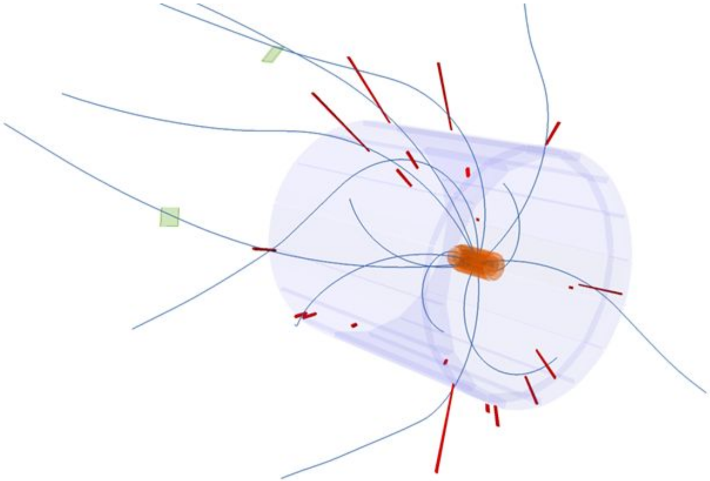

Measurement of the branching ratio and CKM Matrix element $|V_{cb}|$ in inclusive $B \to X_c l\nu$ semileptonic decays at Belle II

Rajeshwari Roy, Florian Bernlochner, Markus Prim, Munira Khan

57. Herbstschule HEP

Sept 1-11, 2026

With funding from the:

Federal Ministry of Research, Technology and Space

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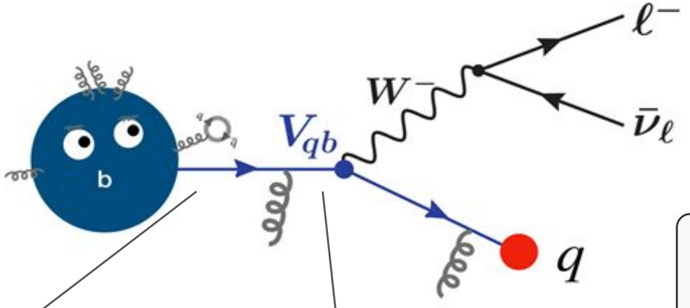
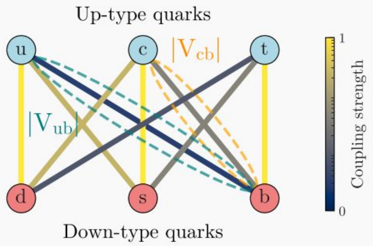
What is interesting about semileptonic B decays?



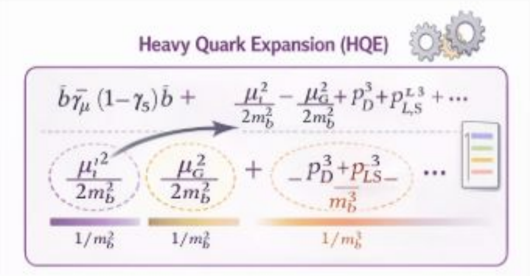
Quark mixing



- How large are the $b \leftrightarrow u$ and $b \leftrightarrow c$ couplings?

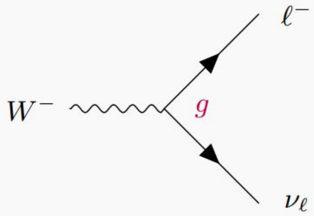
V_{cb}, V_{ub} **puzzle**

QCD dynamics



- Test Heavy Quark Expansion? Lattice QCD form factors?

Lepton flavor universality



- Does the W couple equally to different lepton flavors?

$R(D)$, $R(D^*)$ **anomaly**

Semileptonic decays give access to rich kinematics

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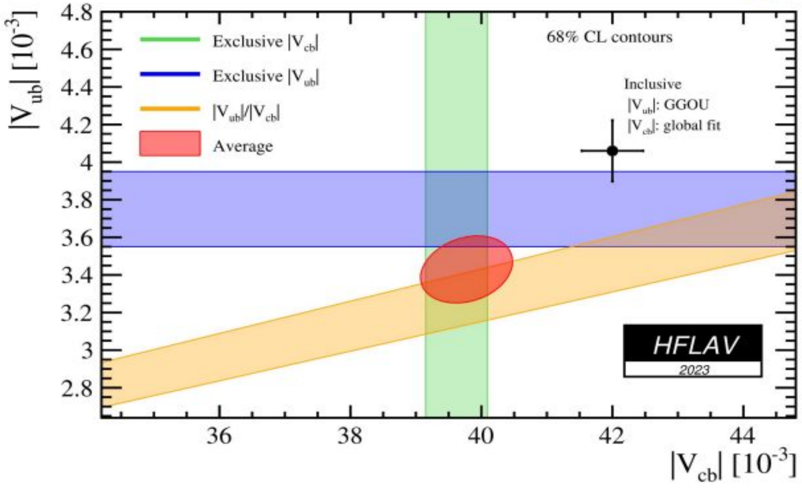
Why is measuring the branching ratio interesting?

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

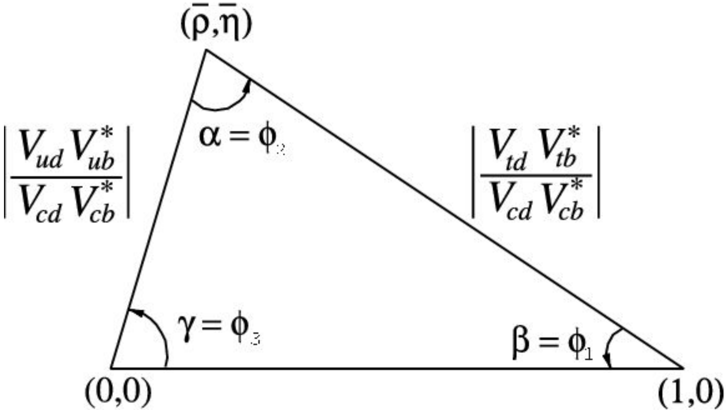
- ❖ Enables precision measurement of CKM matrix elements, which tests SM
- ❖ A fundamental measurement of parameter $|V_{cb}|$
  - ➢ Precise measurement of the BR gives direct sensitivity to $|V_{cb}|$
  - ➢ Reduces the tension of inclusive *vs* exclusive determinations

    → scope of European Strategy of Particle Physics

$$|V_{cb}|_{\text{incl.}} > |V_{cb}|_{\text{excl.}}$$



- ❖ Unitarity Condition: $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



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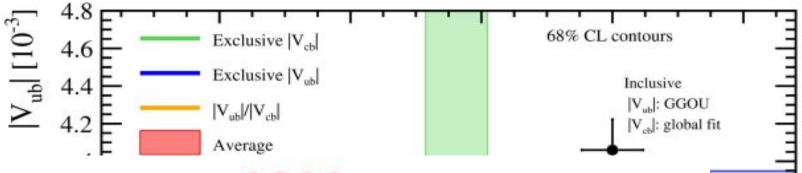
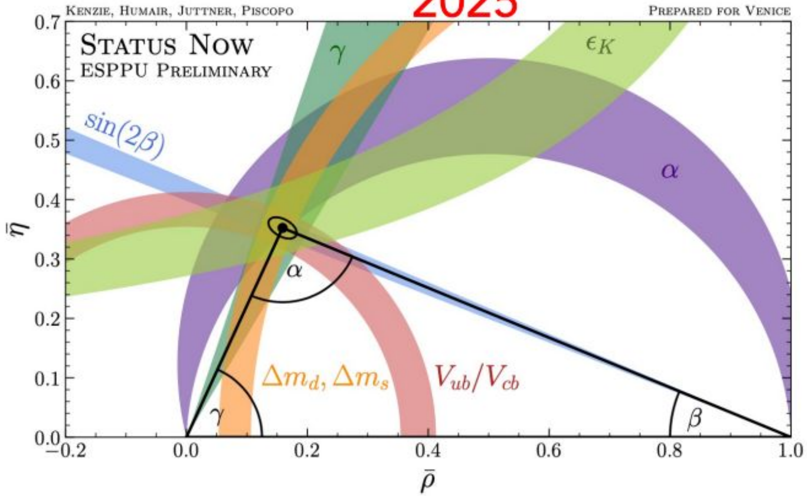
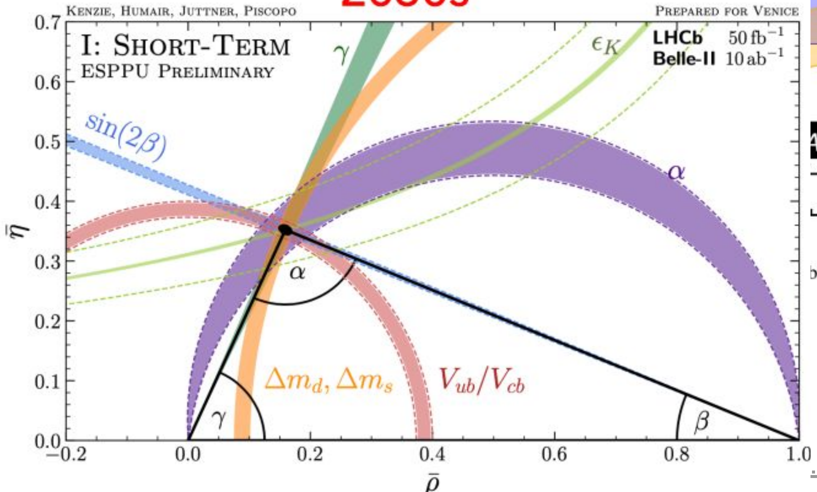


2025



2030s



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Inclusive $|V_{cb}|$

$B \to X_c \ell \nu$
(summing over all charmed final states)

- Described using **Heavy Quark Expansion**

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 f\!\left(\frac{m_c}{m_b}\right) \left[1 + \frac{\mu_\pi^2}{2m_b^2} - \frac{\mu_G^2}{2m_b^2} + \frac{\rho_D^3 + \rho_{LS}^3}{m_b^3} + \cdots\right]$$

μ_π^2 (kinetic energy parameter)
μ_G^2 (chromomagnetic parameter)
ϱ_D^3 (Darwin term)
ϱ_{LS}^3 (spin–orbit term)c

$$\mathcal{B}(B \to X_c \ell \bar{\nu}_\ell) = |V_{cb}|^2 \left[\Gamma(b \to c \ell \bar{\nu}_\ell) + \mathcal{O}\!\left(\frac{1}{m_b^2}, \frac{1}{m_c^2}\right) + \mathcal{O}(\alpha_s) + \cdots\right]$$

  - First non-perturbative corrections appear at $1/m_b^2$

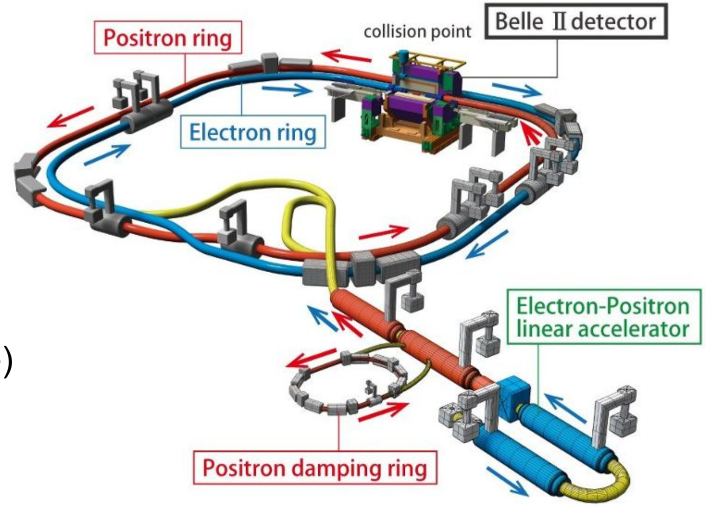
- no dependence on specific hadronic form factors

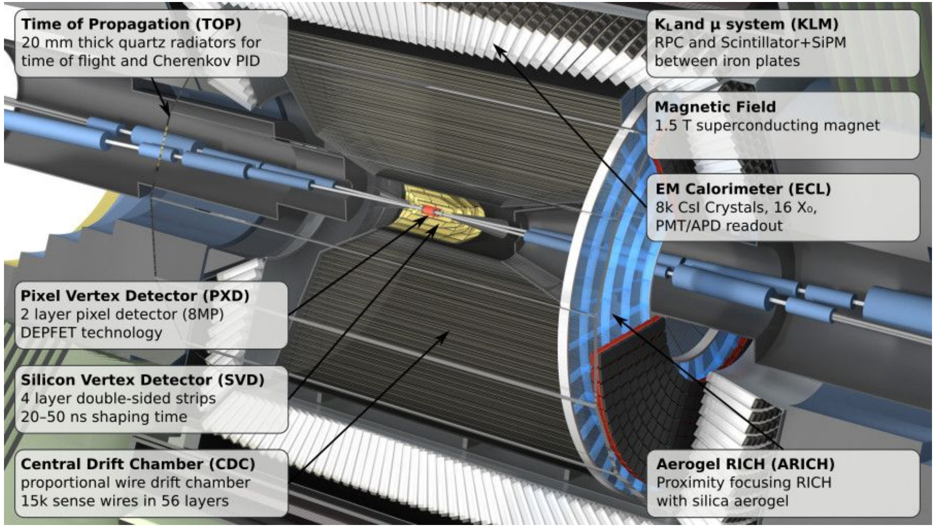
  → **theoretically clean**

The Belle II Experiment

SuperKEKB, Tsukuba, Japan: B factory

- ❖ Asymmetric e^+e^- collider at Y(4S) resonance energy (10.58 GeV)
- ❖ Y(4S) decays into a BB pair with > 96% BF
- ❖ **Very high instantaneous luminosity: 5.3 × 10^{34} cm^{-2} s^{-1}**
- ❖ Data collected so far is ~920 fb^{-1} (~810 fb^{-1} at the Y(4S) resonance)





Belle II Detector

- ❖ 1.5 T Superconducting solenoid
- ❖ Sub-detectors: Tracking, PID and calorimetry
- ❖ Allows precision measurements
- ❖ Excellent missing energy resolution

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Event Reconstruction and Kinematics

- B meson momentum reconstructed using tag-side

$$p_{B\,sig} = p_{e+e-} - p_{B\,tag}$$

- **Signal: $e^- e^+ \to B\bar{B} \to X_c \ell \nu_\ell$**
  - **m_X**: invariant mass of the charm hadronic system X_c

    $$m_X = (p_{B\,sig} - p_l - p_\nu)$$

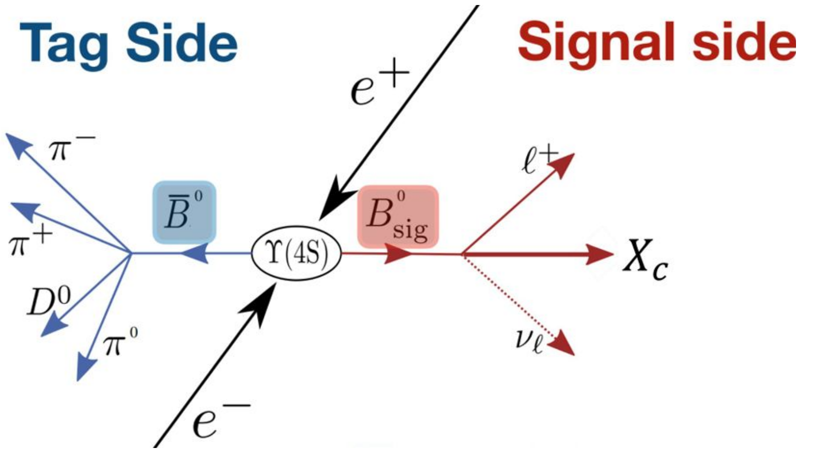
  - **q^2** : invariant mass of the lepton-neutrino system

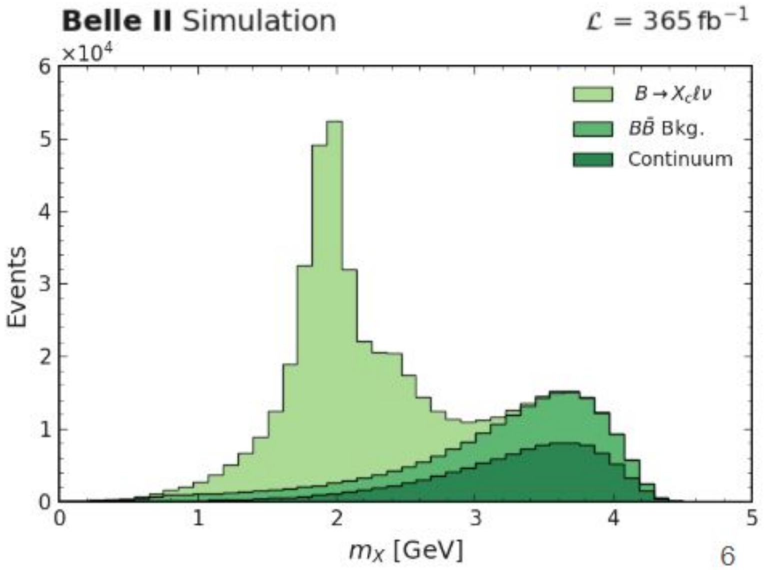
    $$q^2 = (p_{B\,Sig} - p_X)^2 = (p_l + p_\nu)^2$$

  - **$p_l^{(B,\,CMS)}$, $E_l^{(B,\,CMS)}$**: momentum and energy of the lepton

- **$B\bar{B}$ Background: $e^- e^+ \to B\bar{B} \to$ Bkg**
  - Secondary leptons, misidentified leptons, and $B \to X_u \ell \nu_\ell$ background

- **Continuum background: $e^- e^+ \to q\bar{q}$**





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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,** and the incorporated **efficiency corrections**, we can 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

- Examined the unfolded spectrum for $\mathbf{p_l^B}$, $\mathbf{q^2}$ and $\mathbf{cos\ \theta_l}$

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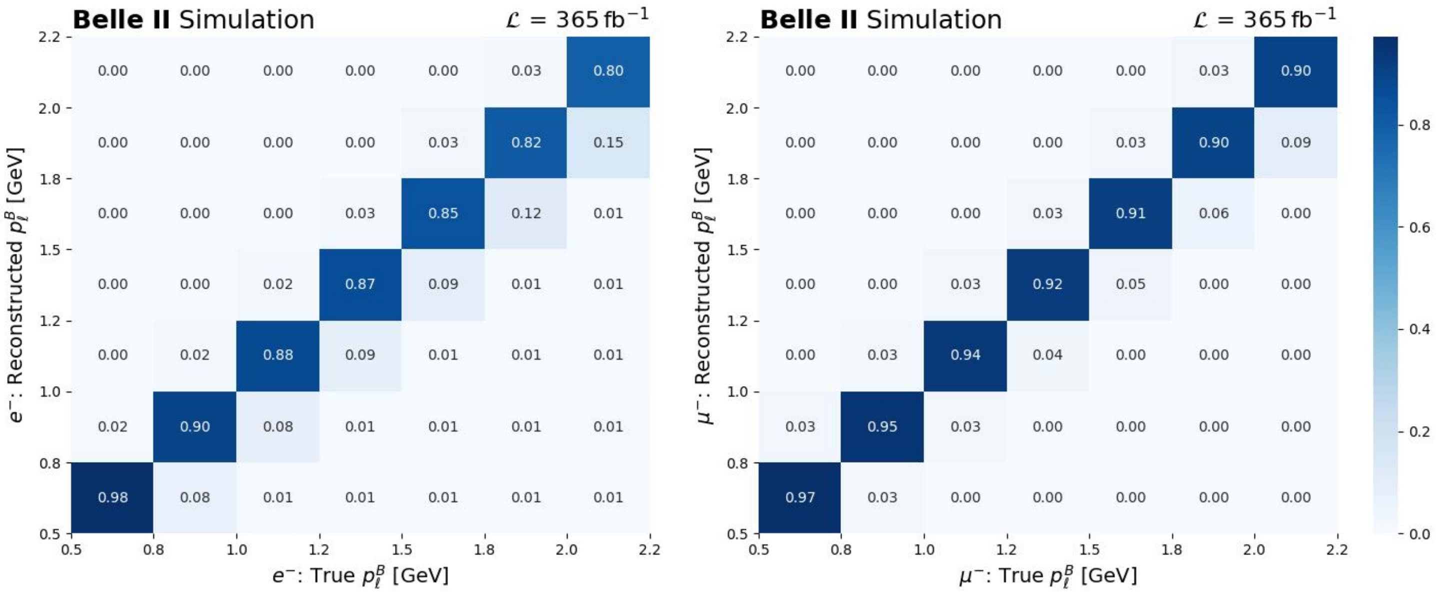
Migration matrices

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

- ❖ 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

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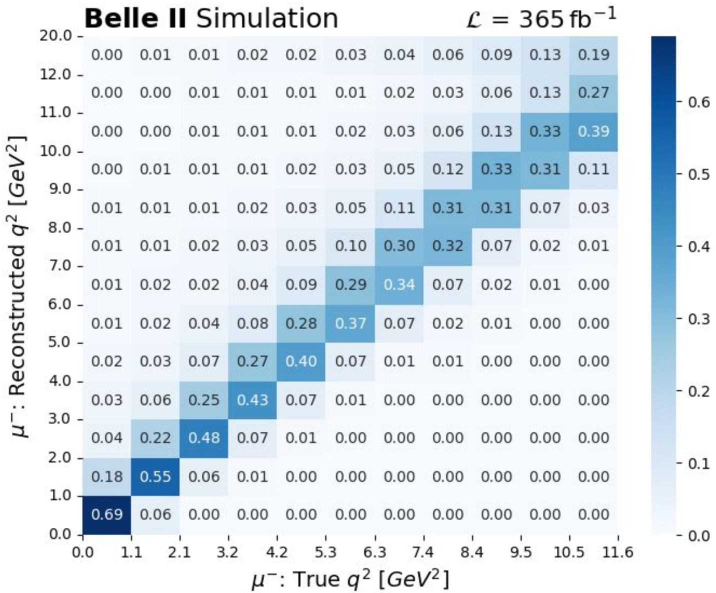

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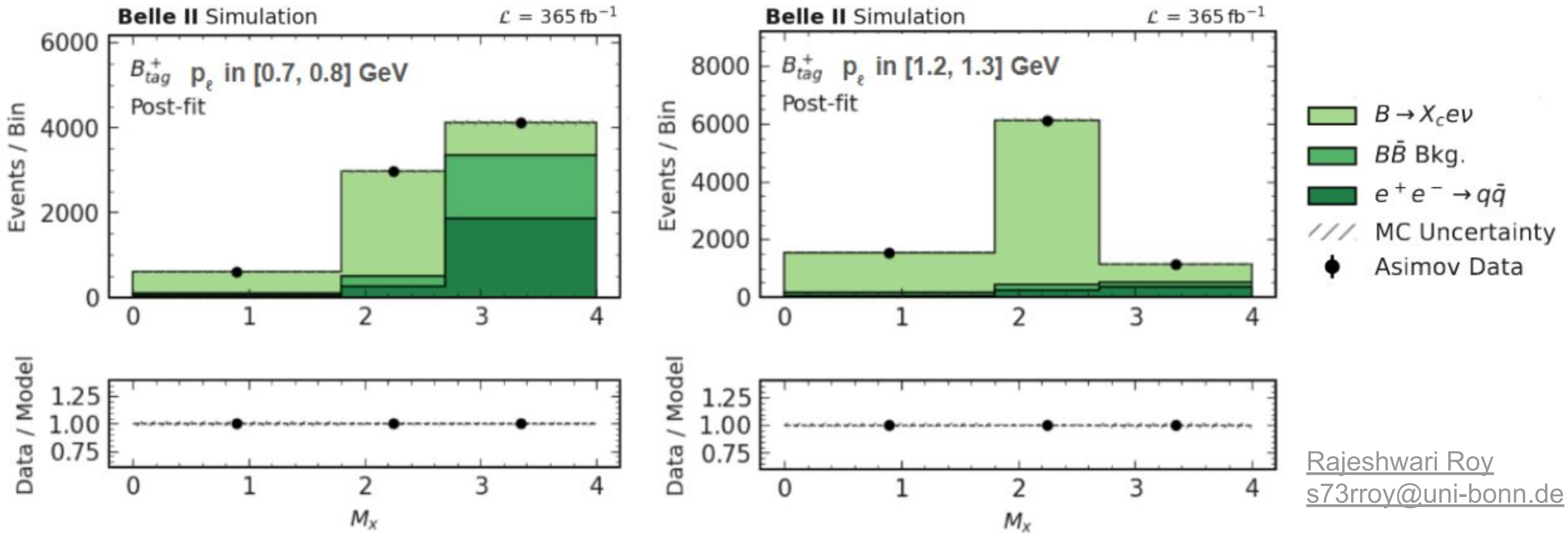
Efficiency Corrections

$$\varepsilon_i = \frac{N_{\mathrm{reco},\,i}}{N_{\mathrm{gen},\,i}}$$

in *i* bins of each kinematic variable of p^B_l

Signal Yields Extraction

- Fitting the lepton momentum $\mathbf{p_l^B \in [0.3, 2.3]}$ in the hadronic mass $\mathbf{m_x}$
- separates charm final states and improves signal–background discrimination, retaining enough statistics



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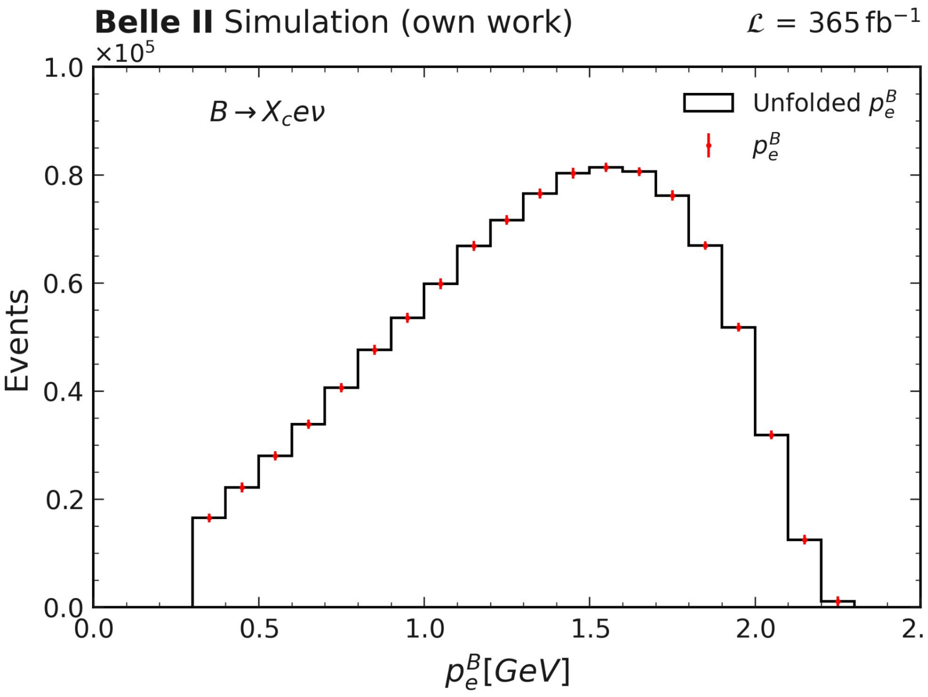
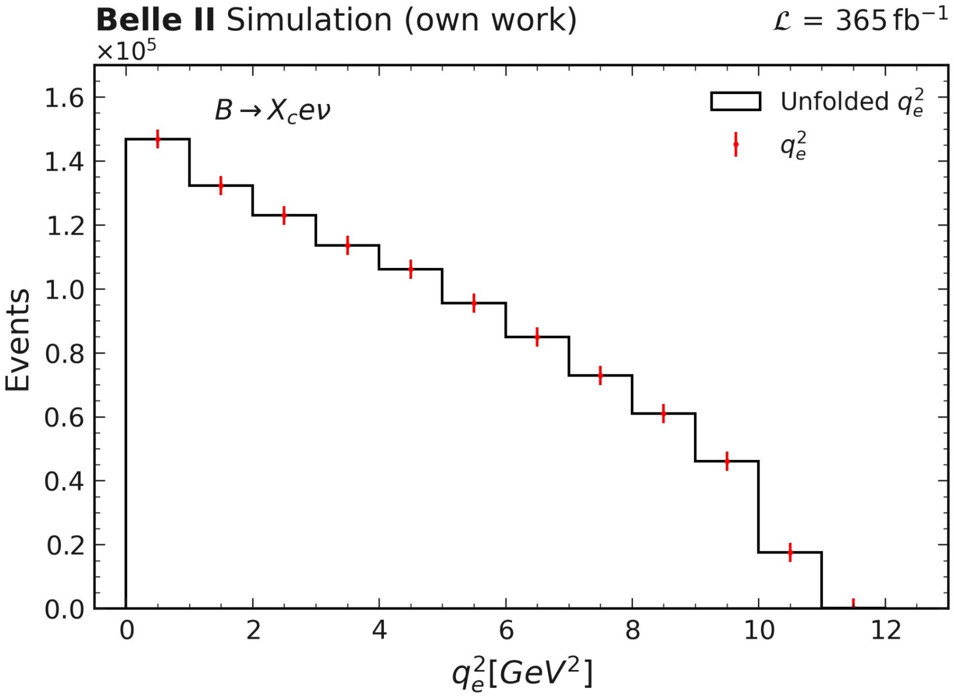
Unfolded spectrum: p_e, q_e^2





Branching Ratio

❖ **Partial branching ratio** for momentum bin *i*

From signal yields extraction

$$\Delta\mathcal{B}_i(B \to X_c \ell \nu) = \frac{N_{\mathrm{sig},i}}{2\,N_{B\bar{B}}\,f_{+,0}\,\varepsilon_i}$$

Efficiency corrections

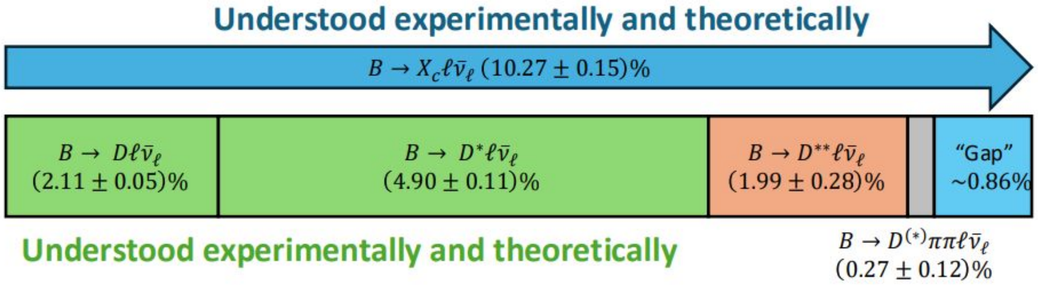
Production fractions (from HFLAV)

$f_{00} = 0.486 \pm 0.006$

$f_{+-} = 0.514 \pm 0.006$

❖ **Absolute branching ratio** from the partial branching ratios

$$\mathcal{B}\left(B \to X_c \ell \nu;\, p_\ell^B > 0.3\ \mathrm{GeV}\right) = \sum_i \Delta\mathcal{B}_i$$



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Results with Asimov data

➢ Electron Channel

$$\mathcal{B}(B \to X_c e \nu_e;\, p_e^B > 0.3\,\mathrm{GeV}) = (10.141 \pm 0.055\,(\mathrm{stat}))\%$$

➢ Muon Channel

$$\mathcal{B}(B \to X_c \mu \nu_\mu;\, p_\mu^B > 0.3\,\mathrm{GeV}) = (10.101 \pm 0.052\,(\mathrm{stat}))\%$$

❖ **R(e/μ):** Test for Lepton Flavor Universality (LFU)

$$R(e/\mu) \equiv \frac{\mathcal{B}(B \to X_c e \nu_e)}{\mathcal{B}(B \to X_c \mu \nu_\mu)} = 1.004 \pm 0.008\,(\mathrm{stat})$$

➢ Confirms SM predictions of $b \to c\ell\nu$

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Systematics using 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: to produce eigenvariations to implement correlated shape variations

Systematics

Branching fraction variations	Form Factor Modelling	Tracking	PID	FEI Tagging

- ❖ The variations generated from sysvar are then used as nuisance parameters in the pyhf model setup as shape modifiers

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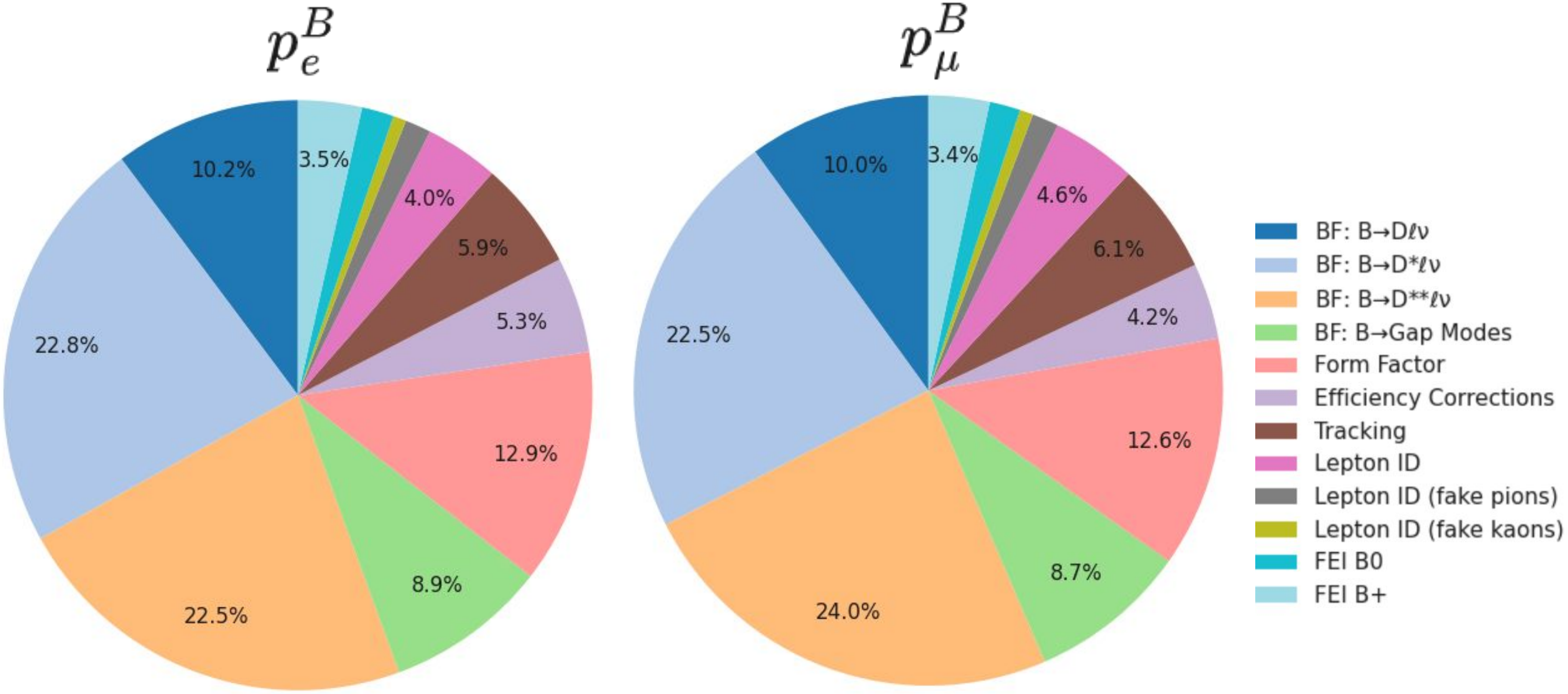
Systematic contributions



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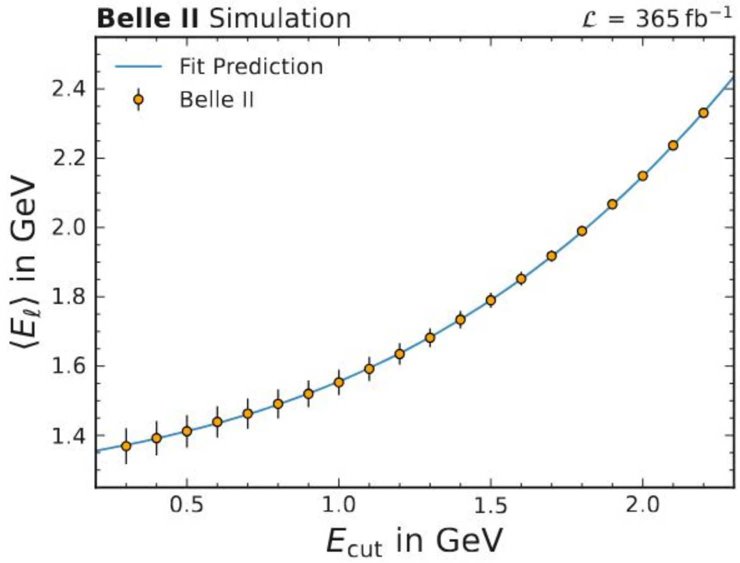
$|V_{cb}|$ determination

- $|V_{cb}|$ is determined using the **Kolya** package
  - Kolya internally considers QCD corrections; a χ^2 fits the predicted *moments* to the HQE parameters
- **Inputs to the fit:** partial branching ratios, uncertainty covariance matrices
- **Outputs of the fit:** Results of the sensitivities on $|V_{cb}|$ and the HQE parameters

	Central Value	Uncertainty
$\lvert V_{cb}\rvert$	42.351	0.246
$m_b^{\mathrm{MS}}(m_b)$	4.174	0.004
$m_c^{\mathrm{MS}}(3\,\mathrm{GeV})$	1.004	0.005
$\alpha_s(m_Z)$	0.118	0.000
$\mu(m_b^{\mathrm{kin}})$	1.203	0.020
$\mu(m_c^{\mathrm{MS}})$	1.874	0.00
$\mu(\alpha_s)$	8.493	0.749
μ_π	0.387	0.008
μ_G	0.118	0.017
ρ_D	0.110	0.001
ρ_{LS}	0.067	0.058



$$|V_{cb}| = (42.2 \pm 0.5) \times 10^{-3} \quad \text{(inclusive)}$$

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Summary

- Studies of **$B \rightarrow X_c \ell \nu$ decays** help look into quark mixing and test HQE and LFU
- Precise measurement of the BR gives direct sensitivity to $|V_{cb}|$
- Long tension of inclusive and exclusive measurements of $|V_{cb}|$
- Inclusive $|V_{cb}|$ is described by the HQE and has no dependence on specific hadronic form factors
  $\rightarrow$ **theoretically clean**
- **Differential measurements of p_l^B, q^2 and $\cos\theta_l$ provide complementary information** on the inclusive decay kinematics and allow detector effects to be studied and corrected
- **Unfolded spectra and their moments provide the experimental input for the HQE fit**, allowing $|V_{cb}|$ and the non-perturbative heavy-quark parameters to be constrained

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THANK YOU!

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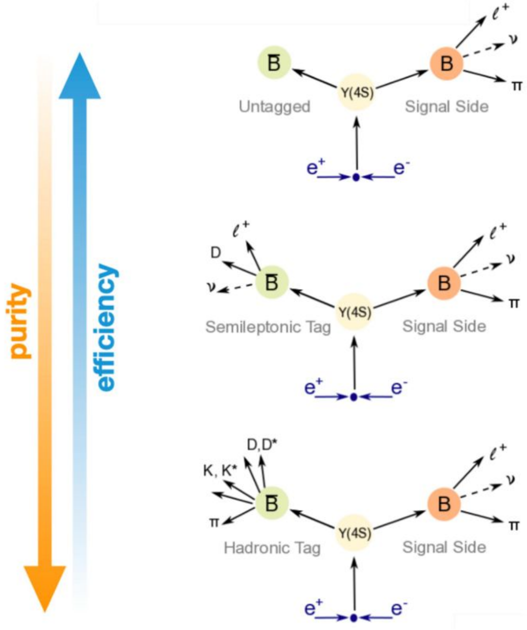
BACKUP

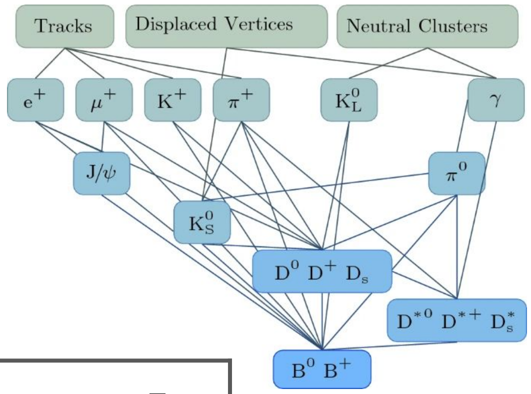
Tagging

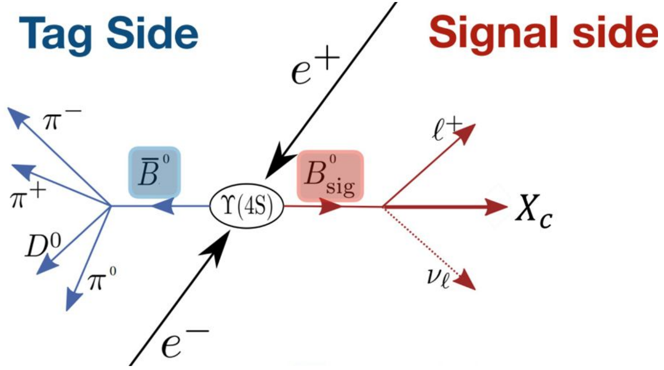


B_{tag}

Reconstructed via **Hadronic tagging**
(no final state leptons/neutrinos)

Using *Full Event Interpretation (FEI)* algorithm





Selection	Purpose
-0.15 < ΔE < 0.10 GeV	Reconstructed B energy matches beam energy
m_{bc} > 5.24 GeV	Keeps sideband for calibration study
m_{bc} > 5.27 GeV	Improves purity of correctly reconstructed B mesons
$\mathcal{P}_{FEI}$ > 0.01	Removes poorly reconstructed tag candidates

Continuum suppression	Reduces jet-like $e^-e^+ \to q\bar{q}$
Best candidate choice	Avoids multiple counting, selects most signal-like B
Off-resonance m_{bc} correction	Accounts for CM energy difference in off-resonance data

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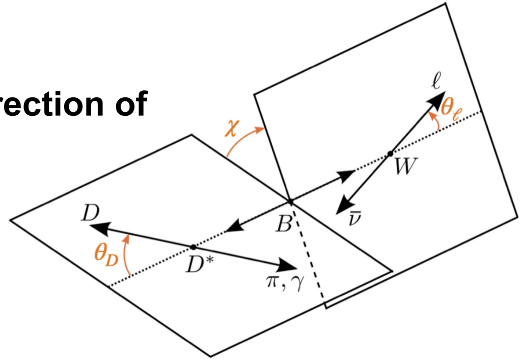
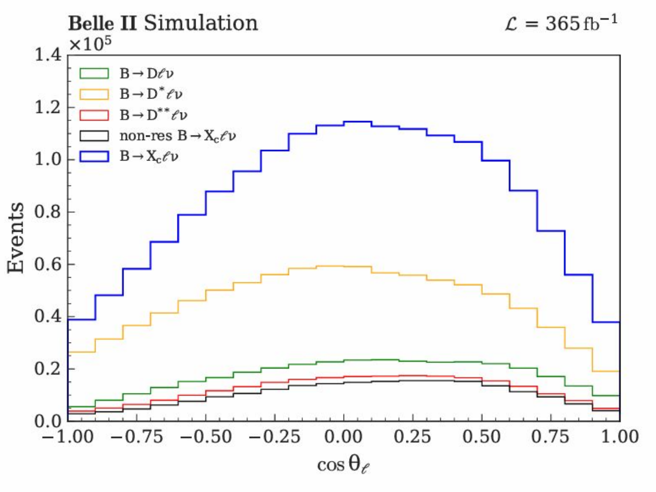
cos θ_ℓ

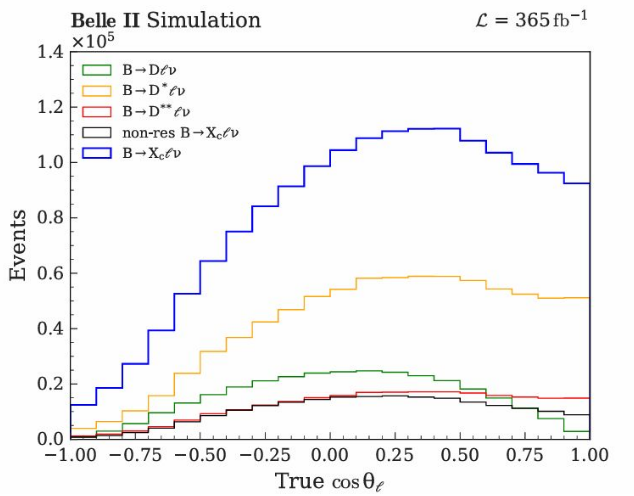
- Angle **between the direction of the W boson** (in B rest frame) and the **direction of the lepton** (in W rest frame)
  - $p_W = p_{B\ sig} - p_X$
  - Boost the W in the B-rest frame
  - Boost lepton into CMS frame of W

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





(a) Reconstructed cos θ_ℓ



(b) Generated (truth-level) cos θ_ℓ

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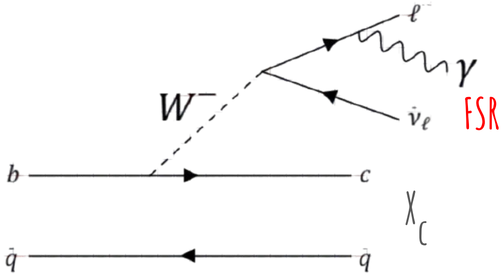
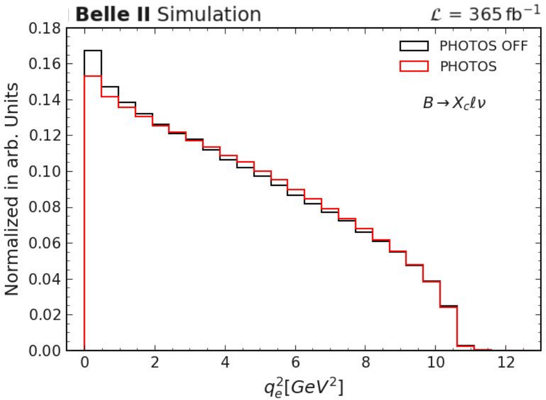
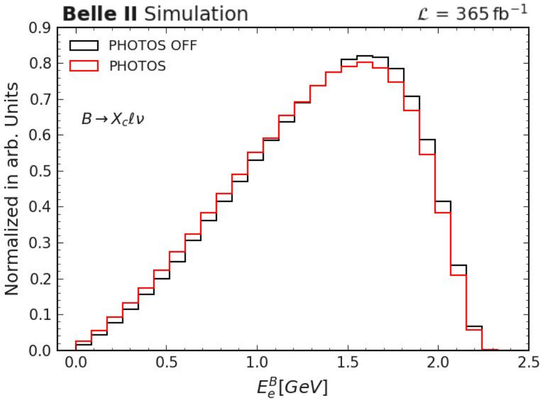
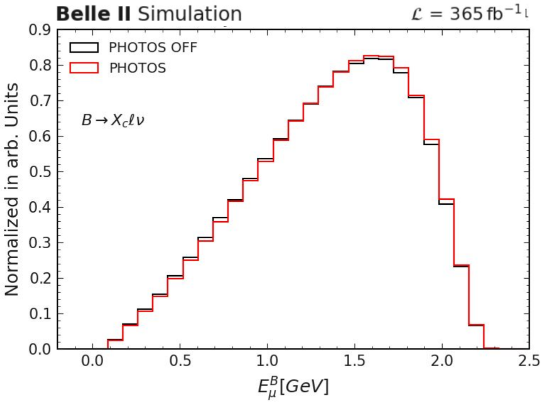
Final State Radiation Photons

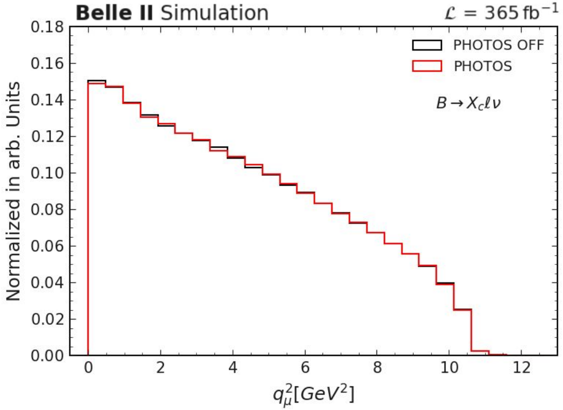


- ❖ photons emitted by charged leptons after the decay process
- ❖ In $B \rightarrow X_c \ell \nu$ decays, FSR modifies:
  - ➢ Lepton energy (E_ℓ)
  - ➢ Momentum transfer squared (q^2)









- ❖ FSR effects are more significant for electrons as compared to muons

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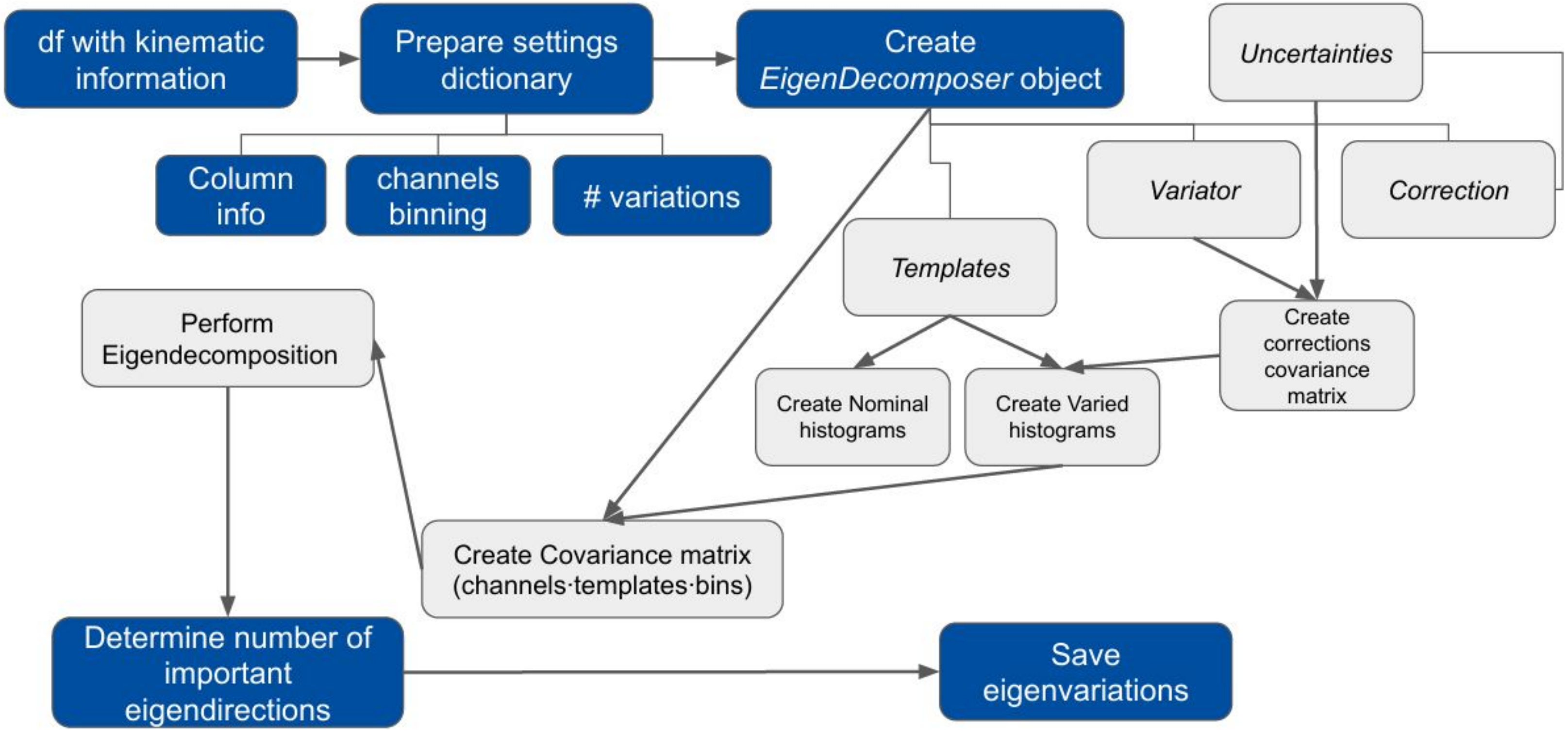
Producing Eigenvariations



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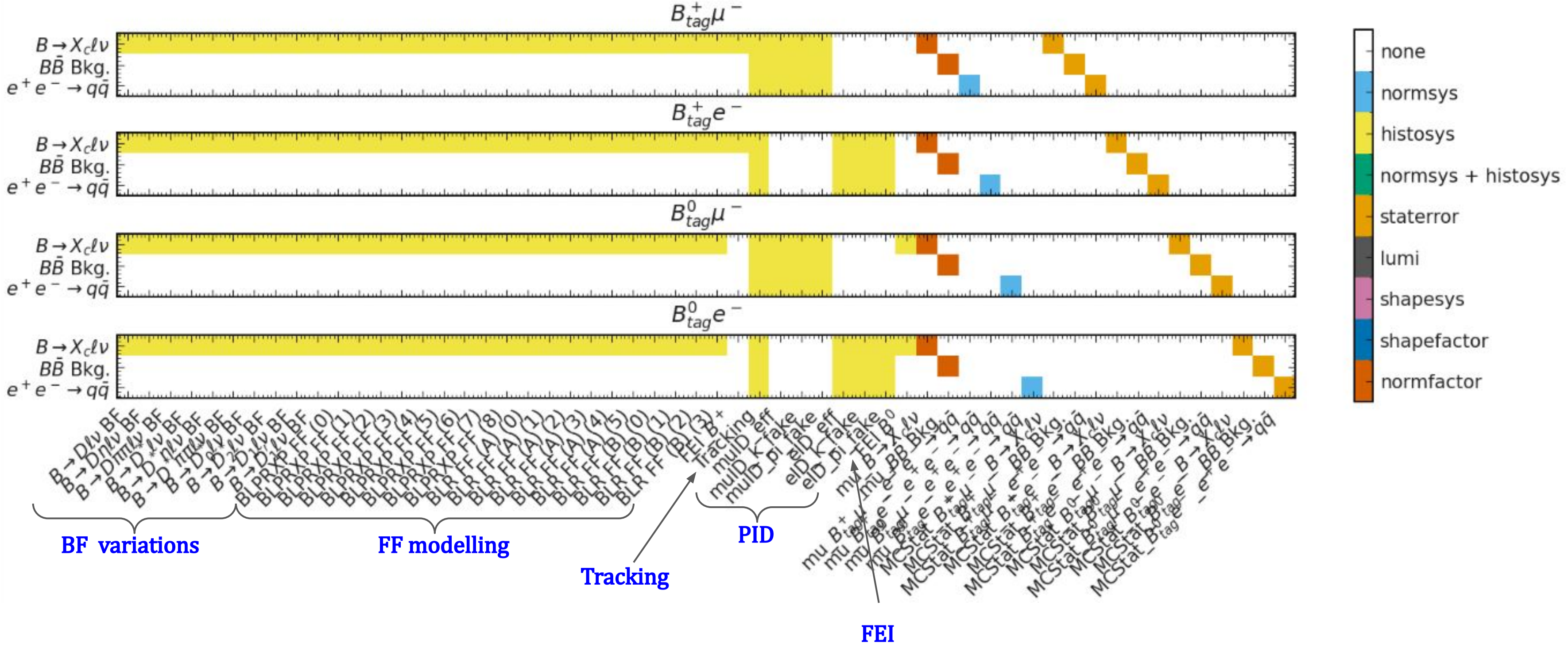
Incorporating variations from SysVar in this analysis

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

Systematic profile



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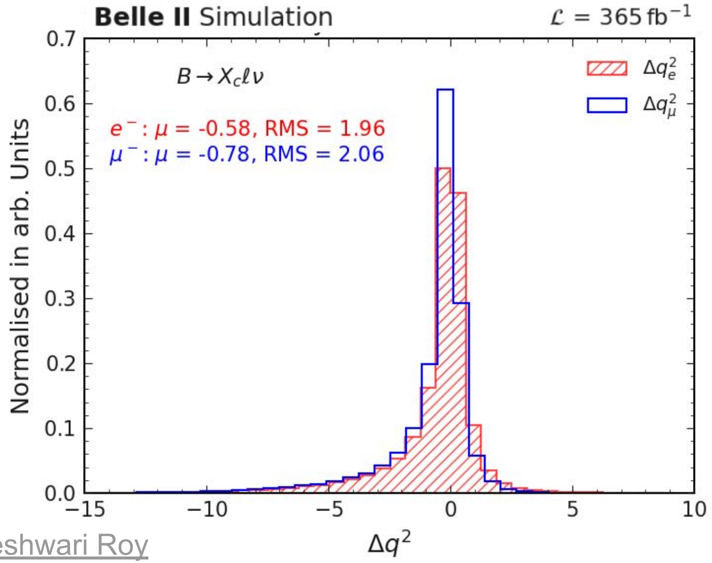
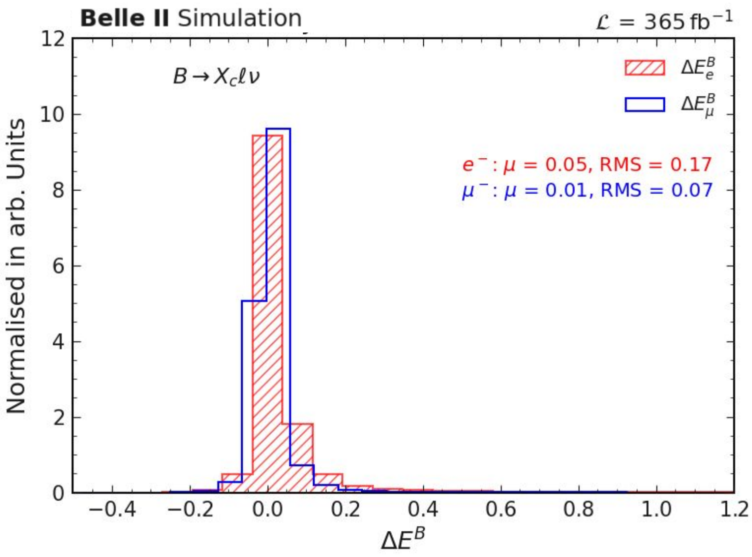
Distributions of Δq^2 and ΔE_l^B

- 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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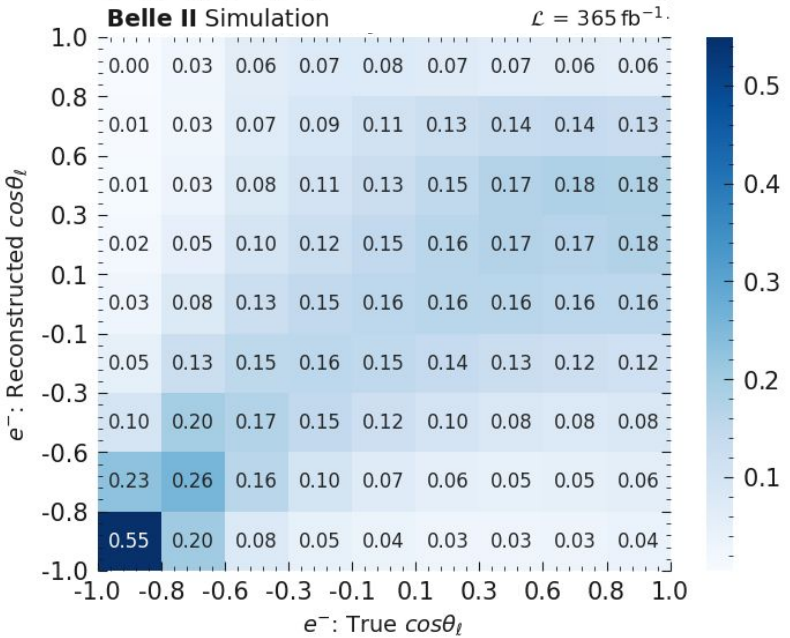
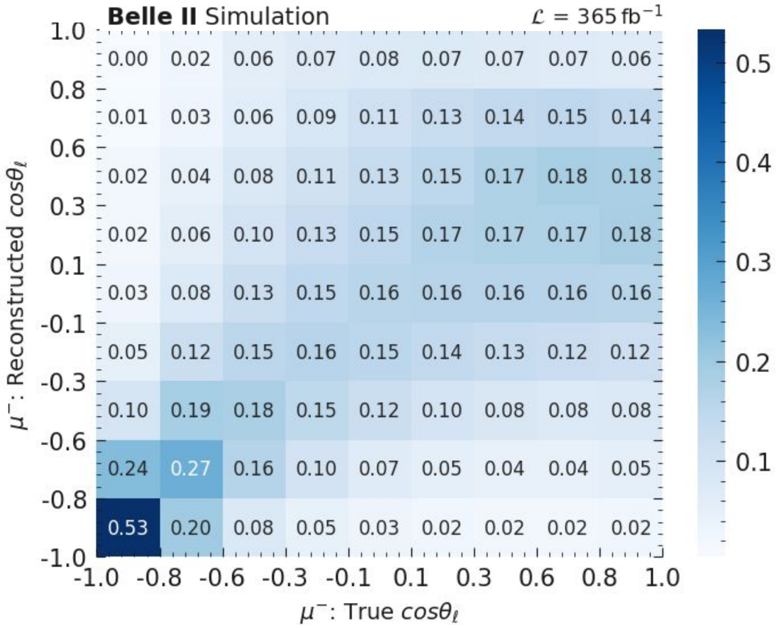
cos θ_ℓ migration matrix





- ❖ Smearing because of missing neutrino, boosts in two frames

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