Measurements of Radiative and Electroweak Penguin Decays of B at Belle

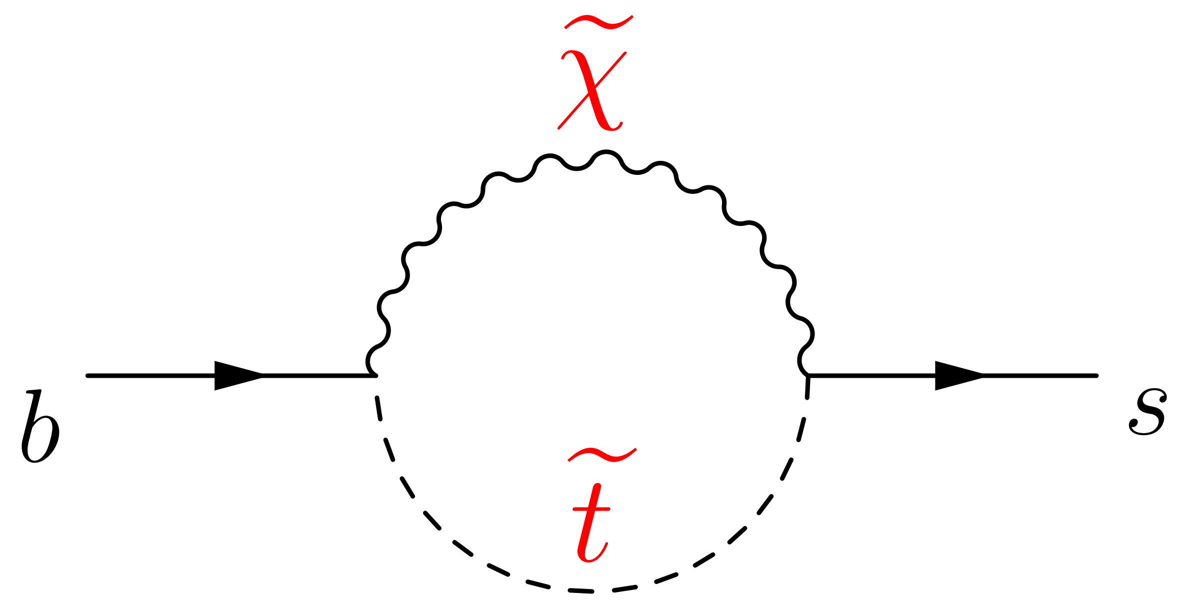
Jared Yamaoka | PNNL
on behalf of the **Belle Collaboration**
2 Dec 2014

Belle

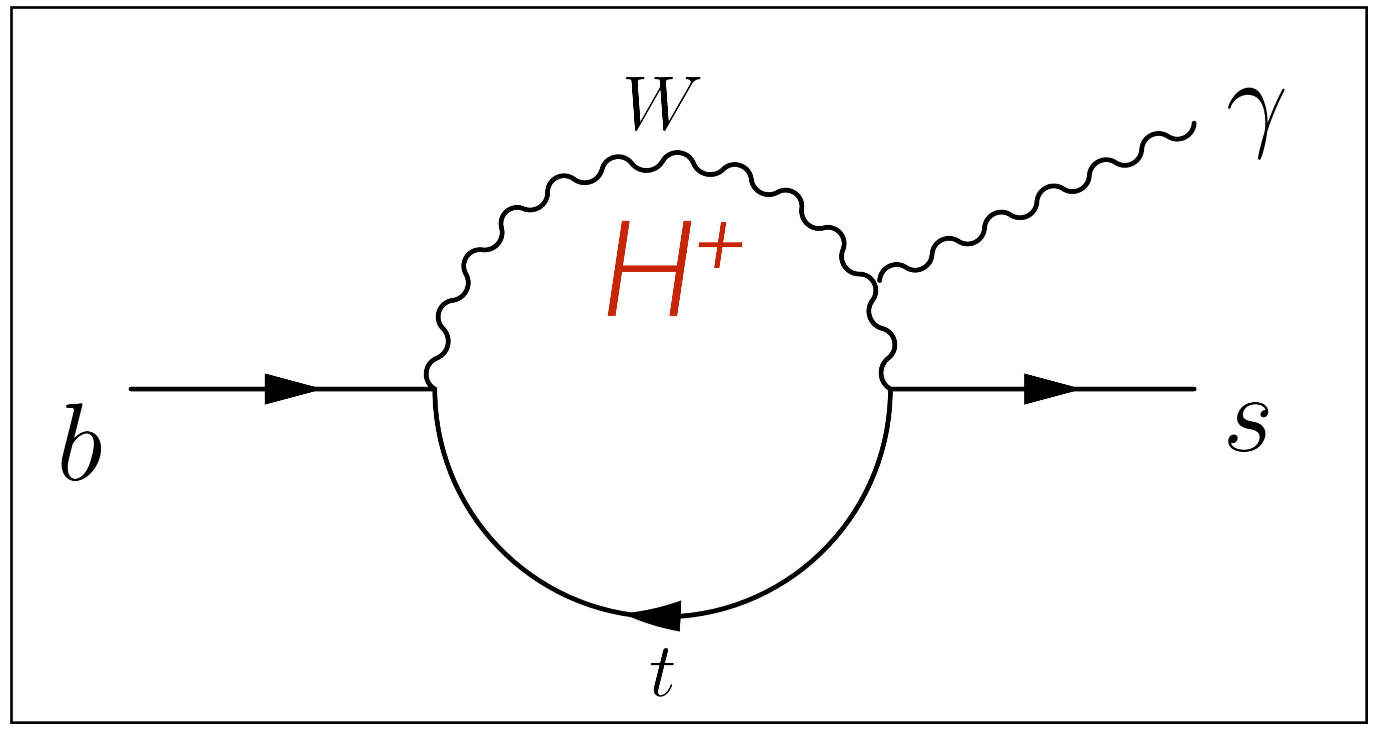
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

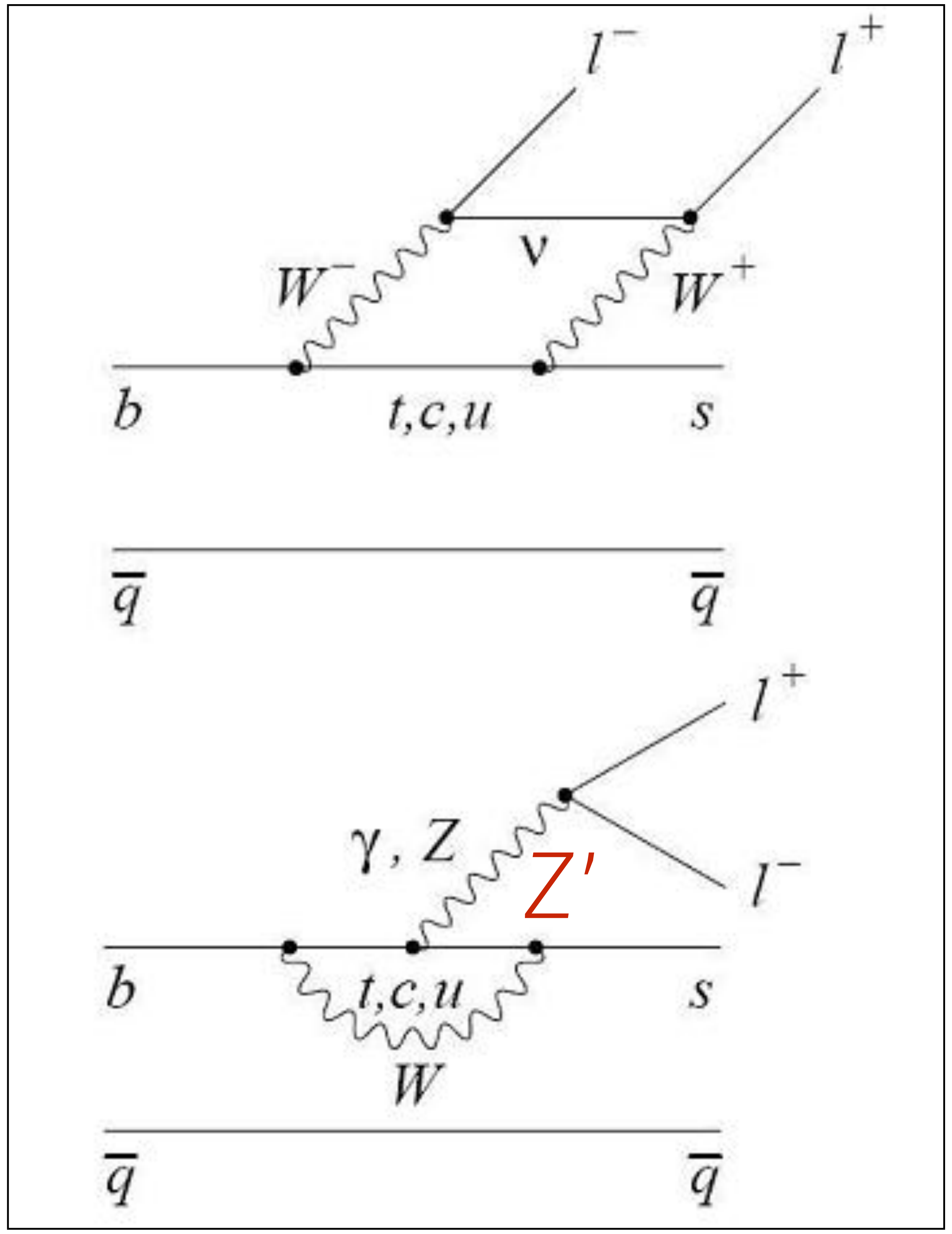
$b \to s$ Electroweak Decay

- $b \to s$: Flavor Changing Neutral Current (FCNC). Not possible at tree level.
- Penguin diagrams: Sensitive to new particles entering the loops.



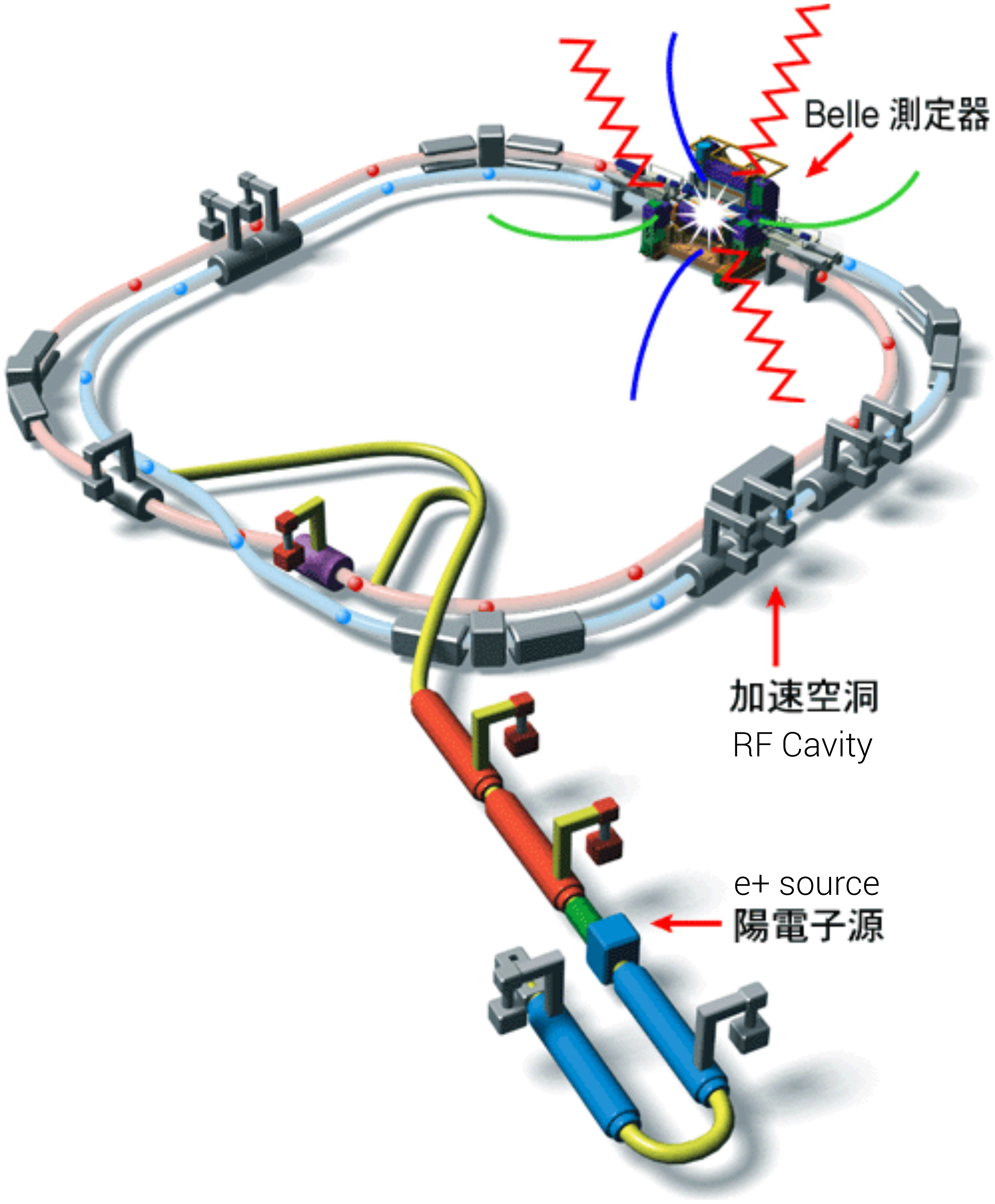
- Beyond the SM contributions can be large **Sensitive to NP on the TeV scale**

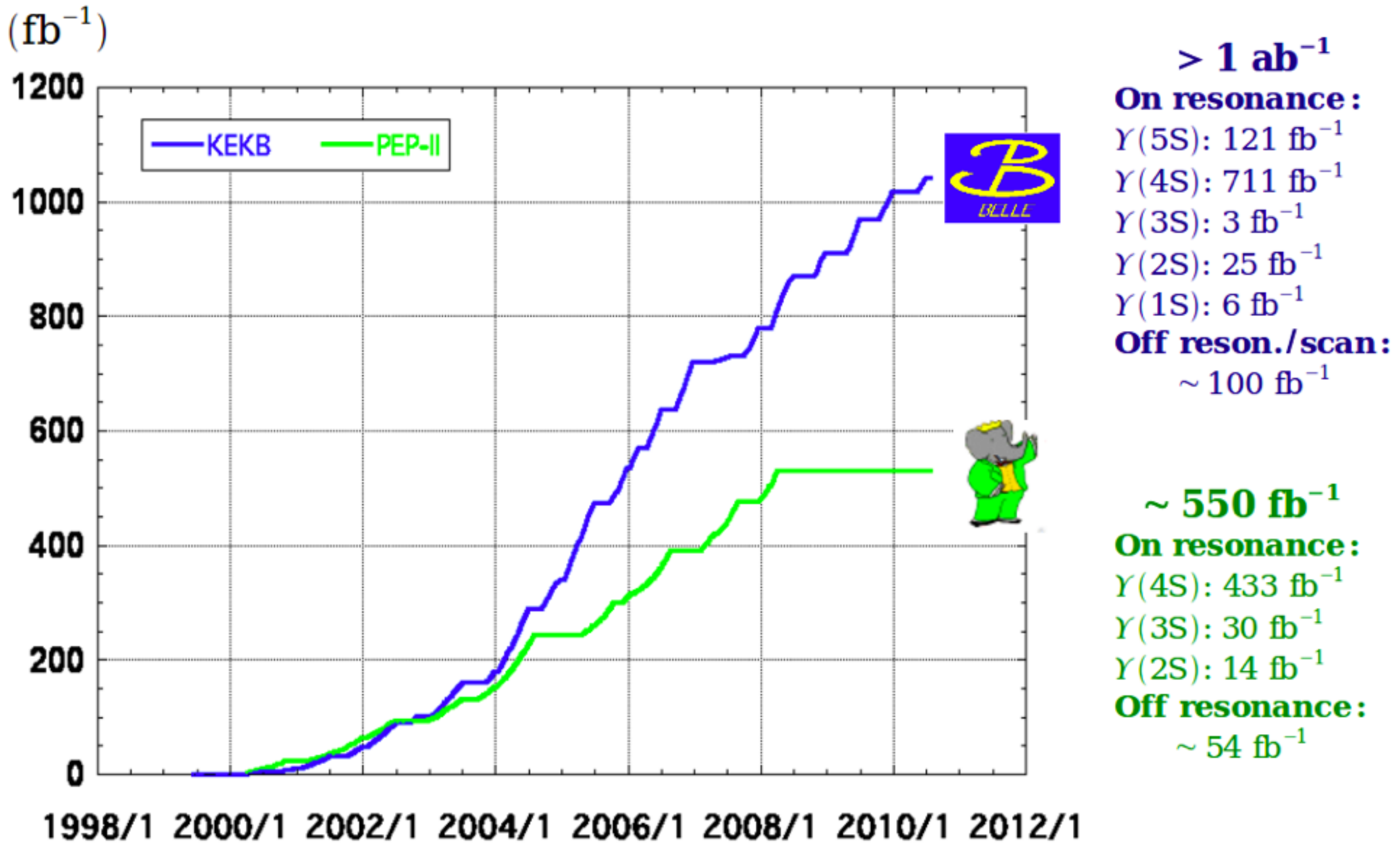




Observable via: Decay Rate
Kinematical Distributions (A_{fb})

KEKB at KEK

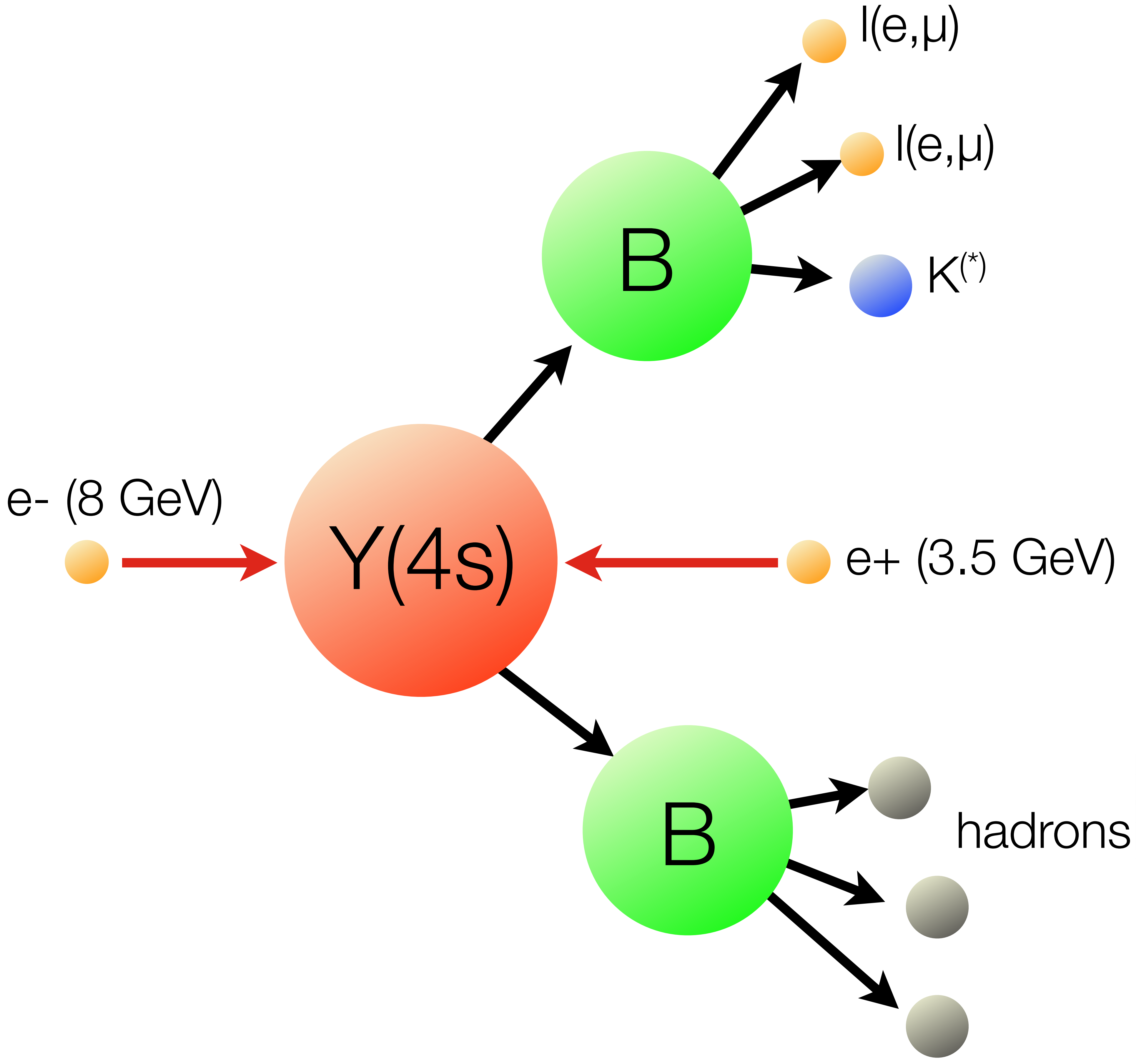


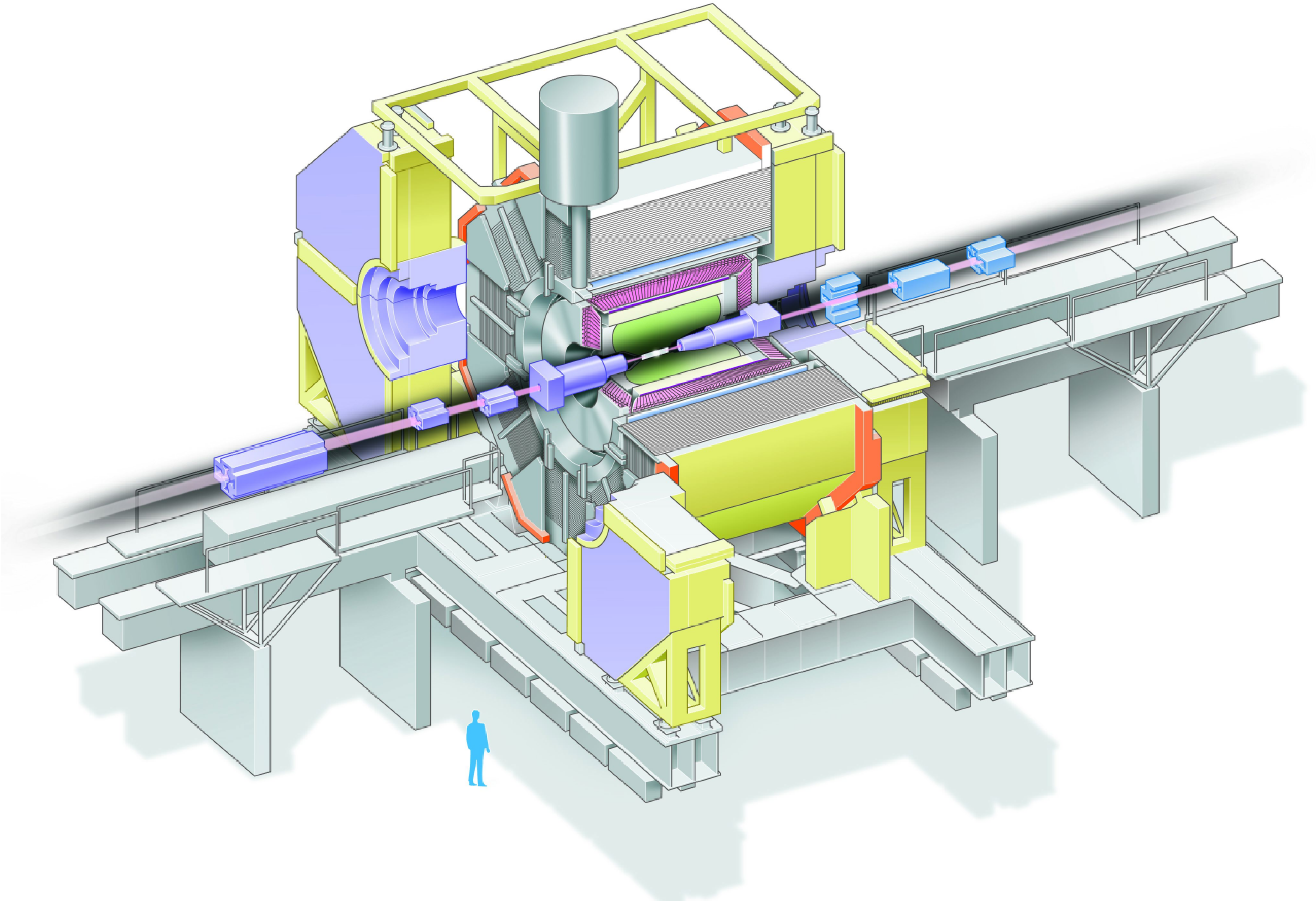


- Results use World's Largest Y(4s) Data Set
  - 772 Million BB pairs
- ~100 fb^{-1} off resonance can used for background estimate (*see* $B \to X_{s+d}\,\gamma$)
- **Currently being upgraded, SuperKEKB to collect ~50 times the current data set.**

Belle Detector

- Tracking
- PID
- Energy Measurement
- K_L/Muon





Belle Detector

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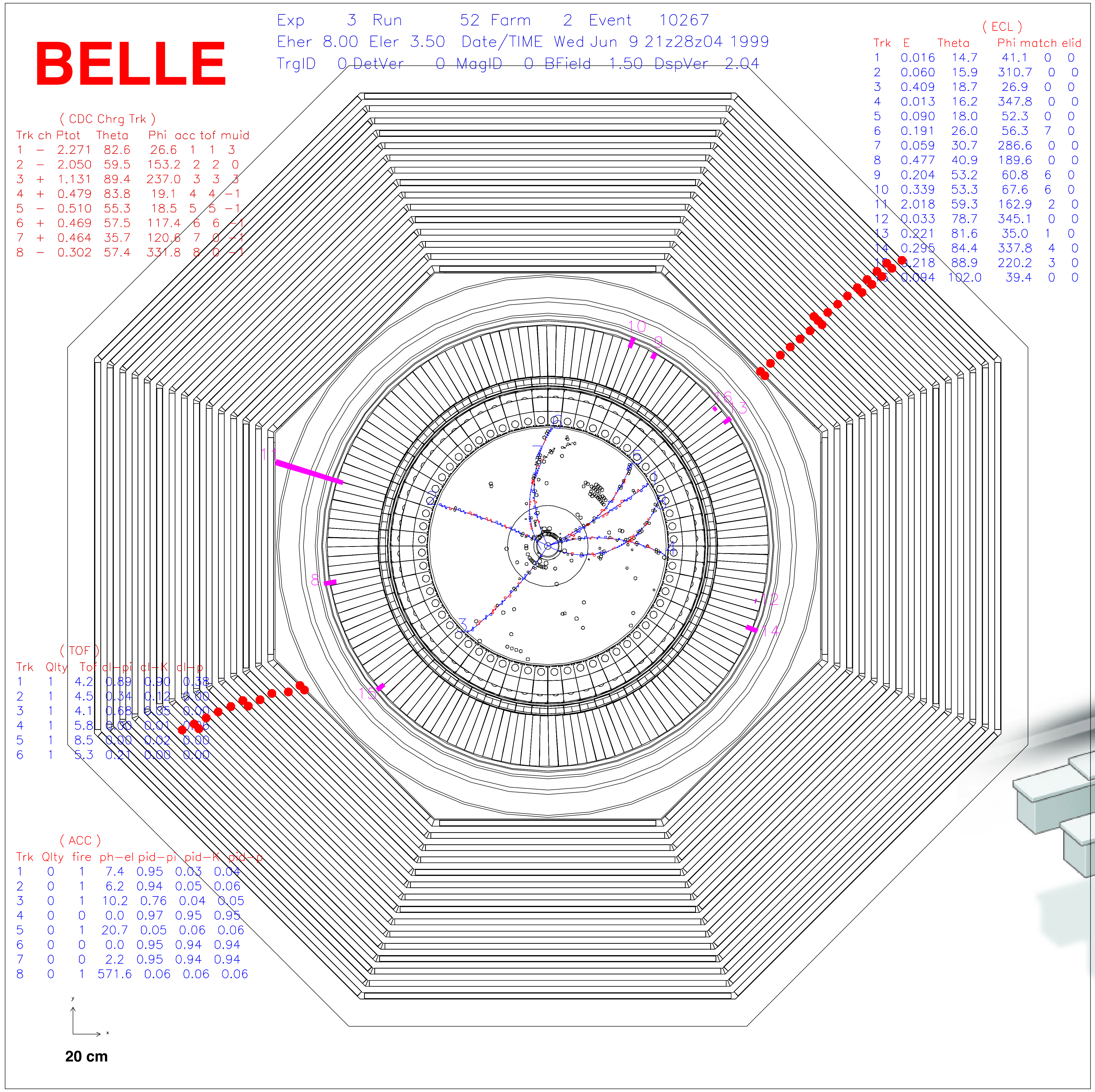
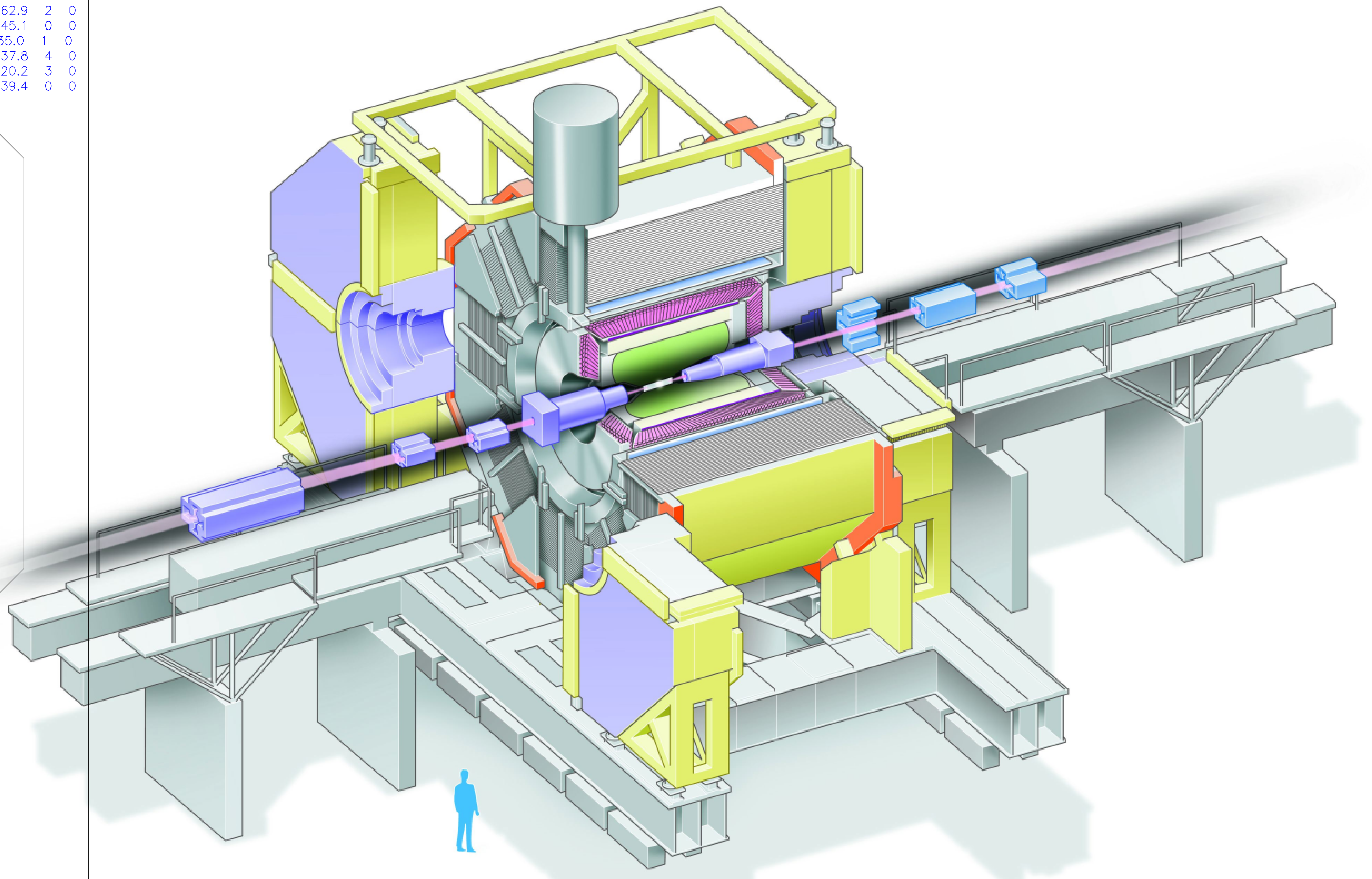
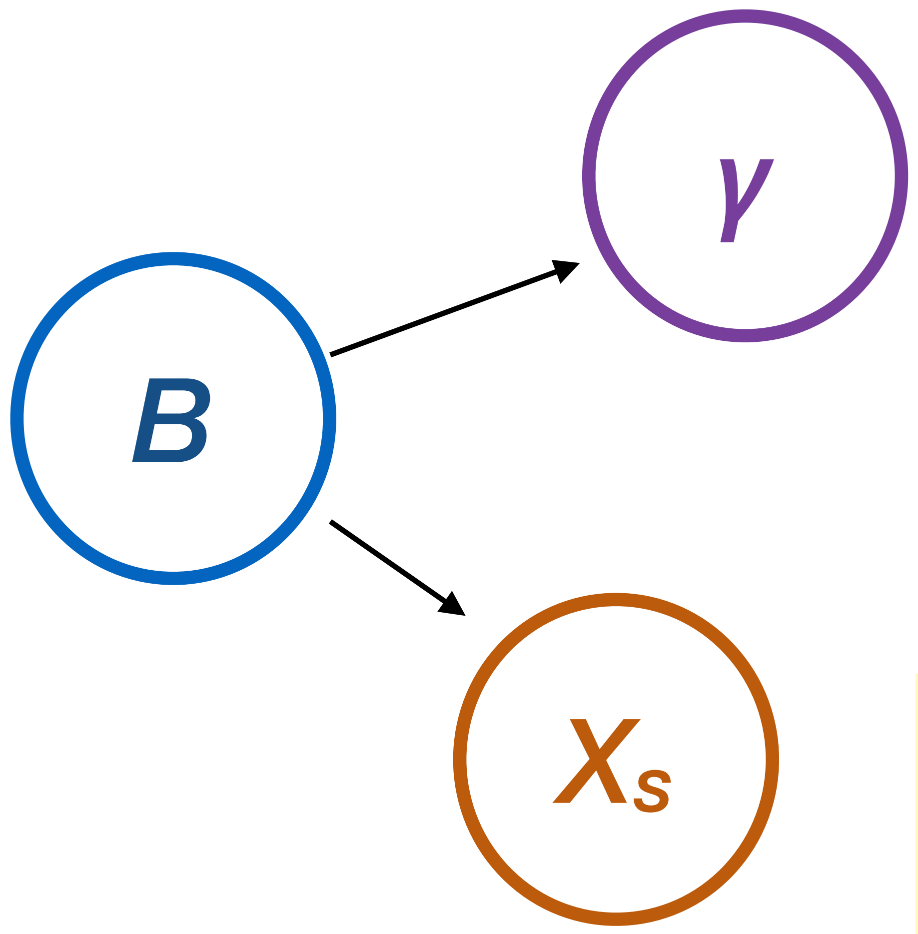




B→$X_s\gamma$ with Sum of Exclusive



$E^*_\gamma > 1.8$ GeV (CM)

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

- Inclusive has less theoretical uncertainty from hadronization.
- Belle full inclusive: PRL 103, 241801 (2009)

$$\mathrm{BF}(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$$

- Use **sum of exclusive**
  - Different systematics
  - **38** exclusive $\boldsymbol{X_s}$ states (~**70**% of total)
- Signal yields are extracted in bins of M_{Xs} between 0.6-2.8 GeV/c^2

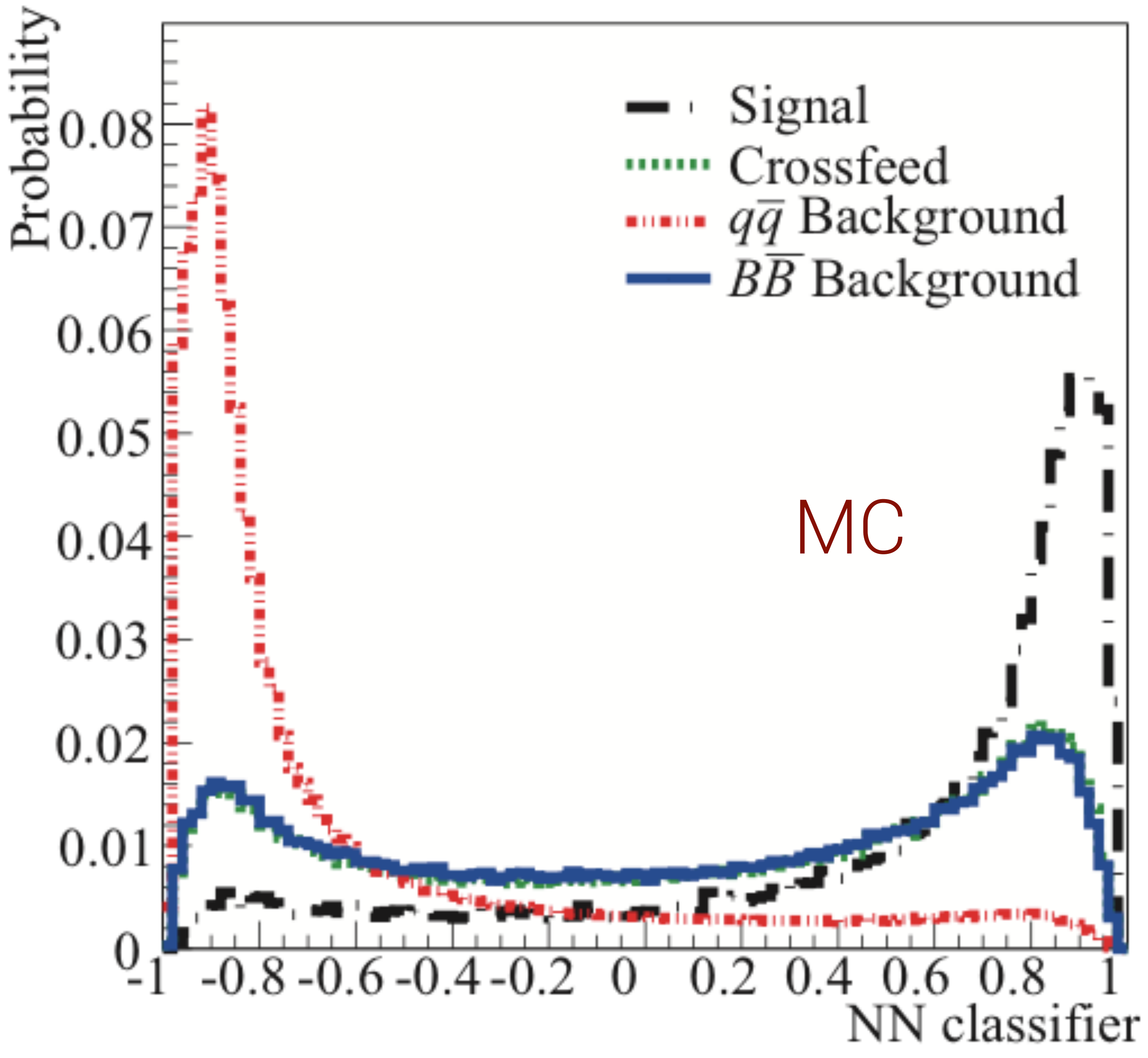
Table 4.1: Reconstructed X_s final states

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	$K_s\eta\pi^+\pi^-$		

$B \to X_s\gamma$: Background Suppression

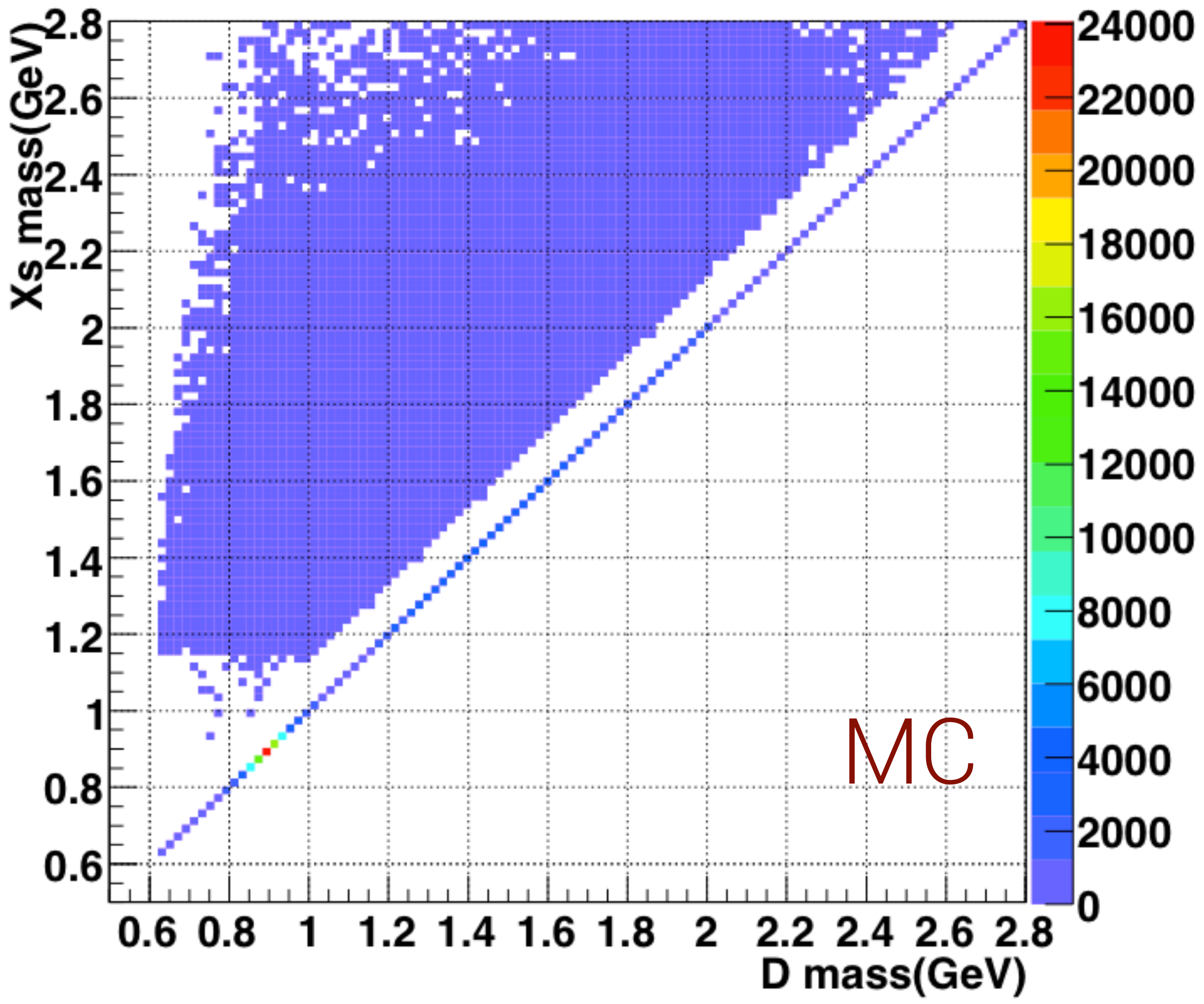
Continuum: e+e-→qq (q=u,d,s,c)

- Suppressed with Neural Network
  - Topological and Kinematic variables

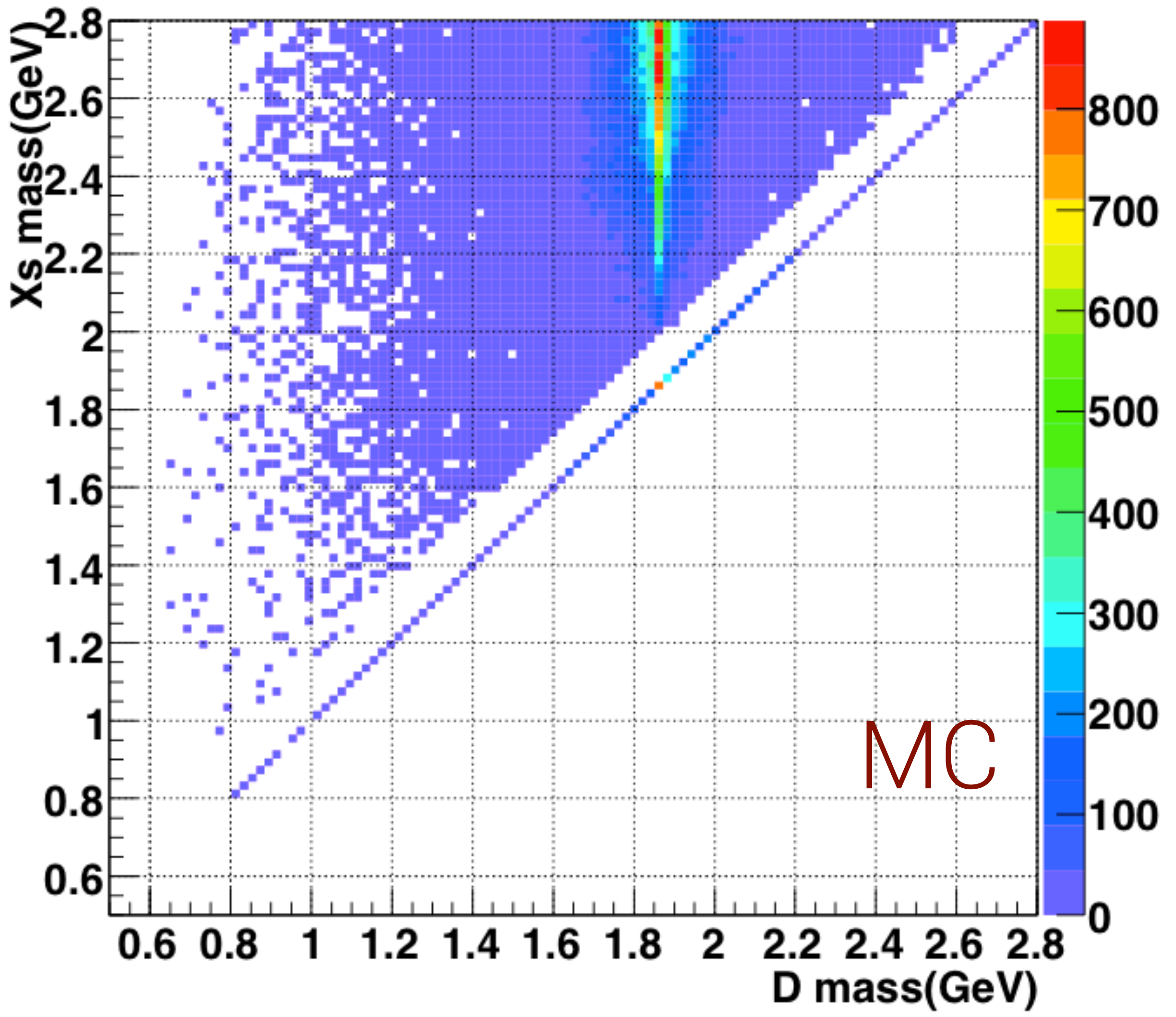


Peaking background from D decays is suppressed with a D veto

$$B \to D^{(*)} \rho^+$$
$$\rho^+ \hookrightarrow \pi^+\pi^0$$
$$D^{(*)} \hookrightarrow K\pi\pi$$



(a) Signal

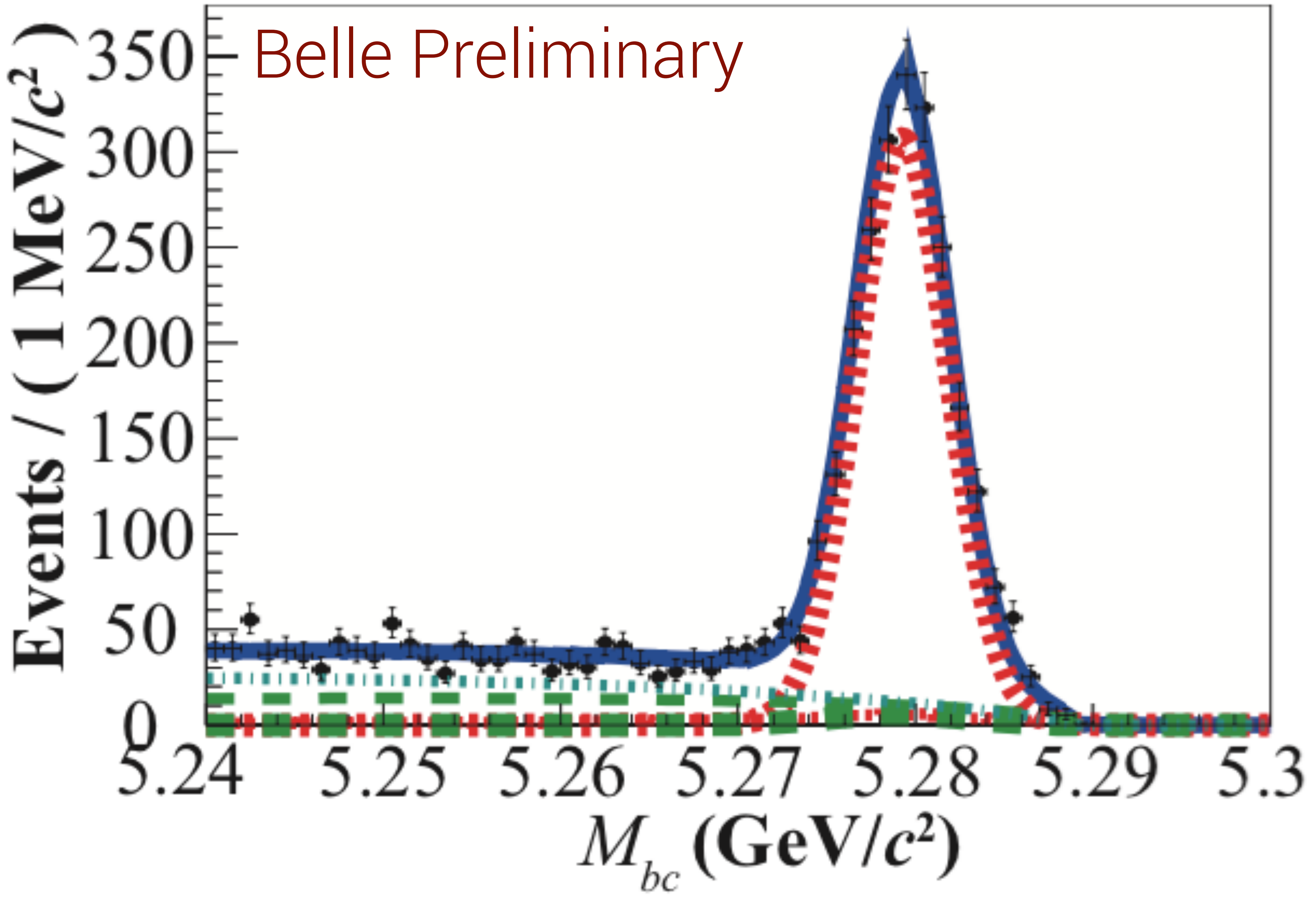


(b) $B\overline{B}$ background

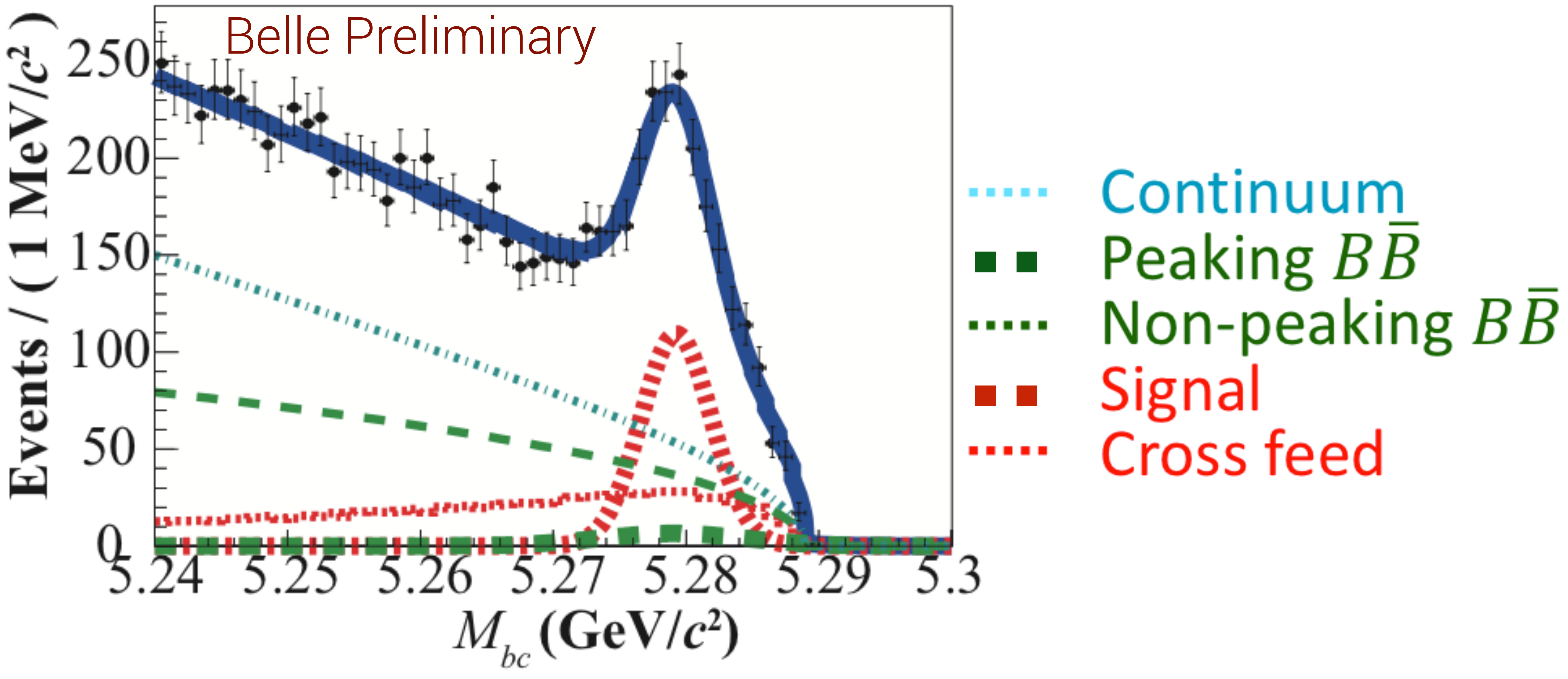
B→$X_s\gamma$: Signal Extraction

- Branching fraction is extracted by **M_{bc}** fit in **19 M_{X_s} bins**
  - 0.6 < M_{X_s} < 2.8 GeV/c^2

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



(c) $0.8 < M_{X_s} < 0.9$ (GeV/c^2)



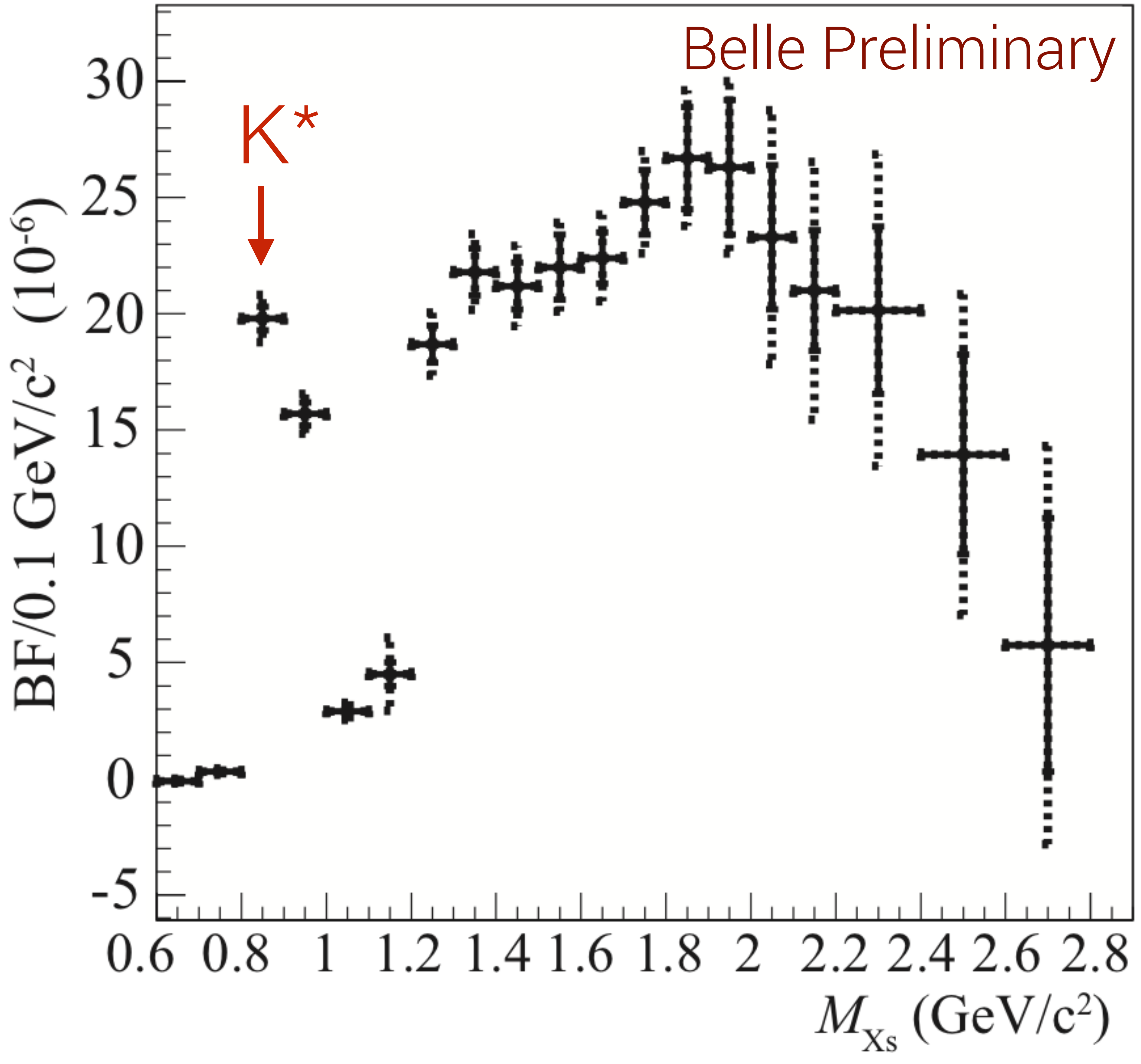
(k) $1.6 < M_{X_s} < 1.7$ (GeV/c^2)

$B \rightarrow X_s \gamma$: Results

With M_{X_s} < 2.8 GeV/c² (E^*_γ > 1.9 GeV)

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

Belle Preliminary



- **Systematics**
  - Calibrate X_s hadronization
    - Signal efficiency depends on model
    - Pythia parameters are tuned by comparing data with MC
  - Missing modes uncertainty
    - Estimated using different Pythia parameters

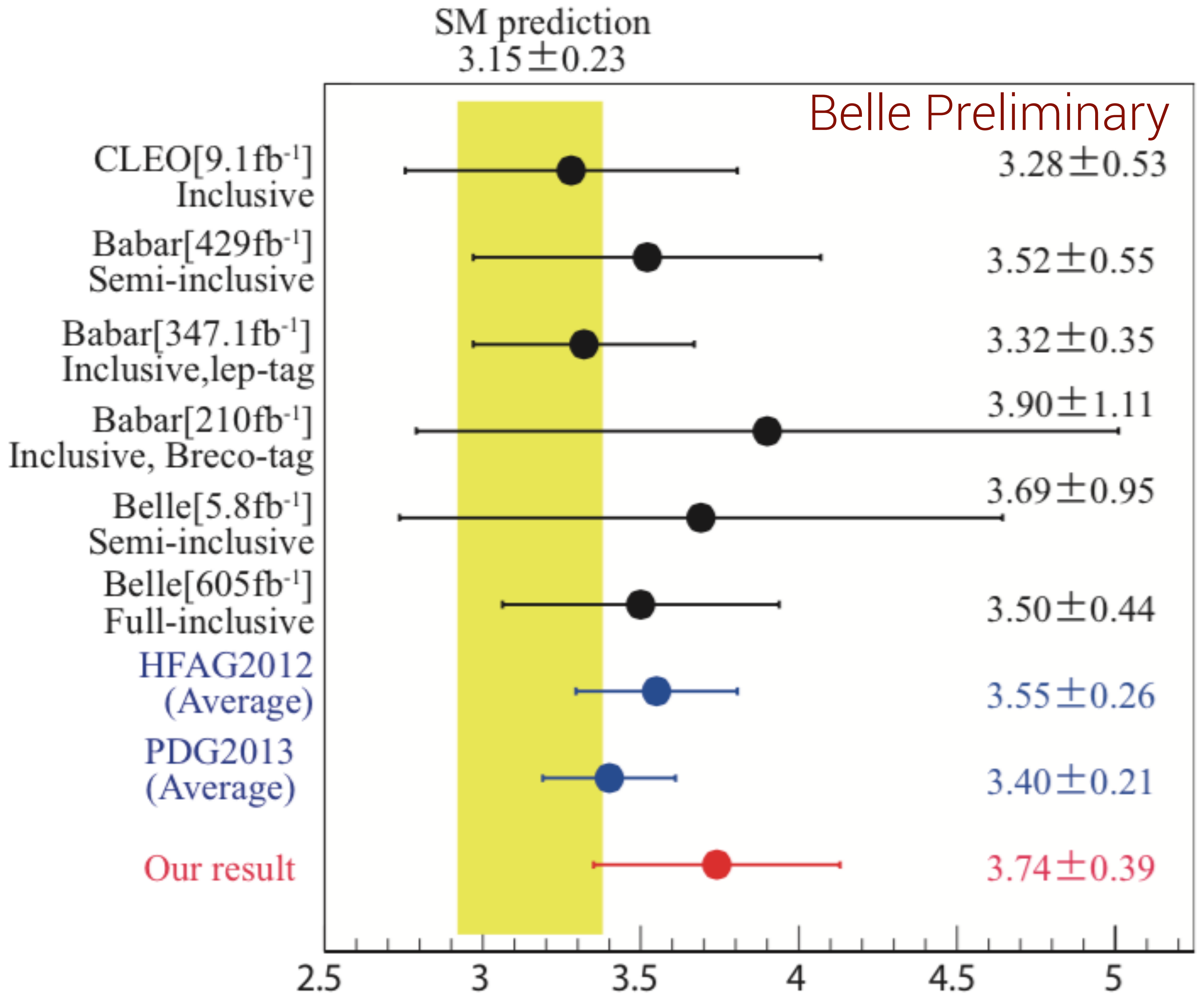
Source	Systematic uncertainty (%)
$B\overline{B}$ counting	1.37
Detector response	2.98
Background rejection	3.38
M_{bc} PDF	5.06
Hadronization model	6.66
Missing mode	1.59
Total	9.3

$B \to X_s \gamma$: Comparison to SM

Extrapolated BF to E^*_γ > 1.6 GeV to compare with the SM prediction

$$\mathcal{B}(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4} \quad (E^*_\gamma > 1.6\ GeV)$$

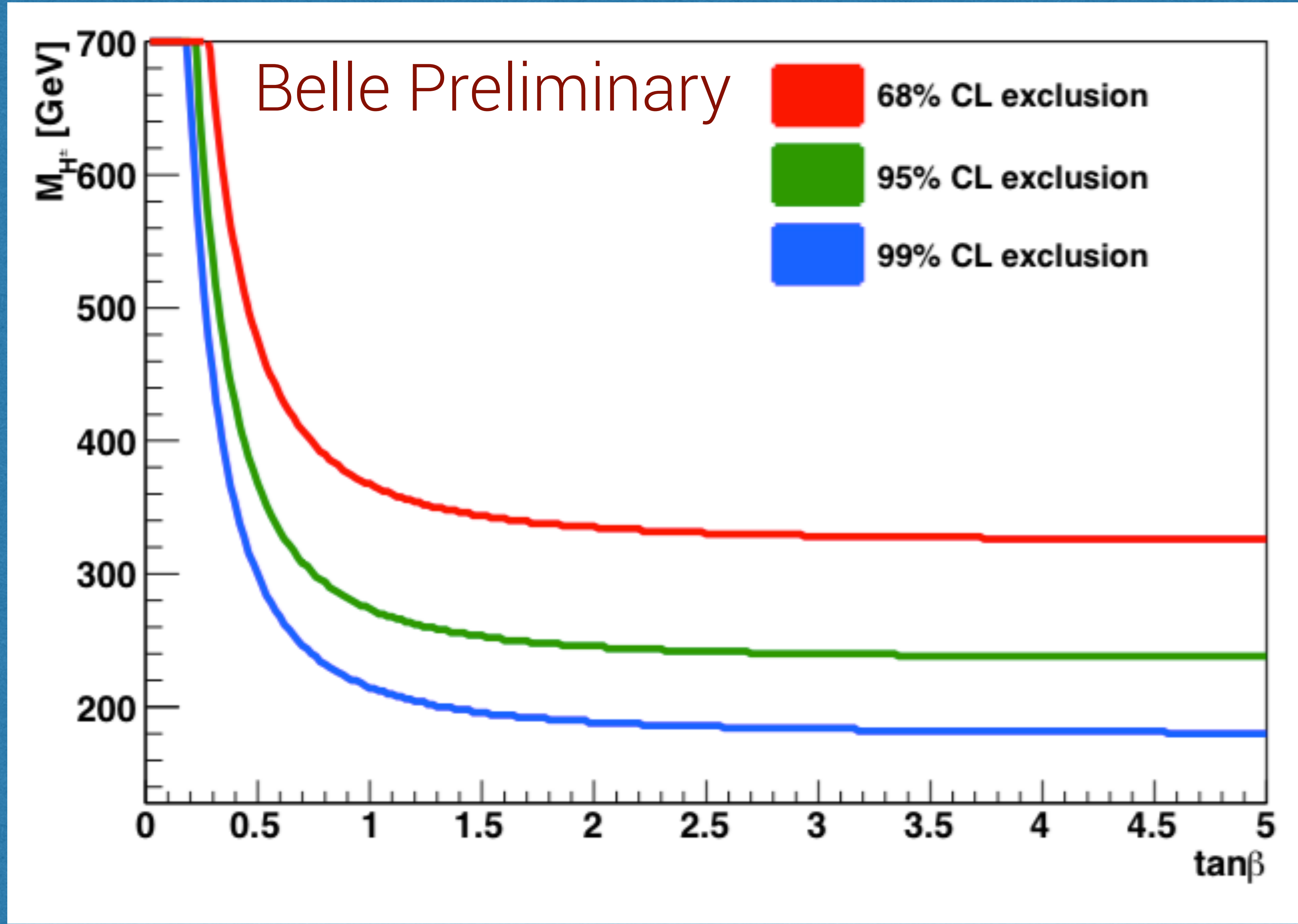
Belle Preliminary



Consistent with the SM prediction within 1.3σ

PRL 98, 022002 (2007)

Interpreting in the 2HDM we can constrain the mass in the M_{H+}/tanβ plane



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

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

- Cancelation due to unitarity
- Small theory uncertainty

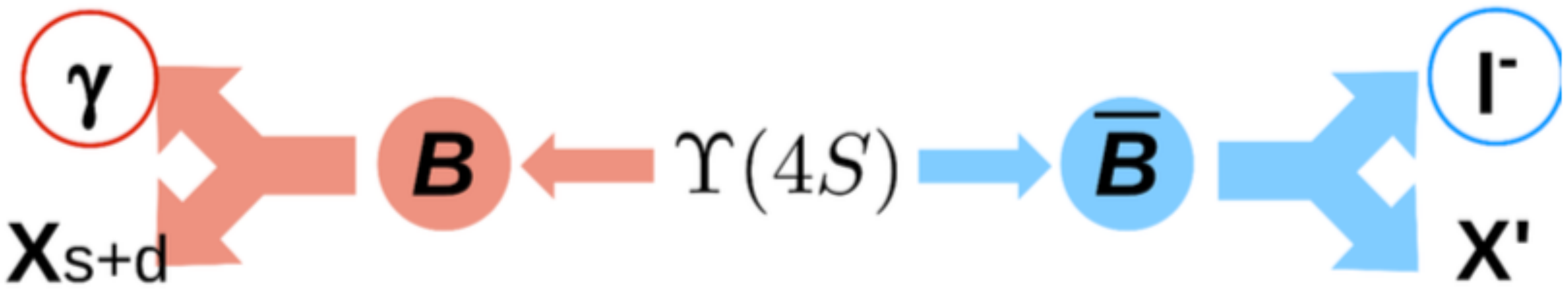
A_{CP} expected to be ~0

Channel	BF	A_{CP}
$B \to X_s\gamma$	$(3.61 \pm 0.41) \times 10^{-4}$	-0.6% – 2.8%
$B \to X_d\gamma$	$(1.38 \pm 0.25) \times 10^{-5}$	-62% – 14%
$B \to X_{s+d}\gamma$		~ 0

Benzke et.al PRL 106, 141801 (2011)

Inclusive Analysis

- Only reconstruct photon (signal) and lepton (tag)
  - $1.7 < E^*_\gamma < 2.8$ GeV (CM)
  - $1.1 < p_l < 2.25$ GeV/c (CM)

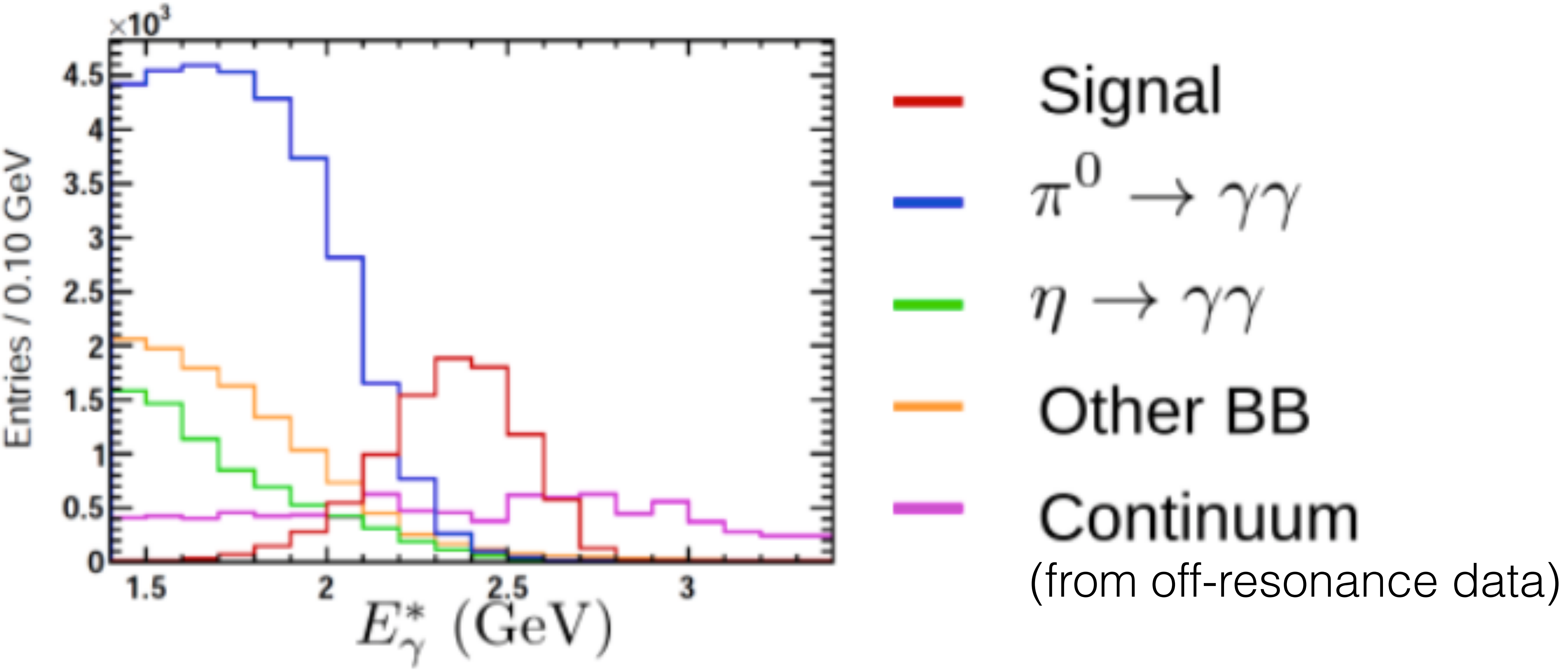


$A_{CP}(B\to X_{s+d}\gamma)$: Background

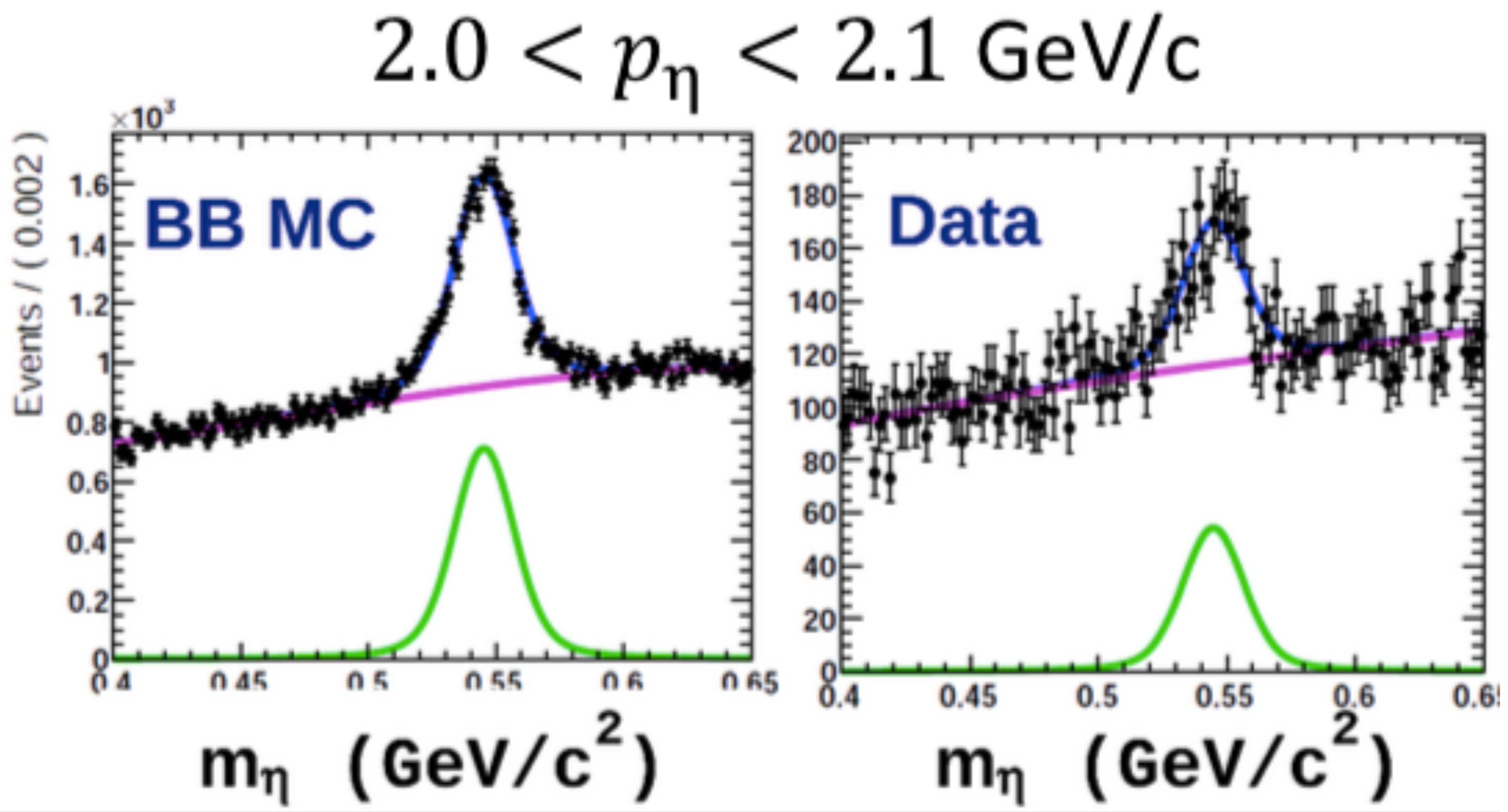
Background Suppression

- Mass veto for $\pi^0(\eta)\to\gamma\gamma$
- BDT used for continuum suppression
  - Topology/Kinematics
  - Isolation for γ

Background Calibration



- $\pi^0(\eta)$ bkg calibrated from MC in p bins
- Factor estimated in $B\to X\pi^0/\eta$ in data and MC



$A_{CP}(B \rightarrow X_{s+d}\gamma)$: Corrections

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

The raw A_{CP} is taken straight from the tag lepton

2. Correct for Wrong Tag (Dilution):

- BB Mixing
- leptons from **D decay**
- K/π **miss ID** as lepton

Source	Value
w_{mix}	0.0913±0.0015
$w_{D\text{-}Lep}$	0.0431±0.0036
w_{misID}	0.0069±0.0034
w_{total}	**0.1413±0.0052**

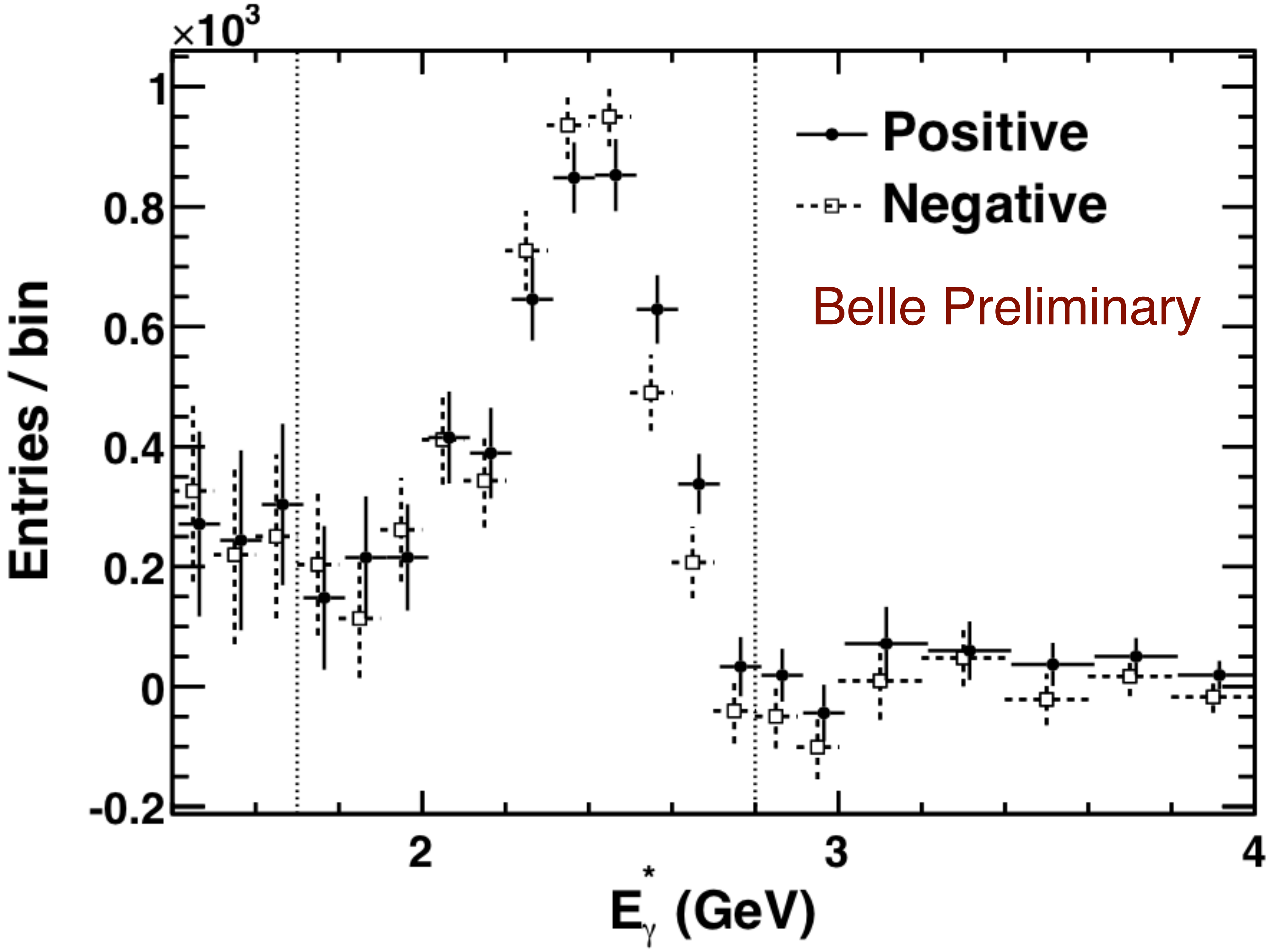
1. Correct for Bias:

- Asymmetry from detector:
  - **Lepton ID**: A_{det} = (0.11 ± 0.07)%
  - **Tracking**: A_{det} = (-0.01 ± 0.21)%
- Asymmetry from **BB bkg**:
  - A_{bkg} = (-0.14 ± 0.78)%

$$A_{CP}^{true} = \frac{1}{1-2w}(A_{CP}^{raw} + A_{det} + A_{bkg})$$

$A_{CP}(B \to X_{s+d}\gamma)$: Results

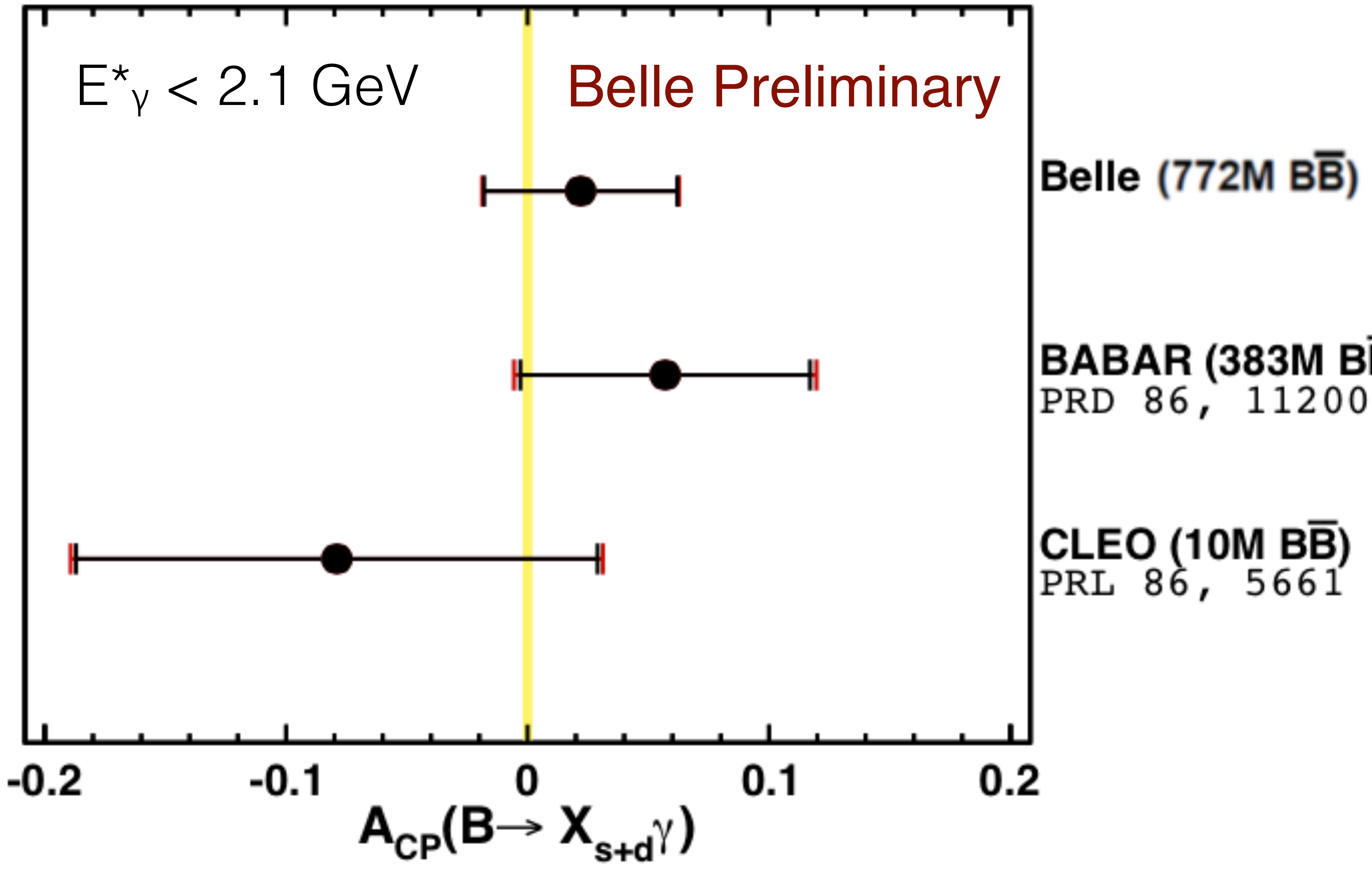
Spectrum after Background subtraction



After all corrections:

$$A_{CP}(B \to X_{s+d}\gamma) = (2.23 \pm 4.02 \pm 0.78)\%$$

Belle Preliminary

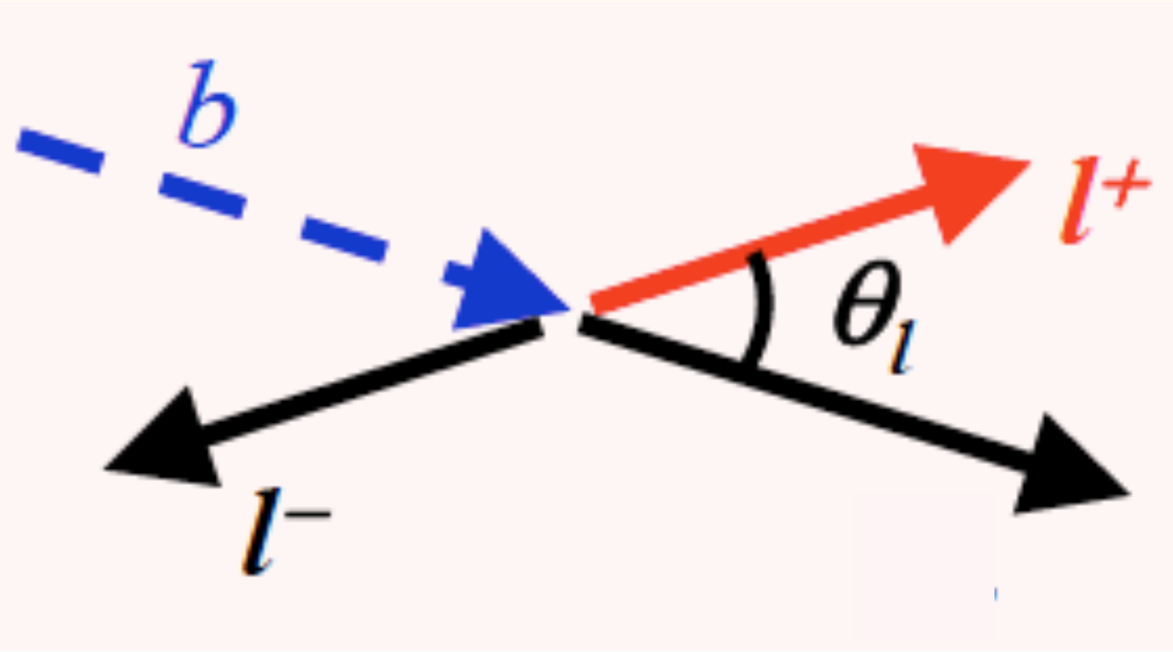


- Consistent with the SM
- **Most precise measurement of A_{CP}**
  - Statistically limited

Inclusive $B \to X_s ll$

- Inclusive has less theoretical uncertainty than $B \to K^{(*)} l^+l^-$ (which LHCb sees several discrepancies from SM)
- Sum of exclusive method, with 36 modes of which 20 are used for A_{fb}
- The fraction of all X_s decays covered by 20 final states is ~50 %

$$A_{FB} \equiv \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



Sensitive to Wilson Coefficients

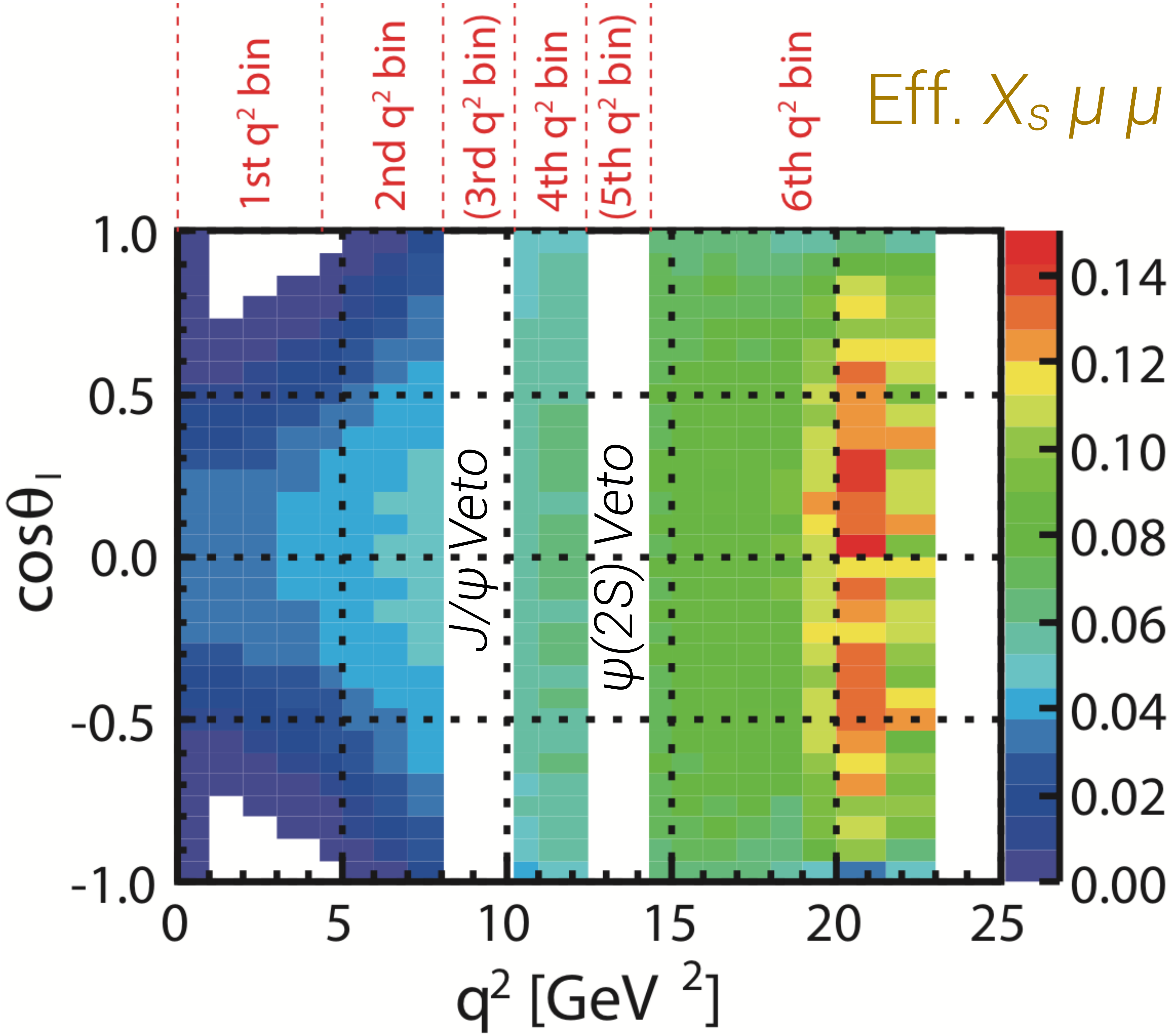
$$A_{FB} \propto -\mathrm{Re}\left[\left(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}\right) C_{10}^*\right]$$

$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$

- Neural network is employed for backgrounds suppression
  - Semi-leptonic B decays
  - Continuum (u,d,s,c)

Inclusive $B \to X_s ll$: Signal Extraction

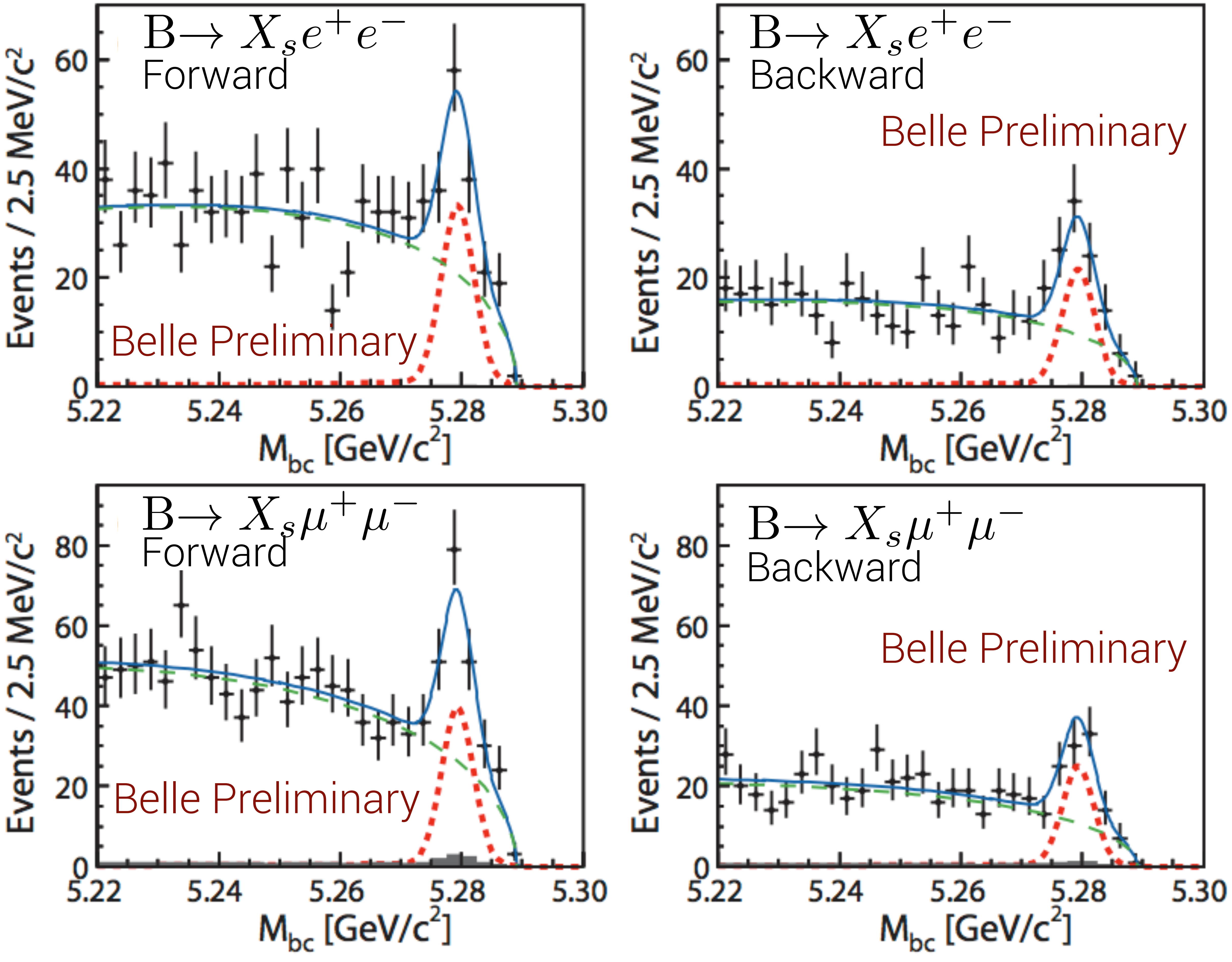
- Signal extraction: Divide into q^2 bins and fit M_{bc} for forward/backward events in e/μ channels.
- After we correct for efficiency, we then apply a linear scale factor determined from MC to obtain the final A_{FB}



Inclusive B→$X_s$ll: Signal Fits

Unbinned Maximum Likelihood Fits

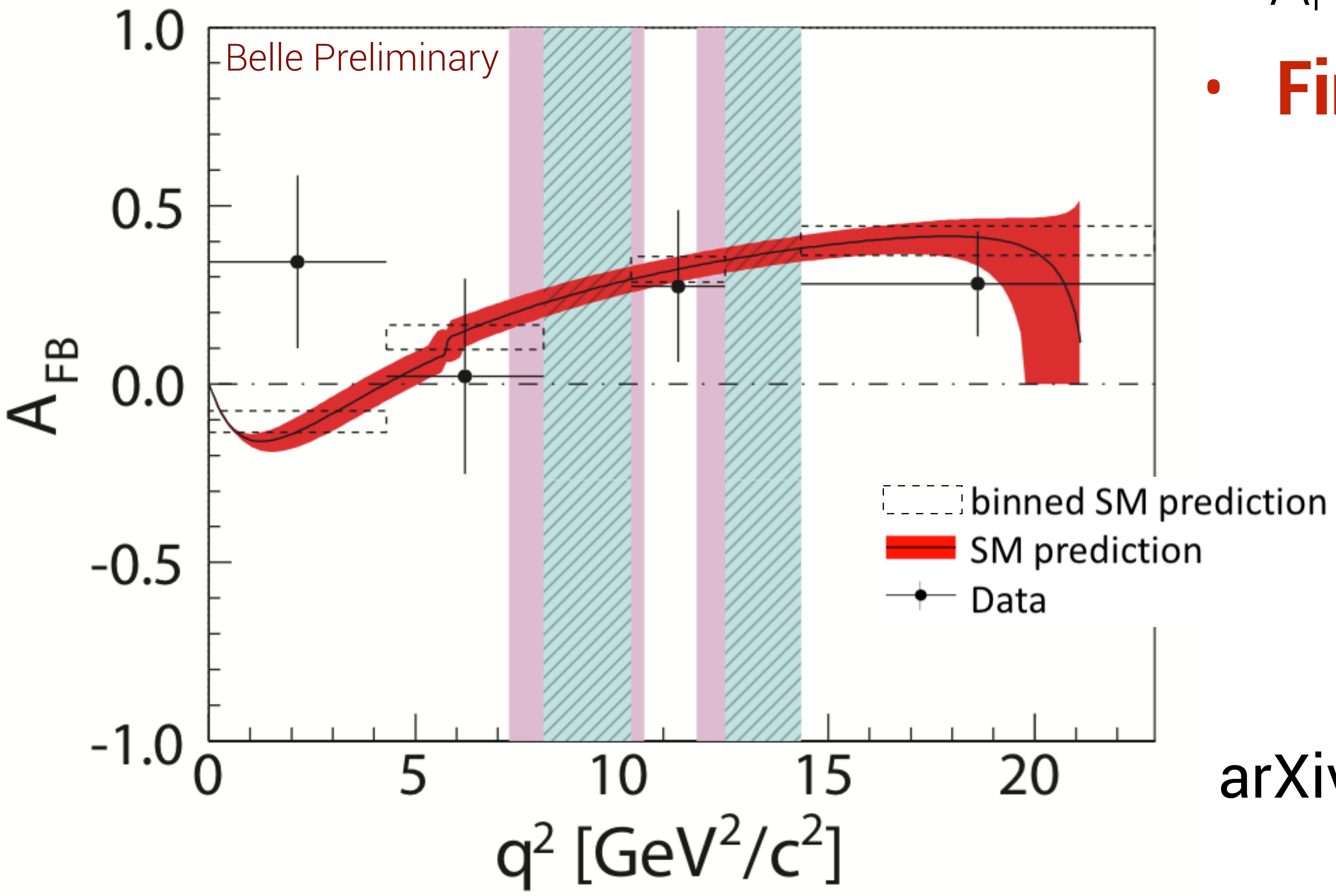
All Bins



- **Total Signal Yields**
  - N_{sig}^{ee} = 140 ± 19 (stat)
  - $N_{sig}^{\mu\mu}$ = 161 ± 20 (stat)

- Dominate Systematics
  - Linear scale correction
  - Peaking background
    - J/ψ leakage
    - Double miss ID from B→D*π

Inclusive $B \to X_s ll$: Result



- A_{FB} consistent with SM
- **First inclusive measurement of A_{FB}**

Bin 1: **Consistent with SM at 1.8σ**
Bin 3/4: **Exclude $A_{FB} < 0$ with 2.3σ**

arXiv:1402.7134; **SUMBITTED TO PRL**

Prospects for the future

- **Belle II will be an even more powerful tool to explore EWP and radiative decays**

Belle2 TDR (arXiv:1011.0352v1)

Observable	Belle 2006 ($\sim$0.5 ab^{-1})	Belle II/SuperKEKB (5 ab^{-1})	Belle II/SuperKEKB (50 ab^{-1})	LHCb† (2 fb^{-1})	LHCb† (10 fb^{-1})
Radiative/electroweak $b \to s$ transitions					
$\mathcal{S}_{K^0_S \pi^0 \gamma}$	0.32	0.10	0.03	-	-
$\mathcal{B}(B \to X_s \gamma)$	13%	7%	6%	-	-
$A_{CP}(B \to X_s \gamma)$	0.058	0.01	0.005	-	-
C_9 from $A_{FB}(B \to K^* \ell^+ \ell^-)$	-	11%	4%		
C_{10} from $A_{FB}(B \to K^* \ell^+ \ell^-)$	-	13%	4%		
C_7/C_9 from $A_{FB}(B \to K^* \ell^+ \ell^-)$	-		5%		7%
R_K		0.07	0.02		0.043
$\mathcal{B}(B^+ \to K^+ \nu \nu)$	†† $< 3\ \mathcal{B}_{\rm SM}$		30%	-	-
$\mathcal{B}(B^0 \to K^{*0} \nu \bar{\nu})$	†† $< 40\ \mathcal{B}_{\rm SM}$		35%	-	-
Radiative/electroweak $b \to d$ transitions					
$\mathcal{S}_{\rho\gamma}$	-	0.3	0.15		
$\mathcal{B}(B \to X_d \gamma)$	-	24% (syst.)		-	-

Conclusions

- **The FCNC B decays are a rich topic than can be used to explore beyond the Standard Model**
- **Br($B \to X_s\gamma$) Sum of Exclusives** (Radiative decay: $b \to s\gamma$)
  - $\mathcal{B}(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4} \quad (E^*_\gamma > 1.6\ GeV)$
  - Most precise result with sum of exclusives
- **A_{CP}($B \to X_{s+d}\gamma$) Inclusive** (Radiative decay: $b \to s+d\gamma$)
  - $A_{CP}(B \to X_{s+d}\gamma) = (2.23 \pm 4.02 \pm 0.78)\% \quad (E^*_\gamma < 2.1\ GeV)$
  - Most precise result
- **$B \to X_s l^+l^-$ Sum of Exclusive** (Penguin decay: $b \to s\ l^+l^-$)
  - First analysis of its kind
  - Low q^2 : Consistent with SM at 1.8σ
  - High q^2 : Exclude $A_{FB} < 0$ with 2.3σ

♓: *Back Up* :♓

$B \to X_s \gamma$ with Sum of Exclusive

Table 4.1: Reconstructed X_s final states

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	$K_s\eta\pi^+\pi^-$		

$B \rightarrow X_s \gamma$ with Sum of Exclusive

- D^0 without π^0/η : 1835< M_{D^0} <1895 MeV/c^2
- D^+ without π^0/η : 1840< M_{D^+} <1900 MeV/c^2
- D^0 with π^0/η: 1800< M_{D^0} <1905 MeV/c^2
- D^+ with π^0/η : 1805< M_{D^+} <1910 MeV/c^2

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

$$N^{+}_{\rm obs} = (1-\omega)N^{+}_{\rm true} + \omega N^{-}_{\rm true}$$
$$N^{-}_{\rm obs} = (1-\omega)N^{-}_{\rm true} + \omega N^{+}_{\rm true}$$
$$A^{\rm obs}_{\rm CP} = \frac{N^{+}_{\rm obs} - N^{-}_{\rm obs}}{N^{+}_{\rm obs} + N^{-}_{\rm obs}} = (1-2\omega)\frac{N^{+}_{\rm true} - N^{-}_{\rm true}}{N^{+}_{\rm true} + N^{-}_{\rm true}},$$