Results of Radiative & Annihilation Penguin B Decays at Belle

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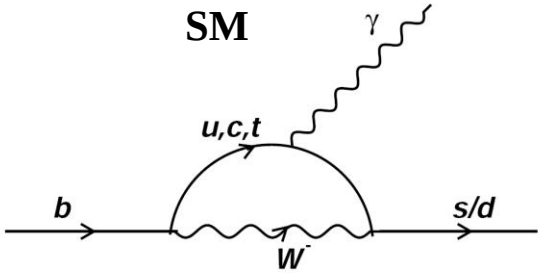
International Workshop On Deep-Inelastic Scattering

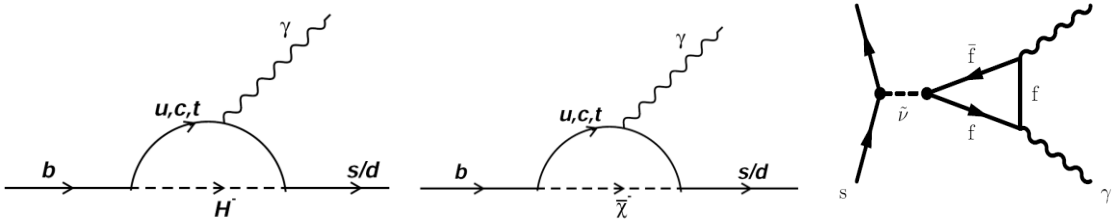
Theoretical Motivations

b → s,d transitions: FCNC process, forbidden at tree level in the SM.

SM



New Physics



- Sensitive to new physics.

  Observables such as BF, A_{CP}, A_{FB}, Isospin asymmetry could be modified by the presence of new physics.

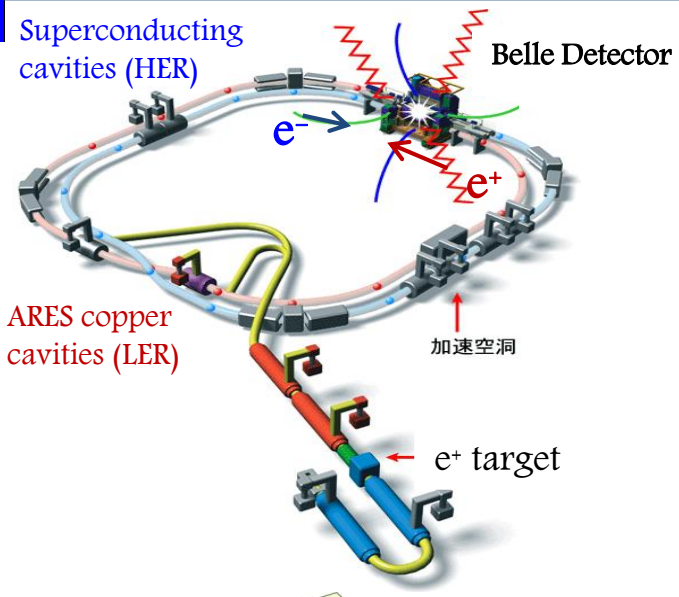
- Sensitive to electromagnetic Wilson coefficient C_7. (Rev. Mod. Phys. 68, 1125 Buchalla, Buras and Lautenbacher)

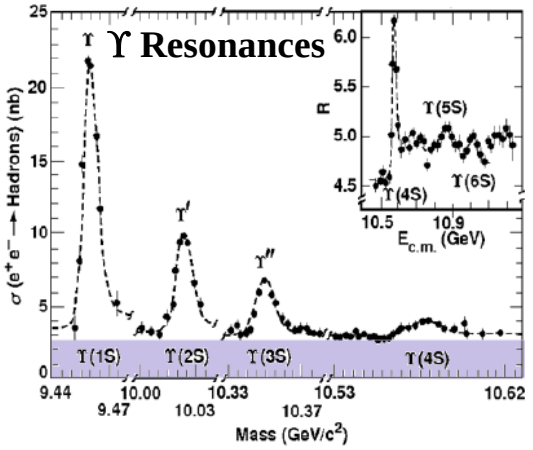
$$B(b \to s\gamma) = \frac{G_F{}^2 \alpha_{em} m_b{}^5 |Vts^* V_{tb}|^2}{34\pi^4} |C_7{}^{\text{eff}}|^2 + \cdots$$

- A measurement of $B_s \to \gamma\gamma$ could be a useful test of hadronic dynamics.

  (JHEP 08, 054 (2002) S.W. Bosch and G. Buchalla)

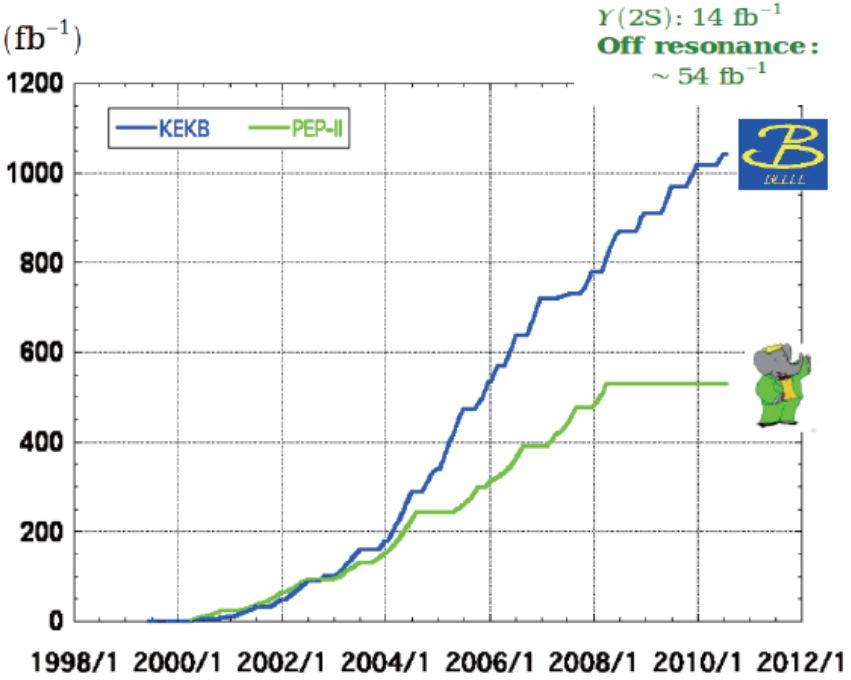
Experimental Setup





> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

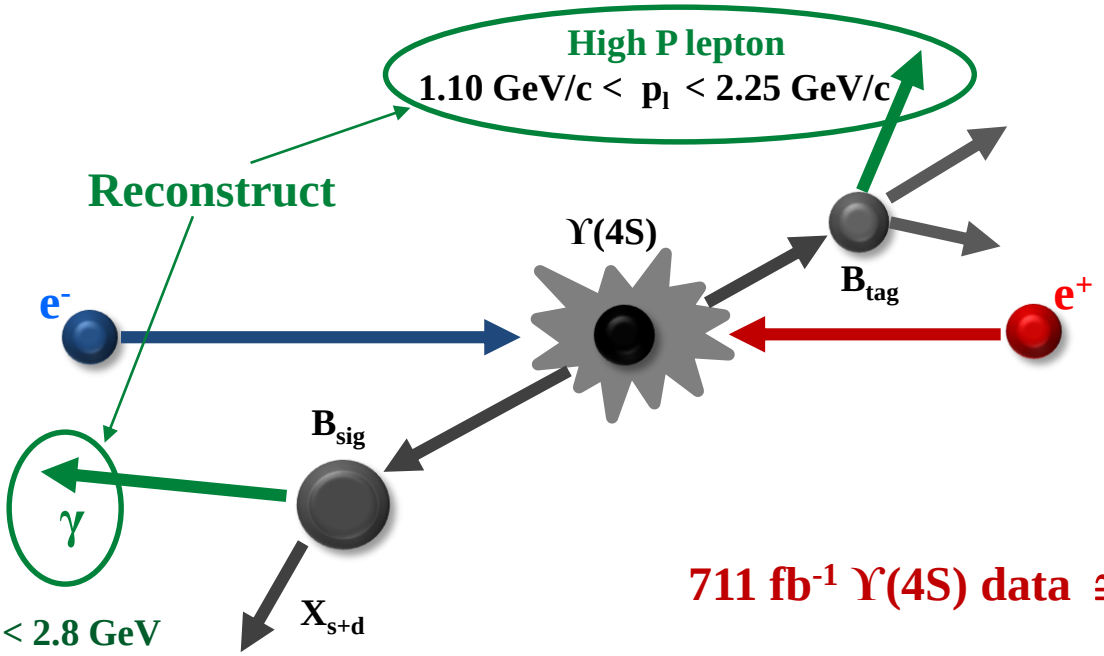


Currently, KEKB and Belle is being upgraded to SuperKEKB & Belle11, SuperKEKB to collect ~50 times the current data.

CP asymmetry measurements in inclusive $B \to X_{s+d}\gamma$

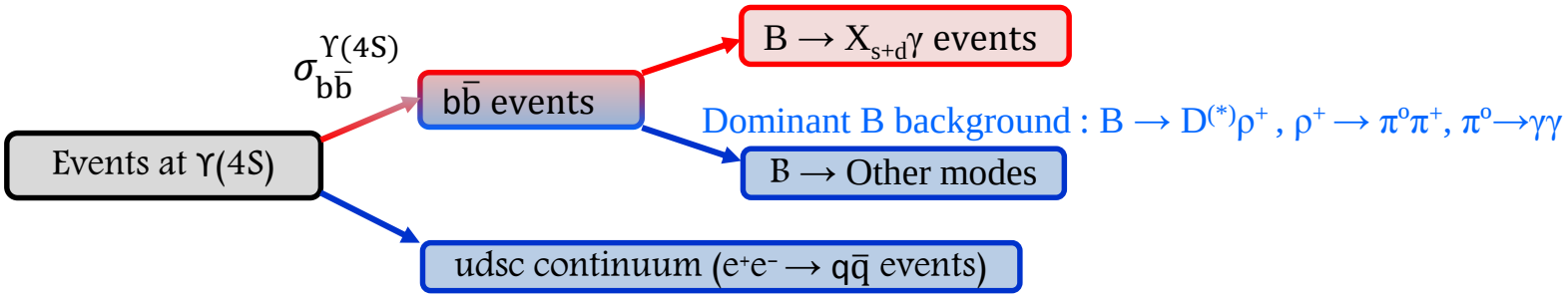
Analysis Technique

Inclusive analysis with leptonic tag.



1.7 GeV < E_γ < 2.8 GeV

711 fb^{-1} Υ(4S) data ≅ 772 × 10^6 $B\bar{B}$ pairs.



Belle, PRL 114, 151601 (2015)

CP asymmetry measurements in inclusive $B \to X_{s+d}\gamma$

$$A_{CP} = \frac{\Gamma(\bar{B} \to X_{s,d}\gamma) - \Gamma(\bar{B} \to X_{s,d}\gamma)}{\Gamma(\bar{B} \to X_{s,d}\gamma) + \Gamma(\bar{B} \to X_{s,d}\gamma)} = \frac{N^+ - N^-}{N^+ + N^-}$$

SM Expectations and Recent Results

- CP asym. measurements in $B \to X_s\gamma$, $B \to X_d\gamma$ & $B \to X_{s+d}\gamma$ are in agreement with SM.

  $A_{CP}(B \to X_{s+d}\gamma)$ – CLEO PRL 86, 5661 (2001), Babar PRD 86, 112008 (2012)
  $A_{CP}(B \to X_s\gamma)$ – Belle PRL 93, 031803(2004), Babar PRD 90, 092001 (2014)

- In $A_{CP}(B \to X_{s+d}\gamma)$, $X_s\gamma$ and $X_d\gamma$ almost completely cancels due to CKM matrix unitarity.
  SM prediction : $A_{CP}(B \to X_{s+d}\gamma) \sim 10^{-9}$ only due to U-spin breaking effects.

Channel	A_{CP}(SM)
$B \to X_s\gamma$	[-0.6% , +2.8%]
$B \to X_d\gamma$	[-62% ,+14%]
$B \to X_{s+d}\gamma$	0

PRL 106, 141801 (2011)

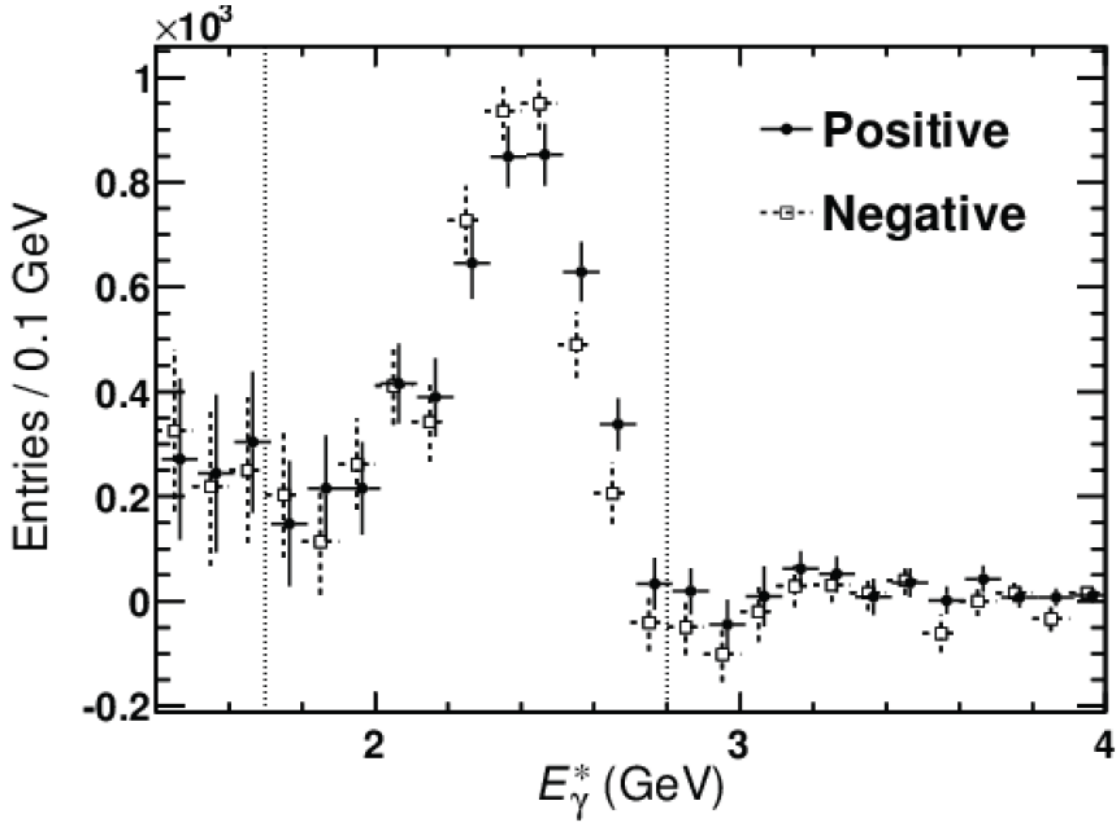
$A_{CP}(B \to X_{s+d}\gamma) \sim 10^{-9}$

- New physics such as SUSY with minimal flavour violation predict $A_{CP}(B \to X_{s+d}\gamma)$ upto a level of +2%.

CP asymmetry measurements in inclusive $B \to X_{s+d}\gamma$

Analysis Results

$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-} = (2.2 \pm 3.9 \pm 0.9)\% \text{ for } E_\gamma^* > 2.1 \text{ GeV, consistent with SM prediction.}$$

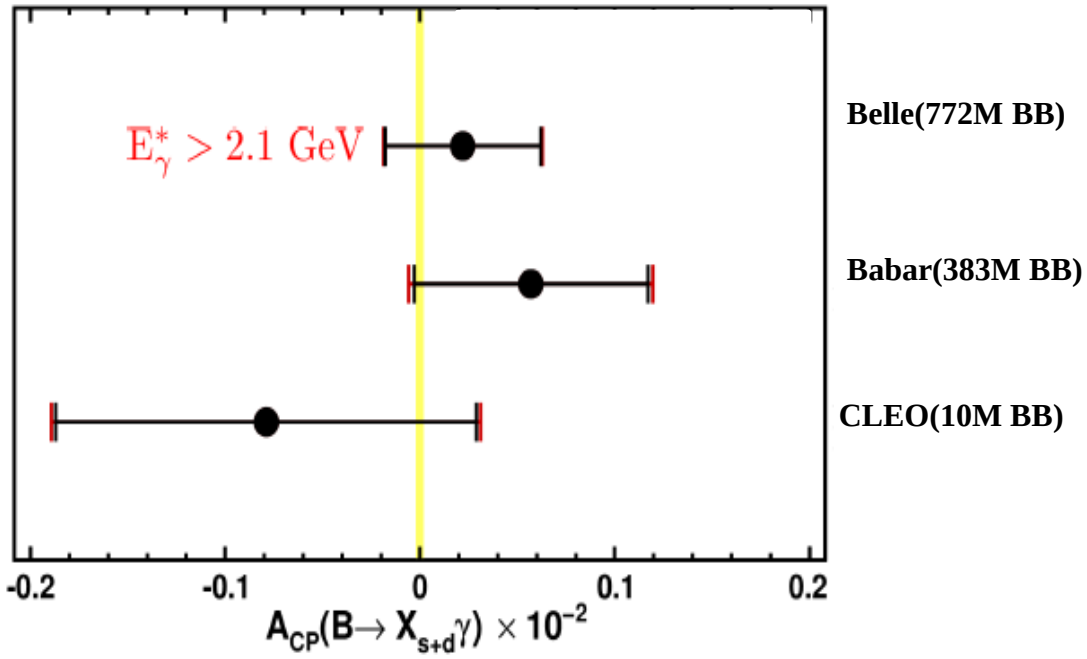


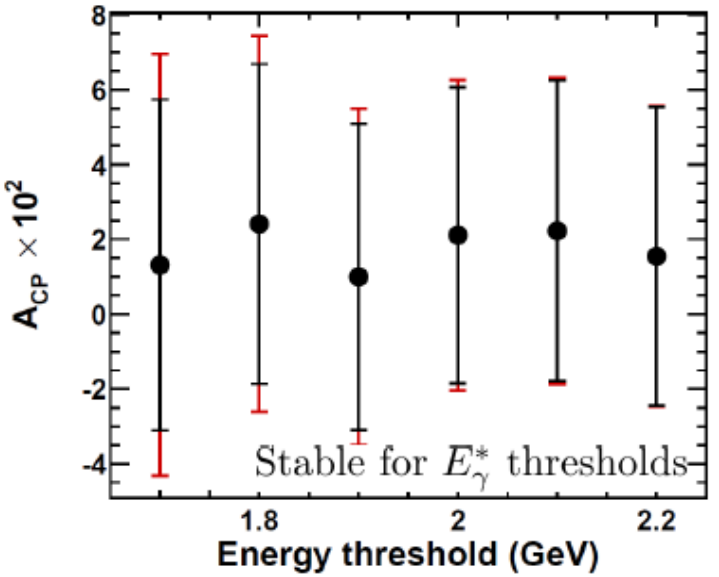
Background subtracted E_γ spectrum in the C.M. system.

Belle, PRL 114, 151601 (2015)

CP asymmetry measurements in inclusive $B \to X_{s+d}\gamma$

Analysis Results and Summary





A_{CP} as a function of E_γ^* threshold.

Summary :

- Most precise measurement of A_{CP}
  - Statistically dominated
  - Leading systematic comes from BB background asymmetry

- Consistent with SM and other experiments.

Belle, PRL 114, 151601 (2015)

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

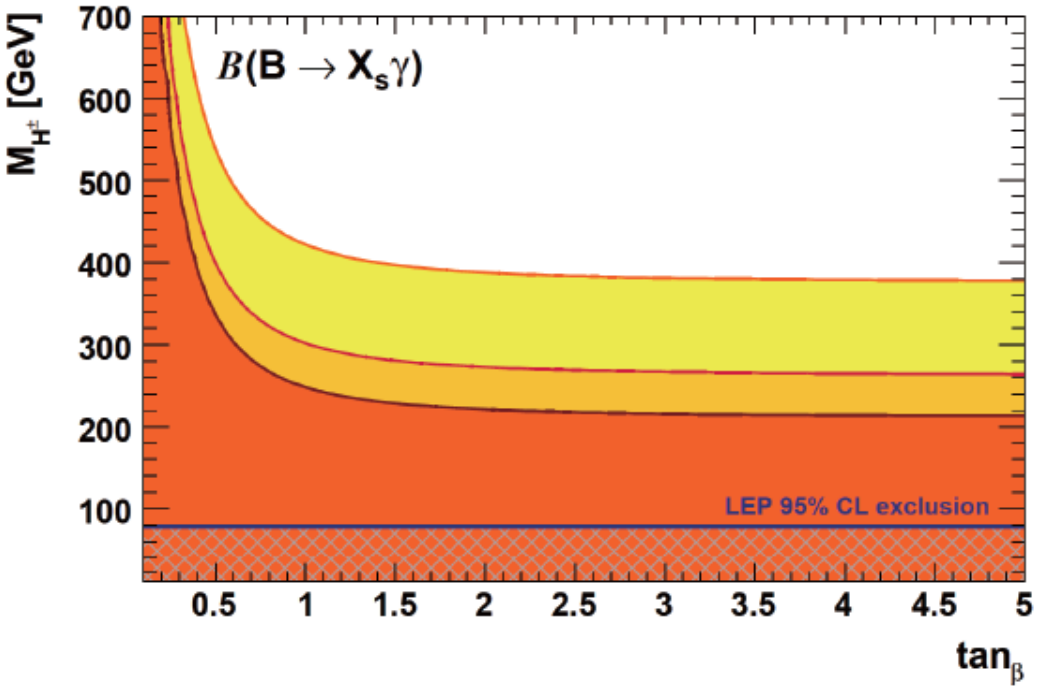
SM Expectations and Recent Results

- SM calculations : Theory calculation at NNLO

$B_{SM}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for $E\gamma > 1.6$ GeV (PRL 98, 022002, 2007 M. Misiak et. al.)

- Experimental Average

$B(B \to X_s\gamma) = (3.43 \pm 0.20) \times 10^{-4}$ (PDG 2014)

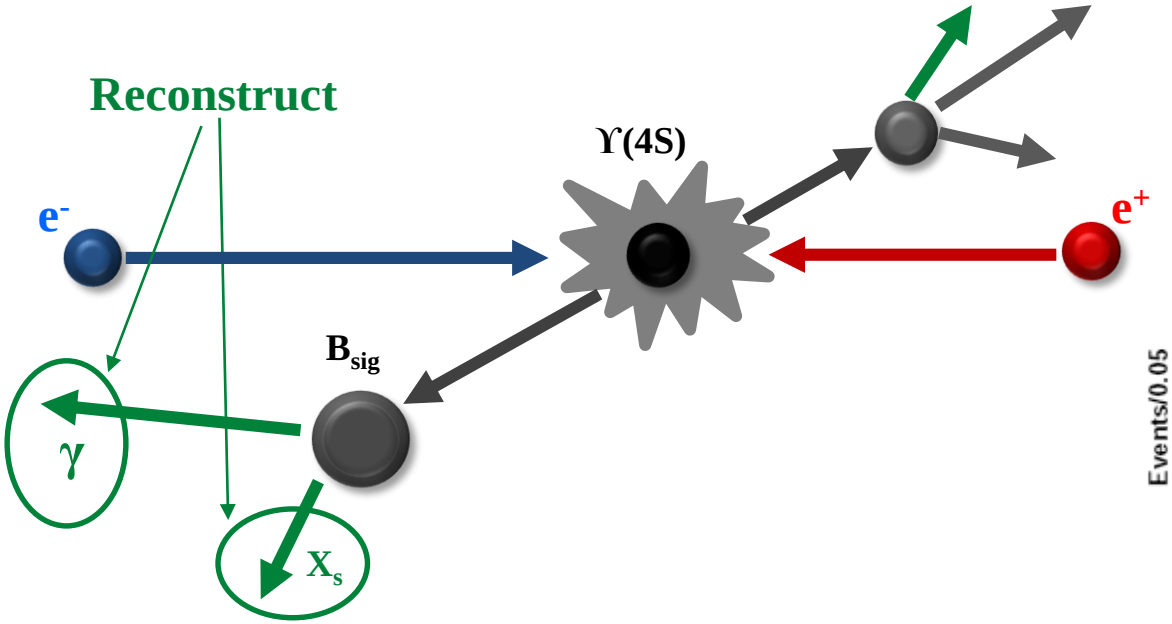


68% CL exclusion
95% CL exclusion
99% CL exclusion

Two-sided 68%, 95% and 99% CL exclusion region in the 2HDM parameter plane M_H versus tanβ

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Analysis Technique

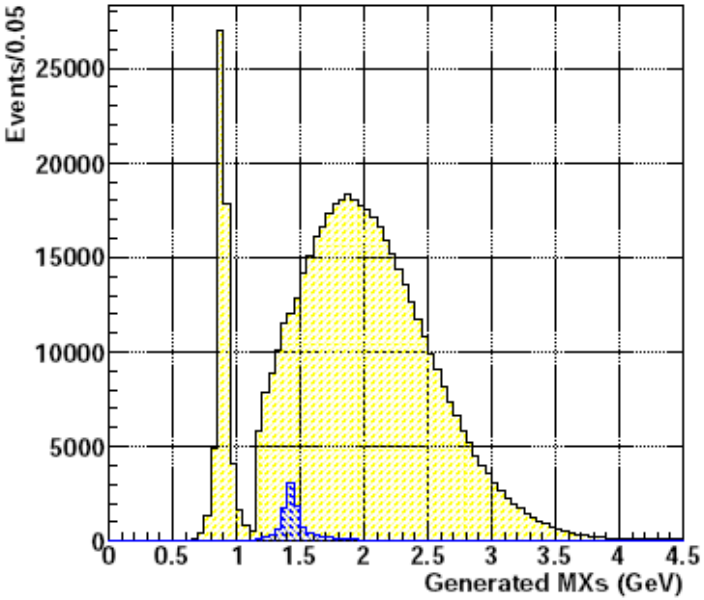


$M_{X_s} < 2.8$ GeV

Reconstruct as many modes as possible to minimize the systematic uncertainty from the hadronization model in the MC.

38 modes reconstructed.

711 fb^{-1} Υ(4S) data
≅ 772 × 10^6 $B\bar{B}$ pairs.



X_s mass distribution

Belle, PRD 91, 052004 (2015)

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

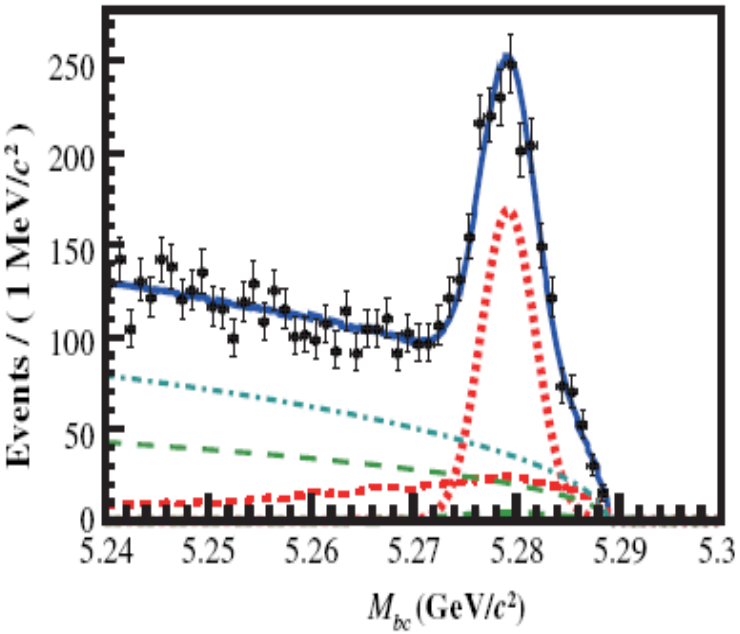
Analysis Results

Signal Efficiency : ~ 2.1%.

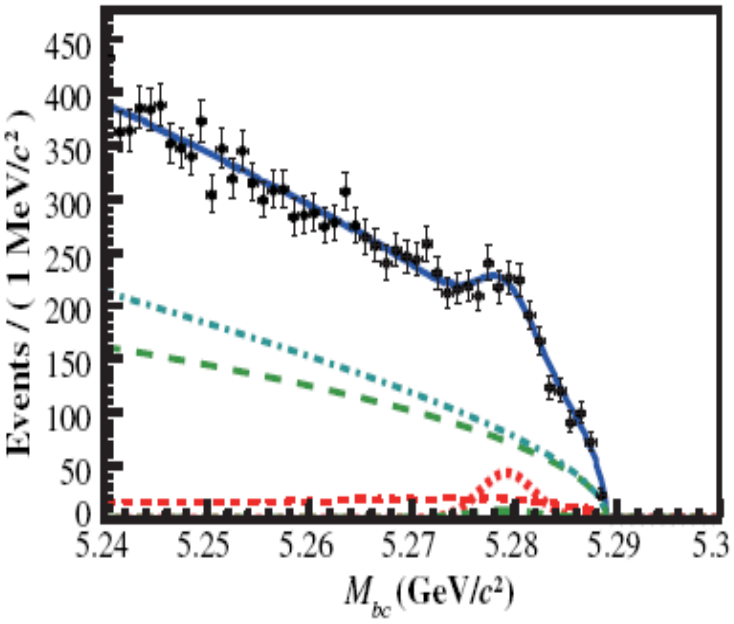
BF is extracted in 19 $M(x_s)$ bins of M_{bc}.

Continuum
Peaking BB
Non peaking BB
Signal
CrossFeed

Example plots:



$1.3 < M_{Xs} < 1.4$ (GeV/c^2)

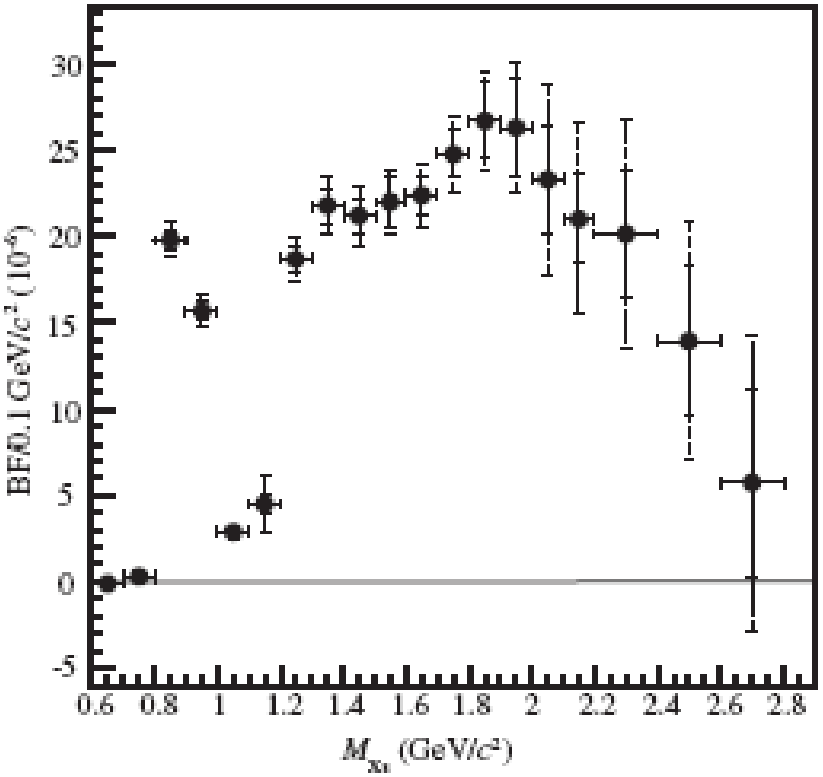


$2.1 < M_{Xs} < 2.2$ (GeV/c^2)

Belle, PRD 91, 052004 (2015)

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Analysis Results



Branching Fraction :

$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$

for $E_\gamma{}^* > 1.8$ GeV and $0.6 \leq M_{Xs} \leq 2.8$ GeV/c^2

Extrapolated branching fraction to 1.6 GeV :

$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$

Partial branching fraction as a function of M_{Xs}

——— Statistical

- - - - - - - - - - Statistical + Systematic

Belle, PRD 91, 052004 (2015)

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Analysis Results

Source	Systematic Uncertainty (%)
BB counting	1.37
Detector Response	2.98
Background Rejection	3.38
M_{bc} PDF	5.06
Hadronization Model	6.66
Missing mode	1.59
Total	**9.3**

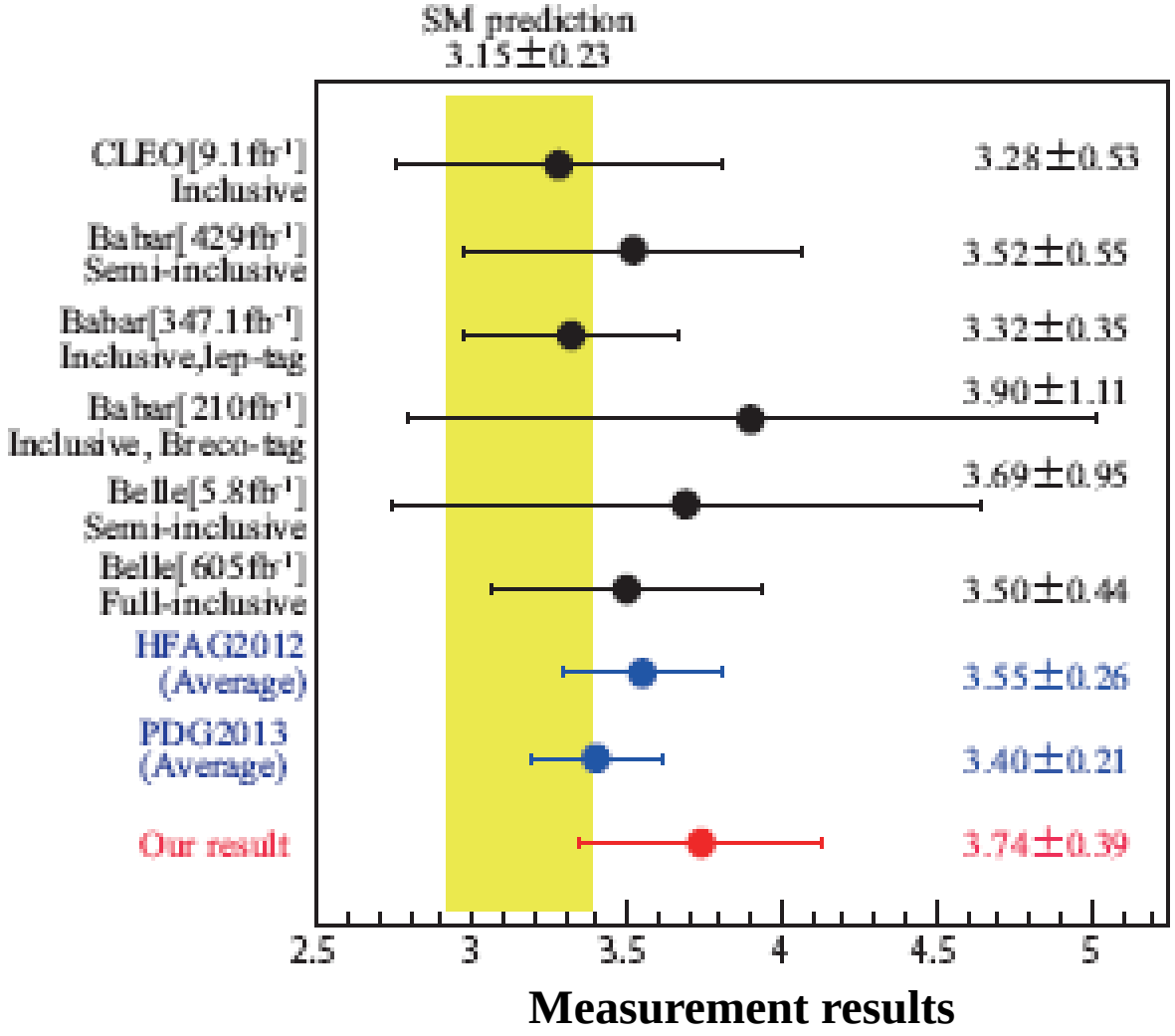
← **Dominant sources**

Systematic Uncertainties

Belle, PRD 91, 052004 (2015)

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Analysis Results and Summary



- **New PDG 2015 Average**

$$\mathcal{B}(\bar{B} \to X_s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$$

Summary : Results consistent with SM and other experiments.

Belle, PRD 91, 052004 (2015)

Study of exclusive mode $B \to \varphi\gamma$

SM Expectations and Recent Results

- SM calculations

$B_{SM}(B \to \varphi\gamma) = 10^{-12} - 10^{-11}$, extremely suppressed.

(EPJC36, 97 (2004), EPJC69, 139 (2010), Chin. Phys. Lett. 23, 2684 (2006))

- Previous Results

$B(B \to \varphi\gamma) < 8.5 \times 10^{-7}$ (PRD 72, 091103(2005), Babar experiment)

The Analysis

711 fb^{-1} Υ(4S) data $\cong$ 772 $\times$ 10^6 $B\bar{B}$ pairs.

- A loose cut is applied on the classifier output (C_{NB}) and C'_{NB} calculated.

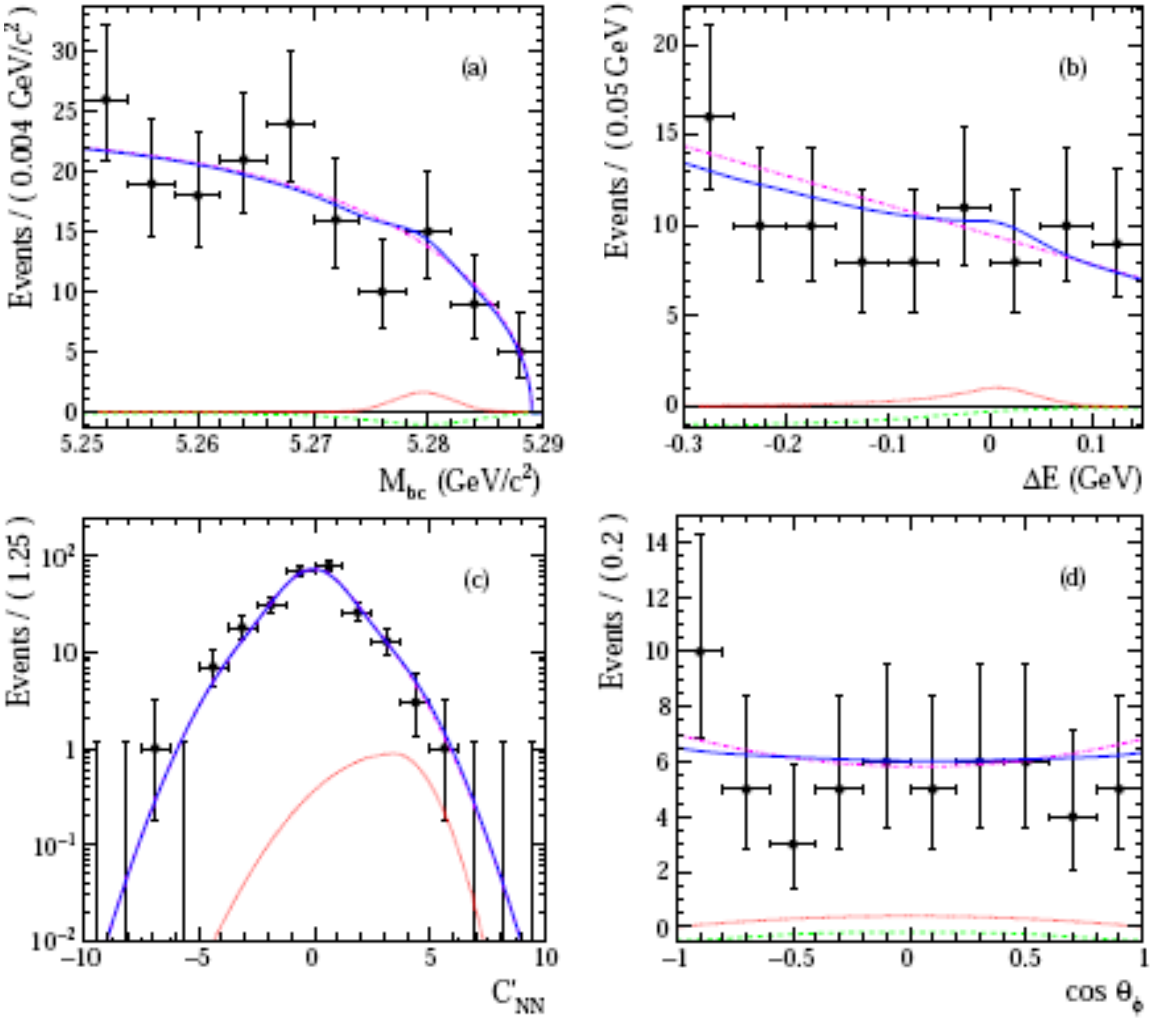
$$C'_{NB} = \log\left[\frac{(C_{NB} - C_{NB,cut})}{(C_{NB,max} - C_{NB})}\right]$$

- 4D extended maximum likelihood fit performed.

Belle, arXiv:1603.0654[hep-ex], Submitted to PRD

Study of exclusive mode B →φγ

Analysis Results and Summary



Signal Yield = $-3.4^{+4.6}_{-3.8}$

90 % CL upper limit =

1.0×10^{-7}

Summary : Found no evidence for B →φγ. Provided most stringent upper limit till date.

Belle, arXiv:1603.0654[hep-ex], Submitted to PRD

Study of exclusive modes $B_s \to \gamma\gamma$ and $B_s \to \phi\gamma$

SM Expectations and Recent Results

- SM calculations

$B_{SM}(B_s \to \phi\gamma) = (3.9 - 4.3) \times 10^{-5}$ with around 30 % uncertainty
(PRD 75, 054004 (2007), EPJC 55, 577-595 (2008), PRD 85, 014008 (2012))

$B_{SM}(B_s \to \gamma\gamma) = (0.18 - 2.45) \times 10^{-6}$
(PRD 56, 9 (1997), JHEP 08 (2002) 054, PLB 415: 395, 1997, PRD 85, 014008 (2012))

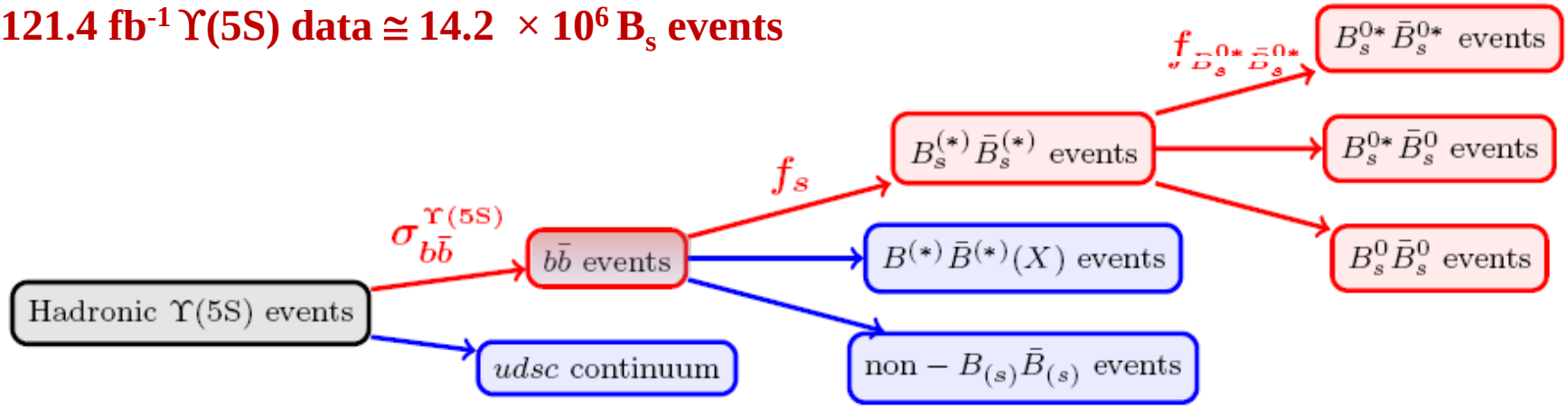
- Previous Results

$B(B_s \to \phi\gamma) = \left(5.7^{+1.8}_{-1.5}\,(stat.)^{+1.2}_{-1.1}(syst.)\right) \times 10^{-5}$ (PRL 100 121801(2008), Belle)

$B(B_s \to \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$ (NPB 867, 1 (2013), LHCb)

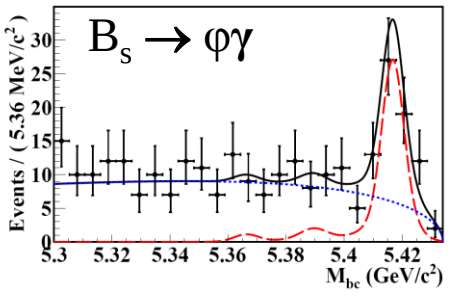
$B(B_s \to \gamma\gamma) < 8.7 \times 10^{-6}$ (PRL 100 121801(2008), Belle)

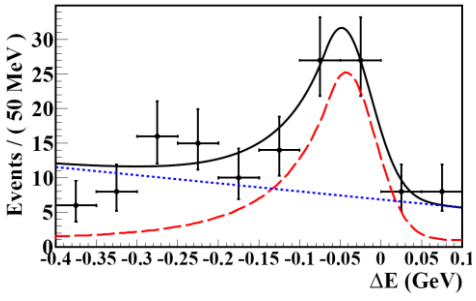
121.4 fb^{-1} Υ(5S) data ≅ 14.2 × 10^6 B_s events

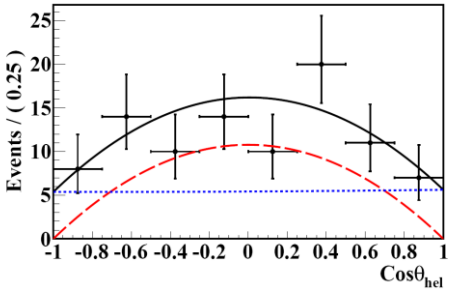


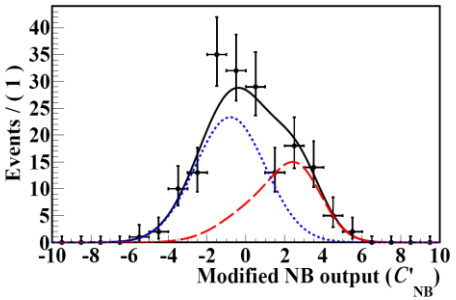
Study of exclusive modes $B_s \to \gamma\gamma$ and $B_s \to \phi\gamma$

Analysis Results and Summary



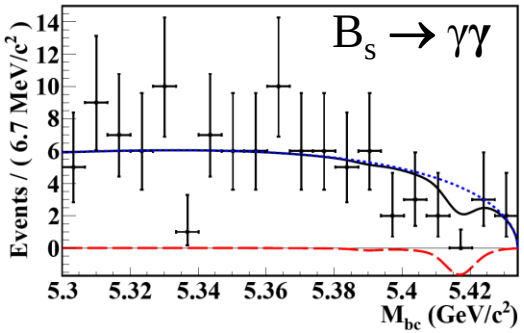


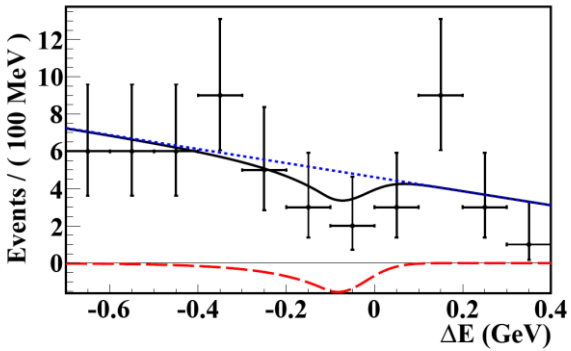




Signal Efficiency : (36.1 ± 0.1)%. Signal Yield = 91^{+14}_{-13}

Branching Fraction : $\mathcal{B}(B_s \to \phi\gamma) = (3.5 \pm 0.5(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.6(f_s)) \times 10^{-5}$





Signal Efficiency : (14.0 ± 0.1)%.

Signal Yield = $-3.89^{+3.7}_{-2.6}$

90 % CL upper limit = 3.1×10^{-6}

Summary :
- $B_s \to \phi\gamma$ BF is in agreement with SM prediction and recent experimental results.
- Found no evidence for $B_s \to \gamma\gamma$ and put the stringent upper limit till date.

Belle, PRD 91, 011101(R)(2015)

Summary

- All the experimental results are in agreement with SM prediction.
- Put stringent upper limits and made precise BF measurements.
- Results:
  - $\mathcal{B}(\bar{B} \rightarrow X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$ ($E_\gamma{}^* > 1.8$ GeV)
  - $A_{CP}(B \rightarrow X_{s+d}\gamma) = (2.2 \pm 3.9 \pm 0.9)\%$
  - $\mathcal{B}(B \rightarrow \varphi\gamma) < 1.0 \times 10^{-7}$ (90% C.L.)
  - $\mathcal{B}(B_s \rightarrow \varphi\gamma) = (3.5 \pm 0.5(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.6(f_s)) \times 10^{-5}$
  - $\mathcal{B}(B_s \rightarrow \gamma\gamma) < 3.1 \times 10^{-6}$ (90% C.L.)

Thank You…

Thank You

BackUp

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Reconstructed Final States

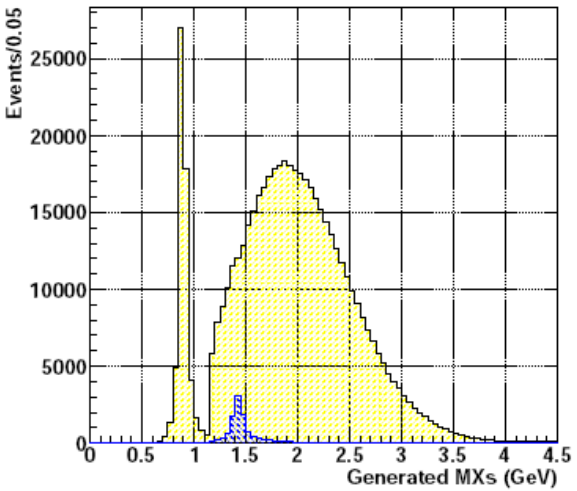
Reconstructed final states				
$K\pi$	$K\pi$	$K_s\pi$	$K\pi^0$	$K_s\pi^0$
$K2\pi$	$K\pi\pi$	$K_s\pi\pi$	$K\pi\pi^0$	$K_s\pi\pi^0$
$K3\pi$	$K\pi\pi\pi$	$K_s\pi\pi\pi$	$K\pi\pi\pi^0$	$K_s\pi\pi\pi^0$
$K4\pi$	$K\pi\pi\pi\pi$	$K_s\pi\pi\pi\pi$	$K\pi\pi\pi\pi^0$	$K_s\pi\pi\pi\pi^0$
$3K$	KKK	KKK_s		
	$KKK\pi$	$KKK_s\pi$	$KKK\pi^0$	$KKK_s\pi^0$
$K\eta$	$K\eta$	$K_s\eta$	$K\eta\pi$	$K_s\eta\pi$
	$K\eta\pi^0$	$K_s\eta\pi^0$	$K\eta 2\pi$	$K_s\eta 2\pi$
	$K\eta\pi\pi^0$	$K_s\eta\pi\pi^0$		
$2\pi^0$	$K\pi^0\pi^0$	$K_s\pi^0\pi^0$	$K\pi\pi^0\pi^0$	$K_s\pi\pi^0\pi^0$
	$K\pi\pi\pi^0\pi^0$	$K_s\pi\pi\pi^0\pi^0$		

$B \to X_s\gamma$ BF with Semi Incl. Reconstruction Method

Photon energy should be monochromatic. However, it is smeared by:

- the Fermi motion of the b quark inside the B meson.
- the QCD corrections.
- the non-zero momentum of the B meson.
- the detector resolution.

The γ energy spectrum & the X_s mass distribution are produced following a Kagan-Neubert model (Eur. Phys. J. C 7:5-27, 1999). The parameters m_b and m_π are taken from the theoretical spectrum having the best fit with the previous Belle fully inclusive result.
(m_b = 4.440 GeV/c^2, m_π^2 = 0.750 GeV^2)



X_s mass distribution