Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ and other electroweak/ radiative penguin processes at Belle II

EPS-HEP 2021

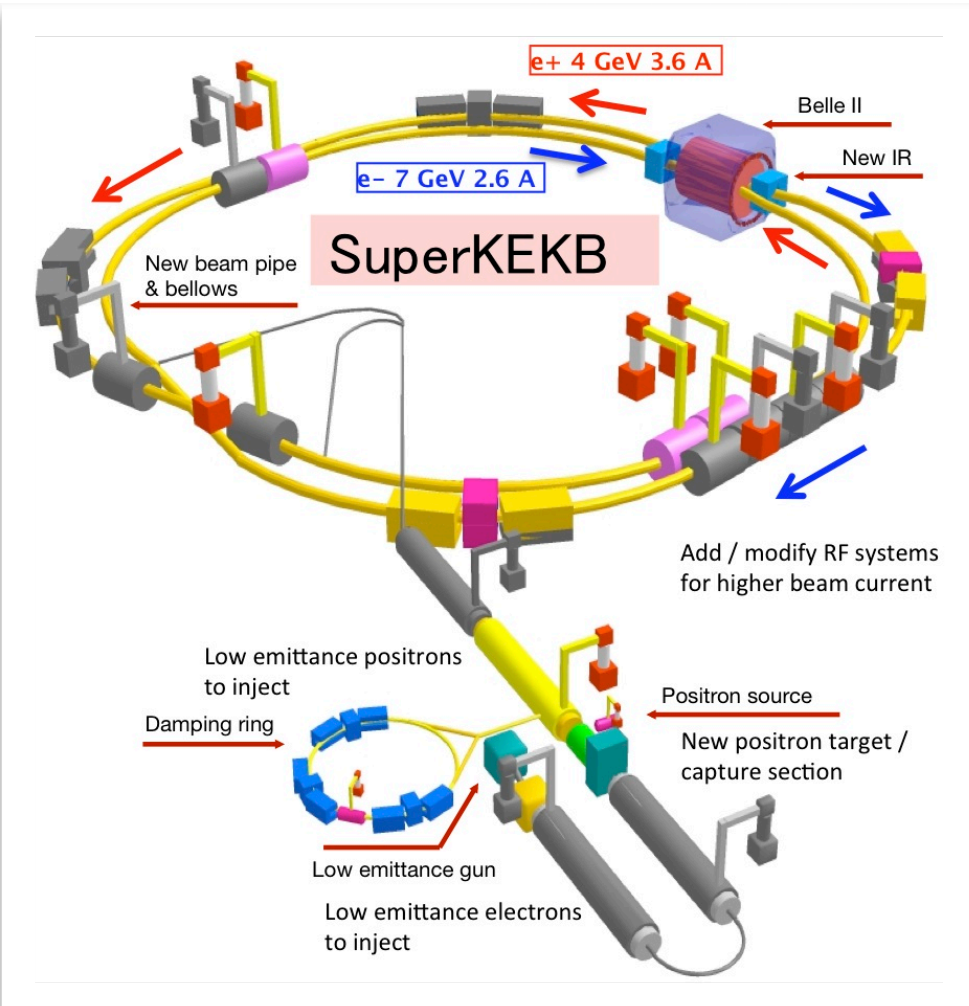
Simon Kurz on behalf of the Belle II collaboration

July 26-30, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

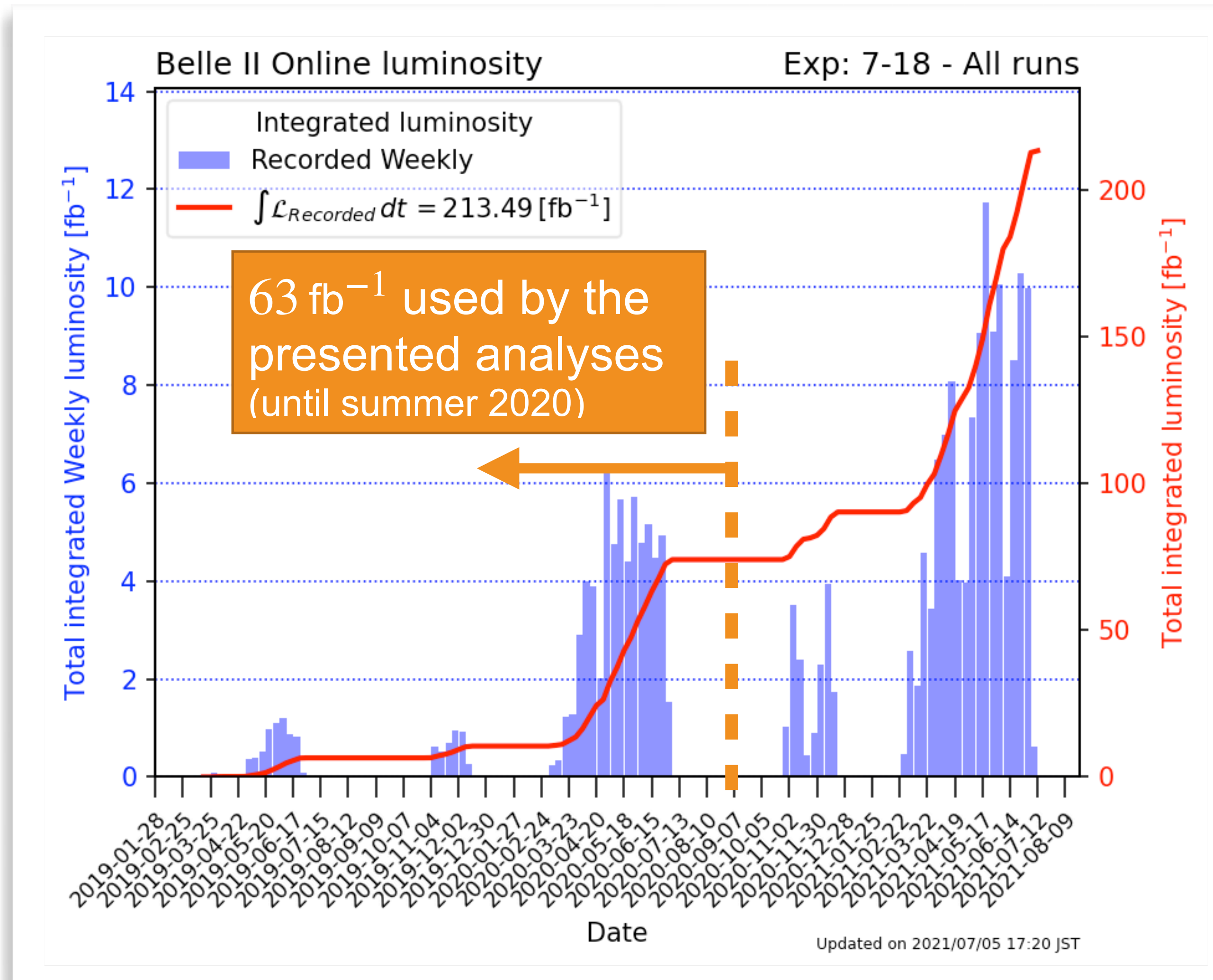
SuperKEKB

B-Factory for the Belle II Experiment



Asymmetric e⁺e⁻ *B*-factory to study CP-violation and rare decays

- $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV
  - >96% decay to $B\bar{B}$
- Forward boost of $B\bar{B}$ system



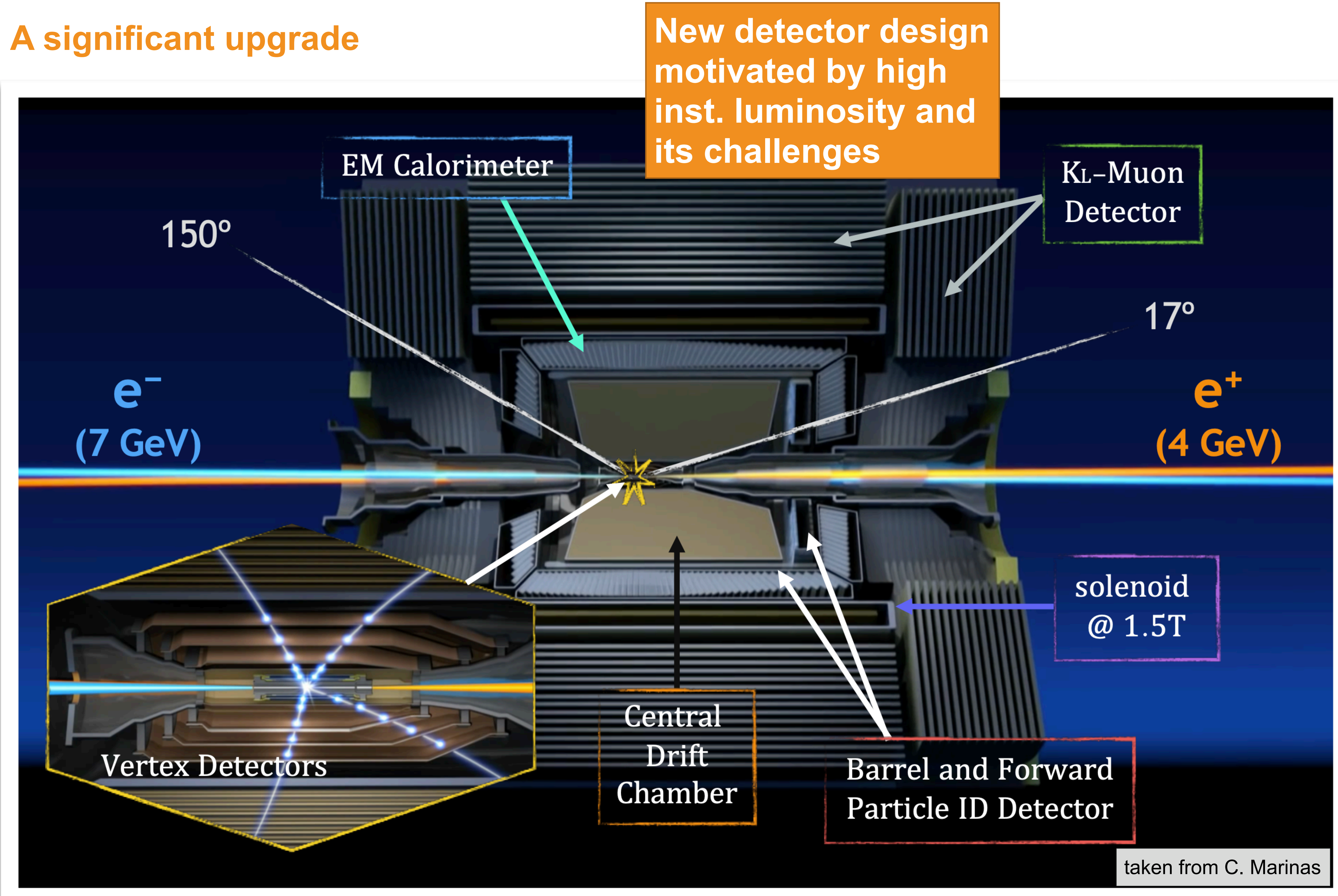
… and $9\ \mathrm{fb}^{-1}$ of off-resonance data (60 MeV below $\Upsilon 4S$)

Set world record: highest instantaneous luminosity of $L = 3.1 \times 10^{34}$ cm^{-2}s^{-1}

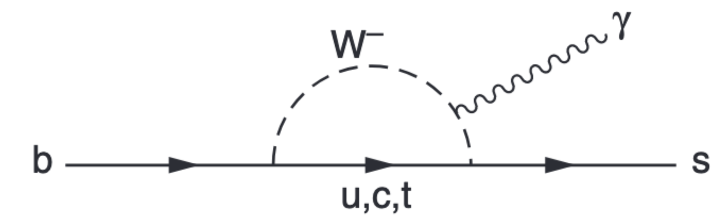
- Total recorded luminosity of $213.49\ \mathrm{fb}^{-1}$ until summer shutdown
- Target: $50\ \mathrm{ab}^{-1}$ (50x Belle)

The Belle II Detector

A significant upgrade



Overview and First Results

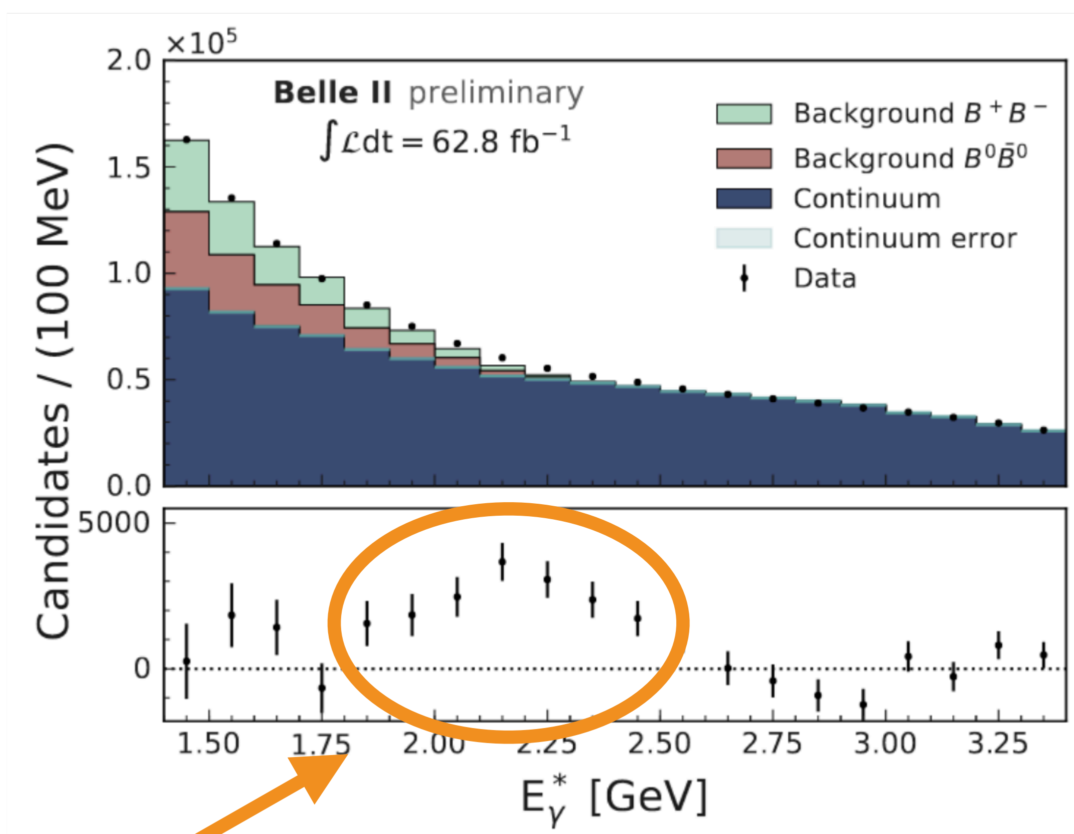


Observation of $B \to X_s\gamma$ decays BELLE2-NOTE-PL-2021-004

- FCNC $b \to s\gamma$ transition sensitive to many SM extensions
- **Measure inclusive photon energy spectrum**
  - Expect monochromatic (smeared) photon spectrum with $E^*_\gamma > 1.4$ GeV

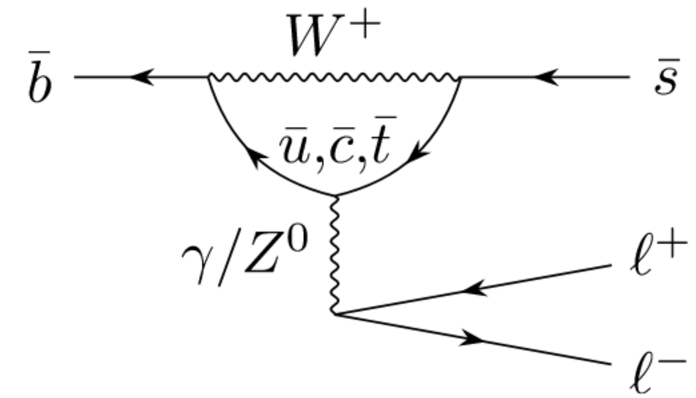
In a Nutshell
(of course, there are more subtleties)

1. Simple selection requirements
2. Designated π^0 and η veto
3. Suppression of continuum background (BDT using event-shape variables)
4. Subtract expected contributions from continuum and B backgrounds from data (using off-resonance data and sidebands)
5. **Excess clearly visible in expected region**



Measurement with more data in preparation!

Overview and First Results



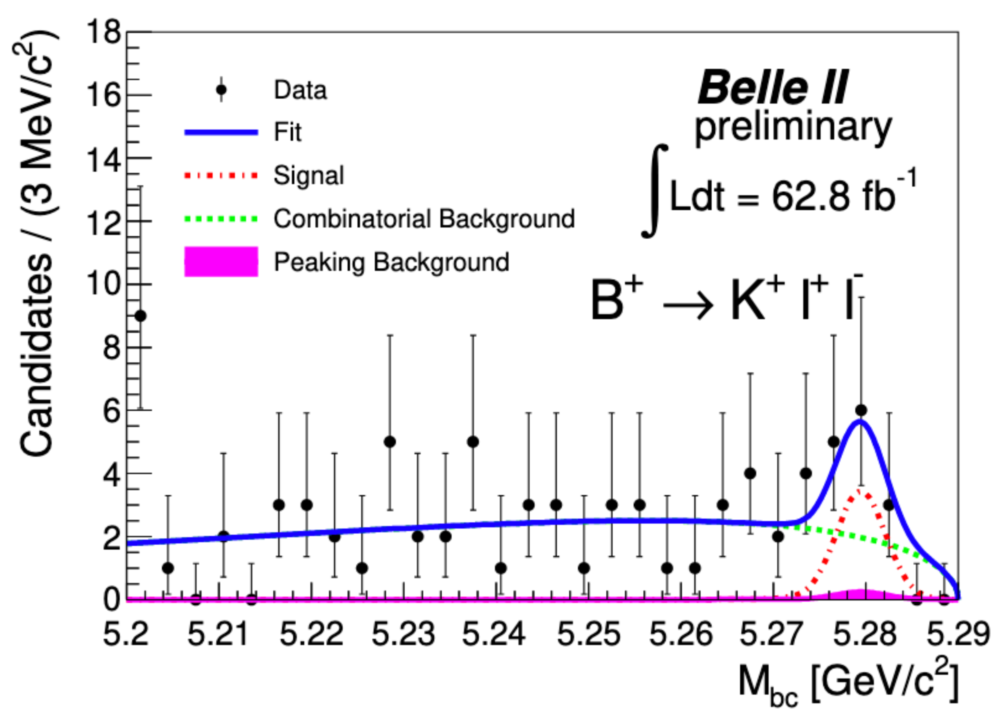
Study of $B^\pm \to K^\pm \ell^+ \ell^-$ BELLE2-NOTE-PL-2020-014

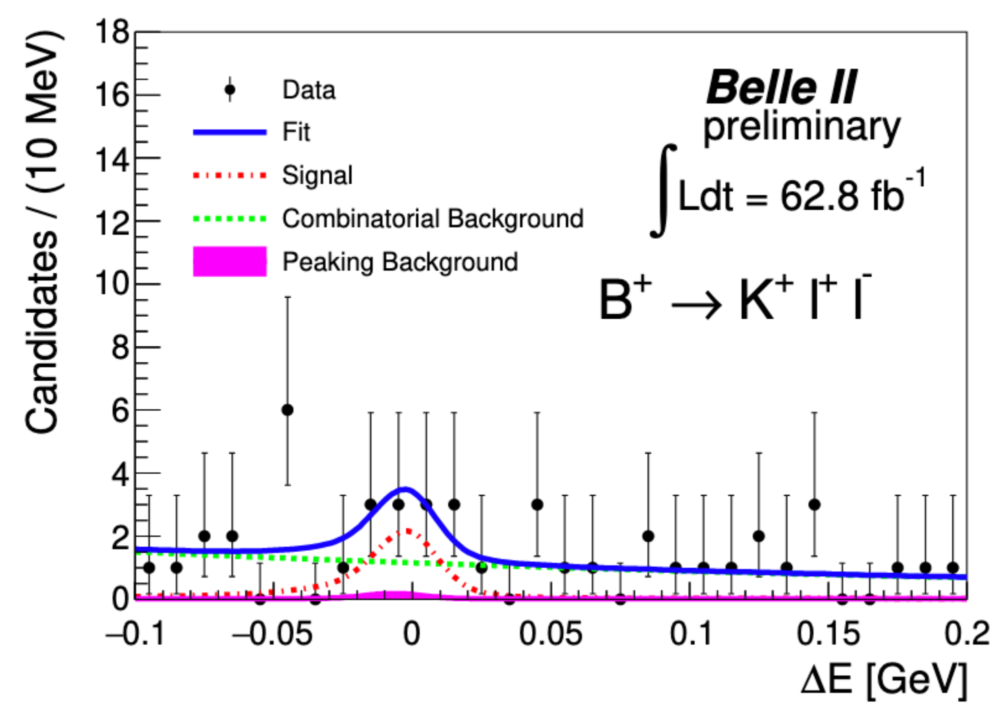
- Important to have independent measurement of **FCNC decay** $B^\pm \to K^\pm \ell^+ \ell^-$ (with $\ell = e, \mu$) to shed more light onto results from **LHCb** **arXiv:2103.11769 (submitted to Nature Physics)**
- **Rediscovery** of $B^\pm \to K^\pm \ell^+ \ell^-$:

Observed $8.6^{+4.3}_{-3.9} \pm 0.4$ (stat./syst.) signal events in 2D fit (M_{bc}, ΔE)

$$M_{bc} = \sqrt{s/(4c^4) - p_B^{*2}/c^2}$$

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



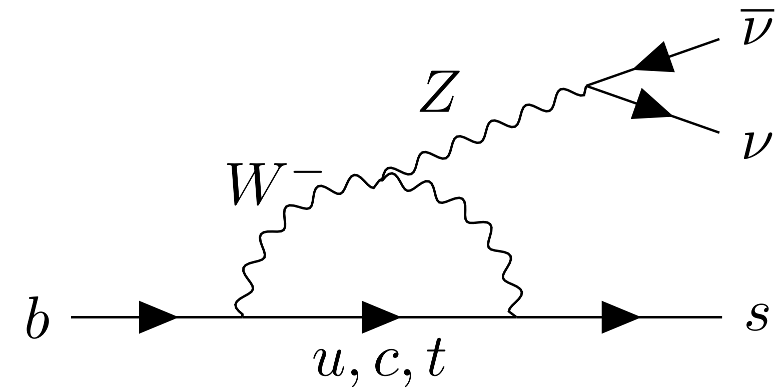


- Available data not enough to determine key observables like branching fraction, isospin asymmetry, R_K (ratio of *BRs* of muon and election channel)
  - Prepare/rehearse analysis using $B \to J/\Psi(\ell^+\ell^-)\,K$ (with $K = K^\pm, K^0_S$) control sample (same final state but large BR)

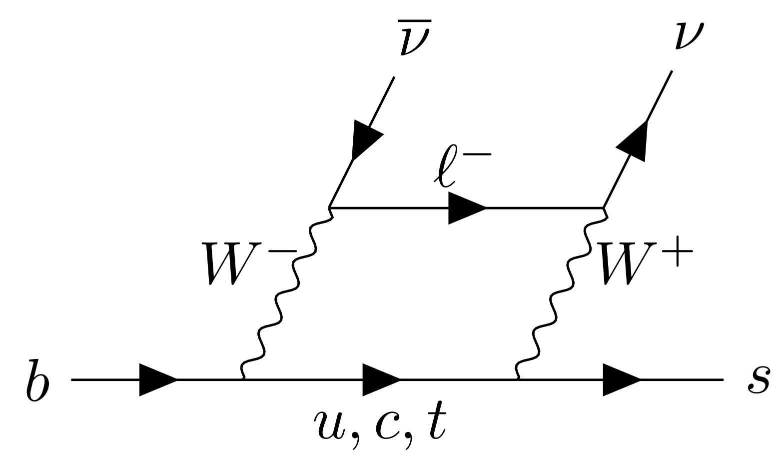
What we can already do…

Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

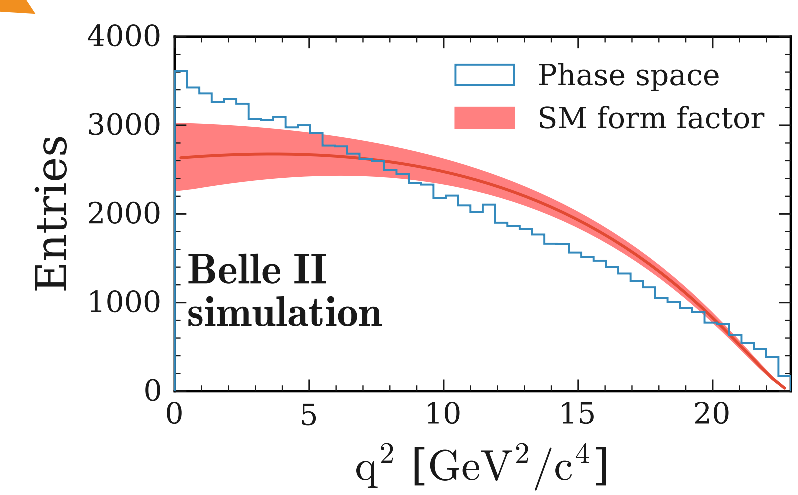
- Complementary probe of BSM physics scenarios **proposed to explain anomalies** observed in $b \to s\ell\bar{\ell}$ transitions arXiv:2005.03734, including recent measurement of R_K by LHCb arXiv:2103.11769 (submitted to Nature Physics)



- … but **does not suffer from charm-loop** contributions
  $\mathscr{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ arXiv:1606.00916
  (uncertainty dominated by $B \to K$ form factor, simulation weighted with FFs arXiv:1409.4557)



- Flavour-changing neutral current process $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ **not observed yet**



- Many other BSM models can be constrained like dark matter PRD 98, 055003 (2018), leptoquarks PRD 102, 015023 (2020), axions PRD 101, 095006 (2020)

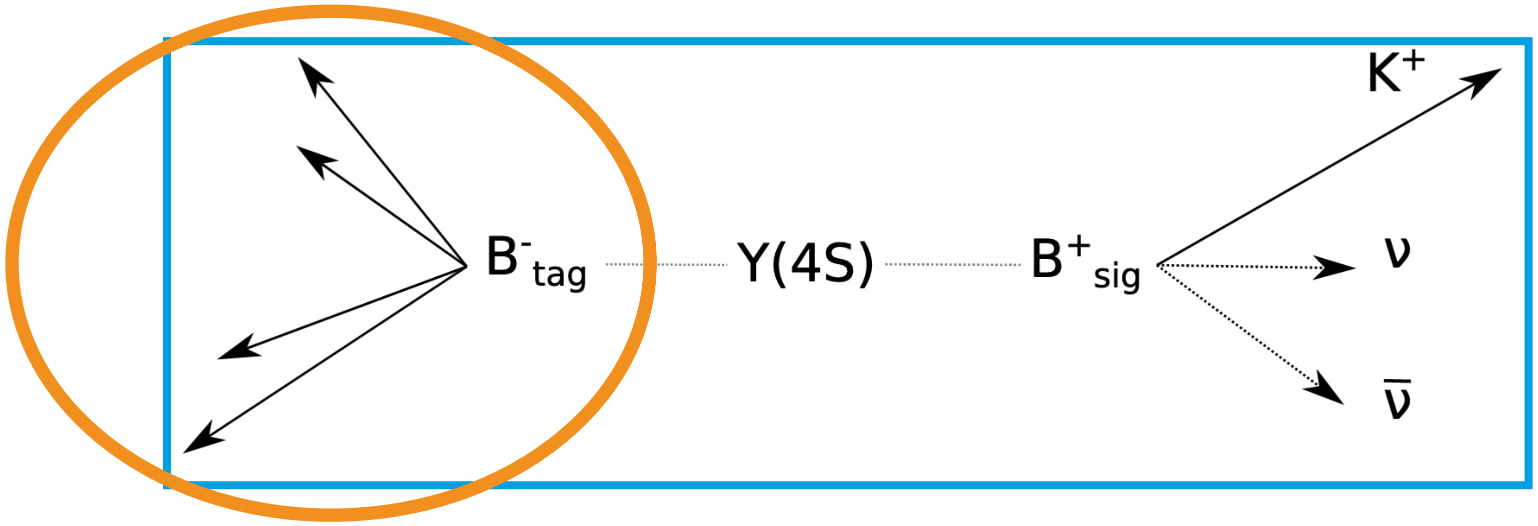
Analysis Strategy: Inclusive Tagging

Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

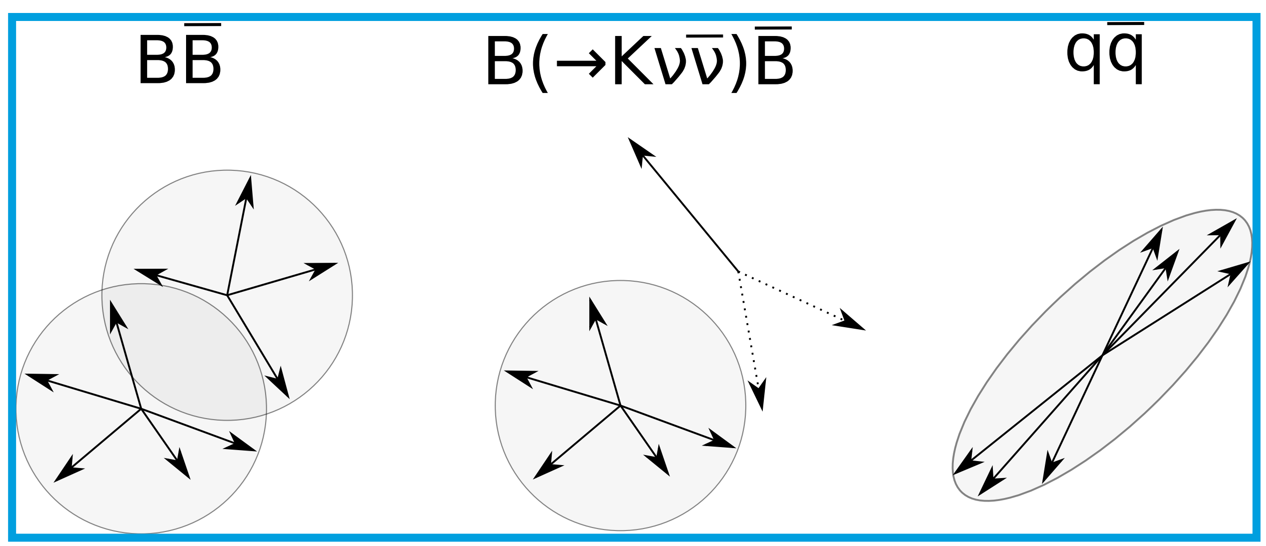
- Previous searches **explicitly reconstruct the second *B* meson**
  - **semi-leptonic tag:** signal efficiency of ~0.2% (Belle, PRD 96, 091101 (2017))
  - **hadronic tag:** signal efficiency of ~0.04% (BaBar, PRD 87, 112005 (2013))

- **Idea: exploit distinct topology and kinematics to achieve higher signal efficiency** (~4%) (rather spherical, missing energy, displaced kaon track,…)

Semi-leptonic/hadronic tag



Inclusive tagging



Overview

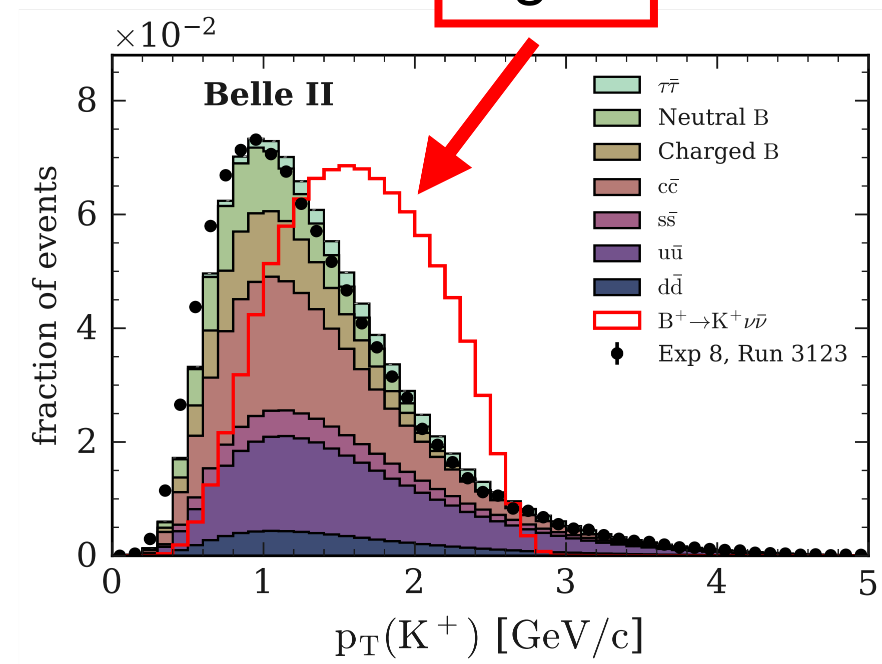
Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

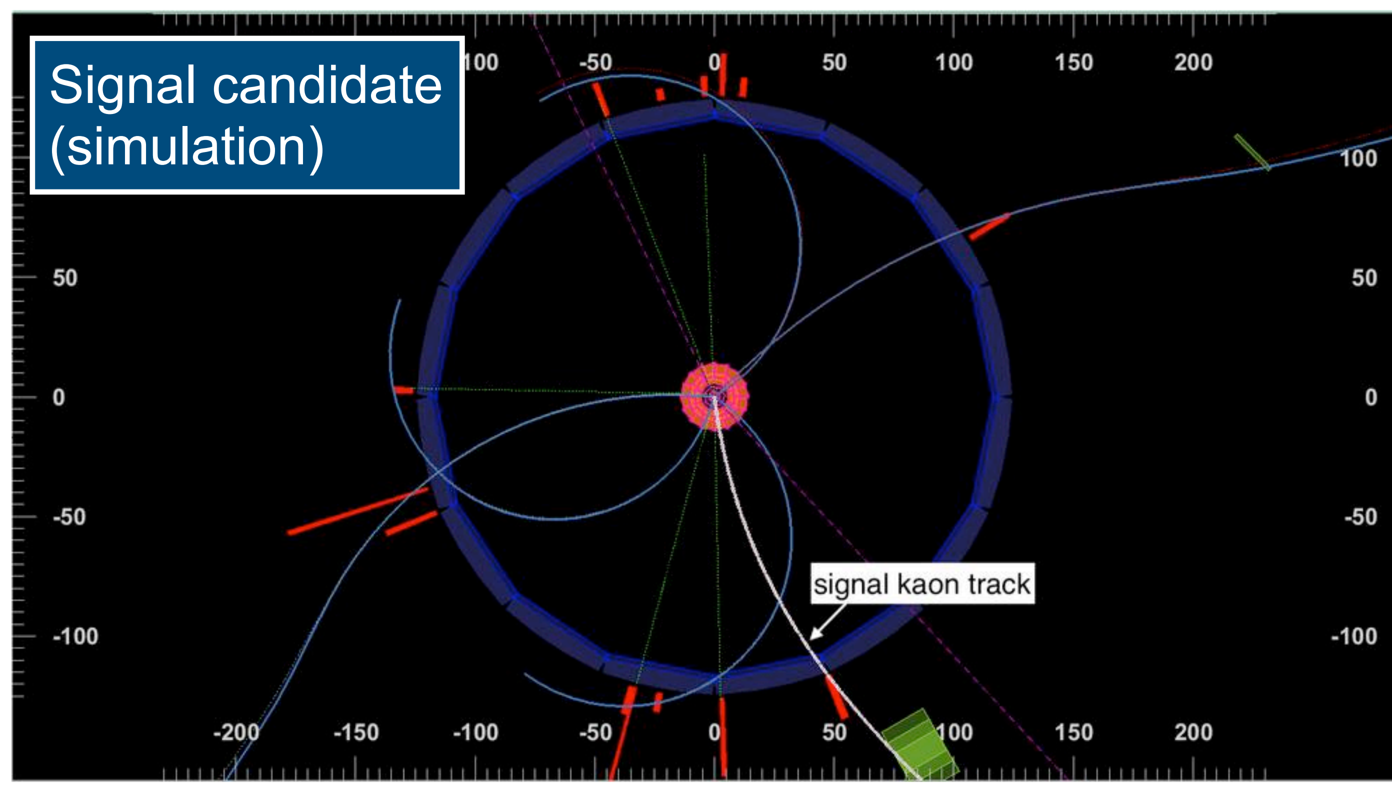
1. **Basic event selection** (mainly $4 \leq N_{\text{tracks}} \leq 10$)
2. **Select highest p_{T} track as signal kaon candidate**
3. **Train BDT to identify signal** (topology, rest-of-event, missing energy, vertex separation,…)
4. **Validate the BDT** using data of $B^{+} \to K^{+} + J/\psi_{(\to \mu^{+}\mu^{-})}$ decays where the muons can be removed to mimic signal
5. **Use off-resonance data** (60 MeV below $\Upsilon(4S)$) to constrain yields from continuum processes ($q\bar{q}, \tau\bar{\tau}$)
6. Statistical **interpretation**

correct candidate in 78% of cases

require kaon identification (PID)

Signal

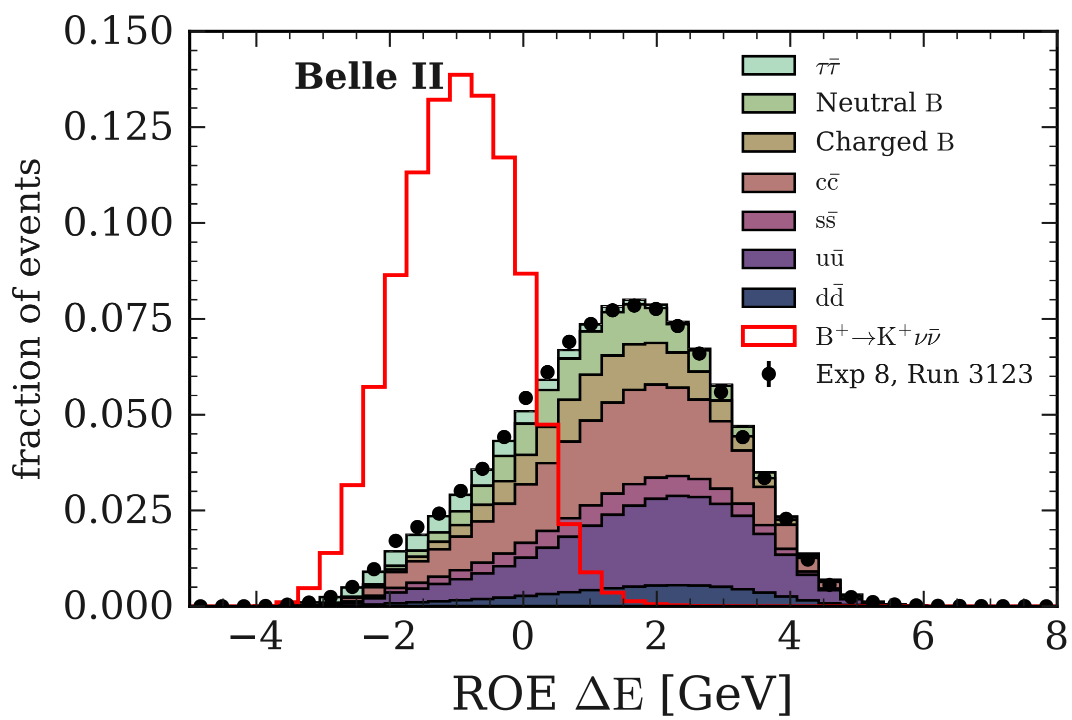




Training of Binary Event Classifier

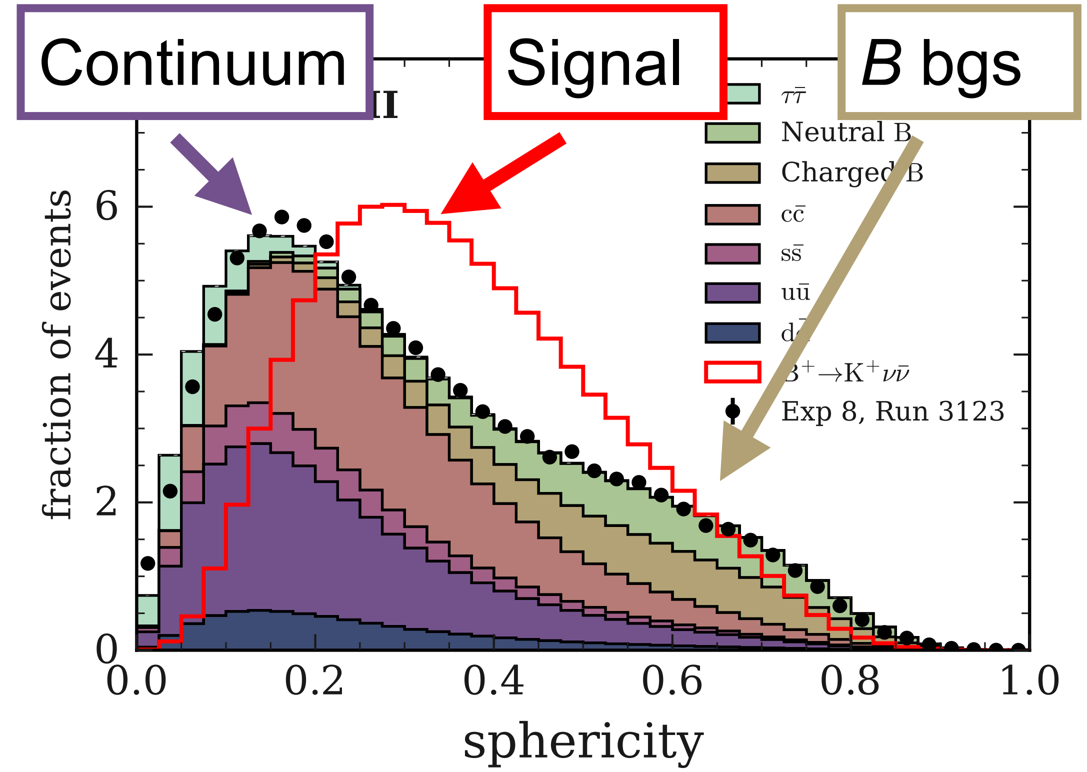
Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

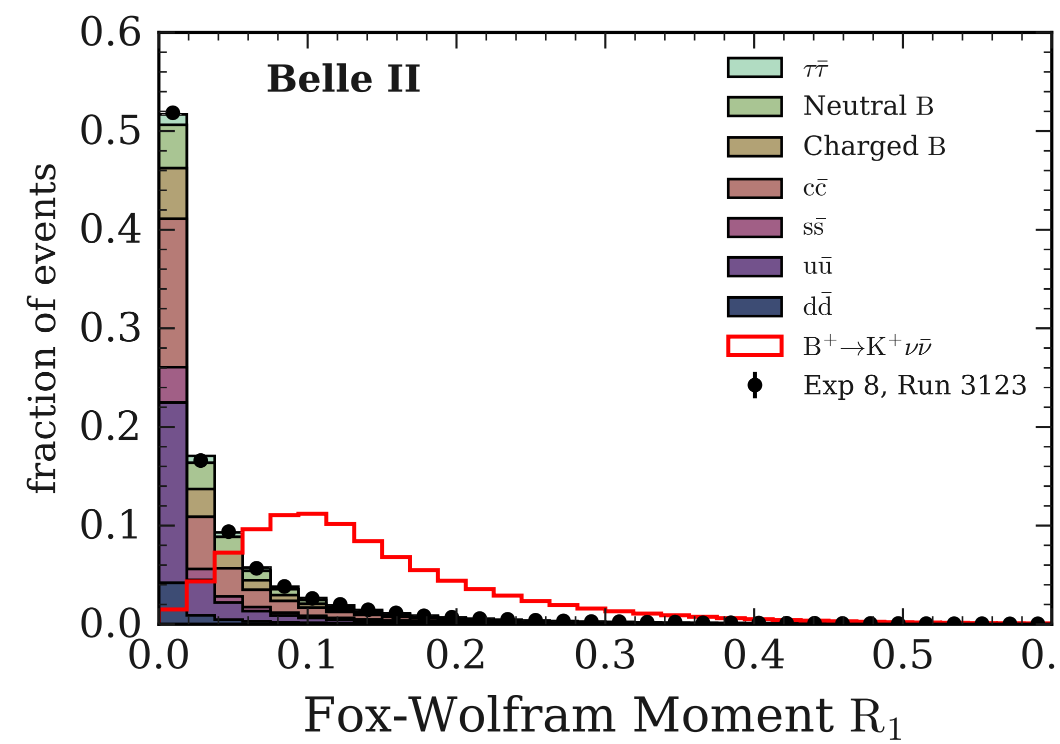
- **Select features for training of BDT:** excluded variables with little discrimination power or poor modelling in simulation
  - **Resulting in 51 training variables**



$$\Delta E = E_B{}^{*} - \sqrt{s}/2$$ (E^* of second B meson)

- Background: random combination of objects from both B mesons, some objects might be missing





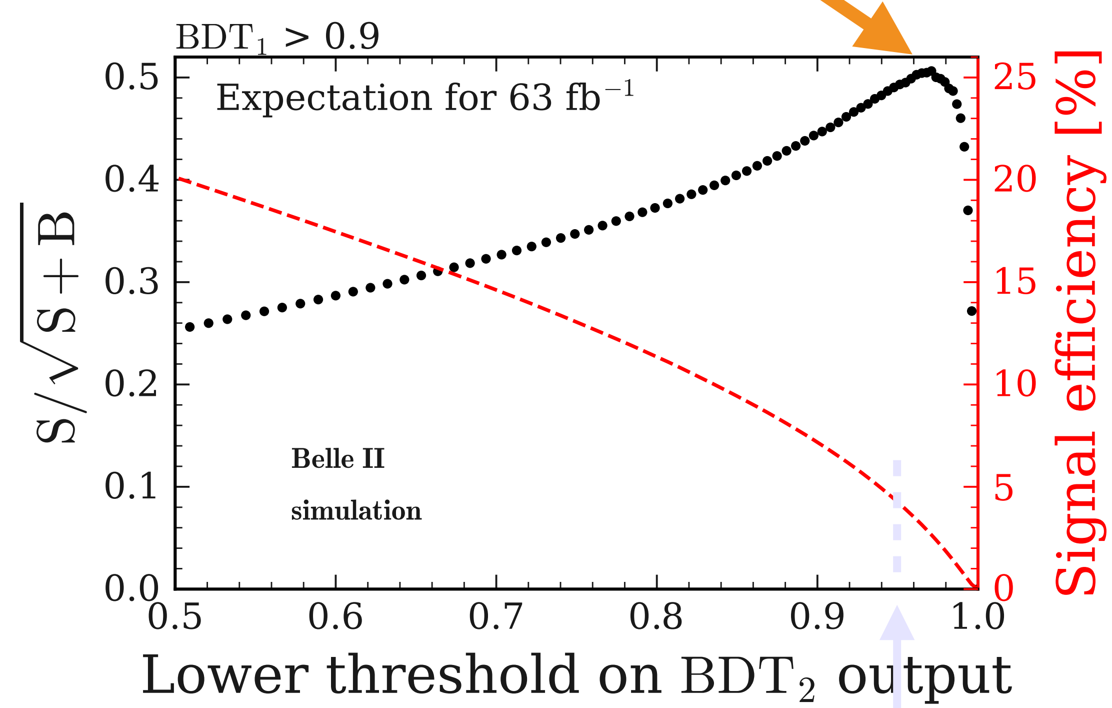
- R1: Momentum imbalance in the event, signal has neutrinos

Boosting to Signal Region

Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

- **2-step procedure**: $\mathrm{BDT}_1 \to \mathrm{BDT}_2$
  - Train BDT_1 with **51 variables**
  - Select events with $\mathrm{BDT}_1 > 0.9$ and train BDT_2 with larger sample (same training variables)
  - Significant improvement in discrimination power

Maximum sensitivity at $\mathrm{BDT}_2 \gtrsim 0.95$

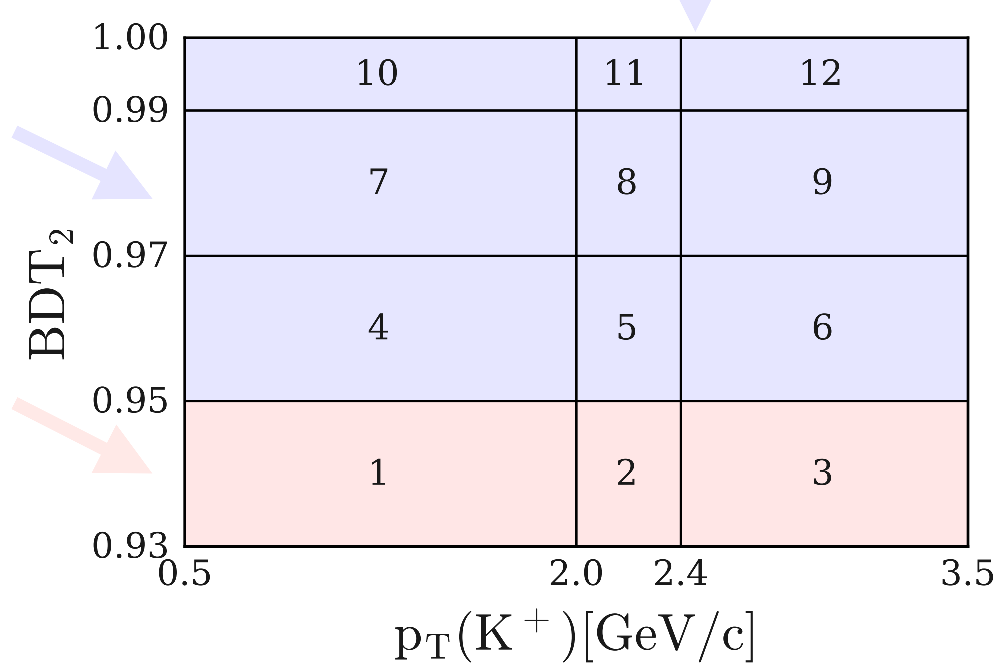


Signal Efficiency ~4.3% (SM signal)

- Define 2×12 regions in $\mathrm{BDT}_2 \times p_{\mathrm{T}}(K^{+})$ space (on- and off-resonance data)
  - important to constrain background yields in fit (see later)

Signal Regions

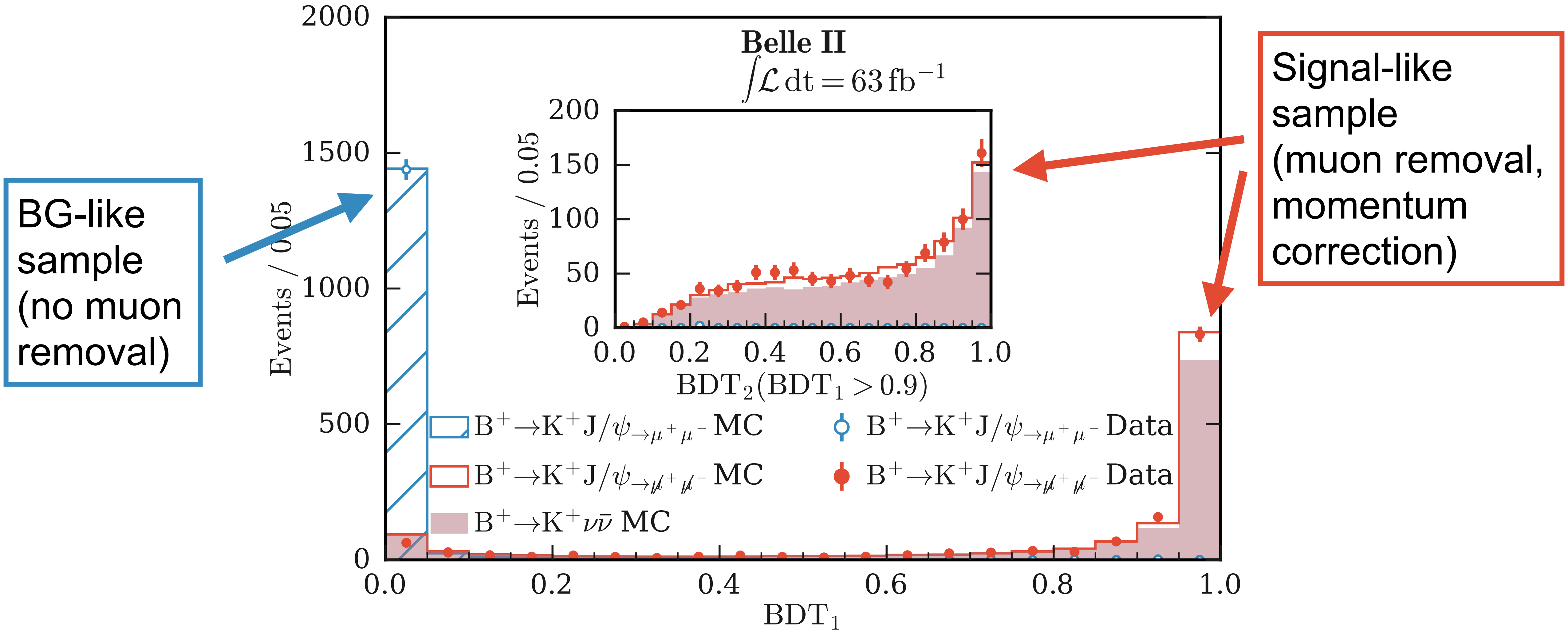
Control Regions



Validation Channel: $B^+ \to K^+ + J/\psi_{(\to\mu^+\mu^-)}$

Search for $B^\pm \to K^\pm \nu\bar{\nu}$ arXiv:2104.12624

- **Compare response of BDTs in data and simulation:**
  - Reconstruct J/ψ from two muons and remove them to mimic signal neutrinos
  - Correct kaon momentum using simulated signal events (2- vs 3-body decay)
- **High level of agreement:**
  - Fraction of events in signal region (BDT$_2 > 0.95$, data/simulation) $= 1.06 \pm 0.10$



Extraction of Signal Yields

Factor wrt. SM expectation (4.6×10^{-6})

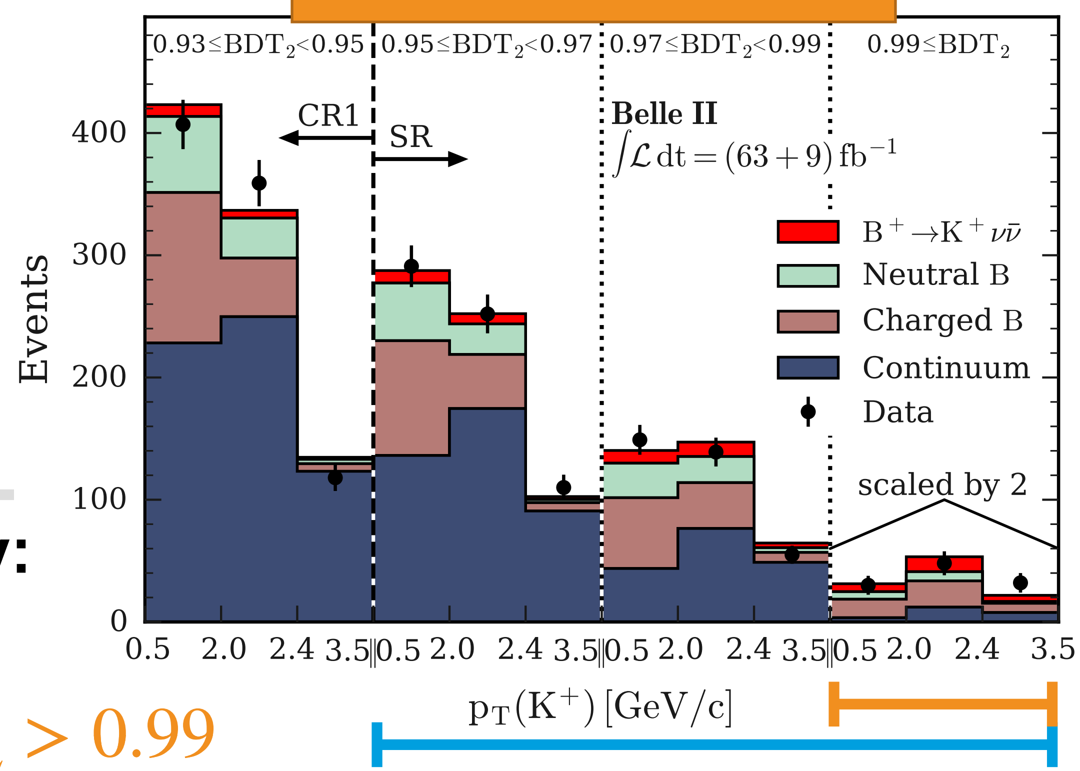
Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

➡ **Perform a binned maximum likelihood fit to extract signal strength μ**

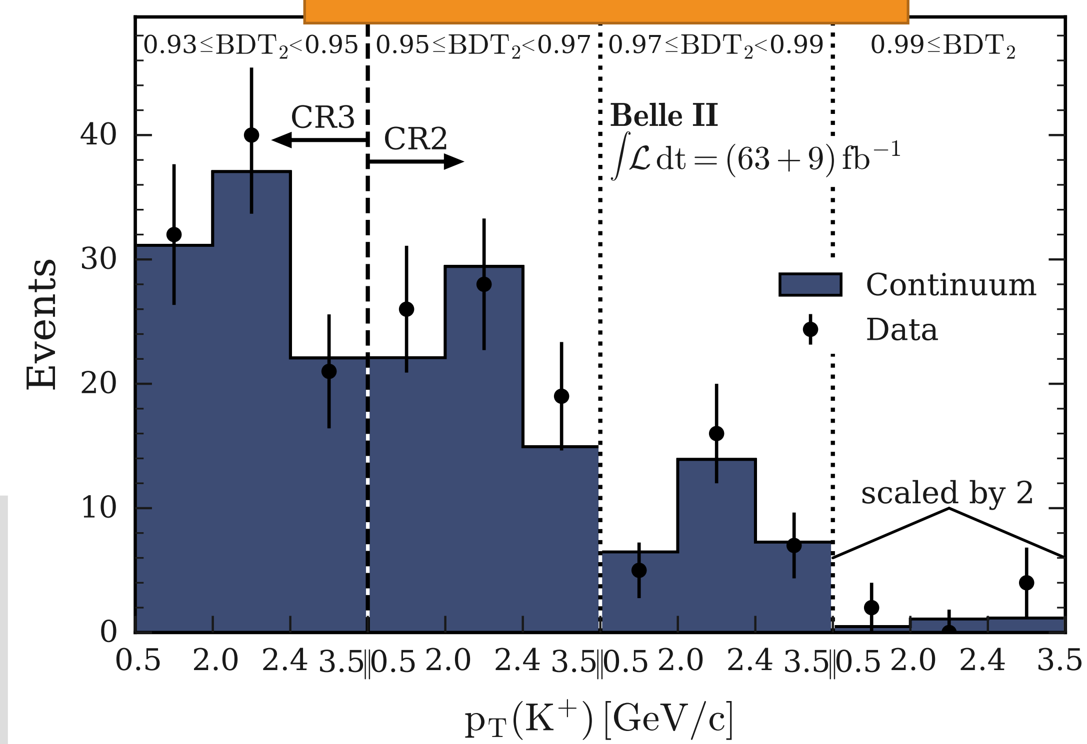
- Templates for background and signal yields from simulation
- Systematic uncertainties included as nuisance parameters (event count modifiers)
- **Leading systematic uncertainty:** background normalisation of individual contributions

Yields after simultaneous fit of all 24 regions

On-resonance Data



Off-resonance Data



Signal purity:
6% for SR
22% for $\mathrm{BDT}_2 > 0.99$

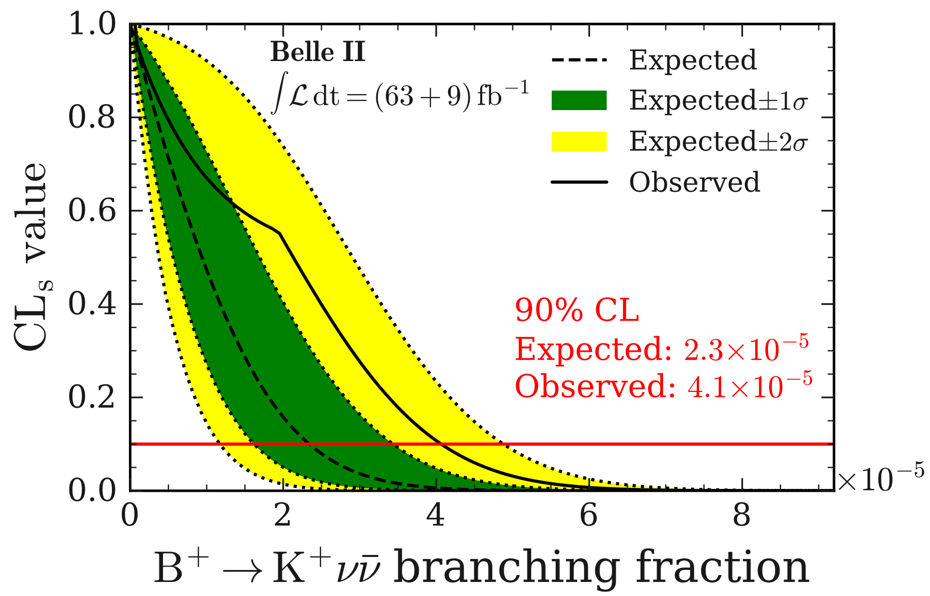
- **Measured signal strength** $\mu = 4.2^{+3.4}_{-3.2} = 4.2^{+2.9}_{-2.8}(\mathrm{stat})^{+1.8}_{-1.6}(\mathrm{syst})$
  - Total uncertainty from profiled likelihood scan around minimum; statistical component derived using toys

Results

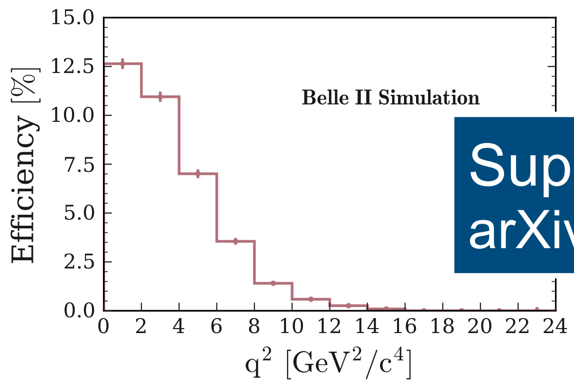
SM expectation:
$\mathscr{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$

Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$ arXiv:2104.12624

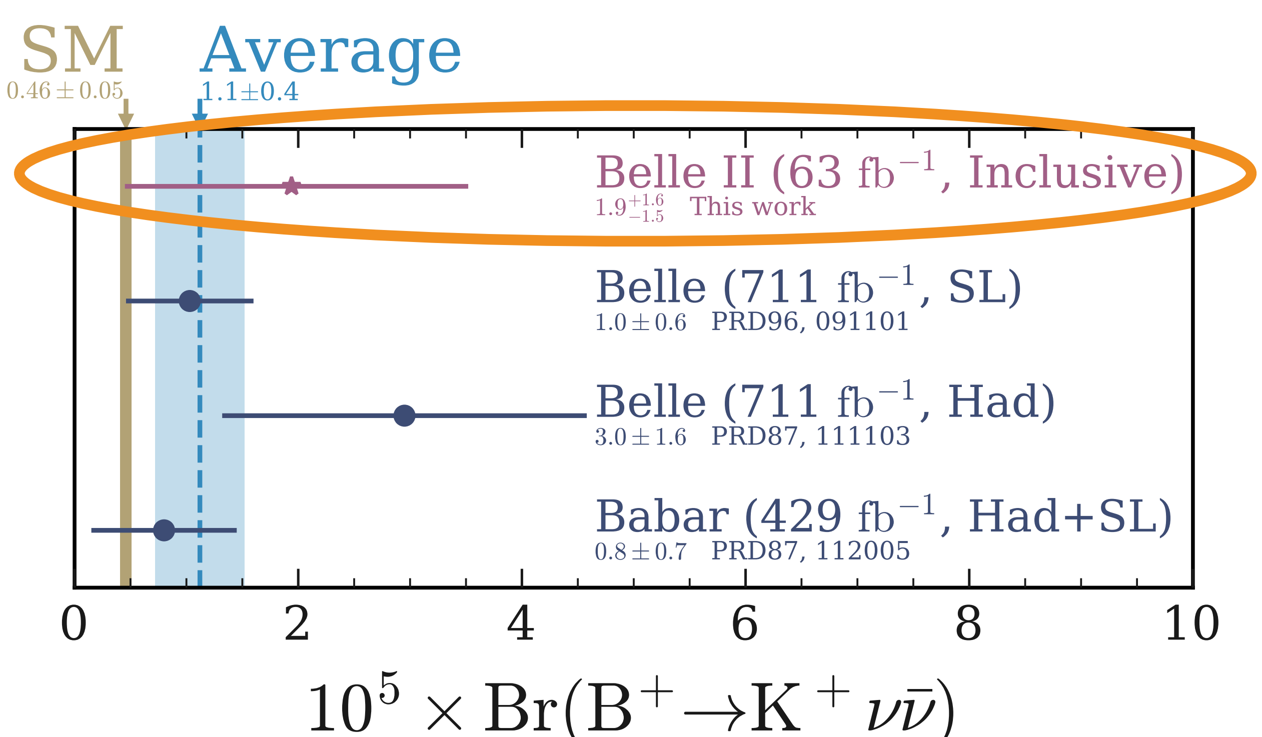
No signal observed; setting upper limit on BR using CLs method (assuming SM signal)



- $\mathscr{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5}$ @ 90 % CL
- **For reinterpretation:** signal efficiency as a function of the invariant mass of the dineutrino system



Supplemental material
arXiv:2104.12624



Our result!

- When converted to the same luminosity, **our measurement is better*) than semi-leptonic tagging by 10-20%**
- … **and than hadronic tagging by a factor 3.5!**

*) assuming the total uncertainty on the branching-fraction scales with $1/\sqrt{L}$

Summary

… interesting times are ahead of us!

- First excellent result **with prospects** prove the **high capabilities** of (relatively) new **Belle II** experiment

- **Great performance** of novel **inclusive tagging** used to study $B^\pm \to K^\pm \nu\bar{\nu}$ decays
  - Follow-up analysis in preparation:
    - more data (3x more on tape)
    - additional channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$)
    - improved technique (neural net)
  - Combination with results using semi-leptonic/hadronic tagging expected to further increase sensitivity (statistically independent events)
  - We may actually be able to **observe** $B^\pm \to K^\pm \nu\bar{\nu}$ soon **for the first time**!

Belle II is ready to look for new physics and make precision measurements of SM parameters

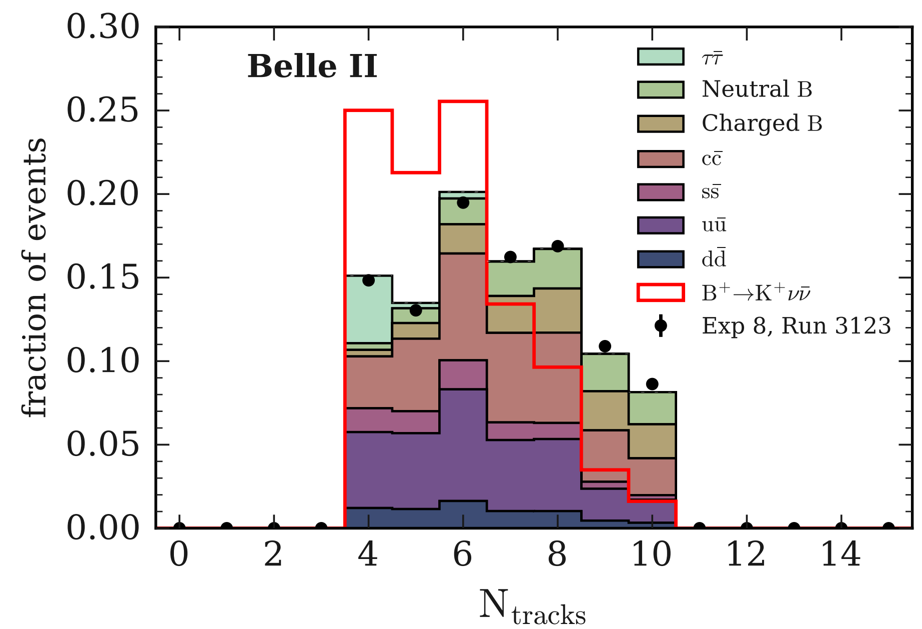
Backup

Signal Selection and Event Cleaning

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

Signal *B* has to be reconstructed as a single charged Kaon

- Select highest p_T track in the event as Kaon candidate (correct match in 78% of signal events)
- Require at least 1 PXD hit on Kaon candidate track (ensures high resolution of the track impact parameter)



Basic event cleaning and background rejection

- Tracks

  0.1 GeV $< p_T$, $|dz| < 3$ cm, $dr < 0.5$ cm, θ in CDC Acceptance

- Photons

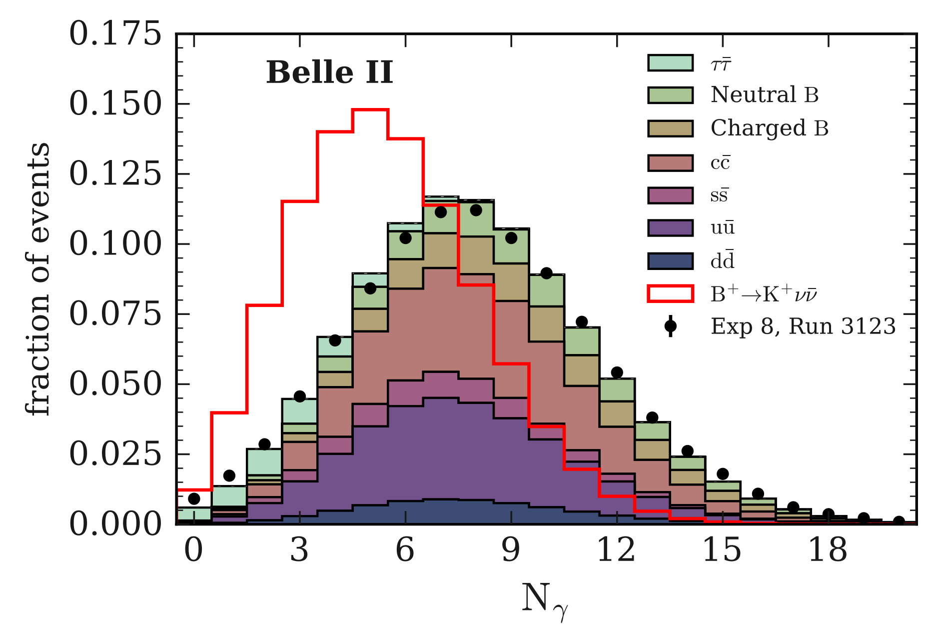
  0.1 GeV $< E_\gamma$, θ in CDC Acceptance

- All Objects

  $E < 5.5$ GeV

- Background rejection

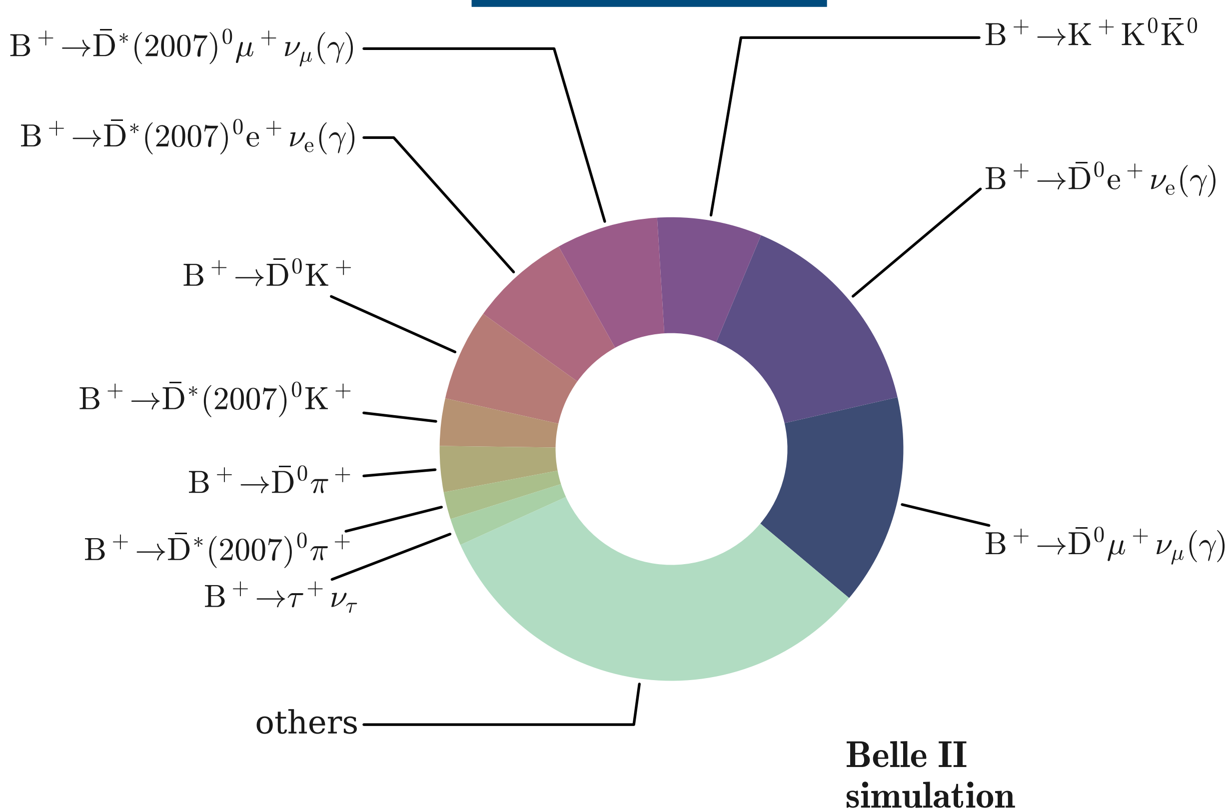
  $4 \le N_{tracks} \le 10$, $E_{visible} > 5.5$ GeV, $17° < \theta_{miss} < 160°$

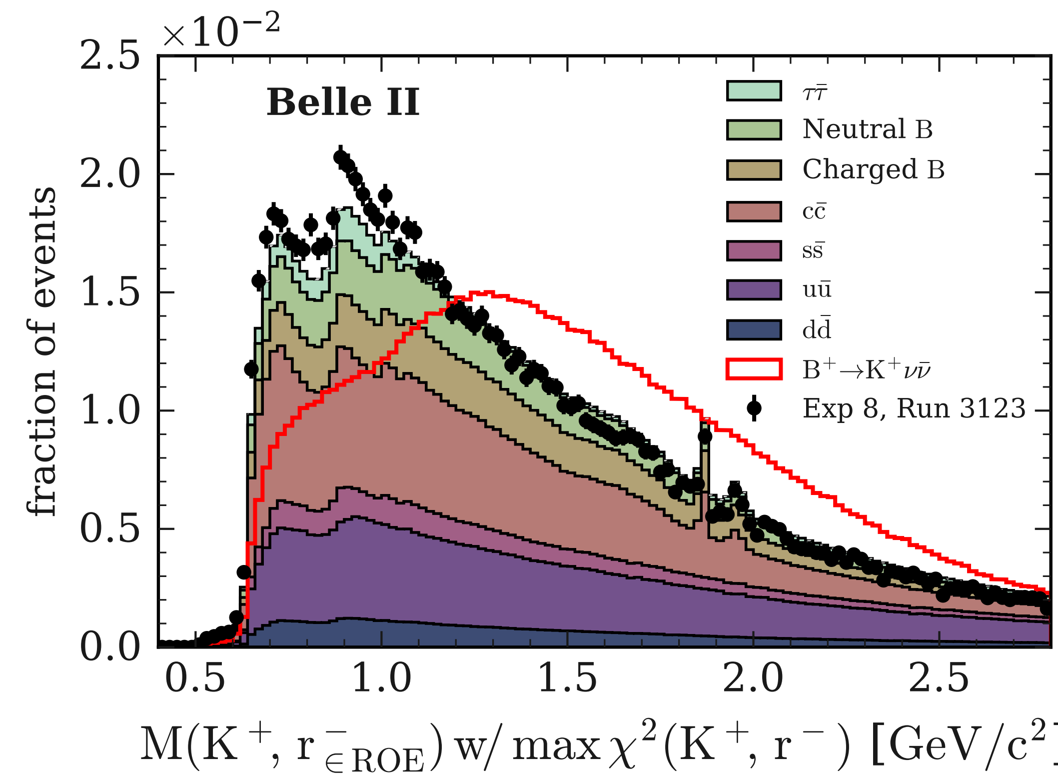


Input Variables: D0/D+ Suppression

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

BDT2>0.93



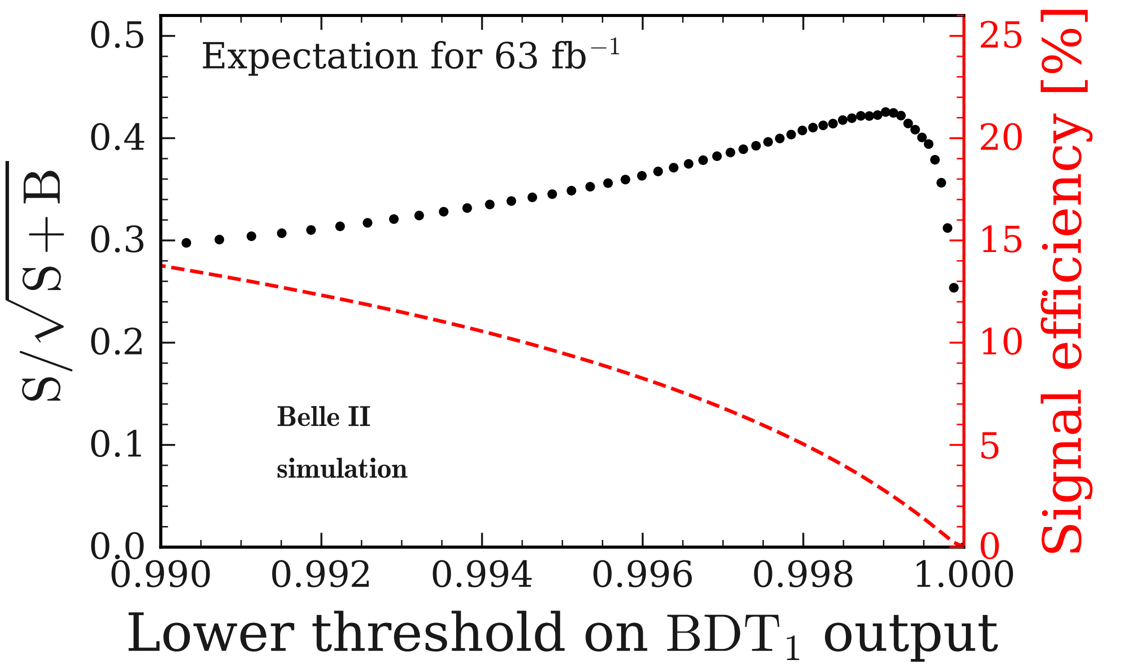


- **Significant fraction of background events for the high purity region comes from D0/D+ decays**
  - Dedicated variables to identify them

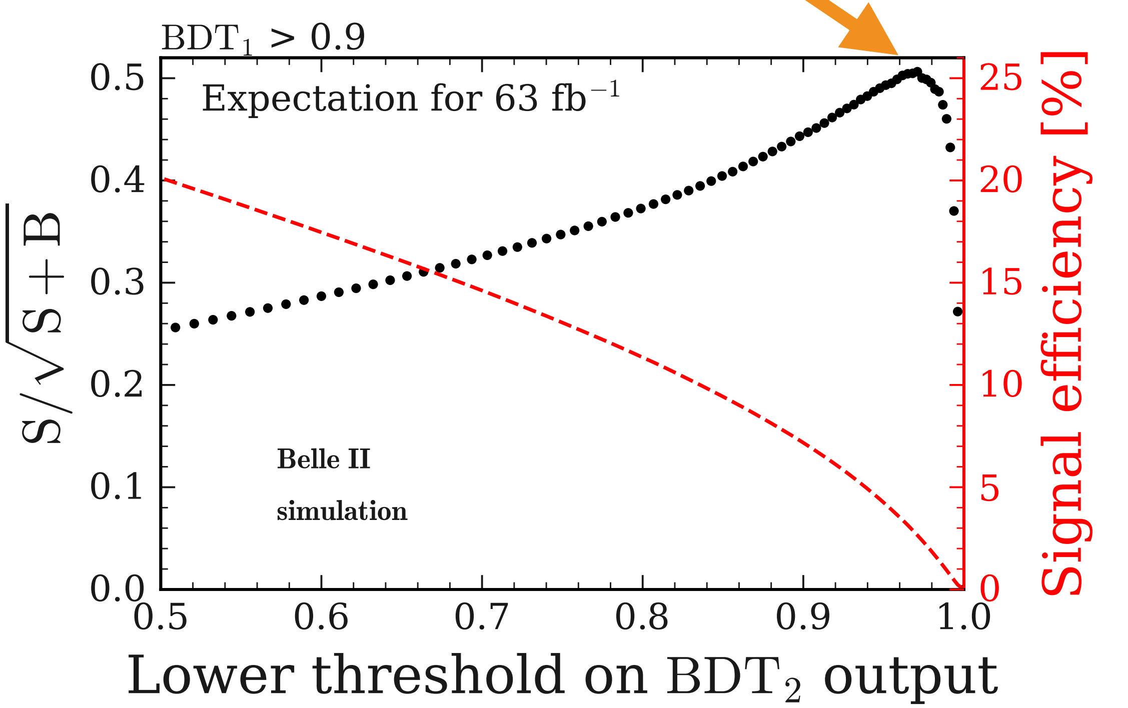
Boosting to Signal Region

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

- **2-step procedure**: increase training statistics at high BDT values
  - Select events with $\mathrm{BDT}_1 > 0.9$ and train BDT_2 with larger sample (same training variables)
  - Significant improvement in discrimination power
- Overfitting under control for both BDTs
- **Additional BDT used to correct modelling of continuum simulation**
  - BDT trained to distinguish off-resonance data from continuum simulation (and derive weights)
  - Same input variables as other BDTs



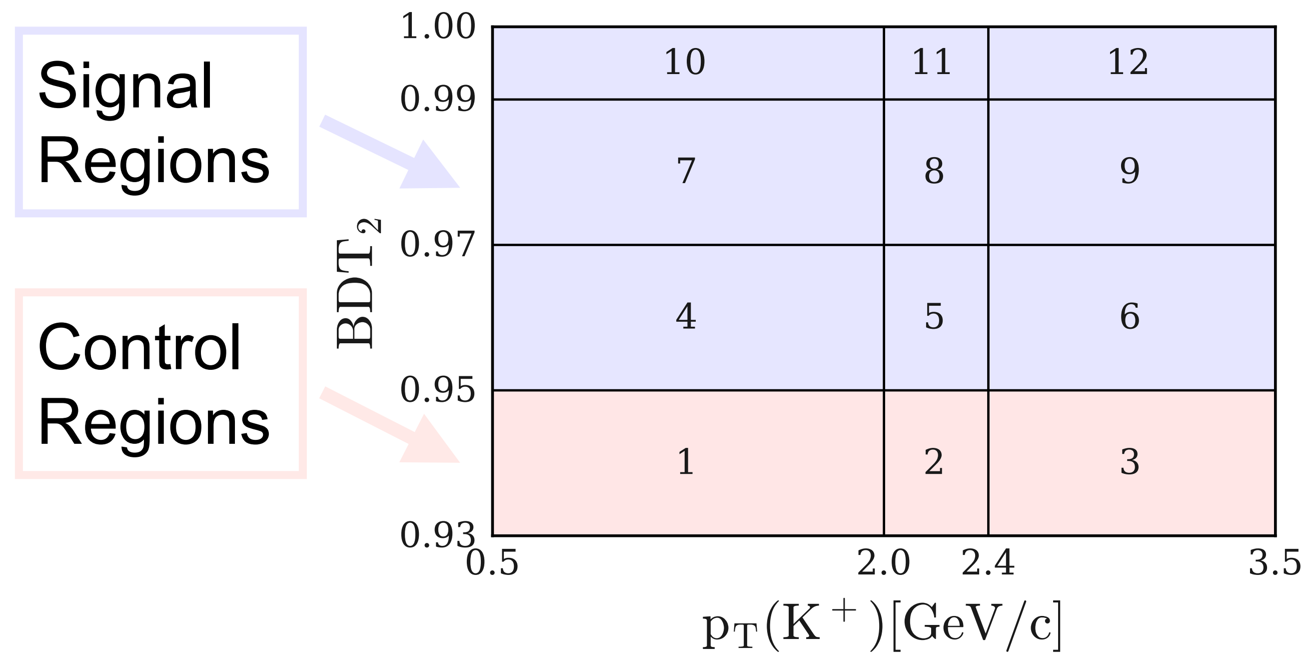
Maximum sensitivity at $\mathrm{BDT}_2 \approx 0.95$



Definition of Signal and Control Regions

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

- **Define 24 Signal and Control Regions:**
  - 12 regions in $\mathrm{BDT}_2 \times p_{\mathrm{T}}(K^{+})$ space
  - Each defined in on- and off-resonance data
  - 9 SRs and 3+12 CRs to constrain background yields
  - Binning optimised for available integrated luminosity
  - Signal efficiency of 4.3% (for SM)



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