$b \to s/d\ \gamma$ and $b \to s/d\ \ell^+\ell^-$ decays

Hiroyuki Nakayama (KEK IPNS)

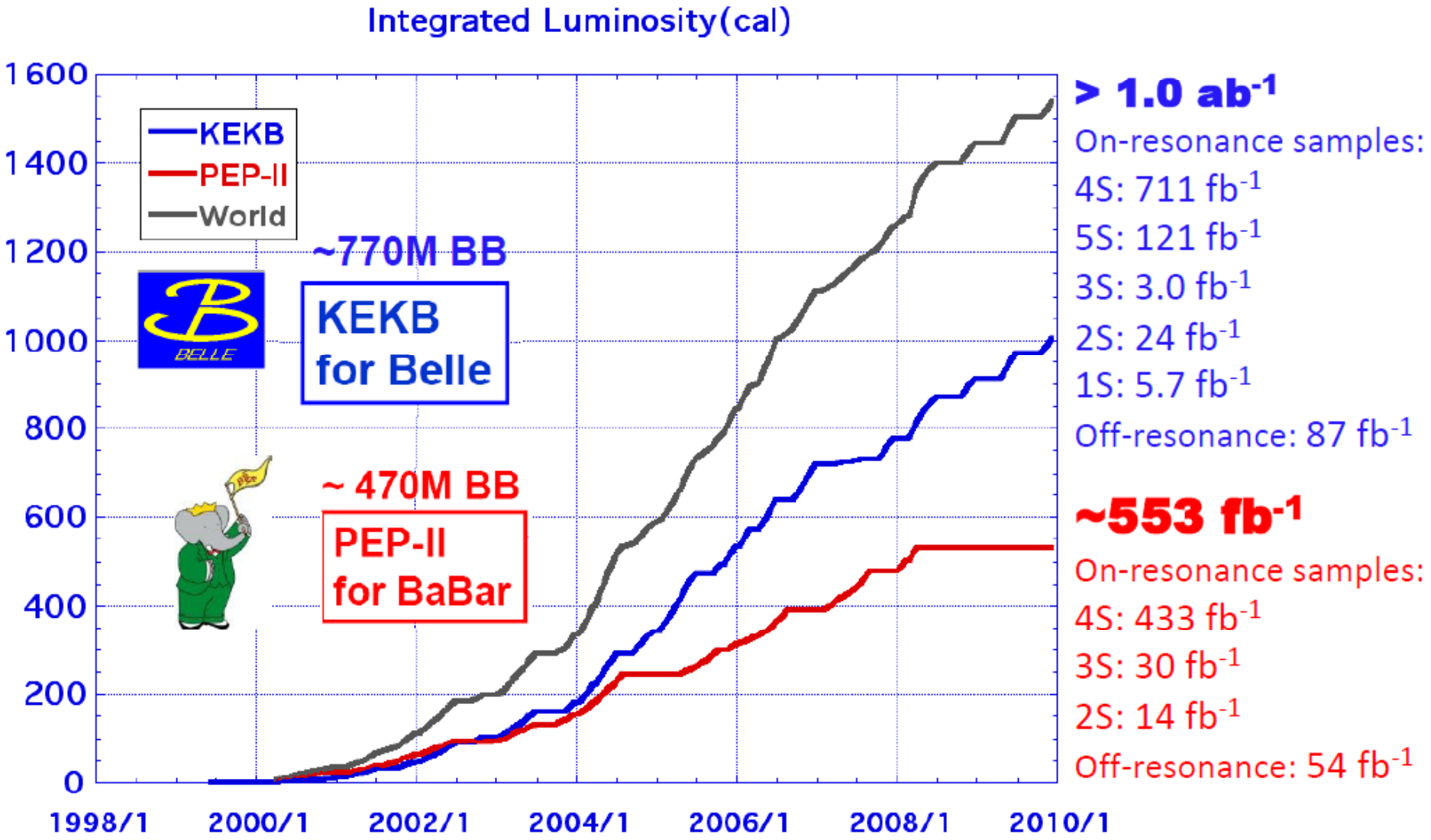
May 26, 2010

FPCP 2010, Torino, Italy

Contents

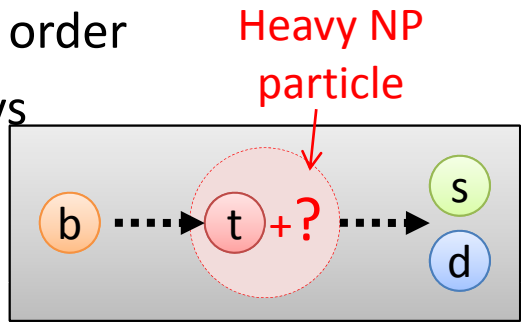
- Introduction: B factory
- FCNC decays
- $b \rightarrow s\,\gamma$
  - Exclusive : $B \rightarrow K^{*}\gamma$ (BF, A_{CP}, A_I), $B \rightarrow K\eta^{(\prime)}\gamma$, $K\phi\gamma$ (BF, A_{cp}, S/C)
  - Inclusive: $B \rightarrow X_s\gamma$ (BF, E_γ spectrum)
- $b \rightarrow d\,\gamma$
  - Exclusive: $B \rightarrow \rho/\omega\,\gamma$ (BF, $|V_{td}/V_{ts}|$)
  - Semi-inclusive: $B \rightarrow X_d\,\gamma$ (BF, $|V_{td}/V_{ts}|$) new from BaBar
- $b \rightarrow s\,\ell^{+}\ell^{-}$
  - Exclusive : $B \rightarrow K^{(*)}\,\ell^{+}\ell^{-}$ (BF, q^2 spectrum, F_L, A_{FB})
  - Semi-inclusive : $B \rightarrow X_s\,\ell^{+}\ell^{-}$ (BF, q^2 spectrum)
- $b \rightarrow d\,\ell^{+}\ell^{-}$
  - Exclusive : $B \rightarrow \pi\,\ell^{+}\ell^{-}$ (BF upper limit)

Luminosity at B factories



Introduction: FCNC decays

- Flavor Changing Neutral Current (FCNC) decays
  - Forbidden at tree level, one loop or box at lowest order
  - Good tool to dig out the heavy particles in B decays
- FCNC observables
  - Branching fractions
    - Exclusive: many results, but hard to interpret
      because of larger theoretical uncertainty
    - Inclusive: theoretically clean, but experimentally hard
  - Other observables
    - Energy/q^2 spectrum, $A_{FB,}$ A_{CP}, TCPV
  - Wilson Coefficients
    - More direct (model-independent) comparison with theory

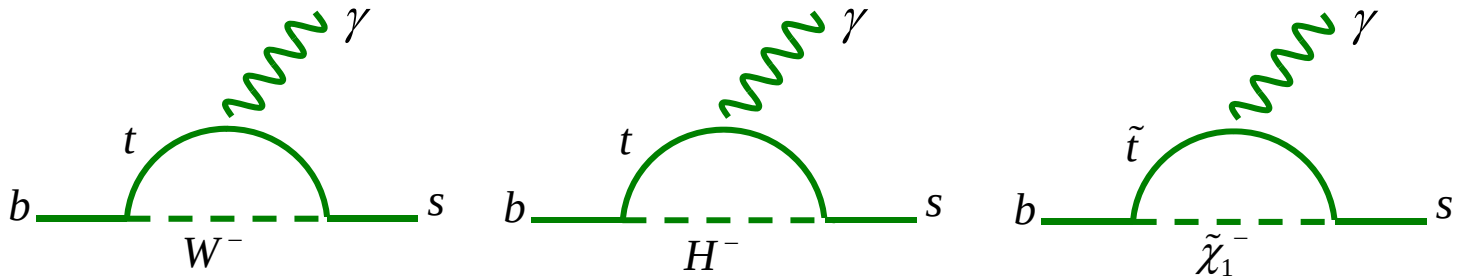


$b \rightarrow s\,\gamma$ decays

- Rich program
  - BF and moment measurements
  - CP asymmetry
  - Time-dependent CP asymmetry
  - Isospin asymmetry

$$\Delta_{0-} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

- Sensitive to NP
  - Reliable theory calculations are available for comparison



Exclusive: B→K*(892)γ

383M BB

PRL 103, 211802 (2009)

- Branching Fractions

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.47 \pm 0.10 \pm 0.16) \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (4.22 \pm 0.14 \pm 0.16) \times 10^{-5}$$

- CP asymmetry

$$\mathcal{A} = -0.003 \pm 0.017 \pm 0.007$$
$$-0.033 < \mathcal{A} < 0.028 \quad \text{(90\% CL)}$$

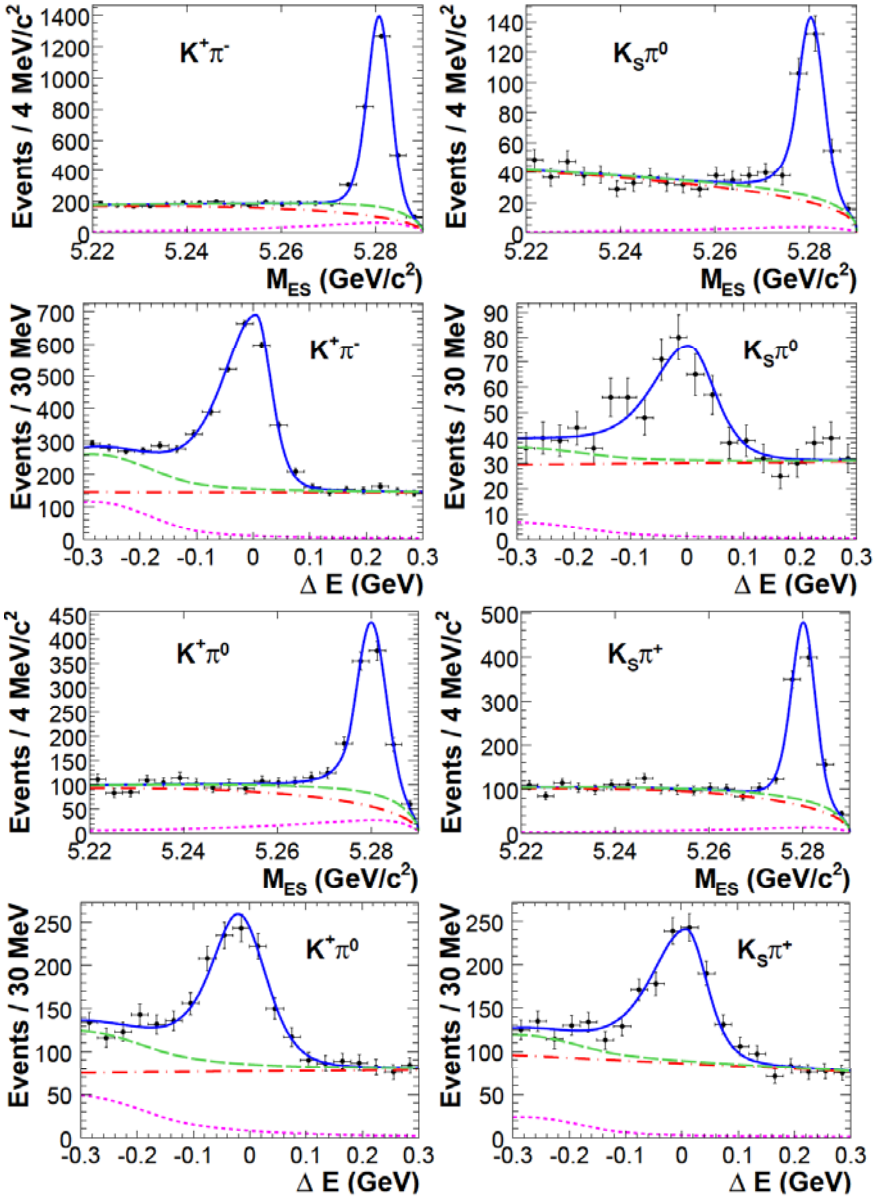
SM prediction: ~1% (Nucl. Phys. B 434, 39 (1995))

- Isospin asymmetry

$$\Delta_{0-} = 0.066 \pm 0.021 \pm 0.022$$
$$0.017 < \Delta_{0-} < 0.116 \quad \text{(90\% CL)}$$

SM prediction: 2~10%

(PRD 72, 014013 (2005), Phys. Lett. B 539, 227(2002))



Exclusive: B→Kηγ

465M BB

PRD 79, 011102 (2009)

- Branching Fractions

$$\mathcal{B}(B^+ \to \eta K^+ \gamma) = (7.7 \pm 1.0 \pm 0.4) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to \eta K^0 \gamma) = (7.1^{+2.1}_{-2.0} \pm 0.4) \times 10^{-6}$$

- Integrated charge asymmetry

$$\mathcal{A}_{ch} = (-9.0^{+10.4}_{-9.8} \pm 1.4) \times 10^{-2}$$

- Time-dependent CPV

First result for this mode

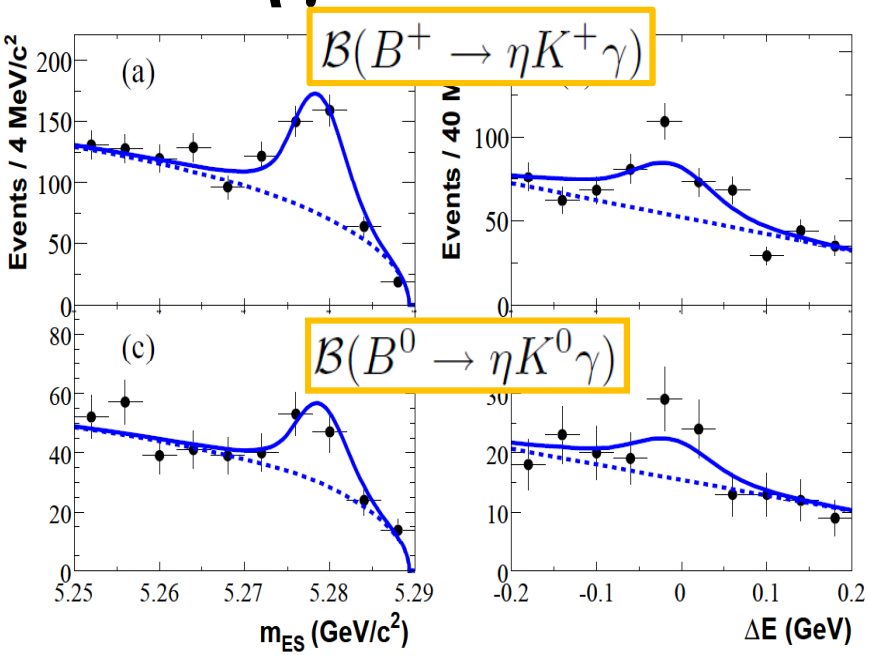
$$S = -0.18^{+0.49}_{-0.46} \pm 0.12$$
$$C = -0.32^{+0.40}_{-0.39} \pm 0.07$$

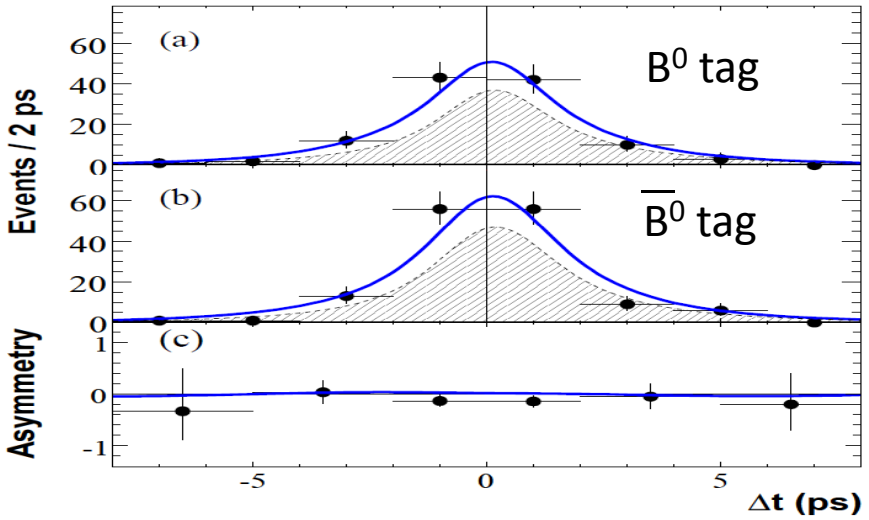
cf. $B^0 \to K_s^0 \rho^0 \gamma$ (Belle 657M BB)

S = 0.11 +- 0.35 $^{+0.05}_{-0.09}$

C = -0.05 +- 0.18 +- 0.06

PRL 101, 251601 (2008)

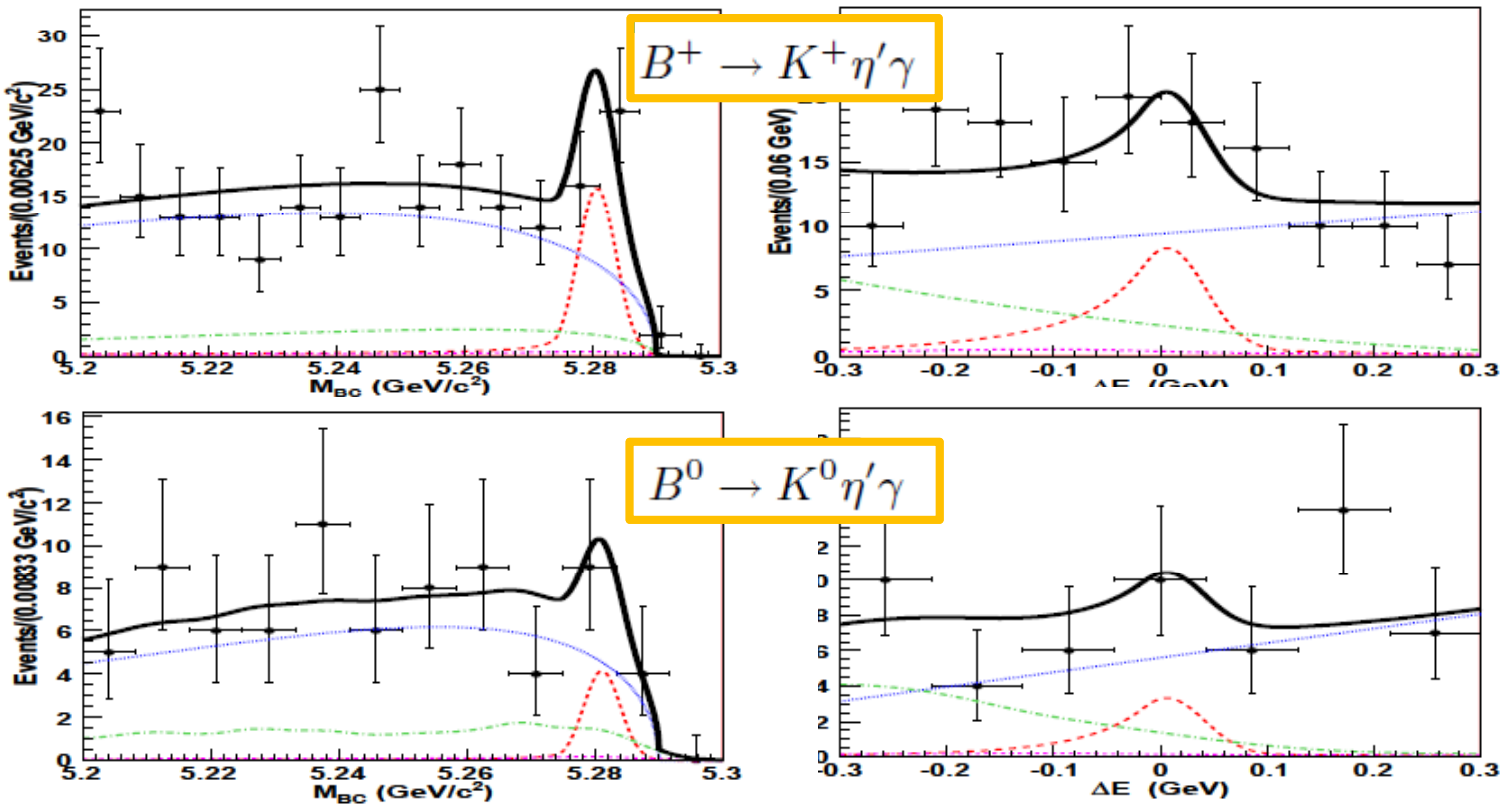




Exclusive: B→Kη'γ

657M BB

arXiv:0810.0804,
submitted to PRD-RC



$$\mathcal{B}(B^+ \to K^+\eta'\gamma) = (3.6 \pm 1.2 \pm 0.4) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^0\eta'\gamma) \leq 6.4 \times 10^{-6} \ (90\%\ \mathrm{CL})$$

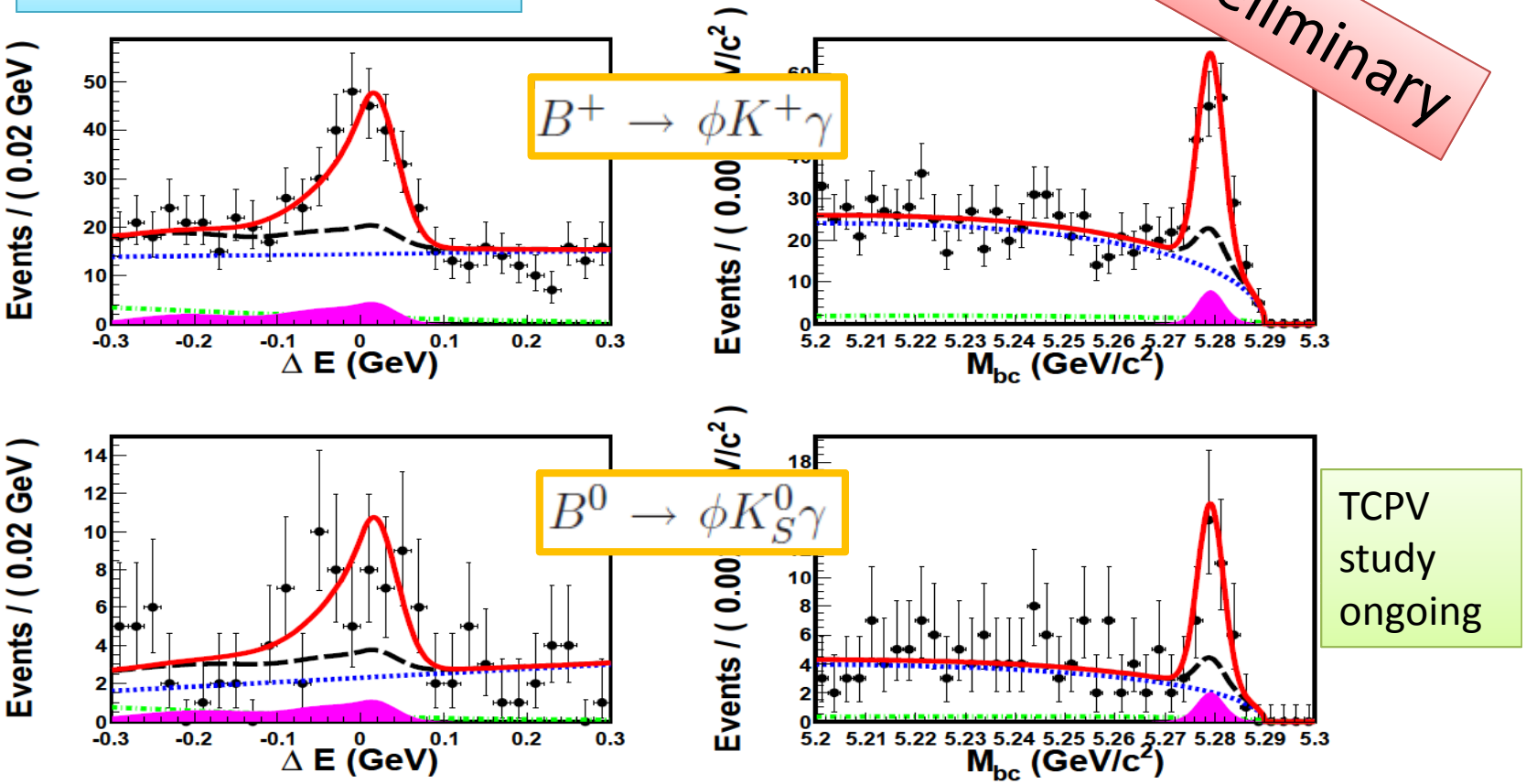
First evidence with
3.3 σ significance

Exclusive: B→Kϕγ

772M BB

arXiv: 0911.1779 (LP09)

Preliminary



TCPV study ongoing

$$\mathcal{B}(B^+ \to \phi K^+ \gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to \phi K^0 \gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$$

First observation with 5.4 σ significance

Inclusive: $B \rightarrow X_s \gamma$

657M BB

PRL 103, 241801 (2009)

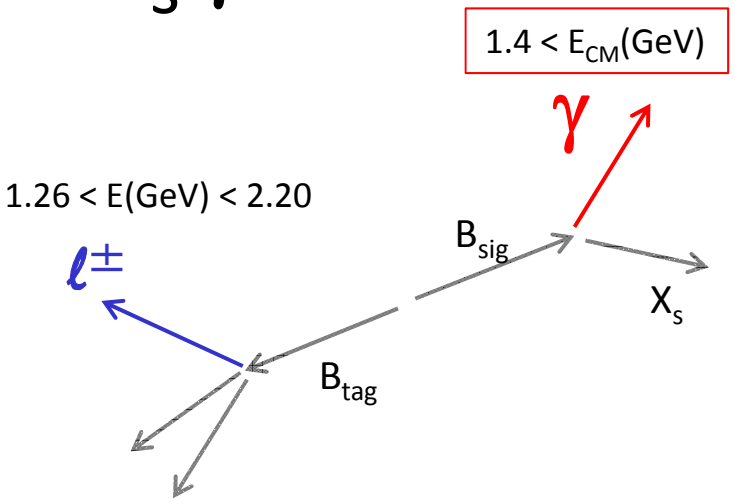
- Fully inclusive
- E_γ threshold: 2.2→1.7GeV
- Branching fraction

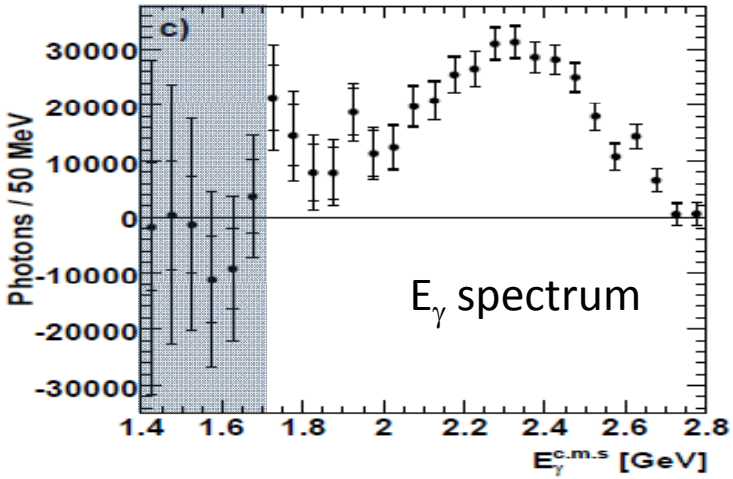
$$\mathrm{BF}\,(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$$
$$1.7\,\mathrm{GeV} < E_\gamma^{\mathrm{c.m.s.}} < 2.8\,\mathrm{GeV}$$

→ Consistent with NNLO SM calculation

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

Misiak et al., PRL 98, 022002 (2007)

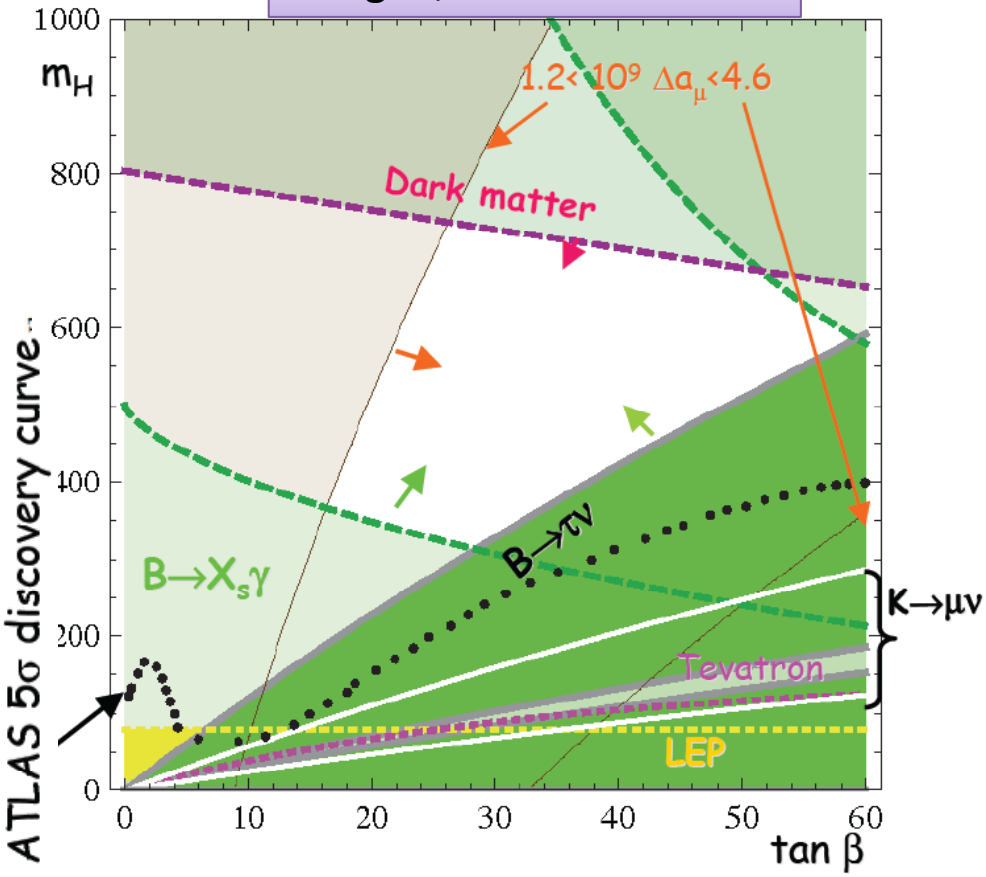




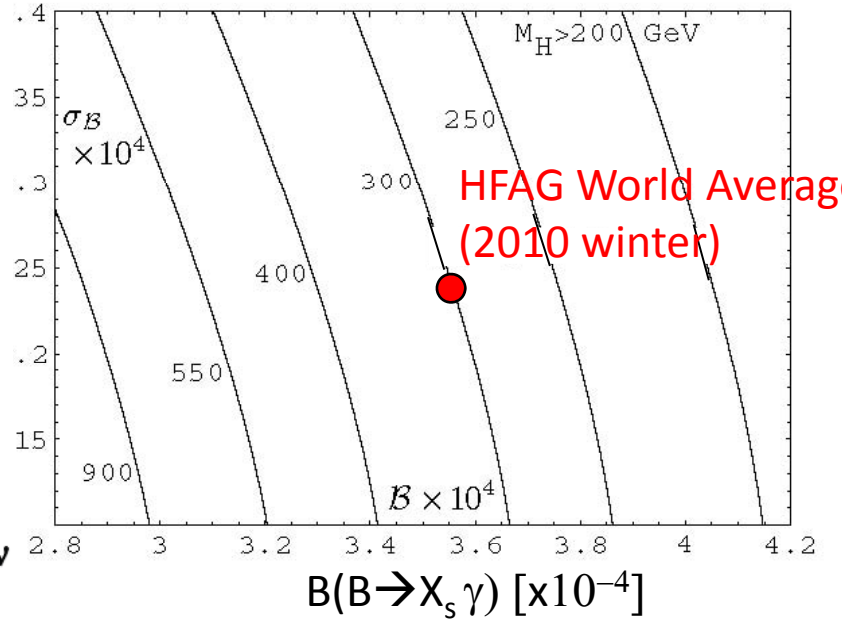
Constraints on NP model($B \to X_s \gamma$)

$b \to s\gamma$ measurements can put strong constraints on some new physics models:
e.g., two Higgs doublet models (THDM) Type-II

G.Eigen, arXiv:0907.4330



U.Haisch, arXiv:0805.2141

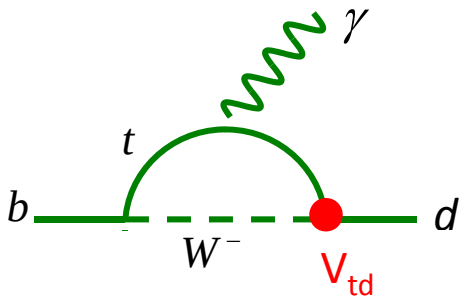


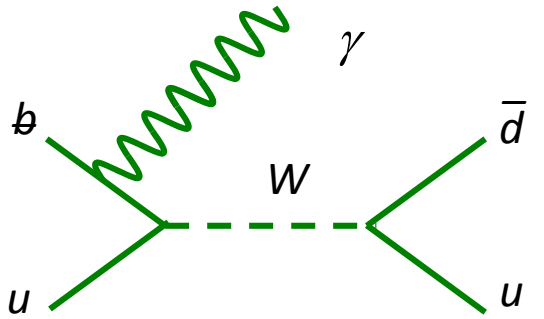
HFAG World Average (2010 winter)

$$M_{H^\pm} \geq 300 GeV \quad \text{(@95\% CL)}$$

b→dγ decays

- More suppressed than b→sγ
- Sensitive to $|V_{td}/V_{ts}|$, by comparison with b→sγ
- Experimental challenges
  - M(K*) is too close to M(ρ), challenging to distinguish from b→sγ
  - O(20) larger bkg from b→sγ mode
- Large contribution from annihilation diagram
  - Direct CPV and isospin asymmetry could be large



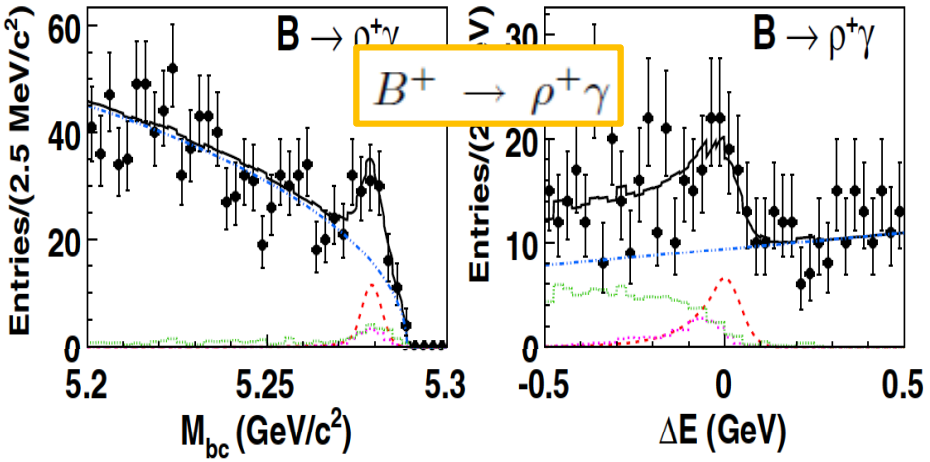


annihilation diagram

Exclusive: B→(ρ/ω)γ

657M BB

PRL 101, 111801 (2008)

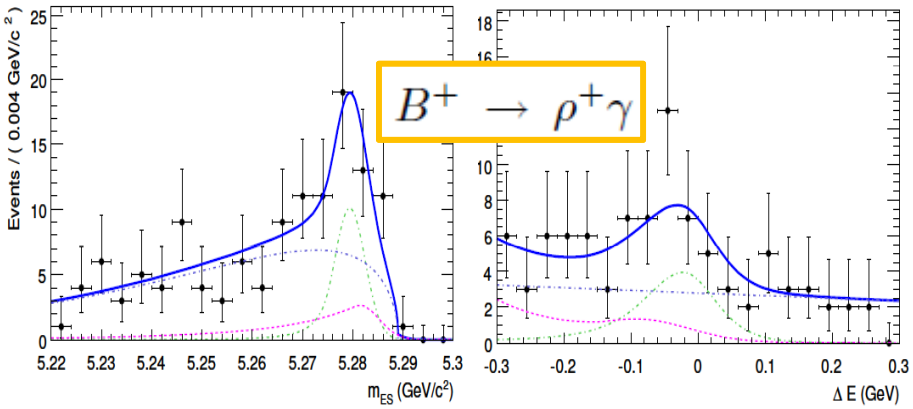


B(B→(ρ/ω)γ)
=(1.14 +- 0.20 $^{+0.10}_{-0.12}$) x 10^{-6}

$|V_{td}/V_{ts}|$ = 0.195 $^{+0.020}_{-0.019}$(exp) +- 0.015 (th)

465M BB

PRD 78, 112001 (2008)

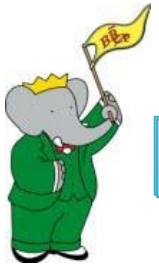


B(B→(ρ/ω)γ)
=(1.63 $^{+0.30}_{-0.28}$ +-0.16) x 10^{-6}

$|V_{td}/V_{ts}|_{\rho/\omega} = 0.233^{+0.025+0.022}_{-0.024-0.021}$

Simultaneous fit to $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$

Recent B→$X_d\gamma$ results from BaBar

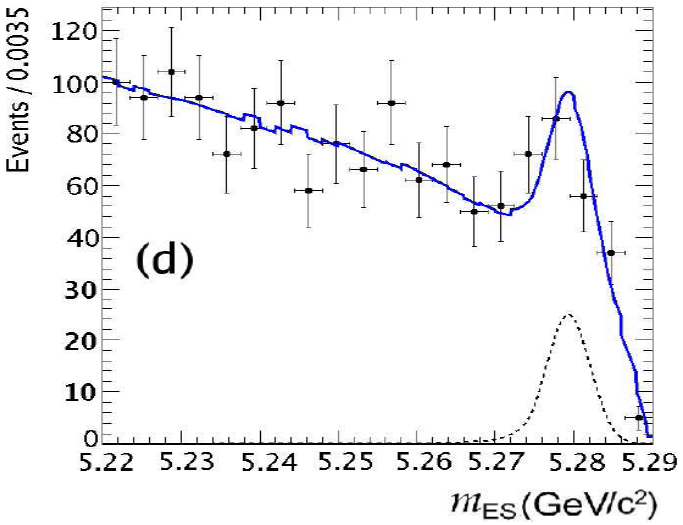


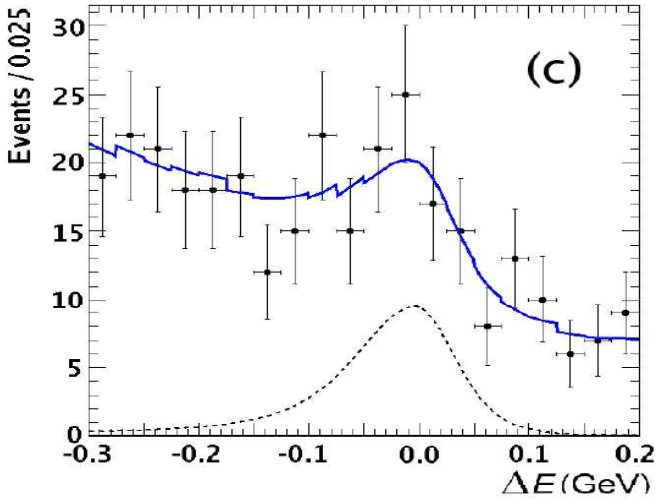
471M BB

!!NEW!!

BaBar new preliminary

- Semi-inclusive
- M(X_d) range is widened: <1.0 GeV to <2.0 GeV
  → Better|Vtd/Vts| determination than in excl. mode





Sum-of exclusive

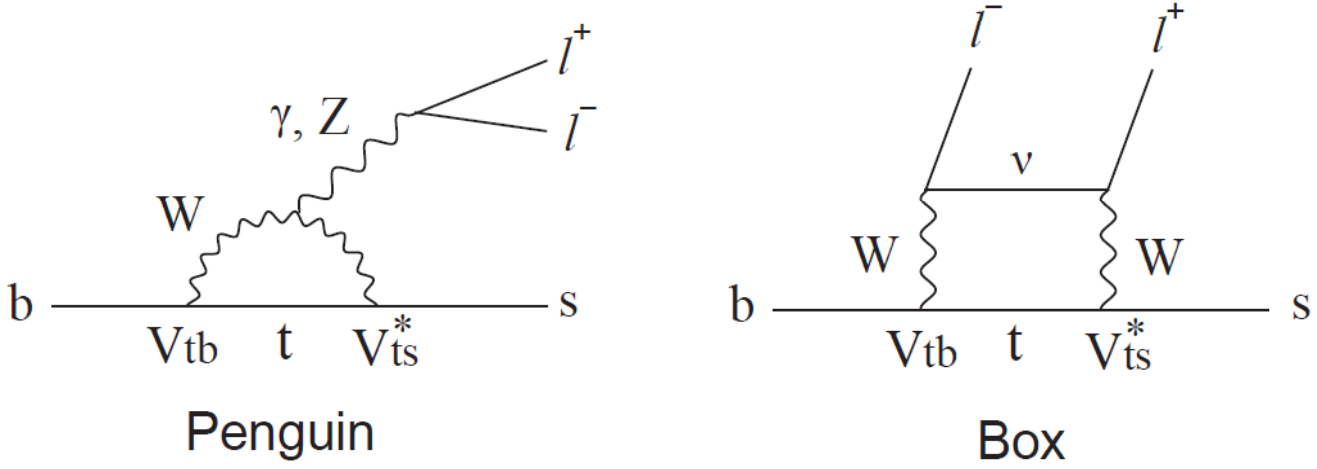
$B \to X_d\gamma$
$B^0 \to \pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^0\gamma$
$B^+ \to \pi^+\pi^-\pi^+\gamma$
$B^0 \to \pi^+\pi^-\pi^0\gamma$
$B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$
$B^+ \to \pi^+\eta\gamma$

B(B→$X_d\gamma$) =(9.2 +- 2.0(stat.) +- 2.3(syst.)) x 10^{-6}

$$|V_{td}/V_{ts}| = 0.199 \pm 0.022(stat.) \pm 0.024(syst.) \pm 0.002(th.)$$

$b \rightarrow s\ell^+\ell^-$

- Two order of magnitude smaller than $b \rightarrow s\gamma$, but rich NP search possibility from lepton pair information
- Observables
  - Branching fraction, q^2 distribution
  - K* longitudinal polarization (F_L)
  - Forward-backward Asymmetry (A_{FB})



Wilson coefficients

- New physics effects can be parameterized as deviations from SM in Wilson coefficients C_7, C_9, C_{10} : $C_i = C_i^{SM} + C_i^{NP}$
- $b \to s\gamma$: sensitive to $|C_7|$ only

$$\mathcal{B}(b \to s\gamma) = \frac{G_F^2 \, \alpha_{EM} m_b^5 |V_{ts}^* V_{tb}|^2}{32\pi^4} |C_7|^2 + \text{corr.}$$

- C_7 : For electro-magnetic operator
- C_9 : For semi-leptonic vector operator
- C_{10}: For semi-leptonic axial vector operator

- $b \to s\ell^+\ell^-$: sensitive to C_7 sign, C_9, C_{10}

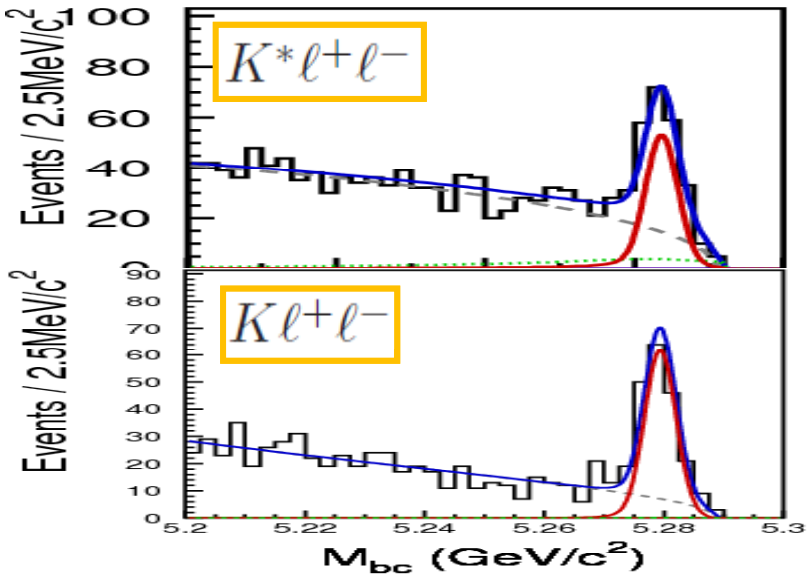
$$\frac{d\Gamma(b \to s\ell^+\ell^-)}{d\hat{s}} = \left(\frac{\alpha_{EM}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2}{48\pi^3} (1-\hat{s})^2 \times \left[(1+\hat{s})(|C_9|^2 + |C_{10}|^2) + 4(1+2/\hat{s})|C_7|^2 + 12\mathrm{Re}(C_7 C_9^*) \right]$$

$$\hat{s} = M_{\ell^+\ell^-}^2 / m_{b,pole}^2$$

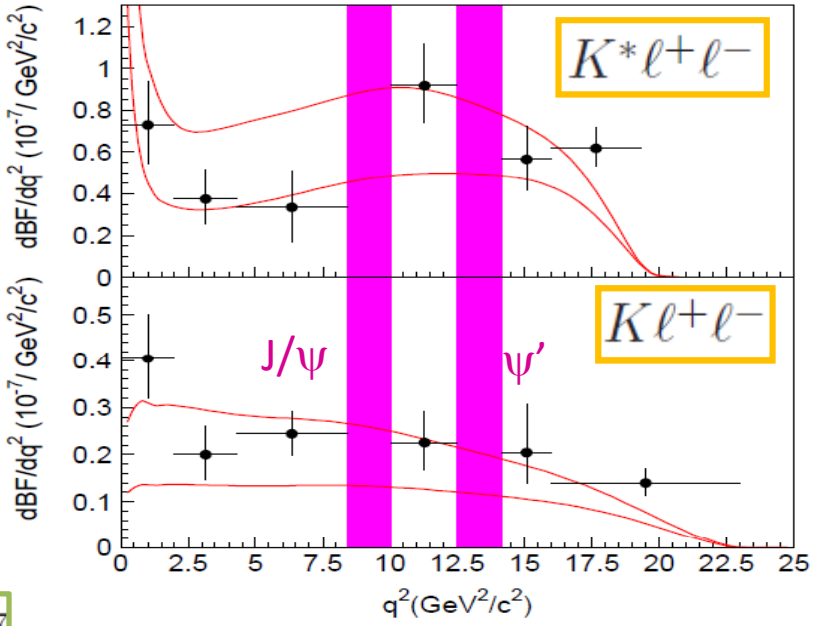
Exclusive: $B \to K^{(*)}\ell^+\ell^-$

657M BB

PRL 103, 171801 (2009)



Differential BF



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

——— : SM prediction with minimum or maximum form factors

384M BB

PRD 79, 031102 (2009)

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.11^{+0.19}_{-0.18} \pm 0.07) \times 10^{-6}$$
$$\mathcal{B}(B \to K\ell^+\ell^-) = (0.394^{+0.073}_{-0.069} \pm 0.020) \times 10^{-6}$$

K* polarization(F_L), FB asymmetry(A_{FB})

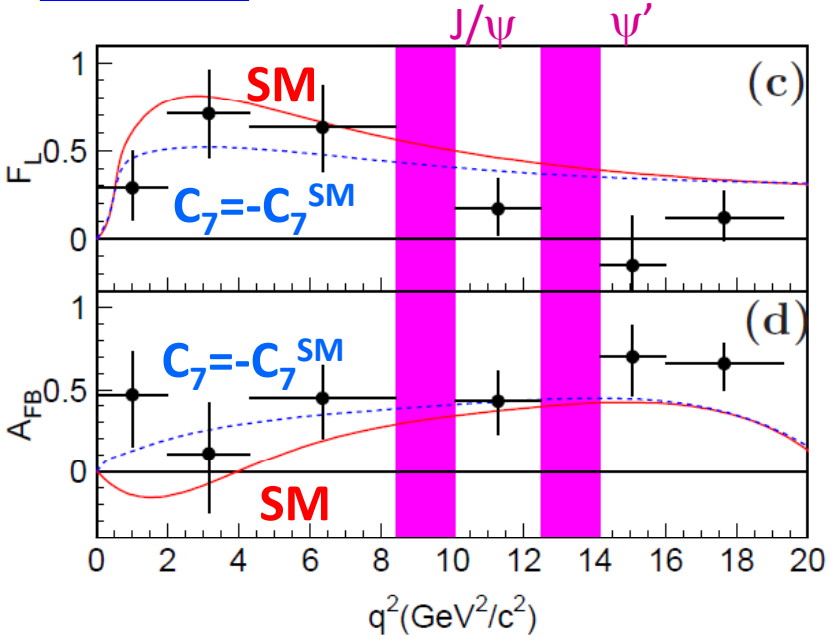
$$\frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2}F_L\cos^2\theta_{K^*} + \frac{3}{4}(1-F_L)(\sin^2\theta_{K^*})$$

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

CDF also measured K*ll A_{FB}
arxiv:1005.2338

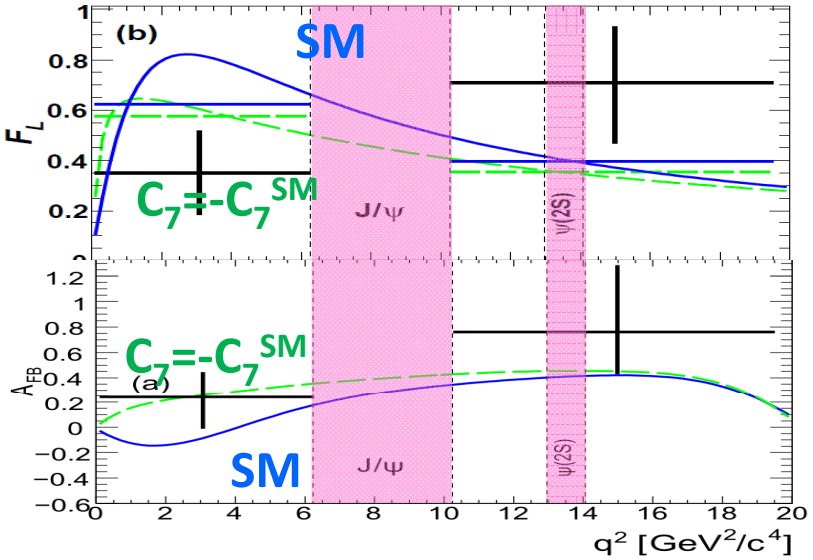
657M BB

PRL 103, 171801 (2009)



465M BB

PRD 79, 031102 (2009)



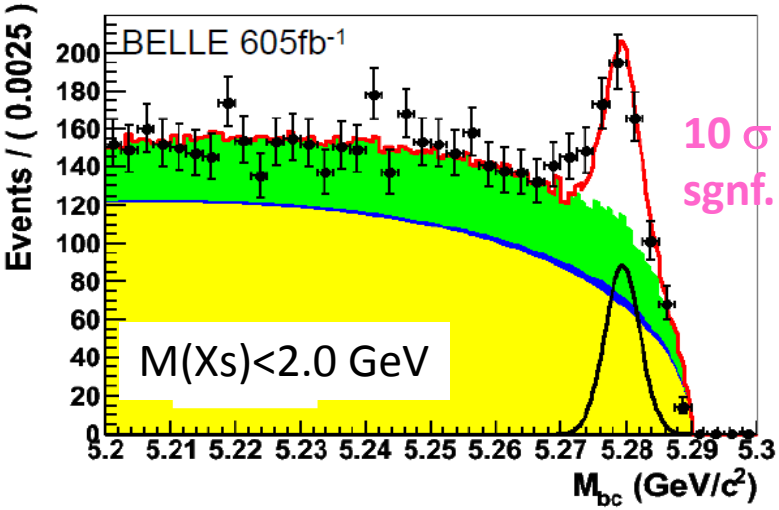
For K*ll A_{FB}, sign-flipped C_7 NP scenario is favored

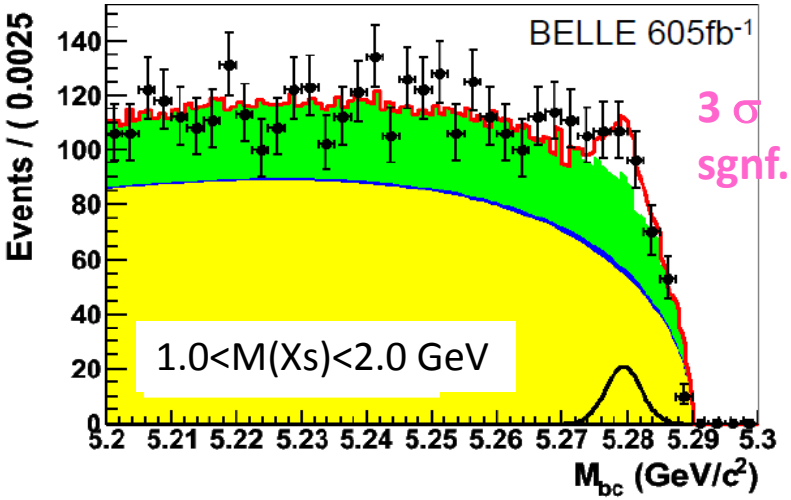
Inclusive: $B \to X_s \ell^+ \ell^-$

657M BB

Preliminary

- Sum of exclusive: $X_s = K^+/K_s + n\pi$ (n=0~4)
- New background sources are taken into account
  - Charmonium higher resonances, Semileptonic decays





$$\mathcal{B}(B \to X_s \ell\ell) = (3.33 \pm 0.80^{+0.19}_{-0.24}) \times 10^{-6}$$

scaled for entire MXs region including >2.0GeV

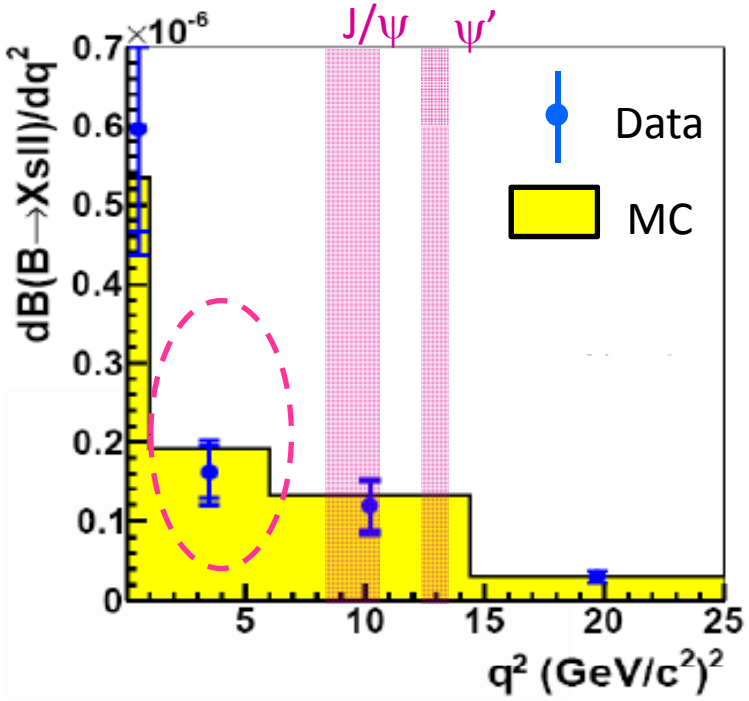
SM NNLO prediction:
(4.4 +- 0.7) x 10^{-6}

Gambino et al., PRL 94, 061803 (2005)

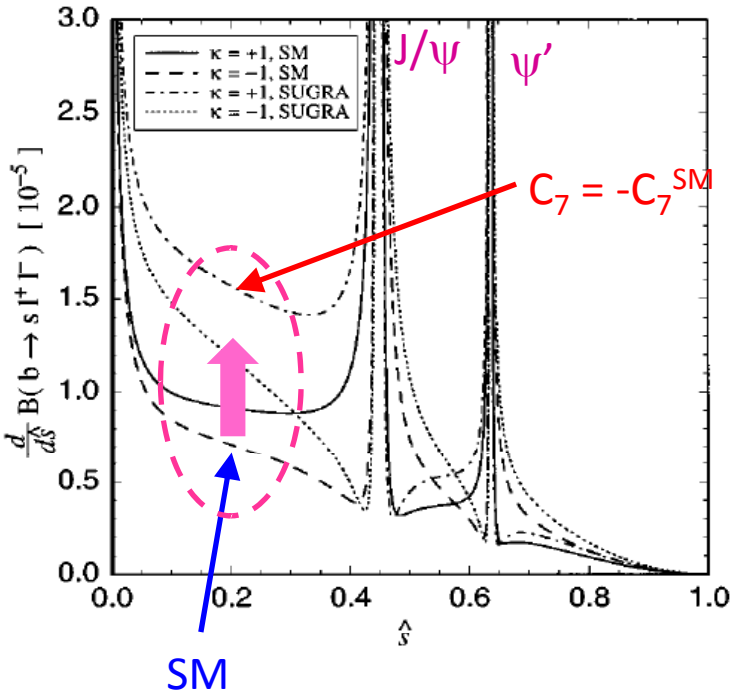
q^2 spectrum($B \to X_s \ell^+ \ell^-$)

657M BB

Preliminary



T.Goto et al. PRD **55** 4273 (1997)



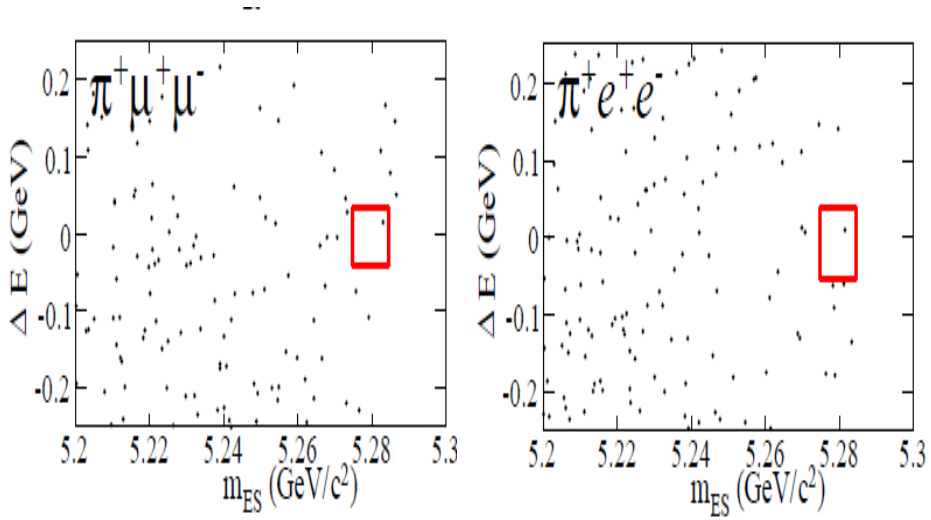
No BF enhancement

→ For BR(Xsll), sign-fllipped C_7 scenario is not favored

B→πℓ⁺ℓ⁻ (exclusive b→dℓ⁺ℓ⁻)

230M BB

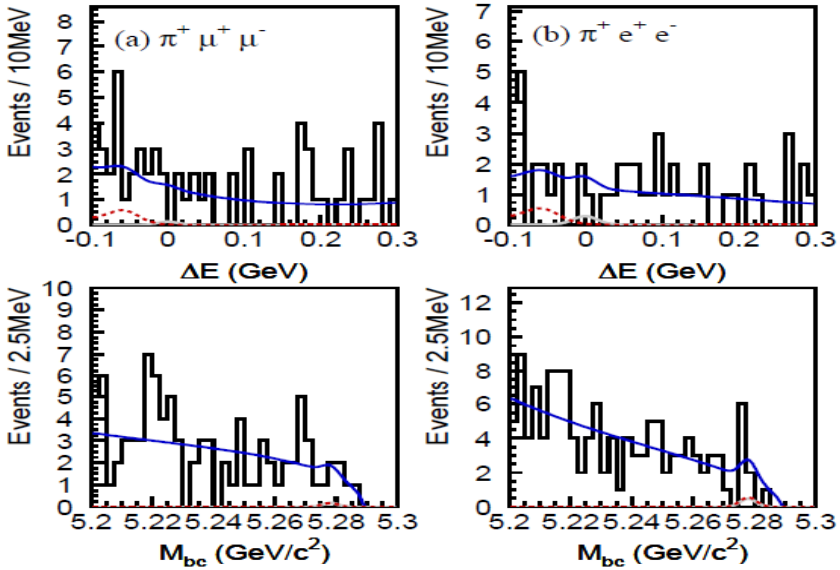
PRL 99 051801 (2007)



$\mathcal{B}(B \to \pi\ell^+\ell^-) < 9.1 \times 10^{-8}$ (90% CL)

657M BB

PRD 78 011101 (2008)



$\mathcal{B}(B \to \pi\ell^+\ell^-) < 6.2 \times 10^{-8}$ (90% CL)

Need significantly more statistics, even better PID

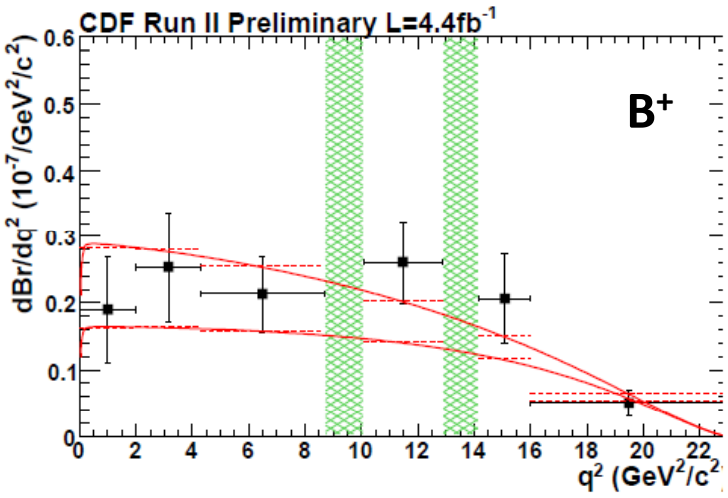
Summary

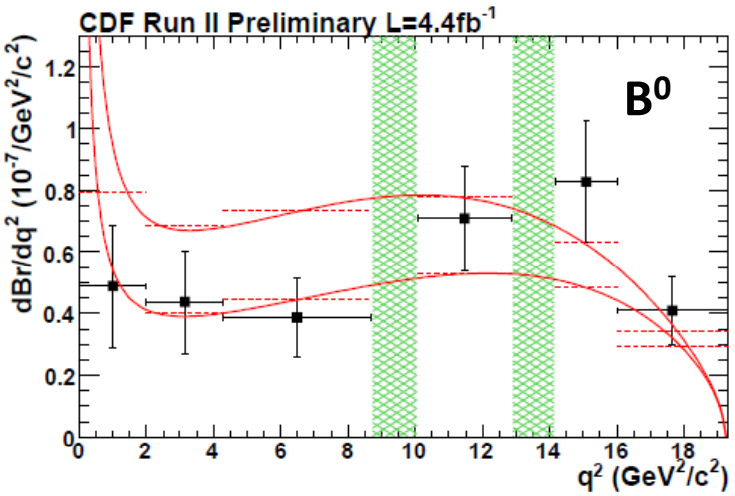
- FCNC decays provide rich opportunities to test SM predictions and search for NP.
- High luminosity (~10^{34} $cm^{-2}s^{-1}$) at B factories has made it possible to study these FCNC decays such as $b \to s\gamma$, $b \to d\gamma$ and $b \to s\ell^+\ell^-$.
- Belle is now analyzing its full 1 ab^{-1} data sample, which has just been reprocessed with significantly improved charged particle tracking.

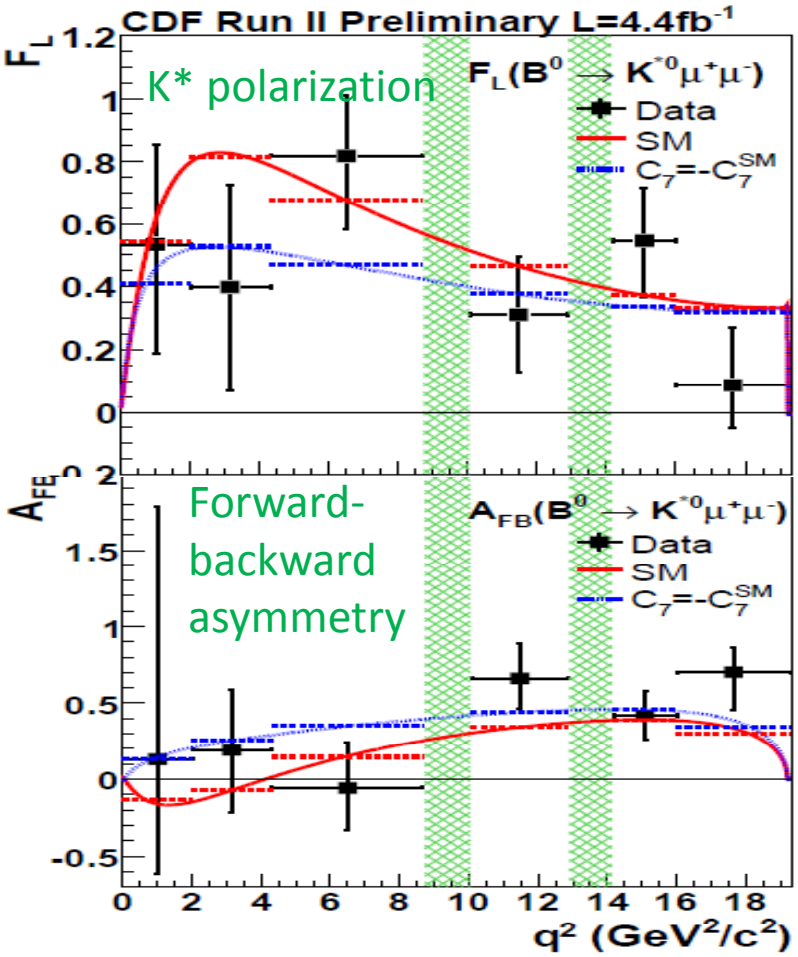
backup

arxiv:0906.2177

B→K*ll, F_L,A_{FB}



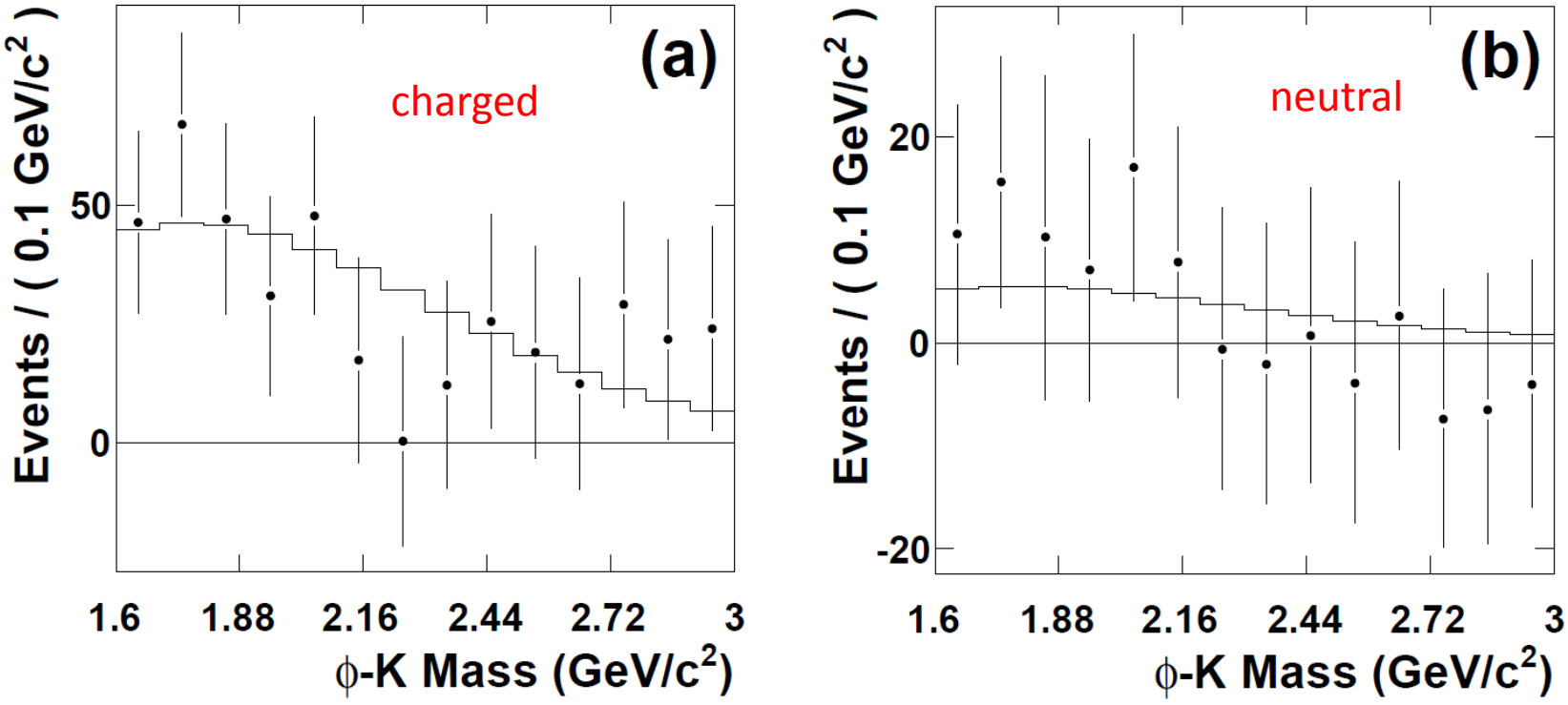




$M_{\phi K}$ ($B \rightarrow \phi K \gamma$)

772M BB

arXiv: 0911.1779 (LP09)



Omitted issues

- $B \rightarrow K^* \gamma$: right-handed current search
- $B \rightarrow K1\gamma$
- $K^{(*)}ll$: e/mu ratio, A_l

References

	Belle	BaBar
$B \to K^* \gamma$	85MBB/ PRD 69, 112001 (2004)	**383MBB/ PRL 103, 211802 (2009)**
$B \to K \eta \gamma$	275MBB/ PLB 610, 23 (2005)	**465MBB/ PRD 79, 011102 (2009)**
$B \to K \eta' \gamma$	**657MBB/ arXiv:0810.0804**	232MBB/PRD 74, 031102 (2006)
$B \to K \phi \gamma$	**772MBB/ arXiv: 0911.1779**	228MBB/ PRD 75, 051102 (2007)
$B \to X_s \gamma$ (full/recoil)	**657MBB/ PRL 103, 241801 (2009)**	210fb-1/ PRD 77, 051103 (2008)
$B \to X_s \gamma$ (semi)	140MBB/ PRL93,0318038 (2004)	383MBB/ PRL 102 161803 (2009) → **471MBB/ BABAR-PUB-10/007**
$B \to (\rho/\omega) \gamma$	**657MBB/ PRL 101, 111801 (2008)**	**465MBB/ PRD 78, 112001 (2008)**
$B \to X_d \gamma$ (semi)	--	**471MBB/ BABAR-PUB-10/007**
$B \to K^* ll$, A_{FB}	**657MBB/ PRL 103, 171801 (2009)**	**384MBB/ PRD 79, 031102 (2009)**
$B \to X_s ll$ (semi)	**657MBB/ Prel. (LP09 Iijima's talk)**	85MBB/ PRL 93, 081802 (2004)
$B \to \pi ll$	**657MBB/ PRD 78 011101 (2008)**	**230MBB/ PRL 99, 051801 (2007)**

Decay	Collab, Lumi.	arXiv link	PRL,PRD ref.	comment
$X_s\gamma$	Belle 6MBB	hep-ex/0103042	Phys.Lett.B511:151-158,2001	
$K\pi\gamma, K\pi\pi\gamma$	Belle 29fb-1	hep-ex/0205025	Phys.Rev.Lett.89:231801,2002	Nishida
$\phi K\gamma$	Belle 90fb-1	hep-ex/0309006	Phys.Rev.Lett.92:051801,2004	
$K^*\gamma$	Belle 85MBB	hep-ex/0402042	Phys.Rev.D69:112001,2004	Nakao
$X_s\gamma$	Belle 140fb-1	hep-ex/0403004	Phys.Rev.Lett.93:061803,2004	
$X_s\gamma$, A_{CP}	Belle 140fb-1	hep-ex/0308038	Phys.Rev.Lett.93:031803,2004	Nishida
$K^+\eta\gamma$	Belle 253fb-1	hep-ex/0411065	Phys.Lett.B610:23-30,2005	Nishida
$K_1^+\gamma$	Belle 140fb-1	hep-ex/0412039	Phys.Rev.Lett.94:111802,2005	
$K_s\pi\gamma$, TCPV	Belle 275MBB	hep-ex/0503008	Phys.Rev.Lett.94:231601,2005	Ushiroda
$X_d\gamma$	Belle 275MBB	hep-ex/0505097	Phys.Rev.D72:011101,2005	
$X_d\gamma$, $\lvert V_{td}/V_{ts}\rvert$	Belle 386MBB	hep-ex/0506079	Phys.Rev.Lett.96:221601,2006	
$X_s\gamma$, A_{CP}	Belle 535MBB	hep-ex/0608017	Phys.Rev.D74:111104,2006	Ushiroda
$X_s\gamma$ E_γ, $\lvert V_{cb}\rvert$, m_b	Belle 140MBB	0803.2158	Phys.Rev.D78:032016,2008	Not measurement
$(\rho/\omega)\gamma, A_I, A_{CP}$	Belle 657MBB	0804.4770v1	Submitted to PRL	Taniguchi
$K_S^0\rho^0\gamma$	Belle 657MBB	0806.1980	Phys.Rev.Lett.101:251601,2008	
$K\eta'\gamma$	Belle 657MBB	0810.0804	Submitted to PRD-RC	
$\phi K^0\gamma$	Belle 772MBB	0911.1779	DPF 09 and Lepton-Photon 09	TCPV ongoing

Decay	Collab, Lumi.	arXiv link	PRL,PRD ref.	comment
$K^*\gamma$	BaBar 23MBB	hep-ex/0110065	Phys.Rev.Lett.88:101805,2002	
$(\rho/\omega)\gamma$	BaBar 84MBB	hep-ex/0306038	Phys.Rev.Lett.92:111801,2004	12 exclusives
$X_s\gamma$ A_{CP}	BaBar 89MBB	hep-ex/0403035	Phys.Rev.Lett.93:021804,2004	
$K_s\pi^0\gamma$, TCPV	BaBar 124MBB	hep-ex/0405082	Phys.Rev.Lett.93:201801,2004	
$K^*\gamma, A_I, A_{CP}$	BaBar 88MBB	hep-ex/0407003	Phys.Rev.D70:112006,2004	
$K_2^*\gamma$	BaBar 89MBB	hep-ex/0409035	Phys.Rev.D70:091105,2004	
$(\rho/\omega)\gamma$	BaBar 211MBB	hep-ex/0408034	Phys.Rev.Lett.94:011801,2005	
$K_s\pi^0\gamma$, TCPV	BaBar 232MBB	hep-ex/0507038	Phys.Rev.D72:051103,2005	
$K\pi\pi\gamma$	BaBar 232MBB	hep-ex/0507031	Phys.Rev.Lett.98:211804,2007	
$X_s\gamma$, E_γ spectrum	BaBar 89MBB	hep-ex/0508004	Phys.Rev.D72:052004,2005	38 exclusives
$K\eta(')\gamma$	BaBar 232MBB	hep-ex/0603054	Phys.Rev.D74:031102,2006	
$X_s\gamma$, A_{CP} for $X_{s,d}\gamma$	BaBar 89MBB	hep-ex/0607071	Phys.Rev.Lett.97:171803,2006	
$\phi K\gamma$	BaBar 228MBB	hep-ex/0611037	Phys.Rev.D75:051102,2007	
$X_s\gamma$, E_γ spectrum	BaBar 210fb-1	0711.4889	Phys.Rev.D77:051103,2008	Recoil Method
$X_s\gamma$	BaBar 383MBB	0805.4796	Phys.Rev.Lett.101:171804,2008	16 exclusives
$K^*\eta_c$, $K^*\eta_{c'}$, $K^*\eta_c\gamma$	BaBar 349MBB	0804.1208	Phys.Rev.D78:012006,2008	
$K\eta\gamma$ S,C	BaBar 465MBB	0805.1317	Phys.Rev.D79:011102,2009	
$(\rho/\omega)\gamma$	BaBar 465MBB	0808.1379	Phys.Rev.D78:112001,2008	
$K_s\pi^0\gamma$, TCPV	BaBar 467MBB	0807.3103	Phys.Rev.D78:071102,2008	
$X\gamma$, $\lvert V_{td}/V_{ts}\rvert$	BaBar 383MBB	0807.4975	Phys.Rev.Lett.102:161803,2009	7 exclusives
$K^*\gamma$ A_{CP}, A_I	BaBar 383MBB	0906.2177	Phys.Rev.Lett.103:211802,2009	

Decay	Collab, Lumi.	arXiv link	PRL,PRD ref.
$X_s ll$	Belle 65MBB	hep-ex/0208029	Phys.Rev.Lett.90:021801,2003
K*ll	Belle 140fb-1	hep-ex/0308044	Phys.Rev.Lett.91:261601,2003
$X_s ll$	Belle 140fb-1	hep-ex/0503044	Phys.Rev.D72:092005,2005
πll	Belle 657MBB	0804.3656	Phys.Rev.D78:011101,2008
K*ll A_{FB}	Belle 657MBB	0904.0770	Phys.Rev.Lett.103:171801,2009
$X_s ll$	Belle 657MBB	Preliminary	LP09
K*ll	BaBar 23MBB	hep-ex/0201008	Phys.Rev.Lett.88:241801,2002
K*ll	BaBar 123MBB	hep-ex/0308042	Phys.Rev.Lett.91:221802,2003
Xsll	BaBar 89MBB	hep-ex/0404006	Phys.Rev.Lett.93:081802,2004
K*ll $A_{CP}A_{FB}$	BaBar 229MBB	hep-ex/0604007	Phys.Rev.D73:092001,2006
πll	BaBar 230MBB	hep-ex/0703018	Phys.Rev.Lett.99:051801,2007
K*ll A_{FB}	BaBar 384MBB	0804.4412	Phys.Rev.D79:031102,2009
K*ll A_{CP}e/μ,A_I	BaBar 384MBB	0807.4119	Phys.Rev.Lett.102:091803,2009
K*ll A_{FB}	CDF, 5fb-1	1005.2338	?