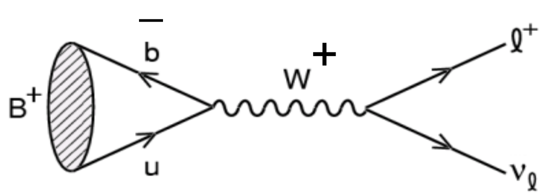
Perspectives for $B \to \tau\nu$ at Belle II

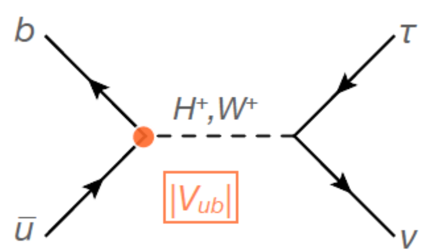
Mario Merola[1], *Elisa Manoni*[3,4], *Guglielmo De Nardo*[1,2]

[1] INFN Napoli, [2] Università di Napoli, [3] INFN Perugia, [4] Università di Perugia

Belle II Italia

Padova, 30/05/16





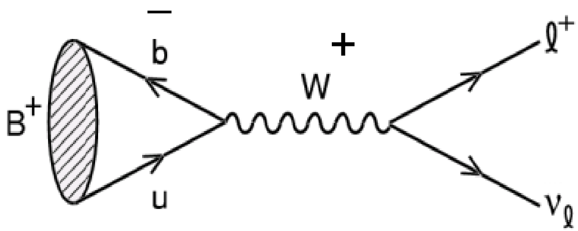
Outline

- Theory introduction and recent results overview
- B-tag reconstruction: Full Event Interpretation
- Selection and signal efficiency estimation
- Sensitivity of the analysis with a luminosity of 0.5 ab^{-1}
- Conclusions and future plans

B leptonic decays (B→lν)

- Helicity suppressed

$$BR_{SM}(B \to \ell \nu) = \frac{G_F^2 m_B \tau_B}{8\pi} f_B^2 |V_{ub}|^2 m_\ell^2 \left[1 - \frac{m_\ell^2}{m_B^2}\right]^2$$

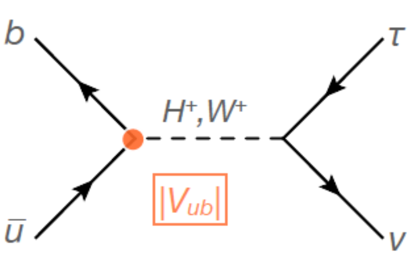


τ:μ:e –> 1 : 10^{-3} : 10^{-7}

- The SM predicts a branching ratio of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = 0.817^{+0.054}_{-0.031} \times 10^{-4}$

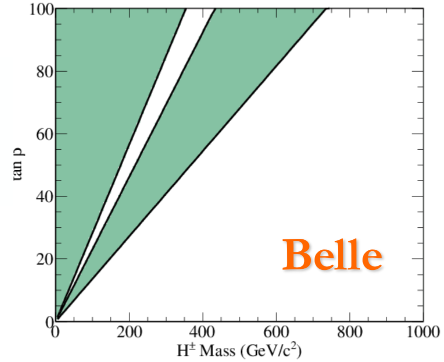
http://ckmfitter.in2p3.fr/

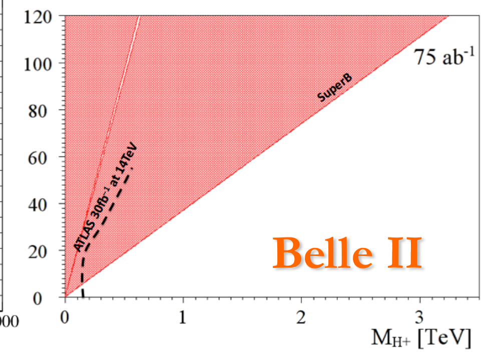
Higgs doublet models predict interference with SM decay with a modification of the branching ratio [PhysRevD.86.054014]



$$B = B_{SM} \times \left(1 - m_B^2 \frac{\tan^2\beta}{m_{H^\pm}^2}\right)^2$$

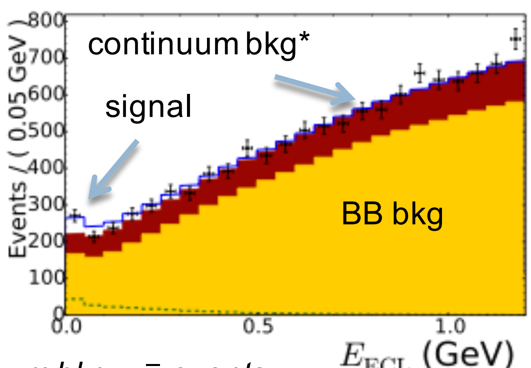
ratio of the two Higgs vacuum expectation values

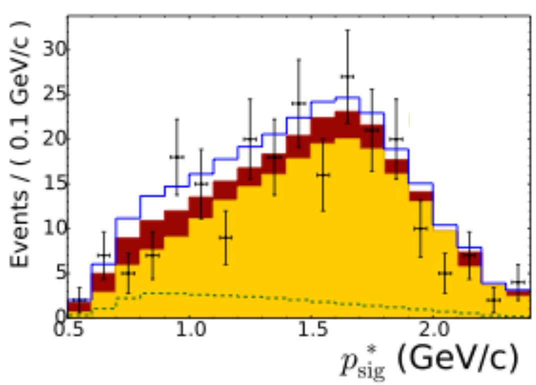




Recent results on $B \to \tau\nu$

- First evidence at Belle (2006) and Babar (2012)
- Most recent measurement (Belle – 2015, using semileptonic tag):
  - use of multivariate techniques (neural network) to reconstruct the tag side
  - the signal side is reconstructed in four modes: $\tau \to \mu\nu\nu, e\nu\nu, \pi\nu, \rho\nu$
  - the signal is extracted through a two-dimensional maximum likelihood fit to the E_{ECL} and p^*_{sig} distributions





*continuum bkg: $q\bar{q}$ events

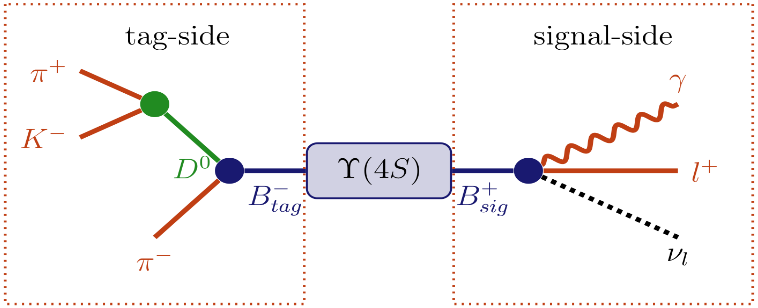
- E_{ECL} (later on called E_{extra}) is the sum of the energies of clusters in the ECL not associated to reconstructed B mesons
- p^*_{sig} is the momentum of the signal side particle in the CM

$$\mathcal{B} = [0.91 \pm 0.19(\text{stat.}) \pm 0.11(\text{syst.})] \times 10^{-4}$$ (evidence at ~4.6 σ level)

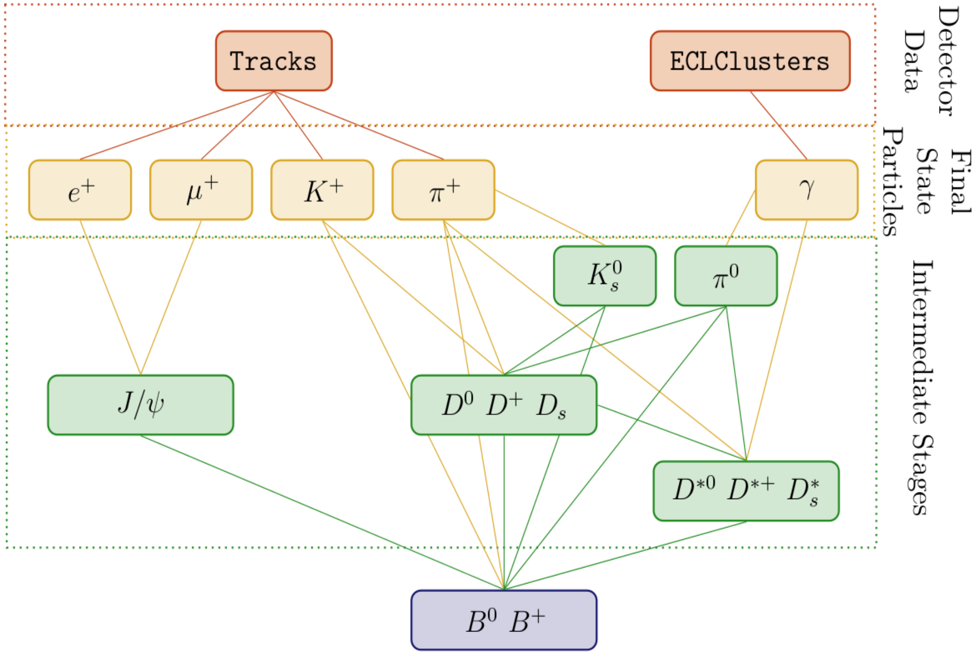
http://arxiv.org/abs/1503.05613v2

Tag side reconstruction in Belle II: Full Event Interpretation (FEI)

- Developed by Thomas Keck*, it's an extension of the Full Reconstruction used in Belle, and uses a multivariate technique to reconstruct the B-tag side through lots of decay modes in a Υ(4S) decay.



- Hierarchical approach: first train multivariate classifiers (MVC) on FSP, then reconstruct intermediate particles and build new dedicated MVC. For each candidate a signal probability ("sigprob") is defined, which represents the "goodness" of its reconstruction.



- Training performed on $100{*}10^6$ B^+B^- / $B^0\bar{B}^0$ events with beam background

- The result of the training is analysis independent.

*https://ekp-invenio.physik.uni-karlsruhe.de/record/48602/files/EKP-2015-00001.pdf

Selection (1)

B tag side

Hadronic tag using FEI

- Cut on FEI output discriminant
- Pick the highest sigprob B candidate
- Pre-selection on B-tag kinematics*

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

* Energy difference: $\Delta E = E_B^* - E_{beam}^*$

B sig side

$B \to \tau\nu$

- 4 tau modes: $\mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\rho\nu$
- $\rho \to \pi\,\pi^0$
- PID, ECL cluster cleaning (see next slide)
- $110 < M(\pi^0) < 150$ MeV
- $625 < M(\rho) < 925$ MeV

Require full reconstruction of tag side and only one additional track in the event

The study presented here has been performed on Belle II MC5 production:
- $100*10^6$ events of $B \to \tau\nu \to$ generic with beam background
- 0.5 ab^{-1} of $B^+B^-/B^0\overline{B}^0$ and continuum with beam background

Selection (2)

PID selection

- Likelihood function based on E/p and dE/dx
- Cut on the LR = L(particle) / (L(e) + L(mu) + L(pi))

Photon selection

- cluster cleaning (to reject photons from beam background) with cuts on photon energy, cluster timing, E9/E25 and minimum distance between the cluster and tracks in the event (separately in forward, barrel and backward detector regions).

Additional cuts (continuum bkg rejection)

- Cut on the angular variable R2, defined as the ratio between the 2nd and 0th Fox-Wolfram moments [PhysRevLett.41.1581]. It is close to 0 for events with spherical symmetry (as BB events) and close to 1 for events with back-to-back topology

Detailed talk in WG1 meeting: https://kds.kek.jp/indico/event/21392/contribution/0/material/slides/0.pdf

More details at the Twiki page: https://belle2.cc.kek.jp/~twiki/bin/view/Physics/Pi0Reco

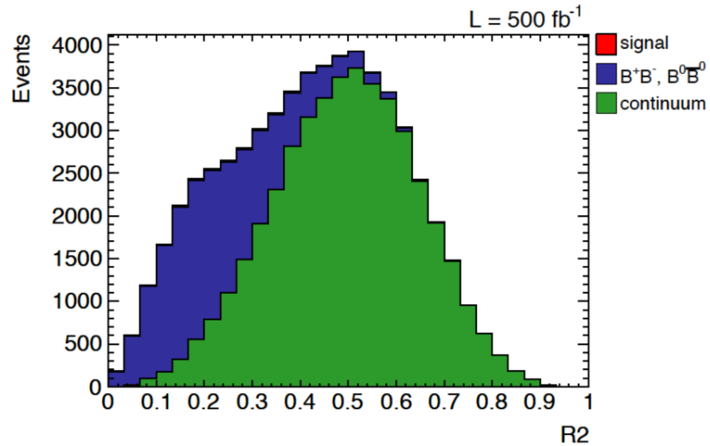
Fox-Wolfram moment

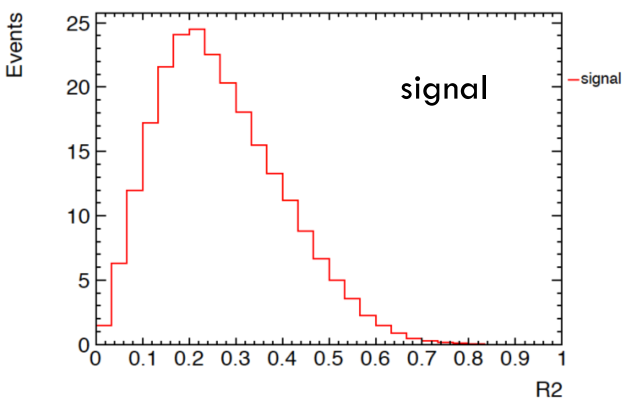
$$H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{W^2} P_l(\cos\vartheta_{ij})$$

visible energy

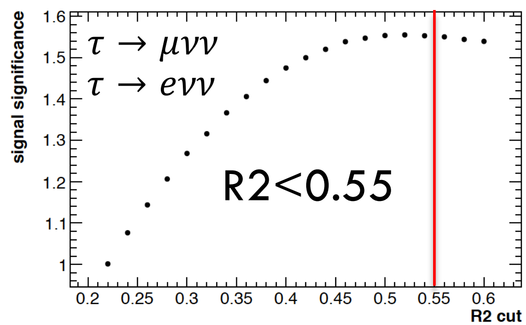
Legendre polynomials

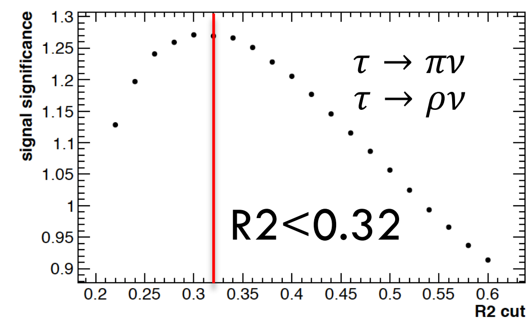
Continuum rejection: R2 variable





The cut on R2 is optimized in order to maximize the signal significance* in the M_{bc} and E_{extra} signal windows (respectively 5.27-5.29 GeV/c^2 and 0-0.5 GeV)



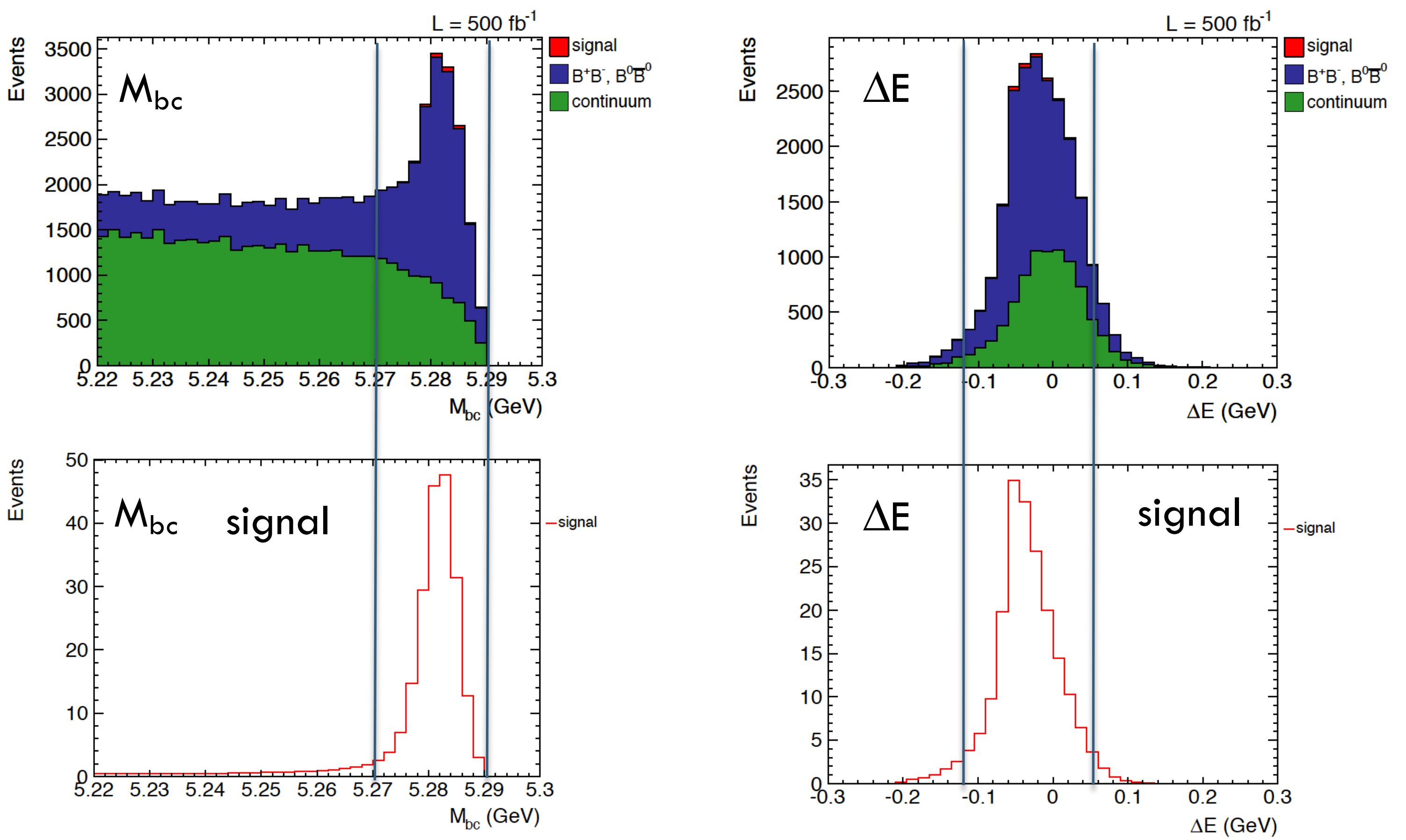


The continuum background mostly affects the hadronic modes → apply a tighter cut

In all the plots shown here and in the next slides the signal and bkg are normalized to 0.5 ab^{-1}

*estimated as S/sqrt(S+B) where S is tau nu and B is BB+continuum bkg, normalized to 0.5 ab^{-1}

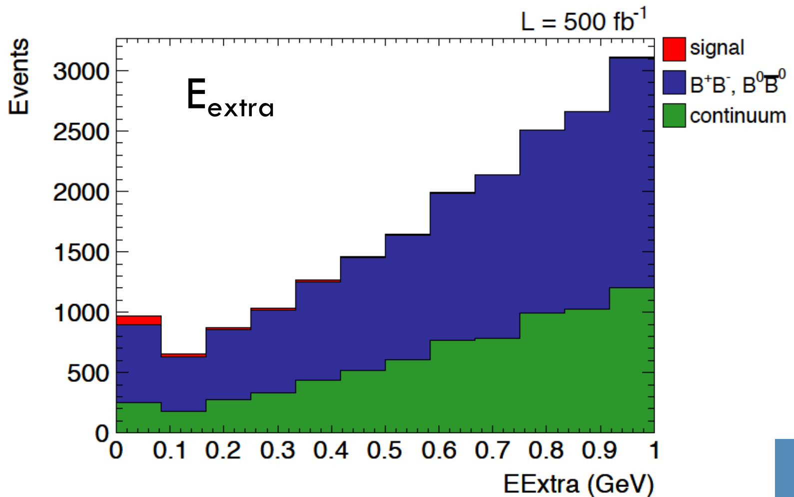
M_{bc} and ΔE

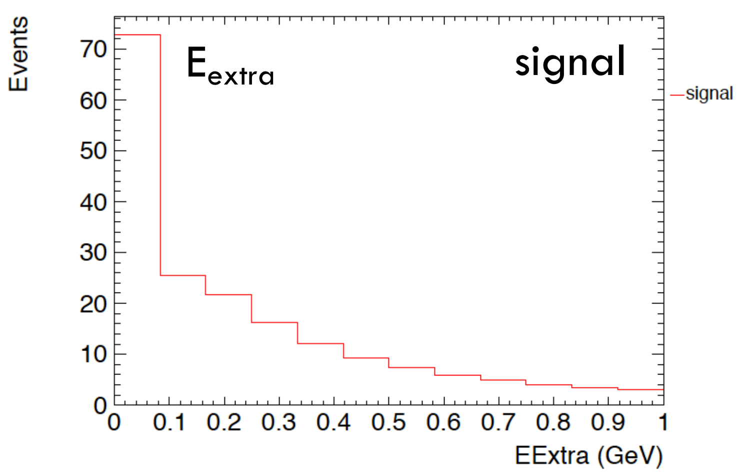


$5.27 < M_{bc} < 5.29\ \mathrm{GeV}/c^2$

$-0.12 < \Delta E < 0.05\ \mathrm{GeV}$

E_{extra} and signal efficiency estimation





Signal and background event yields

Eextra < 1 GeV
- sig: 186 events
- bkg: 20141 events

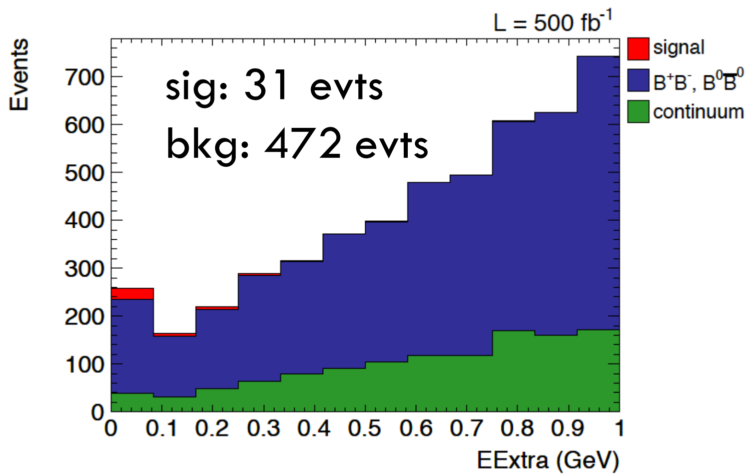
Eextra < 0.2 GeV
- sig: 108 events
- bkg: 1829 events

E_{extra} < 1 GeV	Babar PRD 88, 031102 (2013)	Belle PRL 110, 131801 (2013)	Belle II (this study)
Signal Efficiency (‰)	**0.72**	**1.1**	**4.3**

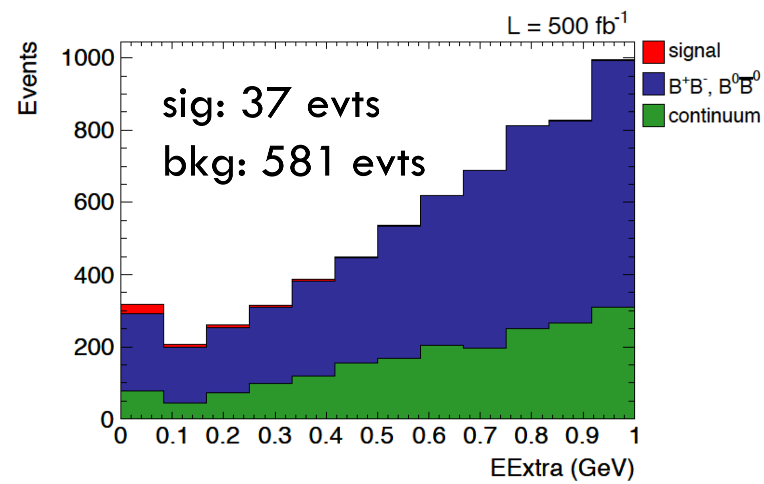
Higher signal efficiency due to: higher b-tag reconstruction efficiency (FEI), looser selection (loose continuum rejection criteria). Belle and Babar measured a background yield of ~1.2-1.5 *10^3 events

Signal and bkg yields separated by modes in E_{extra}<0.2 GeV

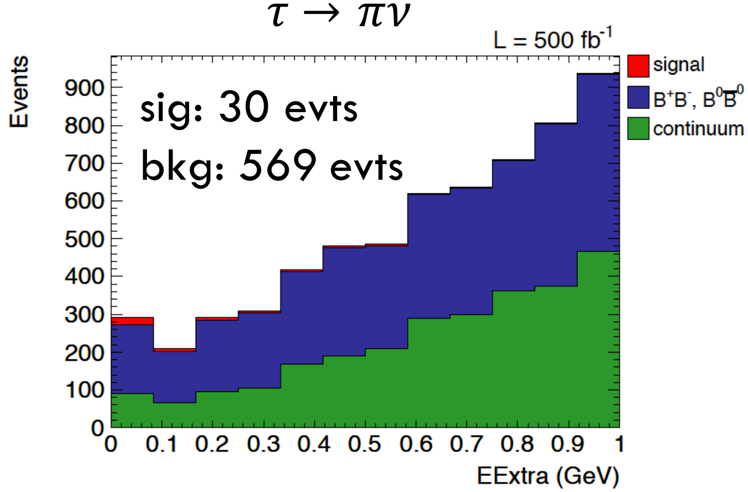
$\tau \rightarrow \mu\nu\nu$



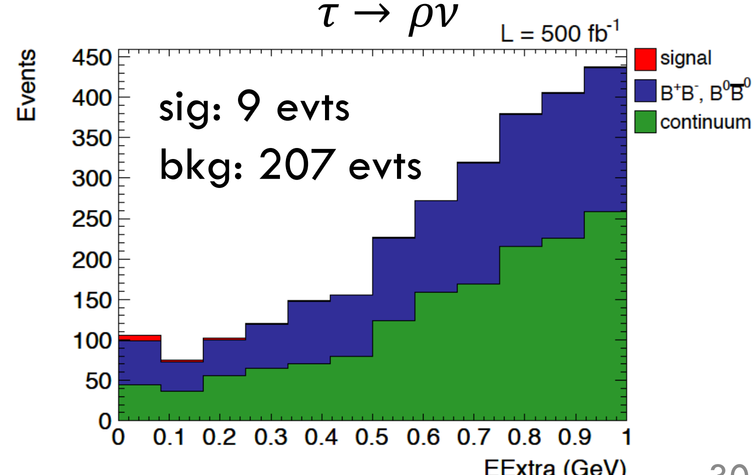
$\tau \rightarrow e\nu\nu$



$\tau \rightarrow \pi\nu$



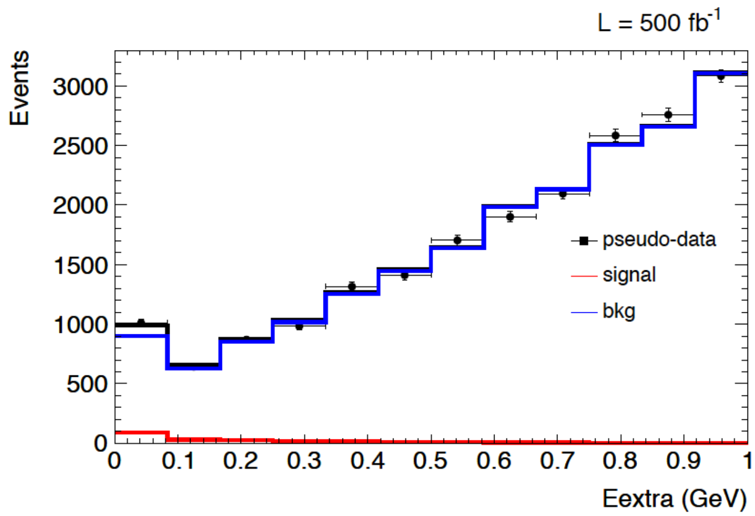
$\tau \rightarrow \rho\nu$

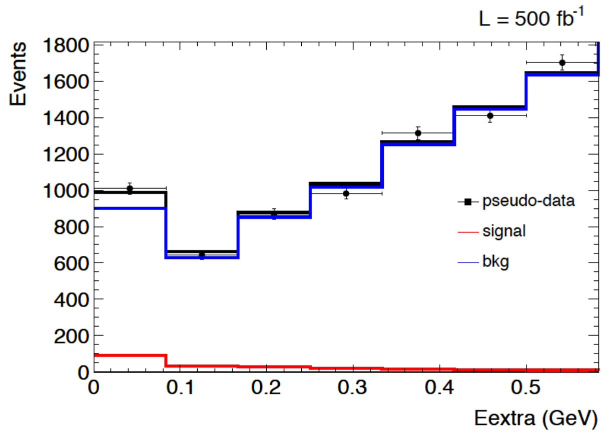


Signal extraction strategy

Perform a 1D fit to the E_{extra} distribution

- Generate a pseudo-dataset according to the signal + background MC expectations
- Perform a template maximum likelihood fit to E_{extra} with two components: signal and background pdfs built from the expected MC distributions



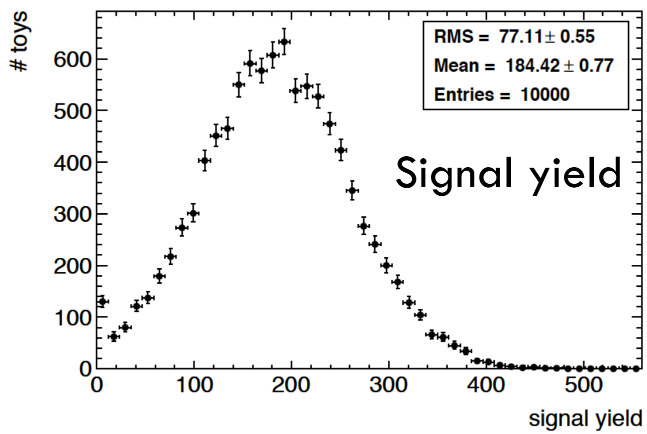


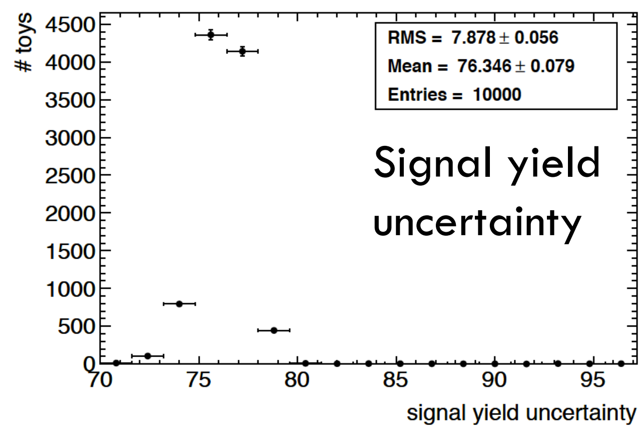
zoom in signal region

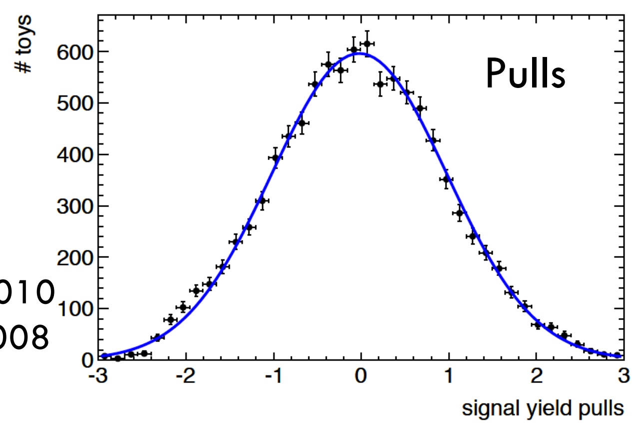
Sig: 229 +/- 76 events
Bkg: 20121 +/- 160 events

Toy MC study and branching ratio measurement

Generate 10000 pseudo-datasets and repeat the fit to evaluate the mean fitted signal yields, the uncertainty and the pulls.







Pulls gaussian fit:
mean = -0.022 ± 0.010
sigma = 1.001 ± 0.008

mean signal yield = 184 evts
mean uncertainty = 76 evts

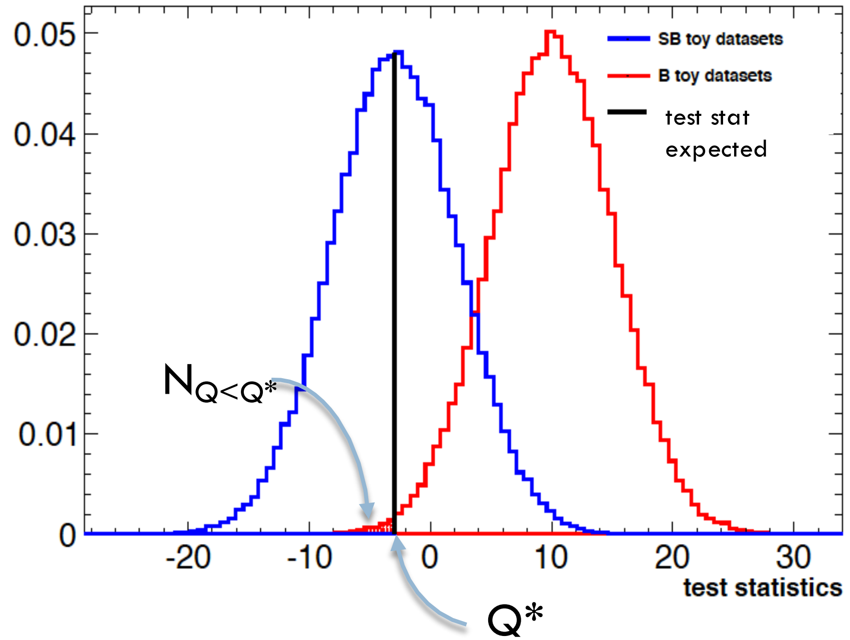
$BR(B \to \tau\nu) = 0.8 \pm 0.3 \times 10^{-4}$

~40% precision

Expected sensitivity of the measurement

- Define the test statistics $Q = -2\ln[L(s+b)/L(b)]$ and perform 100000 pseudo-experiments generating pseudo-datasets sampled from S+B and B only E_{extra} distributions.
- Evaluate the expected p-value of the null hypohesis on the toys background samples as $1-CL_b = N_{Q<Q^*}/N$, where $N_{Q<Q^*}$ is the number of pseudo-experiments with Q lower than the mean of the test statistics distributions on the S+B toy samples Q*, and N is the total number of pseudo-experiments.

blue hist distribution of Q evaluated on S+B toy datasets
red hist: distribution of Q evaluated on B only toy datasets
Black line: expected value of Q in the S+B hypothesis



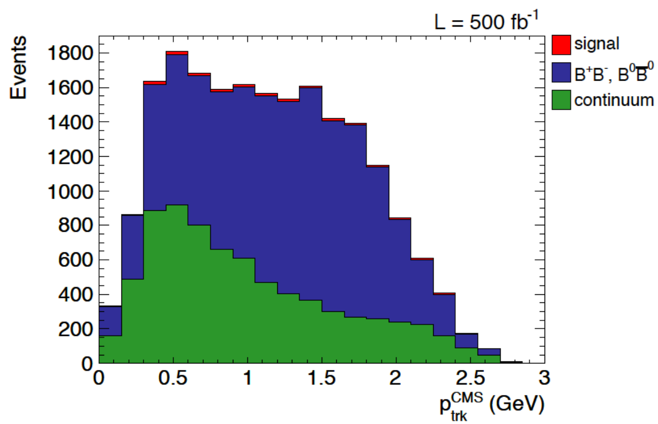
p-val = 0.99718 → significance: 2.8 sigma (stat. only)

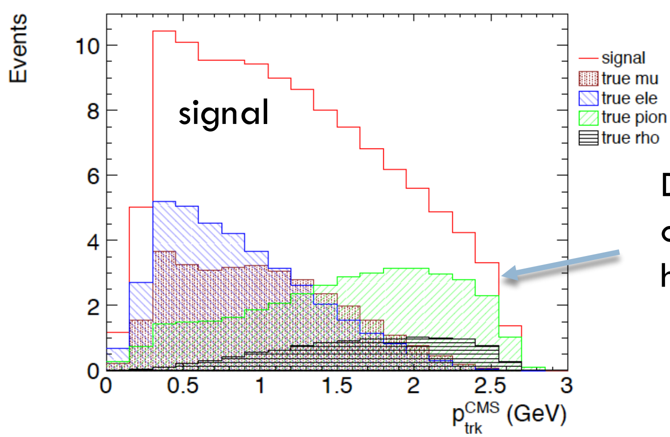
Assuming a conservative 15% systematic uncertainty (Belle and Babar hadronic tag analyses estimated a 13-14%) a very naïve scaling of the significance lead to 2.6 sigma

Future improvements

As done at Belle and Babar, we will exploit other features of the $B \rightarrow \tau\nu$ decay

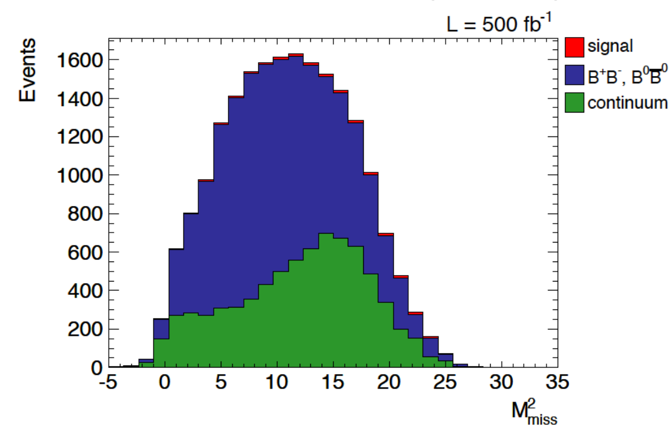
Signal side track momentum in the CM frame, p^*_{sig}

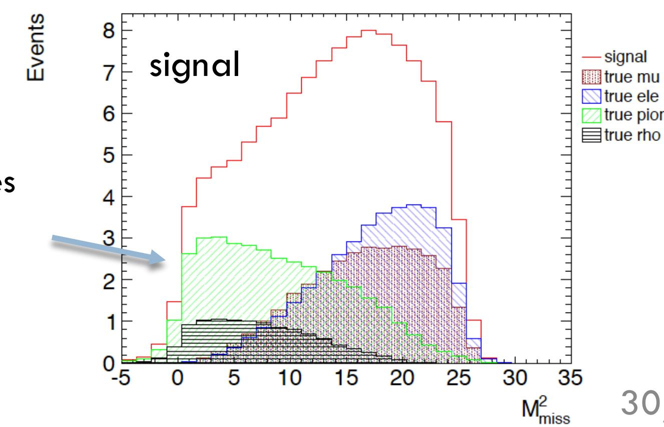




Missing mass squared

$$M^2_{miss} = \left(2E_{beam} - E_{B_{tag}} - E_{B_{sig}}\right)^2 - \left|\vec{p}_{B_{tag}} + \vec{p}_{B_{sig}}\right|^2$$





Different topologies of the leptonic and hadronic modes

Summary (1)

- First study of the $B \rightarrow \tau\nu$ decay has been performed on 0.5 ab^{-1} of Belle II MC5 production
- A baseline selection has been established in order to reject $B^+B^-/B^0\overline{B}^0$ and $q\bar{q}$ continuum background
- Four are the τ decay modes considered: $\mu\nu\nu, e\nu\nu, \pi\nu, \rho\nu$
- The signal efficiency in a fiducial E_{extra} region is found to be 4.3‰
- Sensitivity/precision of the analysis is estimated with toy MC performing maximum likelihood fit to E_{extra} distribution. In 0.5 ab^{-1}, assuming a branching ratio of 0.82×10^{-4}, the expected statistical uncertainty is ~40% and the signal significance is ~2.8 sigma (~2.6 with syst.)

Summary (2)

- Future plans
  - improve signal selection: optimize continuum suppression (using $\cos\theta_{thrust}$)
  - study background composition
  - improve the fit strategy: separate and fit simultaneously the 4 signal decay modes (mu, ele, pi and rho); consider a 2D fit (E_{extra} and p^{*}_{sig} or p^{miss}) or a multivariate discriminant fit (BDT, NN)
  - Realistic evaluation of the impact of systematic uncertainties

B2TiP

- Belle II theory interface platform: https://belle2.cc.kek.jp/~twiki/bin/view/B2TiP
- Last workshop in Pittsburgh 23-25 May: https://kds.kek.jp/indico/event/19723/timetable/#20160523
- The aim is to come out with realistic projections of the precision Belle II will reach in the different studies.
- B2TiP book preparation: timescale in the next slide

B2TiP book

Key Dates

- **Submission to Journal, 31st March 2017**

- 2016 Key dates
  - **May** B2TiP Pittsburgh - presentation of 1 ab^{-1} to 5 ab^{-1} studies.
  - **June** MC6 production based on Software release 7 (removal of legacy tracking, more beam background processes). To be used in some studies
  - **July:** First draft from each chapter sent for soft review. **VERSION 1**
  - **September:** Deadline for response from reviewers.
  - **Oct 31 Hard deadline for delivery of chapters for review prior to the MIAPP B2TiP workshop. VERSION 2**
  - **Nov 15-17** B2TiP Editorial meeting in Nov.
  - **Dec-Feb** Editing and review. We will discourage new contributions in this period. **FINAL VERSION**

B2TiP book

1 Leptonic and Semileptonic B Decays

Section convenors: A. Kronfeld, G. De Nardo, F. Tackmann, R. Watanabe, A. Zupanc

1.1 Introduction

1.2 Leptonic B decays

Authors: G. De Nardo (exp.), M. Merola (exp.), R. Watanabe (th.)

- Theory motivation
- *test of detector performance*
  - B_{tag} reconstruction efficiency
  - extra track, π^0, and K_L vetoes
  - extra energy in the calorimeter resolution
- *$B \to \tau\nu$, $\mu\nu$ measurement*

1.3 Semitauonic decays

1.3.1 $B \to D^{(*)}\tau\nu$

Authors: Y. Sato (exp.), K. Adamczyk (exp.), R. Watanabe (th.)

- *SM*
- *Model independent new physics*
- *projections for $R(D)$, $R(D^*)$*
- *projections for kinematic distributions (q^2, $p_\ell^{(*)}$, p_{D^*}...)*
- *polarization measurement, angular distributions*
- *Exclusion plots*

1.3.2 $B \to \pi\tau\nu$

Authors: R. Watanabe (th.), F. Bernlochner (exp.)

1.3.3 $B \to X_c\tau\nu$

Authors: Z. Ligeti (th.), J. Hasenbusch (exp.),

1.4 Exclusive semileptonic

1.4.1 $B \to D^{(*)}\ell\nu$

Authors: A. Kronfeld (th.), C. Schwanda (exp.)

- Is it useful to measure $B_s \to D_s\ell\nu$??

1.4.2 $B \to \pi\ell\nu$

Authors: A. Kronfeld (th.), A. Zupanc (exp.), M. Lubej (exp.)

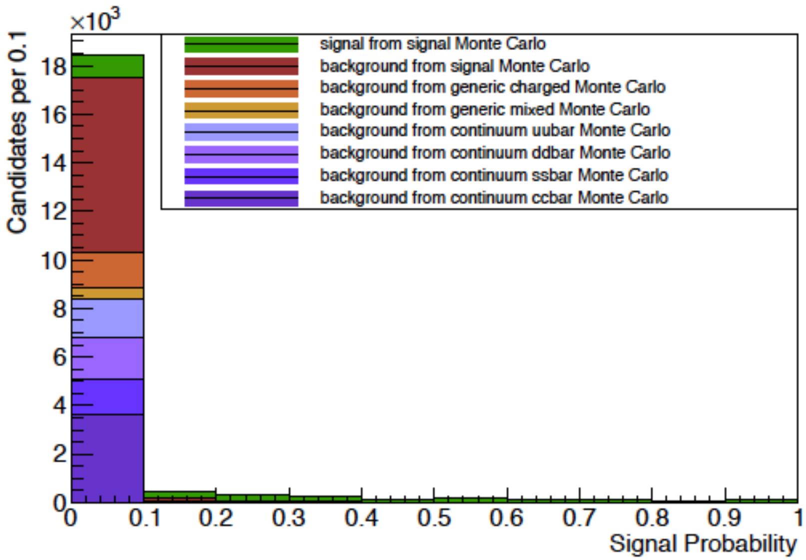
- LQCD updates
- sum rules?
- projections for tagged/untagged measurement
- Can we measure $B_s \to K\ell\nu$? How large $\Upsilon(5S)$ sample is needed?

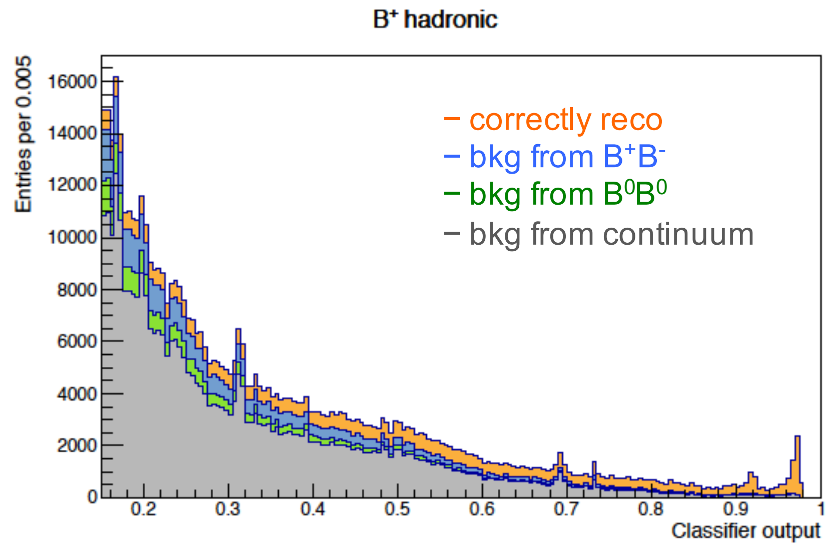
Backup

Full Event Interpretation: variables

- Input variables used to train the multivariate classifiers:
  - PID, tracks momenta, impact parameters (charged FS particles);
  - cluster info, energy and direction (photons);
  - invariant mass, angle between photons, energy and direction (π^0);
  - released energy, invariant mass, daughter momenta and vertex quality ($D^{(*)}_{(s)}$, J/ψ);
  - the same as previous step plus vertex position, ΔE (B);
  - additionally, for each particle the classifier output of the daughters are also used as discriminating variables.

Full Event Interpretation (FEI) performances





from Christian Pulvermacher PhD thesis

Total reconstruction efficiency compared with Belle I

Belle II

B^+ (hadronic)	0.78 %	B^+ (semileptonic)	1.05 %
B^0 (hadronic)	0.59 %	B^0 (semileptonic)	1.17 %

Belle I

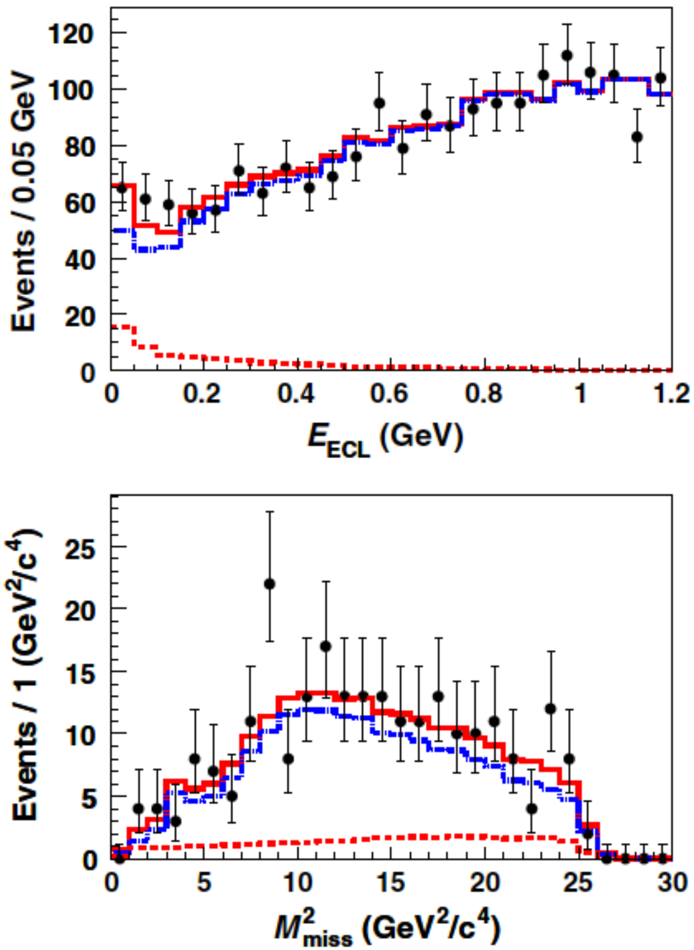
B^+ (hadronic)	0.39 %	B^+ (semileptonic)	0.80 %
B^0 (hadronic)	0.28 %	B^0 (semileptonic)	0.86 %

Belle paper

Belle paper, hadronic tag,
PRL 110, 131801 (2013)

TABLE I. Results of the fit for $B^- \to \tau^- \bar{\nu}_\tau$ yields ($N_{\rm sig}$), detection efficiencies (ϵ), and branching fractions ($\mathcal{B}$). The efficiencies include the branching fractions of the τ^- decay modes. The errors for $N_{\rm sig}$ and $\mathcal{B}$ are statistical only.

Submode	$N_{\rm sig}$	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^- \nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$



Photon cuts

Y4S photons

- E > 72 MeV, -114 < clusterTiming < -46, E9E25>0.800, minC2HDist>39 cm – forward
- E > 71 MeV, -112 < clusterTiming < -48, E9E25>0.805, minC2HDist>29 cm – barrel
- E > 66 MeV, -142 < clusterTiming < -18, E9E25>0.710, minC2HDist>23 cm – backward

Each cut corresponds to an efficiency of photons form physics of 95%

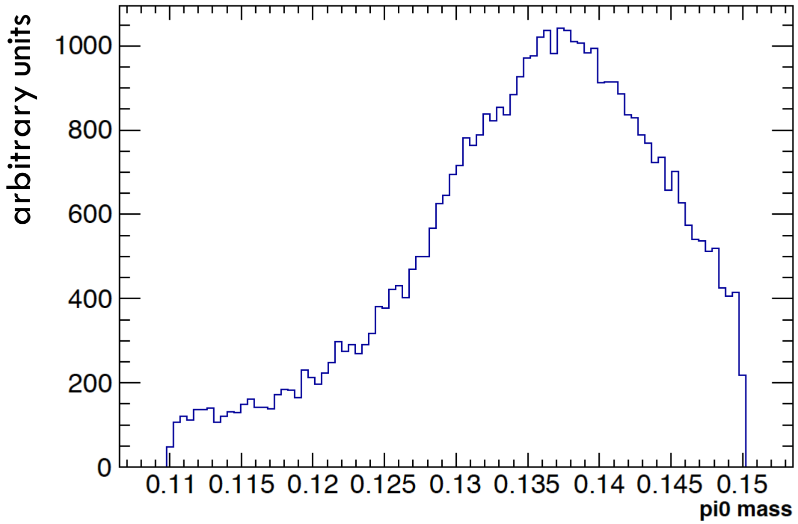
Extra photons

- E > 48 MeV, -121 < clusterTiming < -39, E9E25>0.665, minC2HDist>32 cm – forward
- E > 51 MeV, -123 < clusterTiming < -37, E9E25>0.685, minC2HDist>22 cm – barrel
- E > 49 MeV, -151 < clusterTiming < -9, E9E25>0.650, minC2HDist>24 cm – backward

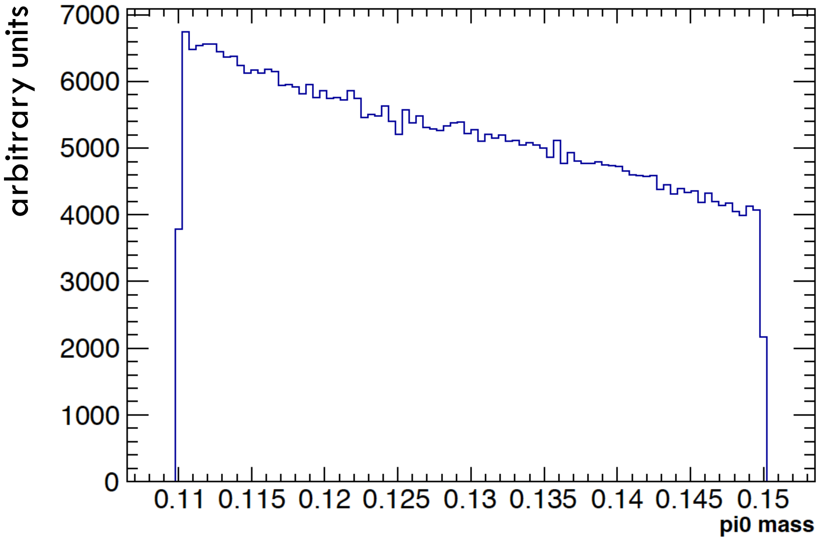
Each cut corresponds to an efficiency of photons form physics of 90%

π^0 mass

After selection



Before selection

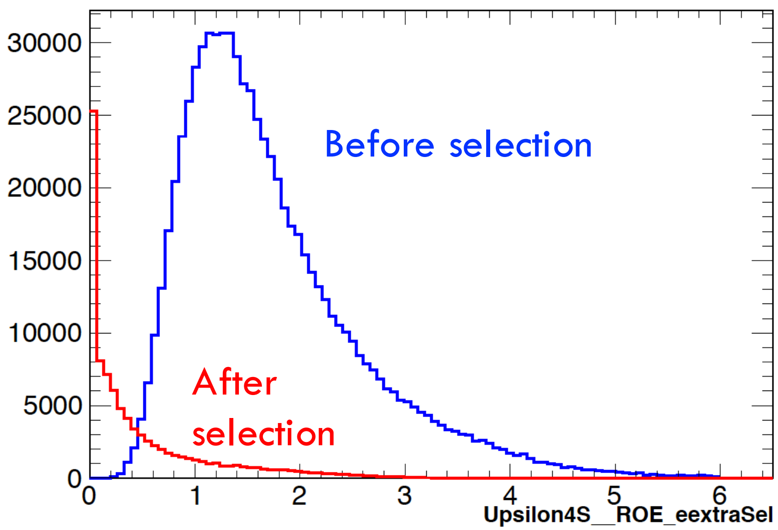


Signal $B \to \tau\nu$ sample

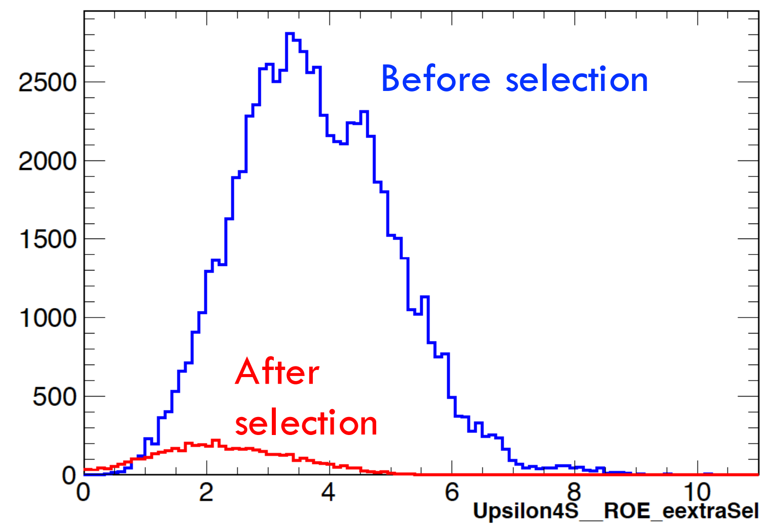
Eextra

Extra cluster cleaning selection

signal $B \rightarrow \tau\nu$



B^+B^- bkg



Photon and PID selection eff: 12.2 %

N.B. before PID selection we have a lot of multiple candidates (particle reconstructed as mu and ele and pi)