$b \to s$ penguin decays
at Belle II

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On behalf of the Belle II collaboration

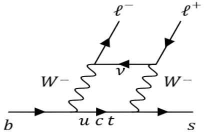
Beauty 2023, Jul 03 - 07

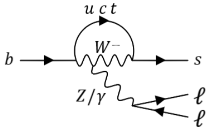
Electroweak and radiative penguin decays

- $b \to s(d)$ flavour changing neutral current transitions **not possible at tree level** in the Standard Model (SM).
- Branching fractions $\simeq 10^{-4} - 10^{-7} \Rightarrow$ "rare" decays.

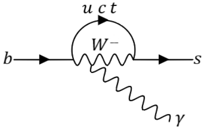
  [JHEP06(2020)175], [PhysRevD.87.034016]
- Highly sensitive to beyond-SM mediator contributions, affecting:
  - Branching fractions
  - Angular distributions
  - CP asymmetries
  - Kinematics
- **Shown today**:
  - $B \to K^* l^+ l^-$
  - $B \to J/\Psi(l^+ l^-)K$ (R_K control channel)
  - Inclusive $b \to s\gamma$

Electroweak penguins:





Electroweak radiative penguin:



Belle II at superKEKB (1/3)

SuperKEKB: 4.0 GeV e^+ - 7.0 GeV e^- collider.

- Luminosity world record: 4.7×10^{34} cm^{-2}s^{-1} On June 22, 2022.

Current status:

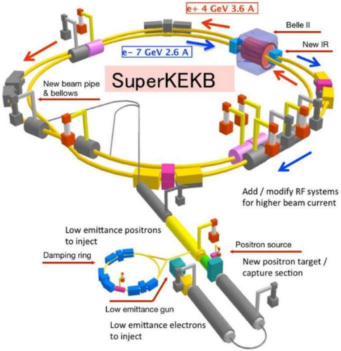
- Collected 424 fb^{-1} of data since 2019.
- Shutdown since June 2022.
- Here we show studies based on a 189 fb^{-1} dataset.

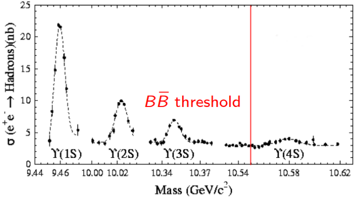
On-resonance data:

- $\sqrt{s} = 10.58$ GeV.
- $\simeq 1\%$ of collisions produce $B\bar{B}$ pairs.
- Clean B sample.

Off-resonance data:

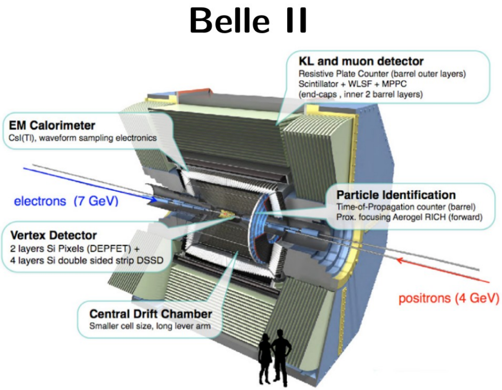
- 60 MeV below $\Upsilon(4S)$ resonance.
- $e^+e^- \to q\bar{q}$ events.
- Control sample for non-resonant (continuum) background.





Belle II detector:

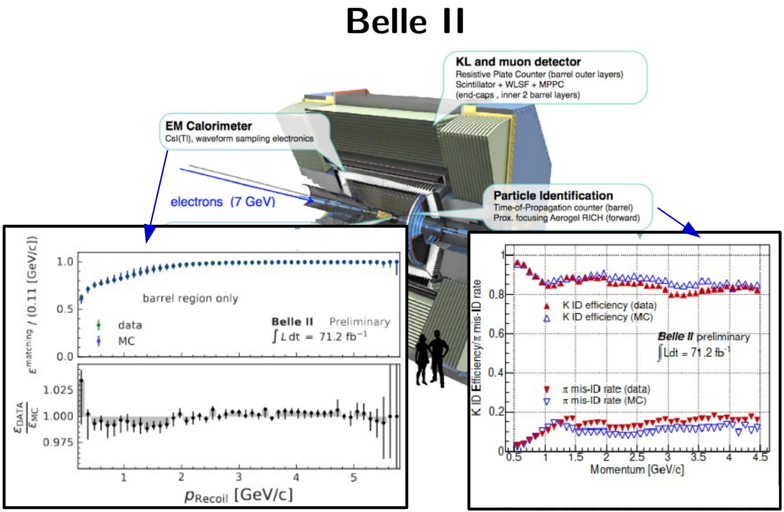
- Flavour universal : similar performances for electrons and muons.
- Optimized for high instantaneous luminosity.
- Collision of point-like particles and 4π detector coverage.



Belle II detector:

- Flavour universal : similar performances for electrons and muons.
- Optimized for high instantaneous luminosity.
- Collision of point-like particles and 4π detector coverage.

$\Rightarrow$ **Strengths: Precision measurements, rare and/or partially invisible decays** (ex: $B \to D\tau\bar{\nu}$).



High photon reconstruction efficiency

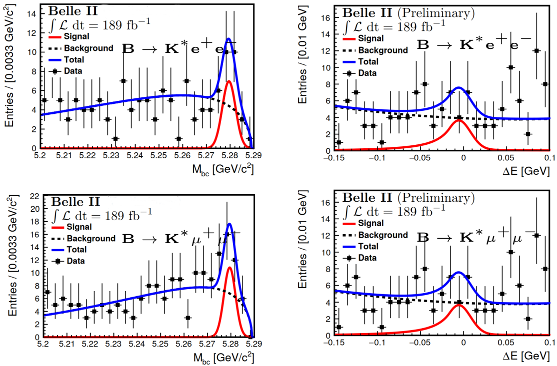
Good particle identification

[BELLE2-NOTE-PL-2021-008]

[BELLE2-NOTE-PL-2020-024]

$$\mathbf{R_{K^*}} = \frac{\mathcal{B}(\mathbf{B} \to \mathbf{K}^* \mu^+ \mu^-)}{\mathcal{B}(\mathbf{B} \to \mathbf{K}^* \mathbf{e}^+ \mathbf{e}^-)}$$

- First step towards $\mathbf{R_{K^*}}$: observation of $B \to K^*(892) l^+ l^-$.
- Reconstruct K^* from K^+ or K^0_S with π^+ or π^0.
- Background suppression: dilepton mass suppression (e.g $J/\Psi \to ll$, photon conversion). Boosted Decision Tree (BDT) to suppress $e^+e^- \to q\bar{q}$.
- Extract signal yield from **2-dimensional fit** to M_{bc} and ΔE.
- $\mathbf{M_{bc}} = \sqrt{\mathbf{E^2_{beam}} - \mathbf{p^{*2}_B}}$ $\quad\quad$ $\mathbf{\Delta E} = \mathbf{E^*_B} - \mathbf{E_{beam}}$
- Precision for e and μ channels in same ballpark ($\simeq 25 - 30\%$).



Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World average ($\times 10^{-6}$)
$B \to K^* e^+ e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

[Prog. Theor. Exp. Phys. 2022, 083C01]

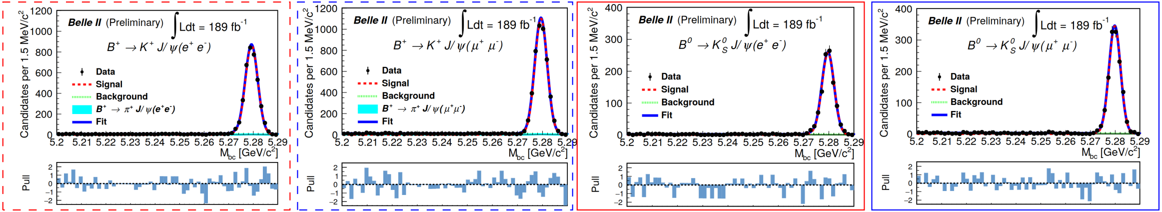
Measurement of $B \to J/\Psi K$ branching ratio and $R_K(J/\Psi)$.

$$\mathbf{R_K(J/\Psi)} = \frac{\mathcal{B}(\mathbf{B \to K J/\Psi(\to \mu^+\mu^-)})}{\mathcal{B}(\mathbf{B \to K J/\Psi(\to e^+e^-)})}$$

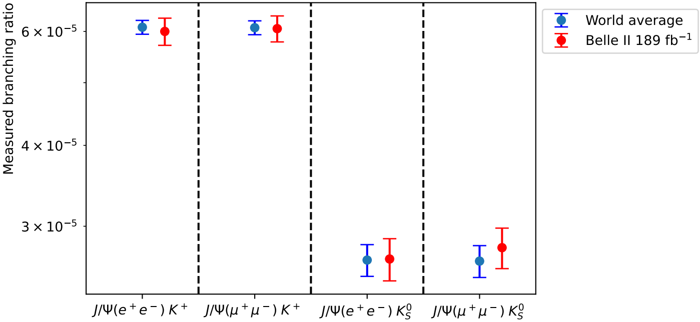
- Not a $b \to s$ transition, **but** an important control channel for $\mathbf{R_K}$.
- Proceeds via a $b \to c$ favored transition.
- Recontruct $B^+ \to K^+ J/\Psi$ and $B^0 \to K^0_S J/\Psi$ decays with $J/\Psi \to e^+e^-/\mu^+\mu^-$.
- J/Ψ and K combined to form B candidates with M_{bc} and ΔE selection.
- Signal yield extracted from fit to M_{bc} and ΔE.

	e^-	μ^-
K^+	30%	37%
K^0_S	20%	25%

Reconstruction efficiencies for the kaon/lepton flavour combinations.



- Main systematic uncertainty from $\Upsilon(4S)$ **branching ratio to B pairs** (2.6%).
- Additional systematic for K_S^0 modes due to **data-MC differences in K_s^0 reconstruction efficiency** (3%).

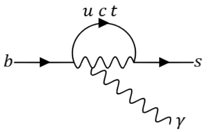


Prog. Theor. Exp. Phys. 2022, 083C01

Belle II measurement of $\mathbf{R_K(J/\Psi)}$:

$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

$b \to s\gamma$ has higher rates and is sensitive differently to NP compared to $b \to sl^+l^-$ or $b \to s\nu\bar{\nu}$.

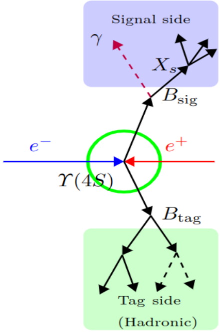


All $b \to s\gamma$ final states are considered $\Rightarrow$ **inclusive** search.
In addition to studying NP ($H^{\pm}$ mass), allows to extract:

- Several SM parameters (e.g m_b) [RevModPhys.88.035008].
- Shape function describing the motion of b-quark inside B meson [PRL **127**, 102001].

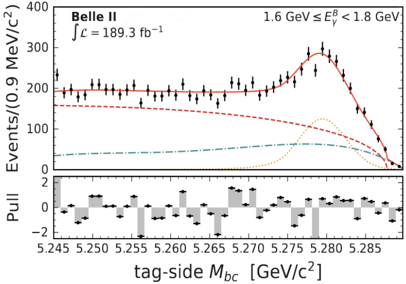
Measurement:

- Inclusive measurement: **only photon constrained** on signal side.
- Large background contribution $\Rightarrow$ challenging to suppress without losing "inclusiveness".
- Tag-side B meson reconstructed with **hadronic tagging** $\Rightarrow$ high purity sample, direct access to E_γ^B, photon energy in B rest frame.
- Tag-side reconstruction efficiency $= 0.44 \pm 0.02\%$



- **Signal candidate**: Highest energy photon in event, $E_\gamma^B > 1.4$ GeV.
- **General background suppression**: BDT trained to suppress events compatible with $e^+e^- \to q\bar{q}$.
  $\Rightarrow$ only use features uncorrelated to E_γ^B and M_{bc}.
- **Signal-side background suppression (photon)**: Veto $\eta \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$.
- **Tag-side background suppression**: B_{tag} M_{bc} fits in bins of E_γ^B $\Rightarrow$ **correctly tagged events count**.

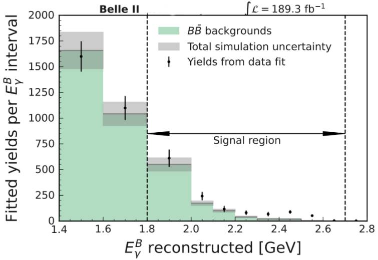
Selection and fit validated on $1.4 < E_\gamma^B < 1.8$ GeV.

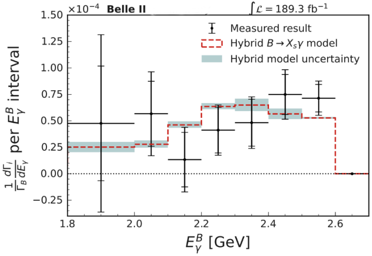


$B \to X_s\gamma$ with hadronic tagging (3/3)

arXiv: 2210.10220

Still correctly tagged non-$B \to X_s\gamma$ background remaining. $\Rightarrow$ Simulation used to estimate the size of this background.





E_γ^B threshold, GeV	Branching fraction ($\times 10^{-4}$)
1.8	$3.54 \pm 0.78 \pm 0.83$
2.0	$3.06 \pm 0.56 \pm 0.47$

- Main systematic effect comes from background data/simulation discrepancies.
- **Competitive with BaBar** (210 fb^{-1}) **measurement:** $3.66 \pm 0.55 \pm 0.60 \times 10^{-4}$ ($E_\gamma^B > 1.9$ GeV) [PRD **77**, 051103]
- **Consistent with world average**: $3.49 \pm 0.19 \times 10^{-4}$ [Prog. Theor. Exp. Phys. 2022, 083C01]

- $b \to s$ transitions are powerful tools to probe the SM.
- Belle II is at the center of the studies on these modes, thanks to its unique access to radiative and missing energy modes.

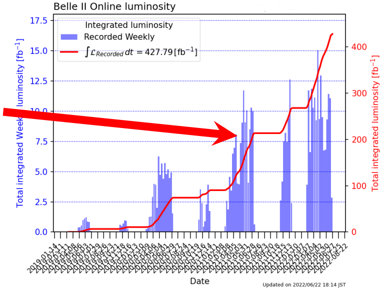
Measurements presented (189 fb^{-1} dataset):

- $B \to KJ/\Psi \Rightarrow$ **Branching ratios, and** $R_K(J/\Psi)$.
- $B \to K^* l^+ l^- \Rightarrow$ **Branching ratios, first steps towards** $\mathbf{R_{K^*}}$.
- $B \to X_s \gamma \Rightarrow$ **First Belle II inclusive measurement of the branching fraction**.

Belle II will provide new exciting EW and Radiative penguins measurements using the full data collected before shutdown.

- Many more Belle II results shown at this conference.
- e.g Yulan's talk for additional $b \to s$ discussions.
- Resuming data taking at the end of this year.

Shown today



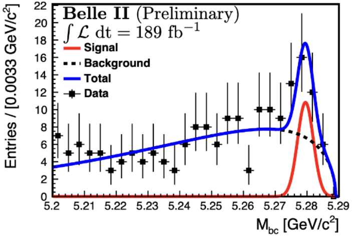
$\Rightarrow$ Stay tuned !

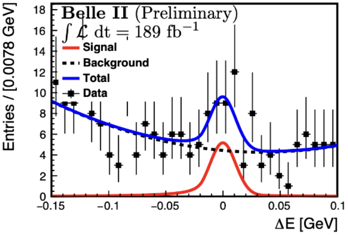
Thank you for listening !

Backup

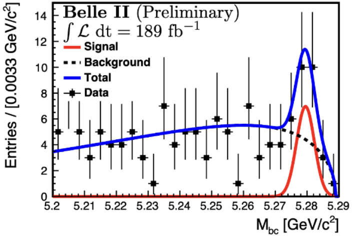
Measurement of $B \to K^* ll$

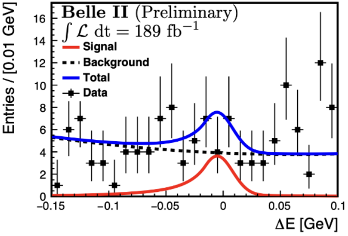
$B \to K^* \mu^+ \mu^-$





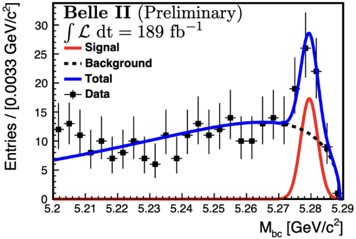
$B \to K^* e^+ e^-$

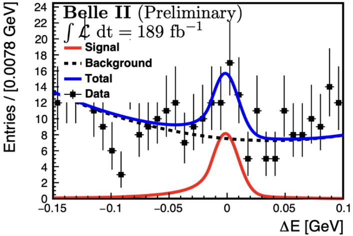




Measurement of $B \to K^* ll$

$B \to K^* l^+ l^-$





Measurement of $B \to K^*ll$

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\mathrm{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\mathrm{GeV}^2$)	24%	9.2%	2.8%

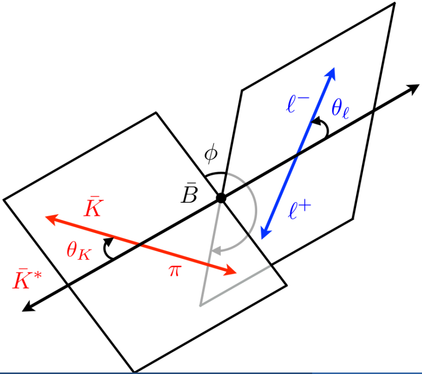
Figure: Prospects for Belle II sensitivity for R_K/R_{K^*} measurements.

Angular analysis in $B \to K^* ll$

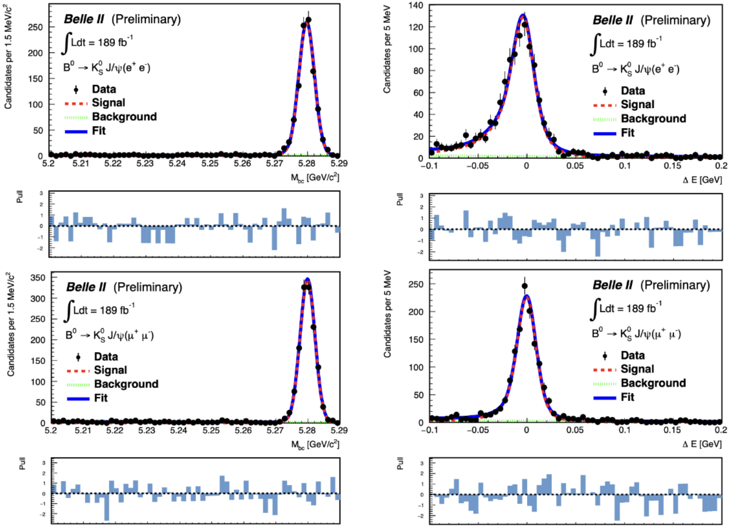
The differential decay rate is given by :

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dcos\theta_l dcos\theta_K d\phi dq^2} = \frac{9}{32\pi}[\frac{3}{4}(1-F_L)sin^2\theta_K + F_L cos^2\theta_K + \frac{1}{4}(1-F_L)sin^2\theta_K cos2\theta_l - F_L cos^2\theta_K cos2\theta_l + S_3 sin^2\theta_K sin^2\theta_l cos2\phi + S_4 sin2\theta_K sin2\theta_l cos\phi + S_5 sin2\theta_K sin\theta_l cos\phi + S_6 sin^2\theta_K cos\theta_l + S_7 sin2\theta_K sin\theta_l sin\phi + S_8 sin2\theta_K sin2\theta_l sin\phi + S_9 sin^2\theta_K sin^2\theta_l sin2\phi]$$

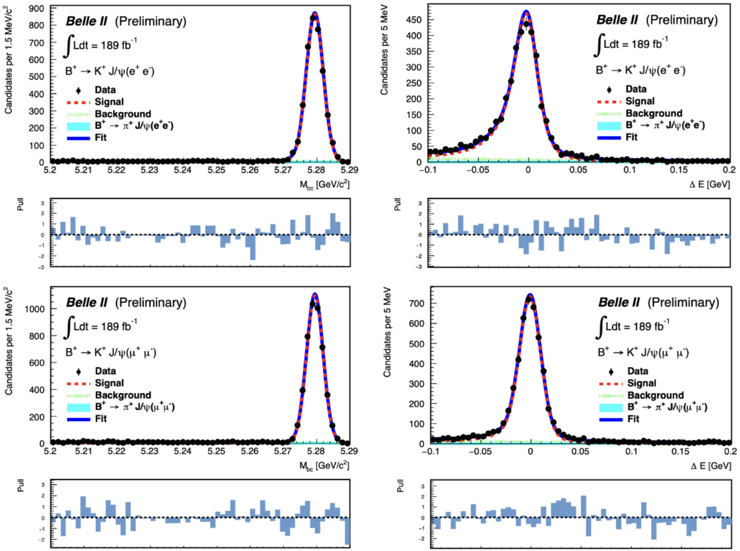
- 8 independent observables in the lepton massless limit:
  - F_L: Fraction of the longitudinal polarization of the K^*.
  - S_6: The forward-backward assymetry of the ll system.
  - $S_{3,4,5,7,8,9}$: The remaining CP-averaged observables.
- F_L and S_i are function of q^2.
- P_i' and Q_i:
  - $P'_{i=4,5,7,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$
  - $Q_i = P_i^{\mu} - P_i^{e}$, $i = 4, 5$
- Any deviation from zero for Q_i would indicate NP.



Measurement of $B \to J/\Psi K$



Measurement of $B \to J/\Psi K$

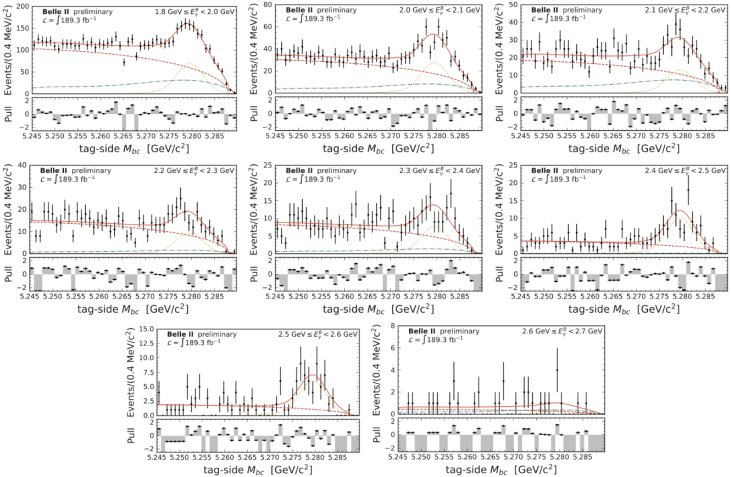


Measurement of $B \to X_s\gamma$

TABLE I: Partial branching fraction measurement results and uncertainties. Note that signal efficiency and background modelling uncertainties are correlated (see Sections 7.2 and 7.3).

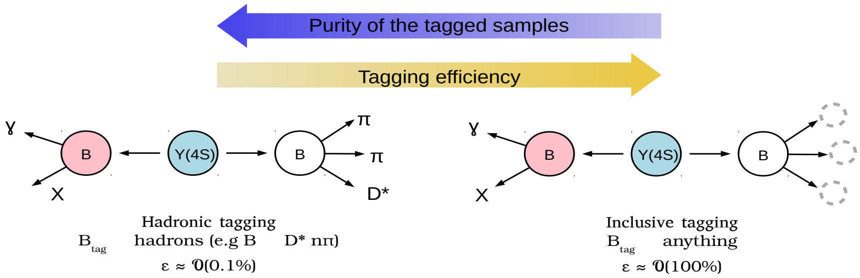
E_γ^B [GeV]	$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma}(10^{-4})$	Statistical	Systematic	Fit procedure	Signal efficiency	Background modelling	Other
1.8-2.0	0.48	0.54	0.64	0.42	0.03	0.49	0.09
2.0-2.1	0.57	0.31	0.25	0.17	0.06	0.17	0.07
2.1-2.2	0.13	0.26	0.16	0.13	0.01	0.11	0.01
2.2-2.3	0.41	0.22	0.10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

Measurement of $B \to X_s\gamma$

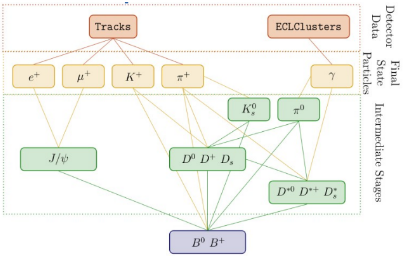


Measurement methods

Some decays studied here have missing kinetic information in the final state of the signal B meson (fully inclusive measurements or neutrinos in the final state).
$\Longrightarrow$ **Specific to e^+e^- B-factories:** use the accompanying B meson (tag-side) to **constrain the signal-side**.

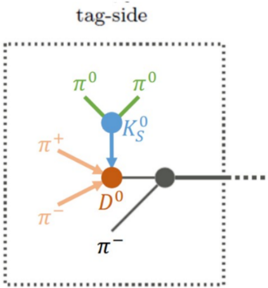


The Full Event Interpretation



How to reconstruct the tag-side ?

- Reconstruction using the **Full Event Interpretation** algorithm (**FEI**).
- Use final state particles to hierarchically reconstruct the most probable B_{tag}.
- Predefined B meson decay lists are used (ex: fully hadronic decays).
- Probability of each candidate to be correct estimated by a multivariate classifier.
- Inclusive tagging does not need to use this algorithm.



Measurements of $B \to J/\Psi(l^+l^-)K$ arXiv: 2207.11275

- Main systematic uncertainty from $\Upsilon(4S)$ **branching ratio to B pairs** (2.6%).
- Additional systematic for K_S^0 modes due to **data-MC differences in K_s^0 reconstruction efficiency** (3%).

What has been measured

$$\mathcal{B}\left(B^+ \to J/\psi\left(e^+e^-\right)K^+\right) = (6.00 \pm 0.10 \pm 0.19) \times 10^{-5}$$
$$\mathcal{B}\left(B^+ \to J/\psi\left(\mu^+\mu^-\right)K^+\right) = (6.06 \pm 0.09 \pm 0.19) \times 10^{-5}$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(e^+e^-\right)K_S^0\right) = (2.67 \pm 0.08 \pm 0.12) \times 10^{-5}$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right)K_S^0\right) = (2.78 \pm 0.08 \pm 0.12) \times 10^{-5}$$
$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

World averages

$$\mathcal{B}\left(B^+ \to J/\psi K^+\right)_{\mathrm{WA}} = (10.20 \pm 0.19) \cdot 10^{-4}$$
$$\mathcal{B}\left(B^0 \to J/\psi K^0\right)_{\mathrm{WA}} = (8.91 \pm 0.21) \cdot 10^{-4}$$
$$\mathcal{B}\left(J/\psi \to e^+e^-\right)_{\mathrm{WA}} = (5.971 \pm 0.032)\%$$
$$\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)_{\mathrm{WA}} = (5.961 \pm 0.033)\%$$

Prog. Theor. Exp. Phys. 2022, 083C01

Measurements of $B \to J/\Psi(l^+l^-)K$

Source	$\mathcal{B}(B \to KJ/\psi)$				R_K		A_I	
	K^+	K^+	K^0_S	K^0_S	K^+	K^0		
	e^+e^-	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$			e^+e^-	$\mu^+\mu^-$
Number of $B\overline{B}$ events	1.5	1.5	1.5	1.5	–	–	–	–
PDF shape	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Electron identification	0.6	–	0.6	–	0.6	0.6	–	–
Muon identification	–	0.4	–	0.4	0.4	0.4	–	–
Kaon identification	0.2	0.2	–	–	–	–	0.1	0.1
K^0_S reconstruction	–	–	3.0	3.0	–	–	1.5	1.5
Tracking efficiency	0.9	0.9	1.2	1.2	–	–	0.4	0.4
Simulation sample size	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$\Upsilon(4S)$ branching fraction	2.6	2.6	2.6	2.6	–	–	2.6	2.6
(τ_{B^+}/τ_{B^0})	–	–	–	–	–	–	0.2	0.2
Total	3.2	3.2	4.4	4.4	0.8	0.8	3.0	3.0

Figure: Systematic uncertainty sources for the $B \to J/\Psi K$ and $R_K(J/\Psi)$ measurements.