Electroweak and radiative penguin decays at Belle and Belle II

Henrikas Svidras
henrikas.svidras@desy.de

On behalf of the Belle and Belle II collaborations

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Analyses overviewed

BELLE | Belle II

Electroweak penguin decays

- $B^0 \to K^{*0}\tau^+\tau^-$

- $B \to K^*\ell^+\ell^-$
- Towards $R(K)$: $B^+(B^0) \to J/\psi\, K^+(K_S^0)$
- $B^+ \to K^+\nu\bar{\nu}$

Electroweak radiative decays

- $B^0 \to K_S^0 K_S^0 \gamma$

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

Electroweak and radiative penguin decays

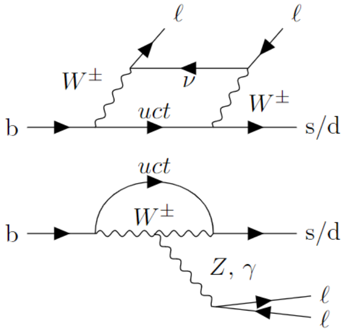
- Flavour changing neutral current is **not possible at tree-level** in the Standard Model
- Mediated by loop/box diagrams
- Branching fractions ~ $10^{-7} - 10^{-4}$ ⇒ **'rare' decays**
- Beyond-SM particles may also mediate $b \to s$ transitions and affect:
  - Branching fractions
  - CP asymmetries
  - Angular distributions

→ measure observables directly and/or as ratios

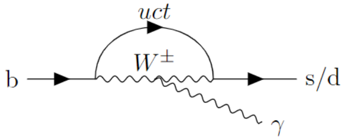
Notable example of a ratio observable:

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

Box and penguin transitions

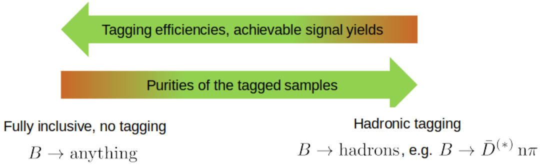


Radiative transitions



Measurement strategies at B factories

- B factories are **excellent suited to study rare decays**
  → Nearly 4π coverage
  → **Low combinatorial background**
  → **Both B mesons can be reconstructed**
- Some studies may have signal B mesons with missing kinematic information, e.g., inclusive measurements, or when neutrinos are present in the final state
  → Accompanying B meson (tag-side) can **constrain the signal side**



Variables for candidate B meson quality:

beam-constrained mass

$$M_{\mathrm{bc}} = \sqrt{(\tfrac{\sqrt{s}}{2})^2 - (p_B^*)^2}$$

energy difference

$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$

where

- $\sqrt{s}$ is the colliding beams' center-of-mass energy
- p_B^*, E_B^* are B meson momentum/energy in the colliding beam rest frame

Thermal imaging Emperor Penguins in Terre Adélie, Antarctica

Electroweak penguins

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

arXiv: 2206.05946

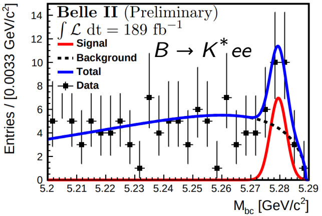
- K^* is used to denote $K^*(892)^0$ and $K^*(892)^+$ implicitly
- Observation of $B \to K^*\ell\ell$ is the **first step towards** R_{K^*}
- Reconstructs K^* from K^+ or K^0_S with π^- or π^0

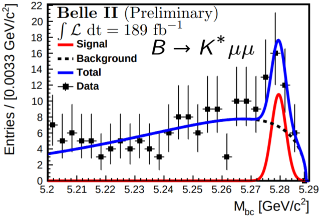
Background suppression:

- **Dilepton mass vetoes:**
  $\Rightarrow B \to J/\psi(\to \ell\ell)K^*$
  $\Rightarrow B \to \psi(2S)(\to \ell\ell)K^*$
  $\Rightarrow B \to K^*\gamma$ photon conversion
- $e^+e^- \to q\bar{q}$: **boosted decision tree** (BDT)

Results:

- **Two-dimensional fit** to $M_{\rm bc}$ and ΔE is performed
- 26% (μ^+)/ 34% (e^+) branching fraction precision



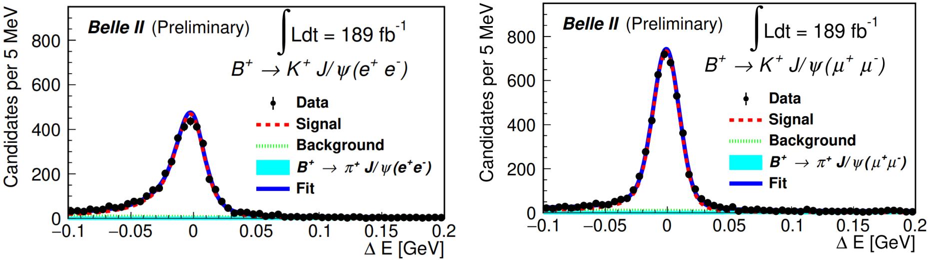


Mode	Observed events	Branching Fraction ($\times 10^{-6}$)	World Average ($\times 10^{-6}$)
$B \to K^*e^-e^-$	22 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^*\mu^+\mu^-$	18 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

Towards $R(K)$: $B^+(B^0) \to J/\psi K^+(K^0_S)$

arXiv:2207.11275

- Not $b \to s$ transition, **BUT** a critical control channel for $R(K)$
- Proceeds via $b \to c$ favored tree level transition $\Rightarrow$ **high branching fraction**
- Reconstruct: $B \to J/\psi[\to \ell\ell]K$ from candidates that succeed a vertex fit
- Extract signal by fitting $M_{\rm bc}$ and ΔE



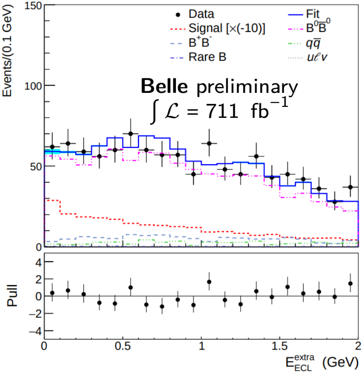
Mode	$n_{J/\psi \to e^+e^-}$	$n_{J/\psi \to \mu^+\mu^-}$	$R_K(J/\psi)$
$B \to K^+ J/\psi$	3706 ± 62	4578 ± 62	$1.009 \pm 0.022 \pm 0.008$
$B \to K^0_S J/\psi$	1052 ± 33	1343 ± 37	$1.042 \pm 0.042 \pm 0.008$

$\to$ **Lepton ID systematic $<1\%$ and smaller compared to Belle [JHEP 03 (2021) 105] result**

$B^0 \to K^{*0}\tau^+\tau^-$

arXiv:2110.03871

- A highly suppressed decay proceeding via FCNC with $\mathcal{B} \sim \mathcal{O}(10^{-7})$ in SM
- 3^{rd} generation version of $B \to K^*\ell\ell$
- Only $B^+ \to K^+\tau^+\tau^-$ limit by BABAR
  $\to \mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90% confidence limit (CL) [PRL **118**, 031802]
- The **first search** for the neutral channel

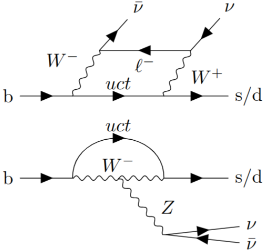


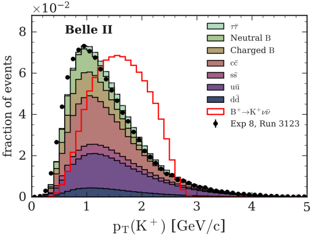
- **Hadronic tagging** is used to reconstruct the accompanying B meson
  Four tracks required:
  $\Rightarrow$Kaon candidate from K^+ and π^-
  $\Rightarrow \tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ or $\tau^- \to \pi^-\nu_\tau$
- **Signal region**, $E_{\mathrm{ECL}}^{\mathrm{extra}} < 0.2$ GeV
  $\to$ The total energy of the neutral clusters detected in the ECL not associated with either tag B meson or signal B meson.
- Binned maximum likelihood fit to $E_{\mathrm{ECL}}^{\mathrm{extra}}$ is performed, **no significant signal found**
  $\to N_{\mathrm{sig}} = -4.9 \pm 6.0$ and $N_{\mathrm{bkg}} = 122.4 \pm 4.9$
  $\to \mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$ at 90% CL

$B^+ \to K^+\nu\bar{\nu}$ (1/2)

PRL **127**, 181802

- $b \to s\nu\bar{\nu}$ are a complementary to $b \to s\ell\ell$ studies
- No $\ell^\pm$ in final state: **sidesteps some theoretical uncertainties**
- Predicted $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \sim 5 \times 10^{-6}$
  [JHEP. 2015, 184 (2015)] , [arXiv:2207.13371]
- Challenging due to presence of neutrinos in the final state
- **Previous analyses use tagged approaches**: low efficiency
  → No analyses thus far observed signal
  → $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 1.6 \times 10^{-5}$ at 90% CL[PDG]
- An *inclusive tagging* technique is **set up for the first time**
- Performed on 63 fb^{-1} of data



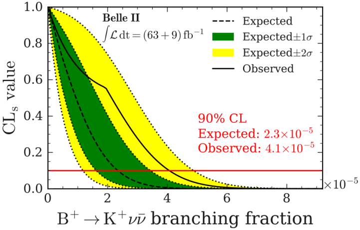


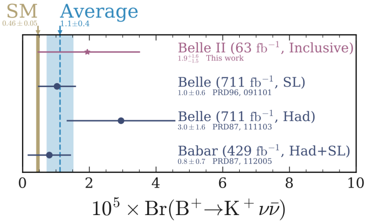
- **Signal candidate:** single highest-p_T kaon track
- **Rest-of-event:** remaining tracks and energy deposits (accompanying B meson)
- Two sequential BDTs are trained that combine **event topology**, signal **kaon and rest-of-event properties**, **vertexing information**, etc. to remove backgrounds

$B^+ \to K^+ \nu\bar{\nu}$ (2/2)

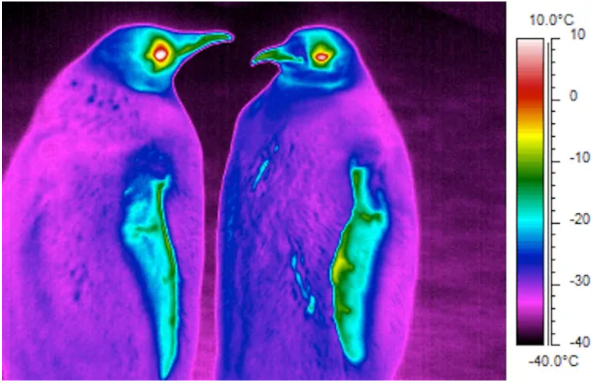
PRL **127**, 181802

- BDT performance in data tested using $B \to K^+ J/\psi(\to \mu^+\mu^-)$ validation channels
- Simultaneous binned maximum likelihood fit is performed in bins of kaon-$p_T \times \mathrm{BDT}_2$





- No statistically significant signal observed: CL is set
- Statistically compatible with other results
- **More sensitive per integrated luminosity compared to tagged methods:**
  → 20% better than semileptonic tagged
  → 350% better than hadronic tagged
- Belle II in a position to provide **world-leading measurements in the near future**

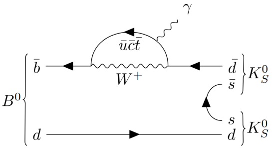


Biol. Lett.9:20121192

Radiative penguins

$B^0 \to K_S^0 K_S^0 \gamma$ (1/2)

PRD **106**, 012006

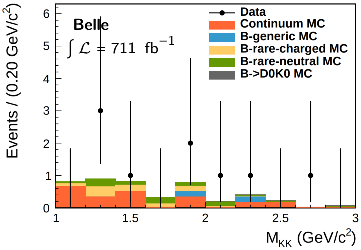


- $b \to d$ transition, **not measured before**
  → only $B \to \rho\gamma$ and $B \to \omega\gamma$ observed exclusively before
- $K_S^0 K_S^0$ system must have an even spin (Bose Einstein stat.)
  → Because it's a radiative decay, $J = 0$ case is excluded
  → Can occur via intermediate tensor states

Neural network used for:

- K_S^0 selection
- dominant $e^+e^- \to q\bar{q}$ suppression

- M_{bc} fit is performed in 10 bins of dikaon mass, $M_{KK} \in (1.0, 3.0)\ \mathrm{GeV}/c^2$
- 2.5% average signal efficiency

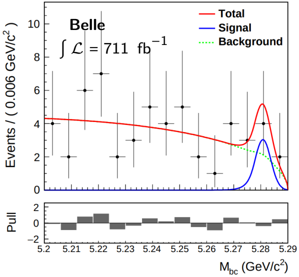


M_{KK} GeV/c^2	Partial BF upper limit at 90% CL (10^{-7})
1.0 – 1.2	0.7
1.2 – 1.4	2.8
1.4 – 1.6	1.7
1.6 – 1.8	1.1
1.8 – 2.0	2.9
2.0 – 2.2	2.5
2.2 – 2.4	2.4
2.4 – 2.6	1.3
2.6 – 2.8	2.3
2.8 – 3.0	1.2

$B^0 \to K_S^0 K_S^0 \gamma$ (2/2)

PRD **106**, 012006

- The number of observed candidate events is 9, **no significant signal found**
- The **expected number of background events** is estimated from MC as 4.5 ± 0.7 **and validated** using a fit to the full $M_{KK} \in (1.0, 3.0)\ \mathrm{GeV}/c^2$ region



- **Upper limits at 90% CL are calculated**:
  - $\mathcal{B}(B \to K_S^0 K_S^0 \gamma) < 5.8 \times 10^{-7}$

    Intermediate tensor states:
  - $f_2(1270) : 3.1 \times 10^{-7}$ $(1.00\ \mathrm{GeV}/c^2 < M_{KK} < 1.44\ \mathrm{GeV}/c^2)$
  - $f_2'(1525) : 2.1 \times 10^{-7}$ $(1.44\ \mathrm{GeV}/c^2 < M_{KK} < 1.63\ \mathrm{GeV}/c^2)$

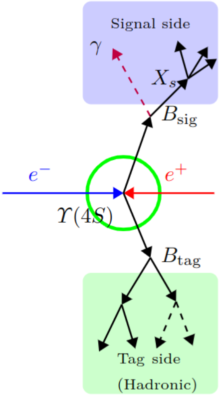
$B \to X_s \gamma$ with hadronic tagging

Motivation:

- All $b \to s\gamma$ final states are considered, hence **inclusive**
  → **Complementary to exclusive**: e.g. form factor uncertainties avoided
- SM parameters describe E_γ spectrum in decaying B rest frame:
  → m_b; Fermi motion of b [PRL. **127**, 102001]

Measurement:

- Inclusive analysis: **only photon constrained** on the signal side
  → Large background process contribution
  → Challenging to suppress them without breaking the 'inclusiveness'
- Accompanying B meson is reconstructed **using hadronic tagging**
  → High purity sample
  → Direct access to E_γ^B, photon energy in signal B meson rest frame
- Hadronic tagged study **performed only once** by BABAR (210 fb^{-1})
  [Phys.Rev.D 77 (2008) 051103]
  → Belle II is **in a position to improve this** in the near future



$B \to X_s\gamma$ with hadronic tagging

ICHEP 2022

Signal candidate: Highest energy photon in event, $E_\gamma^B > 1.4\ \mathrm{GeV}$

General background suppression

- A BDT is trained to suppress events consistent with $e^+e^- \to q\bar{q}$ transition
  → Only use **features that are not correlated** with E_γ^B and M_{bc}

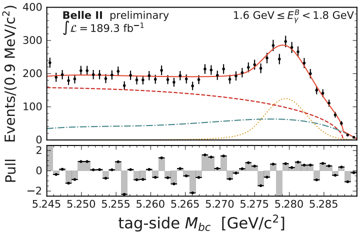
Signal-side (photon) background suppression

- **Main background:** photons consistent with $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays vetoed

Tag-side background suppression

- M_{bc} fits in bins of reconstructed E_γ^B extracts **correctly tagged event counts**
- Continuum and combinatorial $B\bar{B}$ event contributions removed

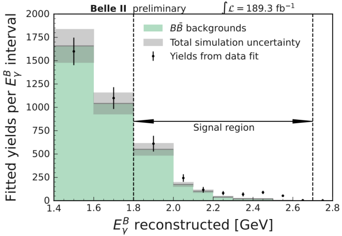
Selections and fit **validated on** $1.4 < E_\gamma^B < 1.8\ \mathrm{GeV}$ **control region**

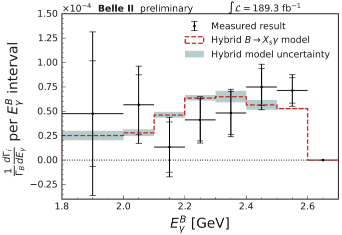


$B \to X_s\gamma$ with hadronic tagging

ICHEP 2022

- After fitting: correctly tagged non-$B \to X_s\gamma$ *can* still remain
  → **Simulation is used to determine** the size of this background





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

⇒ Dominating systematic uncertainties related to data-simulation differences

Competitive with BABAR (210 fb^{-1}) measurement [Phys.Rev.D 77 (2008) 051103] :

3.66 ± 0.85 (stat.) $\pm$ 0.60 (syst.) $\times 10^{-4}$ ($E_\gamma^B > 1.9$ GeV)

Consistent with world average (includes all tagging approaches):

$(3.49 \pm 0.19) \times 10^{-4}$[PDG]

Summary

- $b \to s/d$ transitions are highly interesting for the theoretical and experimental developments in the SM
- Belle / Belle II continue to provide **unique and competitive electroweak penguin results**

Results covered:

- $B^0 \to K^{*0}\tau^+\tau-$
- $B^0 \to K_S^0 K_S^0 \gamma$

} **Updated upper limits**

- $B \to K^* \ell^+ \ell^-$
- $B \to K J/\psi$

} **First steps towards R_K**

- $B^+ \to K^+ \nu\bar{\nu}$ → **New approach, higher sensitivity**
- $B \to X_s \gamma$ with hadronic tagging
  → **First Belle/Belle II $b \to s\gamma$ measurement with this method**

⇒ stay tuned for many more exciting results with larger datasets

Backup

KEKB and SuperKEKB colliders

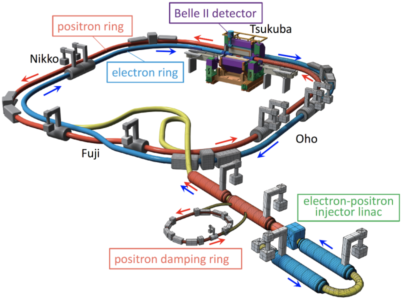
- SuperKEKB is an assymetric e^+e^- collider constructed by upgrading the KEKB B-factory.
- Located in Tsukuba, Japan

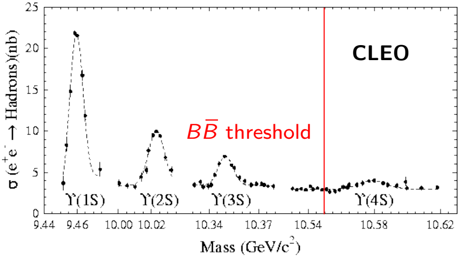
SuperKEKB:

- 4.0 GeV e^+ and 7.0 GeV e^- beams
- ×1.5 beam currents
- ×1/20 vertical beam size
  → **Target:** Up to 20-30 times higher instantaneous luminosity
- Current record instantaneous luminosity: $4.7 \times 10^{34}\,\mathrm{cm}^{-2}s^{-1}$

KEKB:

- 3.0 GeV e^+ and 8.5 GeV e^- beams
- Max. instantaneous luminosity: $2.1 \times 10^{34}\,\mathrm{cm}^{-2}s^{-1}$

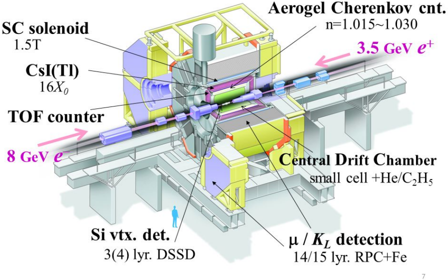




Belle and Belle II detectors

- Collected/collects data of e^+ and e^- collisions at 10.58 GeV center-of-mass energy
- Belle II is an upgraded version of Belle, optimised for higher instantaneous luminosity

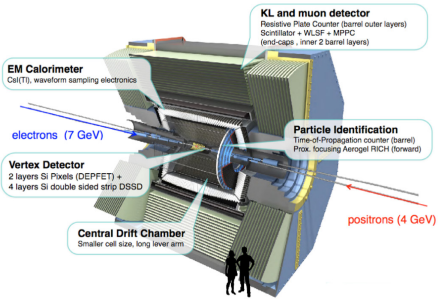
Belle



Largest integrated luminosity collected by a B factory:

- 711 fb^{-1} on $\Upsilon(4S)$ mass
- $\approx$ 100 fb^{-1} below $\Upsilon(4S)$ mass

Belle II



Goal: total integrated luminosity 50 ab^{-1}

- Currently in a 1 year operational pause
- 363 fb^{-1} on $\Upsilon(4S)$ mass
- 42 fb^{-1} below $\Upsilon(4S)$ mass

$B \to K^*\ell\ell$ additional material

Table I. Relative systematic uncertainties (in %) for $B \to K^*\ell\ell$.

Source	Systematic (%)
Kaon identification	0.4
Pion identification	2.5
Muon identification	$^{+1.9}_{-0.8}$
Electron identification	$^{+0.9}_{-0.5}$
K^0_S identification	2.0
π^0 identification	3.4
Tracking	1.2 – 1.5
MVA selection	1.3 – 1.7
Simulated sample size	< 0.5
Signal cross feed	< 1%
Signal PDF shape	0.5 – 1.0%
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)[(\mathcal{B}(\Upsilon(4S) \to B^0\overline{B^0}))$	1.2
Number of $B\overline{B}$ pairs	2.9
Total	$^{+6.7}_{-6.0}$

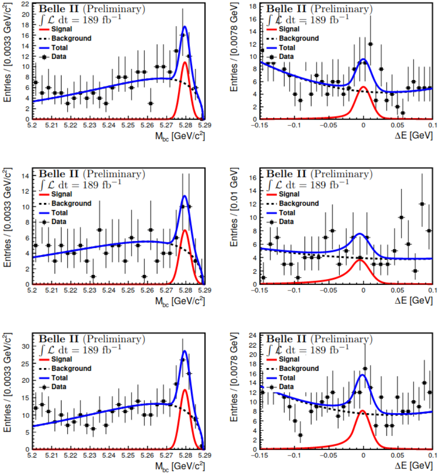
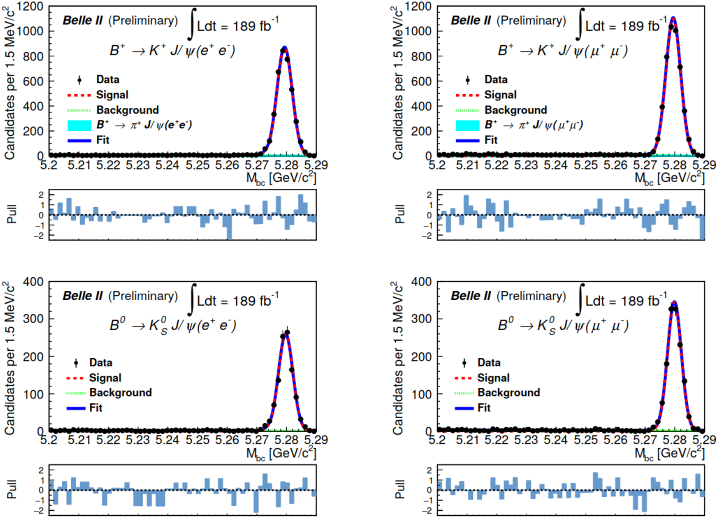


Figure 1. Distributions of M_{bc} (left) and ΔE (right) for $B \to K^*\mu^+\mu^-$ (top), $B \to K^*e^+e^-$ (middle), and $B \to K^*\ell^+\ell^-$ (bottom). Points with error bars are superimposed on the blue (solid curve, which shows the total fit function, while red (solid) and black (dotted) lines represen the signal and background components, respectively. Candidates shown in the ΔE distribution are restricted to $M_{bc} \in [5.27, 5.29]$ GeV/c^2 range and the M_{bc} distributions are restricted to $\Delta E \in [-0.05, 0.05]$ GeV.

J/ψ: $M(\mu^+\mu^-) \notin [2.946, 3.176]$ GeV/c^2, $M(e^+e^-) \notin [2.846, 3.176]$ GeV/c^2, and $\psi(2S)$: $M(\mu^+\mu^-) \notin [3.539, 3.719]$ GeV/c^2, $M(e^+e^-) \notin [3.439, 3.719]$ GeV/c^2.

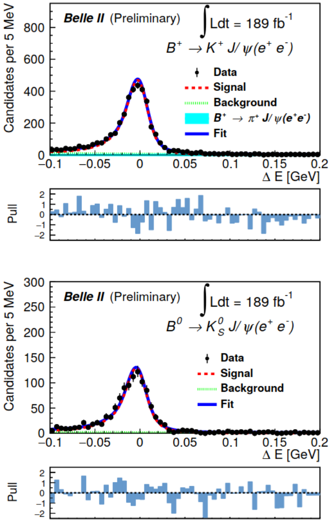
$B \to J/\psi\, K$ aditional material (1/3)

All M_{bc} fits



$B \to J/\psi\, K$ aditional material (2/3)

All ΔE fits



$B \to J/\psi\, K$ additional material (3/3)

Uncertainties:

Table III. Relative systematic uncertainties (%) on $\mathcal{B}(B \to J/\psi K)$, $R_K\,(J/\psi)$, and absolute certainty on $A_I\,(B \to J/\psi K)$.

Source	$\mathcal{B}(B \to K J/\psi)$				R_K		A_I	
	K^+ e^+e^-	K^+ $\mu^+\mu^-$	K^0_S e^+e^-	K^0_S $\mu^+\mu^-$	K^+	K^0	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

Results:

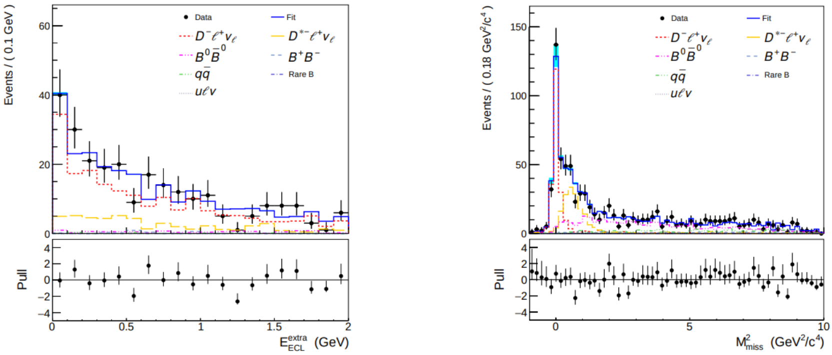
Channel	ϵ (%)	$n_{\rm sig}$	$\mathcal{B}$ (10^{-5})
$B^+ \to J/\psi(e^+e^-)K^+$	30.4	3706 ± 62	$6.00 \pm 0.10 \pm 0.19$
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	37.2	4578 ± 62	$6.06 \pm 0.09 \pm 0.19$
$B^0 \to J/\psi(e^+e^-)K^0_S$	20.4	1052 ± 33	$2.67 \pm 0.08 \pm 0.12$
$B^0 \to J/\psi(\mu^+\mu^-)K^0_S$	25.0	1343 ± 37	$2.78 \pm 0.08 \pm 0.12$

Observable	Measured value
$A_I\,(J/\psi(ee)K)$	$-0.022 \pm 0.016 \pm 0.030$
$A_I\,(J/\psi(\mu\mu)K)$	$-0.006 \pm 0.015 \pm 0.030$
$R_{K^+}\,(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$
$R_{K^0_S}\,(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$

$B^0 \to K^{*0}\tau^+\tau^-$ (1/2) additional material

Validation of analysis procedure using:

- $B^0 \to D^-(\to K^{*0}\pi^-)\ell^+\nu_\ell$ decays



Extracted BF agree well with $(2.31 \pm 0.10)\%$ world average

- $(2.26 \pm 0.17)\%$ (fitting $E_{\mathrm{ECL}}^{\mathrm{extra}}$)
- $(2.19 \pm 0.15)\%$ (M_{miss}^2)

statistical errors only

$B^0 \to K^{*0}\tau^+\tau^-$ (2/2) additional material

Main background suppression requirements:

- $B^0 \to D^-(\to K^{*0}\pi^-)\ell^+\nu_\ell$ and other background suppress using $M_{K\pi^0}$ selection
- M_{miss}: missing mass of event

TABLE I. Summary of the selection criteria imposed on $M_{K^{*0}\pi^-}$ and $M^2_{\rm miss}$ for each of the signal modes.

Signal Mode	$M_{K^{*0}\pi^-}$ (GeV/c^2)	$M^2_{\rm miss}$ (GeV^2/c^4)
$K^{*0}e^+e^-$	> 1.4	> 3.2
$K^{*0}e^\mp\mu^\pm$	> 1.4	> 1.6
$K^{*0}\mu^+\mu^-$	> 1.6	> 1.6
$K^{*0}\pi^\mp e^\pm$	> 1.4	> 2.0
$K^{*0}\pi^\mp\mu^\pm$	> 1.4	> 2.0
$K^{*0}\pi^+\pi^-$	> 1.5	< 9

- Signal efficiency (from simulation): 1.2×10^{-5}
- $M_{\tau\tau} > 3.55$ GeV/c^2 suppresses combinatorial background
- $\mathcal{L}_{\mu,e} > 0.8$, identification efficiency 92%, pion fake rate 2.5%

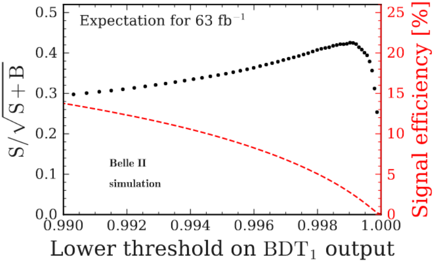
Uncertainties:

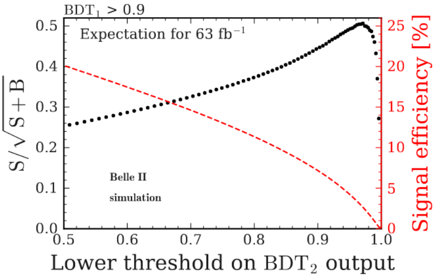
limited MC sample size	5.2%
Tagging efficiency	4.6%
Tracking uncertainty	1.4%
Total particle identification uncertainty	2.55%
Veto uncertainty due to reconstruction efficiency for π^0	0.17%
Veto uncertainty due to reconstruction efficiency for K_S^0	1.56%

The total systematic uncertainty 7.88%

$B \to K\nu\nu$ additional material (1/2)

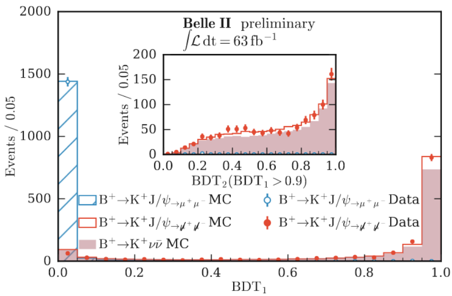
Sequential BDTs:

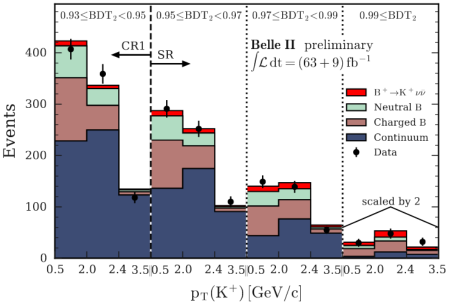




$B \to K\nu\nu$ additional material (1/2)

Validation and signal extraction





- **Total uncertainty:** profile likelihood scan: parameter free fit with different signal strengths fixed around the best fit value
- **Systematic uncertainty:** total – statistical difference in quadrature

$B^0 \to K_S^0 K_S^0 \gamma$ additional material (1/2)

- $K_S^0 K_S^0$ system has a parity $(-1)(-1)(-1)^{\ell}$
- According to Bose-Einsten statistics this needs to be 1
  $\Rightarrow \ell = \text{even}$
- If this proceeds via an intermediate state, $f_2 \to K_S^0 K_S^0$, it must have an even spin number
- $B^0 \to f_2(\to K_S^0 K_S^0)\gamma$, and $J(\gamma) = 1$, helicity= ± 1
- Spin projections against B decay axis must be zero $\to K_S^0 K_S^0$ cannot have spin-0
  $\Rightarrow$ lowest allowed state is $J = 2$

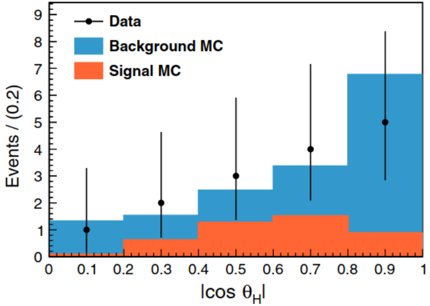
$B^0 \to K_S^0 K_S^0 \gamma$ additional material (2/2)

TABLE II. Systematic uncertainties in branching fractions.

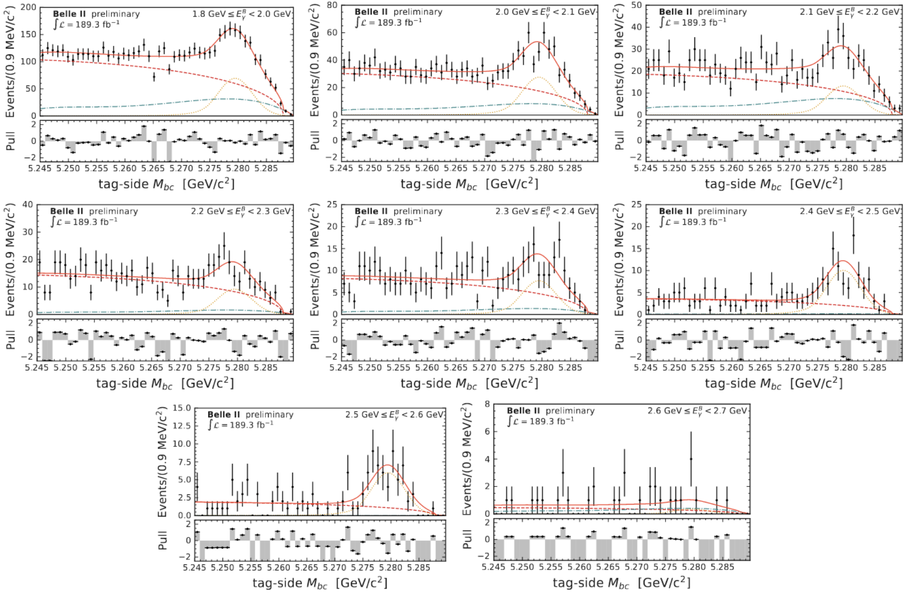
Source	Uncertainty (%)
Number of $B\bar{B}$	1.4
Branching fraction of $\Upsilon(4S) \to B^0\bar{B}^0$	1.2
Photon detection efficiency	2.0
Two K_S^0 reconstruction	1.4
NN selection and π^0/η veto	0.6
MC statistics in $M_{K_S^0K_S^0}$ bin efficiency	0.5–0.7
Total	3.2

Mass bin (GeV/c^2)	ϵ_S (%)	N_{bkg}	σ_{sys} (%)	N_{obs}	S_{90}	U.L. (10^{-7})
1.0–1.2	3.3	0.8 ± 0.3	3.2	0	1.8	0.7
1.2–1.4	3.0	0.9 ± 0.3	3.2	3	6.5	2.8
1.4–1.6	2.7	0.8 ± 0.3	3.2	1	3.6	1.7
1.6–1.8	2.5	0.3 ± 0.1	3.2	0	2.1	1.1
1.8–2.0	2.3	0.8 ± 0.3	3.2	2	5.1	2.9
2.0–2.2	2.2	0.2 ± 0.1	3.2	1	4.2	2.5
2.2–2.4	2.2	0.4 ± 0.2	3.2	1	3.9	2.4
2.4–2.6	2.2	0.2 ± 0.2	3.2	0	2.2	1.3
2.6–2.8	2.3	0.0 ± 0.0	3.2	1	4.2	2.3
2.8–3.0	2.4	0.1 ± 0.0	3.2	0	2.3	1.2

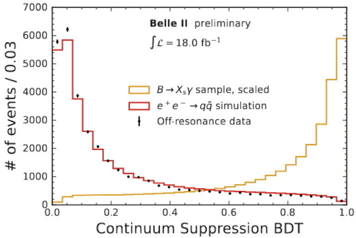
Helicity angle distribution:



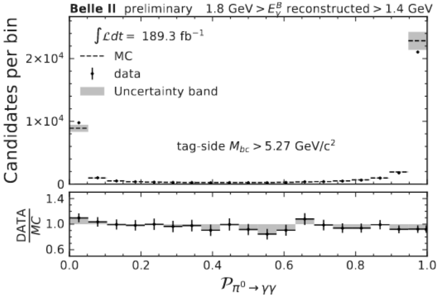
$B \to X_s\gamma$ additional material (1/4)

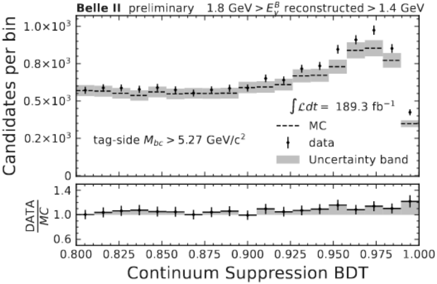


$B \to X_s\gamma$ additional material (2/4)



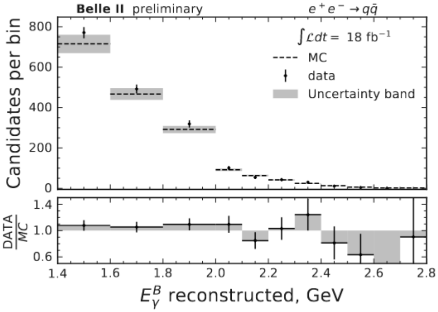
$E_\gamma^B \in [1.4, 1.8]$ GeV **validation**

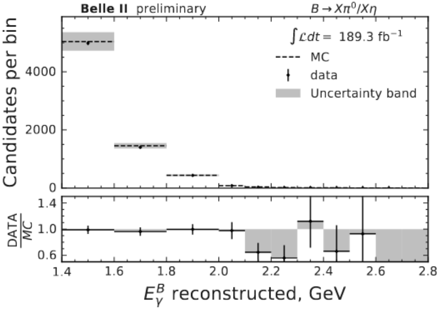




$B \to X_s\gamma$ additional material (3/4)

$e^+e^- \to q\bar{q}$ and $B \to X\pi^0/\eta$ validation





$B \to X_s\gamma$ additional material (4/4)

Partial branching fraction results and 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

Prospects (1/2)

Snowmass white paper: [2207.06307]

$B \to K\nu\bar{\nu}$

Table 3: Baseline (improved) expectations for the uncertainties on the signal strength μ (relative to the SM strength) for the four decay modes as functions of data set size.

Decay	$1\,\text{ab}^{-1}$	$5\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

$B \to K\ell\ell$

Independent check of $R(K)$ anomalies at 5-10 ab^{-1}

$B \to K\tau\tau$

Table 4: Projected branching fraction upper limits for the $B^0 \to K^{*0}\tau\tau$ search in two scenarios (see text).

	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

Prospects (2/2)

Snowmass white paper: [2207.06307]

$B \to X_s\gamma$

Table 5: Projected fractional uncertainties of the $B \to X_s\gamma$ branching fraction measurement for various E_γ^B thresholds. The systematic uncertainty is presented for a baseline scenario when the remaining background is known to the 10% level, and an improved scenario, when the background is known to the 5% level.

Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved)
	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	syst. uncertainty
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%)