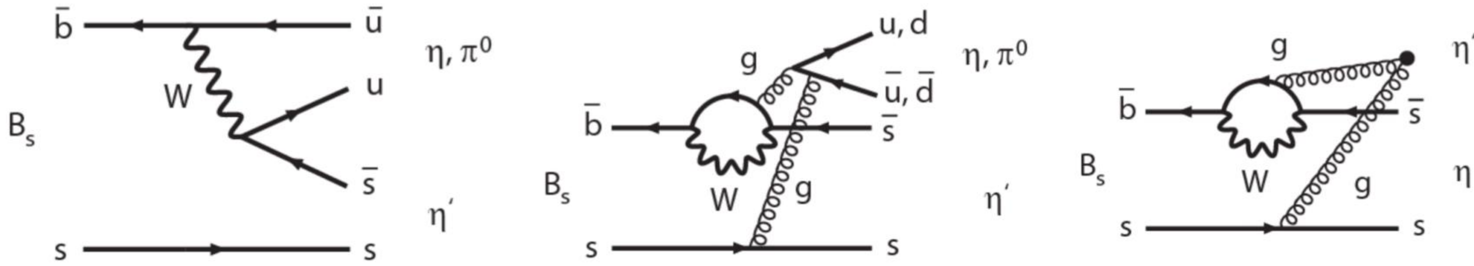
Studies of B and B_s Decays at Belle

Nisar Nellikunnummel
Brookhaven National Laboratory

Search for $B_s \to \eta'\eta$ decay

Introduction



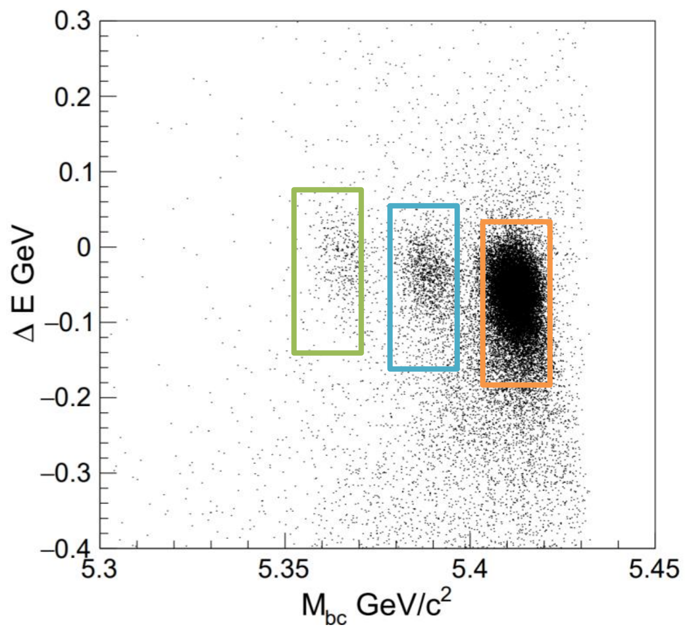
- In the Standard Model charmless hadronic decay $B_s \rightarrow \eta'\eta$ proceeds via b $\rightarrow u$ and b $\rightarrow s$ transitions. Penguin transitions are of special interest since they are sensitive to BSM scenarios.
- Once branching fractions for decays $B_{d,s} \rightarrow \eta\eta, \eta'\eta, \eta'\ \eta'$ are measured, it would be possible to extract CP violating parameters from the data using the formalism SU(3)/U(3). (Yu-Kuo Hsiao *et al.* Phys. Rev. D, **93** 114002 (2016)).
- The expected branching fraction for this decay spans a wide range $(2-4) \times 10^{-5}$.(A. R. Williamson *et al.*, PRD **74** 014003, A. Ali *et al.*, PRD **76** 074018, H.-Y. Cheng *et al.*, PRD **91** 014011)

Data and reconstruction

- We report the results of the first search for the $B_s \to \eta'\eta$ decay using $121.4 fb^{-1}$(6.5 million $B_s\overline{B}_s$ pairs, $N_{B_s^{(*)}\bar{B}_s^{(*)}}$) of data collected at Υ(5S) resonance.
- $\Upsilon(5S)$ could decay (20%) into pairs of $B_s^*\overline{B}_s^*$, $B_s\overline{B}_s^*(+c.c.)$ and $B_s\overline{B}_s$. The excited B_s^* transitions to B_s by emitting a photon.
- We reconstruct $B_s \to \eta'\eta$; $\eta' \to \pi^+\pi^-\eta; \eta \to \gamma\gamma$.
- Variables to identify signal:

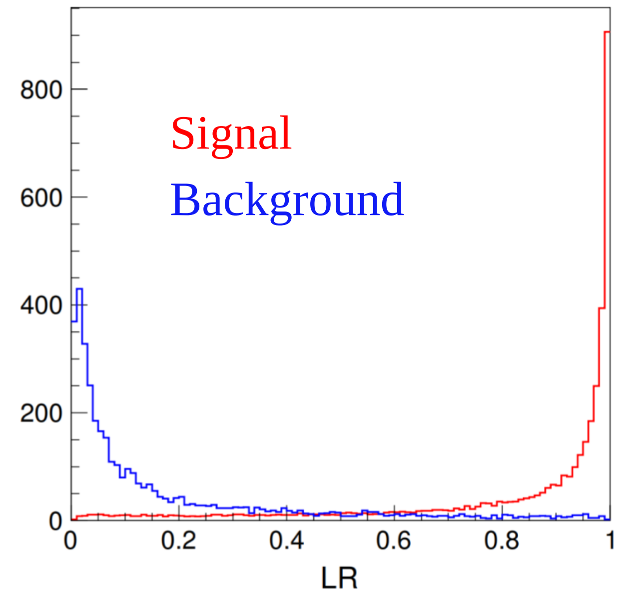
$$M_{bc} = \sqrt{E_{beam}^2 - p_{B_s}^2}$$

$$\Delta E = E_{B_s} - E_{beam}$$



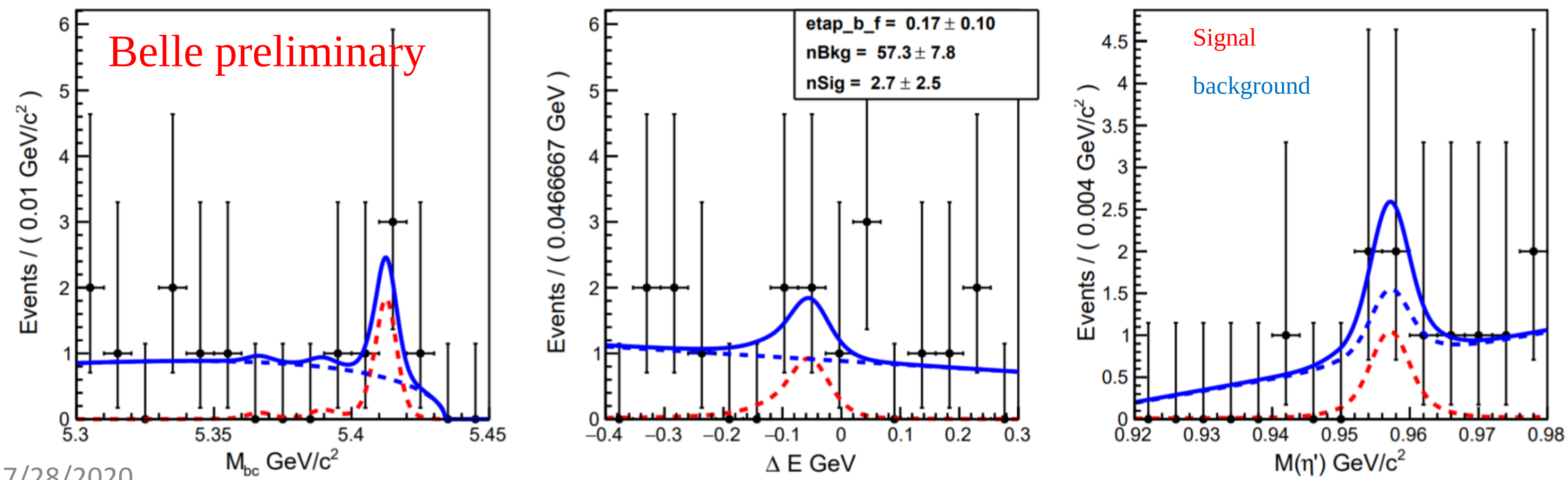
Background and selection

- Background events:
  - Hadronic continuum: due to light quark pairs, $e^+e^- \rightarrow q\bar{q}$. Large momenta of $q\bar{q}$ leads to a "jet-like" topology. The $B_s^0\overline{B}_s^0$ events are distributed isotropically.
  - Peaking background: Due to background events with a real η'. Included in 3D fit.
- Likelihood ratio ($\mathcal{LR}$) derived from Modified FW moments is used to suppress the continuum background.
- $\mathcal{LR}$ selection is optimized for the discovery of $B_s \rightarrow \eta'\eta$ decay.
- Optimized selection $\mathcal{LR} > 0.95$.
- Our selection criteria gives a 10% signal efficiency (ε) for $B_s \rightarrow \eta'\eta$ signal (99% background rejection).



Signal yield from data

- Signal yield is extracted using unbinned extended maximum likelihood fit to M_{bc}, ΔE and $M(\eta')$.
- Signal and background shapes (PDFs) are obtained from Belle MC simulation.
- Signal PDFs are calibrated using the control sample, $B^0 \to \eta' K_S$ signal events in the Υ(4S) data.
- Number of signal events = 2.7 ± 2.5.
- Signal-region projections of the 3D fit:



Upper limit on $\mathcal{B}(B_s \to \eta'\eta)$

- In absence of significant number of signal events, we estimate an upper limit on the branching fraction for $B_s \to \eta'\eta$ decay.
- The fitting model is validated using the ensembles of pseudo-experiments and hence we prepared a 80% confidence belt (CB) using Neyman Construction.
- 90% confidence level (CL) upper limit on branching fraction:

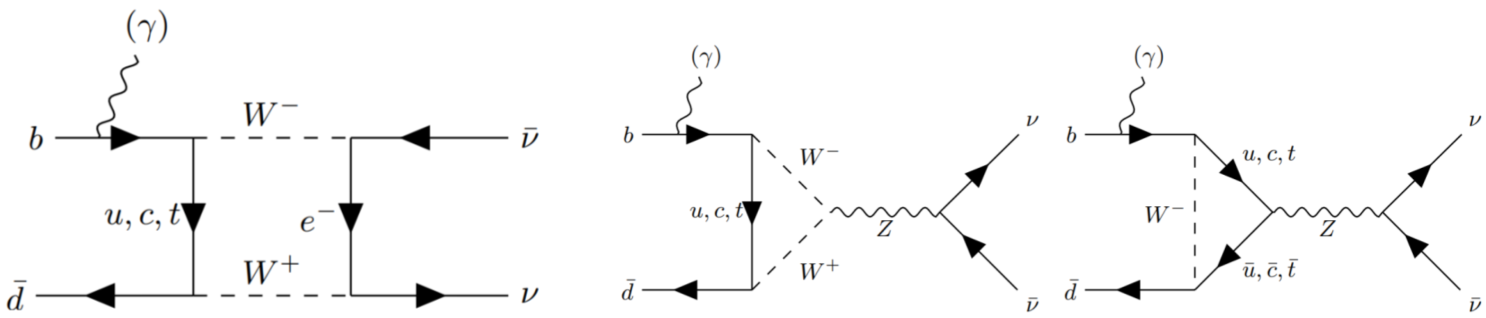
$$\mathcal{B}(B_s^0 \to \eta'\eta) < \frac{N_{\rm UL}^{90\%}}{2 \cdot N_{B_s^{(*)}\bar{B}_s^{(*)}} \cdot \varepsilon \cdot \mathcal{B}_{\rm daughters}}$$

$N_{UL}^{90\%}$ is expected signal yield at 90% CL and obtained from 80% CB.

- Systematic uncertainty is estimated to be 19%.
- Upper limit on the branching fraction, $\mathcal{B}(B_s \to \eta'\eta) < 7.1 \times 10^{-5}$.

B^0 decays to invisible final states $(+\gamma)$

Introduction

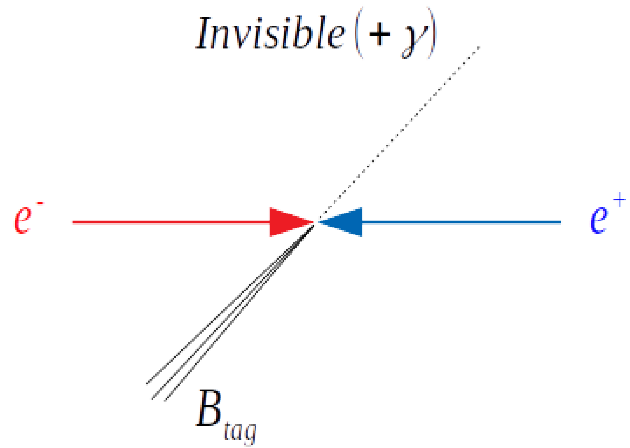


- Search for $B^0 \to$ invisible $(+\gamma)$ decays sensitive to BSM physics. Models with R-parity violation or dark matter contributions predict a branching fraction as high as 10^{-6} to 10^{-7} (A. Dedes *et al*. PRD **65** 015001, A. Badin and A. A. Petrov., PRD **82** (034005)).
- In SM $B^0 \to \nu\bar{\nu}(\gamma)$ is strongly helicity-suppressed (by a factor of (m_ν/m_{B^0})) with an estimated branching fraction of 10^{-25}(G. Buchalla and A. J. Buras, Nucl. Phys. B400, 225).
- A very low background from the SM indicates that a signal of $B^0 \to$invisible$(+\gamma)$ in the current B-factory data would indicate new physics.

Group	Data (fb^{-1})	$\mathcal{B}(B^0 \to \text{invisible})$	$\mathcal{B}(B^0 \to \text{invisible}+\gamma)$	Reference
Belle	424	$< 1.2 \times 10^{-4}$		PRD **86,** 032002
BABAR	606	$< 2.4 \times 10^{-5}$	$< 1.7 \times 10^{-5}$	PRD **86**, 051105

Data and selection

- We use $711 fb^{-1}$ of data at $\Upsilon(4S)$ resonance (772 million $B\overline{B}$ pairs).
- In $B\overline{B}$ events, one B^0 is fully reconstructed (B_{tag}). Nothing ($B^0 \to$ invisible) or a photon ($B^0 \to$ invisible+γ) in the remaining part of the event is considered as a signal candidate.

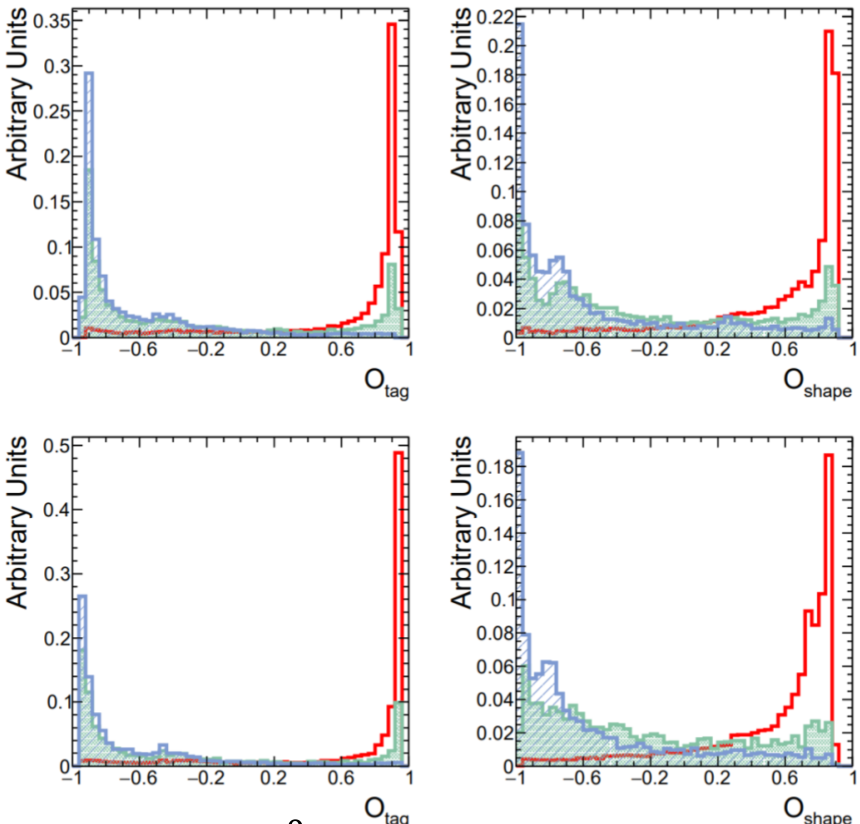


- 1.4 million B_{tag} candidates are reconstructed from hadronic decay channels using an improved algorithm (based on neural network).
- Reconstruction efficiencies of B_{tag} is 0.41% (0.47%) in $B^0 \to \nu\bar{\nu}$ ($B^0 \to \nu\bar{\nu}\gamma$) simulation.
- γ selection for $B^0 \to$ invisible+γ : $E_\gamma > 0.5$ GeV.
- After B_{tag} reconstruction, events with extra tracks, π^0, or K_L^0 are rejected.

Background and variables used to identify signal

- Background:
  1. $e^+e^- \rightarrow q\overline{q}$ (non-B).
  2. B decays through b $\rightarrow c$ (Generic B).
- Two separate neural networks implemented to reject:
  1. Fake B_{tag} (O_{tag})
  2. Events with jet-like topology (O_{shape})
- E_{ECL}: sum of all the remaining energies of ECL clusters.
- $\cos\theta_T$: cosine of the angle between the two thrust axes (B_{tag} and the rest of the event) in the e^+e^- CM frame.

$B^0 \rightarrow$ invisible



$B^0 \rightarrow$ invisible+γ

$B^0 \to$ invisible

- The signal yield for B0 → invisible is extracted from data through fitting variables E_{ECL} and $\cos\theta_T$.
- All PDFs are obtained from MC simulation (non-B component is from off-resonance data).
- $B^{0,\pm} \to D^{*,\pm} l\nu$ are used as control sample to estimate systematics.
- Systematic uncertainty of the signal efficiency is 7.9%.
- Upper limit on branching fraction, $\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$.

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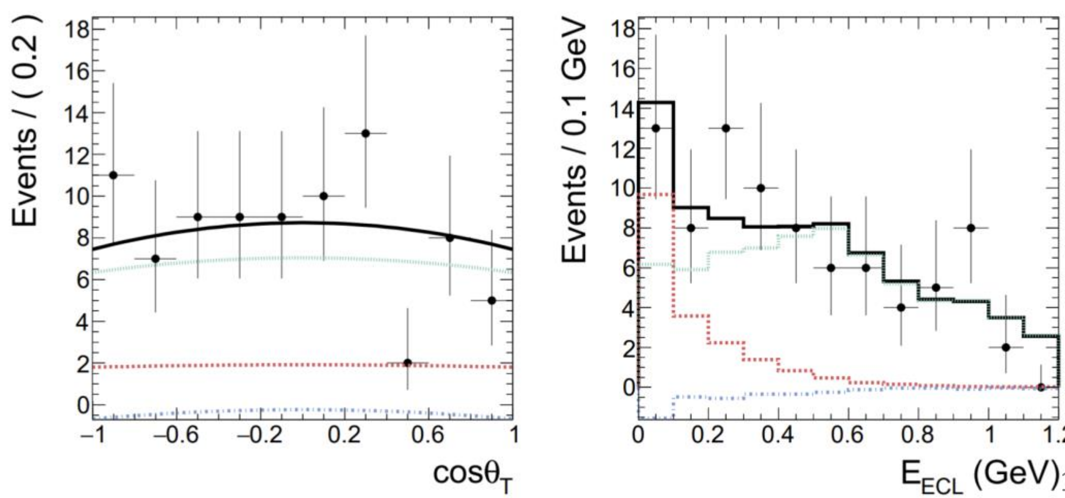
Component	Yields
Signal	$18.8^{+15.3}_{-14.5}$
Generic B	$68.1^{+12.2}_{-11.7}$
Non-B	$-3.9^{+19.5}_{-17.5}$



$B^0 \to \text{invisible} + \gamma$

- Searched by counting events in the bins of $M_{miss}^2 = \left(\vec{P}_{beam} - \vec{P}_{B_{tag}} - \vec{P}_{\gamma}\right)^2$ in E_{ECL} signal box($E_{ECL} < 0.3$ GeV).
- The number of background events in the signal box is estimated from the E_{ECL} data sideband multiplied by a scaling factor obtained from MC.
- Observed numbers of events are all consistent within uncertainties with the expected backgrounds.

	$N_{\rm bkg,box}^{\rm data}$	$N_{\rm box}^{\rm data}$
$B^0 \to \text{invisible} + \gamma$	16.1 ± 6.3	11
bin1	3.2 ± 2.1	2
bin2	1.0 ± 0.8	2
bin3	4.4 ± 2.6	3
bin4	7.1 ± 2.9	4
bin5	6.6 ± 2.9	7

- Systematic uncertainty of the signal efficiency is 8.4%.
- Upper limit on branching fraction, $\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$.

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Summary

- We present a preliminary result of the first search for the decay $B_s \to \eta'\eta$ using full data sample collected by Belle at $\Upsilon(5S)$ resonance.
- In absence of a statistically significant signal, a 90% CL upper limit is set on its branching fraction of 7.1×10^{-5}.
- We report searches for $B^0 \to$ invisible and $B^0 \to$ invisible $+\gamma$ decays using full Belle data sample collected at $\Upsilon(4S)$ resonance.
- We observe no significant signal for either decay and set upper limits on their branching fractions at 90% confidence level of

  $\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$ and $\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$.
- The results on $B^0 \to$ invisible $(+\gamma)$ decays are published in Phys. Rev. D **102**, 012003 (2020).

Backup

$B_s \rightarrow \eta' \eta$

Model	Branching Fraction	Reference
Soft collinear effective theory	$(38 \pm 8) \times 10^{-6}$	A. R. Williamson *et al.* [4]
Perturbative QCD (pQCD)	$(21.0^{+6.0+10.0+0.0}_{-4.6-5.6-0.0}) \times 10^{-6}$	A. Ali *et al.* [5]
QCD factorization (QCDF)	$(41.2^{+27.3+17.8}_{-12.9-13.1}) \times 10^{-6}$	H.-Y. Cheng *et al.* [6]
SU(3) flavor symmetry	$(33.47 \pm 3.64) \times 10^{-6}$	H.-Y. Cheng *et al.* [7]
U(3) flavor symmetry	$- - \times 10^{-6}$	Y.-K. Hsiao *et al.* [2]

Particle	Criteria
γ	$E \geq 50$ MeV (barrel)
	$E \geq 100$ MeV (endcap)
	$E9/E25 \geq 0.75$
$\pi^{\pm}$	$dr \leq 0.3$ cm
	$\lvert dz \rvert \leq 4$ cm
	$p_T \geq 100$ MeV/c
	$KID \leq 0.6$
	$EID \leq 0.85$ MeV/c
η	0.515 GeV/c^2 $\leq M(\gamma\gamma) \leq$ 0.580 GeV/c^2
	$\lvert \cos\theta_{hel} \rvert < 0.97$
η'	0.92 GeV/c^2 $\leq M(\pi^+\pi^-\eta) \leq$ 0.98 GeV/c^2
B_s	$M_{bc} \geq 5.3$ GeV/c^2
	-0.4 GeV $\leq \Delta E \leq$ 0.3 GeV

Control samples for $B^0 \to$ invisible $(+\gamma)$ systematics

- Six $B^{\pm,0}$ decaying to $D^{(*,\pm)} l\nu$ modes are used to estimate the systematic error on efficiency. In all the control sample analysis, one of the B meson is hadronically tagged using Full Recon package, and the signal side is reconstructed in the remaining event. The final state particles used to reconstruct the other B meson in the signal side are removed to mimic $\gamma\nu\bar{\nu}$ case.

$B^0 \to D^- e^+ \nu$	$D^- \to K^+ \pi^- \pi^-$
$B^0 \to D^- \mu^+ \nu$	$D^- \to K^+ \pi^- \pi^-$
$B^- \to D^{*0} e^- \nu$	$D^{*0} \to D^0 \pi^0$; $D^0 \to K^- \pi^+$
$B^- \to D^{*0} \mu^- \nu$	$D^{*0} \to D^0 \pi^0$; $D^0 \to K^- \pi^+$
$B^0 \to D^{*-} e^+ \nu$	$D^{*-} \to \bar{D}^0 \pi^-$; $\bar{D}^0 \to K^+ \pi^-$
$B^0 \to D^{*-} \mu^+ \nu$	$D^{*-} \to \bar{D}^0 \pi^-$; $\bar{D}^0 \to K^+ \pi^-$

Table: control sample modes