Rare and forbidden decays at Belle

ICHEP 2012

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EKP, KIT

Overview

Outline

- B^0 decays to invisible final states
- $B \to h^{(*)} \nu \bar{\nu}$
- Search for heavy neutral lepton

$B^0 \to$ invisible

- $B^0 \to \nu\bar{\nu}$ highly helicity suppressed in the Standard Model ($\mathcal{B} \sim \mathcal{O}(10^{-20})$)

  G. Buchalla,A.J. Buras, Nuc. Phys. B 400, 225 (1993)

- Experimental signature: missing energy and momentum corresponding to the presence of a B^0 meson

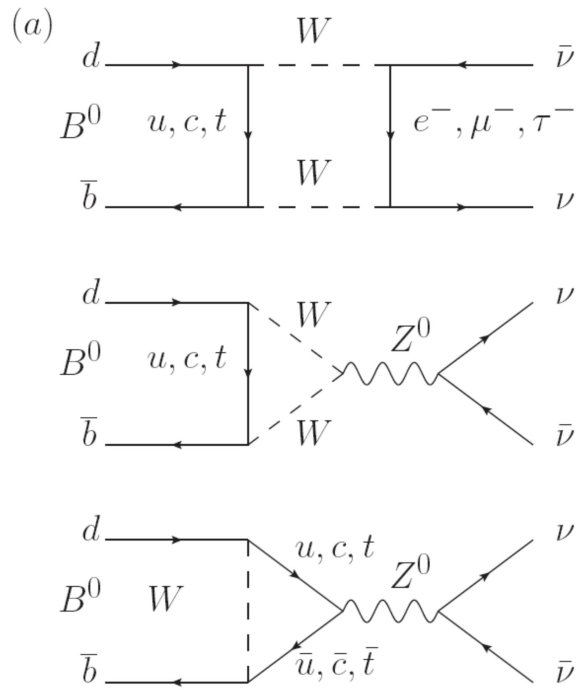


Figure 1.1: Feynman diagrams for $B^0 \to \nu\bar{\nu}$ decay in the Standard Model.

$B^0 \to$ invisible

- $B^0 \to \nu\bar{\nu}$ highly helicity suppressed in the SM ($\mathcal{B} \sim \mathcal{O}(10^{-20})$)

  G. Buchalla,A.J. Buras, Nuc. Phys. B 400, 225 (1993)

- Experimental signature: missing energy and momentum corresponding to the presence of a B^0 meson
- Same signature from new particles beyond the SM
- Example: $B^0 \to \bar{\nu}\chi_1^0$ ($\mathcal{B} \sim \mathcal{O}(10^{-6} - 10^{-7})$)

  A.Dedes,H.Dreiner,P.Richardson, Phys.Rev. D 65, 015001 (2002)

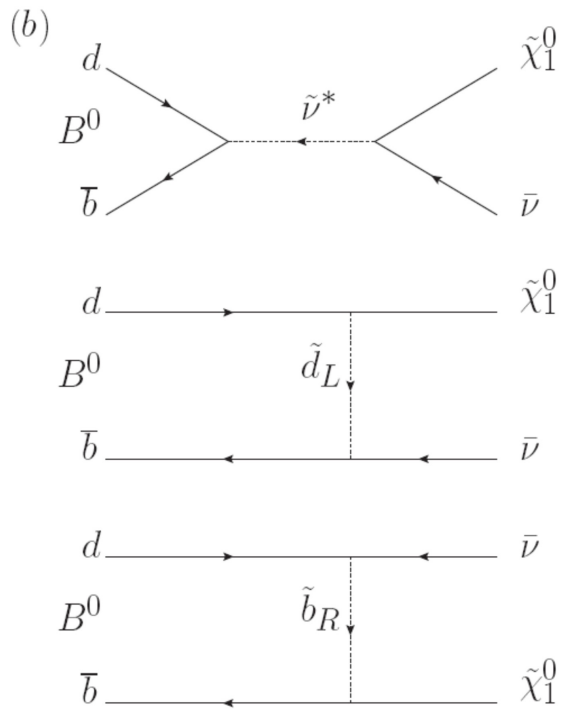
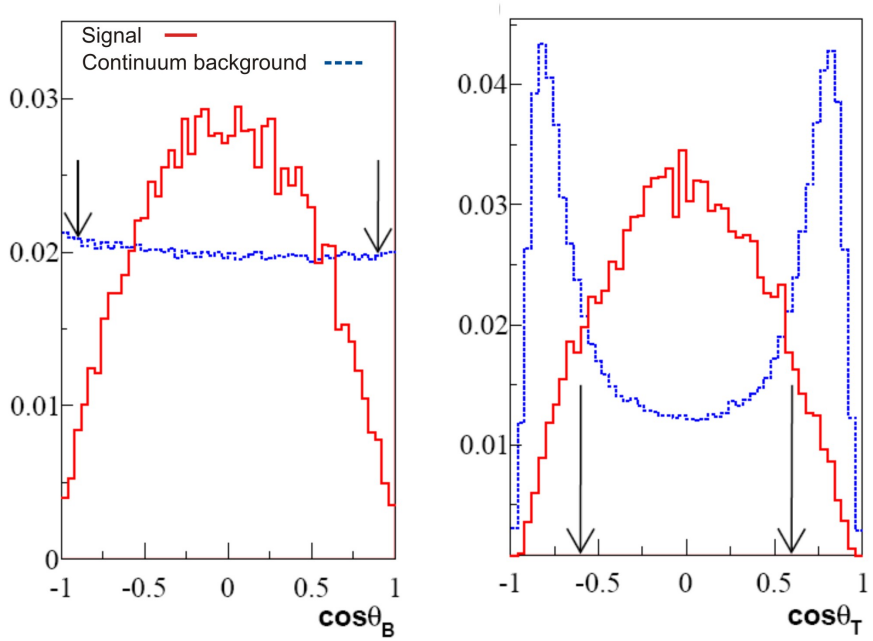


Figure 1.2: Feynman diagrams for $B^0 \to \bar{\nu}\tilde{\chi}_1^0$ decay in the R-parity violation model.

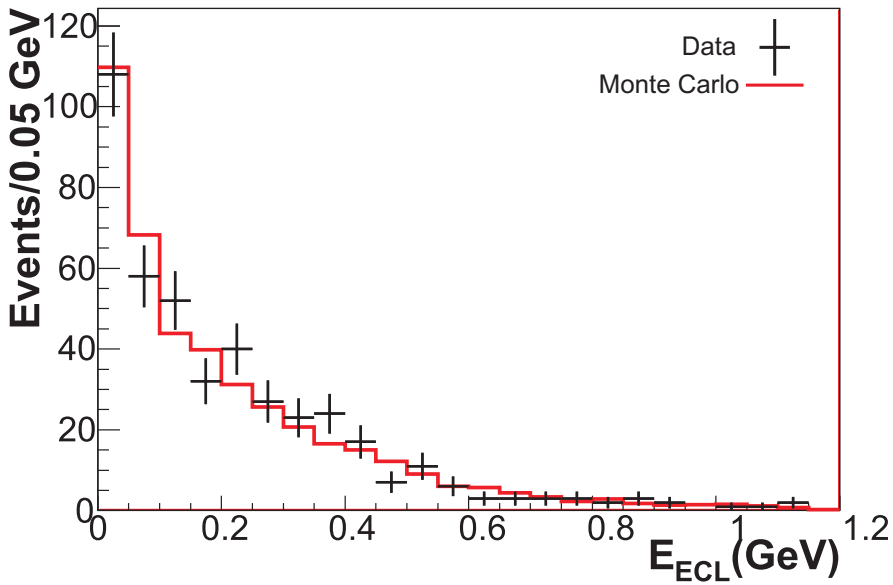
$B^0 \to$ invisible: reconstruction

- Data sample: 605fb^{-1} at the $\Upsilon(4S)$ resonance (657×10^6 $B\bar{B}$ pairs)
- One B meson fully reconstructed in hadronic modes (B_{tag})
- 9.5×10^5 neutral B_{tag} candidates
- Candidate selection requirements: no additional charged tracks, π^0 or K_L^0 candidates left in the event
- Continuum background ($e^+e^- \to q\bar{q}$) suppressed using
  - cut on $\cos\theta_T$: angle between the B_{tag} thrust axis and the beam axis in the CM frame
  - $\cos\theta_B$ to extract the signal yield: angle between the B_{tag} flight direction and the beam axis in the CM frame (cut away the region around ± 1 as differences between data and MC were observed in the sideband)



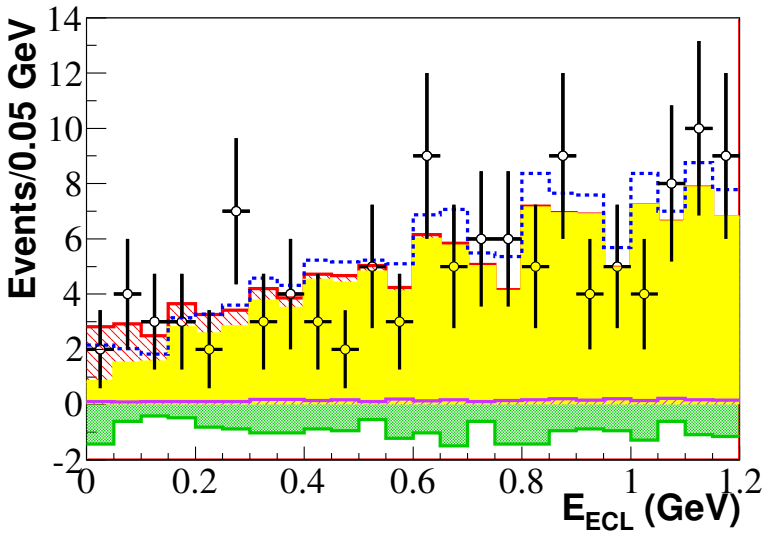
$B^0 \to$ invisible: reconstruction

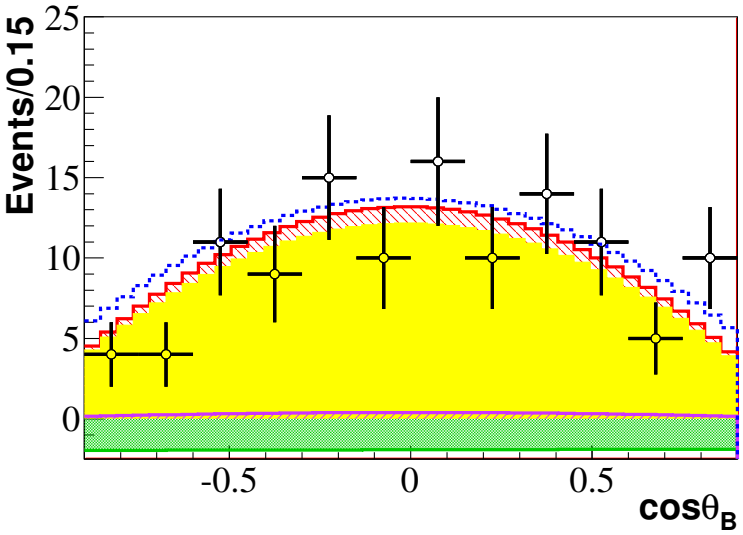
- Most powerful variable: sum of the energies of ECL (electromagnetic calorimeter) clusters that are not associated with B_{tag} tracks or neutrals (E_{ECL})
- The signal yield is extracted from an extended unbinned maximum likelihood fit to E_{ECL} and $\cos\theta_B$
- Most of the background components models obtained from MC simulation (non-B background from off-resonance data)
- Validation of the E_{ECL} simulation using doubly tagged samples: hadronic B_{tag} + $B^0 \to D^{(*)-} l^+ \nu$ ($l = e, \mu$)



Comparison between data and MC for the control samples

$B^0 \to$ invisible: results (*Belle preliminary*)





red: signal PDF

yellow: total background

blue: $B\bar{B}$ background

pink: rare background

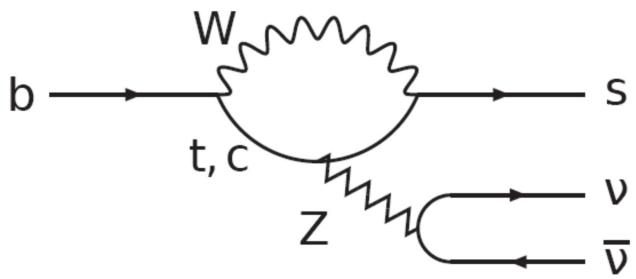
green: continuum background

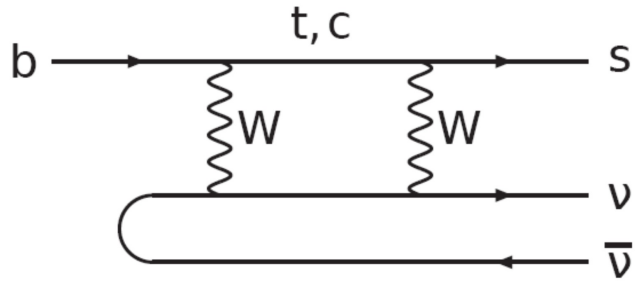
- $N_{sig} = 8.9^{+6.3}_{-5.5}$
- Upper limit: $\mathcal{B}(B \to$ invisible$) < 1.3 \times 10^{-4}$
  (limit estimation performed using the fit likelihood as a function of the branching fraction)

$B \to h^{(*)} \nu \bar{\nu}$

Motivation

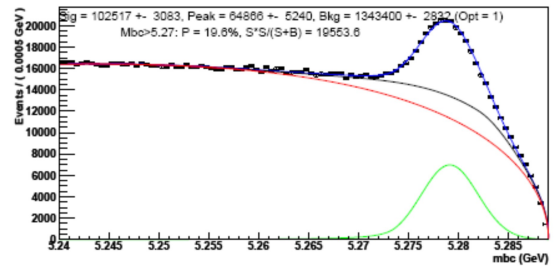
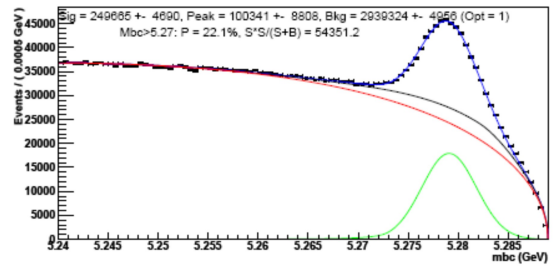
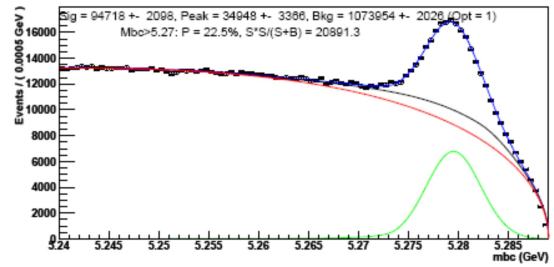
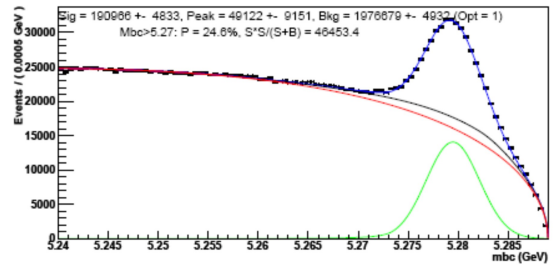
- Flavor changing neutral currents forbidden at tree level
- $b \to s\nu\bar{\nu}$ and $b \to d\nu\bar{\nu}$ highly suppressed
- Very precise theoretical predictions (only one hadron in the final state, no charged leptons)
- Models beyond SM (SUSY, non-standard Z coupling, fourth generation) could enhance these decays





$B \to h^{(*)}\nu\bar{\nu}$: reconstruction

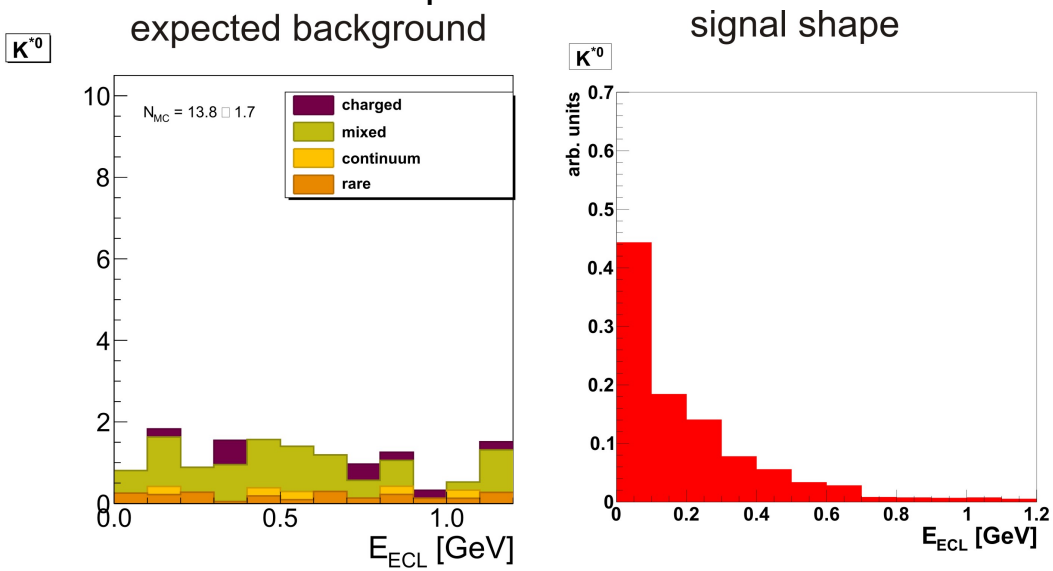
- Larger data sample and improved reconstruction compared to the previous Belle analysis
- Data sample: 711fb^{-1} at the $\Upsilon(4S)$ resonance (771×10^6 $B\bar{B}$ pairs)
- Data reprocessed with new improved tracking
- One B meson fully reconstructed in hadronic modes (B_{tag}) using **new full reconstruction** NIM A 654, 432-440 (2011)
  - 1104 decay channels exclusively reconstructed
  - Hierarchical reconstruction procedure
  - Multivariate approach (neural net package NeuroBayes) instead of cuts
  - Efficiency improvement of factor ~ 2 for the same purity

	Cut-based predecessor	NeuroBayes Full Reconstruction
B^+		
	sig: 103,000 bg: 1,300,000 pur: 19.6 %	sig: 250,000 bg: 2,900,000 pur: 22.1 %
B^0		
	sig: 95,000 bg: 1,100,000 pur: 22.5 %	sig: 191,000 bg: 2,000,000 pur: 24.6 %

$B \to h^{(*)}\nu\bar{\nu}$: reconstruction

- Larger data sample and improved reconstruction compared to the previous Belle analysis
- Find one light meson (K^+, K^*, K_s^0, K^{*0}, π^+, π^0, ρ^+, ρ^0, ϕ)
- No additional charged tracks or π^0 candidates left in the event
- Continuum background ($e^+e^- \to q\bar{q}$) suppressed using
  $\cos\theta_T$: angle between the B_{tag} thrust axis and the beam axis in the CM frame
- Most powerful variable: sum of the energies of ECL (electromagnetic calorimeter) clusters that are not associated with B_{tag} tracks or neutrals (E_{ECL})
- The signal yield is extracted from an extended binned maximum likelihood fit to E_{ECL}

Example: $B^0 \to K^{*0}\nu\bar{\nu}$



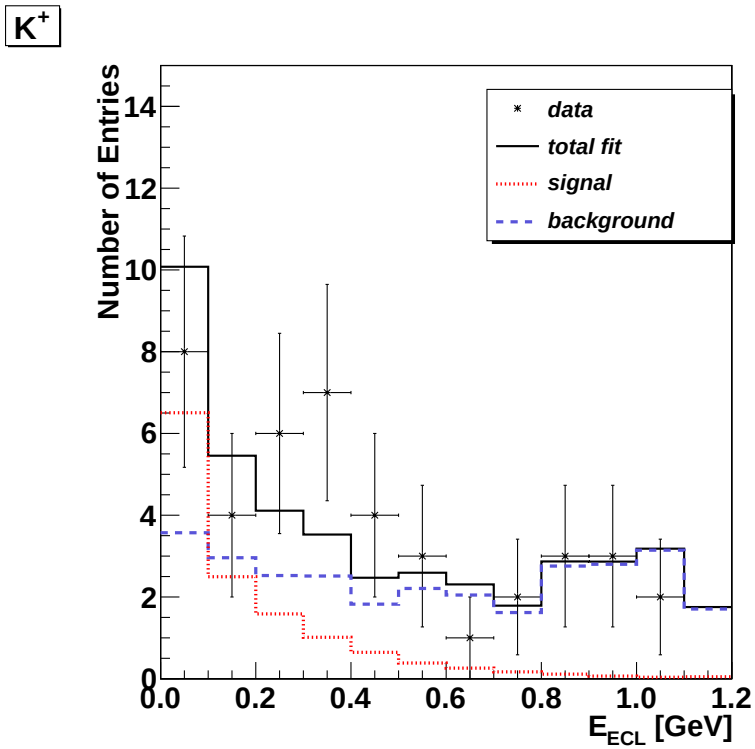
$B \to h^{(*)}\nu\bar{\nu}$: expected limits

- Comparison of sensitivity of the new analysis to the previous one

Channel	Expected branching ratio limit at 90% CL (711fb^{-1})	Expected branching ratio limit at 90% CL, previous Belle analysis (492fb^{-1}) K.-F. Chen et al, Phys. Rev. Lett. 99.22 (2007)
$B^+ \to K^+\nu\bar{\nu}$	2.2×10^{-5}	10×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^+\pi^0$	4.2×10^{-5}	22×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^0_s\pi^+$	4.4×10^{-5}	22×10^{-5}
$B^+ \to \pi^+\nu\bar{\nu}$	3.9×10^{-5}	10×10^{-5}
$B^+ \to \rho^+\nu\bar{\nu}$	9.8×10^{-5}	19×10^{-5}
$B^0 \to K^0_s\nu\bar{\nu}$	7.3×10^{-5}	16×10^{-5}
$B^0 \to K^{*0}\nu\bar{\nu}$ $K^{*0} \to K^+\pi^-$	5.0×10^{-5}	20×10^{-5}
$B^0 \to \pi^0\nu\bar{\nu}$	3.6×10^{-5}	10×10^{-5}
$B^0 \to \rho^0\nu\bar{\nu}$	16.5×10^{-5}	16×10^{-5}
$B^0 \to \phi\nu\bar{\nu}$	9.1×10^{-5}	13×10^{-5}

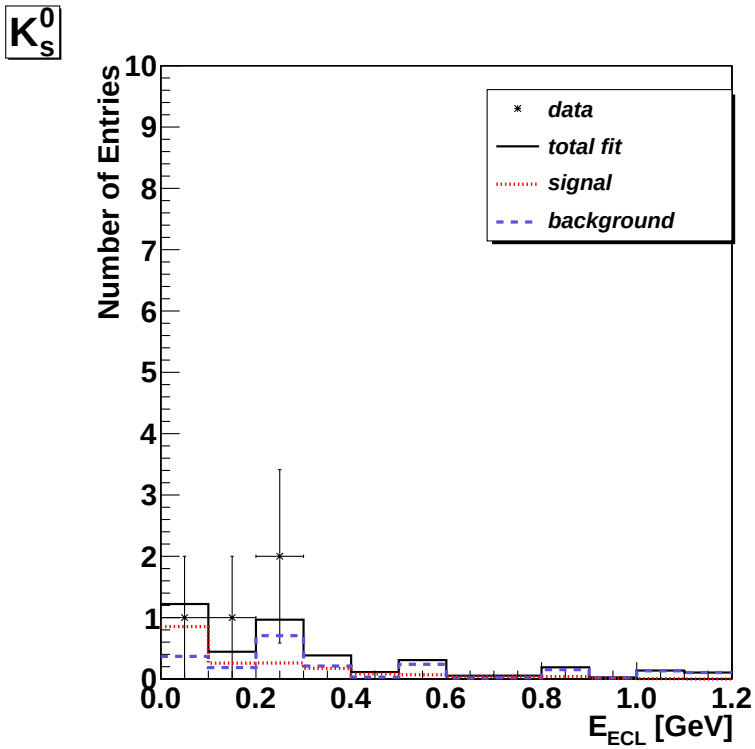
$B \to h^{(*)}\nu\bar{\nu}$: results (*Belle preliminary*)

$B^+ \to K^+\nu\bar{\nu}$



$$N_{Sig} = 13.3^{+7.4}_{-6.6}$$
$$S_{stat} = 2.1\sigma$$
$$S_{stat+syst} = 2.0\sigma$$

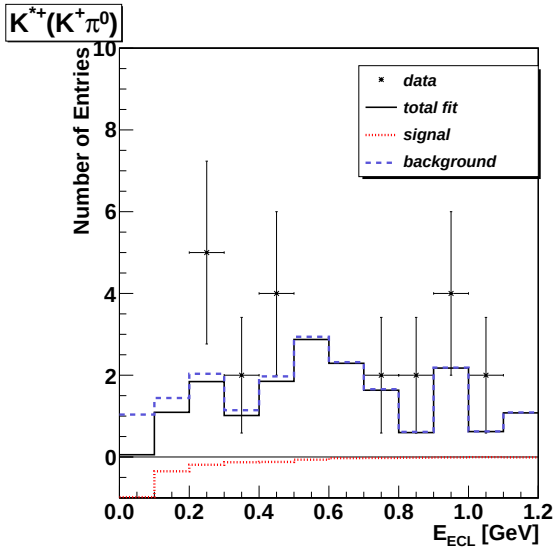
$B^0 \to K^0_s\nu\bar{\nu}$



$$N_{Sig} = 1.8^{+3.3}_{-2.4}$$
$$S_{stat} = 0.6\sigma$$
$$S_{stat+syst} = 0.6\sigma$$

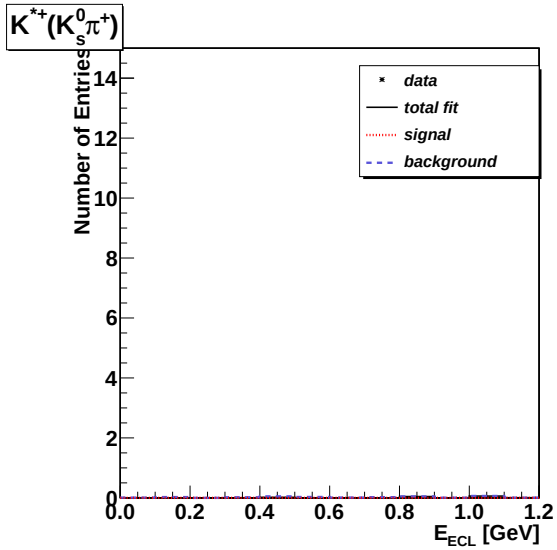
$B \to h^{(*)}\nu\bar{\nu}$: results (***Belle preliminary***)

$B^+ \to K^{*+}(K^+\pi^0)\nu\bar{\nu}$



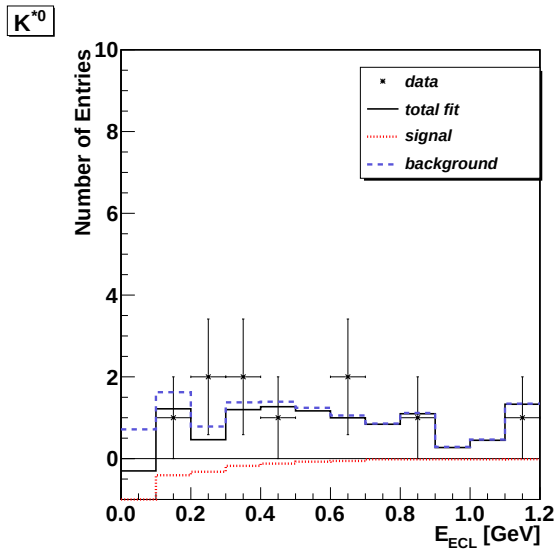
$N_{Sig} = -1.9^{+1.7}_{-1.1}$

$B^+ \to K^{*+}(K^0_s\pi^+)\nu\bar{\nu}$



$N_{Sig} = 0.0$

$B^0 \to K^{*0}\nu\bar{\nu}$

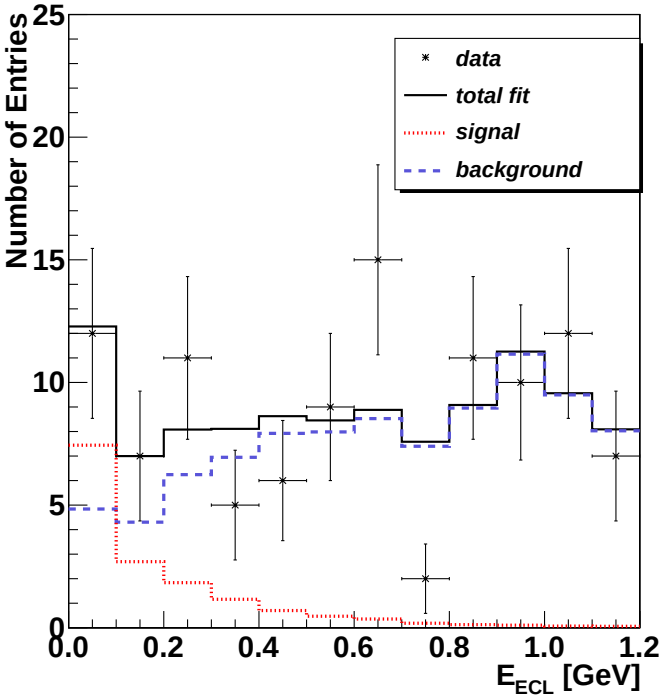


$N_{Sig} = -2.3^{+10.1}_{-3.5}$

$B \to h^{(*)}\nu\bar{\nu}$: results (***Belle preliminary***)

$B^+ \to \pi^+\nu\bar{\nu}$

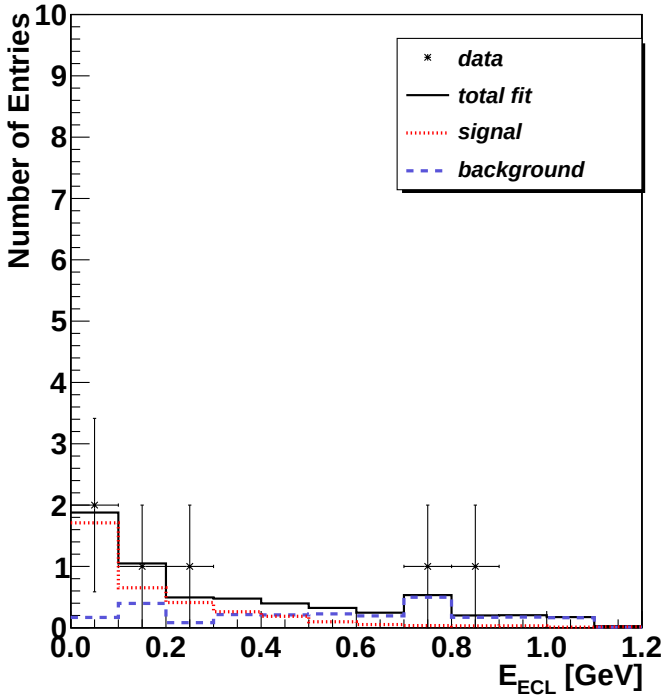
π^+



$$N_{Sig} = 15.2^{+7.1}_{-6.2}$$
$$S_{stat} = 2.8\sigma$$
$$S_{stat+syst} = 2.6\sigma$$

$B^0 \to \pi^0\nu\bar{\nu}$

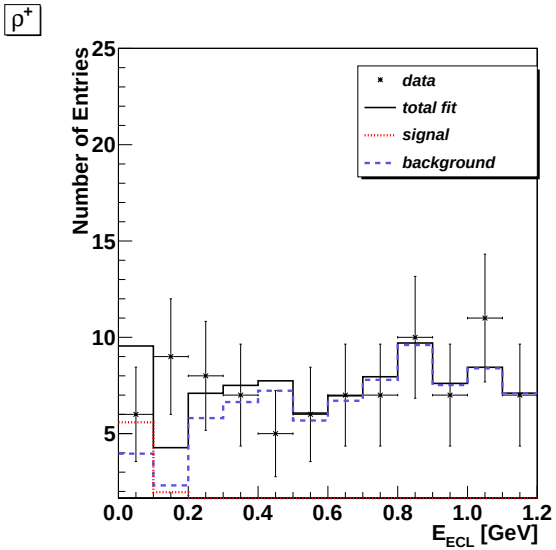
π^0



$$N_{Sig} = 3.5^{+2.6}_{-1.9}$$
$$S_{stat} = 2.2\sigma$$
$$S_{stat+syst} = 2.0\sigma$$

$B \to h^{(*)}\nu\bar{\nu}$: results (*Belle preliminary*)

$B^+ \to \rho^+\nu\bar{\nu}$

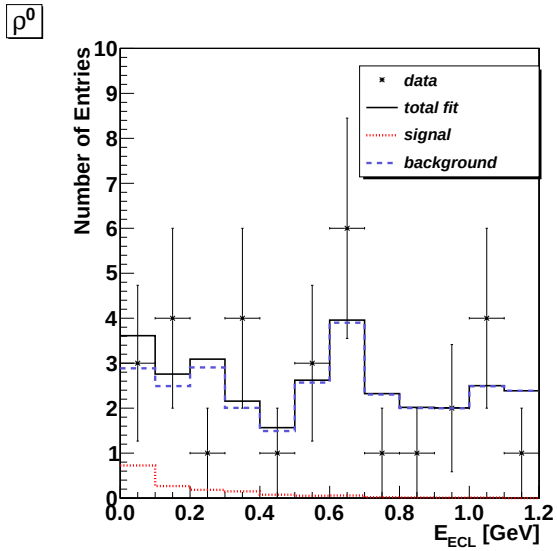


$N_{Sig} = 11.3^{+6.3}_{-5.4}$

$S_{stat} = 2.3\sigma$

$S_{stat+syst} = 1.7\sigma$

$B^0 \to \rho^0\nu\bar{\nu}$

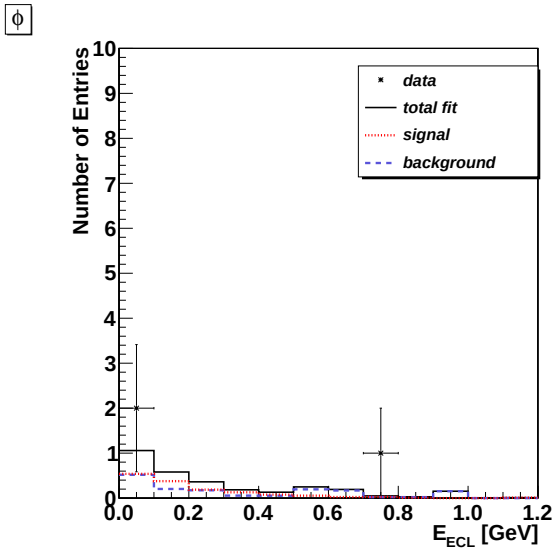


$N_{Sig} = 1.6^{+5.0}_{-4.1}$

$S_{stat} = 0.4\sigma$

$S_{stat+syst} = 0.4\sigma$

$B^0 \to \phi\nu\bar{\nu}$



$N_{Sig} = 1.5^{+2.85}_{-0.9}$

$S_{stat} = 0.6\sigma$

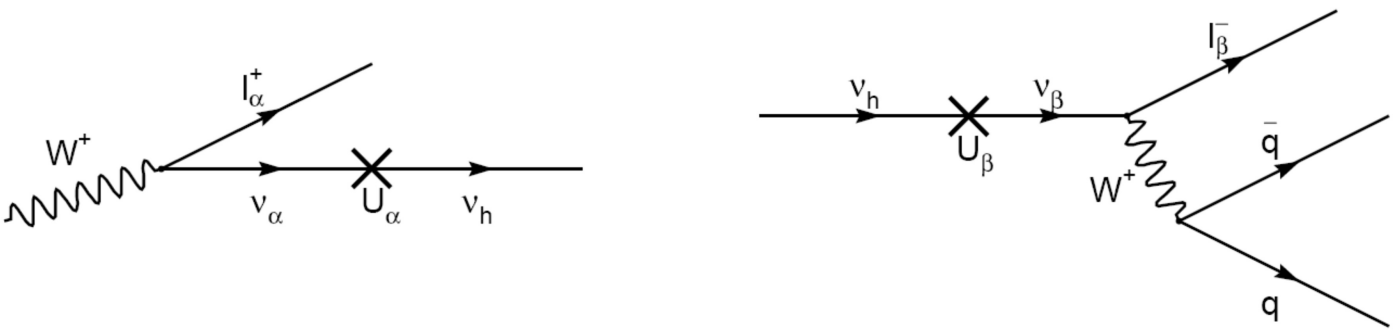
$S_{stat+syst} = 0.5\sigma$

$B \to h^{(*)}\nu\bar{\nu}$: results (***Belle preliminary***)

Channel	Branching ratio limit at 90% CL	Branching ratio limit at 90% CL previous Belle analysis	PDG limit at 90% CL
$B^+ \to K^+\nu\bar{\nu}$	5.5×10^{-5}	1.4×10^{-5}	1.3×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^+\pi^0$	3.3×10^{-5}	14×10^{-5}	8×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^0_s\pi^+$	2.9×10^{-5}	14×10^{-5}	8×10^{-5}
$B^+ \to \pi^+\nu\bar{\nu}$	9.8×10^{-5}	17×10^{-5}	10×10^{-5}
$B^+ \to \rho^+\nu\bar{\nu}$	21.4×10^{-5}	44×10^{-5}	15×10^{-5}
$B^0 \to K^0_s\nu\bar{\nu}$	9.4×10^{-5}	16×10^{-5}	5.6×10^{-5}
$B^0 \to K^{*0}\nu\bar{\nu}$ $K^{*0} \to K^+\pi^-$	5.4×10^{-5}	34×10^{-5}	1.2×10^{-5}
$B^0 \to \pi^0\nu\bar{\nu}$	6.9×10^{-5}	22×22^{-5}	22×10^{-5}
$B^0 \to \rho^0\nu\bar{\nu}$	20.8×10^{-5}	44×10^{-5}	44×10^{-5}
$B^0 \to \phi\nu\bar{\nu}$	12.5×10^{-5}	5.8×10^{-5}	5.8×10^{-5}

$B \rightarrow$ heavy neutral lepton

- Mass generation in SM: coupling of the Higgs boson to left and right components of the particle
- No right-handed neutrino in SM $\rightarrow$ neutrinos should be massless
- Neutrino oscillation show that neutrinos do have a mass
- $\Rightarrow$ sterile right-handed neutrinos?
- Heavy neutral leptons appear in many models beyond SM(SUSY, νMSM, GUT)



a) *b)*

FIG. 1. Heavy neutrino production *(a)* and decay *(b)* diagrams.

- No strong interaction (lepton)
- No weak interaction (right handed)
- No electromagnetic interaction (neutral)
- Only way to interact: mixing with left-handed neutrinos

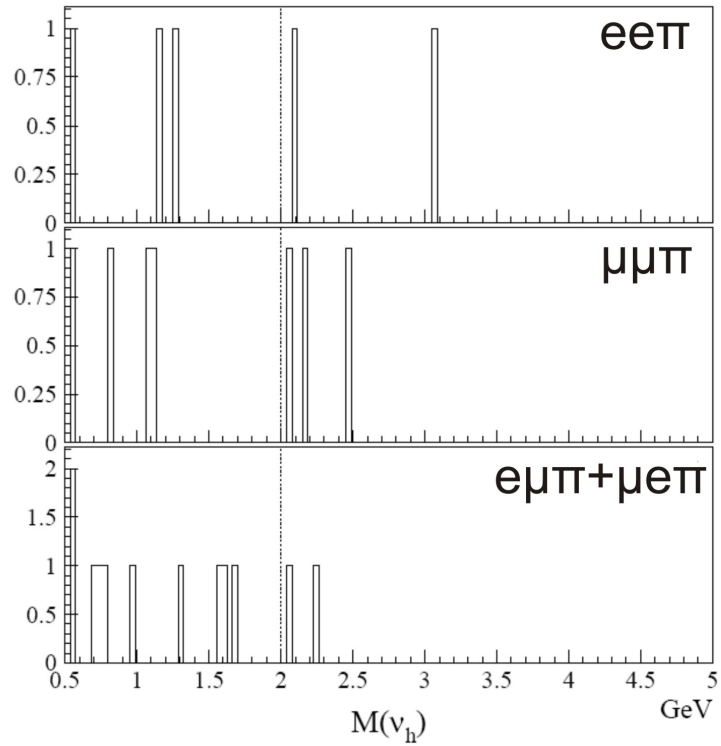
$B \to \nu_h$: reconstruction

- Search for $B \to l\nu_h(X)$, $\nu_h \to l\pi$ decays ($l = e, \mu$)
- $M(\nu_h) = M(l_1\pi)$
- 'small' masses ($<$ 2GeV): pick out $B \to D^{(*)}l\nu_h$,
  'large' masses ($>$ 2GeV): inclusive reconstruction)
- Distinctive feature of ν_h: large flight length ($c\tau \sim 20$m)
- Selection to strongly suppress the background:
  - Strict lepton identification requirements to suppress physical background from decay with similar topology
  - ν_h vertex quality requirements to suppress combinatorial background
- Background reduced by a factor $\sim 10^6$
- Efficiency depends on B meson decay mode and ν_h mass ($\sim 3.3\% - 17\%$)

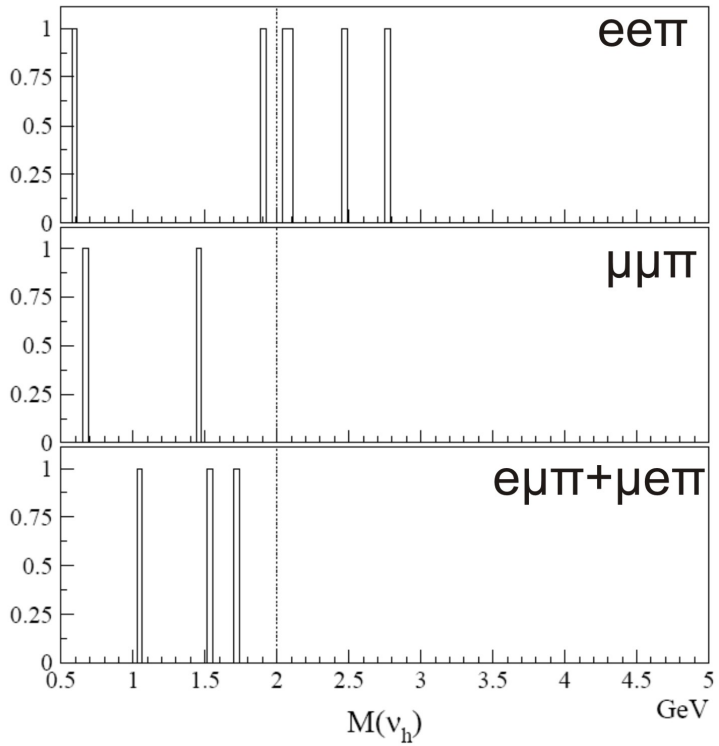
$B \to \nu_h$: results (***Belle preliminary***)

Expectations from MC (obtained from 3 streams)	Results on data
$ee\pi$: 2.3 ± 1.0	$ee\pi$: 6 ± 2.5
$\mu\mu\pi$: 2.3 ± 0.9	$\mu\mu\pi$: 2 ± 1.4
$e\mu\pi + \mu e\pi$: 4.0 ± 1.2	$e\mu\pi + \mu e\pi$: 3 ± 1.7

Expectation from MC

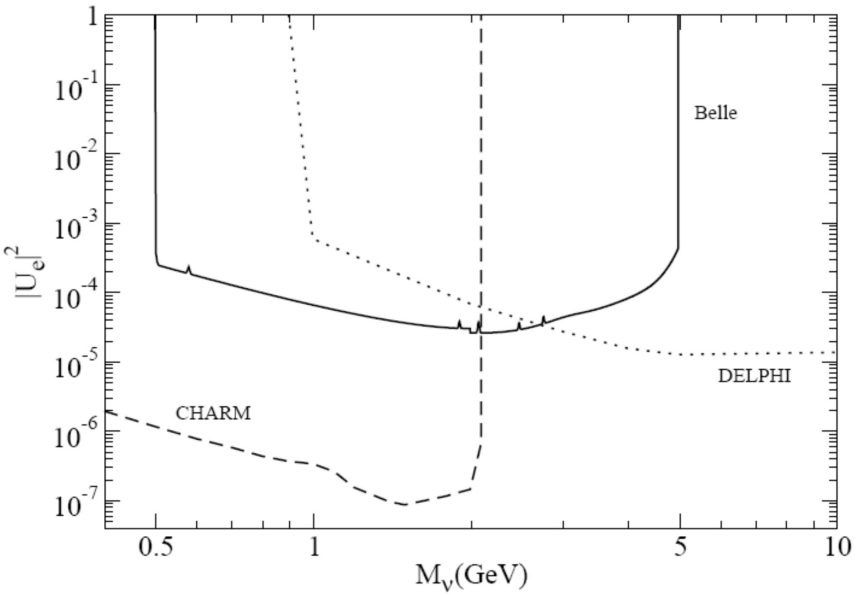


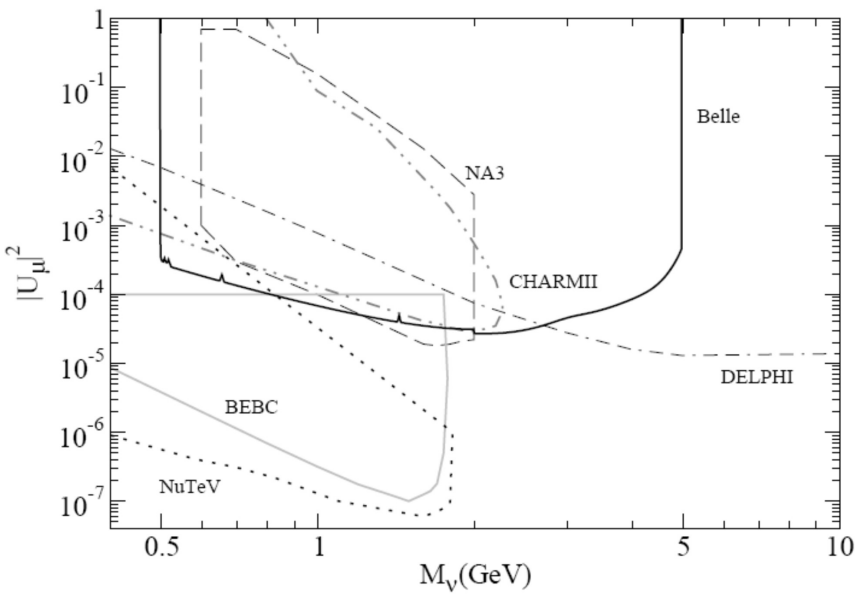
Results on data



$B \to \nu_h$: results (*Belle preliminary*)

- Upper limit on mixing in the mass range $0.5 - 5$ GeV/c^2 was set
- Maximum sensitivity is reached around 2 GeV/c^2
- Upper limit for product branching fraction was set:
  $\mathcal{B}(B \to l\nu_h(X)) \times \mathcal{B}(\nu_h \to l\pi) < 6.6 \times 10^{-7}$ for $l = e, \mu$





Summary

Summary

- Search for rare decays offers an opportunity to search for New Physics beyond the Standard Model
- In the clean environment of Belle a study of decays with neutrinos in the final state is possible using the full reconstruction
- No significant signal observed in $B^0 \to \nu\bar{\nu}$ and $B^0 \to h^{(*)}\nu\bar{\nu}$: upper limits were evaluated
- Search for heavy neutrinos was performed and limit on the mixing was set

BACKUP

Full reconstruction

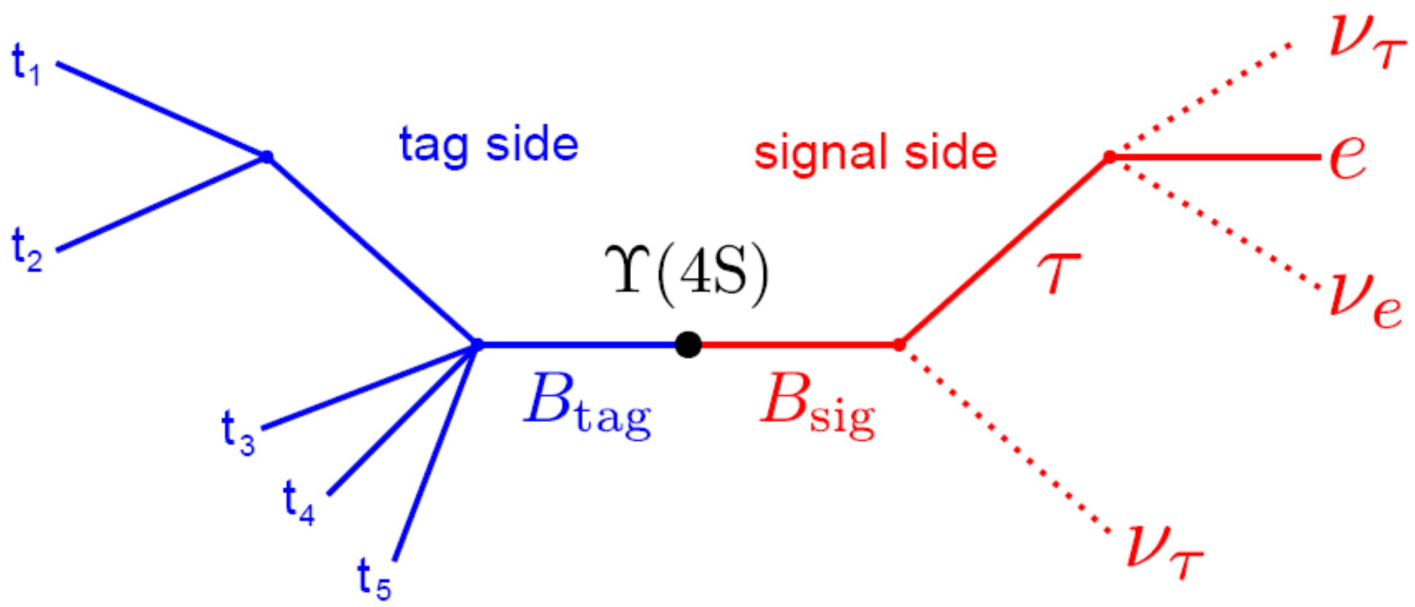


Figure 1: Exemplary fully reconstructed event. The B_{sig} (signal side) is the decay of physics interest, while the B_{tag} (tag side) is the other B meson, reconstructed by the full reconstruction method.

Full reconstruction

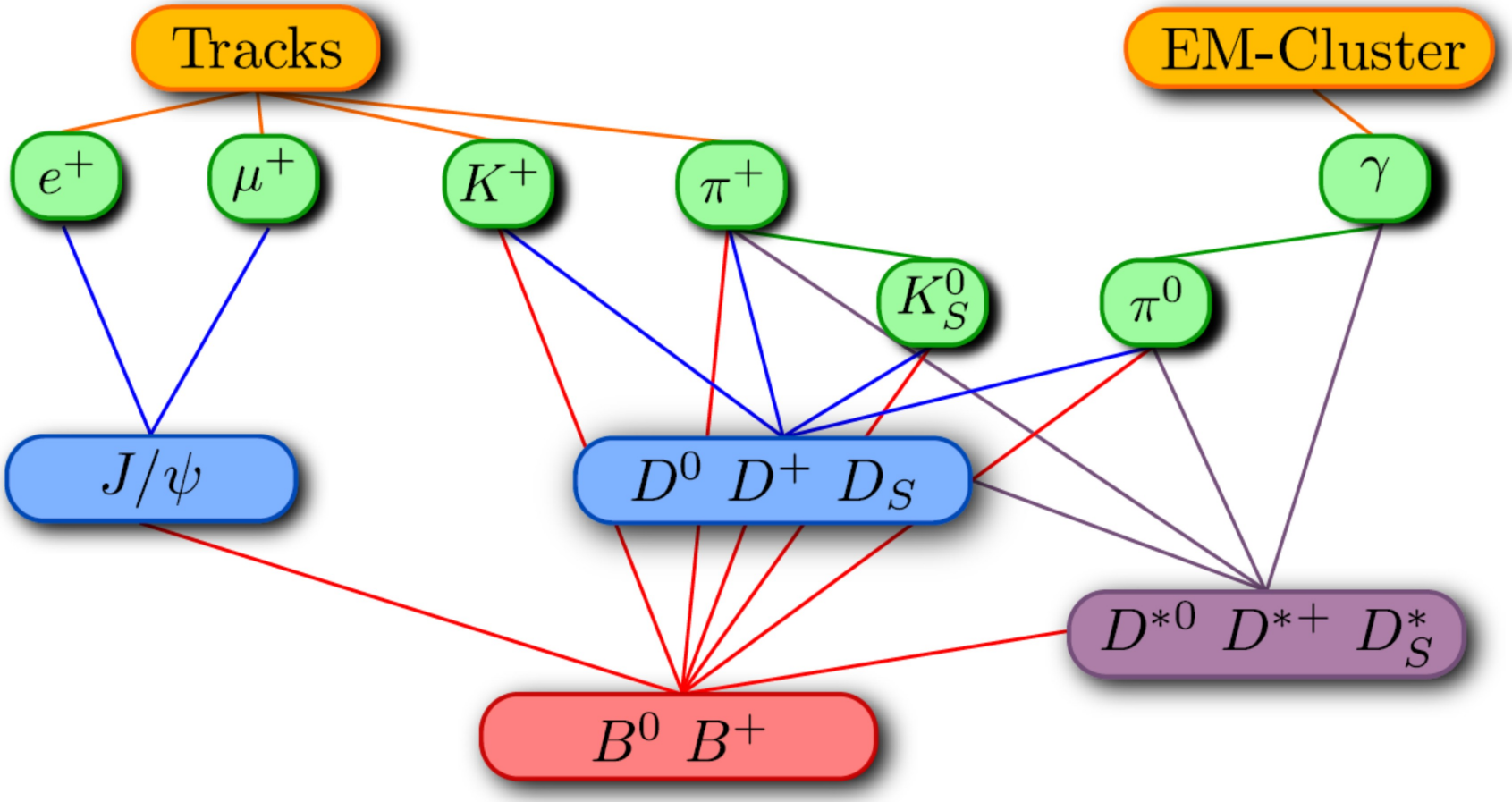
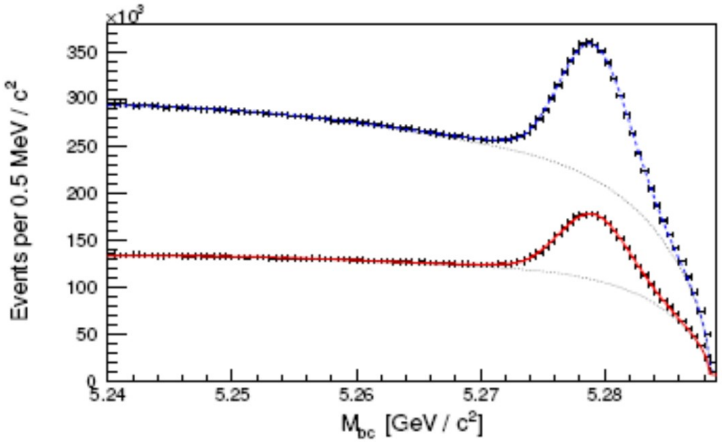
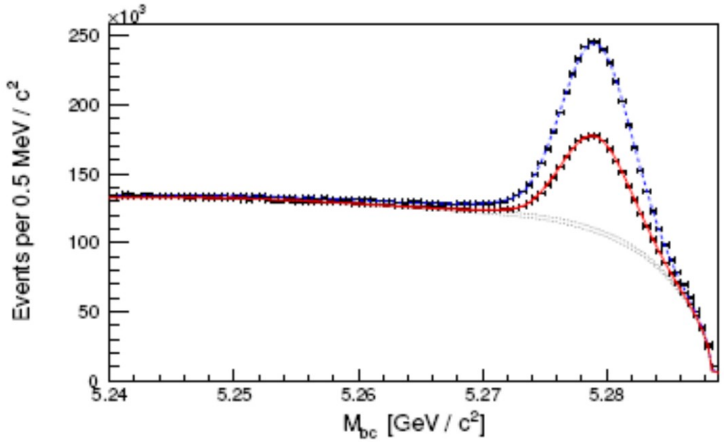


Figure 3: The 4 stages of the full reconstruction

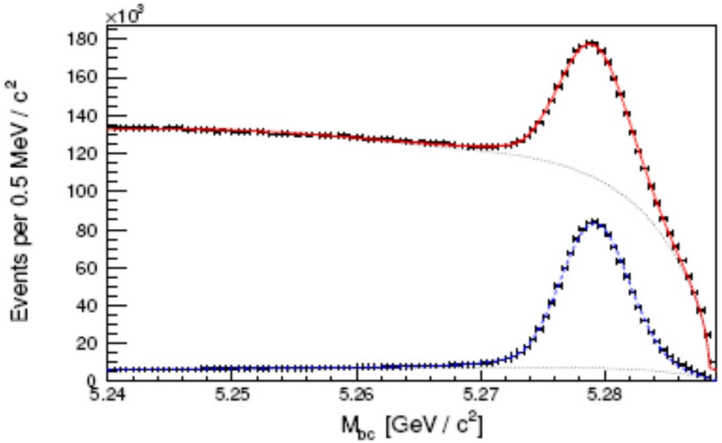
Full reconstruction



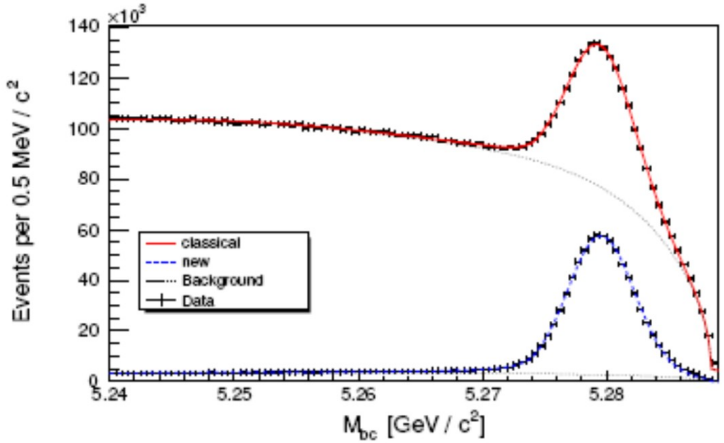
(a) B^+ selection with roughly equal purity



(b) B^+ selection with roughly equal background level



(c) B^+ selection with roughly equal efficiency



(d) B^0 selection with roughly equal efficiency

$B \to h^{(*)}\nu\bar{\nu}$: signal side selection

- B_{tag}:
  - Correct charge combination with the signal-side candidate
  - $M_{bc} > 5.27$ GeV
  - -0.08 GeV$< \Delta E < 0.06$ GeV
  - $BTagNBout > 0.02$
- No remaining π^0 candidates or charged tracks
- Missing momentum: $-0.86 < \cos\theta_{miss} < 0.95$ (to avoid events with particles escaping through the beam pipe)
- Continuum supression: $-0.8 < \cos_{TOB} < 0.7$ (ngle between the thrust axis of the B_{sig} and the rest of the charged tracks)
- Momentum of the light meson: 1.6GeV$< p <$ 2.5GeV

$B \to h^{(*)}\nu\bar{\nu}$: number of events

Channel	Expected total number of background events (Monte Carlo)	Observed number of events in data
$B^+ \to K^+\nu\bar{\nu}$	33.6 ± 2.7	43
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^+\pi^0$	17.2 ± 1.9	21
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K_s^0\pi^+$	2.4 ± 0.7	0
$B^+ \to \pi^+\nu\bar{\nu}$	$101,4 \pm 4.7$	107
$B^+ \to \rho^+\nu\bar{\nu}$	117.0 ± 5.1	90
$B^0 \to K_s^0\nu\bar{\nu}$	3.4 ± 0.9	4
$B^0 \to K^{*0}\nu\bar{\nu}$ $K^{*0} \to K^+\pi^-$	13.8 ± 1.7	10
$B^0 \to \pi^0\nu\bar{\nu}$	7.3 ± 1.3	6
$B^0 \to \rho^0\nu\bar{\nu}$	$33,7 \pm 2.7$	31
$B^0 \to \phi\nu\bar{\nu}$	2.1 ± 0.6	3

$B \to h^{(*)}\nu\bar{\nu}$ signal efficiency

Channel	branching fraction factor	$\epsilon_{sig}[10^{-5}]$ raw	averaged B_{tag} correction	$\epsilon_{sig}[10^{-5}]$ final
$B^+ \to K^+\nu\bar{\nu}$	-	71.6	0.79	56.76 ± 0.67
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^+\pi^0$	0.33	22.5	0.8	17.89 ± 0.66
$B^+ \to K^{*+}\nu\bar{\nu}$ $K^{*+} \to K^0_s\pi^+$	$0.692 \times 0.666 \times 0.5$	12.9	0.79	10.20 ± 0.60
$B^+ \to \pi^+\nu\bar{\nu}$	-	42.3	0.8	33.8 ± 0.52
$B^+ \to \rho^+\nu\bar{\nu}$	-	17.1	0.78	13.47 ± 0.32
$B^0 \to K^0_s\nu\bar{\nu}$	0.692	11.93	0.70	8.36 ± 0.29
$B^0 \to K^{*0}\nu\bar{\nu}$ $K^{*0} \to K^+\pi^-$	0.66	18.5	0.74	14.4 ± 0.40
$B^0 \to \pi^0\nu\bar{\nu}$	-	23.4	0.71	16.6 ± 0.34
$B^0 \to \rho^0\nu\bar{\nu}$	-	8.8	0.72	6.34 ± 0.21
$B^0 \to \phi\nu\bar{\nu}$	0.492	7.9	0.73	5.77 ± 0.15