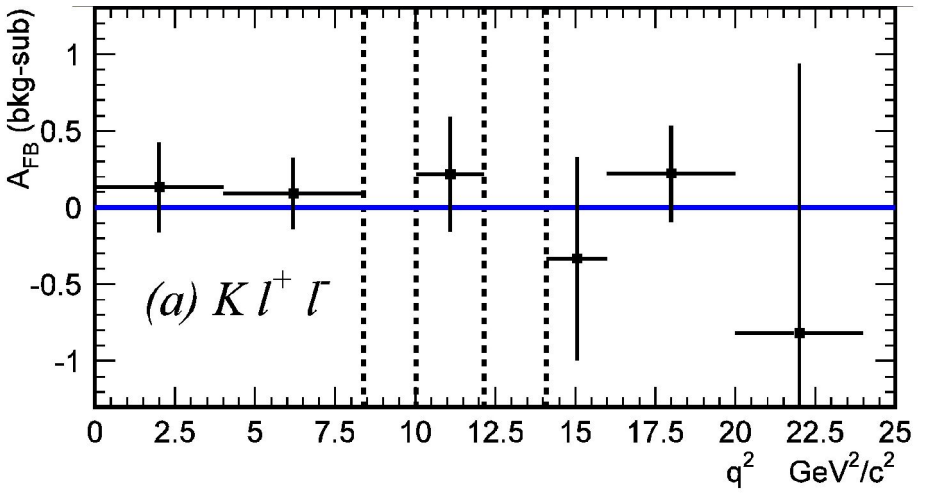
$$A_{FB}(q^2) = \frac{\int_{-1}^{1} \mathrm{sgn}(\cos\theta)\, g(q^2,\theta)\, dq^2}{\int_{-1}^{1} g(q^2,\theta)\, d\cos\theta\, dq^2}$$

Event categories:
signal, correctly and incorrectly tagged cross-feeds from $B \to K^{(*)}l^+l^-$ dilepton background(80%),K*lh background (h=K, π) (17%), K*hh and ψ background

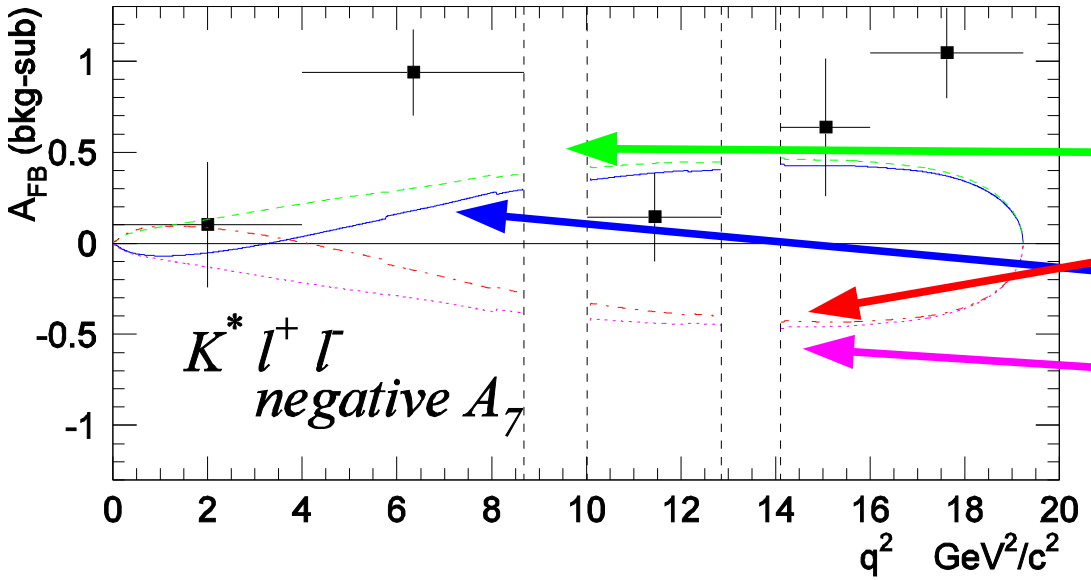
Null test with $K^+l^+l^-$

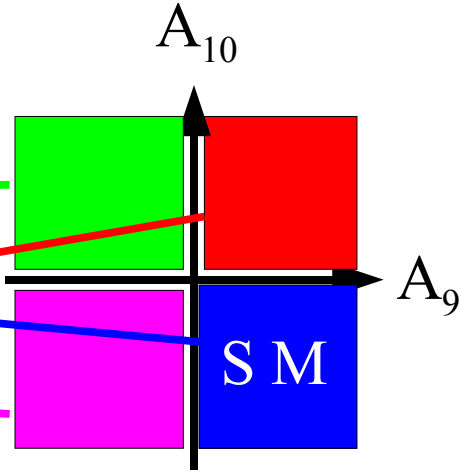
$A_{FB}(B^+ \to K^+l^+l^-) = 0.10 \pm 0.14 \pm 0.01$

consistent with zero



Fit Results and Confidence Contours





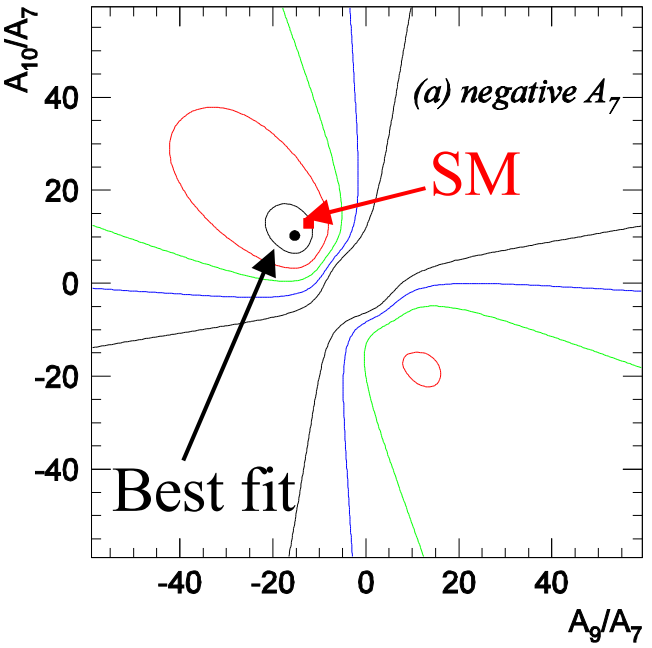
$-1401 < A_9 A_{10}/A_7^2 < -26.4$, (95% CL)

sign of $A_9 A_{10}$ positive excluded

$A_{FB}(K^* l^+ l^-) = 0.50 \pm 0.15 \pm 0.02$, with $A_7 = -0.330$

Wilson Coefficients: (A_7 SM) -PRL96,251801-

$$A_9/A_7 = -15.3\,^{+3.4}_{-4.8} \pm 1.1,$$
$$A_{10}/A_7 = 10.3\,^{+5.2}_{-3.5} \pm 1.8,$$



Summary

- $b \rightarrow d\gamma$: Observation of a new quark level b to d transition.

  $|V_{td}/V_{ts}|$ consistent with B_S - $\bar{B}_S$ Mixing and CKM fit.

- $b \rightarrow s\gamma$ TCP : Error on S,A from $B^0 \rightarrow K_S \pi^0 \gamma$ reduced, consistent with zero.

- $b \rightarrow s\gamma$ inclusive : HFAG average agrees with SM.

  Measured HQE parameters and constrains charged Higgs mass.

- $b \rightarrow s l^+ l^-$: Fit to $B \rightarrow K^* ll$ $A_{FB}(q^2)$ gives Wilson coeffs

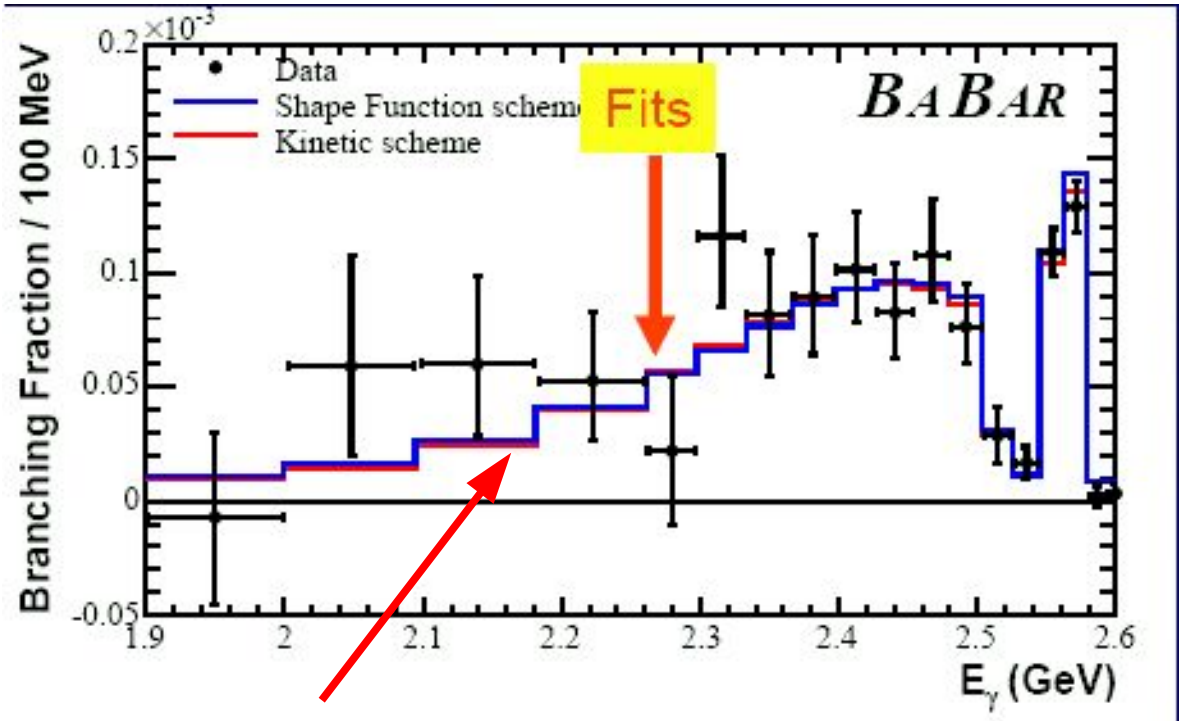
  - Large forward-backward asymmetry observed

  - No New Physics with positive $A_9 * A_{10}$

Backup

Semi-Inclusive B → X_s γ measurement

- Reconstruct as many modes as possible
- Photon energy resolution 1~5 MeV, while Full inclusive ~45 MeV



Shape function from Exponential Model (hep-ph/0504071)
Babar 81.5fb^{-1} – PRD72,052004 (2005)

BaBar:

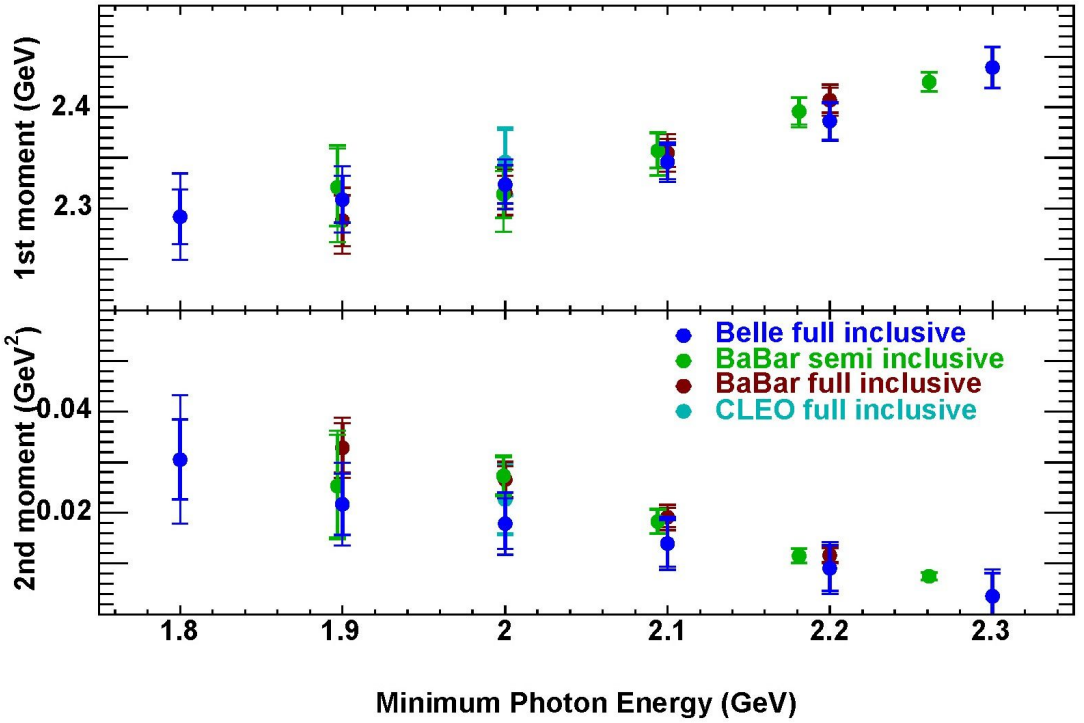
- 38 Modes(B → Kπγ, Kππγ, K3πγ,Kη(π)γ,KKK(π)γ, ...)
- 0.1 GeV bins of $M(X_s)$

equivalent to

$$E_\gamma = \frac{M_B^2 - M(X_s)^2}{2 M_B}$$

bins

Moments



1st moment $\langle E\gamma \rangle$

2nd moment $\langle (\langle E\gamma \rangle - E\gamma)^2 \rangle$

- Observables to be directly compared with predictions.

- Universal parameters in operator product expansion (several available schemes: kinetic scheme, shape function scheme).

- Kinetic scheme: evaluate m_b (b quark mass) and μ_π^2 (Fermi momentum) from a fit to spectrum.

- D. Benson NP **B710**, 371 (2005) -

- M. Neubert PLB **612**, 13 (2005) -

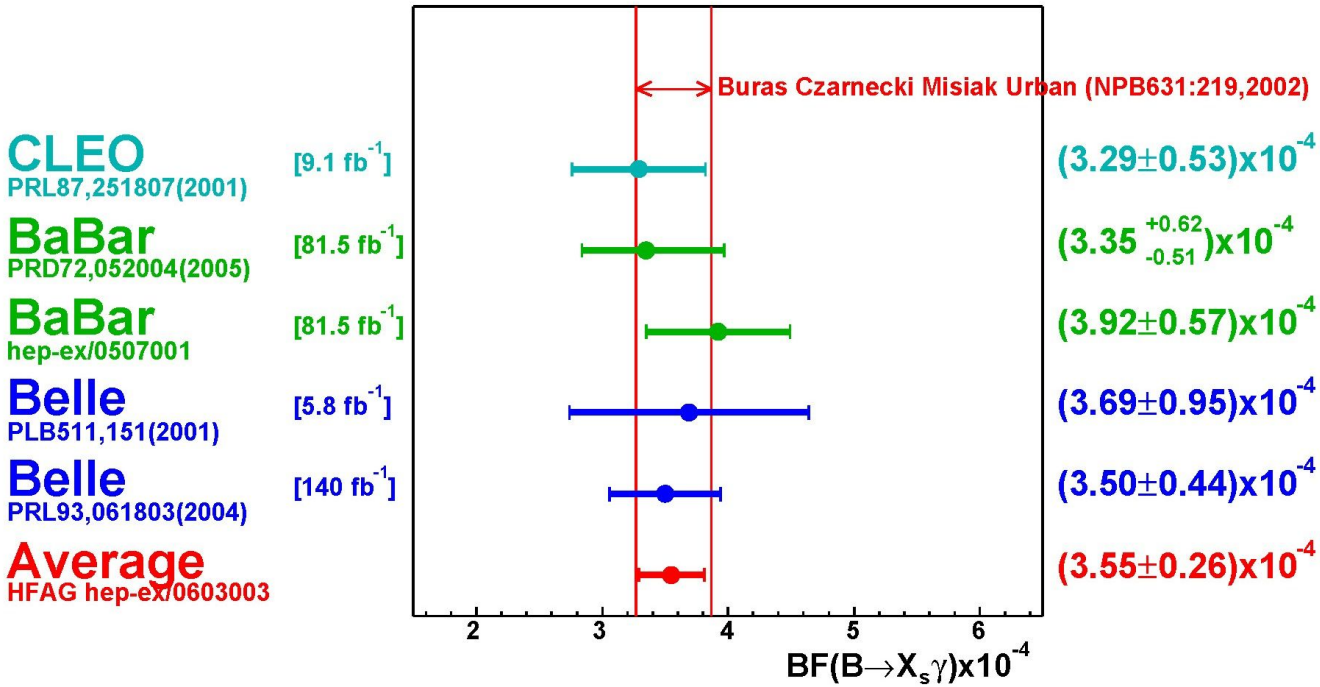
$B \rightarrow X_s \gamma$ branching fraction

- All measurements scaled to $E_\gamma = 1.6$GeV (where theory predictions stands -avoid dependence on heavy quark distribution function-)

- Then average BF is calculated

- Heavy Flavor Averaging Group (HFAG), hep-ex/0603003-

$$BF(B \rightarrow X_s \gamma ; E_\gamma > 1.6\,\mathrm{GeV}) = (355 \pm 24^{+9}_{-10} \pm 3) \times 10^{-6}$$



OPE and Wilson Coefficient

- Effective Hamiltonian is expressed in term of Operator Product Expansion.

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

  - $O_{1,2}$: current current operator
  - $O_{3\text{-}6}$: QCD penguin operator
  - $O_{7,8}$: electro- and chromo-magnetic operator
  - $O_{9,10}$: semileptonic operator
  - C_i: Wilson coefficient

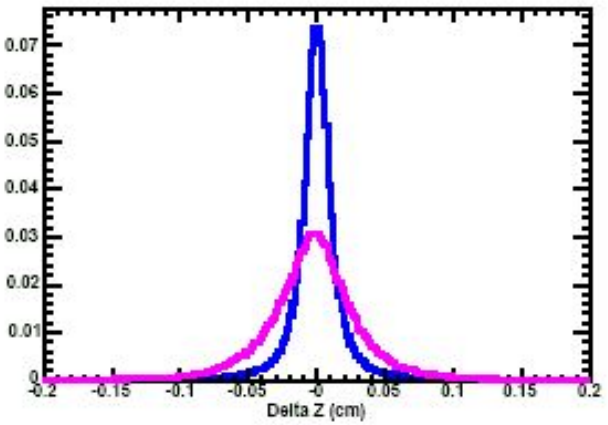
$$\begin{aligned}
\mathcal{O}_1 &= (\bar{s}_\alpha \gamma_\mu L c_\beta)(\bar{c}_\beta \gamma^\mu L b_\alpha),\\
\mathcal{O}_2 &= (\bar{s}_\alpha \gamma_\mu L c_\alpha)(\bar{c}_\beta \gamma^\mu L b_\beta),\\
\mathcal{O}_3 &= (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\beta),\\
\mathcal{O}_4 &= (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu L q_\alpha),\\
\mathcal{O}_5 &= (\bar{s}_\alpha \gamma_\mu L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\beta),\\
\mathcal{O}_6 &= (\bar{s}_\alpha \gamma_\mu L c_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu R q_\alpha),\\
\mathcal{O}_7 &= \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu}(m_s L + m_b R) b_\alpha F^{\mu\nu},\\
\mathcal{O}_8 &= \frac{g}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu}(m_s L + m_b R) T^a_{\alpha\beta} b_\beta G^{a\mu\nu},\\
\mathcal{O}_9 &= \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell}\gamma_\mu \ell,\\
\mathcal{O}_{10} &= \frac{e^2}{16\pi} \bar{s}_\alpha \gamma^\mu L b_\alpha \bar{\ell}\gamma_\mu \gamma_5 \ell,
\end{aligned}$$

- Each Wilson coefficient is the strength of a corresponding short distance operator.
- Precise measurement of Wilson coeffs. is one of the goals for B physics.
- For b→sγ and b→sll, only O_7, O_9 and O_{10} appear in the Hamiltonian.

New Physics changes the Wilson Coefficients

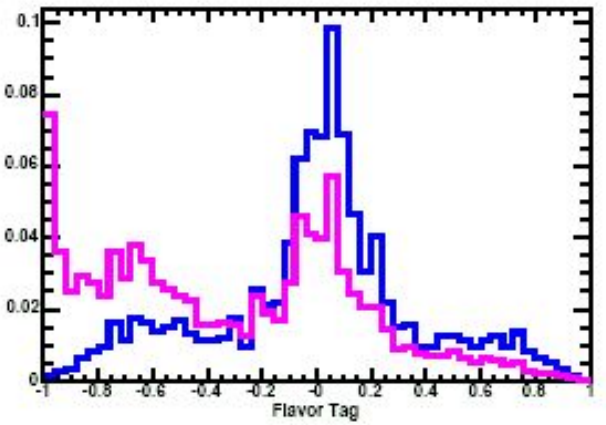
$B \to \rho\gamma$ and $B \to \omega\gamma$ analysis

- More specific background suppression (Belle's analysis)
  1. π^0 and $\eta \to \gamma\gamma$ rejection (copious!)
  2. K^* veto in $M(\text{“}K\text{”}\pi)$ (to suppress $B \to K^*\gamma$)
  3. Helicity angle of ρ/ω decay (discriminate $\rho\gamma$ vs $\rho\pi^0$, etc)
  4. B meson direction ($1 - \cos^2\theta_B$ for $\Upsilon(4S) \to B\overline{B}$)
  5. Vertex displacement (Δz) from other B ($\Delta z \sim 0$ for $q\overline{q}$)
  6. Flavor-tag algorithm of the other B ($q\overline{q}$ is neither B or $\overline{B}$-like)
- Combine 4, 5 and event-shape Fisher into a likelihood ratio, and flavor-tag quality dependent cut on it (BaBar uses neural net)

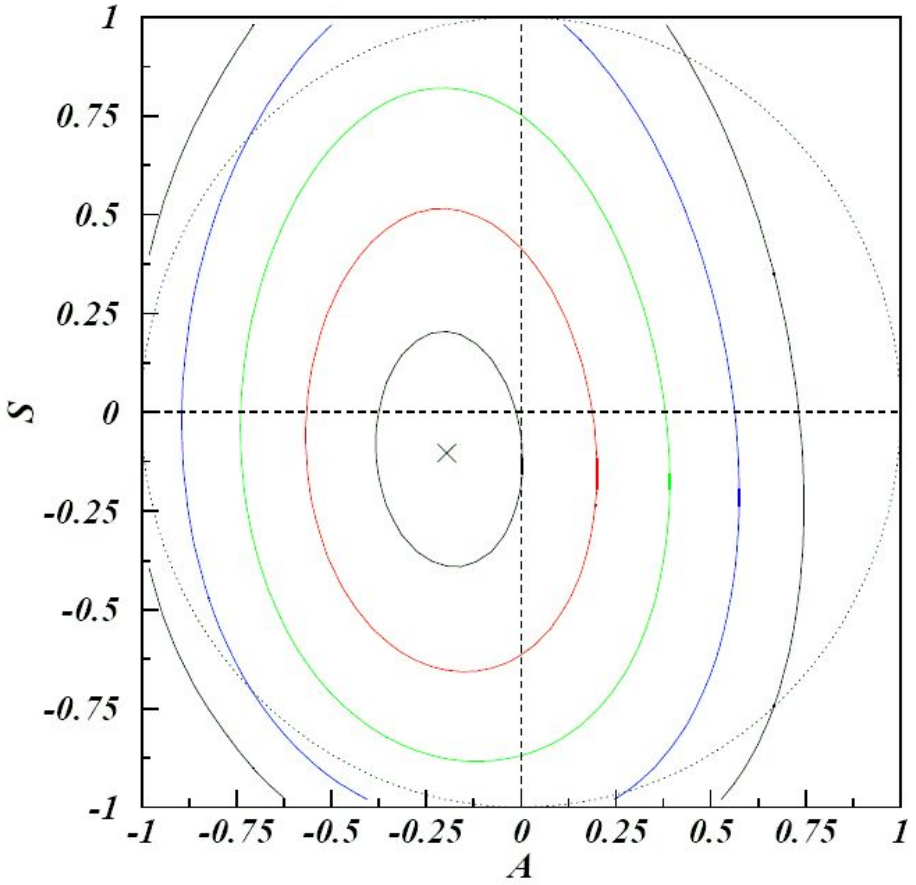


⇐ Δz for signal and continuum

Flavor-tag quality ⇒



Contour and Systematic for $B^0 \to K_s \pi^0 \gamma$



category	$\mathcal{S}$	$\mathcal{A}$
physics	0.009201	0.012314
background Δt	0.007177	0.003541
flavor tagging	0.007120	0.004745
signal fraction	0.060995	0.032658
fit bias	0.005853	0.003742
resolution function	0.025238	0.009851
vertex reconstruction	0.009238	0.021139
tag-side interference	0.002000	0.041000
sum	0.068321	0.059094

TABLE XIV: $[K_S^0\pi^0\gamma]$ Systematic Error Summary