Study of $B \to \tau\nu$

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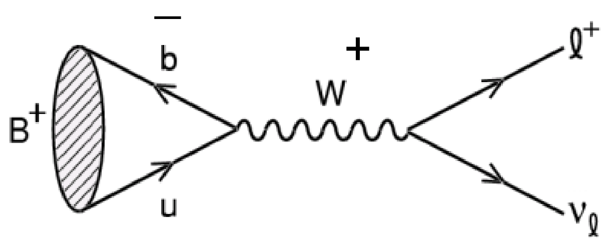
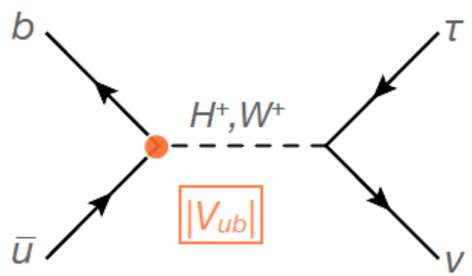
Belle II Italia

Pisa, 20/11/17





Outline

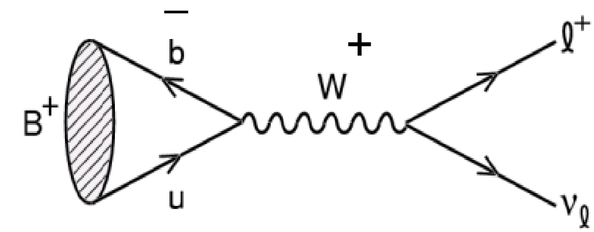
new w.r.t. last meeting

- Theory introduction and recent results overview
- Analysis status (as of B2TiP report)
- Impact of new extra clusters selection
- Physics validation – performances comparison MC8 / MC9
- Conclusions and future plans

B leptonic decays ($B \to l\nu$)

- Helicity suppressed

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

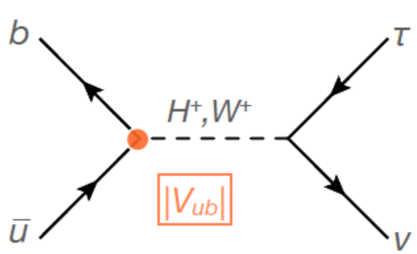


$\tau:\mu:e \to 1 : 10^{-3} : 10^{-7}$

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

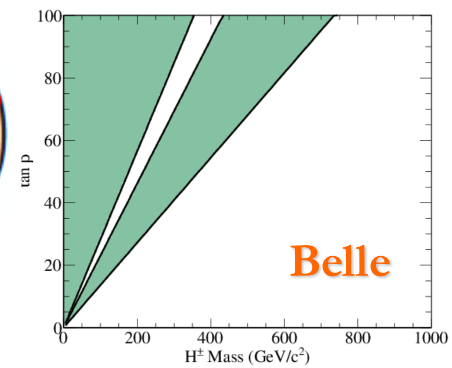
http://ckmfitter.in2p3.fr/

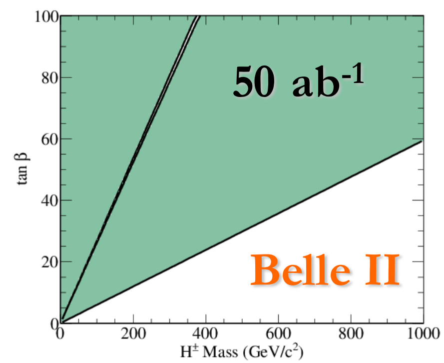
Higgs doublet models predict interference with SM decay with a modification of the branching ratio [PhysRevD.86.054014]



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

ratio of the two Higgs vacuum expectation values





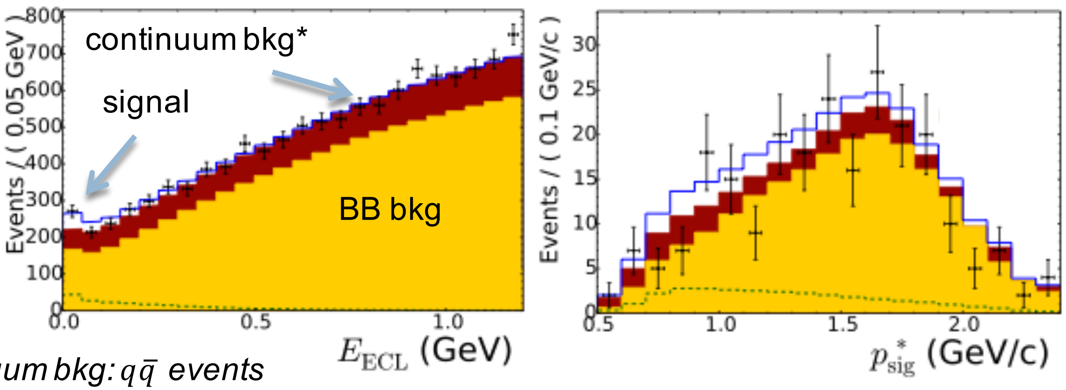
Recent results on $B \to \tau\nu$

- 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)

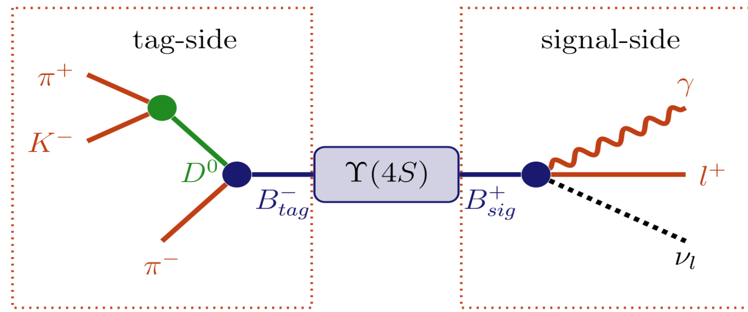
http://arxiv.org/abs/1503.05613v2

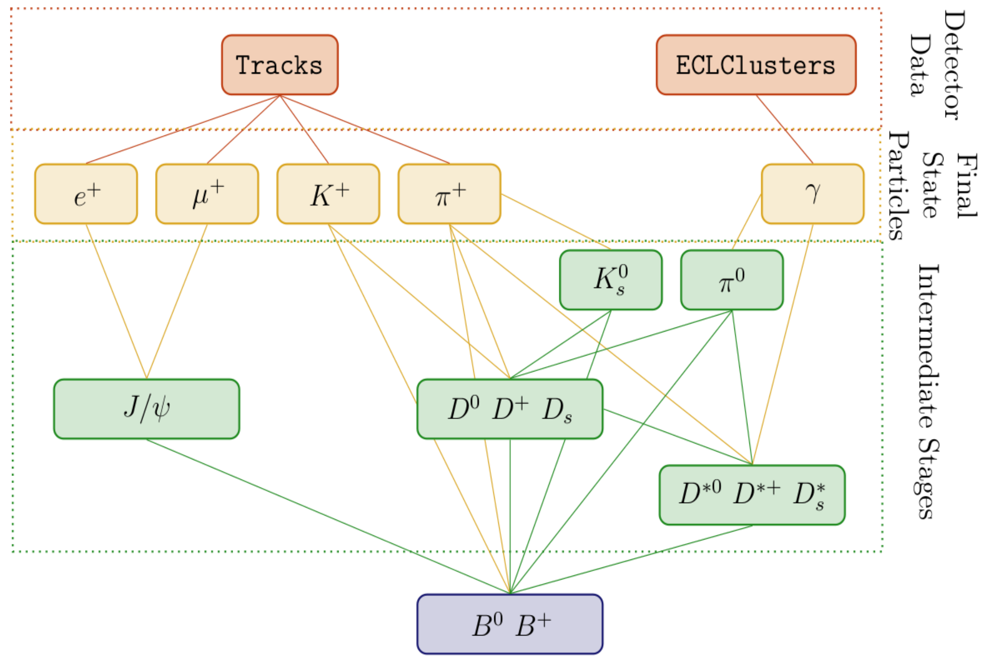
Tag side reconstruction: Full Event Interpretation (FEI)

- 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 is defined, which represents the "goodness" of its reconstruction.

- Training performed on $B^+B^-/B^0\bar{B}^0$ events with beam background at KEKCC





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

Analysis status (B2TiP)

https://docs.belle2.org/record/389/files/BELLE2-PUB-DRAFT-2016-008.pdf

Selection (1)

B tag side

Hadronic tag using FEI

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

* Beam-constrained mass: $M_{bc} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$

* Energy difference: $\Delta E = E^{*}_{B} - E^{*}_{beam}$

B sig side

$B \to \tau\nu$

- 4 tau modes: $\mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\pi\,\pi^{0}\nu$
- PID, ECL cluster cleaning (see next slide)
- $110 < M(\pi^0) < 160$ MeV
- $625 < M(\rho) < 925$ MeV

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

Run on MC5 production:
- $100 \cdot 10^6$ events of $B \to \tau\nu \to$ generic with beam background
- 1 ab^{-1} of $B^+B^-/B^0\overline{B}^0$ and continuum with beam background

https://confluence.desy.de/display/BI/Computing+MC5Release4Physics

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 and π^0 selection

Cluster cleaning (to reject photons from beam background) with cuts on photon energy, cluster timing and E9/E25 (separately in forward, barrel and backward detector regions). Details at the confluence page: https://confluence.desy.de/display/BI/Physics+Pi0+and+extra+clusters+cleaning

Continuum rejection

- MVA with boosted decision trees to separate back-to-back topology from events with spherical symmetry (BB). See backup for details

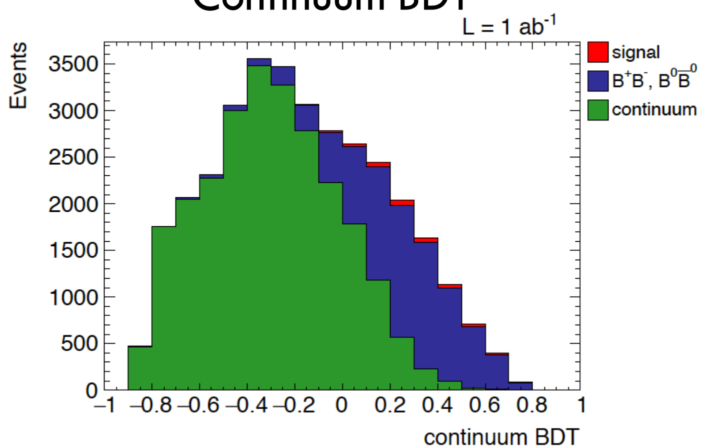
In the post-B2TiP analysis:

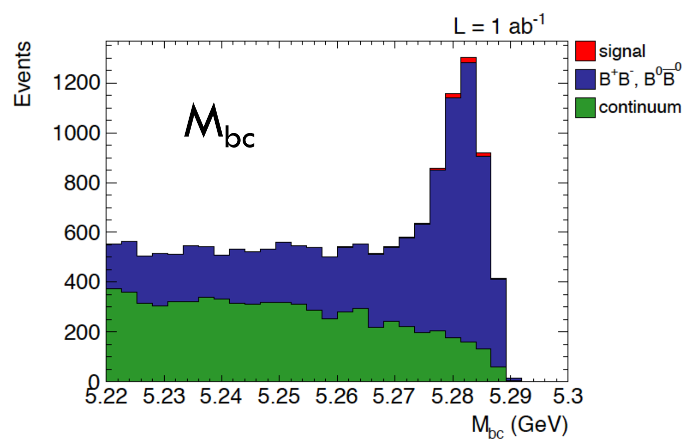
Follow PID recommendations: https://confluence.desy.de/display/BI/Physics+StandardParticles

New extra energy and pi0 selection (see my talk in the tools session this morning)

Background rejection

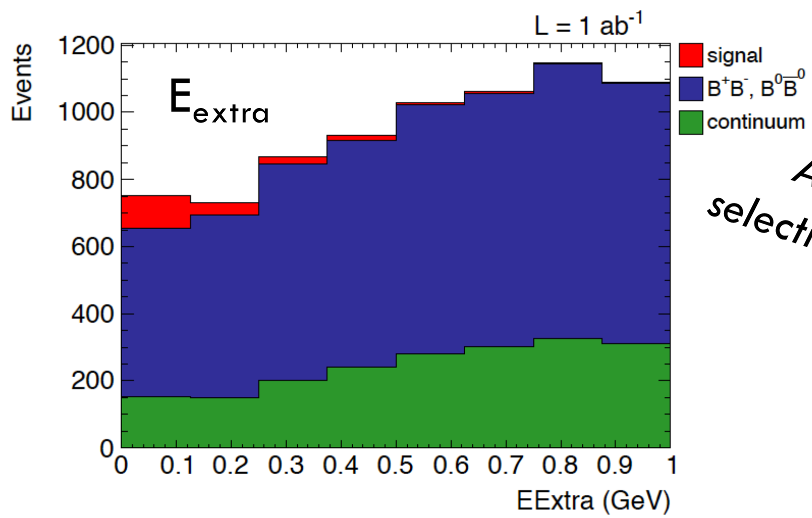
Continuum BDT





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

Cuts on the BDT, M_{bc} ΔE, missing mass, and signal side track momentum are optimized maximizing the FOM* in the M_{bc} and E_{extra} signal windows (respectively 5.275-5.29 GeV/c^2 and 0-0.2 GeV). Optimization for hadronic and leptonic tau decay modes separately



After selection cuts

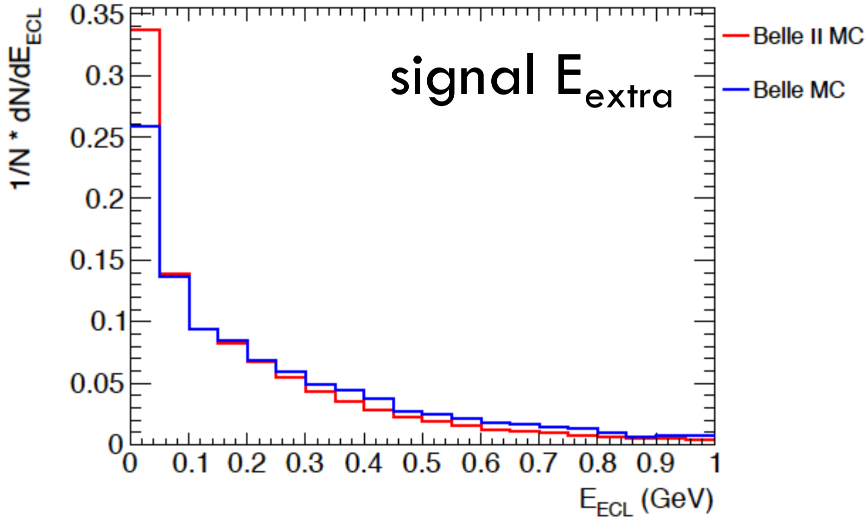
* S/sqrt(S+B) where S is $B \to \tau\nu$ and B is BB+continuum bkg, normalized to 1 ab^{-1}

Selection efficiency and comparison with Belle MC

Signal and background event yields in 1 ab^{-1}

	E_{ECL}	< 1 GeV	< 0.25 GeV
Belle II	# background events	7420	1348
	# signal events	188	136
	signal efficiency (‰)	2.2	1.6
Belle*	# background events	2160	365
	# signal events	97	60
	signal efficiency (‰)	1.2	0.7

*PRL 110, 131801 (2013)



- In Belle II we have higher bkg contamination and higher signal efficiency
- Statistical improvement (S/sqrt(S+B)), but we need to evaluate the systematics impact (e.g. uncertainty on the peaking background)

- E_{extra} has a narrow peak at 0 for Belle II MC → better extra clusters reconstruction despite higher beam background

Branching ratio and projection with systematic uncertainties

- Branching ratio: fit to the E_{extra} distribution for toy MC pseudo-datasets and take mean and width of the results

- p-value determination: use the test statistics Q = L(s+b)/L(b) evaluated on pseudo-datasets sampled from S+B and B only E_{extra} distributions.

$BR(B \to \tau\nu) = 0.82 \pm 0.24 \times 10^{-4}$ ~30% precision

p-val = 0.000385 → significance: 3.4 σ

in 1 ab^{-1}

- The main systematic uncertainties are: signal and background E_{Extra} PDFs, branching fractions of the peaking backgrounds, tagging efficiency, and K^0_L veto efficiency (followed by the signal efficiency and others)

Systematics extrapolation based on Belle II note*

Integrated Luminosity (ab^{-1})	1	5	50
statistical uncertainty (%)	29.2	13.0	4.1
systematic uncertainty (%)	12.6	6.8	4.6
total uncertainty (%)	31.6	14.7	6.2

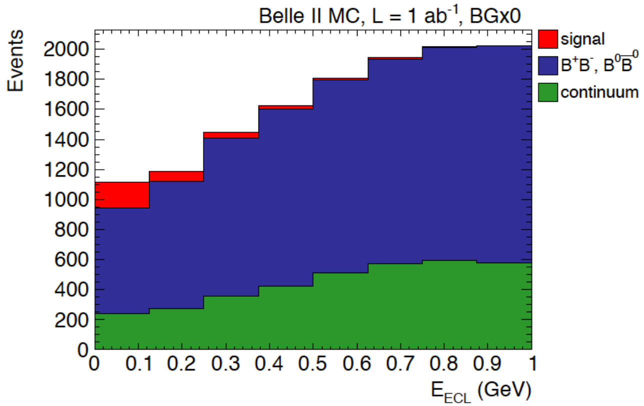
luminosity needed for B → tau nu 5σ observation is 2.6 ab^{-1}

* Belle2-note-0021
https://confluence.desy.de/download/attachments/35838603/belle2-note-0021.pdf?version=1&modificationDate=1468937879217&api=v2

Impact of beam background

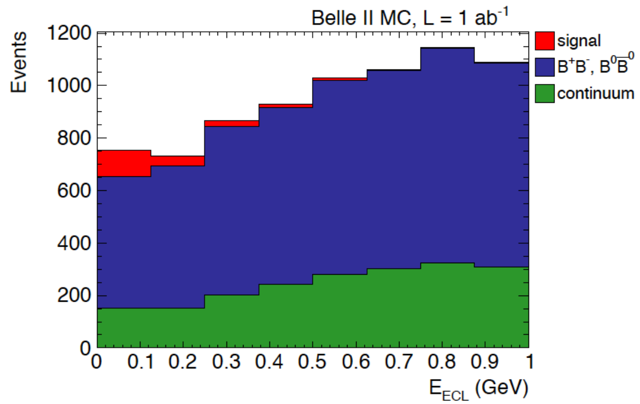
- Impact of beam background evaluated re-performing the study described above on MC5 samples without beam background

BGx0



E_{ECL}	< 1 GeV	< 0.25 GeV
# background events	12835	2062
# signal events	332	238
signal efficiency (‰)	3.8	2.7

BGx1



E_{ECL}	< 1 GeV	< 0.25 GeV
# background events	7420	1348
# signal events	188	136
signal efficiency (‰)	2.2	1.6

- Toy MC: expected precision for BGx0 is 20% (30% for BGx1) with a significance > 5σ in 1 ab^{-1}

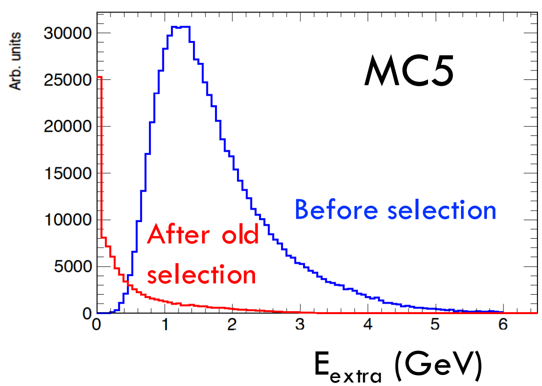
Analysis update

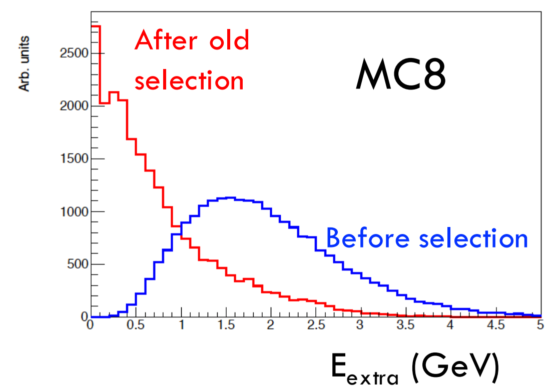
Selection update

- PID selection
  - Use the release-09 recommended working points (95-99% efficiencies)
    https://confluence.desy.de/display/BI/Physics+StandardParticles

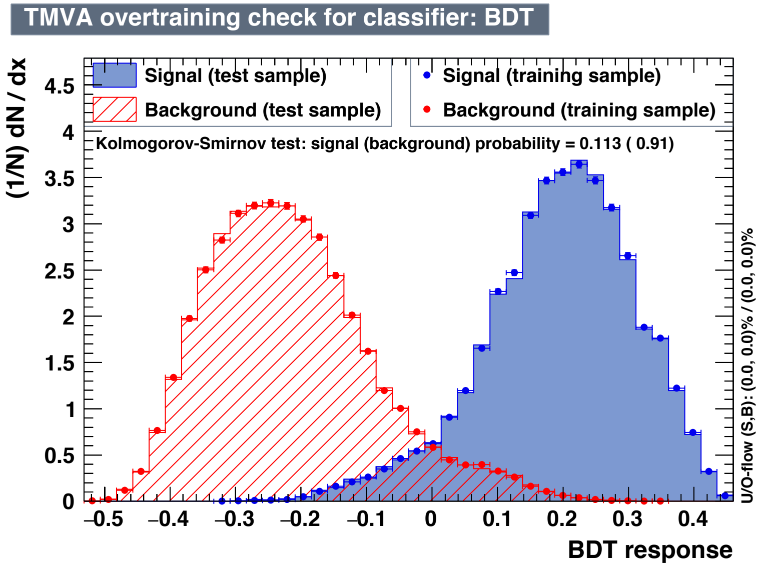
- Extra clusters and pi0 selection
  - See presentation at the tools session this morning: MVA classifiers trained for the extra clusters and pi0s
  - The selection used in the analysis presented before performs much worse with the increased level of background of the last MC campaigns (MC8 and MC9)

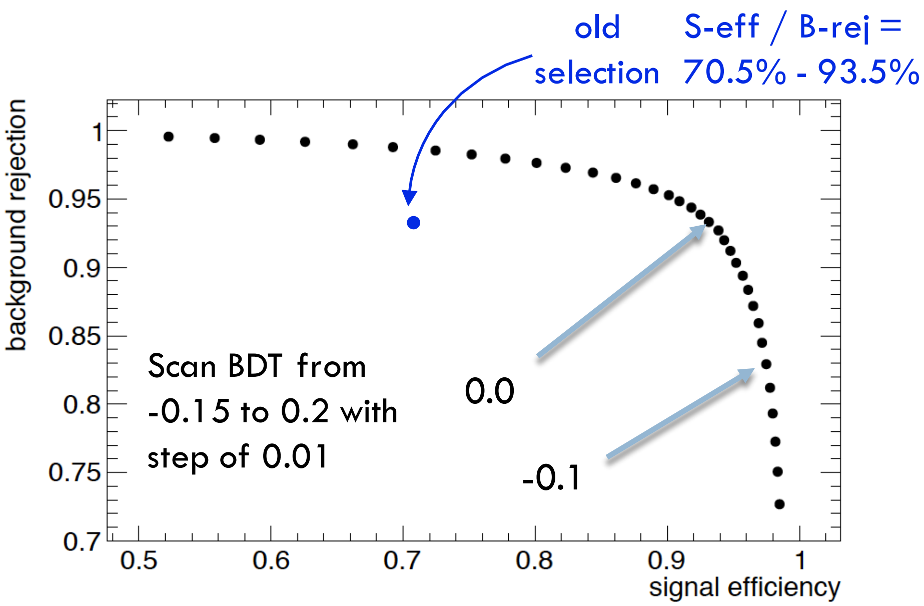
E_{extra} in $B \rightarrow \tau\nu$ events with the old selection





Extra clusters MVA





- Consider cluster variables: energy, timing and cluster shape

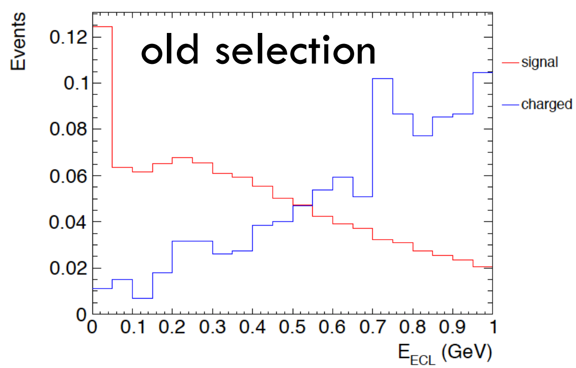
- Train a BDT with $B \rightarrow \tau\nu$ events from MC9 production bgx1 (using TMVA)

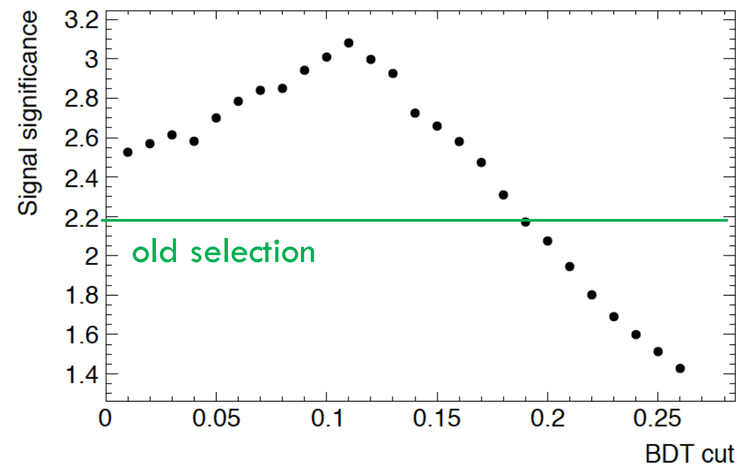
At same signal efficiency level, we have ε_{bkg}=1.5% with respect to 6.5% of old selection –> ~80% more bkg rejected

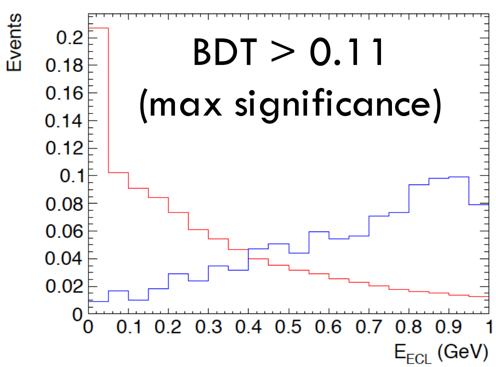
To choose the optimal cut point look at the E_{extra} distributions for $B \rightarrow \tau\nu$ and generic BB (next slide)

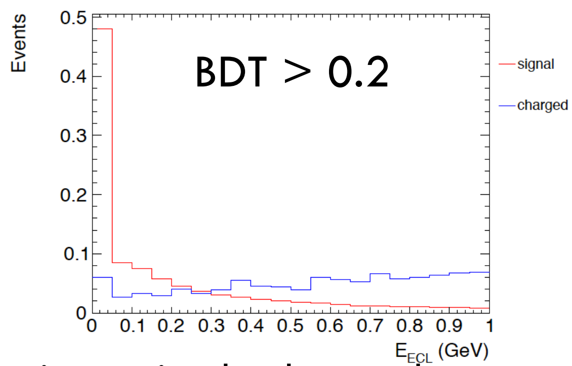
Extra clusters MVA: performance on E_{extra} distribution

- E_{extra} distribution for tau nu signal and B^+B^- background with $M_{bc} > 5.27$ GeV

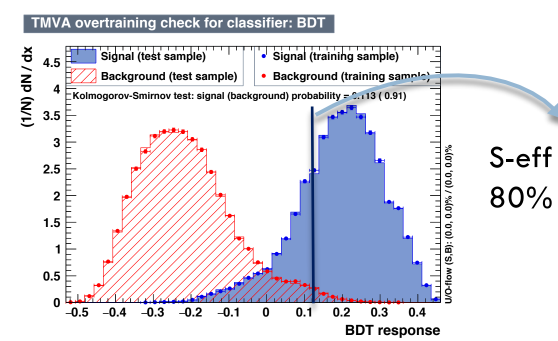








Significance evaluated as S/sqrt(S+B) in $E_{extra} < 0.2$ GeV, where S is tau nu and B is B^+B^-. Normalized to 1 ab^{-1}



S-eff / B-rej = 80% / 97.5%

Better signal shape but increasing background yield in signal region ($E_{extra} < 0.2$ GeV)

MC9 bgx1: $B \to \tau\nu$ and B^+B^-

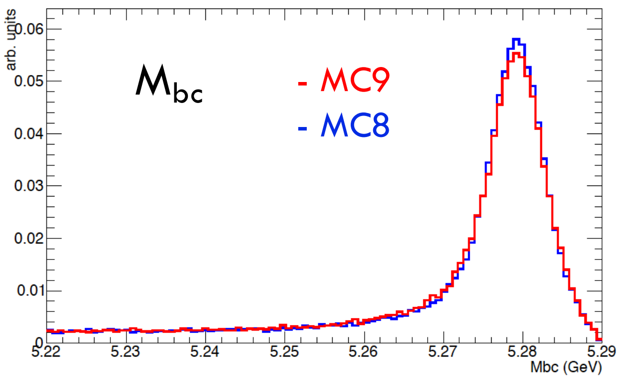
WG1 validation

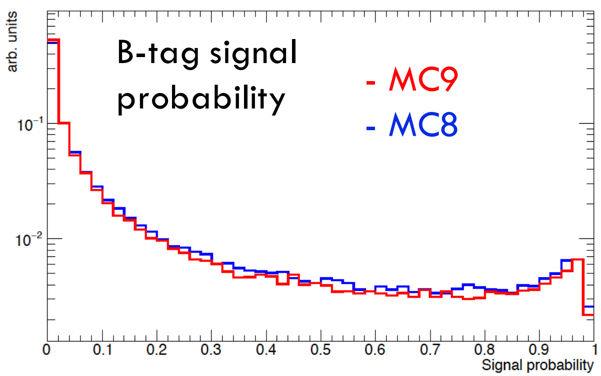
https://confluence.desy.de/display/BI/Data+Production+Validation

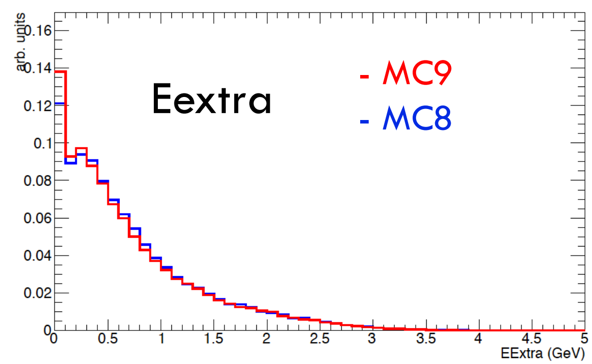
- Within the leptonic, semi-leptonic and missing energy B decays working group we have four modes for analysis validation: $B \to \tau\nu$, $B \to \pi l\nu$, $B \to D^{*}l\nu$, $B \to D^{*}\tau\nu$
- The basic idea is set up a simple analysis for each mode and check the effect of the changes from a software release to an other

$B \longrightarrow \tau\nu$

- Comparison between MC8 and MC9 (bgx1)

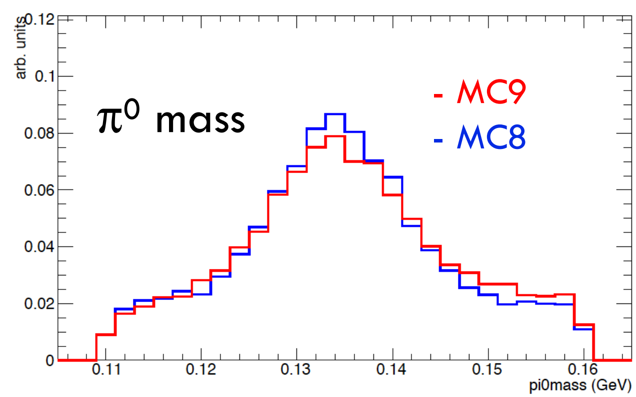






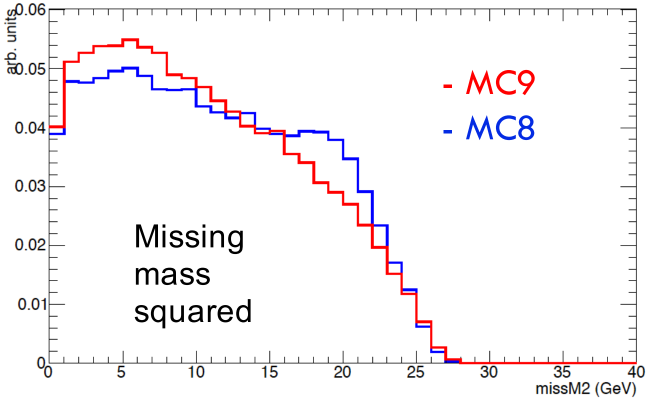
Brief summary of the reconstruction steps:

- Reconstruct the B-tag with Full Event Interpretation and pick the best candidate per event
- Require only 1 track on the signal side, PID (four τ decay channels considered: $\mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\pi\,\pi^0\nu$) and neutrals quality criteria

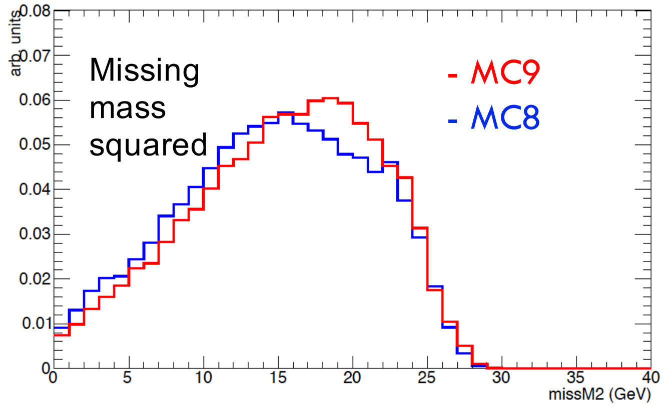


$B \longrightarrow \tau\nu$: leptonic and hadronic tau modes

hadronic modes



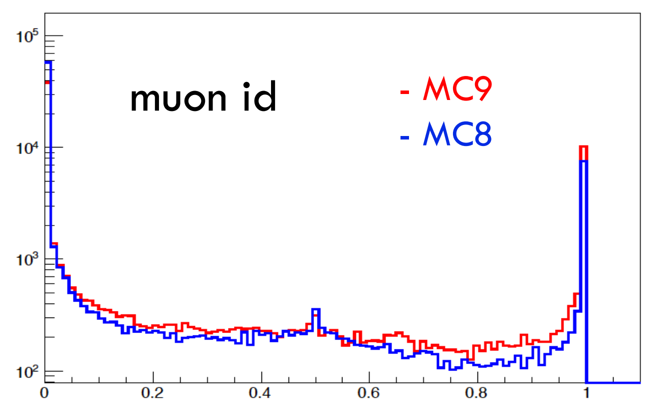
leptonic modes



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

efficiency	MC9/MC8
TOT	84%
Lep modes (mu/ele)	99% (135% / 81%)
Had modes ($\pi\nu$ / $\pi\,\pi^0\nu$)	75% (76% / 73%)

electron: eid; muon: muid and !(eid)
pion: piid and !(muid) and !(eid)



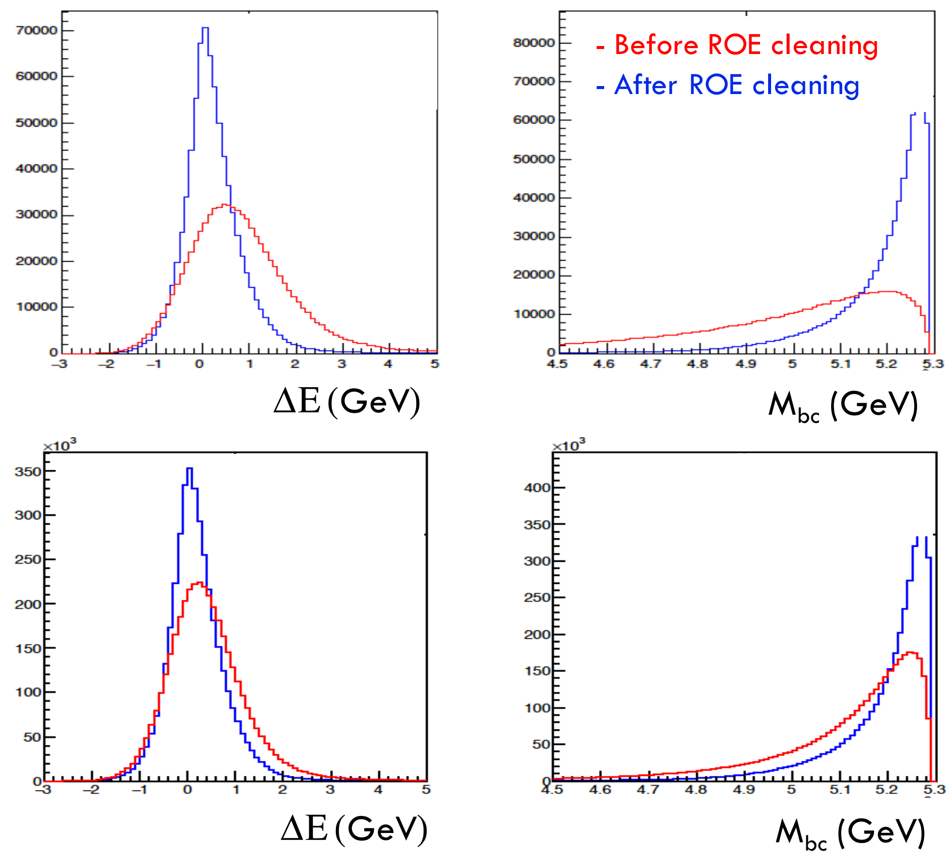
Improvement of muid in MC9

$B \longrightarrow \pi l \nu$ validation

Comparison between MC8 and MC9

MC8

MC9



- Reconstruct the signal $B \to \pi l \nu$
- Apply tracks and cluster cleaning* to the Rest of Event (ROE) of the signal

*remove tracks originating far from the IP and remove low energetic / out-of-time clusters

MC9/MC8 ~ 82%

"Before ROE" distribution looks better in MC9: from release 09 we have a new 99% efficient cut on the cluster timing at mdst level ($|t|/dt99 < 1$ for $E < 50$MeV, where dt99 is the time containing the 99% of the signal)

Summary and plans

- $B \to \tau\nu$ sensitivity study on 1 ab^{-1} of MC5 production: precision on the branching ratio measurement found to be 30% (3.4σ stat. only) with beam bkg, and 20% (>5σ stat. only) without beam bkg. Including systematic uncertainties the observation (5σ) is expected at 2.6 ab^{-1}

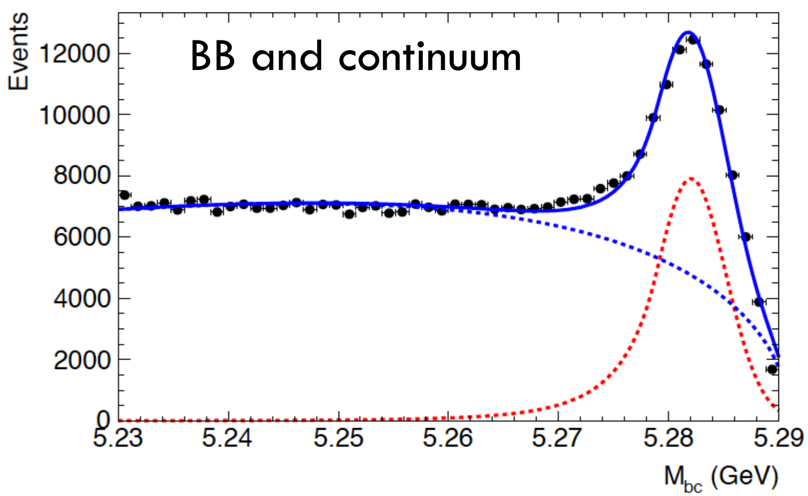
- Analysis update with last MC9 campaign
  - New MVA selection for extra clusters and π^0 - improvement of signal / BB separation in E_{extra}
  - To do list:
    - Evaluate the impact of the MVA on the branching ratio measurement (after continuum suppression and selection cuts)
    - Study the peaking background - KL veto
    - Signal extraction: 2D fit with E_{extra} and missing mass

- Validation studies comparing MC8 and MC9 show improved PID and robust reconstruction against beam background

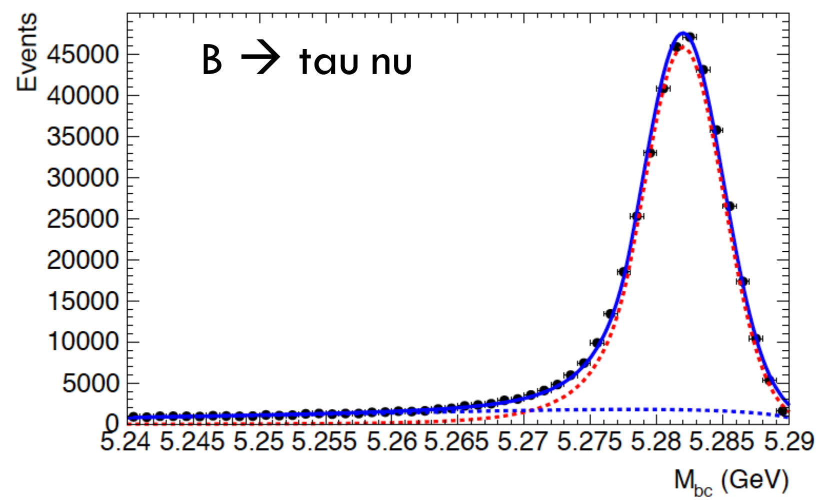
Backup

Purity after FEI reconstruction

• Purity of the background and signal samples is evaluated via fit to M_{bc} distribution with Argus (combinatorics) + double gaussian (true B candidates)



Purity ~50%



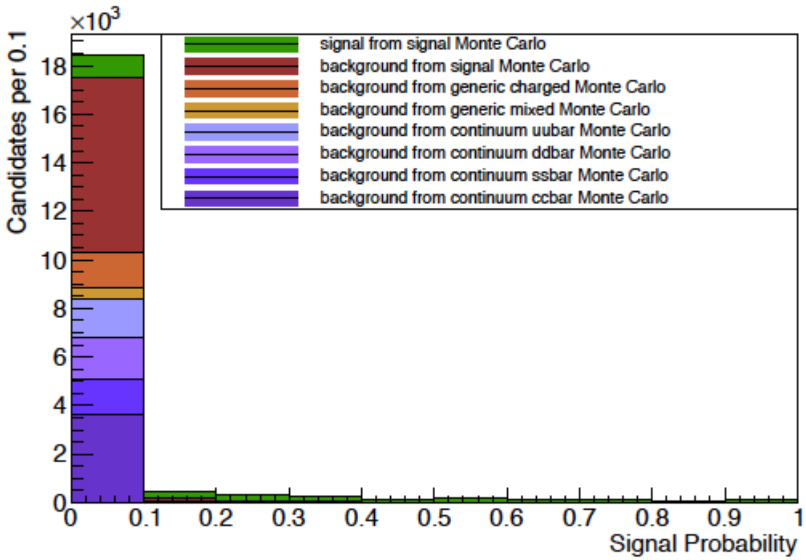
Purity ~93%

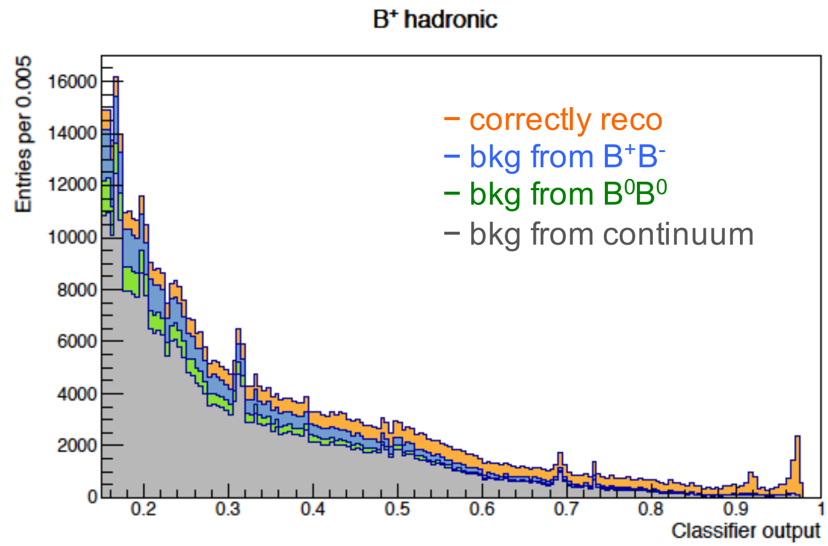
continuum rejection applied

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)

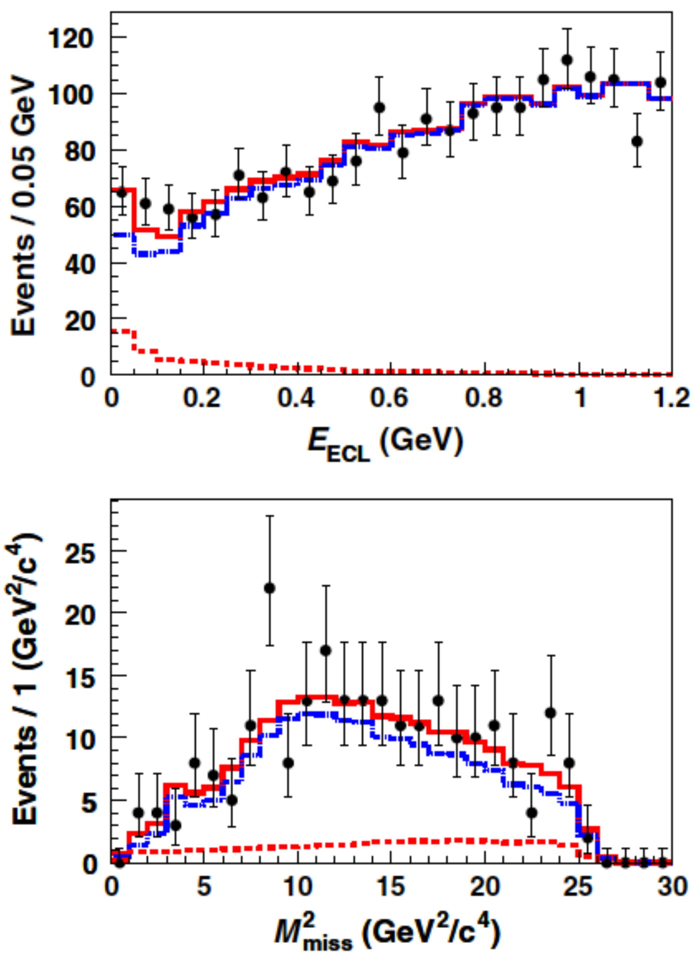
Entire Belle data sample ~ 700 fb^{-1}

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

Submode	N_{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	$0.72^{+0.27}_{-0.25}$

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$

Significance: 3.0 σ



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%

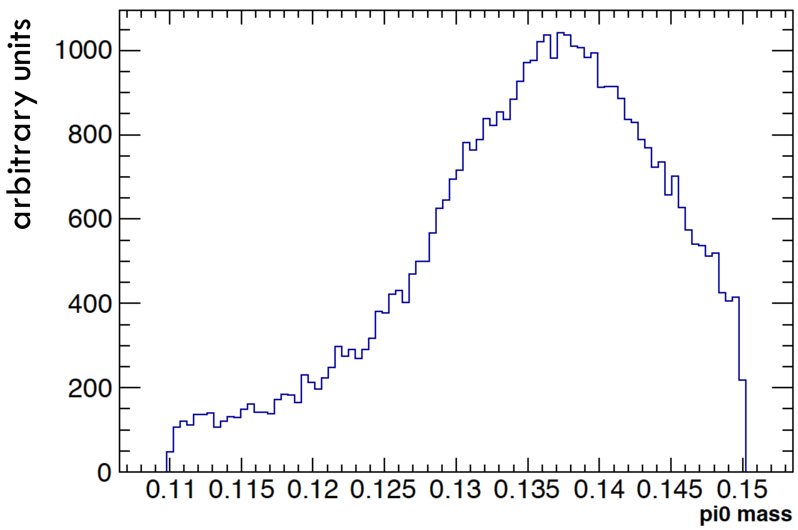
Extra photons

- 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

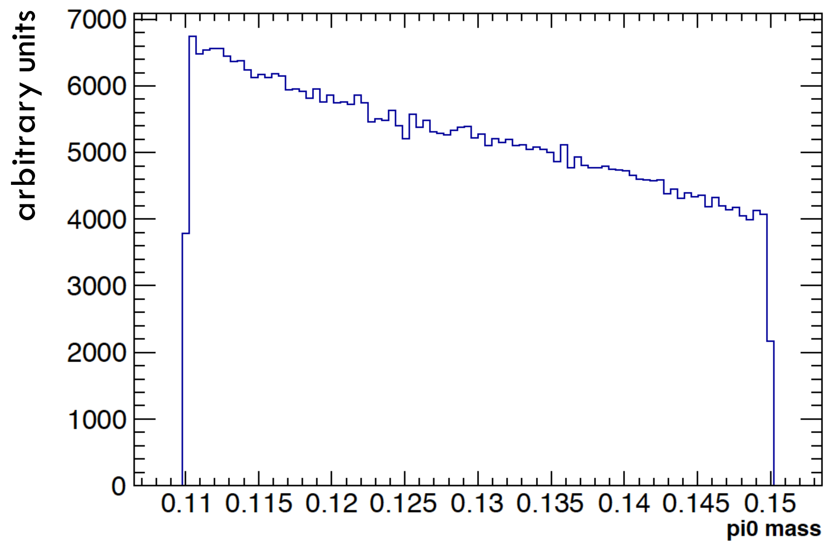
Each cut corresponds to an efficiency of photons form physics of 90%

π^0 mass

After selection



Before selection

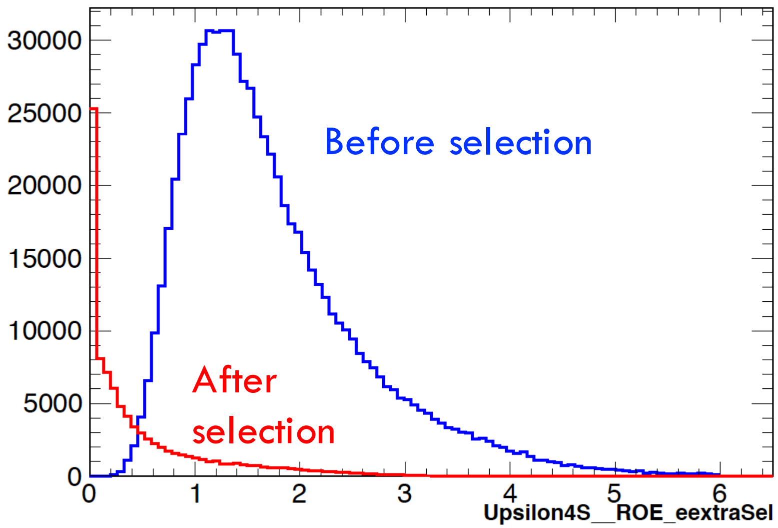


Signal $B \rightarrow \tau\nu$ sample

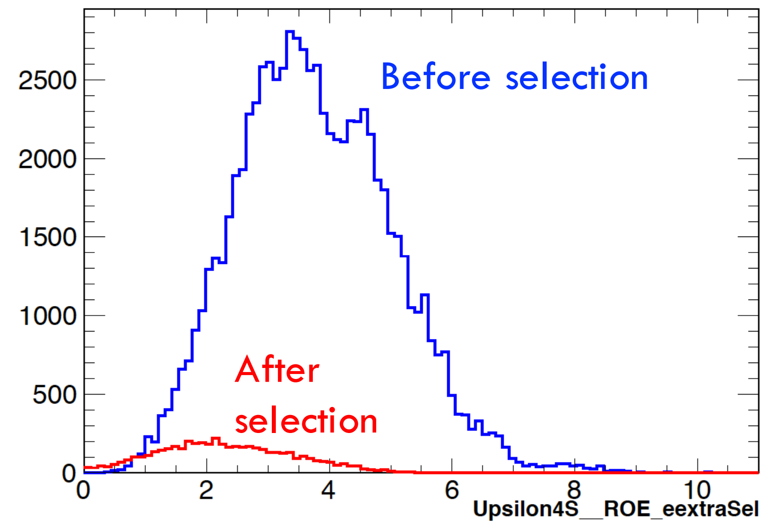
Eextra

Extra cluster cleaning selection

signal $B \to \tau\nu$



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)

Continuum rejection - BDT

- Input Variables: R2, Cosθ_{th} , Cleo Cones and Kakuno Super Fox-Wolfram (KSFW) moments: 30 variables

  - R2: $R_2 = H_2/H_0$ where $H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{W^2} P_l(\cos\vartheta_{ij})$ are the Fox-Wolfram moments
  - Cosθ_{th} : $\left|\cos(\vartheta_{thrust})\right| = \frac{|\vec{p}_B \cdot \hat{T}|}{|\vec{p}_B|}$ where T is the thrust axis of the rest of the event
  - Cleo Cones: momentum flow around the B thrust axis in 9 angular bins
  - KSFW: $KSFW = \sum_{l=0}^{4} R_l^{so} + \sum_{l=0}^{4} R_l^{oo} + \gamma \sum_{n=1}^{N_t} |(P_t)_n|$

so: particles from b-tag and ROE are considered

oo: particles from ROE only are considered

scalar sum of the transverse momentum of each particle

c: charged,
n: neutral,
m: missing

$$R_l^{so} = \frac{\alpha_{cl} H_{cl}^{so} + \alpha_{nl} H_{nl}^{so} + \alpha_{ml} H_{ml}^{so}}{E^*_{beam} - \Delta E}$$

l odd $H_{cl}^{so} = \sum_i \sum_{jx} Q_i Q_{jx} |p_{jx}| P_l(\cos\theta_{i,jx})$

l even $H_{xl}^{so} = \sum_i \sum_{jx} |p_{jx}| P_l(\cos\theta_{i,jx})$

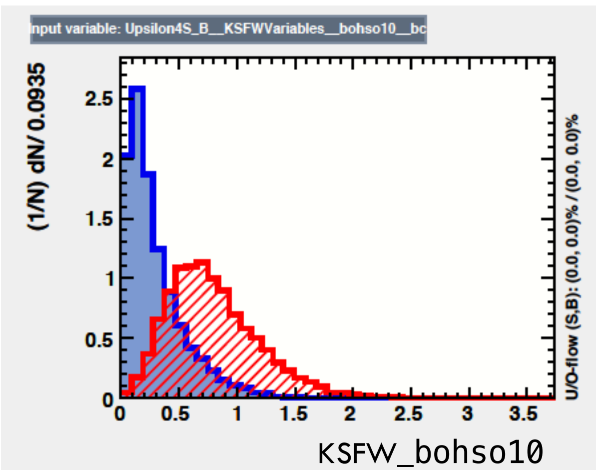
l odd $R_l^{oo} = \sum_j \sum_k \beta_l Q_j Q_k |p_j||p_k| P_l(\cos\theta_{j,k})$

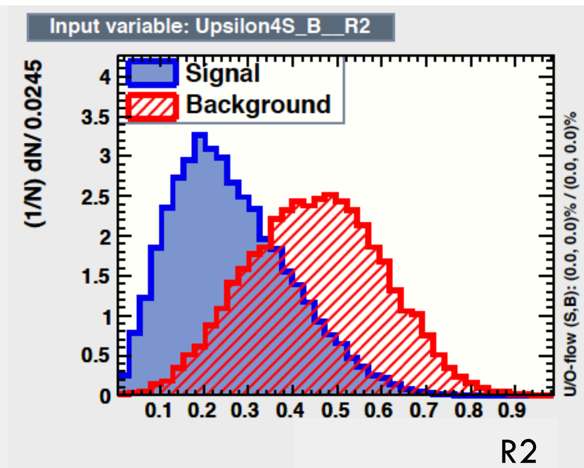
l even $R_l^{oo} = \sum_j \sum_k \beta_l |p_j||p_k| P_l(\cos\theta_{j,k})$

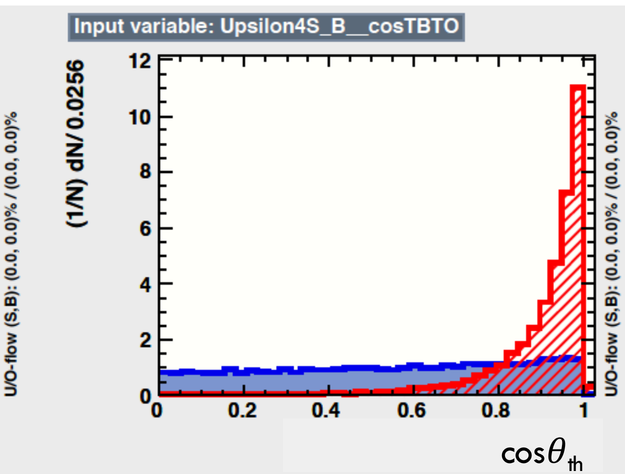
Continuum rejection - BDT

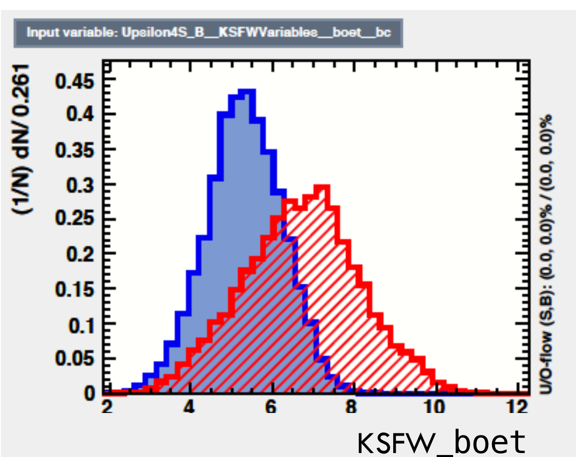
- BDT training
  - Preselection cuts on M_{bc} (5.27-5.29 GeV/c^2) and E_{extra} (< 0.3 GeV)
  - 20000/3000 events used for signal/background training (~3/10% of the entire samples)
  - Remove the "less powerful" (according to the BDT variable ranking) and highly correlated variables → 20 variables left with a negligible degradation of the BDT performances (i.e. ROC curve integral)

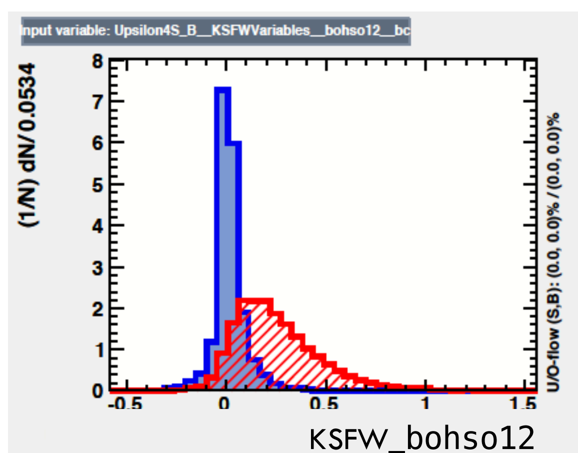
Highest ranked variables







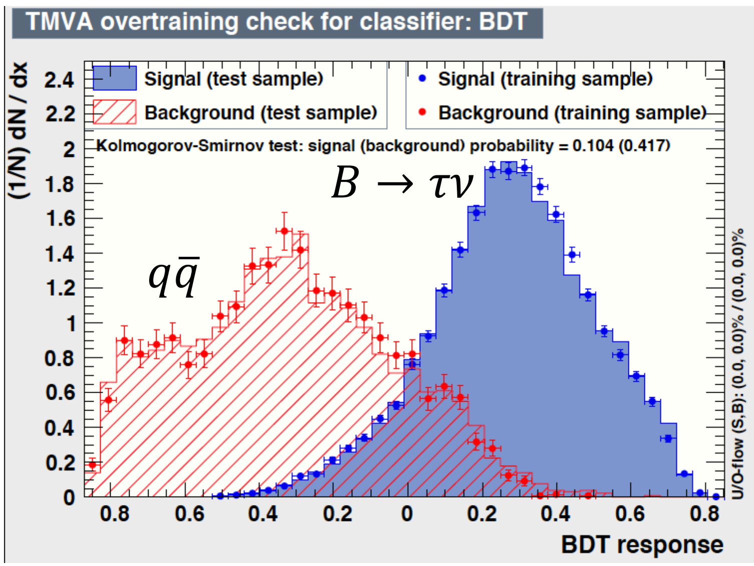


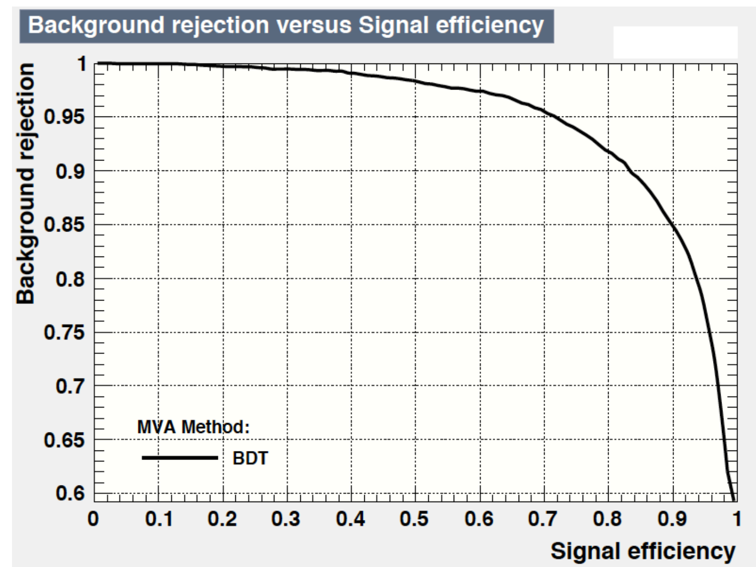


Signal: $B \to \tau\nu$

Background: $q\bar{q}$

Training results





Overtraining under control
Limited statistics for the backgrounds

ROC curve

- Good separation power

B → tau nu projections

Hadronic tag

Integrated Luminosity (ab^{-1})	1	5	50
statistical uncertainty (%)	29.2	13.0	4.1
systematic uncertainty (%)	12.6	6.8	4.6
total uncertainty (%)	31.6	14.7	6.2

Semileptonic tag

Integrated Luminosity (ab^{-1})	1	5	50
statistical uncertainty (%)	19.0	8.5	2.7
systematic uncertainty (%)	17.9	8.7	4.5
total uncertainty (%)	26.1	12.2	5.3