Rare and forbidden B and tau decays in Belle

24 July, 2014

(on behalf of Belle Collaboration)

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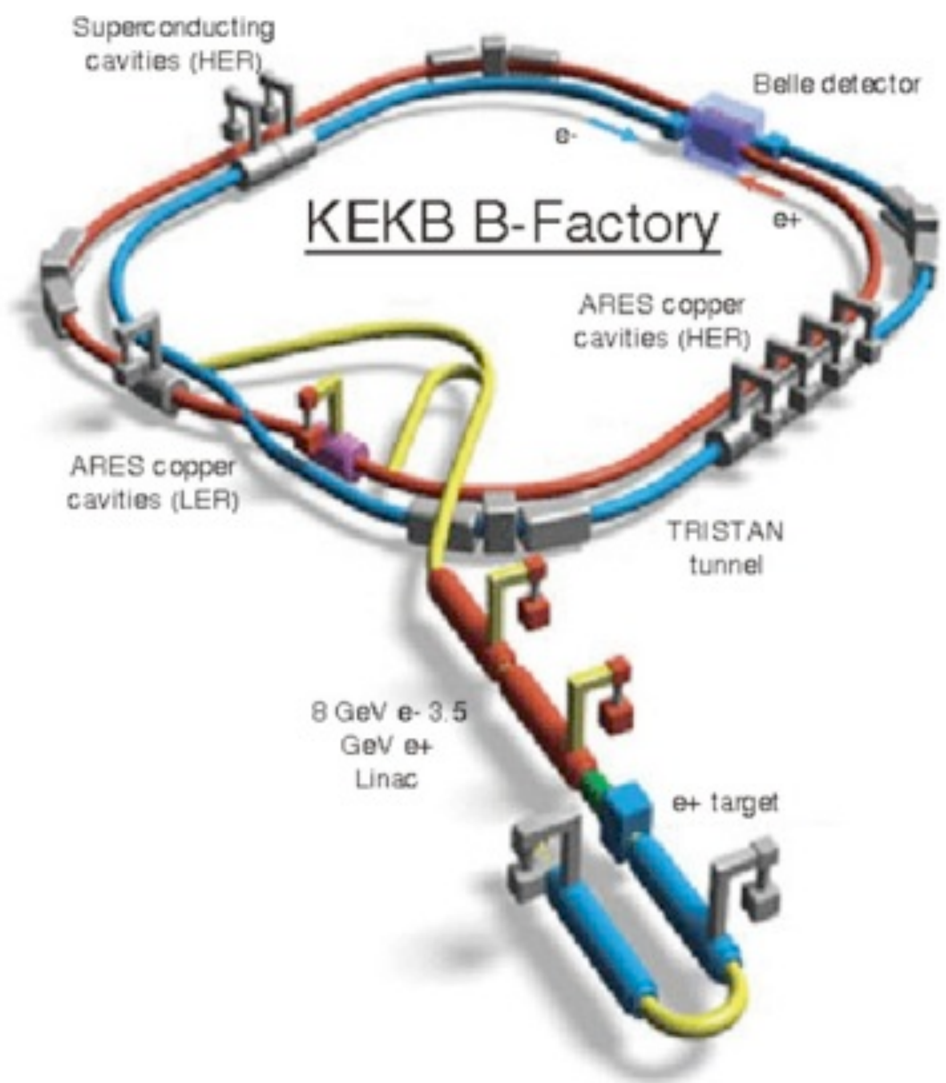
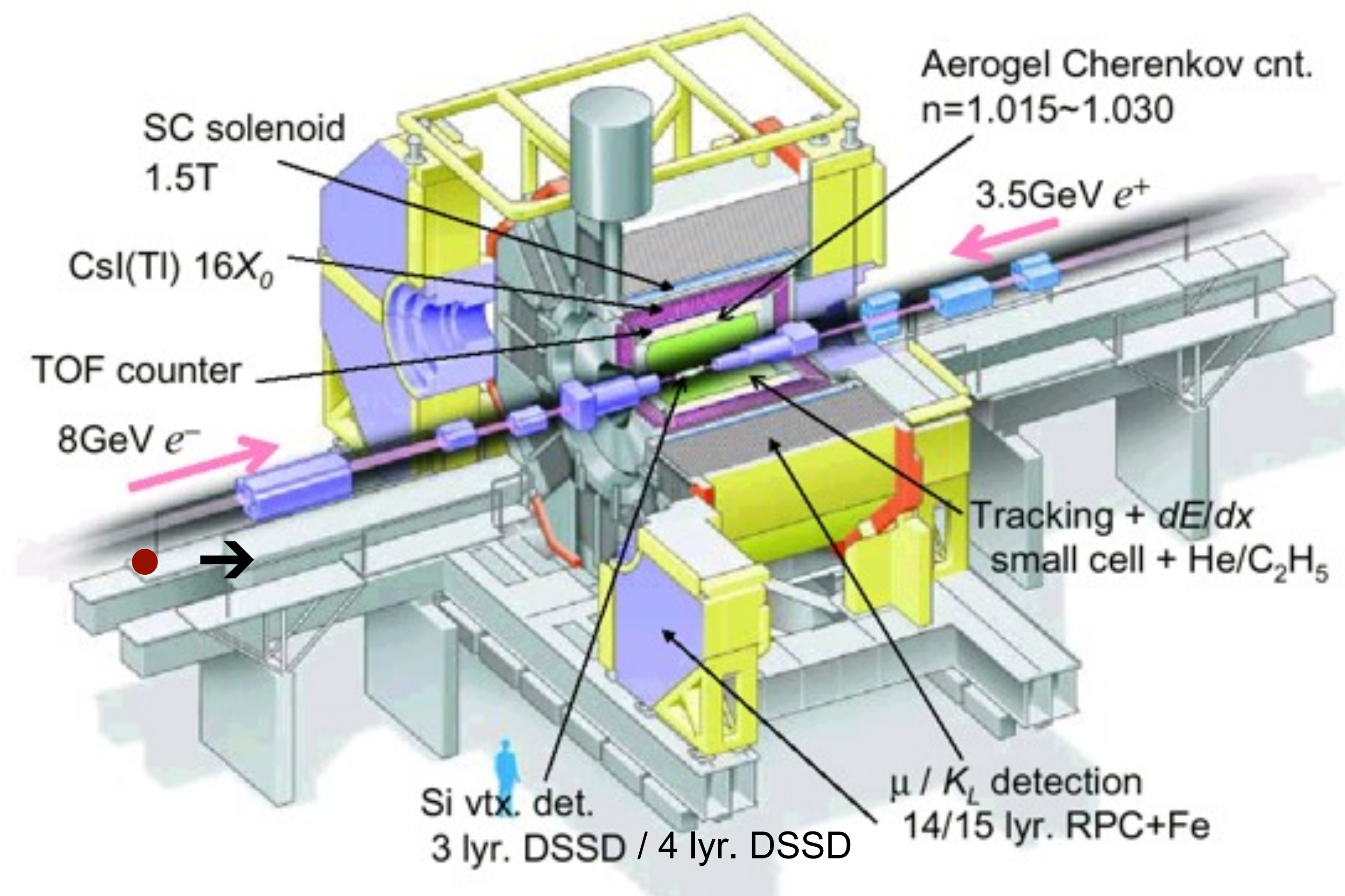
KEKB and Belle Experiment



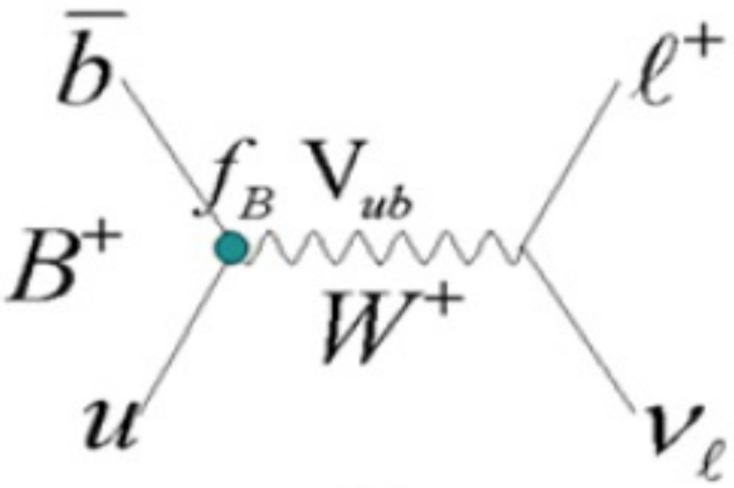


- 4π detector + known initial state ➔ perfect environment for studies of B decays with neutrinos in final state
- Collected full data set : ~710 fb^{-1} at Υ(4S) ➔ 772 × 10^6 BB-bar pairs

$B^+ \rightarrow e^+\nu_e$ and $B^+ \rightarrow \mu^+\nu_\mu$

Y. Yook, et al., arXiv:1406.6356v1

Physics Motivation



SM Predictions:

$\mathcal{B}(B \rightarrow e\nu) \sim 10^{-11}$

$\mathcal{B}(B \rightarrow \mu\nu) \sim 10^{-7}$

$\mathcal{B}(B \rightarrow \tau\nu) \sim 10^{-4}$

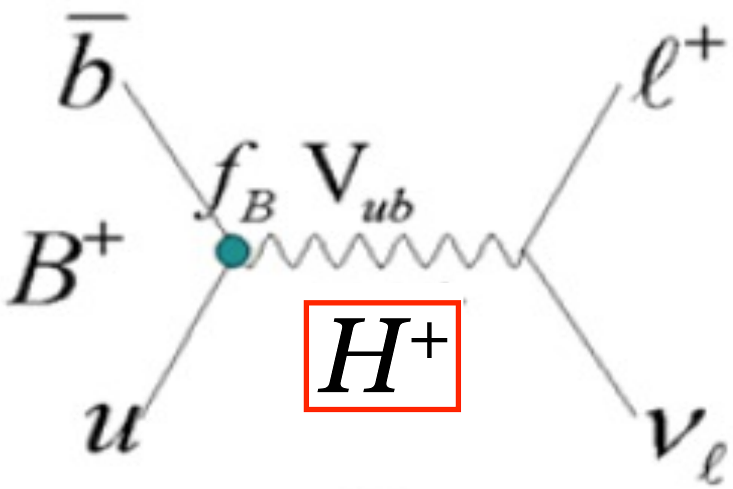
Helicity suppressed in the SM

$$\mathcal{B}(B^+ \rightarrow l^+\nu_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

Origin of uncertainty
$|V_{ub}|$ given by a fit to the full CKM unitarity triangle
f_B given from lattice QCD calculations

- A clean process for the measurement of $f_B^2 \cdot |V_{ub}|^2$ within the SM
- Evidence of $B^+ \rightarrow \tau^+\nu$ from Belle and BABAR experiments
  - $[0.72\ ^{+0.27}_{-0.25}\ (\text{stat}) \pm 0.11\ (\text{syst})] \times 10^{-4}$ PRL 110, 131801 (2013)
  - $[1.8\ ^{+0.9}_{-0.8}\ (\text{stat}) \pm 0.4\ (\text{bkg. syst}) \pm 0.2\ (\text{other syst})] \times 10^{-4}$ PRD 77, 011107(R) (2008)

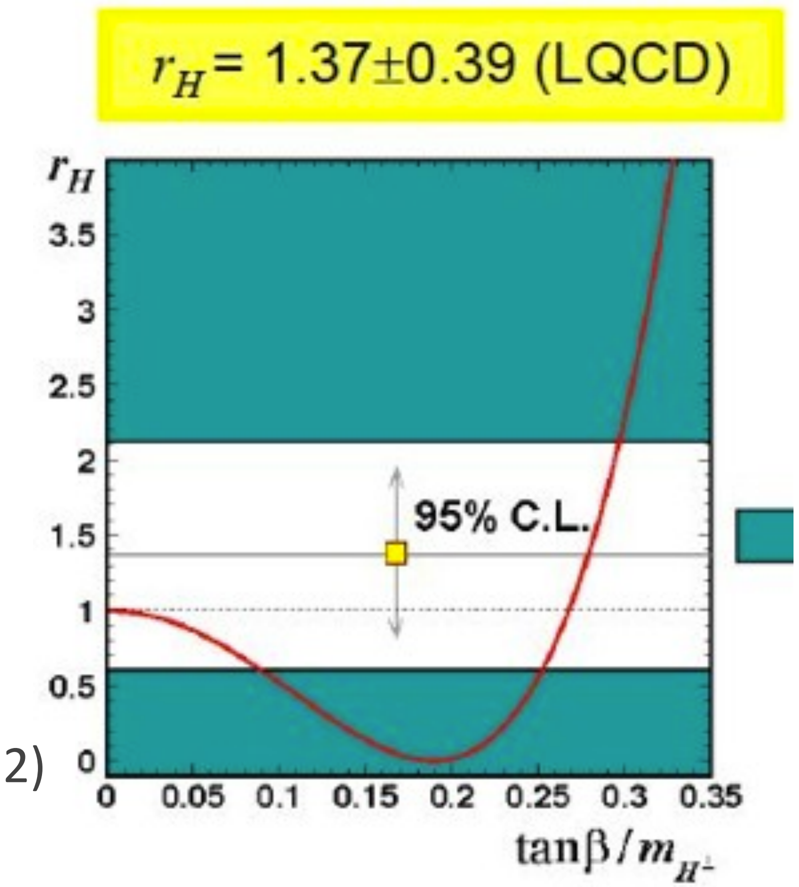
Physics Motivation



- New Physics (NP) contributions might interfere with SM and modify SM expectation
- Most prominent: $H^\pm$ from 2-Higgs-Doublet-Models (2HDM) in MSSM

r_H

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



Physics Report 516, 1 (2012)

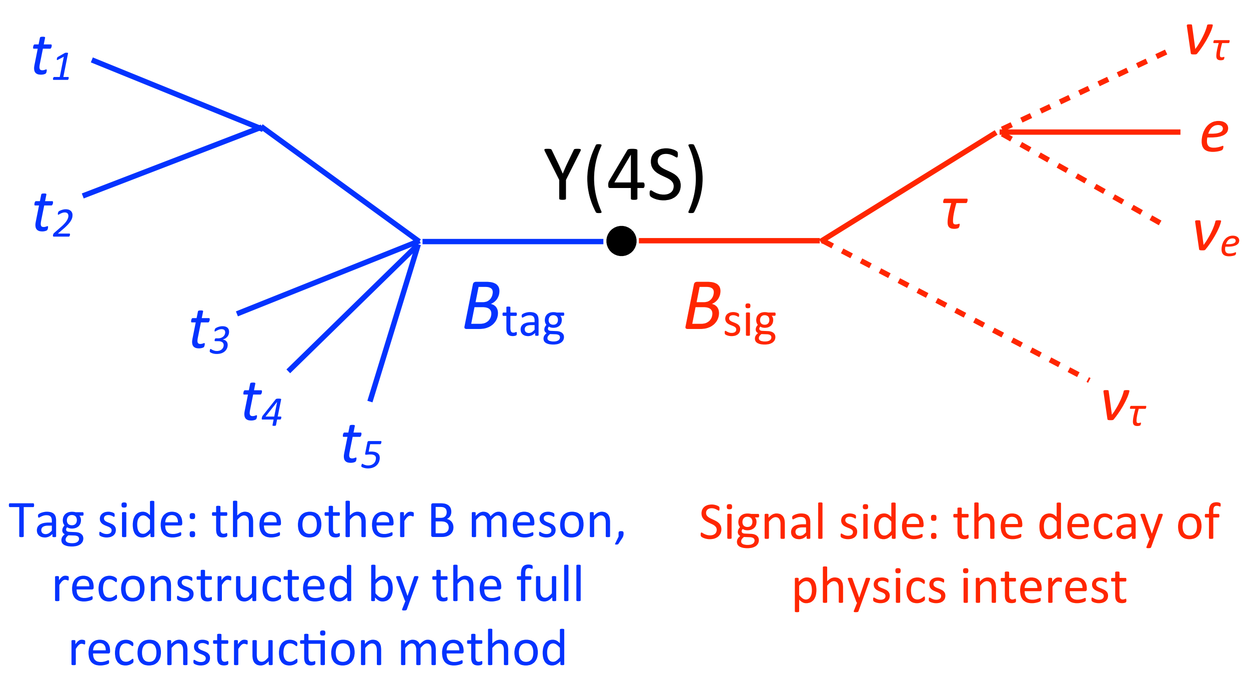
$$R^{ll'} = \mathcal{B}\left(B^+ \to l^+ \nu_l\right) / \mathcal{B}\left(B^+ \to l'^+ \nu_l\right)$$

- In NP models with MFV (Minimal Flavor Violation), the ratios are expected to be nearly unmodified from SM expectations — V. Cirigliano et al., Nucl. Phys. B 728, 121 (2005)
- In GUT model, the ratios $R^{e\mu}$ and $R^{e\tau}$ may increase to more than one order of magnitude above SM expectation due to the enhancement of the electron mode

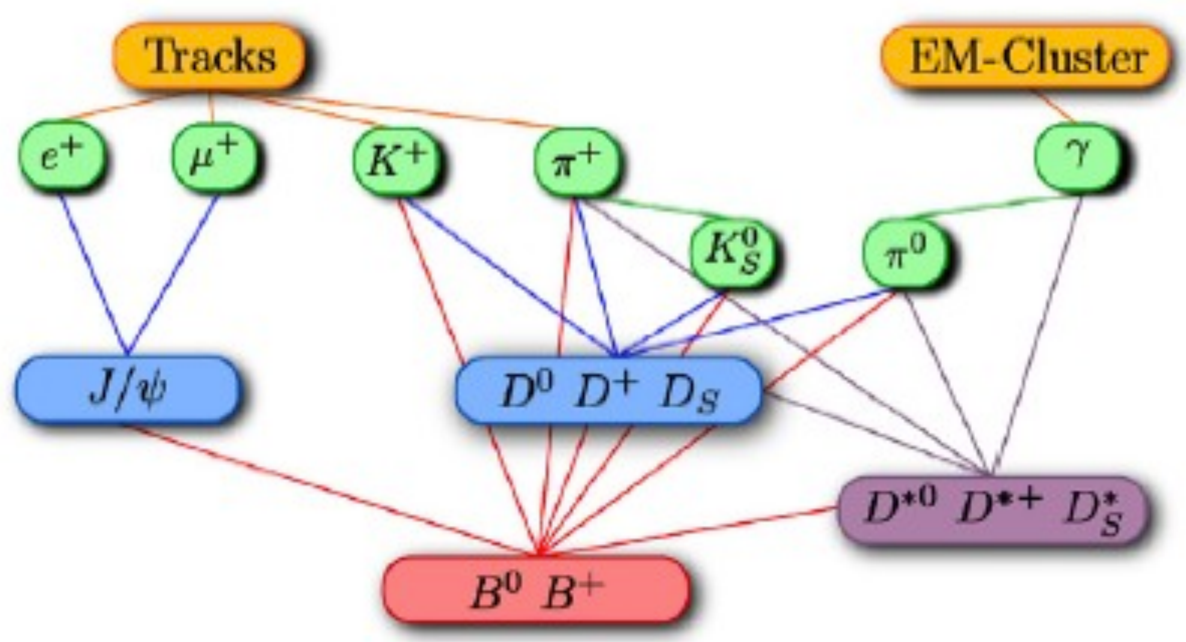
A. Filipuzzi and G. Isidori, Eur. Phys. J. C64, 55 (2009)

Hadronic Tagging Method

M. Feindt et al., NIMA 654, 432 (2011)



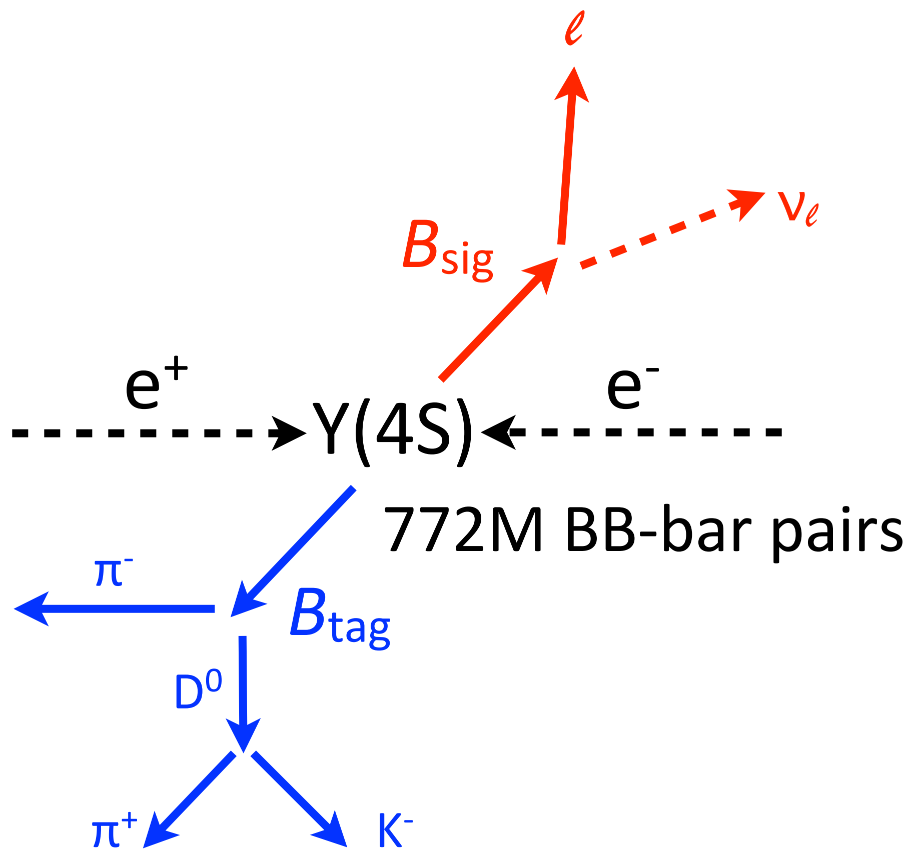
Exemplary fully reconstructed event



four stages of the full reconstruction

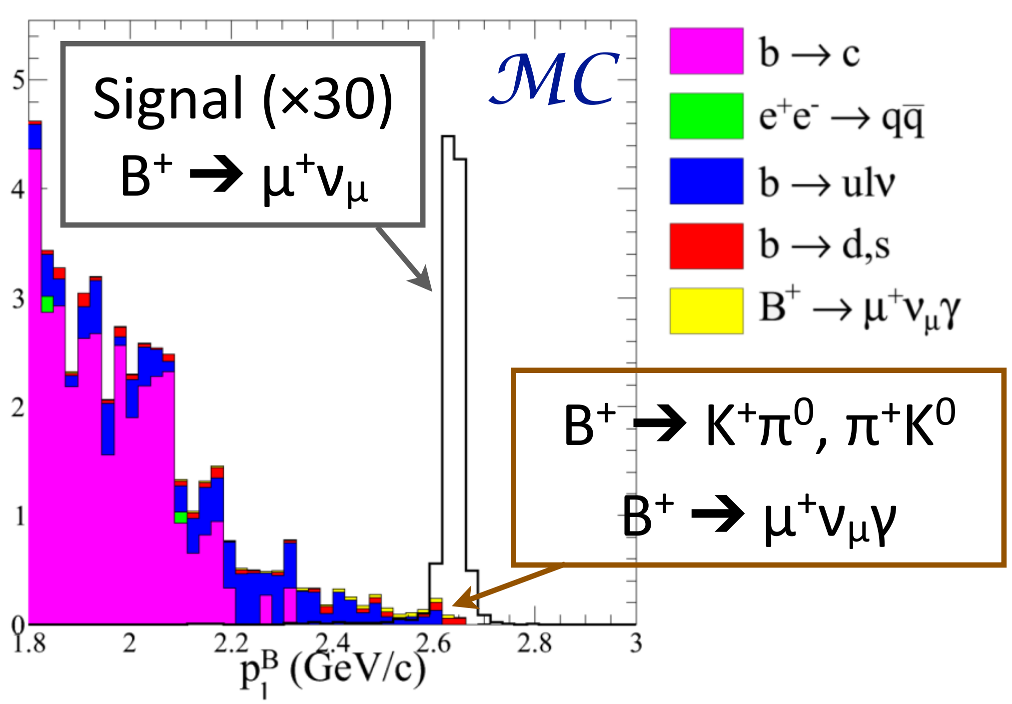
- Complete tagging of a B in Y(4S) ➔ BB-bar decays
  - full reconstruction of a B_{tag} in a hadronic channel:
    - taking over 1000 decay chains into account
    - B.F.(Y(4S) ➔ BB-bar) ~ 96%
- Constrain the charge, flavour, four-momentum of B_{tag} and B_{sig}
- Results in high purity and increased efficiency, ~0.28% (old method: 0.14%)
- Good suppression of e^+e^- ➔ qq-bar (q = u, d, s, c)
- Good ways to reconstruct modes with invisible particle

Analysis Strategy



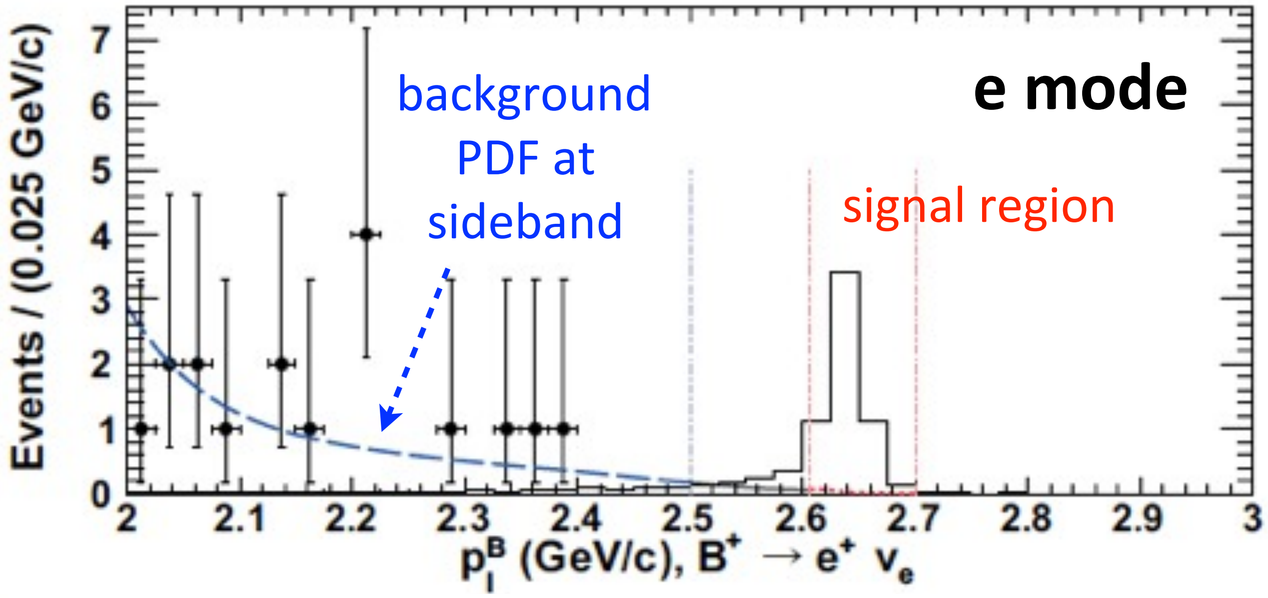
- On signal side, one single track (e or μ) required
- 2-body decay: clear signature in B_{sig} rest frame

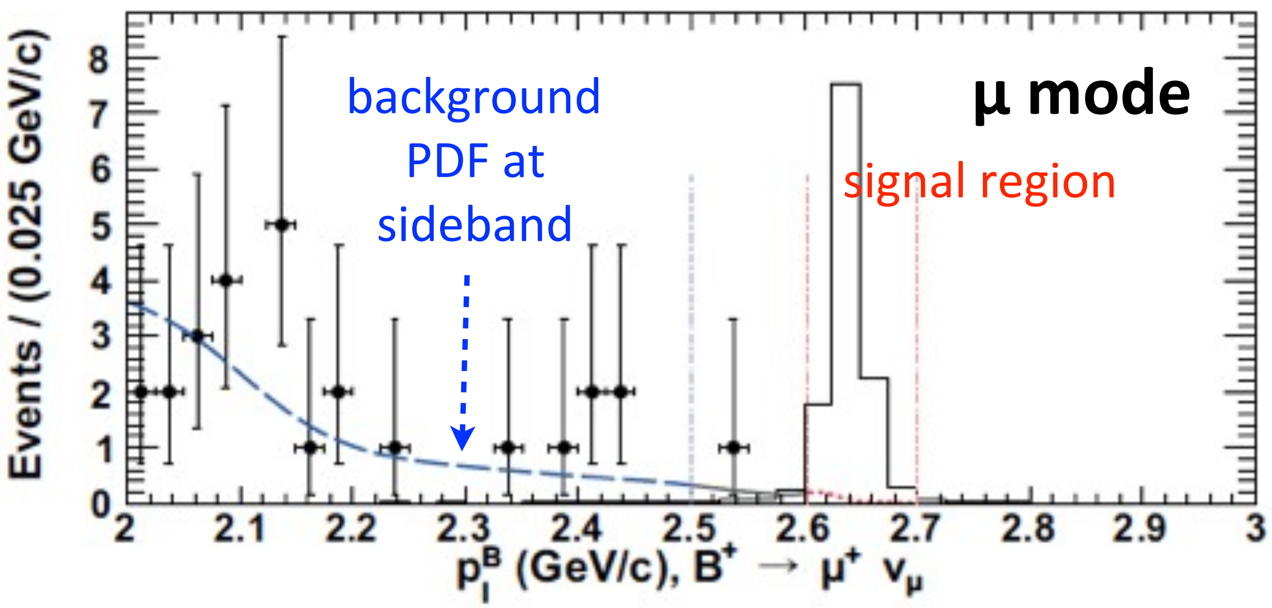
- Signal extraction variable: $\mathbf{p_l^B}$
  (lepton momentum at the rest frame of B_{sig})
- Sharp-peaking near 2.64 GeV/c
- Very clean signal with low BG



- Background estimation:
  - Fit the sideband of p_l^B (2-2.5 GeV/c)
    → extrapolate the BG into the signal region
    (~2.6-2.7 GeV/c)
  - Dedicated MC modeling for peaking BG at signal region

Signal Extraction





- No signal events observed
  ➔ Upper limit is calculated using Feldman-Cousins method

$$\mathcal{B}(B^+ \rightarrow l^+\nu) < \frac{S_{90}}{2\varepsilon_s N_{B^+B^-}}$$

B ➔ lν	ε_s [%]	N_{bkg}	N_{obs}
eν	0.086	0.10 ± 0.04	0
μν	0.102	$0.26^{+0.09}_{-0.08}$	0

$\mathcal{B}$(B ➔ eν) < 3.4 × 10^{-6}
$\mathcal{B}$(B ➔ μν) < 2.7 × 10^{-6}
@ 90% C.L.

Previous measurements @ 90% C.L.

Hadronic Tagging

$\mathcal{B}$(B ➔ eν) < 5.2×10^{-6}
$\mathcal{B}$(B ➔ μν) < 5.6×10^{-6} 342 fb^{-1}
BABAR PRD 77, 091104 (2008)

Loose Tagging

$\mathcal{B}$(B ➔ eν) < 9.8×10^{-7} 253 fb^{-1}
Belle PLB 647, 67 (2007)
$\mathcal{B}$(B ➔ μν) < 1.0×10^{-6} 426 fb^{-1}
BABAR PRD 79, 091101 (2009)

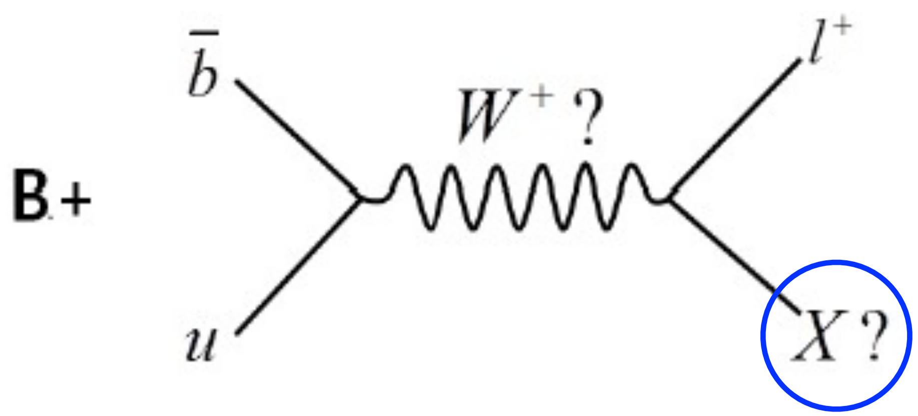
Search for Massive Neutral Lepton

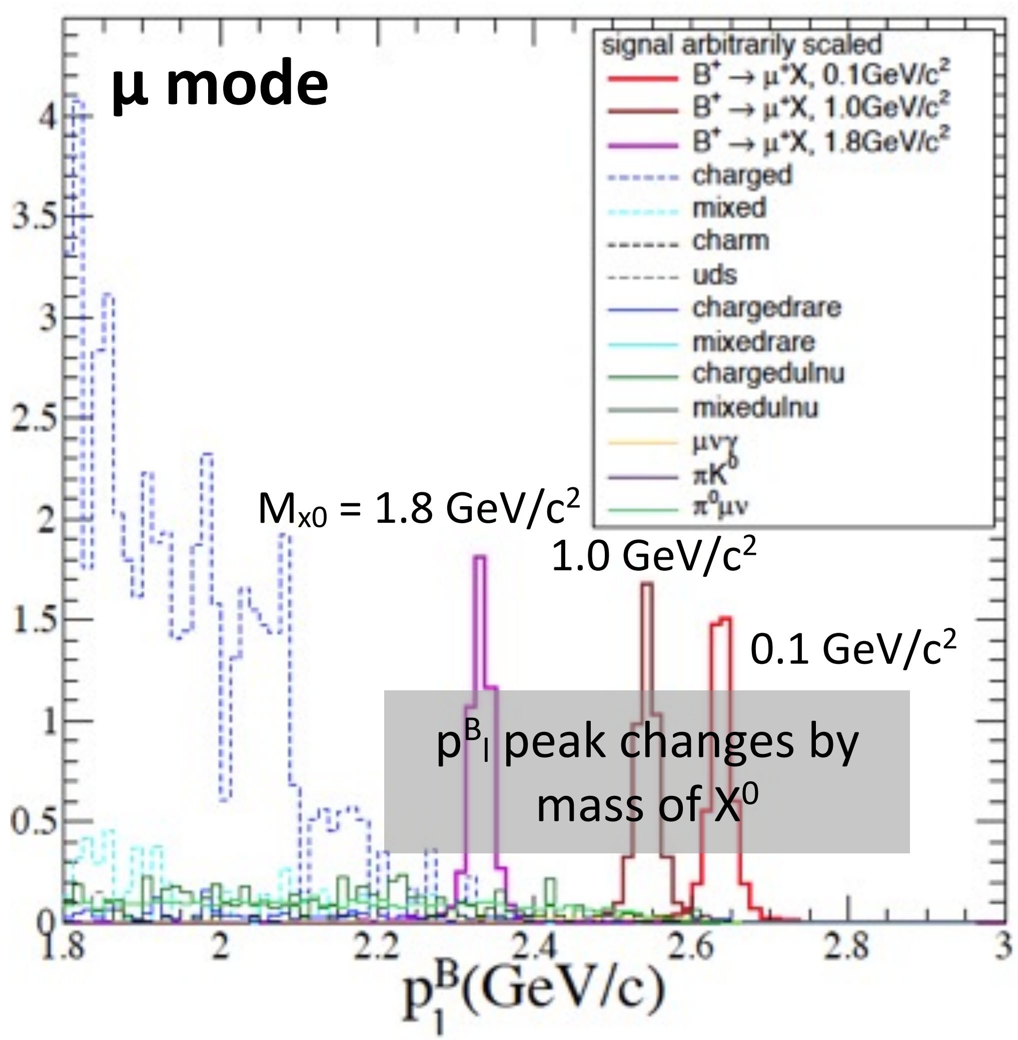
$B^+ \rightarrow l^+X^0$: search for massive invisible particle X^0

$B \rightarrow (X)l^+\nu_{heavy}$: search for heavy neutrino

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

$B^+ \to l^+X^0$





- Search for **new** neutrino-like, heavy fermion X^0
- Covered mass range: 0.1 GeV/c^2 ~ 1.8 GeV/c^2 in steps of 0.1 GeV/c^2
- Similar to $B \to l\nu$ analysis
  - except:
    looser momentum cut and
    looser impact parameter selection

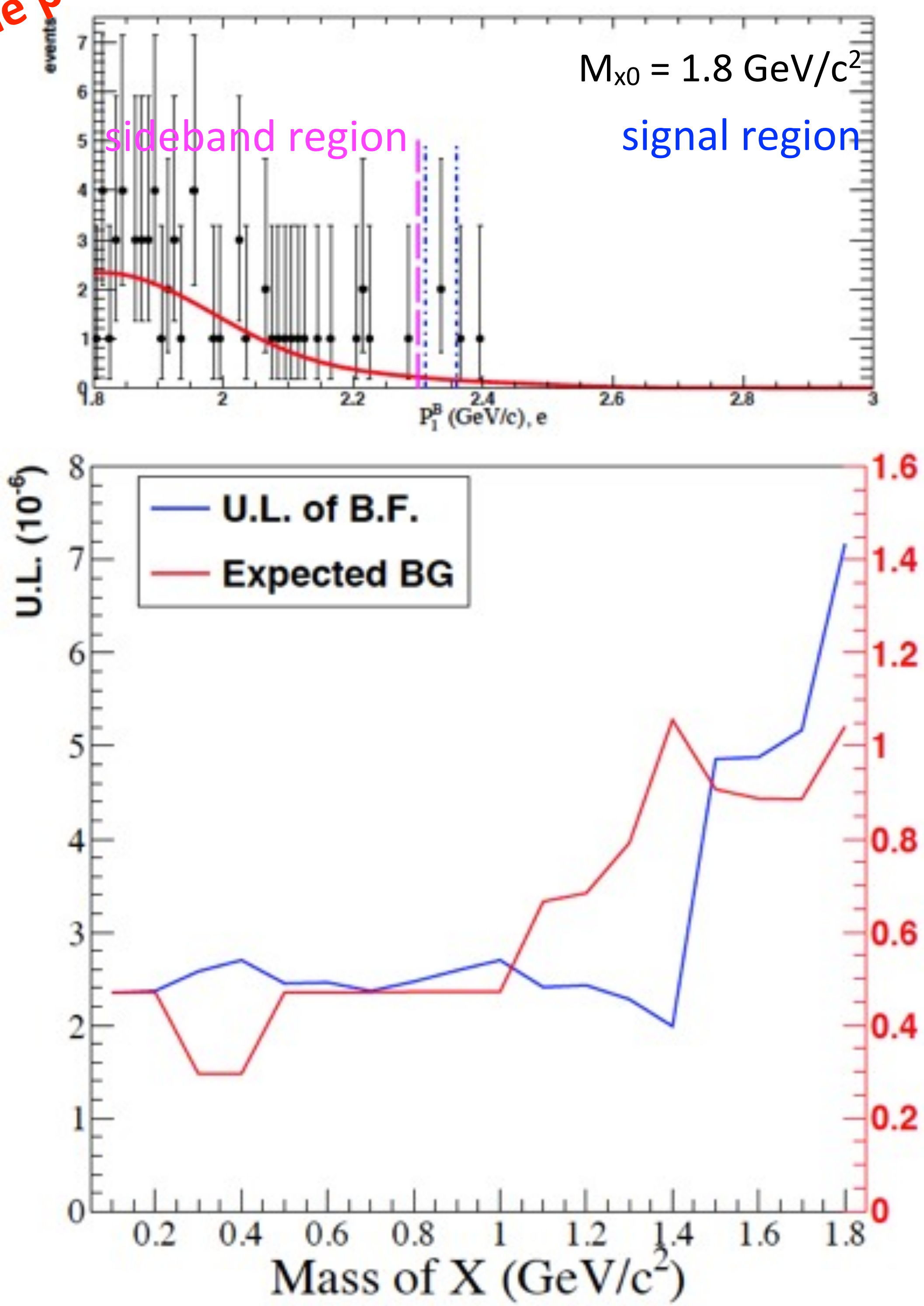
mode	p_l^{lab}	dz [cm]	dr [cm]
$B^+ \to l^+X$	p_l^{lab}> 1.0 GeV/c	$\lvert dz \rvert < 2.0$	dr < 0.5
$B^+ \to l^+\nu$	p_l^{lab} > 1.8 GeV/c	$\lvert dz \rvert < 1.5$	dr < 0.05

- Similar systematics
- p_l^B also shows good separation
- Signal region optimized to lowest expected upper limit

$B^+ \to l^+X^0$

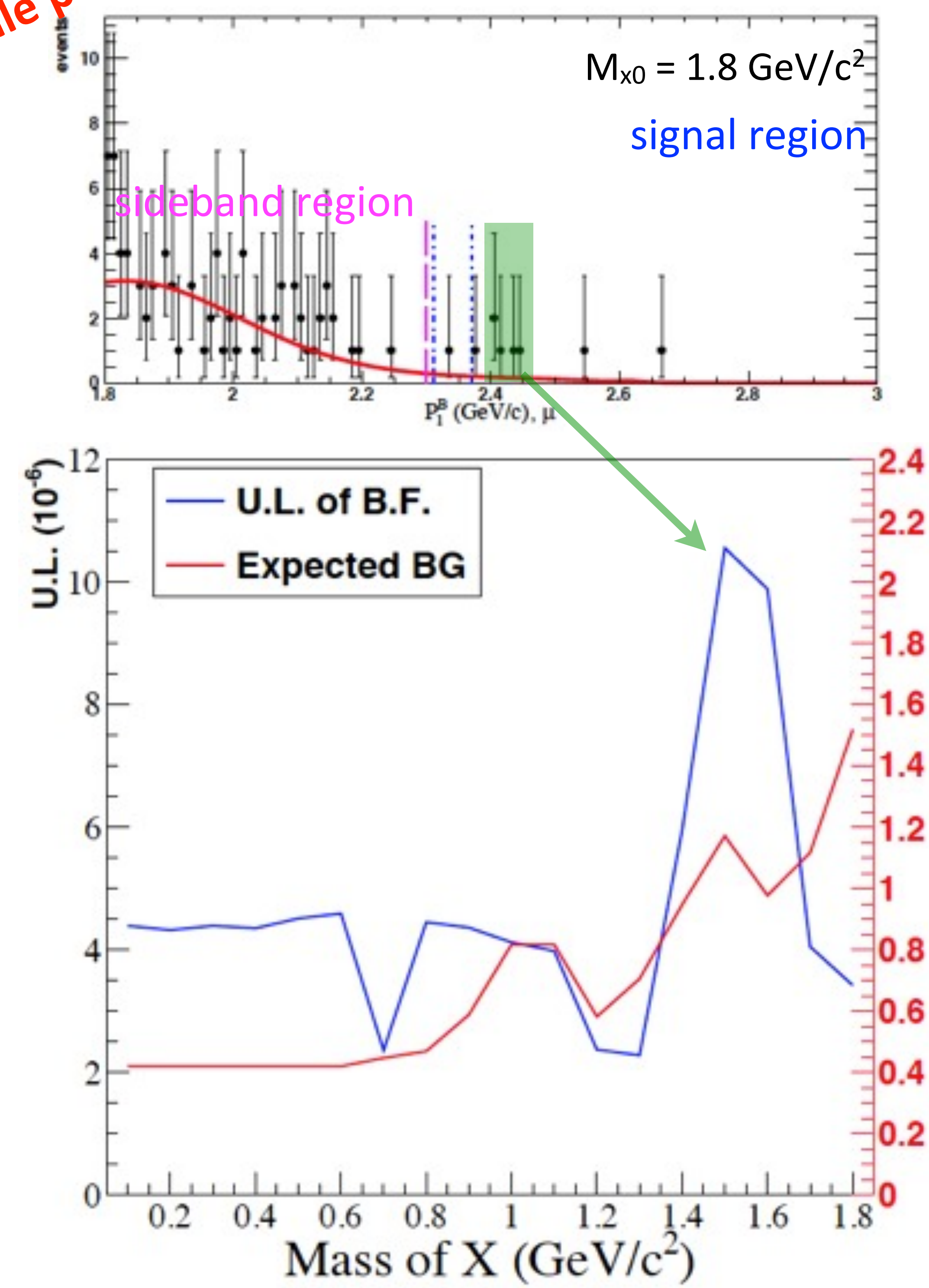
e mode

Belle preliminary



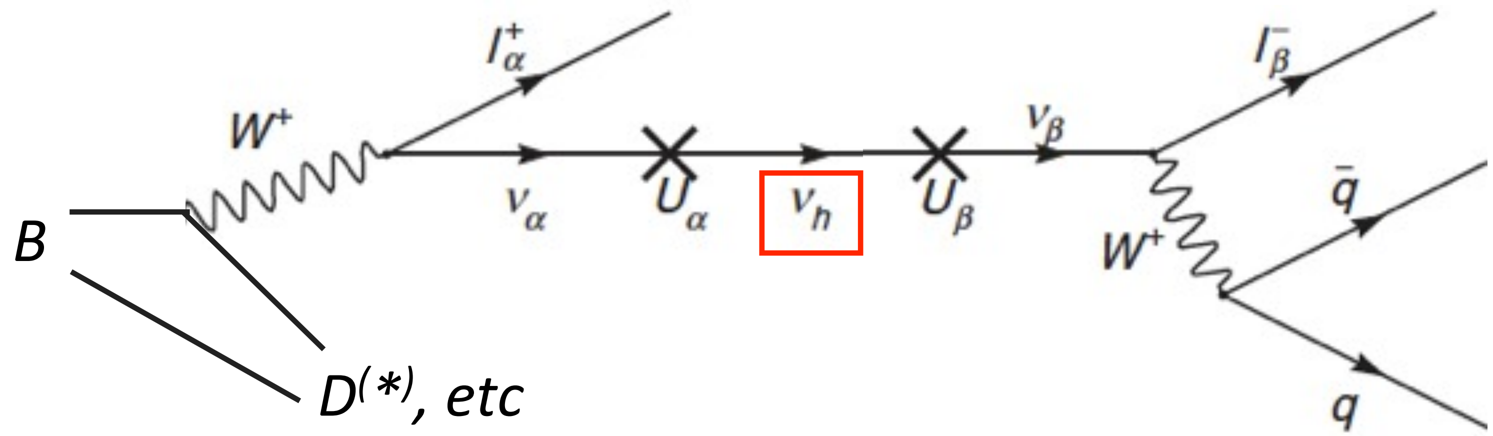
μ mode

Belle preliminary



$B \to (X)l\nu_h$

- $m_\nu > 0$ from experimental data while SM assumes 0 mass
- Heavy neutrinos (ν_h) are assumed in many models beyond the SM
- ν_h interacts only by mixing with a left-handed neutrino by a unitary transformation



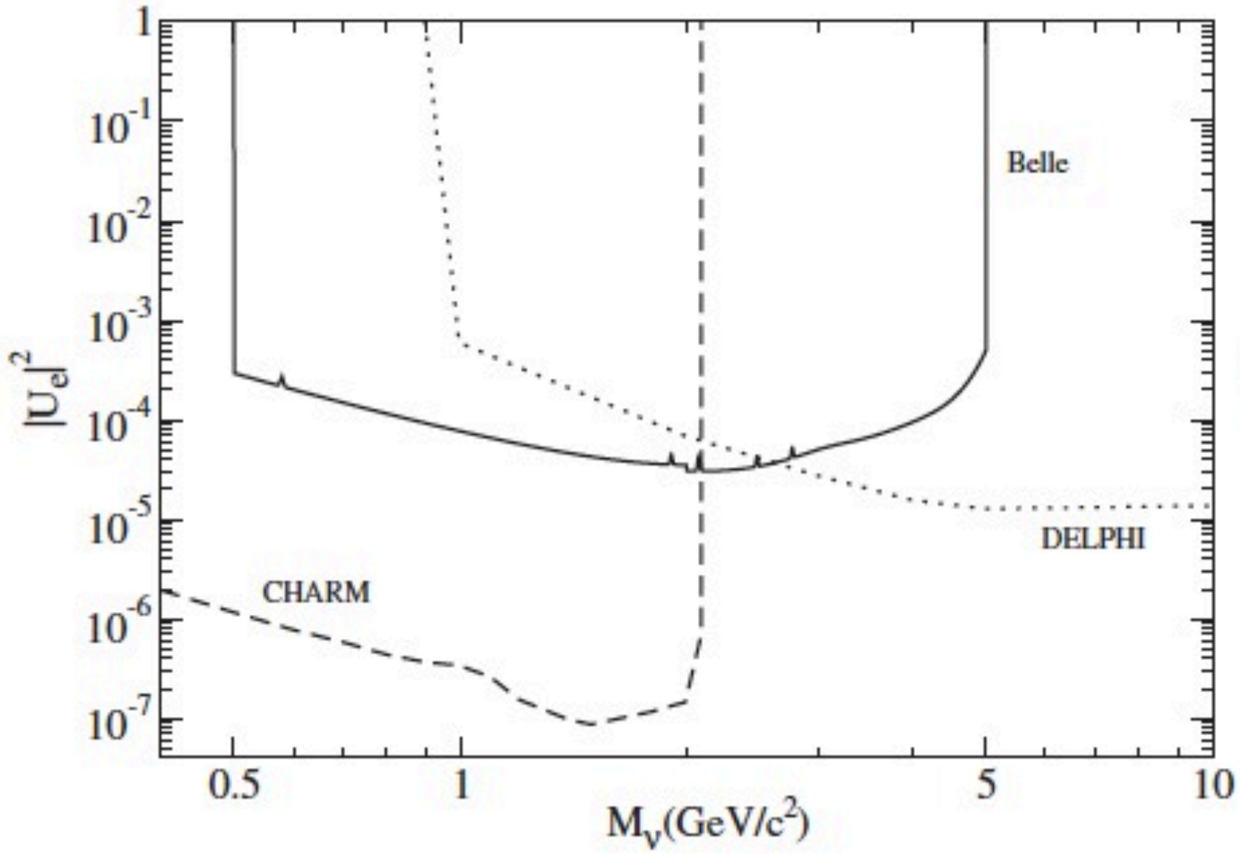
Heavy neutrino production and decay diagram

- Search for $B \to (X)l_2^+\nu_h$
  - if ν_h is Majorana, $\nu_h \to l_1^+\pi^-$ or $l_1^-\pi^+$
  - if ν_h is Dirac, $\nu_h \to l_1^-\pi^+$
- Search range of heavy neutrino : $0.5\ GeV/c^2 \leq M(\nu_h) \leq 5.0\ GeV/c^2$
- Approach separately for large and small $M(\nu_h)$
  - $M(\nu_h) < 2.0\ GeV/c^2$: look for X = D or D* using recoil mass
  - $M(\nu_h) > 2.0\ GeV/c^2$: look for X = $D^{(*)}$, light meson, nothing

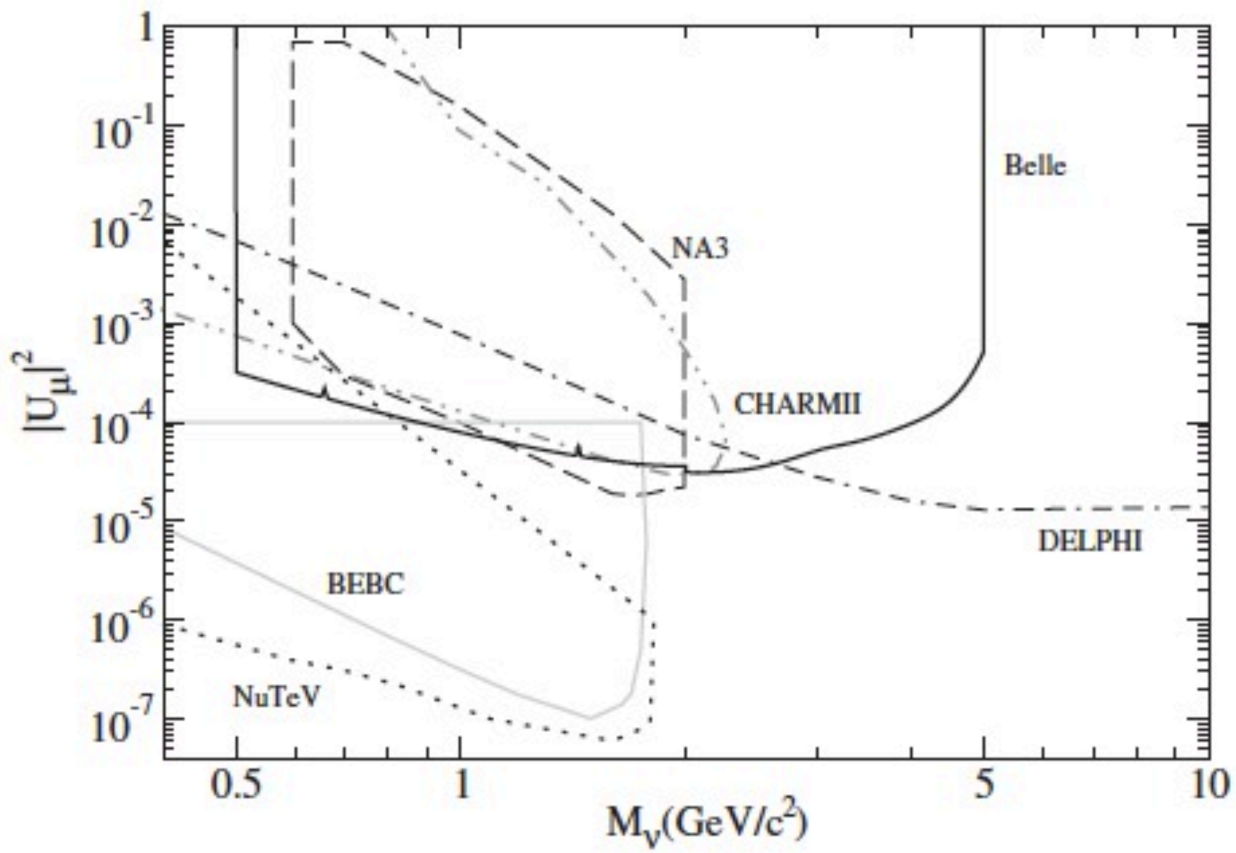
- Background suppression
  - QED background : by N(track) > 4
  - Decays with similar topology : by strict lepton ID, vertex quality, and distance l-π vertex
  - Combinatorial background : by distance btw the closest associated hit in SVD/CDC to vertex of ν_h

$B \rightarrow (X)l\nu_h$

$|U_e|^2$



$|U_\mu|^2$



- Upper limits on ν_h - ν_l mixing ($|U_l|$) are obtained in the range 0.5 GeV/c^2 ≤ $M(\nu_h)$ ≤ 5.0 GeV/c^2
- Corresponding upper limit for the product branching fraction (for $M((\nu_h)$ = 2 GeV/c^2)

$$\mathcal{B}(B \rightarrow (X)l\nu_h) \times \mathcal{B}(\nu_h \rightarrow l\pi^+) < 7.2 \times 10^{-7} \text{ for } l = e \text{ or } \mu$$

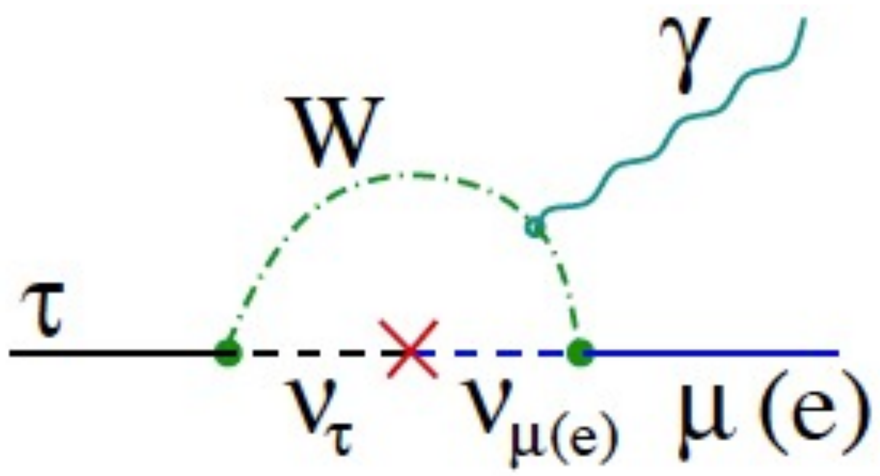
Lepton Flavor Violation in Tau Decays

$\tau \rightarrow l^{+}hh'$

l : electron or muon, $h^{(')}$: charged pion or kaon

Y. Miyazaki, et al., PLB 719 (2013) 346

Lepton Flavor Violation in Tau Decays



Model	B(τ → μγ)	B(τ → lll)
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

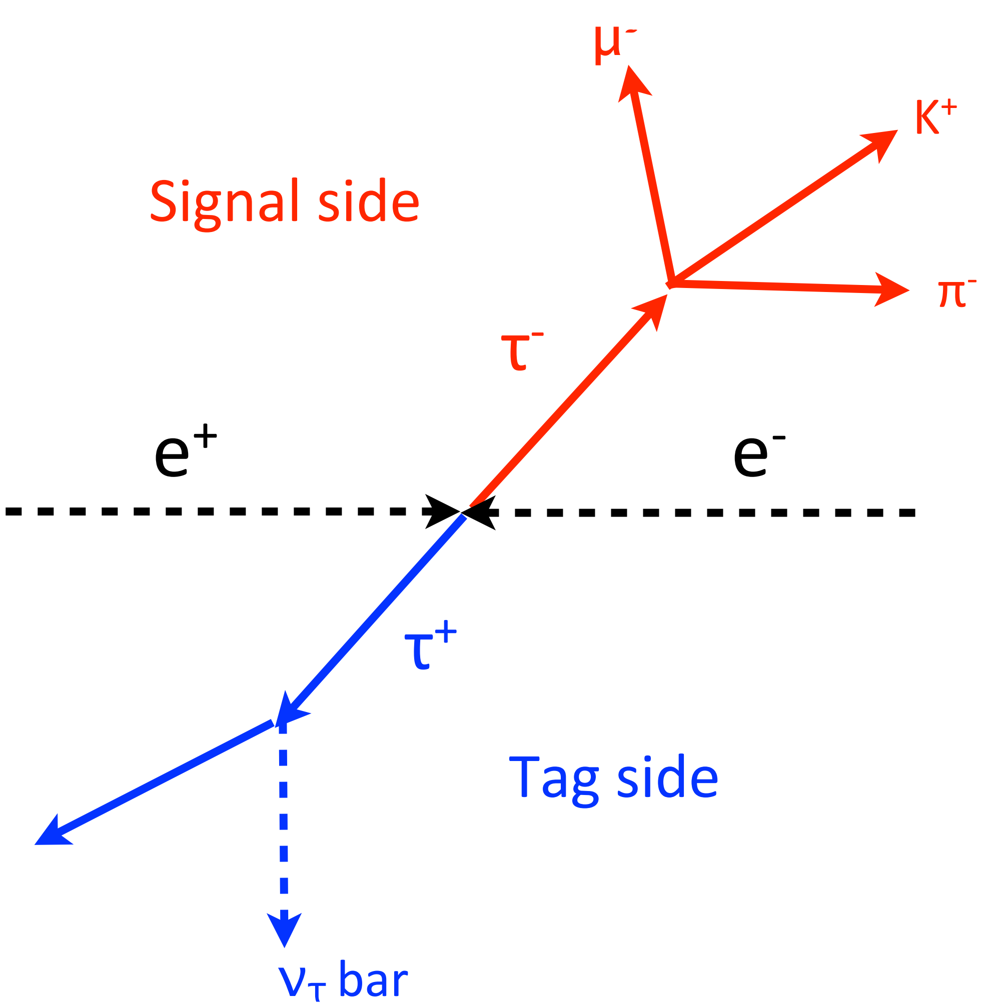
- Probability of LFV decays of charged lepton is extremely small in the SM

$$\mathcal{B}(\tau \to l\nu) \sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$

- Many models beyond the SM predict LFV decays with the branching fractions up to ≤ 10^{-8}. As a result, observation of LFV is a clear signature of New Physics
- τ lepton is a good tool to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes
- Study of the different τ LFV decay modes allows us to test various NP models

Data Set and Method

Process	σ [nb]
$e^+e^- \rightarrow$ qq-bar (q = u, d, s, c)	3.39
$e^+e^- \rightarrow$ bb-bar	1.05
$e^+e^- \rightarrow \tau^+\tau^-(\gamma)$	0.919

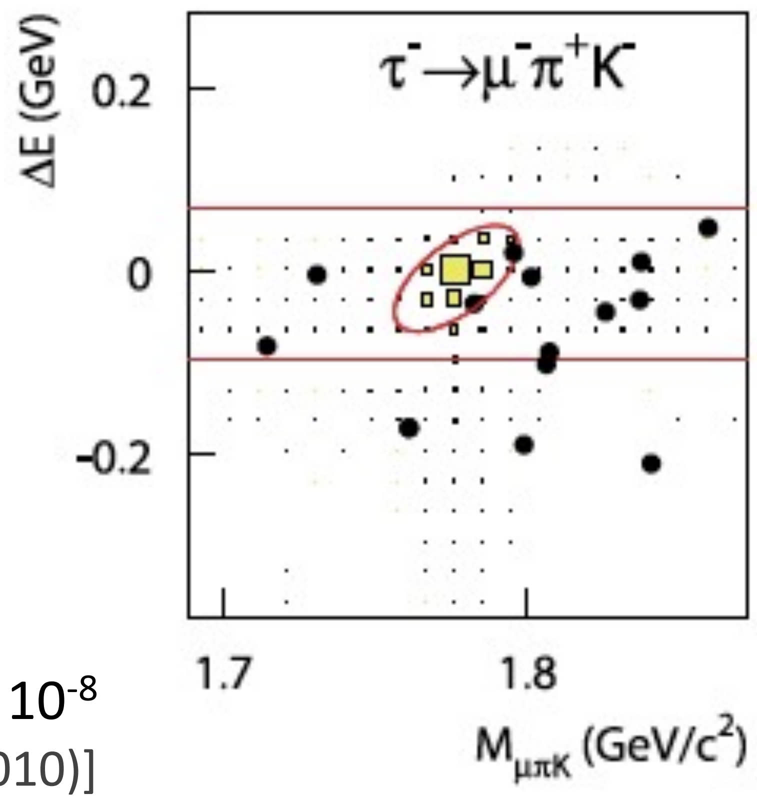


- **854 fb^{-1}** data sample used
  - collected at or below Υ(4S) and Υ(5S) resonances
- In total of 14 modes were investigated
  - 8 LFV $\tau^- \rightarrow l^-h^+h'^-$ and 6 lepton-number-violating $\tau^- \rightarrow l^+h^-h'^-$ decays
    (l : electron or muon, h, h' : pions or Kaons)
- Blind analysis performed
  - Search for signal events on the M_{inv} vs. ΔE plane
    ($M_{inv} \approx M_\tau$, $\Delta E = E_{LFV} - E_{beam} \approx 0$)
- Tag one τ by its 1-prong decay ($B_{1\text{-prong}}$ ~ 85%), the other τ is required to produce the LFV final state
- Background suppression
  - Opening angle btw missing momentum ($\mathbf{p}_{miss}$) and charged track on the tag side : $\cos\theta^{CM}_{tag\text{-}miss}$
  - Selection on the thrust : T
  - Missing mass :
    $m^2_{miss} = E^2_{miss} - p^2_{miss} = (E_{total}-E_{vis})^2 - p^2_{miss}$

τ → l⁺hh'

Results

- One event in the signal region was found for $\tau^- \to \mu^+\pi^-\pi^-$ and $\tau^- \to \mu^-\pi^+K^-$, no events for the other 12 modes
- For all modes the number of observed signal events agree with the number of expected background events



$$\mathcal{B}(\tau \to lhh') < \frac{S_{90}}{2N_{\tau\tau}\varepsilon}$$

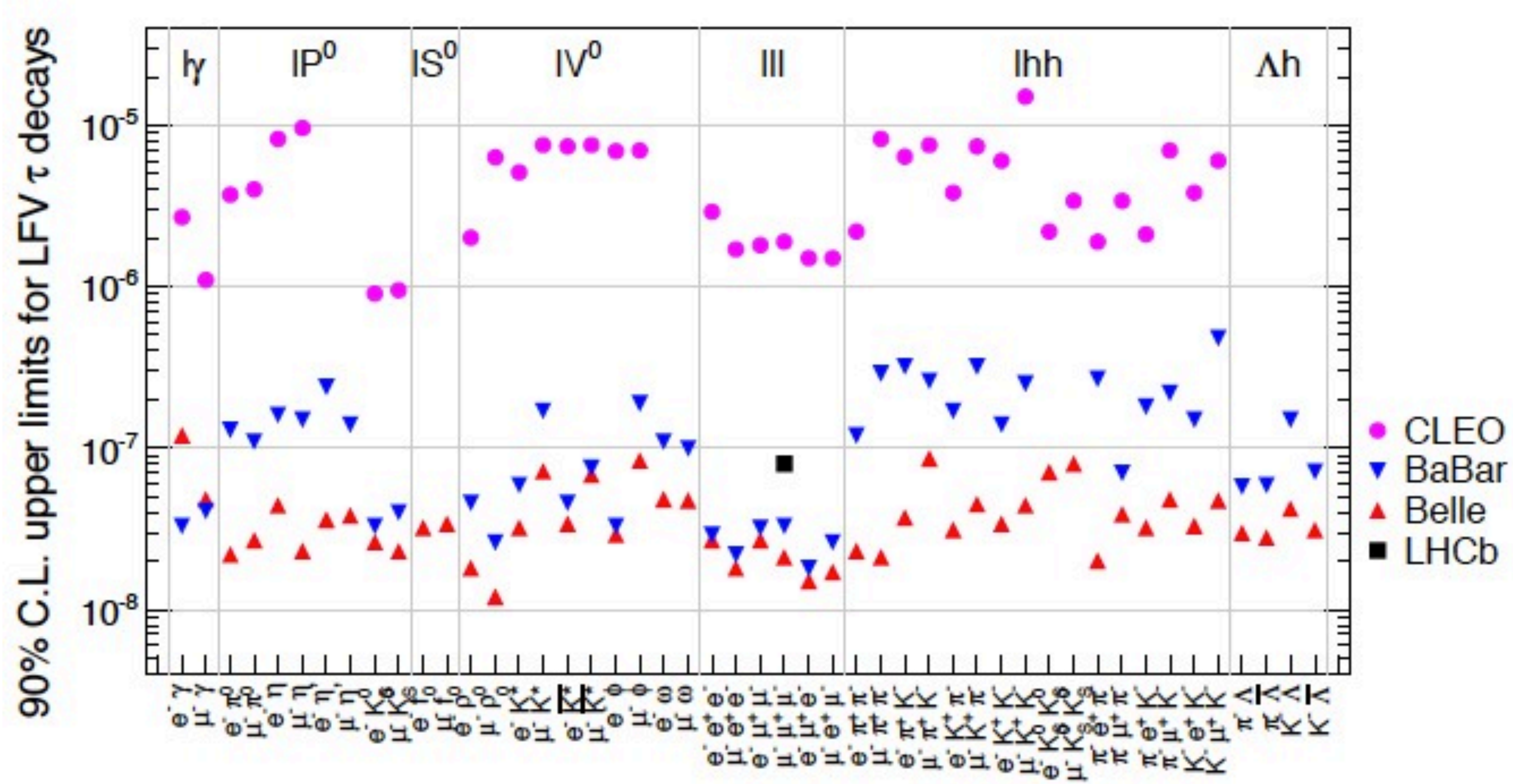
S90 : the number of signal events including systematic uncertainty
$N_{\tau\tau}$: the number of $\tau^+\tau^-$ pairs, 782×10^6
ε : signal efficiency

- Obtained upper limits at 90% C.L.: **$\mathcal{B}(\tau \to lhh') < (2.0 \sim 8.6) \times 10^{-8}$**

previous result with 671 fb^{-1}: $(3.3 \sim 16) \times 10^{-8}$
[Y. Miyazaki et al., Phys. Lett. B 682, 355 (2010)]

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2

Results on LFV of τ decays



48 different LFV modes were studied at Belle
The world best upper limits were obtained

Recently, first U.L. for BNV and LNV τ decays with protons is obtained from LHCb

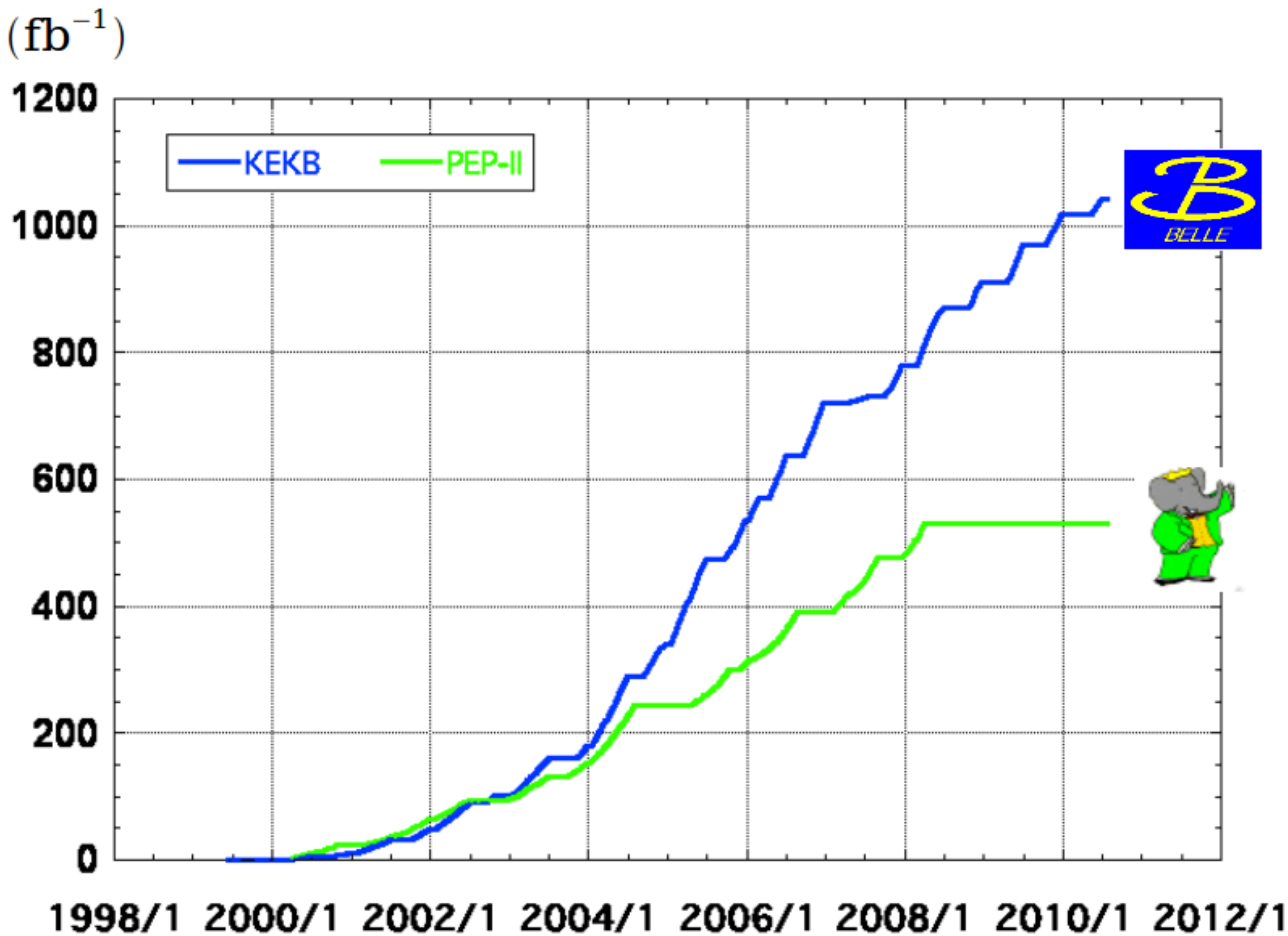
R. Aaij, et al., PLB 724, 36 (2013)

Summary

- A study of decays with neutrinos in the final state is possible using the hadronic tagging method
- Most stringent limits on **$B^+ \rightarrow l^+\nu$** are obtained
  - $\mathcal{B}(B \rightarrow e\nu) < 3.4 \times 10^{-6}$ @90% C.L.
  - $\mathcal{B}(B \rightarrow \mu\nu) < 2.7 \times 10^{-6}$ @90% C.L.
- Performed **search for heavy neutral lepton-like particles**
  - $B^+ \rightarrow l^+X^0$, where X^0 can be any invisible (and possibly massive) fermion particle and in preliminary results, the upper limits are $O(10^{-6})$ for $0.1\ GeV/c^2 < M_x < 1.8\ GeV/c^2$
  - U.L. on mixing of ν_h-ν_l is set in the mass range of $0.5\ GeV/c^2 \sim 5.0\ GeV/c^2$
- Up to now, no hints for NP contribution from leptonic B decays
- We studied 48 different **LFV modes in tau decays**, 46 of them were analyzed with almost full data sample and obtained upper limits on the branching fractions are of the order of 10^{-8}

BACKUP SLIDES

Integrated luminosity of B factories



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

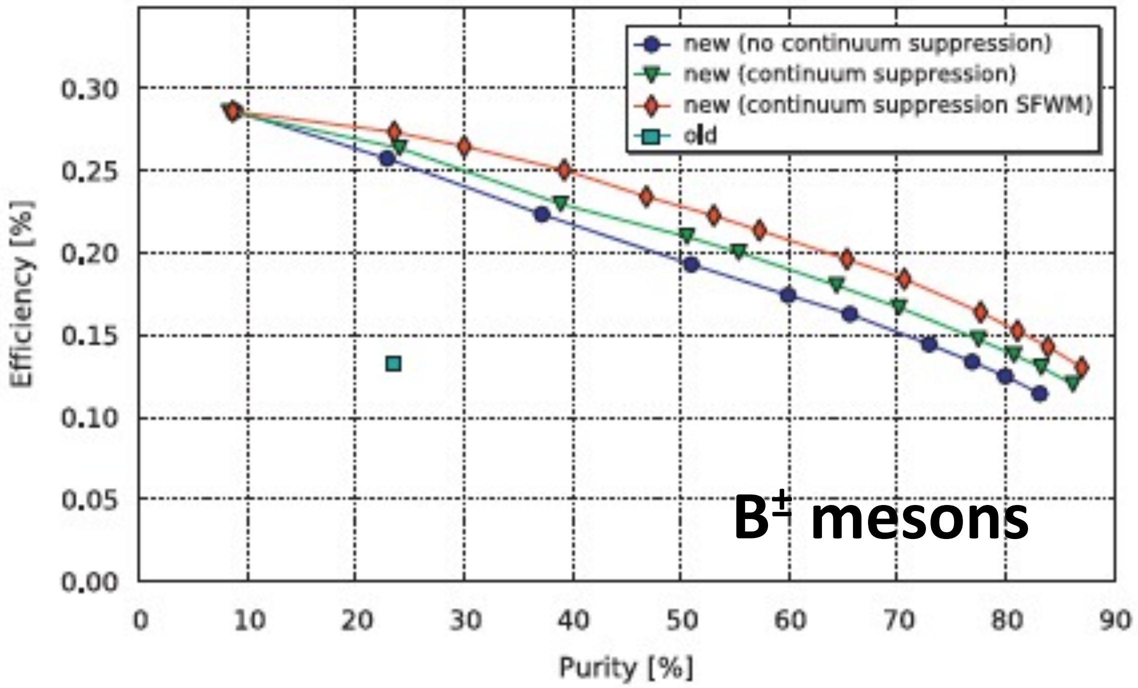
$\Upsilon(3S)$: 30 fb^{-1}

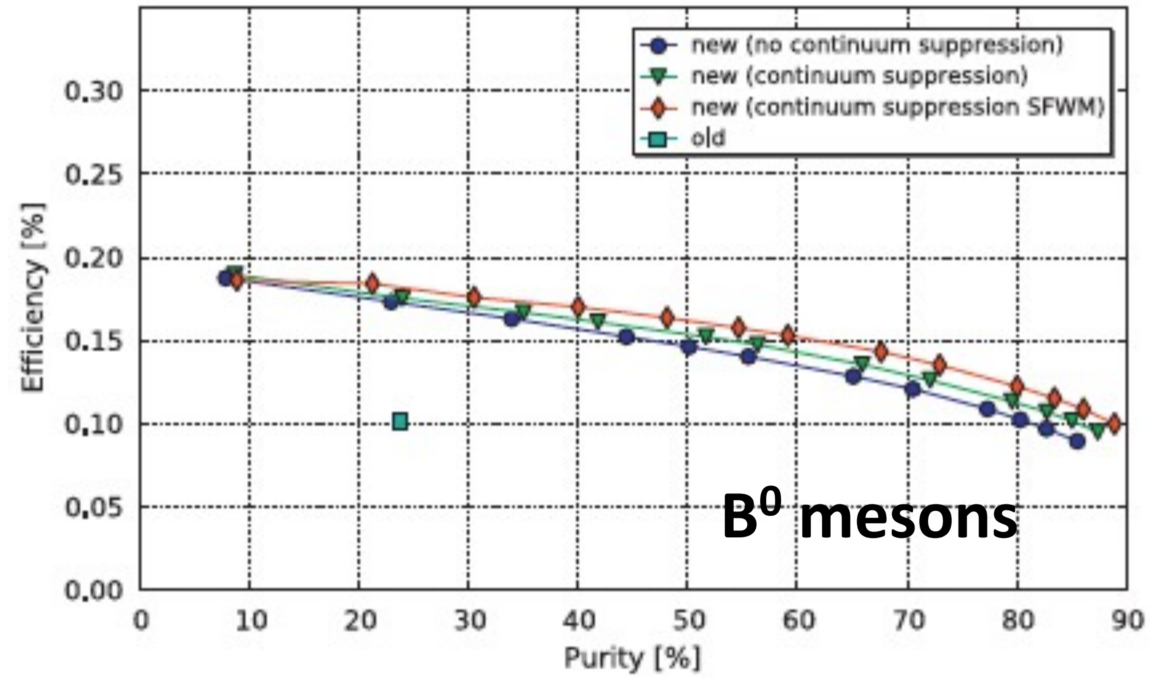
$\Upsilon(2S)$: 14 fb^{-1}

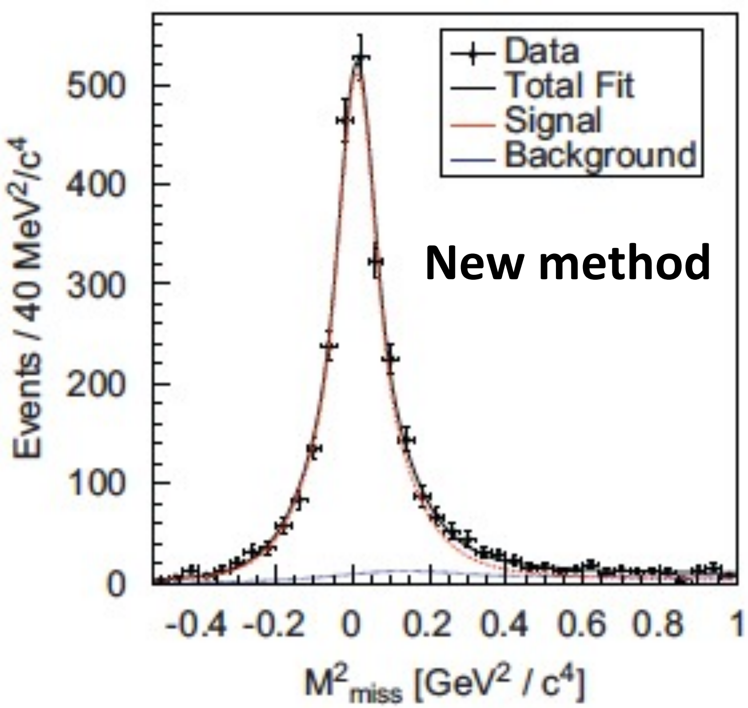
Off resonance:

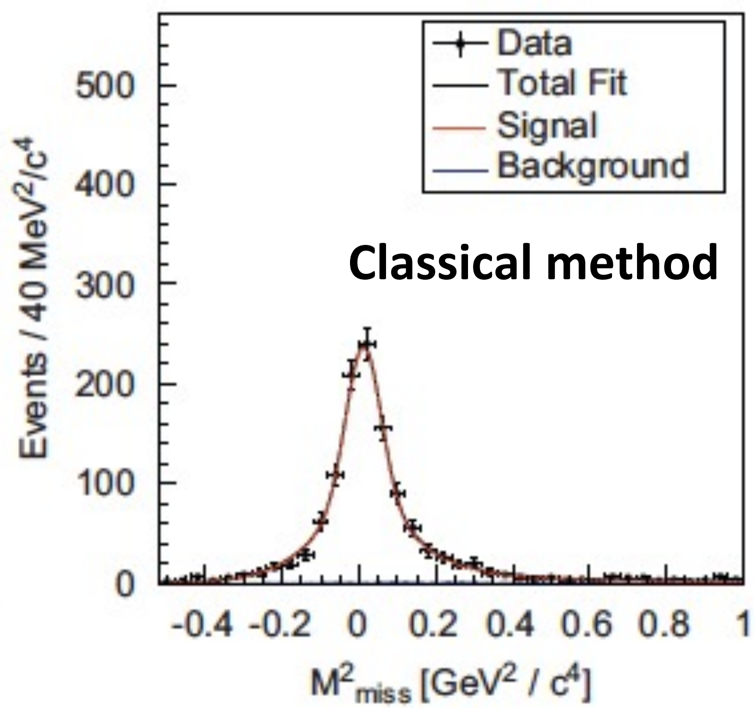
$\sim 54\ fb^{-1}$

B tagging Purity-Efficiency





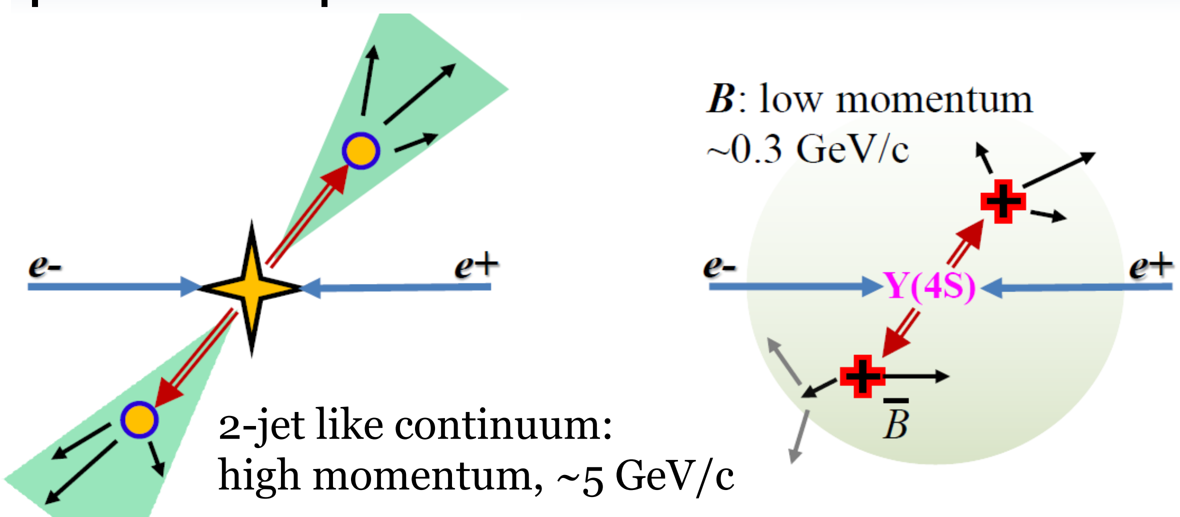


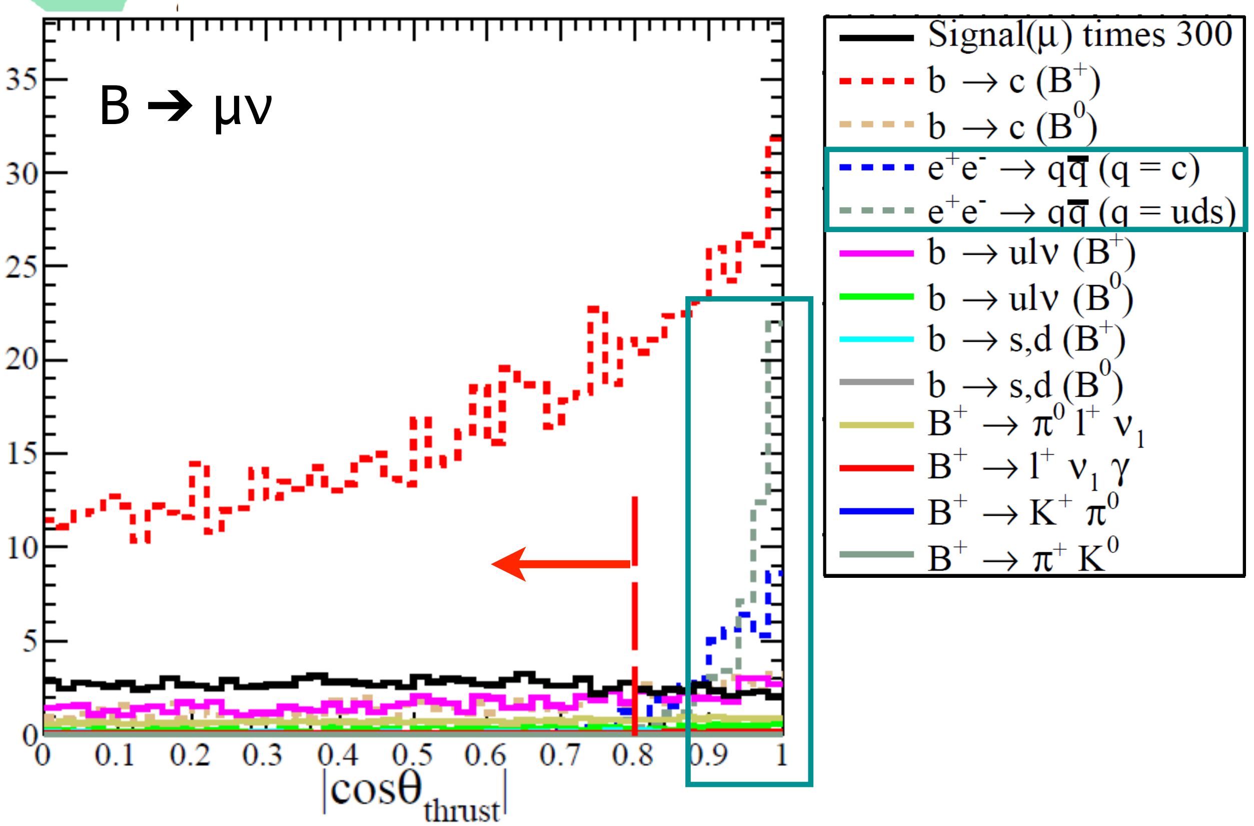


Missing mass distributions for $B^0 \rightarrow D^{*-} l^+ \nu_l$ decays of new and classical full reconstruction tool

$B^+ \rightarrow l^+\nu_l$ Background Suppression

$|\cos\theta_{thrust}|$



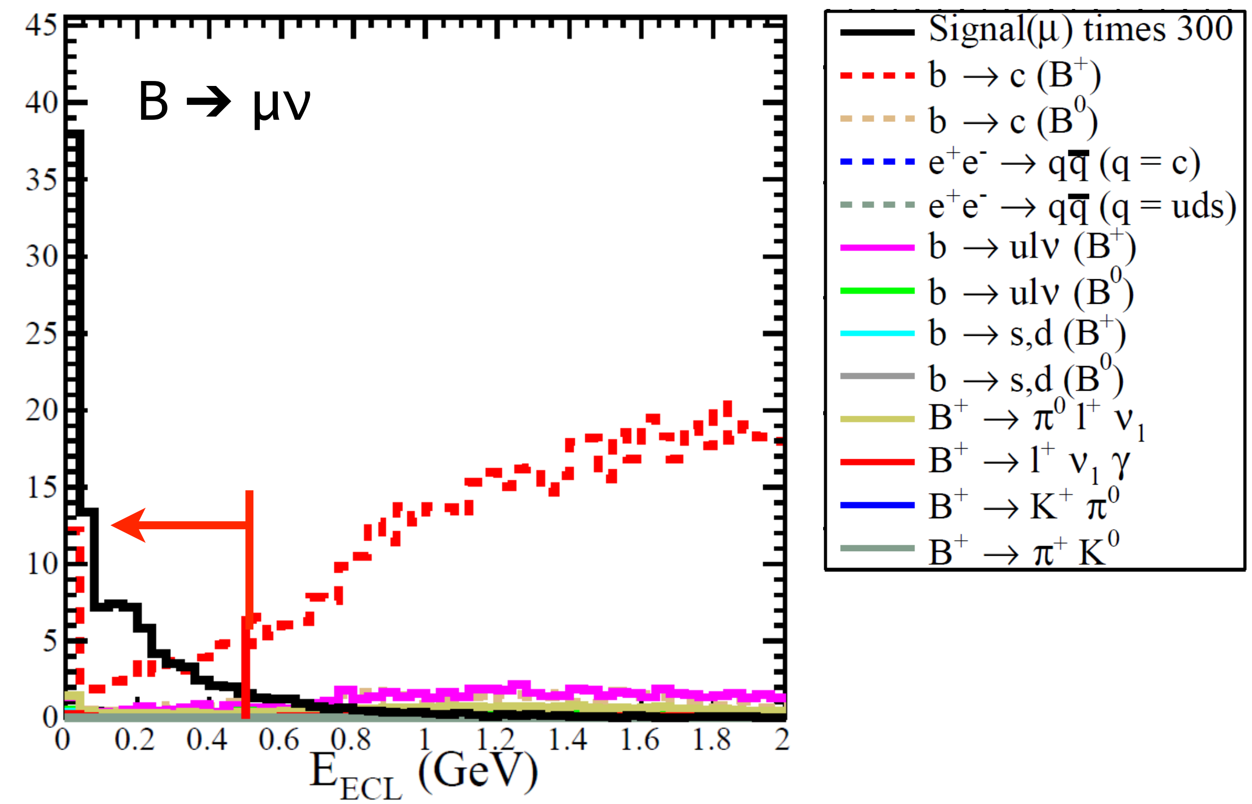


θ_{thrust}: angle between the thrust axis of B_{tag} particle and the lepton's momentum in CM frame

E_{ECL}

$$E_{ECL} = E_{Total} - E_{Btag} - E_l$$

No extra energy deposits in the ECL (apart from the lepton and B_{tag})



$B^+ \rightarrow l^+X^0$

Event Selection

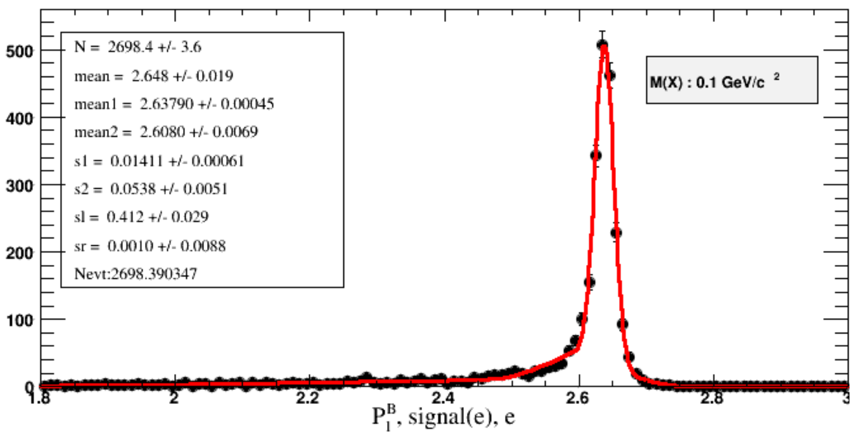
Particle identity	Track quality	Continuum suppression	Quality of tagged-B meson
$L_e > 0.9$	$\|dz\| < 2.0$ cm	$\|\cos\theta_{thrust}\| < 0.9$ for e mode	$\|\Delta E\| < 0.05$ GeV
$L_\mu > 0.9$	$\|dr\| < 0.5$ cm	$\|\cos\theta_{thrust}\| < 0.8$ for μ mode	$M_{bc} > 5.27$ GeV/c^2
			$O_{NB} > 10^{-6}$

E_{ECL} : remaining energy of ECL calorimeter

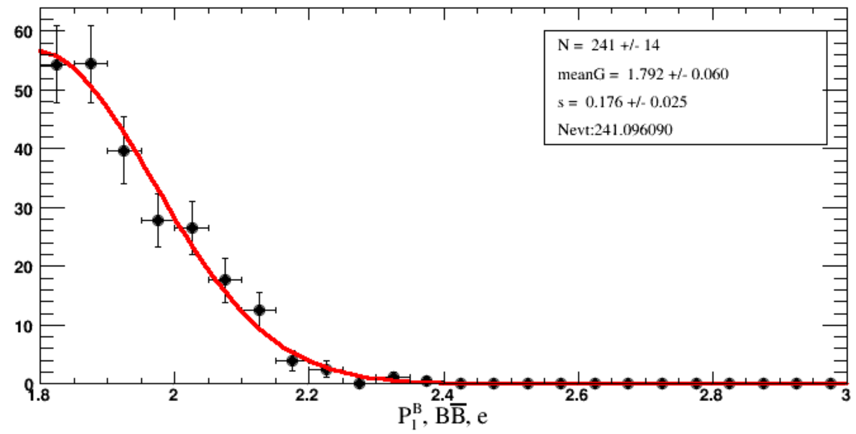
p^B_l : signal lepton's momentum in the signal B rest frame

p^B_l peak changes by mass of X^0

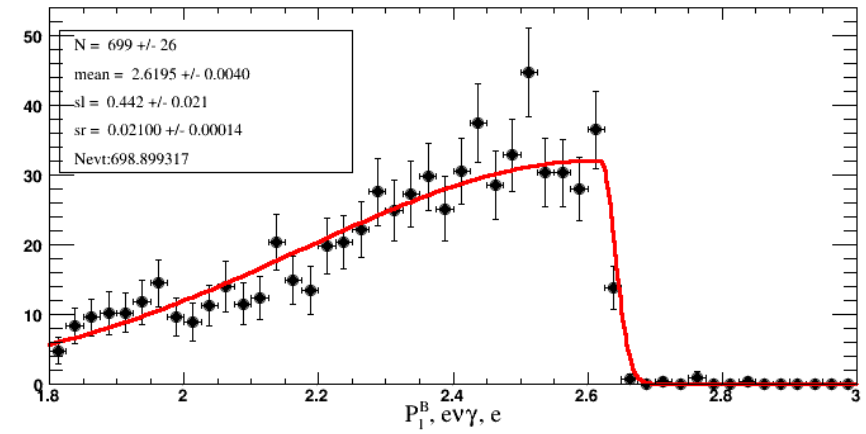
➔ p^B_l cut should be optimized for each X^0 mass



Fitting signal



Fitting background



Fitting peaking background

$B^+ \to l^+ X^0$

Systematics

M(X) (GeV/c^2)	e mode: Statistical uncertainty	e mode: Total uncertainty	μ mode: Statistical uncertainty	μ mode: Total uncertainty
0.1	1.72%	6.1%	1.78%	6.0%
0.2	2.18%	6.2%	1.80%	6.1%
0.3	1.70%	6.1%	1.80%	6.0%
0.4	1.73%	6.1%	1.81%	6.1%
0.5	1.53%	6.0%	1.87%	6.1%
0.6	1.74%	6.1%	1.88%	6.1%
0.7	1.71%	6.1%	1.82%	6.1%
0.8	1.71%	6.1%	1.80%	6.1%
0.9	1.74%	6.1%	1.83%	6.1%
1.0	1.74%	6.1%	1.83%	6.1%
1.1	1.63%	6.0%	1.79%	6.0%
1.2	1.74%	6.1%	1.83%	6.1%
1.3	1.83%	6.1%	1.84%	6.1%
1.4	1.72%	6.1%	1.82%	6.1%
1.5	1.75%	6.1%	1.82%	6.1%
1.6	1.74%	6.1%	1.82%	6.1%
1.7	1.80%	6.1%	1.83%	6.1%
1.8	1.75%	6.1%	1.81%	6.1%

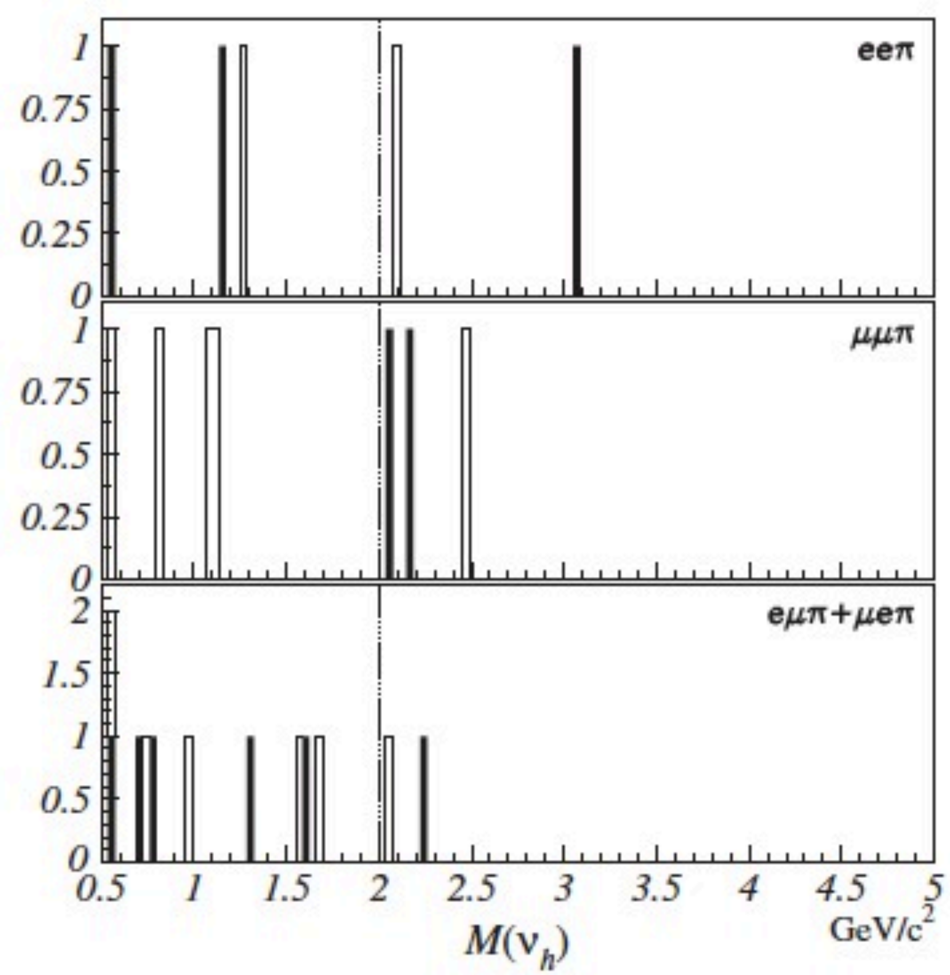
B → (X)lν$_h$

Signal Extraction

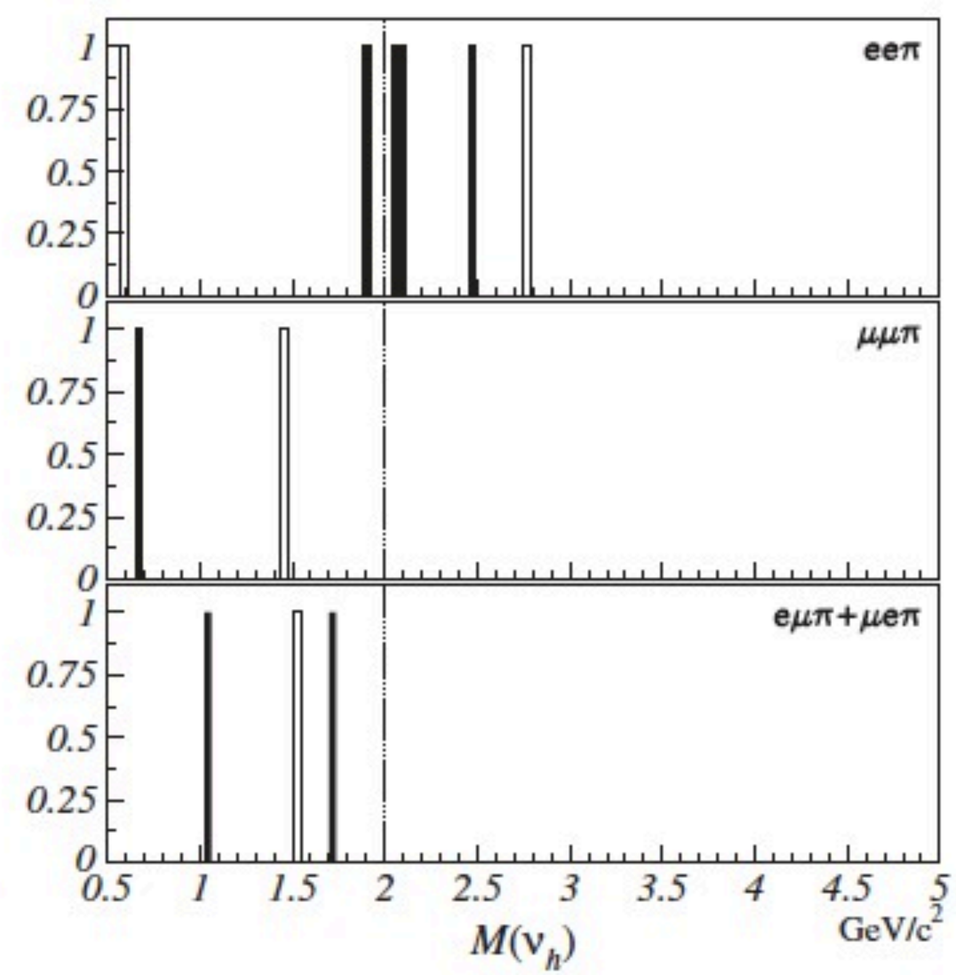
Obtained yield and expectation from MC

mode	MC expected	Data
$ee\pi$	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

generic MC (unscaled)



data



D. Gorbunov and M. Shaposhnikov, JHEP 0710, 015 (2007)

$$n(\nu_h) = 2N_{BB} B(B \to \nu_h) B(\nu_h \to l\pi) \frac{m\Gamma}{p} \int \varepsilon(x) dx$$

$$= |U_\alpha|^2 |U_\beta|^2 \; 2N_{BB} f_1(m) f_2(m) \frac{m}{p} \int \varepsilon(x) dx$$

Number of neutrinos detected

➔ Expect upper limit of branching fraction

$\tau \to l^+hh'$

Event Selection

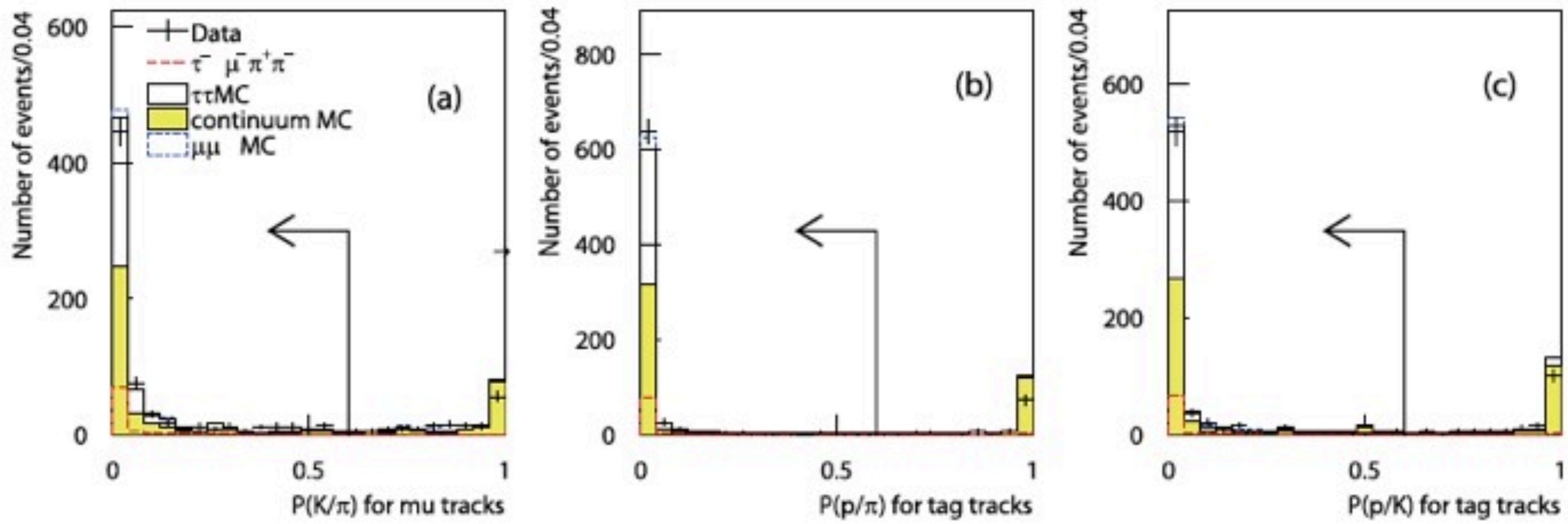


Fig. 1. (a) $\mathcal{P}(K/\pi)$ for muon tracks, (b) $\mathcal{P}(p/\pi)$ and (c) $\mathcal{P}(p/K)$ for hadronic tags, for $\tau^- \to \mu^-\pi^+\pi^-$ candidate events. Signal MC ($\tau^- \to \mu^-\pi^+\pi^-$) distributions are normalized arbitrarily while the background MC distributions are normalized to the data luminosity. The selected regions are indicated by arrows.

Table 1
Selection criteria for kaon identification $\mathcal{P}(K/\pi)$ and magnitude of thrust (T).

Mode	$\mathcal{P}(K/\pi)$	T
$\tau \to \mu\pi\pi$	–	$0.90 < T < 0.98$
$\tau \to \mu K\pi$	> 0.9	$0.92 < T < 0.98$
$\tau \to \mu KK$	> 0.8	$0.92 < T < 0.98$
$\tau \to e\pi\pi$	–	$0.90 < T < 0.97$
$\tau \to eK\pi$	> 0.8	$0.90 < T < 0.97$
$\tau \to eKK$	> 0.6	$0.90 < T < 0.98$

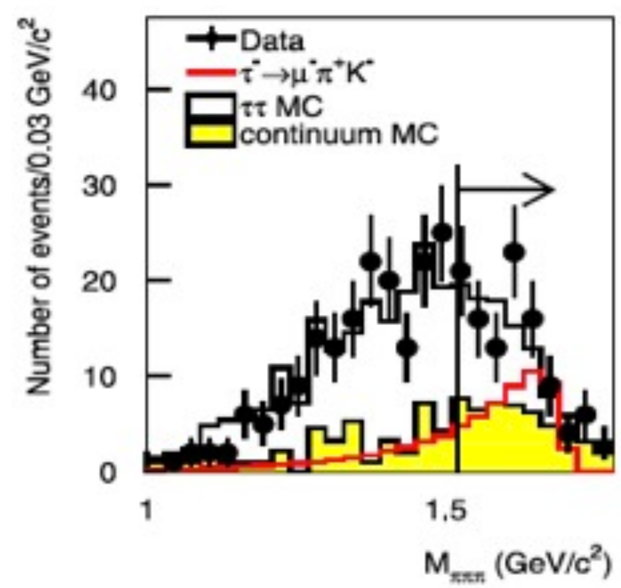
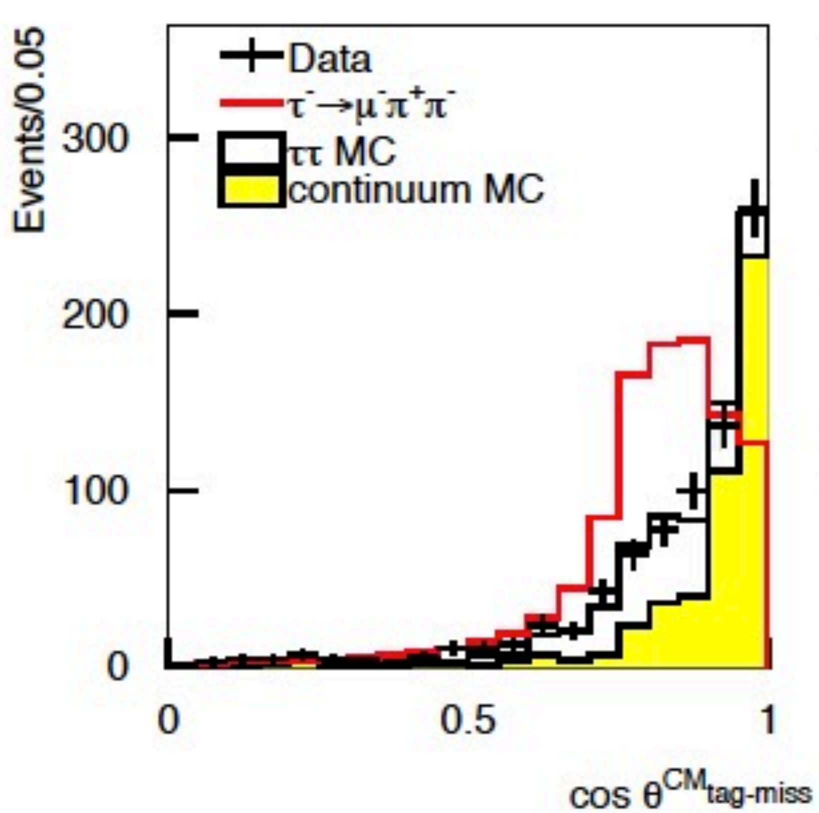
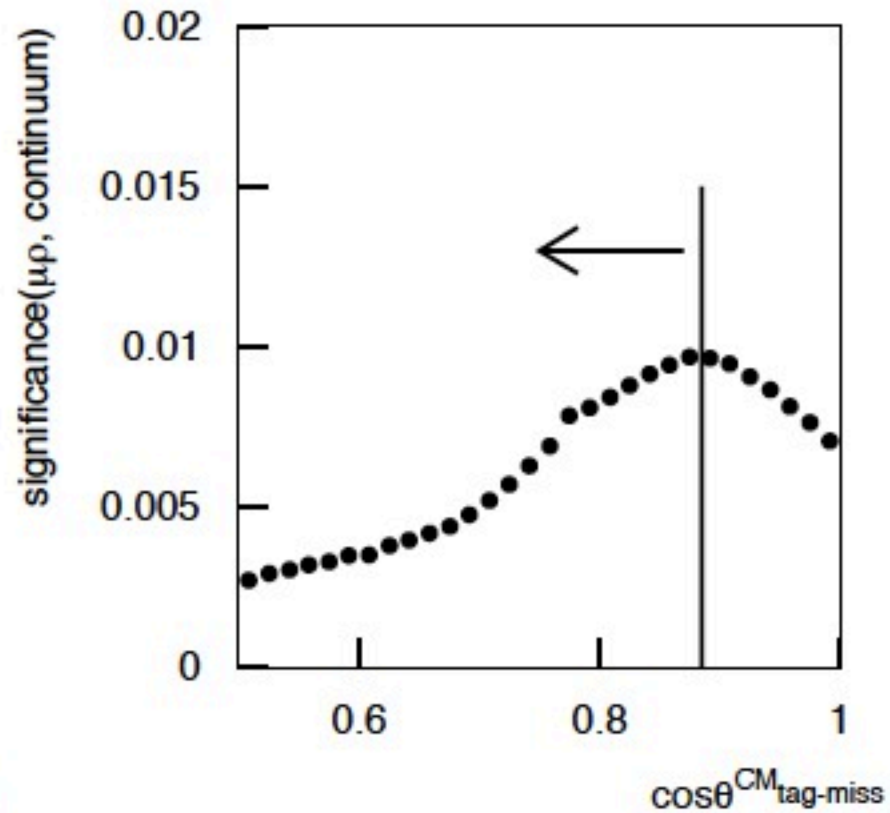
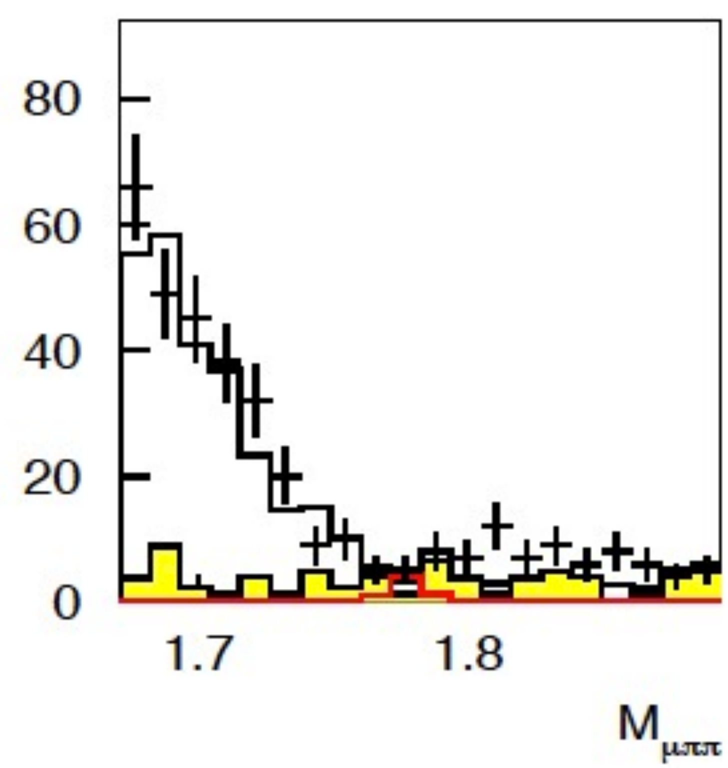


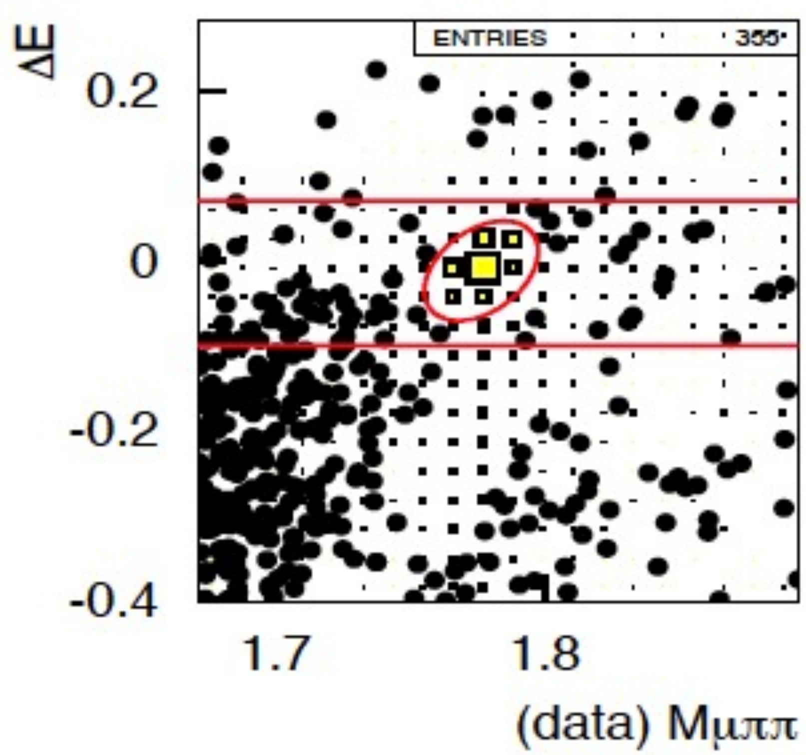
Fig. 2. Invariant mass distribution of three charged tracks on the signal side with the pion mass assigned to each track ($M_{\pi\pi\pi}$) for $\tau^- \to \mu^-\pi^+K^-$ candidate events. Signal MC ($\tau^- \to \mu^-\pi^+K^-$) distributions are normalized arbitrarily while the background MC distributions are normalized to the data luminosity. The selected regions are indicated by the arrow.

τ → l⁺hh′ Opening angle and Signal region









Invariant mass distribution and scatter plot btw Mμππ and ΔE after continuum reduction selection for the μ-π+π- mode.

red : signal MC

open : generic ττ MC

yellow filled : continuum MC

crossed points : data