Electroweak and radiative penguin decays
at Belle II

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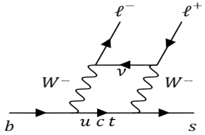
On behalf of the Belle II collaboration

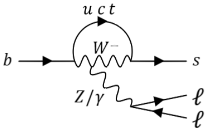
CIPANP 2022, Aug 29 - Sep 04

Electroweak and radiative penguin decays

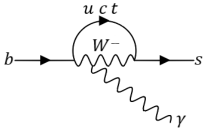
- $b \to s(d)$ flavour changing neutral current transitions **not possible at tree level** in the Standard Model (SM).
- Branching fractions $\simeq 10^{-4} - 10^{-7} \Rightarrow$ "rare" decays.
- Highly sensitive to beyond-SM mediator contributions, affecting:
  - Branching fractions.
  - Angular distributions.
  - CP asymmetries.
  - Kinematics.

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:

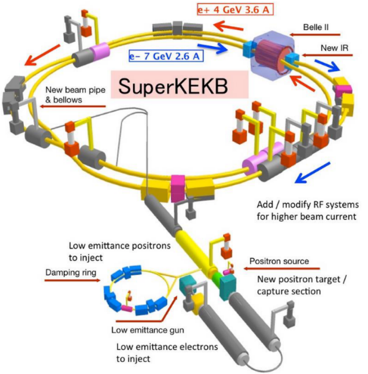
- Collected 424 fb^{-1} of data since 2019.
- Here we show studies based on 63 fb^{-1} and 189 fb^{-1} datasets.

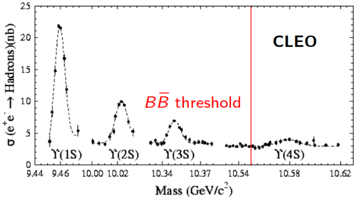
On-resonance data:

- $\sqrt{s} = 10.58$ 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 continuum background.



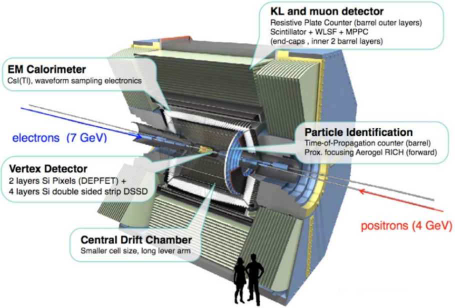


Belle II at superKEKB (2/3)

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



Belle II

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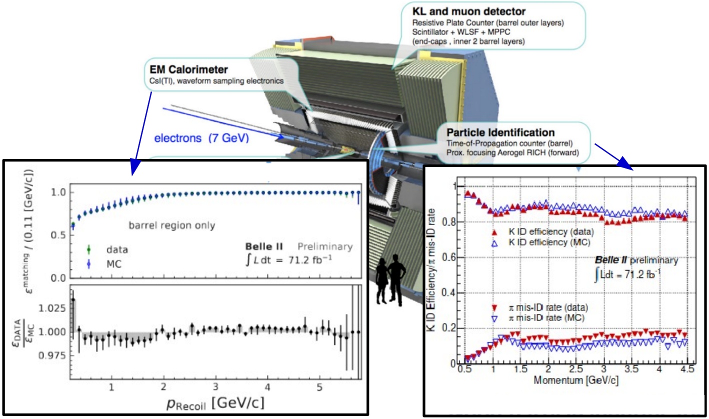


High photon reconstruction efficiency

Good particle identification

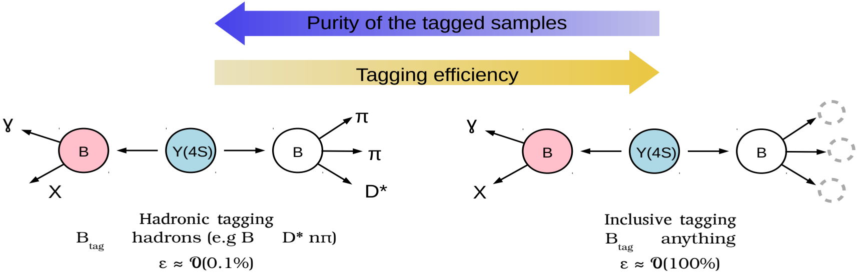
[BELLE2-NOTE-PL-2021-008]

[BELLE2-NOTE-PL-2020-024]

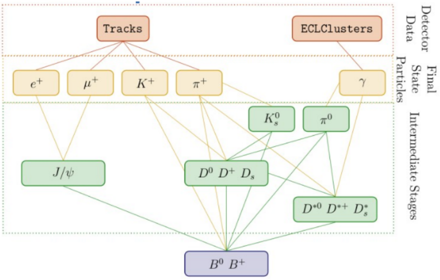
$\Rightarrow$ **Strengths: Precision measurements, rare and partially invisible decays** (ex: $B \to D\tau\bar{\nu}$). Just started a shutdown to upgrade the detector and improve the beampipe.

Measurement methods

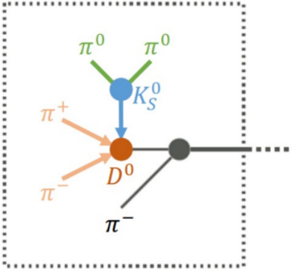
Some decays studied here have missing kinetic information in the final state of the signal B meson (fully inclusive measurements or neutrinos in the final state).
$\Longrightarrow$ **Specific to $\mathrm{e}^+\mathrm{e}^-$ B-factories:** use the accompanying B meson (tag-side) to **constrain the signal-side**.



The Full Event Interpretation



tag-side



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.

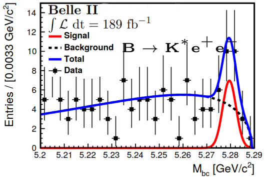
Towards R_K, R_{K^*} (1/2) arXiv: 2206.05946

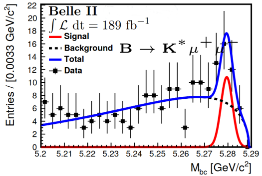
Belle II able to provide independent checks of $\mathbf{R_{K^*}}$ anomalies ([JHEP **08**(2017)055]) with enough data (few ab^{-1}). Here search with 189 fb^{-1}

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

- 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.
- Precision for e and μ channels in same ballpark ($\simeq 25 - 30\%$).

$$\mathbf{M_{bc}} = \sqrt{\mathbf{E^2_{beam}} - \mathbf{p^{*2}_B}} \qquad \mathbf{\Delta E} = \mathbf{E^*_B} - \mathbf{E_{beam}}$$

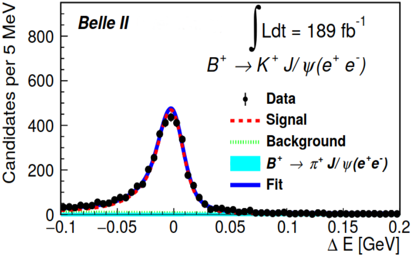


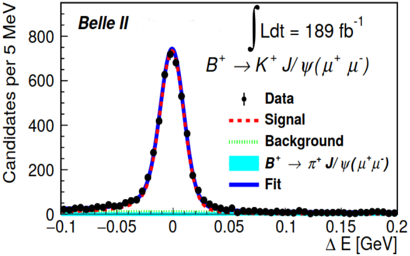


Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World average ($\times 10^{-6}$)
$B \to K^* e^+ e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

Measurement of $B \to J/_{\Psi} K$.

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





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

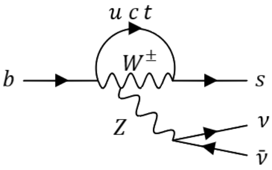
$$\epsilon_{B^+ \to K^+}/\epsilon_{B^0 \to K^0_S} = \mathbf{e} : 30\%/20\%,\ \mu : 37\%/25\%.$$

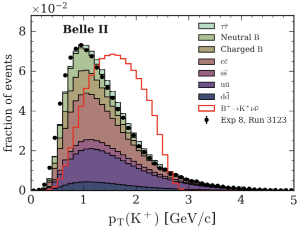
Observable	Belle II	Belle (2021)
$R_{K^+}(J/_{\Psi})$	$1.009 \pm 0.022 \pm 0.008$	$0.0994 \pm 0.011 \pm 0.010$
$R_{K^0_S}(J/_{\Psi})$	$1.042 \pm 0.042 \pm 0.008$	$0.0993 \pm 0.015 \pm 0.010$

[JHEP, **03**, 105 (2021)]

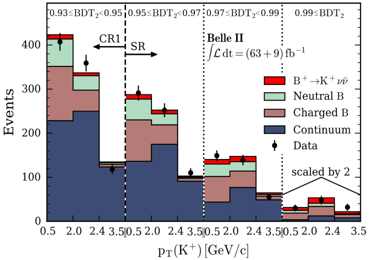
Complementary to $b \to sll$.
Avoids some theoretical uncertainties (no amplitude with virtual photon).

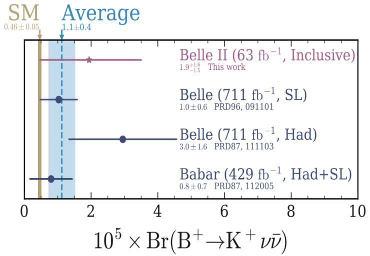
- **Challenges**:
  - Rare: $Br_{SM} = (4.6 \pm 0.5) \times 10^{-6}$ [arXiv: 1606.00916].
  - Two neutrinos in the final state $\Rightarrow$ unique to Belle II.
- Previous analyses used **tagged** approaches: low efficiency.
  - No signal observed thus far.
  - $Br(B^+ \to K^+\nu\bar{\nu}) < 1.6 \times 10^{-5}$ at 90% CL.
- Here, an **inclusive** approach is used to search for $B^+ \to K^+\nu\bar{\nu}$ with 63 fb^{-1}.
  - **Single candidate**: single highest p_T kaon track
  - **Rest of event**: remaining tracks and energy deposits (tag-side B meson).
  - Use two sequential BDTs trained on kinematics, event-topology, vertexing, etc. to **suppress background**.





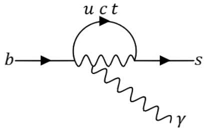
- BDT performance on data tested using $B^+ \to K^+ J/_\Psi(\mu^+\mu^-)$.
- Signal from maximum likelihood fit in bins of $p_T(K^+)$ and BDT output.
- No statistically significant signal observed.
- Upper limit at 90% CL: $Br(B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5}$.
- Belle II capable of providing **world-leading measurements in the near future**.





$B \to X_s\gamma$ with hadronic tagging (1/3)

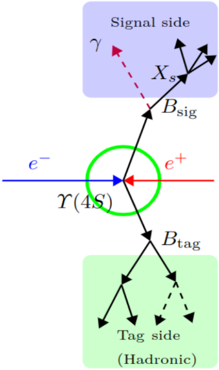
$b \to s\gamma$ has higher rates and is sensitive differently to NP compared to $b \to s\nu\bar{\nu}$.
All $b \to s\gamma$ final states are considered $\Rightarrow$ **inclusive** search. In addition to studying NP ($H^{\pm}$ mass), allows to extract:



- 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:

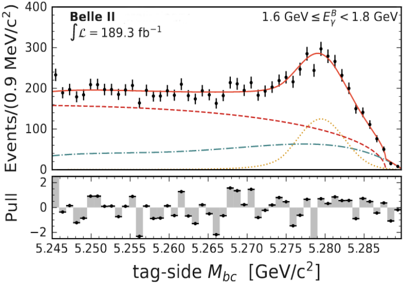
- Inclusive measurement: **only photon constrained** on signal side.
- Large background contribution $\Rightarrow$ challenging to suppress without losing "inclusiveness".
- Tag-side B meson reconstructed with **hadronic tagging** $\Rightarrow$ high purity sample, direct access to E_γ^B, photon energy in B rest frame.
- Hadronic tagged study performed once by **BaBar** (210 fb^{-1}) [PRD **77**, 051103].



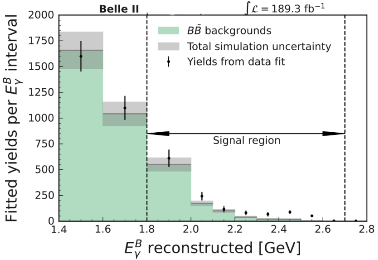
$B \to X_s\gamma$ with hadronic tagging (2/3)

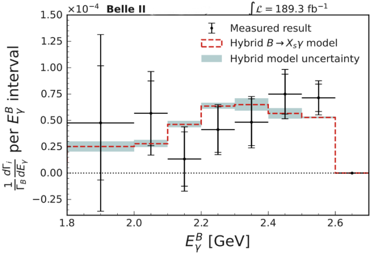
- **Signal candidate**: Highest energy photon in event, $E_\gamma^B > 1.4$ GeV.
- **General background suppression**: BDT trained to suppress events compatible with $e^+e^- \to q\bar{q}$.
  $\Rightarrow$ only use features uncorrelated to E_γ^B and M_{bc}.
- **Signal-side background suppression (photon)**: 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.



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** $(210\ \text{fb}^{-1})$ **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**: $3.49 \pm 0.19 \times 10^{-4}$

Summary

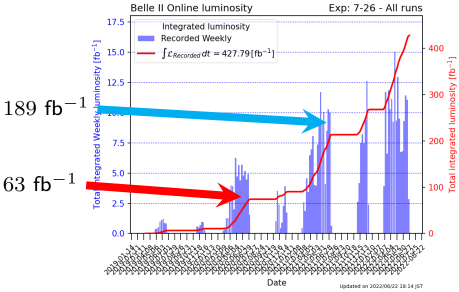
- $b \to s$ transitions are powerful tools to probe the SM.
- Belle II is at the center of the studies on these modes, thanks to its unique access to radiative and missing energy modes.

Measurements presented:

- $B \to K^* l^+ l^-$ and $B \to KJ/_\Psi \Rightarrow$ **First steps towards $\mathbf{R_K}$.** $(189\ \text{fb}^{-1})$
- $B^+ \to K^+ \nu\bar{\nu} \Rightarrow$ **New approach, upper limit on branching fraction.** $(63\ \text{fb}^{-1})$
- $B \to X_s \gamma \Rightarrow$ **First Belle II inclusive measurement of the branching fraction** $(189\ \text{fb}^{-1})$

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

$\Rightarrow$ Stay tuned !

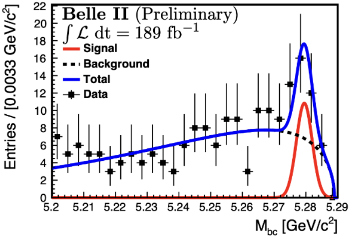


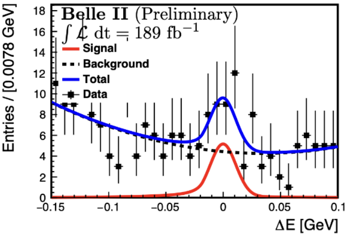
Thank you for listening !

Backup

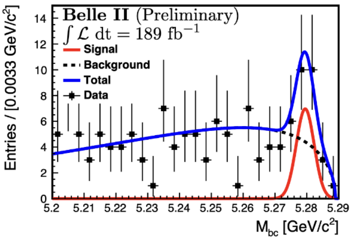
Measurement of $B \to K^* ll$

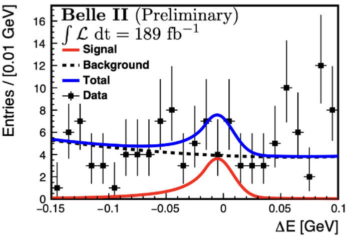
$B \to K^* \mu^+ \mu^-$





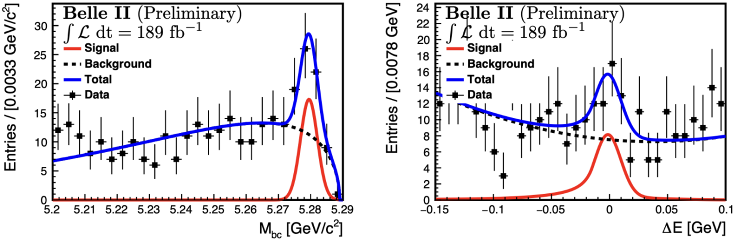
$B \to K^* e^+ e^-$





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%

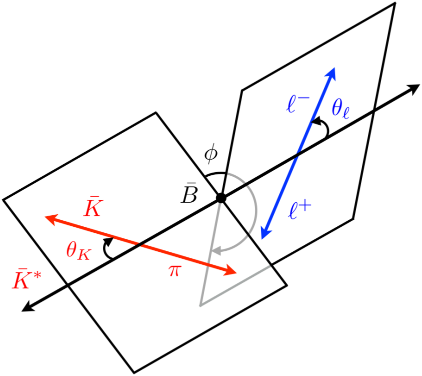
Figure: Prospects for Belle II sensitivity for R_K/R_{K^*} measurements.

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

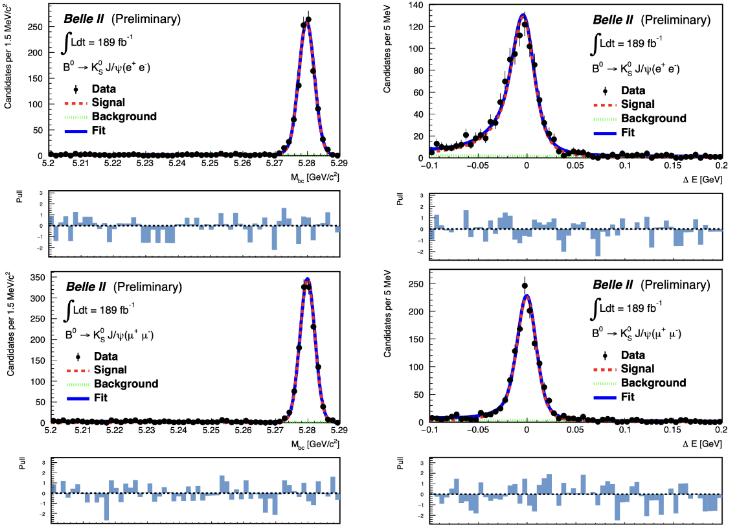
The differential decay rate is given by :

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

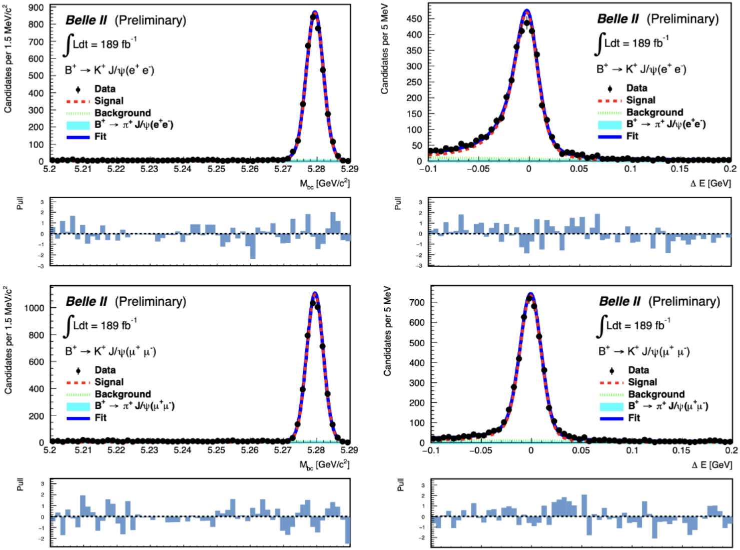
- 8 independent observables in the lepton massless limit:
  - F_L: Fraction of the longitudinal polarization of the K^*.
  - S_6: The forward-backward assymetry of the ll system.
  - $S_{3,4,5,7,8,9}$: The remaining CP-averaged observables.
- F_L and S_i are function of q^2.
- P_i' and Q_i:
  - $P'_{i=4,5,7,8}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