HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Search for the rare electroweak decay $B^+ \to K^+ \nu\bar{\nu}$ in the early Belle II dataset

[2104.12624]

Cyrille Praz, *on behalf of the Belle II collaboration*

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Belle II talks at PHENO 2021

- Soumen Halder, *Results and Prospects of Radiative and Electroweak Penguin Decays at Belle (II)*, [link].
- Güney Polat, *Tau physics prospects at Belle II*, [link].
- Katharina Dort, *Dark-sector physics at Belle II*, [link].
- Sebastiano Raiz, *Charmless B decays at Belle II*, [link].
- Christoph Schwanda, *Beauty physics from Belle II*, [link].
- Chiara La Licata, *The re-discovery of the decays for the CP violation measurements*, [link].
- Cyrille Praz, *Search for the rare electroweak decay $B^+ \to K^+ \nu\bar{\nu}$ in the early Belle II dataset*, [link].

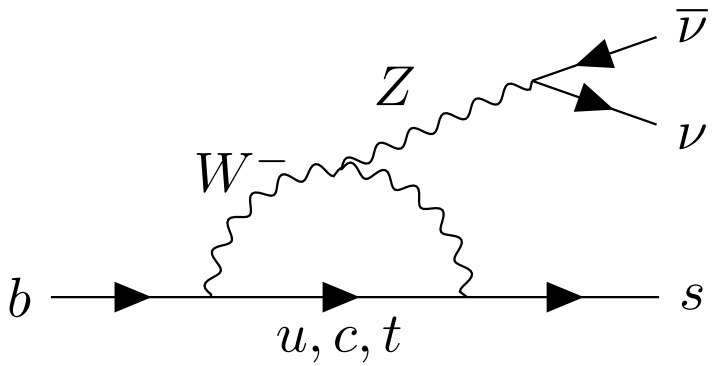
Outline

1. Theoretical motivation
2. The Belle II experiment
3. Search for $B^+ \to K^+ \nu\bar{\nu}$ decays
   - Introduction
   - Binary classification
   - Signal-strength extraction
4. Conclusion and outlook

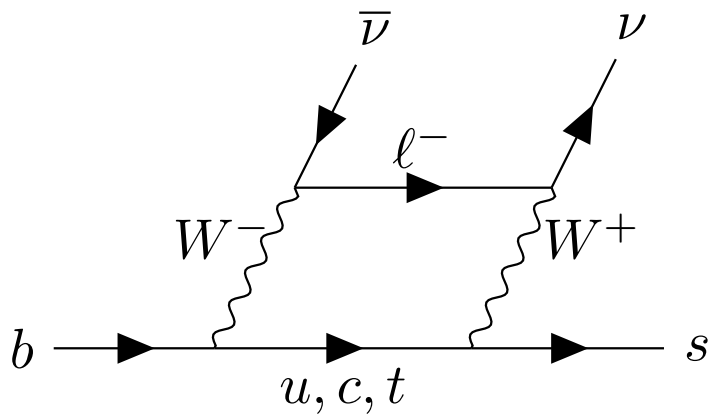
Lowest-order Standard Model diagrams for $b \to s\nu\bar{\nu}$

- $B^+ \to K^+\nu\bar{\nu}$ is suppressed in the SM and has never been observed.

- Loop



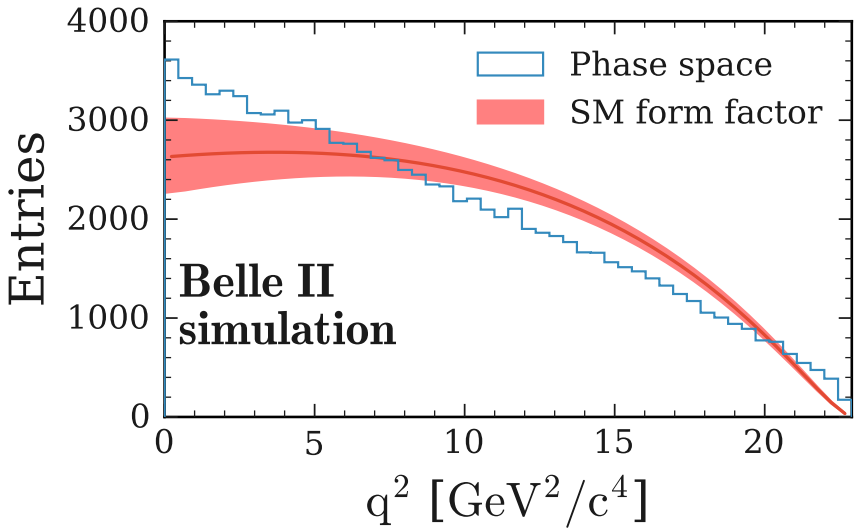
- Box



- Since ν_e, ν_μ and ν_τ contribute, this process is sensitive to potential lepton flavour universality violation.

Branching fraction in the Standard Model

- Standard Model (SM) prediction:
  - $\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{SM}} = (4.6 \pm 0.5) \times 10^{-6}$ [1606.00916].
  - 10% theoretical uncertainty mainly from $B \to K$ form factors.
- $B \to K$ form factors taken from [1409.4557] used for signal simulation.



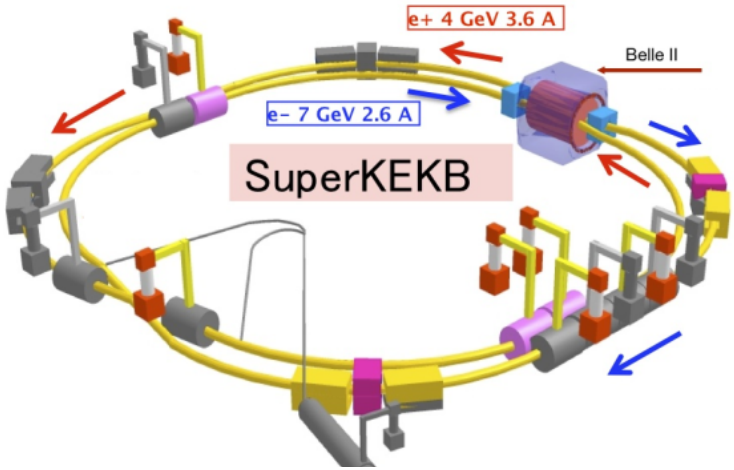
Beyond the Standard Model

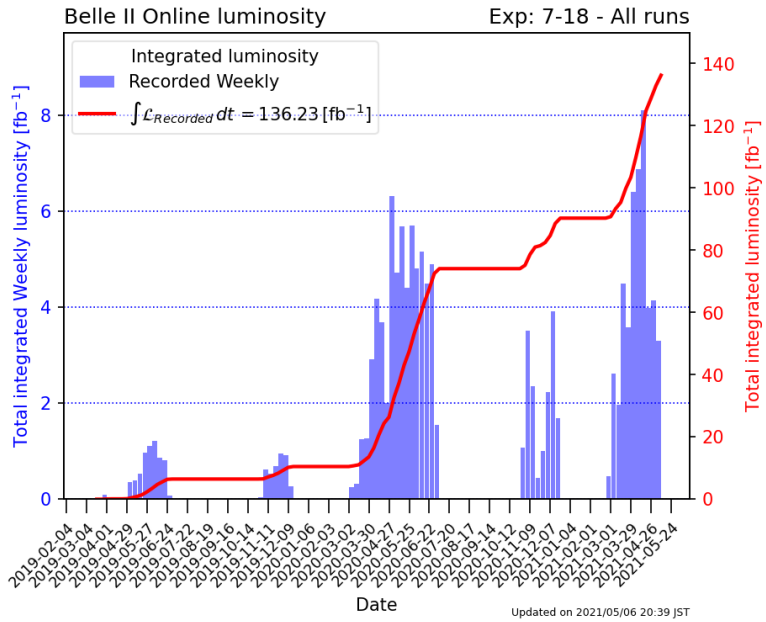
- Multiple models beyond the SM constrained by $\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})$:
  - leptoquarks [1806.05689].
  - axions [2002.04623].
  - dark matter particles [1911.03490].
  - ...

Outline

The SuperKEKB accelerator

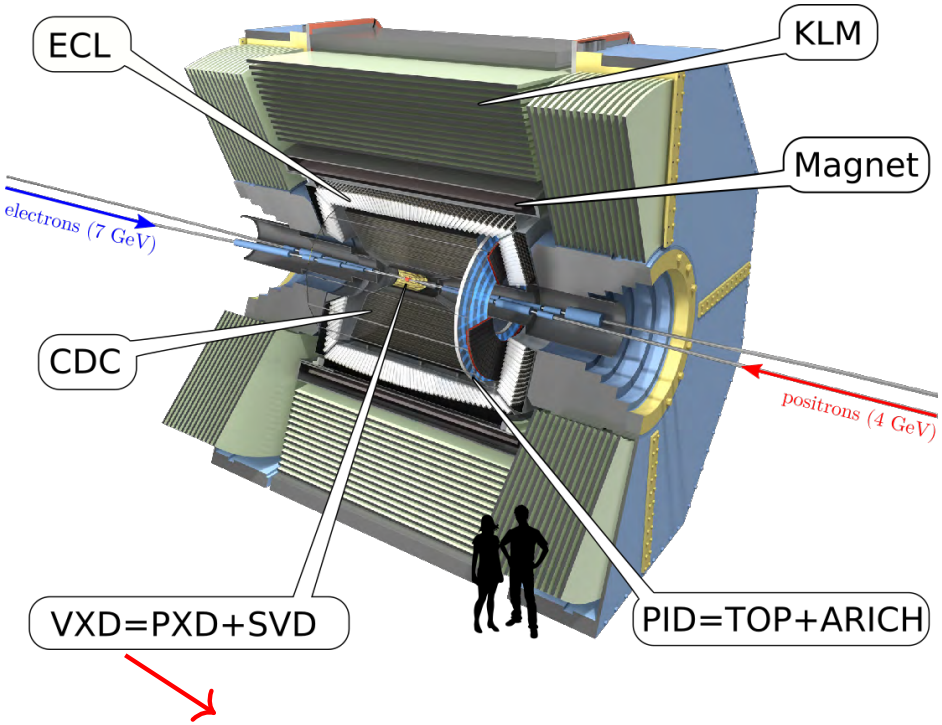
- e^+e^- collider in Tsukuba, Japan.
- $\sqrt{s} = 10.6\,\mathrm{GeV} = \mathrm{m}(\Upsilon(4S))$.
- $\mathrm{BR}(\Upsilon(4S) \to B\bar{B}) > 96\%$.
- $\int_{2019}^{\text{Summer 2020}} L\,\mathrm{dt} \approx 63\,\mathrm{fb}^{-1}$.
- World highest instant. luminosity.
  - $L = 2.4 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ achieved in June 2020.

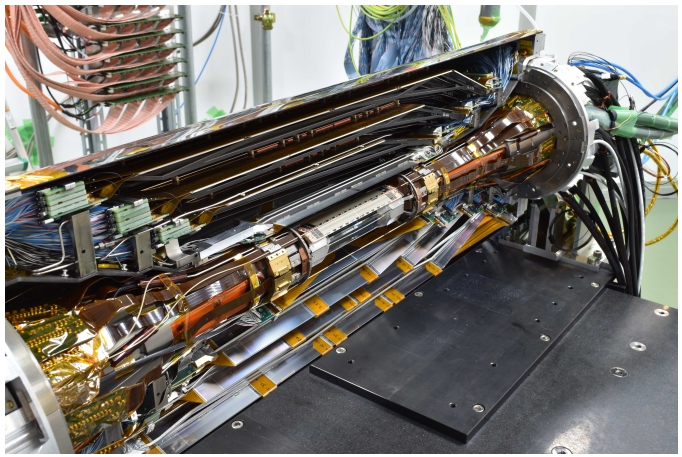




The Belle II detector

- Pixel Detector (PXD).
- Silicon Vertex Detector (SVD).
- Central Drift Chamber (CDC).
- Calorimeter (ECL).
- Aerogel Ring-Imaging Cherenkov (ARICH).
- Time-Of-Propagation (TOP) counter.
- K_L^0 and μ detection (KLM).





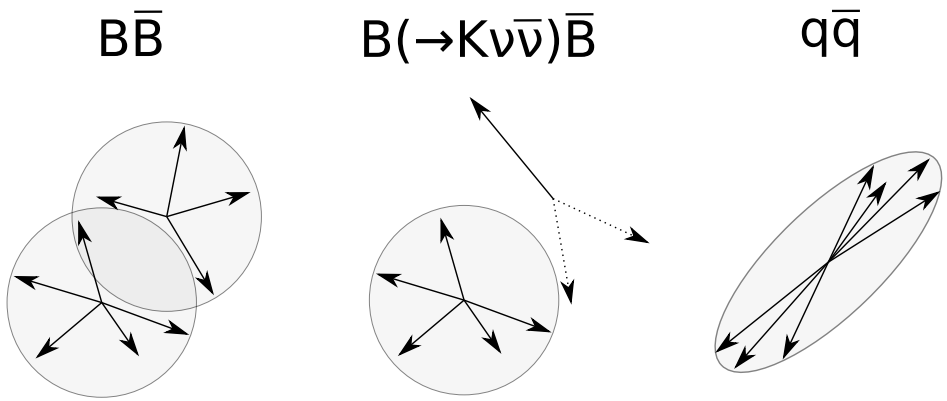
Outline

Data samples

- $63\,\text{fb}^{-1}$ collected at $\sqrt{s} = \text{m}(\Upsilon(4S))$ ("on-resonance").
- $9\,\text{fb}^{-1}$ collected at $\sqrt{s} = \text{m}(\Upsilon(4S)) - 60\,\text{MeV}$ ("off-resonance").

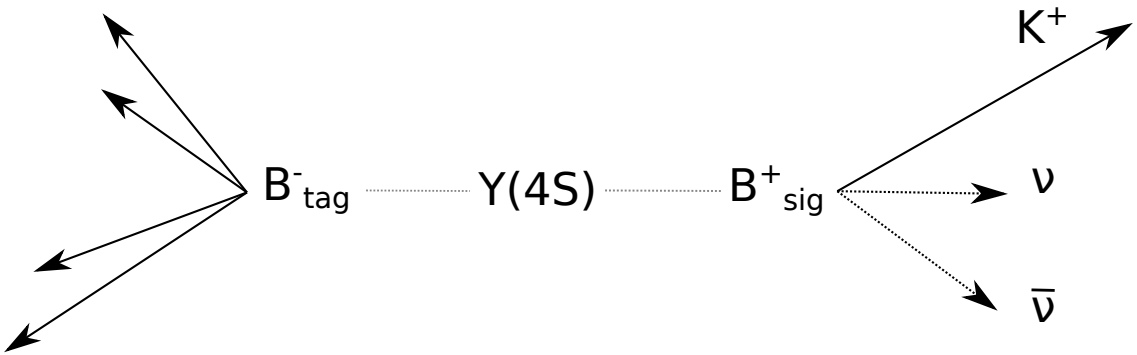
Signal and background after high-level trigger

- Signal.
  - $e^+e^- \to \Upsilon(4S) \to B^+(\to K^+\nu\bar{\nu})B^-$.
- Background.
  - Generic B-meson decays: $e^+e^- \to \Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0$.
  - Continuum events: $e^+e^- \to q\bar{q}$ or $\tau^+\tau^-$ ($q = u, d, s, c$ quarks).



B-meson tagging

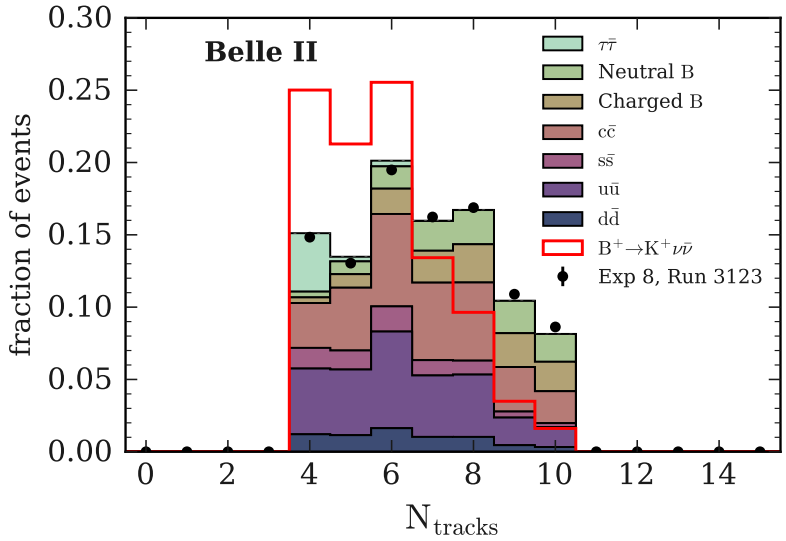
- Previous searches used tagged approaches, where the second B-meson is reconstructed...
  - ...in a hadronic decay: $\varepsilon_{\text{sig}} = \mathcal{O}(0.04\%)$ [1303.7465].
  - ...in a semileptonic decay: $\varepsilon_{\text{sig}} = \mathcal{O}(0.2\%)$ [1702.03224].

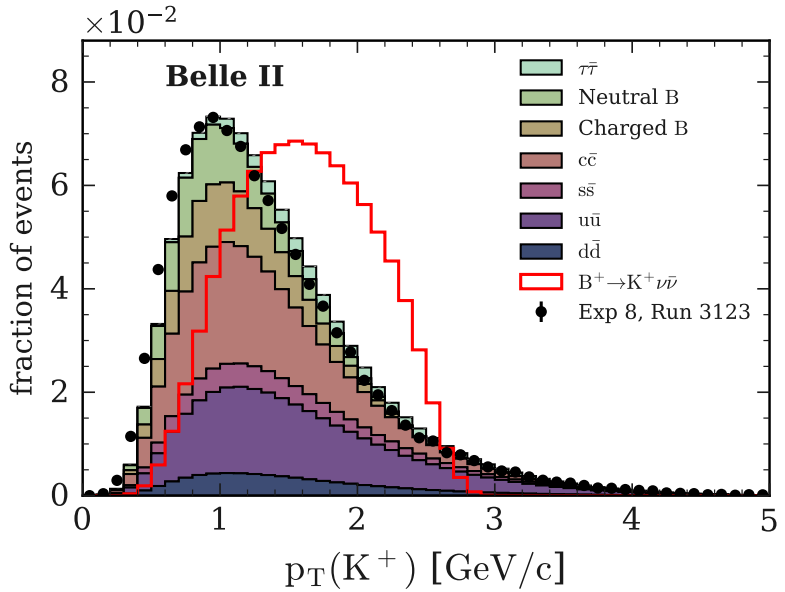


- In the following, an inclusive tagging approach is used.
  - No explicit reconstruction of the second B-meson.
  - Exploitation of the distinctive topological features of $B^+ \to K^+\nu\bar{\nu}$.

Signal kaon candidate selection and event pre-selection

- Basic track cleanup:
  - $p_T > 0.1\,\mathrm{GeV}/c$, $\theta \in$ CDC, $|dr| < 0.5\,\mathrm{cm}$, $|dz| < 3.0\,\mathrm{cm}$.
- Highest-p_T clean track in event as K^+ candidate.
  - Correct candidate in 80% of the cases.
  - # PXD hits ≥ 1.
  - PID requirement to suppress pion background.
- Loose preselection:
  - $4 \leq N_{\mathrm{tracks}} \leq 10$.
  - $0.3 < \theta(\mathbf{p_{miss}}) < 2.8\,\mathrm{rad}$.
  - $E_{\mathrm{visible}} > 4\,\mathrm{GeV}$.

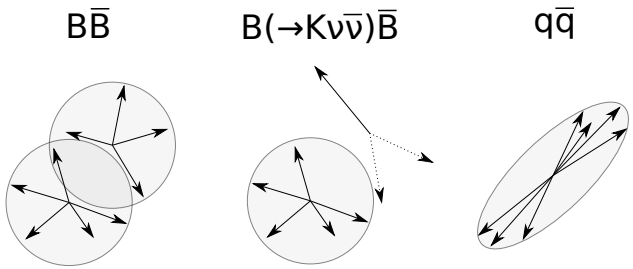


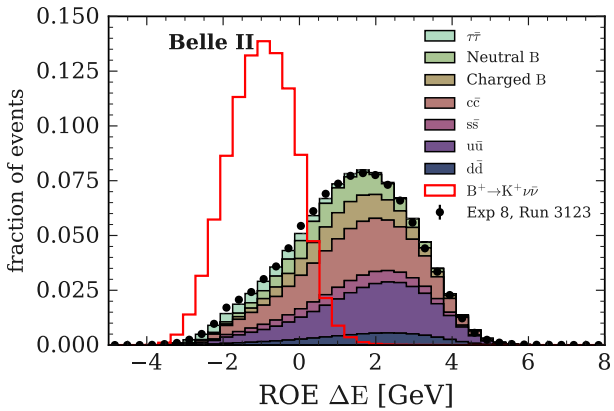


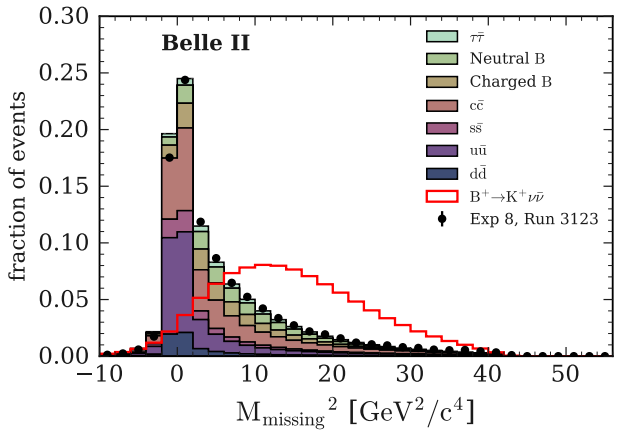
Outline

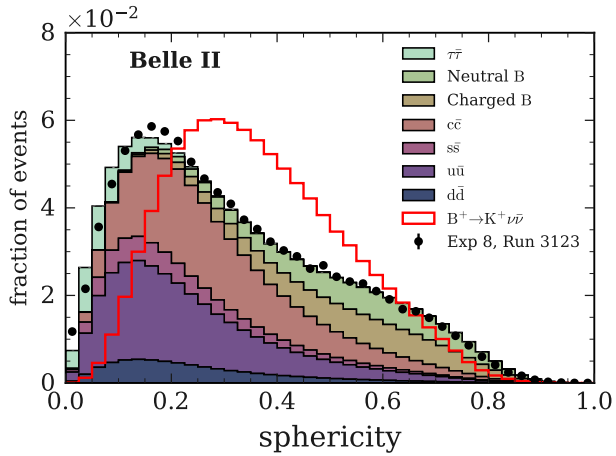
Features

- Boosted decision trees (BDT) [1609.06119] trained with 51 features.
  - Event topology (Fox-Wolfram moments, sphericity, ...).
  - Rest-of-event (ROE) variables.
  - Missing energy, momentum.
  - Vertex separation.
  - ...



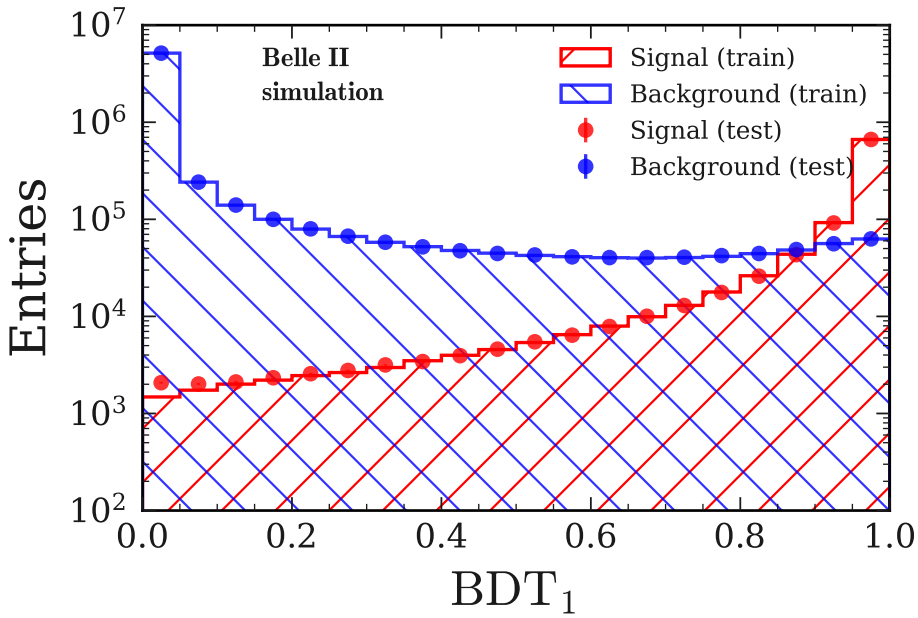


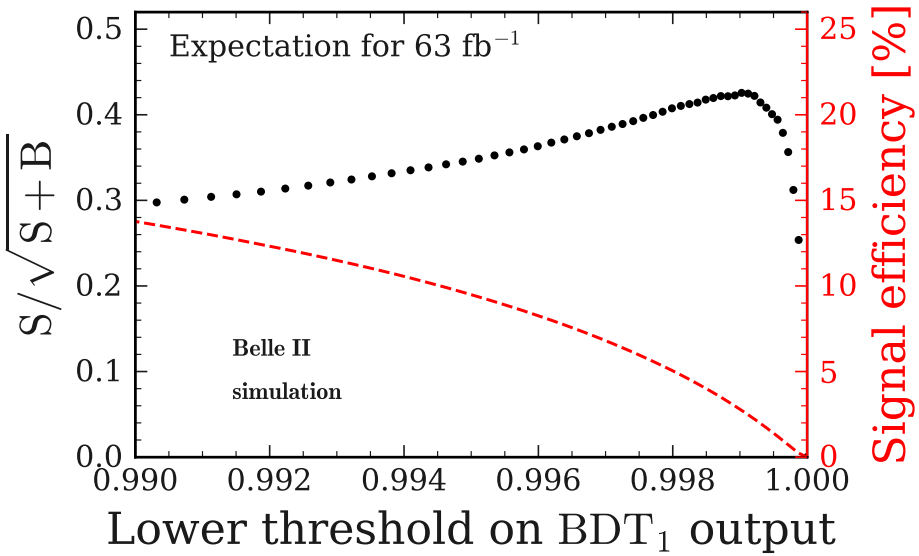




First binary classifier

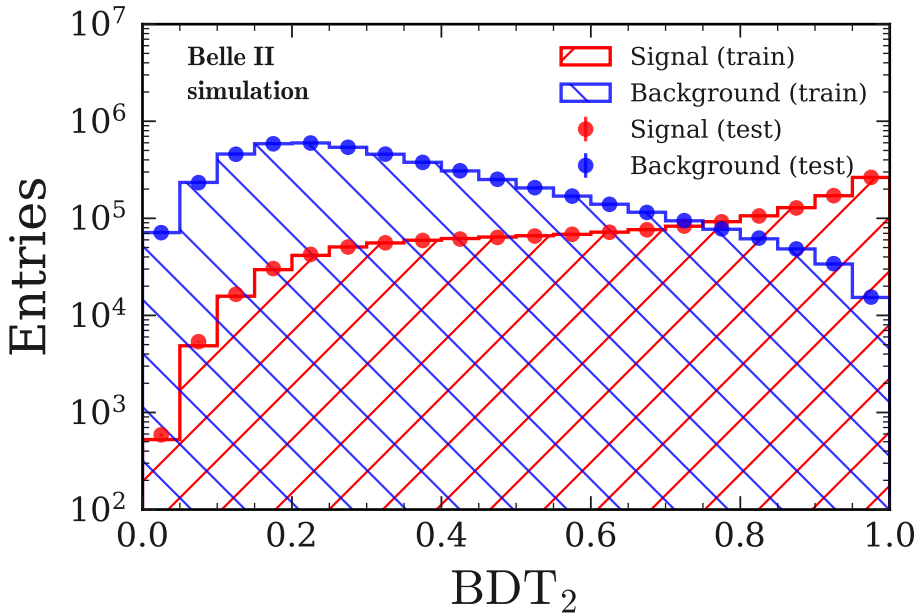
- Train BDT_1 on $\mathcal{O}(10^7)$ simulated events.
- Next step: increase the train sample size for high BDT_1 values.

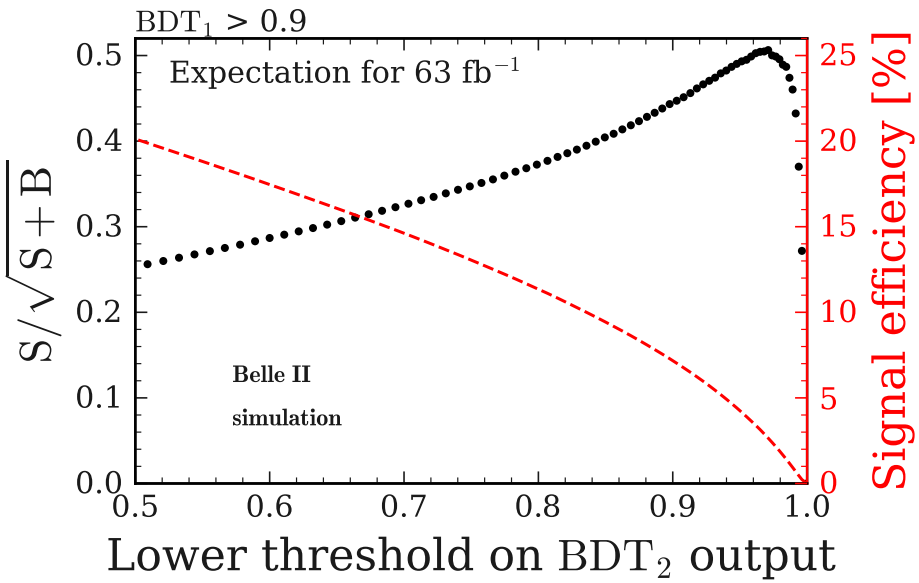




Second binary classifier

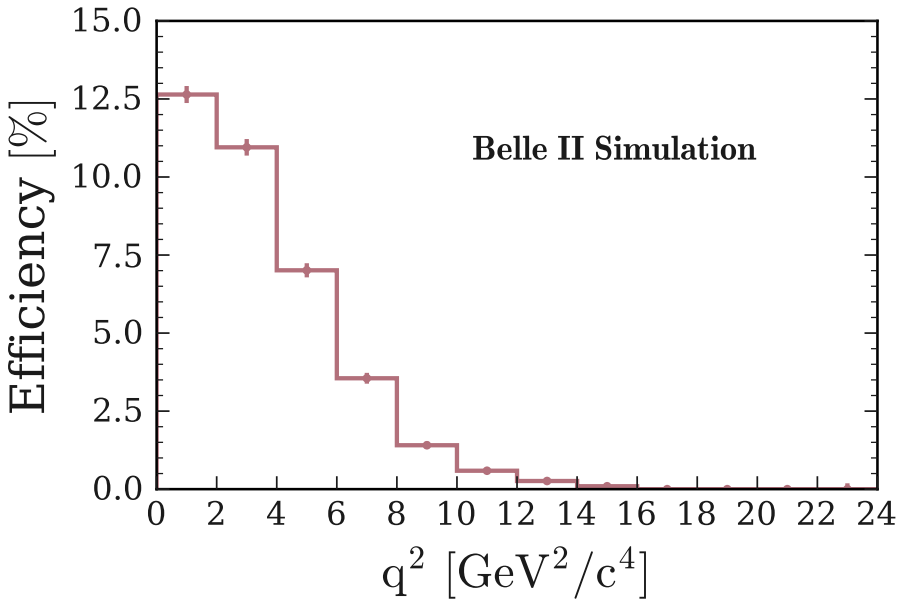
- Train BDT_2 on $\mathcal{O}(10^7)$ simulated events with $\mathrm{BDT}_1 > 0.9$.
- $\max(S/\sqrt{S+B})$ reached around $\mathrm{BDT}_2 > 0.95$.

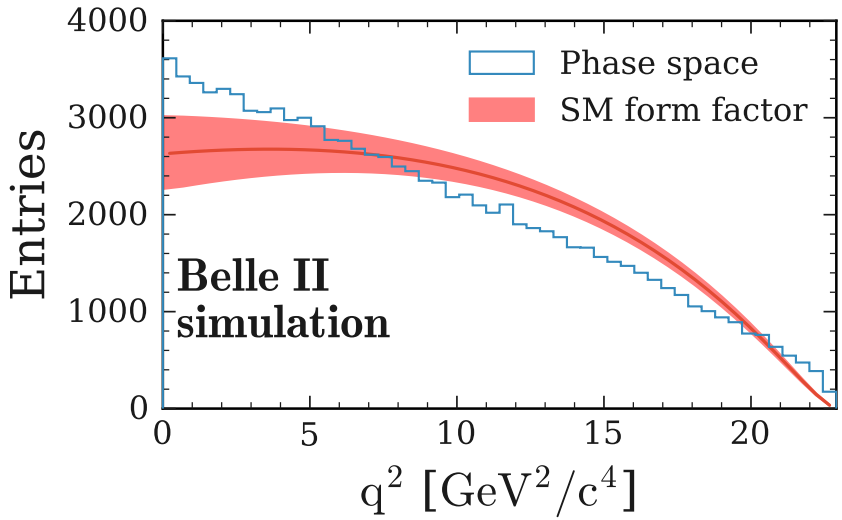




Signal efficiency at $\mathrm{BDT}_2 > 0.95$

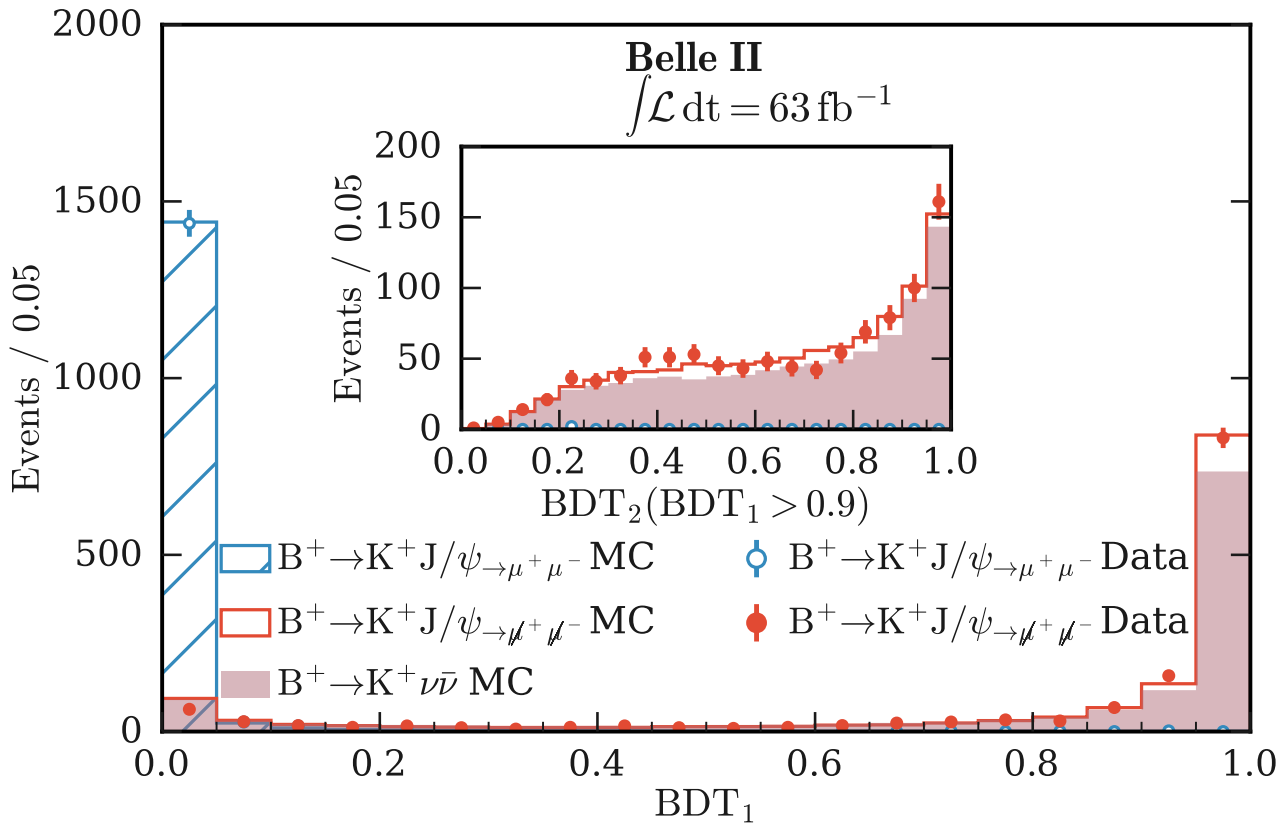
- At $\mathrm{BDT}_2 > 0.95$, the signal efficiency is 12.5% for $q^2 \approx 0$ and drops to zero for $q^2 > 16\,\mathrm{GeV}^2/c^4$.
  - Sensitive to potential light dark matter candidates.





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

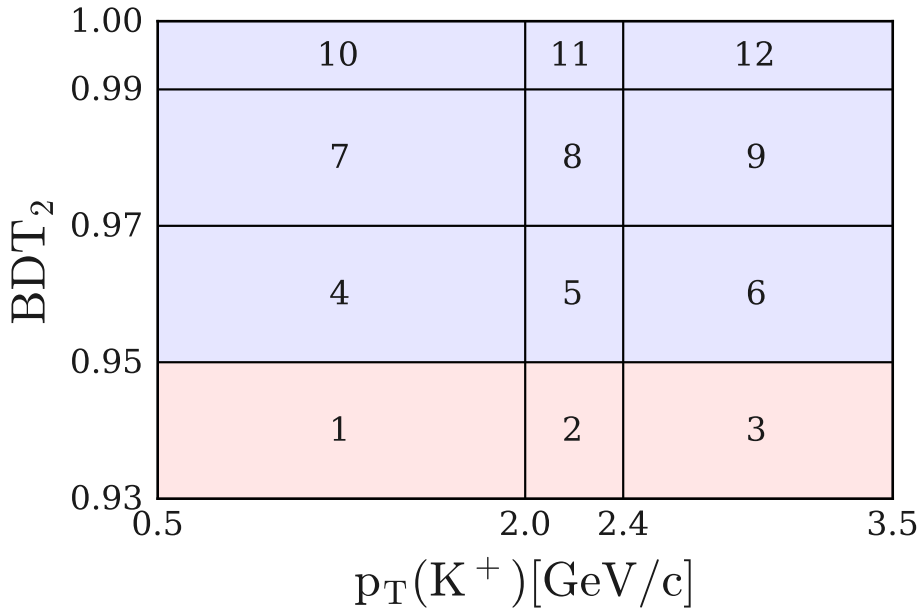
- To check the data-simulation agreement, $B^+ \to K^+ J/\psi (\to \mu^+ \mu^-)$ decays are selected.
  - Muons are removed from the reconstruction to mimic the signal.
  - Kaon 3-momentum is sampled from simulated signal events.



Outline

Statistical model

- Binned likelihood defined in the $\mathrm{BDT}_2 \times p_\mathrm{T}(K^+) \times \sqrt{s}$ space.
- $4 \times 3 \times 2 = 24$ bins.
  - $\mathrm{BDT}_2 \in [0.93, 0.95, 0.97, 0.99, 1.00]$.
  - $p_\mathrm{T}(K^+) \in [0.5, 2.0, 2.4, 3.5]\,\mathrm{GeV}/c$.
  - $\sqrt{s} \in \{\mathrm{m}(\Upsilon(4S)), \mathrm{m}(\Upsilon(4S)) - 60\,\mathrm{MeV}/c^2\}$.



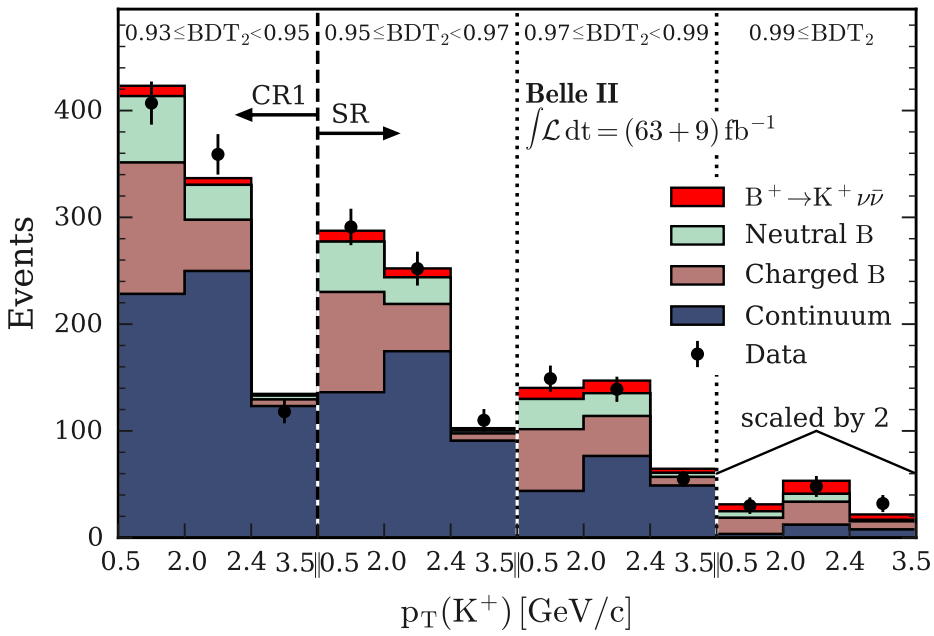
Statistical model

- Likelihood function = product of Poisson probability density functions combining the information from the 24 bins.
  - Templates for the yields of the signal and background derived from simulation.
  - Implementation in the pyhf package, maximum-likelihood fit using scipy.
- Fit parameters:
  - Signal strength μ (factor w.r.t. SM expectation for signal yield).
  - Nuisance parameters to include the systematic uncertainties *via* event-count modifiers.
    - Main systematic source: background yield normalisation.

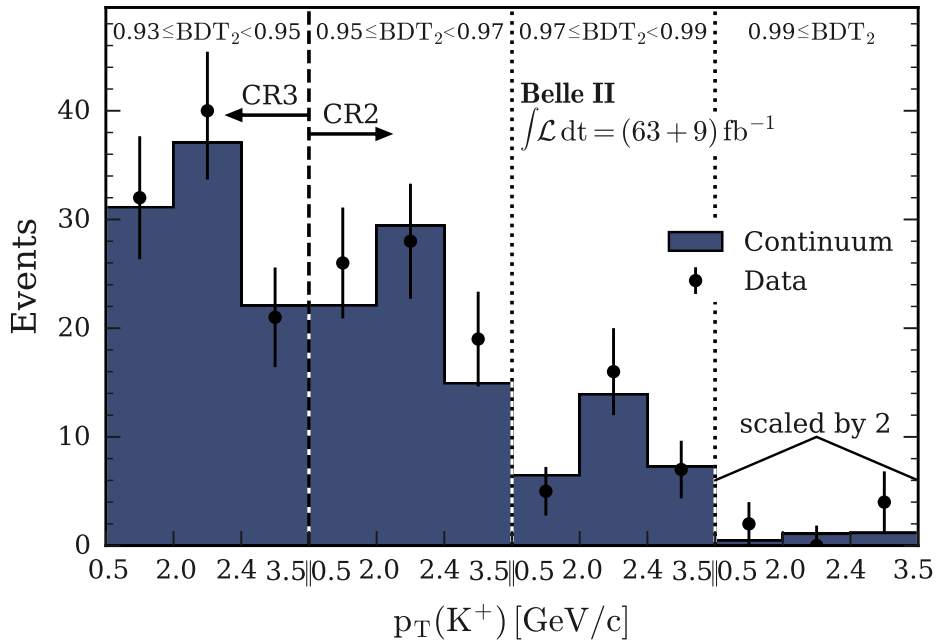
Fit to data

- Maximum-likelihood fit to 24 bins of the $\mathrm{BDT}_2 \times p_\mathrm{T}(K^+) \times \sqrt{s}$ space.

- On-resonance.

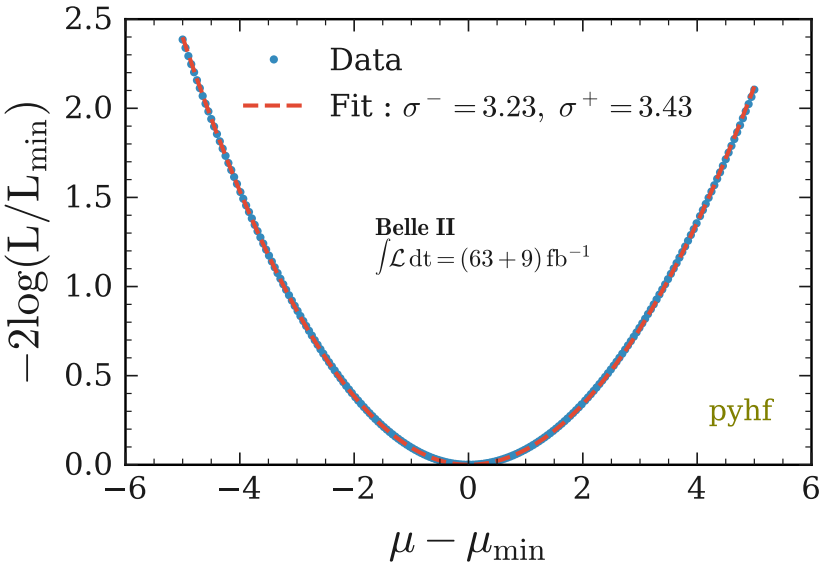


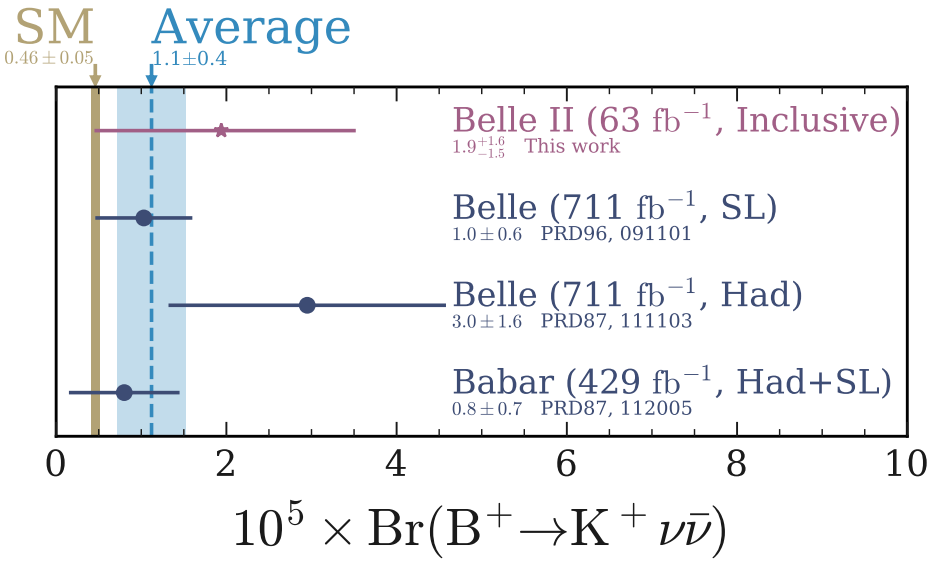
- Off-resonance.



Result

- $\mu = 4.2^{+3.4}_{-3.2} = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst})$.
- $\text{BR}(B^+ \to K^+\nu\bar{\nu}) = \left[1.9^{+1.6}_{-1.5}\right] \times 10^{-5} = \left[1.9^{+1.3}_{-1.3}(\text{stat})^{+0.8}_{-0.7}(\text{syst})\right] \times 10^{-5}$.

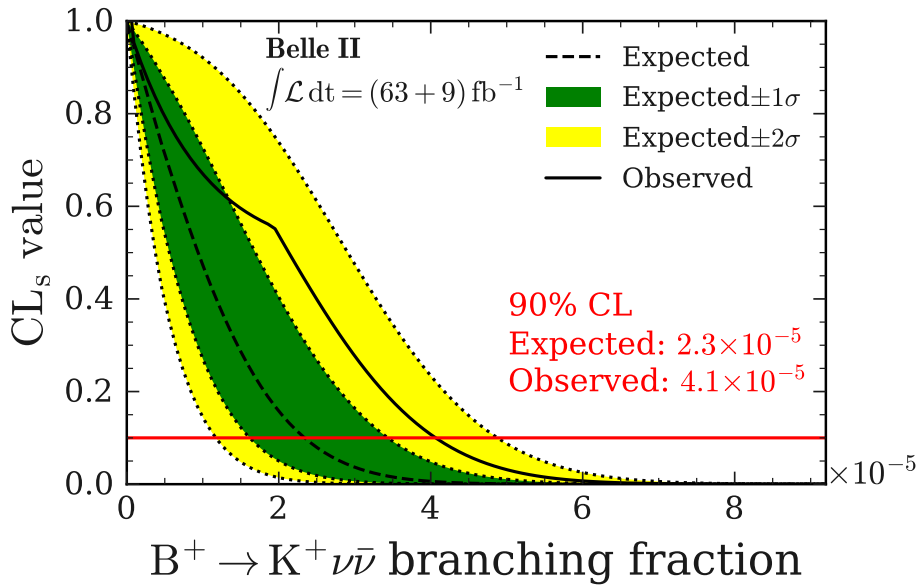




- Total uncertainty on μ: profile likelihood scan, fitting the model with fixed values of μ while keeping the other fit parameters free.

Limit setting

- Expected and observed upper limits on the branching fraction are determined using the CLs method.



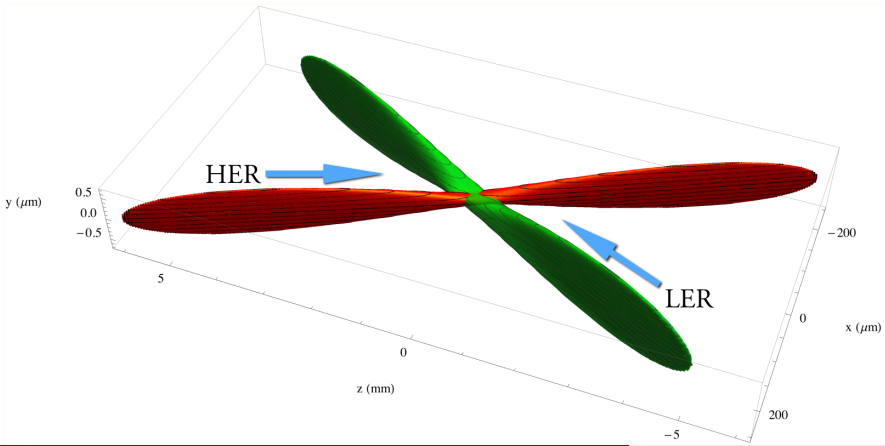
Conclusion and outlook

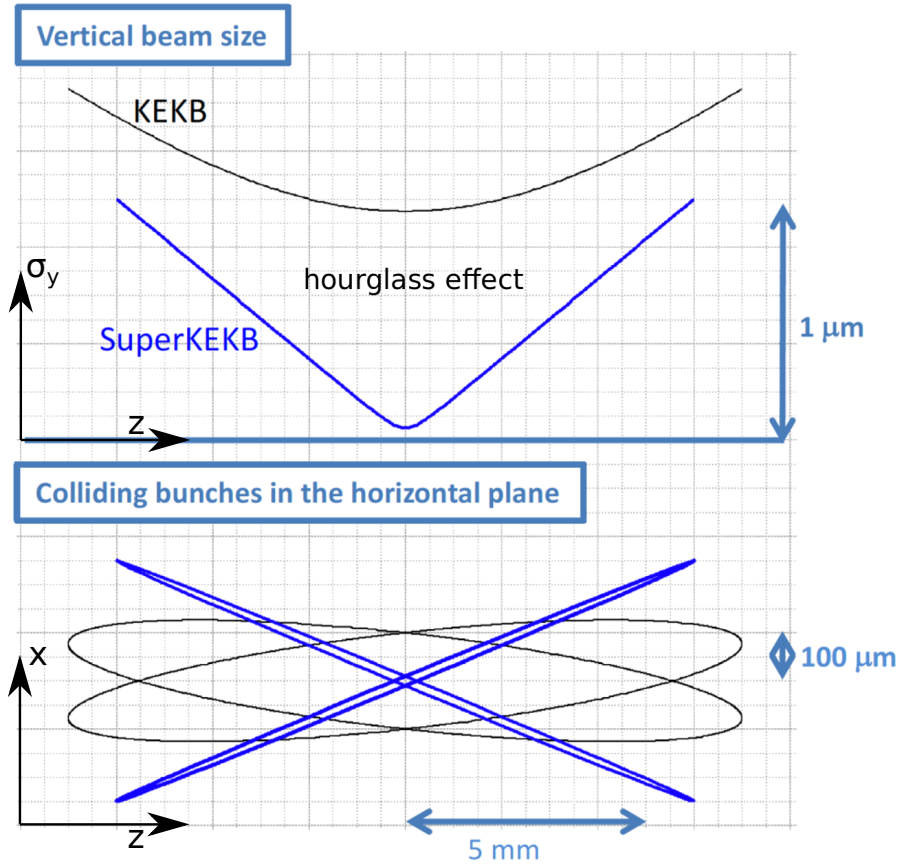
- Search for $B^+ \to K^+ \nu\bar{\nu}$ decays with an inclusive tagging approach was performed at Belle II with $(63 + 9)\,\mathrm{fb}^{-1}$ of data.
- $\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu}) = \left[1.9^{+1.6}_{-1.5}\right] \times 10^{-5}$.
- Pre-print version of the article available [2104.12624].
- Next iteration of the analyis will include:
  - More data.
  - More channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K^0_S \nu\bar{\nu}$, ...).
  - More classifiers (neural networks).

Thank you for your attention!

Nano-beam scheme (idea from Pantaleo Raimondi)

- Goal: $\beta_y^* = 0.3\,\mathrm{mm}$.
- Hourglass effect limited if $\sigma_z^{eff} < \beta_y^*$.
- Half crossing angle:
  - $\phi_x \approx 40\,\mathrm{mrad}$.
- Nominal beam spot parameters:
  - $\sigma_x \approx 10\,\mu\mathrm{m}$.
  - $\sigma_z^{eff} = \frac{\sigma_x}{\sin\phi_x} \approx 0.25\,\mathrm{mm}$.
  - $\sigma_y \approx 50\,\mathrm{nm}$.

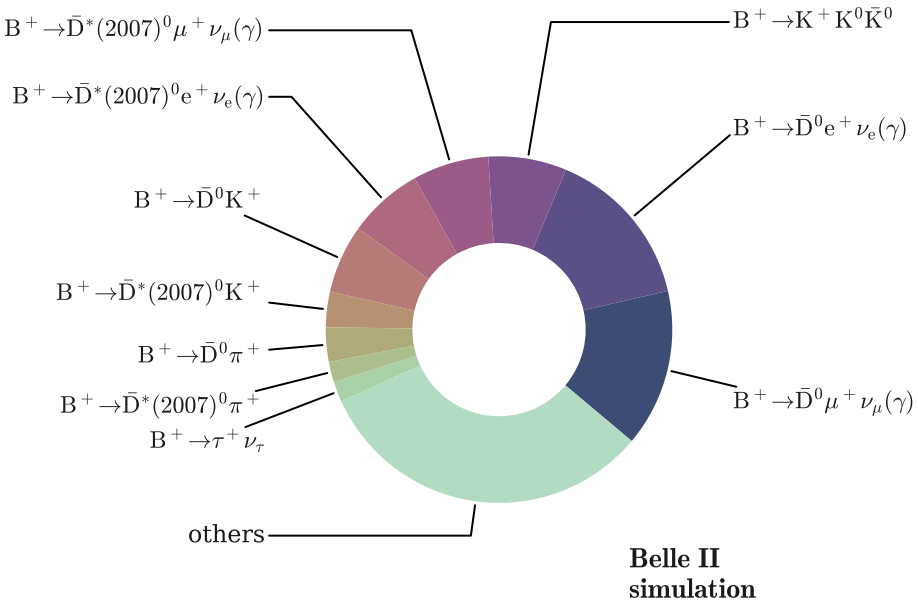


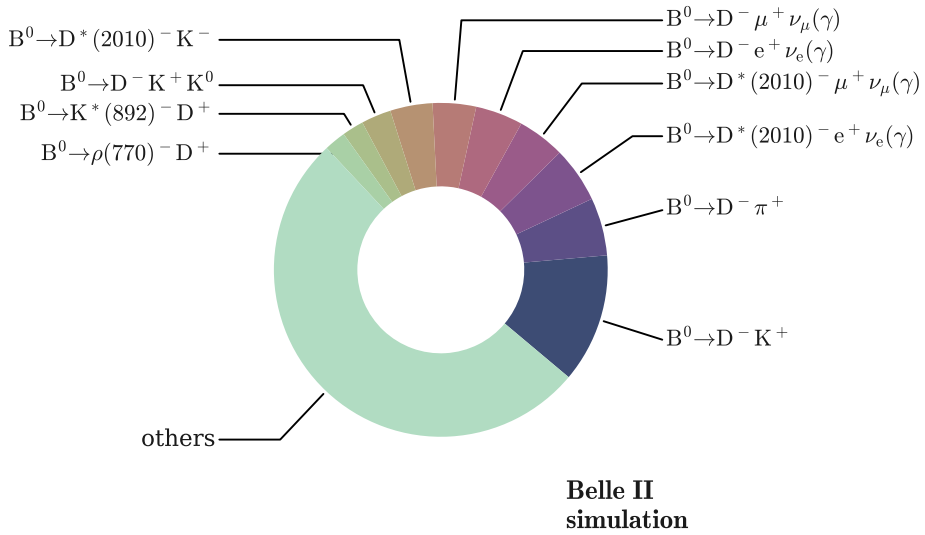


[BELLE2-TALK-CONF-2018-142]
[1809.01958]

Background composition at $\mathrm{BDT}_2 > 0.93$

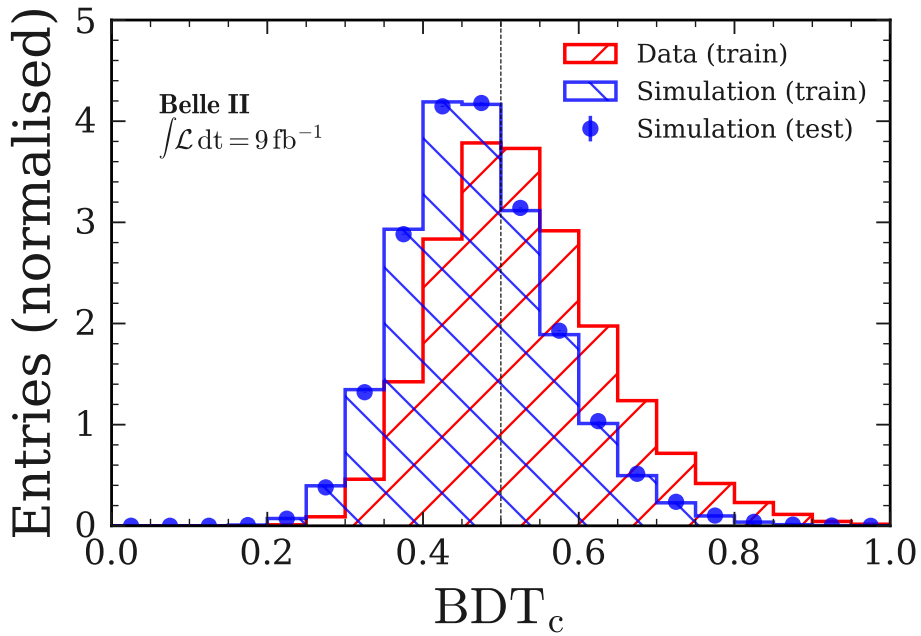
- At $\mathrm{BDT}_2 > 0.93$, D-mesons contribute a lot to the remaining background from B-meson decays.





Simulation reweighting using a classifier [doi:10.1088/1742-6596/368/1/012028]

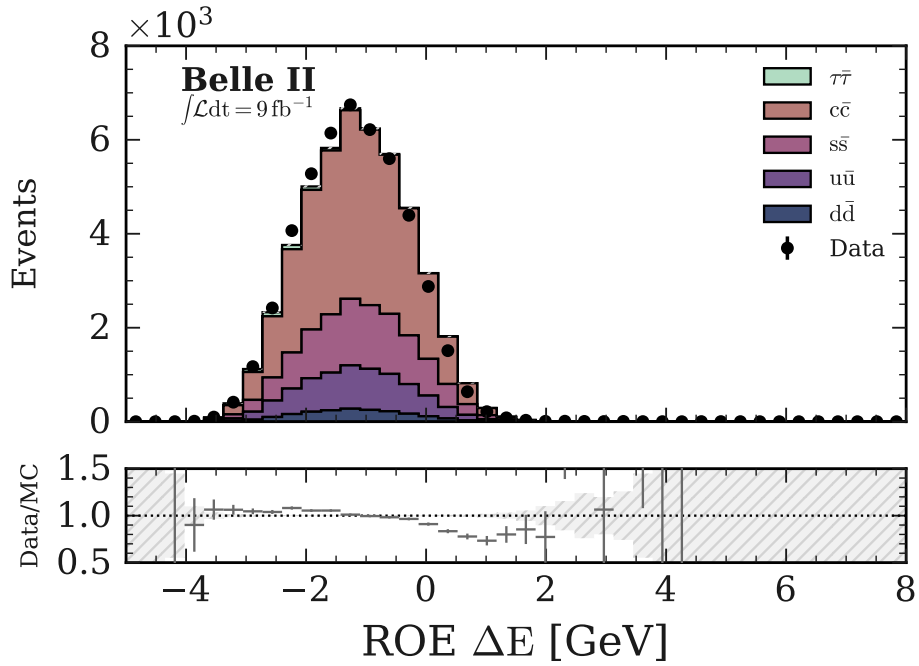
- Data-driven method to correct mismodeling in simulation.
  1. Train a binary classifier ($\mathrm{BDT_c}$) to distinguish simulation *vs* data.
  2. Given the output p of $\mathrm{BDT_c}$, the simulated events are weighted according to $p/(1-p)$.



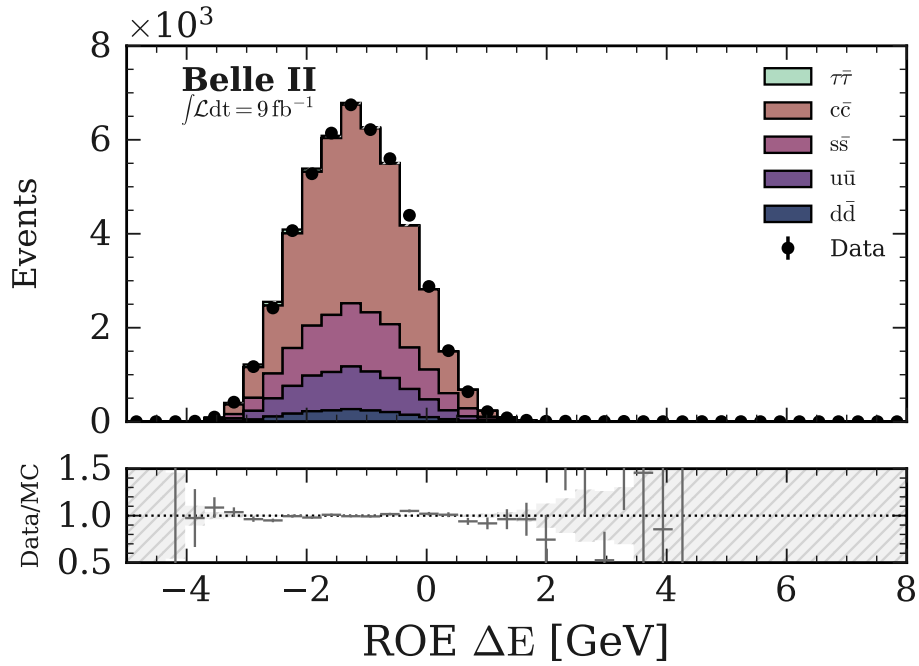
Simulation reweighting using a classifier [doi:10.1088/1742-6596/368/1/012028]

- This reweighting procedure improves the data-simulation agreement for off-resonance data.

Before reweighting:



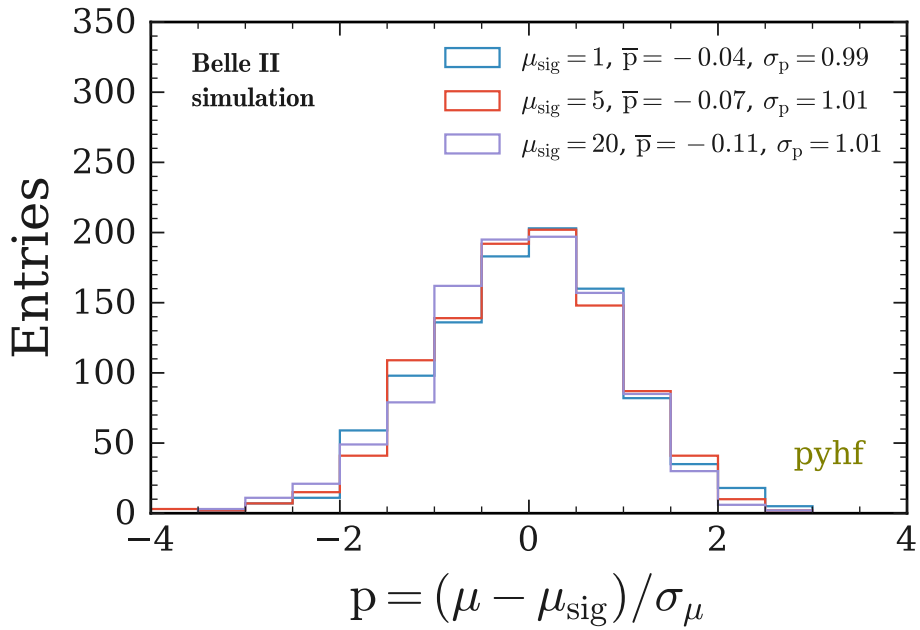
After reweighting:



Fit validation

- Toys generated for the simulated data set.
  - Poisson statistical fluctuations.
  - Gaussian systematic fluctuations.

- Signal injection study, $\mu_{\text{sig}} \in \{1, 5, 20\}$.



- Data-model compatibility.