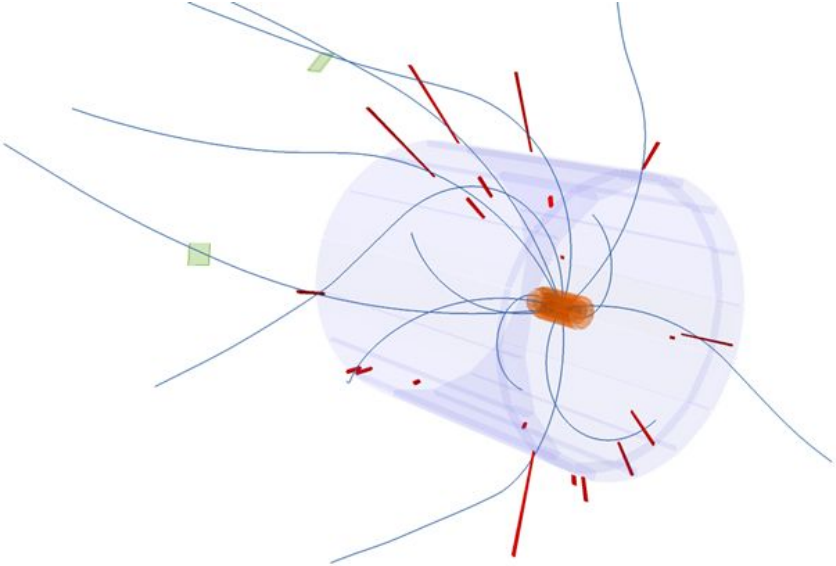

Measurement of the differential branching ratio and lepton angle in semileptonic $B \to X_c l\nu$ decays

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With funding from the:

Federal Ministry of Research, Technology and Space

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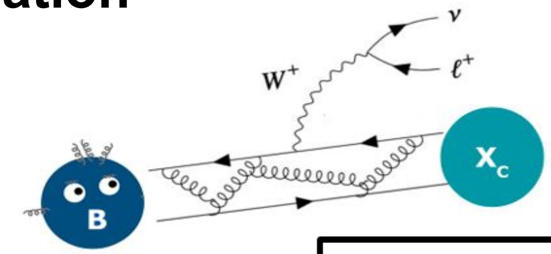
Motivation



$e^+e^- \rightarrow q\bar{q}$

continuum

Signal

$e^+e^- \rightarrow B\bar{B} \rightarrow X_c\,\ell\,\nu_l$

$e^+e^- \rightarrow B\bar{B} \rightarrow bkg$

background

- ➔ Reconstructed dataset: MC15rd with hadronic FEI skim
- ➔ Channels studied: e^-, μ^-

Objective: **Extracting $|V_{cb}|$ from the branching fraction measurements**

- Resolution studies of various kinematic variables
- Efficiency calculation performed with and without FSR photons (PHOTOS)
- Efficiency corrections and unfolding to obtain the truth-level spectrum of kinematic variables
- Signal yield extraction via $\mathbf{m_X}$ fitting in bins of $\mathbf{p_l^B}$, $\mathbf{q^2}$ and $\mathbf{\cos\theta_l}$:
- Resolution studies via migration matrix
- Systematics

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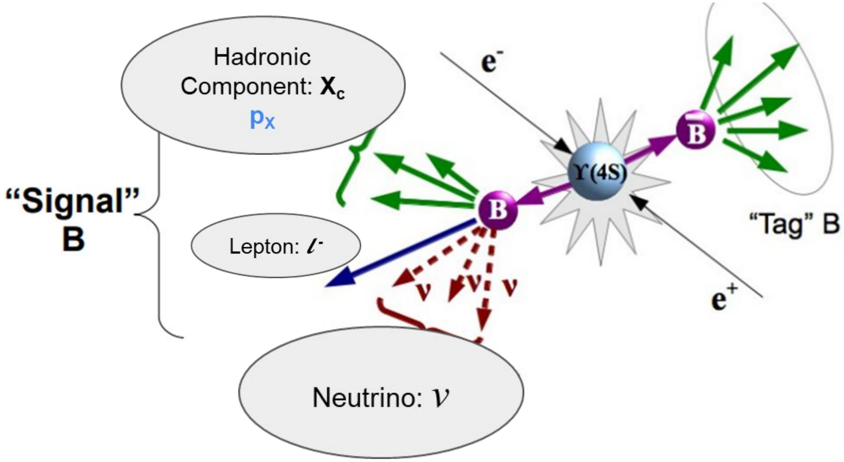
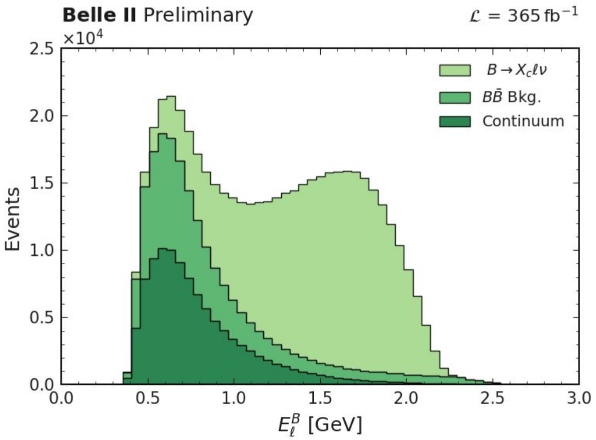
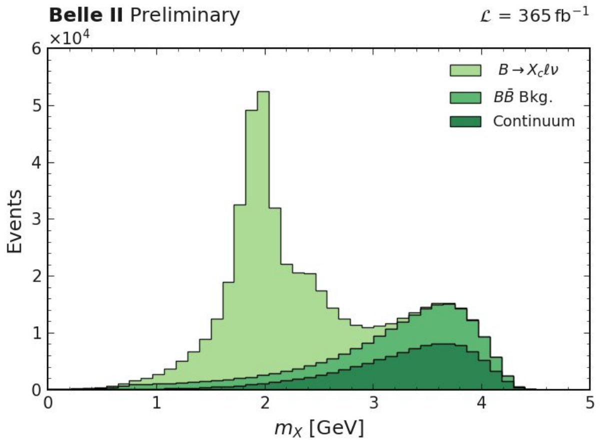
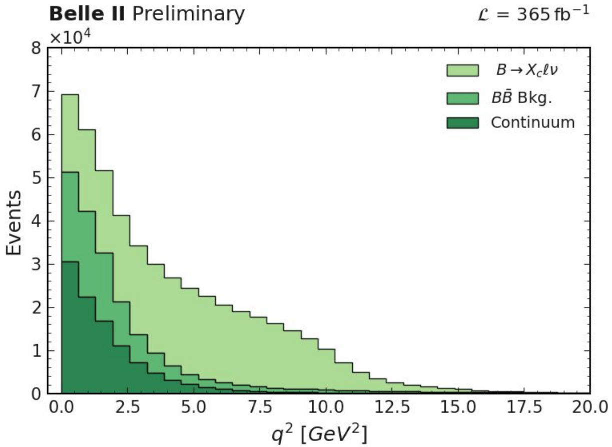
Analysis Outline

- Study kinematic variables:
  - Leptons kinematics: $\mathbf{p_l^B}$, $\mathbf{E_l^B}$
  - Hadronic system (X_c) invariant mass:
    $\mathbf{m_X} = (p_{\text{Signal B}} - p_l - p_\nu)$
  - Momentum transfer:
    $\mathbf{q^2} = (p_{\text{Signal B}} - p_X)^2 = (p_l + p_\nu)^2$
  - Lepton Angle: $\cos \boldsymbol{\theta_l}$





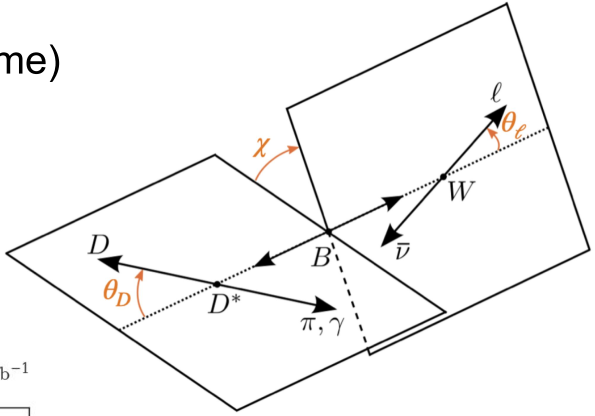




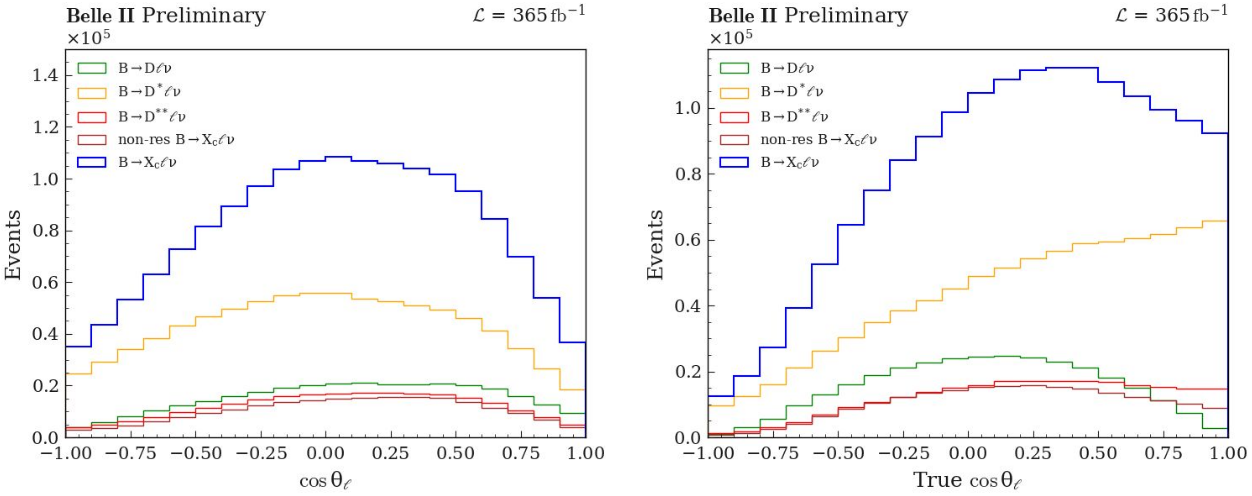
LEPTON ANGLE: cos θ_l

The angle **between the direction of the W boson** (in B rest frame) and the **direction of the lepton** (in W rest frame)

- $p_W = p_B - p_X$
- Boost lepton into CMS frame of W
- cos(p_W in B rest frame, p_l in W rest frame)



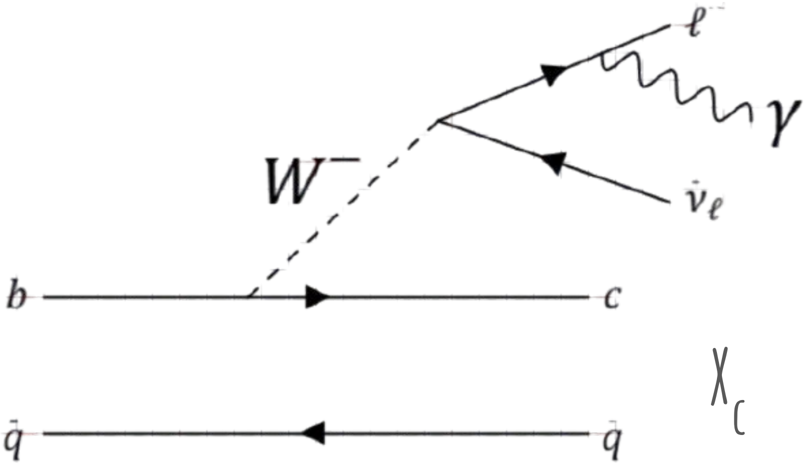
$$\cos\theta_l = \frac{p_W^{B-frame}\, p_l^{W-frame}}{|p_W^{B-frame}|\,|p_l^{W-frame}|}$$



Reconstructed and True cos $\boldsymbol{\theta}_l$

- Inspected components of p_W in the B rest frame
- Inspected components of p_X in the ROE frame

FSR PHOTONS (PHOTOS)



FSR

X_c

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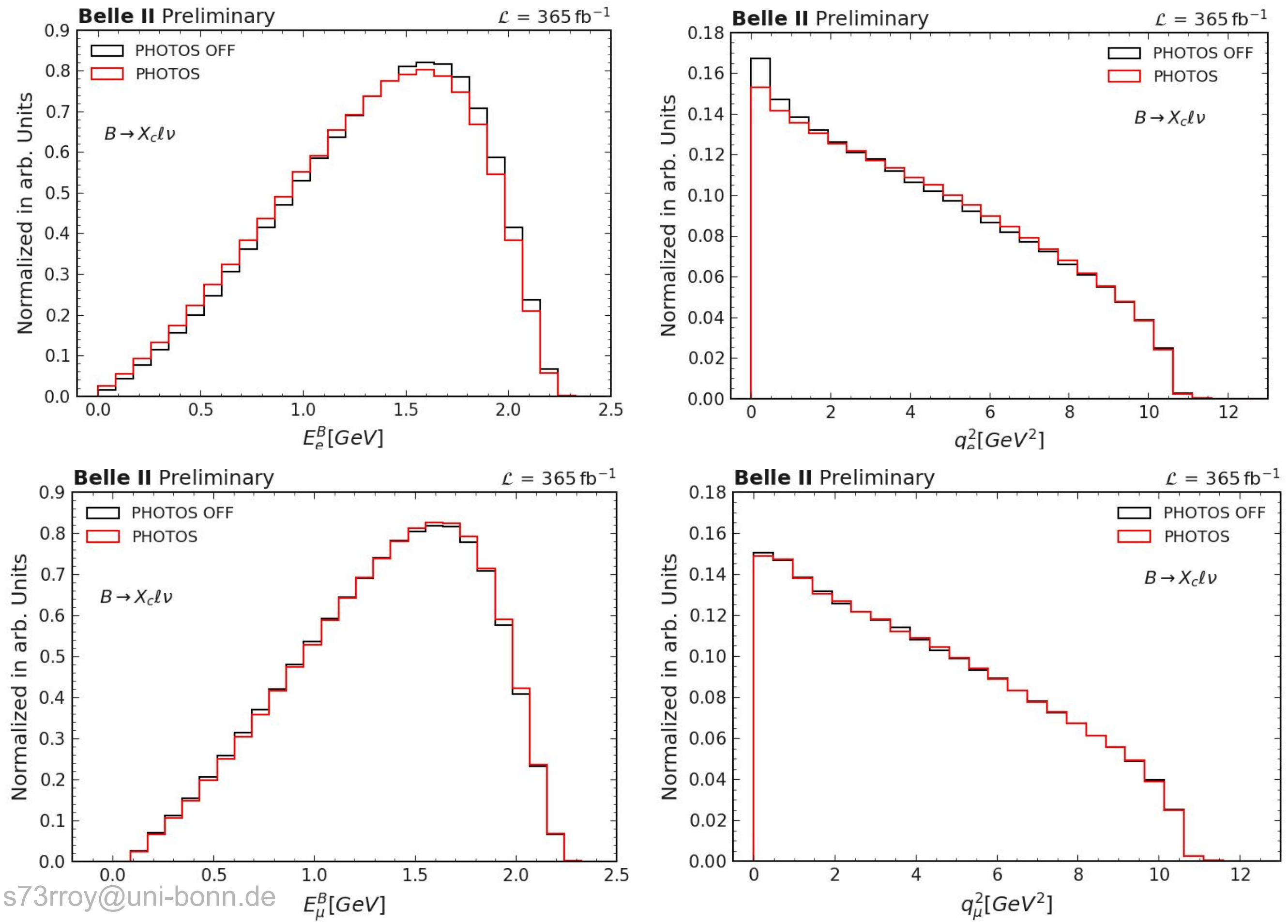
Inspection of q^2 and E_l^B



- From the E_l^B distribution, we can conclude that for muons FSR is less significant

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MOMENTUM STUDY OF THE TAG B MESON

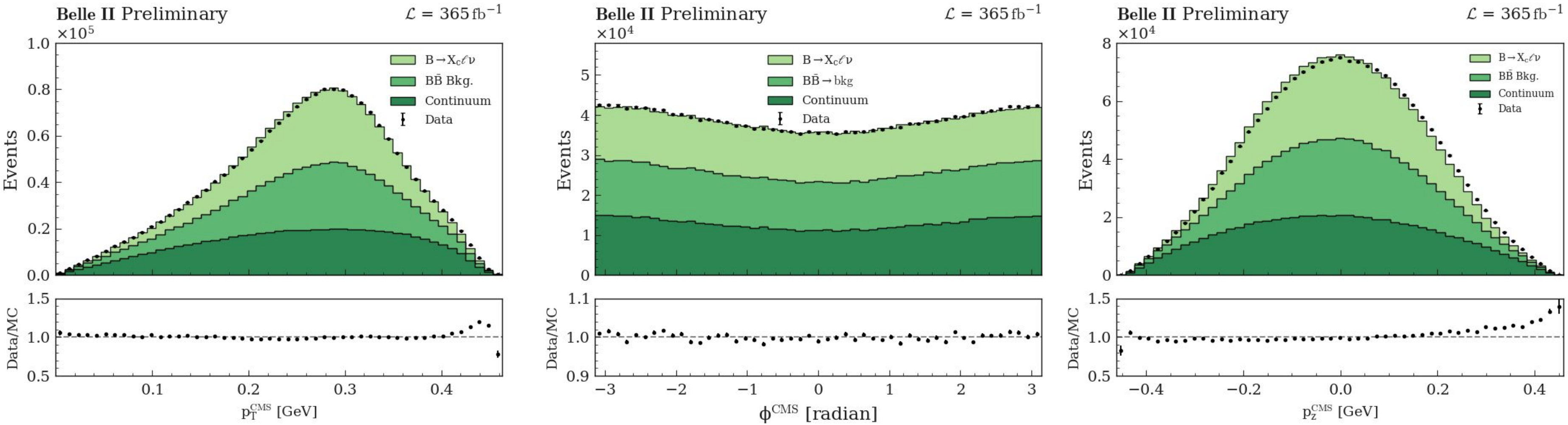
B_{tag} momentum

- Allows us to fully reconstruct the kinematics of B-meson decays
- This improves event selection and background suppression, enhancing precision measurements of $|V_{cb}|$

p_T: transverse momentum

ϕ: azimuthal angle

p_z: longitudinal momentum



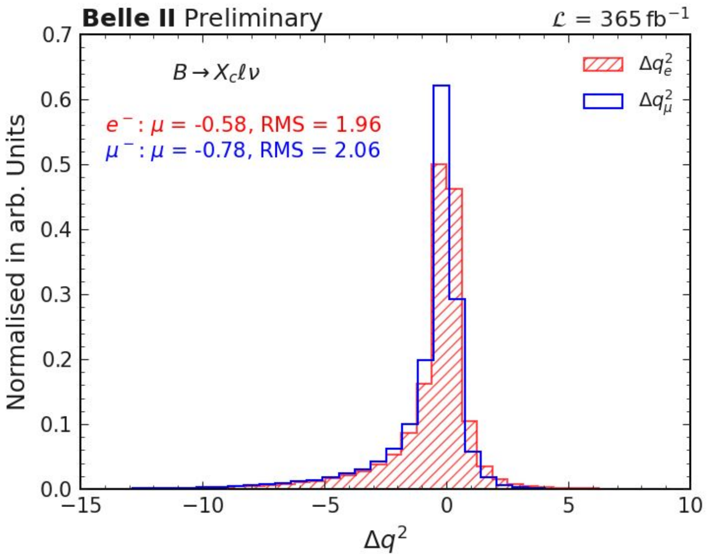
RESOLUTION STUDY

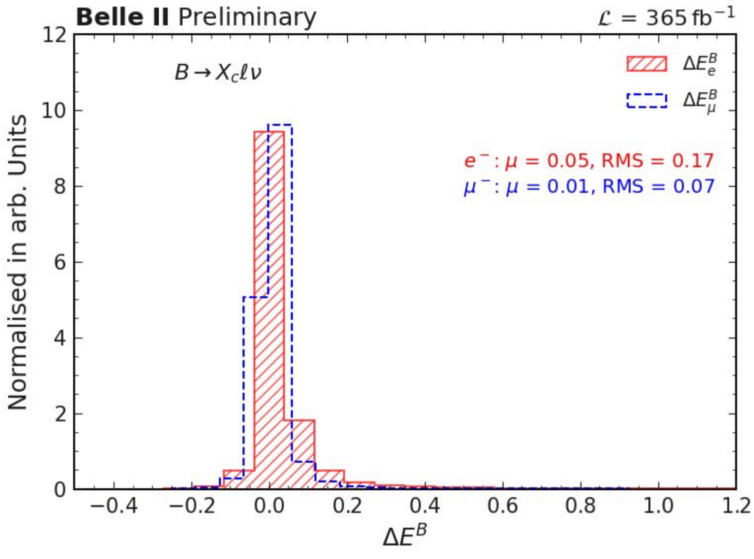
Distributions of Δq^2 and ΔE_l^B

- Quantify the resolution of our reconstruction
- Understanding the smearing between *true* and *reconstructed* kinematics is essential to correct measurements

$\Delta q^2 = q^2_{true} - q^2_{reco}$

$\Delta E_l^B = E_l^B{}_{true} - E_l^B{}_{reco}$





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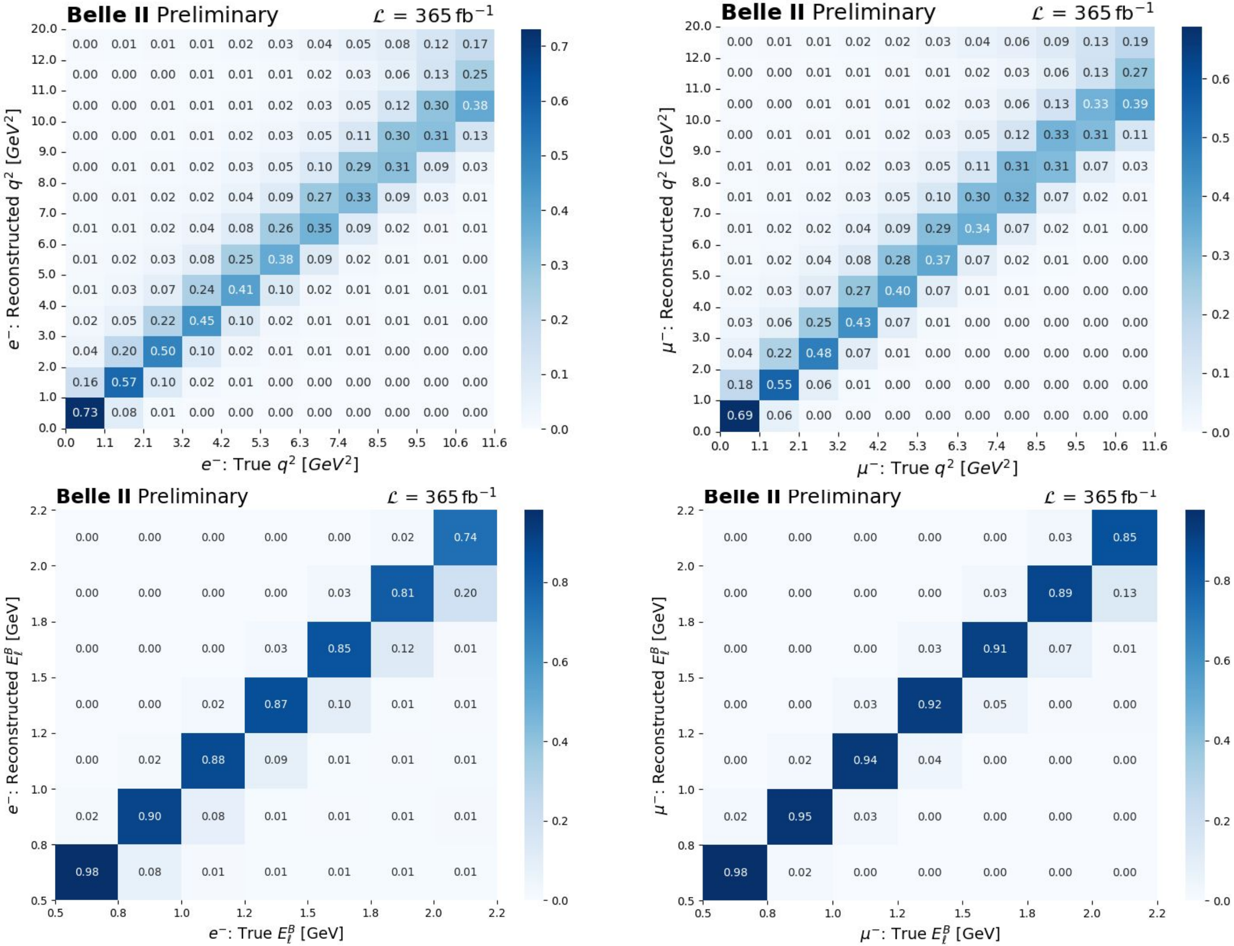
Migration Matrix Construction

- MC samples for $B \to X_c \ell \nu$: containing both the *true* generator-level quantities and the detector-level reconstructed quantities
- These events include detector response, acceptance, and reconstruction effects

$$\boxed{\mathcal{M}_{ij} = P(measured\ in\ bin\ i \mid true\ in\ bin\ j)}$$

- Each simulated event is assigned to its true bin j and reconstructed bin i,
- A 2D histogram over many events, shows how events of a kinematic variable **“migrate”** from its true bin into a reconstructed bin
- $\boldsymbol{M}$ encodes the smearing and efficiency of the detector
- Used in **unfolding**: correcting the measured spectrum back to the truth level
- Ensures that extracted physics quantities (differential decay rates, form factors, V_{cb}) are not biased by detector effects

q^2 and E_l^B resolutions



- Muons have better resolution as compared to electrons
- Electrons lose energy via bremsstrahlung and showering, smearing the measurement

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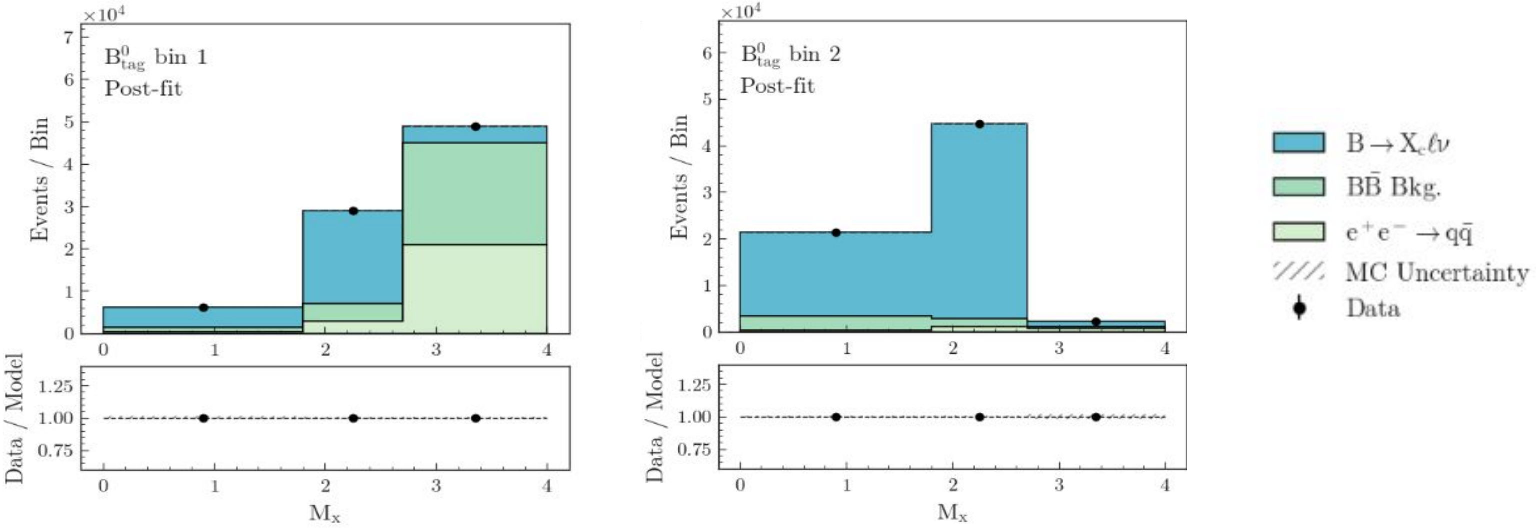
SIGNAL YIELDS EXTRACTION

Fitting hadronic mass M_X

- Considering the kinematic variables :$\mathbf{p_l^B}$, $\mathbf{q^2}$ **and cos** $\boldsymbol{\theta_l}$ in fine bins
- In each bin, fitting the hadronic mass $\mathbf{m_X}$ distribution in three coarse bins
  - Using a pyhf model to set up the signal, background and continuum templates
  - Using cabinetry to obtain the fit yields for thr signal events ($B \rightarrow X_c l \nu$)



- Fitting in m_X **separates different final states, stabilizes unfolding, and reduces detector smearing**, while still keeping enough statistics for precision

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UNFOLDING

We want the true distribution of the kinematic variable and not the smeared one!

- Using the migration matrix inversion, the signal yields obtained and incorporating efficiency corrections, we obtain the unfolded truth level spectrum

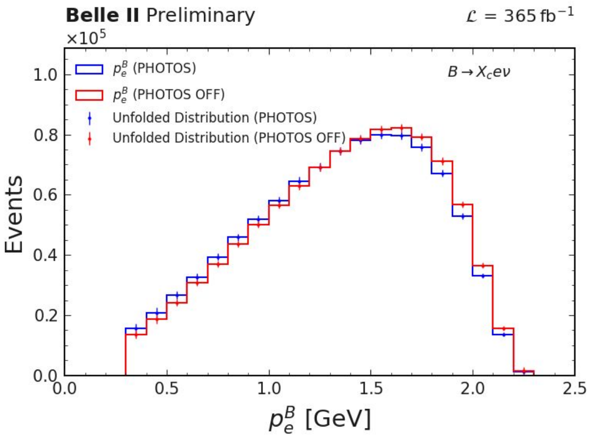
$$\boxed{Unfolded\ Distribution = \mathcal{M}^{-1} .\ \mathcal{E}^{-1} .\ (post\ fit\ yields)_{X_c l\nu}}$$

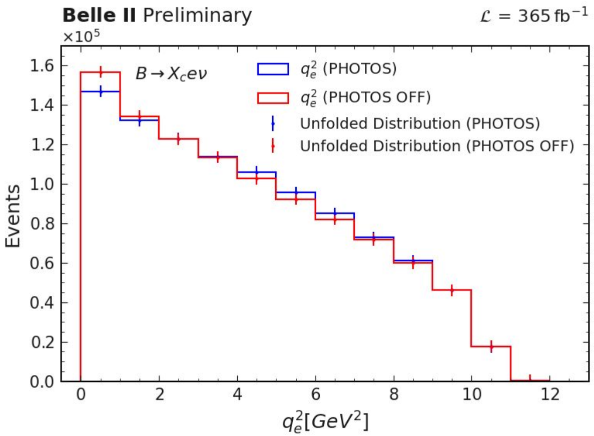
Migration Matrix

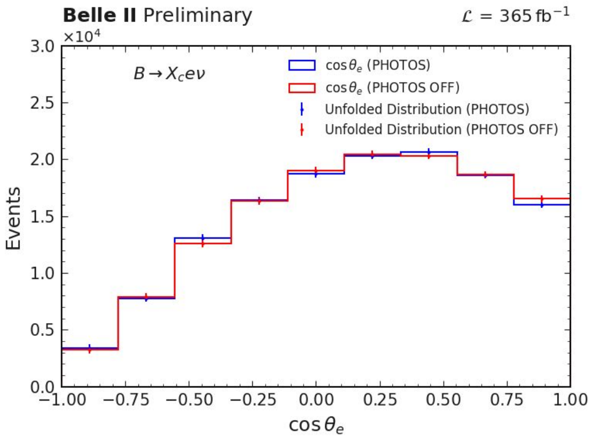
Efficiency corrections

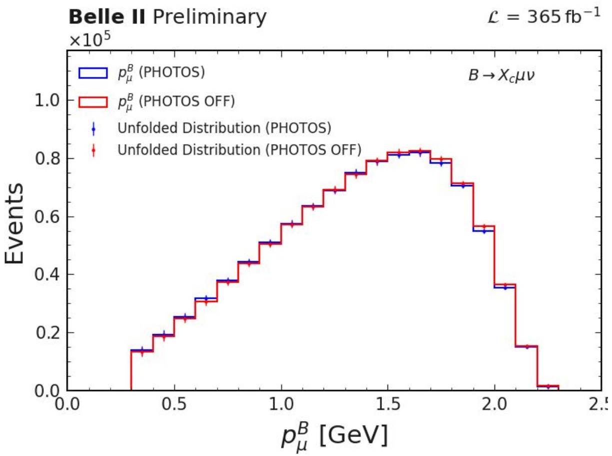
- Examining the unfolded spectrum for p_l^B, q^2 and cos $\boldsymbol{\theta}_l$

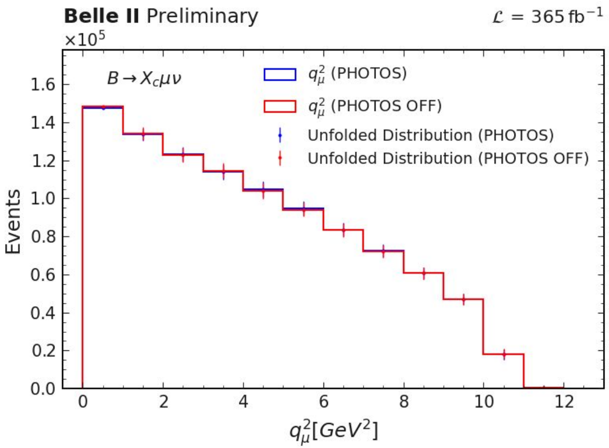
Unfolded spectrum: with/without FSR photons

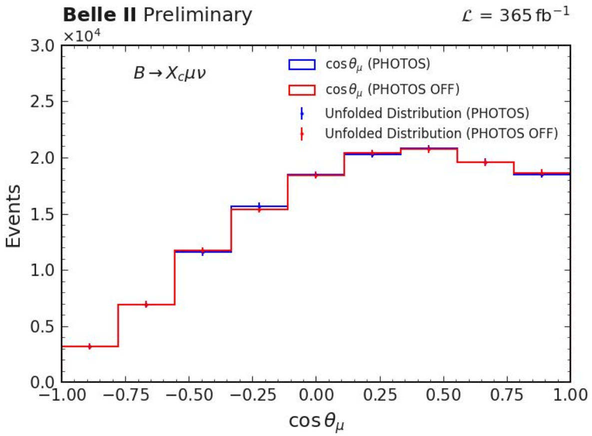










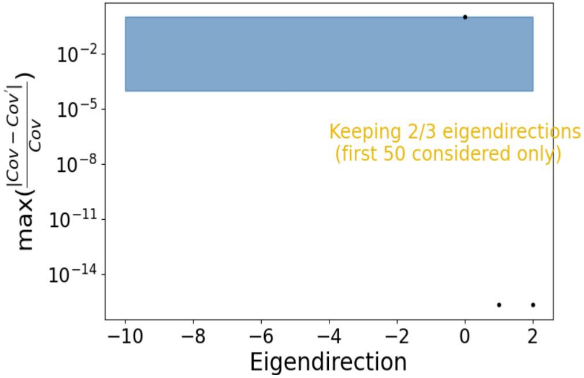


SYSTEMATICS

SysVar

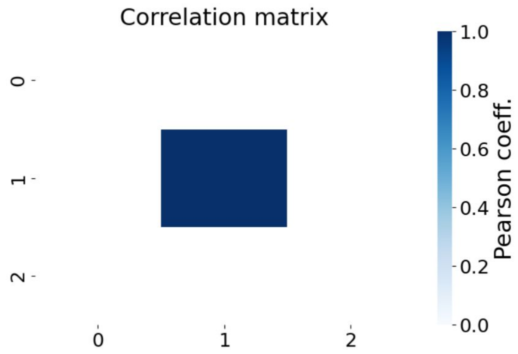
Tool for Enhancing Consistency in the Treatment of Systematics

Is there a consistent way of handling arbitrary correlations arising from systematic effects that affect shapes in simultaneous template fits?



SysVar is a Python-based tool:

- Generate Variations of Data/MC Corrections
- Build templates and template variations for a non-parametric fit
- Covariance Matrix: (channels x templates x bins) to produce eigenvariations to implement correlated shape Variations



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Incorporating variations from SysVar in this analysis

Systematic	Description
BF (Branching Fractions)	Uncertainty from input branching fractions of D, D^*, D^{**} and Gap channels affects MC normalization
FEI (Full Event Interpretation)	Efficiency mismodeling for B^0 and B^+ tag reconstruction between data and MC
FF (Form Factors)	Uncertainty from hadronic form factor modeling in semileptonic BB decays impacts shapes and efficiencies
Tracking	Charged-particle tracking efficiency differences between data and MC.
Lepton ID	- **eff**: efficiency of true lepton identification - **fake kaons**: kaons mis -ID as leptons - **fake pions**: pions mis -ID as leptons

Summary

- Study of reconstructed kinematic variables: m_X, E_l^B, p_l^B, q^2
- Effect of FSR photons on E_l^B and q^2
- Calculation of lepton angle cos θ_l
- Signal extraction by fitting the invariant hadronic mass in bins of the lepton momentum, momentum transferred squared and lepton angle
- Unfolding with efficiency corrections
- Systematics: BF, FEI, FF, Tracking, LeptonID using sysvar
- Incorporating these systematics in the pyhf model

Next Steps

- Branching Fraction calculation using pyhf incorporating each of the systematics

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BACKUP

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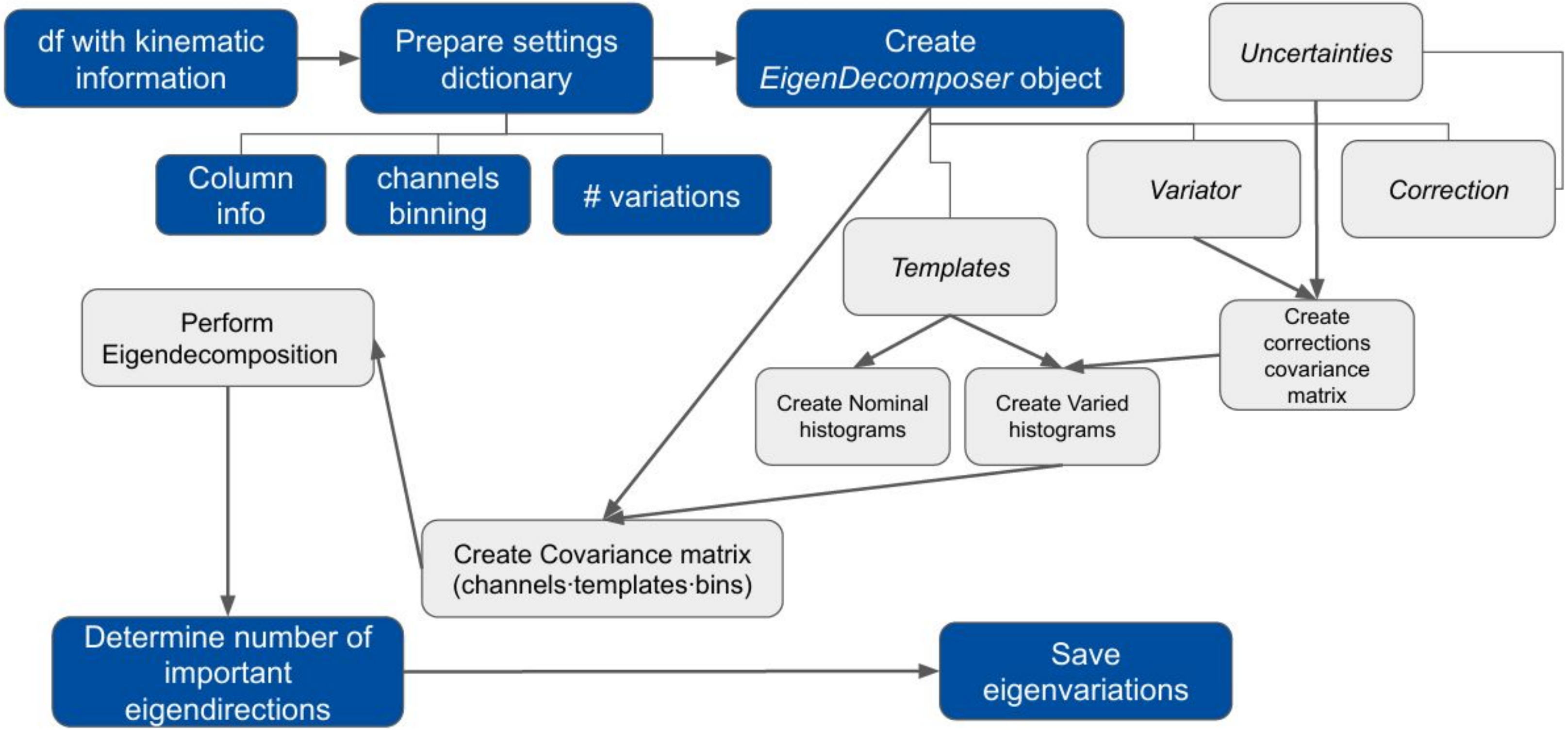
Producing EigenVariations



SysVar provides all the necessary tools to prepare a global simultaneous fit that keeps track of all the correlations consistently

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Unfolding

$$Unfolded\ yields = \mathcal{M}^{-1}\ @\ signal\ post\ fit\ yields$$

$$\mathcal{E} = \frac{Unfolded\ Yields}{N_{gen}(in\ p_l^B\ true\ bins)}$$