Inclusive & Exclusive B Decays with Radiative and Electroweak Penguins at Belle

Kurtis Nishimura
University of Hawaii at Manoa
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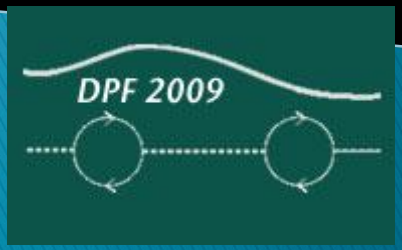
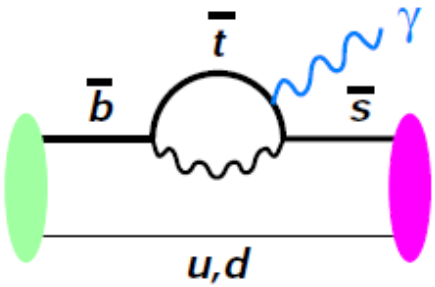


Outline

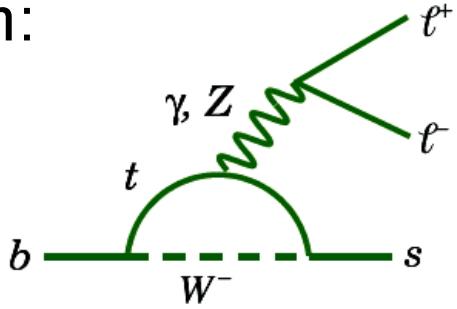
- Introduction
- Radiative penguin decays:
  - Inclusive: $b \to s\gamma$
  - Exclusive: $B \to K\eta'\gamma$
- Electroweak decays:
  - Exclusive: $B \to K^{(*)}\ell\ell$
- Summary

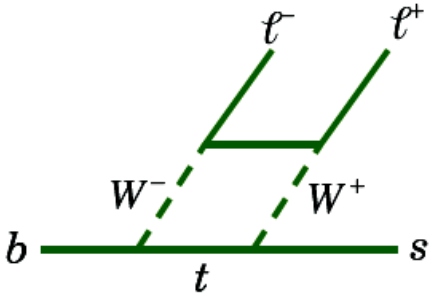
Introduction

- $b \to s\gamma$, $b \to s\ell\ell$
  - Flavor changing neutral current (FCNC) processes, forbidden at tree level ➔ sensitive to new physics.
  - For $b \to s\gamma$, via radiative penguin:



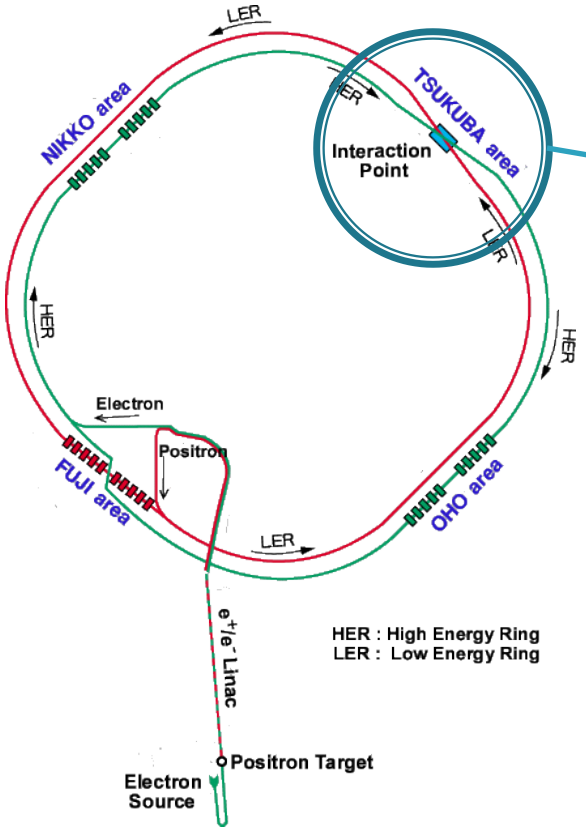
  - For $b \to s\ell\ell$, via Z/γ penguin or W^+/W^- box diagram:

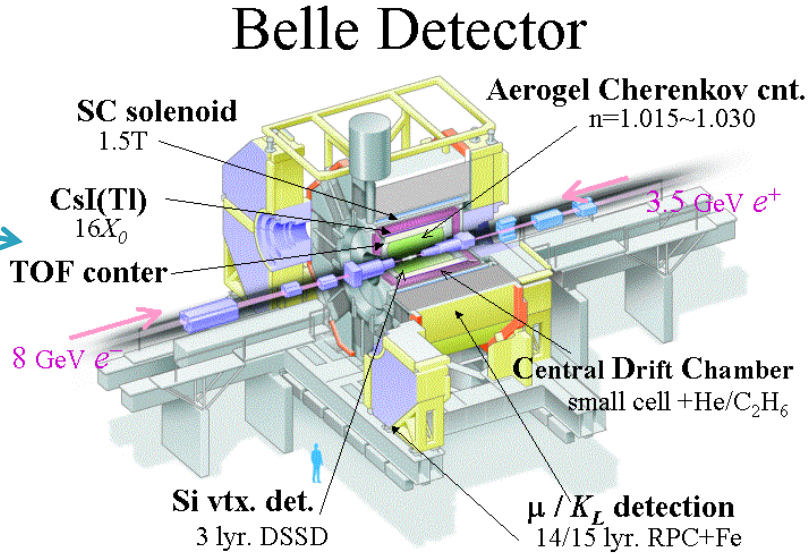




Introduction

- Belle detector, KEKB collider @ KEK in Tsukuba, Japan





- World record peak luminosity:

$$2.1 \times 10^{34} cm^{-2} s^{-1}$$

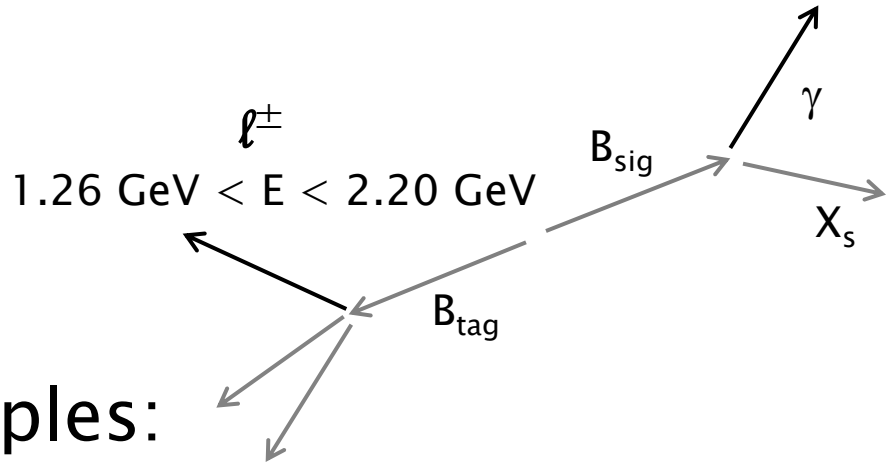
- Total integrated luminosity:

~ 950 fb^{-1} (750 fb^{-1} @ $\Upsilon(4S)$)

arXiv:0907.1384, subm. to PRL

Inclusive b → s γ Reconstruction

- Fully inclusive measurement:
  - Only γ reconstructed on signal side, $E_\gamma^{cms} > 1.4$ GeV
  - Two streams: with lepton from tag side (NEW) and without
    - Lepton tag helps to reduce continuum background



- Data samples:
  - 605 fb^{-1} on resonance (657M $B\overline{B}$ pairs)
  - 68 fb^{-1} off resonance: 60 MeV below $\Upsilon(4S)$

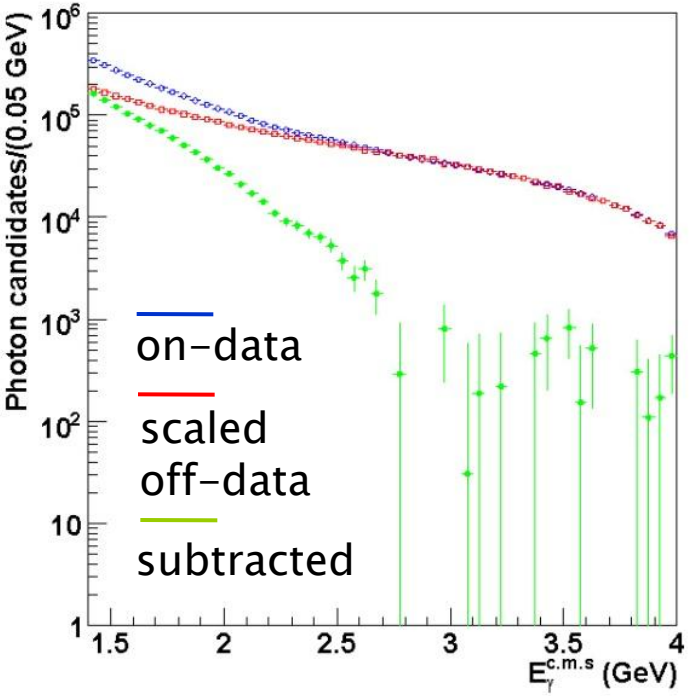
arXiv:0907.1384, subm. to PRL

$b \to s \gamma$ Backgrounds

- Continuum
  - Suppressed w/ Fisher discriminants based on energy-flow and event-shape.
  - Remaining continuum subtracted using off-resonance data:

$$N^{B\bar{B}}(E_\gamma^{CMS}) = N^{ON}(E_\gamma^{CMS}) - \alpha C_\varepsilon N^{OFF}(F_E E_\gamma^{CMS})$$

α: lumin. ratio, $\sqrt{s}$ dependence, ~8.8
C_ε: efficiency corr.;
F_E: corr. factor due to lower mean E_γ in off-data

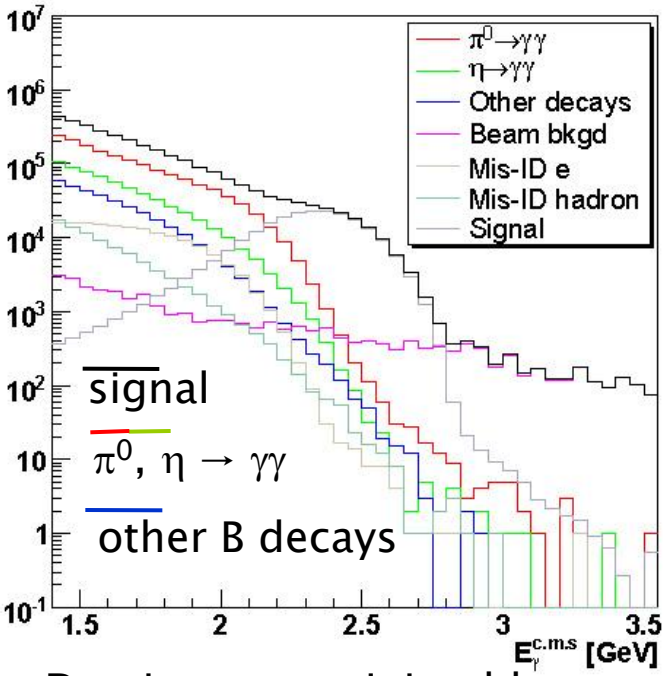


arXiv:0907.1384, subm. to PRL

$b \to s \gamma$ Backgrounds

- Non-continuum backgrounds:
  - γ from π^0, η (after vetoes)
  - Other real γ (e.g., from ω, J/ψ, η')
  - Mis-IDed e^- as γ
  - Other non-γ ECL clusters
  - Beam background
- Control samples in data:
  - $B \to \pi^0 X$, ηX
    - Used to correct MC shapes/yields
  - $D^0 \to K^- \pi^+ \pi^0$
    - Used to study veto efficiencies
  - Timing information used to study/suppress pile-up events (hadronic + Bhabha)
  - Beam background studied w/ random triggers.

after vetoing π^0, $\eta \to \gamma\gamma$

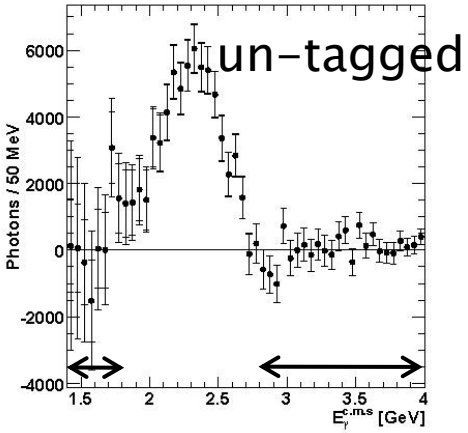


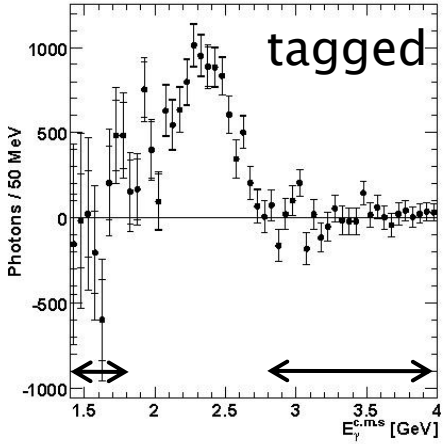
Dominant remaining bkg. from π^0, $\eta \to \gamma\gamma$

arXiv:0907.1384, subm. to PRL

$b \to s \gamma$ Spectra

- Raw spectra without & with lepton tags

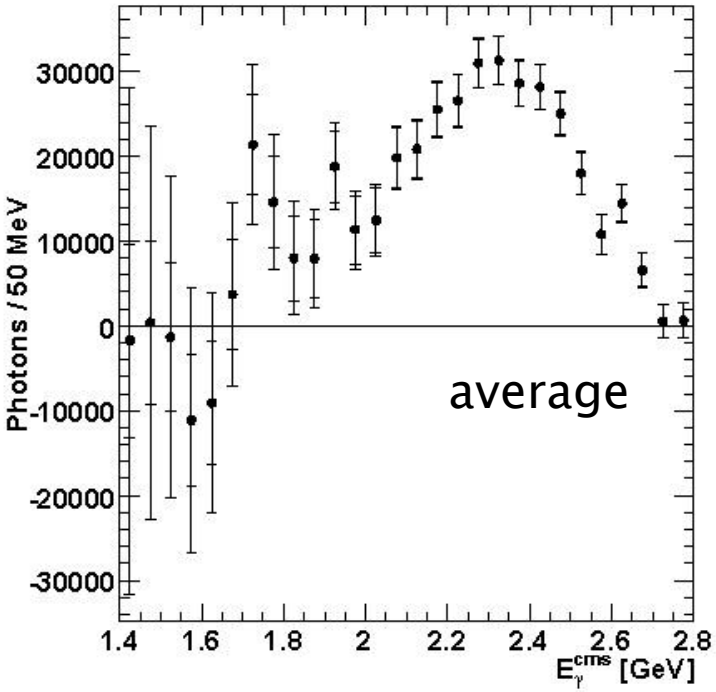




$\longleftrightarrow$:control regions (no yield expected)

-1629 ± 4894 1245 ± 4349 -745 ± 889 292 ± 410

- Combined spectrum
  - Corrected for selection efficiency.
  - Properly includes statistical correlations between tagged/untagged spectra.



$b \to s\,\gamma$ Branching Fraction

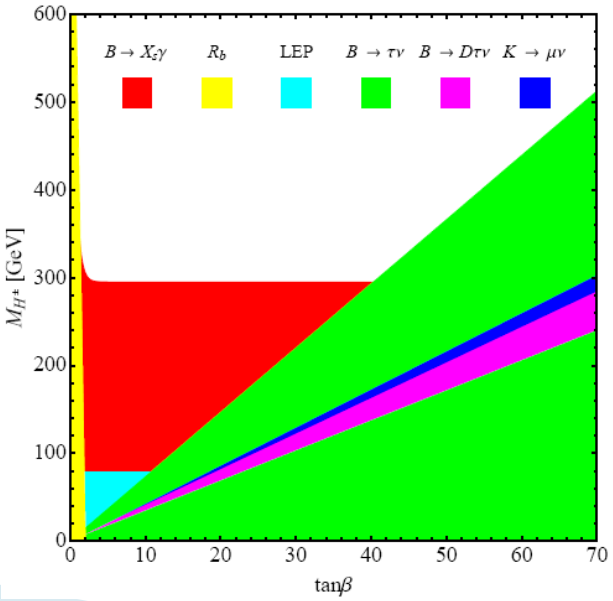
Belle result [arXiv:0907.1384 (subm. to PRL)]:

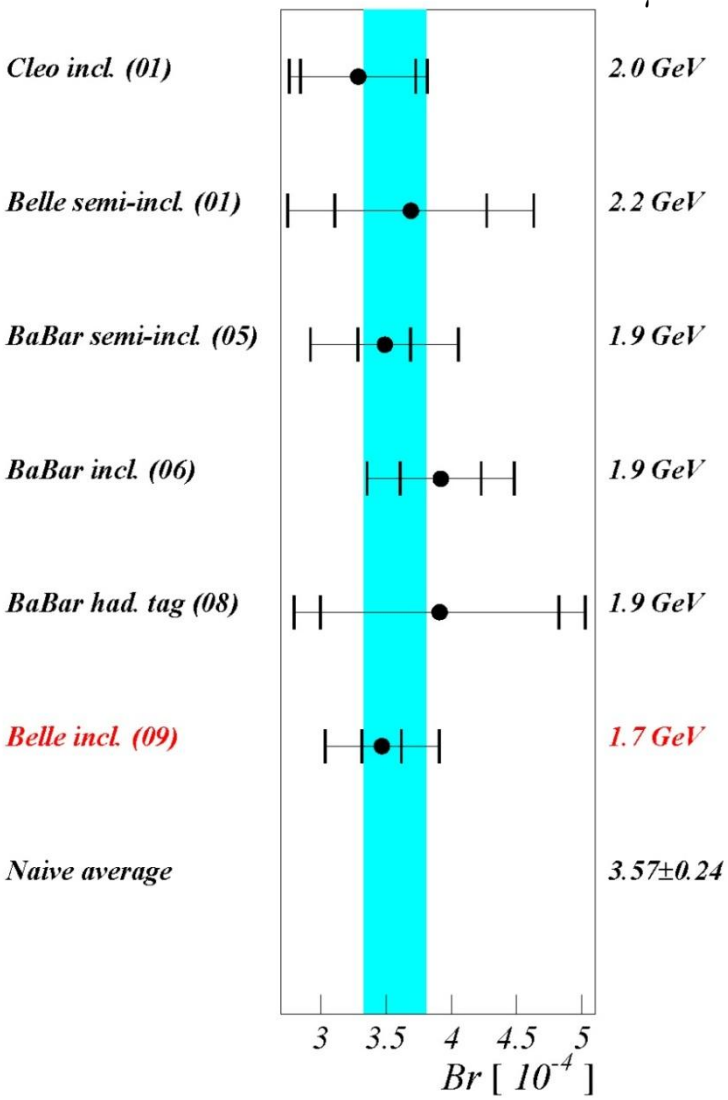
$$\mathcal{B}(B \to X_s\gamma; 1.7GeV < E_\gamma < 2.8GeV) = (3.47 \pm 0.15 \pm 0.40) \times 10^{-4}$$

Consistent with NNLO SM calculations [Misiak et al., PRL98, 022002 (2007)]:

$$\mathcal{B}_{SM}(B \to X_s\gamma; E_\gamma > 1.6GeV) = (3.15 \pm 0.23) \times 10^{-4}$$

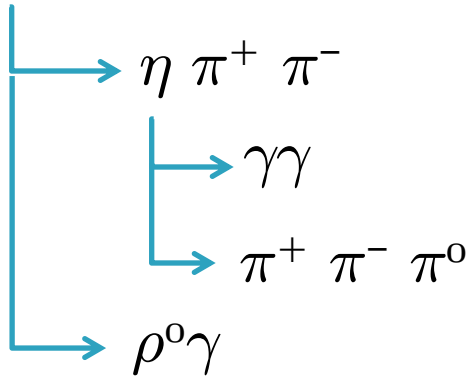
Places strong constraints on some NP models: e.g., type II THDM [Ulrich Haisch, arXiv:0805.2141]





Exclusive $b \to s\,\gamma$: $B \to K\,\eta'\,\gamma$

- Not yet observed.
- Exclusive modes useful to check hadronisation models for $B \to X_s\gamma$, $B \to X_s ll$
- Sufficient statistics with $K_S\eta'\gamma$ would allow search for time dependent CPV (right-handed currents).
- Reconstruction:
  - $B \to K\,\eta'\,\gamma$

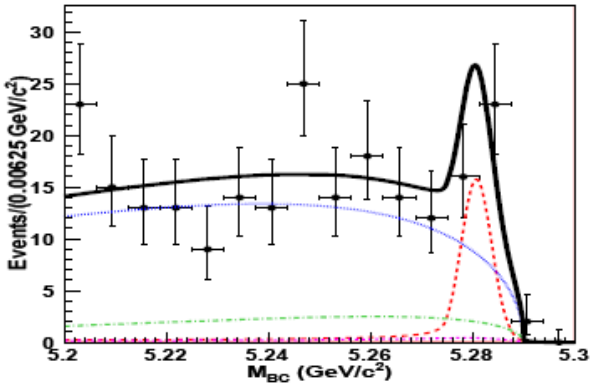


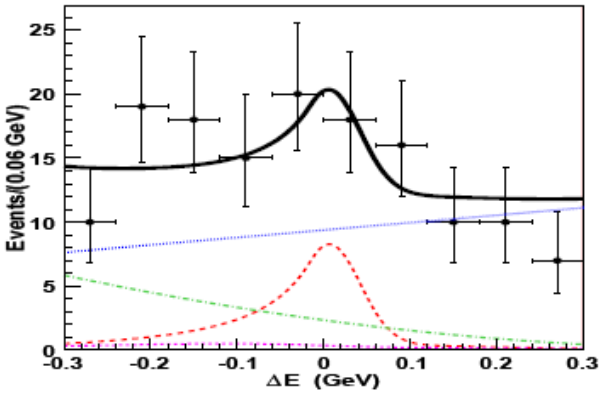
- $M(K\eta') < 3.4$ GeV
- Veto $D^0 \to K^-\pi^+$
  - $1.84 < M(K\pi) < 1.89$ GeV/c^2
- Veto $J/\psi \to \eta'\gamma$
  - $3.07 < M(\eta'\gamma) < 3.12$ GeV/c^2
- 2D fit performed on M_{bc}, ΔE
  - Submodes are combined for fitting.

$B \to K \eta' \gamma$ w/ 605 fb^{-1}

To be subm. to PRD (RC)

$B^+ \to K^+ \eta' \gamma$





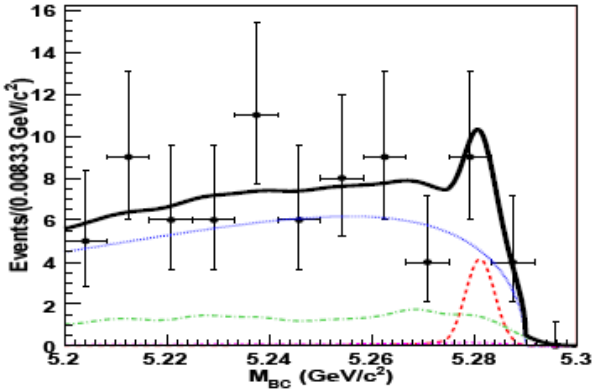
Fit components:

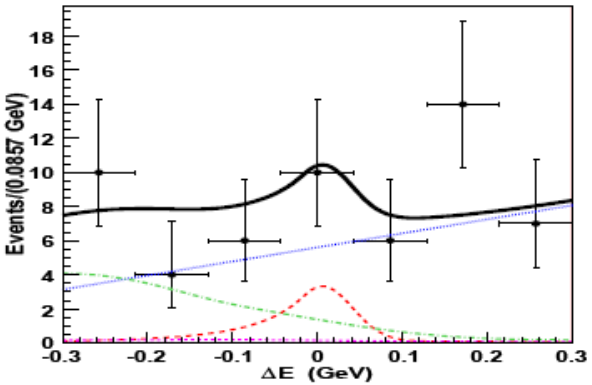
----- signal

..... qq

- - - BB

$B^0 \to K_S \eta' \gamma$





First evidence for
$B^+ \to K^+ \eta' \gamma$ (3.3σ)

New upper limit for
$B^0 \to K_S \eta' \gamma$

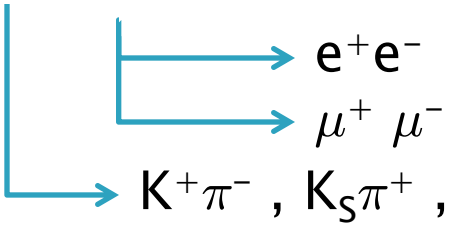
Partial branching fractions (for $M_{K\eta'} < 3.4$ GeV/c^2).

Mode	Yield(events)	$\mathcal{B}(10^{-6})$	$\mathcal{S}(\sigma)$	UL(10^{-6})
$B^+ \to K^+\eta'\gamma$	$32.6^{+11.8}_{-10.8}$	$3.6 \pm 1.2 \pm 0.4$	3.3	5.6
$B^0 \to K^0_S\eta'\gamma$	$5.1^{+5.0}_{-4.0}$	$2.5^{+2.4+0.4}_{-1.9-0.5}$	1.3	6.4

BELLE

Exclusive b → sll : B → $K^{(*)}$ l^+l^-

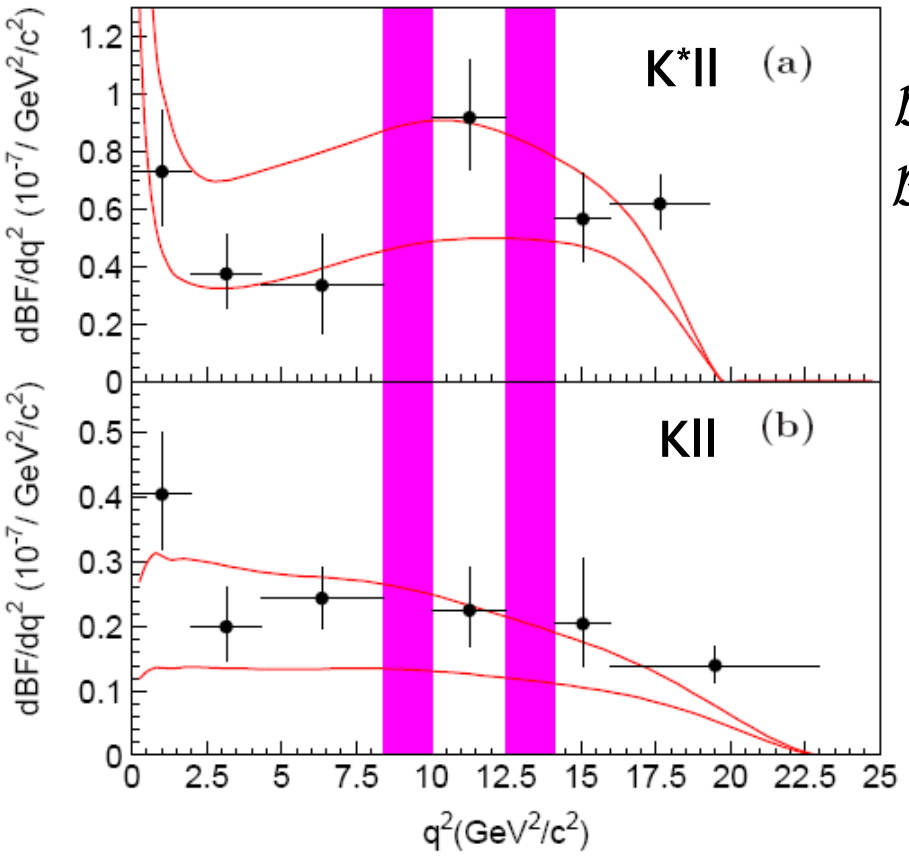
- Reconstruction in 10 final states:
  - B → $K^{(*)}$ l^+l^-



*Electron bremsstrahlung photons recovered (w/i 50 mrad cone, $20 < E_\gamma < 500$ MeV)

- Backgrounds:
  - Continuum & semi-leptonic decays: suppressed with Fisher discriminant based on event-shape, M_{miss}
  - B → DX : veto on $M_{K\mu}$ and $M_{K\mu\pi}$
  - B → J/ψ (ψ') X : vetoes on q^2 regions:
    - $8.68 < q^2 < 10.09$; $12.86 < q^2 < 14.18$ for $\mu^+\mu^-$
    - $8.11 < q^2 < 10.03$; $12.15 < q^2 < 14.11$ for e^+e^-
- 2D fit in M_{bc} and $M_{K\pi}$ in 6 bins of q^2

Branching Fractions for $B \to K^{(*)} l^+l^-$



: J/ψ (ψ') veto regions

: SM expectation w/ mininum & maximum form factors from [Ali et al. PRD 66, 034002 (2002)]

- Total branching ratios:

$$\mathcal{B}(B \to K^* \ell^+ \ell^-) = (10.7^{+1.1}_{-1.0} \pm 0.9) \times 10^{-7}$$
$$\mathcal{B}(B \to K \ell^+ \ell^-) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$$

- Lepton flavor ratios:
  - Definition:

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$

  - Sensitive to Higgs emission, photon pole, potential NP.
  - Measured / SM values:

$$R_{K^*} = 0.83 \pm 0.17 \pm 0.07, R_{K^*}^{SM} = 0.75$$
$$R_K = 1.03 \pm 0.19 \pm 0.06, R_K^{SM} = 1.0$$

arXiv:0904.0770, subm. to PRD (RC)

F_L, A_{FB}, and A_I for $B \to K^* l^+l^-$

- Longitudinal polarization fraction (F_L) for K*ll
  - Extracted from θ_{K^*} (angle between K and opposite of B flight directions in K^* rest frame):

$$\frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2}F_L\cos^2\theta_{K^*} + \frac{3}{4}(1-F_L)(\sin^2\theta_{K^*})$$

- Forward-backward asymmetry (A_{FB}) for K*ll
  - Extracted from θ_{Bl} (angle between lepton and opposite of B flight directions in dilepton rest frame).

$$\frac{d\Gamma}{d\cos\theta_{B\ell}} = \frac{3}{4}F_L\sin^2\theta_{B\ell} + \frac{3}{8}(1-F_L)(1+\cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}$$

- Isospin asymmetry (A_I) for both K^*ll and Kll.

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0})\times\mathcal{B}(K^{(*)0}\ell^+\ell^-) - \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}{(\tau_{B^+}/\tau_{B^0})\times\mathcal{B}(K^{(*)0}\ell^+\ell^-) + \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}$$

Lifetime ratio (1.071)

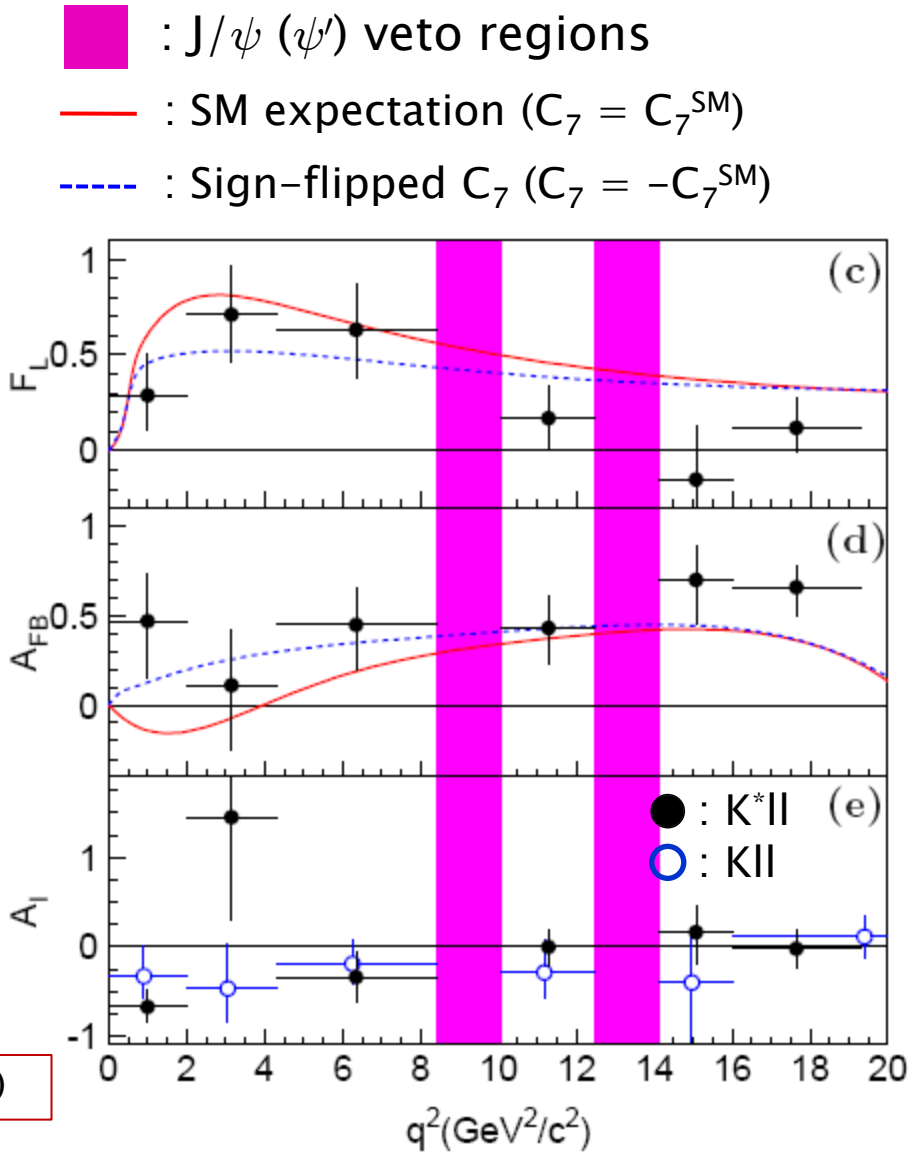
arXiv:0904.0770, subm. to PRD (RC)

F_L, A_{FB}, and A_I for $B \to K^* l^+l^-$

- K*ll longitudinal polarization fractions (F_L):
  - Consistent with SM.
- K*ll forward-backward asymmetry (A_{FB}):
  - ~2.7σ diff. from SM, hints at possible C_7 ➔ $-C_7^{SM}$
- Isospin-asymmetry (A_I):
  - Consistent with SM.
  - Combined for $q^2 < 8.68$

$$A_I(B \to K^*\ell^+\ell^-) = -0.29^{+0.16}_{-0.16} \pm 0.09 \quad \sigma = 1.37$$
$$A_I(B \to K\ell^+\ell^-) = -0.31^{+0.17}_{-0.14} \pm 0.08 \quad \sigma = 1.75$$
$$A_I(B \to K^{(*)}\ell^+\ell^-) = -0.30^{+0.12}_{-0.11} \pm 0.08 \quad \sigma = 2.22$$

arXiv:0904.0770, subm. to PRD (RC)



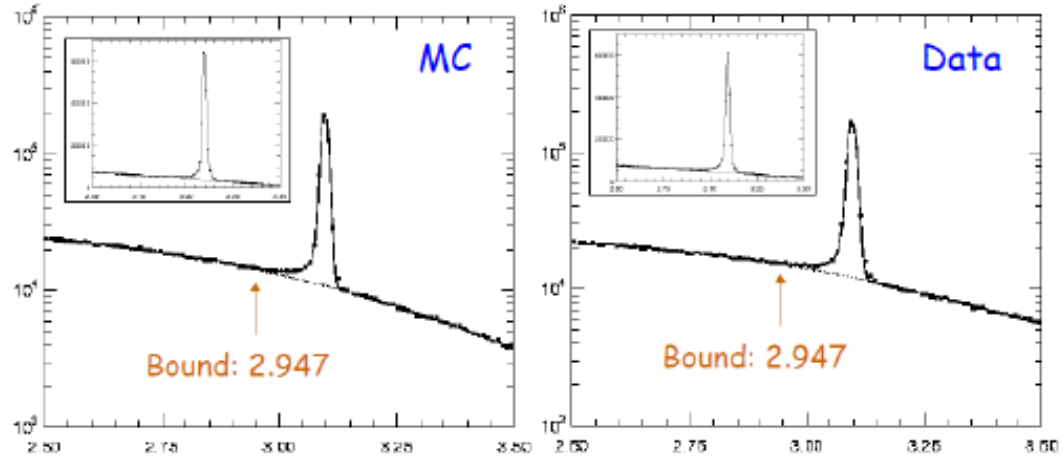
Summary

- Inclusive b→ sγ branching ratio: arXiv:0907.1384, subm. to PRL
  - $\mathcal{B}(B \to X_s\gamma; 1.7GeV < E_\gamma < 2.8GeV) = (3.47 \pm 0.15 \pm 0.40) \times 10^{-4}$
  - Consistent w/SM, strongly constrains NP (e.g., charged Higgs mass)
- Exclusive B → K η' γ To be subm. to PRD (RC)
  - First evidence for $B^+ \to K^+ \eta' \gamma$
    $\mathcal{B}(B^+ \to K^+\eta'\gamma; M_{K\eta'} < 3.4GeV/c^2) = (3.6 \pm 1.2 \pm 0.4) \times 10^{-6}$
  - 90% CL upper limit for $B^0 \to K_S \eta' \gamma$
    $\mathcal{B}(B^0 \to K^0\eta'\gamma; M_{K\eta'} < 3.4GeV/c^2) < 6.4 \times 10^{-6}$
- Exclusive B → $K^{(*)}l^+l^-$ arXiv:0904.0770, subm. to PRD (RC)
  - Lepton flavor ratios, longitudinal polarization fraction, isospin asymmetry consistent with SM.
  - Forward backward asymmetry ➔ opposite sign C_7?
  - Need more luminosity: e.g., Super KEKB / Belle-II, LHCb

» Backup

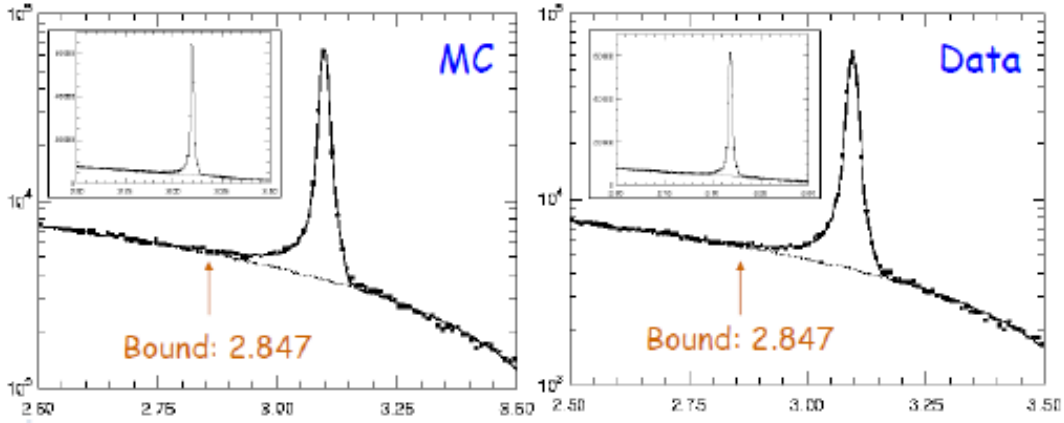
$B \to K^{(*)}ll$

J/ψ tail (inclusive J/ψ sample)



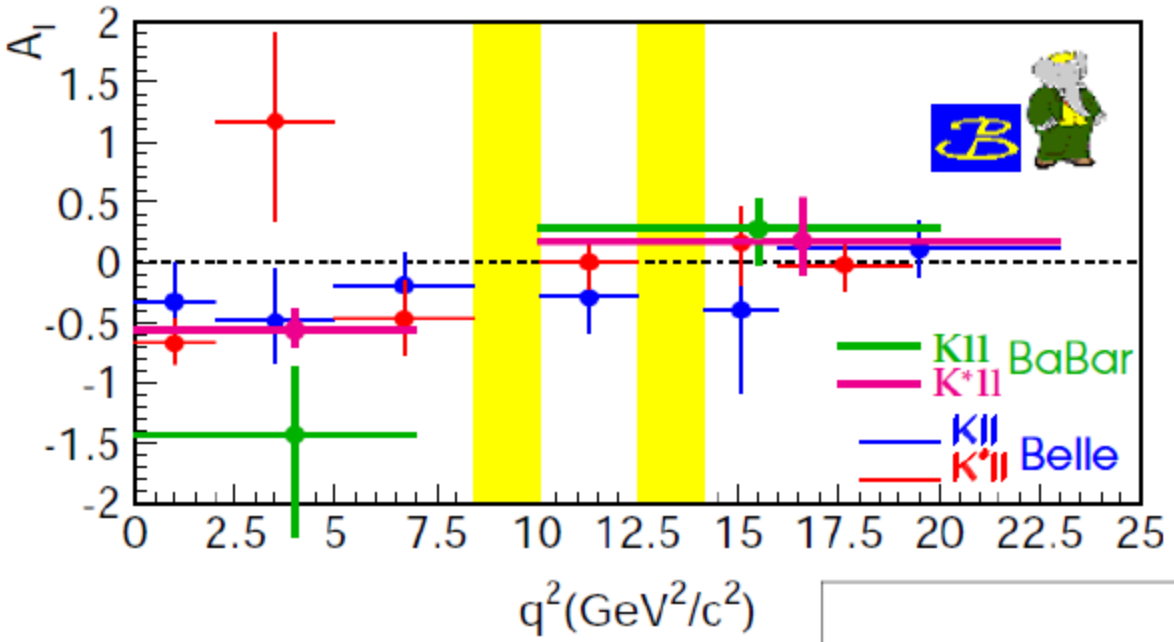
Muon mode

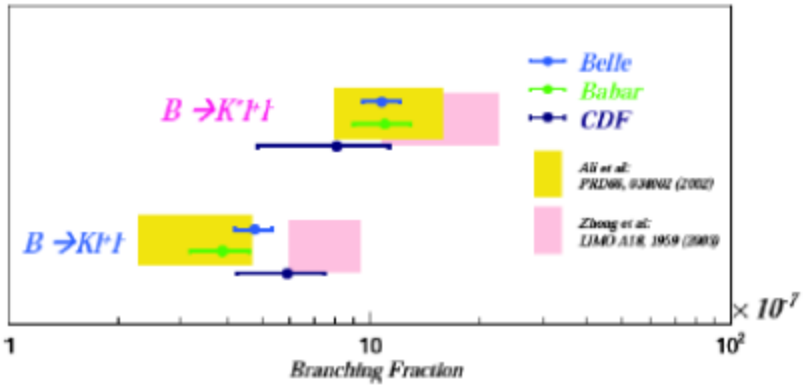
MC tail slightly longer than data



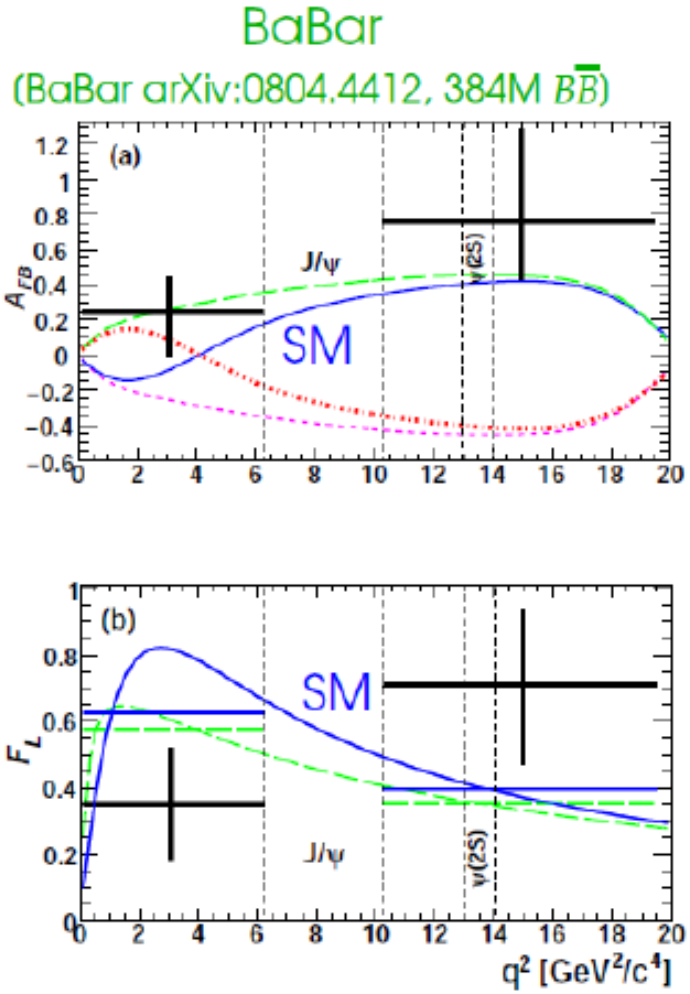
Electron mode

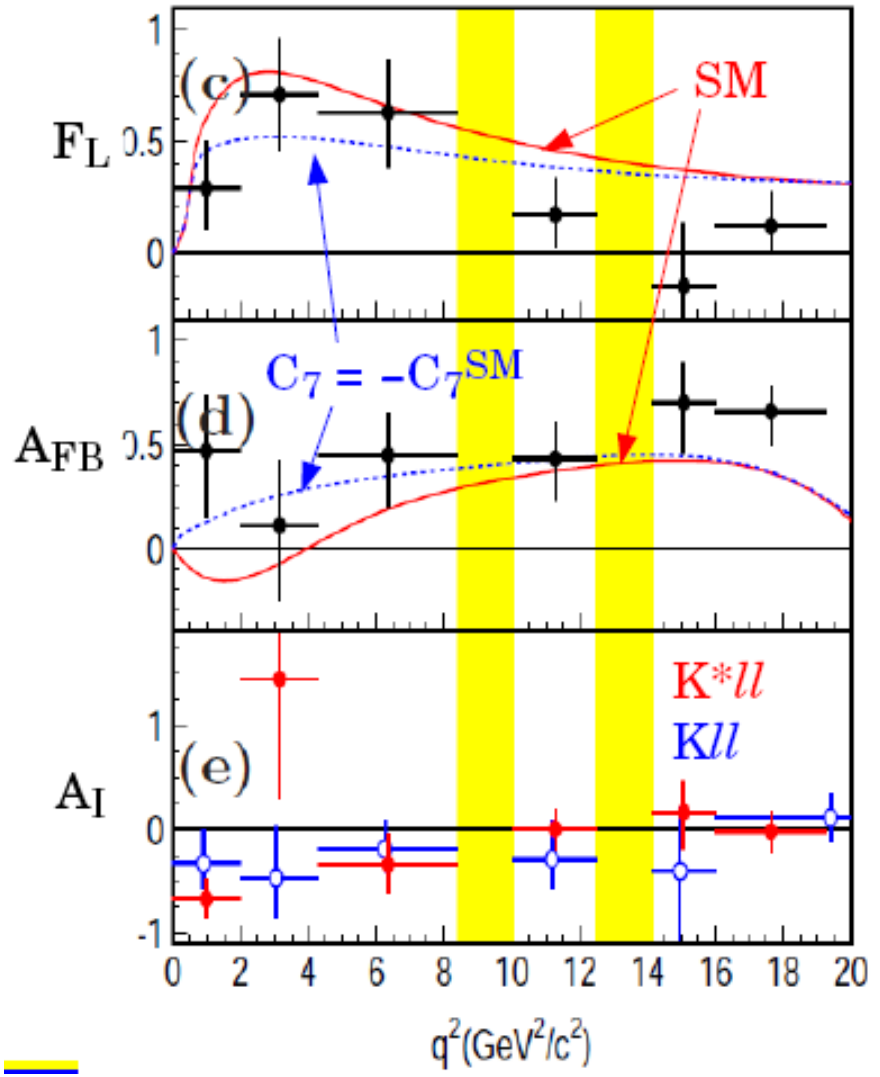
$B \to K^{(*)}ll$


A_I
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
$q^2(GeV^2/c^2)$
Kll
K*ll
BaBar
Kll
K*ll
Belle


Belle
Babar
CDF
B →K*l+l-
B →Kl+l-
× 10⁻⁷
1
10
10²
Branching Fraction

$B \to K^{(*)}ll$


BaBar
(BaBar arXiv:0804.4412, 384M $B\bar{B}$)
(a)
A_{FB}
J/ψ
ψ(2S)
SM
(b)
F_L
SM
J/ψ
ψ(2S)
q^2 [GeV^2/c^4]


(c)
F_L
SM
(d)
A_{FB}
$C_7 = -C_7^{SM}$
(e)
A_I
K*ll
Kll
q^2(GeV^2/c^2)

Wilson coeffients and $B \to K^* \ell^+ \ell^-$

- Wilson coefficients to identify type of new physics

  C_7 for magnetic penguin operator $[\frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu}]$

  (size is determined from $b \to s\gamma$, but sign is from $b \to s\ell^+\ell^-$)

  C_9 for vector electroweak operator $[(\bar{b}s)_{V-A}(\bar{\ell}\ell)_V]$

  C_{10} for axial-vector electroweak operator $[(\bar{b}s)_{V-A}(\bar{\ell}\ell)_A]$

- Foward-backward asymmetry ($A_{\rm FB}$) and Wilson coefficients

  $$A_{\rm FB}(q^2) = -C_{10}^{\rm eff}\xi(q^2)\left[Re(C_9^{\rm eff})F_1 + \frac{1}{q^2}C_7^{\rm eff}F_2\right]$$

  (similar to γ-Z interference at high energy)

- Angular distributions to extract FB asymmetries

  K^* logitudinal polarization F_L from kaon angle θ_K

  $$\frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

  Forward-backward asymmetry $A_{\rm FB}$ from lepton angle θ_ℓ

  $$\frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{\rm FB}\cos\theta_\ell$$