On Backgrounds in $B^- \to K^- \nu\overline{\nu}$ and their Treatment at Belle II

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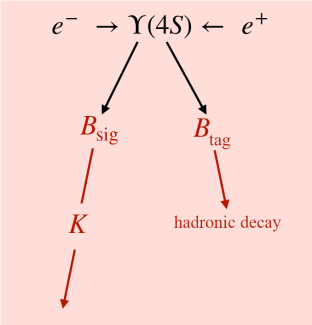
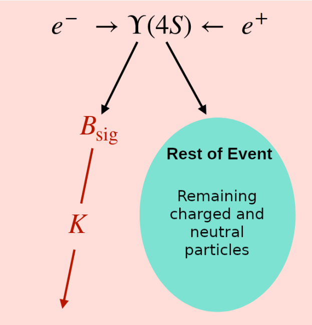
Beyond the Flavour Anomalies V

How to Reconstruct $B \to K\nu\bar{\nu}$ at Belle II

Well-known kinematics and $\Omega \approx 4\pi$ coverage at Belle II allow two types of reconstruction:



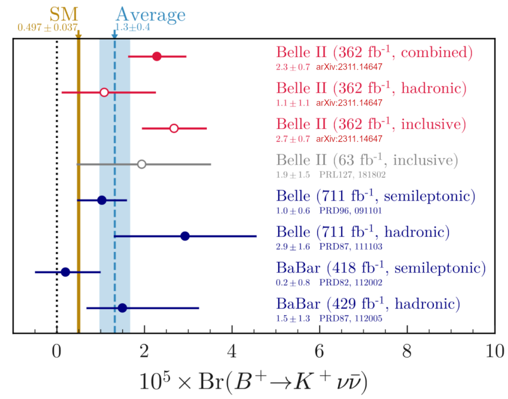
Exclusive reconstruction using B_{tag} reconstruction.
Low efficiency, high purity.



Inclusive reconstruction using event kinematics & topology.
High efficiency, low purity.

Evidence for $B^- \to K^- \nu\bar{\nu}$ by Belle II (arXiv:2311.14647)

- Main challenge is large background contamination, which requires strong suppression.
- Inclusive and exclusive reconstruction operate largely on orthogonal data sets.
- Combined result is compatible with SM at $2.7\,\sigma$.



This talk focuses on *inclusive method*, (also validated in $B^+ \to \pi^+ K^0$).

Background Classes

Backgrounds that could be suppressed further at the cost of signal efficiency:

Reducible Backgrounds

B decays with kaons from D decays

- 52% semilept. with missing energy
- 47% hadronic
- 1% leptonic

fake K from particle mis-identification

B decays with baryon-antibaryon pairs

$B^- \to K^- K^0 \overline{K^0}$

...

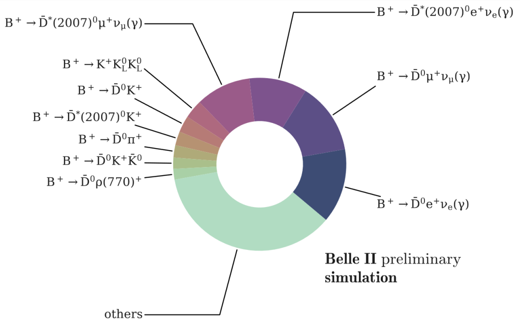
Backgrounds that can hardly be suppressed further:

Interfering Backgrounds

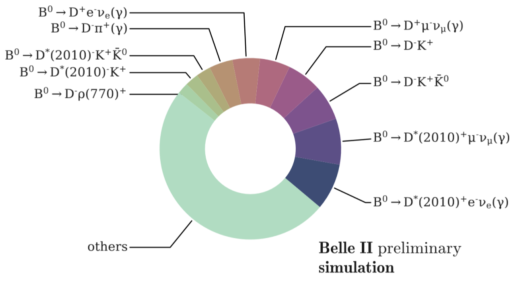
$B^- \to \tau^-(\to K^- \nu)\overline{\nu}$ [Kamenik, Smith 0908.1174]

- added incoherently to B^- backgrounds
- distribution included in `HistFactory` likelihood
- assumes SM dynamics

Reducible Backgrounds



Charged B background in inclusive reconstruction.



Neutral B background in inclusive reconstruction.

Leading types of B background decays

Candidate B	Fraction (%)
$B \to D(KX)l\nu_l X$	17.2
$B \to D^*[\pi D(KX)]l\nu_l$	16.1
$B \to D^{(*)}(X)KX$	11.7
$B \to D(KX)X$	2.9 ...
...	

candidate K, assigned to B_{tag}

D suppression:
mass and vertex of K and 1-2 charged particles is input to BDT.

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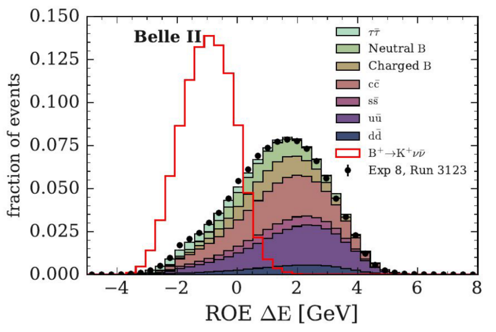
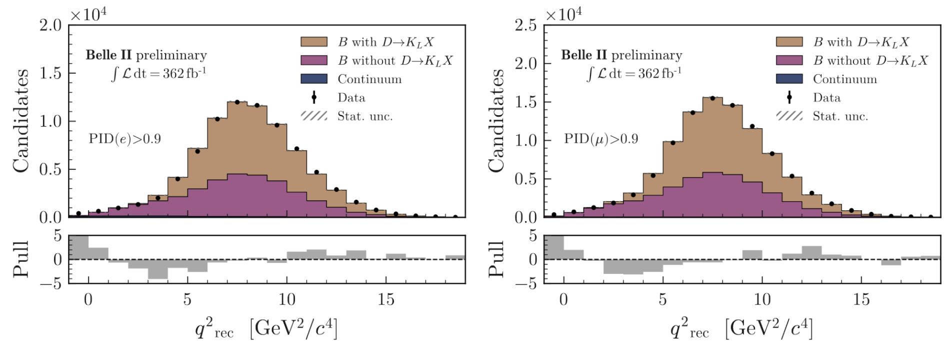


Most important input to BDT:
Energy difference of ROE and $\sqrt{s}/2$ in cms.
signal: < 0 due to missing particles.
bkg: > 0 due to falsely assigned particles.

Backgrounds with $D \to K_L^0 X$

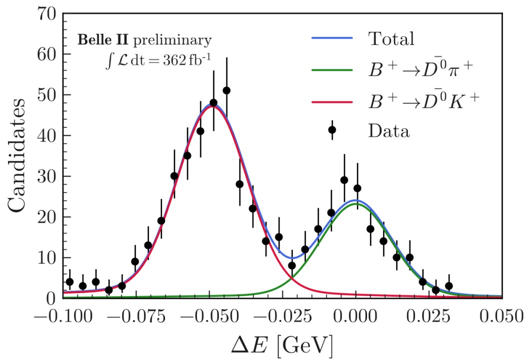
- Fraction of charm meson decays to K_L^0 is less known and needs cross-check.
- Extract correction weights in pion sidebands.
- Correction weights validated in lepton sidebands.



Validation of $B \to KD(K_L^0 X)$ weights in electron (left) and muon (right) sideband.

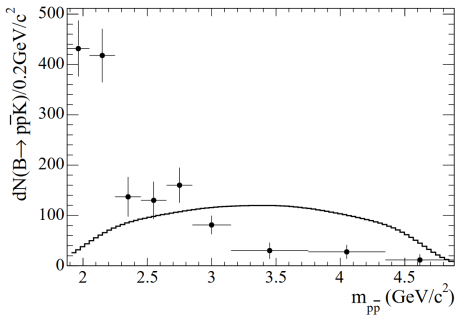
Fake K from particle mis-identification

- Particle identification simulation is imperfect.
- Correction weights extracted from pure π, K samples in $D^{*+} \to \pi^+ D^0 (K^- \pi^+)$.
- Correction weights cross-checked in $B^- \to D^0 (K^+ \pi^-) h^-$ with $h \in [\pi, K]$. Lepton mis-identification negligible.



Treatment of $B^- \to K^- n\bar{n}$ background

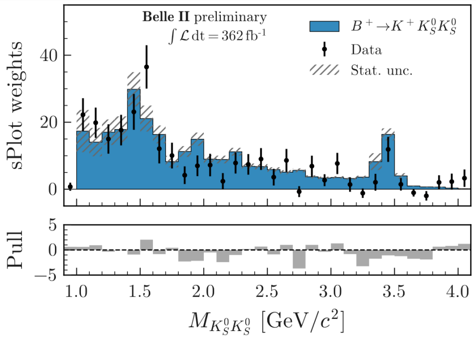
- Weak detector interaction of $n, \bar{n}$ mimics signal.
- Not yet measured but **assume threshold enhancement effect from B $\to$ Kp$\bar{\text{p}}$**.
- **Presuming isospin symmetry**, simulation is reweighted to $B^0 \to K^0 p\bar{p}$.
- Reweighting affects extracted signal strength by $\Delta\mu = -0.2$ and increases efficiency to half the signal effiency.
- Systematic uncertainty derived from full exclusion of $B^- \to K^- n\bar{n}$.



Threshold enhancement effect in $B^- \to K^- p\bar{p}$ at BaBar[a] versus 3-body phase-space simulation.

[a] hep-ex 0507012

$B^- \to K^- K^0 \overline{K^0}$ backgrounds



- $B^- \to K^- K_S^0 K_S^0$ are reweighted according to 1201.5897.
- **Assuming isospin symmetry**, same weights are applied to $B^- \to K^- K_L^0 K_L^0$.
- Using $B^- \to K^- K_S^0 K_S^0$ as signal mode with a fit in ΔE, obtain *sweights* to extract $m_{K_S^0 K_S^0}$ for signal in data.
- Good agreement with signal simulation after reweighting.

K_L^0 reconstruction efficiency

Backgrounds with K_L^0 mimic signal due to weak detector response and uncertainties in simulation.

- Cross-check K_L^0 reconstruction efficiency in $e^+e^- \to \gamma\phi(K_L^0 K_S^0)$.
- K_L^0 momentum can be inferred from $\sqrt{s}$ and remaining final state particles:

$$P_{K_L^0} = P_{e^+e^-} - P_\gamma - P_{K_S^0}$$

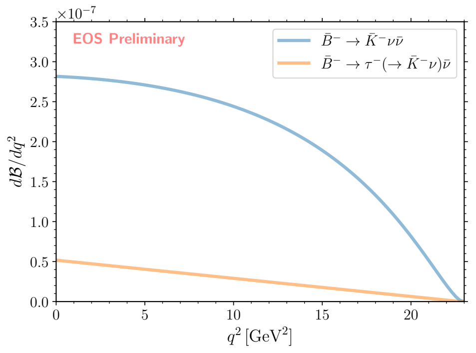
- Geometrically associate calorimeter clusters with K_L^0 momentum and find

$$\epsilon(K_L^0) = \frac{\#K_L^0 \text{ with cluster}}{\#K_L^0 \text{ total}} \quad \Rightarrow \quad \Delta\epsilon = \frac{\epsilon_{\text{simulation}}(K_L^0)}{\epsilon_{\text{data}}(K_L^0)} \approx 1.17.$$

- Simulation of K_L^0 adjusted by $\Delta\epsilon$ with 50% uncertainty as syst. uncertainty.

Interfering Backgrounds

Theory Predictions for $B^- \to \tau^-(\to K^-\nu)\bar{\nu}$ in the SM



- $B^- \to \tau^-(\to K^-\nu)\bar{\nu}$ pollutes signal through intermediate on-shell τ contributions

[Kamenik,Smith 0908.1174]

- SM shape and normalization of background known
- kinematic distribution distinct from signal
  - signal: phasespace suppr. competes with form factor
  - background: linear q^2
- can BSM physics modify shape or norm?
- aim: prepare for reinterpretation of both signal and irreducible background(s)
  - Nora's ongoing master project at RU Nijmegen

Theory Predictions for $B^- \to \tau^-(\to K^-\nu)\overline{\nu}$ beyond the SM

preliminary results

- assuming only left-handed neutrinos contribute, the shape of the long-distance background is fixed to SM-like shape, regardless of WET-like BSM contributions to $B^- \to \tau^-\overline{\nu}$ or $\tau^- \to K^-\nu$ interactions
- only interference of operators with different ν chiralities allows for a helicity flip of the τ, leads to a different shape of the background in a BSM scenario
- implementing combined WET-aware MC of signal and this background in *EOS*

outlook

- continue with study of background for $B^- \to K^{*-}\nu\overline{\nu}$

Conclusion

- First evidence for $B^- \to K^- \nu\bar{\nu}$ at Belle II, consistent with SM at $2.7\,\sigma$.
- Novel inclusive reconstruction method, cross-checked with traditional hadronic B tagging.
- Backgrounds contributions validated in data-driven tests.
- Interfering background stable in shape under BSM interpretation
- Main phenomenological bottlenecks:
  - Assumption on $B \to K K_S K_S \iff B \to K K_L K_L$ isospin symmetry.
  - Size of isospin asymmetry in $B \to K p\bar{p} \iff B \to K n\bar{n}$.
  - Assumption on same threshold enhancement effect in $B \to K p\bar{p} \iff B \to K n\bar{n}$.
  - Background $B \to K_S K_L K_L$ experimentally challenging. Ideas for constraint?
- Work ongoing in $B \to h\nu\bar{\nu}$ with $h \in [K^{*0}, K^{*+}, K_S^0]$.

Backup

Systematic Uncertainties

Source	Correction	Uncertainty type	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2 NP	50%	0.88
Normalization of continuum background	—	Global, 5 NP	50%	0.10
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.48
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	+30%	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	< 0.01
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.07
Hadronic energy scale	-10%	Shape, 1 NP	10%	0.36
K^0_L efficiency in ECL	-17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
Simulated sample size	—	Shape, 156 NP	$O(1\%)$	0.52

Leading B^- and B^0 background decays

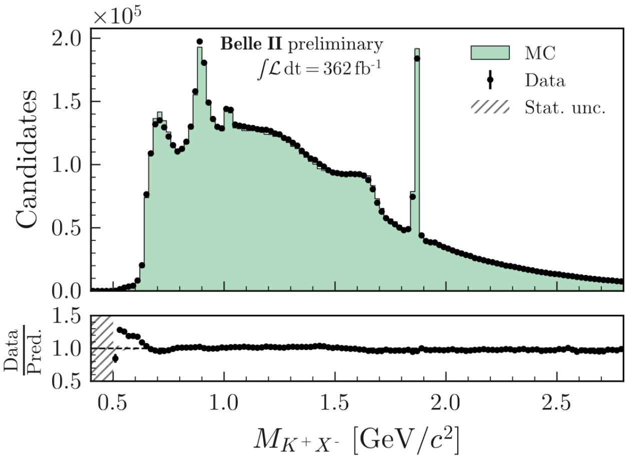
Signal B	Fraction (%)
$B^\pm \to D^0 \mu^\pm \nu_\mu$	12.0
$B^\pm \to D^*(2007)^0 \mu^\pm \nu_\mu$	9.1
$B^\pm \to D^0 e^\pm \nu_e$	8.7
$B^\pm \to D^*(2007)^0 e^\pm \nu_e$	6.7
$B^\pm \to D^0 e^\pm \nu_e \gamma$	4.1
$B^\pm \to K^\pm K_L^0 K_L^0$	3.5
$B^\pm \to D^*(2007)^0 e^\pm \nu_e \gamma$	3.3
$B^\pm \to D^0 K^\pm$	3.1
$B^\pm \to D^*(2007)^0 K^\pm$	2.6
$B^\pm \to D^0 \pi^\pm$	2.3

Signal B	Fraction (%)
$B^0 \to D^*(2010)^\pm \mu^\pm \nu_\mu$	7.1
$B^0 \to D^\pm K^\pm K^0$	6.5
$B^0 \to D^\pm K^\pm$	6.1
$B^0 \to D^*(2010)^\pm e^\pm \nu_e$	5.1
$B^0 \to D^\pm \mu^\pm \nu_\mu$	4.6
$B^0 \to D^\pm \pi^\pm$	3.4
$B^0 \to D^\pm e^\pm \nu_e$	3.3
$B^0 \to D^*(2010)^\pm K^\pm K^0$	2.7
$B^0 \to D^*(2010)^\pm e^\pm \nu_e \gamma$	2.4
$B^0 \to D^*(2010)^\pm K^\pm$	2.4

Decays with exotic D^{**} mesons amount to 3% and 5% respectively.

Vertices and masses of signal K and 1 or 2 charged particles enter BDT to identify D decays.

Signal K and One Charged Particle Invariant Mass



B meson backgrounds with baryon-antibaryon pairs

Decay	Reference	$\mathcal{B}$	Other Assumption	$\mathcal{B}$ estimate for $B^+ \to K^+ \nu\bar{\nu}$
$B^+ \to n\bar{n}K^+$	BaBar [21]	2.9×10^{-6}	iso	2.9×10^{-6}
$B^+ \to n\bar{n}\pi^+$	Belle [22]	1.8×10^{-6}	iso, $\pi \to K$ misID	1.8×10^{-8}
$B^0 \to n\bar{n}K^{*0}$	?		iso and missing π^0	2.9×10^{-7}
$B^+ \to n\bar{n}K^{*+}$	Belle [22]	2.9×10^{-6}	iso, missing π^0	2.9×10^{-7}
$B^+ \to p\bar{n}K^0_L$	?	2.9×10^{-6}	$p \to K^+$ misID	2.9×10^{-8}
$B^0 \to n\Lambda K^+K^-$	Belle [23]	4×10^{-6}	iso, missing π^0 and K^-	4×10^{-8}
$B^0 \to \bar{n}\bar{\Lambda}K^+K^-$	Belle [23]	4×10^{-6}	iso and missing π^0 and K^-	1×10^{-8}
$B^+ \to \bar{n}\bar{\Lambda}K^+K^0_L$	?	4×10^{-6}	iso, missing π^0 and missing $\bar{n}$	4×10^{-8}
$B^+ \to \Lambda\Lambda(1520)K^+$	Belle [23]	2×10^{-6}	iso, missing π^0 and K^0_L/N	2×10^{-8}
$B^+ \to \Lambda\Lambda K^+$	Belle [24]	3×10^{-6}	iso , 2 missing π^0s	3×10^{-8}
$B^+ \to n\bar{n}l\nu$	LHCb [25]	1×10^{-5}	iso and $l \to K^+$ misID	3×10^{-7} (3 leptons)
$B^+ \to n\bar{n}l\nu\gamma$	not measured	1×10^{-4}	iso, $l \to K^+$ misID , HS lifted, missing γ	1×10^{-6} (3 leptons)
$B^0 \to n\bar{p}l\nu$	LHCb [25]	1×10^{-5}	iso, $\bar{p} \to K^+$ misID, missing l	1×10^{-8} (1 leptons)
$B^0 \to n\bar{n}K^+\pi^-$	LHCb [26]	6×10^{-6}	iso, missing π^-	6×10^{-7}
$B^0 \to D^0 n\bar{n}$	Belle [27]	3.5×10^{-5}	iso, missing 1 to 3 tracks	1×10^{-6}
$B^0 \to D^0 n\Lambda$	Belle [28]	1.4×10^{-5}	iso, missing 2 particles	1×10^{-7}
Total				6.4×10^{-6}