JENNIFER3 Kickoff Meeting

Study of $B^+ \to K^+ \nu\bar{\nu}$ with inclusive tag in Belle

A. Basith, G. Inguglia, **N. Maslova**

nadiia.maslova@oeaw.ac.at

27/01/2025

European Research Council
Established by the European Commission

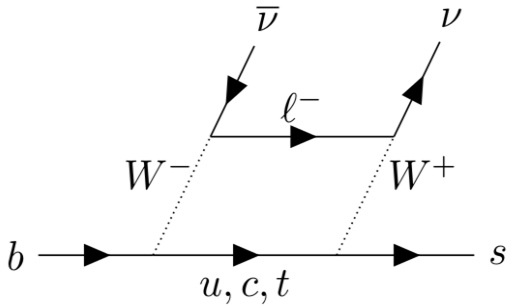
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

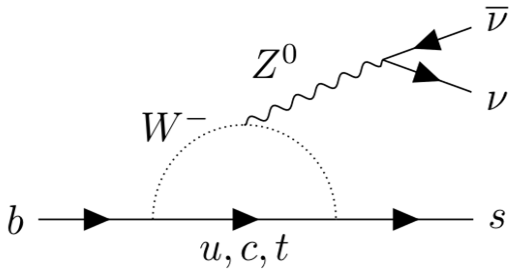
Introduction

- Flavour changing neutral current $b \to s\nu\bar{\nu}$ transitions offer powerful probe of SM
  - Occur only at loop level → highly suppressed
  - Absence of charged leptons in final state → clean theoretical predictions

- Highly sensitive to any possible new physics contributions
  - Mediators in loops or new tree level diagrams
  - Sources of missing energy (i.e. s+DM)

SM: BR($B^+ \to K^+\nu\nu$) = 5.58 ± 0.38x10^{-6} [2207.13371]





Introduction

Previous Belle searches:

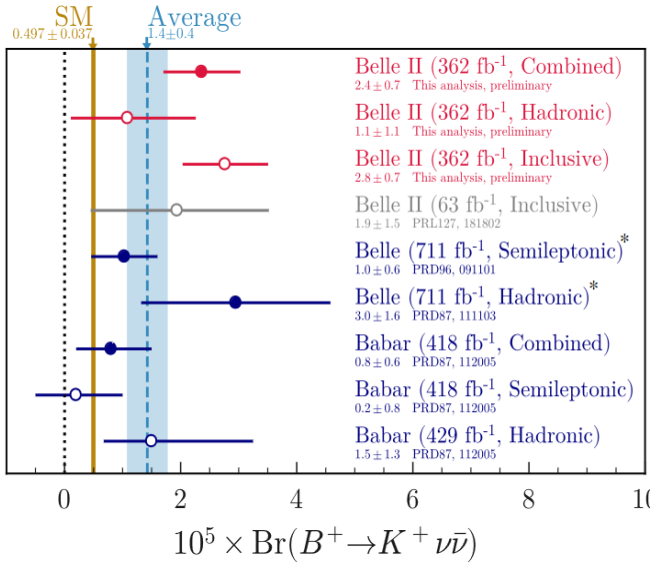
- Hadronic tagged analysis - BR($B^+ \to K^+ \nu\nu$) = 3.0±1.6x10^{-5}
- Semileptonic tagged analysis - BR($B^+ \to K^+ \nu\nu$) = 1.0±0.6x10^{-5}

Belle (**711 fb^{-1}**)
uncertainty: 0.5x10^{-5}

$\sqrt{L}$

Increase in luminosity could see comparable uncertainty to Belle semileptonic analysis

Belle II (**362 fb^{-1}**)
Incl. uncertainty: 0.7x10^{-5}

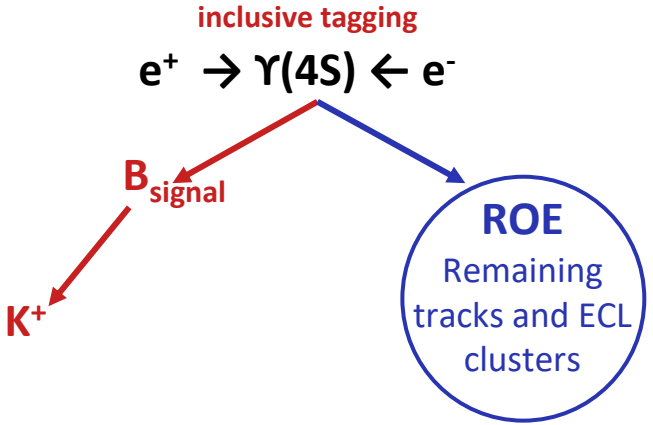


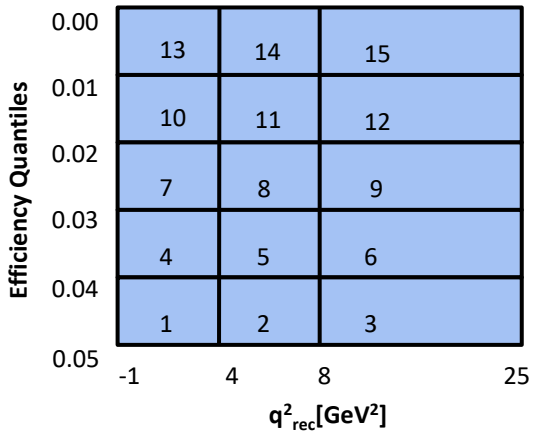
Analysis overview

- Selection of $B^+ \to K^+ \nu\nu$ is challenging due to small branching fractions and missing energy from neutrinos
- Use inclusive tagging - signal Kaon + rest of event made of remaining tracks and clusters
- Main steps:
  - Selection of Kaon candidate and some basic event selection criteria
  - Background suppression with 2 BDT classifiers
  - Validation studies of signal efficiency and background modelling
  - 2D binned maximum likelihood fit for extraction of signal strength:

$$\mu = \frac{\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})}{\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})_{\mathrm{SM}}}$$

  - On-resonance and off-resonance channels used, fit to 1% eff. Quantile vs. 3 q^2 bins
- Similar general analysis outline as Belle II study -> independent MC samples and validation

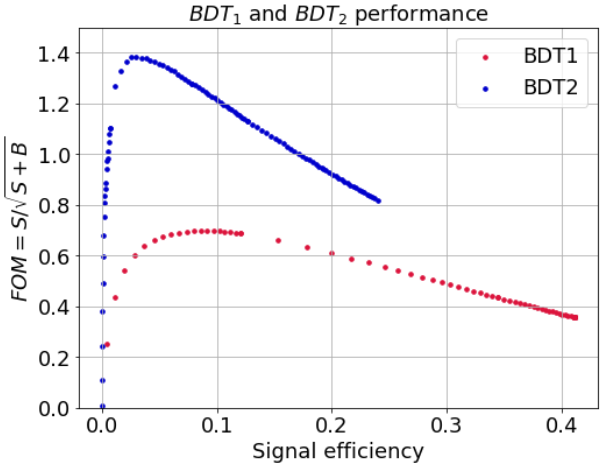


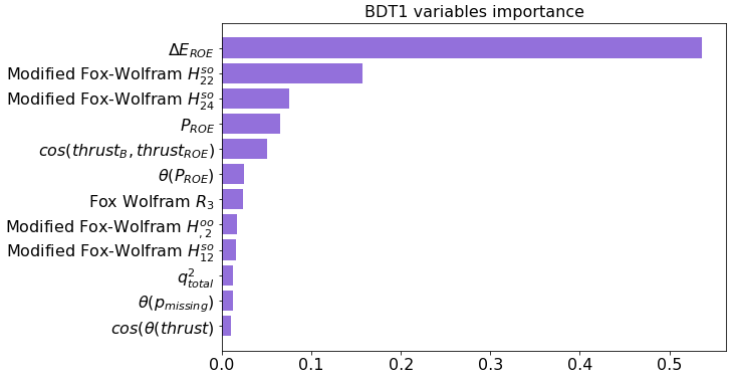


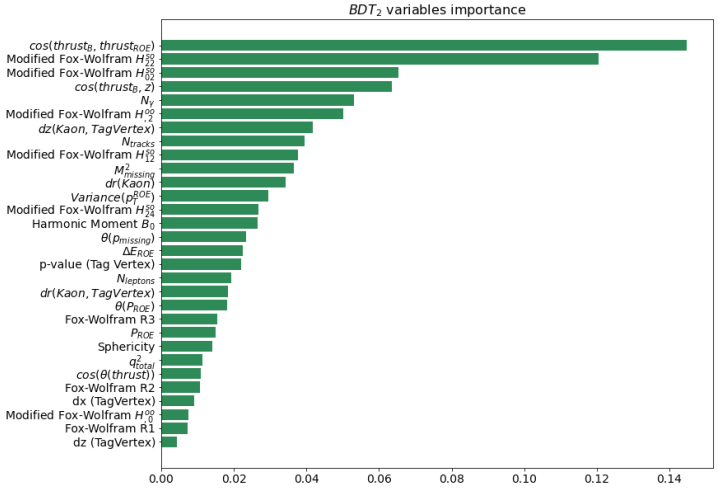
Selection

1. **BDT_1**
   a. Trained on sampled 5% of available generic MC (continuum, BBbar, low-multiplicity samples) and dedicated signal sample
   b. 12 input variables - main separation power from ROE ΔE, roe P and Fox-Wolfram $H_{m,2}$
   c. Cuts out large bulk of clear backgrounds (continuum processes)

1. **BDT_2**
   a. Same 12 variables + 18 more
   b. Much stronger signal selection ability - highest purity region selected for fitting
   c. Trained on sampled 10% of generic MC after BDT1 (continuum, BBbar, low-multiplicity samples) and dedicated signal sample



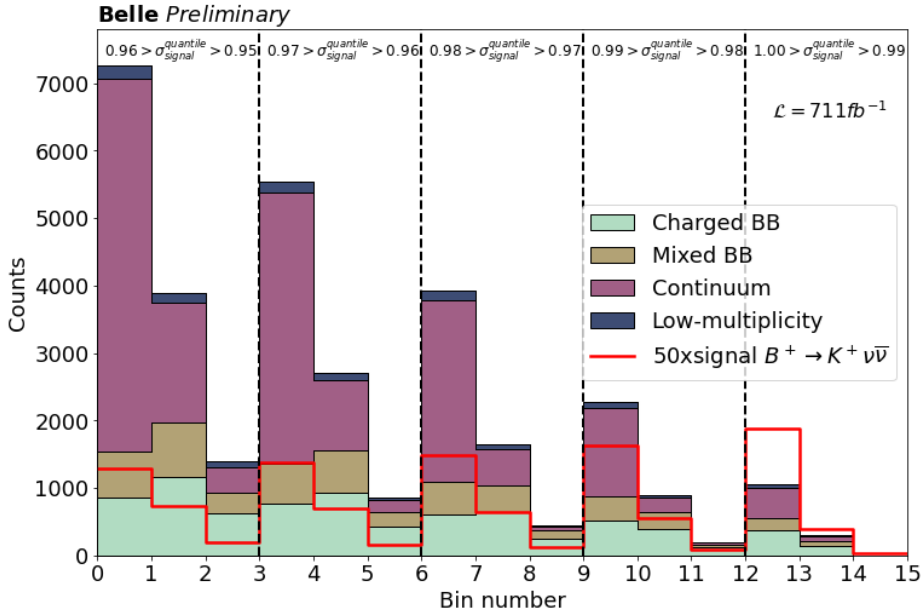




Background composition

- Large amount of continuum in less sensitive bins
- In $B\bar{B}$: **B→D$^{(*)}$lν** backgrounds most dominant in 5% signal efficiency region, affected by D→K^0_L mismodelling in MC
- **$B^+ \to K^+K^0K^0$** and **$B^+ \to K^+nn$** - modelled in generic MC according to phase-space assumptions, corrections for branching fractions are then applied

Decay	Fraction, %
1. $B^+ \to \overline{D}^0 \mu^+ \nu_\mu$	10.3914
2. $B^+ \to \overline{D}^0 e^+ \nu_e$	7.9187
3. $B^+ \to \overline{D}^*(2007)^0 \mu^+ \nu_\mu$	5.2443
4. $B^+ \to \overline{D}^*(2007)^0 e^+ \nu_e$	3.8254
5. $B^+ \to \overline{D}^0 K^+$	3.705
6. $B^+ \to \overline{D}^0 \pi^+$	3.1702
7. $B^+ \to \overline{D}^*(2007)^0 K^+$	2.34
8. $B^+ \to \overline{D}^*(2007)^0 \pi^+$	2.1714
9. $B^+ \to \rho(770)^+ \overline{D}^0$	1.7037
10. $B^+ \to \overline{D}^*(2007)^0 \rho(770)^+$	0.952

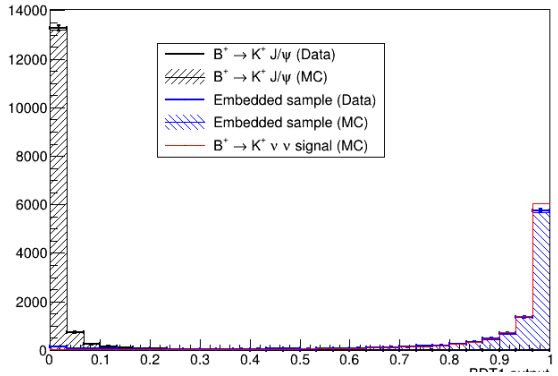


Validation studies

- Signal efficiency validation
  - Embedded $B^+ \to K^+ J/\psi(\mu^+\mu^-)$
- Background modelling validation
  - Continuum
    - Off-resonance
  - On-resonance side-band
    - Away from signal region ($BDT_2 < 0.9$)
  - $B \to D(*) \to K^0_L$ decays
    - PID sidebands - both pion and lepton
  - Others - modelling of BF
    - $B \to K^+ nn$
    - $B \to K^+ K^0 K^0$
- PID and neutral reconstruction validation
  - pion → kaon fakes
    - dedicated B → hD(Kπ) sample
  - Others
    - $\phi(K^0_S K^0_L)$ γ - K_L efficiency checks

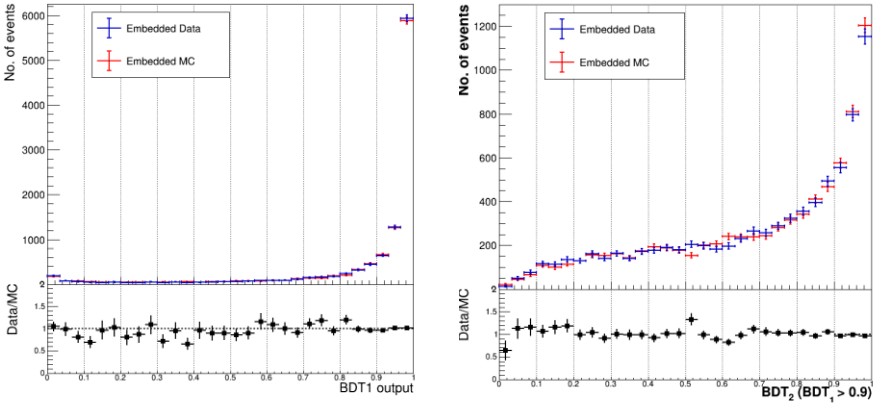
Signal embedding: $B^+ \to K^+ J/\psi(\mu^+\mu^-)$

- $B^+ \to K^+ J/\psi(\mu^+\mu^-)$ sample → remove $J/\psi(\mu^+\mu^-)$ → add kaon from $B^+ \to K^+ \nu\bar{\nu}$ signal MC ("signal embedding")
- Good agreement between embedded MC and embedded data



Selection efficiency in the signal region for the embedded data and MC samples

Sample	Efficiency
Data	0.0622 +/- 0.0020
MC	0.0633 +/- 0.0020
Ratio	**0.9833 +/- 0.0443**



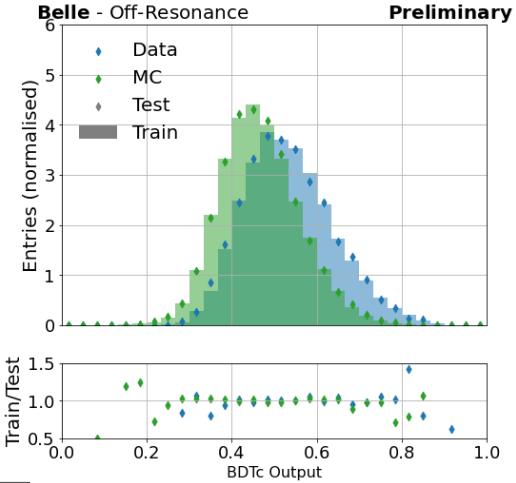
The data-MC comparison of BDT1 (left) and BDT2 (right) outputs

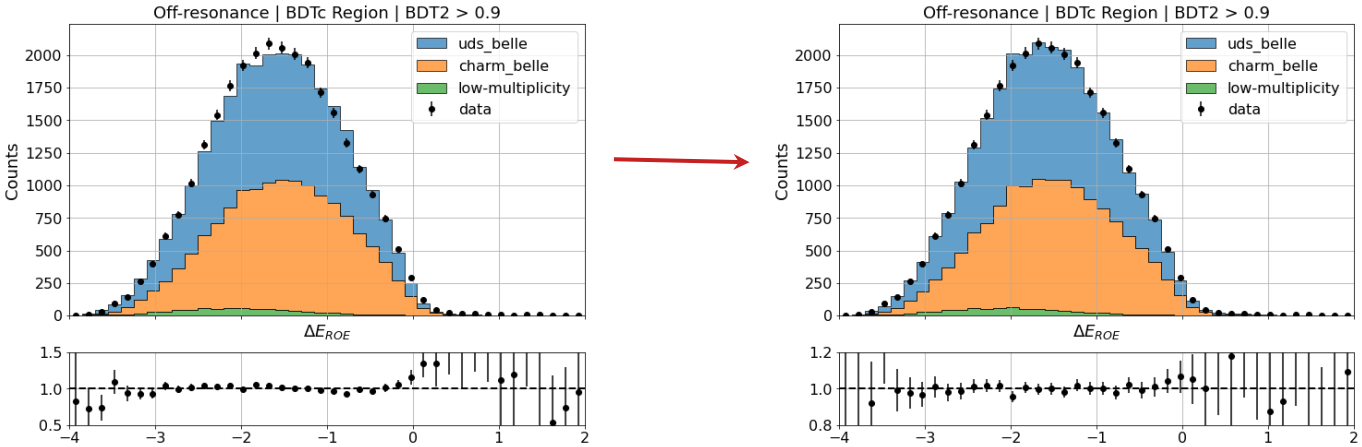
Off-resonance control sample

- Slight mismodelling of continuum data/MC after BDT1 is observed in off-resonance control sample
- A dedicated BDT (called BDTc) is trained to correct for **shape** disagreement
- MC events are assigned weight according to the output of BDTc as:

$$w = \frac{p}{1-p}$$

- Improved data/MC agreement with the BDTc reweighting applied



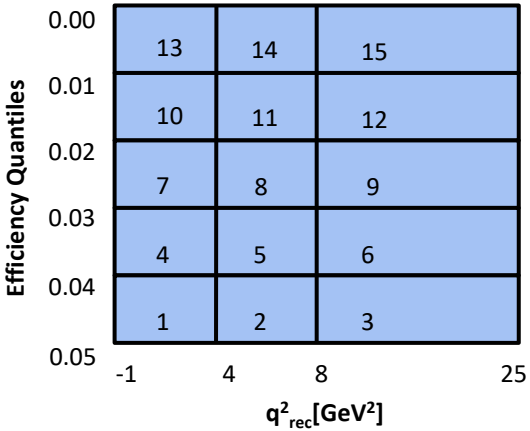


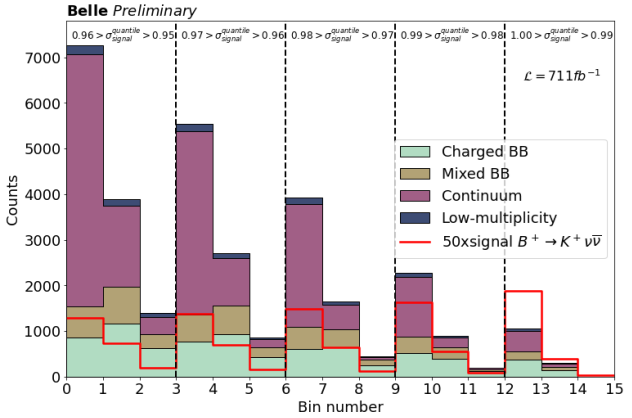
Signal extraction

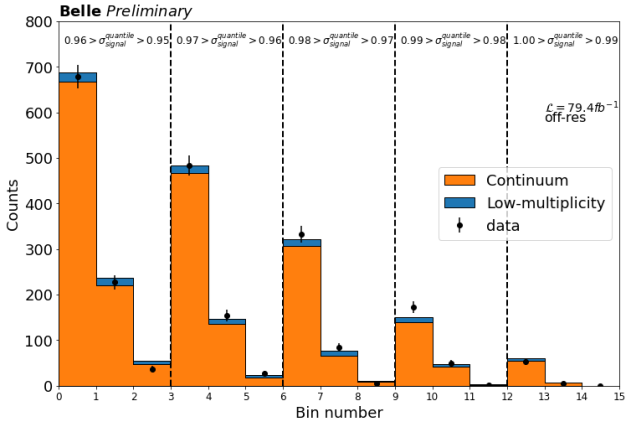
- Simultaneous binned maximum likelihood fit of 15 bins $\eta(BDT_2)$ x q^2_{rec}, with both on-resonance and off-resonance channels - template fit in pyhf
- Measure signal strength

$$\mu = \frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{SM}}$$

- Systematic uncertainties included as nuisance parameters - correlations between off-resonance channel and continuum samples in on-resonance channel

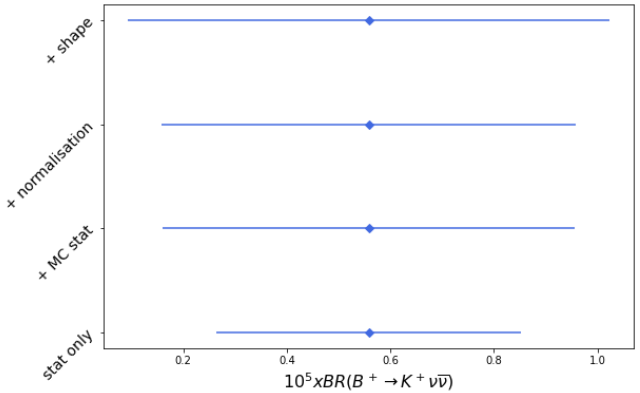






Systematic uncertainties

Source	MC Correction	$N_{nuis.param.}$	Uncertainty Size
$B\overline{B}$ norm.	-	1 Global	70%
Leading $B\overline{B}$ backgrounds	-	10, Shape	$\mathcal{O}(1\%)$
$B \to D^{(**)}$ modelling	-	10, Shape	50%
$B^+ \to K^+ n\bar{n}$ modelling	bin-dependent	1, Shape	100%
$B \to (D \to K^0_L)$ modelling	+35%	1, Shape	10%
Signal FF	bin-dependent	1, Shape	6-18%
Continuum norm	-	1 Global	70%
Continuum shape	-	1, Shape	2%
Low-multi norm	-	1 Global	70%
Low-multi shape	-	1, Shape	2%
$B^+ \to K^+K^0K^0$ shape	bin-dependent	1, Shape	2%
K^0_L efficiency	+10%	1 Global	10%
Luminosity	-	1 Global	TBD
particle ID	bin-dependent	1 Global	TBD
Tracking	-	1 Global	0.35%
MC statistics	-	90, Shape	-



Current total uncertainty estimation (preliminary):
BF=0.504±0.47x10^{-5}

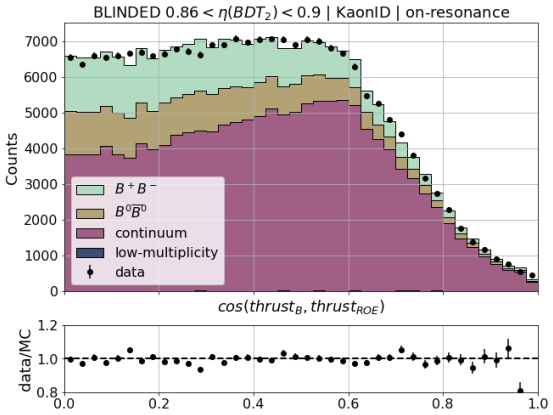
**off-resonance check*
**pionID and muonID sidebands checks*
**reweighting according to Babar studies*
**q2 distribution reweighted according to theory prediction*

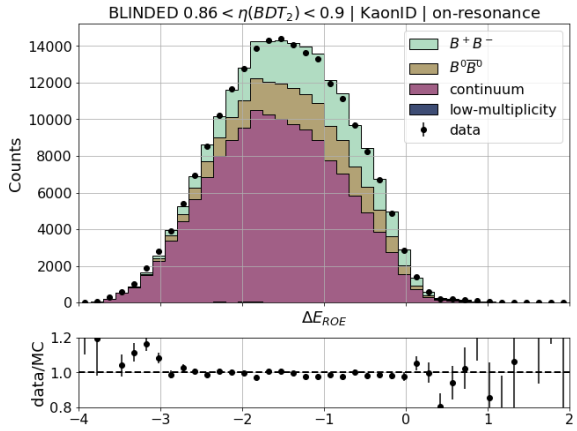
Summary

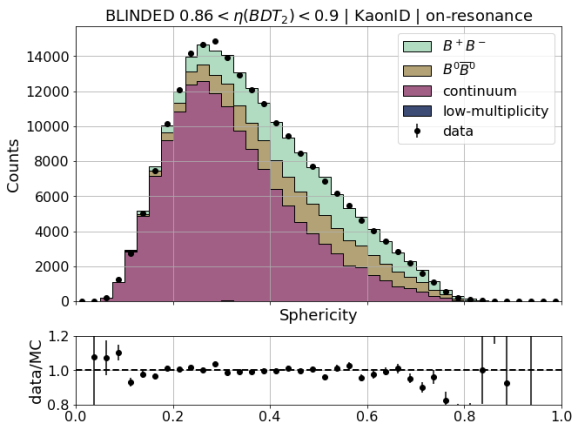
- Inclusive analysis of $B^+ \to K^+ \nu\bar{\nu}$ decays using full 711 fb^{-1} Belle data:
  - Preliminary sensitivity comparable to Belle II inclusive tag
  - Selection and signal region optimisation completed
  - Background suppression using two consecutive BDTs
  - Extensive validations studies completed
    - Corrections determined from off-resonance sideband checks
    - Signal efficiency validated using embedded sample
    - Good agreement in on-resonance sideband ($BDT_2 < 0.9$)
    - $D \to K_L^0$ scaling determined from pion and muon sideband checks
  - Simultaneous binned 2D maximum likelihood fit of on-resonance and off-resonance samples for extraction of $B^+ \to K^+ \nu\bar{\nu}$ signal strength
  - Ongoing work to finalize all systematic sources in template fit
- **Aiming for summer conferences 2025**

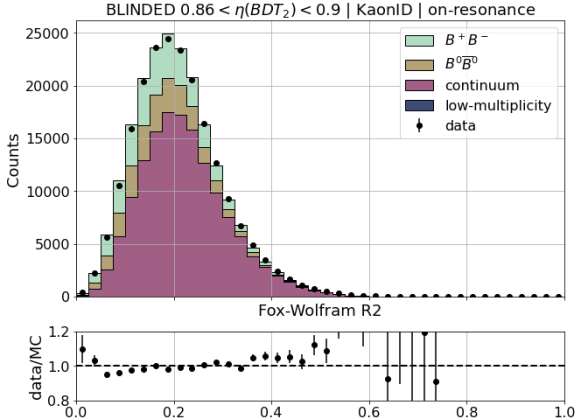
Backup

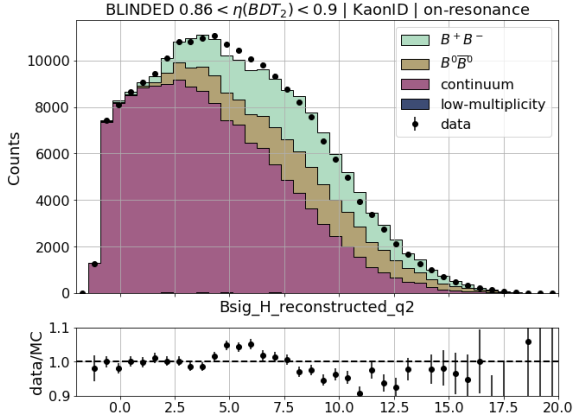
On-resonance sideband

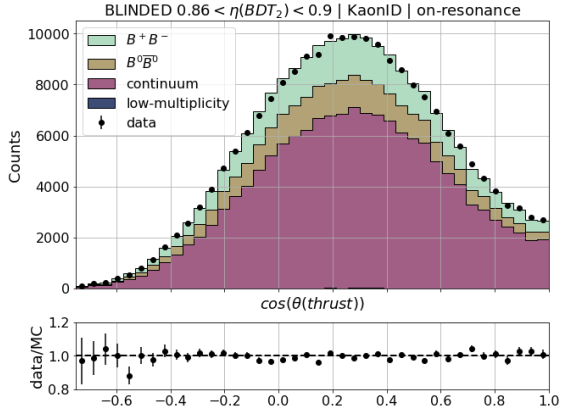




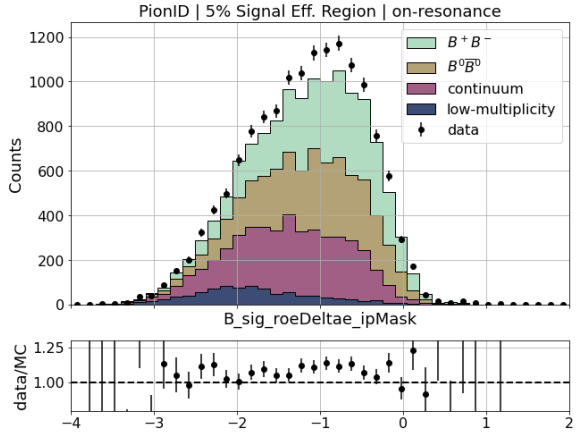


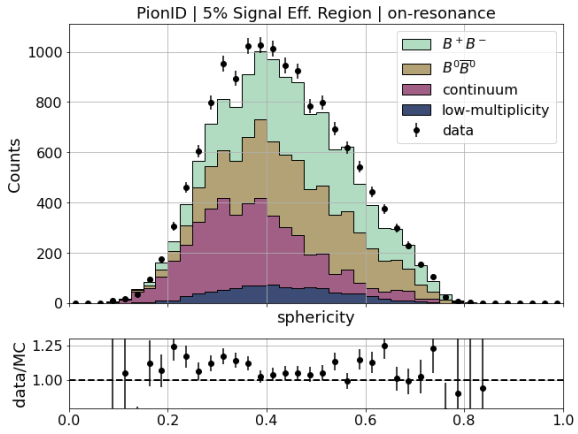


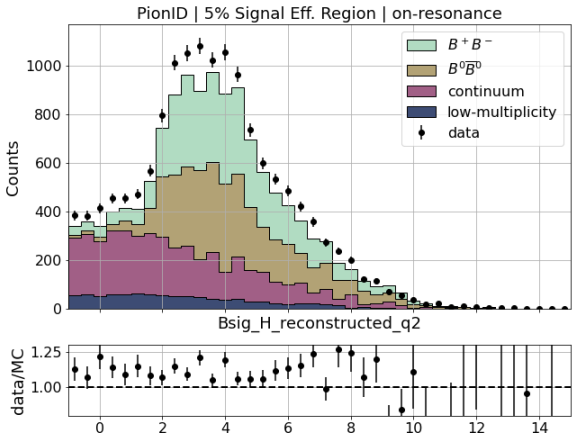


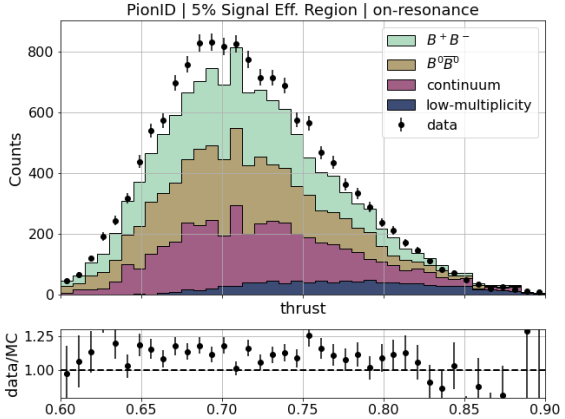


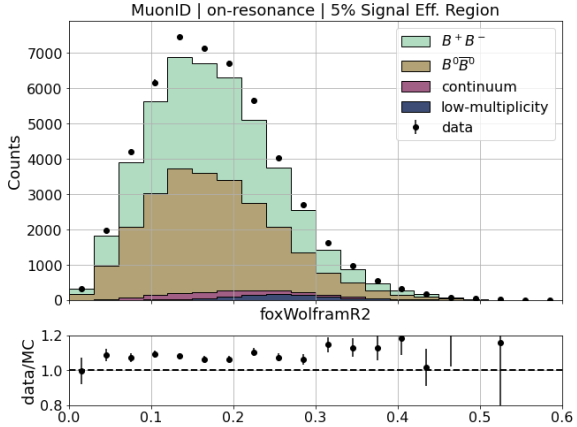
PionID sideband - on-resonance

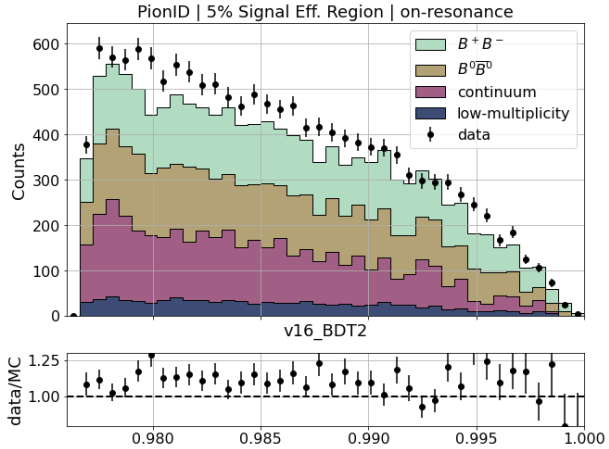








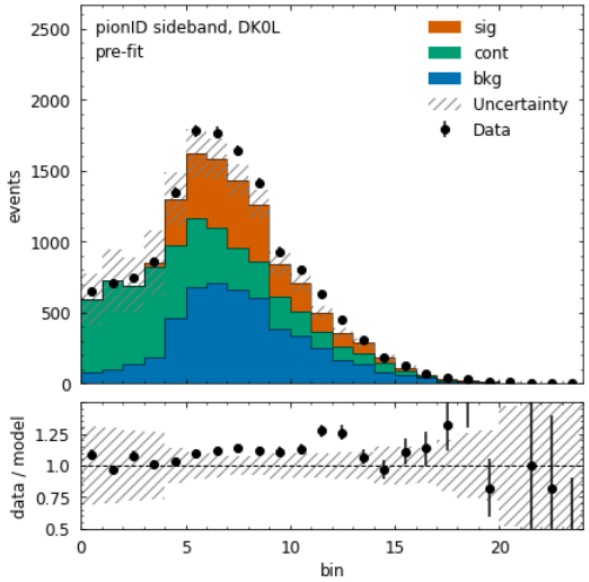




PionID sideband - on-resonance

Fit to determine D->K0L scaling

mu	1.39236	0.0627678
bkg_norm	0.069394	0.992569
cont_norm	0.0773284	0.0901136



In fit:

variable used - q^2

mu - parameter of interest

other B bkg normalisation - vary by 1%

continuum normalisation - vary by 50%