Experimental status of $b \to (s, d)\nu\bar{\nu}$ decays

Pablo Goldenzweig

KIT

CKM 2016

TIFR, Mumbai, India

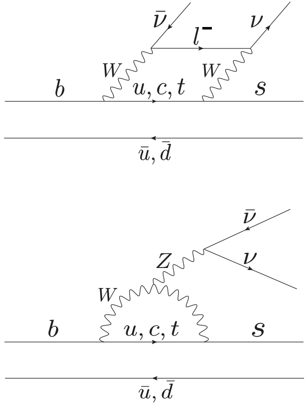
28 Nov. - 2 Dec., 2016

Karlsruhe Institute of Technology BELLE

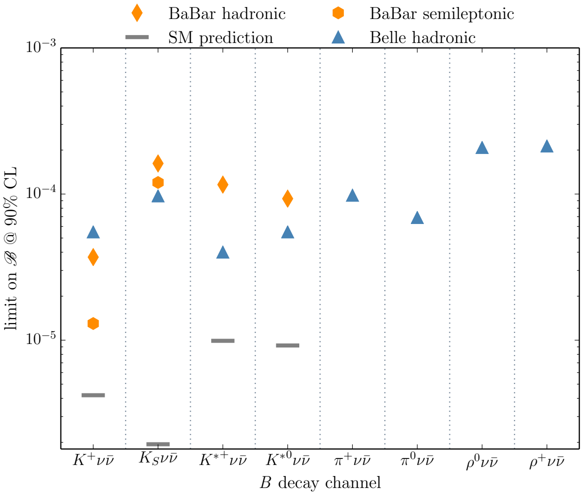
- **Theoretical motivation**
- **Existing measurements**
- **Belle's new measurement of $b \to (s, d)\nu\overline{\nu}$ with the semileptonic tagging method**
- **Interpretation and comparison to existing measurements.**

Introduction

- Flavor changing neutral currents forbidden at tree level make $b \to (s,d)\nu\bar{\nu}$ highly suppressed.
- Theoretical calculations of $\mathcal{B}$ cover the range: 2.4×10^{-7} $(\pi^+\nu\bar{\nu}) \Rightarrow 9.2 \times 10^{-6}$ $(K^{*+}\nu\bar{\nu})$, where the $B \to (\pi,\rho)\nu\bar{\nu}$ decays are further suppressed by a factor of $|V_{td}/V_{ts}|^2$.
  JHEP, 02:184 (2015), **PRD 92, 074020 (2015)**
- Theoretically clean due to a maximum of one electromagnetically interacting charged particle in the final state, as opposed to $K^{(*)}l^+l^-$ decays.
- Several new physics models (SUSY, non-standard Z coupling) could enhance these decays.



One-loop box (top) and electroweak penguin (bottom) for $b \to s\nu\bar{\nu}$ decays



PRD 82, 112002 (2010), ◇ **PRD 87, 112005 (2013)**, **PRD 87, 111103(R) (2013)**

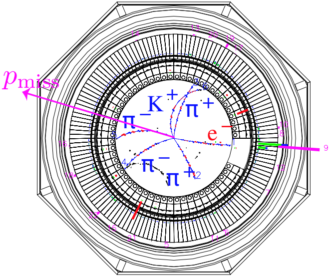
$459 M B\bar{B}$ $471 M B\bar{B}$ $772 M B\bar{B}$

◇ Also includes: $\mathcal{B}(J/\psi \to \nu\bar{\nu}) < 3.9 \times 10^{-3}$, $\mathcal{B}(\psi(2S) \to \nu\bar{\nu}) < 15.5 \times 10^{-3}$, $\mathcal{B}(B^0 \to \phi\nu\bar{\nu}) < 8.7 \times 10^{-5}$

New measurement of $B \to h^{(*)}\nu\overline{\nu}$ with the semileptonic tagging method with the full Belle dataset of $772 \times 10^6 B\overline{B}$ pairs

$h^{(*)} = K^+, K_S^0, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0$

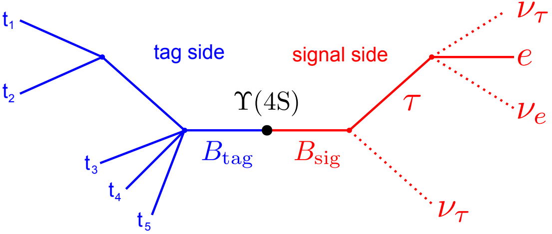
Typical B factory event



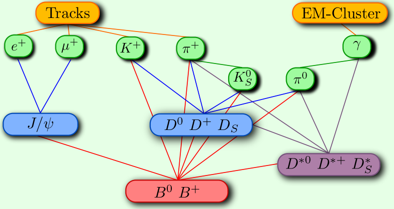
$B^+_{tag} \to \bar{D}^0\pi^+\pi^+\pi^-$
$\hookrightarrow K^+\pi^-$

$B^-_{sig} \to \tau^-\bar{\nu}_\tau$
$\hookrightarrow e^-\bar{\nu}_e\nu_\tau$

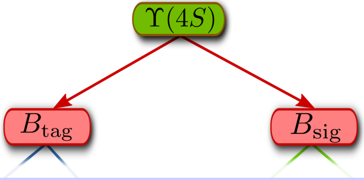
Tag- and signal-side of the full reconstruction



- Hierarchical reconstruction of the B_{tag} using NeuroBayes[1].
- Check if the remaining particles in the detector are consistent with the signal signature.



[1] Nucl. Instrum. Meth. A654: 432 (2011)



Tagging techniques

Purity →

← Efficiency

Inclusive	Semileptonic	Hadronic
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(2\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$
Very large statistics; Also very large background	Mid-range reconstruction efficiency; Less information about B_{tag} due to neutrino	Cleaner sample Knowledge of $p(B_{\text{sig}})$; Lower tagging efficiency

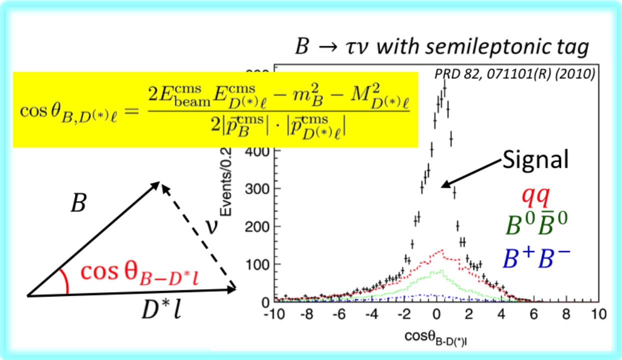
Reconstruction I

This semileptonically tagged sample provides a statistically independent and more efficient sample of reconstructed $B\overline{B}$ events as compared to the hadronically tagged sample.

Tag semileptonic B-decay: Combine D^{*+} and oppositely-charged lepton candidates and calculate the cosine of the angle between the B momentum and the D^*l in the $\Upsilon(4S)$ frame.

$\Rightarrow$

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E^{\rm cms}_{\rm beam}E^{\rm cms}_{D^{(*)}\ell} - m_B^2 - M^2_{D^{(*)}\ell}}{2|\vec{p}^{\,\rm cms}_B| \cdot |\vec{p}^{\,\rm cms}_{D^{(*)}\ell}|}$$



✓ **tag candidates:** $\cos\boldsymbol{\theta}_{B\text{-}D^*\ell} \in [-1, 1]$

Output of the network used to identify real $B_{\rm tag}$ candidates ($\mathcal{N}_{\rm tag}$) can be interpreted as the probability of the $B_{\rm tag}$ meson to be a real one in a generic sample.

- Reconstruct one light meson: K^+, K_S^0, K^{*+}, K^{*0}, π^+, π^0, ρ^+, ρ^0. Invariant mass window of K^* & ρ optimized via $N_S/\sqrt{N_S+N_B}$.
- No additional charged tracks or π^0 candidates left in the event.
- Veto events with reconstructed K_L candidates.
- Suppress $e^+e^- \to q\bar{q}$ background with a neural network using topological variables.

Fraction of events with multiple $\Upsilon(4S)$ candidates up to 20%. Best candidate taken to be that with the highest $\mathcal{N}_{\rm tag}$, i.e., candidate with the highest probability for being correctly reconstructed.

Train a NN to separate signal from background:

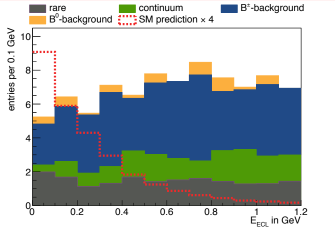
- Optimize a cut on the network output by maximizing a Punzi-FoM: $\varepsilon/\left(\frac{n_\sigma}{2}+\sqrt{B}\right)$

	ε in 10^{-3}	exp. # of background
$B^+ \to K^+\nu\bar{\nu}$	2.16	103.6
$B^0 \to K_S^0\nu\bar{\nu}$	0.91	22.4
$B^+ \to K^{*+}(\to K^+\pi^0)\nu\bar{\nu}$	0.25	11.1
$B^+ \to K^{*+}(\to K_S^0\pi^+)\nu\bar{\nu}$	0.32	24.1
$B^0 \to K^{*0}\nu\bar{\nu}$	0.51	24.8
$B^+ \to \pi^+\nu\bar{\nu}$	2.92	474.0
$B^0 \to \pi^0\nu\bar{\nu}$	1.42	41.0
$B^+ \to \rho^+\nu\bar{\nu}$	0.82	62.4
$B^0 \to \rho^0\nu\bar{\nu}$	1.11	172.5

Extract the signal yield by fitting the Extra Energy in the Calorimeter:

Sum of energies of neutral clusters not associated with reconstructed particles

$$E_{ECL} = \sum E_{\text{Calor.}} - \left(\sum E_{\text{tag}} + \sum E_{\text{sig}}\right)$$



Extensive Toy MC studies performed to estimate sensitivity: 1K bkgd.-only samples generated and fit for yield estimate. Fit bias estimated from ensemble tests and corrected for in fit to data. (plot for $K^+\nu\bar{\nu}$) **Preliminary**

Charm B decay & $q\bar{q}$ background for $K^+\nu\bar{\nu}$ in $E_{ECL} \in (0, 1.2)$ GeV.

Dominant $b \to c$ contribution from semileptonic B decays.

Preliminary

	contribution in %
continuum	22.6
2 leptons missing	15.3
K_Ls and lepton missing	6.5
lepton and hadrons missing	24.1
2 charged hadrons missing	1.7
wrong B type	3.8
hadronic, K_L missing	24.1
hadronic π^0 missing	1.0
no match	0.0
other	1.0

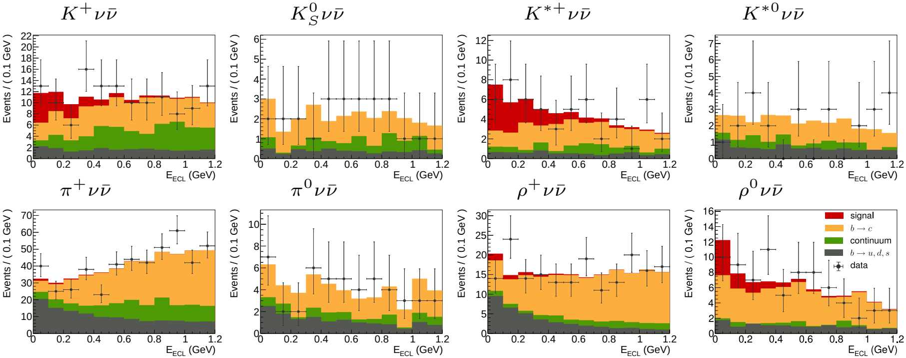
Fit to data

Karlsruhe Institute of Technology

BELLE

Extended binned ML fit to E_{ECL}:

Preliminary



- Histogram templates to model signal and bkgds from charm B decay, charmless B decay, and continuum.
- Relative fractions of the background components fixed to MC expectations.
- Signal and overall background yield allowed to vary.

Channel	Observed N_{sig}	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	1.9σ
$K_S^0\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	0.0σ
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	2.3σ
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	0.0σ
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	0.0σ
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	0.0σ
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	0.3σ
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	1.2σ

Systematic uncertainties

Karlsruhe Institute of Technology

BELLE

Preliminary

	$K^+\nu\bar{\nu}$	$K^0_S\,\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$	$\pi^+\nu\bar{\nu}$	$\pi^0\nu\bar{\nu}$	$\rho^+\nu\bar{\nu}$	$\rho^0\nu\bar{\nu}$
K^0_L veto	0.2	0.2	0.1	0.2	0.6	0.4	0.6	0.0
fixed fraction	0.4	0.3	0.1	0.2	1.3	0.1	0.1	1.0
continuum correction	2.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0
tag correction	0.5	0.2	0.1	0.1	1.9	0.1	0.2	0.5
shape uncertainty	2.6	1.3	1.8	1.7	4.5	1.5	2.3	3.4
fit bias	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.2
total	3.4	1.4	1.8	1.8	5.9	1.6	2.4	3.6

- Uncertainties related to the signal yield (table [absolute]) are estimated by refitting the data with each quantity varied by $\pm 1\sigma$, with the exception of the shape uncertainty which is evaluated from Toy MC studies.

- Remaining uncertainties include: π^0 and charged track veto (4%); raw track requirement (1%); particle ID efficiency (2%) π^0 efficiency (4%), K^0_S efficiency (2.2%) $N_{B\bar{B}}$ (1.4%).

Upper limits

Karlsruhe Institute of Technology

BELLE

Preliminary

Channel	Efficiency	Expected Limit	Measured Limit
$K^+\nu\bar{\nu}$	2.16×10^{-3}	0.8×10^{-5}	1.9×10^{-5}
$K^0_S\,\nu\bar{\nu}$	0.91×10^{-3}	1.2×10^{-5}	1.3×10^{-5}
$K^{*+}\nu\bar{\nu}$	0.57×10^{-3}	2.4×10^{-5}	6.1×10^{-5}
$K^{*0}\nu\bar{\nu}$	0.51×10^{-3}	2.4×10^{-5}	1.8×10^{-5}
$\pi^+\nu\bar{\nu}$	2.92×10^{-3}	1.3×10^{-5}	1.4×10^{-5}
$\pi^0\nu\bar{\nu}$	1.42×10^{-3}	1.0×10^{-5}	0.9×10^{-5}
$\rho^+\nu\bar{\nu}$	1.11×10^{-3}	2.5×10^{-5}	3.0×10^{-5}
$\rho^0\nu\bar{\nu}$	0.82×10^{-3}	2.2×10^{-5}	4.0×10^{-5}

- **Expected (exp.) and observed upper limits at the 90% confidence level** (including systematic uncertainties)

Combine charged and neutral modes:

Preliminary

- The systematic uncertainties are evaluated on independent MC and data control samples for charged and neutral modes.
  $\Rightarrow$ *Can be considered uncorrelated.*
- Add the -$\mathcal{L}$ and scale the $\mathcal{B}$ of the neutral modes by τ_B^+/τ_B^0 and repeat the calculation of the limit:

$$\mathcal{B}(B \to K\nu\bar{\nu}) < 1.6\times10^{-5}$$

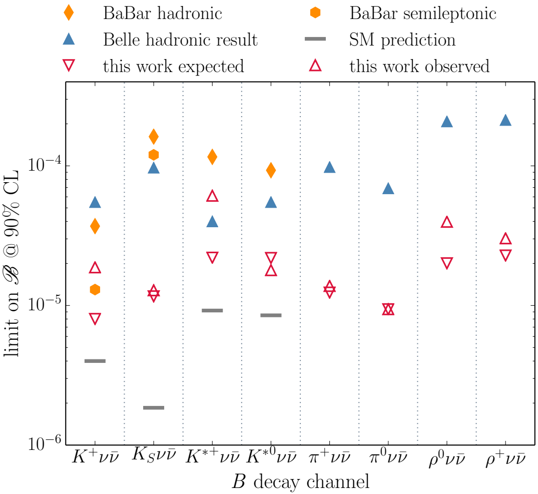
$$\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7\times10^{-5}$$

$$\mathcal{B}(B \to \pi\nu\bar{\nu}) < 0.8\times10^{-5}$$

$$\mathcal{B}(B \to \rho\nu\bar{\nu}) < 2.8\times10^{-5}$$

Comparison with other measurements

Preliminary



Worlds most stringent limits obtained for:

$$B^0 \to K_S^0\nu\bar{\nu},\ B^0 \to K^{*0}\nu\bar{\nu},\ B^{+/0} \to \pi^{+/0}\nu\bar{\nu},\ B^{+/0} \to \rho^{+/0}\nu\bar{\nu}$$

Summary

- **New measurement of $\mathcal{B}(B \to h^{(*)}\nu\bar{\nu})$ with the semileptonic tagging method by Belle.**
- **Highest significance in the $B \to K^{*+}\nu\bar{\nu}$ channel (2.3σ).**
- **Worlds best limits set on $B^0 \to K_S^0\nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$, $B^{+/0} \to \pi^{+/0}\nu\bar{\nu}$, and $B^{+/0} \to \rho^{+/0}\nu\bar{\nu}$.**
- **None of the limits excludes SM predictions and all leave room for contributions from new physics.**
- **To be submitted to PRD this month.**

$\Rightarrow$ *See talk by Saurabh Sandilya later this session on Belle II prospects for rare decays.*