Measurements of inclusive $B \to X_u l \nu$ decays with hadronic tagging

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HELMHOLTZ

Belle II

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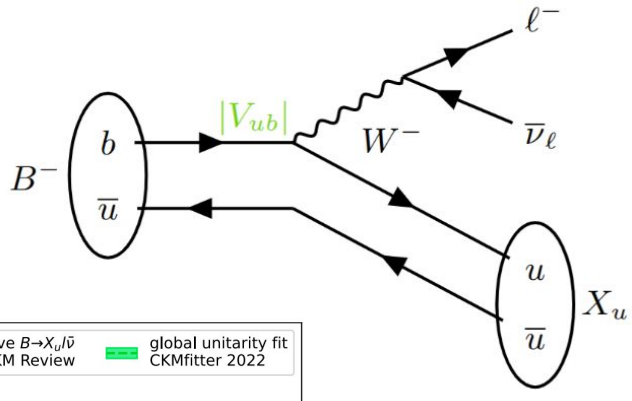
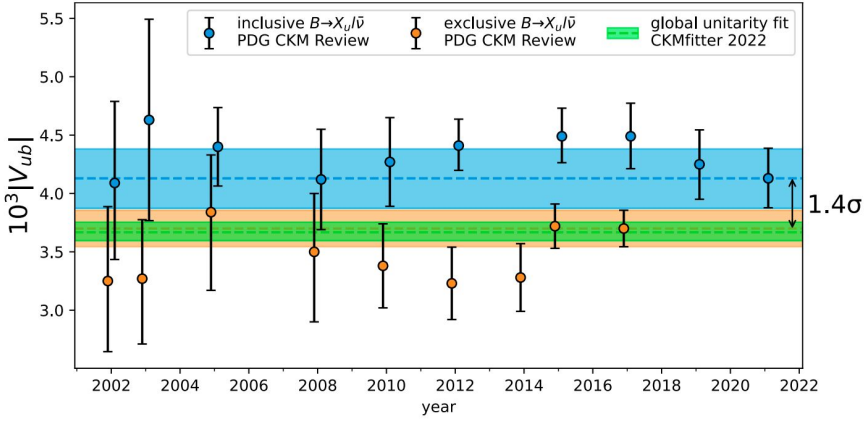
DESY.

Introduction

- **Semi-leptonic** decays
  - $B \rightarrow X_u\, l\, \nu$
  - $B \rightarrow X_c\, l\, \nu$

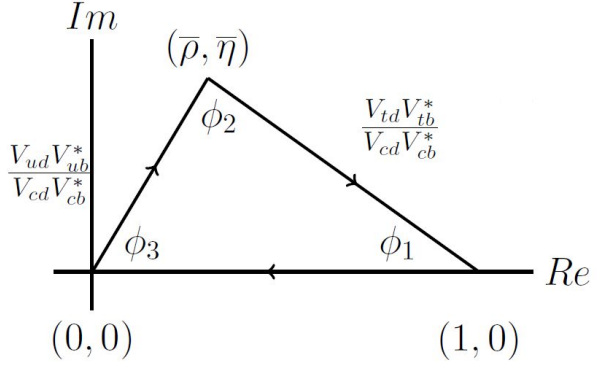


- **Two ways** to measure $|V_{ub}|$
  - **Exclusive** decays
    - $B \rightarrow \pi\, l\, \nu$, $B \rightarrow \rho\, l\, \nu$ …
  - **Inclusive** decays



$$|V_{ub}| = (4.13 \pm 0.12^{+0.13}_{-0.14} \pm 0.18) \times 10^{-3}$$ PDG incl.

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$$ PDG excl.



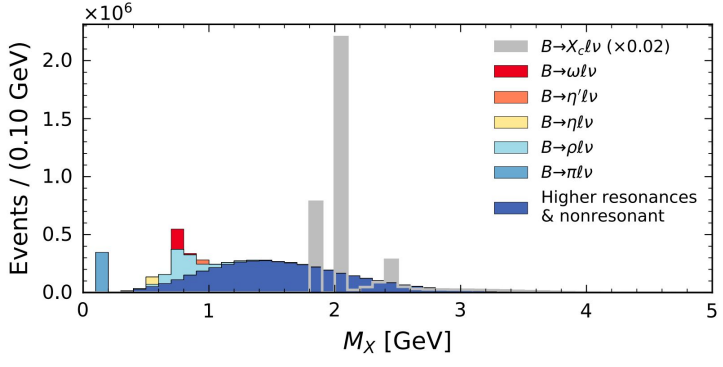
Theory

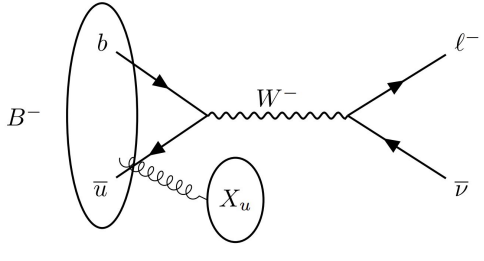
$B \to \pi\, l\, \nu$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$

- Exclusive decays depend on form factors

- **Inclusive** decays
  - Based on **Heavy Quark Expansion**
  - Large **B → X_c l ν background** ($|V_{cb}|^2$ / $|V_{ub}|^2$ ~ 100)
  - → **cuts** in phase space (ex: M_x < 1.7 GeV)
  - → **HQE breaks down**
  - Sensitivity on **Shape Function**(s)
    - Leading-order SF extracted from B → X_s γ
  - **Different models**: BLNP, DFN, GGOU…
  - Weak Annihilation ?





$B \to X_c \ell \nu$ (×0.02)
$B \to \omega \ell \nu$
$B \to \eta' \ell \nu$
$B \to \eta \ell \nu$
$B \to \rho \ell \nu$
$B \to \pi \ell \nu$
Higher resonances & non-resonant

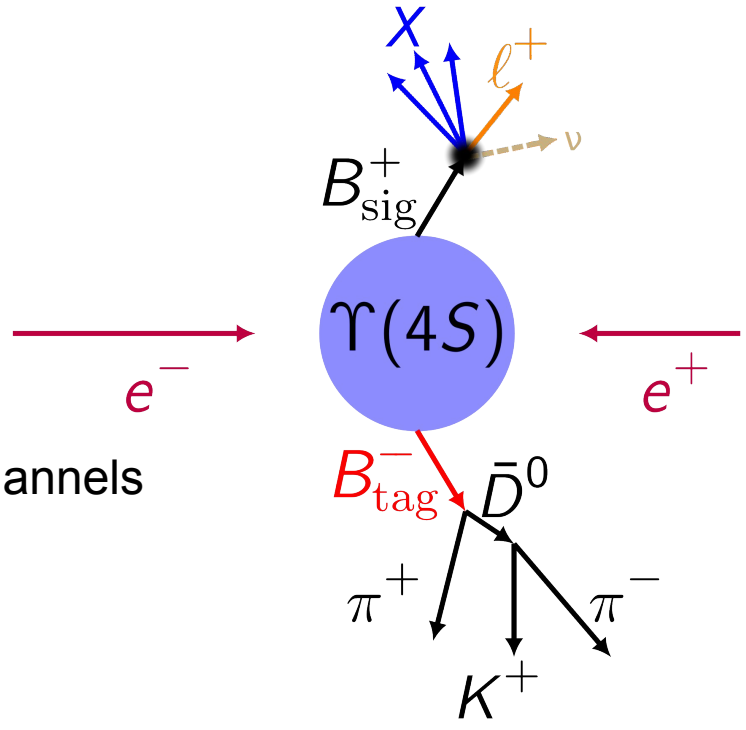
Outline

- **Inclusive B → X_u l ν partial Branching Ratio measurement and extraction of $|V_{ub}|$**
- **Inclusive B → X_u l ν differential Branching Ratio measurement**
- **Inclusive Weak Annihilation B → X_u l ν measurement**
- All 3 analyses performed with the Full Event Interpretation hadronic tag

Event reconstruction

Full Event Interpretation

- 3 types of tagging
  - Inclusive (untagged)
  - Semi-leptonic
  - **Hadronic**



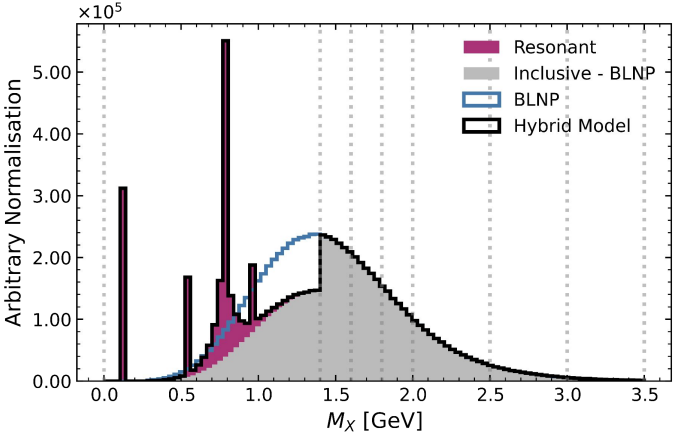
- **B_{tag} reconstructed** in its hadronic decay channels
  - Accurate information about the event
  - Background suppression
- **Lepton reconstructed**
- **Neutrino** → missing energy
- **Hadronic system X** → rest-of-event
- 3 important variables: **M_X, q^2, E_l**

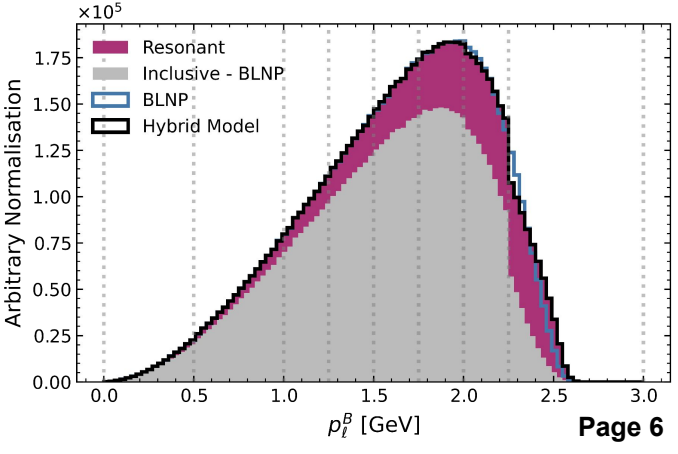
Modelling

$$\Delta\mathcal{B}_{ijk}^{\text{incl}} = \Delta\mathcal{B}_{ijk}^{\text{excl}} + w_{ijk} \times \Delta\mathcal{B}_{ijk}^{\text{incl}}$$

- Inclusive **B → X_u l ν**: signal
  - Combine **resonant** (π, ρ, ω, η, η') and **non-resonant** contribution (BLNP, DFN)
  - **Hybrid model**
- Inclusive **B → X_c l ν**: main background
  - No model for non-resonant contribution
  - → Sum of resonant modes (D, D*, D**) and "gap" modes
- Other backgrounds
  - Υ(4S) → $q\bar{q}$ (continuum)
  - Fake/secondary leptons
- Weak Annihilation contribution
  - Dedicated measurement

B → X_u l ν

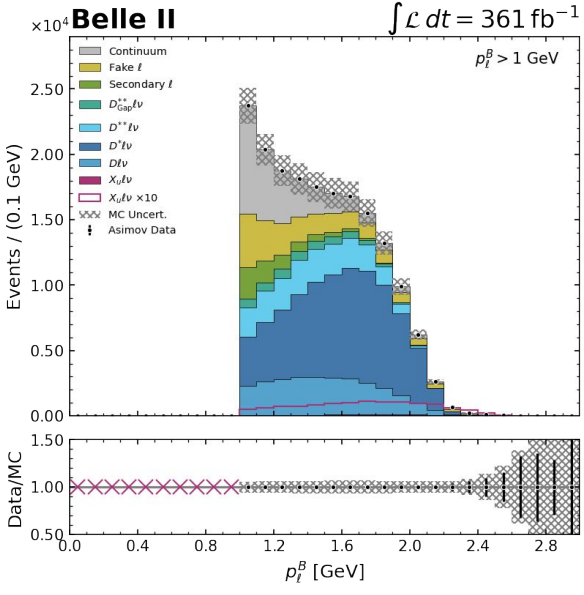


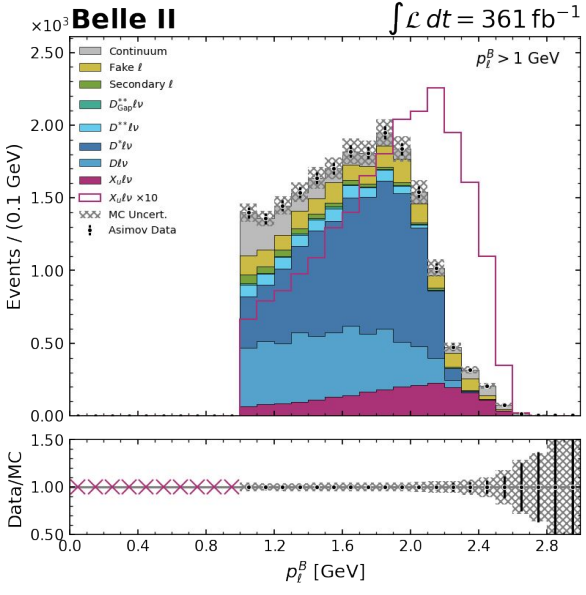


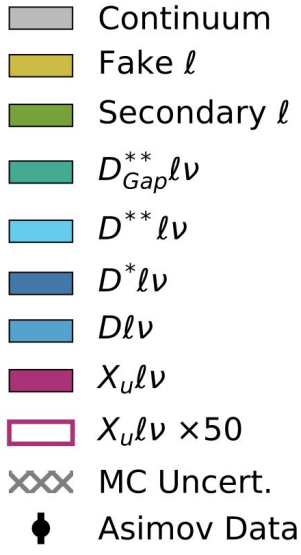
$B \rightarrow X_u$ l v partial Branching Ratio

Background suppression

Example: lepton energy





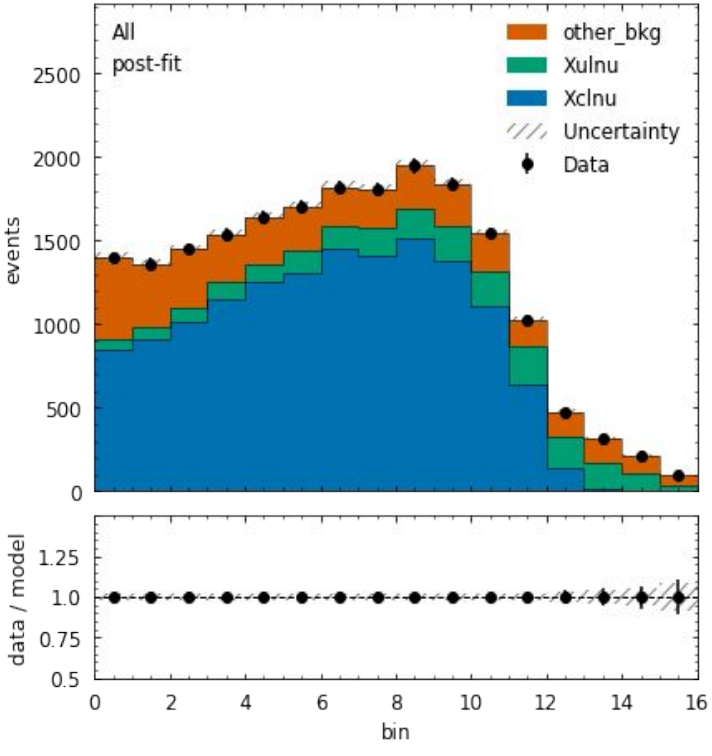


Pre-classifier **Post-classifier**

- **Multivariate classifier**
  - **Neural Networks**: distinguish signal from background sources using training features (missing mass, number of kaons and pions…)
  - Signal efficiency = 37%
  - Background retention = 2%

$|V_{ub}|$ extraction

- Extract **partial Branching Fraction**
- **Binned fit**
- **3 templates**
  - Signal: $B \rightarrow X_u\, l\, \nu$
  - Main background: $B \rightarrow X_c\, l\, \nu$
  - Other backgrounds (fake/secondary leptons + continuum)
- Example: E_l^B with 16 bins from 1.0 to 2.7 GeV
- Different fitted variables + different phase space regions
- Validation: toys, linearity check

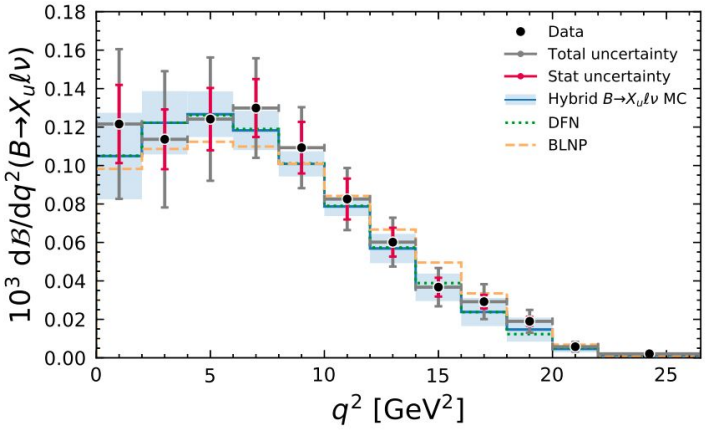


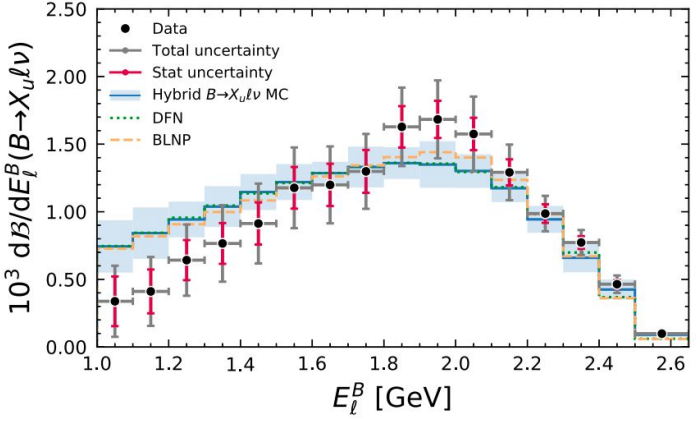
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}}{\tau_B \Delta\Gamma_{\mathrm{th}}}}$$

$B \rightarrow X_u l \nu$ differential Branching Ratio

Differential B → X_u l ν measurement

Taken from Belle measurement





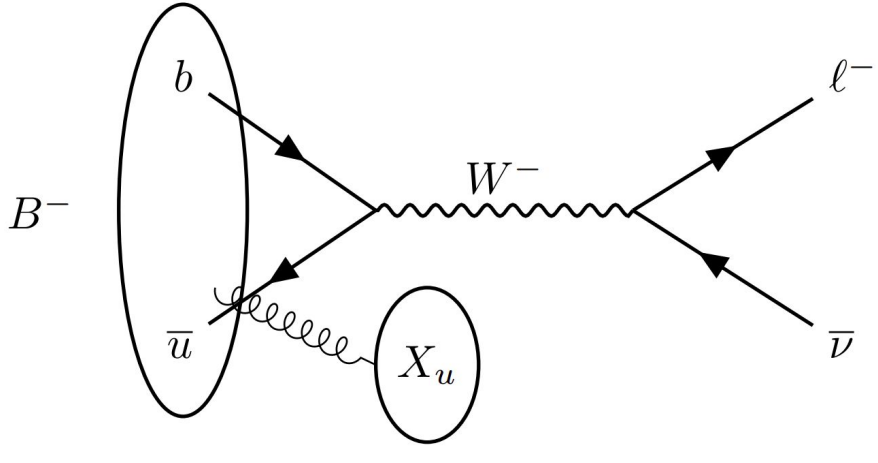
- **Shape information** on kinematic variables → crucial to evaluate models and extract HQE parameters
- **Subtract background** using fitting procedure
  - Resolution is key: $|E_{miss} - p_{miss}|$ cut for example
- **Unfold signal yields**
  - Next step, work in progress

$B \to X_u l \nu$ via Weak Annihilation

Weak Annihilation

- Weak Annihilation contribution enters inclusive **B → X_u l ν modelling at O($1/m_b^3$)**
  - **Not included** in most available B → X_u l ν models
  - **Poorly understood theoretically**
  - Sub-leading but **sizeable uncertainty** in inclusive $|V_{ub}|$ extraction
  - Expected to become **more important** as experimental uncertainty and other modelling **uncertainties shrink**
- One attempt at a direct measurement at CLEO
  - $\Gamma_{WA} / \Gamma_{b\to u} < 7.4\%$ at 90% C.L.

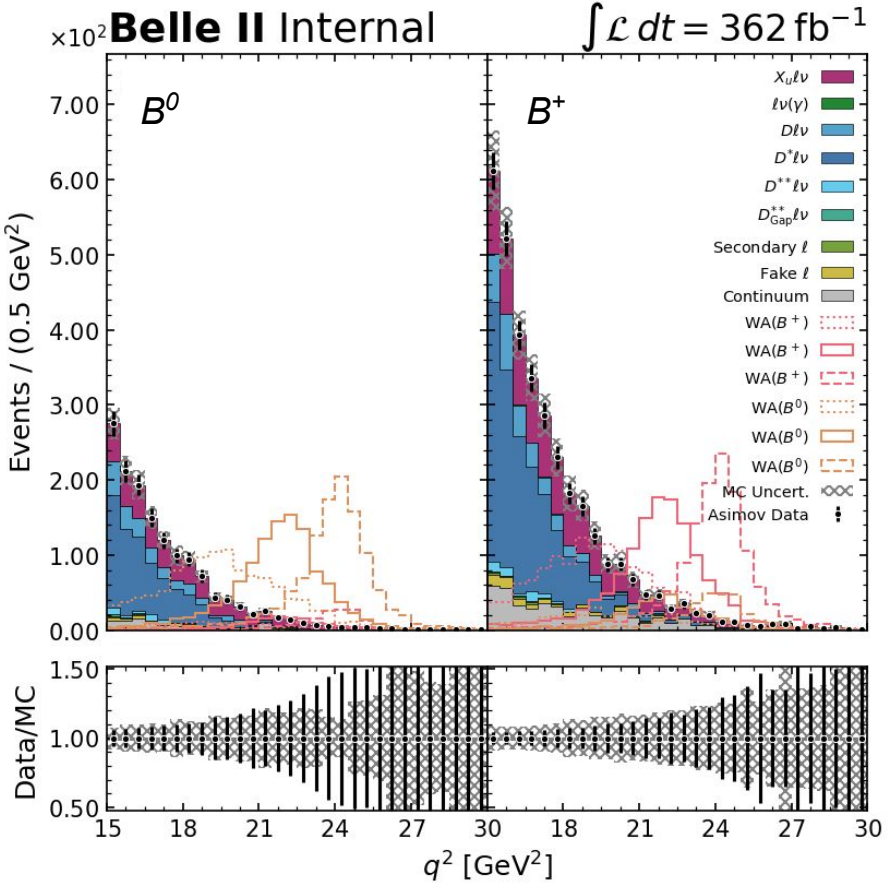
- **Soft hadronic system**
- → Weak Annihilation visible at high q^2/El



Weak Annihilation

- **Shape of peak is poorly known**
  - → scan a range of models built from off-shell W
  - Peaks in q^2 distribution of different widths around m_B^2

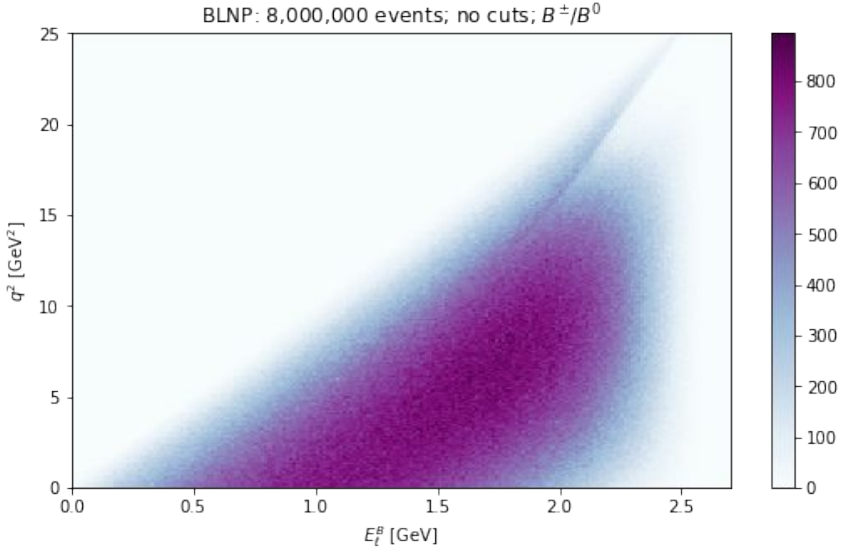
- Goal is to **extract a limit on WA** contribution
- Fitting procedure set up, checks in control regions



OUTLOOK AND CONCLUSIONS

Signal modelling issues

- No ideal model
  - **DFN**: outdated
  - **GGOU**: large discrepancy between model predictions and experimental results observed → new version in preparation
  - **BLNP**: various issues spotted
    - Negative hybrid weights
    - Excess of events near kinematical boundaries
  - Other models considered not suitable by theory community (DGE, ADFR)



- In contact with Keri Vos (Maastricht)
  - Possible switch to DFN

Summary

- **Status of analyses**
  - Most of the technology in place
  - Finalising the fitting procedure
  - Looking at data-MC agreement in side-bands

- **Outlook**
  - Sensitivity projections for inclusive $|V_{ub}|$

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ inclusive					
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5−4.5	3.4−5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5−4.5	3.0−4.8

THANK YOU FOR YOUR ATTENTION !

BACKUP

Preselection

- **Lepton selection**
  - BDTe > 0.9 or muonID_noSVD > 0.9
  - dr < 1 cm
  - | dz | < 3 cm
  - nCDCHits > 0
  - thetaInCDCAcceptance
  - correctBremsBelle for electrons

- **Standard FEI selections**
  - M_{bc} > 5.27 GeV
  - -0.15 < ΔE < 0.10 GeV
  - sigProb > 0.01
  - cosTBTO < 0.9
  - Best tag candidate selection: highest FEI tag probability
  - BCS: Highest lepton momentum

- **ROE nominal mask**
  - Track cuts
    - dr < 1 cm
    - | dz | < 3 cm
    - nCDCHits > 0
    - thetaInCDCAcceptance
    - CurlTrackTagger(mva)
  - Cluster cuts, regions: forward/barrel/backward
    - p_t > 0.02 / 0.03 / 0.02 GeV
    - clusterZernikeMVA > 0.35 / 0.15 / 0.40
    - clusterTiming < 200

- **J/ψ and photon conversion vetoes**
  - Combine signal lepton with oppositely charged tracks
  - J/ψ μμ: 3.07 < $M_{\mu\mu}$ < 3.12 GeV
  - J/ψ ee: 3.02 < M_{ee} < 3.13 GeV
  - γ_{ee} : M_{ee} < 0.04 GeV

Corrections
Modelling

- **Branching fractions** ($B \to X_u\, l\, \nu$, $B \to X_c\, l\, \nu$, $D \to X\, l\, \nu$)
- **Form Factor**: eFFORT for $B \to X_u\, l\, \nu$, Hammer for $B \to X_c\, l\, \nu$
  - Reweighting:
    - $B \to \pi, \rho, \omega, l\, \nu$: BCL
    - $B \to \eta^{(')}\, l\, \nu$: ISGW2 → LCSR
    - $B \to D / D^{*}\, l\, \nu$: BGL → BLPRXP
    - $B \to D^{**}\, l\, \nu$: BLR (LLSW)
- **Hybrid weights**

Corrections

Experimental

- **Tagging**: MC15 corrections
- **Lepton ID**: MC15 tables
- **Kaon** ID
- **K_s** efficiency
- **Slow π** efficiency
- **Continuum** reweighting

Systematics
Modelling

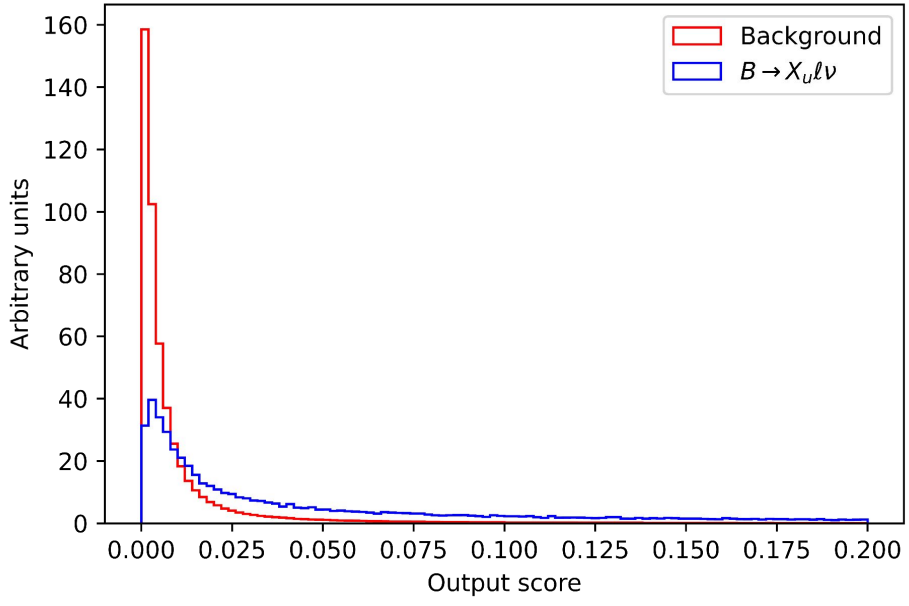
- **Branching fractions**
- **Form factor** variations
- **Inclusive model** parameter variations
- γ_s variations
- $f^{+-/00}$

Systematics
Experimental

- **Tagging**: MC15 corrections
- **Lepton ID**: MC15 tables
- **Kaon** ID
- **K_s** efficiency
- **Slow π** efficiency

Selections

- **Lepton** selections
- **Tag-side B** selections
- **Rest-of-Event** selections

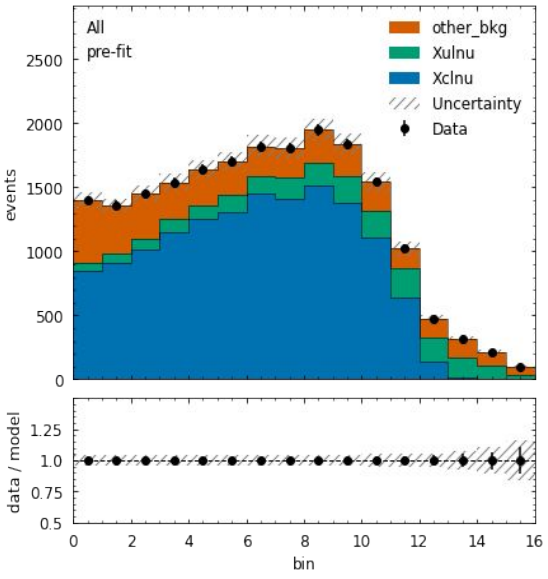


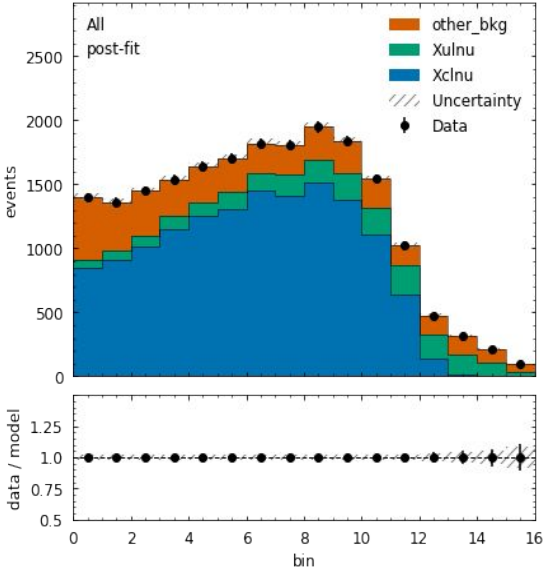
- **Multivariate** (Machine Learning) selections
  - **Neural Networks**: distinguish signal from background sources using training features (missing mass, number of kaons and pions…)
  - Additional procedure to reduce correlation between NN output and El, q2, M_x

Branching ratio extraction

Pyhf

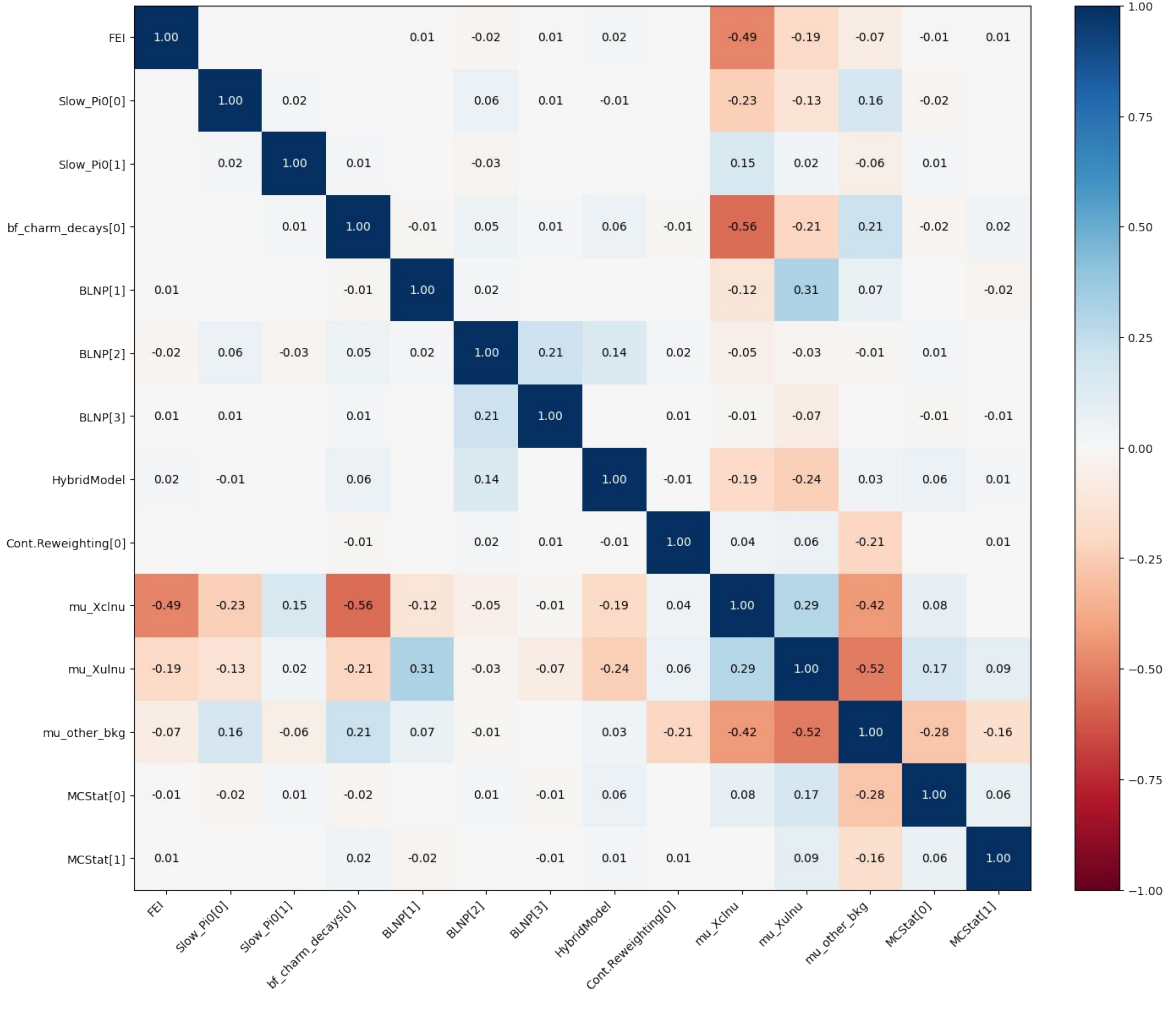
- Extract **partial Branching Fraction**
- **Binned fit**, 1 nuisance parameter per systematic source
- **3 templates**
  - Signal: $B \rightarrow X_u \, l \, \nu$
  - Main background: $B \rightarrow X_c \, l \, \nu$
  - Other backgrounds (fake/secondary leptons + continuum)
- **⇒ 1 POI + 165 NPs**
- Example: E_l^B with 16 bins from 1.0 to 2.7 GeV
- Sample: benchmark MVA cut





Correlation matrix

Post-fit



Signal extraction
Branching fraction

- Branching fraction
  - Optimise MVA cut

$$\frac{\Delta \mathrm{BF}(E_\ell^B > 1\mathrm{GeV})_{\mathrm{Asimov}}}{\sqrt{\sigma_{\mathrm{stat}}^2 + \sigma_{\mathrm{syst}}^2}}$$

Workflow ready, in validation

Number of signal events extracted from fit

$$\Delta\mathcal{B}\left(B \to X_u \ell^+ \nu_\ell; \mathrm{Reg.}\right) = \frac{\hat{\eta}_{\mathrm{sig}} \cdot \epsilon_{\Delta\mathcal{B}(\mathrm{Reg.})}}{4\left(\epsilon_{\mathrm{tag}} \cdot \epsilon_{\mathrm{sel}}\right) \cdot N_{BB}}$$

lepton = e/μ, pair of B mesons

$$\epsilon_{\mathrm{tag}} \cdot \epsilon_{\mathrm{sel}} = \frac{N_{\mathrm{sig}}^{\mathrm{sel}}}{N_{\mathrm{gen}}^{\mathrm{tot}}}$$

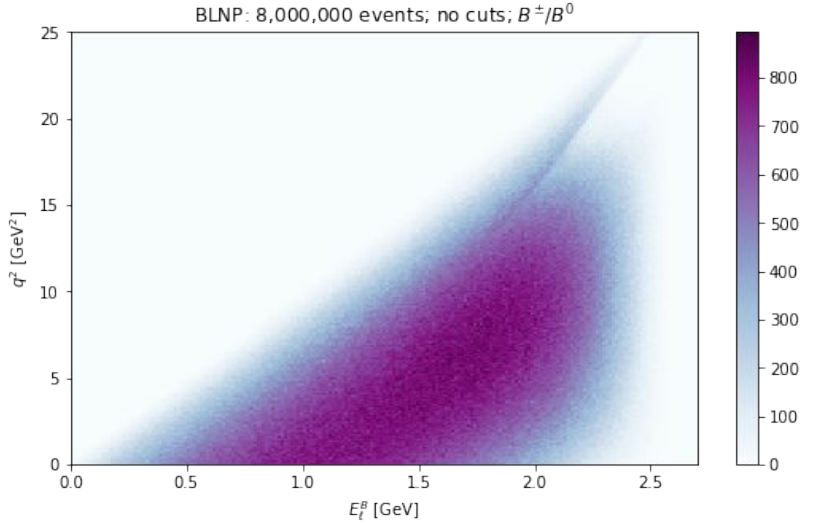
$$\epsilon_{\Delta\mathcal{B}(\mathrm{Reg.})} = \frac{N_{\mathrm{gen}}^{\mathrm{PS}}}{N_{\mathrm{gen}}^{\mathrm{tot}}}$$

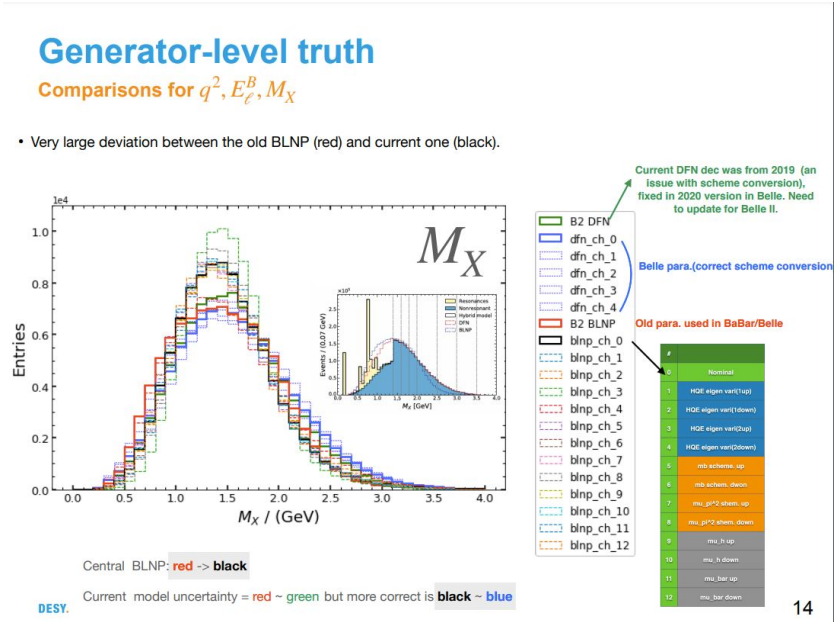
independent to detector effects

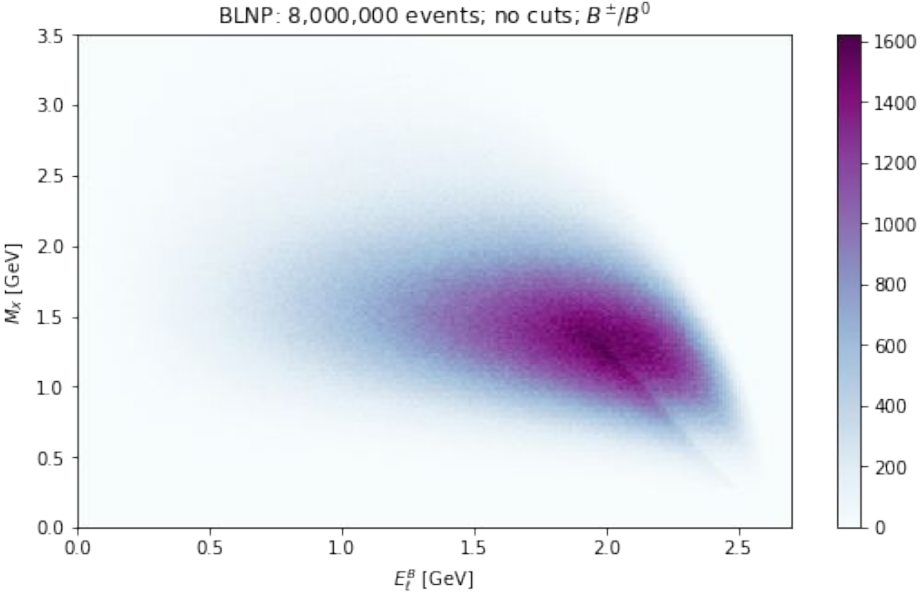
Signal modelling issues
BLNP

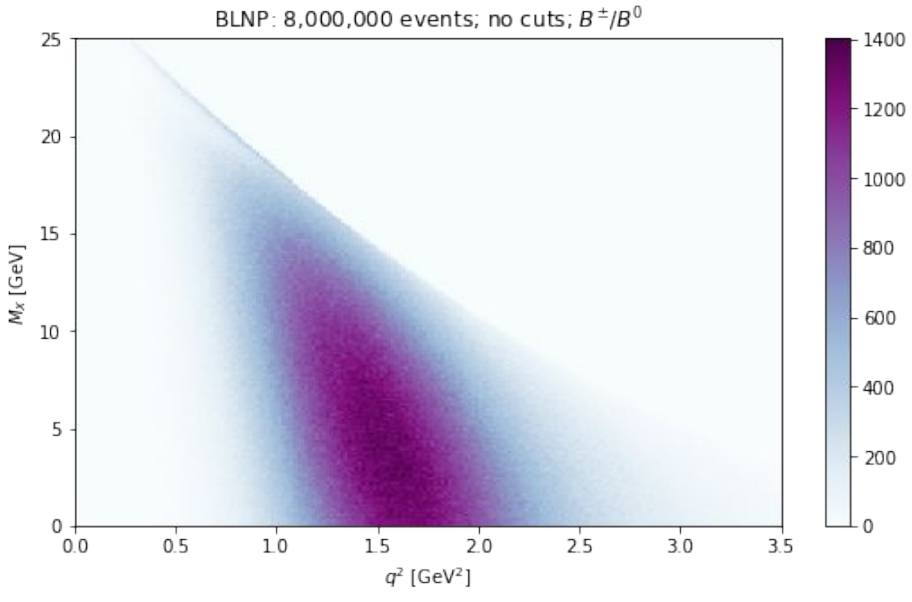
- Issues spotted in BLNP model
  - Negative hybrid weights with new input parameter values
    - Setting them to 0 leads to slight over-estimation of BR
  - Excess of events near kinematical boundaries
  - M_x spectrum
  - E_l endpoint

- In contact with Keri Vos (Maastricht)
  - Possible switch to DFN






BLNP: 8,000,000 events; no cuts; $B^{\pm}/B^{0}$
M_X [GeV]
E_l^B [GeV]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
200
400
600
800
1000
1200
1400
1600


BLNP: 8,000,000 events; no cuts; $B^{\pm}/B^{0}$
M_X [GeV]
q^2 [GeV^2]
0
5
10
15
20
25
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
200
400
600
800
1000
1200
1400

SIMBA

- SIMBA
  - Extract various parameters (m_b, CKM matrix elements…) by fitting $B \rightarrow X_s\gamma$ and $B \rightarrow X_u\, l\, \nu$