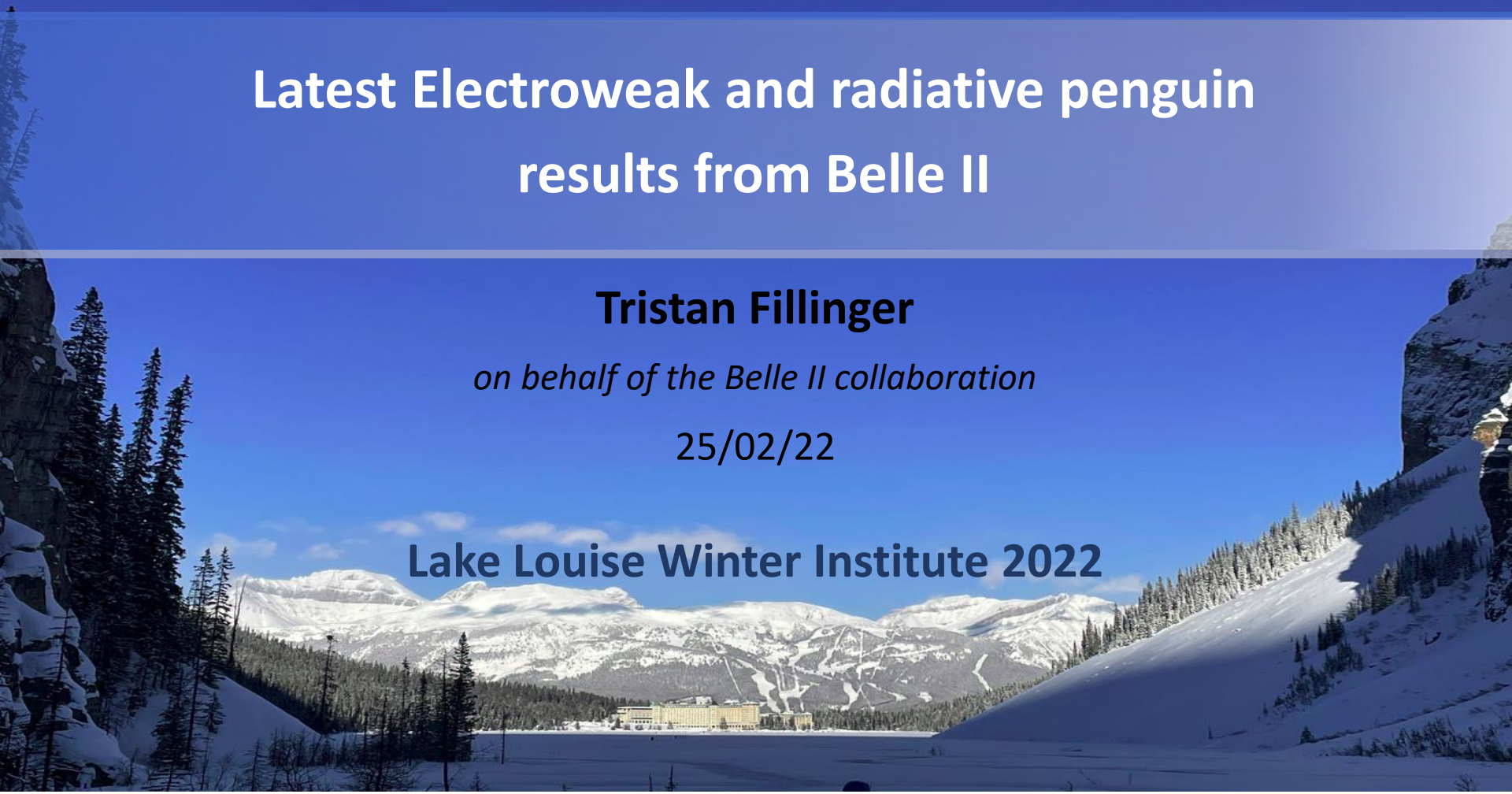
Latest Electroweak and radiative penguin results from Belle II

Tristan Fillinger

on behalf of the Belle II collaboration

25/02/22

Lake Louise Winter Institute 2022



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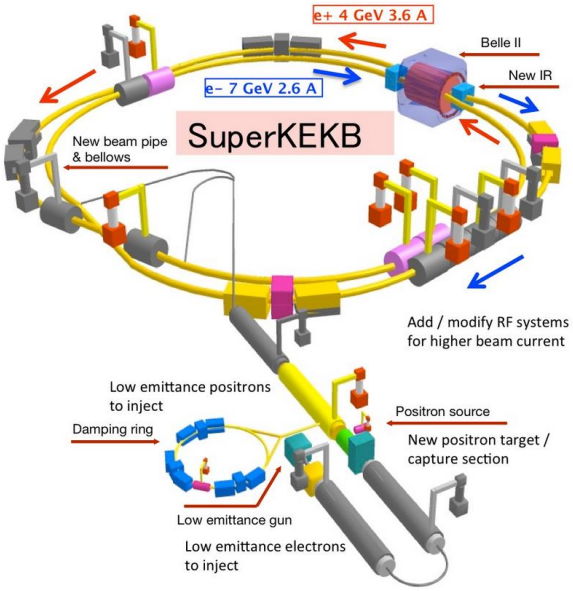
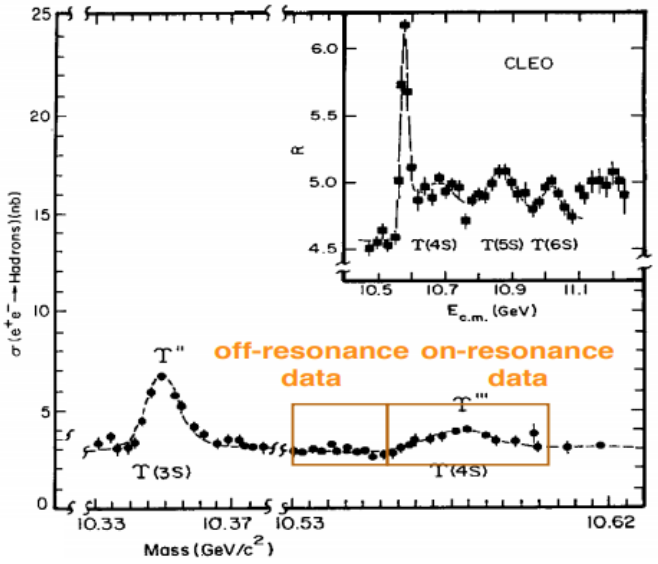
Belle II

SuperKEKB collider and Belle II

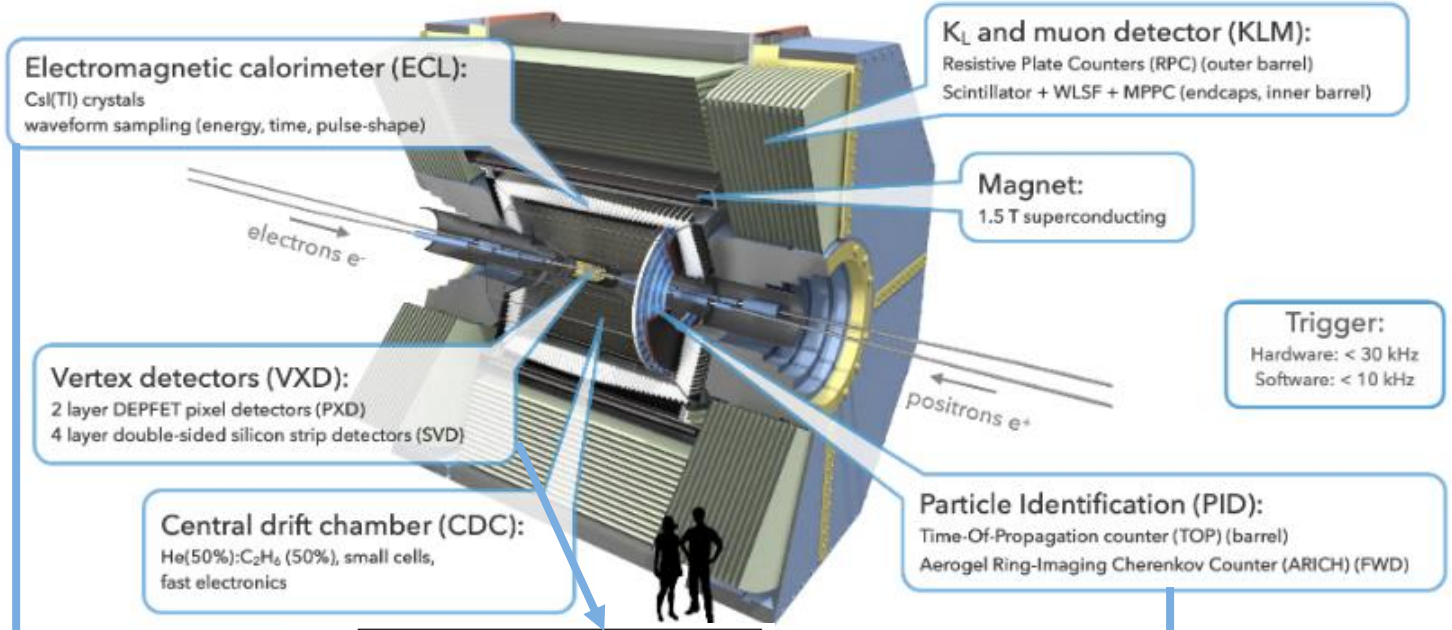


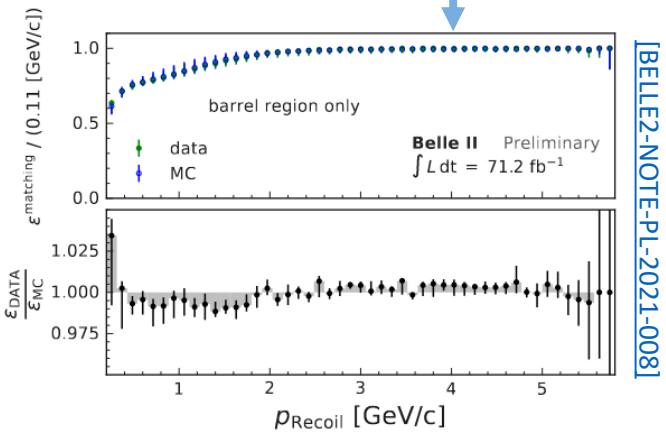


- Electron (7 GeV) - Positron (4 GeV) collider
- **KEKB upgrade:**
  - x 1.5 currents
  - x 1/20 vertical beam size (**Nanobeam scheme**)
    → Target up to 30 x higher $\mathcal{L}_{inst}$
  - Higher beam backgrounds
- Build to run on high Υ masses (from Υ(3S) to Υ(6S))
- On-resonance data:
  - Around $\sqrt{s} = 10.58$ GeV
    → Υ(4S) resonance → $B\overline{B}$
    → Clean B sample
- Off-resonance data:
  - 60 MeV below Υ(4S) resonance
  - $e^+e^- \rightarrow q\overline{q}$, $\tau^+\tau^-$, e^+e^- where q = (u, d, s, c)
    → Control sample for continuum background

Belle II detector

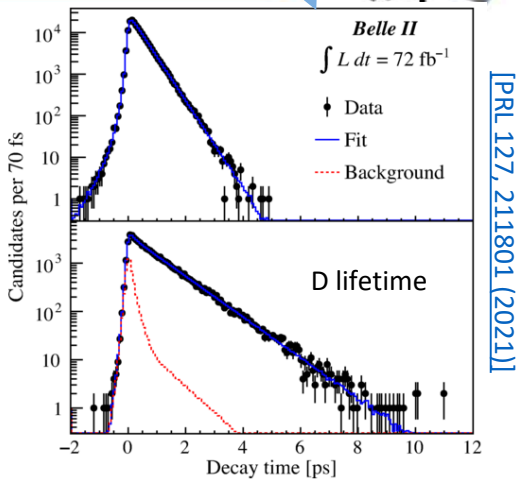
- Designed to give similar or better performance than Belle even with lower boost and higher beam backgrounds





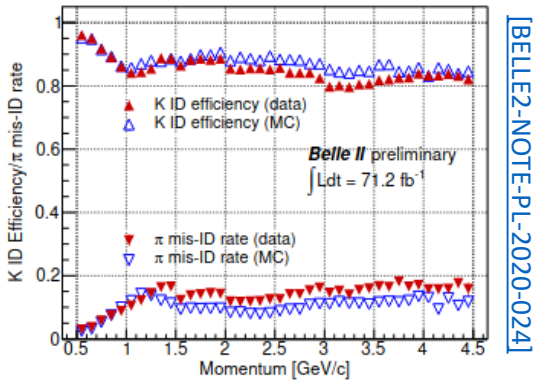
[BELLE2-NOTE-PL-2021-008]

High photon reconstruction efficiency



[PRL 127, 211801 (2021)]

Factor 2 improvement in proper time resolution



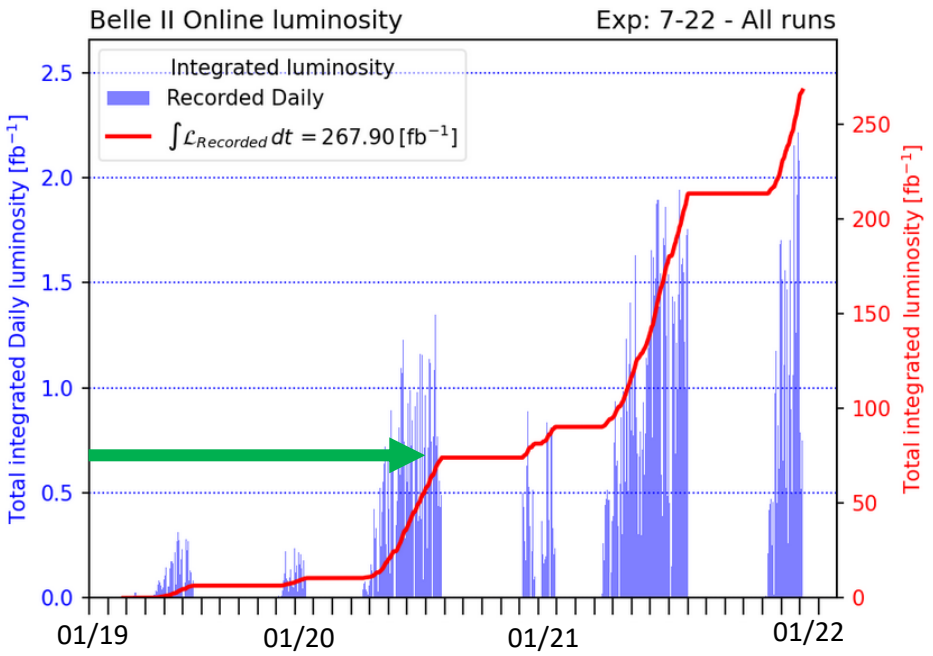
[BELLE2-NOTE-PL-2020-024]

Good particle identification

Luminosity

Status

- Collected **~ 268 fb^{-1}** since April 2019
- **Record-breaking instantaneous luminosity:**
  3.8 x 10^{34} cm^{-2}s^{-1} (last: LHC 2.14 x 10^{34} cm^{-2} s^{-1})
- Ramping up toward the target luminosity
- **Highest daily integrated luminosity: 2.2 fb^{-1}**
- **All shown results**
  - 63 fb^{-1} on-resonance
  - 9 fb^{-1} off-resonance

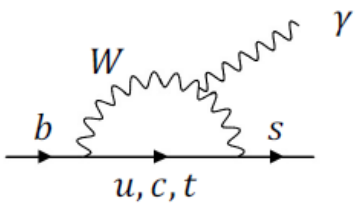


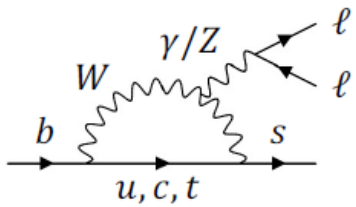
Goal: 50 ab^{-1}

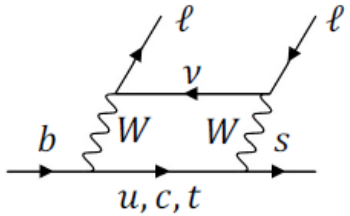
Electroweak and radiative penguin decays

- Flavor changing neutral current (FCNC) transitions occurring at loop level only → Highly suppressed

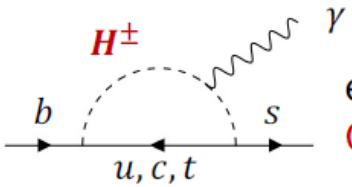
- Focus on b → s transitions:



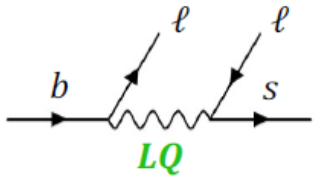




- Interesting as NP can appear either in a loop or mediate FCNC at the tree level



e.g. Charged Higgs



e.g. Leptoquark

- Tensions with respect to SM

- **Measurements presented here:**

- **Radiative penguin decays:**
  - Measurement of $\mathcal{B}(B \to K^* \gamma)$ (exclusive)
  - Observation of $B \to X_{(s,d)}\gamma$ (inclusive)

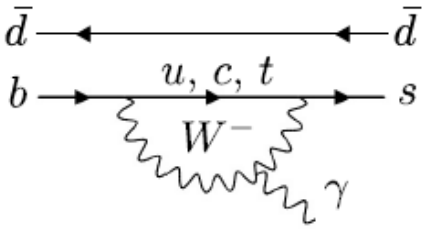
- **Electroweak penguin decays:**
  - Study of $B^+ \to K^+ l^+ l^-$ (exclusive)
  - Search for $B^+ \to K^+ \nu\bar{\nu}$ (exclusive)

Measurement of $\mathcal{B}(B \to K^* \gamma)$

[arxiv:2110.08219]

Belle II

Status



- Short term: measure $\mathcal{B}(B \to K^* \gamma) = \mathcal{O}(10^{-5})$
- Long term: measure more NP sensitive variables:
  - CP violation asymmetry A_{CP}:

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

  - Isospin asymmetry Δ_{0+} :

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

- Latest measurement from Belle with 772 x 10^6 $B\overline{B}$ pairs
  → 3.1σ evidence for the isospin symmetry violation [PRL 119, 191802 (2017)]

Measurement of $\mathcal{B}(B \to K^* \gamma)$

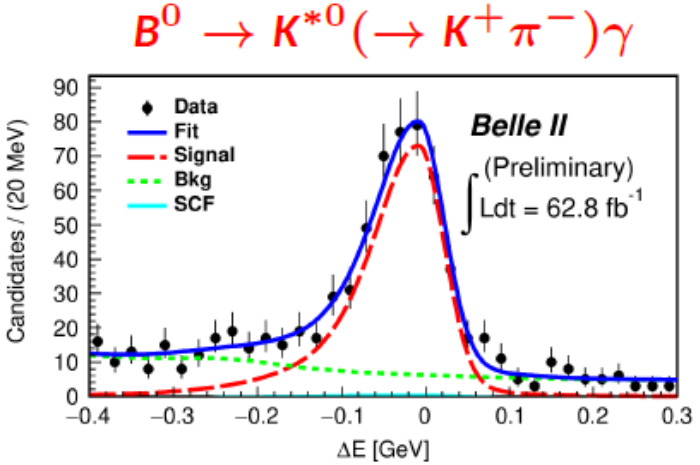
[arxiv:2110.08219]

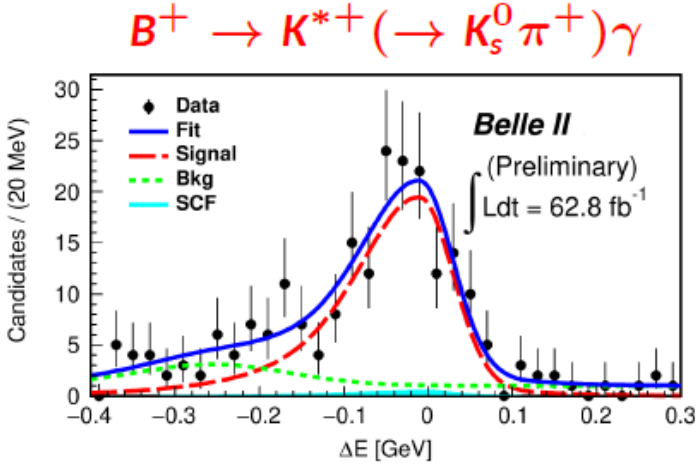
Analysis strategy

- Full decay chain reconstruction: K^{*0} ($K^+\pi^-$, $K_S^0\,\pi^0$), K^{*+} ($K^+\,\pi^0$, $K_S^0\,\pi^+$); $K_S^0 \to \pi^+\,\pi^-$, $\pi^0 \to \gamma\gamma$
- Signal E_γ cut around energy expected from 2 body decays
- Main backgrounds from misreconstructed $B\overline{B}$ events and combinatorial background
- Continuum events with γ coming from π^0 or η
  - π^0 / η veto: Remove events consistent with (π^0, η) kinematics + BDT suppression with event-based variables

Signal extraction

- Unbinned ML fit to **ΔE** = difference between observed and expected B-meson energy





Results

Mode	$\mathcal{B}_{\text{meas}}$ $[10^{-5}]$	$\mathcal{B}_{\text{PDG}}$ $[10^{-5}]$
$B^0 \to K^{*0}\gamma$	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^+ \to K^{*+}\gamma$	$5.2 \pm 0.4 \pm 0.3$	3.92 ± 0.22

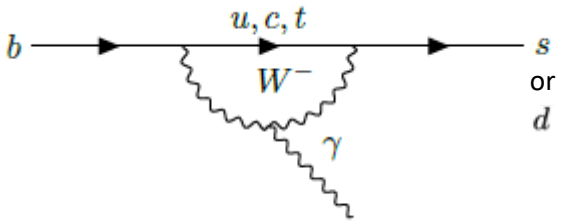
Consistent with world average

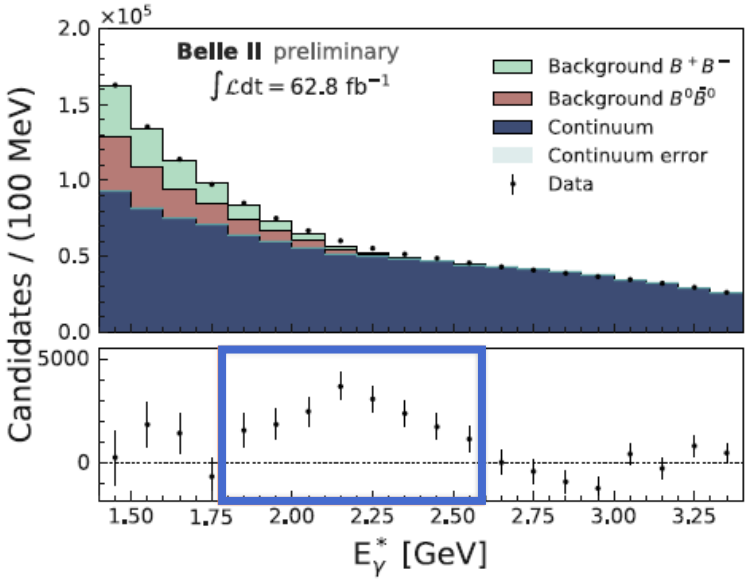
Observation of $B \to X_{(s,d)}\gamma$

[BELLE2-NOTE-PL-2021-004]

Status

- Short term: first observation of $B \to X_{(s,d)}\gamma$
- Long term: measurement of $\mathcal{B}\left(B \to X_{(s,d)}\gamma\right)$
  - NP scenario: charged Higgs [EPJC 78 8, 675 (2018)]





Analysis strategy

- Reconstruct high energy γ on signal side
  - Standard selection with π^0-η veto
- Reduction of the continuum backgrounds using BDT trained with event shape variables
- Expected backgrounds obtained from off-resonance (continuum) and Monte-Carlo simulation ($B\overline{B}$)

Signal extraction

- Excess wrt total expected background on photon energy spectrum

Result

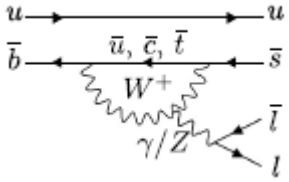
- **Excess compatible with $B \to X_{(s,d)}\gamma$ signal**

Study of $B^+ \to K^+ l^+ l^-$

[BELLE2-NOTE-PL-2021-005]

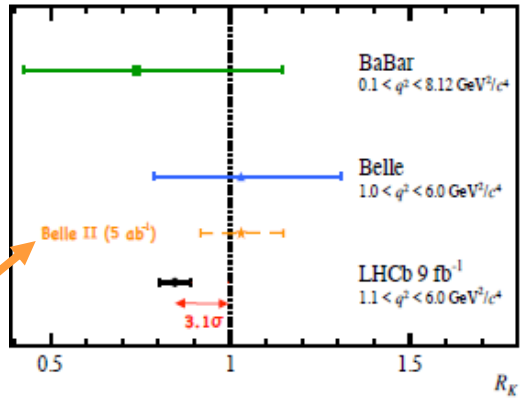
Status

- Short term: Reconstruction of $B^+ \to K^+ l^+ l^-$
- Long term: Measurement of R(K):



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

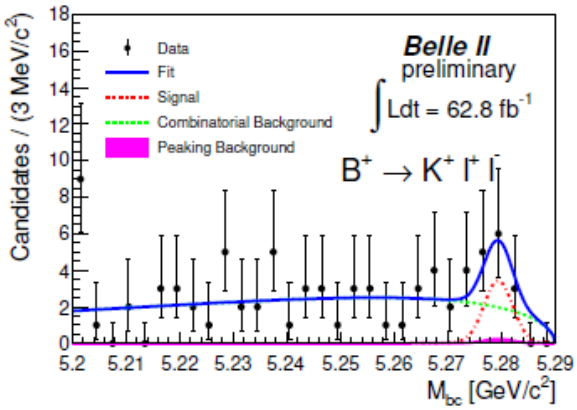
- 3.1σ evidence for LFU violation by LHCb
- **Belle II with > 5-10 ab^{-1} will provide significant independent information on R(K)**



[arxiv:2103.11769]

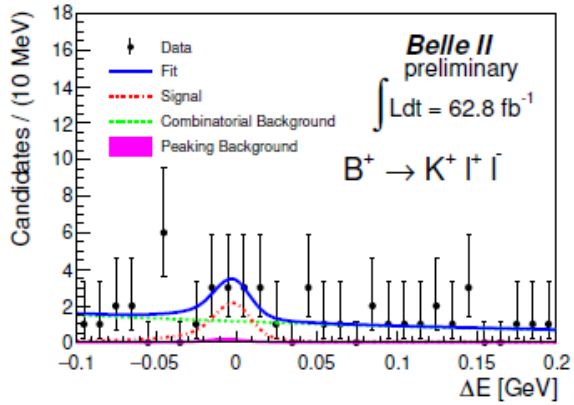
Analysis strategy

- Muon and electron modes reconstructed
- Background suppression with BDT using event shape and vertex information



Signal extraction

- Simultaneous ML fit to the beam energy constrained mass M_{bc} and ΔE



Result

- $N_{sig} = 8.6\ ^{+4.3}_{-3.9}$ (stat) ± 0.4 (syst)
- Hint for $B^+ \to K^+ l^+ l^-$ signal

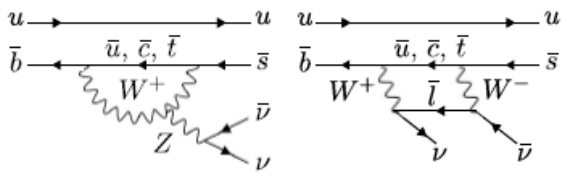
Search for $B^+ \to K^+ \nu\bar{\nu}$

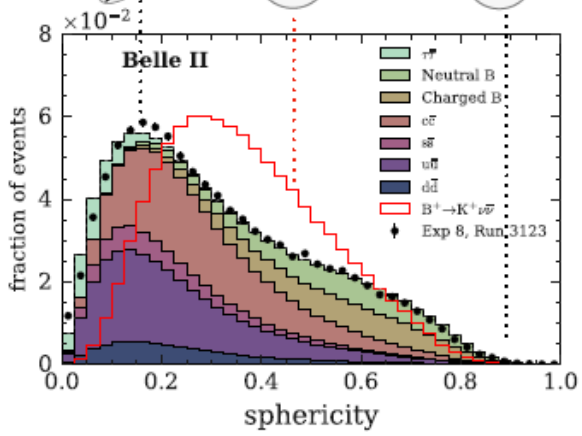
[PRL 127, 181802 (2021)]

Belle II

Status

- $B^+ \to K^+ \nu\bar{\nu}$ never been observed yet
  - SM: $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ = (4.6 $\pm$ 0.5) x 10^{-6}
  - Best upper limit: 1.6 x 10^{-5} at 90% CL set by BaBar [PRD 87, 112005 (2013)]
  - NP scenarios:
    - Loop level: Leptoquarks, Axions…
    - Final state: Dark Matter



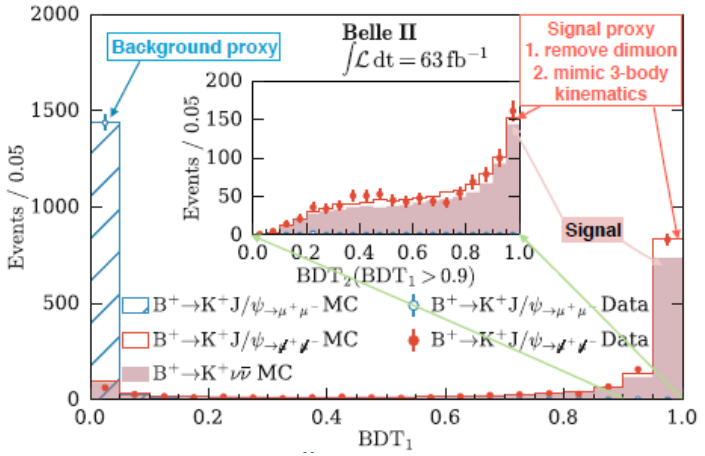


Analysis strategy

- Select highest-p_T track with at least 1 hit in the vertex detector, then reconstruct the remaining tracks and clusters in the event
- Minimise the background contamination with two nested BDTs trained on event topology, missing energy, vertex separation and very distinct signal kinematics

- 20x higher signal efficiency wrt to BaBar (exclusive reconstruction) $\varepsilon_{sig} = 4.3\%$; ($\varepsilon_{sig}^{BaBar} = 0.2\%$)

- Validation with control channel: $B^+ \to J/\psi\,(\to \mu^+\,\mu^-)\,K^+$



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

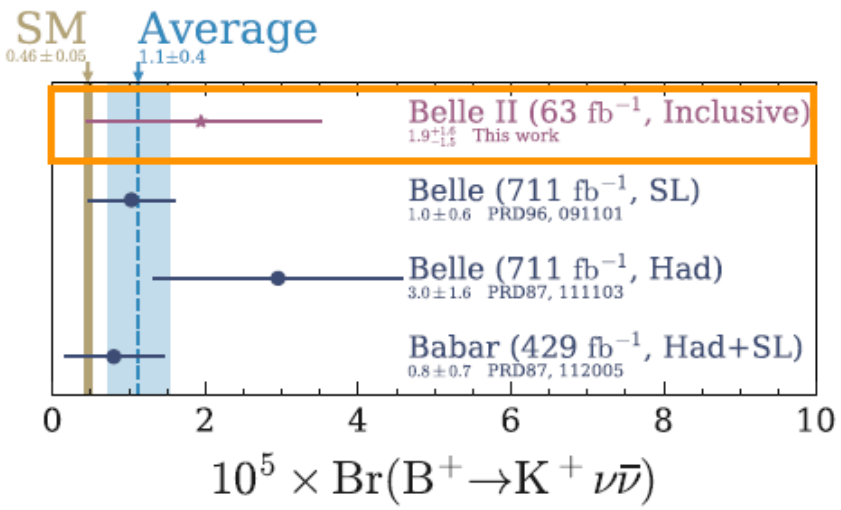
[PRL 127, 181802 (2021)]

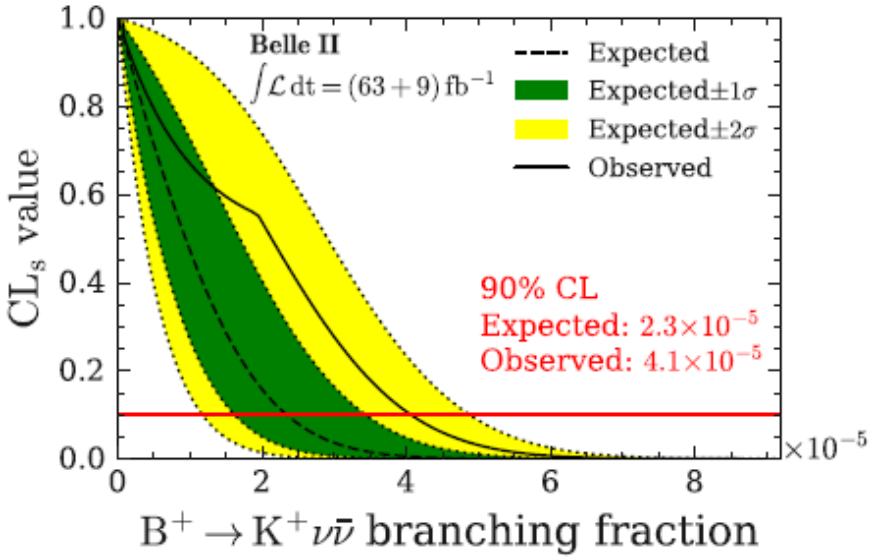
Signal extraction

- Binned simultaneous ML fit to p_T (K^+) x BDT_2 to extract signal strength μ

Result

- **No significant signal is observed, limit of 4.1 x 10^{-5} at 90% CL is set**
- **Competitive with "only" 63 fb^{-1}**





Prospects

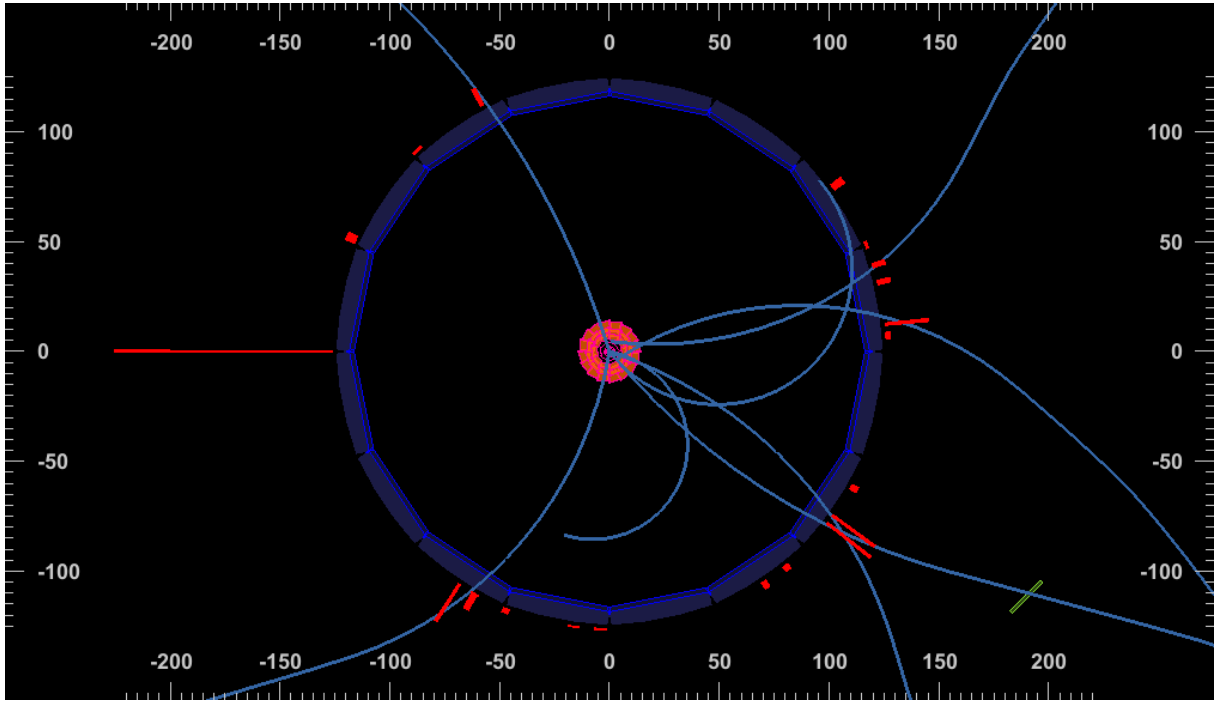
- Bigger data set
- Includes more channels to be studied

Summary

- **The first electroweak and radiative penguin signals have been seen at Belle II**
  - More channels to be investigated soon

- **First published Belle II B-physics paper**
  - Search for $B^+ \to K^+ \nu\bar{\nu}$: highly **competitive limit** with "only" 1/10 of previous B-factory dataset

- **More to come soon** (4x bigger dataset on tape, improved analysis techniques)



Thank you for your attention

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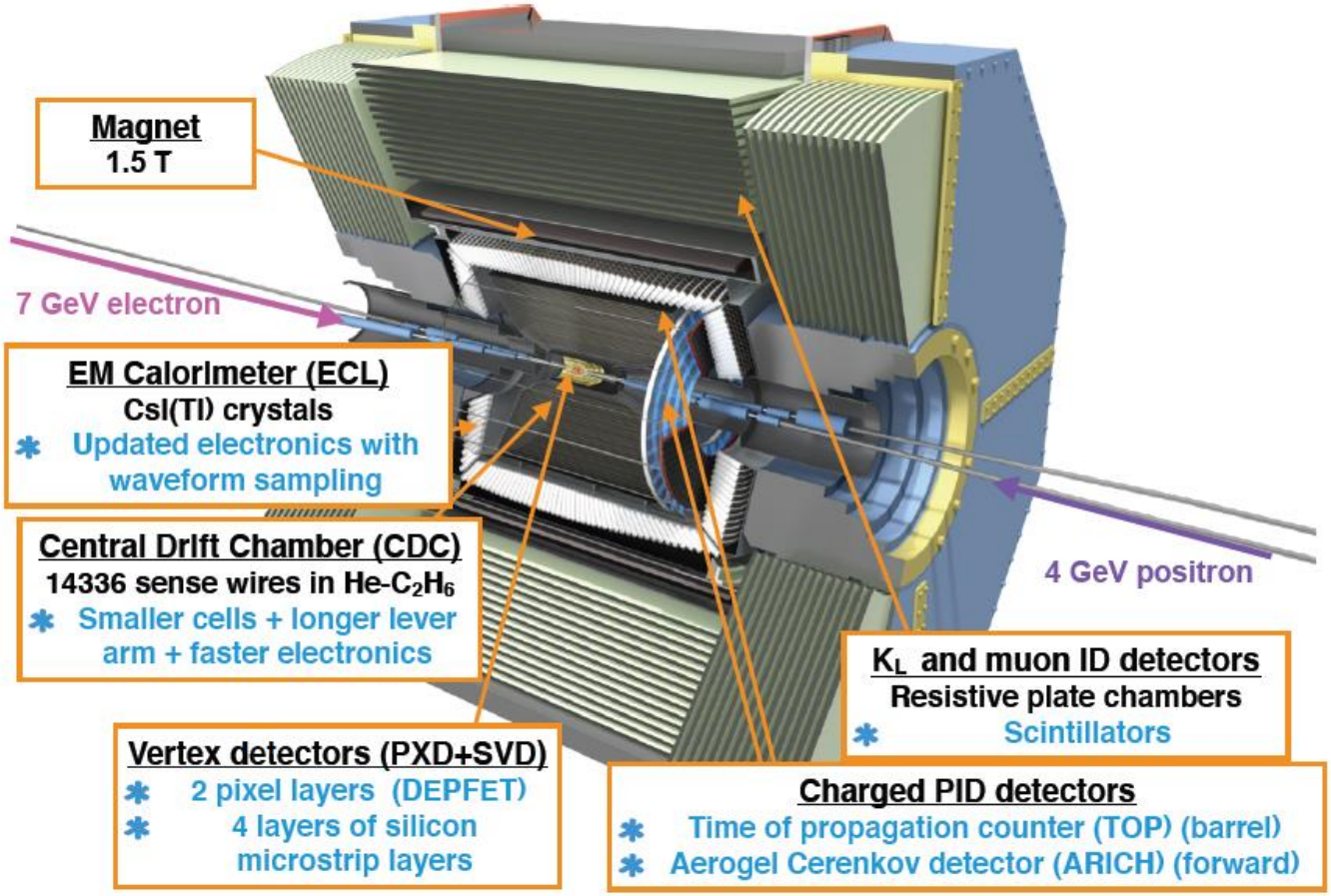
Belle II

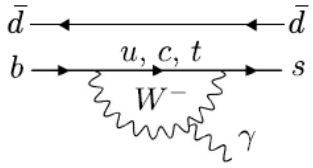
Belle II detector



- Designed to give similar or better performance than Belle even under higher backgrounds
- DAQ and trigger systems upgraded

Measurement of $\mathcal{B}(B \to K^* \gamma)$

[arxiv:2110.08219]



- Latest measurement from Belle with 772 x 10^6 $B\overline{B}$ pairs
  → 3.1σ evidence for the isospin symmetry violation:

Observable	Belle [PRL 119, 191802 (2017)]	SM [JHEP 04,027 (2017)] [PRD D88, 094004 (2013)]
$\mathcal{B}(B^0 \to K^{*0}\gamma)$	$(3.96 \pm 0.07 \pm 0.14) \times 10^{-5}$	$(3.48 \pm 0.81) \times 10^{-5}$
$\mathcal{B}(B^+ \to K^{*+}\gamma)$	$(3.76 \pm 0.10 \pm 0.12) \times 10^{-5}$	$(3.43 \pm 0.84) \times 10^{-5}$
$A_{CP}(B^0 \to K^{*0}\gamma)$	$(-1.3 \pm 1.7 \pm 0.4)\%$	$(0.3 \pm 0.1)\%$
Δ_{0+}	$(+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$	$(4.9 \pm 2.6)\%$

- **Challenge**: in future Δ_{0+} will be dominated by f_{+-}/f_{00}, A_{CP} will be statistically limited

Measurement of $\mathcal{B}(B \to K^* \gamma)$

[arxiv:2110.08219]

Belle II

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

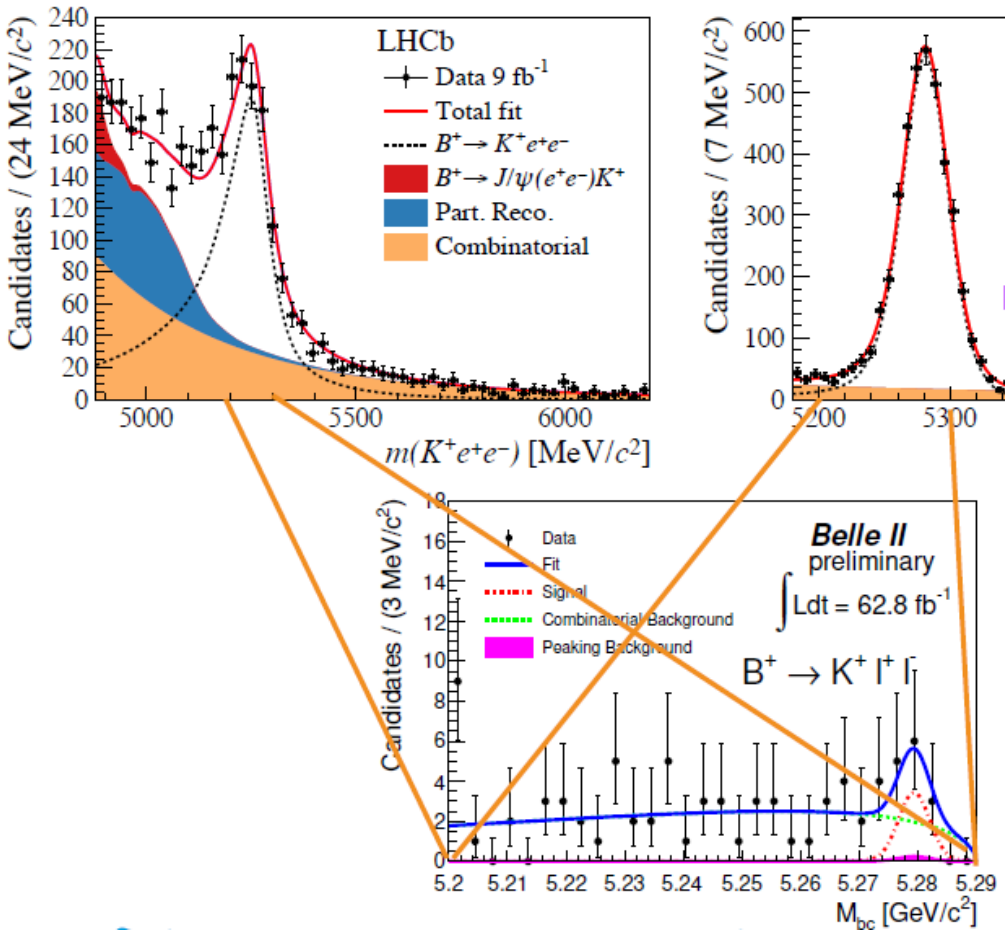
Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K^0_S\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K^0_S\pi^+]\gamma$
No. of $B\overline{B}$ events	1.6	1.6	1.6	1.6
Photon selection	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$	$^{+0.2}_{-0.4}$
π^0/η veto	3.8	3.8	3.8	3.8
Pion identification	0.6	—	—	0.6
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	$^{+13.2}_{-12.4}$	$^{+7.9}_{-8.9}$	$^{+7.0}_{-7.3}$

$B^+ \to K^+ l^+ l^-$: Systematics

Table XXVIII. The BF systematic for $B \to KJ/\psi(\ell\ell)$ modes (in %)

Source	$K^+J/\psi(\mu^+\mu^-)$	$K^+J/\psi(e^+e^-)$	$K^0_SJ/\psi(\mu^+\mu^-)$	$K^0_SJ/\psi(e^+e^-)$
No. of $B\bar{B}$ pairs	2.70	2.70	2.70	2.70
PDF shape parameters				
MVA criteria				
Electron identification	–	1.32	–	1.50
Muon identification	1.50	–	1.50	–
Kaon identification	0.93	0.93	0.93	0.93
K^0_S reconstruction	–	–	7.87	7.87
Tracking	2.73	2.73	3.64	3.64
Signal efficiency	0.05	0.05	0.09	0.09
Total				

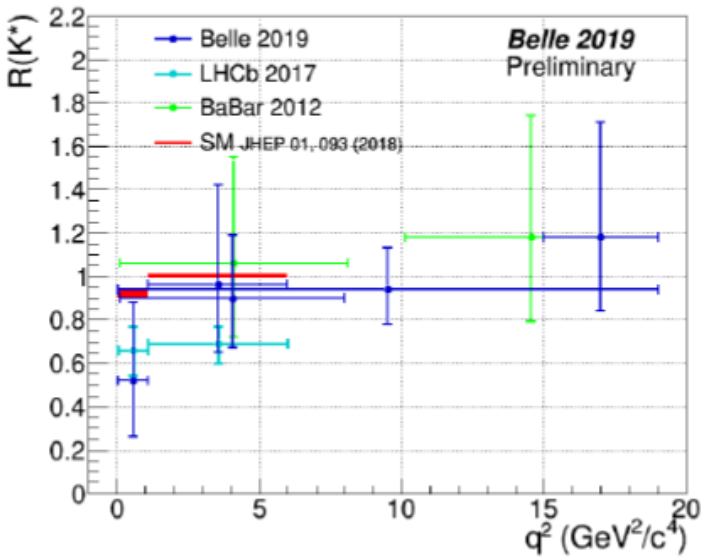
(R(K*)) : Belle II vs LHCb



	Belle II	LHCb
Signal	K^+, K_S	K^+
Same K e e Statistics	1 ab^{-1}	1 fb^{-1}
B->K mu mu Efficiency	30 %	~5 %
B->K e e Efficiency	30 %	<5% Lower due to tracking and trigger
B->K e e Resolution	Better thanks to M_{bc}	Worse because of Brems
High q^2 bin	Accessible	Hard

- In comparison to LHCb, 3 differing aspects to consider: efficiency, statistics and resolution
- Electrons (and muons) in Belle II have better resolution thanks to M_{bc}

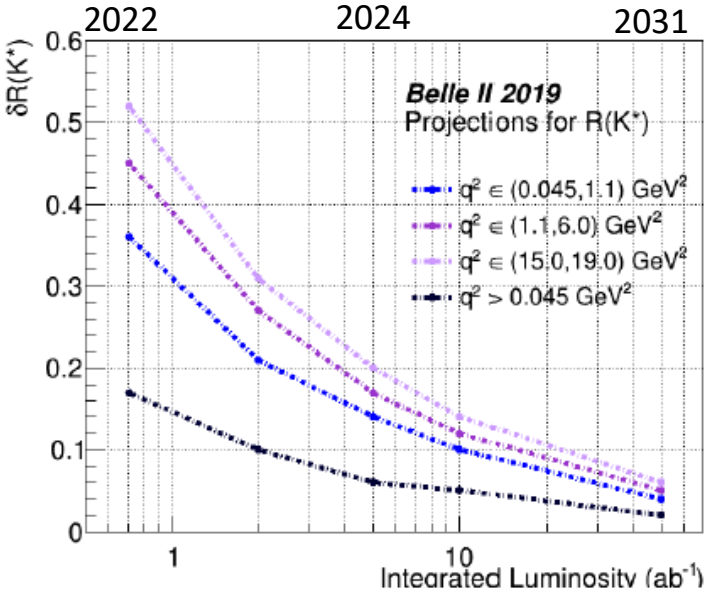
(R(K*)) : Prospects

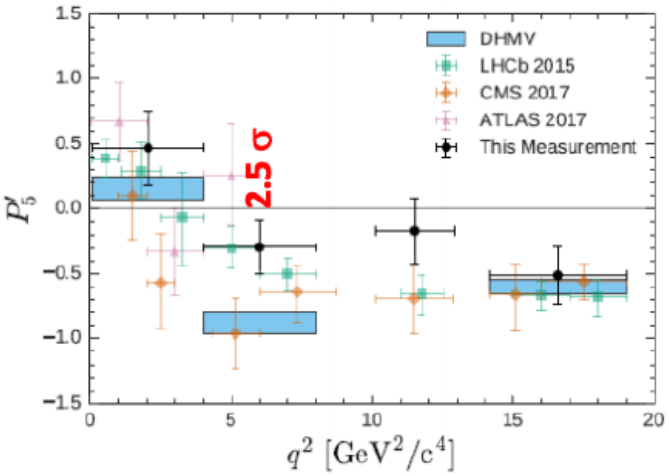


Belle (R(K*))

- Largest deviation in the low q^2 bin

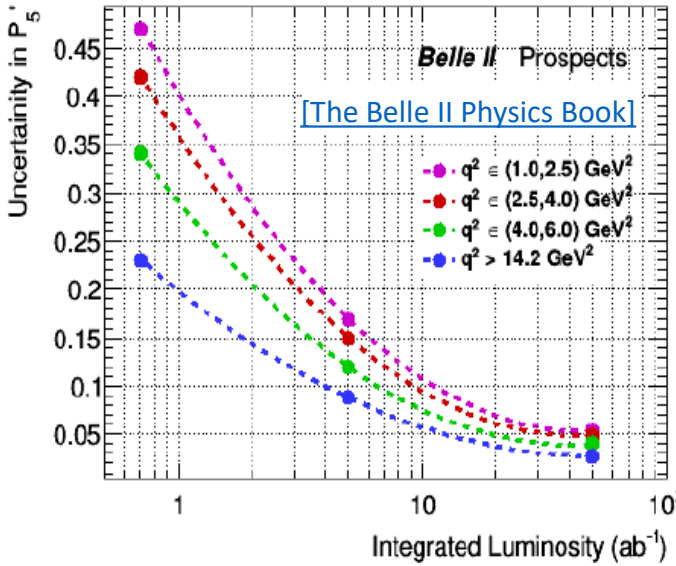
[Belle arXiv: 1904.02440]





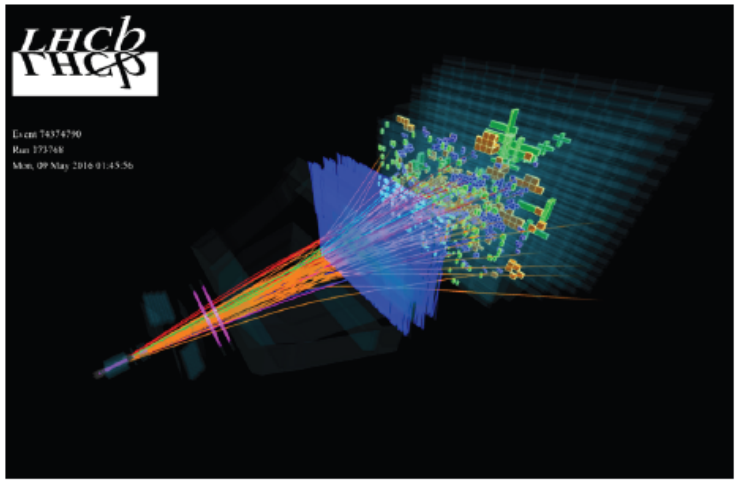
Belle P'_5 [Belle Phys. Rev. Lett. 118, 111801]

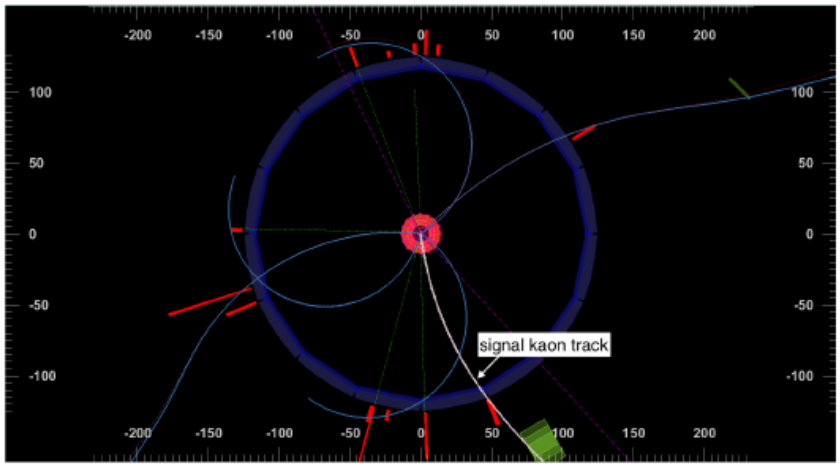
- The largest deviation with 2.6σ observed in muon channel
- Electron channel is deviating with 1.1σ
- With 2.8 ab^{-1} the uncertainty on P'_5 (both e & μ) will be comparable to LHCb 3 fb^{-1} (μ only)



$B^+ \to K^+ \nu\bar{\nu}$: LHCb vs Belle II

LHCb	Belle II
single-arm detector longitudinal momentum of B not known	hermetic detector known initial state kinematics pro @ neutral object reconstruction (photon, K_L)





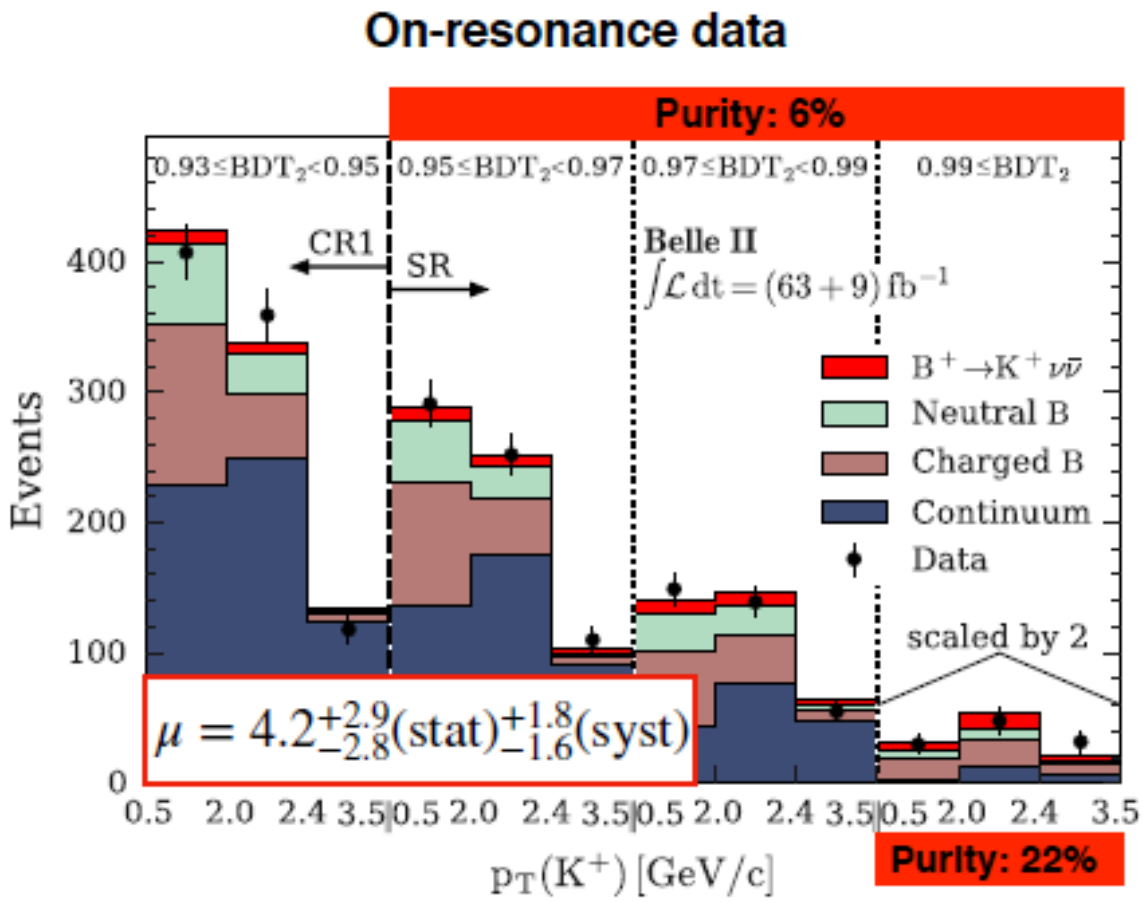
- $B^+ \to K^+ \nu\bar{\nu}$ **is a golden channel at Belle II:** clean environment and well defined initial state but still challenging as two neutrinos in the final state leave no signature

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

[PRL 127, 181802 (2021)]

Signal extraction

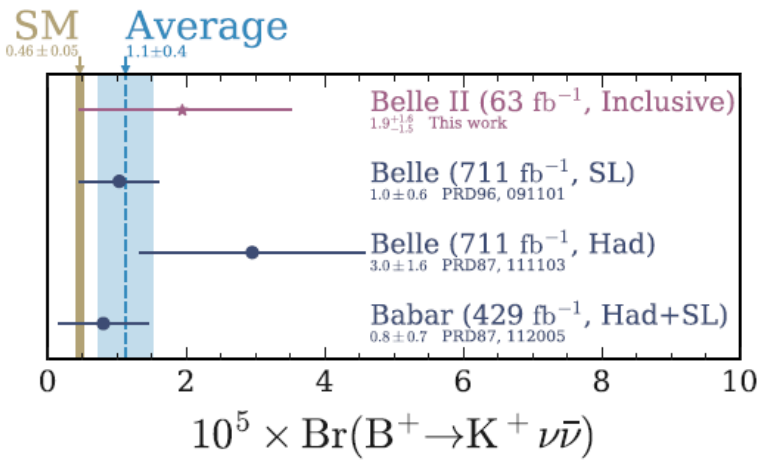
- Binned simultaneous ML fit to p_T (K^+) x BDT_2 to extract signal strength μ



$B^+ \to K^+ \nu\bar{\nu}$: Comparison with other measurements

- **Competitive limit**
- **Comparison with other experiments** via σ_{BR} assuming same luminosity ⟶ the performance of inclusive tag:
  - 3.5% better than hadronic tag
  - 20% better than semileptonic tag
  - 10% better than combined hadronic and semileptonic tag

Experiment	Year	Observed limit on BR($B^+ \to K^+ \nu\bar{\nu}$)	Approach	Data [fb^{-1}]
BABAR	**2013**	$< 1.6 \times 10^{-5}$ **[Phys.Rev.D87,112005]**	**SL + Had tagging**	429
Belle	**2013**	$< 5.5 \times 10^{-5}$ **[Phys.Rev.D87,111103(R)]**	**Had tagging**	711
Belle	**2017**	$< 1.9 \times 10^{-5}$ **[Phys.Rev.D96,091101(R)]**	**SL tagging**	711
Belle II	**2021**	$< 4.1 \times 10^{-5}$	**Inclusive tagging**	63



$B^+ \to K^+ \nu\bar{\nu}$: Prospects

- **Bigger dataset** (+ possible combination with Belle dataset)
- **Attacking biggest systematic** (background normalizations, e.g continuum modelling)
- **More channels** (K^*, K_S^0 , K^{*+}...)
- **Possible improvement in background suppression** (use of NN architecture, discriminating vars)
- **Combined analysis of inclusive and exclusive tagged events**

$10^5 \times \sigma_{BR}$ uncertainty for next analyses, assuming 25% improvement + 40% K_S^0

	$63\ \text{fb}^{-1}$ (arXiv:2104.12624)	$197\ \text{fb}^{-1}$ (Summer 2021 – current lumi)	$450\ \text{fb}^{-1}$ (Summer 2022 – expected)	$(450+700)\ \text{fb}^{-1}$ (+ Belle I sample)
$\sigma_{BR}(K^+)$	1.55	0.78	0.52	**0.32**
$\sigma_{BR}(K^+ + K_S^0)$	-	0.68	0.45	**0.28**

Preliminary