Belle II prospect: Leptonic decays and Tagging algorithms

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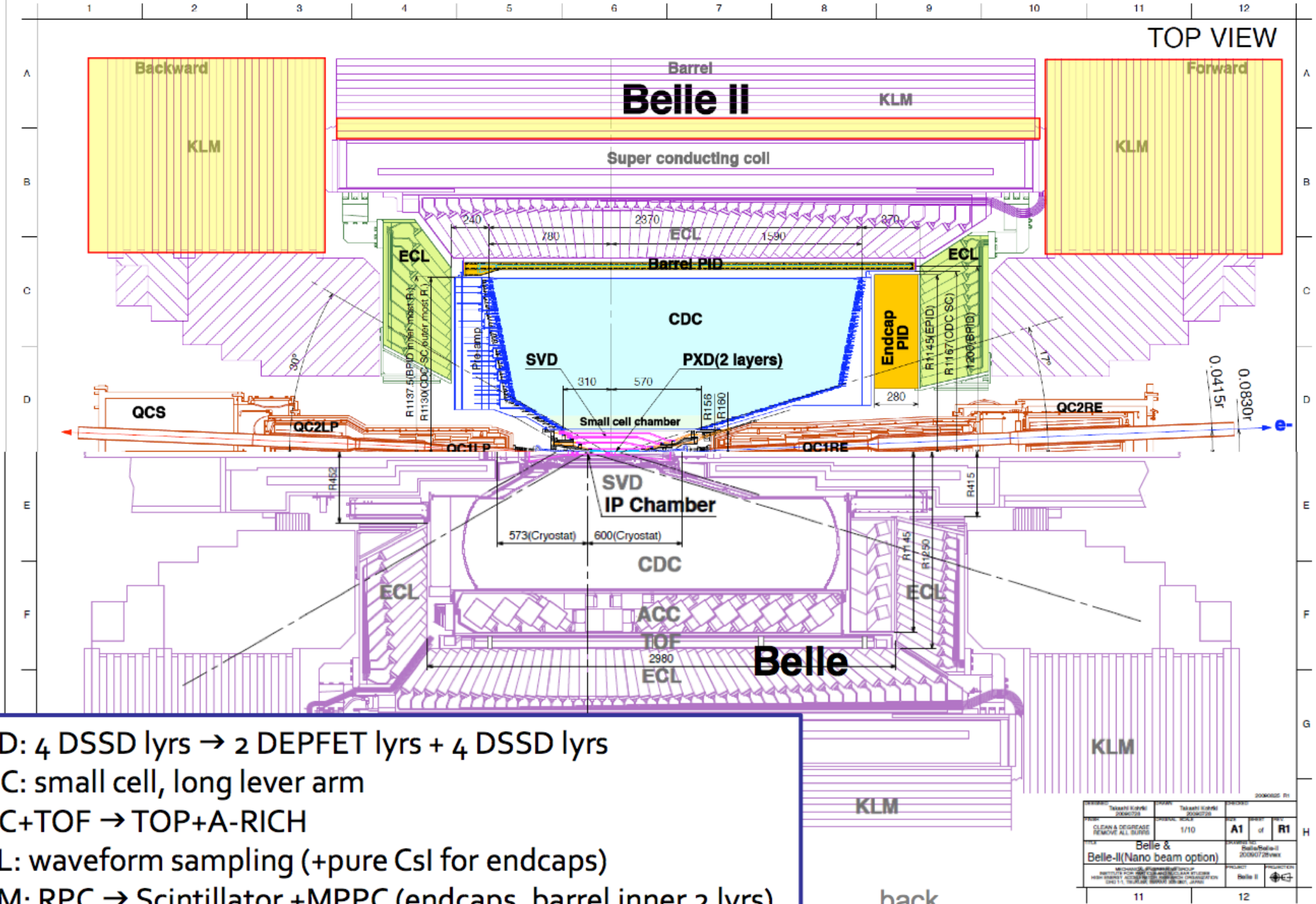
Mini-workshop on B → D* τ ν decays and related topics
Nagoya, Japan, 27-28 March 2017

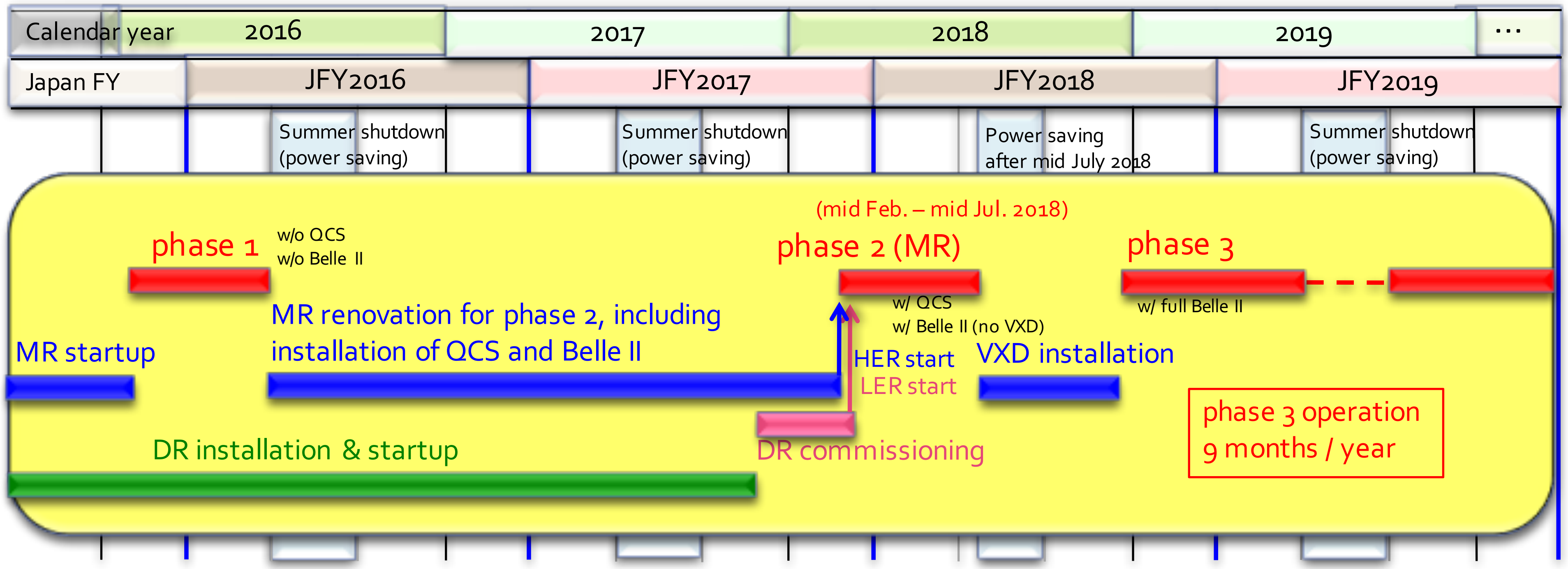
Belle II experiment



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

back

Belle II timeline



Belle II unique capabilities

Exactly 2 quantum correlated B mesons at Y(4S)

No trigger bias – almost 100% for B pairs

Excellent efficiency and resolution in tracking as well as in detecting photons, K_L, π^0
→reconstruction of intermediate resonances
→Dalitz plot studies

Clean environment (compared to hadron machines) allows "full interpretation" of the event
→ powerful tool for physics with missing energy (many neutrinos) or fully inclusive analyses

Large sample of B, D, and τ with low background

Physics deliverables

Improved precision on CKM elements and UT angles

Measurement for CP violation phases:

Inclusive measurements $b \to s/d\,\gamma$ $b \to s\,l\,l$

Missing energy modes
$B \to l\,\nu$ $B \to K\,\nu\,\nu$, $B \to X_{u,c}\,l\,\nu$

LFV in $\tau \to l\,\gamma$, $l\,l\,l$

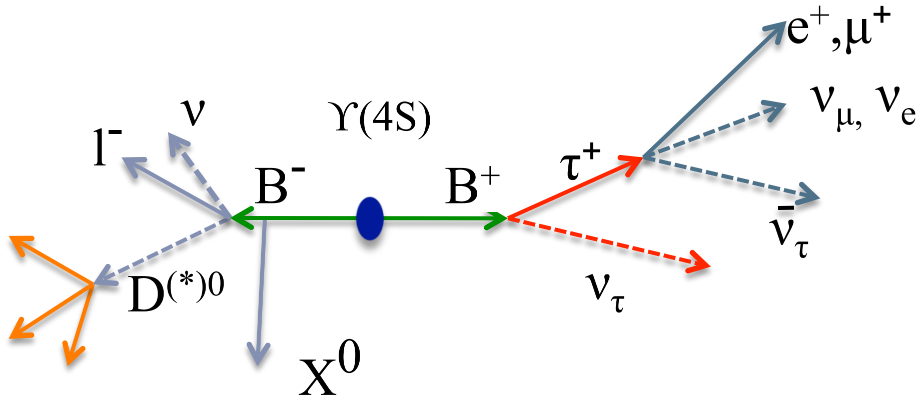
Dark matter, spectroscopy, Hidden sector

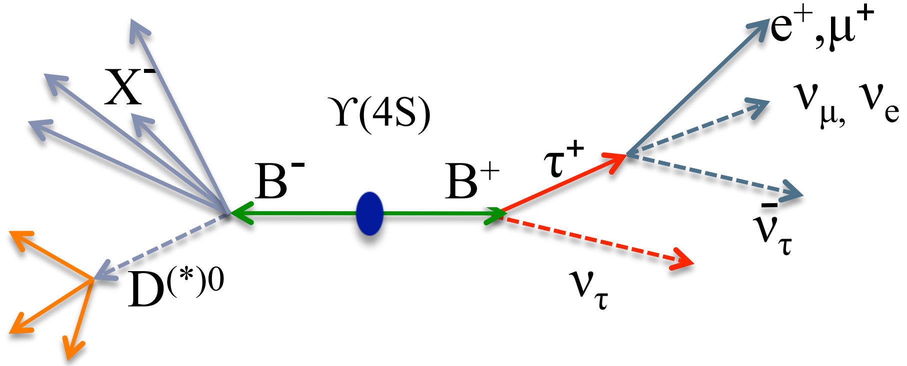
Full event interpretation (tagged analyses)

- For signal with weak exp. signature like
  - Decay with missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- background rejection improved fully reconstructing the companion B (tag)

- Tag with semileptonic decays
  - PRO: Higher efficiency ε_{tag} ~ 1.5%
    CON: more backgrounds, B momentum unmeasured
- Tag with hadronic decays
  - PRO: much cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} ~ 0.2%

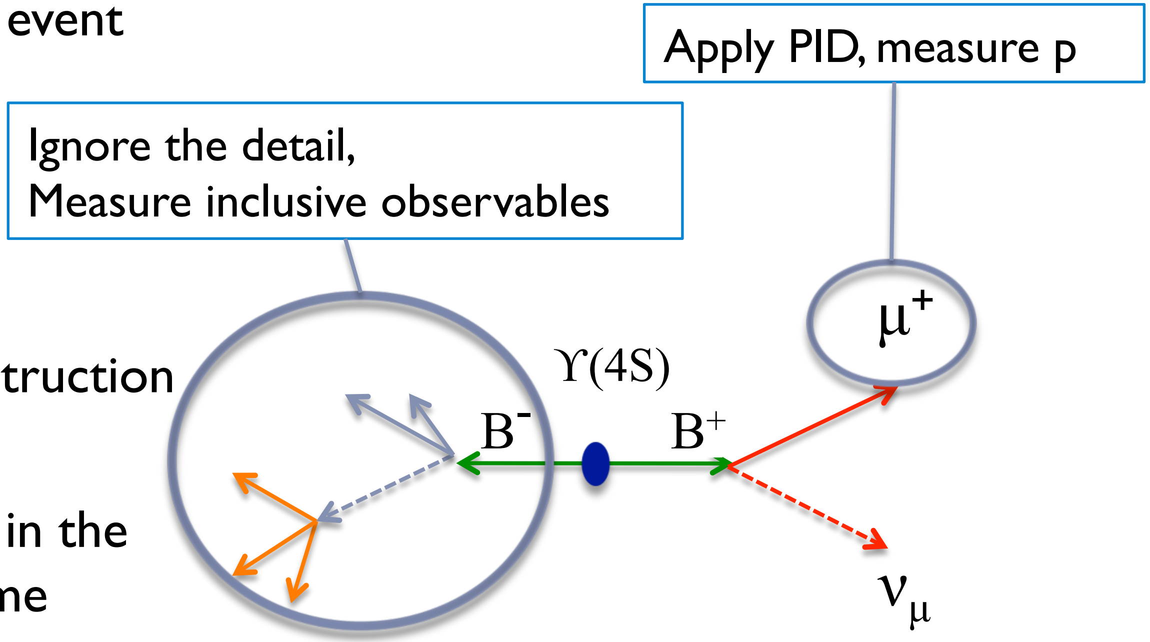
Fully reco **Look for signal**





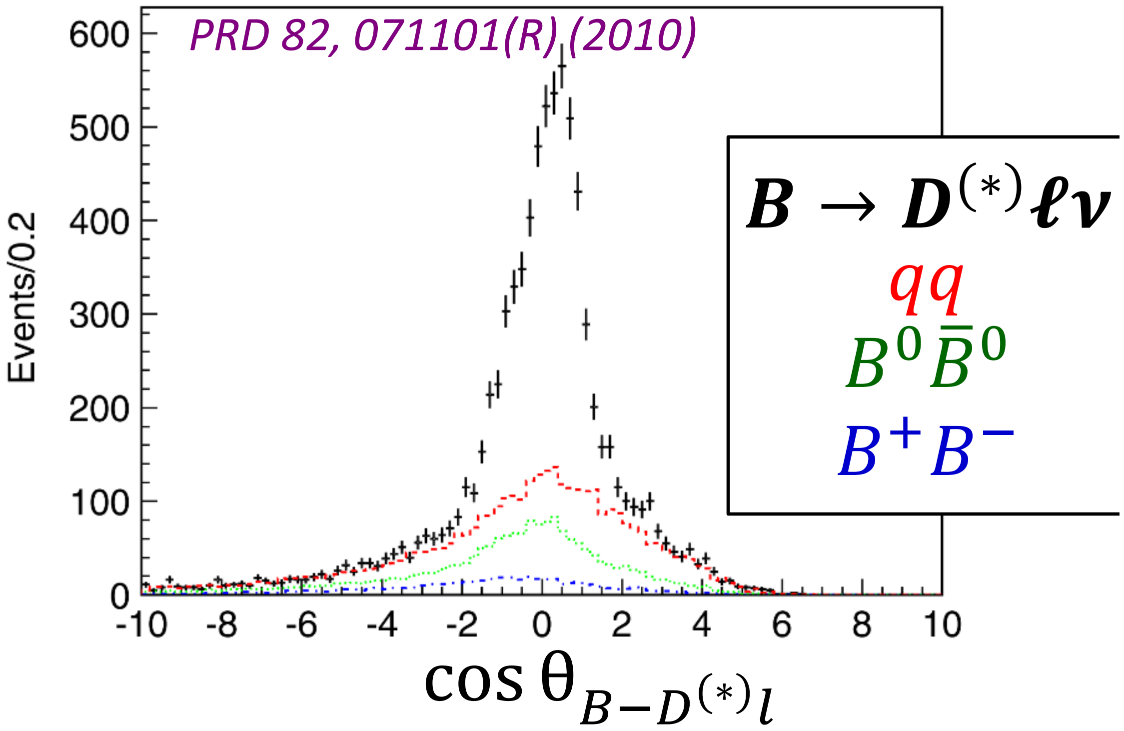
Untagged analyses may still be competitive

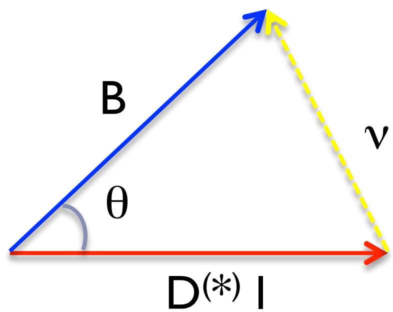
- Inclusive on the rest of the event when the signal signature strong enough
- B → π l ν
  - Loose neutrino reconstruction
- B → μ ν
  - Monochromatic muon in the final state in B rest frame
    - Smeared in the CM frame



High efficiency but large backgrounds, too

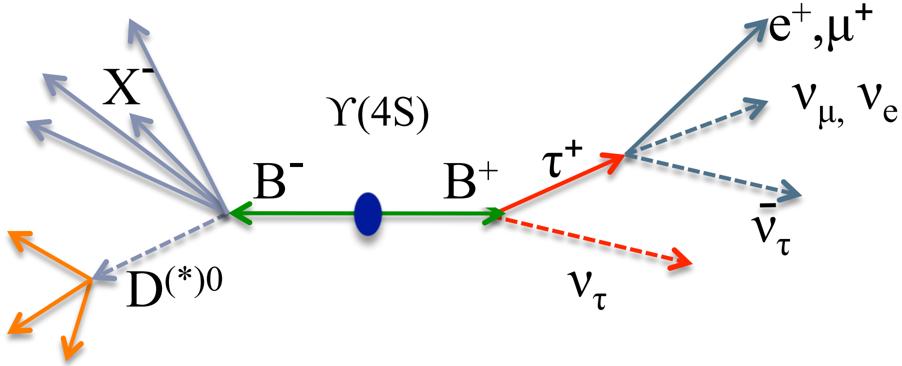
Tag with B semileptonic decays





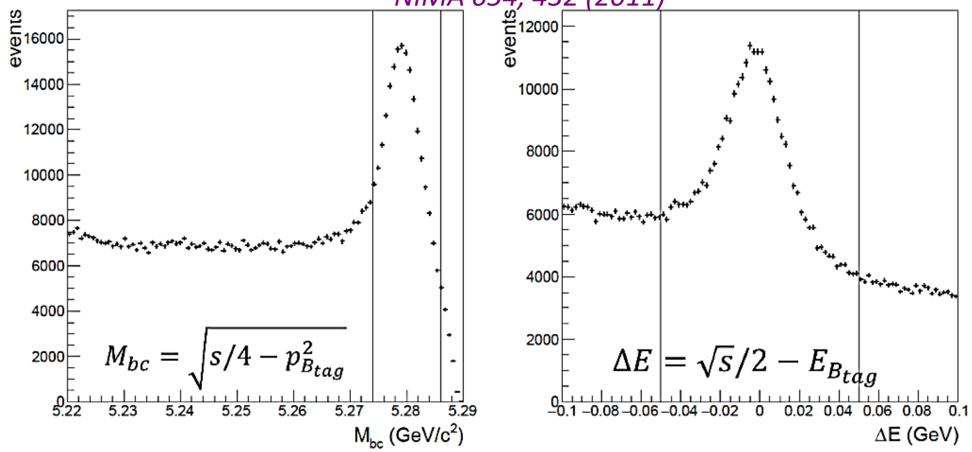
$$\cos\theta_{B-D^{(*)}l} = \frac{2E_{beam}E_{D^{(*)}l} - m_B^2 - m_{D^{(*)}l}^2}{2\,p_B\,p_{D^{(*)}l}}$$

Tag with hadronic decays



$\boldsymbol{M_{bc}} = \sqrt{E_{\text{beam}}^2 - \vec{p}_{B_{\text{tag}}}^{\,2}}$ $\boldsymbol{\Delta E} = E_{\text{beam}} - E_{B_{\text{tag}}}$

NIMA 654, 432 (2011)



Babar and Belle reconstruct as many as possible decay modes of the D and combinations making up X

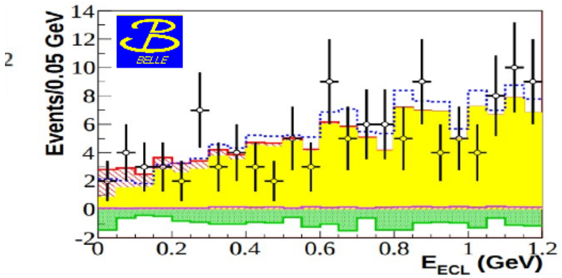
Many combinations per event.

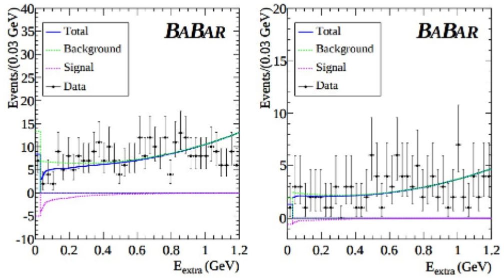
BaBar determine the purity on data to rank the decay modes

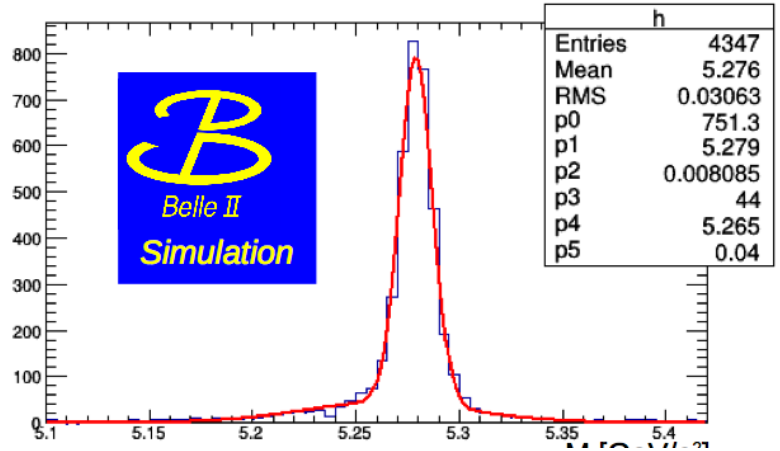
Belle use a multilevel MVA tool Neurobayes to determine the quality of the tag

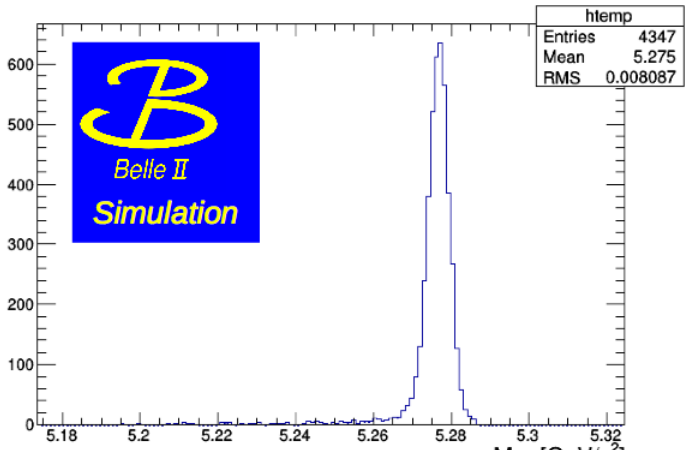
Missing energy modes: even invisible

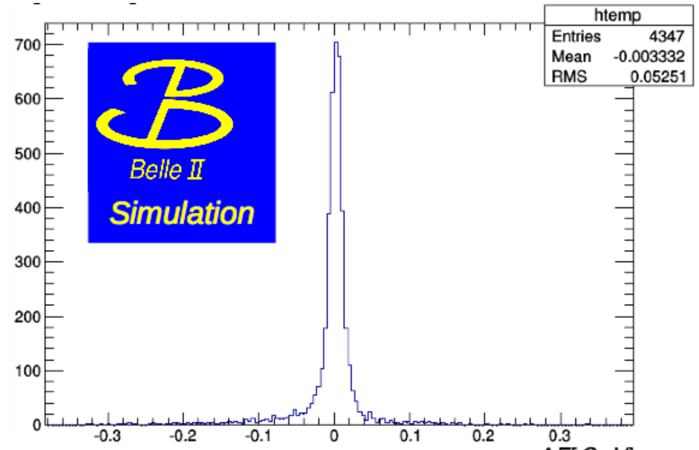
Invisible
or
B → ν ν











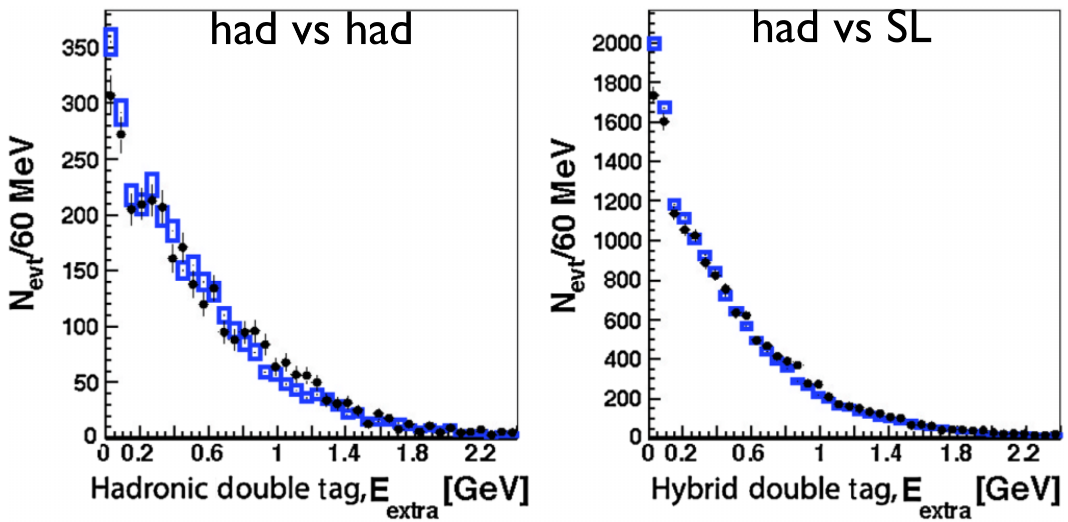
Fully reconstructed events (double tags)

To correct MC mis-modeling:

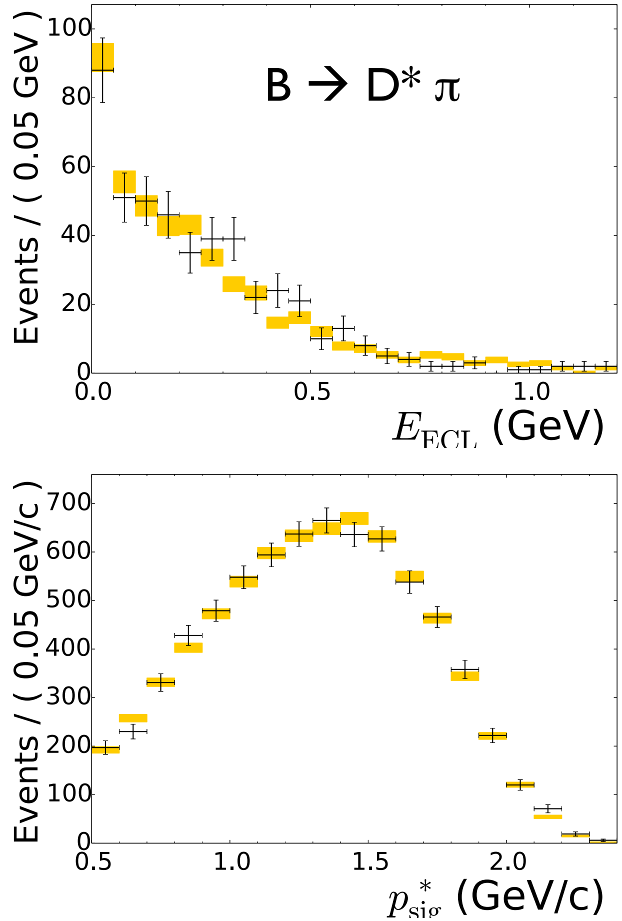
- Signal shape (cal. extra energy)
- Reconstruction efficiency

Use double hadronic or hadronic-semileptonic tags or a clean subset of them

B → τ ν with hadronic tags (BaBar)



B → τ ν with SL tags (Belle)
PRD 92 051102



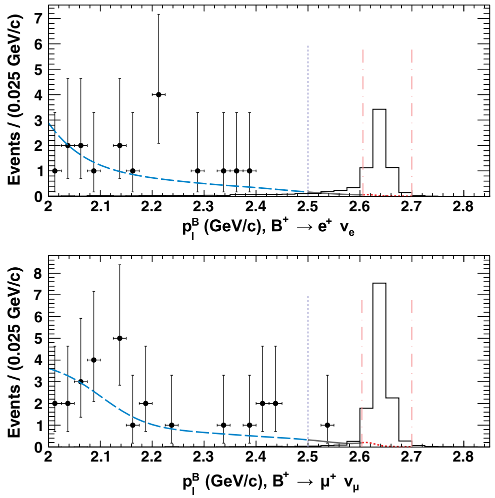
Fully reconstructed events (double tags)

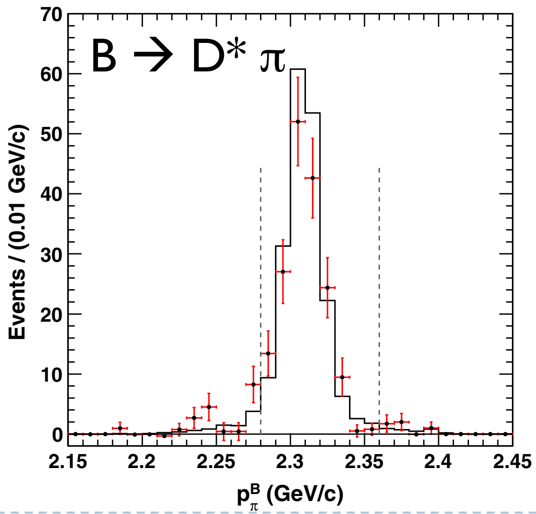
To correct MC mis-modeling:

- Signal shape (lepton momentum)
- Reconstruction efficiency

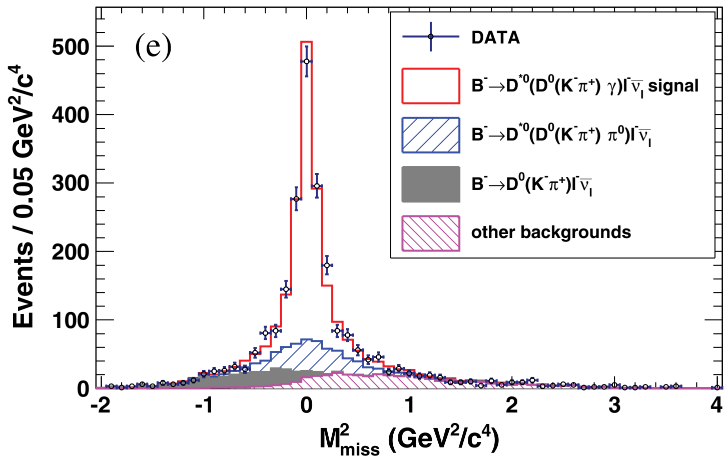
Use double hadronic or hadronic-semileptonic tags or a clean subset of them

Belle B → e ν, μ ν search - PRD 91 052016 (2015)





B → D* l ν

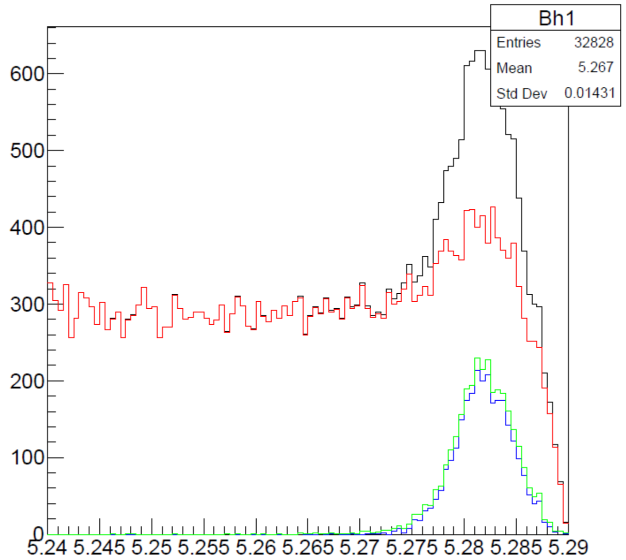


MC Truth matching with tagged B

Must be careful on how to use
MC to count the yield of correctly reconstructed B.

Most of Belle analyses relies more on MC background simulation but
use data control samples to correct it

BaBar usually removes "combinatorial" and continuum under the peak fitting data and MC consistently. CS are used to correct efficiencies as well



$$B^+ \longrightarrow \overline{D}^{*0} \pi^+$$
$$\hookrightarrow \overline{D}^0 \pi^0$$
$$\hookrightarrow \gamma\, \gamma$$

From the same mother B meson.

From another source, such as other B decay or beam background.

Tag related systematics

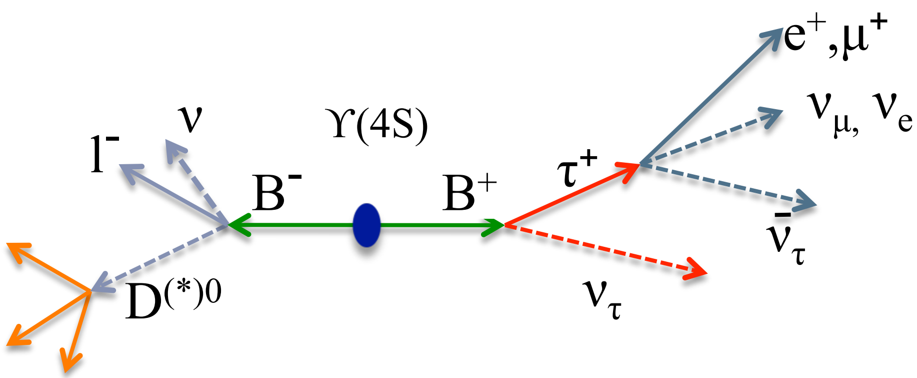
Systematic uncertainty on the signal reconstruction efficiency due to the MC mismodeling of tag B reconstruction

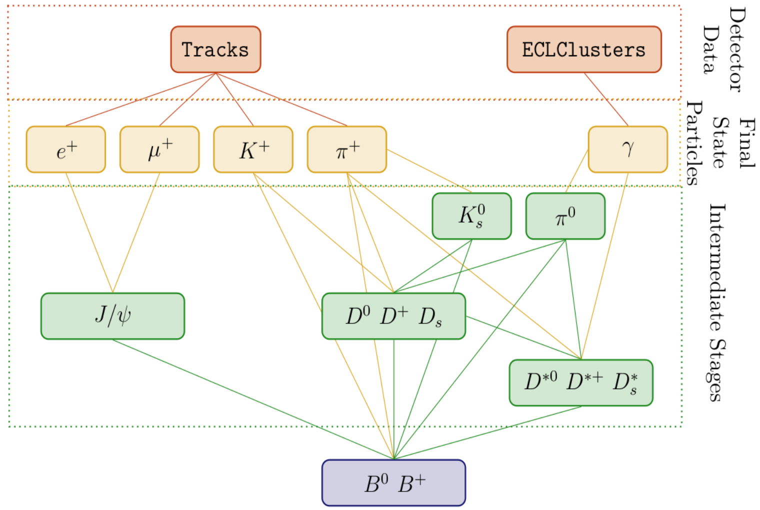
$B \rightarrow \tau\nu$ analysis	Tag syst.
BABAR Had	5%
BABAR SL	4%
Belle Had	7%
Belle SL	13%

Specific procedure details are different among the analyses but all use a sample of fully reconstructed events (with same B tag as the signal mode)

The systematic uncertainty is mostly due to the statistics of the sample
We expect this uncertainty to scale down with luminosity for Belle II $\rightarrow$ 2%
… to be proved!

Belle II : Full event Interpretation





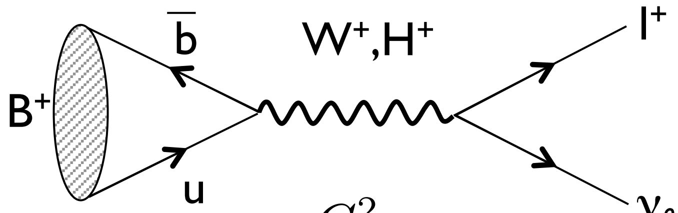
- Input variables used to train the multivariate classifiers:
  - PID, tracks momenta, impact parameters (charged FS particles);
  - cluster info, energy and direction (photons);
  - invariant mass, angle between photons, energy and direction (π^0);
  - released energy, invariant mass, daughter momenta 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.

$B \to l\,\nu$

Very clean theoretically, hard experimentally

SM contribution helicity suppressed

Sensitive to NP contribution (charged Higgs)

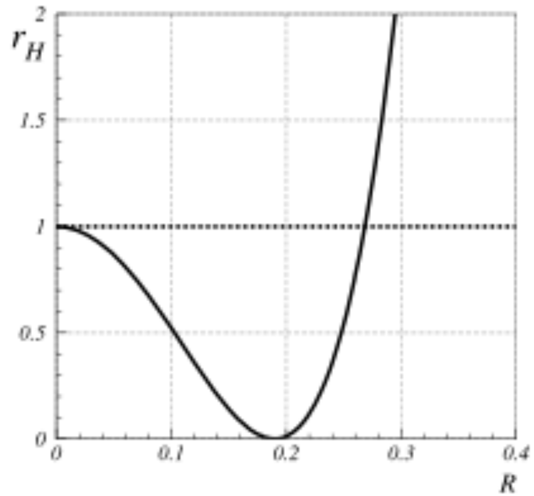


$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B \to l\nu) = \mathcal{B}(B \to l\nu)_{SM} \times r_H$$

$$r_H = (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$

in 2HDM type II



STANDARD MODEL PREDICTIONS

Mode	$\mathcal{B}(B^+ \to \ell^+ \nu_\ell)$	
$\tau\nu_\tau$	$(1.01 \pm 0.29) \times 10^{-4}$	*Accessible with current data sets*
$\mu\nu_\mu$	$\sim 0.45 \times 10^{-6}$	*Need Belle II statistics*
$e\nu_e$	$\sim 0.8 \times 10^{-11}$	*Beyond the reach of experiments*

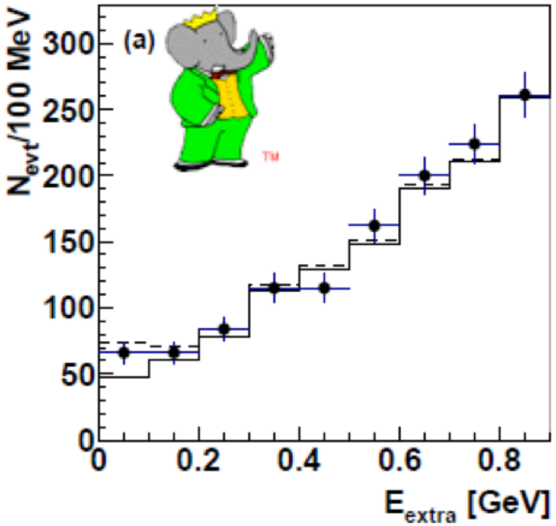
Belle II can also test lepton flavour universality

$$R^{\tau e} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}$$

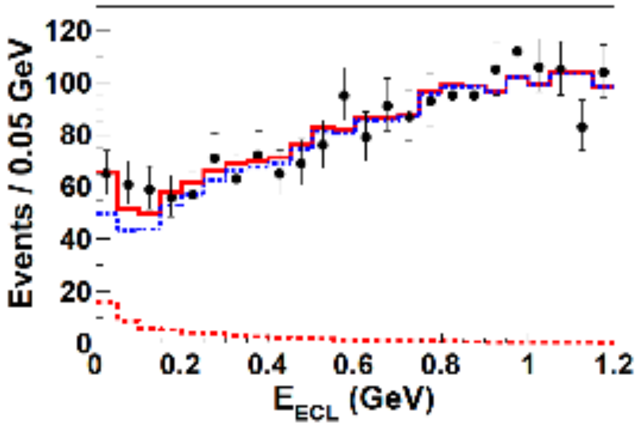
$$R^{\tau\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}$$

Belle and BaBar measurements

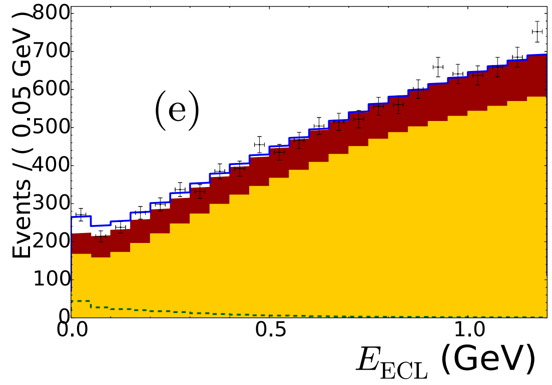
BaBar Hadronic tag
PRD 88 031102



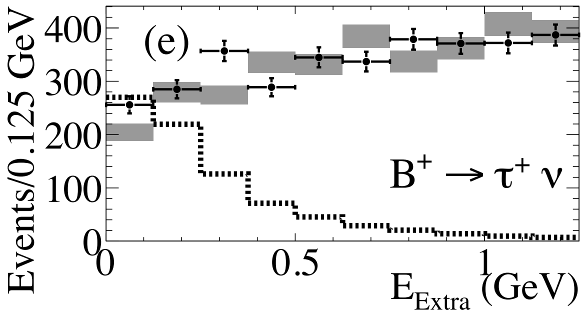
Belle Hadronic tag
PRL 110 131801



Belle SL tag
PRD 92 051102



BaBar SL tag
PRD 81 051101



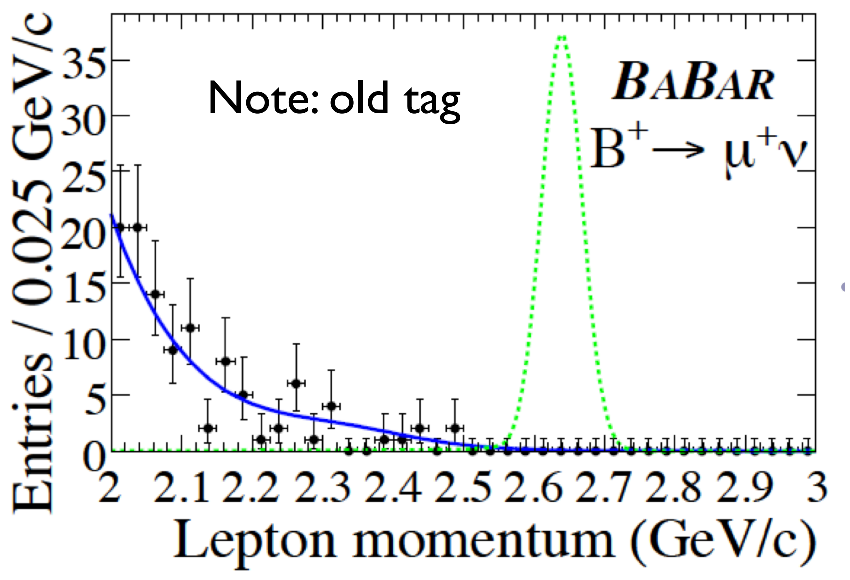
Analysis	Measurement (10^{-4})
BABAR Had	1.8 ± 0.5 ± 0.2
BABAR SL	1.7 ± 0.8 ± 0.2
Belle Had	0.7 ± 0.3 ± 0.1
Belle SL	1.25 ± 0.28 ± 0.27

B → μ ν and B → e ν

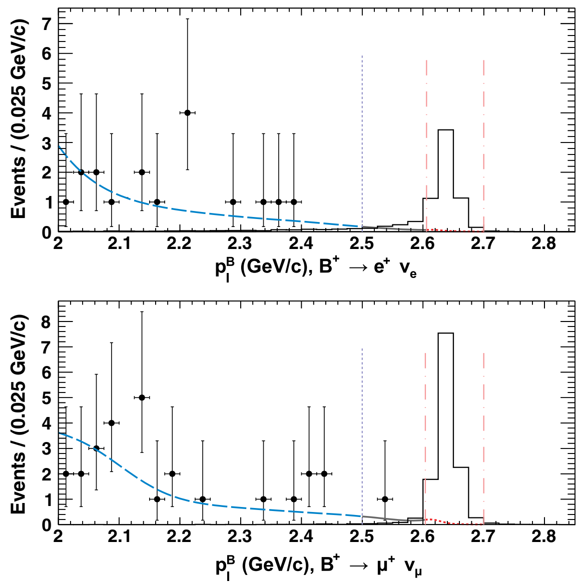
Monochromatic lepton in the B rest frame

Almost background free with tagged analyses

Hadronic tag BaBar



Hadronic tag Belle



But best upper limits measured with untagged method

BF (B → μ ν) < 1.0 x 10-6 BABAR PRD 79 011101 (2009)

BF (B → e ν) < 0.98 x 10-6 BELLE PLB 647 (2007) 67

$B \rightarrow \tau \nu$ study with Belle II simulation

B tag side

Full event interpretation
trained trained on generic BB

1) Pre-selection on B-tag kinematics
2) Select the candidate with highest FEI output discriminant
3) FEI not trained against continuum: additional BDT based on event shape variables

B sig side

- Only one track not overlapping with tag
- PID and neutral objects reconstruction developed for Belle II
- Specific ECL cluster selection for $\pi 0$ and extra cluster reconstruction (more severe beam background in Belle II)
- Loose requirement on $M(\pi^0)$ and $M(\rho)$

1 ab^{-1} Belle II Full simulation with nominal beam background overlaid

Event shape variables in the 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

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

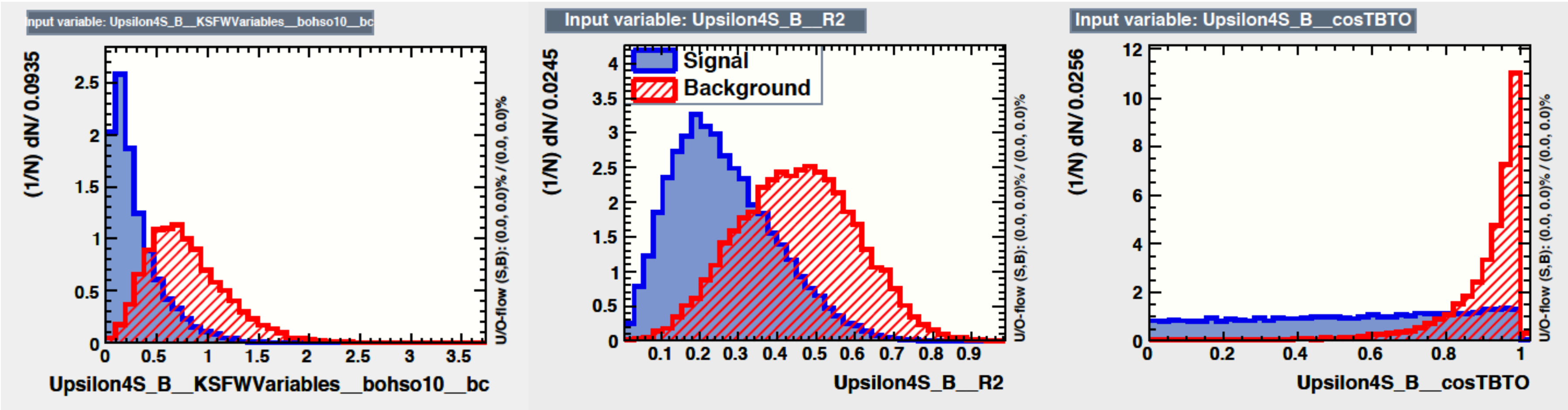
l odd $\quad H_{cl}^{so} = \sum_i \sum_{jx} Q_i Q_{jx} |p_{jx}| P_l(\cos\theta_{i,jx})$

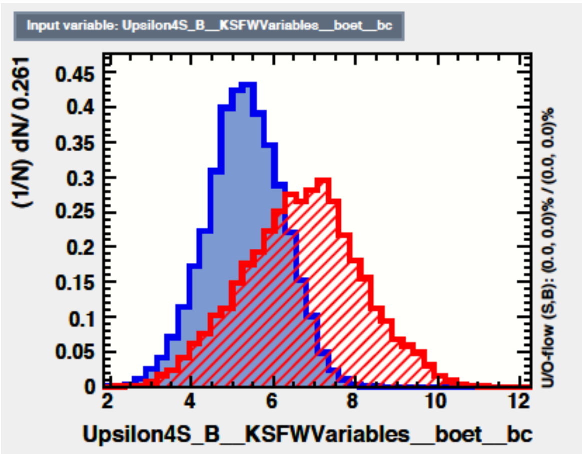
l even $\quad H_{xl}^{so} = \sum_i \sum_{jx} |p_{jx}| P_l(\cos\theta_{i,jx})$

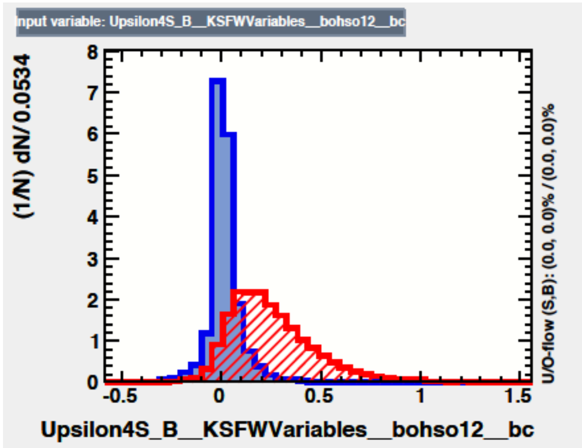
l odd $\quad R_l^{oo} = \sum_j \sum_k \beta_l Q_j Q_k |p_j||p_k| P_l(\cos\theta_{j,k})$

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

Continuum rejection



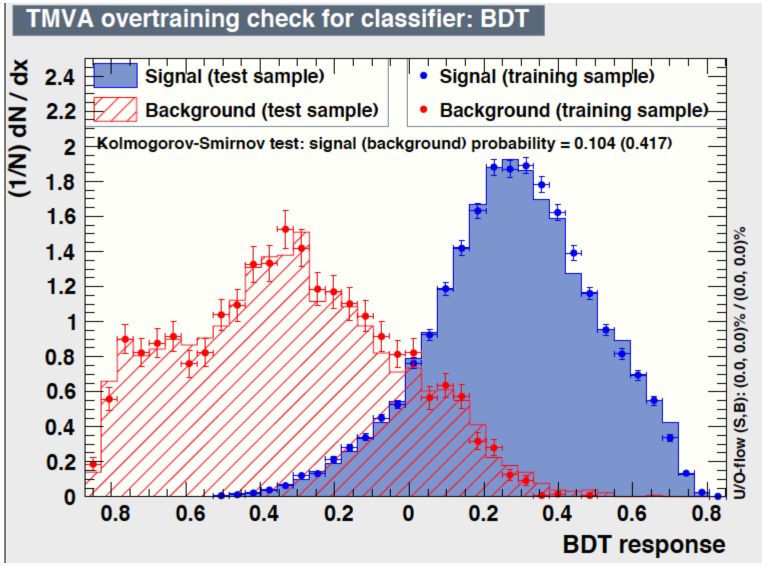


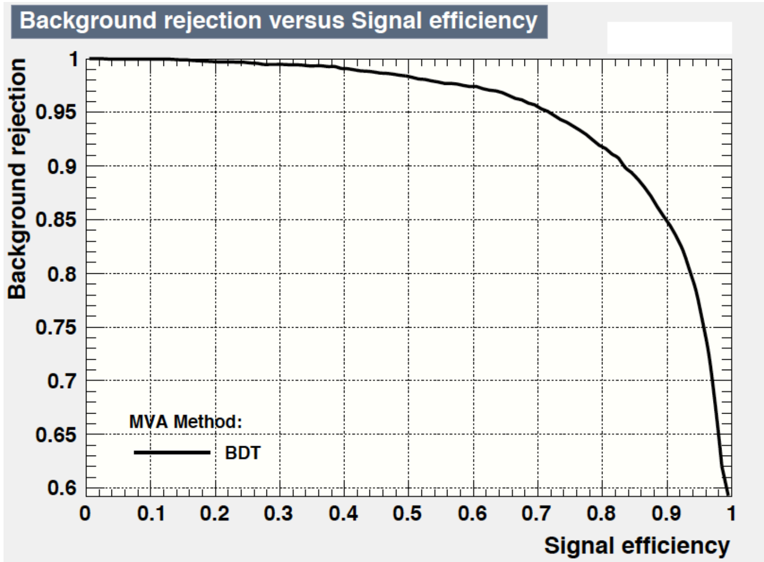


Signal: $B \to \tau\nu$

Background: qq

Continuum rejection

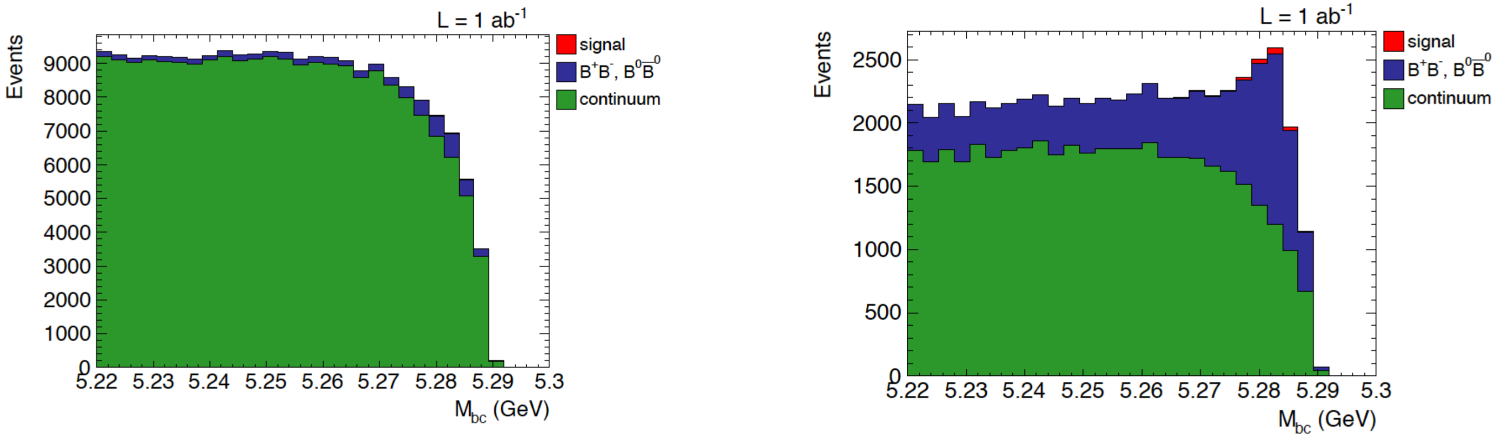




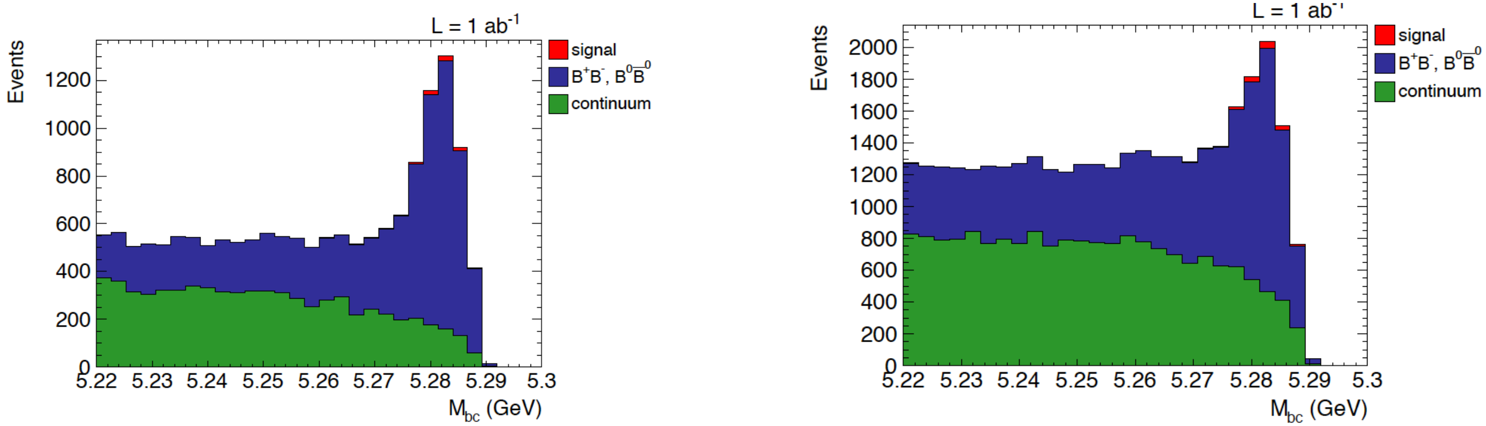
Overtraining under control
Limited statistics for the backgrounds

FEI: Tag B + 1 prong

Before
BDT cuts

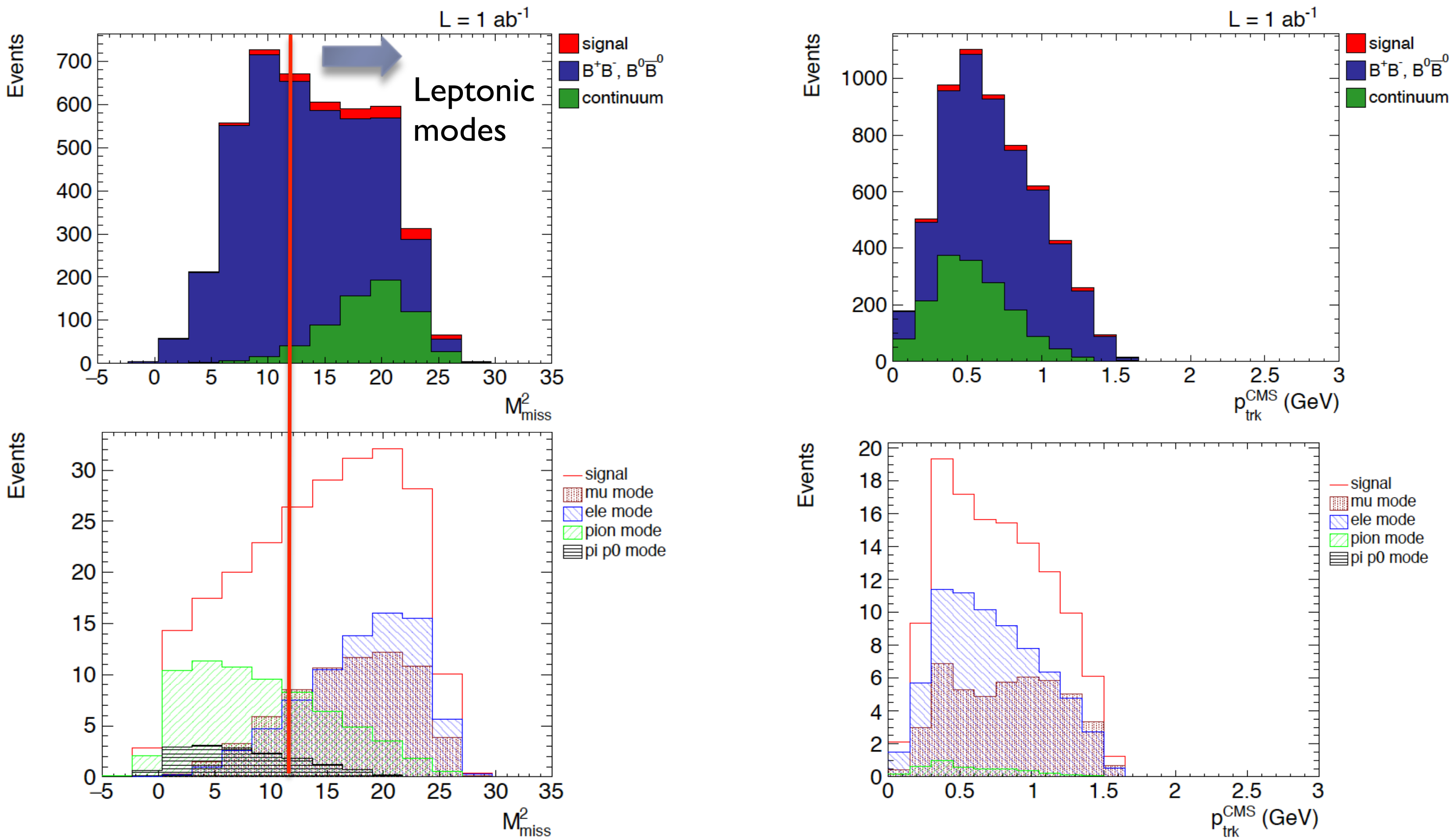


After
BDT cuts



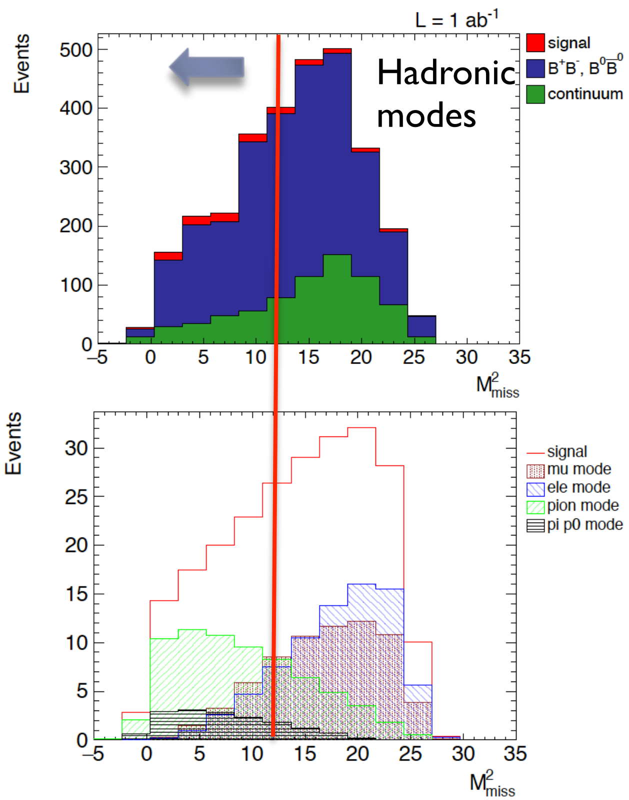
Maximizing a S/sqrt(S+B) in a signal region of extra energy

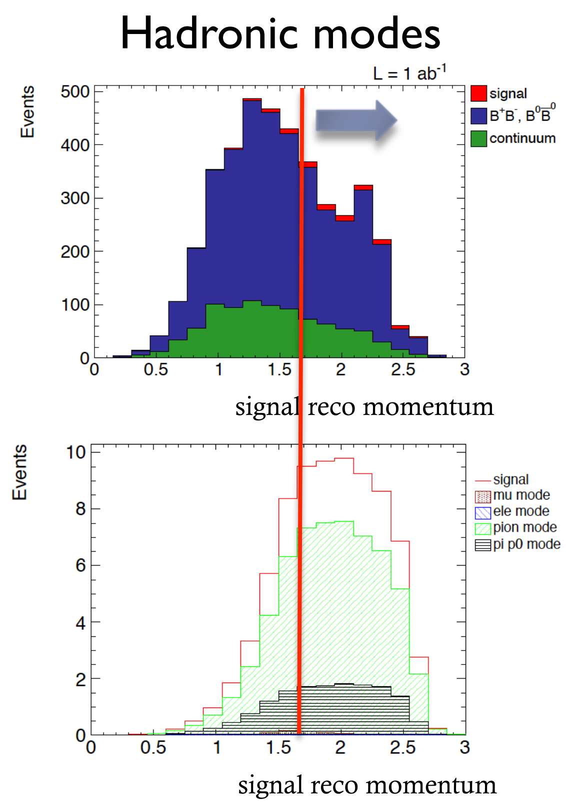
Leptonic modes selection optimization



MM^2 > 12 GeV^2 and no cut on lepton momentum maximizes S/ sqrt(S+B) in the signal region of low extra energy

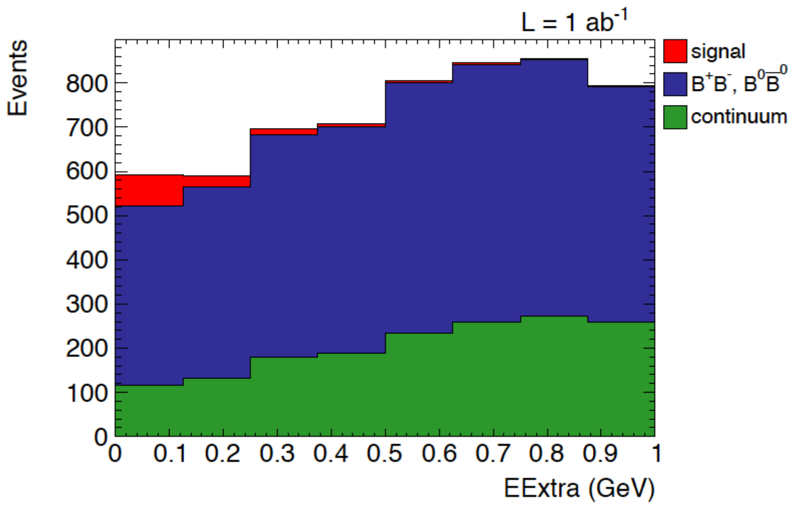
Hadronic modes optimization

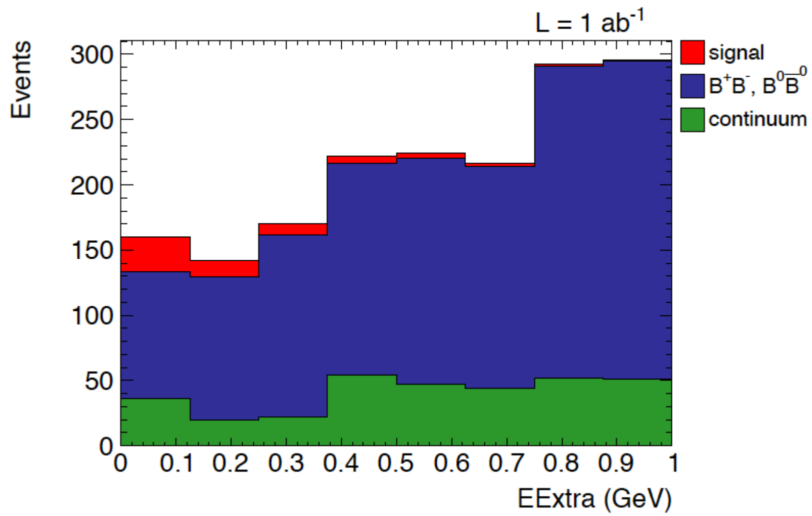




$MM^2 < 12\ GeV^2$ and $p > 1.6$ GeV cut on lepton momentum maximizes S/ sqrt(S+B) in the signal region of low extra energy

Selected events





$E_{extra} < 1$ GeV	Babar PRD 88, 031102 (2013)	Belle PRL 110, 131801 (2013)	Belle II (this analysis)
Signal Efficiency (‰)	**0.72**	**1.1**	**2.2**

#events in (0 - 1.0) GeV	Lep channels	Had channels	Total
Signal	**126**	**62**	**188**
Background	**5758**	**1662**	**7420**

#events in (0 - 0.2) GeV	Lep channels	Had channels	Total
Signal	**88**	**35**	**123**
Background	**817**	**196**	**1013**

Statistical uncertainty with 1 ab^{-1}

- Perform a 1D fit to the E_{extra} distribution
  - Generate a pseudo-dataset according to the signal + background MC expectations
  - Assuming BR of 0.85×10^{-4}
  - Perform a template maximum likelihood fit to E_{extra} with two components: signal and 4 background pdfs built from the expected MC distributions

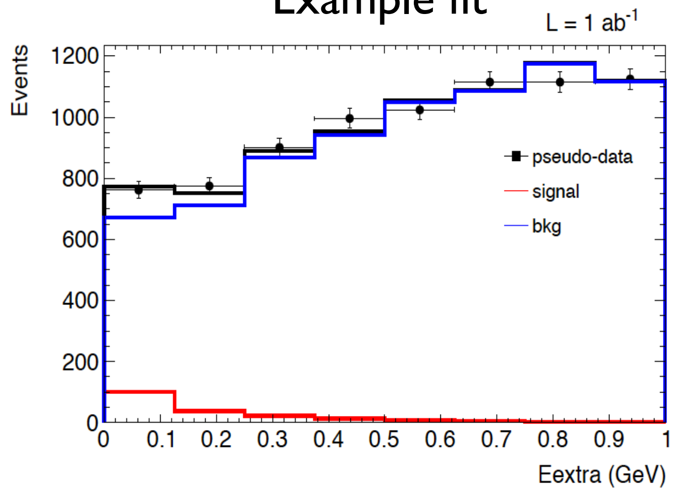
- Toy MC with 20000 pseudo-datasets:

mean fitted signal yield = 188 evts → no bias
mean uncertainty = 55 evts

$$BR(B \to \tau\nu) = 0.83 \pm 0.24 \times 10^{-4}$$

~30% precision

Example fit

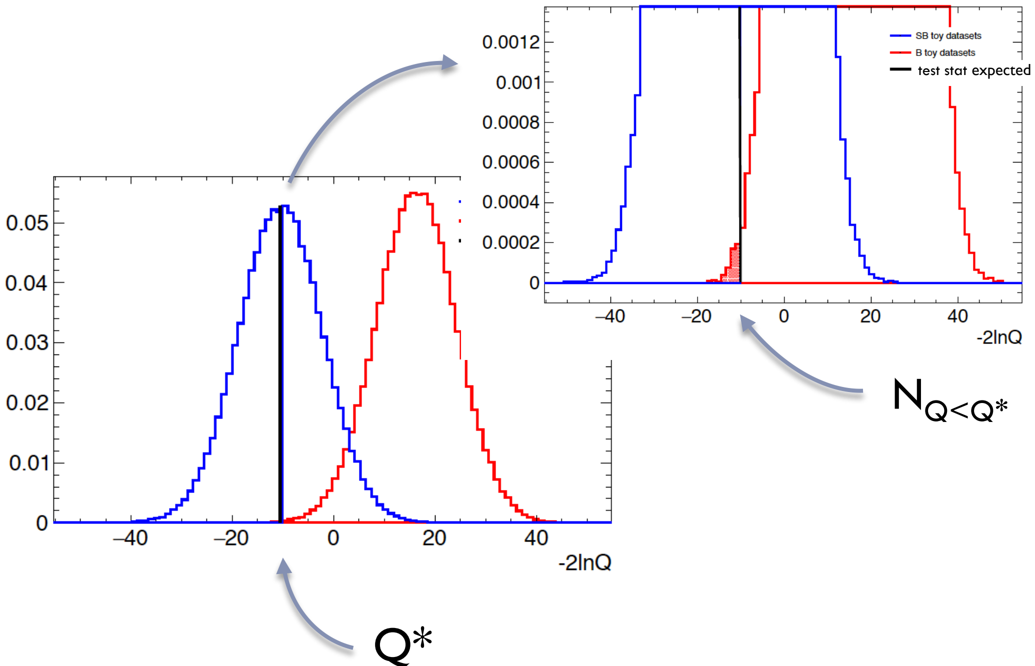


Statistical uncertainty reduced to 20% without beam background

Expected significance with 1 ab^{-1}

- Define the test statistics $Q = -2\ln[L(s+b)/L(b)]$ and perform 200000 pseudo-experiments generating pseudo-datasets sampled from S+B and B only E_{extra} distributions.
- Evaluate the expected p-value of the null hypothesis on the toys background samples as $1\text{-}CL_b = N_{Q<Q^*}/N$, 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 = 0.000385 → significance: 3.4 σ

Projections to 5 ab^{-1} and 50 ab^{-1}

For now we can only guess-estimate from past measurements how systematics may improve

Main contributors like background shape, signal shape, tag efficiency are limited by the statistics available to assess them. → 2%
Others like peaking backgrounds depend on branching ratio measurements of rare decays. → 3%

Belle B → τ ν hadronic tag

TABLE II. Summary of the systematic errors for the $B^- \to \tau^- \bar{\nu}_\tau$ branching fraction measurement.

Source	$\mathcal{B}$ systematic error (%)
Signal PDF	4.2
Background PDF	8.8
Peaking background	3.8
B_{tag} efficiency	7.1
Particle identification	1.0
π^0 efficiency	0.5
Tracking efficiency	0.3
τ branching fraction	0.6
MC efficiency statistics	0.4
K_L^0 efficiency	7.3
$N_{B^+B^-}$	1.3
Total	14.7

Belle II B → τ ν 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

Conclusions

- Hadronic and semi leptonic tagging is a powerful tool for measurements of B decays with missing energy
  - Exploited by BaBar and Belle
  - Related systematic uncertainties expected to scale with statistics
- We studied the $B \rightarrow \tau\ \nu$ with hadronic tagging in Belle II full simulation with expected beam background
  - To check the sensitivity / immunity to it
  - Results encouraging 20% (no BG) – 30% (full BG)
- For semileptonic tagging we have not a Belle II simulation
  - Scaling by statistics we have similar statistical uncertainty (20%)
- For purely leptonic modes untagged analyses looks superior
  - Expect by extrapolation 7% precision on $B \rightarrow \mu\ \nu$ with 50 ab^{-1}