Inclusive Radiative B meson decays at Belle

$b \to s\gamma$

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1. Introduction
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   - method
   - background treatment
   - corrected spectra
3. Results
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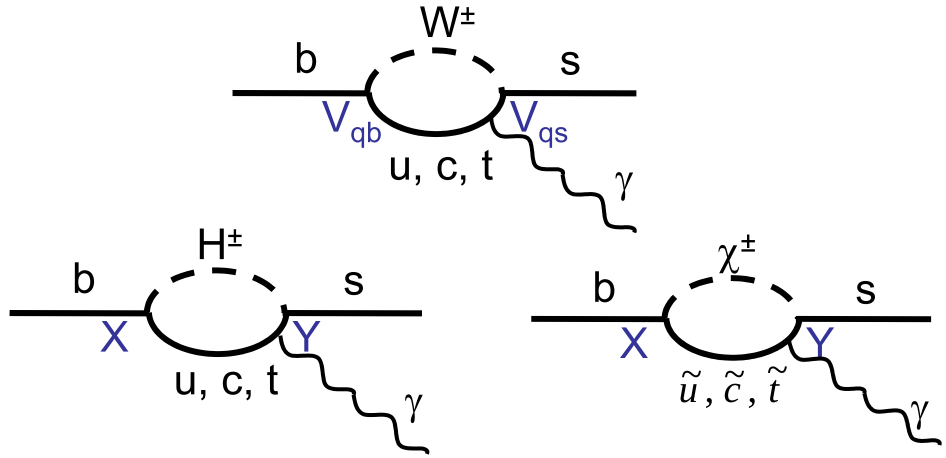
Introduction

Motivation

FCNC process;
sensitive to NP in loop;



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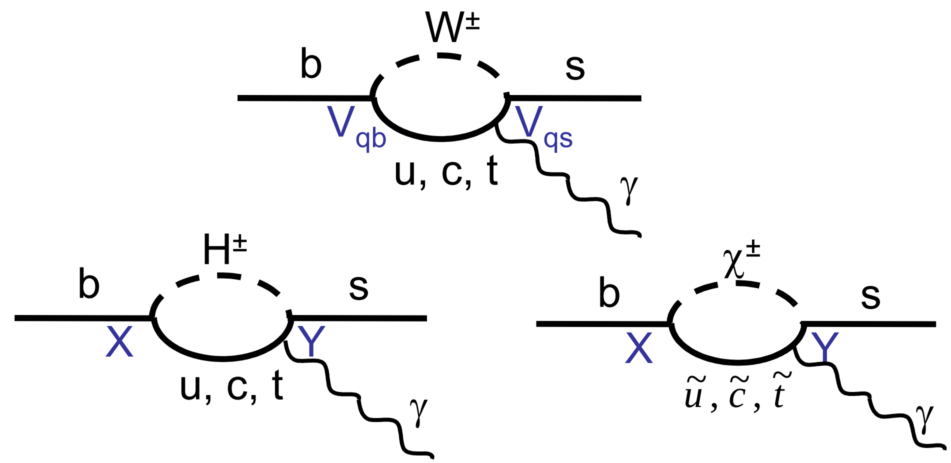

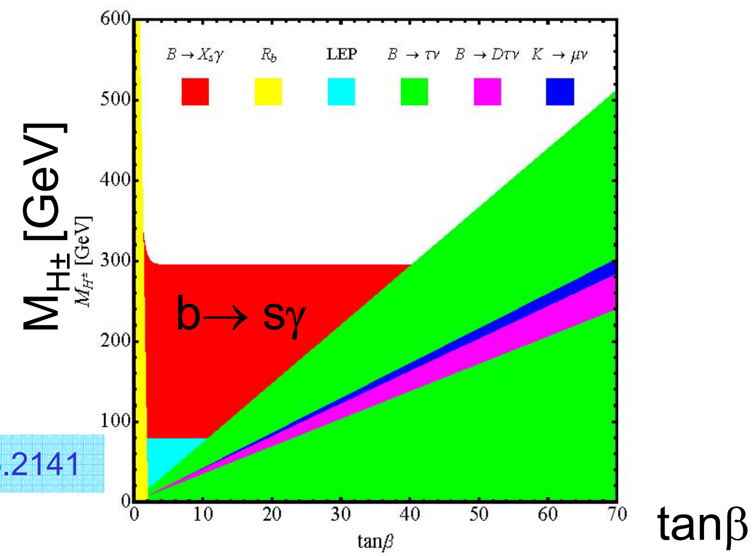

U. Haisch, arXiv:0805.2141

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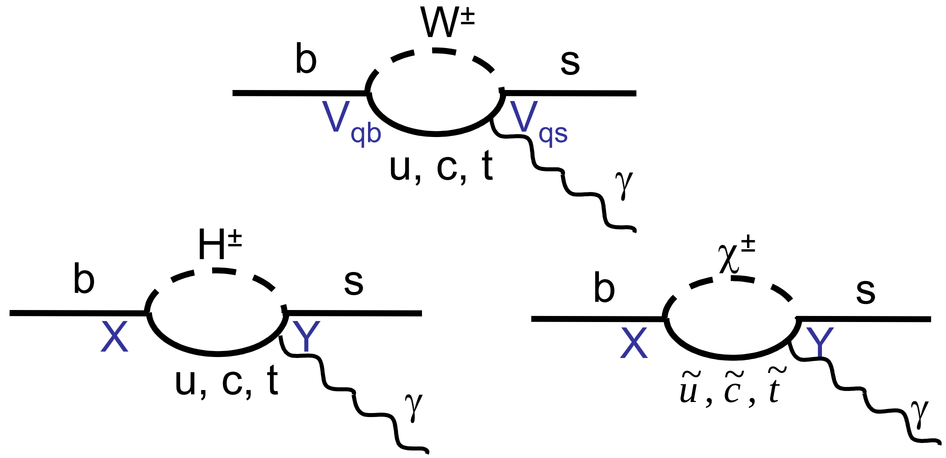

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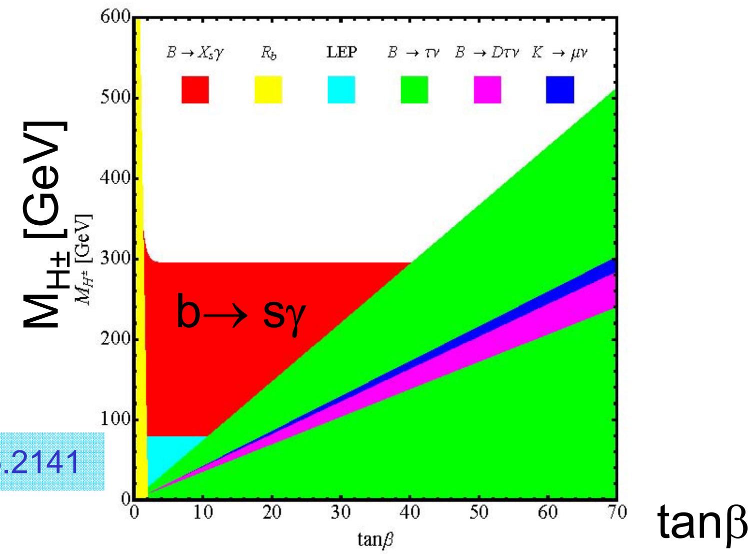


also

parton level: $E_\gamma \approx m_b/2$;
$d\Gamma/dE_\gamma \to$ determ. of m_b, Fermi motion (μ_π^2) $\to V_{ub}, V_{cb}$

$$\Gamma(b \to c(u)\ell\nu) = f(\underbrace{m_b, m_c}_{O(1)}, \underbrace{\mu_\pi, \mu_G}_{O(1/m_b^2)}, \underbrace{\rho_D, \rho_{LS}}_{O(1/m_b^3)})$$

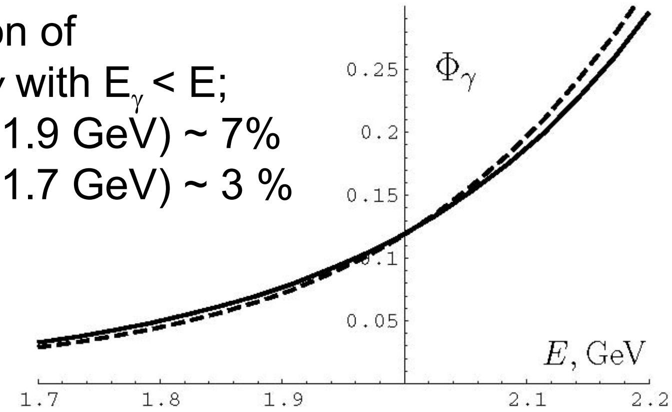
$$\frac{d\Gamma(b \to s\gamma)}{dE_\gamma} = g(m_b, m_c, \mu_\pi, \mu_G, \rho_D, \rho_{LS})$$

Introduction

I. Bigi, N. Uraltsev, Int.J.Mod.Phys. A17, 4709 (2002)

Difficulties

fraction of
$b \to s\gamma$ with $E_\gamma < E$;
$\Phi_\gamma(E=1.9\ \text{GeV}) \sim 7\%$
$\Phi_\gamma(E=1.7\ \text{GeV}) \sim 3\ \%$



theory:
parameter extraction from partial $Br(E_\gamma > E_{cut}) \to$ extrapolation needed;

I. Bigi, N. Uraltsev, Int.J.Mod.Phys. A17, 4709 (2002)

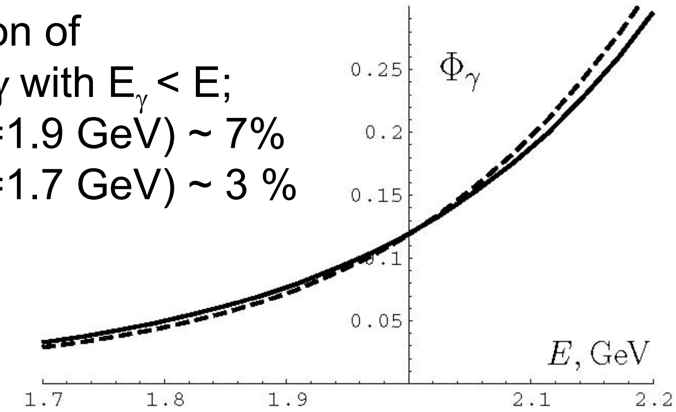
Introduction

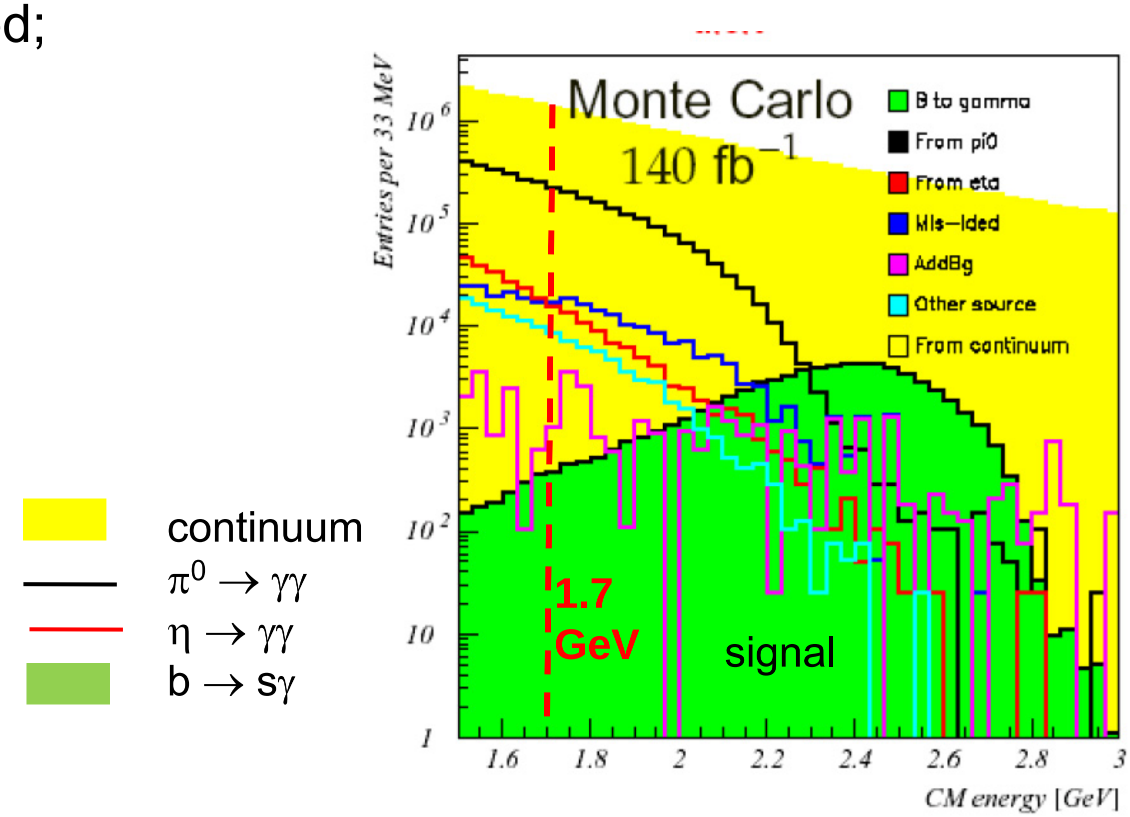
Difficulties

theory:
- parameter extraction from partial Br(E_γ>E_{cut}) $\rightarrow$ extrapolation needed;

experiment:
- measure low E_γ $\rightarrow$ huge bkg.

fraction of
$b \rightarrow s\gamma$ with $E_\gamma < E$;
Φ_γ(E=1.9 GeV) ~ 7%
Φ_γ(E=1.7 GeV) ~ 3 %





Measurement

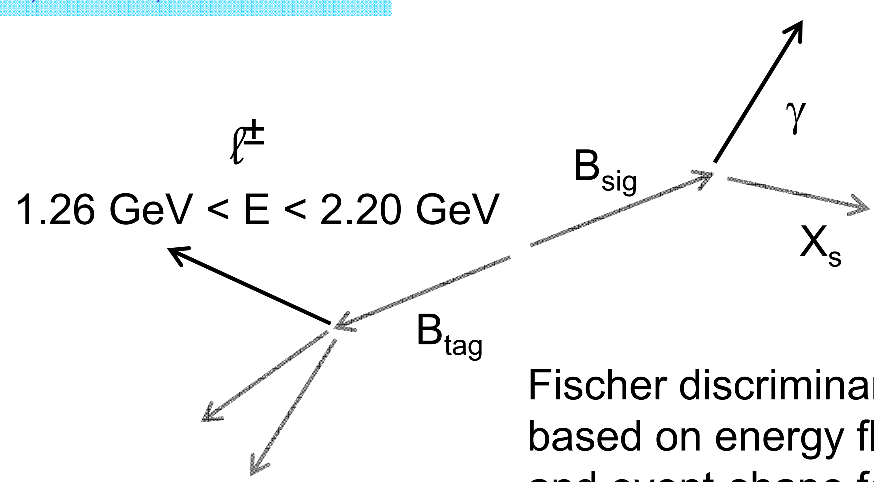
Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

Inclusive measurement

only γ on signal side reconstructed;

two samples: tagged/untagged;

similar sensitivity,
largely stat. independent, profit from combination



Fischer discriminant based on energy flow and event-shape for continuum supp.

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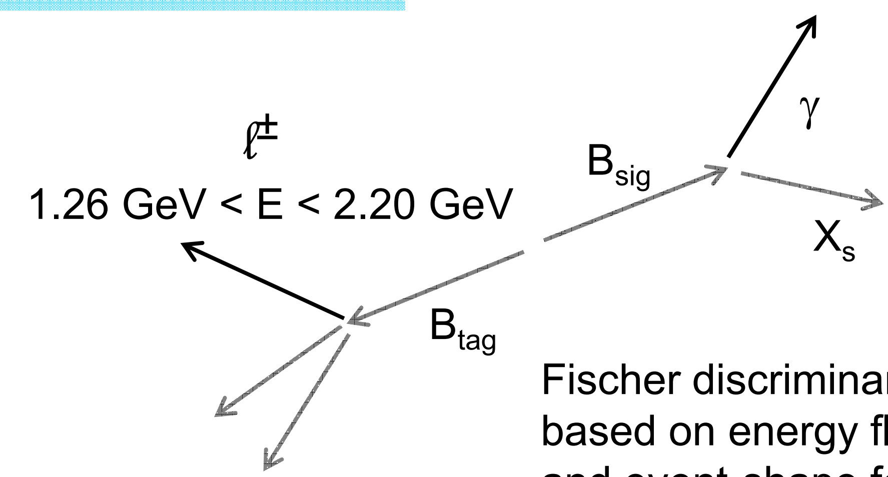
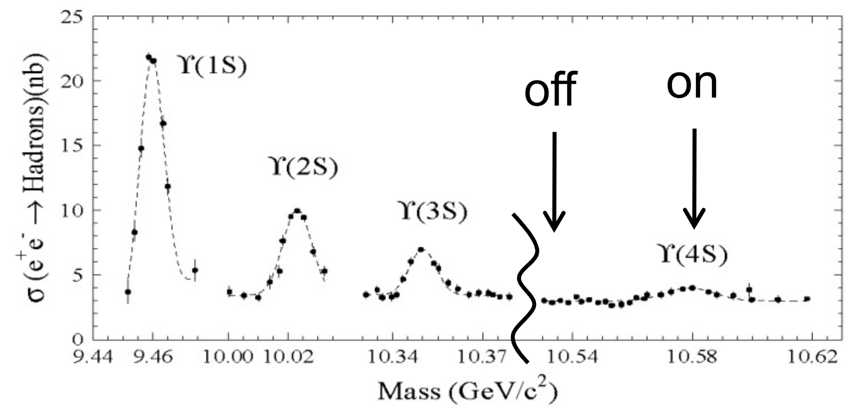


Fischer discriminant based on energy flow and event-shape for continuum supp.

Background treatment

subtract luminosity scaled E_γ distribution for off-data from on-data (continuum bkg.);



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

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

Measurement

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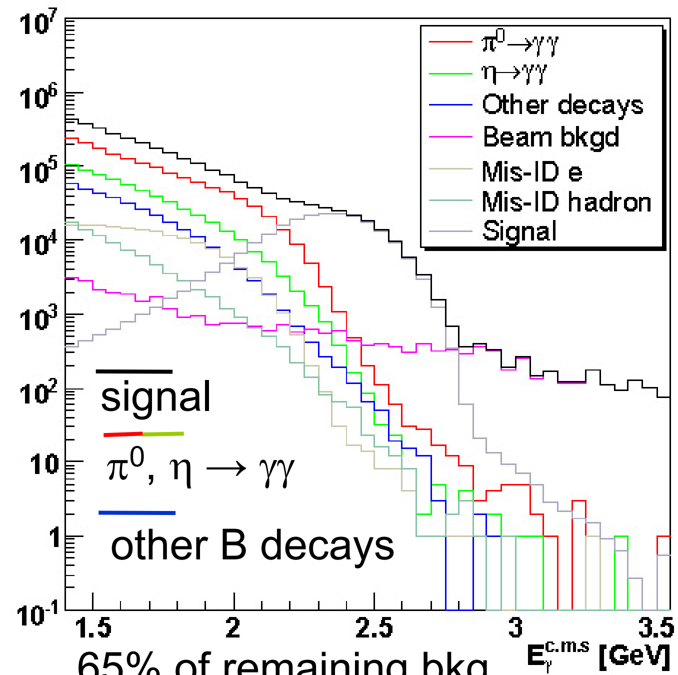
Background treatment

explicit veto $\pi^0, \eta \to \gamma\gamma$;

individual remaining bkg. categories taken from MC;

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



65% of remaining bkg. from $\pi^0, \eta \to \gamma\gamma$

Measurement

Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

Background treatment

explicit veto $\pi^0, \eta \rightarrow \gamma\gamma$;

individual remaining bkg. categories taken from MC;
shape and yield corrected by data control samples;

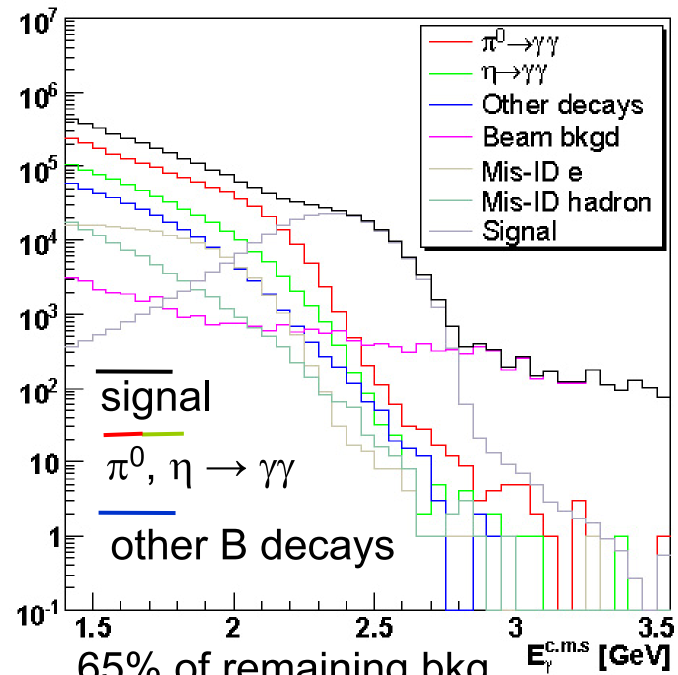
- inclusive B$\rightarrow \pi^0$X, ηX samples reconstructed in data (off- data subtraction) and MC; 5%-10% correction to MC yield;

- veto eff. measured by partialy reconstructed $D^0 \rightarrow K^-\pi^+\pi^0$;

- timing info for EM calorim. clusters (overlapping evts.: hadronic + Bhabha);

- beam background from random trigger events;

after vetoing $\pi^0, \eta \rightarrow \gamma\gamma$



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Measurement

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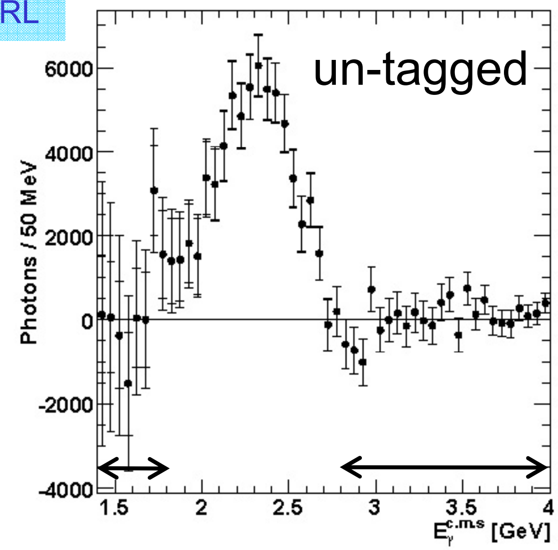
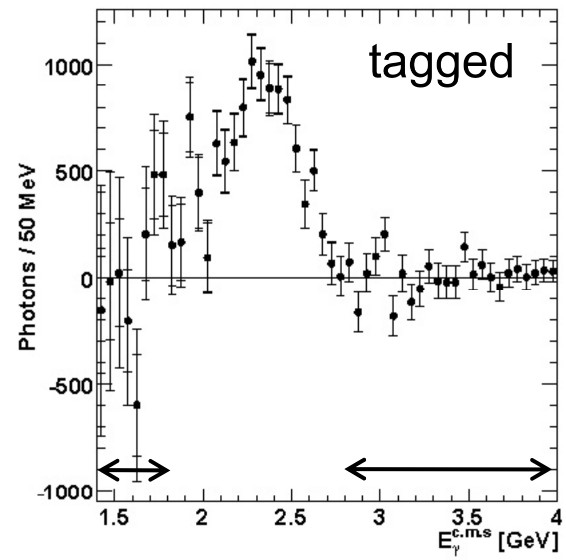
raw spectra

each bkg. (scaled by control samples) subtracted;



control region: -1629±4894 1245±4349



-745±889 292±410

Measurement

Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

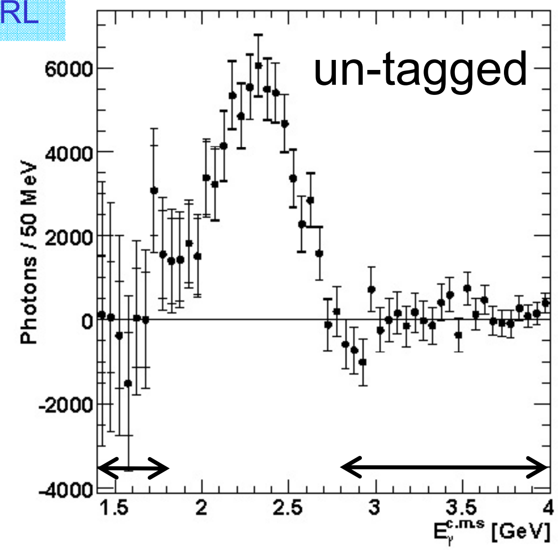
raw spectra

each bkg. (scaled by control samples) subtracted;

corrected spectra

correct for select. eff. ($\varepsilon_{untag} \sim 15\%$, $\varepsilon_{tag} \sim 2.5\%$);

average tagged and un-tagged spectra taking stat. correlation into account ($\rho \sim 0.1$);



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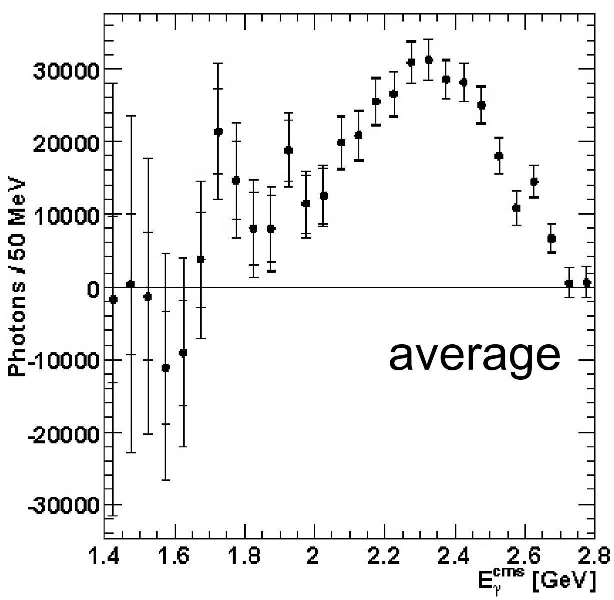

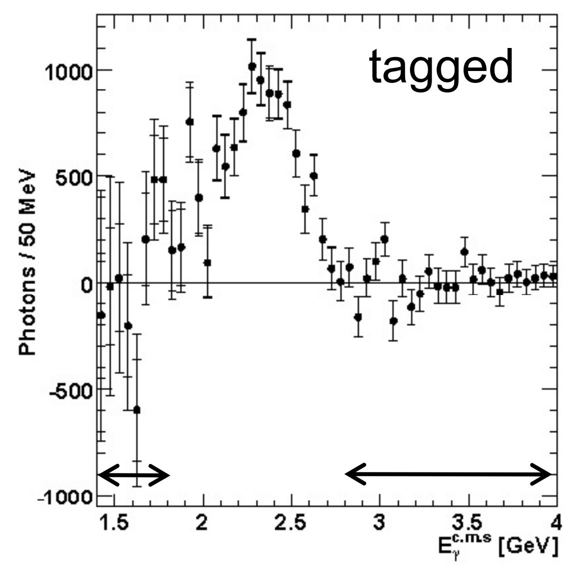

-745±889   292±410

Results

Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

corrected spectra

unfolding $E_\gamma^{meas} \rightarrow E_\gamma^{true}$
calibrated using radiative di-muon evts
(average E_γ resolution 2%);

correct for EM cluster detection eff.;

correct for $B \rightarrow X_d\gamma$ ($R_{d/s}$=4.5% ± 0.3%)

boost to B meson rest frame

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Branching fraction

$$Br(B \rightarrow X_s\gamma; 1.7\,GeV < E_\gamma < 2.8\,GeV) = (3.47 \pm 0.15 \pm 0.40) \cdot 10^{-4}$$

main syst. uncertainties:

from B background other than π^0, η (varied by 20%, using various models);

correction factors in off-data subtraction;

Results

Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

corrected spectra

- unfolding $E_\gamma^{meas} \rightarrow E_\gamma^{true}$ calibrated using radiative di-muon evts (average E_γ resolution 2%);
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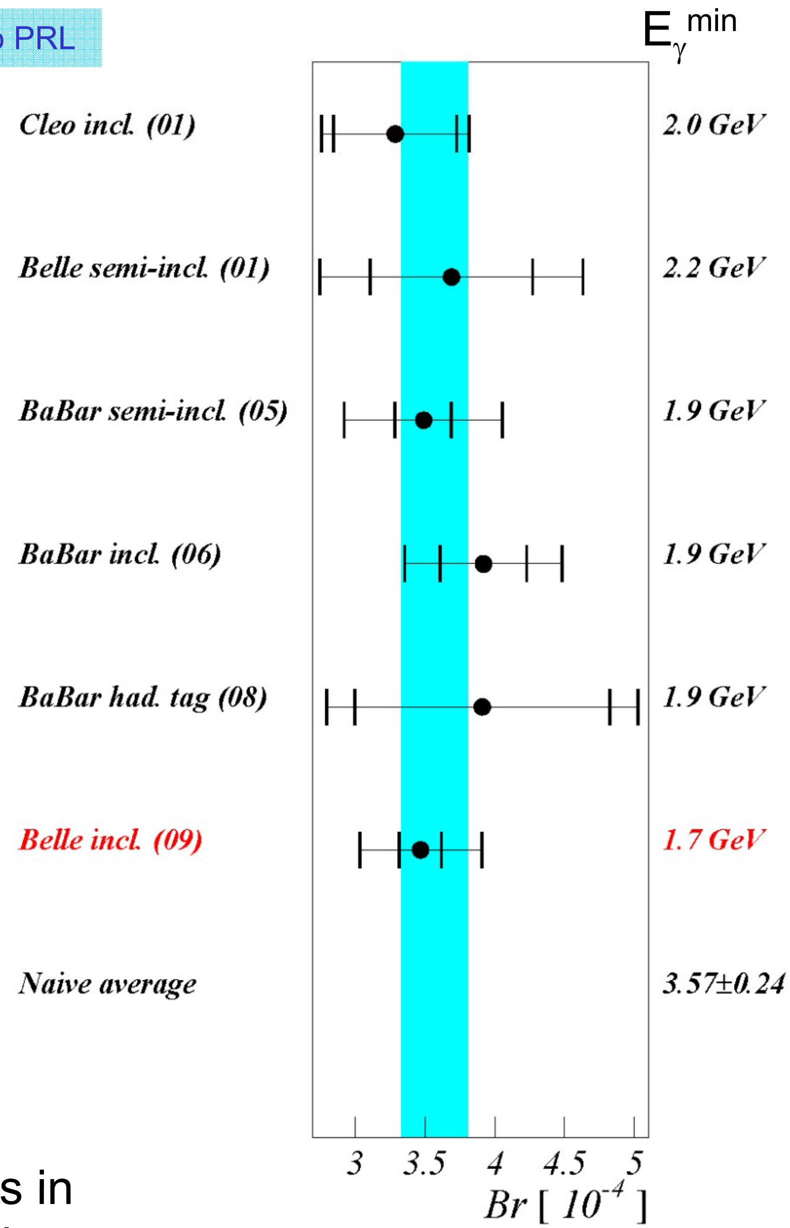

$$Br(B \rightarrow X_s\gamma; 1.6\,GeV < E_\gamma)$$

Results

Belle, arXiv:0907.1384, 605 fb^{-1}, subm. to PRL

Moments

moments (and Br's) given for various E_γ^{min}

$$\langle E_\gamma \rangle = (2.282 \pm 0.015 \pm 0.051)\, GeV$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = (0.0428 \pm 0.0047 \pm 0.0202)\, GeV^2$$

@ E_γ^{min} =1.7 GeV

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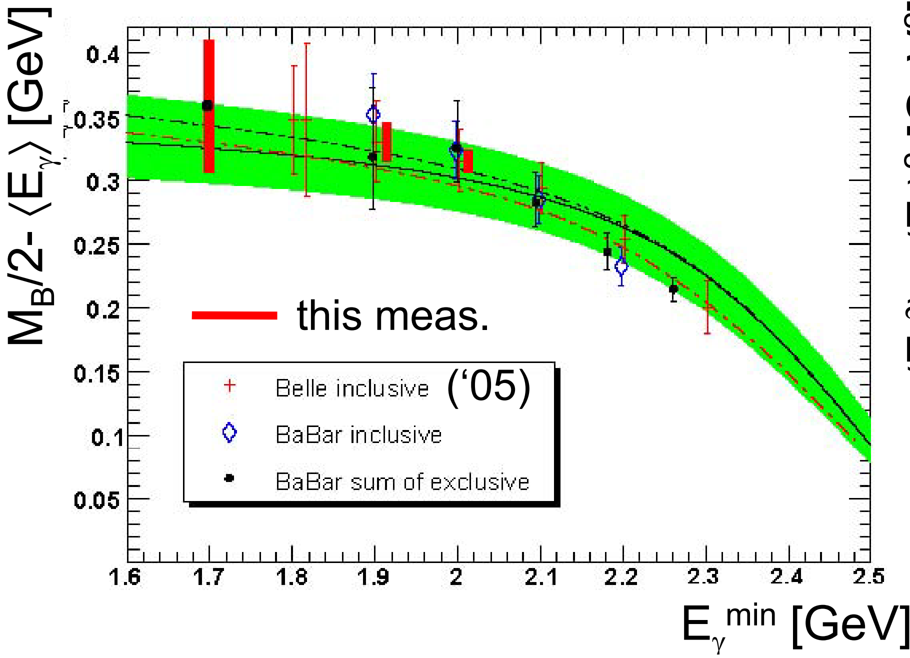
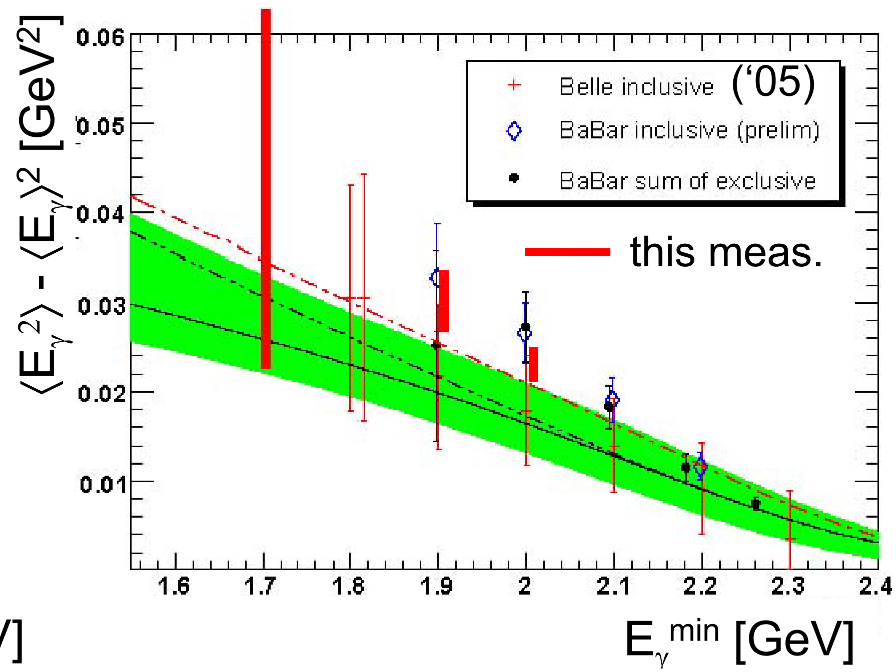
J.R. Andersen, E. Gardi, JHEP 0701, 029 (2007)





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@ E_γ^{min} =1.7 GeV

Constraints

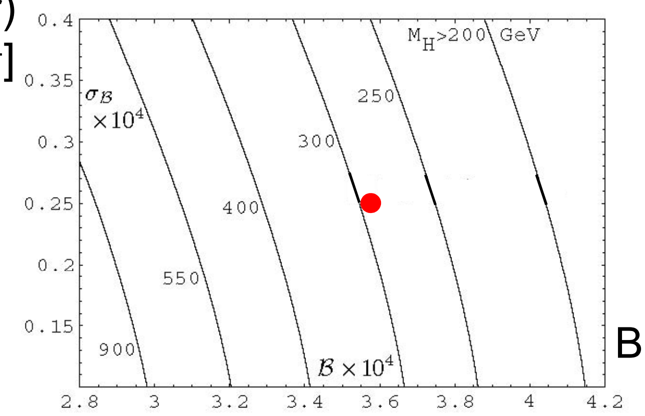
constraints on type-II 2HDM

$$Br^{SM}(B \to X_s\gamma; 1.6\,GeV < E_\gamma) = (3.15 \pm 0.23) \cdot 10^{-4}$$

$$Br(B \to X_s\gamma; 1.6\,GeV < E_\gamma) = (3.57 \pm 0.24) \cdot 10^{-4}$$

$M_{H\pm} \geq 300$ GeV @95% C.L.

M. Misiak et al., PRL98, 022002 (2007)



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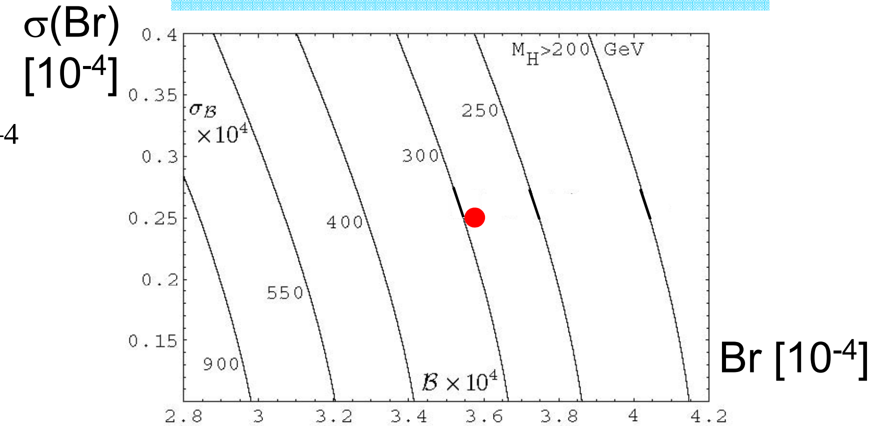
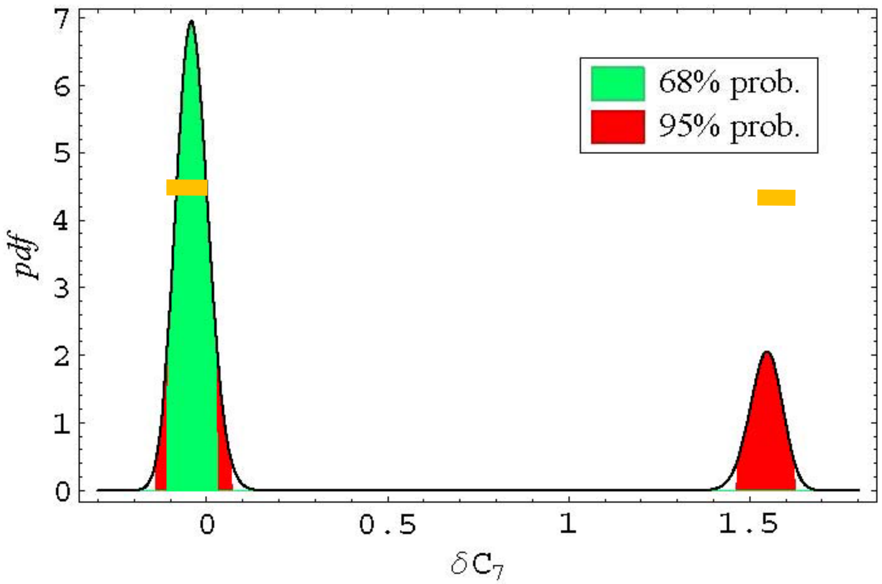


constraints on Wilson coeff., MFV

using
- $Br(B \to X_s\gamma)$,
- $Br(B \to X_s\ell\ell; q^2)$,
- $Br(K \to \pi\nu\nu)$,
- $Br(B_s \to \mu\mu)$,
- $A_{FB}(B \to K^*\ell\ell; q^2)$;

using $Br(B \to X_s\gamma)$ only

T. Hurth et al., Nucl.Phys. B808, 326 (2009)



$$\mathcal{B}(B \to X_s\gamma)(E_\gamma > 1.6\text{GeV}) = 3.13(23) \times 10^{-4} \times (1 - 2.28\delta C_7 + 1.51\delta C_7^2)$$

Summary

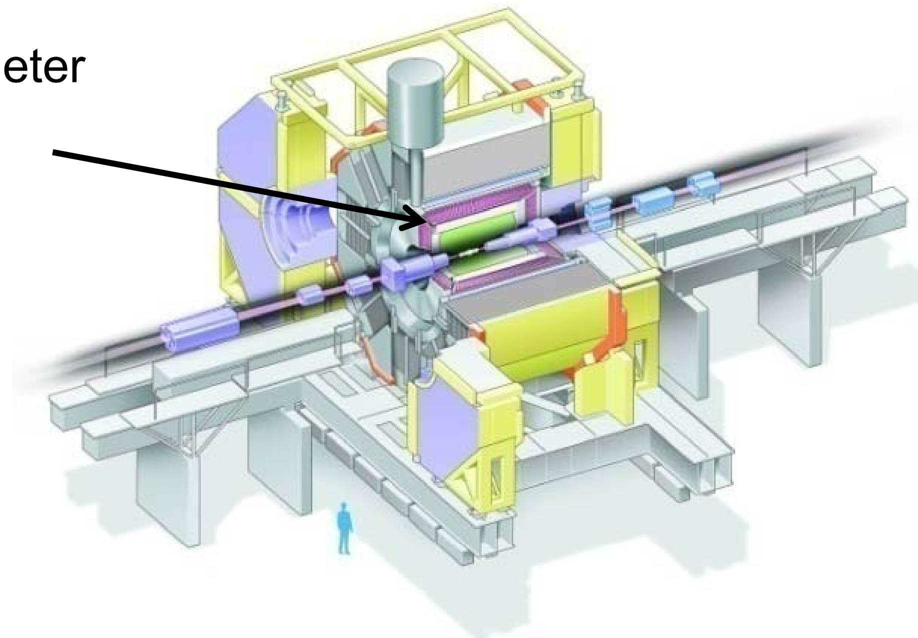
- measured Br and $d\Gamma/dE\gamma$ of inclusive $B \to X_s \gamma$ decays;
- lowest $E\gamma^{min}$ (=1.7 GeV);
- most precise measurement up to date;
- constraints on NP models and QCD parameters used in V_{cb}, V_{ub} determination;

Detector more

$$\frac{\sigma(E)}{E} \approx \frac{1.3\%}{\sqrt{E[GeV]}}$$

$$\sigma_{pos} \approx \frac{5\,mm}{\sqrt{E[GeV]}}$$

EM calorimeter
CsI ($16X_0$)



b→ cℓν more

relation b→ cℓν /b→ sγ
in OPE

Benson et al., Nucl.Phys. B665, 367 (2003)

$$\Gamma_{\rm sl}(b\to c) = \frac{G_F^2\, m_b^5(\mu)}{192\,\pi^3}\,|V_{cb}|^2\,(1+A_{\rm ew})\,A^{\rm pert}(r,\mu)$$

$$\left[z_0(r)\left(1-\frac{\mu_\pi^2(\mu)-\mu_G^2(\mu)+\frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{2m_b^2(\mu)}\right) - 2(1-r)^4\frac{\mu_G^2(\mu)+\frac{\rho_D^3(\mu)+\rho_{LS}^3(\mu)}{m_b(\mu)}}{m_b^2(\mu)} + d(r)\frac{\rho_D^3(\mu)}{m_b^3(\mu)} + \ldots\right]$$

$$r = m_c^2(\mu)/m_b^2(\mu)$$

$$\mu_\pi^2(\mu) \equiv \frac{1}{2M_B}\langle B|\bar b(i\vec D)^2 b|B\rangle_\mu\,, \qquad \mu_G^2(\mu) \equiv \frac{1}{2M_B}\langle B|\bar b\frac{i}{2}\sigma_{jk}G^{jk}b|B\rangle_\mu$$

$$\rho_D^3(\mu) \equiv \frac{1}{2M_B}\langle B|\bar b(-\frac{1}{2}\vec D\cdot\vec E)b|B\rangle_\mu\,, \qquad \rho_{LS}^3(\mu) \equiv \frac{1}{2M_B}\langle B|\bar b(\vec\sigma\cdot\vec E\times i\vec D)b|B\rangle_\mu$$

	Kinetic scheme	1S scheme
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ_D, ρ_{LS}	ρ_1, $\tau_{1\text{-}3}$

b→ cℓν more

relation b→ cℓν /b→ sγ
in OPE

Benson et al., Nucl.Phys. B710, 371 (2005)

$$\langle E_\gamma\rangle^{\rm pert}|_{E_\gamma>E_{\rm cut}}=\frac{m_b}{2}\left[1-\left[a_1(x;\mu)+\hat{a}_1(x)\right]\frac{\alpha_s}{\pi}-\left[b_1(x;\mu)+\hat{b}_1(x)\right]\frac{\beta_0}{2}\left(\frac{\alpha_s}{\pi}\right)^2\right]$$

$$\langle E_\gamma^2-\langle E_\gamma\rangle^2\rangle^{\rm pert}|_{E_\gamma>E_{\rm cut}}=\left(\frac{m_b}{2}\right)^2\left[\left[a_2(x;\mu)+\hat{a}_2(x)\right]\frac{\alpha_s}{\pi}+\left[b_2(x;\mu)+\hat{b}_2(x)\right]\frac{\beta_0}{2}\left(\frac{\alpha_s}{\pi}\right)^2\right]$$

$$a_1(x;\mu)=a_1(x;0)-\frac{4}{3}C_F\frac{\mu}{m_b}-\frac{13}{18}C_F\frac{\mu^3}{m_b^3}$$

$$b_1(x;\mu)=b_1(x;0)-\frac{4}{3}C_F\left(\ln\frac{M}{2\mu}+\frac{8}{3}\right)\frac{\mu}{m_b}-\frac{13}{18}C_F\left(\ln\frac{M}{2\mu}+\frac{319}{130}\right)\frac{\mu^3}{m_b^3}$$

$$a_2(x;\mu)=a_2(x;0)-\frac{1}{3}C_F\frac{\mu^2}{m_b^2}+\frac{4}{9}C_F\frac{\mu^3}{m_b^3}$$

$$b_2(x;\mu)=b_2(x;0)-\frac{1}{3}C_F\left(\ln\frac{M}{2\mu}+\frac{13}{6}\right)\frac{\mu^2}{m_b^2}+\frac{4}{9}C_F\left(\ln\frac{M}{2\mu}+2-\frac{1}{20}\right)\frac{\mu^3}{m_b^3}\,.$$

$$\begin{aligned}\langle E_\gamma\rangle &\simeq \langle E_\gamma\rangle^{\rm pert}+\langle E_\gamma\rangle^{\rm power}+\tfrac{1}{2}\tilde{\delta}m_b,\\ \langle E_\gamma^2-\langle E_\gamma\rangle^2\rangle &\simeq \langle E_\gamma^2-\langle E_\gamma\rangle^2\rangle^{\rm pert}+\langle E_\gamma^2-\langle E_\gamma\rangle^2\rangle^{\rm power}-\tfrac{1}{12}\tilde{\delta}\mu_\pi^2.\end{aligned}$$

$$\begin{aligned}\langle E_\gamma\rangle^{\rm power} &= \frac{\mu_\pi^2-\mu_G^2}{4m_b}-\frac{5\rho_D^3-7\rho_{LS}^3}{12m_b^2}-\frac{c_2}{c_7}\frac{\rho_{LS}^3}{54m_c^2}\\ \langle E_\gamma^2-\langle E_\gamma\rangle^2\rangle^{\rm power} &= \frac{\mu_\pi^2}{12}-\frac{2\rho_D^3-\rho_{LS}^3}{12m_b}+\mathcal{O}\left(\frac{1}{m_b^2}\right)\,.\end{aligned}$$

$b \to c\ell\nu$ more

relation $b \to c\ell\nu / b \to s\gamma$
in OPE

I. Bigi, N. Uraltsev, Int.J.Mod.Phys. A17, 4709 (2002)

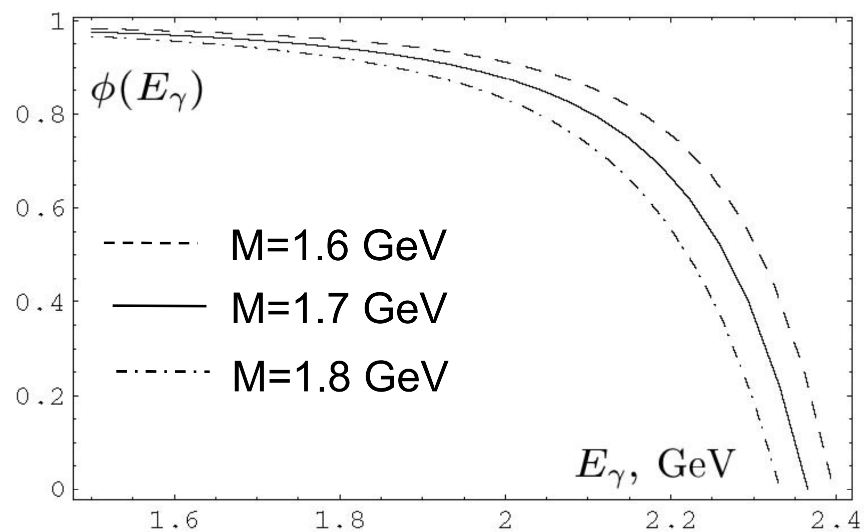
fraction of
$b \to u\ell\nu$ with $M_X < M$

$$1 - \Phi_{\rm sl}(M) = \int_0^{\frac{M_B}{2} - \frac{M^2}{2M_B}} {\rm d}E_\gamma\ \phi(E_\gamma, M) \frac{1}{\Gamma_{bs\gamma}} \frac{{\rm d}\Gamma_{bs\gamma}}{{\rm d}E_\gamma}\ ,$$

$$\phi(E_\gamma, M) = 1 - \frac{2r^3}{(1-y)^3} + \frac{r^4}{(1-y)^4}\ , \qquad y = \frac{2E_\gamma}{M_B}\ , \qquad r = \frac{M^2}{M_B^2}\ .$$

high E_γ: weight function $\phi(E_\gamma)$ small,
$d\Gamma/dE_\gamma$ spectrum less important;

$E_\gamma \leq 2$ GeV: weight function $\phi(E_\gamma) \sim 1$,
importat to measure $d\Gamma/dE_\gamma$
precisey to low E_γ



$b \to s\gamma$ OPE more

$b \to s\gamma$
in OPE

in $b \to s\gamma$ cut on $E_\gamma > E_{cut}$ used experimentally;
this limits the theoretical accuracy of inclusive B decays treatment;
$E_{cut} \to$ new scale $\Delta = M_B - 2E_{cut}$;
some non-perturbative effects described as series in $1/\Delta$;

D. Benson et al., Nucl.Phys. B710, 371 (2005)

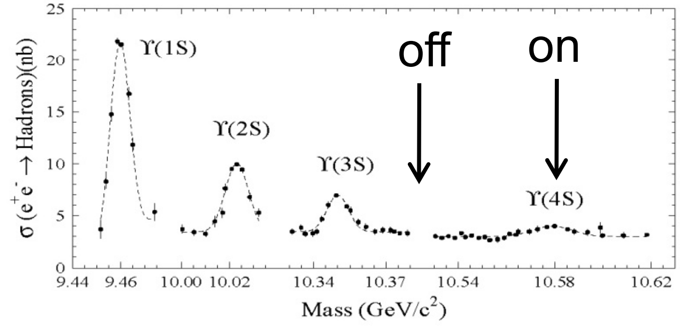
if E_{cut} high $\to$ questionable series expansion;
biases for $E_{cut} > 1.85$ GeV, breakdown for $E_{cut} > 2.1$ GeV;

further discussion in Z. Ligeti et al., PRD78, 114014 (2008)

$b \to s\gamma$ Off-data scaling more

Belle, arXiv:0804.1580,605 fb^{-1}

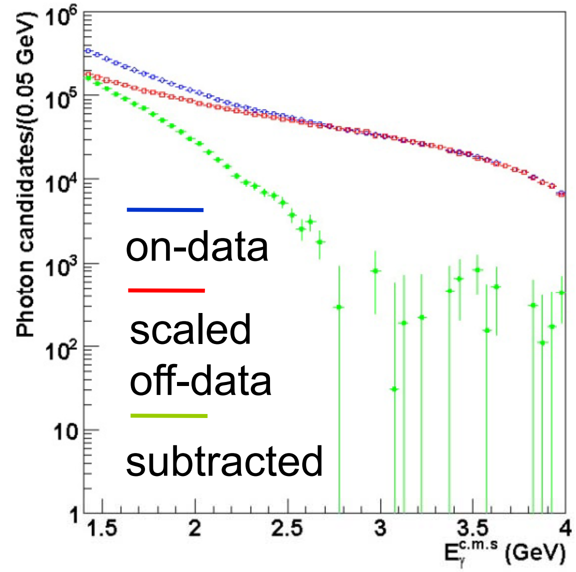
L_{on} = 605 fb^{-1}
L_{off} = 68 fb^{-1}



bkg. treatment

subtract lumin. scaled off-data from on-data (continuum bkg.);

$$N^{B\bar{B}}(E_\gamma^{c.m.s(ON)}) = N^{ON}(E_\gamma^{c.m.s(ON)}) - \alpha \cdot \frac{\epsilon^{ON}_{Hadronic}}{\epsilon^{OFF}_{Hadronic}} \cdot \frac{\epsilon^{ON}_{B\to X_s\gamma}}{\epsilon^{OFF}_{B\to X_s\gamma}} \cdot F_N \cdot N^{OFF}(F_E E_\gamma^{c.m.s(OFF)})$$



α: lumin. ratio, including s dependence, ~8.8

$\varepsilon_{hadronic,B\to Xs\gamma}^{ON,OFF}$: efficiency of hadronic and signal selection;

$F_{N,E}$: corr. factor due to lower mean E_γ and multiplicity in off-data

b→ sγ Moments more

Belle, arXiv:0804.1580,605 fb^{-1}

	$\mathcal{B}(B \to X_s\gamma)$ (10^{-4})				$\langle E_\gamma \rangle$ (GeV)				$\Delta E_\gamma^2 \equiv \langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2$ (GeV^2)			
E_γ^B [GeV]	1.70	1.80	1.90	2.00	1.70	1.80	1.90	2.00	1.70	1.80	1.90	2.00
Value	3.47	3.38	3.23	3.03	2.282	2.294	2.311	2.334	0.0428	0.0370	0.0302	0.0230
±statistical	0.15	0.13	0.11	0.10	0.015	0.011	0.009	0.007	0.0047	0.0029	0.0019	0.0014
±systematic	0.40	0.25	0.16	0.11	0.051	0.028	0.014	0.008	0.0202	0.0081	0.0029	0.0013
±boost	0.01	0.01	0.02	0.02	0.002	0.002	0.004	0.005	0.0012	0.0005	0.0008	0.0009

1±0.12 1±0.06 1±0.023 1±0.008 1±0.48 1±0.12

$b \rightarrow s\gamma$ extrapol. more

extrapol. factors to E_γ=1.6 GeV used by HFAG:

E_γ=1.7 GeV	0.985 ± 0.004
E_γ=1.9 GeV	0.936 ± 0.010
E_γ=2.0 GeV	0.894 ± 0.016

E. Barberio et al. (HFAG), arXiv:0808.1297

$b\to s\gamma$ tag/untag more

MC study: same FOM ($N_{sig}/\delta N_{sig}$) for tagged/un-tagged sample;

data
un-tagged sample:

$$Br(B\to X_s\gamma;1.8\,GeV<E_\gamma)=(3.24\pm0.17\pm0.25)\cdot10^{-4}$$

tagged:

$$Br(B\to X_s\gamma;1.8\,GeV<E_\gamma)=(3.50\pm0.19\pm0.35)\cdot10^{-4}$$

combined:

$$Br(B\to X_s\gamma;1.8\,GeV<E_\gamma)=(3.38\pm0.13\pm0.25)\cdot10^{-4}$$

$b \to s\gamma$ MC

sum of exclusive $K^*\gamma$ and inclusive;

inclusive: X_s BW J=1 resonance, m=2.4 GeV, Γ=1.5 GeV
hadronized by JETSET and reweighted according to

Kagan-Neubert
Dressed Gluon Exponentiation
Bosch-Lange-Neubert-Paz models
Gambino-Giordano
Benson-Bigi-Uraltsev

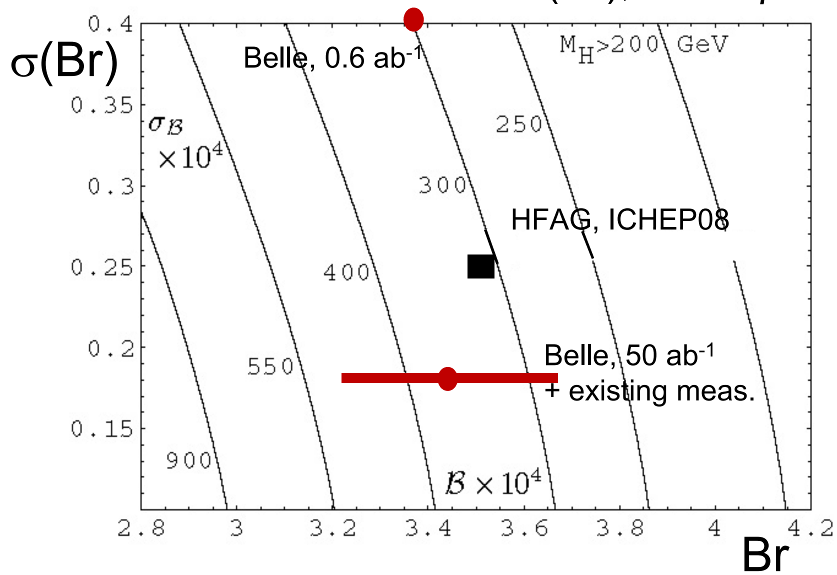
$b \rightarrow s\,\gamma$ decays outlook more

for E_γ^{min}=1.6 GeV
(comparison to theory)
~few x more data needed

M. Misiak et al., PRL98, 022002 (2007)

L.L. can get as high as ~500 GeV

95% C.L. lower limit on m(H±), all tanβ



$b \to s\gamma$ CPV more

D. Atwood et al., PRL79, 185 (1997)

t-dependent CPV

in SM: helicity structure of effective Hamiltonian

$b_R \to s_L \gamma_L \quad \propto m_b$ (since W in loop couples to b_L spin flip required)

or

$b_L \to s_R \gamma_R \quad \propto m_s$

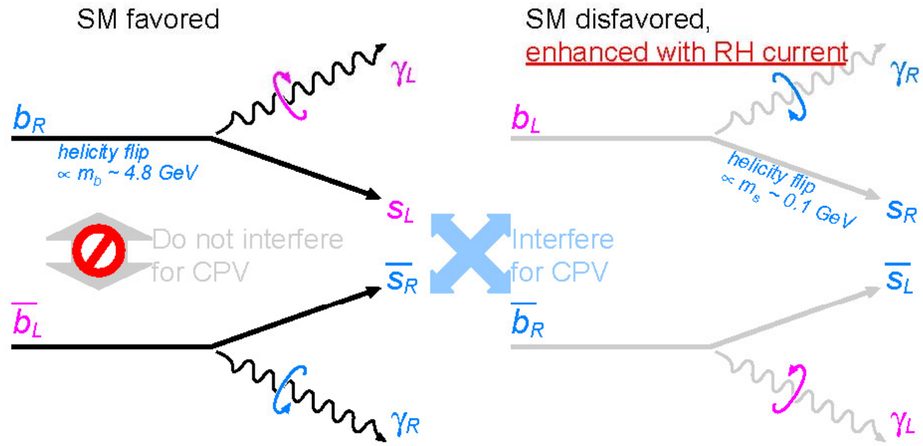
interference

mixing/no-mixing for

$b_R \to s_L \gamma_L \quad \propto m_b$

$b_R \to \overline{b}_R \to \overline{s}_L \gamma_L \quad \propto m_s$

CPV in SM $\propto m_s/m_b$



appropriate modes: $K^{*0}(K_s\pi^0)\gamma$, $K_s\eta\gamma$, $K_s\phi\gamma$ (ang. analysis necessary), ...

NP with heavy right-handed fermions in loop can enhance CPV;

b → sγ CPV more

t-dependent CPV

D. Atwood et al., PRL79, 185 (1997)

in SM: $S_{CP}(K^*\gamma) \sim (2m_s/m_b)\sin 2\phi_1 \sim 0.04$

Left-Right Symmetric Model: $S_{CP}(K^*\gamma) \sim 0.67 \sin 2\phi_1 \sim 0.5$

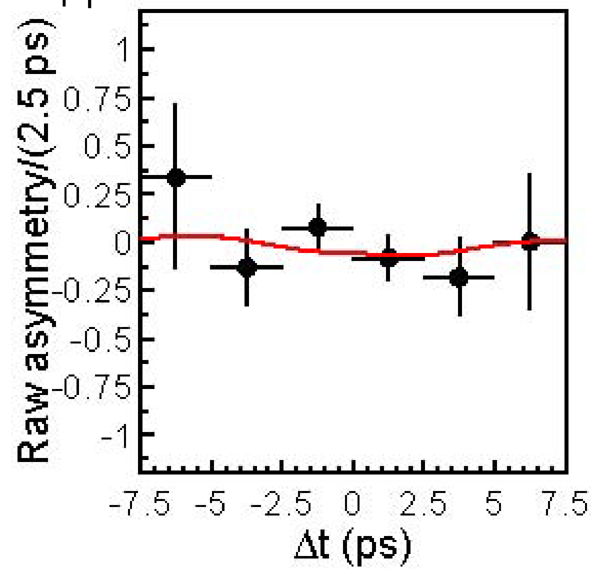
$S_{CP}(K_s\pi^0\gamma) = -0.10 \pm 0.31 \pm 0.07$

$A_{CP}(K_s\pi^0\gamma) = -0.20 \pm 0.20 \pm 0.06$

for $m(K_s\pi^0) < 1.8$ GeV (mainly $K^*\gamma$)

largest syst. from signal fract. and resol. f.

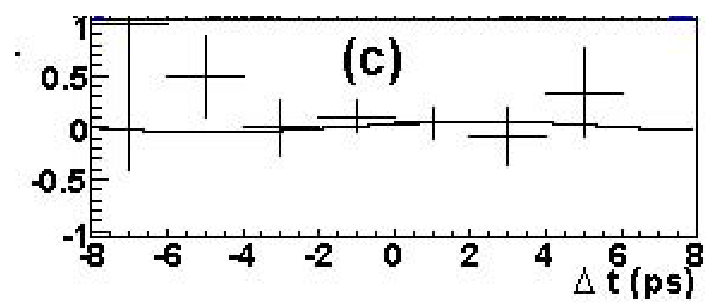
Belle, PRD74, 111104 (2006), 535M BB



important additional improvements with upgraded SVD (K_s - IP vtx)

similar sensitivity for $K_s\rho^0\gamma$ (dilution from $K^*\pi\gamma$)

Belle, PRL101, 251601(2008), 657M BB



$b \to s\gamma$ CPV more

t-dependent CPV

expectation:

main syst. scales with luminosity

$\sigma(S(K_s\pi^0\gamma))=0.09$ @5 ab^{-1}

0.03 @50 ab^{-1} (~SM value)

+20% increase in K_s acceptance with SVD

DCPV

suppressed by $|V_{ub}V_{us}^*/V_{tb}V_{ts}^*|$, $\alpha_s(m_b)$ (strong phase), $(m_c/m_b)^2$ (GIM);

OPE:

$A_{CP}(B\to X_s\gamma) = (0.44\pm^{0.24}{}_{0.14})\%$ T. Hurth et al., Nucl.Phys. B704, 56 (2005)

semi-inclusive analysis:

$K+(1\text{-}4)\pi$; $KKK(\pi)$, $K_SKK(\pi)$;

$A_{CP}(B\to X_s\gamma;M_{Xs}<2.1\ \text{GeV}) = (0.2\pm5.0\pm3.0)\%$ Belle, PRL93, 031803 (2004), 140 fb^{-1}

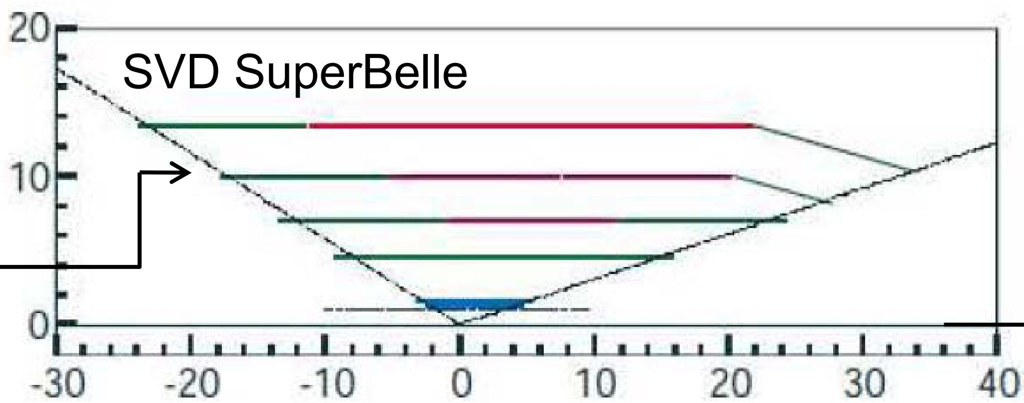
syst.: bias (detector charge asymmetry), possible bkg. asymmetry, uncertainty of M(Xs) shape

$D\pi$ control sample	measured asymmetries in other decay modes	non-scaling

$b \to s\gamma$ SVD more

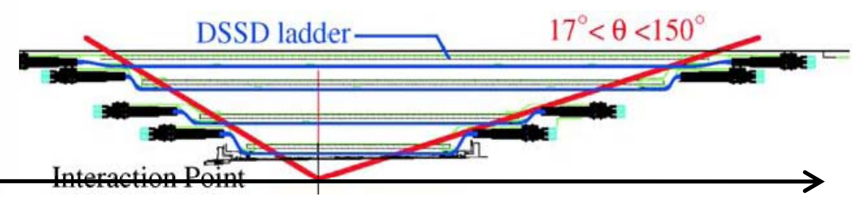
to scale

r [cm]

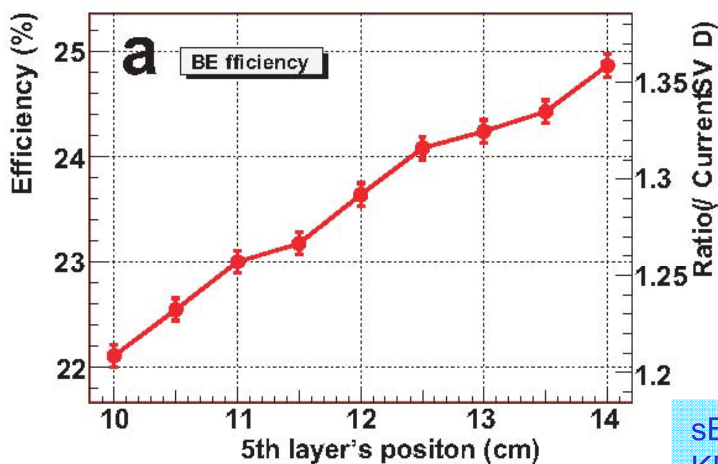


z [cm]

SVD Belle

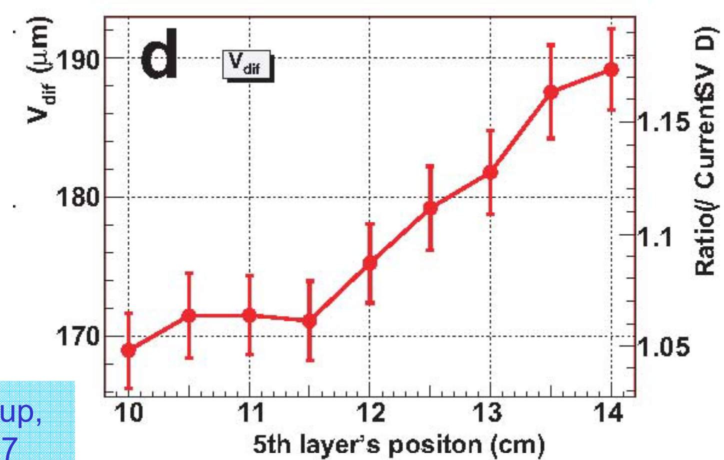


(if two SVD layers/π required)



ε for K_s reconst.

sBelle Design Group,
KEK Report 2008-7



Δz resolution

in $B \to K^{*0}\gamma$

Constraints on Wilson coeff. more

constraints on NP in C_i

$Br(B \to X_s \gamma)$,
$Br(B \to X_s \ell\ell)$,
$Br(K \to \pi\nu\nu)$
$Br(B_s \to \mu\mu)$,
no $Br(B \to K^* \ell\ell)$
(large th. uncertainty)

J. Kamenik, arXiv:0805.2363