Electroweak and radiative penguin decays at Belle II

Flavor Physics and CP Violation (FPCP) 2022: B physics

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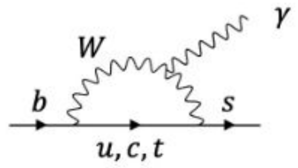
on behalf of the Belle II collaboration

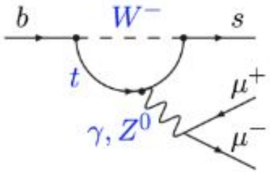
24 May 2022

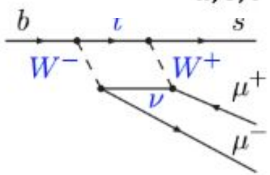
Outline

- Electroweak and radiative penguin decays ⇋ New Physics
- Belle II experiment and its performance
- Radiative $b \to s$ decay measurements
    - $B \to K^* \gamma$ exclusive
    - $B \to X_s \gamma$ inclusive
- Electroweak $b \to s$ decay measurements
    - LFU violation in $b \to s\, l^+ l^-$
    - Search for $b \to s\, \nu \bar{\nu}$
- Summary

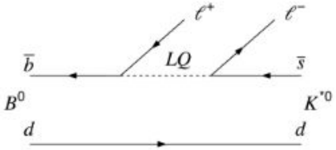
Electroweak and radiative penguins



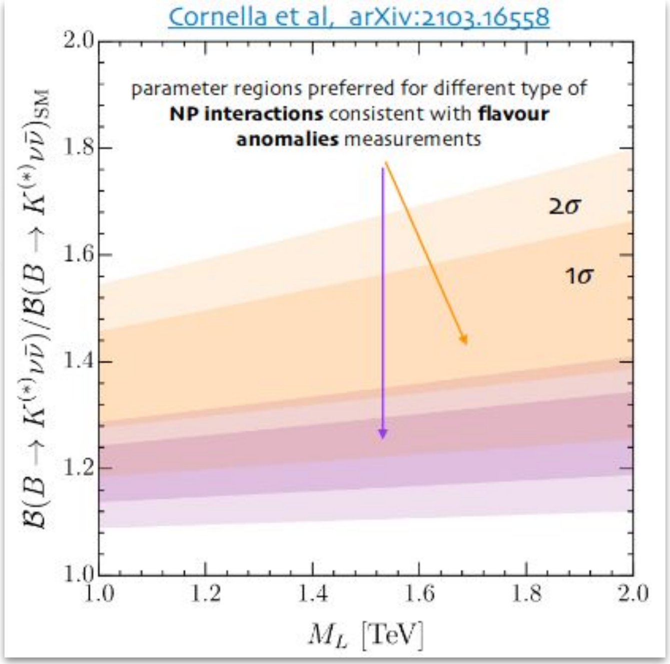




- b → s (d) transition: Flavour Changing Neutral Current prohibited @ tree level in the standard model (SM):
  - 10^{-7} - 10^{-5} predicted BF with 10-30% uncertainties (dominated by soft QCD effects)
  - more precise predictions for angular observables, asymmetries and ratios.



- New Physics (NP) can enter as:
  - new mediators in loop and box or new tree level diagrams
  - new sources of missing energy (e.g. in b → s ν ν̄)
- Can modify rates, asymmetries, angular distributions
  → variety of interesting channels and observables



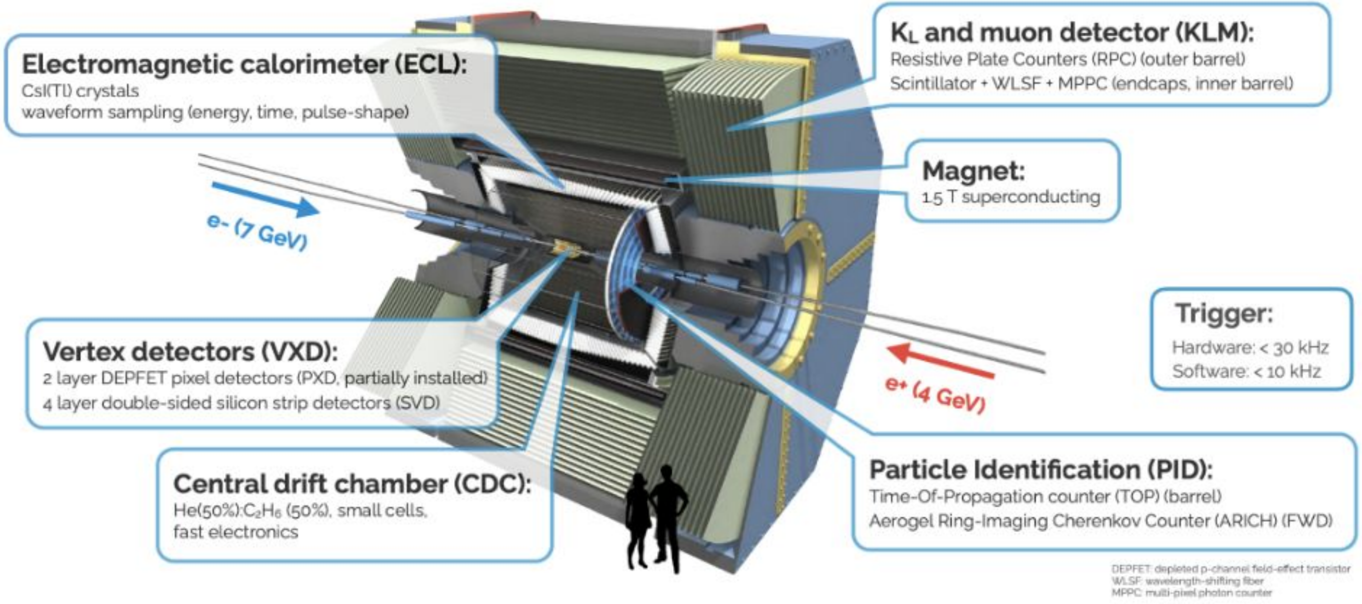
Belle II @ SuperKEKB

Collected: ~400 fb^{-1}

10 year goal: 50 ab^{-1}

World record instantaneous luminosity:
> 4 x 10^{34} $cm^{-2}s^{-1}$

All results presented here are with 63 fb^{-1} and 190 fb^{-1} data.

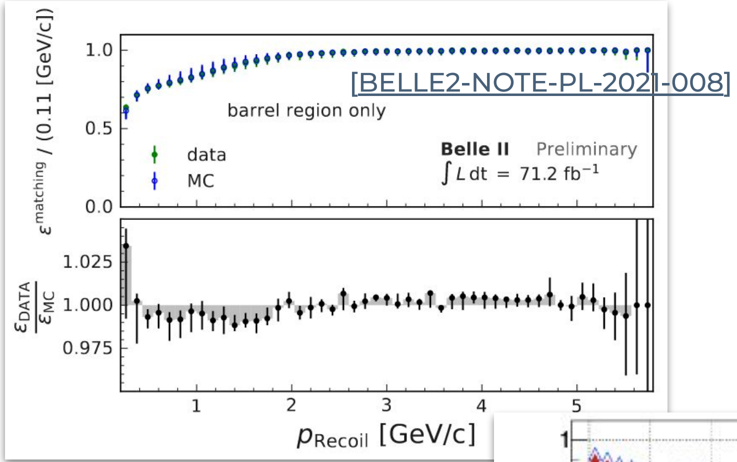


SuperKEKB and Belle II detector already described by previous Belle II speakers

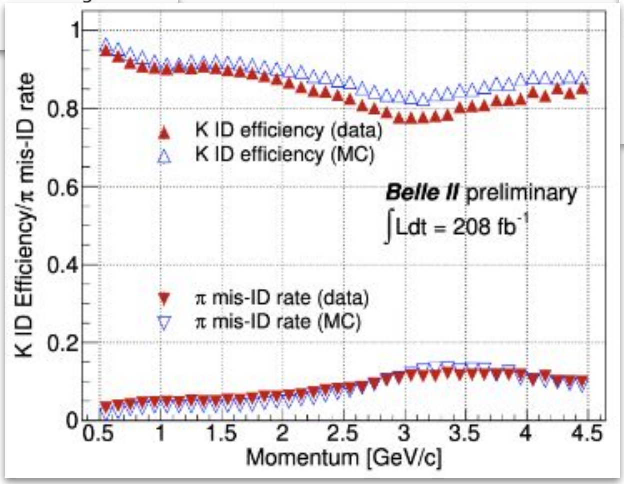
[talk by Chunhui CHEN]

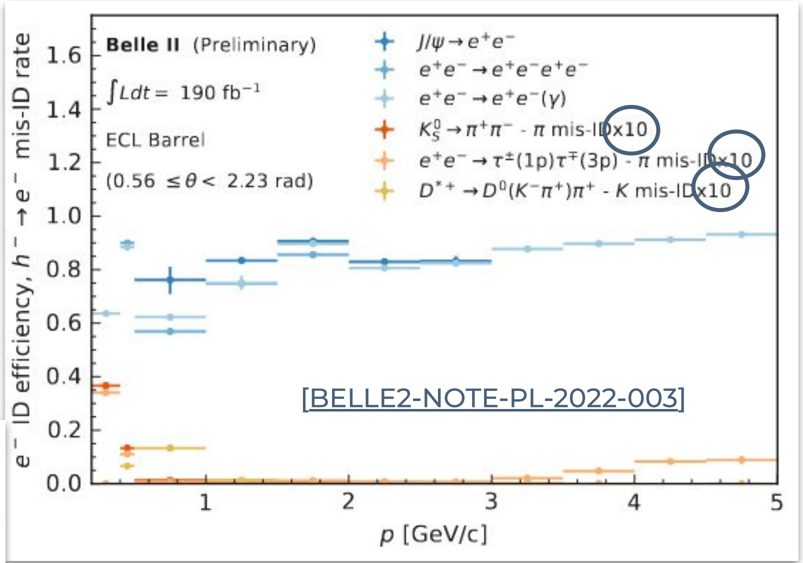
e^+e^- @ 10.58 GeV → $\Upsilon(4S)$ → $B\bar{B}$: clean events where the initial state is well known.

Belle II: performance highlights



High γ detection efficiency and good energy resolution

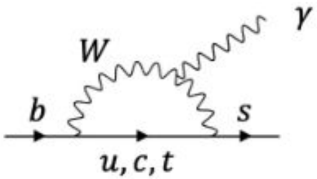




Good Kaon ID and Lepton ID improvements in progress

Radiative b → s decays

- b → s γ has higher rates than b → s l l, variety of reconstruction techniques feasible at Belle II
- Current state of the art on B → K* γ and B → X_s γ : measurements from Belle (full statistics, 711 fb^{-1}):



	B → K* γ	B → X_s γ
BF Precision	3% [3]	10% [2] b → s γ inclusive BF theoretically well described in SM[5], [6]
A_{CP}	consistent with 0 and SM predictions [1], [3], [4]	
Δ_{0+}	first evidence for isospin violation @ 3.1 σ [3]	consistent with 0 [1]

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)},$$

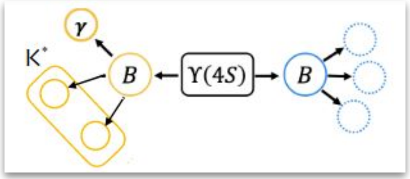
$$\Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)},$$

[1] Phys.Rev.D 99 (2019) 3, 032012
[2] Phys.Rev.D 91 (2015) 5, 052004
[3] Phys.Rev.Lett. 119 (2017) 19, 191802
[4] hep-ph/1608.02556
[5] Phys.Rev.Lett. 98 (2007) 022002
[6] Phys.Rev.Lett. 98 (2007) 022003

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

[hep-ex:2110.08219]

- Full reconstruction of only one B in the event

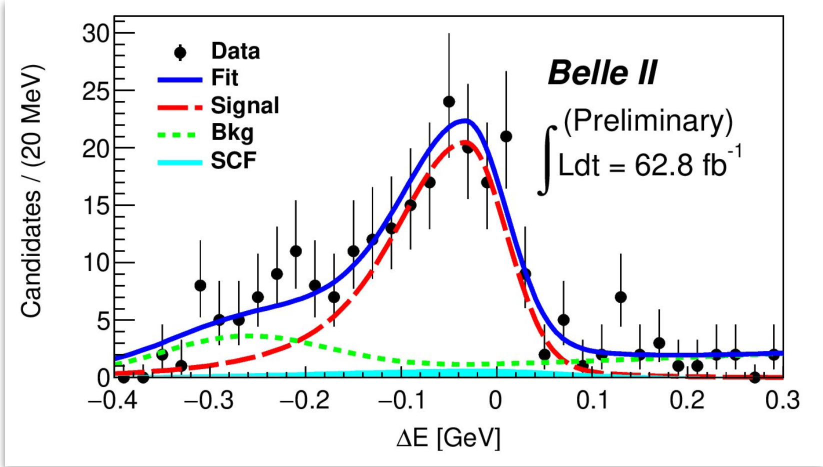


- Signal yield extracted from unbinned maximum likelihood fit to ΔE

- Measured branching fractions:

Mode	$\mathcal{B}_{meas}$ [10^{-5}]
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$5.4 \pm 0.6 \pm 0.4$

[hep-ex:2110.08219]



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

- Main systematic contributions: fit modelling, mis-modelling of π^0 /η veto and selection variables in simulation (depending on the mode)
- Update with available dataset ongoing to measure BF and isospin asymmetry

$B \to X_s \gamma$ first results

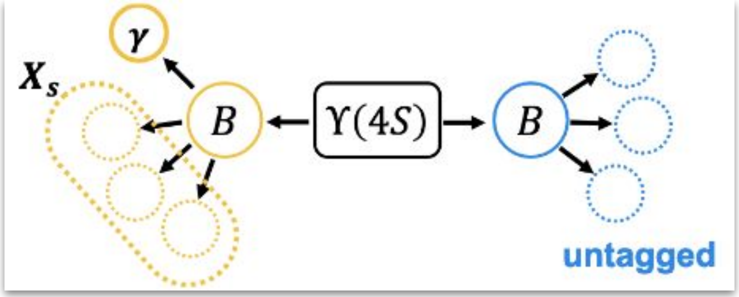
- $B \to X_s \gamma$ with untagged method

- Reconstruct only high energy γ from signal side.

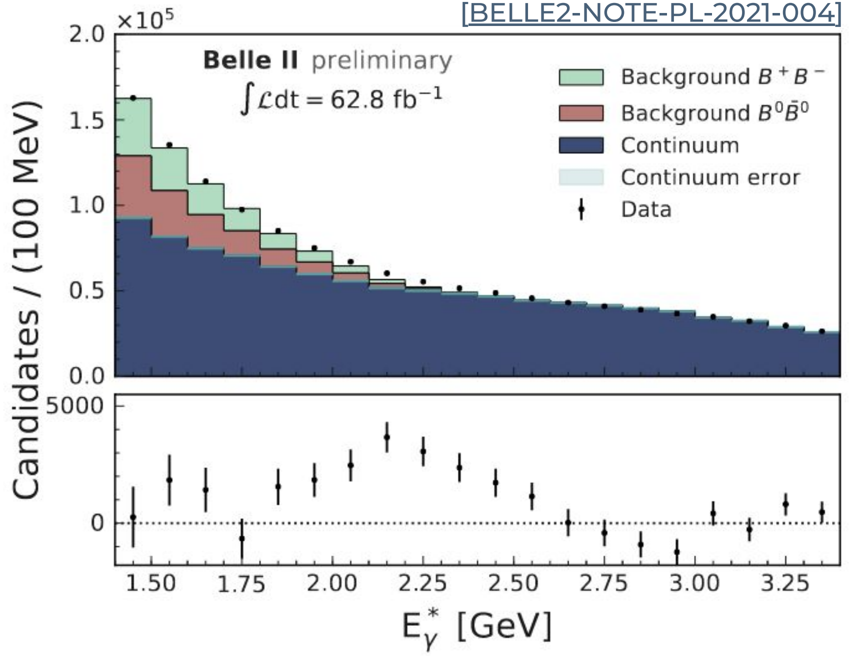
- Signal photon spectrum obtained by subtracting expected background from data
    - $B\bar{B}$ estimated from simulation
    - $q\bar{q}$ from off-resonance data (9.2 fb^{-1})

- Excess observed consistent with inclusive $B \to X_{(s,d)}\gamma$ signal

- Tagged analysis is also in development.

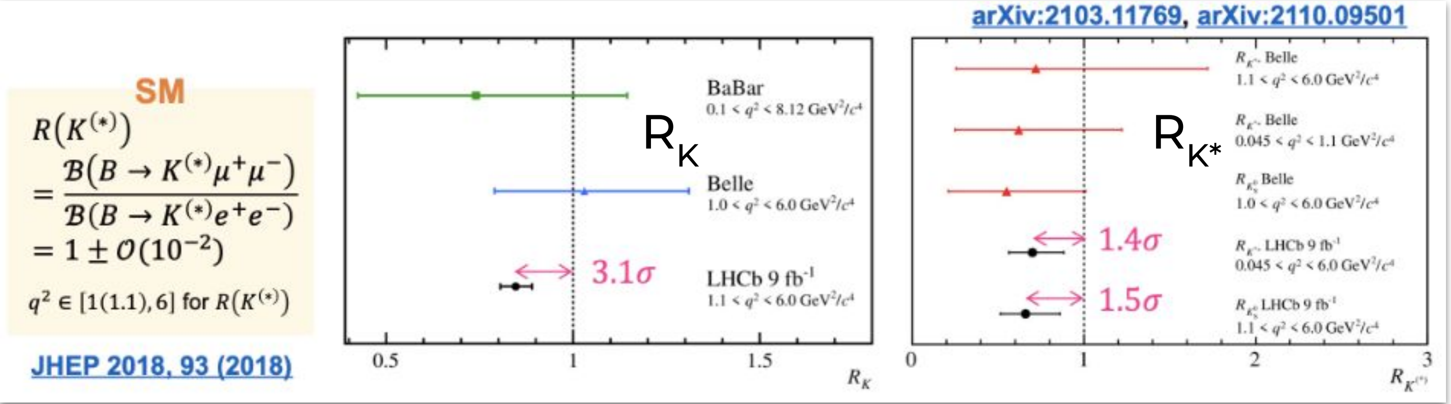


[BELLE2-NOTE-PL-2021-004]



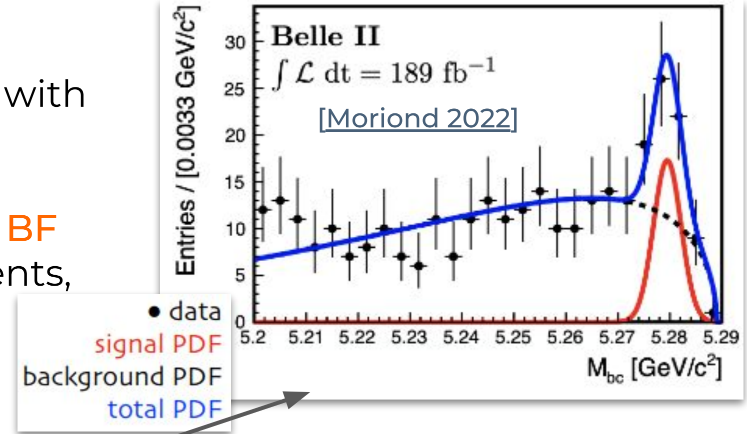
LFU violation in b → s l l

State of the art: 3.1σ evidence for LFU violation in R_K by LHCb.



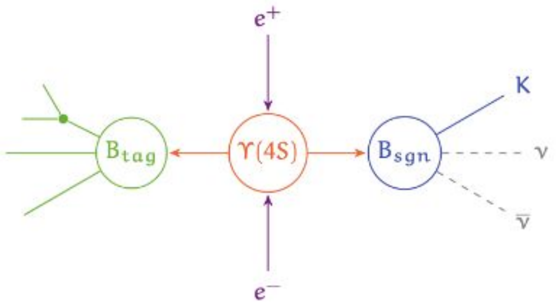
- Belle II enjoys nearly symmetric electron/muon reconstruction performance, and can:
  - provide independent check of $R(K^{(*)})$ anomalies with > 5-10 ab^{-1}
  - measure $R(X_s)$
  - provide independent measurement of absolute BF for e and μ (e.g. constraint on C_9 Wilson coefficients, separately for the two modes).

- $B^+ \to K\,l\,l$ with 63 fb^{-1}: 2.7 σ significance for signal
- $B^+ \to K^*\,l\,l$ with 190 fb^{-1}: BF in entire q^2 range excluding J/ψ and ψ(2S) resonances

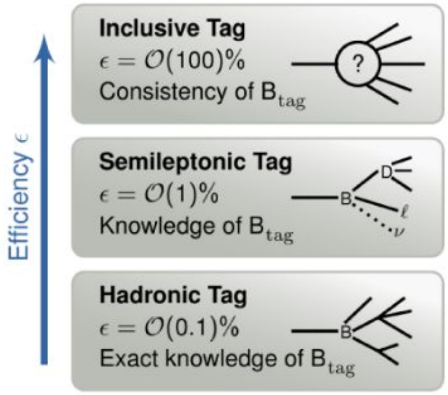


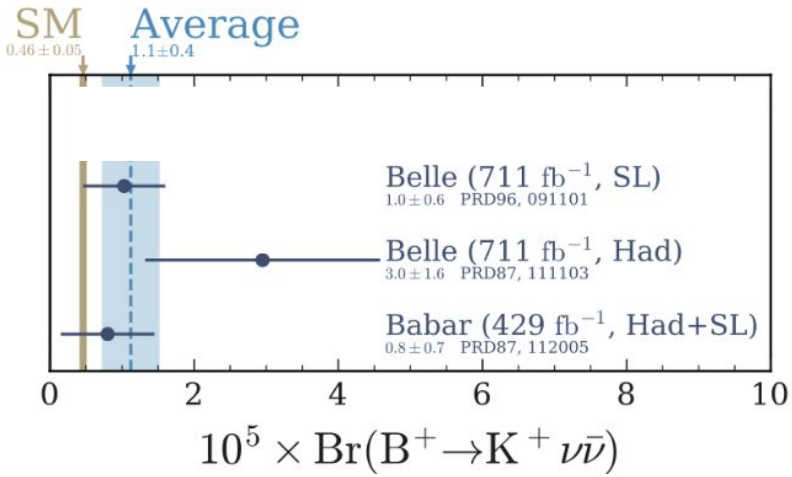
Beam-constrained mass: $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$

$B^+ \to K^+ \nu \bar{\nu}$ search: B-tagging



- Connected to flavour anomalies, one of the missing energy modes unique to Belle II.
- SM expectation: $(4.6 \pm 0.5) \times 10^{-6}$
  [J. High Energ. Phys. 2015, 184 (2015)]
- Key ingredient in BaBar and Belle searches:
  hadronic and semileptonic tag side reconstruction, tag efficiency at (sub-)percent.





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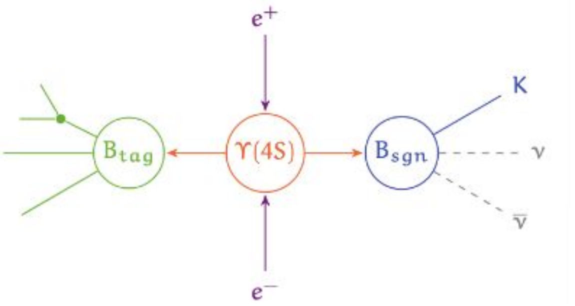
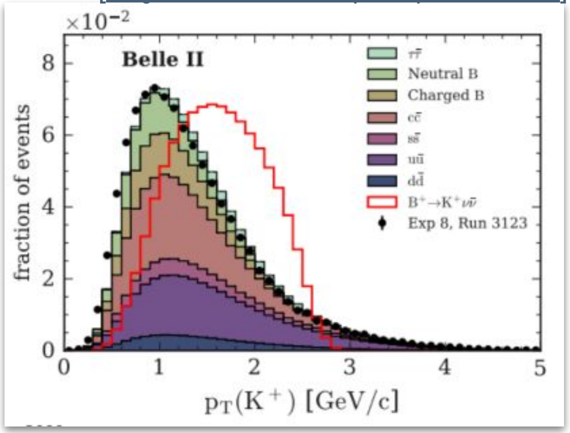
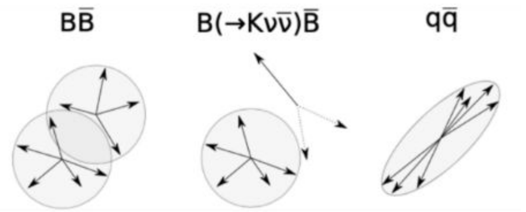


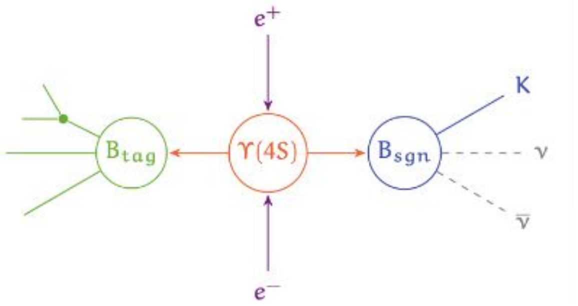
[Phys.Rev.Lett. 127 (2021) 18, 181802]



Using novel inclusive tag approach:
- Signal kaon = highest p_T track
- Associate all other tracks and clusters to other B in the event.
- Use multivariate approach (2 BDTs in cascade) based on kinematics, event shape and vertexing variables to suppress background.
- Signal efficiency ~ 4.3 % (SM signal)



$B^+ \to K^+ \nu \bar{\nu}$ search



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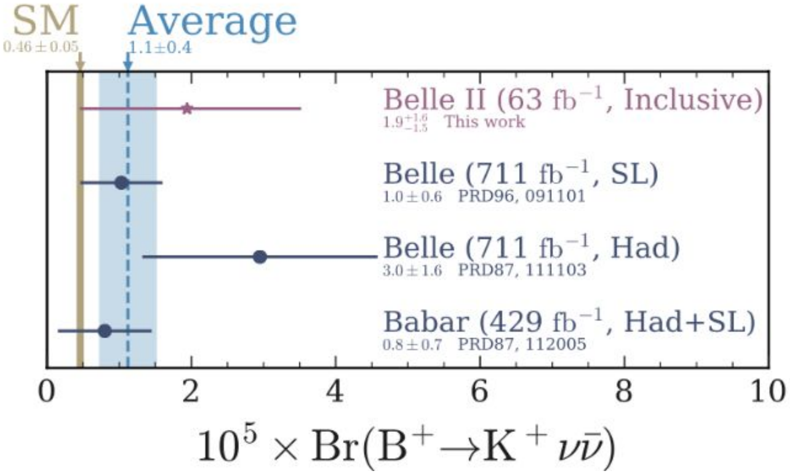
  [J. High Energ. Phys. 2015, 184 (2015)]
- Key ingredient in BaBar and Belle searches:
  hadronic and semileptonic tag side reconstruction, tag efficiency at (sub-)percent.
- Extract signal from simultaneous maximum likelihood fit to on-resonance + off- resonance data in bins of $p_T(K^+)$ and second BDT.
- Inclusive tag method offers 20% (wrt SL) - 350% (wrt Hadronic tag) improvement on uncertainty of BF.



Summary

- $b \to s$ transitions are powerful probes for physics beyond SM.

- Belle II is accumulating high quality data.
    - unique environment to study radiative decays and missing energy modes.
    - healthy complementarity with LHCb on LFU violation tests in $b \to s\, l\, l$ modes.
    - can perform independent BF measurement for $B \to K^{(*)}\, e\, e$ and $B \to K^{(*)}\, \mu\, \mu$ final states with similar performances.

- Inclusive and exclusive measurements on $b \to s\, \gamma$ decays.

- $B^+ \to K^+\, \nu\, \bar{\nu}$ inclusive measurement in the same ballpark wrt Belle and BaBar tagged measurements with only ~1/10 Belle statistics.

Backup

Projections for B → K* γ search

[Belle II Physics for Snowmass]

Table 6: Projected statistical and systematic (absolute) uncertainties of relevant observables from $B \to K^*\gamma$ decays.

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%

Projections for $B \to X_s \gamma$ search

[Belle II Physics for Snowmass]

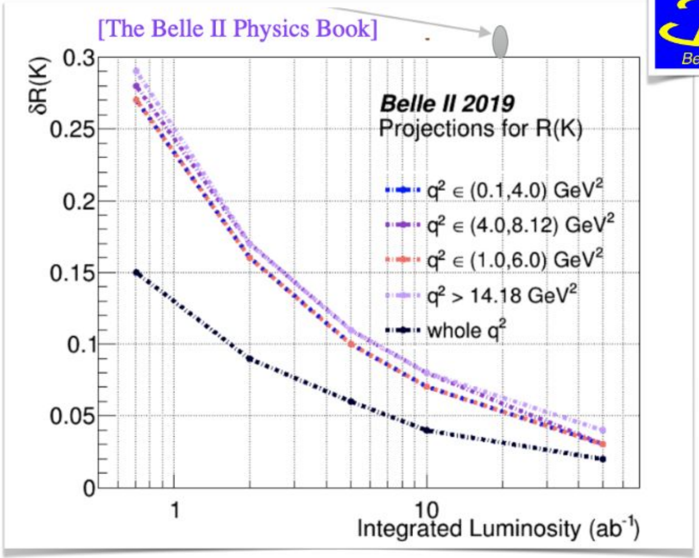
Table 5: Projected fractional uncertainties of the $B \to X_s\gamma$ branching fraction measurement for various E_γ^B thresholds. The systematic uncertainty is presented for a baseline scenario when the remaining background is known to the 10% level, and an improved scenario, when the background is known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

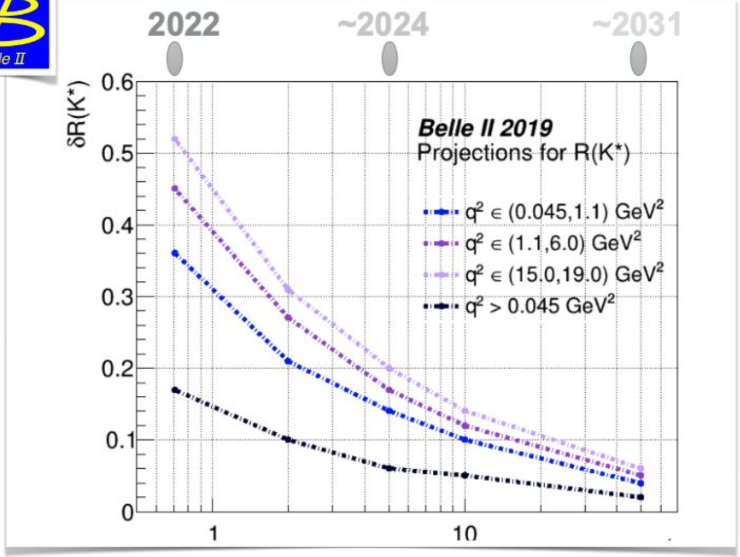
Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved)
	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	syst. uncertainty
1.4 GeV	10.7%	6.4%	4.7%	2.2%	10.3% (5.2%)
1.6 GeV	9.9%	6.1%	4.5%	2.1%	8.5% (4.2%)
1.8 GeV	9.3%	5.7%	4.2%	2.0%	6.5% (3.2%)
2.0 GeV	8.3%	5.1%	3.8%	1.7%	3.7% (1.8%)

LFU violation in b → s l⁺ l⁻ : Projection

- Belle II, enjoys nearly symmetric electron/muon reconstruction performance, and can:
  - provide independent check of $R(K^{(*)})$ anomalies with > 5-10 ab^{-1}

The Belle II Physics Book, PETP 2019, 123C01 (2019)





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

[Moriond 2022]

$$\mathcal{B}(B \to K^* \mu\mu) = (1.19 \pm 0.31 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^* ee) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^* \ell\ell) = (1.25 \pm 0.30 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$

PDG averages

$(1.06 \pm 0.09) \times 10^{-6}$

$(1.19 \pm 0.20) \times 10^{-6}$

$(1.05 \pm 0.10) \times 10^{-6}$

- Precision for electron and muon channels in the same ballpark
- Limited by sample size
- Electron channel "only" 2.5σ worst wrt PDG, expected to became competitive with 1 ab^{-1}

Projections for $B^+ \to K^+ \nu \bar{\nu}$ search

[Belle II Physics for Snowmass]

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	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	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)

Training variables for $B^+ \to K^+ \nu \bar{\nu}$ search

Variables related to the kaon candidate

- Azimuthal angle of the kaon momentum at the POCA
- d_r and d_z of the kaon track
- Cosine of the polar angle of the kaon 3-momentum at the POCA

Variables related to the kaon candidate do not include $p_{\mathrm{T}}(K^+)$, because the data are binned in this variable and in BDT_2 in the last stage of the analysis.

Variables related to the tracks and energy deposits of the rest of the event (ROE)

- Three variables corresponding to the x, y, z components of the vector from the average interaction point to the ROE vertex
- d_r and d_z of the kaon track with respect to the ROE vertex
- Invariant mass of the ROE
- χ^2 of the ROE vertex fit
- p-value of the ROE vertex fit
- Variance of the transverse momentum of the ROE tracks
- Polar angle of the ROE momentum
- Magnitude of the ROE momentum
- Magnitude of the ROE thrust in the center-of-mass system (CMS) [4]
- Difference between the ROE energy in the CMS and $\sqrt{s}/2$

Training variables for $B^+ \to K^+ \nu \bar{\nu}$ search

Variables related to the entire event

- Magnitude of the event thrust in the CMS
- Number of charged lepton candidates ($e^{\pm}$ or $\mu^{\pm}$)
- Number of photon candidates, number of charged particle candidates and sum of the two
- Square of the total charge of tracks
- Cosine of the polar angle of the thrust axis in the CMS
- Zeroth-order and second-order harmonic moments with respect to the thrust axis in the CMS [5]
- Seven modified Fox-Wolfram moments calculated in the CMS [6]
- Polar angle of the missing three-momentum in the CMS
- Square of the missing invariant mass
- Event sphericity in the CMS [4]
- First, second and third normalized Fox-Wolfram moments in the CMS [5]
- Cosine of the angle between the kaon track and the ROE thrust axis in the CMS

Variables related to the D^0/D^+ suppression

As mentioned in the main text, D^0 candidates are obtained by fitting the kaon candidate track and each track of opposite charge in the ROE to a common vertex; D^+ candidates are obtained by fitting the kaon candidate track and two ROE tracks of appropriate charges. In both cases, the best candidate is the one having the best vertex fit quality.

- d_r and d_z of the best D^0 candidate vertex and of the best D^+ candidate vertex
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit

- Mass of the best D^0 candidate
- Median p-value of the vertex fits of the D^0 candidates