59th Rencontres de Moriond 2024: Electroweak Interactions & Unified Theories

La Thuile, 24th March 2025

$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ measurement with the hadronic FEI at Belle II

Giovanni Gaudino*

on behalf of Belle II collaboration

*gaudino@na.infn.it

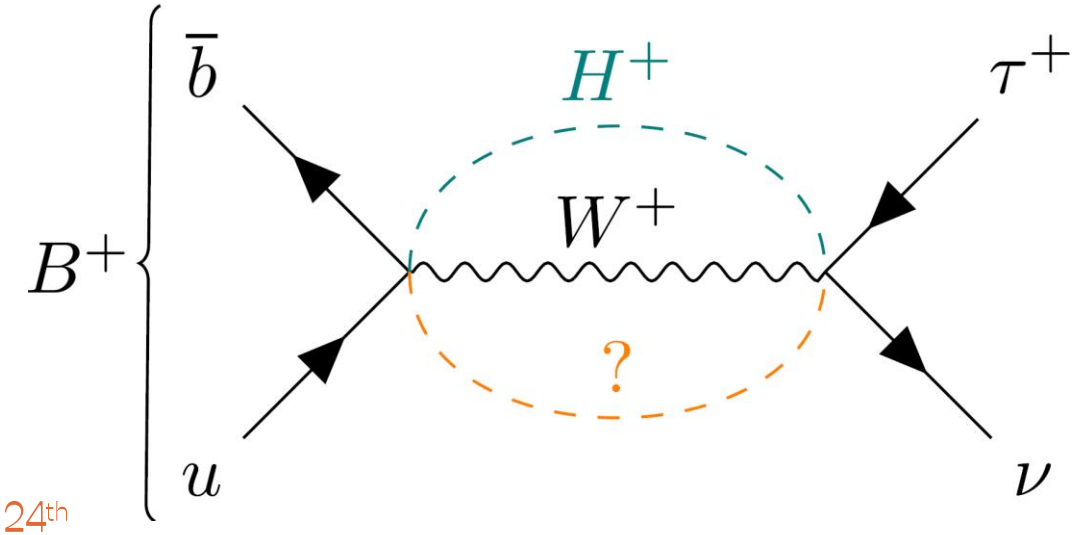
Leptonic B decays

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

→ Decays with **helicity suppression**

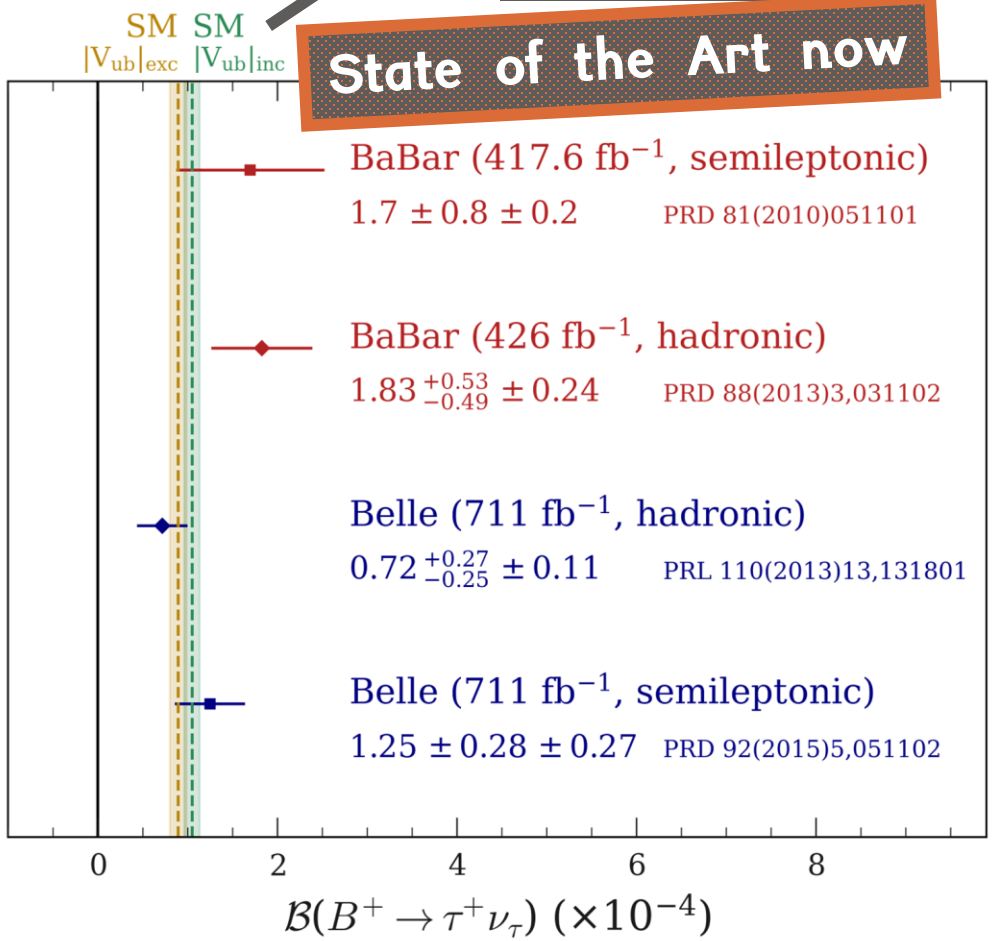
$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} m_B m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 \left|V_{ub}\right|^2 \tau_B$$

- Very **clean** theoretically, very **hard** experimentally
- Neither Belle nor BaBar observed at "**5σ**" $B \to \tau\nu$



New HFLAV determination

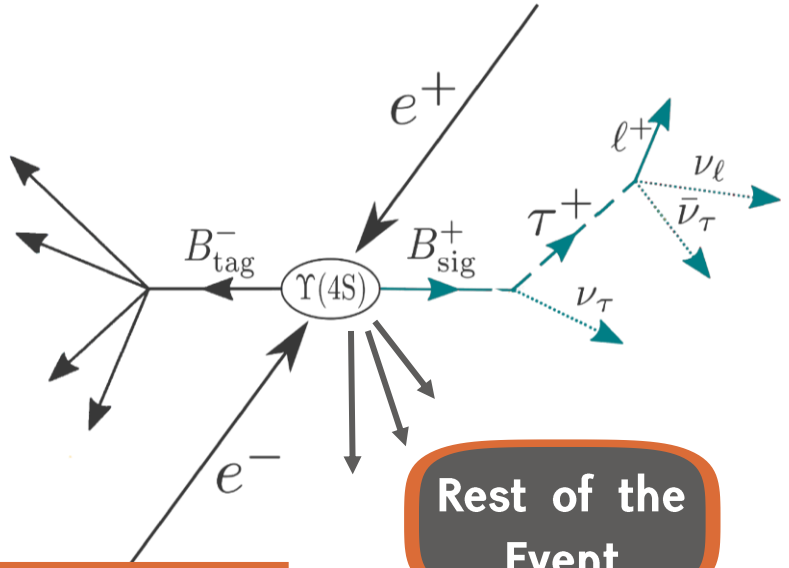
State of the Art now



Event Selection and dataset

One B meson is fully reconstructed using a multivariate algorithm, Full Event Interpretation (FEI) with Hadronic Tagging.

1. $\mathcal{O}_{FEI} > 10^{-2}$
2. $-0.15 < \boldsymbol{\Delta E} = \boldsymbol{E_B^*} - \sqrt{s}/2 < 0.1\ GeV$
3. $M_{bc}c^2 = \sqrt{s/4 - (p_B^* c)^2} > 5.27\ GeV$



Signal is searched through $\boldsymbol{\tau}$ **decays**

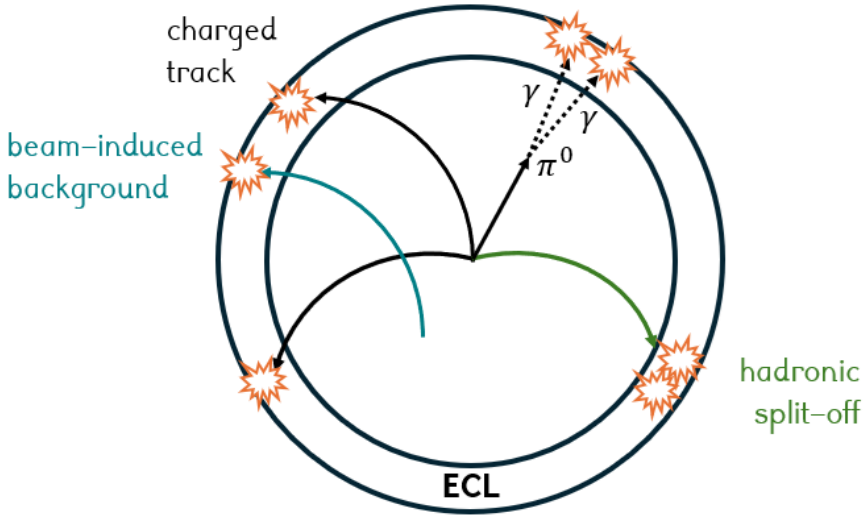
1. $\tau^+ \to \boldsymbol{e}^+\nu_e\bar{\nu}_\tau$
2. $\tau^+ \to \boldsymbol{\mu}^+\nu_\mu\bar{\nu}_\tau$
3. $\tau^+ \to \boldsymbol{\pi}^+\bar{\nu}_\tau$
4. $\tau^+ \to \rho^+\bar{\nu}_\tau$ with $\rho^+ \to \boldsymbol{\pi}^+\boldsymbol{\pi}^0$

Backgrounds
$e^+e^- \to q\bar{q}$
$e^+e^- \to \tau^+\tau^-$
$e^+e^- \to B^+B^-$
$e^+e^- \to B^0\overline{B^0}$

Rest of the Event:

It is crucial to reject fake photons in the ECL from background

Sum of all the cleaned clusters energy → $\boldsymbol{E_{ECL}^{extra}}$.



Missing Quantities:

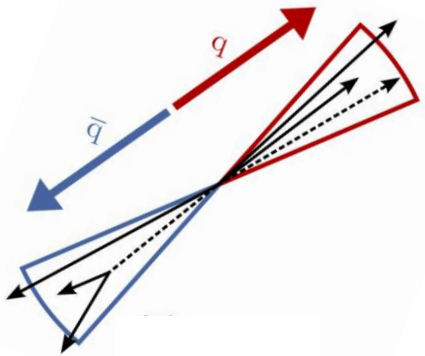
We build the missing part of each event using also the information of the Rest of Event:

$$p_{miss} = p_{beams} - p_{B_{tag}} - p_{track} - p_{ROE}$$

We will use the Extra ECL Energy and the missing mass squared to extract the signal yield

Signal Selection Strategy

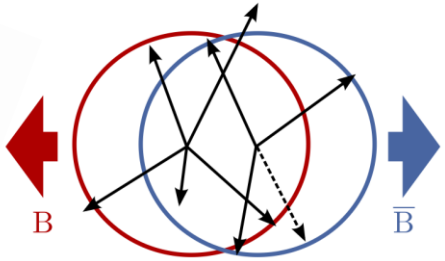
Continuum



$e^+e^- \to \tau^+\tau^-$

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

$B\overline{B}$



$p(B) \approx 0.3\,GeV/c$

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

Continuum Suppression

MVA: 2 BDTs trained, one for leptonic and one for hadronic τ^+ decays. **BDT output** $\to \mathcal{O}_{CS}$

Features = only variables not correlated with our fit variables.

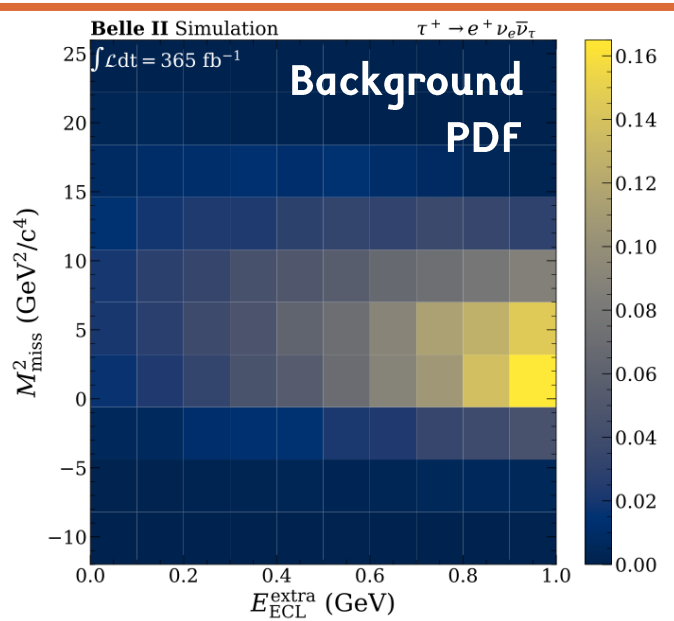
Plots in the backup.

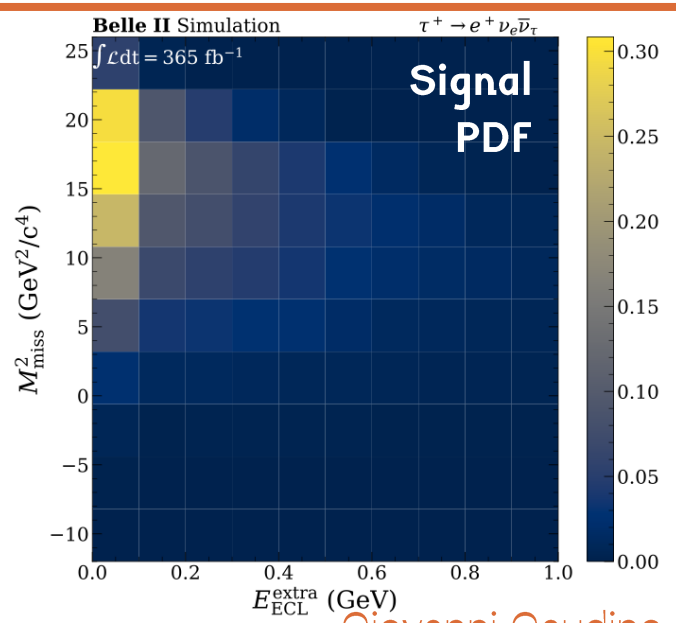
Signal Enhancement

The selection optimization is done performing **maximum likelihood fits** E_{ECL}^{extra} **vs** M_{miss}^2 on simulation PDFs.

Important variables to enhance the signal:

- **Momentum of the π/ρ (higher than the background)**
- **Continuum Suppression Output**





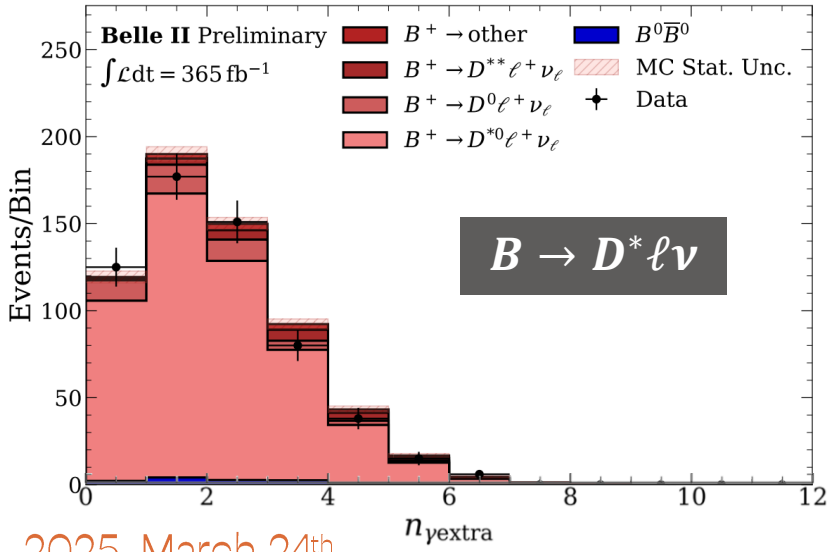
Validation

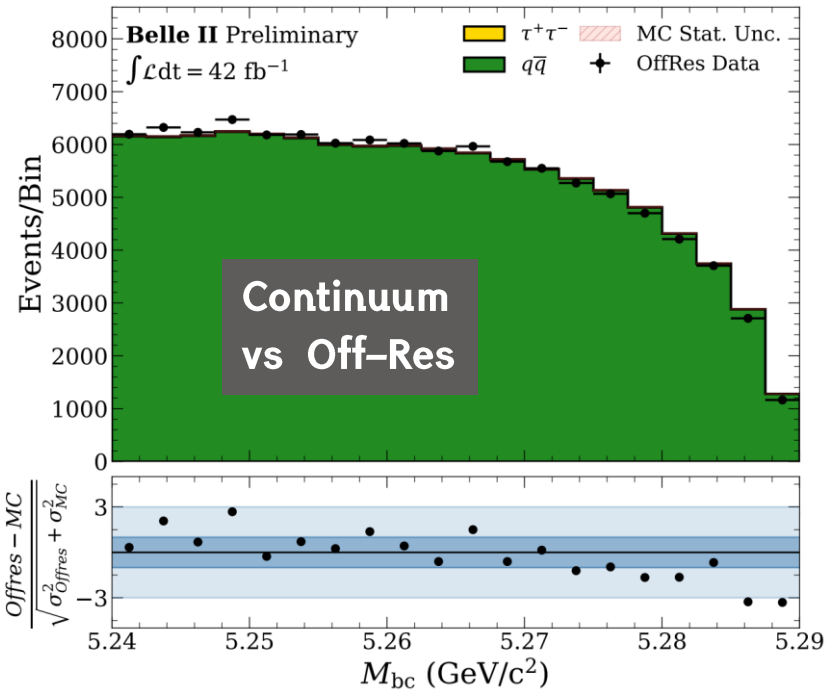
Continuum normalization and validation

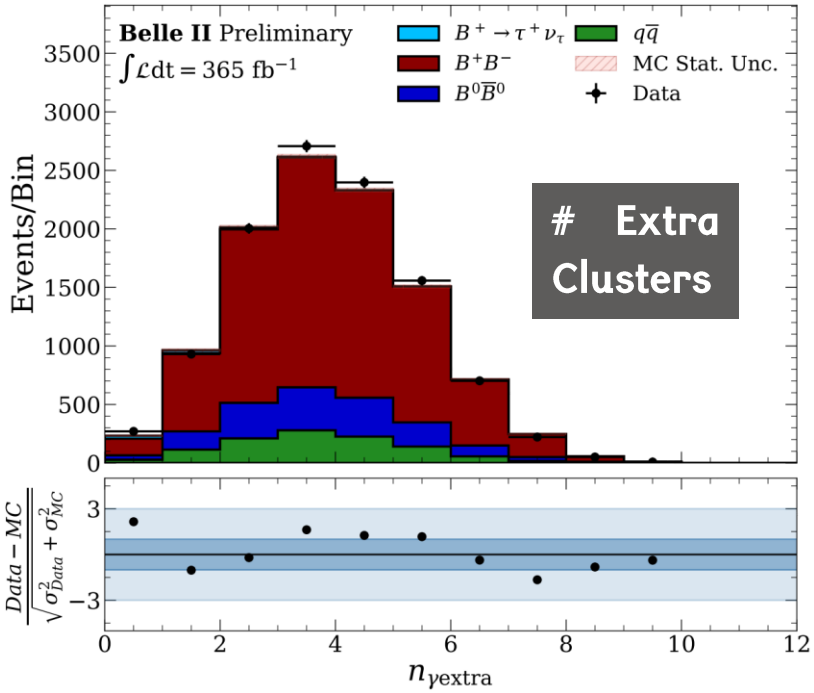
$q\bar{q}$ backgrounds validated in data sample collected 60 MeV below $\Upsilon(4S)$ resonance

Validation of extra clusters efficiency

Use control samples in the table below to validate simulation of energy deposit in the calorimenter and correct extra photons multiplicity







Validate signal efficiency

Embedding: Reconstruct $B^+ \to J/\psi K^+$, and replace $J/\psi K^+$ with $\tau\nu$ for data and MC

Similar Channel: Recontruct $B^+ \to D^{*0}\ell\nu$ to double check the signal efficiency

Main Sample	Continuum	$B\overline{B}$	Sig. $\tau \to \ell\nu\nu$	Sig. $\tau \to h\nu$
Control Sample	Off-resonance Data	Extra Tracks	$B \to D^*\ell\nu$	Double Tag

Results

arXiv:2502.04885, PRD Submitted

Statistical uncertainty dominates **(33% stat, vs 15% syst.)**

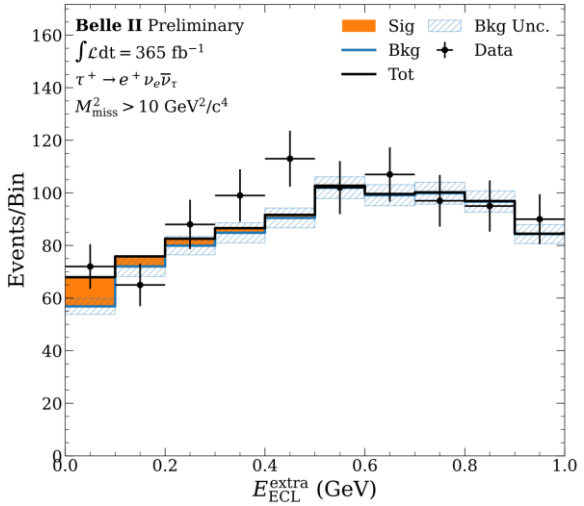
Main Systematics:

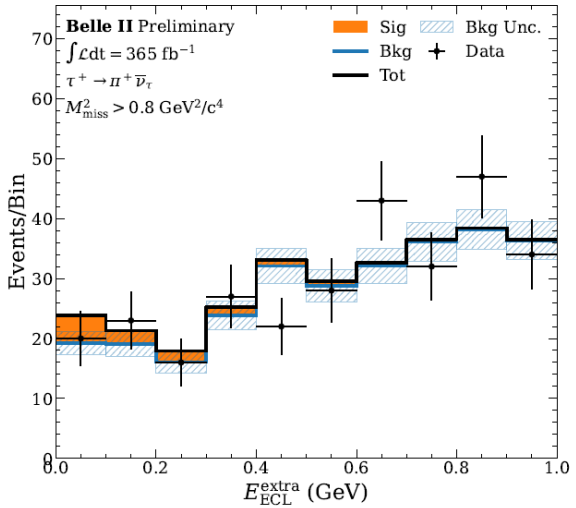
1. *Simulation sample size*
2. *Fit variables PDF corrections*
3. *Decays branching fraction in PDG*

3.0σ with respect to background-only hypothesis

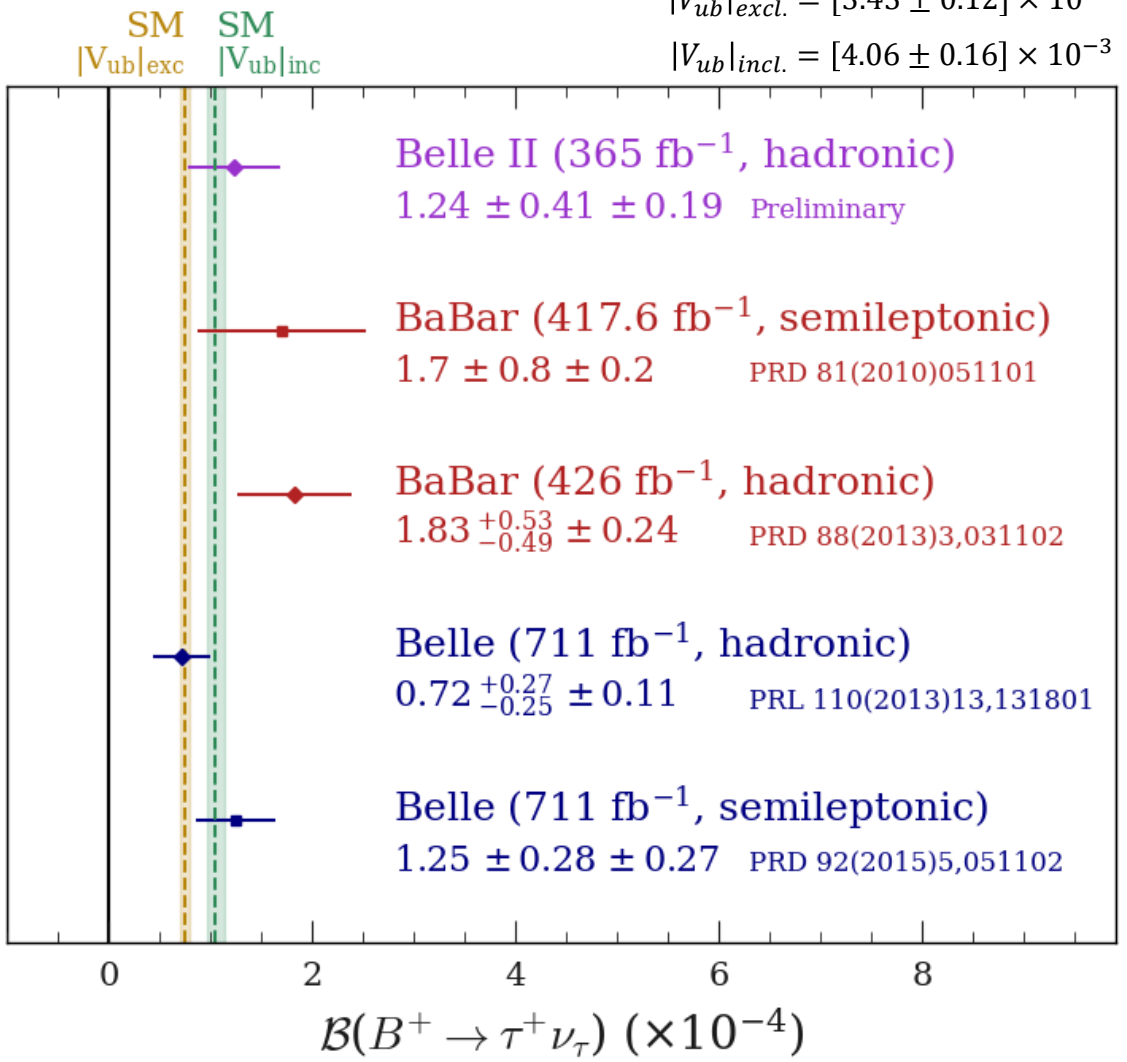
Assuming the SM, and using $f_B = 190.0 \pm 1.3$ MeV from Lattice QCD:

$$|V_{ub}| = \left(4.41^{+0.74}_{-0.89}\right) \times 10^{-3}$$





$$|V_{ub}|_{excl.} = [3.43 \pm 0.12] \times 10^{-3}$$
$$|V_{ub}|_{incl.} = [4.06 \pm 0.16] \times 10^{-3}$$



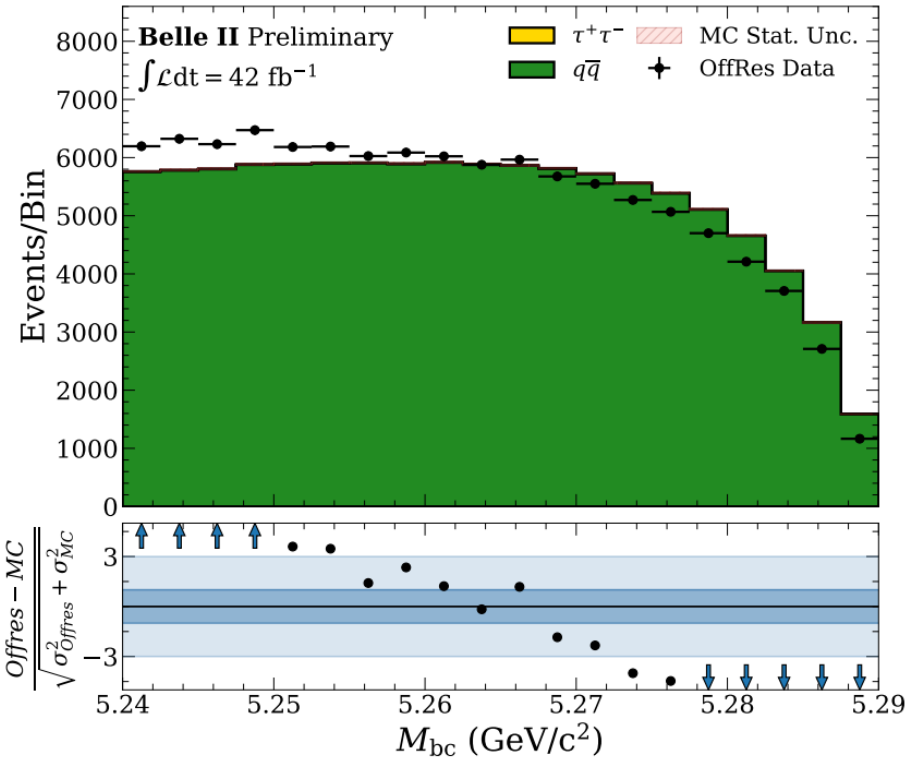
$$\mathcal{B}(B^+ \to \tau^+ \nu) = (1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-4}$$

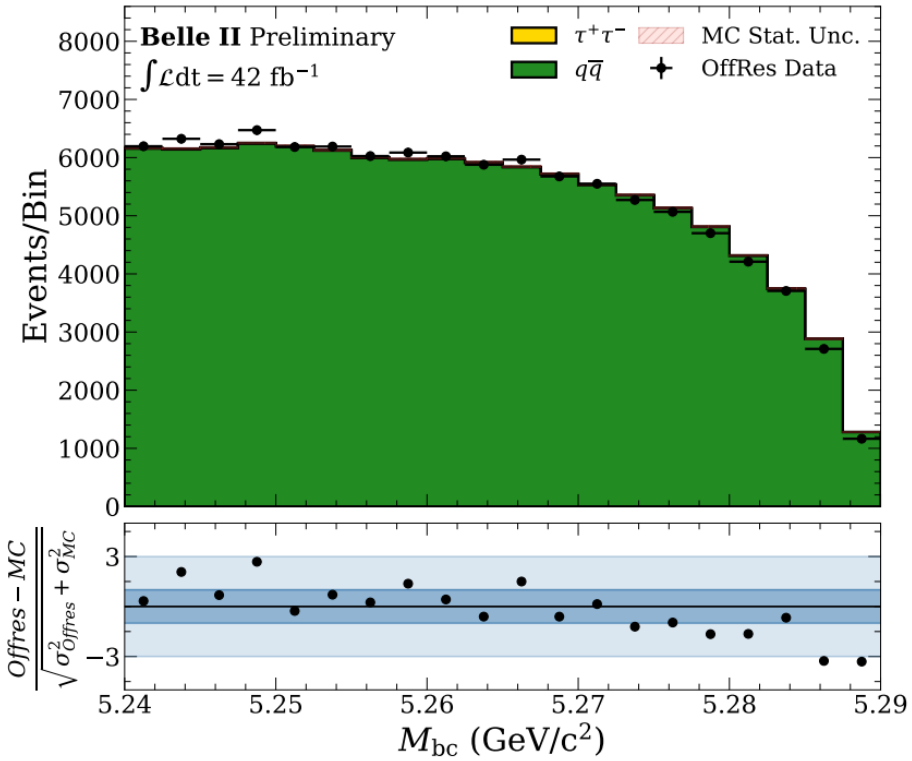
Thanks for the attention!

since 1966
Rencontres de Moriond

Continuum reweighting BDT

We enhance MC simulation accuracy by adjusting events using multivariate analysis (MVA) to identify and correct data–MC differences. We use a Fast Boosted Decision Tree (FBDT) classifier for reweighting. Calibration involves 200/fb of continuum MC events and all off–resonance data (42/fb).





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

$$\Delta E_{off} = \left(\frac{E_{on}}{E_{off}}\right) E_B^* - \frac{E_{on}}{2}$$

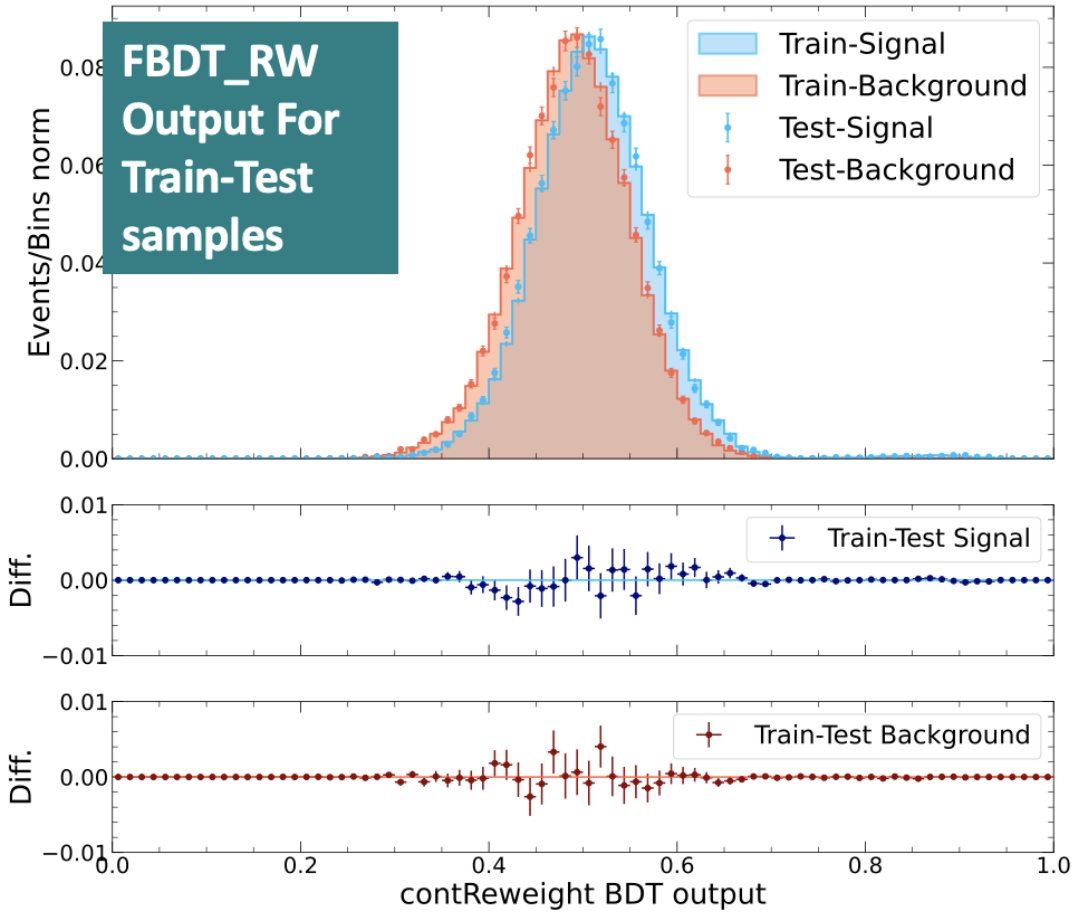
$$M_{bc,off} = \sqrt{\frac{E_{on}^2}{4} - \frac{E_{on}^2}{E_{off}^2} p_B^{*2}}$$

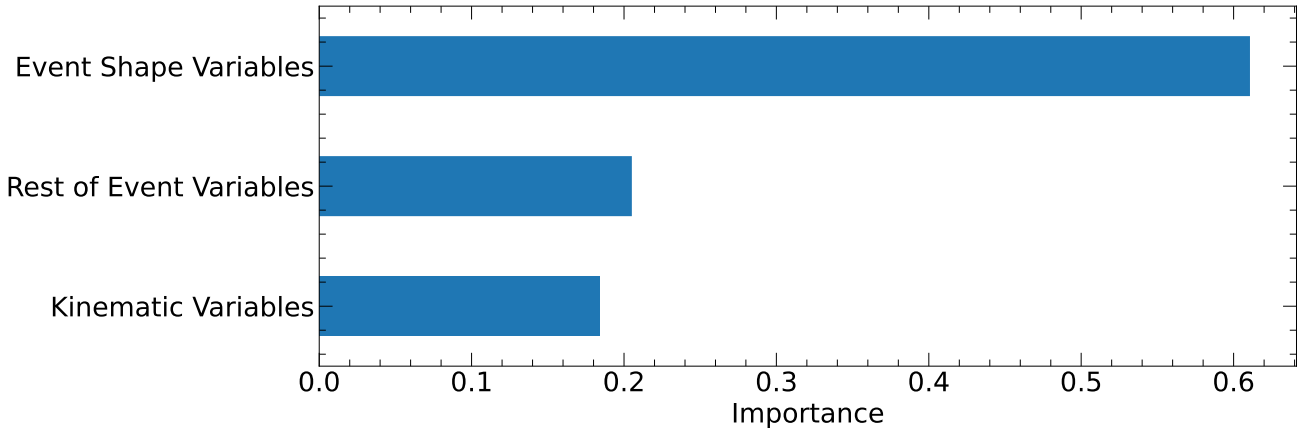
Variables distributions before and after the correction

Continuum reweighting BDT

We train a FastBDT using **Off–Res data as "Signal"** and **MC continuum as "Background" to correct the MC shape to Off–Res data.**

- 1.3M events, Train/Test sample 80%/20%





The discriminator output is transformed in an event–by–event weight to correct MC shape:

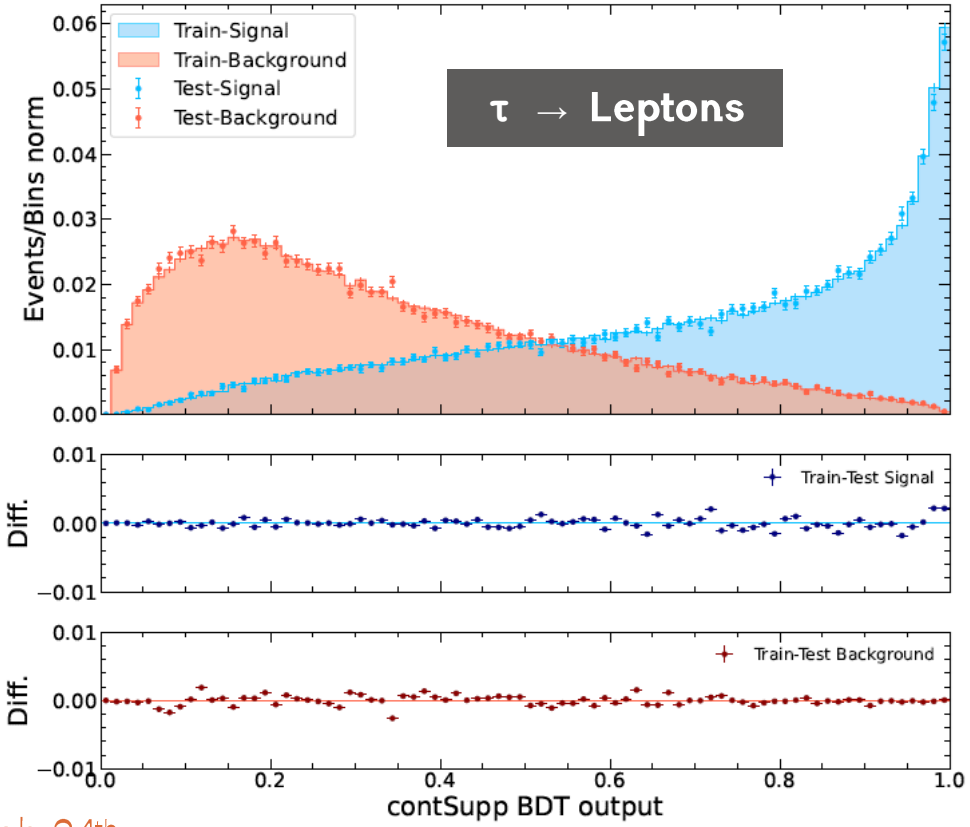
$$w_i = \frac{\mathcal{O}_{CR,i}}{1 - \mathcal{O}_{CR,i}}$$

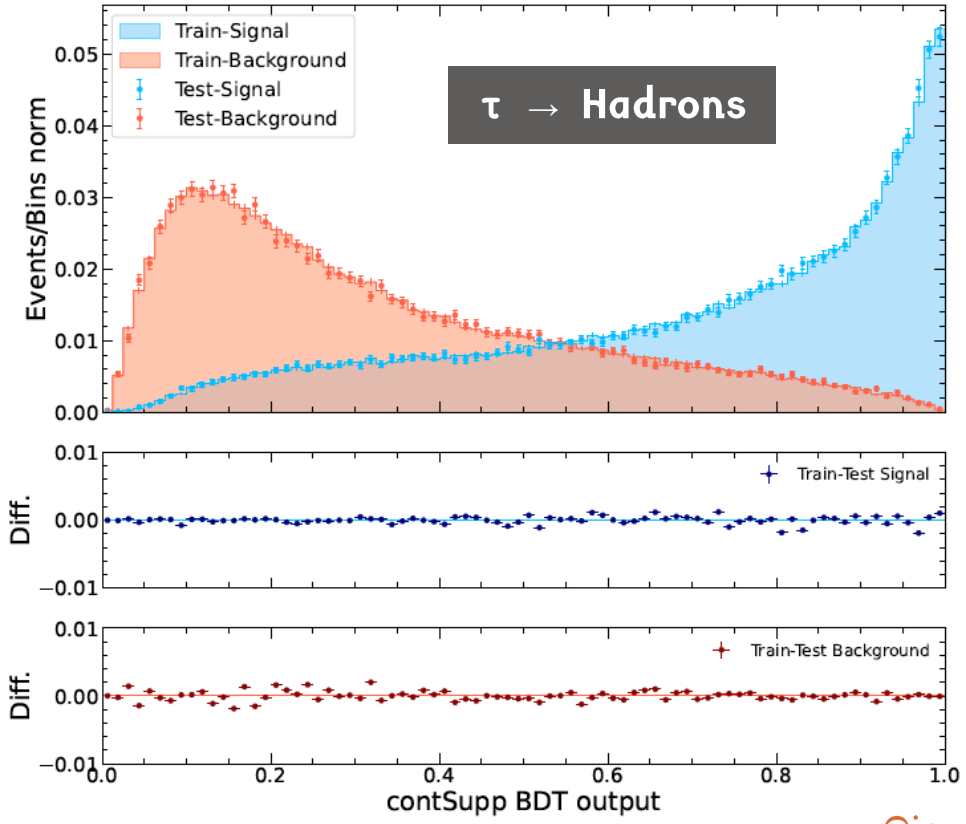
Continuum Suppression BDT

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

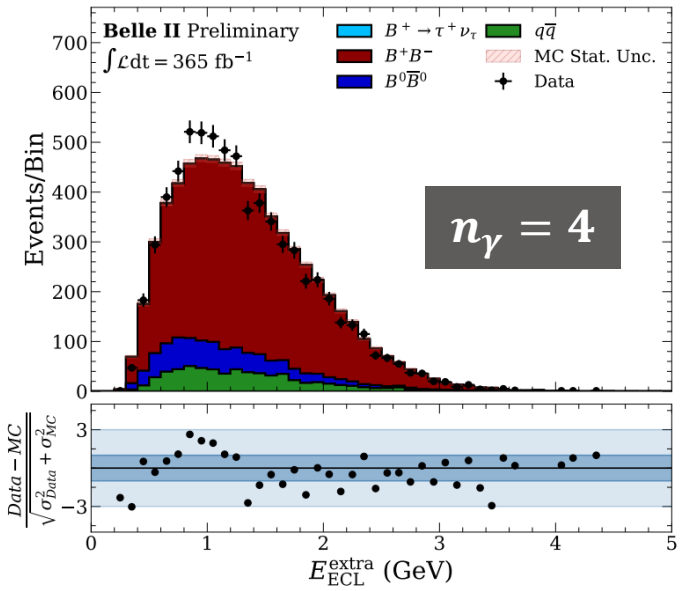
In the training, the weights from continuum reweighting are used.

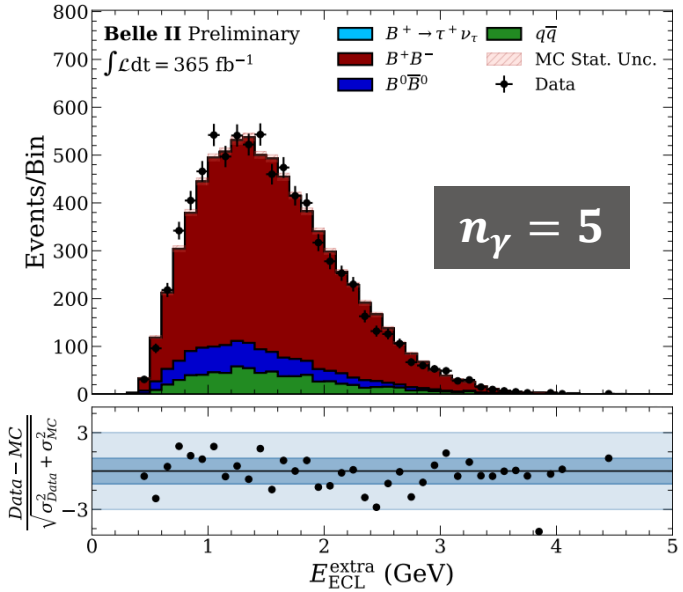
- 300K events, Train/Test sample 80%/20%
- Signal/Background events ratio = 1
- Features = only variables with good Data/MC agreement and less correlated with our fit variables.

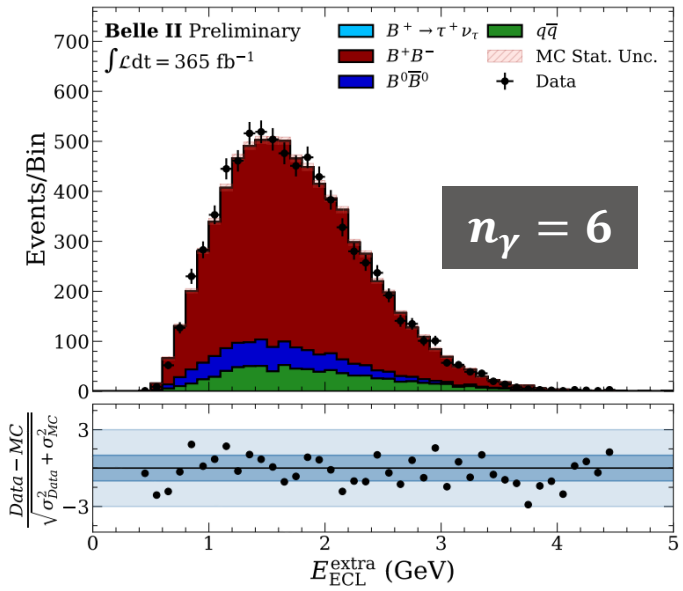


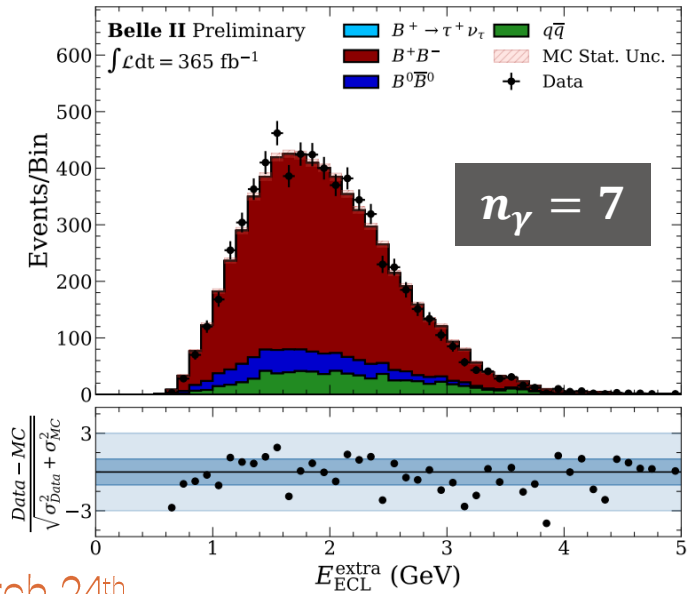


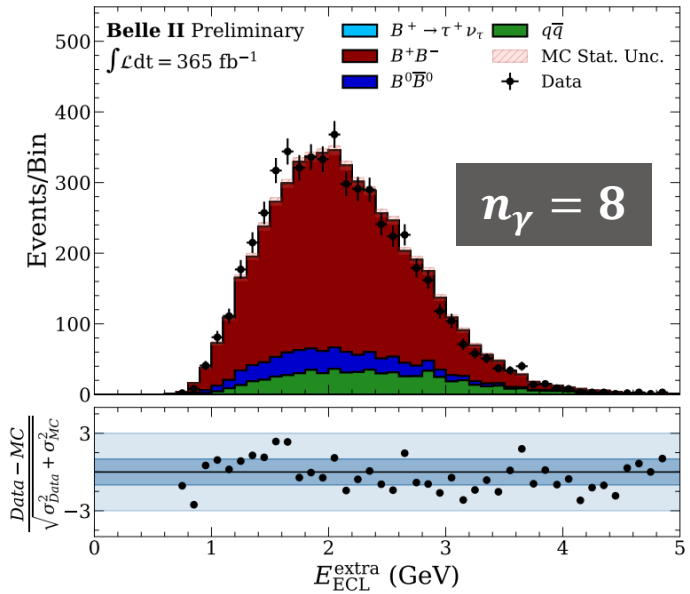
Study of Extra Clusters

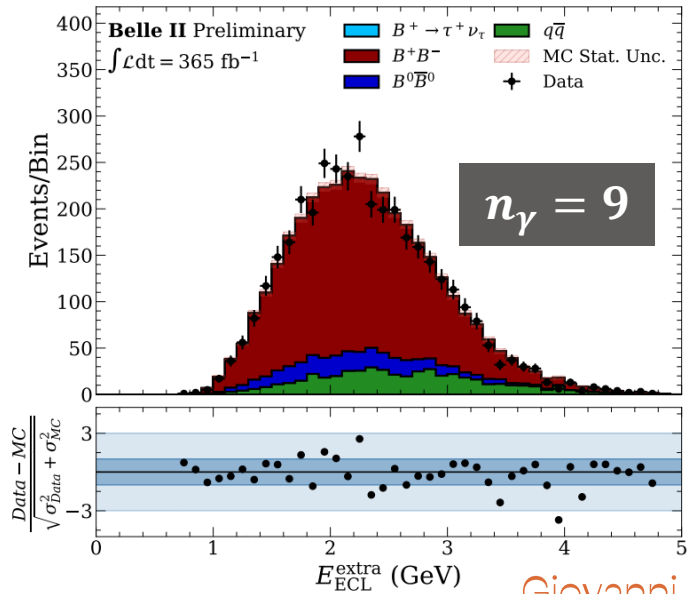








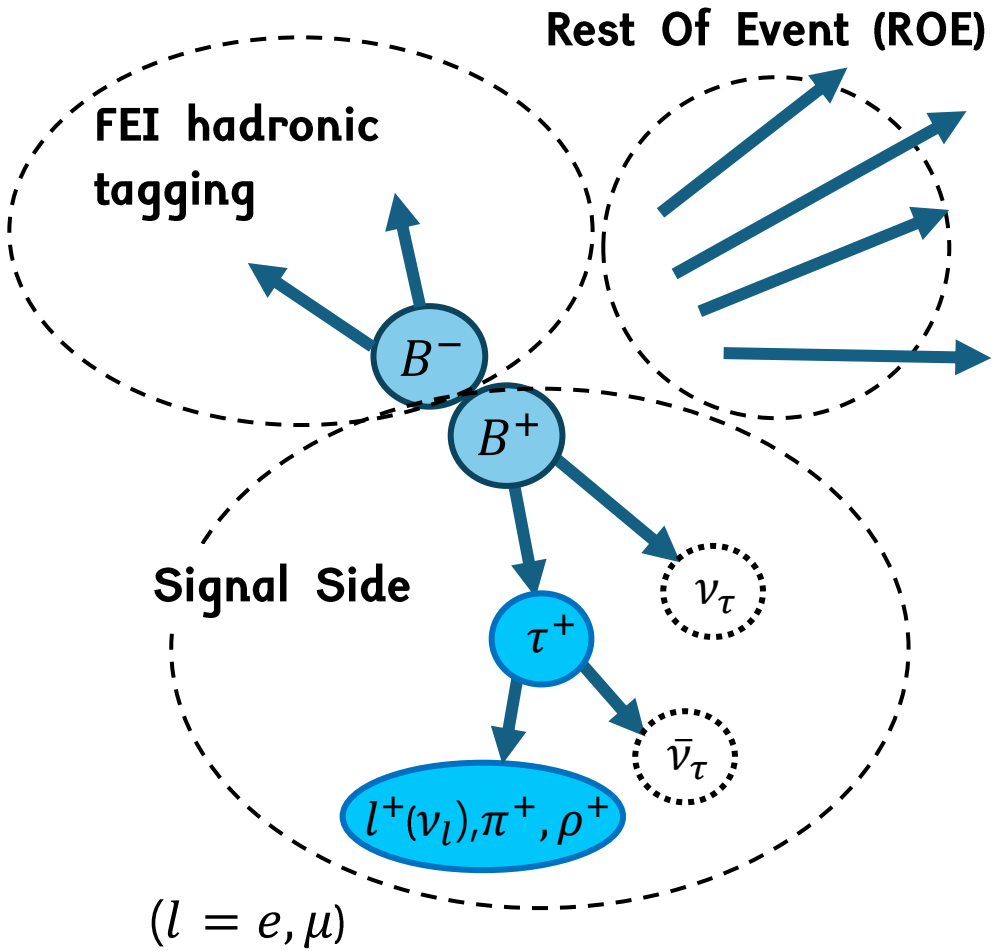




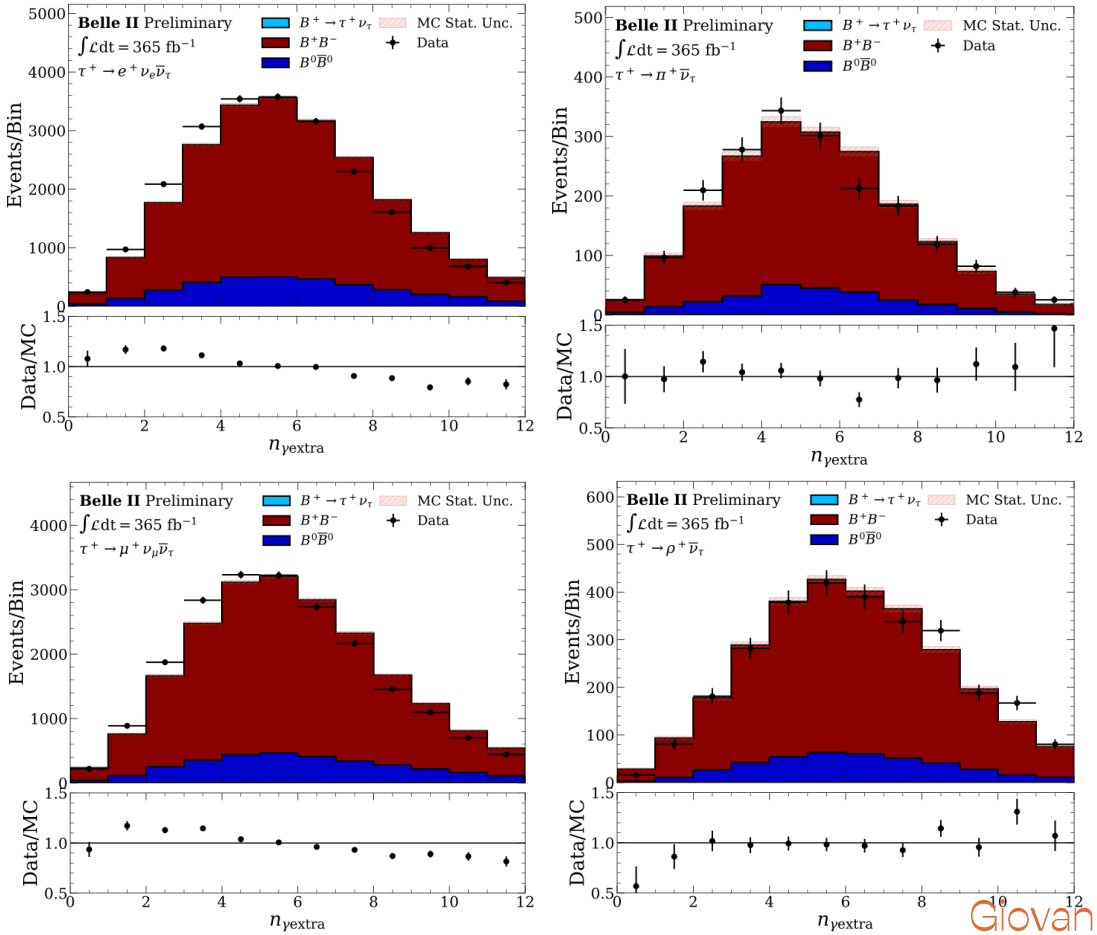
Extra Tracks Control Sample

For the main channel, we require no charged tracks in the ROE.
In this control samples, $N_{ROE\,Tracks} > 1$

→ **same background composition but no signal events.**

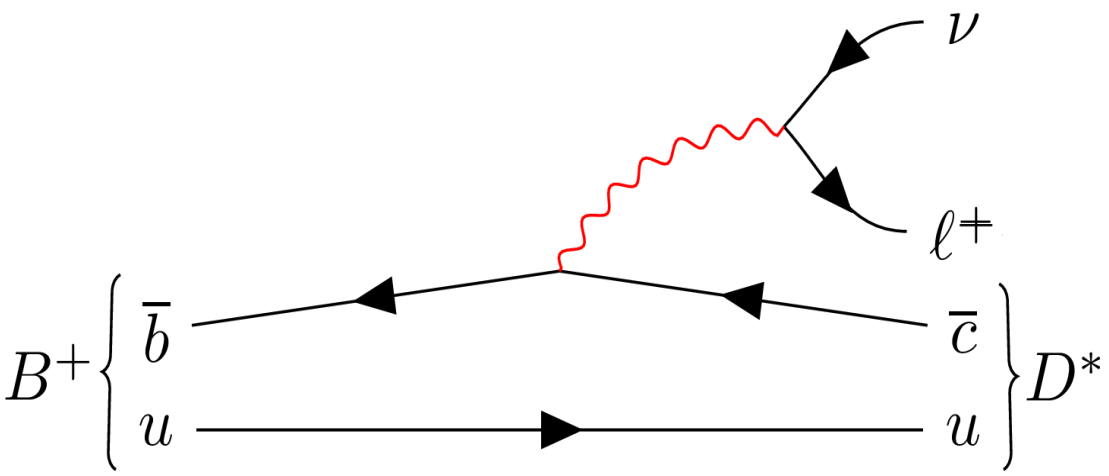


We apply same reconstruction and selection as for the main analysis.



$B^+ \to D^{*0} \ell^+ \nu_\ell$ control sample

In this control sample we have is one lepton and the D^{*0} is fully reconstructed through hadronic decays. → $\boldsymbol{E_{ECL}^{extra}}$ **peaks at 0.**



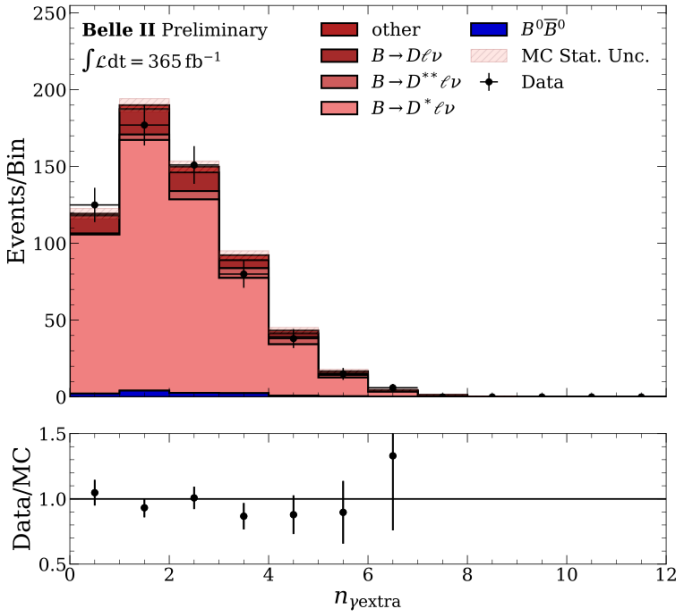
D^* decays

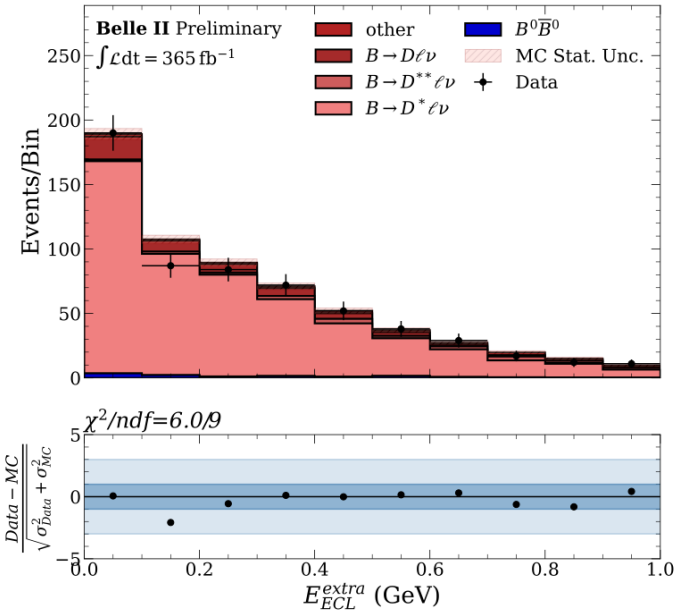
- $D^* \to D\gamma$
- $D^* \to D\pi^0$

D decays

- $D \to K\pi$
- $D \to K\pi\pi\pi$
- $D \to K_S\pi\pi$

We apply same reconstruction and selection as for the main analysis.

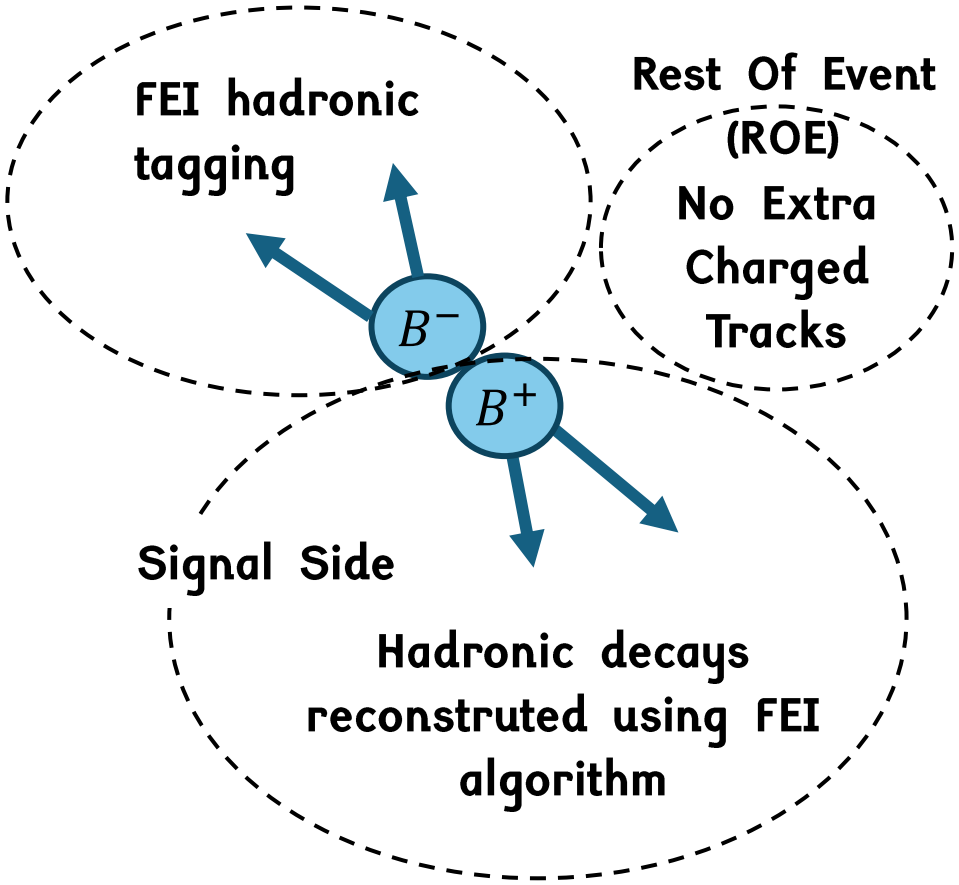




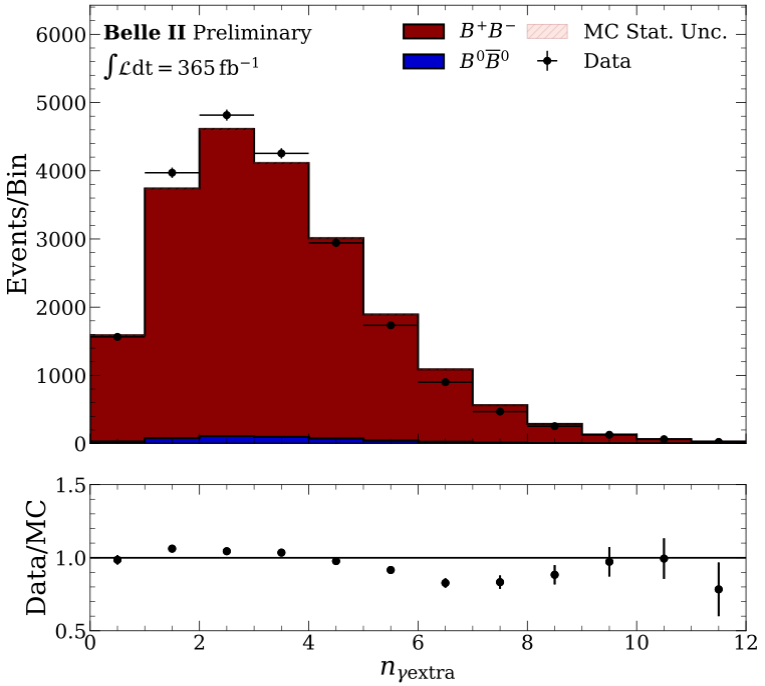
We also check the agreement of signal selection efficiency in data and MC and find a **Data/MC ratio equal to 0.96 ± 0.04 → no further efficiency correction is applied.**

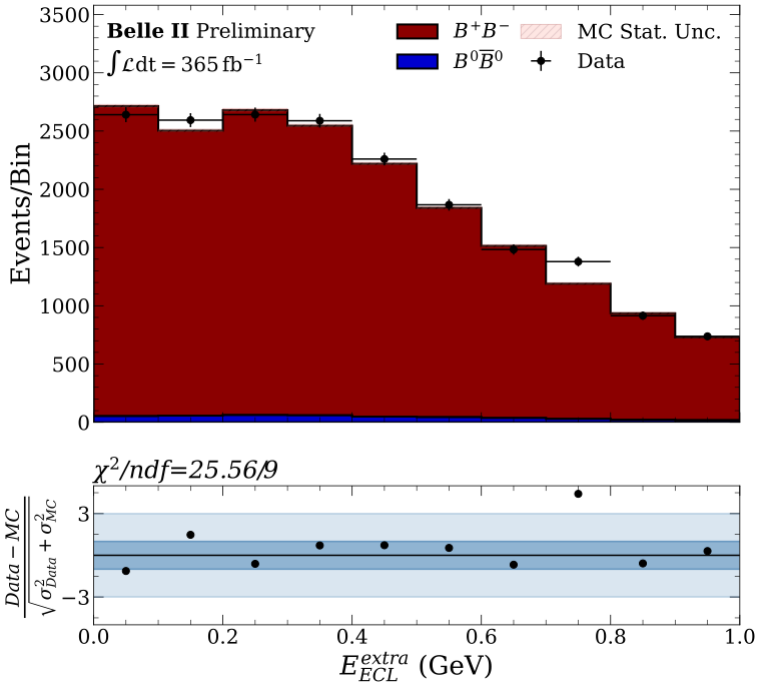
Double Tag Control Sample

We reconstruct the **two B candidates using the hadronic tagging FEI alogritm**.
As for the haronic signal channel, the decay is fully reconstructed.



We apply same reconstruction and selection as for the main analysis.





Systematics Budget

Source	Syst.
Simulation statistics	13.3%
Fit variables PDF corrections	5.5%
Decays branching fractions in MC	4.1%
Tag B^- reconstruction efficiency	2.2%
Continuum reweighting	1.9%
π^0 reconstruction efficiency	0.9%
Continuum normalization	0.7%
Particle identification	0.6%
Number of produced $\Upsilon(4S)$	1.5%
Fraction of B^+B^- pairs	2.1%
Tracking efficiency	0.2%
Total	15.5%

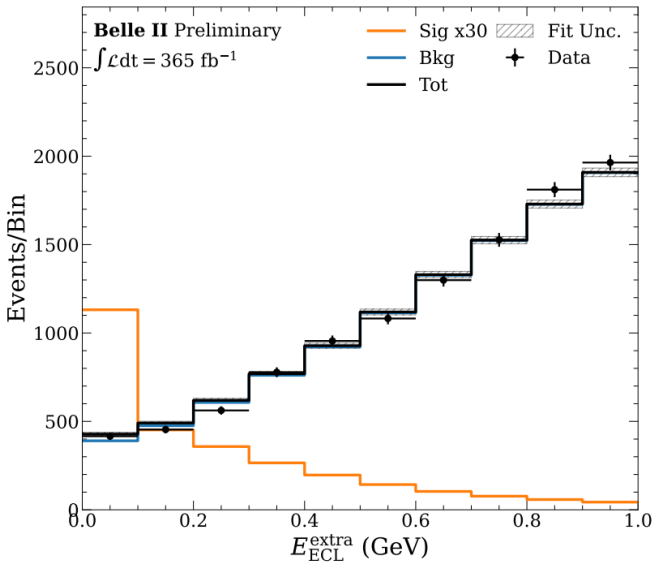
It is expected to reduce using more simulations.

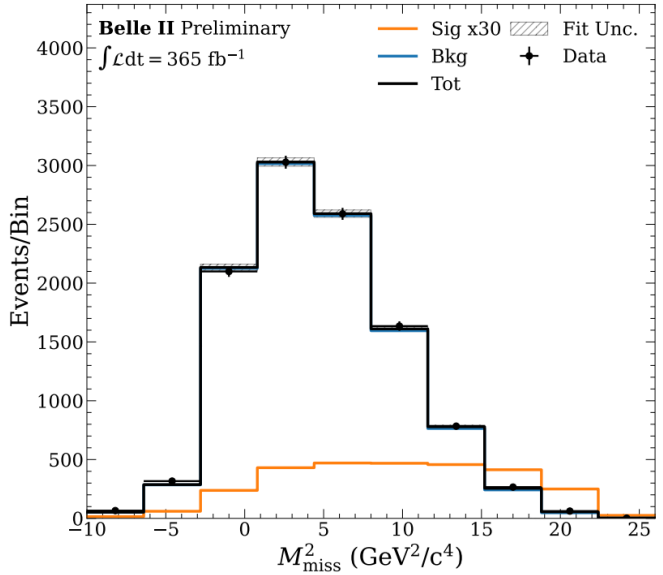
It is expected to reduce with increasing luminosity and better modeling of ECL photons in MC simulations.

The effect of each source on the final result is estimated by fluctuating the assumptions several times and propagating the effect on the PDF shapes, generating in this way a set of alternative PDFs.

When uncertainties do not affect the signal yields, they are propagated directly to the BR.

After Fit Plots





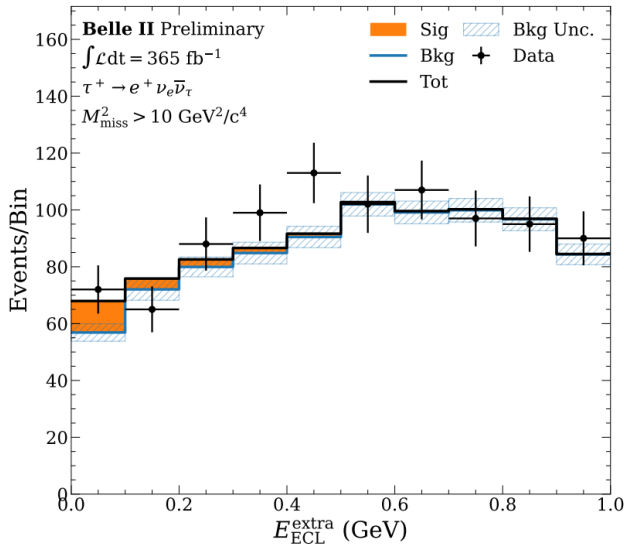
	$\epsilon(10^{-4})$	$\epsilon(10^{-4})$ Belle
e^+	7.3	3.0
μ^+	7.6	3.1
π^+	3.4	1.8
ρ^+	3.1	3.4

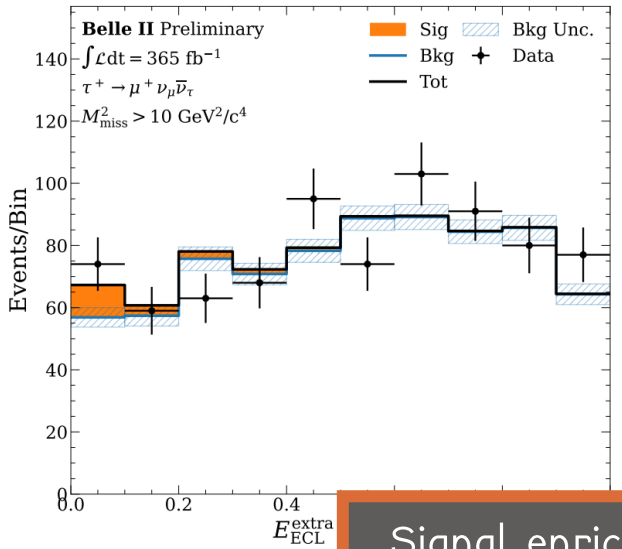
Each ϵ_k includes the τ^+ branching fractions and cross-feed as predicted by MC and calibrated on control samples.

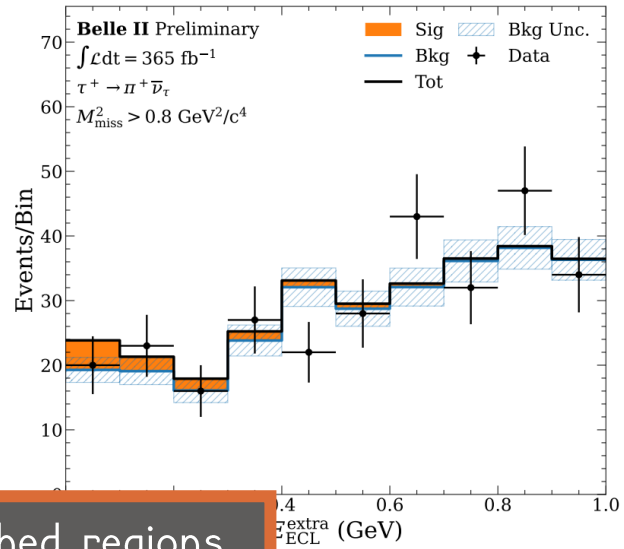
Five free parameters: four background yields and one common branching fraction.

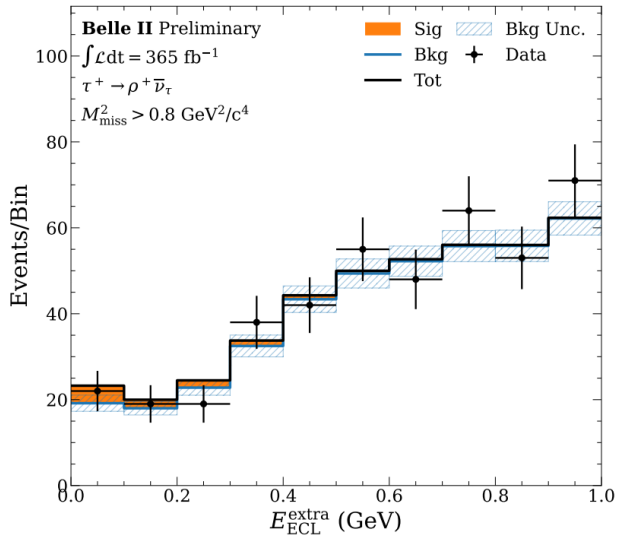
E_{ECL}^{extra} and M^2_{miss} 2D PDFs from the MC calibrated on the control samples.

$$n_{s,k} = 2n_{\Upsilon(4S)} \cdot f^{+-} \cdot \epsilon_k \cdot B(B^+ \to \tau^+ \nu_\tau)$$









Signal enriched regions