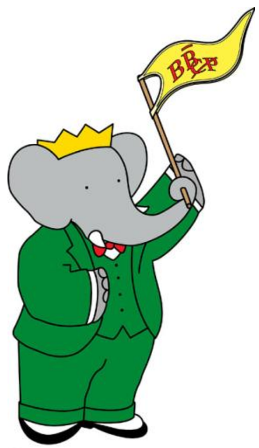
FPCP

Buzios . Rio . Brasil 2013

B decays with significant missing energy



(on behalf of Belle Collaboration)

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Introduction

$$B \to h^{(*)}\nu\bar{\nu}$$
$$B^0 \to invisible(\gamma)$$
$$B^+ \to \ell^+\nu_\ell$$
$$B \to (X)\ell\nu_{heavy}$$

- Rare B-decays with neutrinos.
- Theoretically clean.
- Small Standard Model branching fraction.
- Provides a good place to test the Standard Model .

- All results are from blind analysis.

Hadronic Tagging Method

Complete tagging of a B in $\Upsilon(4S) \rightarrow B\bar{B}$

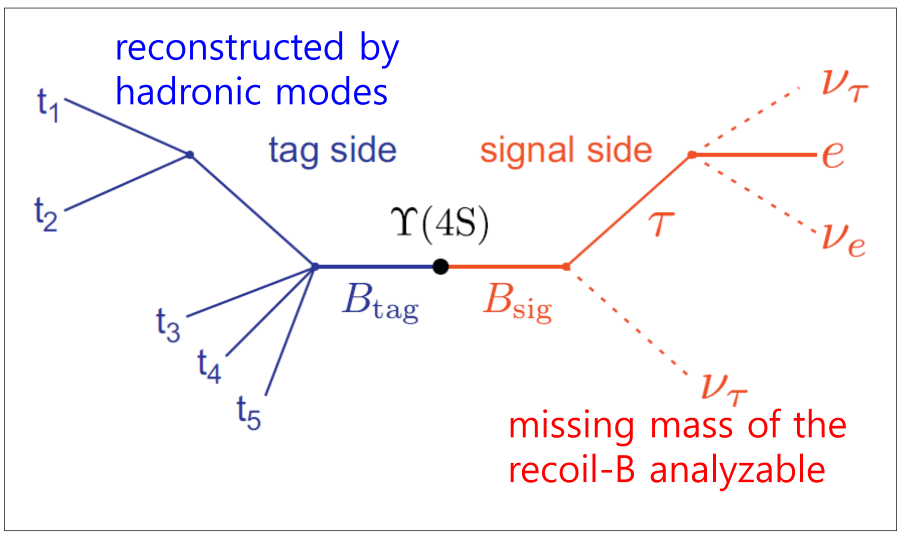
→ $B.F.(\Upsilon(4S) \rightarrow B\bar{B}) \sim 96\%$

→ Constrain the charge, flavor, & $(E, \vec{p})$ of B_{sig}

→ Results in very high-purity (but with low efficiency)

→ Good continuum (e^+e^- → u,d,s,c) suppression

→ Reconstructs rare processes with neutrinos



<Varibles on B_{tag} obtained by Hadronic Tagging>

$M_{bc} \equiv \sqrt{E_{beam}^2 - p_B^2}$: Beam constrained mass

$\Delta E \equiv E_{beam} - E_B$: Energy difference in B_{tag} and E_{beam}

(center of mass frame)

(m_{ES}: BABAR's equivalent to M_{bc} at Belle)

Today…

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

$B^0 \rightarrow invisible(\gamma)$

$B^+ \rightarrow \ell^+\nu_\ell$

4/6 analyses use hadronic tagging method.

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

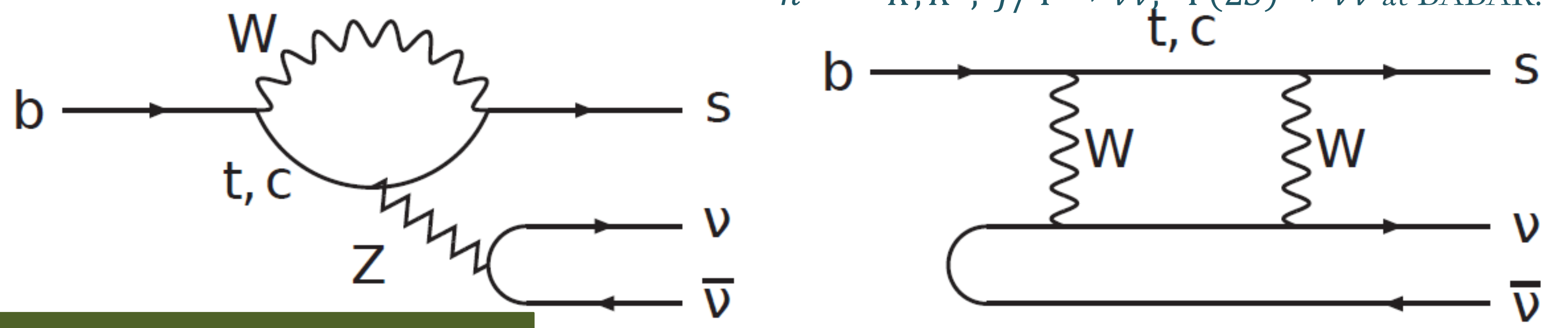
$h^{(*)} = K, K^*, \pi, \rho, \phi$ at Belle.
$h^{(*)} = K, K^*; \ J/\Psi \to \nu\bar{\nu}, \ \Psi(2S) \to \nu\bar{\nu}$ at BABAR.

Submitted to PRD(RC). arXiv:1303.3719[hep-ex].

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

$h^{(*)} = K, K^*, \pi, \rho, \phi$ at Belle.
$h^{(*)} = K, K^*,\ J/\Psi \to \nu\bar{\nu},\ \Psi(2S) \to \nu\bar{\nu}$ at BABAR.



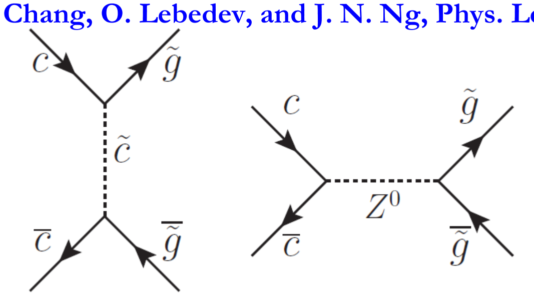
$B.F_{SM}(B^+ \to K^{*+}\nu\bar{\nu}) = (6.8 \pm 2.0) \times 10^{-6}$
$B.F_{SM}(B^+ \to K^+\nu\bar{\nu}) = (4.4 \pm 1.5) \times 10^{-6}$

< Feynmann diagrams for $b \to s\nu\bar{\nu}$ transition in Standard Model >

W. Altmannshofer, A. J. Buras, D. M. Straub, and M. Wick, JHEP 0904, 022 (2009).

- FCNC in the SM: EW Penguin/Box.
  - Branching fraction for $b \to d\nu\bar{\nu}$ further suppressed by a factor of $|V_{td}/V_{ts}|^2$
  - $B^0 \to \phi\nu\bar{\nu}$: Decays via a not yet to observed penguin → much lower branching fraction.
- An interesting place to test physics beyond SM
  - Branching fraction deviation→ Predictions of massive particles w/ additional loop contribution?
  - Modification of q^2 distribution ($q \equiv$ Energy-momentum transfer from b to $\nu\bar{\nu}$).→LDM ?

L. N. Chang, O. Lebedev, and J. N. Ng, Phys. Lett. B 441, 419 (1998).



< SUSY decays of $c\bar{c}$ to a pair of goldstinos via c-squark and Z^0>

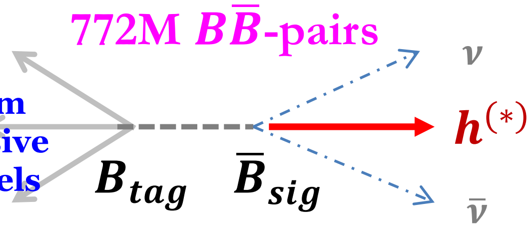
- $B \to K + charmonium$ process provides an window to search for $charmonium \to \nu\bar{\nu}$.
- Possible branching fraction enhancement expected according to various New Physics Scenarios.

<u>Both Belle and BABAR use hadronic tagging.</u>

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

$h^{(*)} = K, K^*, \pi, \rho, \phi$

Hadronic tagging from 1104 exclusive b→c channels



$M_{bc}, \Delta E, O_{\mathrm{NB}}$: B_{tag} quality control

$O_{\mathrm{NB}} \equiv$ A Neural Network output interpret as Bayesian probability on B_{tag}.

Backup: Details on O

Reconstruct $h(*)$ w/ right charge to B_{tag}

$K_S^0 \to \pi^+\pi^-,\ \pi^0 \to \gamma\gamma,\ K^{*0} \to K\pi,\ K^{*+} \to K_S^0\pi^+ / \pi^0 K^+,$
$\rho^0 \to \pi^+\pi^-, \rho^+ \to \pi^+\pi^0$

No additional charged tracks or π^0

Reduce BG with a particle missing along the beam pipe:

$\boldsymbol{cos\theta_{miss}} \equiv polar\ angle\ of\ missing\ momentum\ in\ CM\ frame$

(-0.86~0.95)

1.6 GeV/c < p^*(h momentum in B_{sig} rest frame) < 2.5 GeV/c

Lower-bound **rejects BG from $b \to c$ charm decays,**

Upper-bound **rejects BG from 2-body B decays(e.g. $B \to K^*\gamma$).**

Backup: Precise Description
Backup: Validation

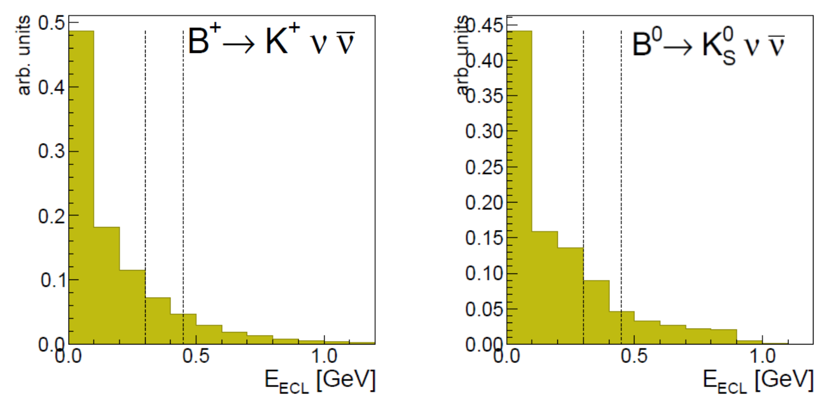
$$E_{ECL} \equiv E_{TOTAL} - E_{B_{tag}} - E_{signal-particles}.$$

- Remaining energy in the ECL not associated with B_{tag} or particles used to reconstruct the signal side.
  - Well reconstructed signal events peak near 0.

A powerful variable often used with analyses with ν_ℓ's.

Signal Extraction by an extended binned maximum likelihood fit in E_{ECL} (0-1.2 GeV).

arXiv:1303.3719[hep-ex].



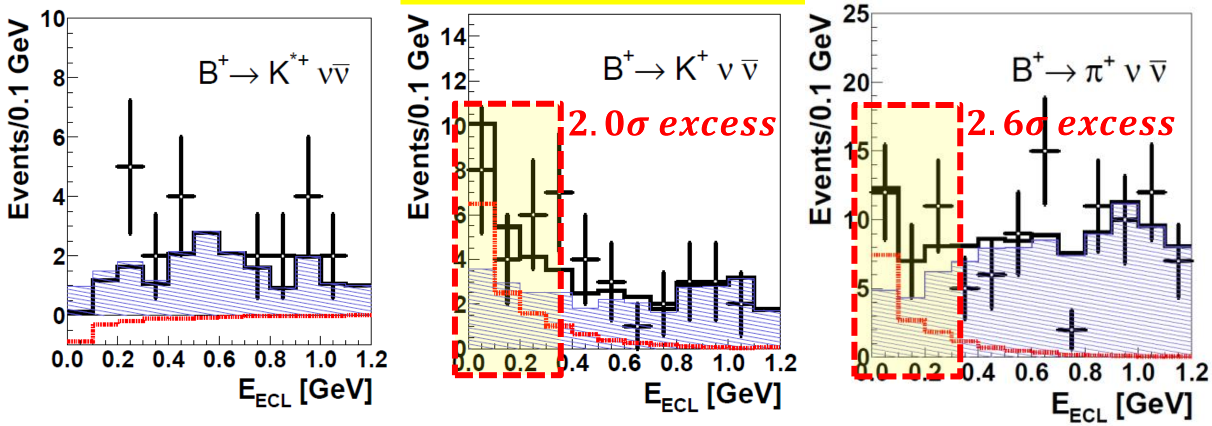
<Signal MC distribution in E_{ECL} window>

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

BELLE

Signal Extraction by an extended binned maximum likelihood fit to E_{ECL} (0-1.2 GeV).

arXiv:1303.3719[hep-ex].



Total fit result
Signal contribution
BG component
Experimental Data

No significant signal observation.

Systematic uncertainty dominated by the statistical uncertainty of BG model due to stringent signal selection.

$$BF = N_{sig}/(N_{B\bar{B}} \cdot \epsilon_{sig})$$

N_{sig}: signal yield
$N_{B\bar{B}}$: # of BB pairs
ϵ: signal selection efficiency

$B \to h\nu\bar{\nu}$	Significance	B.F. Upper Limit($\times 10^{-5}$)
K^+	2.0σ	5.5
K_S^0	0.7σ	9.7
K^{*+}		4.0
K^{*0}		5.5
π^+	2.6σ	9.8
π^0	1.9σ	6.9
ρ^+	1.7σ	21.3
ρ^0	0.4σ	20.8
ϕ	0.5σ	12.7

Backup: pub. table
Backup: systematics
Backup: plots for all modes

the most stringent up to date.

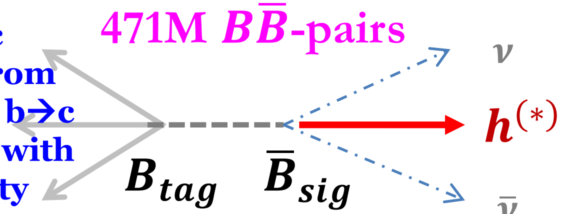
Submitted to PRD(RC). arXiv:1303.3719[hep-ex].

$B \to K^{(*)}\nu\bar{\nu}$: Method

$+B \to K^*(c\bar{c})$: $J/\Psi \to \nu\bar{\nu}, \Psi(2S) \to \nu\bar{\nu}$

Hadronic tagging from exclusive b→c channels with high purity

$M_{bc}, \Delta E$



$B_{tag} \to DX^-$ where X^- refers to a combination of π/K up to 5.

Reconstruct $K^{(*)}$ w/ right charge to B_{tag}

$B \to K^+\nu\bar{\nu}, B \to K_S^0\nu\bar{\nu}$

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

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

No additional tracks.

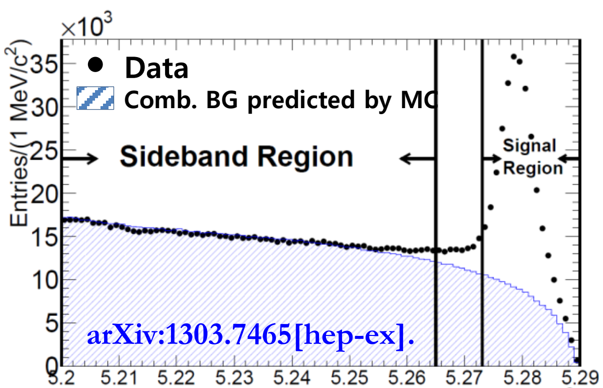
Continuum suppression with Likelihood Ratio cut with event-shape variables. Backup: Description

Require low E_{extra} optimized for respective channel.

$s_B \equiv q^2/m_B^2$: weighted mass of the $\nu\bar{\nu}$ system.

For non-charmonium modes: $0 < s_B < 0.3$ (Corresponds to $p^B_{K^{(*)}} > 1.8(1.7)\mathrm{GeV}/c$)

For charmonium modes: identified in s_B equivalent to the mass of J/Ψ or $\Psi(2S)$.



$<M_{bc}$ distribution$>$

$$\mathcal{B}_i = \frac{N_i^{\mathrm{obs}} - (N_i^{\mathrm{peak}} + N_i^{\mathrm{comb}})}{\varepsilon_i^{\mathrm{sig}} N_{B\bar{B}}} \quad (i \equiv each\ channel)$$

N_i^{peak}: peaking BG from correct B_{tag}

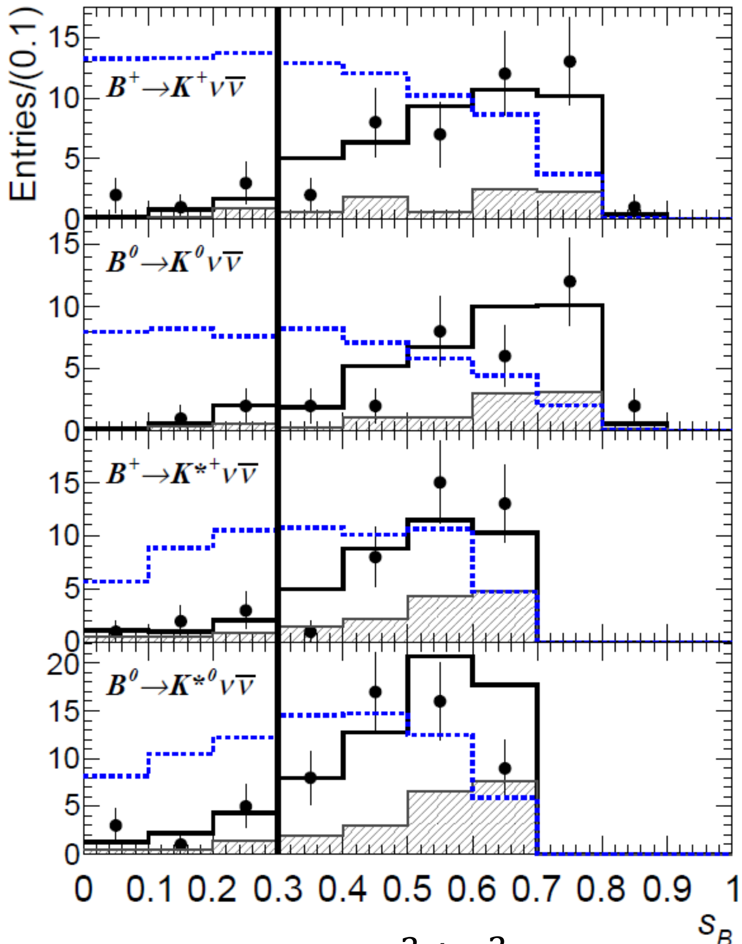
N_i^{cont}: combinatorial BG (extrapolated from M_{bc} sideband data)

Major fraction of peaking BG from $D^{(*)}\ell\nu$ process with a lepton missing.

$B \to K^{(*)}\nu\bar{\nu}$: Signal Extraction

$+B \to K^*(c\bar{c})$: $J/\Psi \to \nu\bar{\nu}, \Psi(2S) \to \nu\bar{\nu}$

Signal $K^{(*)}\nu\bar{\nu}$ region **arXiv:1303.7465[hep-ex].**



$s_B \equiv q^2/m_B^2$

Backup: systematics
Backup: descriptive table

K^{*+}	K^{*0}	K^+	K^0
< 11.6	< 9.3	0.4-3.7	< 8.1
< 7.9		0.2-3.2	

<U.L. of Branching Fraction for $B \to K^{(*)}\nu\bar{\nu} \times 10^5$>

For the $J/\Psi \to \nu\bar{\nu}, \Psi(2S) \to \nu\bar{\nu}$.

$B.F.(J/\Psi \to \nu\bar{\nu}) < 3.9 \times 10^{-3}$

$B.F.(\Psi(2S) \to \nu\bar{\nu}) < 15.5 \times 10^{-3}$

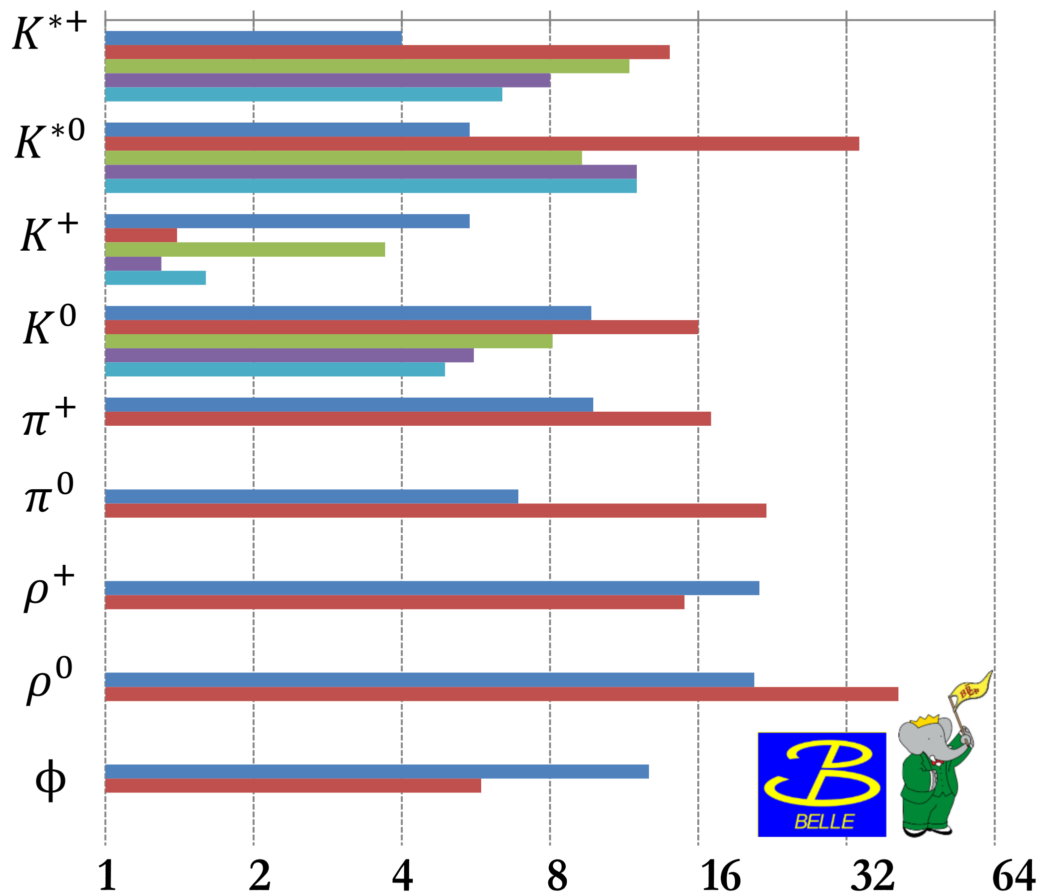
Backup: fit plots for charmonium
Backup: result table in publication

@ 90% C.L.

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

Belle 2013 result <u>supercedes</u> Belle 2007.



Branching Fraction Upper Limit (10^{-5})

(in log scale of base 2)

Backup: NOT in Log scale

Belle 2013, 772M $B\bar{B}$, Had.
Belle 2007, 535M $B\bar{B}$, Had.

Babar 2013, 471M $B\bar{B}$, Had.
Babar, 08' 10', ~460M $B\bar{B}$, SL.
Babar, Combined.

Had. : Hadronic Tagging Method
SL. : Semi-leptonic Tagging Method

Belle 2007 : PRL 99, 221802 (2007).
Babar 08' : PRD 78, 072007 (2008).
Babar 10' : PRD 82, 112002 (2010).

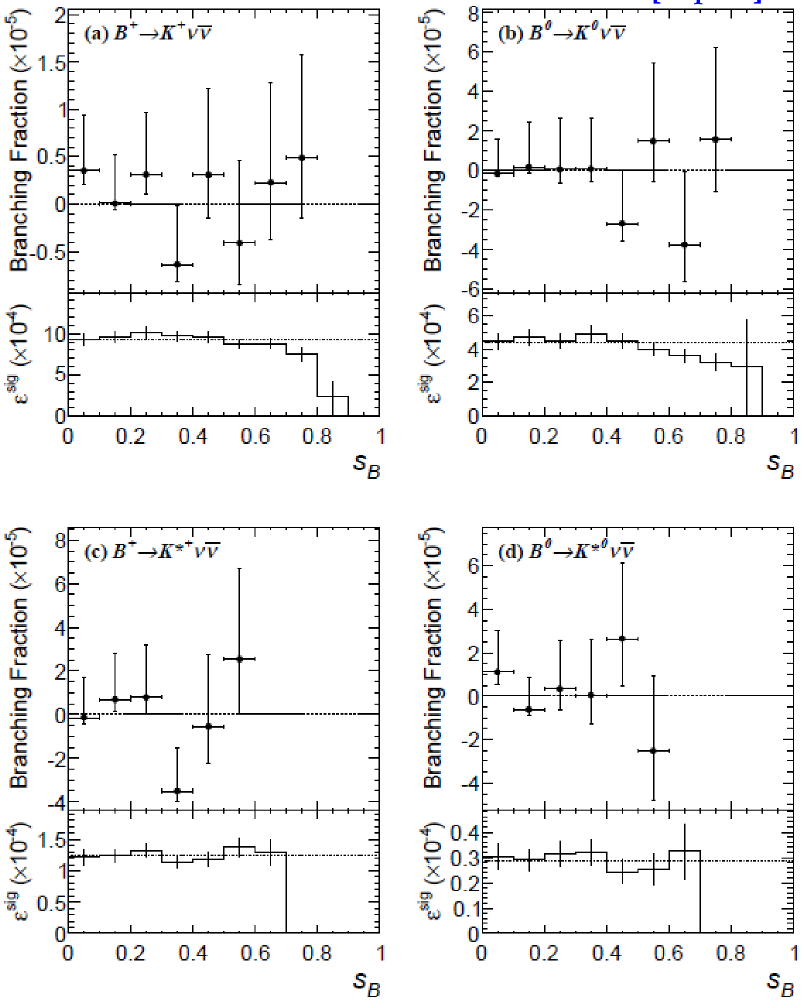
	K^*	K
2013 Had.	7.9	0.2-3.2
Prev. SL+2013 Had.		1.7

<Babar's Had. + SL. Combined Result>

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

W. Altmannshofer, A. J. Buras, D. M. Straub, and M. Wick, JHEP 0904, 022 (2009) .

arXiv:1303.7465[hep-ex].

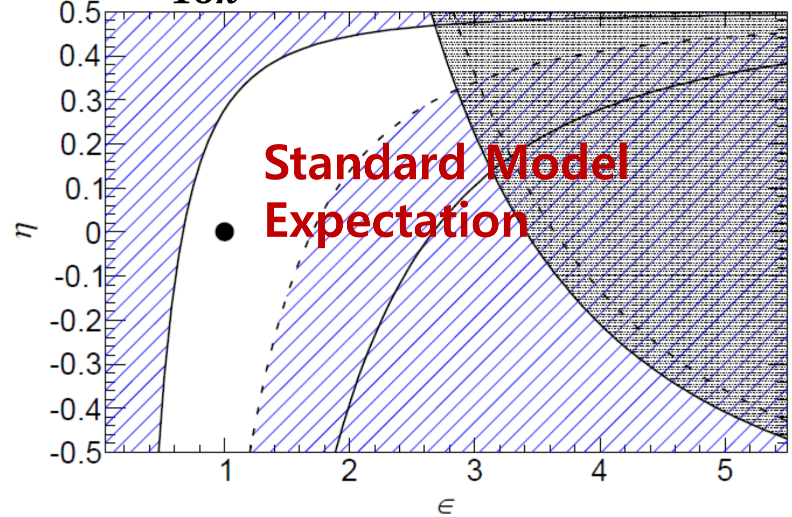


<Branching fraction according to s_B>

$$s_B \equiv q^2/m_B^2$$

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^*(C_L^\nu O_L^\nu + C_R^\nu O_R^\nu)$$

$$O_{L(R)} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$



$$\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\mathrm{SM}}^\nu|}, \quad \eta \equiv \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu*})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

<90% C.L. constraints on ϵ/η >

Exclusion from…

- Limits of this analysis
- 08′, 10′ semileptonic tag analyses
- $B \to K\nu\bar{\nu}$
- $B \to K^*\nu\bar{\nu}$

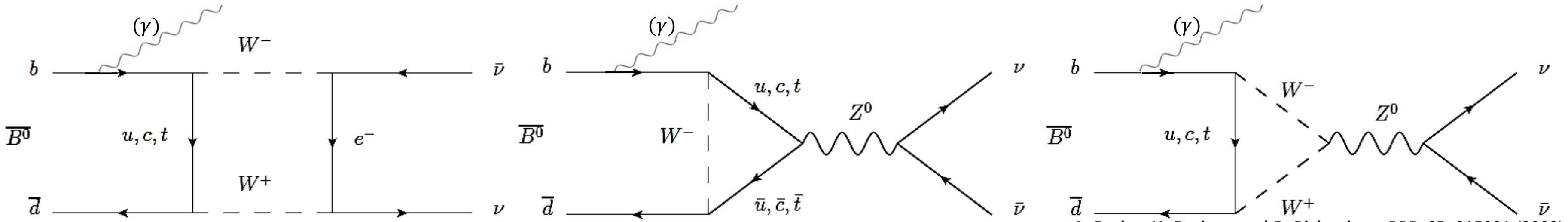
Parameters of Wilson coefficients in consistency with the Standard Model.

$B^0 \to invisible\ (+\gamma)$

Belle: PRD 86, 032002 (2012).

BABAR: PRD 86, 051105(R) (2012).

$B^0 \to invisible$: Motivation



A. Dedes, H. Dreiner, and P. Richardson, PRD 65, 015001 (2002).

G. Buchalla, and A.J. Buras, Nuclear Physics B 400(1-3), 225 – 239 (1993))

$$\mathcal{B}(B^0 \to \nu\bar{\nu}) = \tau_{B^0}\frac{G_F^2}{\pi}\left(\frac{\alpha}{4\pi\sin^2\Theta_W}\right)^2 F_{B^0}^2 m_\nu^2 m_{B^0}\sqrt{1-4m_\nu^2/m_{B^0}^2}\,|V_{tb}^* V_{td}|^2 Y^2(x_t)$$

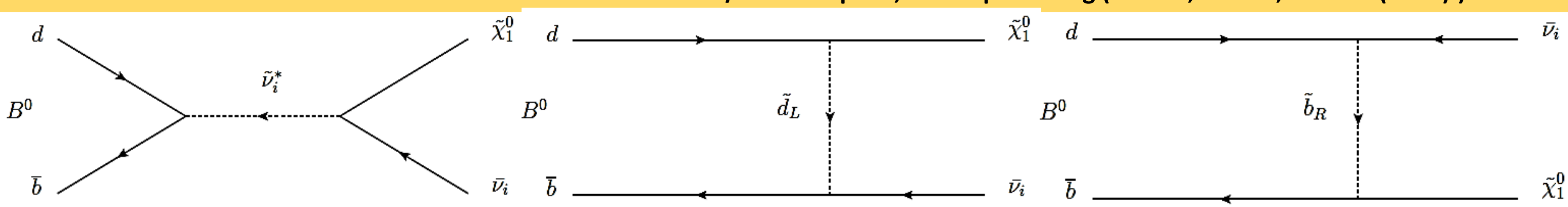
<The SM Feynman diagrams and branching fraction of $B \to invisible$>

- B decays with no remaining product in the detector (ν or hyphothetical).
- Low m_ν + Helicity suppression (SM) → Nearly invisible signature within the SM.
- Measurements of $B^0 \to invisible$? → A clear signature of New Physics!
  - NP scenario **branching fraction enhancement**, existence of **hypothetical particles.**

(e.g. $B^0 \to \bar{\nu}\tilde{\chi}_1^0$ from R-parity violating SUSY with $10^{-7} < B.F. < 10^{-6}$). T. Adams et al. (NuTeV Collab.), PRL 87, 041801 (2001). A. Dedes, H. Dreiner, and P. Richardson, PRD 65, 015001 (2002).

- Previous Result: $BF(B^0 \to invisible) < 22 \times 10^{-5}, BF(B^0 \to (+\gamma)) < 4.7 \times 10^{-5}$ @ 90% $C.L.$

w/ 89M BB-pairs, Semileptonic tag (BABAR, PRL 93, 091802 (2004).)



T. Adams et al. (NuTeV Collab.), PRL 87, 041801 (2001).
A. Dedes, H. Dreiner, and P. Richardson, PRD 65, 015001 (2002).

<The R-parity violating Feynman diagrams of $B \to invisible$>

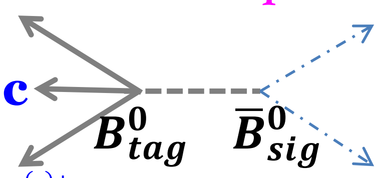
$B^0 \rightarrow invisible$: Method

657M $B\bar{B}$-pairs

$M_{bc}, \Delta E,$
$\cos\theta_T, \cos\theta_B$

Tagging from b→c events

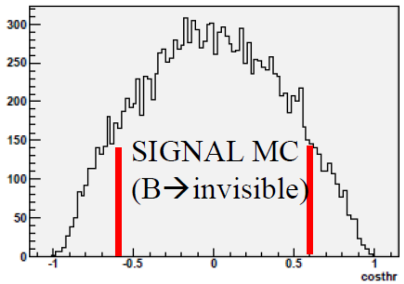
($B^0 \rightarrow D^{(*)-}\pi^+, D^{(*)-}\rho^+, D^{(*)-}a_1^+, D^{(*)-}D_s^{(*)+}$)

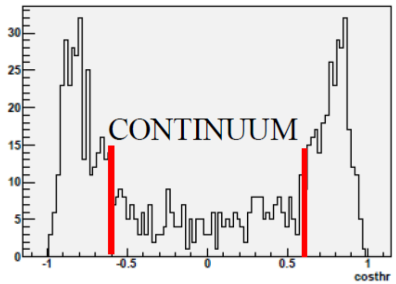


Invisible signal side

(no additional particle aside from B_{tag})

Reject tracks, π^0, K_L
E_{ECL}(Strongest)

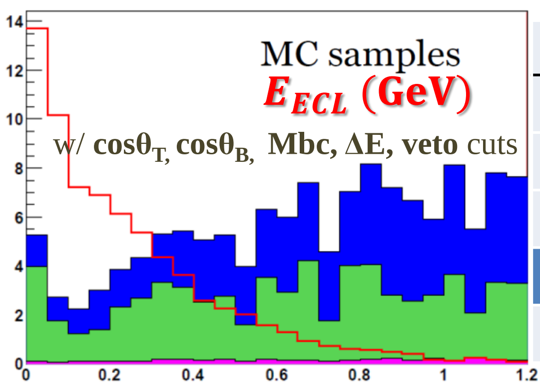




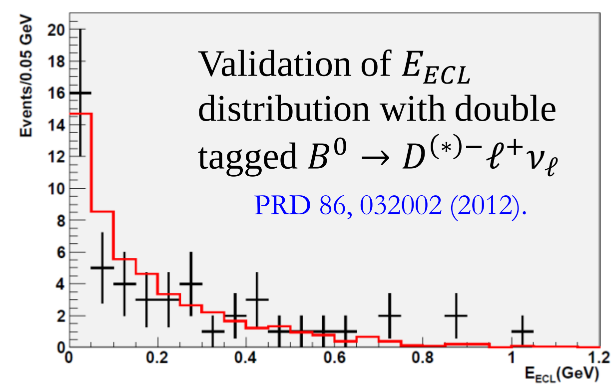
Main backgrounds from continuum events:
Suppressed w/ $\cos\theta_T, \theta_T \equiv \angle(\text{beam, thrust of } B_{tag})$
$|\cos\theta_B| < 0.9, \theta_B \equiv \angle(\text{beam}, B_{tag} \text{direction})$

Backup: Analysis Detail

<Continuum suppression w/ $\cos\theta_T$>



Expected events from MC study	
b → c decays	67±3
b → s,d decays	3.7±0.3
Non-B (Continuum+Tau-Pair)	64±16
Total	**137±16**
Signal (assumed BF = 10^{-6})	0.1

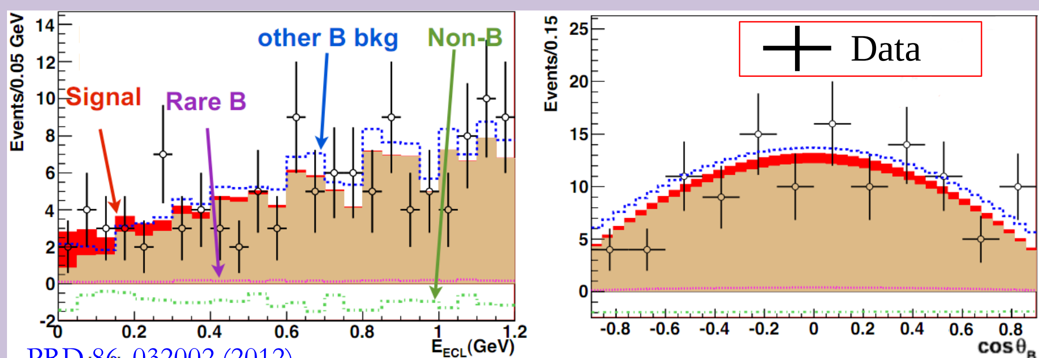


$B^0 \rightarrow invisible$: Signal Extraction

- 2-D PDF Construction in…
  - E_{ECL}: Discrete histogram function (Energy threshold within 0 – 0.05 GeV)
  - $cos\theta_B$: Legendre Polynomials
- Combined PDF: $P(E_{ECL}, cos\theta_B) = P(E_{ECL}) \times P(cos\theta_B)$

$\mathcal{B} = N_{\text{sig}}/(\epsilon \cdot N_{B\bar{B}})$
N_{sig}: signal yield
$N_{B\bar{B}}$: # of BB pairs
ϵ: signal selection efficiency

RESULT !



Sources	Yield
Signal	**9±6**
b→c BG	$\mathbf{132^{+22}_{-23}}$
Non-B BG	$\mathbf{-23^{+22}_{-17}}$
Rare-B BG	**~4**
Total	**121**

PRD 86, 032002 (2012).

<Result of unbinned extended likelihood fit to the experimental data>

A new result with hadronic tagging method.

$N_{sig} = 8.9^{+6.3}_{-5.5}(stat)^{+2.6}_{-2.7}(syst)$: No significant signal can be seen.

B.F.($B^0 \rightarrow invisible$) < 1.3×10^{-4} @ 90% C.L.

C. –L. Hsu, P. Chang, et al. (Belle collab.), PRD 86, 032002 (2012).

* Syst. uncertainty of signal efficiency dominated by **B_{tag} uncertainty efficiency**.

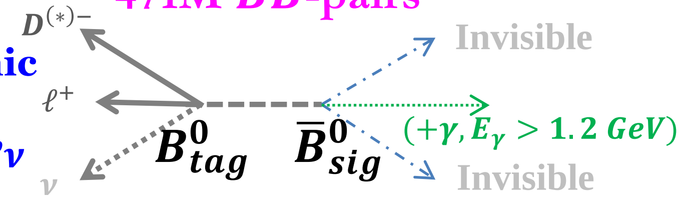
* Syst. uncertainty on signal yield are due to **MC statistic**.

$B^0 \to invisible\ (+\gamma)$: Method

$471M\ B\bar{B}$-pairs

Compared to hadronic tagging:
Higher reconstruction efficiency.
No full kinematics on B_{tag}.

Semi-leptonic Tagging in
$B^0 \to D^{(*)}\ell\nu$



Invisible signal side $(+\gamma)$
(no additional particle aside from B_{tag})

-tag side-

Only one ν not detected in B_{tag}: $\boldsymbol{cos\theta_{B,D^{(*)}-\ell}} \equiv \frac{2E_B E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell}|}$ (-5.5~1.5 in CM frame)

-signal side-

No charged tracks from B_{sig}.

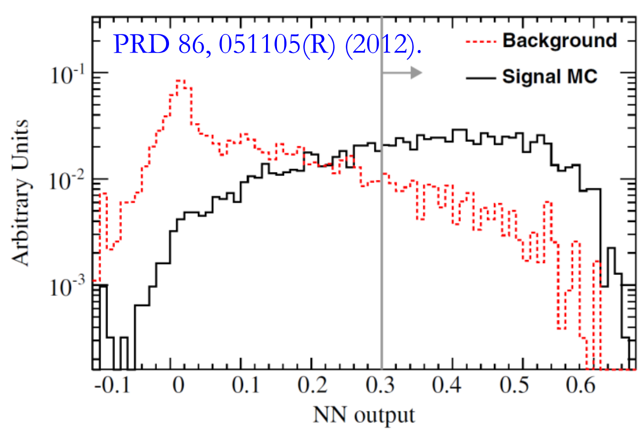
Reduce BG with a particle missing along the beam pipe:

$cos\theta_{miss} \equiv polar\ angle\ of\ missing\ momentum\ in\ CM\ frame$ (-0.9~0.9)

An artificial Neural Network output with event shape and B_{tag}/Signal side kinematic variables.

(e.g. $cos\theta_{B,D^{(*)}-\ell}$, p_ℓ^{CM}, cosine of angle between thrust axis of an event to $\vec{p}_{D^{(*)}\ell}^{\,CM-frame}$ direction … **backup**)

Backup:NN-details

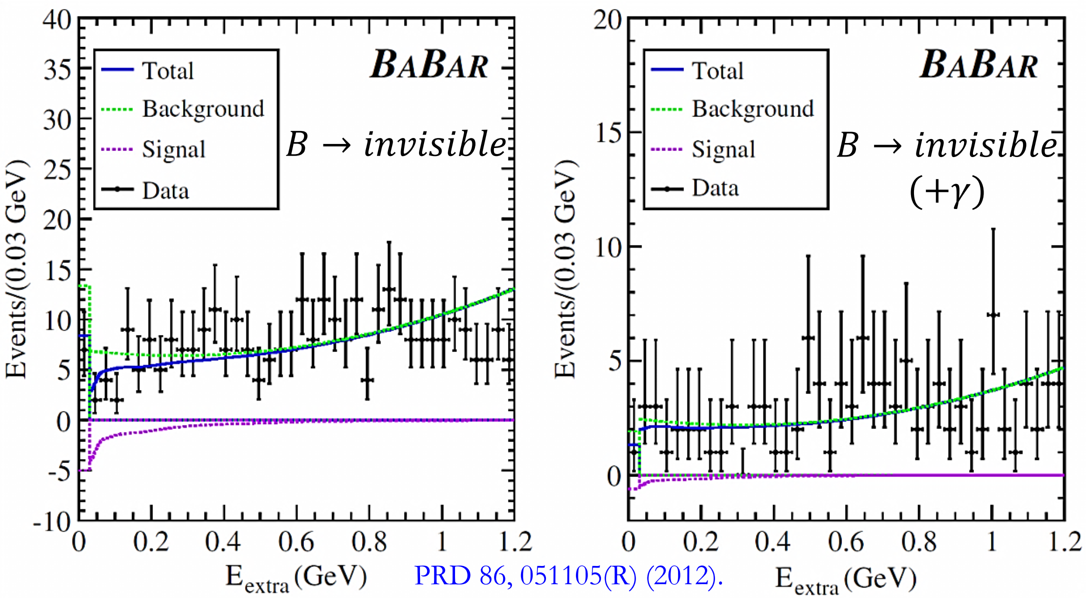


Optimization of NN output based on expected BF upper limit with MC & Off. Res. data.

After these BG suppression procedures.

Signal extraction in $0 < E_{extra} < 1.2$ GeV with PDF obtained from…
- Signal PDF: detailed MC
- Background PDF: $m_D, m(D^* - D)$ sideband experimental data

$B^0 \to invisible\ (+\gamma)$: Signal Extraction



Source	$B^0 \to$ invisible	$B^0 \to$ invisible + γ
Normalization errors		
B-counting	0.6%	0.6%
Efficiency errors		
Tagging efficiency	3.5%	3.5%
m_D (Δm) selection	1%	1.3%
Preselection	3%	2.4%
Neural network	6.1%	8.2%
Single photon	⋯	1.8%
Total	7.7%	9.5%
Yield errors (events)		
Background parameter	15.8	6.5
Signal parameter	2.0	1.2
Fit technique	⋯	1.0
E_{extra} shape	0.1	1.8
Total	15.9	6.9

Mode	N_{sig}	N_{bkg}
$B^0 \to$ invisible	-22 ± 9	334 ± 21
$B^0 \to$ invisible + γ	-3.1 ± 5.2	113 ± 12

* Dominant systematic uncertainty from data/MC discrepancy in NN variables & parameterization of BG E_{extra} PDF.

Backup: Systematics

semi-leptonic tagging(471M BB), the best limit so far.

$$B.F\left(B^0 \to invisible\right) < 2.4 \times 10^{-5}$$

$$B.F\left(B^0 \to invisible + \gamma\right) < 1.7 \times 10^{-5} \quad E_\gamma > 1.2\text{GeV}$$

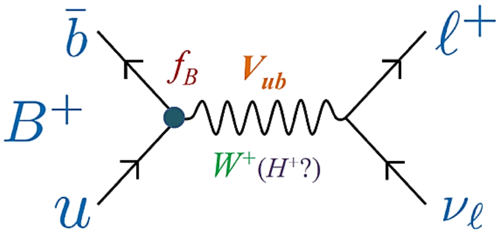
$$@\ 90\%\ C.L.$$

J.P. Lees et al. (The BABAR collab.), PRD 86, 051105(R) (2012).

$$B^+ \to \ell^+ \nu_\ell$$

$\ell = e, \mu$

$B^+ \to \ell^+ \nu_\ell$: Motivation



$\mathcal{B}(B \to e\nu)_{SM} \sim 10^{-11}$
$\mathcal{B}(B \to \mu\nu)_{SM} \sim 3.5 \times 10^{-7}$
$\mathcal{B}(B \to \tau\nu)_{SM} \sim 10^{-4}$

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

<The Feynmann diagram, SM branching fraction, order of B.F$(B \to \ell^+\nu_\ell)$ >

Up-to-date results: $B \to \ell\nu$

(Loose Tagging)

$B.F.(B^+ \to e^+\nu_e) < 9.8 \times 10^{-7}$ $253 fb^{-1}$

Belle Collab., PLB 647, 67 (2007).

$B.F.(B^+ \to \mu^+\nu_\mu) < 1.0 \times 10^{-6}$ $426 fb^{-1}$

BABAR Collab., PRD 79, 091101 (2009).

(Hadronic Tagging)

$B.F.(B^+ \to e^+\nu_e) < 5.2 \times 10^{-6}$

$B.F.(B^+ \to \mu^+\nu_\mu) < 5.6 \times 10^{-6}$ $342 fb^{-1}$

BABAR Collab., PRD 77, 091104 (2008).

@ 90% C.L.

<Currently most stringent limit for $B \to \ell\nu$ at Belle and BABAR>

- A clean process for the measurement of f_B, $|V_{ub}|^2$, within the SM.
- Helicity suppression in the SM → $\mathrm{B.F.} \propto m_\ell^2$
- Evidence of $B^+ \to \tau^+\nu_\tau$ from Belle and BABAR experiments. →
- Deviation from the SM may reveal New Physics ! (e.g. 2HDM(type2), lepto-quark)

Dr. Andrej Bozek's "$B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$" talk on Monday !

2HDM(type2)

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell)_{2HDM} = \mathcal{B}(B^+ \to \ell^+\nu_\ell)_{SM} \times \left(1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$$

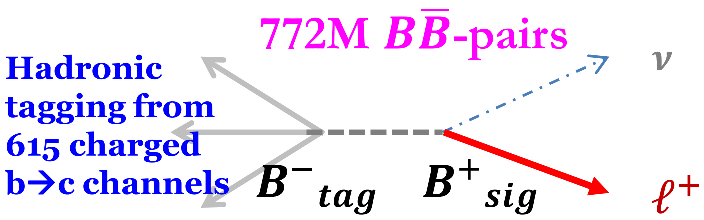
W. Hou, Phys. Rev. D. 48, 2342 (1993).

Result presented today is…

An update using full $\Upsilon(4S)$ data ($711 fb^{-1}$/772M) / Hadronic tagging

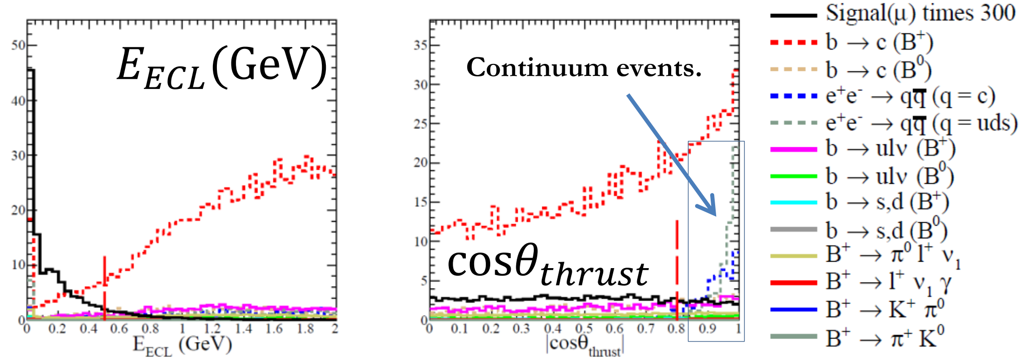
$B^+ \to \ell^+ \nu_\ell$: Method

$\ell = e, \mu$

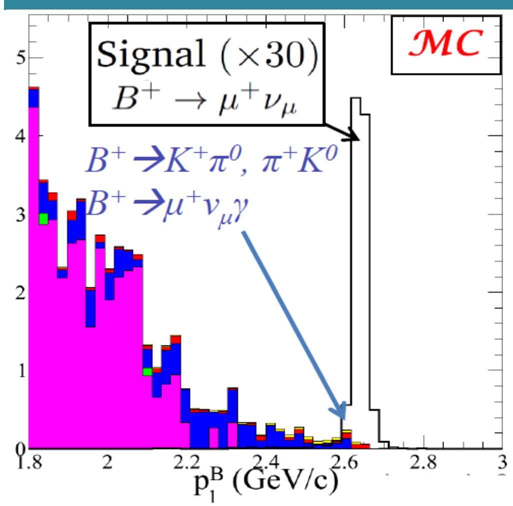


$M_{bc}, \Delta E, \mathcal{O}_{\mathrm{NB}}$: B_{tag} quality control

<MC distribution of $cos\theta_{thrust}$ and E_{ECL} for $B \to \mu\nu$ search>



- Require only one track which is identified to be a lepton on the B_{sig} side.
- Continuum suppression using $cos\theta_{thrust}$.
  - θ_{thrust}: angle between the thrust axis of B_{tag} particle and the lepton's momentum in CM frame.
- E_{ECL} cuts: Expecting no extra deposit in ECL aside from B_{tag} and the lepton.



- $p_\ell^B \equiv$ the momentum of lepton at B_{sig} rest frame.
- Sharp-peaking near 2.64 GeV/c due to 2-body decay.
- **Very clean signal with low BG (<<1).**

Analysis Strategy:

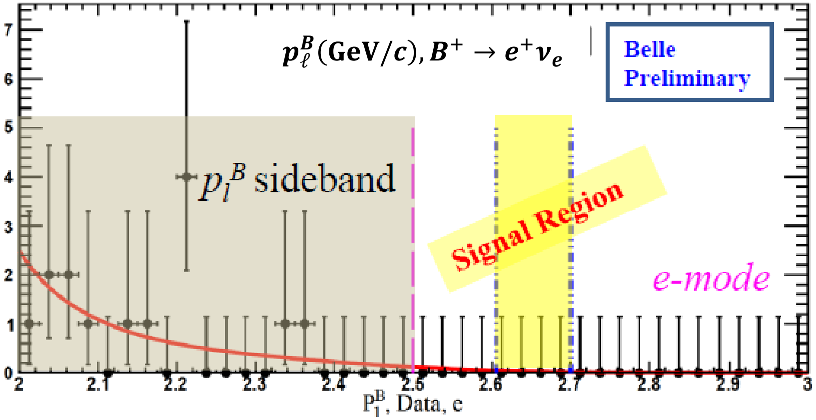
Backup: Validation
Backup: BG Models

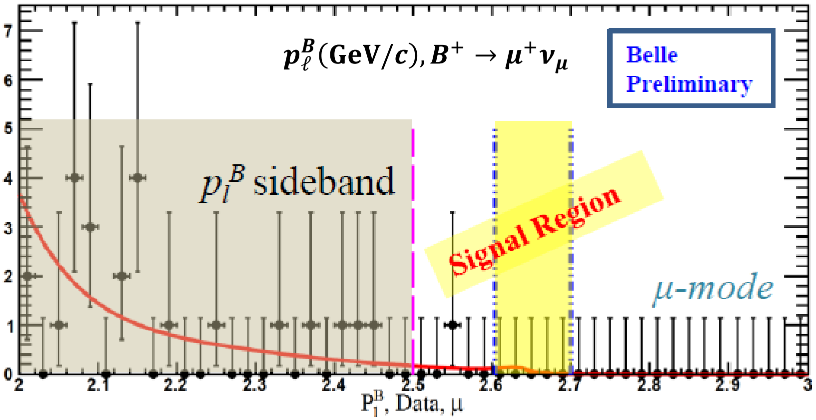
Fit the sideband of p_ℓ^B (2 – 2.5 GeV/c) to extrapolate the background into the signal region (~2.6 – 2.7 GeV/c).
Dedicated MC modeling for peaking BG at signal region.

<Signal Enhanced plot of p_ℓ^B for $B \to \mu\nu$ search>

$B^+ \to \ell^+ \nu_\ell$: Signal Extraction

$\ell = e, \mu$





$$B.F. = \frac{N_{obs} - N_{bkg}}{N_{B\bar{B}} * \epsilon_{sig}}$$

- Counting data yield in **unblinded** signal region.
- No signal events observed in signal p_ℓ^B window.
- Branching fraction Upper Limit calculated according to Feldman-Cousins method.
  G.J. Feldman and R.D. Cousins, PRD57, 3873 (1998).

* Uncertainties on N_{bkg} from

1. Data statistical error in p_ℓ^B sideband
2. Branching Fraction uncertainties of BG
3. Fit Parameters

* Dominant uncertainty of ϵ_{sig} is due to p_ℓ^B shape uncertainty.

Backup: Systematic

$B \to \ell\nu$	ϵ_{signal}	N_{bkg}	N_{obs}
e	0.091	$0.11^{+0.08}_{-0.06}$	0
μ	0.115	$0.33^{+0.10}_{-0.08}$	0

A new update with hadronic tagging method.

$$B.F.(B^+ \to e^+\nu_e) < 3.5 \times 10^{-6}$$
$$B.F.(B^+ \to \mu^+\nu_e) < 2.5 \times 10^{-6}$$
$$@\ 90\%\ C.L.$$

Publication preparation underway.

<Summary of N_{bkg}, ϵ_{sig}, Observed data yield in signal region, B.F. upper limit>

$$B \to (X)\ell\nu_h$$

ν_h: Heavy Neutrinos

Belle: PRD 87, 071102(R) (2013).

$B \to (X)\ell\nu_h$: Motivation

$\nu_h \equiv$ Heavy Neutrinos

- $m_\nu > 0$ from experimental data while the SM assumes 0 mass.
- **Heavy neutrinos (ν_h) in many models beyond the SM**
  - νMSM: addition of 3 RH neutral leptons. **T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. B 631, 151 (2005). T. Asaka and M. Shaposhnikov, Phys. Lett. B 620, 17 (2005).**
    - Neutrino Oscillation, Dark Matter, Baryogenesis("w/ larger mass sterile particles") explainable
  - Also expected from SUSY, GUT, models with exotic Higgs representations.

Properties of ν_h → Sterile

- Lepton: no strong interaction.
- Right-handedness: no weak interaction.
- Neutral: no EM interaction.

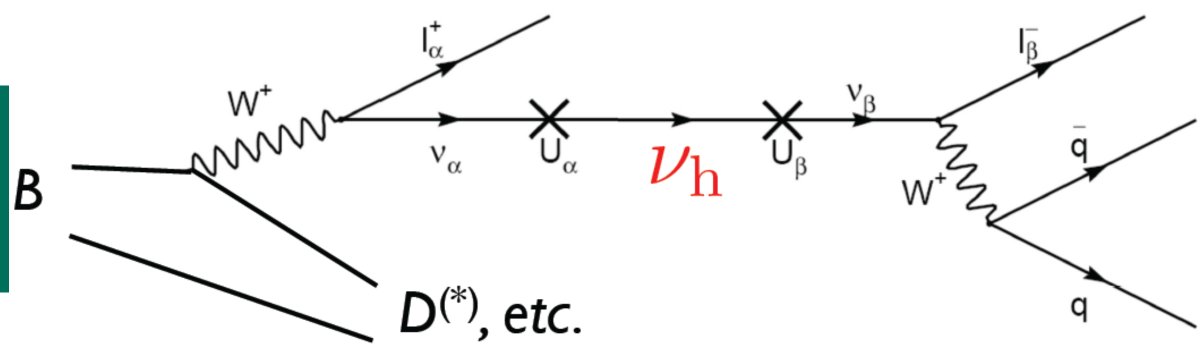
How it interacts?

- Only by mixing with a left-handed neutrino by a unitarity transformation.

$\nu_\alpha = \Sigma_i U_{\alpha i} \nu_i$ (**α=flavor eigenstates, i=mass eigenstates**)

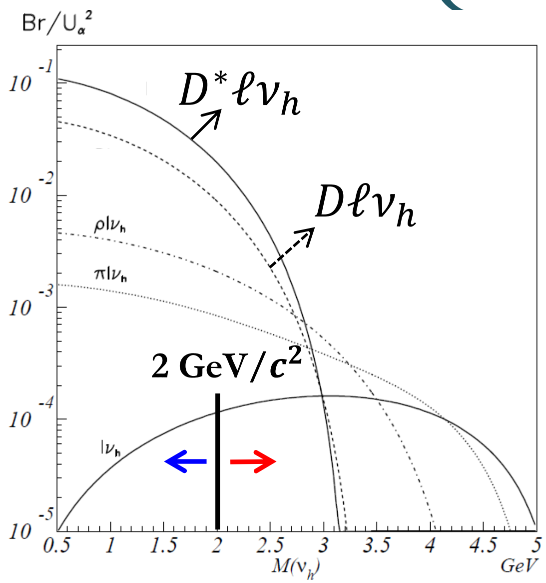
We define… $U_\alpha \equiv U_{\alpha\nu_h}$

Search for $B \to (X)\ell_2^{\pm}\nu_h$ where
$\nu_h \to \ell_1^{\pm}\pi^{\mp}$ (Dirac or Majorana)
$0.5\ \mathrm{GeV}/c^2 < \mathrm{M}_{\nu_h} < 5\ \mathrm{GeV}/c^2$



<Heavy neutral lepton production and decay diagram>

$B \to (X)\ell\nu_{heavy}$: Method



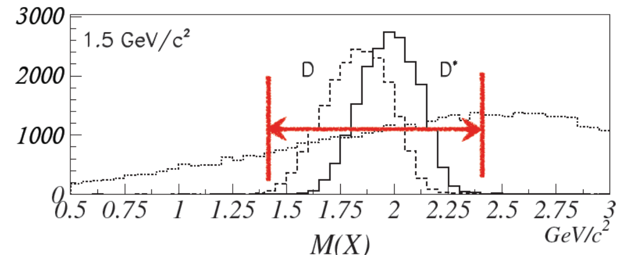
<$B.F(B \to X\ell\nu_h)$ at $|U_\alpha|^2 = 1$>

Separate treatment for large / small $M(\nu_h)$

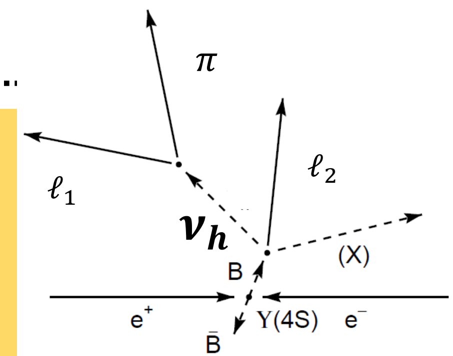
"small": $M(\nu_h) < 2.0GeV/c^2$, $X = D^{(*)}$ dominant

$D^{(*)}$ identified by "Missing Mass" : $M_X^2 \equiv (E_{CM} - E_{\ell_1\ell_2\pi})^2 - P_{\ell_1\ell_2\pi}^2 - P_B^2$

"large": $M(\nu_h) > 2.0GeV/c^2$, $X = D^{(*)}$, light meson, nothing



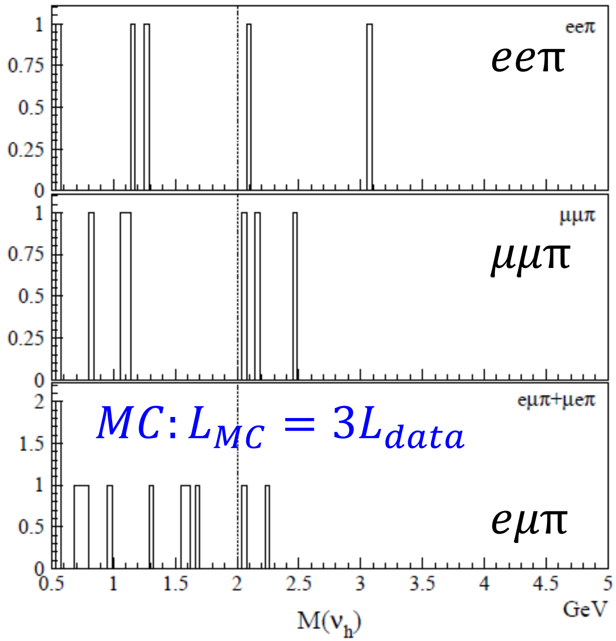
<M_X distribution for small $M(\nu_h)$ search>

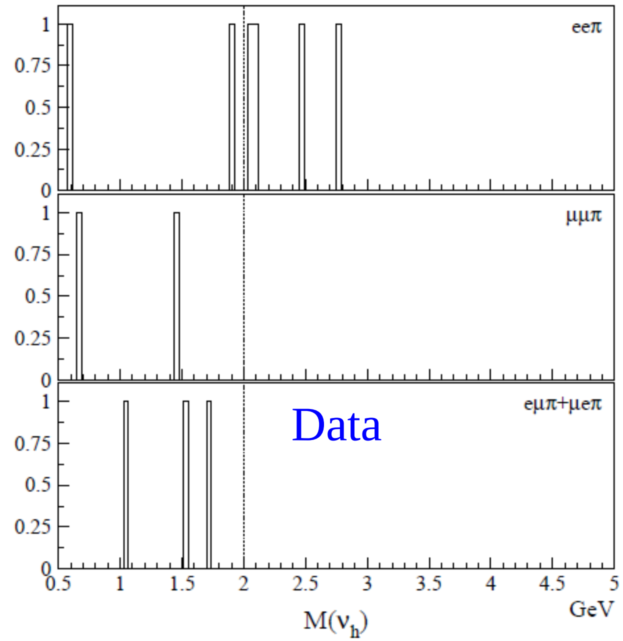


Background Suppression

- **QED background: $N(track) > 4$**
- **Decays with similar topology.**
  - $K_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\gamma \to e^+e^-$, etc…
  - Handled with tight particle ID, vertex quality, and distant $\ell - \pi$ vertex ($c\tau > 20m$ for $M_{\nu_h} = 1\text{GeV}/c^2$, $U_\alpha^2 < 10^{-4}$)
- **Combinatorial background.**
  - Daughter track originating from IP → Distance between the closest associated hit in SVD/CDC to vertex of ν_h can distinguish the background from signal.

$B \to (X)\ell\nu_{heavy}$: Signal extraction





PRD 87, 071102(R) (2013).

mode	MC expected	Data
$e e\pi$	1.7 ± 0.7	6 ± 2.4
$\mu\mu\pi$	2.3 ± 0.9	2 ± 1.4
$e\mu\pi + \mu e\pi$	4.0 ± 1.2	3 ± 1.7

<Obtained Yield and expectation from MC>

$$n(\nu_h) = 2N_{BB}\,\mathcal{B}(B \to \nu_h)\,\mathcal{B}(\nu_h \to \ell\pi)\,\frac{m\Gamma}{p}\int \varepsilon(x)dx$$
$$= |U_\alpha|^2|U_\beta|^2\,2N_{BB}\,f_1(m)\,f_2(m)\,\frac{m}{p}\int \varepsilon(x)dx,$$

~1 with low Γ

$$dP(x) = \frac{m\Gamma}{p}\boxed{\exp\left(-\frac{mx\Gamma}{p}\right)}dx$$

Probability of a particle with decay width Γ with momentum p traveling in segment dx.

$$|U_\alpha|^2 f_1(m) = \mathcal{B}(B \to \nu_h)$$
$$|U_\beta|^2 f_2(m) = \Gamma(\nu_h \to \ell\pi) = \mathcal{B}(\nu_h \to \ell\pi)\Gamma$$

x: distance to heavy neutrino decay vertex from IP.
ϵ: reconstruction efficiency.

D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007) [arXiv:0705.1729 [hep-ph]].

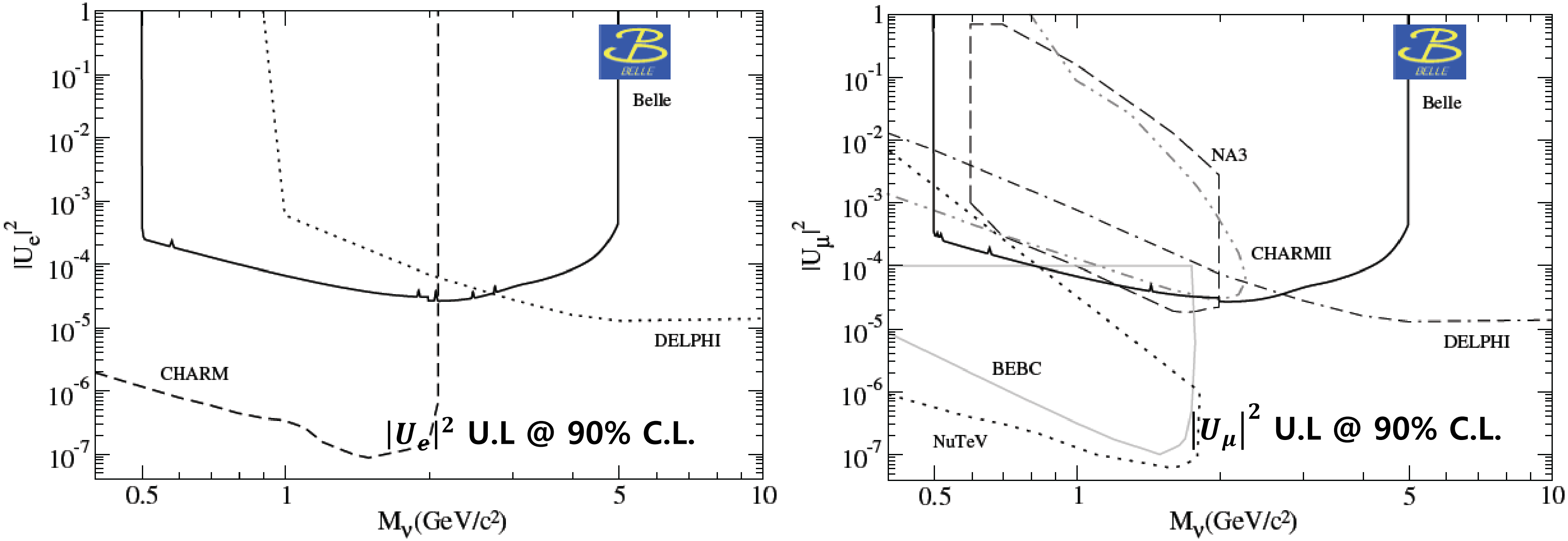
Backup: Details

Upper limit calculated in Feldman-Cousins method.

$B \to (X)\ell\nu_{heavy}$: $|U_\alpha|^2$ upper limits

BELLE

Backup: the $|U_\alpha|^2$ plots in the publication.



- Upper limits on $\nu_h - \nu_\ell$ mixing ($|U_\ell|$) in the mass range $0.5 < M_{\nu_h} < 5\ \text{GeV}/c^2$ obtained. (Maximum sensitivity near $2\ \text{GeV}/c^2$)
  U.L. calculated according to a method described in G.J. Feldman and R.D. Cousins, PRD57, 3873 (1998).
- Corresponding branching fraction U.L.
  - $\boldsymbol{BF(B \to (X)\ell\nu_h) \times BF(\nu_h \to \ell\pi^+) < 7.2 \times 10^{-7}}$

D.Liventsev, *et al.* (Belle collaboration), PRD 87, 071102(R) (2013).

Conclusion

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

$$B^0 \to invisible(\gamma)$$

$$B^+ \to \ell^+\nu_\ell$$

$$B \to (X)\ell\nu_{heavy}$$

- Rare decay searches as a probe for New Physics Scenario was carried out in Belle and Babar collaboration.
  - Many updates on U.L. of branching fraction using hadronic tagging method.
  - U.L. on mixing of $\nu_h - \nu_\ell$ was set in the mass range of 0.5 – 5.0 GeV/c^2.
  - The an update with an order more stringent B.F. upper limit in $B^0 \to invisible(\gamma)$ from semi-leptonic tagging from BABAR.
- No evidence of signal, consistent with the Standard Model.
- Anticipating for the high sensitivity of Belle-II !

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OBRIGADO

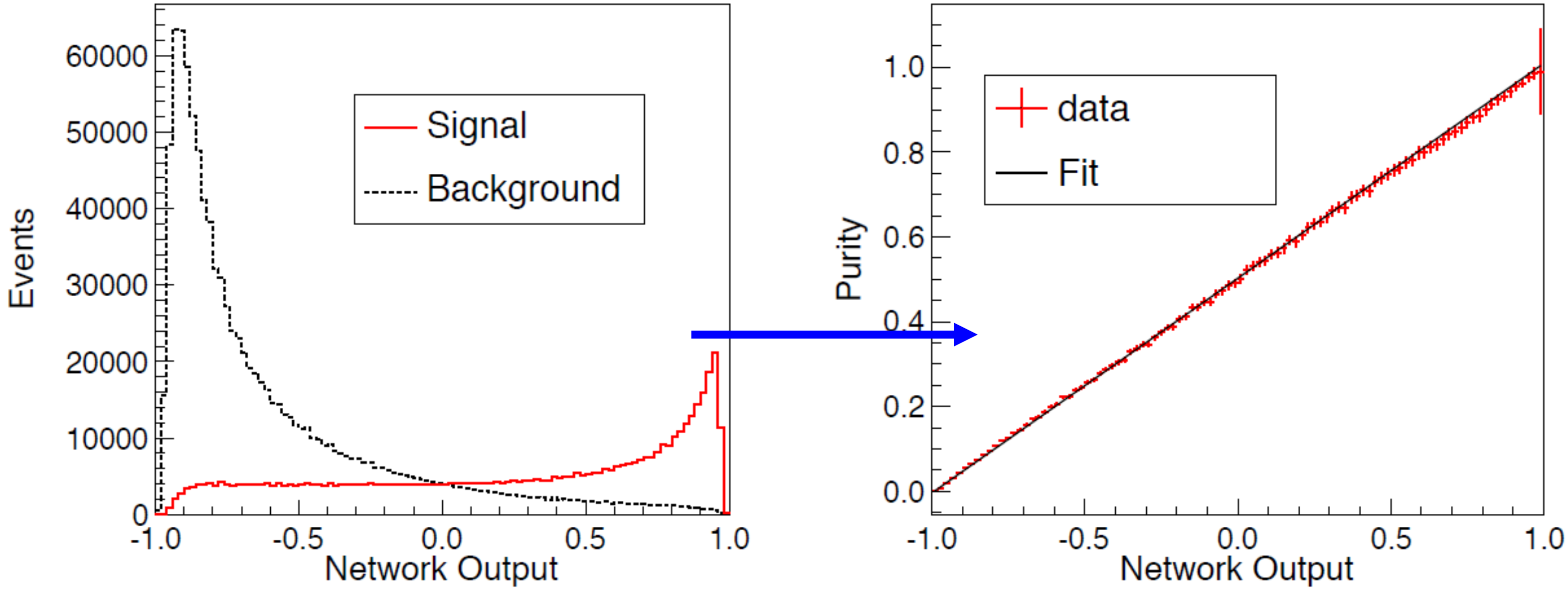
and

BACKUPS

Hadronic Tagging Method

Back to p.6

- Modified hadronic tagging with Neurobayes algorithm?



<π^0 candidate classification example.>

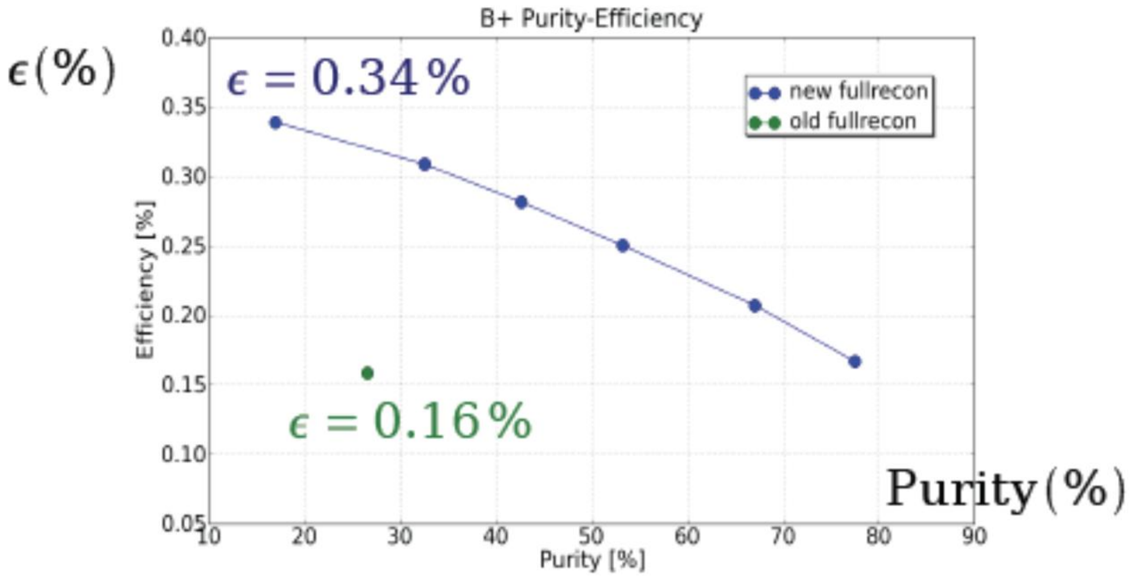
Network output linearly related to the Bayesian probability of articulate reconstruction of a candidate.

M. Feindt, F. Keller, M. Kreps, T. Kuhr, S. Neubauer, D. Zander, A, Zupanc, Nucl.Instrum.Meth.A654:432-440,2011

Hadronic Tagging Method

Back to p.6

- Modified hadronic tagging with Neurobayes algorithm?



<π^0 candidate classification example.>

Higher efficiency with addition of B/D reconstruction modes.

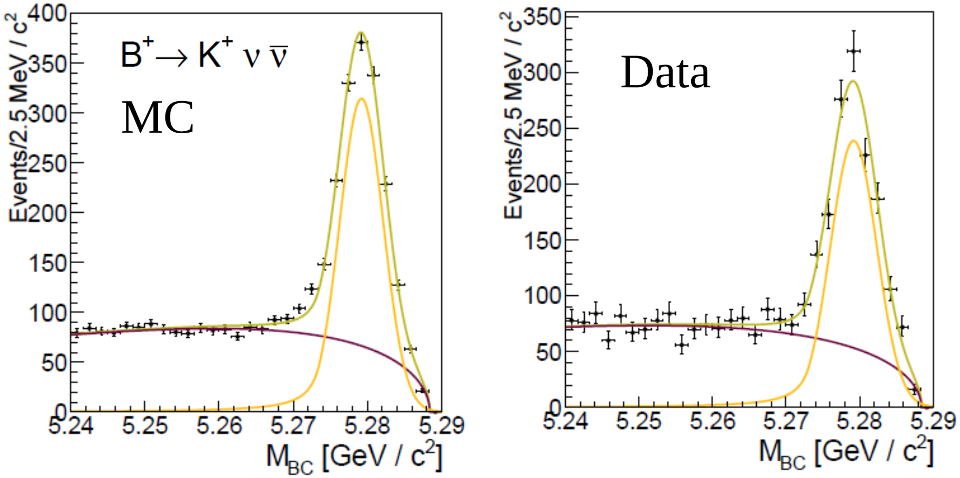
Purity/Efficiency control with Neural-network output (NB_{out}).

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

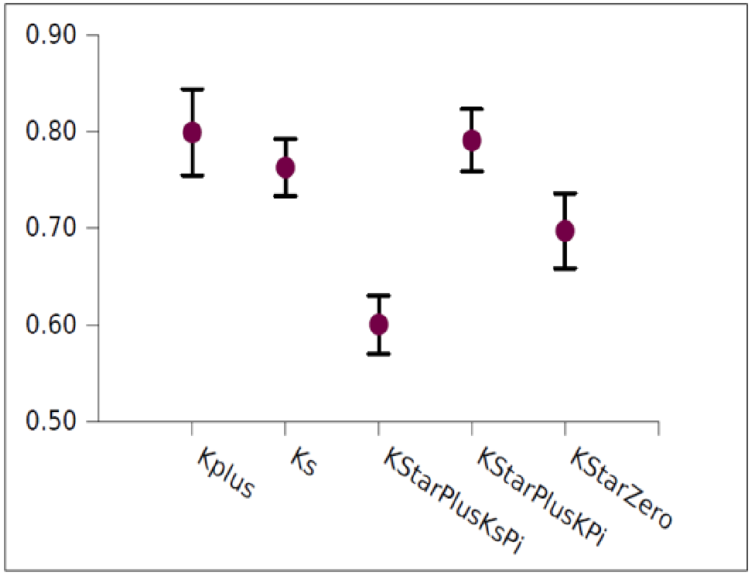
$h^{(*)} = K, K^*, \pi, \rho, \phi$ at Belle.
$h^{(*)} = K, K^*,\ J/\Psi \to \nu\bar{\nu},\ \Psi(2S) \to \nu\bar{\nu}$ at BABAR.

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

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



MC/data calibration of B_{tag} efficiency



- B-tag calibraton by Mbc fit.

Hnunu: event selection

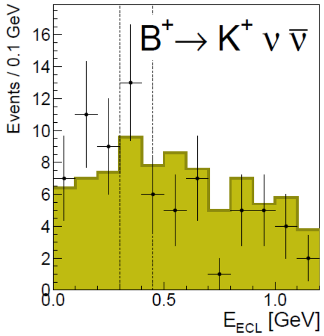
Back to p.6

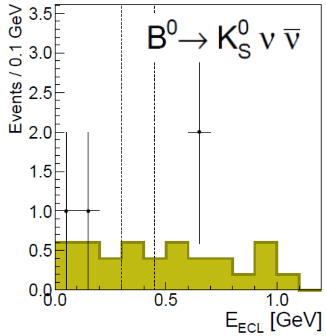
Cut (short name)	Description
BTagChargeCombination	B_{Tag} candidate with the corresponding charge combination (neutral-neutral, positive-negative, negative-positive)
$M_{bc} > 5.27\,\mathrm{GeV}$	lower cut on M_{bc} of the B_{Tag} candidate
$-0.08\,\mathrm{GeV} < \Delta E < 0.06\,\mathrm{GeV}$	cut on ΔE of the B_{Tag} candidate
BTagNBout > 0.02	lower cut on the NB_{out} of the B_{Tag} candidate
NRemainingPi0 $= 0$	no additional Pi^0 candidate should be left, standard π^0 cuts applied
NRemainingTracksAll $= 0$	no additional track should be left, no quality cuts on the veto tracks applied
$-0.86 < cos\theta_{mis} < 0.95$	the missing-momentum should not point into the beam-pipe
$E_{ECL} < 1.5\,\mathrm{GeV}$	upper cut on the extra energy in the calorimeter
$\vec{p}^{*} > 1.6\,\mathrm{GeV}$	lower cut on the momentum in B_{Sig} rest frame to reduce background from charm decays
$\vec{p}^{*} < 2.5\,\mathrm{GeV}$	upper cut on the momentum in B_{Sig} rest frame to reduce background from two-body B-decays

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

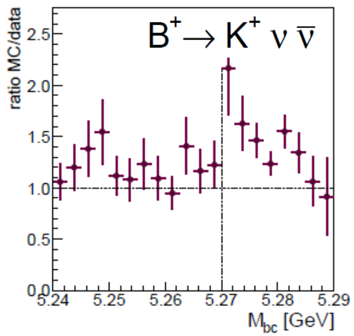
$h^{(*)} = K^+, K_S^0, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho^+, \rho^0, \phi$

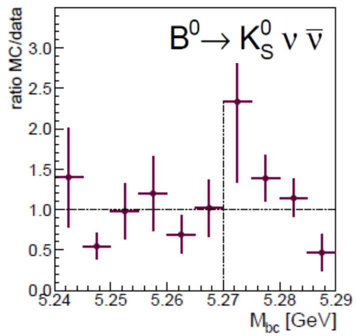
[Back to p.6]



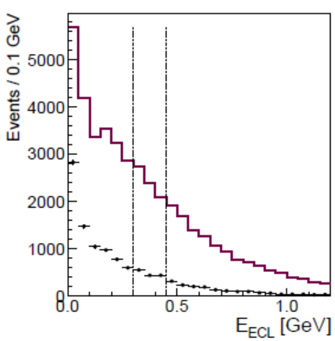


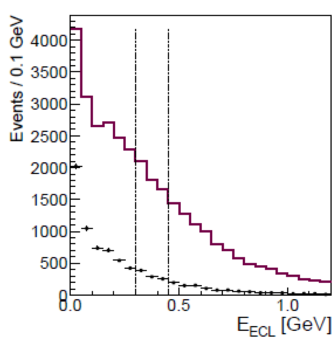
E_{ECL} Comparison of data/MC
in the M_{bc} sideband of $M_{bc} < 5.27$ GeV/c^2





M_{bc} Comparison of data/MC
in the E_{ECL} sideband of $E_{ECL} > 0.45$ GeV

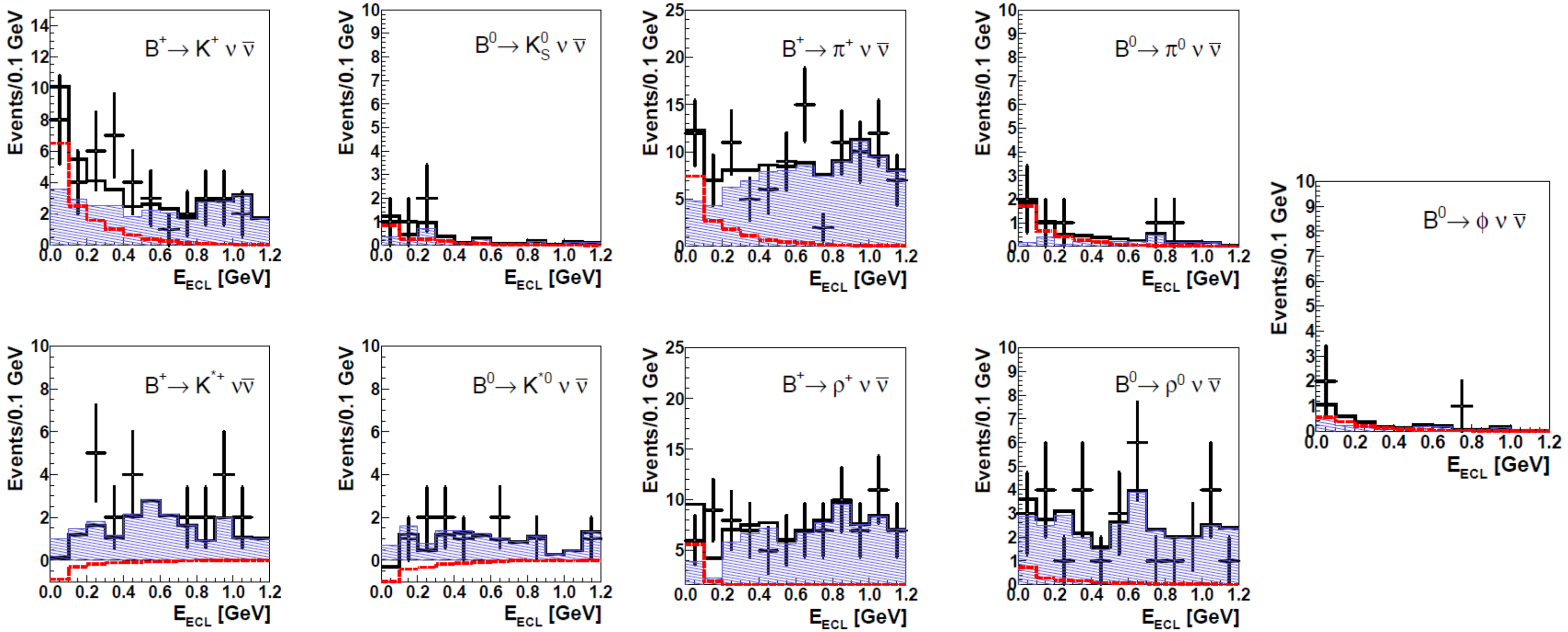




Charged track / π^0 rejection efficiency consistency check with data/MC using $B \to D^{(*)}\ell\nu$ control sample.

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

Back to p.7



- Fit to E_ECL for all h(*) modes

Submitted to PRD(RC). arXiv:1303.3719[hep-ex].

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

Back to p.7

Channel	$K^+\nu\bar{\nu}$	$K_S^0\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$	$\pi^+\nu\bar{\nu}$	$\pi^0\nu\bar{\nu}$	$\rho^+\nu\bar{\nu}$	$\rho^0\nu\bar{\nu}$	$\phi\nu\bar{\nu}$
Signal yield [events]									
Background model	2.1	0.9	1.5	0.5	0.9	0.4	4.0	0.4	0.5
Fit bias	–	–	0.2	0.6	–	0.4	–	0.1	0.6
Signal normalization [%]									
Track and π^0 rejection	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
B_{tag} correction	4.2	4.5	4.2	4.5	4.2	4.5	4.2	4.5	4.5
Signal MC statistics	1.2	3.5	3.7	2.8	1.5	2.1	2.3	3.3	2.6
Track, π^0 and K_S^0 reconstruction efficiency	0.3	2.3	4.1	0.4	0.4	4.0	4.2	0.7	1.4
Particle identification	2.0	4.0	2.0	4.0	2.0	–	2.0	4.0	4.0
$N_{B\bar{B}}$	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Form factors	2.0	5.4	3.8	6.4	1.9	1.6	2.9	4.5	7.5

Submitted to PRD(RC). arXiv:1303.3719[hep-ex].

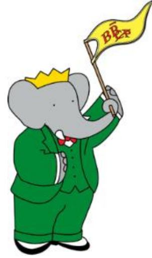
$B \to h^{(*)}\nu\bar{\nu}$: Result

Back to p.7

Mode	$N_{\rm tot}$	$N_{\rm sig}$	Significance	$\epsilon, 10^{-4}$	Upper limit
$B^+ \to K^+\nu\bar{\nu}$	43	$13.3^{+7.4}_{-6.6}(\text{stat}) \pm 2.3(\text{syst})$	2.0σ	5.68	$< 5.5 \times 10^{-5}$
$B^0 \to K^0_s\nu\bar{\nu}$	4	$1.8^{+3.3}_{-2.4}(\text{stat}) \pm 1.0(\text{syst})$	0.7σ	0.84	$< 9.7 \times 10^{-5}$
$B^+ \to K^{*+}\nu\bar{\nu}$	21	$-1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$	–	1.47	$< 4.0 \times 10^{-5}$
$B^0 \to K^{*0}\nu\bar{\nu}$	10	$-2.3^{+10.2}_{-3.5}(\text{stat}) \pm 0.9(\text{syst})$	–	1.44	$< 5.5 \times 10^{-5}$
$B^+ \to \pi^+\nu\bar{\nu}$	107	$15.2^{+7.1}_{-6.2}(\text{stat}) \pm 1.4(\text{syst})$	2.6σ	3.39	$< 9.8 \times 10^{-5}$
$B^0 \to \pi^0\nu\bar{\nu}$	6	$3.5^{+2.6}_{-1.9}(\text{stat}) \pm 0.6(\text{syst})$	1.9σ	1.66	$< 6.9 \times 10^{-5}$
$B^+ \to \rho^+\nu\bar{\nu}$	90	$11.3^{+6.3}_{-5.4}(\text{stat}) \pm 4.1(\text{syst})$	1.7σ	1.35	$< 21.3 \times 10^{-5}$
$B^0 \to \rho^0\nu\bar{\nu}$	31	$1.6^{+5.0}_{-4.1}(\text{stat}) \pm 0.4(\text{syst})$	0.4σ	0.64	$< 20.8 \times 10^{-5}$
$B^0 \to \phi\nu\bar{\nu}$	3	$1.4^{+2.9}_{-0.9}(\text{stat}) \pm 0.8(\text{syst})$	0.5σ	0.58	$< 12.7 \times 10^{-5}$

Submitted to PRD(RC). arXiv:1303.3719[hep-ex].

$B \rightarrow h^{(*)}\nu\bar{\nu}$: Sel. Criteria



Back to p.8

$cos\theta_T$: B-tag thrust vs all other particles
$cos\angle(beam, \vec{p}_{missing})$
$p_{B_{tag}}$, 2nd-0th FW moment

$$\rightarrow \mathcal{L}_B \equiv \frac{\prod_j \mathcal{P}_B(x_j)}{\prod_j \mathcal{P}_B(x_j) + \prod_j \mathcal{P}_q(x_j)} > 53\%$$

LHR cut of "mostly" shape variables.

$$r_{\mathrm{clus}} < 15^\circ, \text{ where } r_{\mathrm{clus}} \equiv \sqrt{(\Delta\theta)^2 + \tfrac{2}{3}(Q_K \cdot \Delta\phi - 8^\circ)^2}$$

Decision of Signal fragments in comparison to IP-Signal momentum

Channel	K^+	K^0	$[K^+\pi^0]$	$[K^0_S\pi^+]$	$[K^+\pi^-]$	$[K^0_S\pi^0]$
E_i [GeV]	0.11	0.28	0.18	0.29	0.31	0.33

E_extra conditions for each channel

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

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Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
			$B \to K^{(*)}\nu\bar{\nu}$			
$N_i^{\rm peak}$ $\mathcal{B}$'s	2.8	2.8	2.8	2.8	2.8	2.8
s_B resolution	3.6	3.6	3.6	3.6	3.6	3.6
Total $N_i^{\rm peak}$ syst.	6.8	8.9	8.8	9.7	10.0	10.9
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	6.7	8.8	8.8	11.4	11.7	12.4
			$J/\psi \to \nu\bar{\nu}$			
$N_i^{\rm peak}$ $\mathcal{B}$'s	3.5	3.5	3.5	3.5	3.5	3.5
$m_{\nu\bar{\nu}}$ resolution	1.1	2.1	0.4	0.7	0.3	1.3
Total $N_i^{\rm peak}$ syst.	6.2	8.6	8.4	9.3	9.6	10.5
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	5.8	8.3	8.0	10.8	11.1	11.9
			$\psi(2S) \to \nu\bar{\nu}$			
$N_i^{\rm peak}$ $\mathcal{B}$'s	2.8	2.8	2.8	2.8	2.8	2.8
$m_{\nu\bar{\nu}}$ resolution	0.8	2.4	1.0	0.9	1.8	3.1
Total $N_i^{\rm peak}$ syst.	5.8	8.5	8.1	9.1	9.5	10.7
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	5.8	8.4	8.1	10.9	11.2	12.2

<Mode by mode>

Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
$\varepsilon_i^{\rm sig}$ normalization	3.5	3.5	3.5	8.9	8.9	8.9
$N_i^{\rm bkg}$ normalization	2.3	2.3	2.3	6.0	6.0	6.0
K^0_S reconstruction	–	–	1.4	1.4	–	1.4
K^* reconstruction	–	2.8	2.8	–	2.8	2.8
π^0 reconstruction	–	3.0	–	–	–	3.0
$E_{\rm extra}$	4.5	6.0	6.5	6.0	6.0	6.5

<Common factors>

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

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	$B^+ \to [K^+\pi^0]\nu\bar{\nu}$	$B^+ \to [K^0_S\pi^+]\nu\bar{\nu}$	$B^0 \to [K^+\pi^-]\nu\bar{\nu}$	$B^0 \to [K^0_S\pi^0]\nu\bar{\nu}$
$N_i^{\rm peak}$	$1.2 \pm 0.4 \pm 0.1$	$1.3 \pm 0.4 \pm 0.1$	$5.0 \pm 0.8 \pm 0.5$	$0.2 \pm 0.2 \pm 0.0$
$N_i^{\rm comb}$	$1.1 \pm 0.4 \pm 0.0$	$0.8 \pm 0.3 \pm 0.0$	$2.0 \pm 0.5 \pm 0.1$	$0.5 \pm 0.3 \pm 0.0$
$N_i^{\rm bkg}$	$2.3 \pm 0.5 \pm 0.1$	$2.0 \pm 0.5 \pm 0.1$	$7.0 \pm 0.9 \pm 0.5$	$0.7 \pm 0.3 \pm 0.0$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-5})$	$4.9 \pm 0.2 \pm 0.4$	$6.0 \pm 0.2 \pm 0.5$	$12.2 \pm 0.3 \pm 1.4$	$1.2 \pm 0.1 \pm 0.1$
$N_i^{\rm obs}$	3	3	7	2
Limit	$< 19.4 \times 10^{-5}$	$< 17.0 \times 10^{-5}$	$< 8.9 \times 10^{-5}$	$< 86 \times 10^{-5}$
$\mathcal{B}(B^{+/0} \to K^{*+/0}\nu\bar{\nu})$	$(3.3^{+6.2+1.7}_{-3.6-1.3}) \times 10^{-5}$		$(2.0^{+5.2+2.0}_{-4.3-1.7}) \times 10^{-5}$	
Limit	$< 11.6 \times 10^{-5}$		$< 9.3 \times 10^{-5}$	
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$(2.7^{+3.8+1.2}_{-2.9-1.0}) \times 10^{-5}$			
Limit	$< 7.9 \times 10^{-5}$			

	$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$
$N_i^{\rm peak}$	$1.8 \pm 0.4 \pm 0.1$	$2.0 \pm 0.5 \pm 0.2$
$N_i^{\rm comb}$	$1.1 \pm 0.4 \pm 0.0$	$0.9 \pm 0.4 \pm 0.1$
$N_i^{\rm bkg}$	$2.9 \pm 0.6 \pm 0.1$	$2.9 \pm 0.6 \pm 0.2$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-5})$	$43.8 \pm 0.7 \pm 3.0$	$10.3 \pm 0.2 \pm 1.2$
$N_i^{\rm obs}$	6	3
$\mathcal{B}_i$	$(1.5^{+1.7+0.4}_{-0.8-0.2}) \times 10^{-5}$	$(0.14^{+6.0+1.7}_{-1.9-0.9}) \times 10^{-5}$
Limits	$(> 0.4, < 3.7) \times 10^{-5}$	$< 8.1 \times 10^{-5}$
$\mathcal{B}(B \to K\nu\bar{\nu})$	$(1.4^{+1.4+0.3}_{-0.9-0.2}) \times 10^{-5}$	
Limits	$(> 0.2, < 3.2) \times 10^{-5}$	

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

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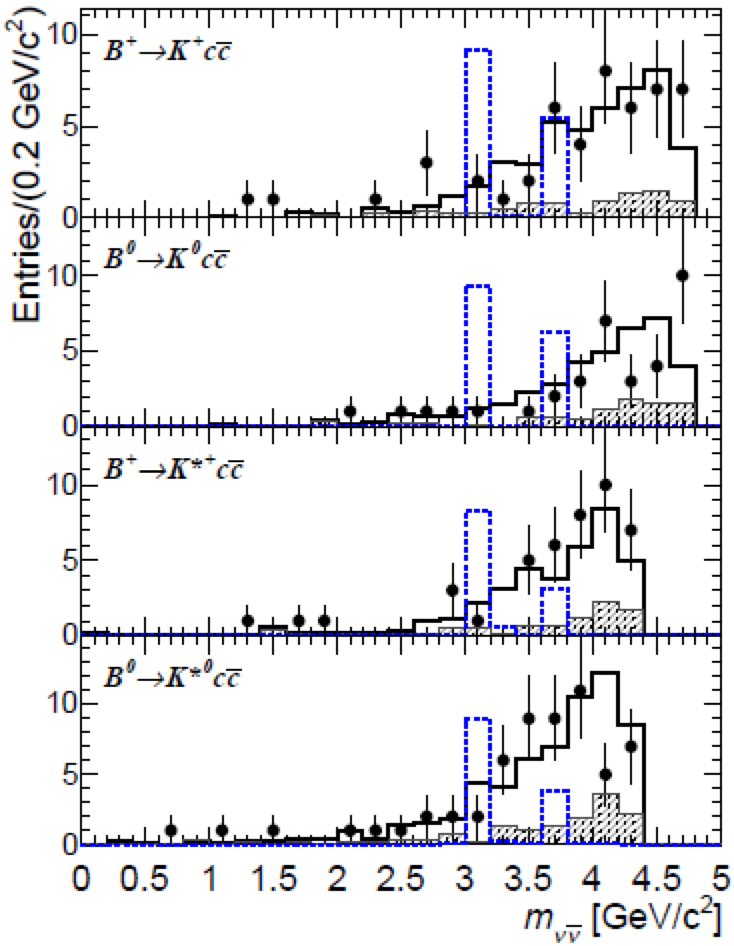

- Data
- Comb. BG predicted by MC
- M_ES peaking
- Signal

After all signal criteria applied.

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

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Channel	K^+	K^0	$K^{*+} \to K^+\pi^0$	$K^{*+} \to K^0_S\pi^+$	$K^{*0} \to K^+\pi^-$	$K^{*0} \to K^0_S\pi^0$
			$J/\psi \to \nu\bar{\nu}$			
$N_i^{\rm peak}$	$0.4 \pm 0.2 \pm 0.0$	$0.7 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.1$	$0.4 \pm 0.2 \pm 0.0$	$2.6 \pm 0.5 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$N_i^{\rm bkg}$	$0.5 \pm 0.2 \pm 0.0$	$0.7 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.0$	$2.8 \pm 0.5 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-8})$	$95.3 \pm 4.4 \pm 5.5$	$19.3 \pm 1.0 \pm 2.1$	$20.9 \pm 1.5 \pm 1.7$	$12.4 \pm 0.8 \pm 1.0$	$36.2 \pm 1.9 \pm 4.0$	$1.8 \pm 0.2 \pm 0.2$
$N_i^{\rm obs}$	1	0	1	0	0	1
$\mathcal{B}(J/\psi \to \nu\bar{\nu})$			$(0.2^{+2.7+0.5}_{-0.9-0.4}) \times 10^{-3}$			
Limit			$< 3.9 \times 10^{-3}$			

Channel	K^+	K^0	$K^{*+} \to K^+\pi^0$	$K^{*+} \to K^0_S\pi^+$	$K^{*0} \to K^+\pi^-$	$K^{*0} \to K^0_S\pi^0$
			$\psi(2S) \to \nu\bar{\nu}$			
$N_i^{\rm peak}$	$1.4 \pm 0.4 \pm 0.1$	$0.6 \pm 0.3 \pm 0.1$	$1.4 \pm 0.4 \pm 0.1$	$1.0 \pm 0.3 \pm 0.1$	$3.5 \pm 0.7 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$N_i^{\rm bkg}$	$1.6 \pm 0.4 \pm 0.1$	$0.7 \pm 0.3 \pm 0.1$	$1.4 \pm 0.4 \pm 0.1$	$1.5 \pm 0.4 \pm 0.1$	$3.9 \pm 0.7 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-8})$	$57.2 \pm 3.5 \pm 3.3$	$13.1 \pm 1.2 \pm 1.4$	$8.1 \pm 1.7 \pm 0.7$	$4.9 \pm 1.1 \pm 0.4$	$14.2 \pm 1.2 \pm 1.6$	$0.6 \pm 0.1 \pm 0.1$
$N_i^{\rm obs}$	3	1	1	3	5	1
$\mathcal{B}(\psi(2S) \to \nu\bar{\nu})$			$(5.6^{+7.4+1.6}_{-4.6-1.4}) \times 10^{-3}$			
Limit			$< 15.5 \times 10^{-3}$			

Submitted to PRD(RC). arXiv:1303.7465[hep-ex].

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

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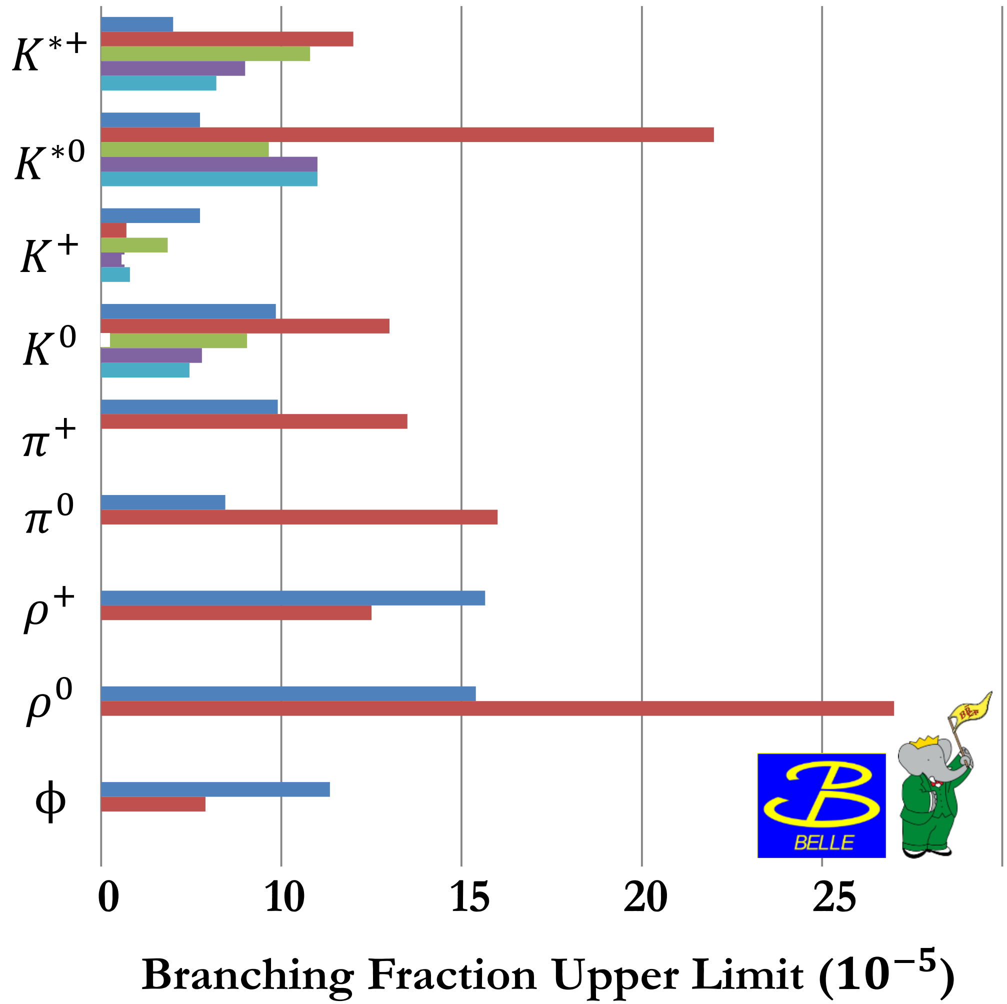
Belle 2013 result supercedes Belle 2007.



Belle 2013, 772M $B\bar{B}$, Had.
Belle 2007, 535M $B\bar{B}$, Had.

Babar 2013, 471M $B\bar{B}$, Had.
Babar, 08' 10', ~460M $B\bar{B}$, SL.
Babar, Combined.

Had. : Hadronic Tagging Method
SL. : Semi-leptonic Tagging Method

Belle 2007 : PRL 99, 221802 (2007).
Babar 08' : PRD 78, 072007 (2008).
Babar 10' : PRD 82, 112002 (2010).

	K^*	K
2013 Had.	7.9	0.2-3.2
Prev. SL+2013 Had.		1.7

<Babar's Had. + SL. Combined Result>

$B^0 \rightarrow invisible: BACKUP$

$B^0 \rightarrow$ *invisible*: PDF modeling

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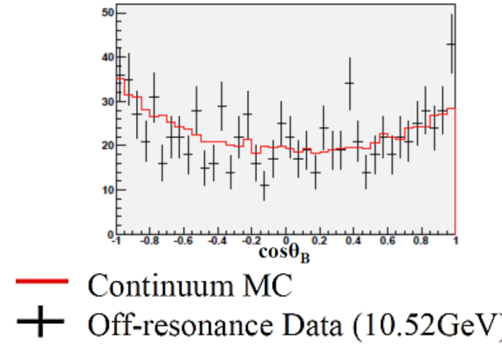
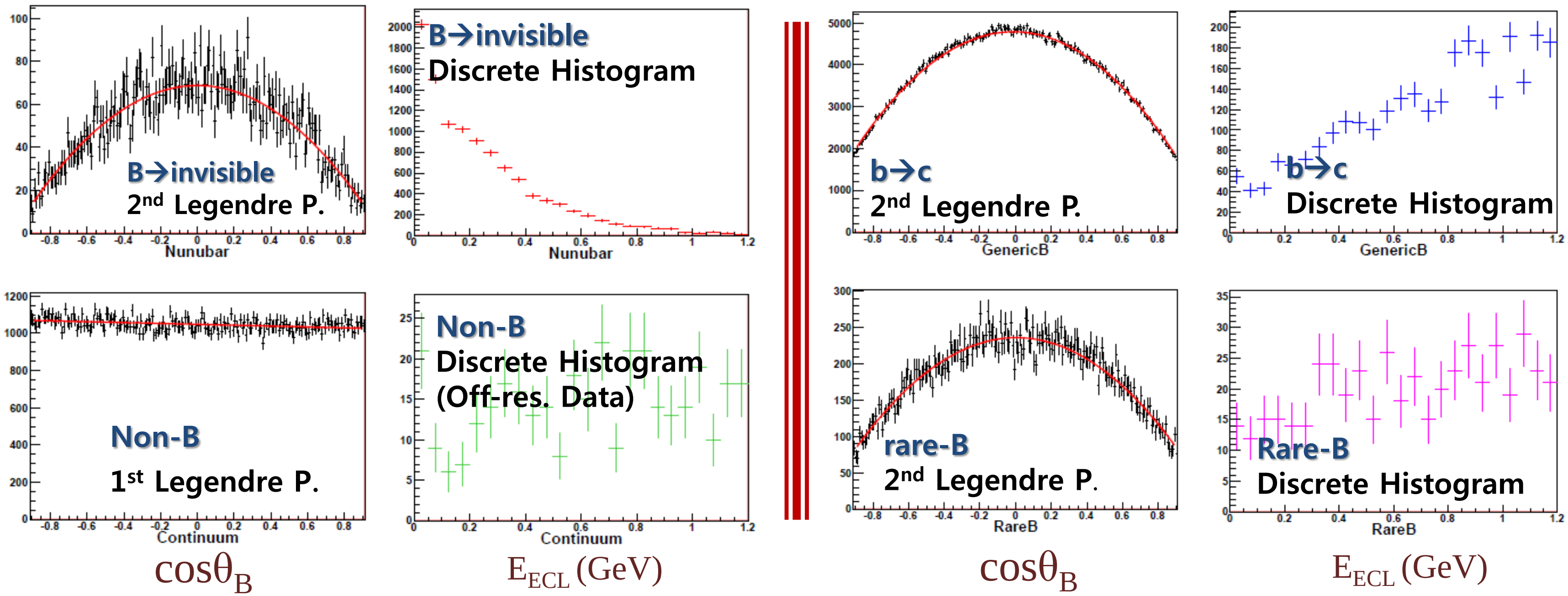
- PDF obtained from unbinned maximum likelihood fits.
- E_{ECL}: Discrete histogram function
  - Energy threshold within 0 – 0.05 GeV
- $cos\theta_B$: Legendre Polynomials
- Combined PDF: $P(E_{ECL}, cos\theta_B) = P(E_{ECL}) \times P(cos\theta_B)$
  - Low correlation between E_{ECL} & $cos\theta_B$





Belle: PRD 86, 032002 (2012).

$B^0 \rightarrow invisible$: Systematics

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Sources	Syst. uncertainty
$N(B\overline{B})$	1.4
Tagging efficiency	8.3
Track veto efficiency	1.6
π^0 veto efficiency	2.0
K_L veto efficiency	2.0
Sum	9.0

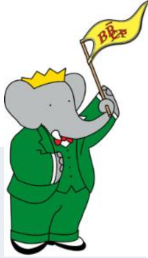
On ϵ_{signal}

Sources	Syst. uncertainty(Events)
Signal	negligible
Generic B BG	$^{+1.6}_{-1.4}$
Rare B BG	± 0.1
Non-B BG	$^{+1.9}_{-1.3}$
Non-B BG(binning effect)	$^{+0.0}_{-1.8}$
Sum	$^{+2.5}_{-2.6}$

On N_{sig}

Belle: PRD 86, 032002 (2012).

$B^0 \to invisible$: Neural Network



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Common	1. $cos\theta_{B,D(*)-\ell}$ 2. $cos\angle(B_{Tag}\ thrust, D(*) - \ell\ momentum)$ 3. p_ℓ^{CM}	
(invisible)	1. Missing Mass 2. B-vertex probability 3. 1^{st}-0^{th} L-momenta in CM 4. Transverse momentum of $D - \ell$ momentum in CM 5. Minimum mass of any two tracks 6. Category 5 for any three tracks	4-6: $D\ell\nu$ tag only
In addition to all that, for (invisible)+γ	*1.* E_γ on the signal side (Lab. Frame) *2.* M_{miss}^{tag}	2: $D\ell\nu$ tag only

BABAR: PRD 86, 051105(R) (2012).

$B^0 \to invisible$: Systematics

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TABLE II. Summary of the systematic uncertainties.

Source	$B^0 \to$ invisible	$B^0 \to$ invisible + γ
Normalization errors		
B-counting	0.6%	0.6%
Efficiency errors		
Tagging efficiency	3.5%	3.5%
m_D (Δm) selection	1%	1.3%
Preselection	3%	2.4%
Neural network	6.1%	8.2%
Single photon	$\cdots$	1.8%
Total	7.7%	9.5%
Yield errors (events)		
Background parameter	15.8	6.5
Signal parameter	2.0	1.2
Fit technique	$\cdots$	1.0
E_{extra} shape	0.1	1.8
Total	15.9	6.9

BABAR: PRD 86, 051105(R) (2012).

$B^+ \to \ell^+ \nu_\ell$ BACKUP

$\ell = e, \mu$

$B^+ \to \ell^+ \nu_\ell$: Validation

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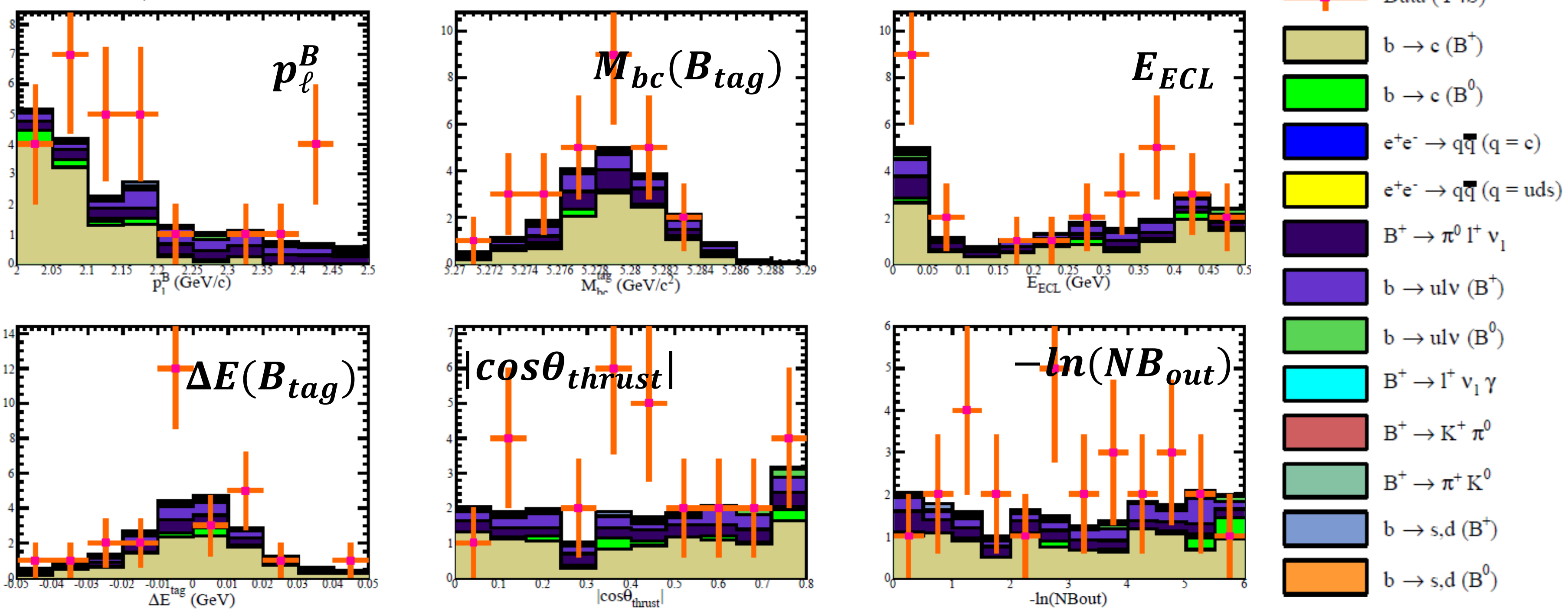
$B^+ \to \mu^+ \nu_\mu$



- Comparison of MC events and the Data in the sideband of p_ℓ^B (2.0 – 2.5 GeV)

	N_{data}	N_{MC}	$\Sigma\chi^2$/n.d.f (p_ℓ^B)
$B^+ \to e^+\nu_e$	18	14	0.39
$B^+ \to \mu^+\nu_\mu$	28	20	0.92

- Tag efficiency correction from a $B \to D^{(*)}\ell\nu_\ell$ control sample study applied.
- A good agreement between MC events and the experimental Data.

$B^+ \to \ell^+\nu_\ell$: Background Modeling

$\ell = e, \mu$

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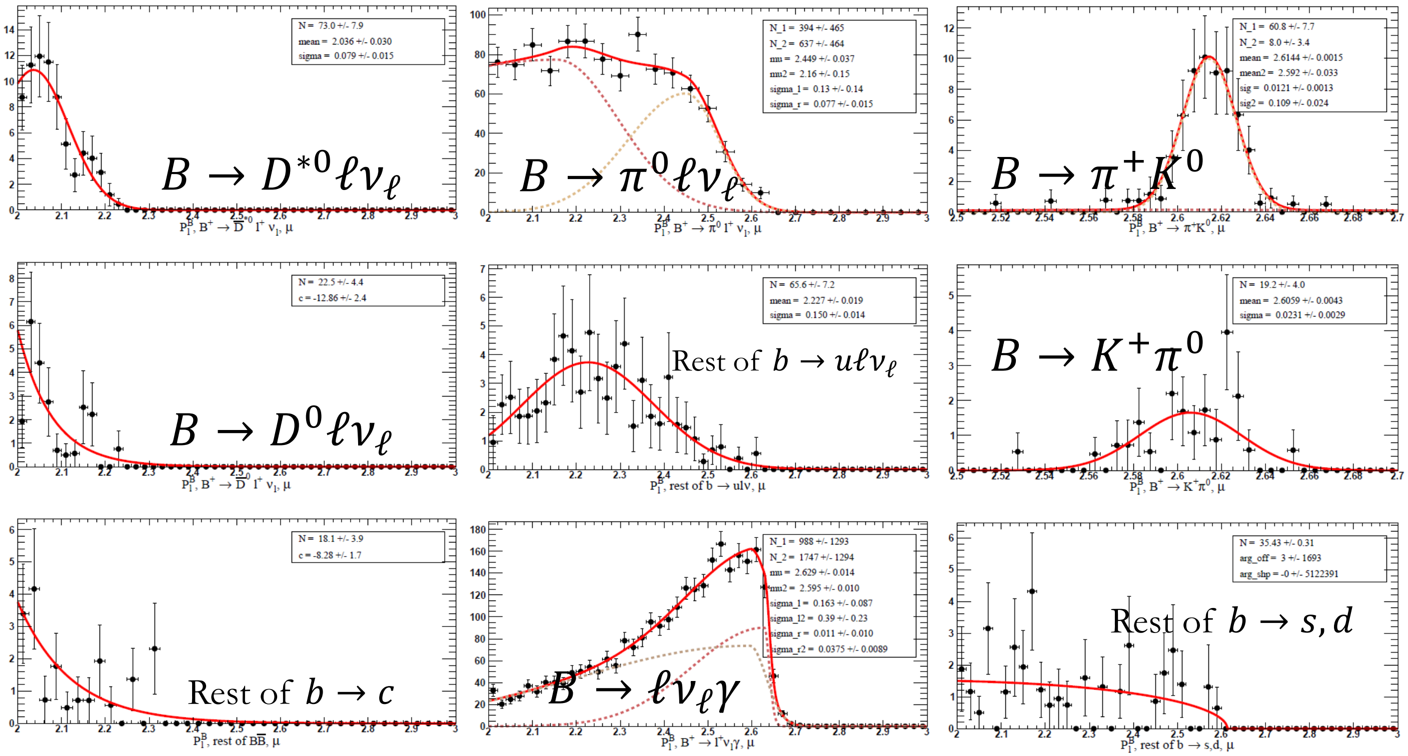
Analysis Strategy:
Fit the sideband of p_ℓ^B (2 – 2.5 GeV/c) to extrapolate the background into the signal region (~2.6 – 2.7 GeV/c).
Dedicated MC modeling for peaking BG at signal region.

1-D unbinned maximum likelihood fit in p_ℓ^B for modeling the BG PDF according to MC samples.

Component-wise fit + Addition in proportion to luminosity.



BG-component by component modeling in $B^+ \to \mu^+\nu_\mu$ search.

$B^+ \to \ell^+ \nu_\ell$: Branching fraction

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- Branching fraction is obtained by $B.F. = \frac{N_{obs} - N_{bkg}}{N_{B\bar{B}} * \epsilon_{sig}}$.
- $N_{bkg} = N_{Data(side)} \times \frac{S_{MC(signal)}}{S_{MC(side)}}$
  - $N_{Data(side)}$: Data yield in the sideband p_ℓ^B obtained from fitting a fixed BG PDF.
  - $\frac{S_{MC(signal)}}{S_{MC(side)}}$: Ratio of MC events in signal and sideband of p_ℓ^B.

  Uncertainties on N_{bkg} from

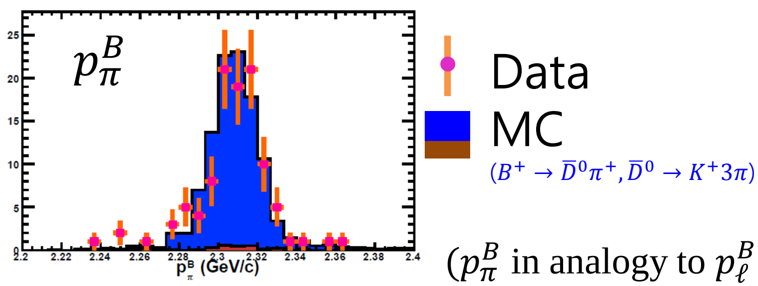
  1. Data statistical error 2. Branching Fraction uncertainties 3. Fit Parameters
  (Varied by 1-σ and accept the difference as the uncertainty)

- ϵ_{sig}: Obtained by counting in the signal region of p_ℓ^B.

Source		Electron Mode	Muon Mode
$N(B\bar{B})$		1.4%	1.4%
Tag efficiency correction		4.2%	4.2%
Signal Efficiency	LID	1.0%	1.0%
	Tracking	0.35%	0.35%
	MC statistics	1.6%	1.5%
	Event shape	11.3%	11.3%
TOTAL(Quadratic Sum)		12.3%	12.3%
$\epsilon_\ell(\%)$		0.092 ± 0.011	0.109 ± 0.013

<ϵ_{sig} systematic uncertainties>

Systematic uncertainty subjected to ϵ_{sig} is dominated by p_ℓ^B shape uncertainty.
(From a $B^+ \to \bar{D}^0\pi^+$ control-sample study)



(p_π^B in analogy to p_ℓ^B)

Not a hadronic
tagging analysis

$B \to (X)\ell\nu_h: BACKUP$

ν_h: Heavy Neutral Lepton

$B \to (X)\ell\nu_h$: Decays into Nu_h

leptonic

Back to p.25

$$\frac{d\mathrm{Br}\left(H^+ \to l_\alpha^+ N\right)}{dE_N} = \tau_H \cdot \frac{G_F^2 f_H^2 M_H M_N^2}{8\pi} |V_H|^2 |U_\alpha|^2 \cdot \left(1 - \frac{M_N^2}{M_H^2} + 2\frac{M_l^2}{M_H^2} + \frac{M_l^2}{M_N^2}\left(1 - \frac{M_l^2}{M_H^2}\right)\right)$$
$$\times \sqrt{\left(1 + \frac{M_N^2}{M_H^2} - \frac{M_l^2}{M_H^2}\right)^2 - 4\frac{M_N^2}{M_H^2}} \cdot \delta\left(E_N - \frac{M_H^2 - M_l^2 + M_N^2}{2M_H}\right),$$

Pseudo-scalar meson semi-leptonic

$$\frac{d\mathrm{Br}\left(H \to H' l_\alpha^+ N\right)}{dE_N} = \tau_H \cdot |U_\alpha|^2 \cdot \frac{|V_{HH'}|^2 G_F^2}{64\pi^3 M_H^2} \times \int dq^2 \Bigg(f_-^2(q^2) \cdot \left(q^2\left(M_N^2 + M_l^2\right) - \left(M_N^2 - M_l^2\right)^2\right)$$
$$+ 2 f_+(q^2) f_-(q^2)\left(M_N^2\left(2M_H^2 - 2M_{H'}^2 - 4E_N M_H - M_l^2 + M_N^2 + q^2\right) + M_l^2\left(4E_N M_H + M_l^2 - M_N^2 - q^2\right)\right)$$
$$f_+^2(q^2)\Bigg(\left(4E_N M_K + M_l^2 - M_N^2 - q^2\right)\left(2M_K^2 - 2M_\pi^2 - 4E_N M_K - M_l^2 + M_N^2 + q^2\right)$$
$$- \left(2M_K^2 + 2M_\pi^2 - q^2\right)\left(q^2 - M_N^2 - M_l^2\right)\Bigg)\Bigg),$$

$$q^2 = (p_l + p_N)^2$$

$V_H = V_{ud}$ for a pion

D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007) [arXiv:0705.1729 [hep-ph]].

$B \to (X)\ell\nu_h$: Decays into Nu_h

Back to p.25

Vector meson semi-leptonic

$$\frac{d\mathrm{Br}\,(H \to V l_\alpha N)}{dE_N} = \tau_H \cdot |U_\alpha|^2 \cdot \frac{|V_{HV}|^2 G_F^2}{32\pi^3 M_H} \times \int dq^2 \left(\frac{f_2^2}{2}\left(q^2 - M_N^2 - M_l^2 + \omega^2 \frac{\Omega^2 - \omega^2}{M_V^2}\right) \right.$$
$$+\frac{f_5^2}{2}\left(M_N^2 + M_l^2\right)\left(q^2 - M_N^2 + M_l^2\right)\left(\frac{\Omega^4}{4M_V^2} - q^2\right) + 2f_3^2 M_V^2 \left(\frac{\Omega^4}{4M_V^2} - q^2\right)\left(M_N^2 + M_l^2 - q^2 + \omega^2\frac{\Omega^2 - \omega^2}{M_V^2}\right)$$
$$+2f_3 f_5\left(M_N^2\omega^2 + \left(\Omega^2 - \omega^2\right)M_l^2\right)\left(\frac{\Omega^4}{4M_V^2} - q^2\right) + 2f_1 f_2\left(q^2\left(2\omega^2 - \Omega^2\right) + \Omega^2\left(M_N^2 - M_l^2\right)\right)$$
$$+\frac{f_2 f_5}{2}\left(\omega^2\frac{\Omega^2}{M_V^2}\left(M_N^2 - M_l^2\right) + \frac{\Omega^4}{M_V^2}M_l^2 + 2\left(M_N^2 - M_l^2\right)^2 - 2q^2\left(M_N^2 + M_l^2\right)\right)$$
$$+f_2 f_3\left(\Omega^2\omega^2\frac{\Omega^2 - \omega^2}{M_V^2} + 2\omega^2\left(M_l^2 - M_N^2\right) + \Omega^2\left(M_N^2 - M_l^2 - q^2\right)\right)$$
$$\left. +f_1^2\left(\Omega^4\left(q^2 - M_N^2 + M_l^2\right) - 2M_V^2\left(q^4 - \left(M_N^2 - M_l^2\right)^2\right) + 2\omega^2\Omega^2\left(M_N^2 - q^2 - M_l^2\right) + 2\omega^4 q^2\right)\right),$$

$$q^2 = \left(p_l + p_N\right)^2$$
$$\omega^2 = M_H^2 - M_V^2 + M_N^2 - M_l^2 - 2M_H E_N$$
$$\Omega^2 = M_H^2 - M_V^2 - q^2$$

$$f_1 = \frac{V}{M_H + M_V}, \quad f_2 = \left(M_H + M_V\right)\cdot A_1, \quad f_3 = -\frac{A_2}{M_H + M_V},$$
$$f_4 = \left(M_V\left(2A_0 - A_1 - A_2\right) + M_H\left(A_2 - A_1\right)\right)\cdot\frac{1}{q^2}, \quad f_5 = f_3 + f_4,$$

D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007) [arXiv:0705.1729 [hep-ph]].

$B \to (X)\ell\nu_h$: Nu_h → pi + lep

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$$\Gamma\left(N \to H^+ l_\alpha^-\right) = \frac{|U_\alpha|^2}{16\pi} G_F^2 |V_H|^2 f_H^2 M_N^3 \cdot \left(\left(1 - \frac{M_l^2}{M_N^2}\right)^2 - \frac{M_H^2}{M_N^2}\left(1 + \frac{M_l^2}{M_N^2}\right)\right)$$
$$\times \sqrt{\left(1 - \frac{(M_H - M_l)^2}{M_N^2}\right)\left(1 - \frac{(M_H + M_l)^2}{M_N^2}\right)},$$

D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007) [arXiv:0705.1729 [hep-ph]].

$B \to X\ell\nu_h$: Prev. Experiment Summary

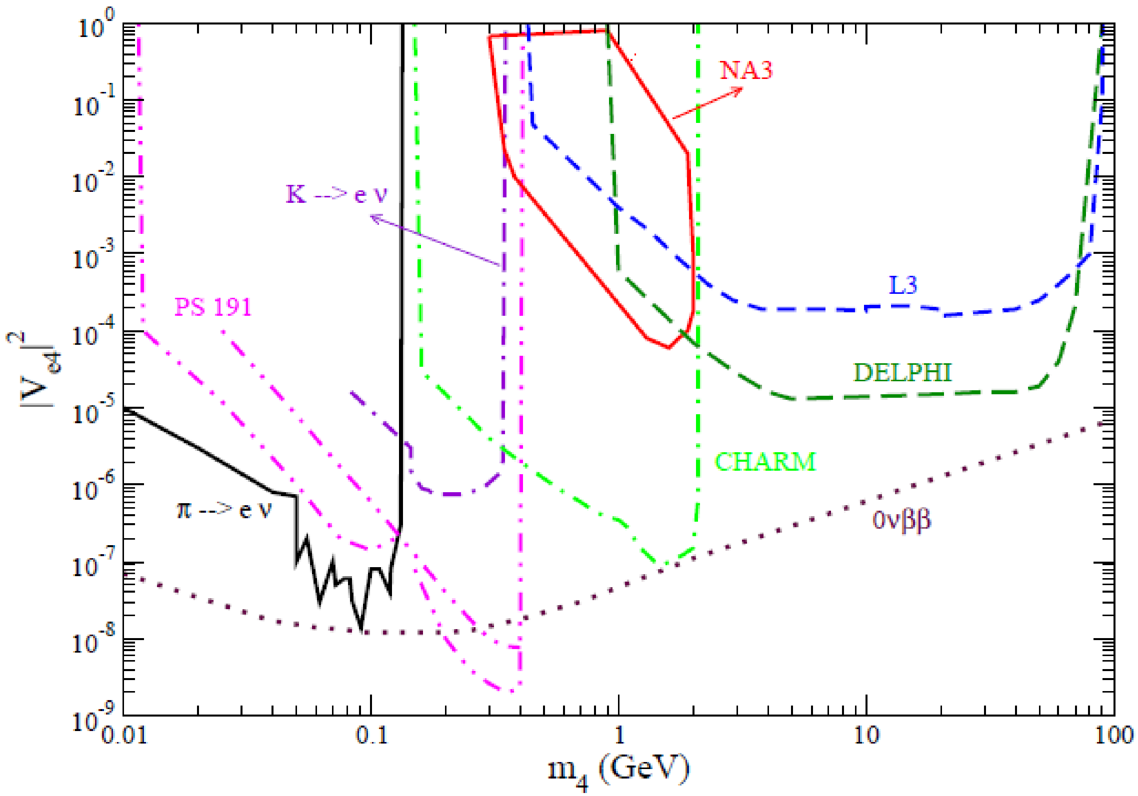
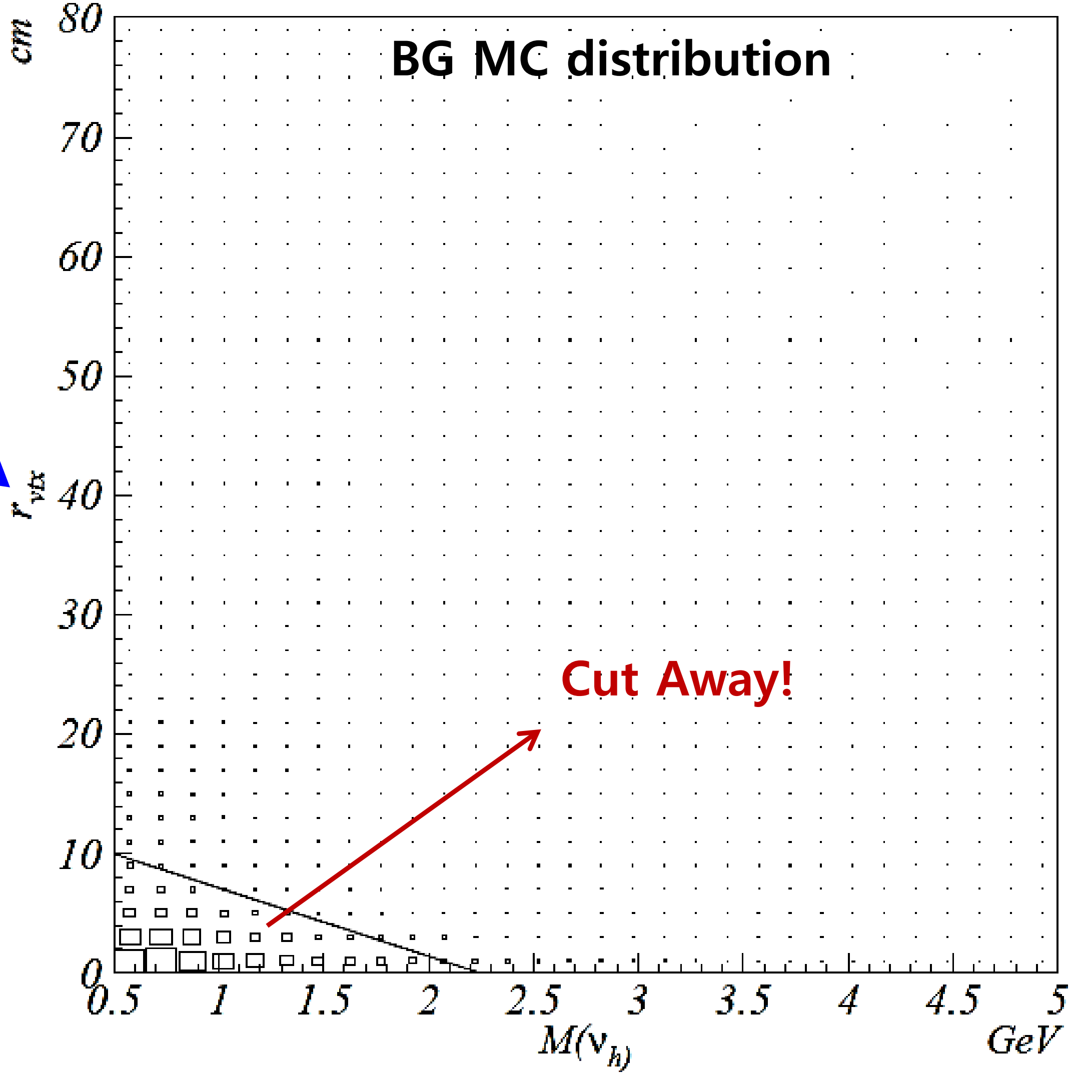


Figure 3. Bounds on $|V_{e4}|^2$ versus m_4 in the mass range 10 MeV–100 GeV. The areas with solid (black) contour labeled $\pi \to e\nu$ and double dash dotted (purple) contour labeled $K \to e\nu$ are excluded by peak searches [83, 85]. Limits at 90% C.L. from beam-dump experiments are taken from ref. [86] (PS191), ref. [87] (NA3) and ref. [88] (CHARM). The limits from contours labeled DELPHI and L3 are at 95% C.L. and are taken from refs. [89] and [90] respectively. The excluded region with dotted (maroon) contour is derived from a reanalysis of neutrinoless double beta decay experimental data [84].

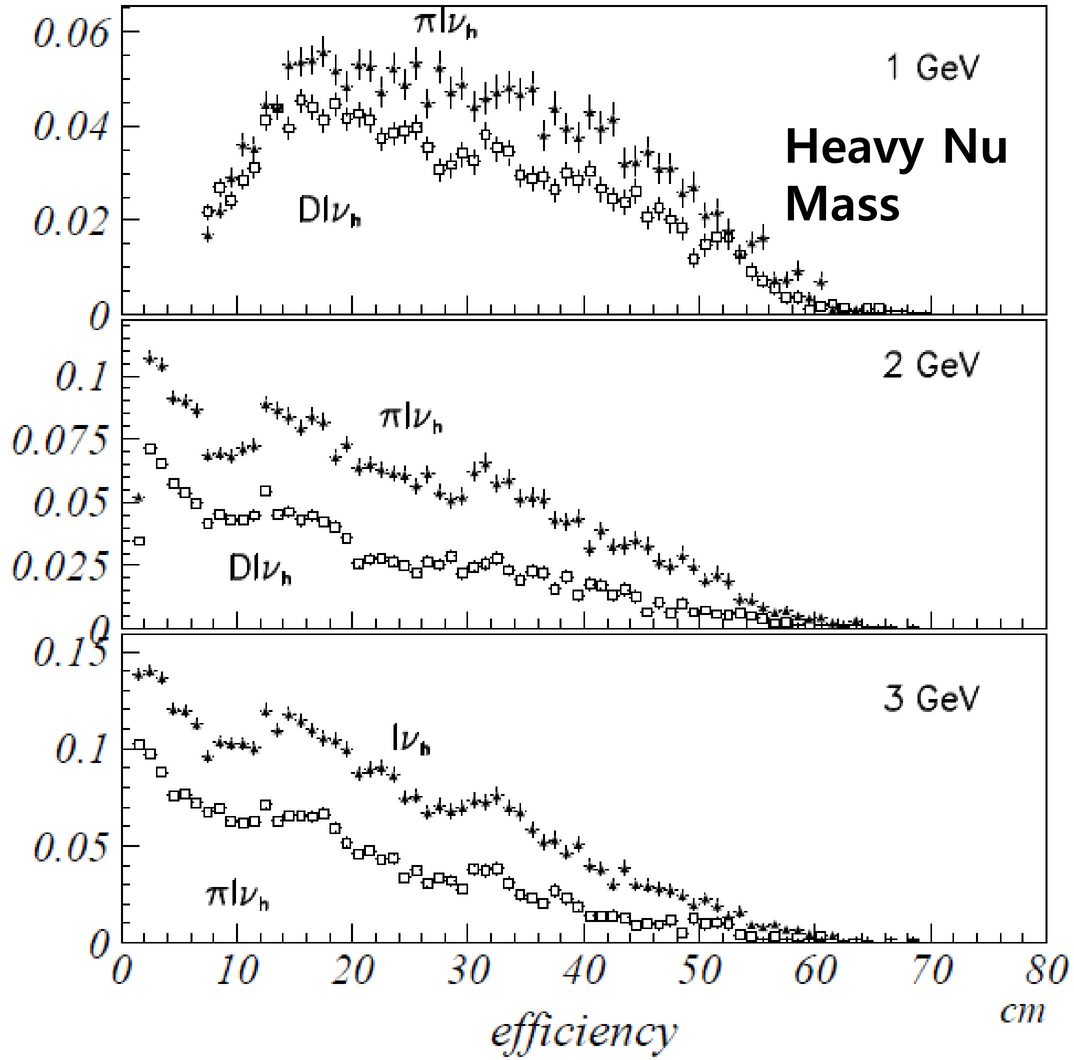
JHEP. 05 (2009) 030.

$B \to X\ell\nu_h$: Backgrounds

Length in x-y plane.



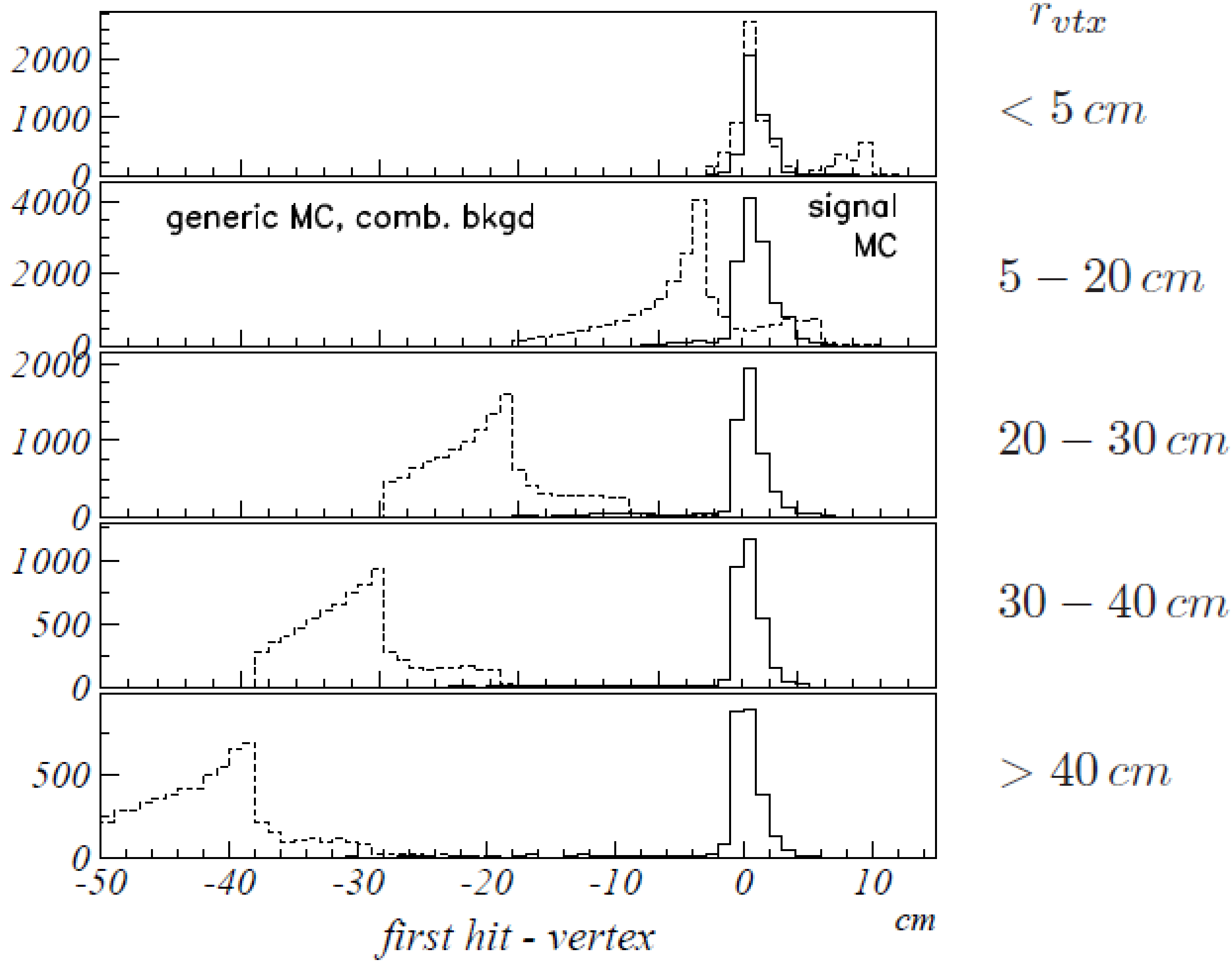
$B \to X\ell\nu_h$: Flight Length vs Eff.



Heavy Nu Mass

FLIGHT LENGTH

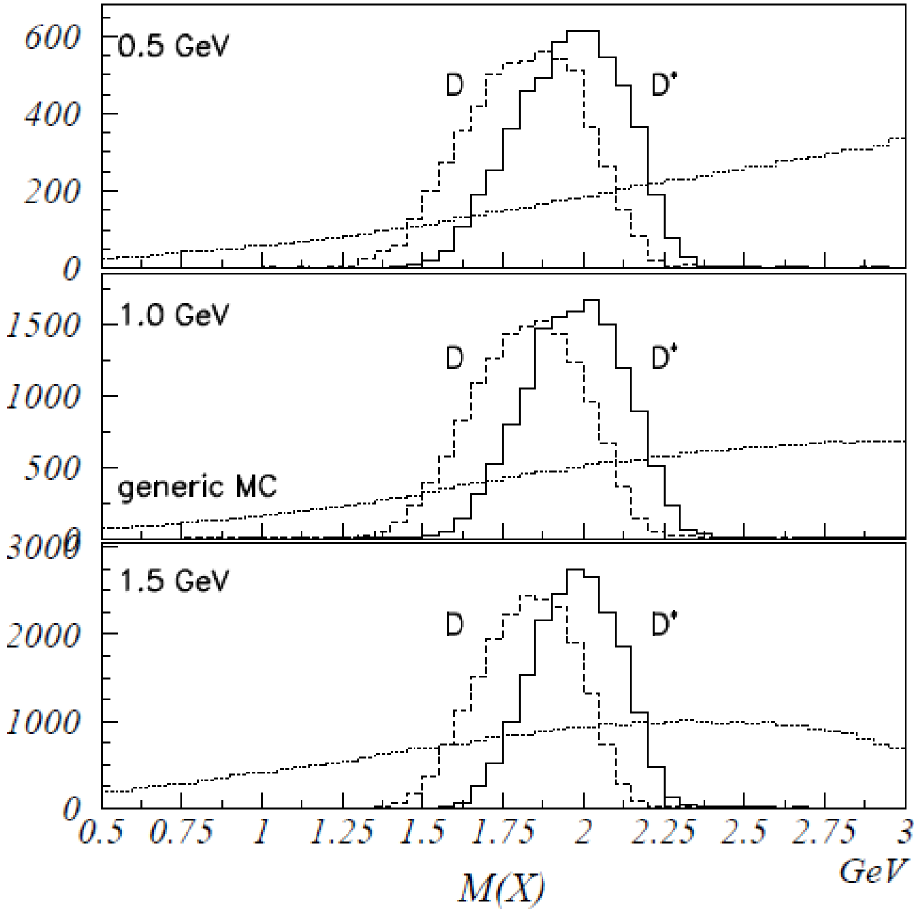
$B \to X\ell\nu_h$: Combinat. BG. Supp.



$$fh = \min(r_\ell, r_\pi) - r_{vtx}.$$

$B \to X\ell\nu_h$: M_x distributions

BELLE



"small": $M(\nu_h) < 2.0GeV/c^2$, $\boldsymbol{X} = \boldsymbol{D}^{(*)}$ dominant

$D^{(*)}$ identified by "Missing Mass" : $M_X^2 \equiv \left(E_{CM} - E_{\ell_1\ell_2\pi}\right)^2 - P_{\ell_1\ell_2\pi}^2 - P_B^2$

"large": $M(\nu_h) > 2.0GeV/c^2$, $\boldsymbol{X} = \boldsymbol{D}^{(*)}$, **light meson, nothing**

$B \to X\ell\nu_h$: Systematics

Requirement	Systematic error, %
tracking	8.7
recoil mass	4.1
$\mathcal{P}_e(\ell_1)$	2.8
$\mathcal{P}_\mu(\ell_1)$	4.9
$\mathcal{P}_e(\ell_2)$	2.3
$\mathcal{P}_\mu(\ell_2)$	3.1
$d\phi$	5.8
dr	3.7
z_{dist}	10.0
χ_1^2	2.9
χ_2^2	10.1
first hit	2.9
lepton veto	1.8
proton veto	1.6
Total	23.2

Belle: PRD 87, 071102(R) (2013).

$B \to X\ell\nu_h$: Mixing upper limit

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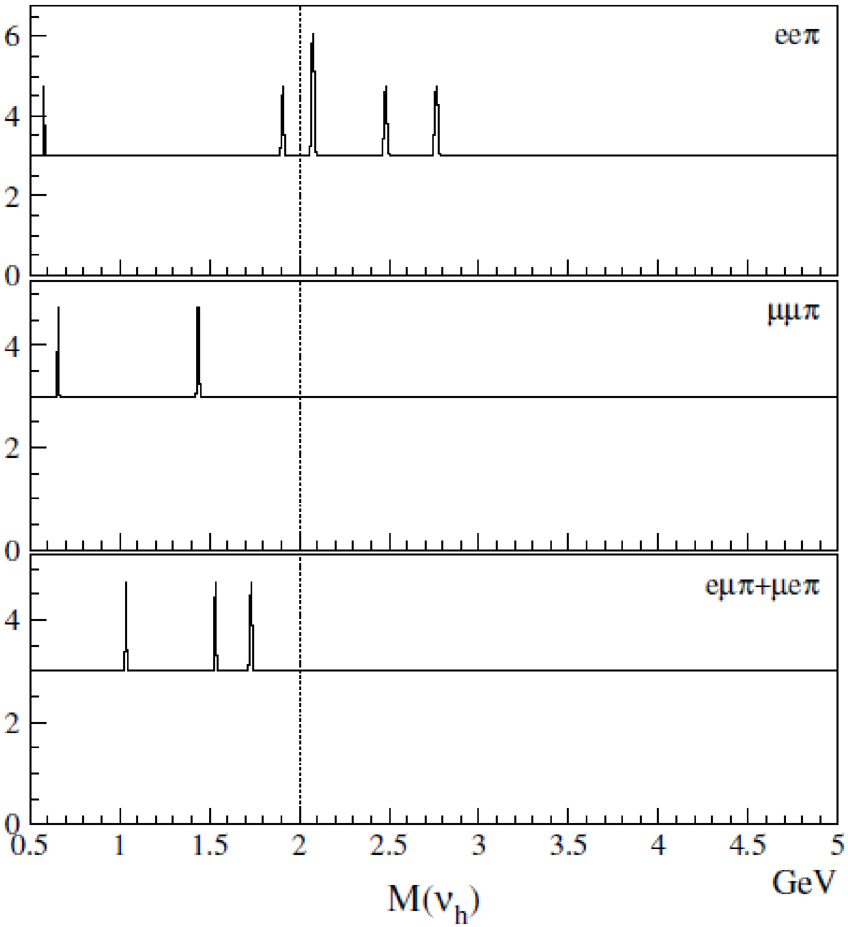
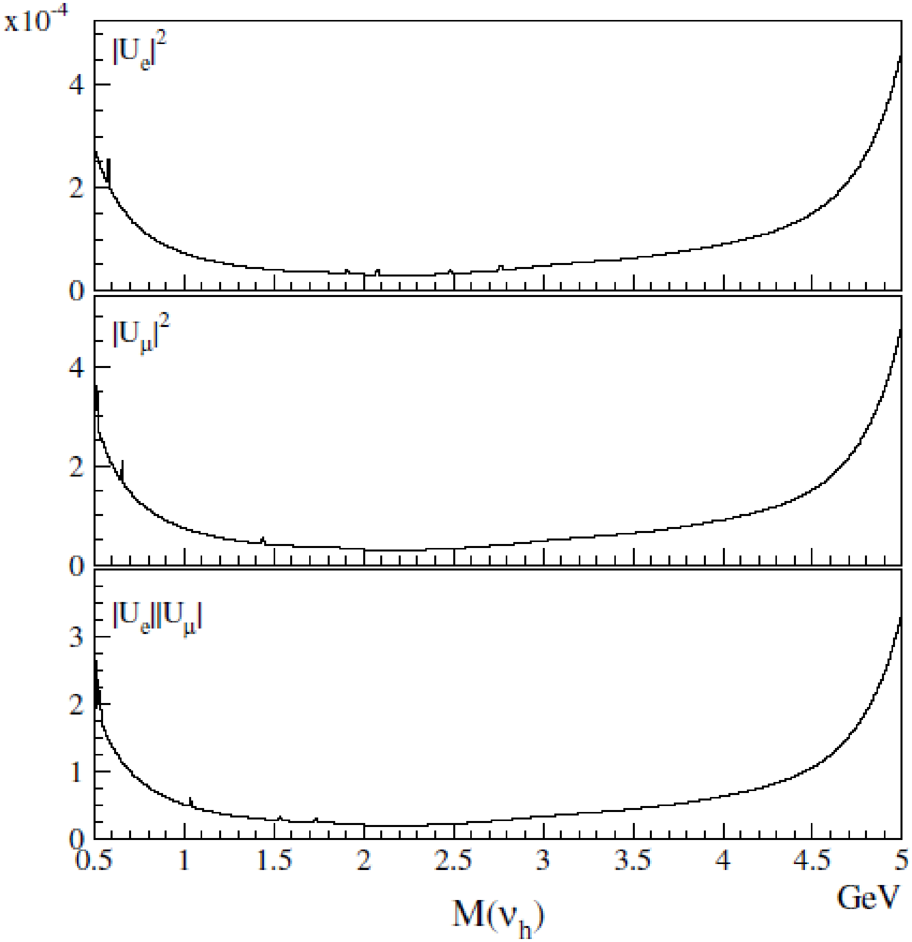


<Upper limits on Events @90% C.L.>



<Upper limits on $|U_\ell|^2$ @90% C.L.>

Belle: PRD 87, 071102(R) (2013).