Electroweak and radiative penguin processes in B decays at Belle

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for the Belle Collaboration

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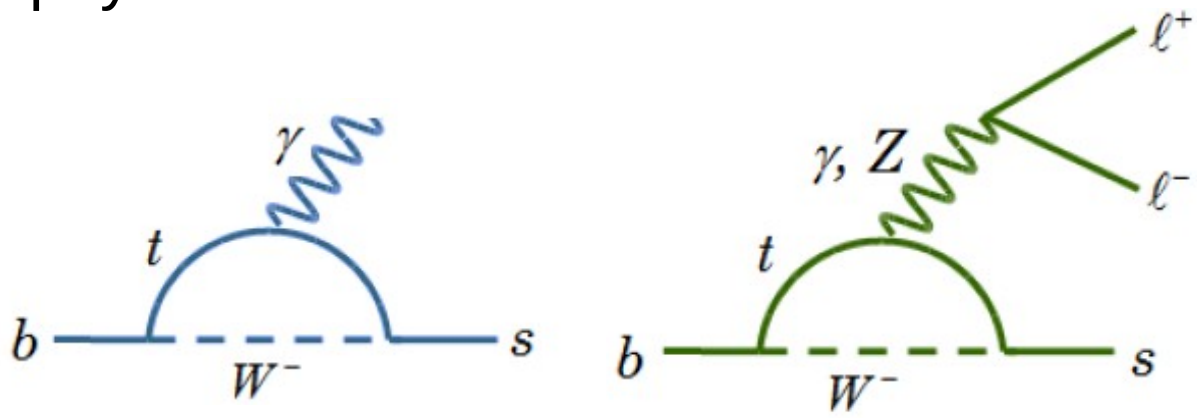
Introduction

- $b \to s,d\ \gamma$ and $b \to s\ l^+l^-$ are FCNC
- Sensitive to new physics:

Standard Model



Non-SM $W^- \to \tilde{\chi},\ H^-$

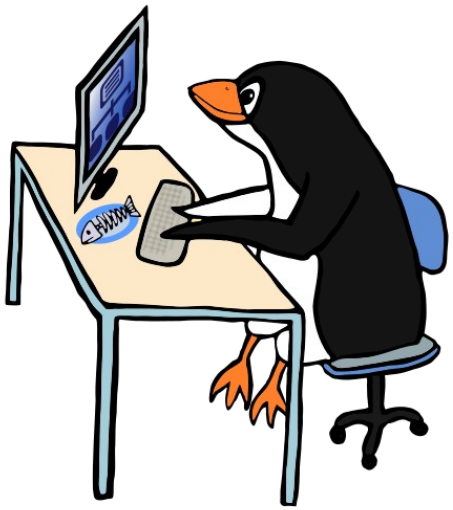
- Observables: BF, A_{CP}, A_{FB}, Isospin asymmetry...
- Constrain non-SM contributions to Wilson coefficients C_i from OPE

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} C_i(\mu) Q_i$$

  - $b \to s\gamma$ determined by C_7
  - $b \to s\ l^+l^-$ determined by C_7, C_9, C_{10}

Covered topics

- **CP asymmetry in $B \to X_{(s+d)}\gamma$** NEW
  - Inclusive
- **Branching fraction $B \to X_s\gamma$** NEW
  - Sum of exclusives
- **Forward- backward asymmetry in $B \to X_s l^+ l^-$**
  - Sum of exclusives
- **Search for $B^0 \to p^+ \overline{\Lambda} \pi^- \gamma$**
  - Exclusive



CP asymmetry in $B \to X_{(s+d)}\gamma$

NEW

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)

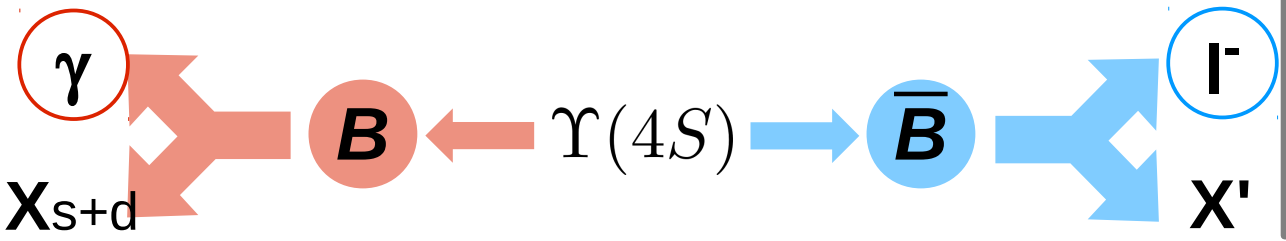
Cancellation due to unitarity, negligible theory error!

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

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

Using tag-lepton charge

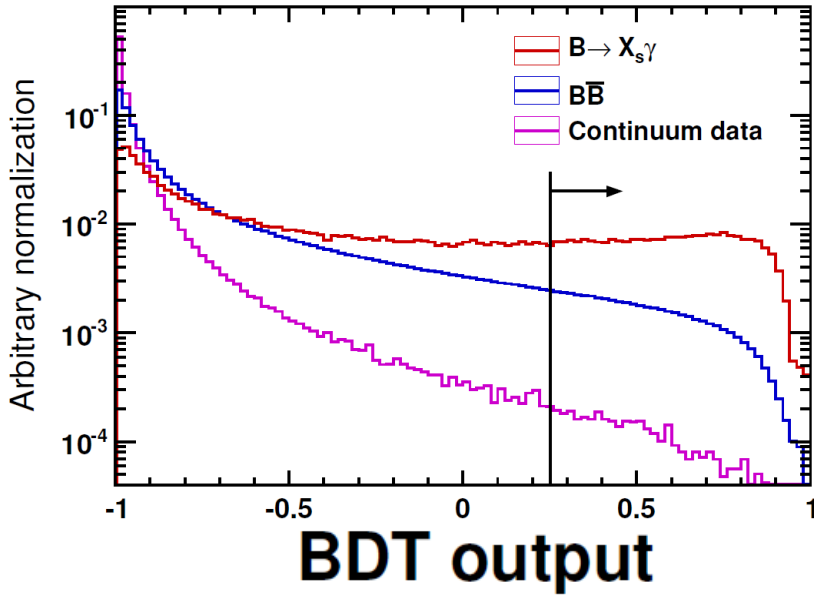
$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}$$

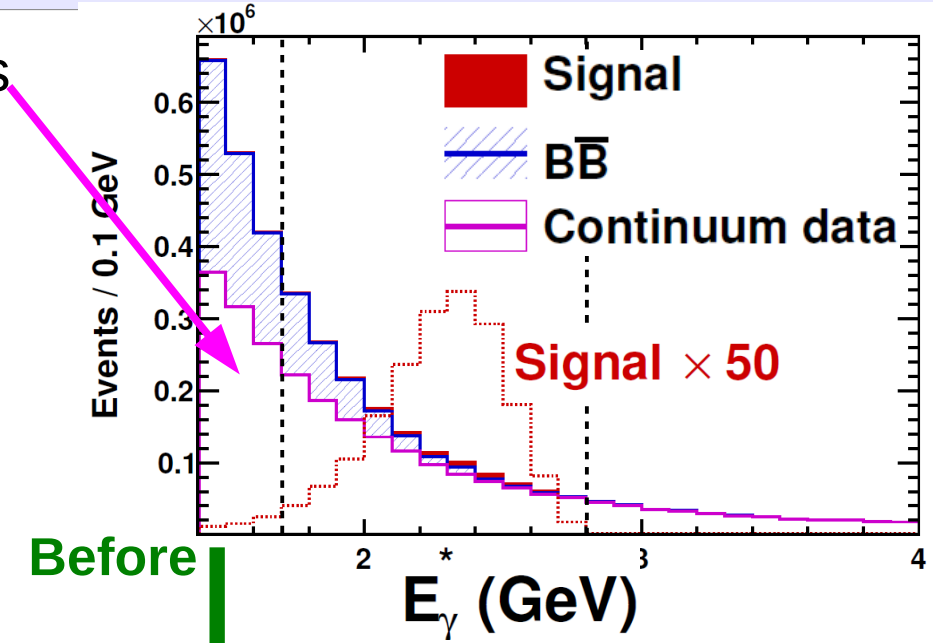


- Inclusive method: reduce model uncertainty but has high background.
- High energy photon (1.7 – 2.8 GeV) and lepton (e, μ) for tagging
- Mass veto for $\pi^0(\eta) \to \gamma\gamma$

Continuum suppression

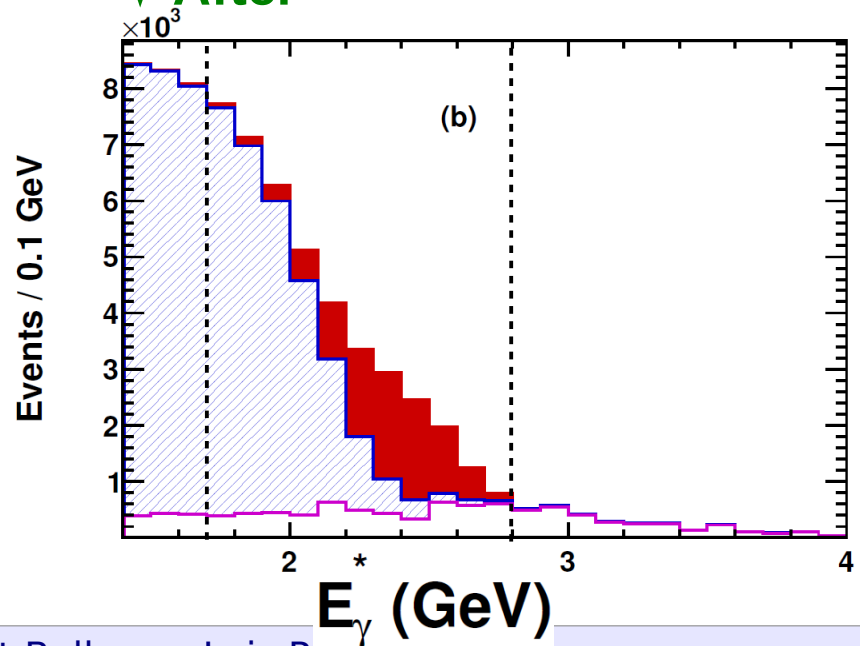
- Continuum $e^+e^- \to q\bar{q}$ **(q=u,d,s,c)**, decay is "jet-like", $B\bar{B}$ is "spherical"
- Characterize "event shape":
  - Topological variables (thrust, Fox-Wolfram moments, ...)
  - Kinematic variables (missing mass, transverse energy, ...)
- Make use of multivariate analysis techniques (NN, BDT, etc.)



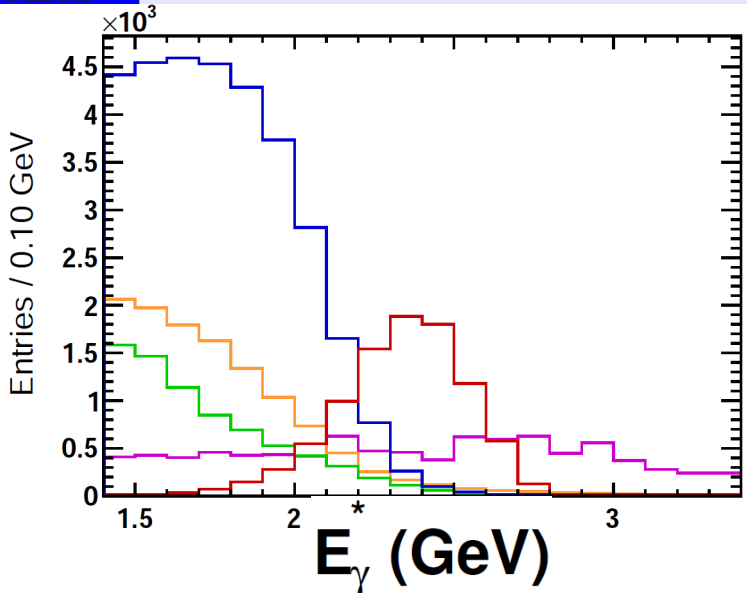


Before

After

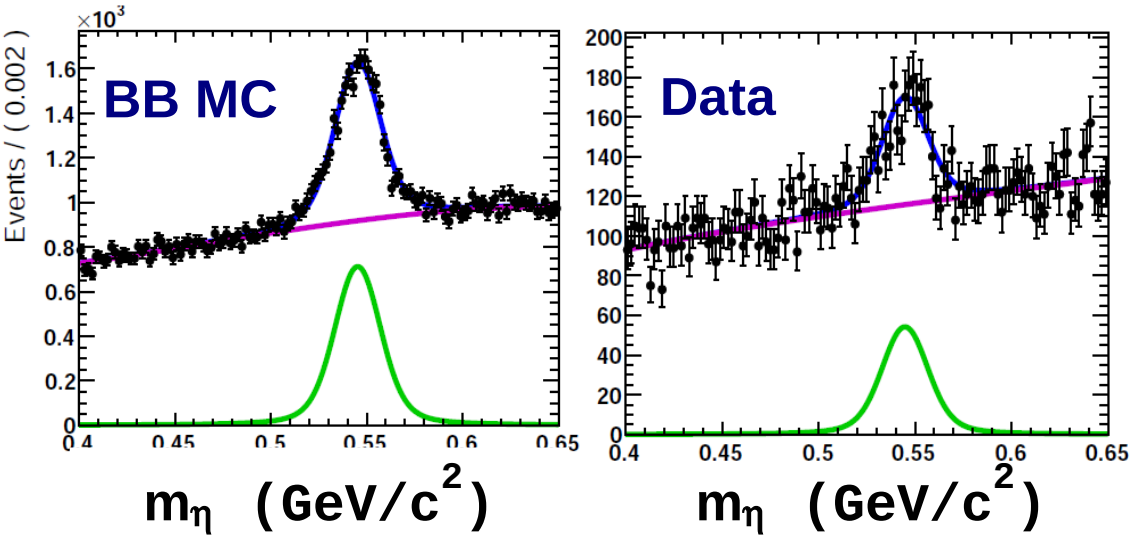


Normalization of background



Signal	21.2%	
$\pi^0 \to \gamma\gamma$	49.5%	Asymmetric decays, not rejected by veto
$\eta \to \gamma\gamma$	7.9%	
Other BB	9.0%	
Continuum	12.4%	→ Off-resonance data

- Remove veto, fit to reconstructed π/η mass, compare data and MC.
- Correct MC in momentum bins: $c_i = \frac{N_{\rm on} - N_{\rm off}}{N_{\rm MC}}$

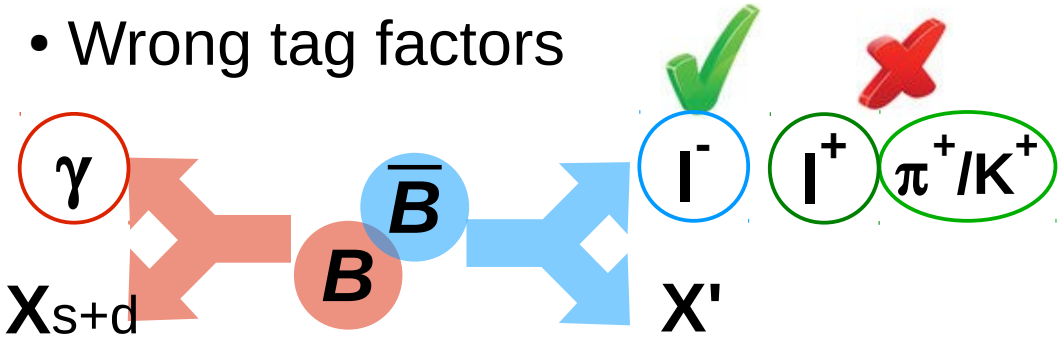


Average normalization factors

Decay	Factor
$B \to X\pi^0$	1.079 ± 0.005
$B \to X\eta$	0.786 ± 0.041

Wrong tag and sources of asymmetry

- Wrong tag factors



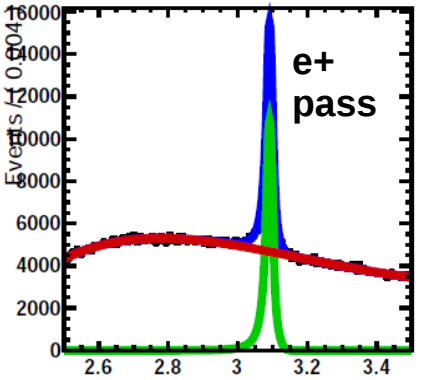
$$\begin{aligned}\omega &= \omega_{\rm osc} + \omega_{2nd} + \omega_{\rm misID} \\ &= 0.1413 \pm 0.0052\end{aligned}$$

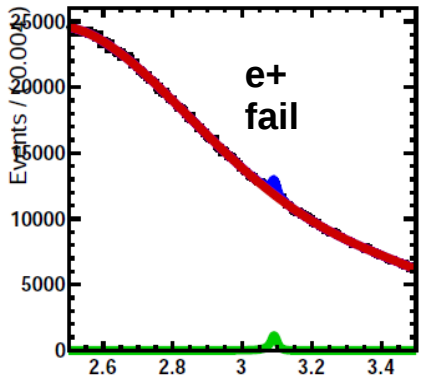
$$A_{\rm CP} = \frac{1}{1-2\omega} A_{\rm CP}^{\rm meas}$$

- Asymmetry in lepton ID, study in $B \to X\, J/\Psi\,(l^+l^-)$, tag-and-probe

$$\varepsilon^{\pm} = \frac{N_{\rm pass}}{N_{\rm pass} + N_{\rm fail}}$$

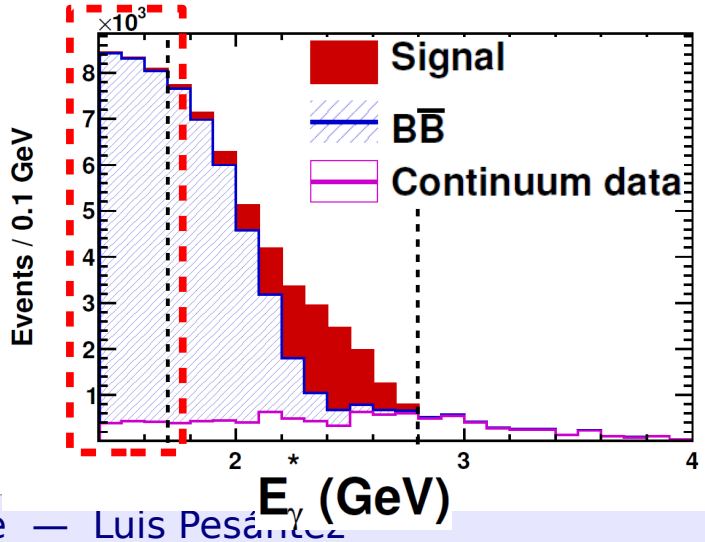
$$A_{\rm det} = \frac{\varepsilon^+ - \varepsilon^-}{\varepsilon^+ + \varepsilon^-} \qquad A_{\rm det} = (0.10 \pm 0.22)\%$$





- Asymmetry in BB bkg: measured in data (E_γ^*< 1.7 GeV)

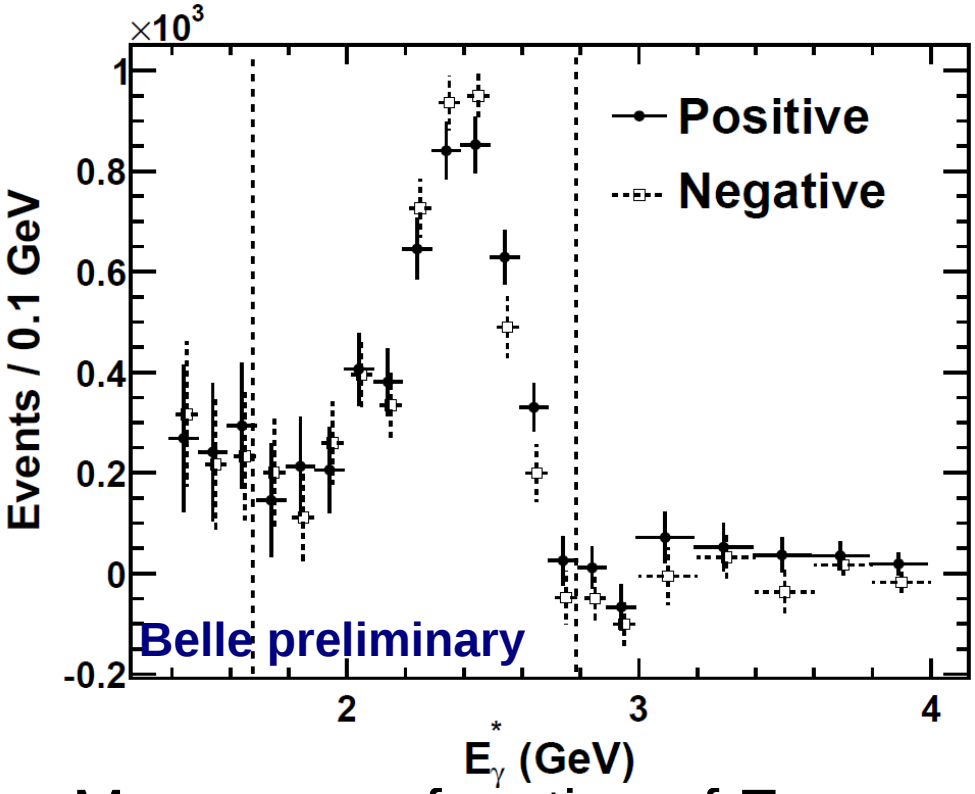
$$A_{\rm bkg} = \frac{N^+ - N^-}{N^+ + N^-} \qquad A_{\rm bkg} = (-0.14 \pm 0.78)\%$$



- These asymmetries are bias!, must correct them

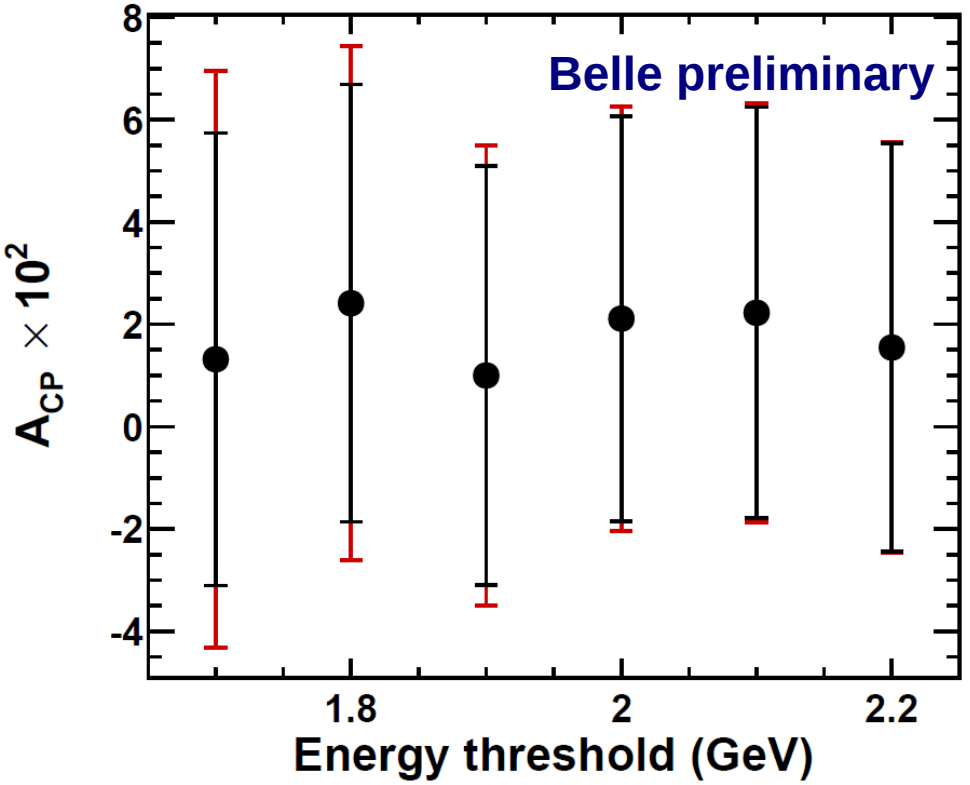
Subtracted $B \to X_{(s+d)}\gamma$ photon spectrum

- Spectrum after subtraction of background:



Asymmetry: $A_{CP}^{meas} = \frac{N^+ - N^-}{N^+ + N^-}$

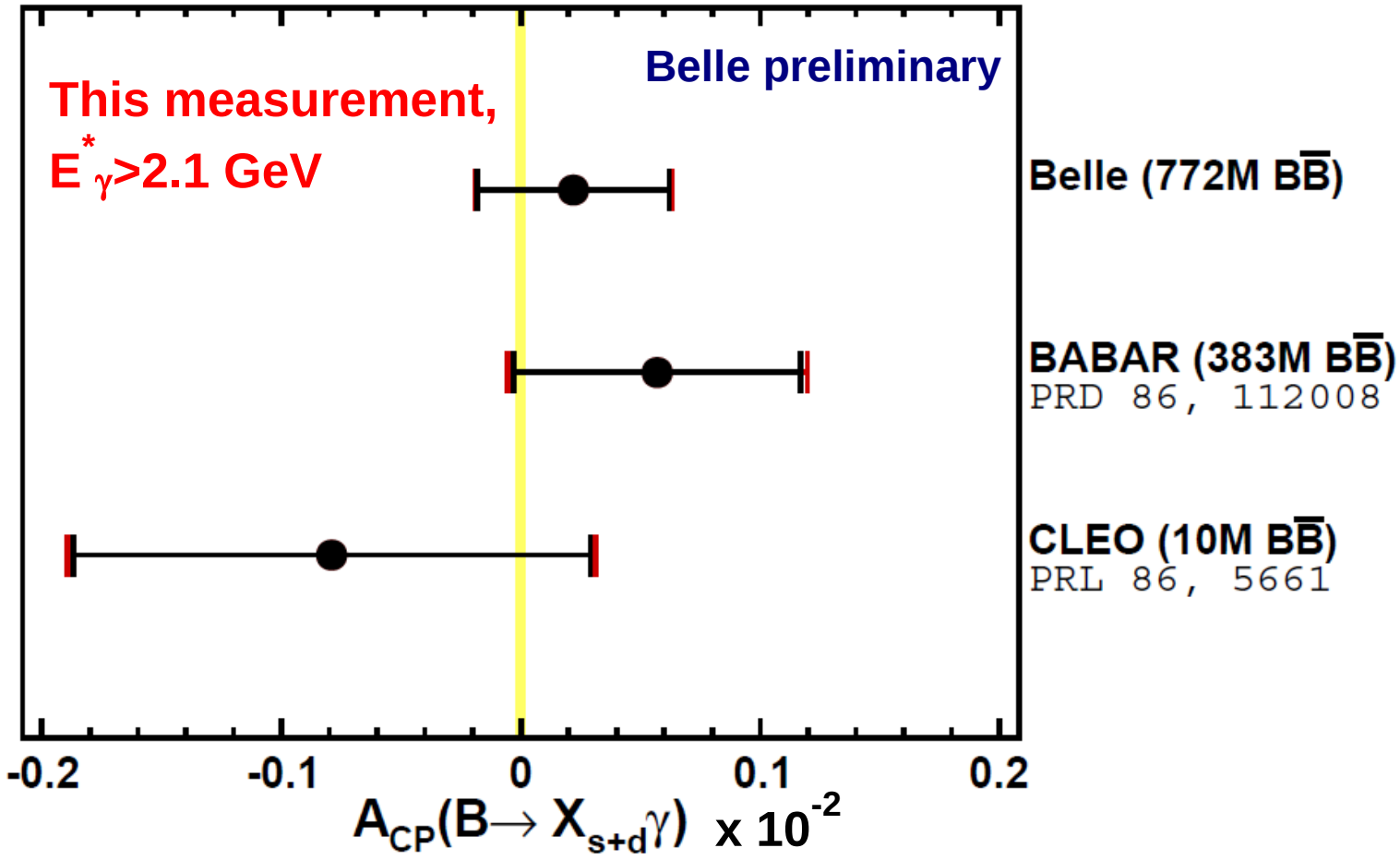
is corrected for wrong tags and bias



- Measure as function of Eγ threshold
- Main systematic from BB bkg asymmetry.
- Statistical uncertainty dominates
- Stable for different thresholds

Result for A_{CP} in $B \to X_{(s+d)}\gamma$

- Most precise measurement of A_{CP}
- Consistent with SM and other experiments



Branching fraction $B \to X_s \gamma$

NEW

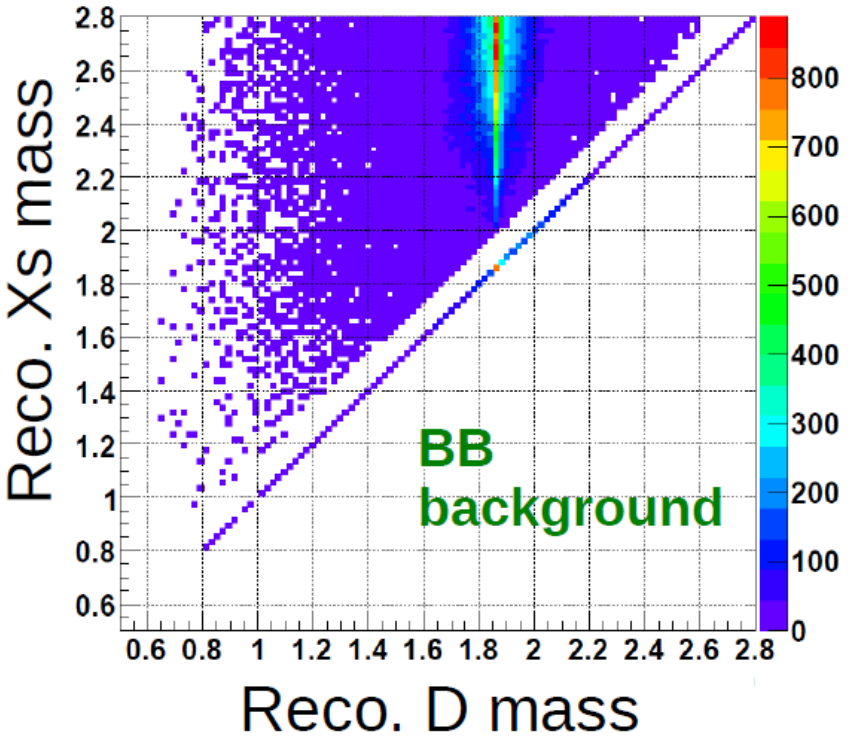
- Sum of exclusives: 38 X_s states (~70% of total).

1 or 3 K (up to 1 K_S),
up to 4 π (up to 2 π^0),
up to 1 η

$$K_s\pi^+,\ K^+\pi^0,\ K_s\pi^+\pi^+\pi^-,\ K_s\eta,\ K^+\eta\pi^-,\ \cdots$$

- Photon energy E_γ>1.8 GeV

- Determine selection efficiency of each channel for BF!
- Selection:
  - Neural network for continuum suppression
  - Mass veto for D mesons (peaking bkg $B \to D^{(*)}(K\pi\pi)\rho$)

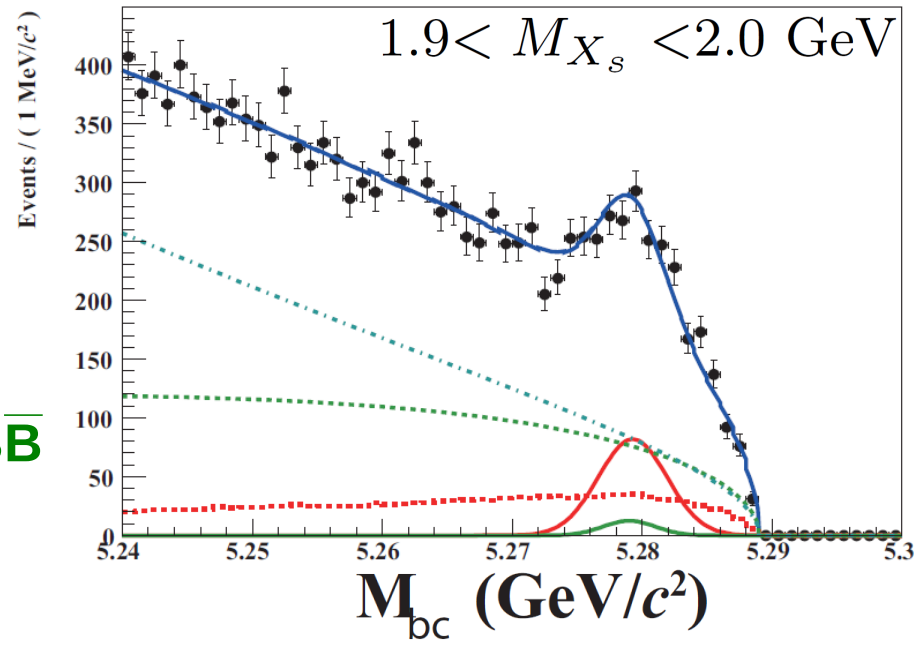


$B \to X_s \gamma$ (sum of exclusives), procedure

- Fit to M_{bc} in 19 M_{Xs} bins

$$M_{\rm bc} \equiv \sqrt{E^2_{beam} - |\vec{p}_B|^2}$$

— Signal
··· Cross feed
— Peaking BG
··· Non-peaking $B\overline{B}$
··· Continuum



- Calibration Xs hadronization:
  - Signal efficiency depends on model.
  - Pythia parameters + data driven calibration.
- Missing modes uncertainty: use different parameters for hadronization.

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

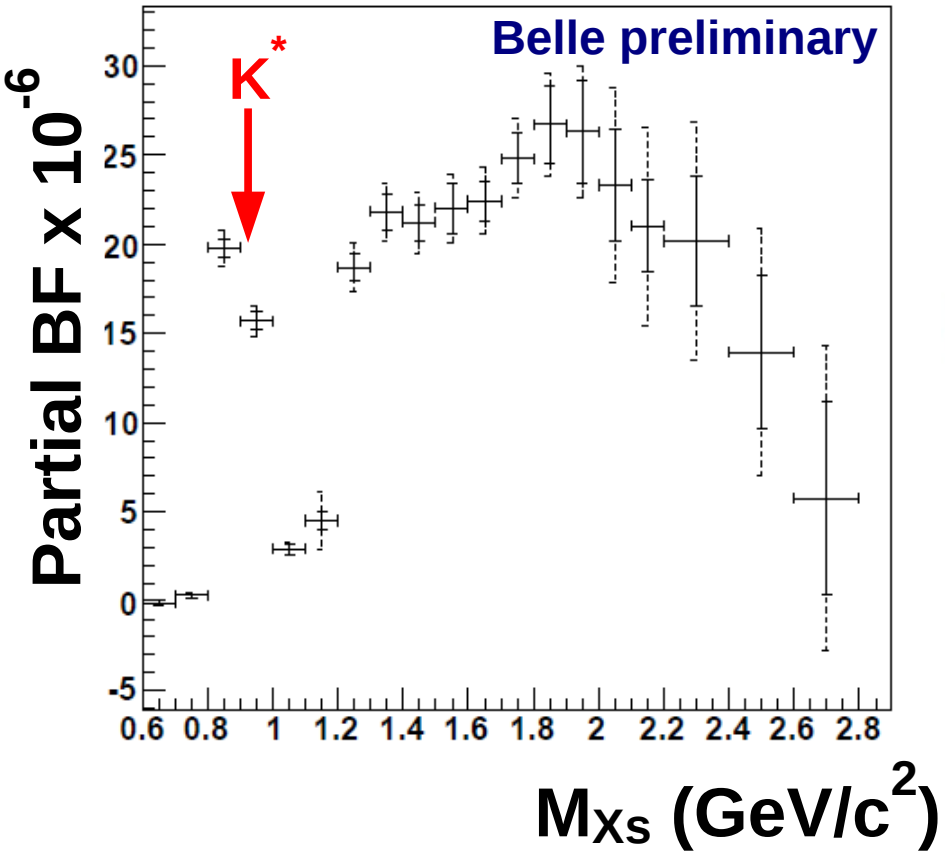
$B \to X_s \gamma$ (sum of exclusives), results

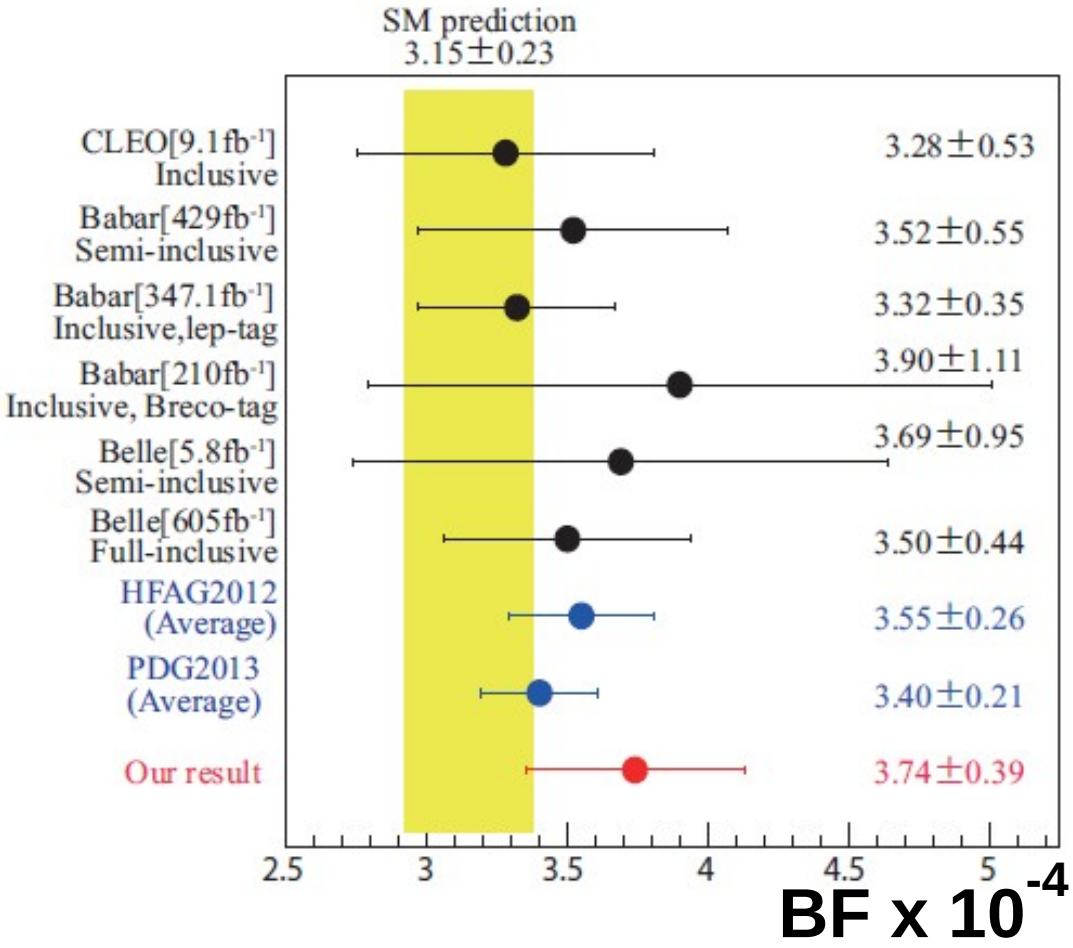
- Measured BF, 710 fb^{-1} (E^*_γ>1.8 GeV and M_{Xs}<2.8 GeV/c^2)

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

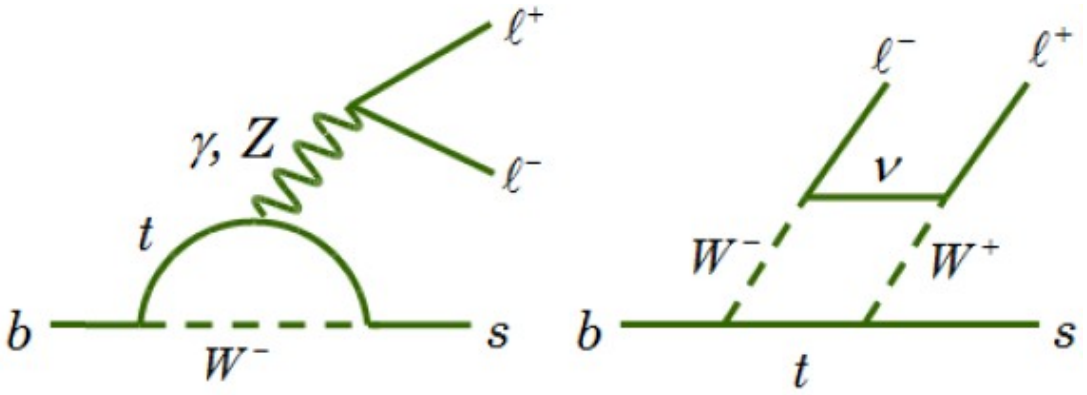
- Extrapolation to E^*_γ>1.6 GeV

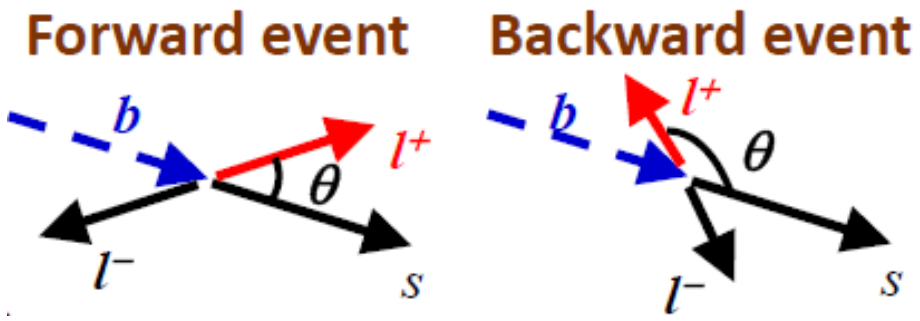
$$\mathcal{BR}(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$$





Forward-backward asymmetry (A_{FB}) in $B \to X_s l^+ l^-$



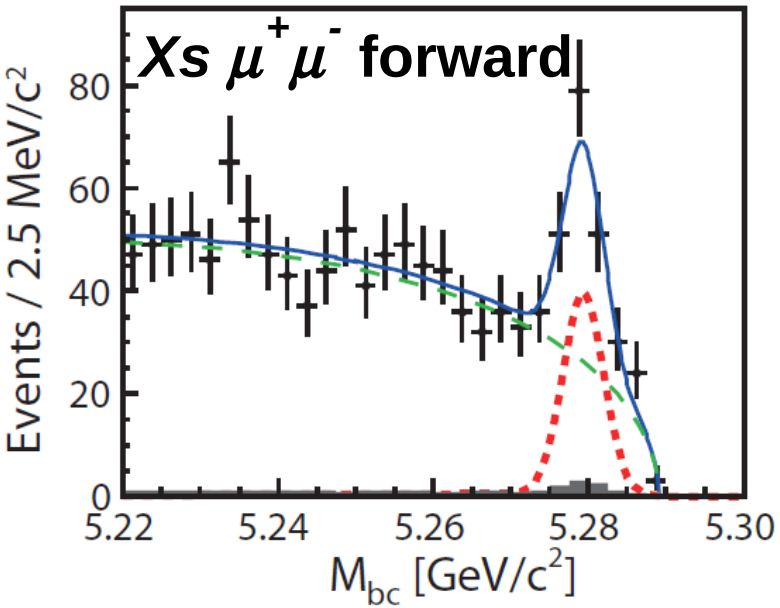


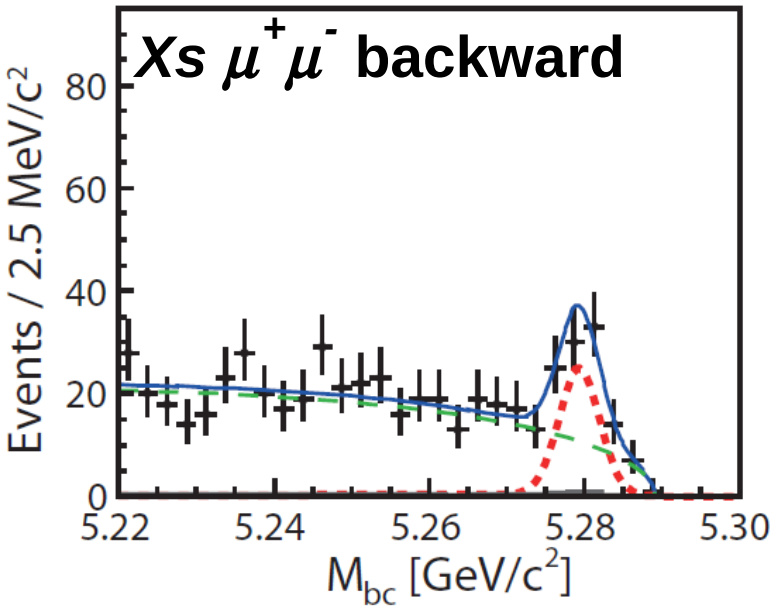
$$\mathcal{A}_{\rm FB} = \frac{N(\cos\theta>0) - N(\cos\theta<0)}{N(\cos\theta>0) + N(\cos\theta<0)}$$

- A_{FB} in $B \to K^{(*)} l^+ l^-$ measured (LHCb, Belle, BaBar). Agree with SM.
- First "sum of exclusives" measurement, has lower theory error!
- 10 exclusive modes used, 50% of total rate
  - K/K_S + up to 4π + e^+e^- or $\mu^+\mu^-$
- NN for suppression of continuum and $B\bar{B}$.
- Veto charmonium: J/Ψ and $\Psi(2S)$
- Measure A_{FB} as function of $q^2 \longrightarrow (q^2 = M^2_{\ell\ell})$

A_{FB} in $B \to X_s l^+ l^-$, signal extraction

- Extract signal: unbinned maximum likelihood fit to M_{bc}
- For e and μ, an each q^2 bin



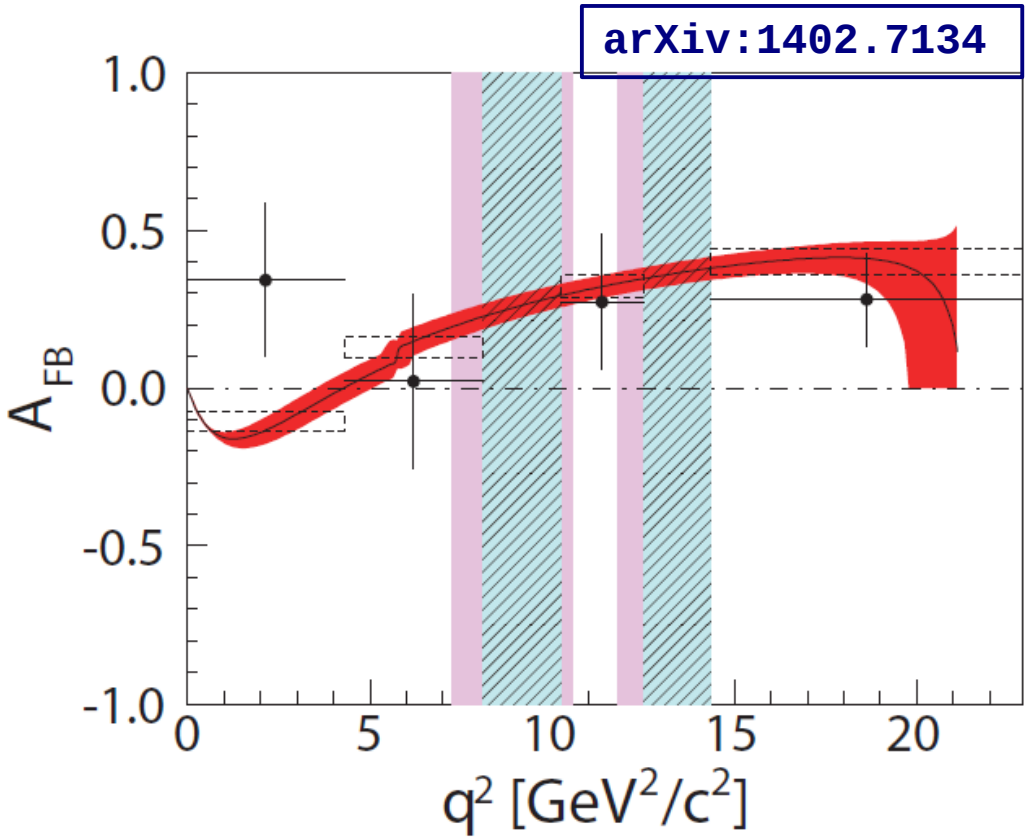


Signal + cross feed
Peaking BG
Combinatorial

Example for μ in $4.3<q^2<8.1$ [GeV^2]

- Low efficiency at low q^2 and $|\cos\theta|\sim1$, shifts value of A_{FB}. Correction α estimated with MC $A_{\rm FB} = \alpha \cdot A_{\rm FB}^{\rm raw}$
- Dominant systematics: α correction, estimation of peaking BG

A_{FB} in $B \to X_s l^+ l^-$, results



SM prediction

SM binned

J/Ψ, Ψ(2S) veto (e^+e^-)

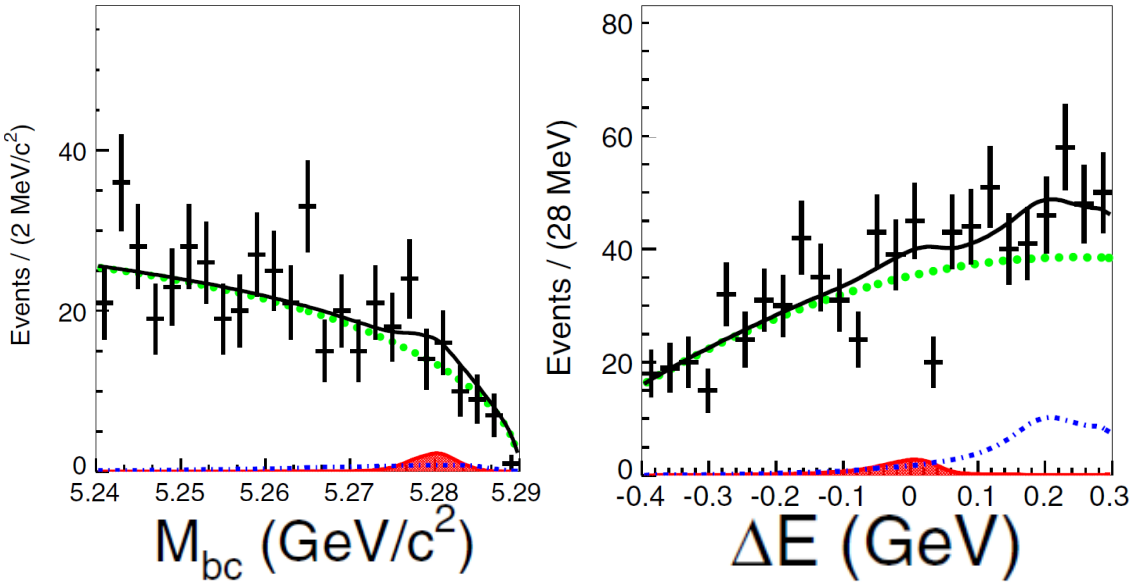
J/Ψ, Ψ(2S) veto ($\mu^+\mu^-$)

	stat.	syst.
bin 1	$0.34 \pm 0.24 \pm 0.02$	
bin 2	$0.04 \pm 0.31 \pm 0.05$	
bin 3	$0.28 \pm 0.21 \pm 0.01$	
bin 4	$0.28 \pm 0.15 \pm 0.01$	

- Consistent with SM, statistical uncertainty dominates
- First bin consistent with SM within 1.8σ
- In OPE, A_{FB} can be written as: $\mathcal{A}_{\rm FB} \propto -C_{10} \cdot \Re\mathfrak{e}\left(2C_7 + \frac{q^2}{m_b^2} C_9\right)$
- In high q^2 region, exclude $C_{10}*C_9>0$ with 2.3σ

Search for $B^0 \to p^+ \bar{\Lambda} \pi^- \gamma$

- Exclusive measurement of $b \to s\gamma$
- Observed hierarchy in baryonic B decays: 4 Body > 3 Body > 2 Body
  - $b \to s$ $\mathcal{B}(B^+ \to p\bar{\Lambda}\pi^+\pi^-) > \mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-) > \mathcal{B}(B^+ \to p\bar{\Lambda})$
  - $b \to c$ $\mathcal{B}(B^0 \to p\bar{\Lambda}_c\pi^+\pi^-) > \mathcal{B}(B^+ \to p\bar{\Lambda}_c\pi^-) > \mathcal{B}(B^0 \to p\bar{\Lambda}_c)$
    - Measured $b \to s\gamma$: $\mathcal{B}(B^+ \to p\bar{\Lambda}\gamma) = (2.45^{+0.44}_{-0.38} \pm 0.22) \times 10^{-6}$ PRD.76.052004



-+++: Data —: Fit result
: Signal + Self-crossfeed
: Continuum
: $B^+ \to p\bar{\Lambda}\pi^0 + B^+ \to p\bar{\Lambda}\gamma$

2D fit in Mbc and ΔE:

$$M_{\rm bc} \equiv \sqrt{E^2_{beam} - |\vec{p}_B|^2}$$
$$\Delta E \equiv E_B - E_{beam}$$

$$N_{\rm sig} = 9.5^{+11.5}_{-10.7}({\rm stat}) \longrightarrow \mathcal{B}({\rm B} \to {\rm p}^+\bar{\Lambda}\pi^-\gamma) < 6.5 \times 10^{-7}$$

90% CL limit

PRD 89, 051103(R) , 2014

- Expected hierarchy is not observed

Summary

- **CP asymmetry in $B \to X_{(s+d)}\gamma$** NEW
  - Most precise result
  - Measured as a function of Eγ
  - Consistent with SM, for Eγ>2.1 GeV $A_{CP} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2}$

  Branching fraction $B \to X_s\gamma$, sum of exclusives NEW
  - Consistent with SM $\mathcal{BR}(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$

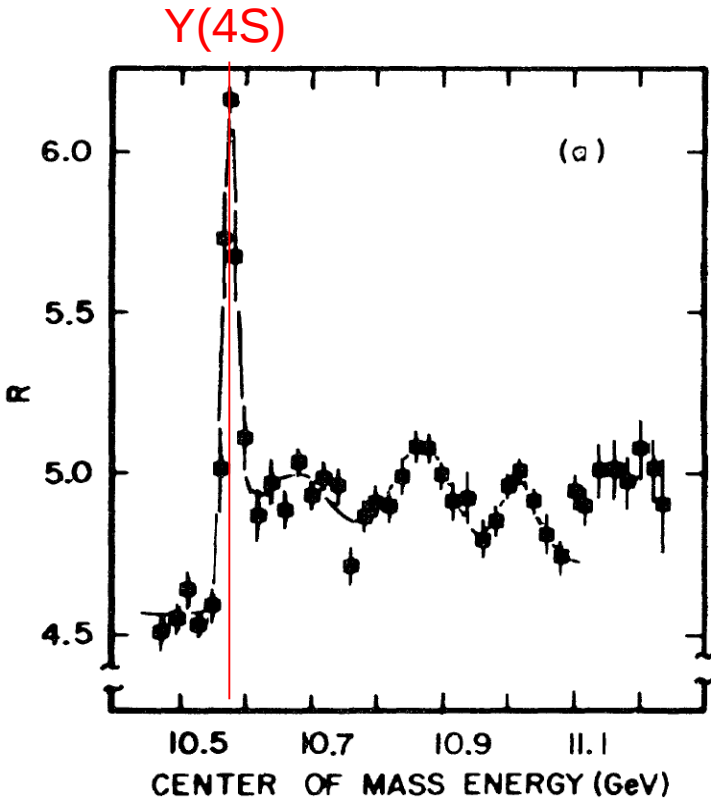
- **Forward- backward asymmetry in $B \to X_s l^+ l^-$**
  - First measurement!
  - High q^2 region excludes $C_{10}{*}C_9 > 0$ with 2.3σ

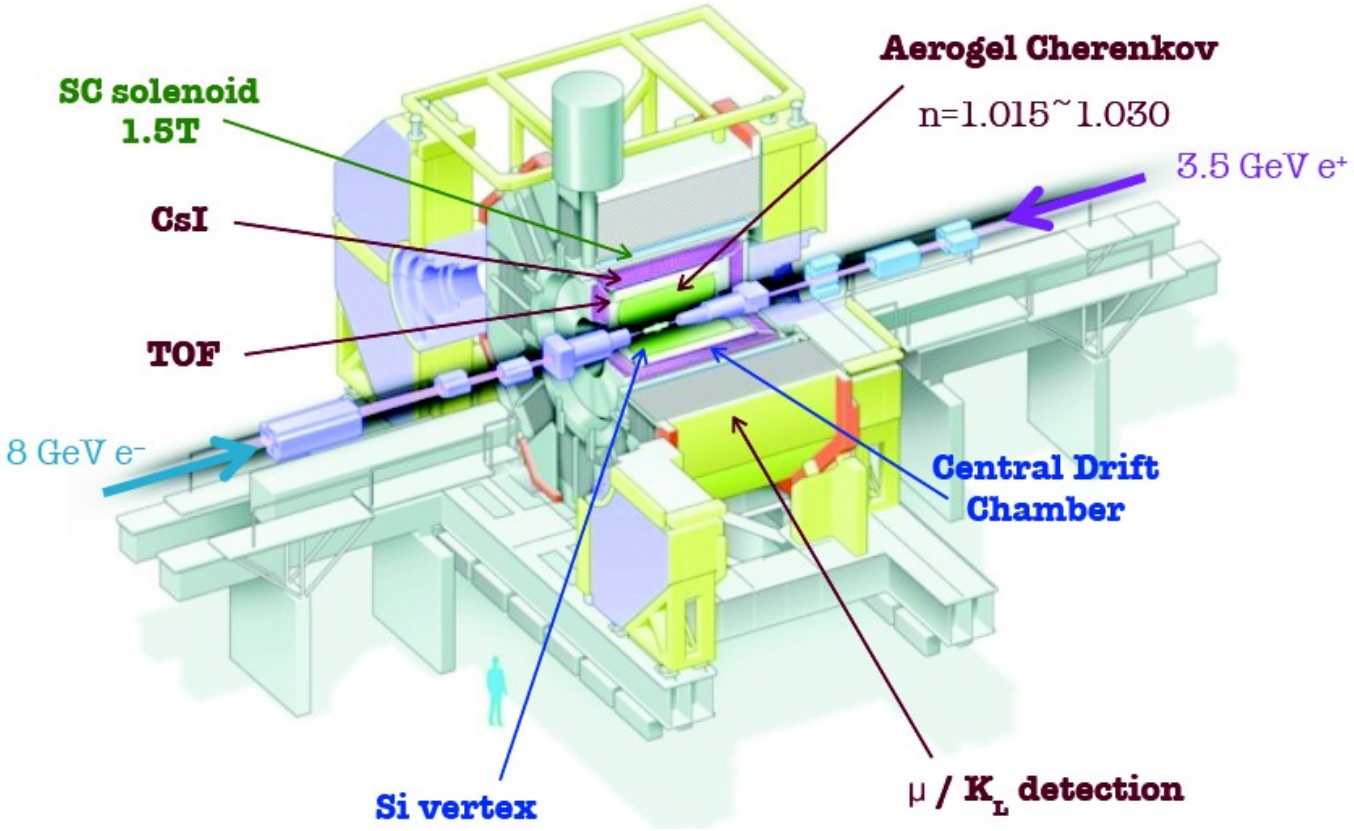
- **Search for $B^0 \to p^+ \bar{\Lambda} \pi^- \gamma$**
  - Upper limit at 90% CL $\mathcal{B}(B \to p^+ \bar{\Lambda} \pi^- \gamma) < 6.5 \times 10^{-7}$

BACKUP

Belle @ KEKB-B factory

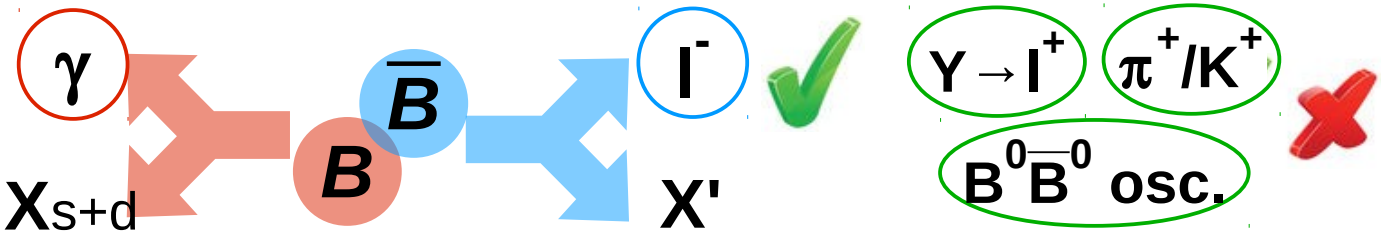
- Asymmetric e+e- collider





$$\begin{array}{lllll} \text{On resonance:} & \sqrt{s} = 10.58\text{GeV} & e^+e^- \to \Upsilon(4S) \to B\overline{B} & 710\text{fb}^{-1} \\ \text{Off resonance:} & \sqrt{s} = 10.52\text{GeV} & e^+e^- \to q\overline{q}(q = u, d, s, c) & 90\text{fb}^{-1} \end{array}$$

Wrong tag factor



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

Wrong tag factors

$$\omega = \omega_{\text{osc}} + \omega_{2nd} + \omega_{\text{misID}}$$

Oscillation probability of B^0 — Fraction of B^0B^0 from $\Upsilon(4S)$

$$\omega_{\text{osc}} = \chi_d \cdot f_{00}$$

$$\omega_{\text{osc}} = (0.0913 \pm 0.0015)$$
$$\omega_{\text{misID}} = (0.0069 \pm 0.0034)$$
$$\omega_{2\text{nd}} = (0.0431 \pm 0.0036)$$

Mainly π/K faking μ

Semileptonic decays of charm

$\overline{B} \to DX \qquad D \to Yl^+\nu$

$$\omega = (0.1413 \pm 0.0052)$$

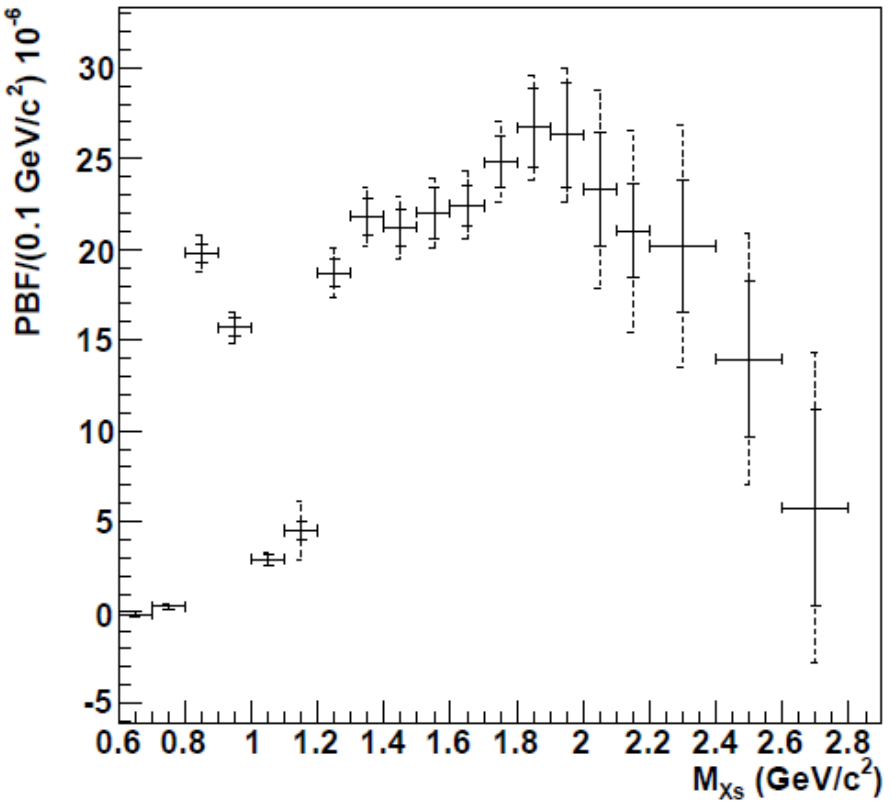
Reconstructed $B \to X_s \gamma$ modes

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 $B \to X_s \gamma$ BF

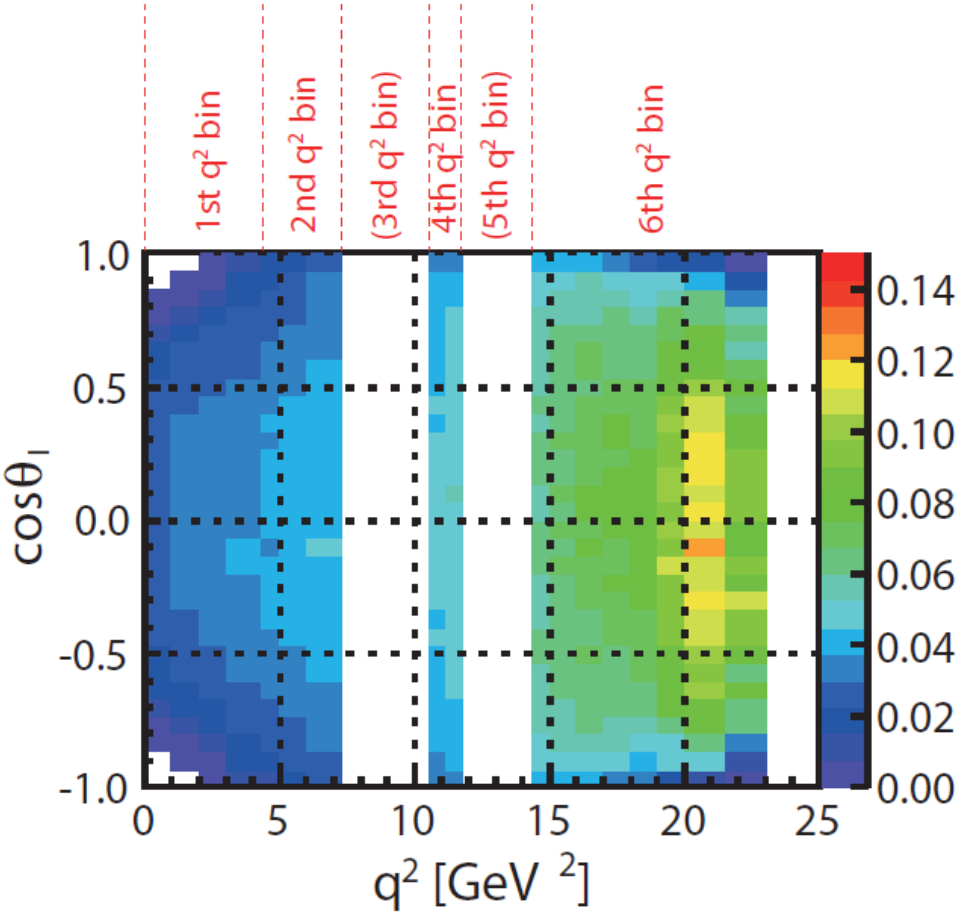
Table 9.12: The partial branching ratio on M_{X_s}

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

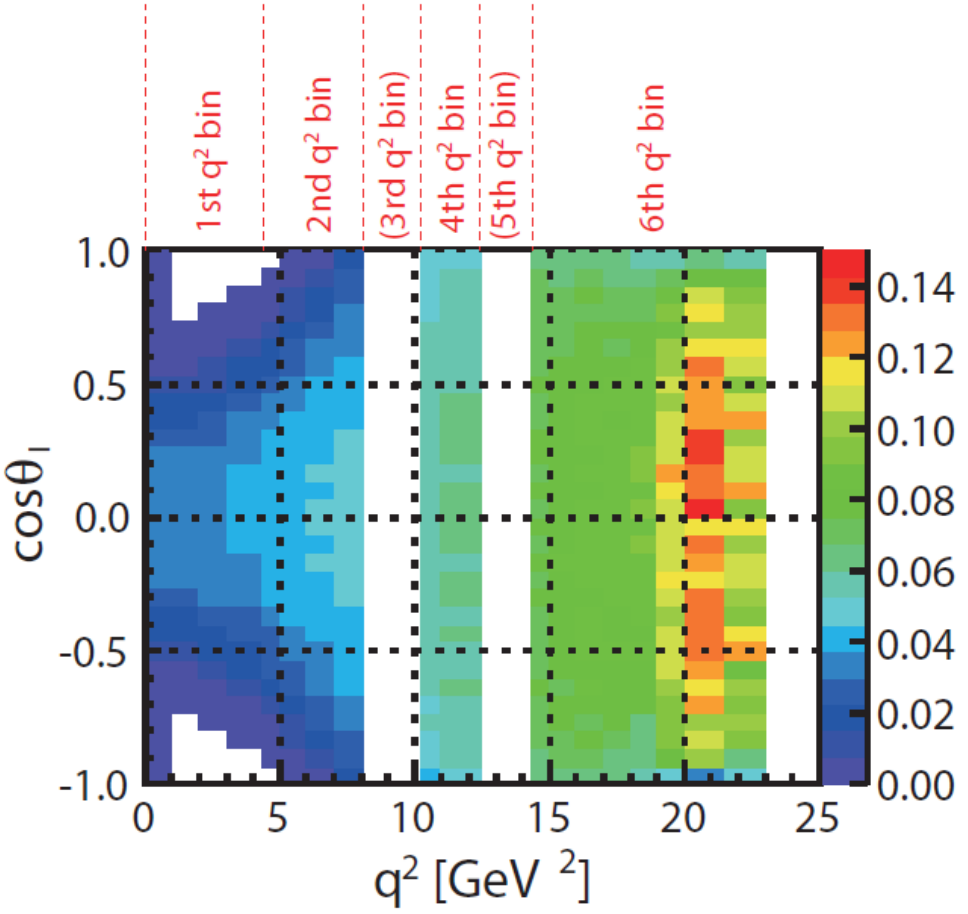


(a) Partial branching ratio.The first solid error is the statistical one and the second dashed error is a quadratic sum of the statistical and systematic errors.

Reconstruction efficiency $B \to X_s l^+ l^-$



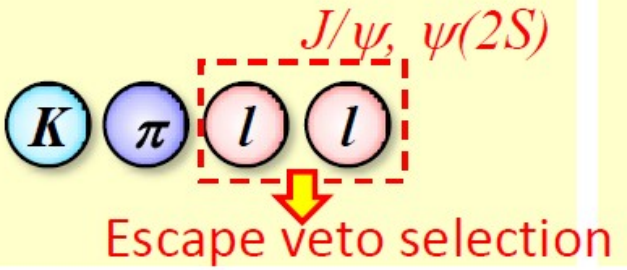
$B \to X_s e^+ e^-$



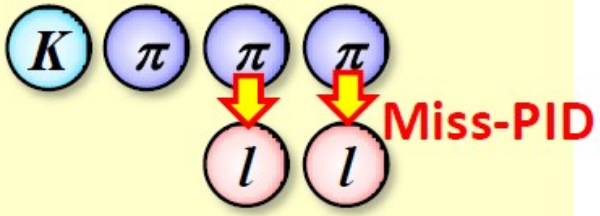
$B \to X_s \mu^+ \mu^-$

Peaking background in $B \to X_s l^+ l^-$

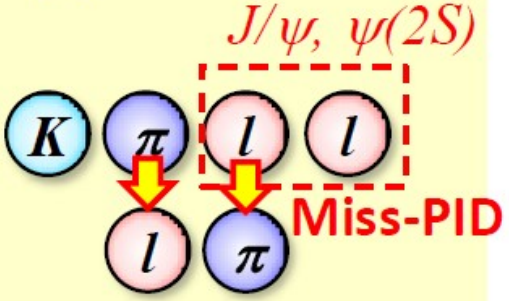
1. charmonium



2. Double miss-PID



3. Swapped miss-PID



Systematic uncertainties A_{FB}

Sources of uncertainties	1st	2nd	3rd	4th
Translation from $\mathcal{A}_{\rm FB}^{\rm raw}$ to $\mathcal{A}_{\rm FB}$	0.019	0.013	0.007	0.003
Peaking background	0.004	0.050	0.007	0.002
Signal modeling	0.004	0.002	0.006	0.006
Signal shape and self cross-feed	0.002	0.002	0.002	0.002
Total	0.020	0.052	0.012	0.007

Systematic uncertainties $B^0 \to p^+ \bar{\Lambda} \pi^- \gamma$

TABLE I. Summary of the systematic uncertainties (in %) on the branching fraction.

$N_{B\bar{B}}$	1.4
Tracking	1.4 (4 tracks)
Hadron identification	0.6 (2 protons)
	1.1 (pion)
Λ selection	3.3
Photon selection	2.2
Reconstruction efficiency (MC statistics)	2.2
$\mathcal{B}(\Lambda \to p\pi^-)$	0.8
$\mathcal{R}$ selection	1.9
PDF shape	4.1
Signal decay model	5.1
Rare B decays	8.2
Total	11.8