Search for $B \to \tau\nu$ with the Hadronic tag at the Belle II experiment

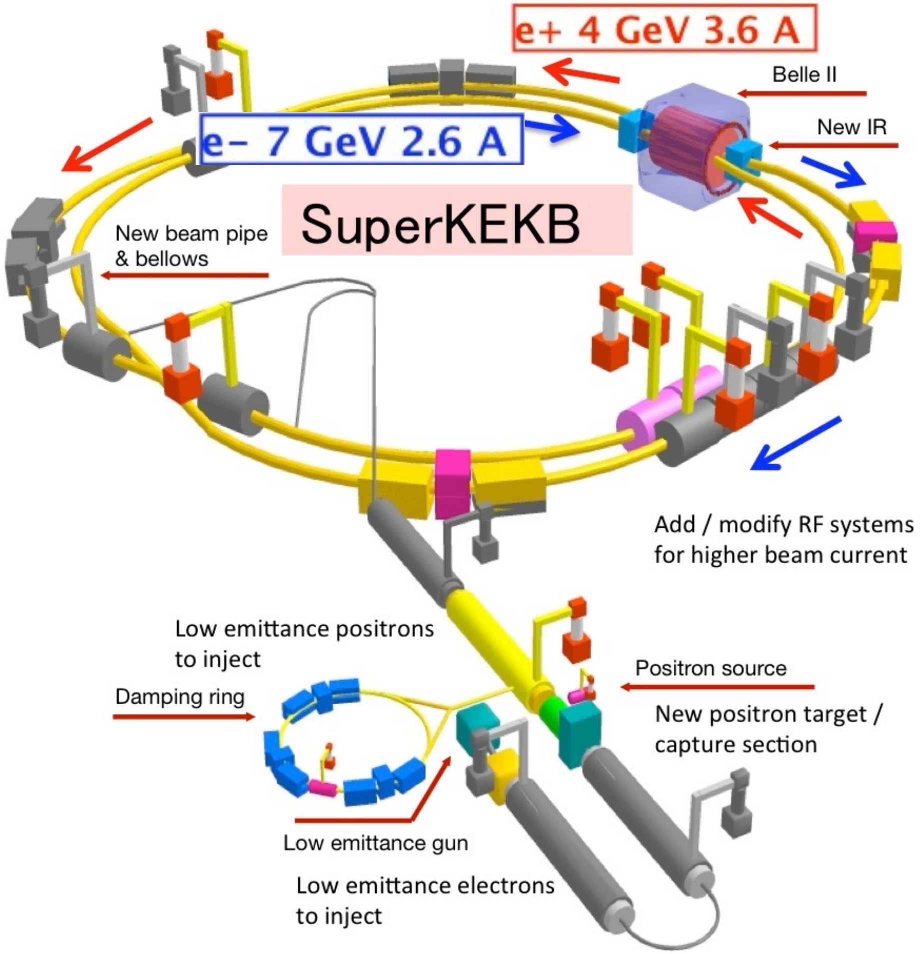
Michele Aversano[A], Guglielmo De Nardo[B], Giovanni Gaudino[B,C], Toru Iijima[A,D,E], Mario Merola[B]

Nagoya University[A], INFN Napoli – University of Napoli Federico II[B], INFN Napoli – Scuola Superiore Meridionale[C], Nagoya KMI[D], KEK IPNS[E]

Flavor Physics Workshop 2023
2023/11/23

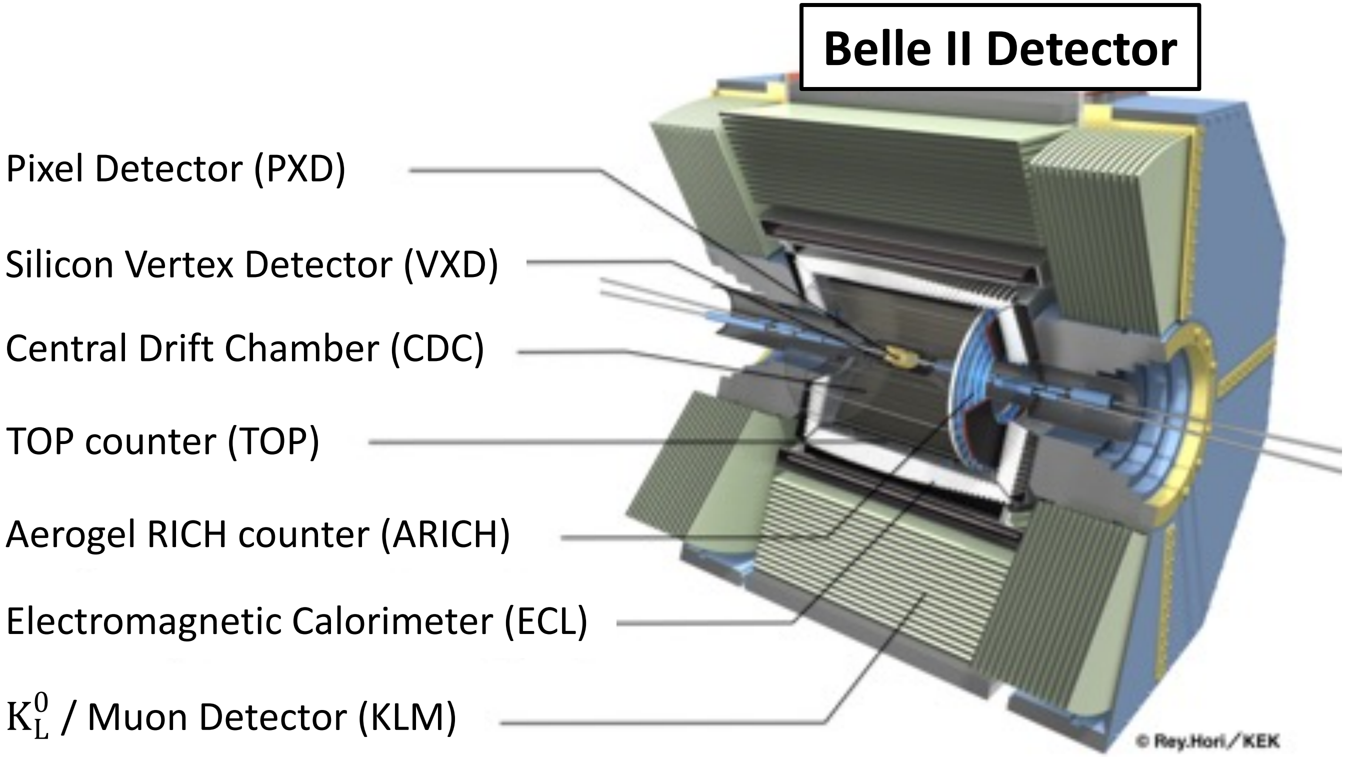
The Belle II Experiment

The Belle II experiment (Tsukuba, Japan) -> Particle Physics experiment that primarily study B mesons properties.



SuperKEKB asymmetric collider

-> $\sqrt{s} = 10.58$ GeV -> Υ(4S) resonance (mainly decays in B meson pairs).



The Belle II Detector -> a general-purpose detector.

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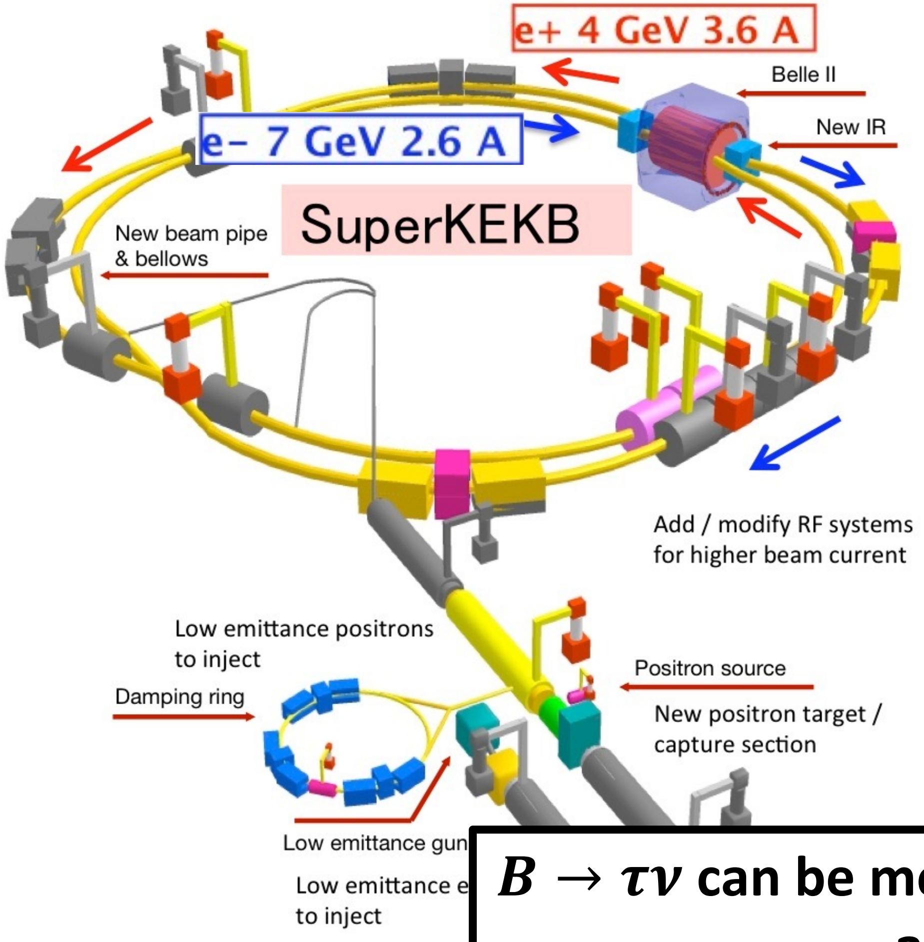
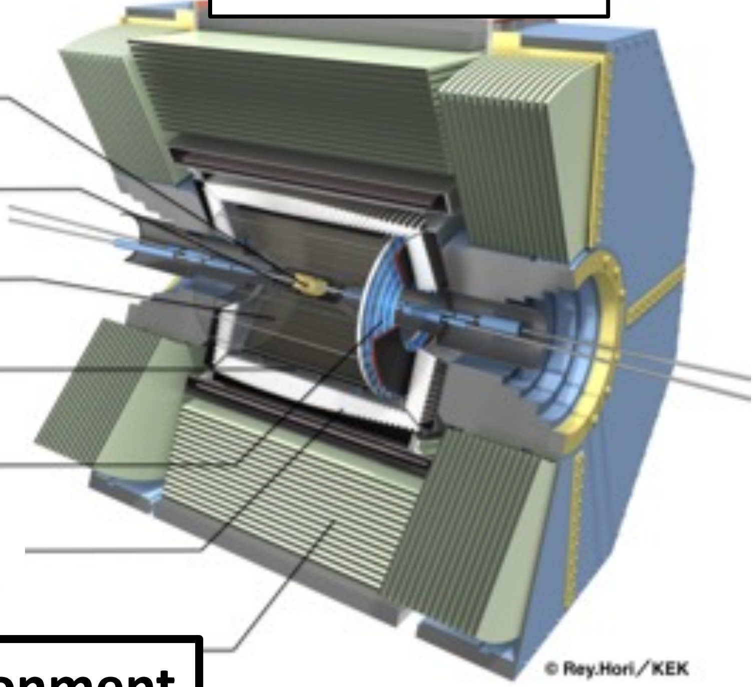


Belle II Detector

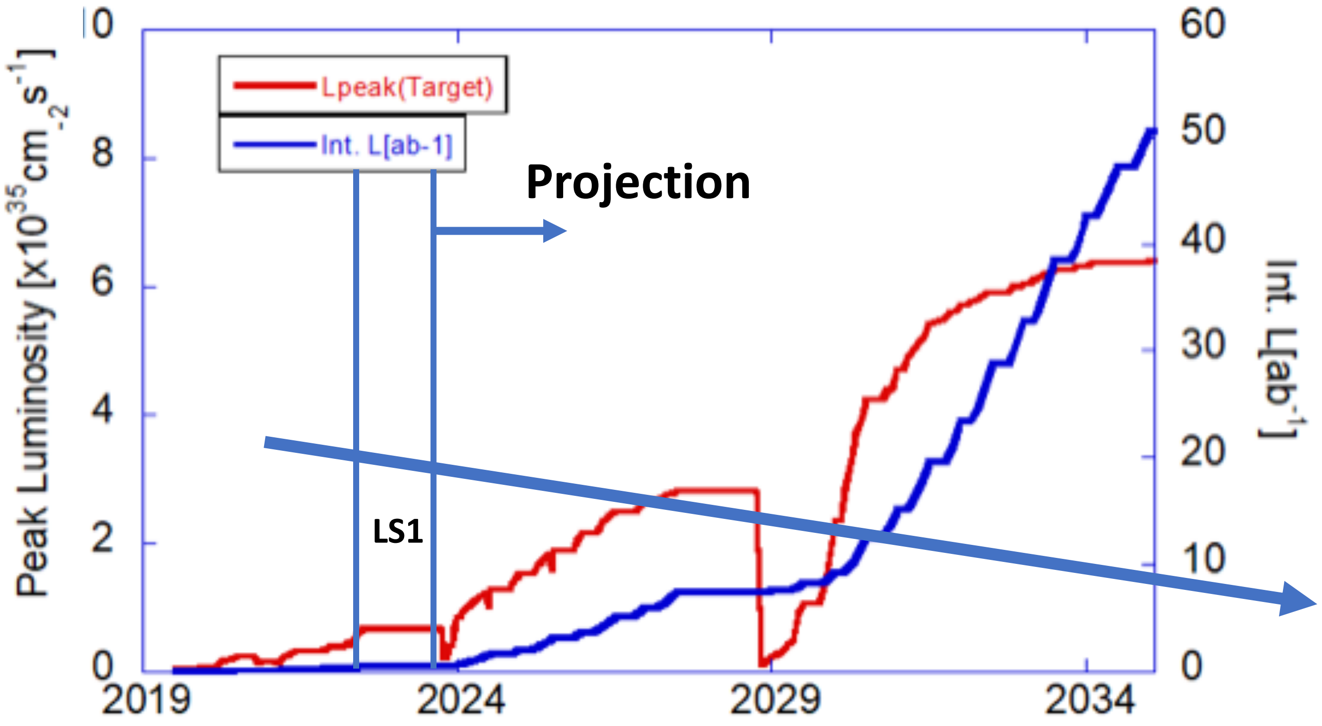


rpose detector.

$B \rightarrow \tau\nu$ can be measured only in a clean environment as the one in Belle II.

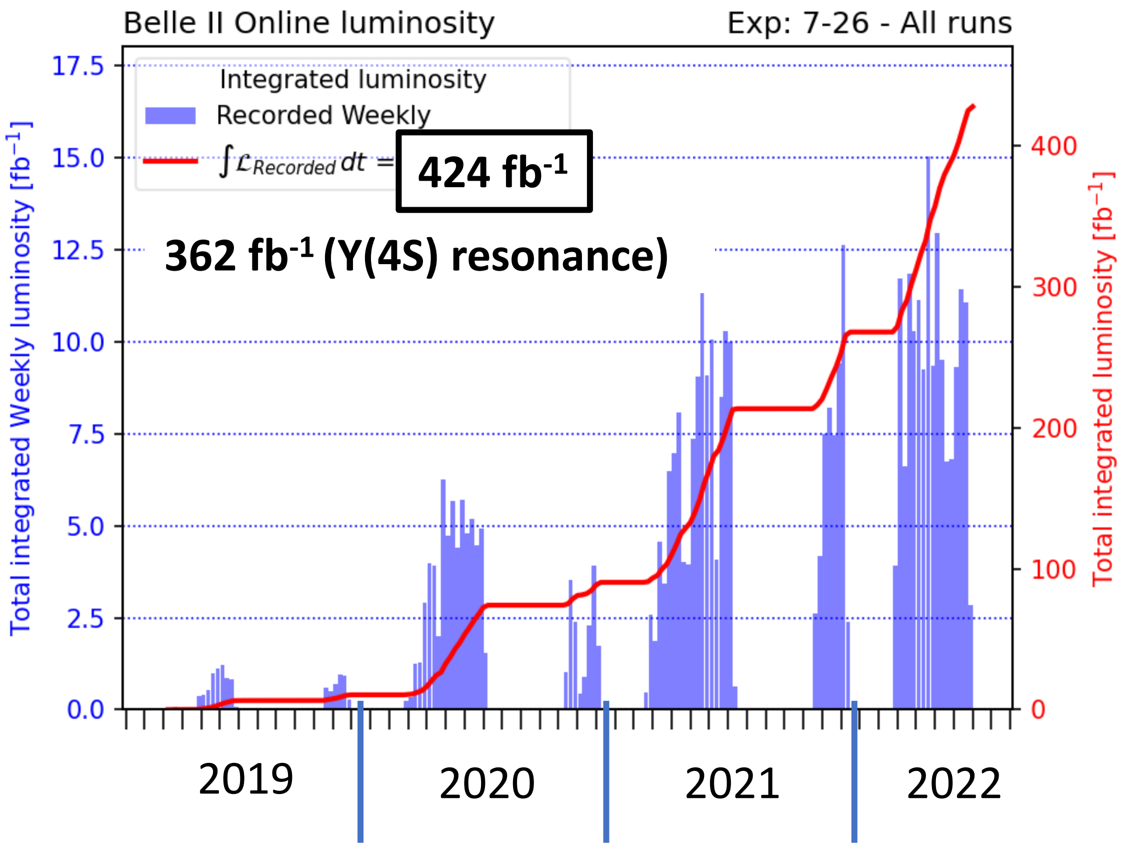
The Belle II Experiment

Collisions with the **complete Belle II detector**: L_{int} = **50 ab^{-1}** expected ~2035.



Until now:

- $L_{peak} \sim 4.7 \cdot 10^{34}$ **cm^{-2} s^{-1} (world record)**



From 2022/06 → Long Shutdown 1 (LS1)

Operation will restart next year

B meson: Leptonic Decays

In SM decays through a b/u quark annihilation mediated by W bosons.

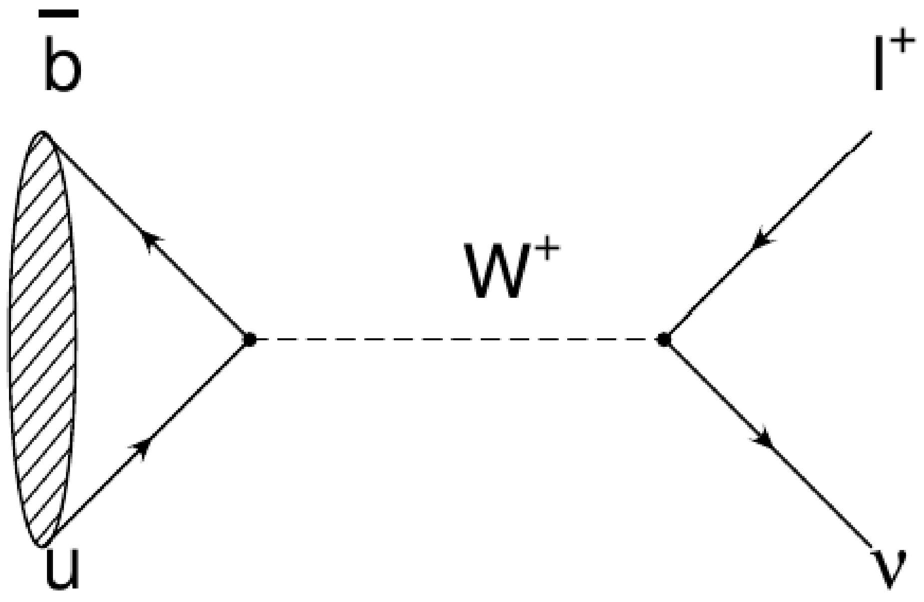
-> Decays with helicity suppression

$$(l = e, \mu, \tau)$$

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

- **Electrons and muons strongly suppressed.**
- **Neither Belle nor BaBar observed at "5σ" $B \to \tau\nu$.**

	$BR(B \to \tau\nu)$ Had Tag	Luminosity
Belle	$\left(0.72^{+0.27}_{-0.25}(stat.) \pm 0.11(sist.)\right) \times 10^{-4}$	771 fb^{-1}
BABAR	$\left(1.83^{+0.53}_{-0.49}(stat.) \pm 0.29(sist.)\right) \times 10^{-4}$	426 fb^{-1}
PDG	$(1.09 \pm 0.24) \times 10^{-4}$	
SM	$(1.18 \pm 0.16) \times 10^{-4}$	



We target to measure the BR with the current dataset of 362 fb^{-1} .

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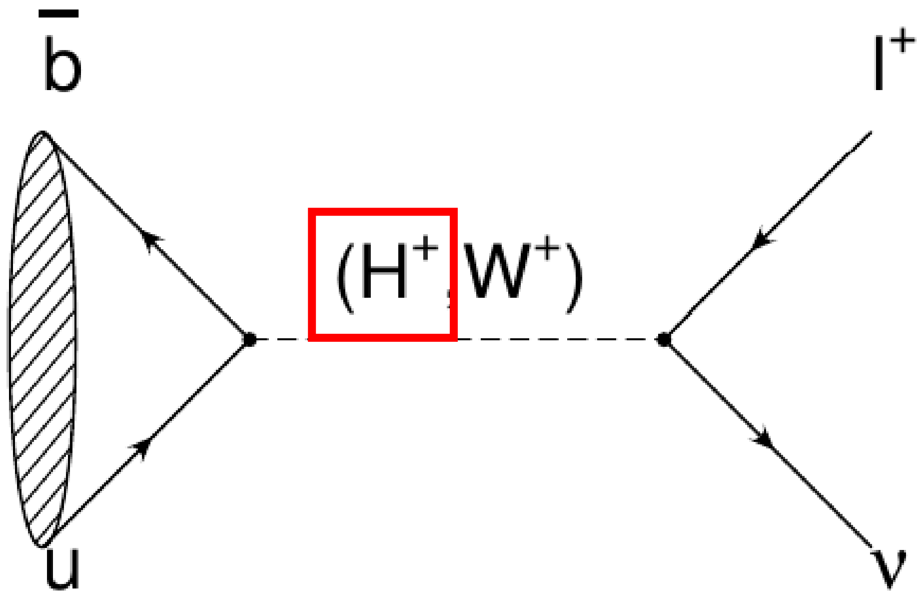


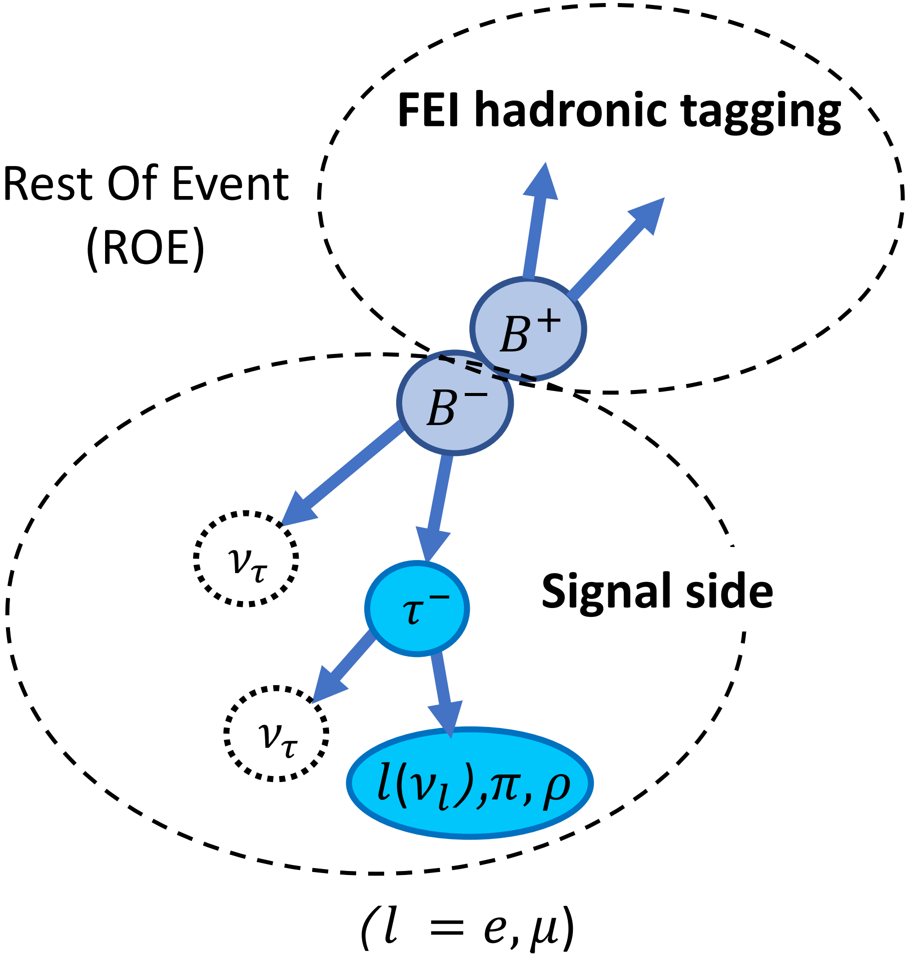
The $B \to \tau\nu$ is also important in New Physics for:

- **two-doublet Higgs model – type II.**
- **lepton flavour universality test (with a future $B \to \mu\nu$ measurement).**

Analysis Workflow

- Reconstruction (ParticleID and track requests)
- Continuum Reweight FastBDT
- Continuum Suppression FastBDT
- Signal best candidate selection
- E_{extra}-M^2_{miss} 2D fit and BR extraction
    - E_{extra} pdfs data-driven correction
    - ToyMC studies
    - Validation with control samples
- Systematic uncertainties estimation

Search for $B \to \tau\nu$ decay



→ **No Extra Tracks (from IP)**

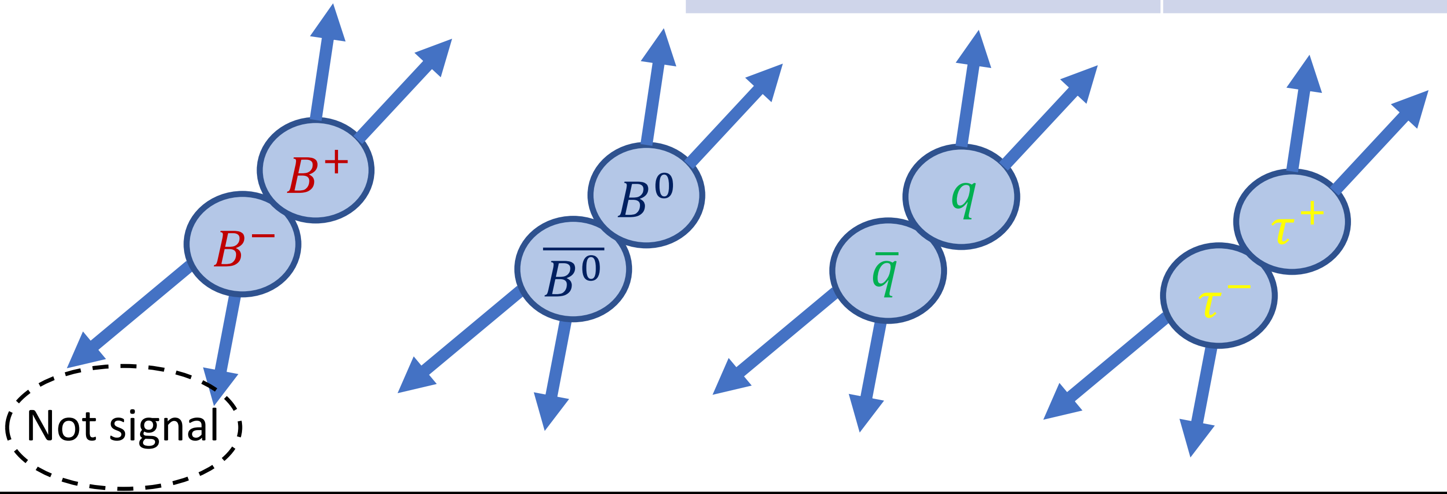
Signal is searched through $\boldsymbol{\tau}$ decays (1-prong):

- $\boldsymbol{\tau \to e\nu_e\nu_\tau}$
- $\boldsymbol{\tau \to \mu\nu_\mu\nu_\tau}$
- $\boldsymbol{\tau \to \pi\nu_\tau}$
- $\boldsymbol{\tau \to \rho\nu_\tau}$ with $\boldsymbol{\rho \to \pi^\pm\pi^0}$

$\sim$71% of the τ Branching Fraction

MC	Data
Signal $\sim 40 \cdot 10^6$ **events** $B^0\overline{B^0}$ **2.8 ab⁻¹** B^+B^- **2.8 ab⁻¹** $q\bar{q}$ **800 fb⁻¹** $\tau^+\tau^-$ **400 fb⁻¹**	**362 fb⁻¹+ Off-res 42fb⁻¹**

Backgrounds:



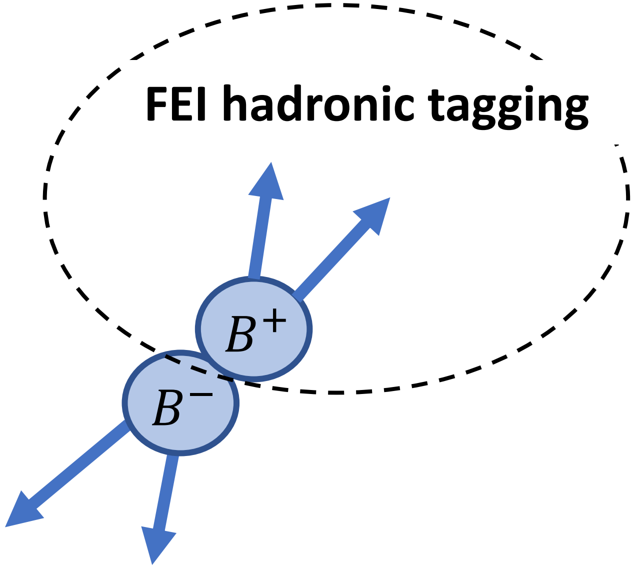
Tag Side Reconstrucion

Signal events (B_{sig}) have weak experimental signature -> **the other B (B_{tag}) is fully reconstructed.**

- **Full Event Interpretation (FEI)**
  -> multivariate tagging method
  -> hierarchical reconstruction of more than 30 exclusive B meson decay chains
  (e.g. $B \to D\, n\pi,\ B \to D^*\, n\pi, B \to J/\psi K, \ldots$)
  -> output → sigProb

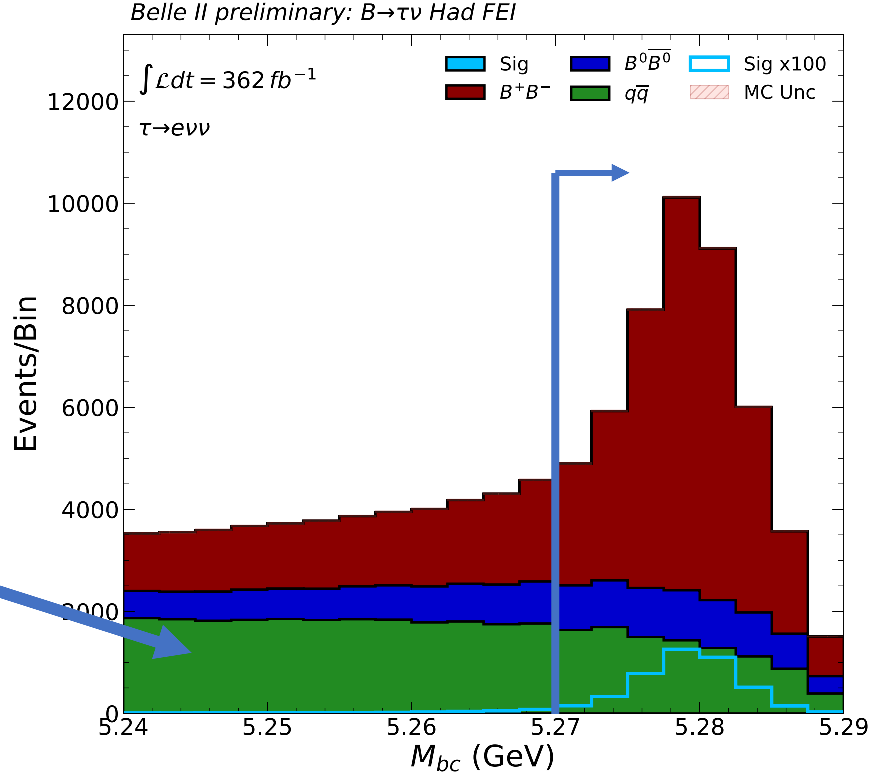
Keck, T., Abudinén, F., Bernlochner, F.U. *et al.* The Full Event Interpretation. *Comput Softw Big Sci* **3**, 6 (2019).

	B^+	B^0
ϵ_{tag}	~0.3%	~0.2%



- **Beam energy-constrained mass**

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$



sigProb > 0.01
$M_{bc} > 5.27$ GeV
(for all the decay modes)

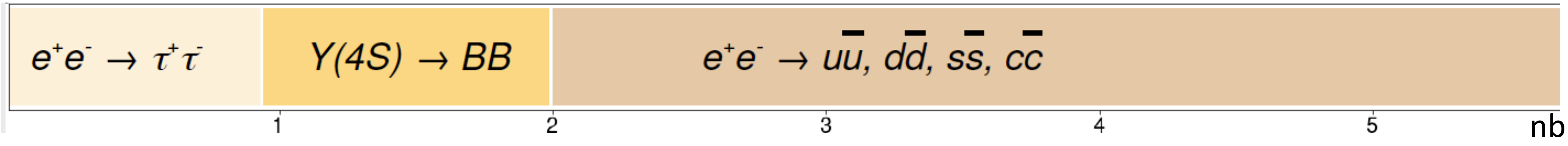
We call **continuum** the $e^+e^- \to q\bar{q}$ and $\tau^+\tau^-$ events

Off-Resonance data

To understand if the MC simulation describes well the continuum, we compare it with Off-Resonance data.

Why?

For e^+e^- collisions at 10.58 GeV (Y(4S) resonance), we have:



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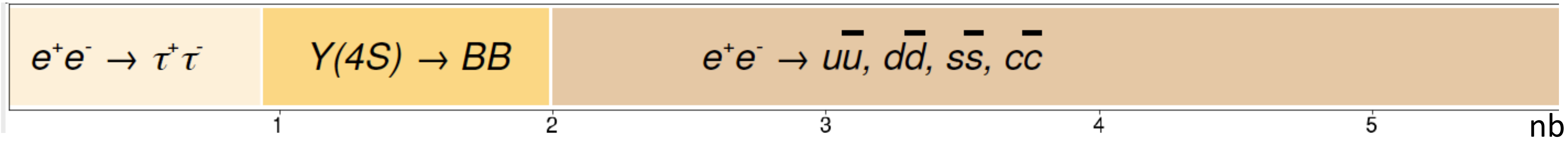
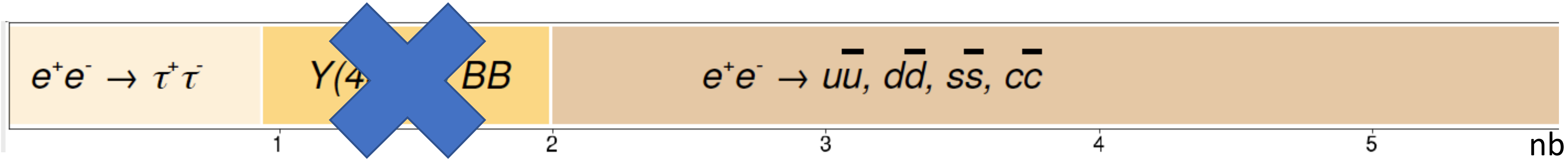


If we reduce the energy under 10.58 GeV -> no B mesons, but just continuum.



Off-Resonance data is taken with 60 MeV under Y(4S) resonance → **pure continuum data sample**.

Off-Resonance data

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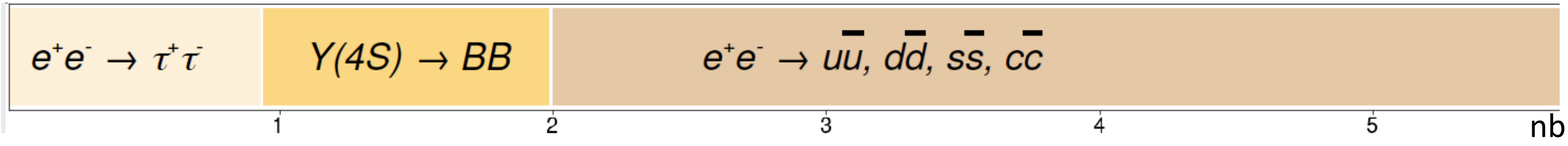

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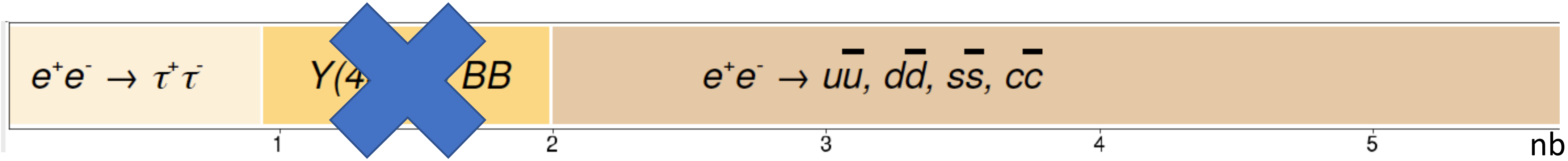


Off-Resonance data is taken with 60 MeV under Υ(4S) resonance → **pure continuum data sample**.

One problem, small integrated luminosity → combine MC statistics and Off-Res data shapes.

Continuum Reweight

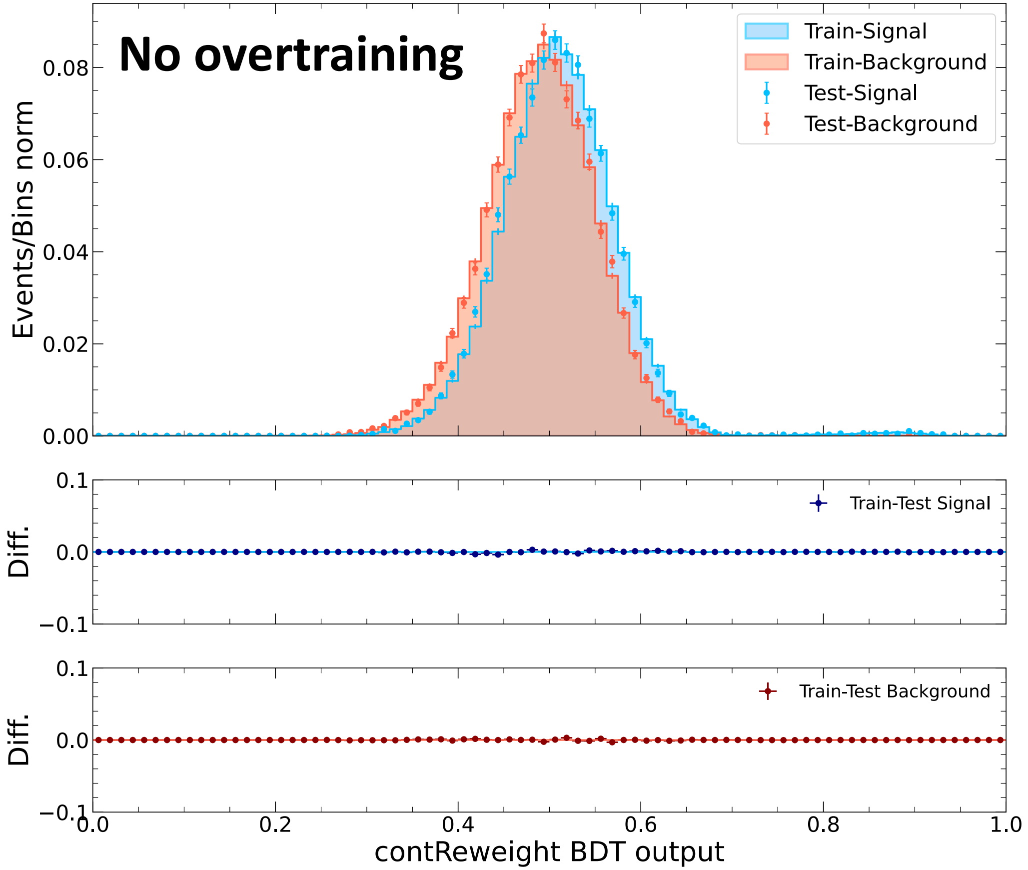
[FastBDT: A speed-optimized and cache-friendly implementation of stochastic gradient-boosted decision trees for multivariate classification]

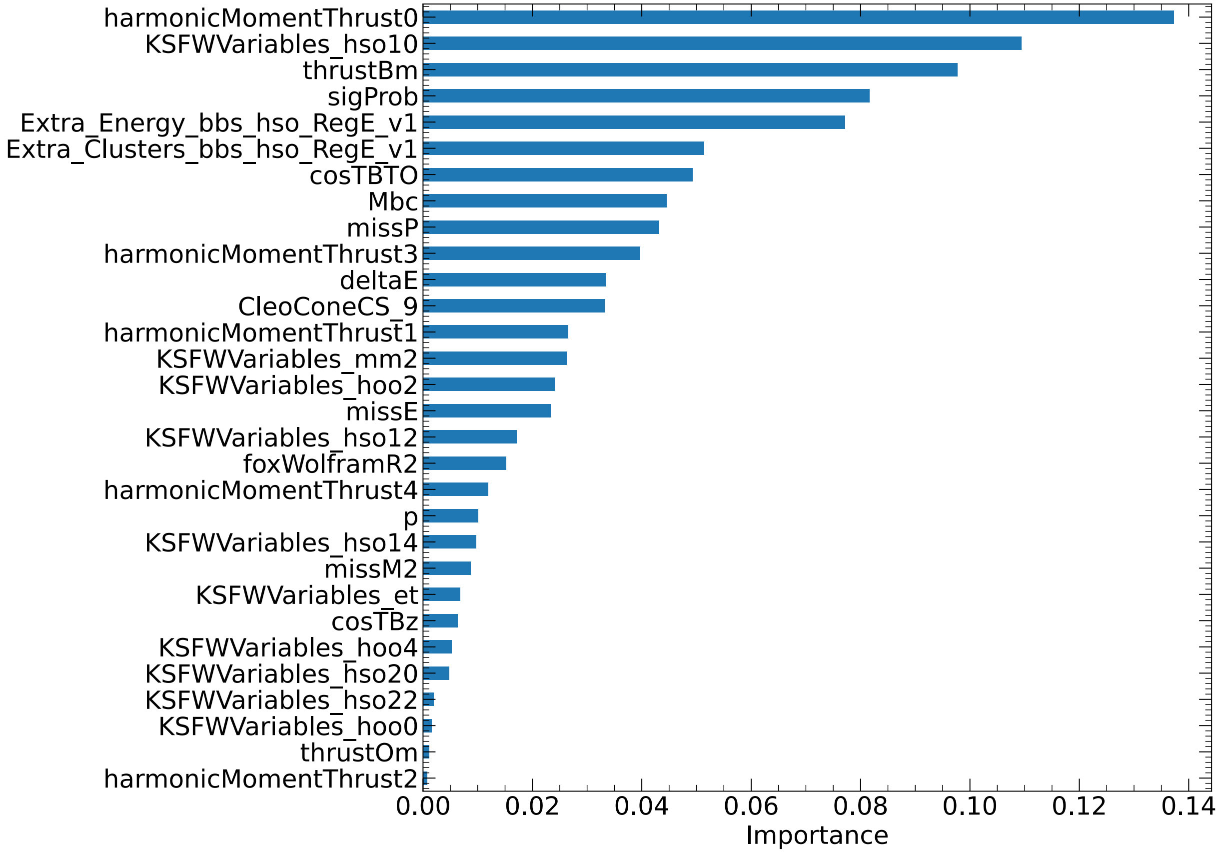
[Advanced event reweighting using multivariate analysis]

We train a FastBDT using **OffRes data as "Signal"** and **MC continuum as "Background"**

- Train/Test sample 80%/20%
- Signal/Background events ratio = 1

$$W_{ContReweight} = \frac{BDT_{output}}{1 - BDT_{output}}$$

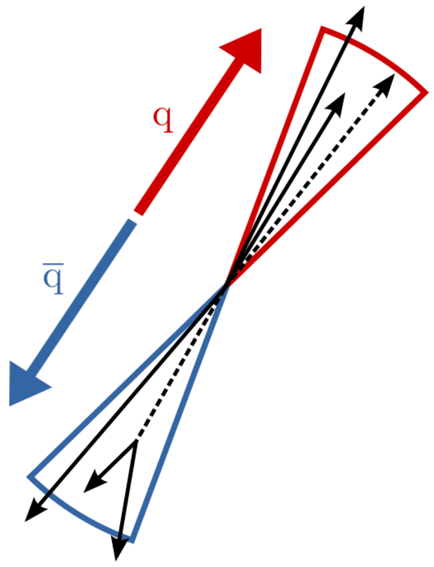




Continuum Suppression

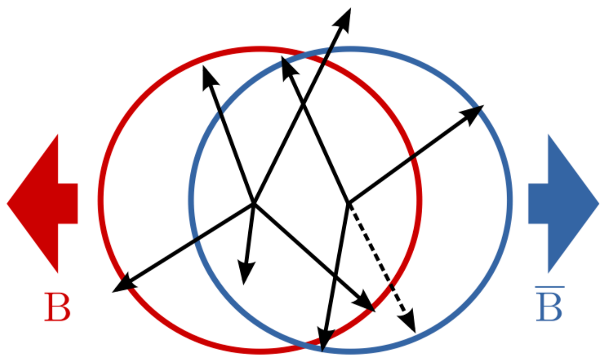
If we look at the **shape of continuum and $B\overline{B}$**, i.e. the momentum-weighted distribution of all particles in the detector → **different behaviour.**

Continuum



$e^+e^- \to q\overline{q} \quad (q \in \{u, d, s, c\})$

$B\overline{B}$



$e^+e^- \to \Upsilon(4S) \to B\overline{B}$

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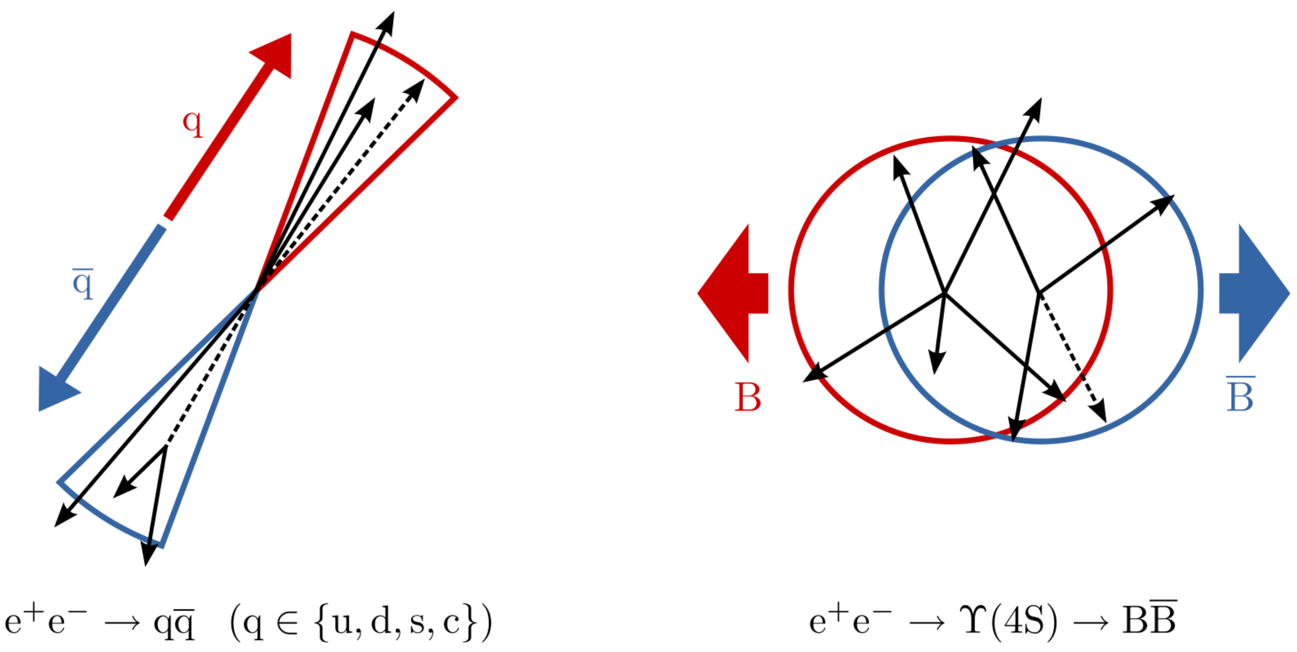
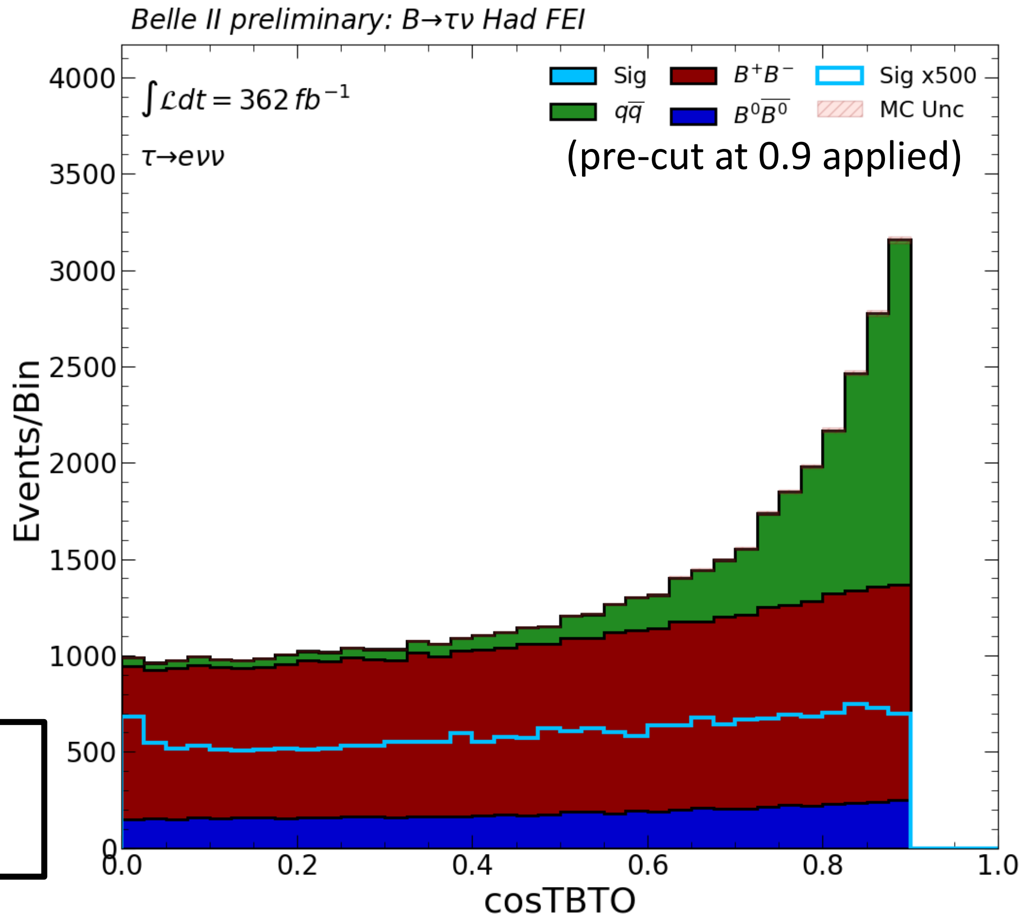


We use variables related to the event shape.



cosTBTO: cosine of angle between thrust axis of B_{sig} and thrust axis of ROE.

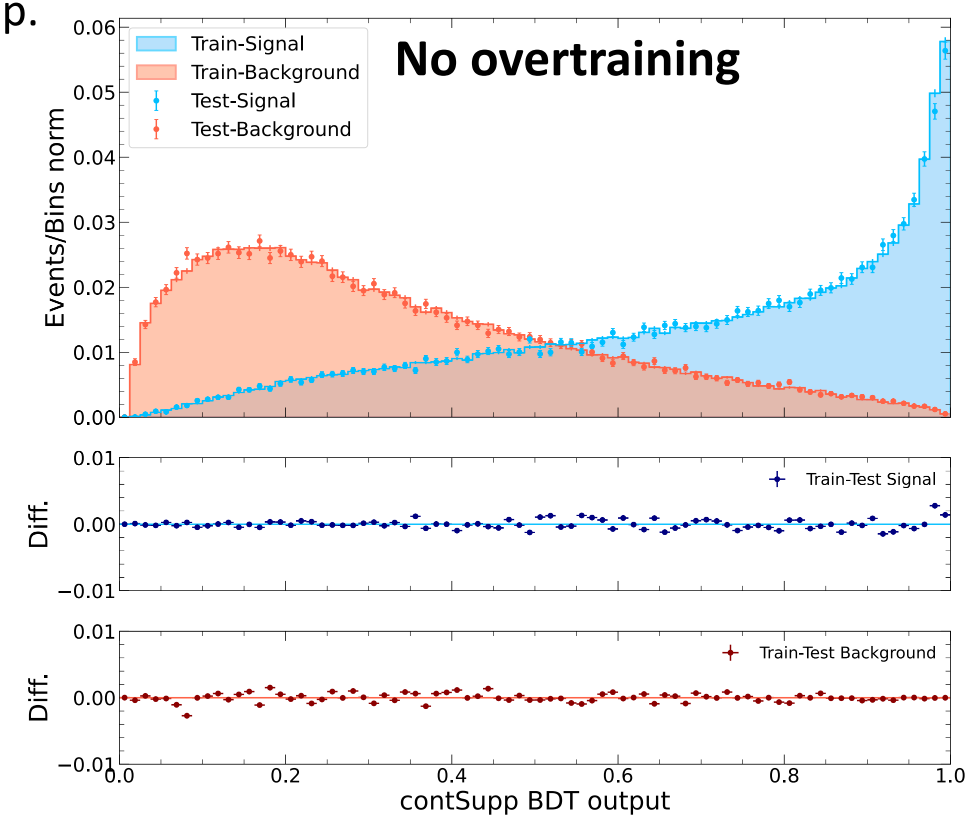
Continuum Suppression

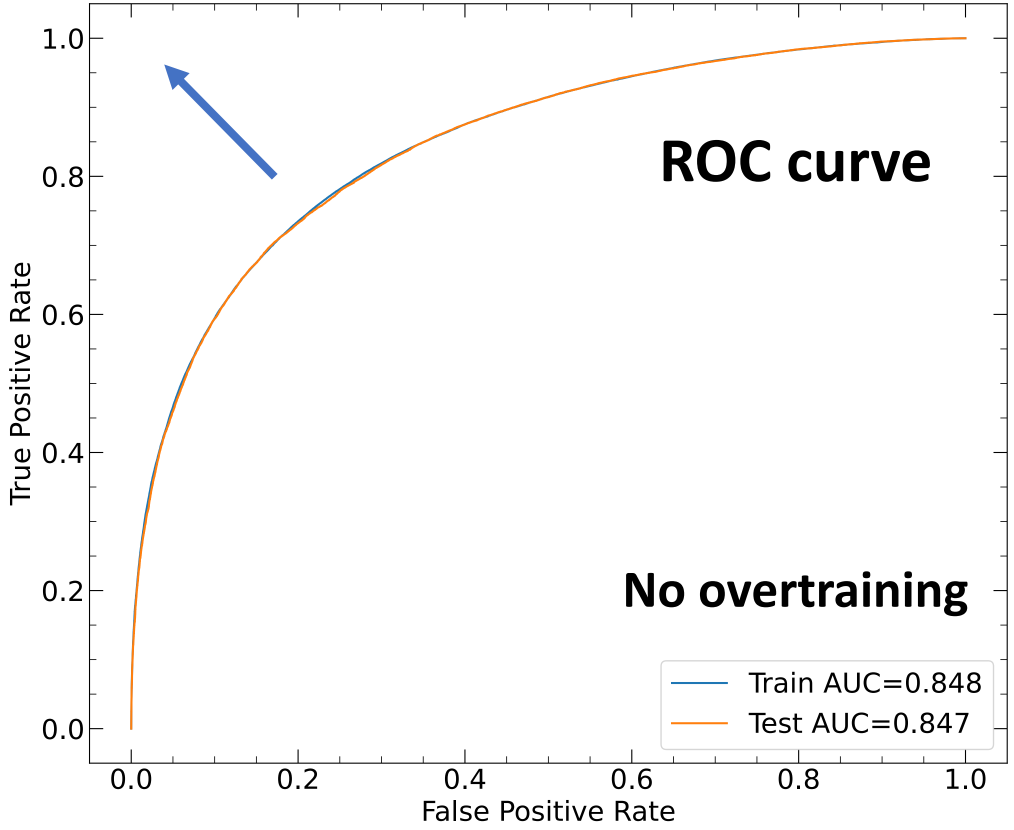
To suppress continuum, we train **2 FastBDT**, one for Leptons and one for Hadrons, using **MC continuum as "Signal"** and **MC $B\overline{B}$ as "Background"**.

In the training, the weights from continuum reweighting are used

- Train/Test sample 80%/20%
- Signal/Background events ratio = 1
- Feauteres = only variables with good Data/MC agreement and less correlated with our fit variables.

Lep.



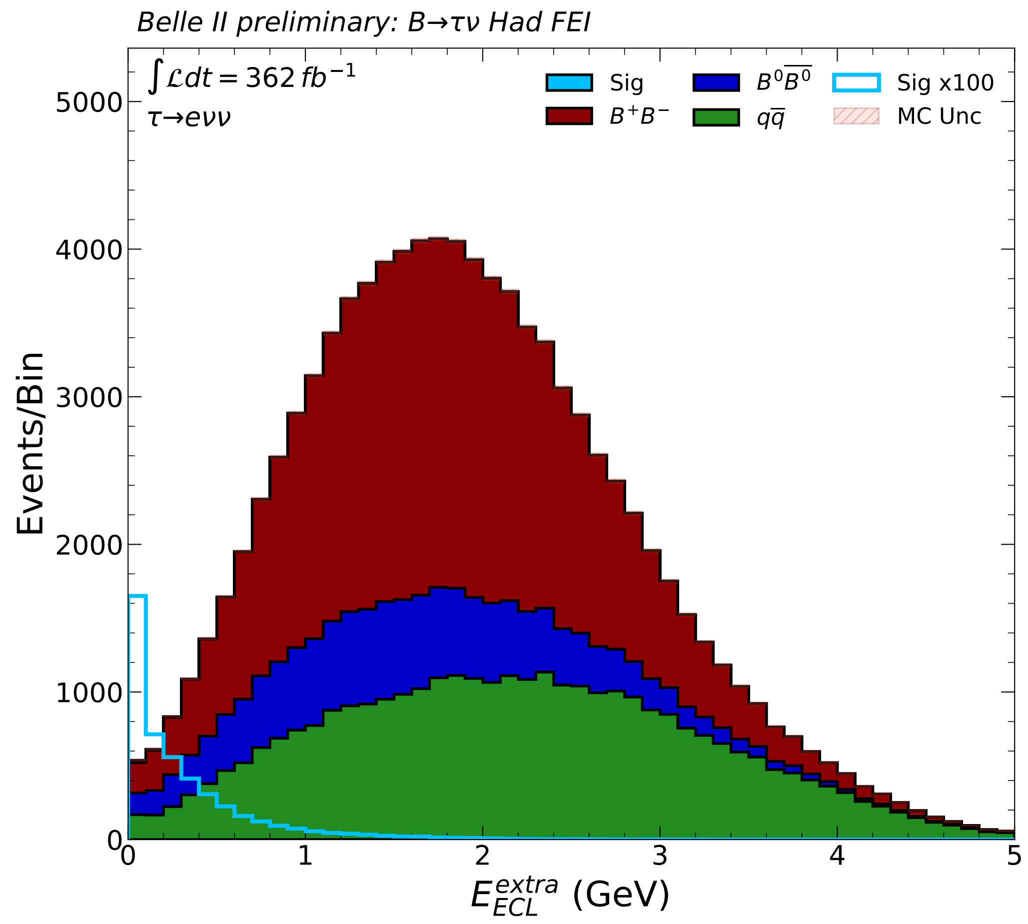


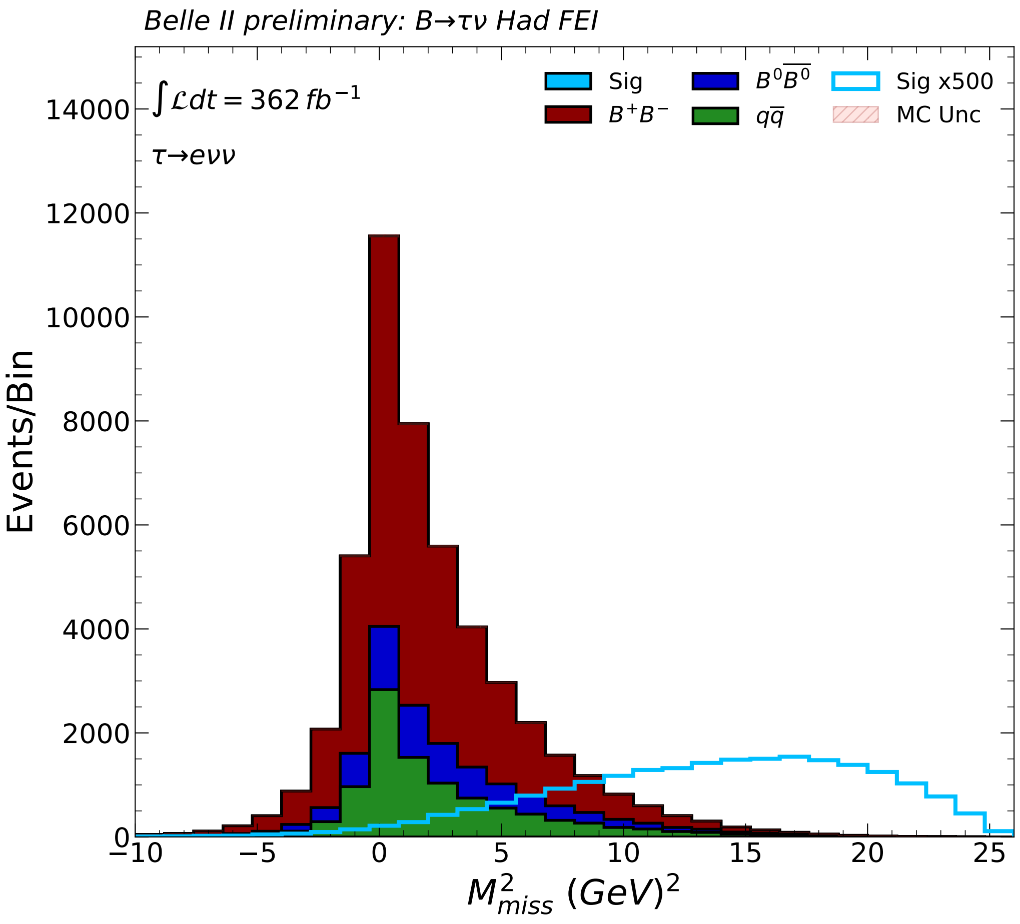
Signal selection

Most discriminating variables for signal:

- E_{ECL}^{extra}**, the extra energy not associated with the** B_{tag} **and** B_{sig} **(Rest of Event).**
- $M_{miss}^2 = E_{miss}^2 - p_{miss}^2$**, squared magnitude of the four-momentum** p_{miss}**.**

A data-driven correction is applied to both the variables to correct the distributions.





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A data-driven correction is applied to both the variables to correct the distributions.

The best cuts have been optimized:

- minimizing a FOM obtained through 5000 Extended ML ToyMC study on the E_{extra}-M_{miss}^2 2D distribution for each cut combination.

$$\boldsymbol{FOM = \frac{\bar{\sigma}_S}{\bar{N}_S}}$$

($\bar{N}_S$ and $\bar{\sigma}_S$ are the mean signal yield and error of the ToyMC)

	eID	μID	πID	sigProb	M_{bc} (GeV)	p (GeV)	ContSupp	$\epsilon(10^{-4})$
e	>0.9			>0.01	>5.27	>0.5	<0.8	7.3
μ		>0.9		>0.01	>5.27	>0.5	<0.8	7.6
π			>0.6	>0.01	>5.27	>1.4	<0.6	3.4
ρ			>0.6	>0.01	>5.27	>1.65	<0.7	3.1

$$\left(\epsilon = \frac{n_{sel}}{n_{gen}}\right)$$

$BR(B \to \tau\nu)$ Extraction with ToyMC

The sensitivity is estimated by producing 10,000 pseudo-datasets through a Simultaneous Extended Maximum Likelihood 2D Fit on E_{ECL}^{extra} and M_{miss}^2.

- **BR set to the PDG value.**
- **PDFs from the MC.**

The Likelihood for each k-mode: (k = e, μ, π, ρ)

$$L_k = \frac{e^{-(n_{s,k}+n_{b,k})}}{(n_{s,k}+n_{b,k})!} \prod_{i=1}^{n_{s,k}+n_{b,k}} \{n_{s,k} \cdot P_k^s(E_{extra}^{i,k}, M_{miss}^{2\ i,k}) + n_{b,k} \cdot P_k^b(E_{extra}^{i,k}, M_{miss}^{2\ i,k})\}$$

$n_{s,k}$ e $n_{b,k}$ sig and bkg yields.

Where:

$$n_{s,k} = N^{MEASURED}(\tau \to k - mode) = N_{BB} \cdot \epsilon_k \cdot BR(B \to \tau\nu)$$

$BR(B \to \tau\nu)$ Extraction with ToyMC

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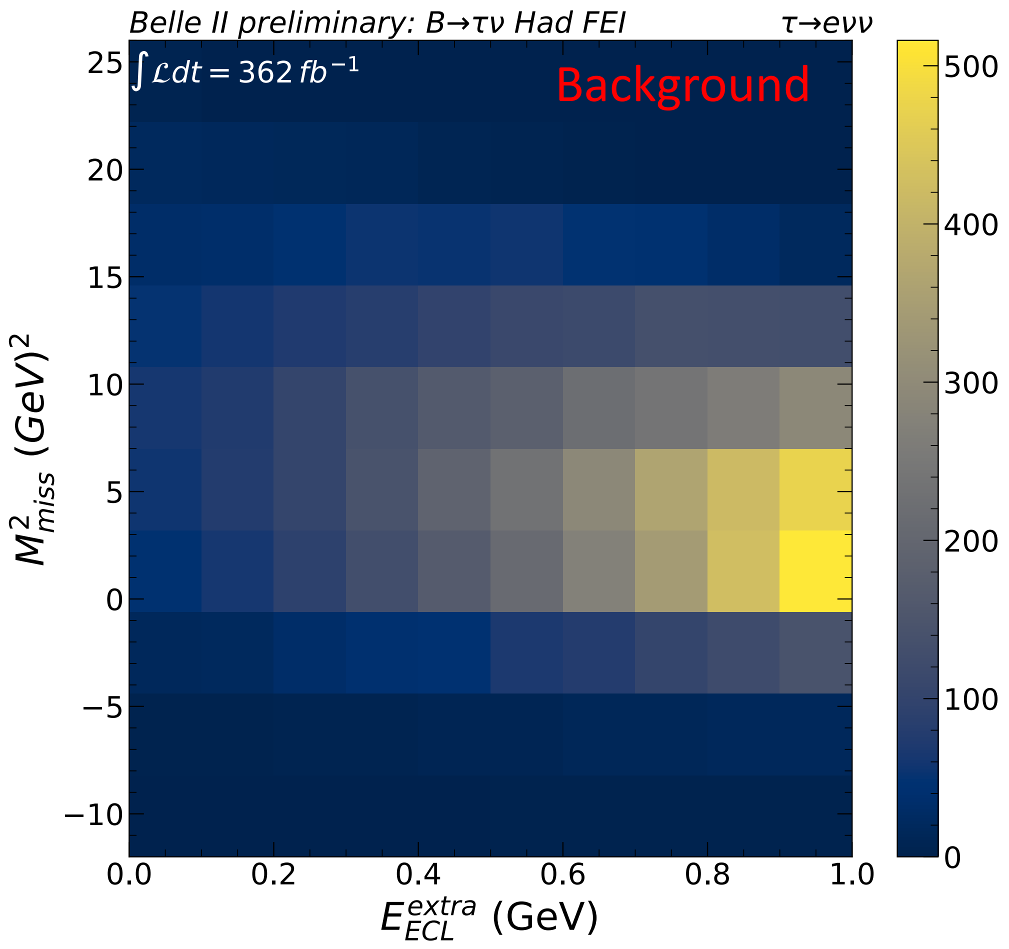
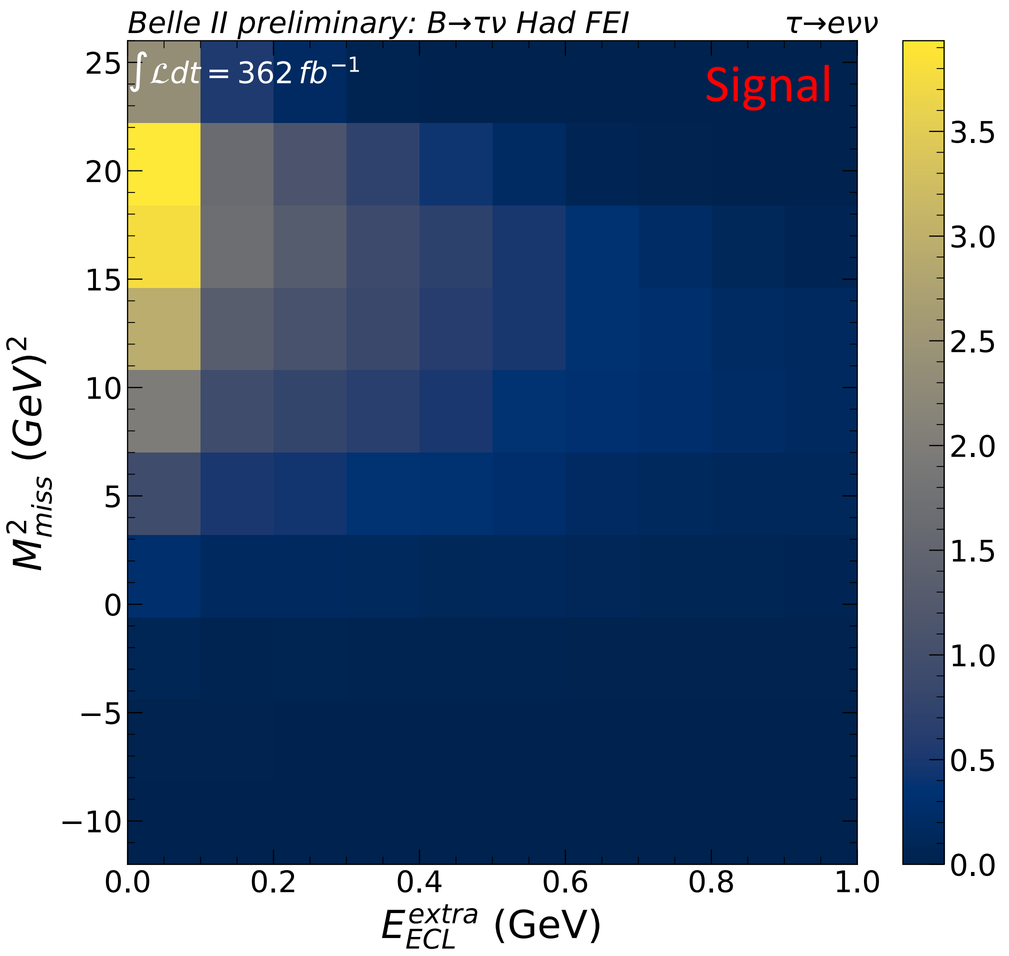
Electron channel (same for muon channel):





$BR(B \to \tau\nu)$ Extraction with ToyMC

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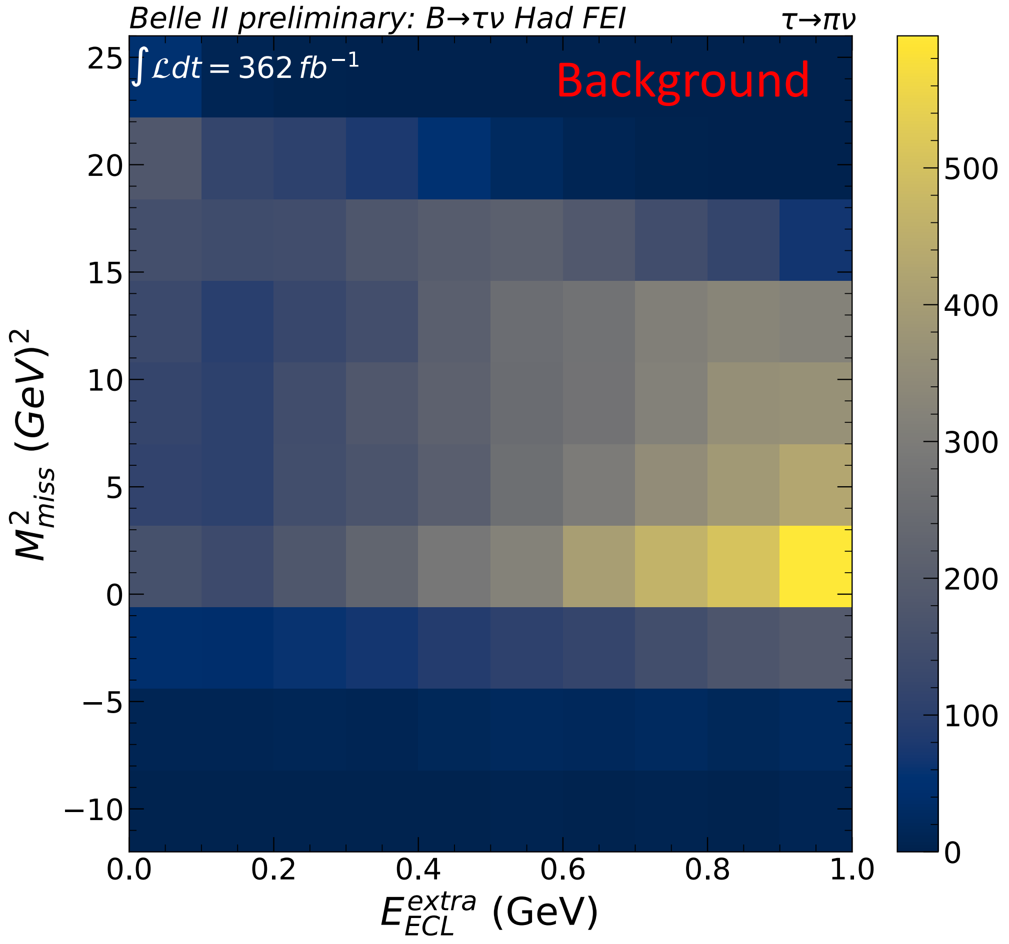
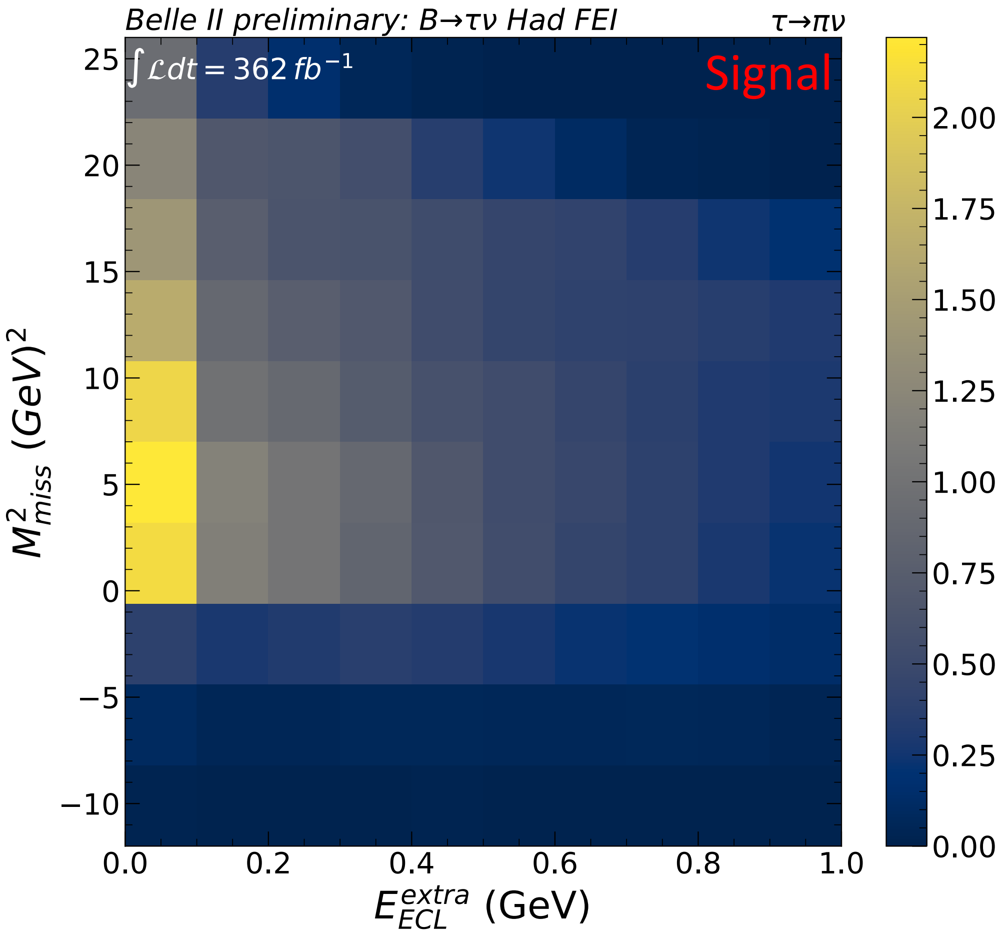
Pion channel (same for rho channel):

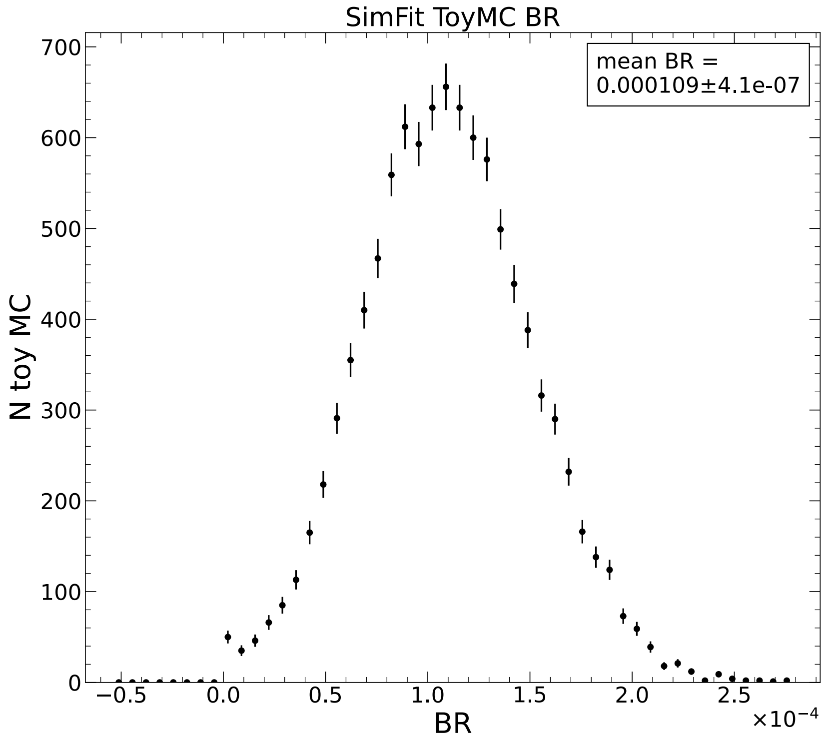


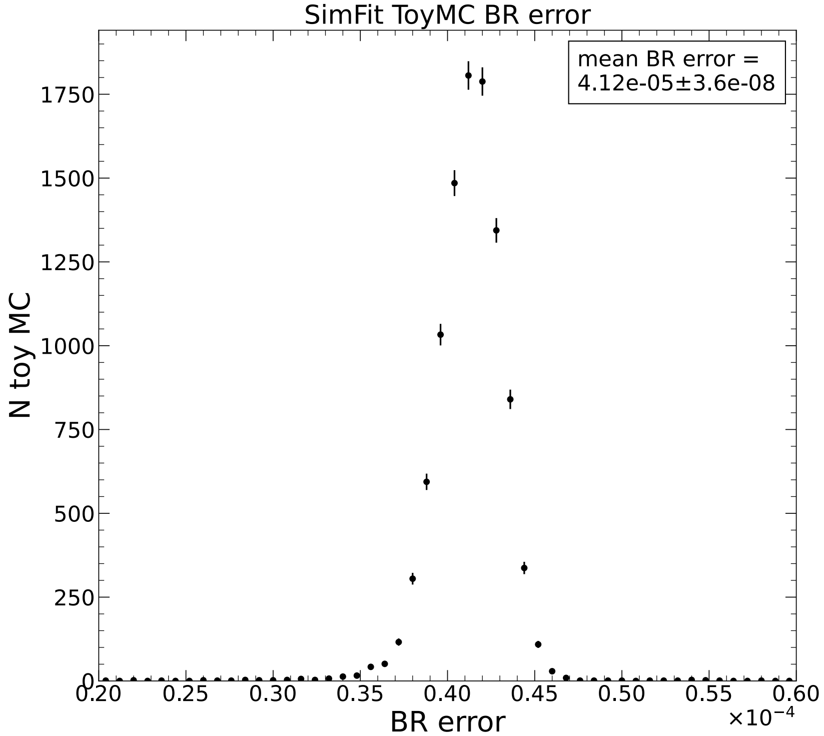


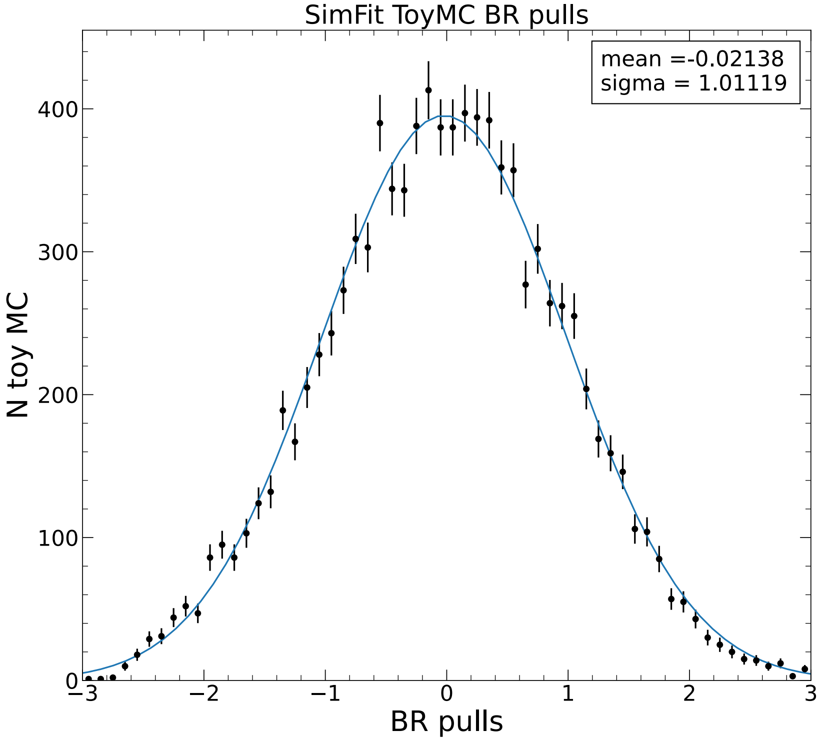
$BR(B \to \tau\nu)$ Extraction with ToyMC

The sensitivity is estimated by producing 10,000 pseudo-datasets through a Simultaneous Extended Maximum Likelihood 2D Fit on E_{ECL}^{extra} and M_{miss}^2.

$BR_{input}(B \to \tau\nu) = 1.09\times10^{-4}$





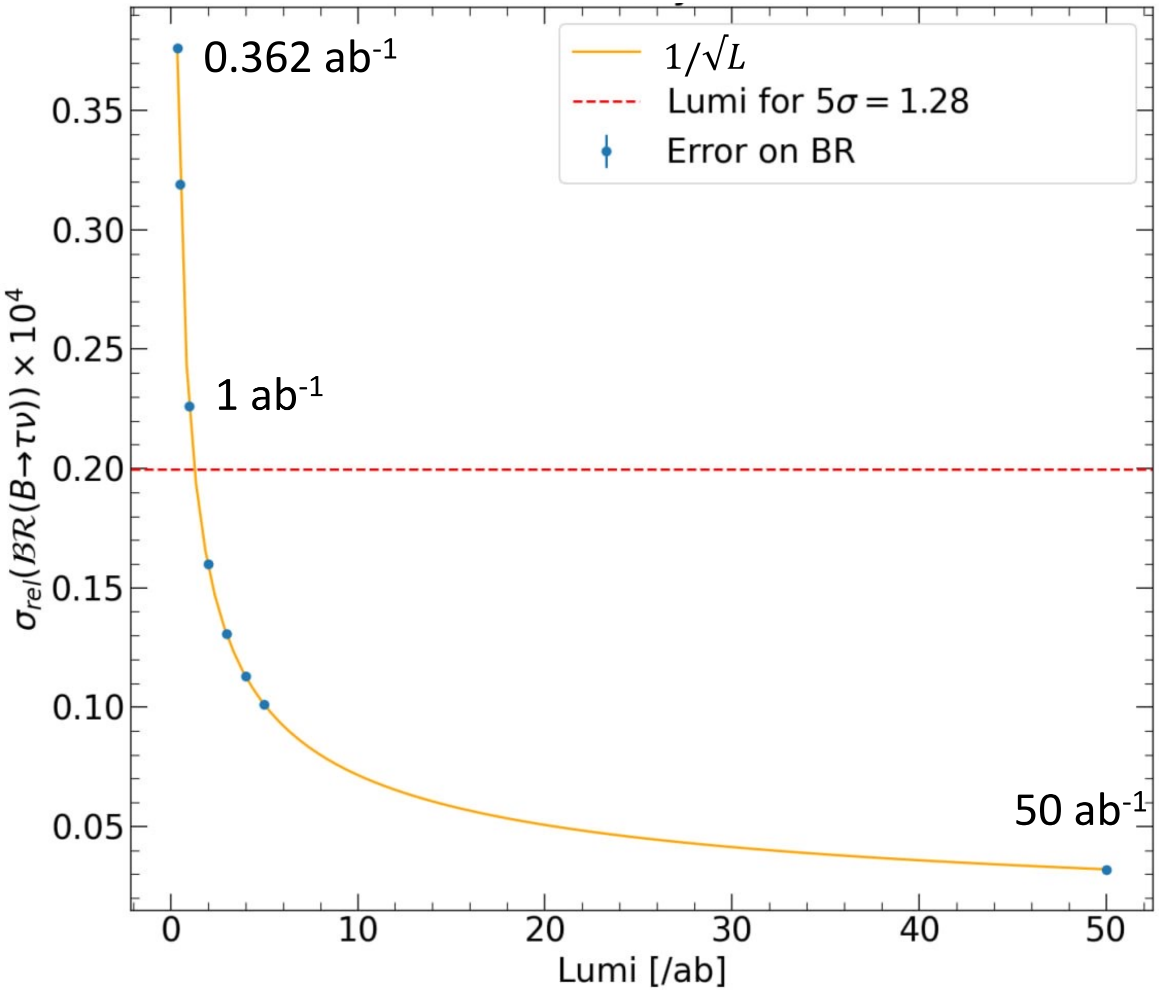


No bias and expected statistical unc. from ToyMC is ~37%

$BR(B \to \tau\nu)$ Extraction with ToyMC

The sensitivity is estimated by producing 10,000 pseudo-datasets through a Simultaneous Extended Maximum Likelihood 2D Fit on E_{ECL}^{extra} and M_{miss}^2.

ToyMC result for increasing luminosity:



At 1.28 ab^{-1} we expect a «5σ» measurment (only stat. uncertainty).

***At 50 ab^{-1} the dominant uncertainty will be the systematic one.**

(expected systematic taken from Prog. Theor. Exp. Phys. 2019, 123C01 arXiv:1808.10567 **[hep–ex])**

Systematic Uncertainties

Source	Sys. Unc. estimation
$n_{B\overline{B}}$	1.5 %
$BR(\Upsilon(4S) \rightarrow B^{+}B^{-})$ (f_{+0})	1 %
Tracking efficiency	0.24 %
Particle Identification	0.5 %
π^{0} reconstruction efficiency	0.6 %
Tag B reconstruction efficiency	1.7 %
E_{extra} PDF	$^{+12.8\%}_{-12.5\%}$
Total	$^{+13.1\%}_{-12.8\%}$

E_{extra} PDF	Sys. Unc. estimation
MC Statistics	9.9 %
Continuum Reweighting	2.4 %
Data-driven Corr.	$^{+7.7\ \%}_{-7.2\%}$
Total	$^{+12.8\%}_{-12.5\%}$

Conclusions

The $B \to \tau\nu$ decay sensitivity was studied with MC simulations corresponding to L_{int} = 362 fb^{-1} .

- The Continuum background is reweighted using Off-res data and suppressed through a FastBDT discriminator trained on MC.

- The signal selection was optimized on MC and ToyMC result:

  Bias negligible, Statistical uncertainty $\sim$ 37% (2.8σ from null hypothesis), Systematic uncertainty $\sim$ 13% ,

  5σ expected with 1.28 ab^{-1} .

- **First Belle II result of $B \to \tau\nu$ Branching Ratio very soon!**

Backup

$BR(B \to \tau\nu)$ Extraction with ToyMC

- $\boldsymbol{BR}$ **set to the Belle value**($\mathbf{0.72{\times}10^{-4}}$)**.**

ToyMC result for 771 fb^{-1} :

Expected statistical uncertainty $\sim \mathbf{38\%}$**.**

Belle $\sim \mathbf{38\%}$.

- $\boldsymbol{BR}$ **set to the BaBar value (**$\mathbf{1.83\ {\times}10^{-4}}$**).**

ToyMC result for 426 fb^{-1} :

Expected statistical uncertainty $\sim \mathbf{20\%}$**.**

BaBar $\sim \mathbf{28\%}$.