Overview of radiative decays at Belle II

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Workshop of physics at high intensity

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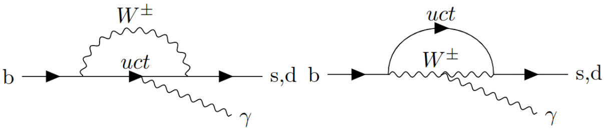
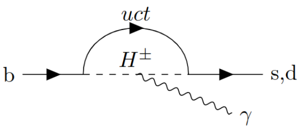
Frascati, Italy

Rare radiative decays

Leading Standard Model diagrams

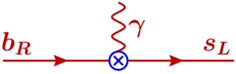


Two-Higgs Doublet Model scenario



$$\mathcal{B}(B \to X_s\gamma) \sim 3.5 \times 10^{-4} \text{ [PDG, 2022]}$$
$$\mathcal{B}(B \to K^*\gamma) \sim 4.2 \times 10^{-5} \text{ [PDG, 2022]}$$

From the lens of effective field-theory and Wilson Coefficients:

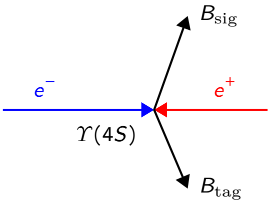


$$\times\ (C_7 + C_7^{\mathrm{NP}})$$

- Exclusive: specific meson-state originating from the $b \to s$
- Inclusive: all meson-states originating from the $b \to s$
  → **Different theory uncertainties**, e.g. no form-factor systematics
- Several SM extensions could contribute in $\mathcal{B}(B \to X_s\gamma)$
  → **Important ingredient** in many global fits [JHEP11(2012)036]
- E_γ spectrum allows to determine m_b and other non-perturbative parameters
  → **Important for $|V_{ub}|$ extraction** from $B \to X_u l\bar{\nu}$ [PRD 78 (2008) 013002]

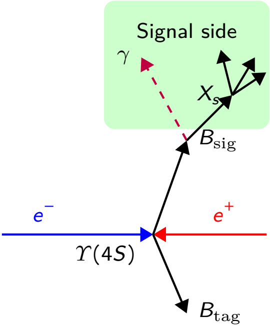
$B \to X_s\gamma$ schematic overview (1/3)

- Belle II detector already presented in the previous talk
- The collision produces two B-mesons at $\sqrt{s} \approx 10.58\ \mathrm{GeV}$
- Label one of them as “signal” the other as “tag”



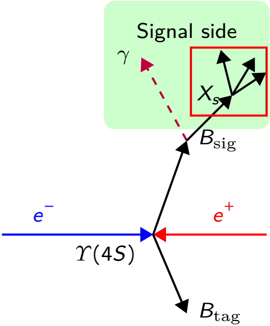
$B \to X_s\gamma$ schematic overview (2/3)

- Consider the “signal”-B meson decays (**signal side**)
- We are looking for $b \to s\gamma$ decays
- The s hadronizes, so any final state originating from s is X_s



$B \to X_s\gamma$ schematic overview (3/3)

- High-energy photon in the event is the signature of the decay
- **Challenge:** differentiate the signal-photon from background-photons



Exclusive: select a final state e.g. K^*, $K^+\pi^-$

Inclusive: apply no constraints to the X_s system

- Use the **photon, event-shape, tag-B** information to **suppress background** processes
- If exclusive: also use X_s system tracks, neutral particles etc.

Content of the talk

The talk will present results from 2 studies and future discussion

- Measurement of photon energy spectrum of inclusive hadronic-tagged $B \to X_s\gamma$ decays
  - arXiv:2210.10220
- Measurement of the branching fraction of $B \to K^*\gamma$
  - arXiv:2110.08219
- Radiative analyses prospects at Belle II

Thermal imaging Emperor Penguins in Terre Adélie, Antarctica

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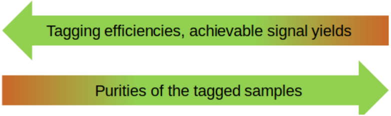
Measurement of the photon-energy spectrum of inclusive $B \to X_s\gamma$

Inclusive measurements at B-factories

One may also **use the kinematic information of the tag-B meson** to constrain the signal side!

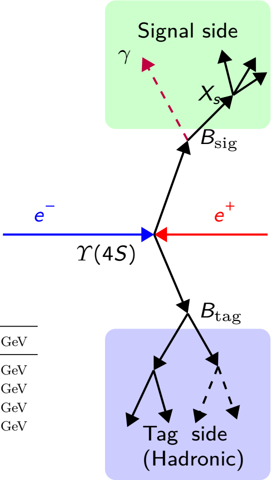


Fully inclusive, no tagging

$B \to \text{anything}$

Hadronic tagging

$B \to \text{hadrons}$, e.g. $B \to \bar{D}^{(*)}\, n\pi$



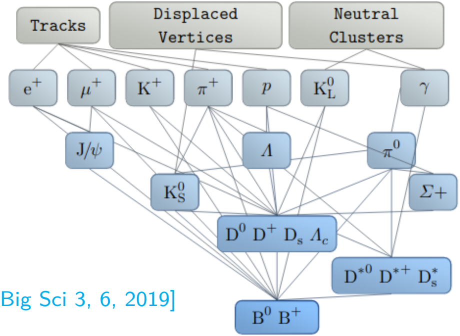
Past measurements:

Year	Experiment	Analysis method	Data on res	$\mathcal{B}(B \to X_s\gamma) \times 10^{-4}$	Threshold
2007	BaBar	Hadronic tag	210 fb^{-1}	$3.66 \pm 0.85(\text{stat.}) \pm 0.60(\text{syst.})$	$E_\gamma^B > 1.9$ GeV
2009	Belle	No-tag/lepton tag	605 fb^{-1}	$3.45 \pm 0.15(\text{stat.}) \pm 0.40(\text{syst.})$	$E_\gamma^B > 1.7$ GeV
2012	BaBar	lepton tag	347 fb^{-1}	$3.21 \pm 0.15(\text{stat.}) \pm 0.29(\text{syst.})$	$E_\gamma^B > 1.7$ GeV
2012	BaBar	Sum-of-exclusive	429 fb^{-1}	$3.29 \pm 0.19(\text{stat.}) \pm 0.48(\text{syst.})$	$E_\gamma^B > 1.7$ GeV
2016	Belle	lepton tag	711 fb^{-1}	$3.12 \pm 0.10(\text{stat.}) \pm 0.19(\text{syst.})$	$E_\gamma^B > 1.6$ GeV

Different tagging → Different experimental uncertainties

Tag side reconstruction

- Use the **F**ull **E**vent **I**nterpretation: tagging algorithm of Belle II
- Semileptonic or hadronic reconstruction possible
- Hierarchical reconstruction starting at detector level objects
- Combines candidate B in $\mathcal{O}(10000)$ decay chains
- Gradient-boosted decision trees (BDTs) assign a candidate probability score $\mathcal{P}_{\mathrm{FEI}}$ at every reconstruction step
- Relative increase in tagging efficiency by 30–50% compared to Belle algorithm



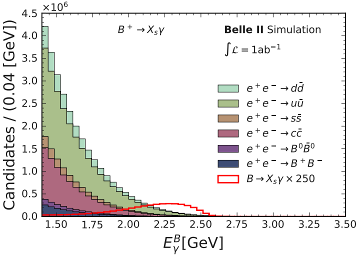
[Comput Softw Big Sci 3, 6, 2019]

Hadronic-tagged measurement

- **Analysis performed on** $189\ \mathbf{fb}^{-1}$ **of Belle II data**
- The tag-B is reconstructed decaying hadronically
  → Can determine charge, flavour, momentum of signal-B
- Results can be **expressed in the signal-**B **rest frame**
  → Optimal frame for theoretical comparisons

Reconstructed samples

- After reconstruction sample is dominated by photons from $e^+e^- \to q\bar{q}$ processes
- Most photons originate in energy-asymmetric $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays
- We select $E_\gamma^B > 1.4\ \mathrm{GeV}$ (signal B rest frame)
- Only take the **highest energy photon in each event**
  → 99+% true for $B \to X_s\gamma$



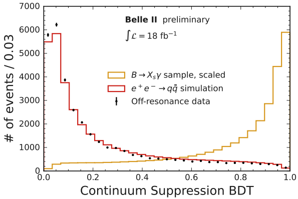
Background suppression

Signal-side background suppression

1. π^0 and η suppression:
   → use MVA to check for consistency with $\pi^0(\eta) \rightarrow \gamma\gamma$
   → combine the photon with lower-energy photon candidates
2. mis-ID photon suppression:
   → use MVA which combines photon calorimeter shower-shape variables

$e^+e^- \rightarrow q\overline{q}$ background suppression

3. Train a dedicated BDT
   → Carefully select all features that shown no correlation with E_γ^B
   → Take only features that are well-modelled in simulation
   → This is checked using 18 fb^{-1} off-resonance data (below $\Upsilon(4S)$)



Selections optimised simultaneously based on figure-of-merit [Punzi, eConf C030908]

Tag-side fitting

- **Tag-side** observable fitting gives further **background subtraction**
- Remove misreconstructed tag-side events:

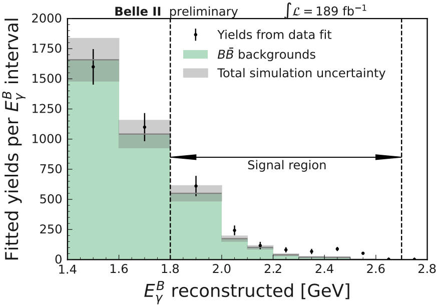
$$M_{bc} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - (p^*_{B,\mathrm{tag}})^2} \quad \Rightarrow \quad \text{For correctly reconstructed: } M_{bc} \to m_B \approx 5.28\ \mathrm{GeV}/c^2$$

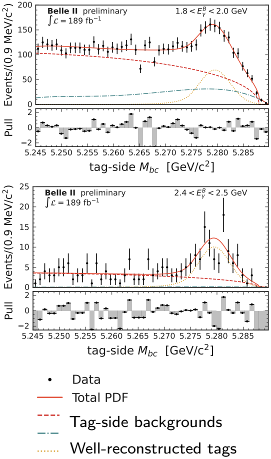
- **Three components** identified in our sample **using simulation**

	Component
accept →	$e^+e^- \to B\bar{B}$ well-reconstructed
discard →	$e^+e^- \to B\bar{B}$ combinatorial
	$e^+e^- \to q\bar{q}$ events

- 11 fitting intervals to extract E_γ^B spectrum:
  → $1.4 - 1.8\ \mathrm{GeV}$: two $200\ \mathrm{MeV}$ wide (control-region for fit)
  → $1.8 - 2.7\ \mathrm{GeV}$: one $200\ \mathrm{MeV}$ and seven $100\ \mathrm{MeV}$ wide **(signal region)**
  → $2.7\ \mathrm{GeV}+$: one 'overflow' bin (control region for fit)
- **We perform the fit on each data interval** using the PDFs for each component

Unboxed fit results





- Each point corresponds to the ‘peaking’ yield in the data fit
- The filled histogram represents peaking yields in simulated background fit (with $B \to X_s\gamma$ removed)
- Clear evidence of signal at high-E_γ^B
- Data points − filled histogram = $B \to X_s\gamma$ spectrum

Branching fraction extraction

- **Statistical uncertainties are dominant**
  → Straightforward bin-by-bin scaling is used for unfolding
  → Use a hybrid-model combining inclusive-$B \to X_s\gamma$ + $B \to K^*\gamma$
- Then the **partial branching fractions** are:

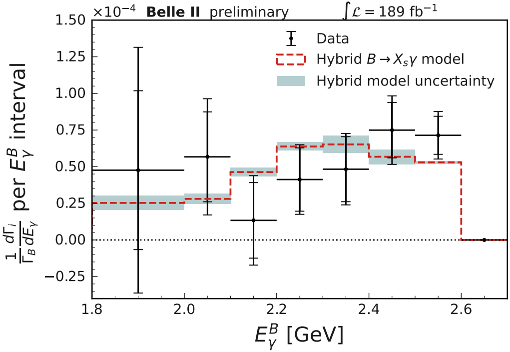
$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma} = \frac{\mathcal{U}_i \cdot (N_i^{\mathrm{DATA}} - N_i^{\mathrm{BKG,\ SIM}} - N_i^{B\to X_d\gamma})}{\varepsilon_i \cdot N_B},$$

$\mathcal{U}_i$ – unfolding factor in bin i

ϵ_i – efficiency factor

$\epsilon_{\mathrm{tagging}} \times \epsilon_{\mathrm{selection}}$

N_B – B meson count in sample



* Signal model-uncertainty combines:

$\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B \to K^*\gamma)$ uncertainty

$B \to X_s\gamma$ model shape uncertainties

Integrated results

Integrated branching fractions and absolute uncertainty:

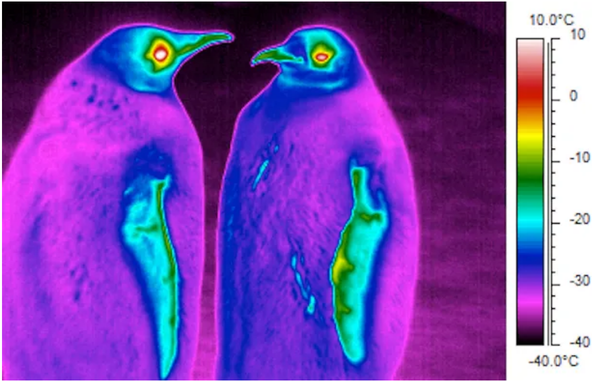
E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat) $\pm$ 0.83 (syst)
2.0	3.06 ± 0.56 (stat) $\pm$ 0.47 (syst)
2.1	2.49 ± 0.46 (stat) $\pm$ 0.35 (syst)

- Agrees with world average: $3.49 \pm 0.19 \times 10^{-4}$
- Compare results to BaBar, **210 fb^{-1}**:
  → $3.66 \pm 0.85(\text{stat.}) \pm 0.60(\text{syst.})$ $[E_\gamma^B > 1.9\ \text{GeV}]$

  → we achieve **comparable systematic error** (extrapolate between thresholds)

  → **statistical error is smaller,** despite less $\int\mathcal{L}$ (tagging, selection differences)

⇒ Belle II in a position to perform world-leading hadronic-tagged measurement



Biol. Lett.9:20121192

Measurement of the $B \to K^{*}\gamma$ branching fraction

$B \to K^*\gamma$ measurement at Belle 2

- Sharp resonance in E_γ near the 2-body decay kinematic limit ($E_\gamma \approx m_B/2$)
  → Relatively high-branching fraction
  → Low-multiplicity final state
- **Evidence for isospin violation** at Belle ($\sim 700\ \text{fb}^{-1}$) [PhysRevLett.119.191802]
  → Belle 2 is in an excellent position to confirm this
- **This presentation covers first Belle II $B \to K^*\gamma$ results on $63\ \text{fb}^{-1}$**
  → measurement of branching fraction

Event selection

Photon selection

- $2.25 < E^*_\gamma < 2.85\ \mathrm{GeV}$
- Reject γ compatible with π^0 and η decays

K^* selection

- K^{*0}, K^{*+}
  → Combining $K^\pm$, K^0_S with $\pi^\pm$,π^0
  → $M_{K^*} \in (0.817, 0.967)\ \mathrm{GeV}/c^2$

B meson candidate

$B \to K^*\gamma$ signal extraction strategy

- Dominant $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) suppressed with a boosted-decision tree
- Kinematic variables for combinatorial background suppression:

Beam-constrained mass

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - (p^*_{B,\mathrm{signal}})^2}$$
$$\Rightarrow M_{\mathrm{bc}} \to m_B \approx 5.28\,\mathrm{GeV}/c^2$$

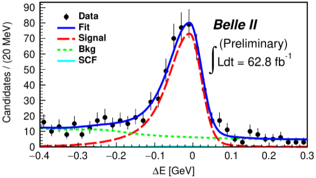
Energy difference

$$\Delta E = E^*_B - \sqrt{s}/2$$
$$\Rightarrow \Delta E \overset{\approx}{\to} 0$$

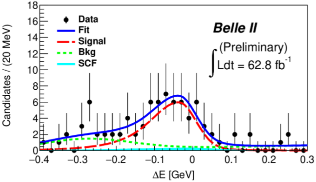
- Significant **background** from B decays to **other kaonic resonances** peak in M_{bc}
- ΔE more sensitive to mass hypothesis (**separates** the contributions)
  → Extract signal by **fitting ΔE in $M_{\mathrm{bc}} > 5.27\ \mathrm{GeV}$ region**

$B \to K^*\gamma$ signal extraction

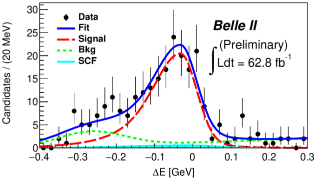
- **Models for different components** in the distribution obtained **in simulation**
- Backgrounds: combinatorial, peaking, misreconstructed signal (SCF in figures)



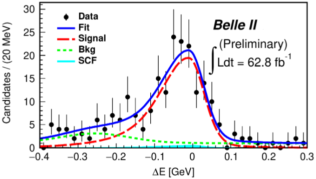
(a) $B^0 \to K^{*0}[K^+\pi^-]\gamma$



(b) $B^0 \to K^{*0}[K^0_S\pi^0]\gamma$



(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$



(d) $B^+ \to K^{*+}[K^0_S\pi^+]\gamma$

Energy difference

$$\Delta E = E_B^* - \sqrt{s}/2$$
$$\Rightarrow \Delta E \overset{\approx}{\to} 0$$

$B \to K^*\gamma$ branching fraction

- **Branching fraction calculation:**

$$\mathcal{B}(B \to K^*\gamma) = \frac{n_{\mathrm{sig}}}{\varepsilon \times N_B \times f^{\pm/00}}$$

n_{sig} – signal yield from the fit

ε – signal efficiency

N_B – number of B candidates

$f^{\pm}\&f^{00}$ – rel. branching fractions of $\Upsilon(4S)$

Main systematic effects

- Misreconstructed signal (~ up to 7%)
- Fitting model (~ up to 7.5%)
- Background suppression (~ up to 6%)

Extracted yields and branching fractions:

Mode	Signal yield	Efficiency (%)	$\mathcal{B}_{\mathrm{meas}}$ $[10^{-5}]$	$\mathcal{B}_{\mathrm{PDG}}$ $[10^{-5}]$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	454 ± 28	15.22 ± 0.03	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	50 ± 10	1.73 ± 0.01	$4.4 \pm 0.9 \pm 0.6$	4.18 ± 0.25
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	169 ± 18	4.84 ± 0.02	$5.0 \pm 0.5 \pm 0.4$	3.92 ± 0.22
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	160 ± 17	4.23 ± 0.02	$5.4 \pm 0.6 \pm 0.4$	3.92 ± 0.22

Results consistent with the PDG values at one (two) standard deviations for neutral (charged)

Upcoming iterations of this analysis will:

→ measure CP & Isospin asymmetry

→ systematically investigate the peaking background contributions

Outlook for radiative analyses at Belle II (1/2)

Inclusive hadronic-tagged $B \to X_s\gamma$

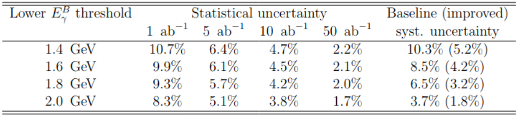
Untagged/lepton-tagged

- Belle II is the only ongoing experiment that can improve the untagged E_γ measurements
- To improve Belle/BaBar results the **post-long-shutdown dataset will need to be awaited**
- Semileptonic tagging may also provide new & unique experimental data

Hadronic-tagged

- Needs **high-statistics** to reach theory precision (5%~) [JHEP06(2020)175]
- The high-purity of E_γ^B spectrum is an **important cross-check** for alternative methods

Expected uncertainties arxiv 2207.06307



Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved) syst. uncertainty
	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	
1.4 GeV	10.7%	6.4%	4.7%	2.2%	10.3% (5.2%)
1.6 GeV	9.9%	6.1%	4.5%	2.1%	8.5% (4.2%)
1.8 GeV	9.3%	5.7%	4.2%	2.0%	6.5% (3.2%)
2.0 GeV	8.3%	5.1%	3.8%	1.7%	3.7% (1.8%)

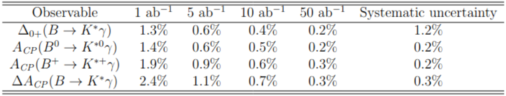
Outlook for radiative analyses at Belle II (2/2)

Exclusive $B \to X_s\gamma$ channels

$B \to K^*\gamma$

- Belle 2 results will remain **sensitive to non-SM contributions** up to the final data set size

Expected uncertainties [arxiv 2207.06307]



Observable	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	Systematic uncertainty
$\Delta_{0+}(B \to K^*\gamma)$	1.3%	0.6%	0.4%	0.2%	1.2%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.4%	0.6%	0.5%	0.2%	0.2%
$A_{CP}(B^+ \to K^{*+}\gamma)$	1.9%	0.9%	0.6%	0.3%	0.2%
$\Delta A_{CP}(B \to K^*\gamma)$	2.4%	1.1%	0.7%	0.3%	0.3%

Other exclusive channels

- $B \to K^+\pi^+\pi^-\gamma$ showed strong evidence of photon-polarisation at LHCb [PhysRevLett.112.161801]
  → Belle II will be able to test this up to a precision of 1%
- $B \to \rho\gamma$ measurements of isospin asymmetry showed weak tensions at Belle [arXiv 0804.4770]
  → Result limited in statistics, combination of Belle & Belle II can significantly increase the precision

Summary

- First radiative results from Belle II presented here
- Inclusive & exclusive techniques have an interesting outlook at Belle II
  ⇒$B \to X_s\gamma$ hadronic-tagged analysis matches the BaBar measurement
  ⇒$B \to K^*\gamma$ will provide important checks of CP & isospin asymmetries
- Belle II will pave the way for many tensions observed in the radiative sector in the upcoming years!

Thank you!

Additional slides

$B \to K^*\gamma$ systematic uncertainties

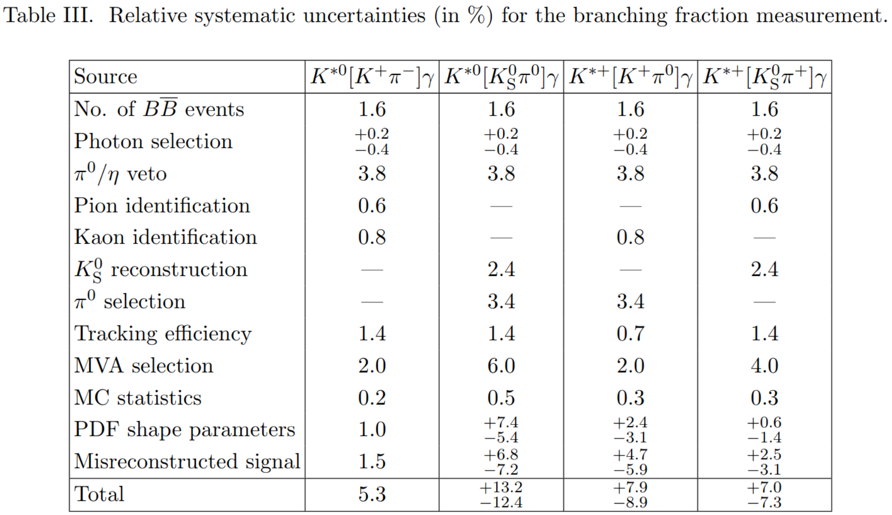


Table III. Relative systematic uncertainties (in %) for the branching fraction measurement.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K^0_S\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
No. of $B\overline{B}$ events	1.6	1.6	1.6	1.6
Photon selection	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$
π^0/η veto	3.8	3.8	3.8	3.8
Pion identification	0.6	—	—	0.6
Kaon identification	0.8	—	0.8	—
K^0_S reconstruction	—	2.4	—	2.4
π^0 selection	—	3.4	3.4	—
Tracking efficiency	1.4	1.4	0.7	1.4
MVA selection	2.0	6.0	2.0	4.0
MC statistics	0.2	0.5	0.3	0.3
PDF shape parameters	1.0	$^{+7.4}_{-5.4}$	$^{+2.4}_{-3.1}$	$^{+0.6}_{-1.4}$
Misreconstructed signal	1.5	$^{+6.8}_{-7.2}$	$^{+4.7}_{-5.9}$	$^{+2.5}_{-3.1}$
Total	5.3	$^{+13.2}_{-12.4}$	$^{+7.9}_{-8.9}$	$^{+7.0}_{-7.3}$

Motivation for asymmetry studies

- Theoretical prediction of branching fraction has a large dependance on form factors for exclusive channels
- Dependance suppressed in ratio observables, such as isospin/& CP assymetries:

$$A_{CP} = \frac{\Gamma(\overline{B} \rightarrow \overline{K}^{*}\gamma) - \Gamma(B \rightarrow K^{*}\gamma)}{\Gamma(\overline{B} \rightarrow \overline{K}^{*}\gamma) + \Gamma(B \rightarrow K^{*}\gamma)}$$

$$\Delta_{0+} = \frac{\Gamma(B^{0} \rightarrow K^{*0}\gamma) - \Gamma(B^{+} \rightarrow K^{*+}\gamma)}{\Gamma(B^{0} \rightarrow K^{*0}\gamma) + \Gamma(B^{+} \rightarrow K^{*+}\gamma)}$$

$B \to X_s\gamma$ systematic uncertainties

E_γ^B [GeV]	$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma}(10^{-4})$	Statistical	Systematic	Fit procedure	Signal efficiency	Background modelling	Other
1.8 – 2.0	0.48	0.54	0.64	0.42	0.03	0.49	0.09
2.0 – 2.1	0.57	0.31	0.25	0.17	0.06	0.17	0.07
2.1 – 2.2	0.13	0.26	0.16	0.13	0.01	0.11	0.01
2.2 – 2.3	0.41	0.22	0.10	0.07	0.05	0.04	0.02
2.3 – 2.4	0.48	0.22	0.10	0.06	0.06	0.02	0.05
2.4 – 2.5	0.75	0.19	0.14	0.04	0.09	0.02	0.09
2.5 – 2.6	0.71	0.13	0.10	0.02	0.09	0.00	0.04