Measurements of radiative B meson decays at *Belle*

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Coverage of this talk

- Radiative Penguin decays of b quark

  >> Reviews on recent works at ***Belle***

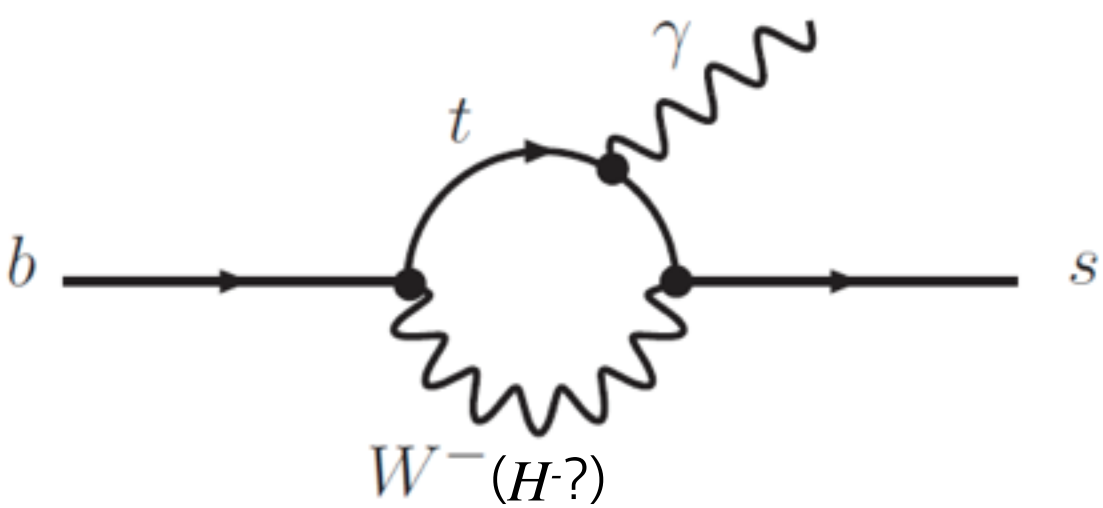
  - Search for $B_s^0 \to \gamma\gamma$ and $B_s^0 \to \phi\gamma$
  - Search for $B^0 \to \phi\gamma$
  - Semi-Inclusive $\mathcal{B}(b \to s\gamma)$
  - Inclusive $A_{CP}(b \to (s+d)\gamma)$

  >>New result at ***Belle***

  - Inclusive $b \to (s+d)\gamma$

Integrated Luminosity at *Belle*
711 fb^{-1} for $\Upsilon(4S)$
121 fb^{-1} for $\Upsilon(5S)$

Introduction to $b \to s\gamma$ decay



Electroweak penguin FCNC processes

highly suppressed in the tree level

H⁻ in 2HDM Type-II or SUSY squarks can enter the loop → BF, A_{CP}

Probe to New Physics

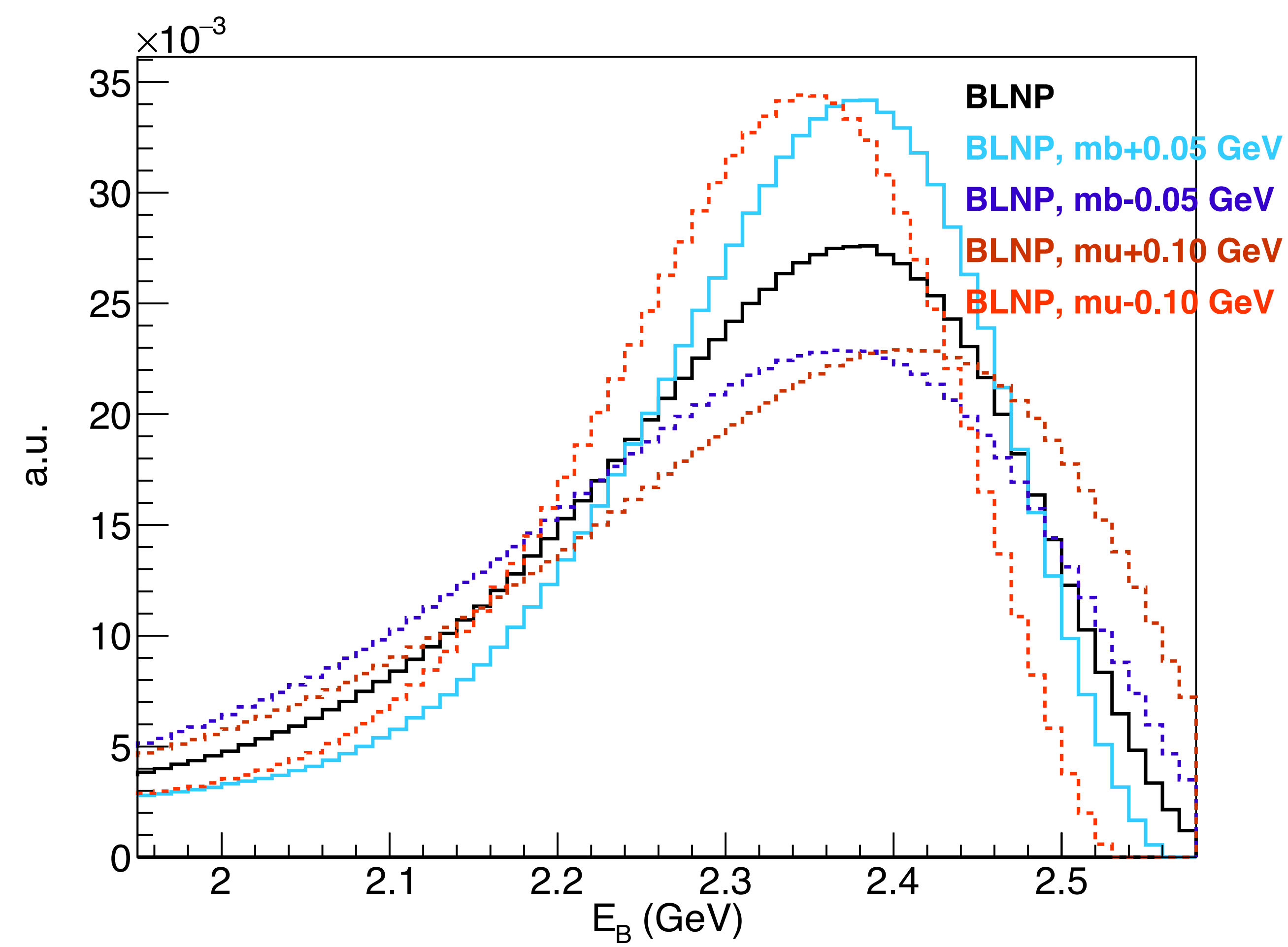
Inclusive spectrum described by m_b and μ_π^2

Significantly dependent on the parameters

Low cutoff necessary for a good prediction on the inclusive BF

$$E_\gamma^{cutoff} = 1.6 \text{ GeV}$$

Measured spectrum can be used to constrain HQE parameters ***Later in this talk!***



Introduction to $b \to s\gamma$ decay

Current SM ***NNLO BF*** [PRL 114, 221801, 2015]

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{NNLO}_{E_\gamma > 1.6GeV} = (3.36 \pm 0.23) \times 10^{-4}$$

HFAG 2016 / PDG 2015 Average

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6GeV} = (3.49 \pm 0.19) \times 10^{-4}$$

BF used to constrain the ***new physics parameters*** [arXiv:1412.7515]

$$M(H^-) > 480 \text{ GeV at } 95\% \text{ CL}$$

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

$$f = X_{s,d}\gamma$$

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

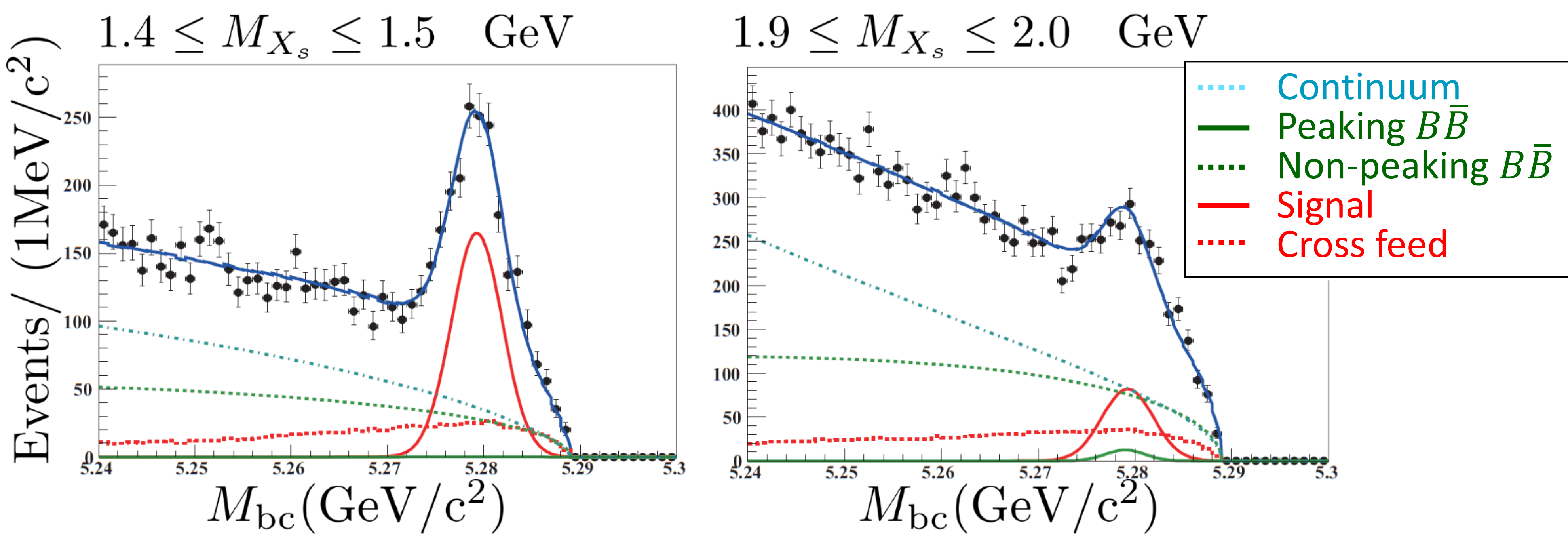
PRL 106, 141801 (2011)

Zero asymmetry predicted by SM for s+d
(cancellation due to CKM unitarity)

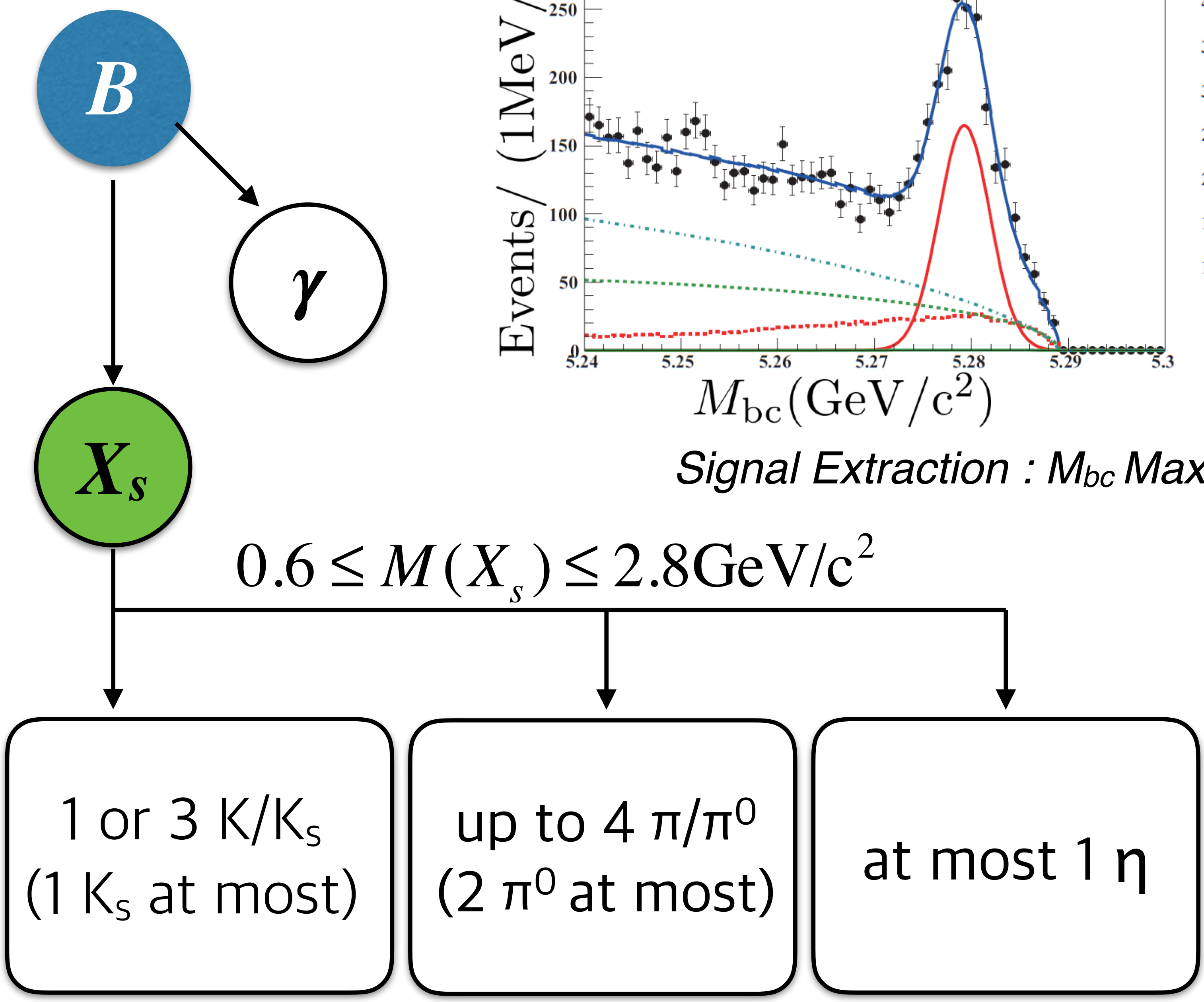
$$A_{CP}^{HFAG} = -0.008 \pm 0.029$$

$\mathcal{B}(\bar{B} \to X_s\gamma)$ with semi-inclusive method

T.Saito, A.ishikawa, H.Yamamoto, et al. (Belle Collaboration), published in PRD 91, 052004 (2015)



Signal Extraction : M_{bc} Maximum Likelihood fit on 19 $M(X_s)$ bins



In total 38 exclusive X_s states (**70% of total BF**)

- continuum suppressed by neural network trained with topological variables
- Peaking D background veto using invariant mass

$\mathcal{B}(\bar{B} \to X_s \gamma)$ with semi-inclusive method

T.Saito, A.ishikawa, H.Yamamoto, et al. (Belle Collaboration), published in PRD 91, 052004 (2015)

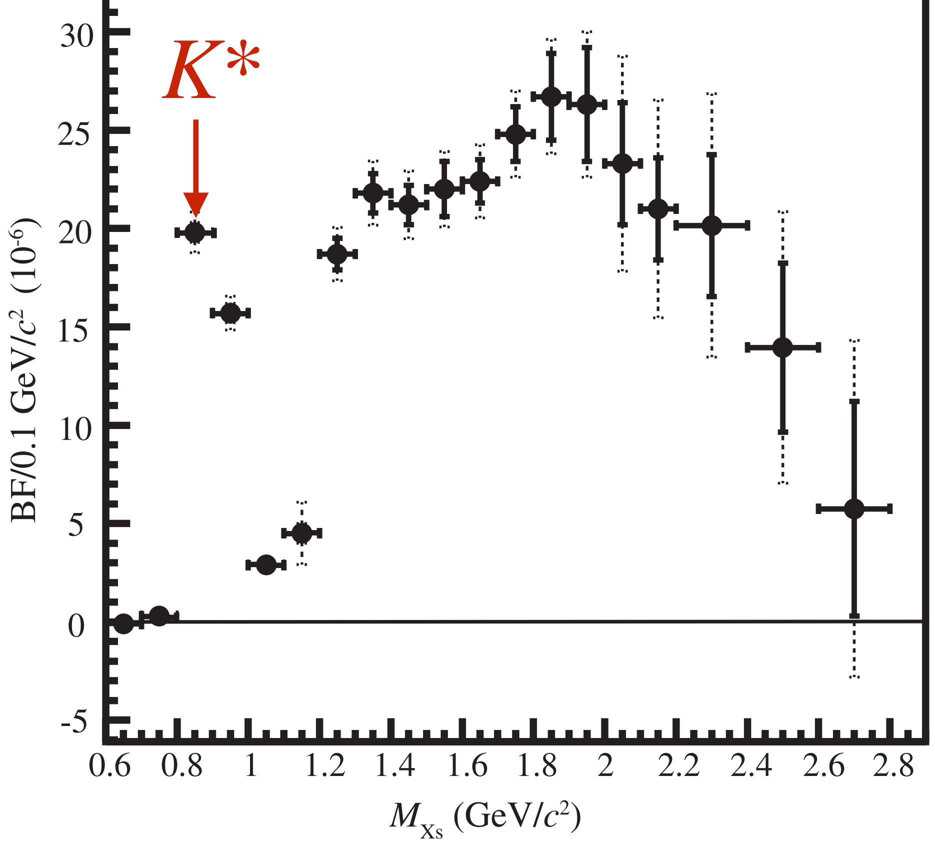
>> Result

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

- The largest systematic uncertainty is associated Hadronization Model (~7%)
- The most precise measurement ever implemented with this method

Source	Systematic uncertainty (%)
$B\bar{B}$ 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

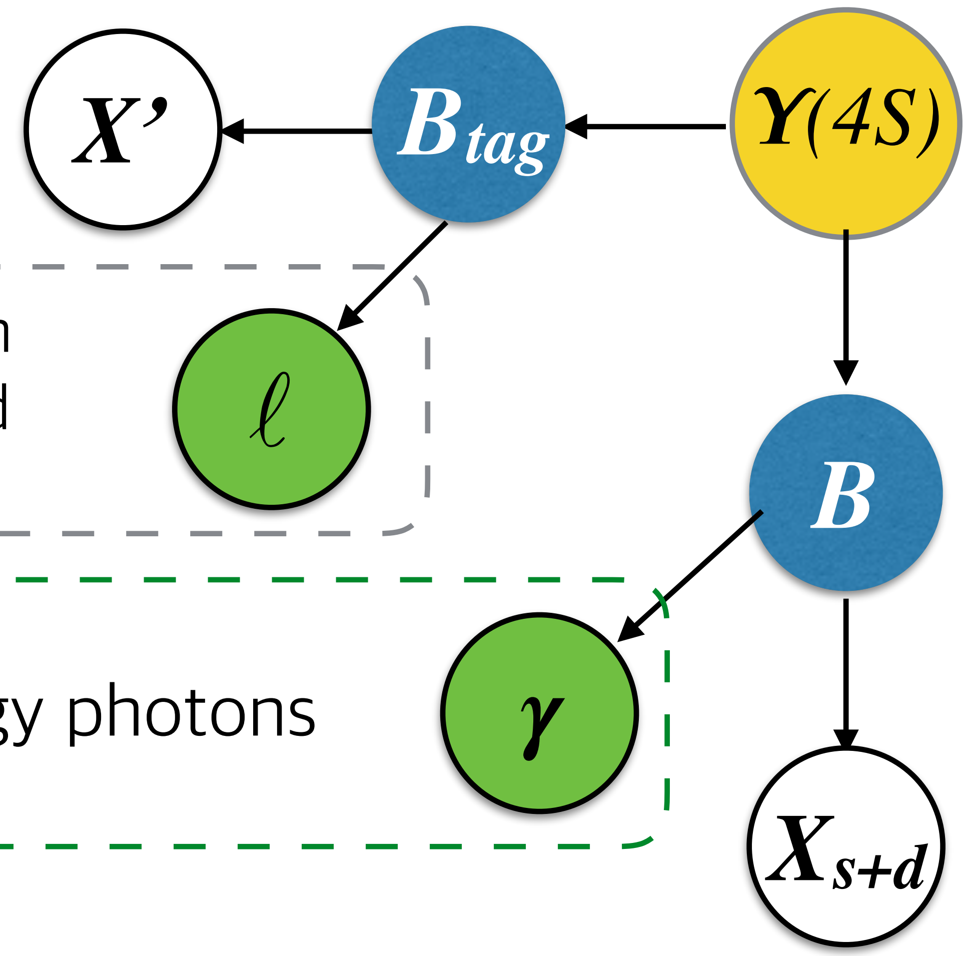
partial BF on M(X_S)



$\bar{B} \to X_{(s+d)}\gamma$ with inclusive method

L. Pesantez, P. Urquijo, J. Dingfelder, et al. (Belle Collaboration), published in PRL 114, 151601 (2015)

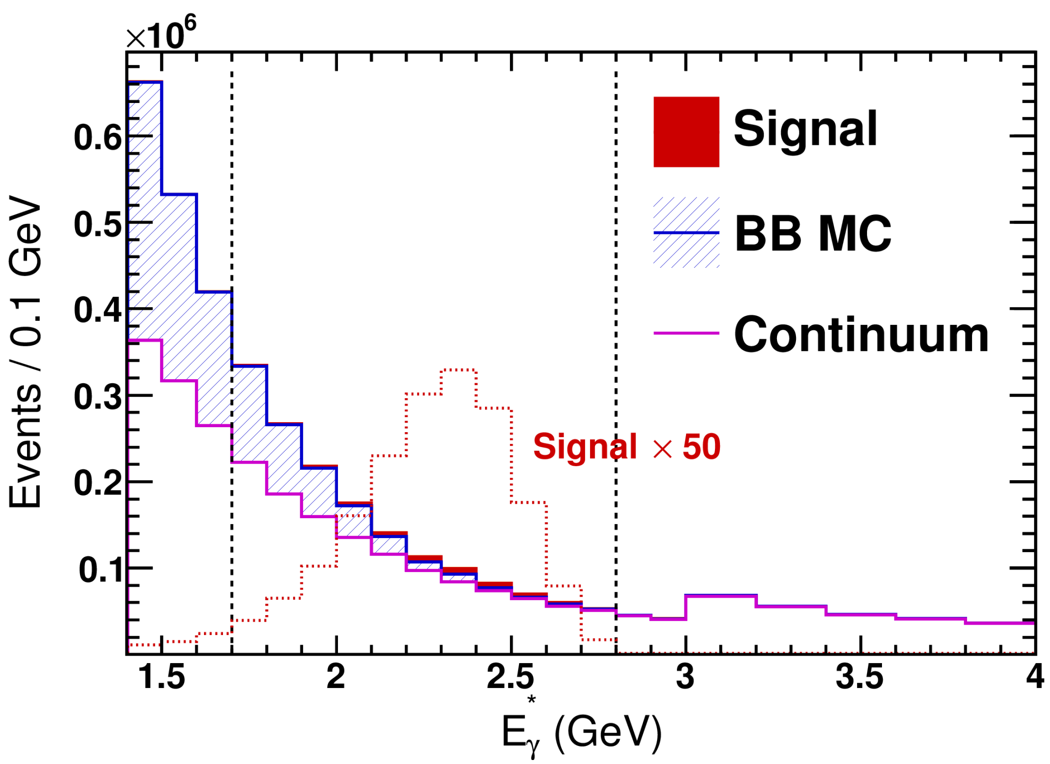
Full-inclusive Method with lepton tagging



High momentum lepton : Continuum suppression
B mesons flavor tagged

→ A_{CP} measurement

Inclusive measurement with high energy photons



Large contribution from π^0 and η

→calibrated using control sample

Large background suppressed by Multivariate analysis

Statistical limit from continuum subtraction

Inclusive $A_{CP}(\bar{B} \to X_{(s+d)}\gamma)$ with lepton tagging

L. Pesantez, P. Urquijo, J. Dingfelder, et al. (Belle Collaboration), published in PRL 114, 151601 (2015)

After bkg subtraction $A_{CP}^{meas} = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)}$

Corrected A_{CP}

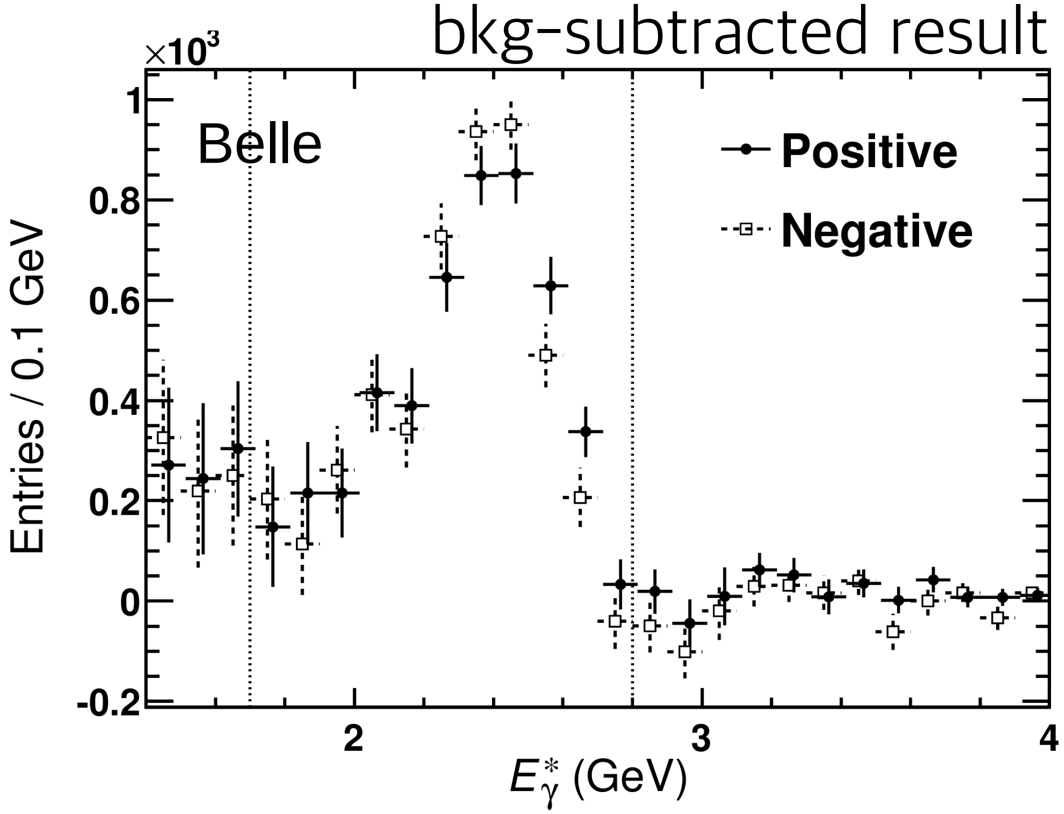
$$A_{CP}^{true} = \frac{1}{1-2\omega}(A_{CP}^{meas} - A_{bkg} - A_{\det})$$

Wrong tag factor ω : ~14% Oscillation, secondary, fakes

Bkg Asymmetry A_{bkg} : ~(0.0±0.7)% in E_γ < 1.7 GeV

Detector induced A_{det} : ~(0.0±0.3)% from $B \to XJ/\psi(\ell^+\ell^-)$

bkg-subtracted result



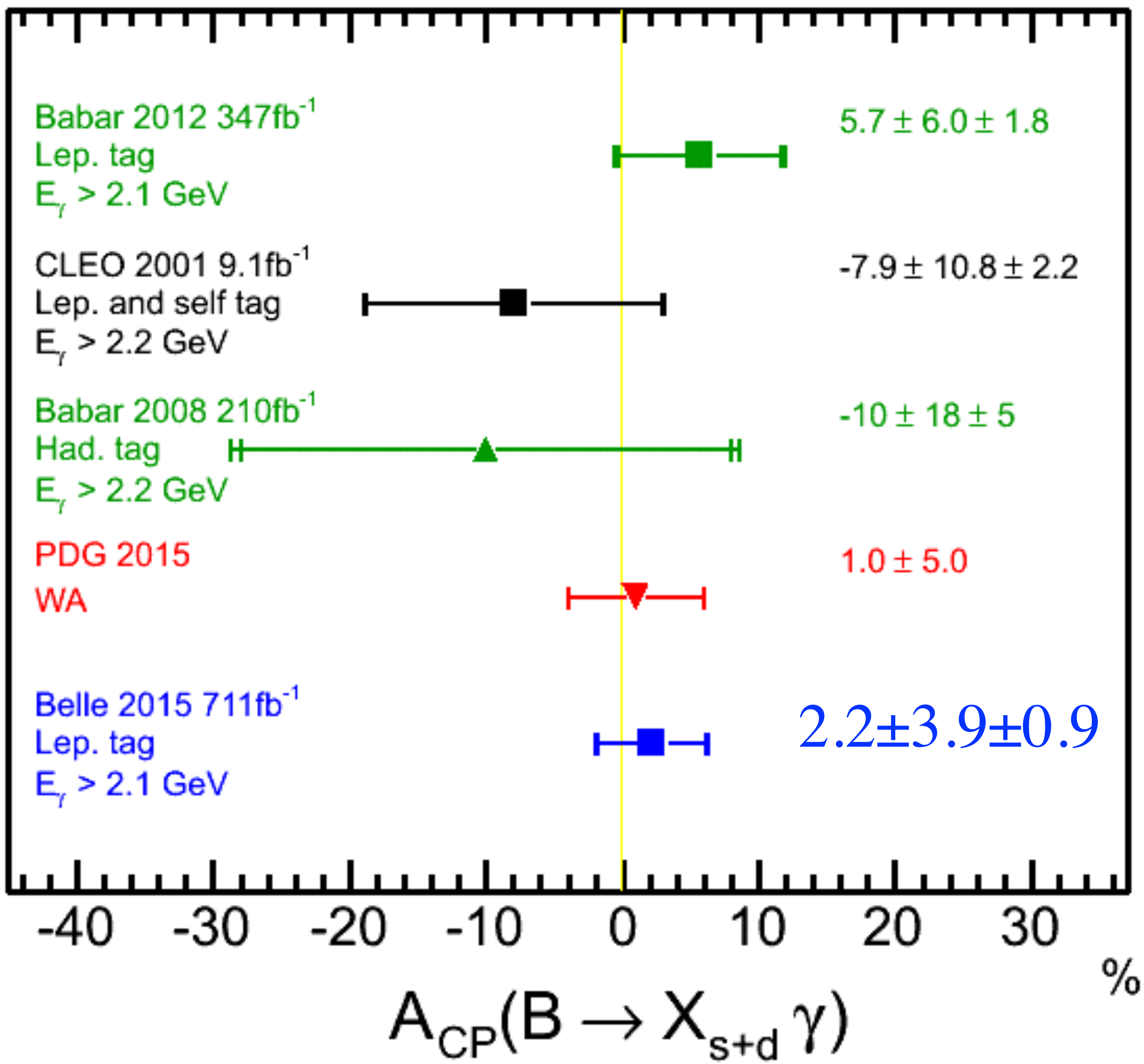
>> *Result*

$$A_{CP}(X_{s+d}\gamma) = (2.2 \pm 3.9_{stat} \pm 0.9_{syst})\%$$

$E^*_\gamma > 2.1$ GeV

The most precise measurement

Summary of Full-inclusive $A_{CP}(\bar{B} \to X_{(s+d)}\gamma)$



HQE parameters from $\bar{B} \to X_{(s+d)}\gamma$ with lepton tagging

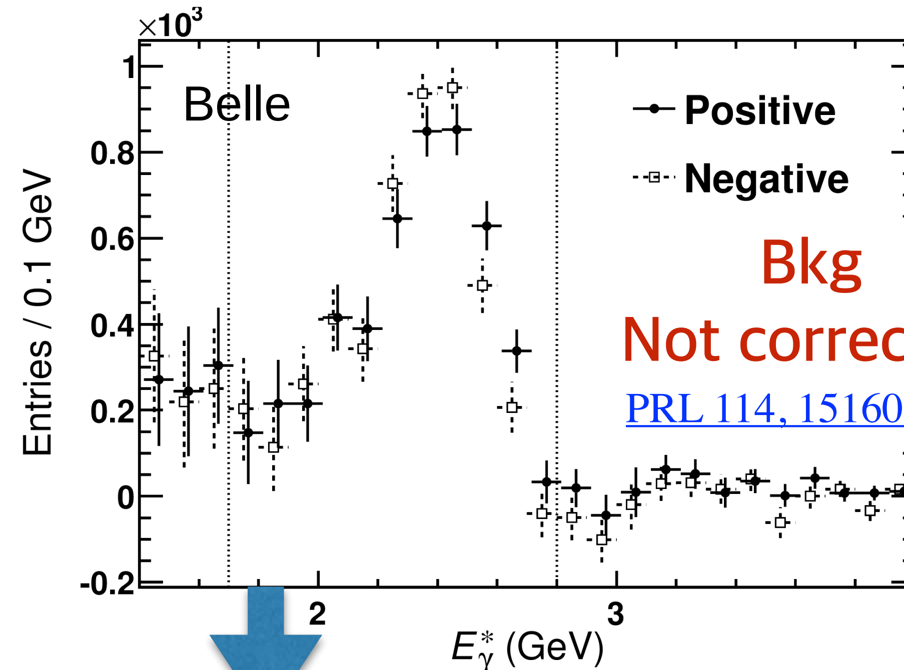
NEW Result!

BELLE-CONF-1606 [arXiv:1608.02344]

>> *Bkg-corrected spectrum*

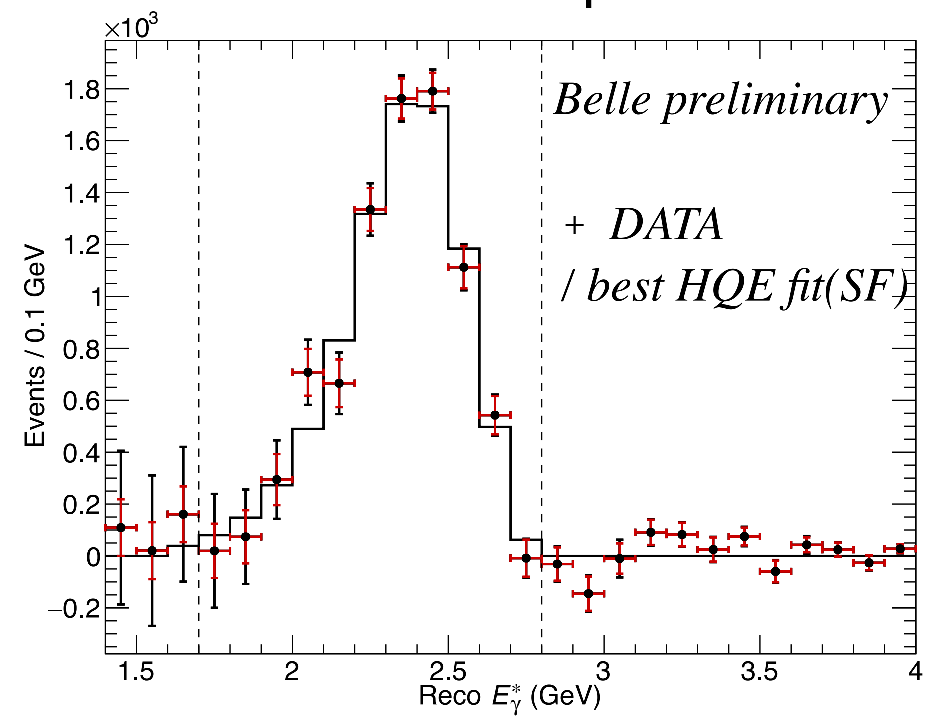
MC Bkg yields corrected with sideband events and control samples (π^0,η, mis-identified hadrons)

The largest systematic uncertainty is from bkg subtraction



Bkg Not corrected
PRL 114, 151601 (2015)

Corrected spectrum



Model-averaged selection efficiency ~2.5%

>> *HQE parameters measurement*

Theoretical spectrum folded :
(in BLNP-SF scheme [PRD 72, 073006 (2005)])

ECAL resolution
Doppler smearing (B-frame to CM-frame)

HQE parameters fitted to minimize χ^2 between the folded theoretical spectrum to the data spectrum.

HQE parameters from $\bar{B} \to X_{(s+d)}\gamma$ with lepton tagging

NEW Result!

BELLE-CONF-1606 [arXiv:1608.02344]

>> *HQE parameters fit result*

$$m_b(SF) = 4.626 \pm 0.028 \text{ GeV/c}^2$$

$$\mu_\pi^2(SF) = 0.301 \pm 0.063 \text{ GeV}^2$$

$$(\rho = -0.701)$$

***Belle** preliminary*

HFAG 2014

$$m_b(SF) = 4.569 \pm 0.023 \pm 0.018 \text{GeV/c}^2$$

$$\mu_\pi^2(SF) = 0.145 \pm 0.089^{+0.020}_{-0.040} \text{ GeV}^2$$

$$(\rho = -0.311)$$

→ ***Good precisions achieved!***

For example, PRD 72, 073006 (2005)
these values may be used to obtain $|V_{ub}|$ in BLNP-SF scheme lowering it by ~6%(3%) for endpoint analysis with E_{lepton}>2.0(1.0) GeV, compared to the HFAG2014 value : $|V_{ub}|^{HFAG}_{BLNP-SF} = (4.45 \pm 0.15^{+0.20}_{-0.21}) \times 10^{-3}$

>> *Moments of the spectrum*

***Belle** preliminary*

Threshold	Mean (GeV)	Variance×10² (GeV²)
1.8	$2.320 \pm 0.034 \pm 0.110 \pm 0.003$	$4.258 \pm 1.118 \pm 3.612 \pm 0.108$
1.9	$2.338 \pm 0.022 \pm 0.046 \pm 0.003$	$3.563 \pm 0.530 \pm 1.156 \pm 0.065$
2.0	$2.360 \pm 0.015 \pm 0.021 \pm 0.003$	$2.869 \pm 0.290 \pm 0.379 \pm 0.047$

Inclusive $\mathcal{B}(\bar{B} \to X_{(s+d)}\gamma)$ with lepton tagging

NEW Result!

BELLE-CONF-1606 [arXiv:1608.02344]

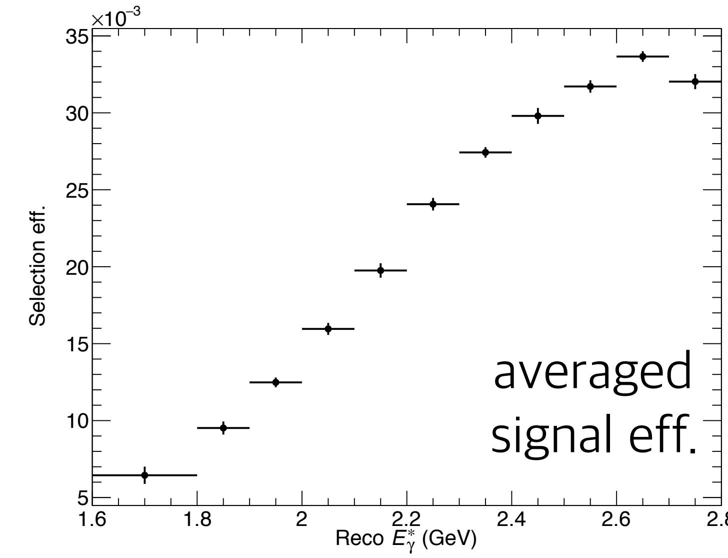
Detector resolution effect unfolded by SVD method

Signal efficiency obtained in average of 3 signal models

Threshold $E^*_\gamma > 1.8$ GeV chosen for the best result

Interpolation factors obtained using all three models

$b \to d\gamma$ is subtracted using $|V_{td}/V_{ts}|^2 \sim 4\%$



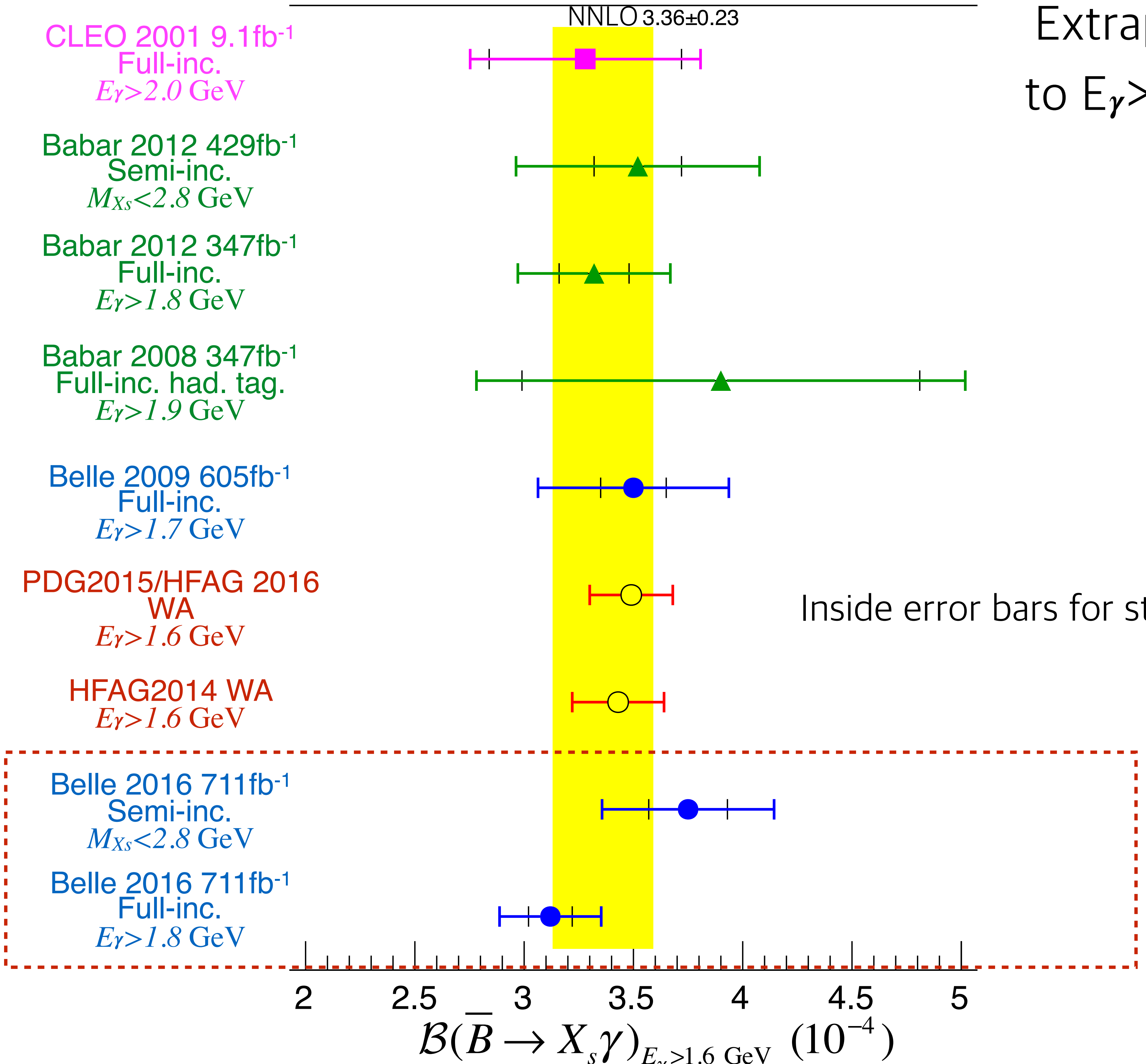
Belle preliminary **Results**

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6GeV} = (3.12 \pm 0.10_{\text{stat}} \pm 0.19_{\text{syst}} \pm 0.08_{\text{model}}) \times 10^{-4}$$

With different thresholds :

Threshold	$\mathcal{B}(\bar{B} \to X_s\gamma)$ (10^{-4})
1.7 GeV	$3.07 \pm 0.11 \pm 0.24 \pm 0.09$
1.8 GeV	$3.02 \pm 0.10 \pm 0.18 \pm 0.08$
1.9 GeV	$2.95 \pm 0.09 \pm 0.14 \pm 0.07$

Summary of $\mathcal{B}(\bar{B} \to X_{(s+d)}\gamma)$



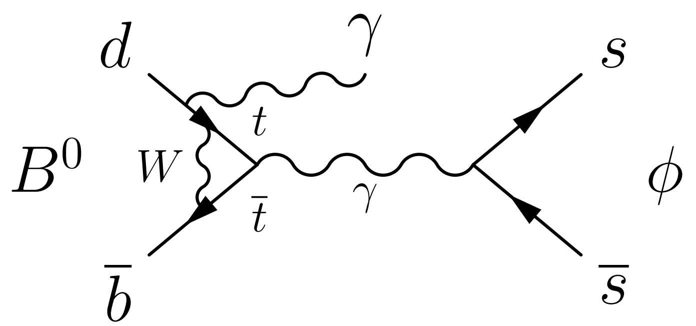
Extrapolated to E_γ>1.6 GeV

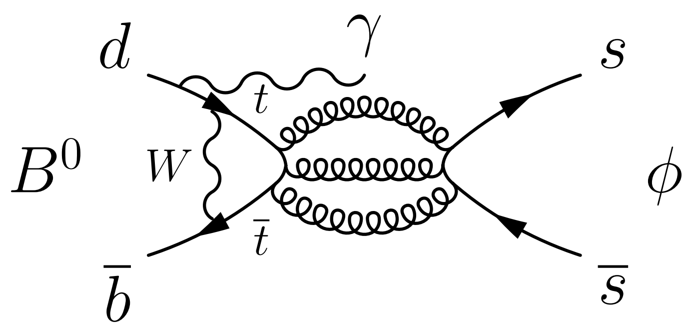
Inside error bars for stat. uncertainties

$\mathcal{B}(B^0 \to \phi\gamma)$ / $\mathcal{B}(B_s^0 \to \phi\gamma)$ & $\mathcal{B}(B_s^0 \to \gamma\gamma)$

D.Dutta, B.Bhuyan, et al. (Belle Collaboration), published in PRD 91, 011101(R) (2015)

Z.King, B.Pal, A.J.Schwartz, et al. (Belle Collaboration), published in PRD 93, 111101 (2016)



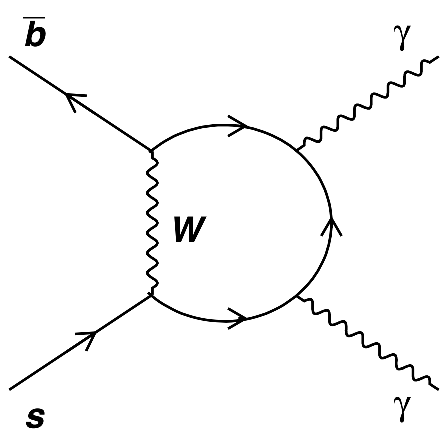


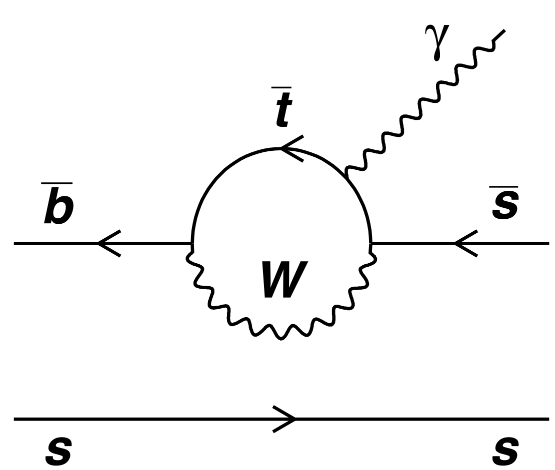
No evidence for $B^0 \to \phi\gamma$ decay, setting its upper limit for BF :

the most stringent limit on BF

$$\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7} \quad \text{at 90\% C.L.}$$

SM Prediction : $O(10^{-11 \sim -12})$





SM prediction:

$$\mathcal{B}(B_s^0 \to \phi\gamma) \approx 4 \times 10^{-5}$$
$$\mathcal{B}(B_s^0 \to \gamma\gamma) \approx (0.5 - 1.0 \times 10^{-6})$$

In R-parity violating (RPV),

BF of $b \to s\gamma\gamma$ can be enhanced significantly

$$\mathcal{B}(B_s^0 \to \phi\gamma) = (3.6 \pm 0.5_{stat} \pm 0.3_{syst} \pm 0.6(f_s)) \times 10^{-5}$$

$$\mathcal{B}(B_s^0 \to \gamma\gamma) < 3.1 \times 10^{-6} \quad \text{at 90\% C.L.}$$

the most stringent limit on BF

Summary

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

$\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7}$

$\mathcal{B}(B_s^0 \to \phi\gamma) = (3.6 \pm 0.4) \times 10^{-5}$

$\mathcal{B}(B_s^0 \to \gamma\gamma) < 8.7 \times 10^{-6}$

- Semi-inclusive $b \to s\gamma$

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

- Inclusive $b \to s\gamma$ with lepton tagging

$A_{CP}(X_{s+d}\gamma) = (2.2 \pm 3.9_{stat} \pm 0.9_{syst})\%$ $\quad E_\gamma^* > 2.1\ \mathrm{GeV}$ *The most precise measurement!*

NEW Result!

$\mathcal{B}(\overline{B} \to X_s\gamma)_{E_\gamma > 1.6 GeV} = (3.12 \pm 0.10_{\mathrm{stat}} \pm 0.19_{\mathrm{syst}} \pm 0.08_{\mathrm{model}}) \times 10^{-4}$

$m_b(SF) = 4.626 \pm 0.028\ \mathrm{GeV/c^2}$

$\mu_\pi^2(SF) = 0.301 \pm 0.063\ \mathrm{GeV}^2 \quad (\rho = -0.701)$

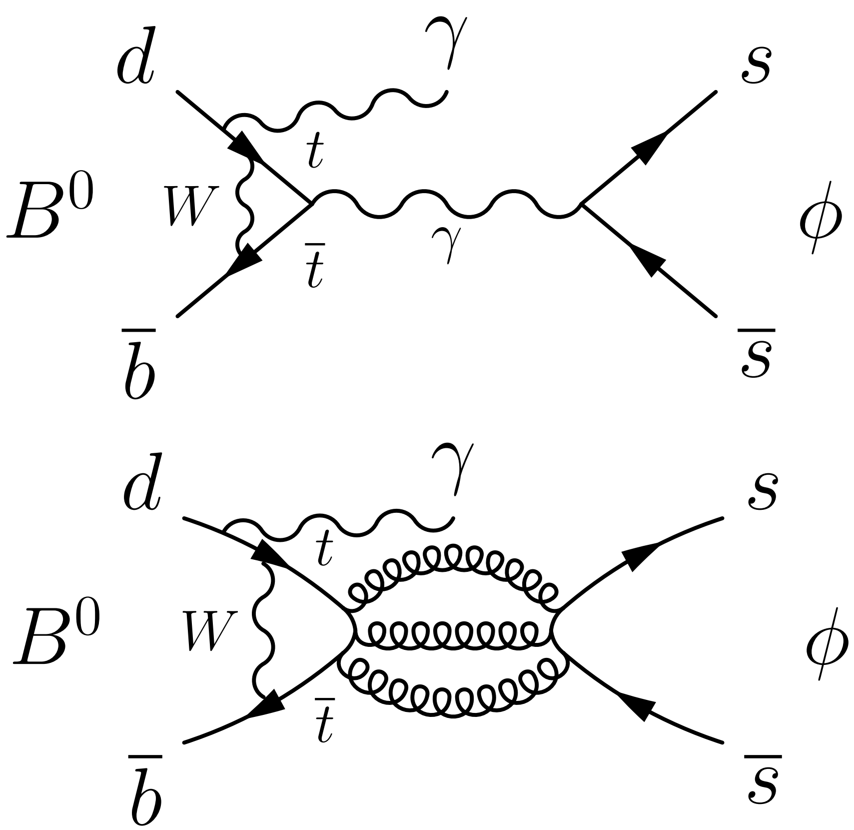
The most precise measurements!

BELLE

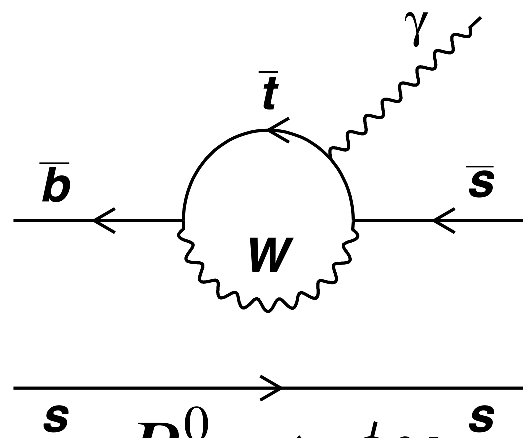
BACKUP

Feynman Diagrams

$b \to d$ annihilation

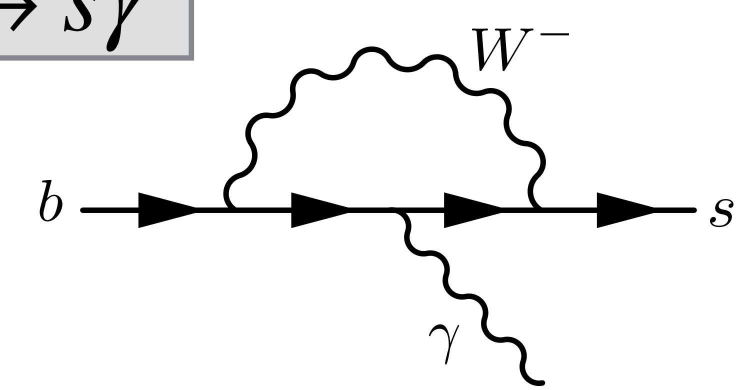


$B^0 \to \phi\gamma$



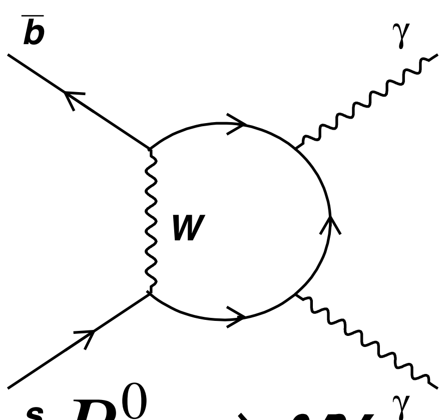
$B_s^0 \to \phi\gamma$

$b \to s\gamma$



$B \to X_s\gamma$

$b \to s\gamma\gamma$



$B_s^0 \to \gamma\gamma$

Observables:

BF, A_{CP}, Δ_{+-}...

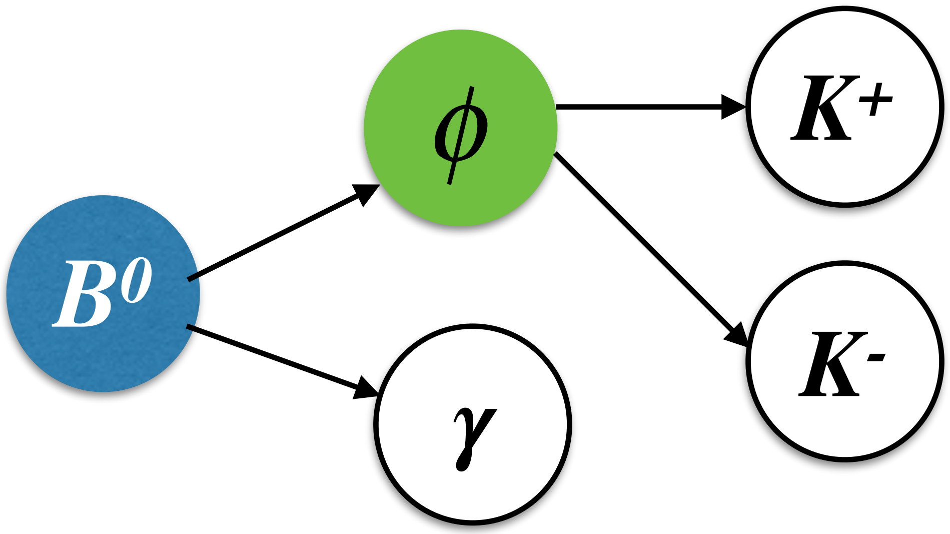
Integrated Luminosity at *Belle*
711 fb^{-1} for Υ(4S)
121 fb^{-1} for Υ(5S)

Electroweak penguin processes highly suppressed in SM corresponding to V_{td}/V_{ts} in CKM matrix
W$^-$ may be replaced with 2HDM H− or SSM squarks

Probe to New Physics

Search for $B^0 \to \phi\gamma$

Z.King, B.Pal, A.J.Schwartz, et al. (Belle Collaboration), published in PRD93, 111101 (2016 June 20)



Event Reconstruction

- ϕ reconstructed via $\phi \to K^+K^-$
- Candidate photon lying in [2.0,2.8] GeV

Background suppression

$\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ >> 50% of them suppressed with likelihoods based on invariant mass

continuum suppression >> Neural Network trained with event topology variables suppressing 89% of qq while retaining 85% of signal

Background composition

- continuum events
- rare charmless b-decays
- a negligible contribution from $b \to c$ process

Search for $B^0 \to \phi\gamma$

Z.King, B.Pal, A.J.Schwartz, et al. (Belle Collaboration), published in PRD93, 111101 (2016 June 20)

Systematic uncertainty

Source	Uncertainty (events)
PDF parameterization	${}^{+1.21}_{-1.14}$
Fit bias	${}^{+0.00}_{-0.08}$
C_{NN} selection efficiency	0.03
C_{NN} background sample	0.02
Tracking efficiency	0.02
PID efficiency	0.05
Photon reconstruction	0.08
MC statistics	0.01
$\mathcal{B}(\phi \to K^+K^-)$	0.03
Number of $B\overline{B}$ events	0.05
Total	${}^{+1.22}_{-1.15}$

Largest uncertainty from fixed PDF parameters

Fitting bias estimated from MC ensembles

Result

No evidence for $B^0 \to \phi\gamma$ decay, setting its upper limit for BF :

$$\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7}$$

at 90% C.L.

previous upper limit(*) : $\mathcal{B}(B^0 \to \phi\gamma) < 8.5 \times 10^{-7}$

(*) B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 72, 091103 (2005)

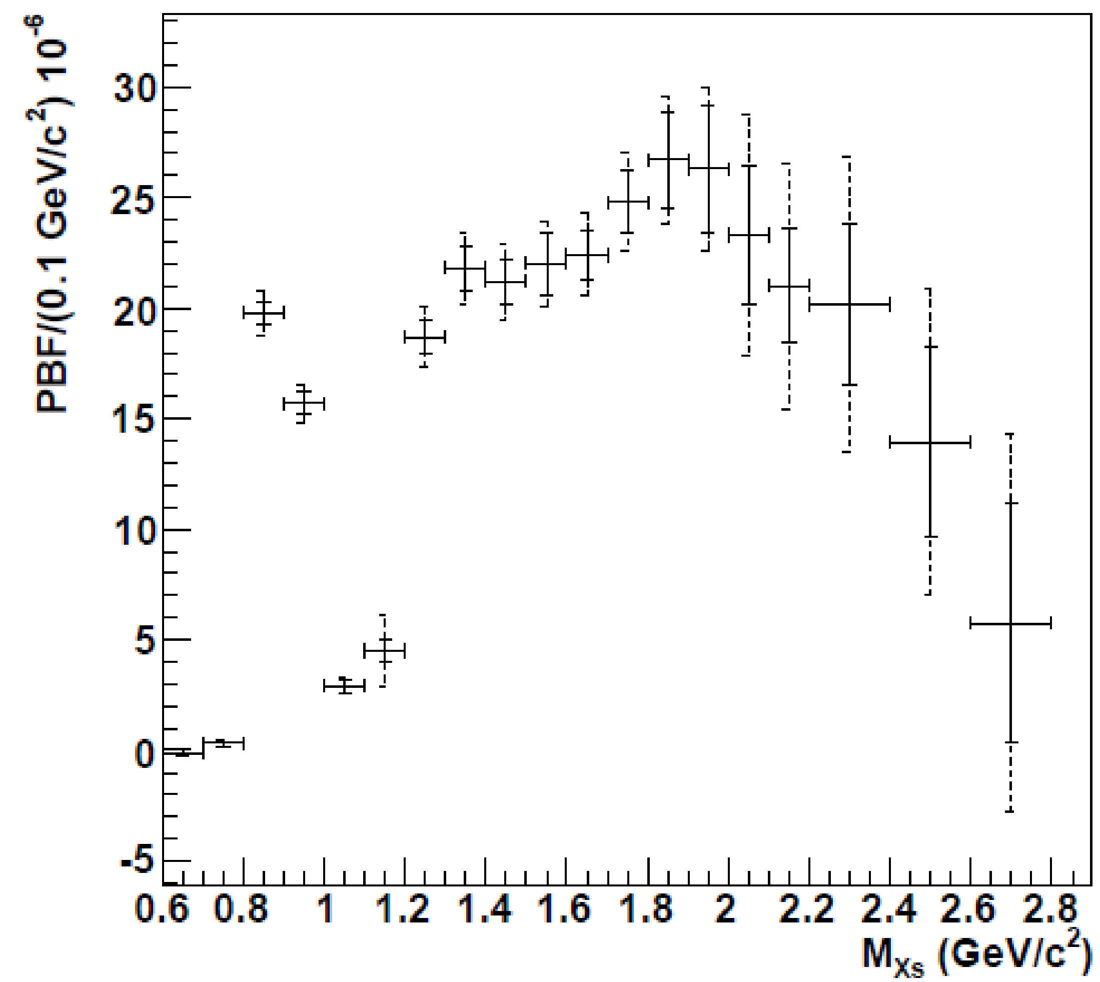
Reconstructed modes

Mode ID	Final state	Mode ID	Final state	Mode ID	Final state
1	$K^+\pi^-$	16	$K_s\pi^+\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
2	$K_s\pi^+$	17	$K^+\pi^0\pi^0$	32	$K_s\eta\pi^+\pi^0$
3	$K^+\pi^0$	18	$K_s\pi^0\pi^0$	33	KKK
4	$K_s\pi^0$	19	$K^+\pi^-\pi^0\pi^0$	34	KKK_s
5	$K^+\pi^+\pi^-$	20	$K_s\pi^+\pi^0\pi^0$	35	KK_sK_s
6	$K_s\pi^+\pi^-$	21	$K^+\pi^+\pi^-\pi^0\pi^0$	36	$K^+K^+K^-\pi^-$
7	$K^+\pi^+\pi^0$	22	$K_s\pi^+\pi^-\pi^0\pi^0$	37	$K^+K^-K_s\pi^+$
8	$K_s\pi^+\pi^0$	23	$K^+\eta$	38	$K^+K^+K^-\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	24	$K_s\eta$		
10	$K_s\pi^+\pi^+\pi^-$	25	$K^+\eta\pi^-$		
11	$K_s\pi^+\pi^0$	26	$K_s\eta\pi^+$		
12	$K_s\pi^+\pi^0$	27	$K^+\eta\pi^0$		
13	$K^+\pi^+\pi^+\pi^-\pi^-$	28	$K_s\eta\pi^0$		
14	$K_s\pi^+\pi^+\pi^-\pi^-$	29	$K^+\eta\pi^+\pi^-$		
15	$K_s\pi^+\pi^+\pi^-\pi^0$	30	$K_s\eta\pi^+\pi^-$		

Partial BF (semi-inclusive)

Table 9.12: The partial branching ratio on M_{X_s}

M_{X_s} bin(GeV/c^2)	$\mathcal{BR}(10^{-6})$
0.6-0.7	-0.1±0.1±0.0
0.7-0.8	0.3±0.1±0.1
0.8-0.9	19.8±0.5±0.9
0.9-1.0	15.7±0.5±0.7
1.0-1.1	2.9±0.3±0.2
1.1-1.2	4.8±0.5±1.5
1.2-1.3	18.7±0.8±1.1
1.3-1.4	21.8±1.0±1.3
1.4-1.5	21.2±1.0±1.4
1.5-1.6	22.0±1.4±1.3
1.6-1.7	22.4±1.1±1.5
1.7-1.8	24.8±1.4±1.7
1.8-1.9	26.7±2.2±1.9
1.9-2.0	26.3±2.9±2.3
2.0-2.1	23.3±3.1±4.5
2.1-2.2	21.0±2.6±4.9
2.2-2.4	40.3±7.2±11
2.4-2.6	27.9±8.6±11
2.6-2.8	11.5±11±13



(a) Partial branching ratio.The first solid error is the statistical one and the second dashed error is a quadratic sum of the statistical and systematic errors.

Partial BF (full-inclusive)

E_γ^* bin	PBF	Stat	Syst	Model	
1.6-1.8	12.3	735.4	243.0	693.9	18.5
1.8-1.9	11.6	441.2	135.0	419.9	10.9
1.9-2.0	16.7	166.7	64.5	153.6	6.1
2.0-2.1	24.2	57.2	39.5	41.1	4.5
2.1-2.2	34.7	31.1	23.4	20.0	4.7
2.2-2.3	47.6	18.6	14.8	10.6	3.9
2.3-2.4	61.1	12.3	10.5	5.6	3.0
2.4-2.5	63.1	10.8	8.8	5.0	3.7
2.5-2.6	43.7	12.4	10.9	5.4	2.6
2.6-2.7	20.1	22.3	20.2	9.3	2.6

TABLE III. Partial branching fractions of the $\bar{B} \to X_{s+d}\gamma$ spectrum and uncertainties, in units of 10^{-6}.

Inclusive $\mathcal{B}(\bar{B} \to X_{(s+d)}\gamma)$ with lepton tagging

NEW Result!

REFERNCE

>> *BF measurement*

Before extrapolation

Belle *preliminary*

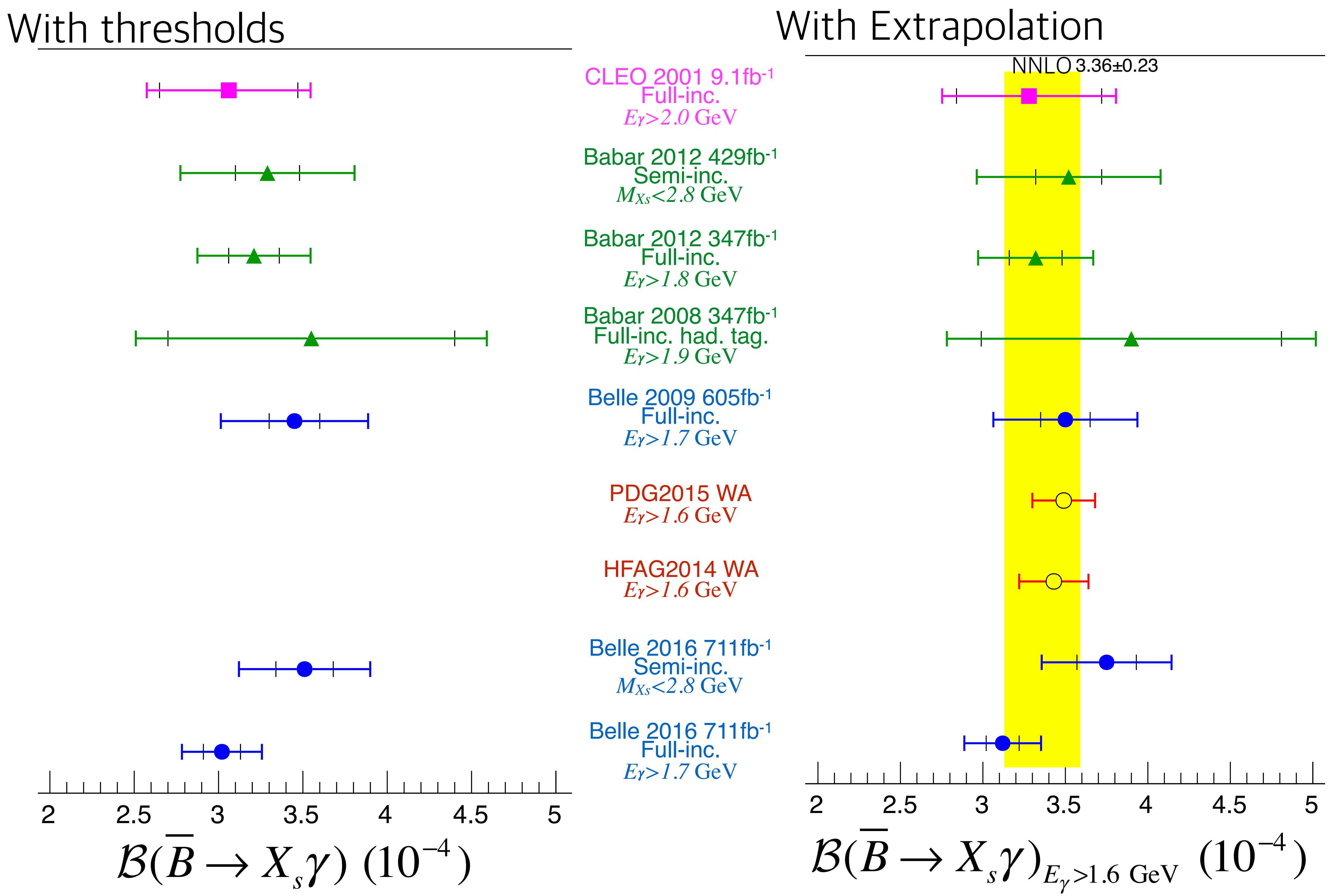
Threshold	$\mathcal{B}(\bar{B} \to X_{(s+d)}\gamma)$ (10^{-4})	$\mathcal{B}(\bar{B} \to X_s\gamma)$ (10^{-4})
1.7 GeV	$3.21 \pm 0.11 \pm 0.25 \pm 0.10$	$3.07 \pm 0.11 \pm 0.24 \pm 0.09$
1.8 GeV	$3.16 \pm 0.10 \pm 0.19 \pm 0.08$	$3.02 \pm 0.10 \pm 0.18 \pm 0.08$
1.9 GeV	$3.08 \pm 0.09 \pm 0.15 \pm 0.07$	$2.95 \pm 0.09 \pm 0.14 \pm 0.07$
2.0 GeV	$2.92 \pm 0.08 \pm 0.12 \pm 0.05$	$2.79 \pm 0.08 \pm 0.11 \pm 0.05$

BF thresholds (full-inclusive)

Threshold	Selection eff. (%)	Conversion factor	$\mathcal{B}_{s+d\gamma}$	$\mathcal{B}_{s\gamma}$
1.7 GeV	2.392 ± 0.070	1.0135 ± 0.0024	$3.21 \pm 0.11 \pm 0.25 \pm 0.10$	$3.07 \pm 0.11 \pm 0.24 \pm 0.09$
1.8 GeV	2.442 ± 0.059	1.0216 ± 0.0031	$3.16 \pm 0.10 \pm 0.19 \pm 0.08$	$3.02 \pm 0.10 \pm 0.18 \pm 0.08$
1.9 GeV	2.508 ± 0.055	1.0334 ± 0.0039	$3.08 \pm 0.09 \pm 0.15 \pm 0.07$	$2.95 \pm 0.09 \pm 0.14 \pm 0.07$
2.0 GeV	2.595 ± 0.045	1.0526 ± 0.0046	$2.92 \pm 0.08 \pm 0.12 \pm 0.05$	$2.79 \pm 0.08 \pm 0.11 \pm 0.05$

TABLE I. Inclusive $\bar{B} \to X_{s+d}\gamma$ and $\bar{B} \to X_s\gamma$ branching fractions for different energy thresholds up to 2.8 GeV, in units of 10^{-4}. The uncertainties are statistical, systematic and from the modeling.

Summary of $\mathcal{B}(\bar{B} \to X_{(s+d)}\gamma)$



Summary of $\mathcal{B}(\overline{B} \to X_{(s+d)}\gamma)$