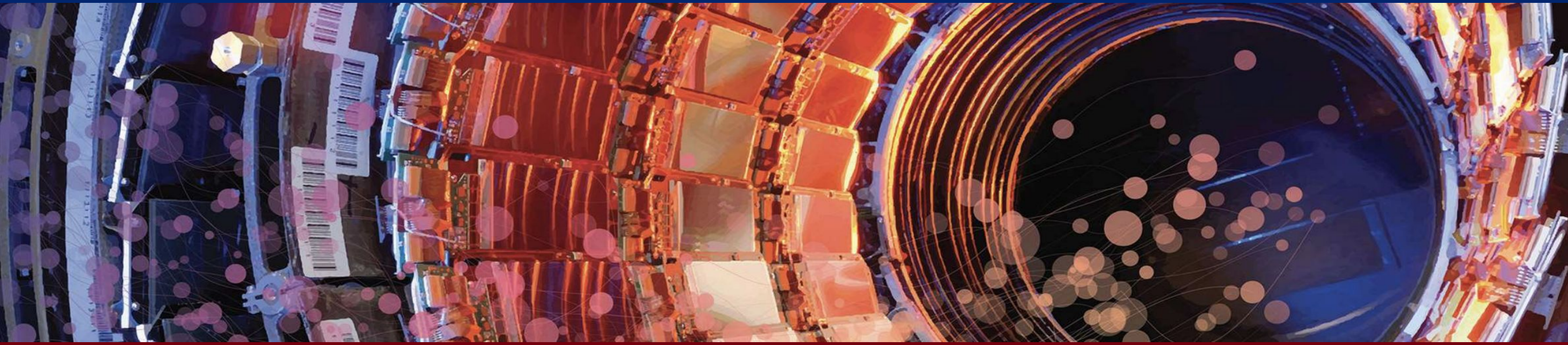
New results on inclusive $B \to X_u \, l \, \nu$ decay from the Belle experiment



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on behalf of the Belle Collaboration

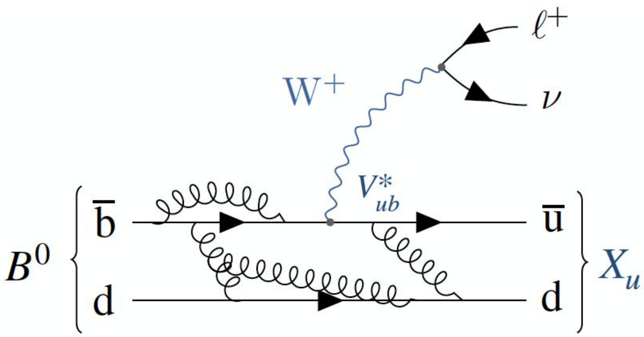
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

BELLE

UNIVERSITÄT BONN

Motivation



HFLAV

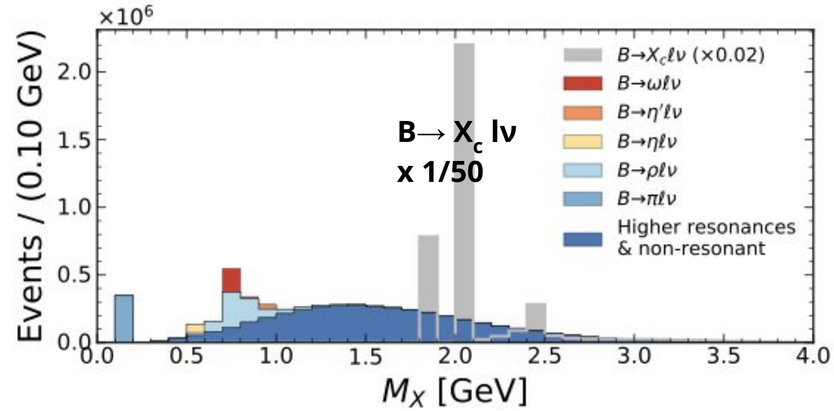
3σ

$$|V_{ub}^{\text{excl.}}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3} \,,$$

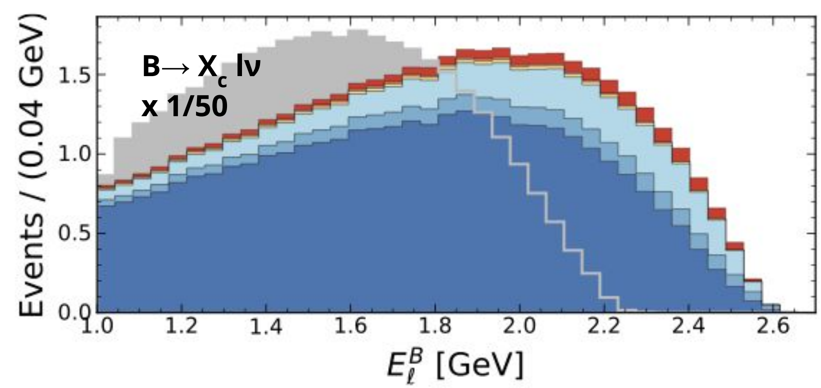
$$|V_{ub}^{\text{incl.}}| = \left(4.32 \pm 0.12^{+0.12}_{-0.13}\right) \times 10^{-3} \,.$$

- **$|V_{ub}|$ puzzle:** ca. **3σ tension** between *exclusive* and *inclusive* determinations

- Measurements challenging due to **$B \to X_c\, l\nu$**

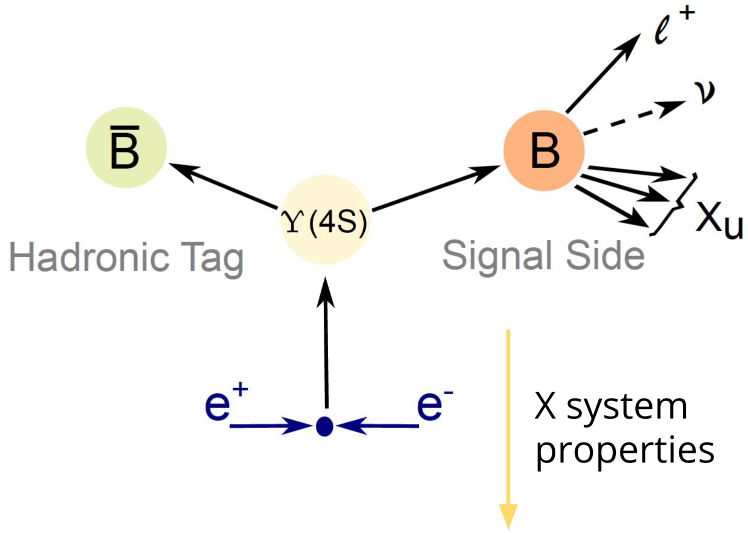


Clear **separation** only **possible** in certain **kinematic regions**, e.g. **lepton endpoint** or **low M_X**



Overview on Reconstruction Strategy

- Using **full Belle** dataset of **711 fb^{-1}**
- **Hadronic tagging** with Neural Networks (ca. **0.3-0.2% efficiency**)



Can fully assign each final state particle to either the tag or signal side

→ Allows to reconstruct X system

Reconstructed kinematic variables

- Hadronic system *X*:

$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p_i}|^2}, \mathbf{p_i}\right) + \sum_i (E_i, \mathbf{k_i})$$

- Missing mass squared:

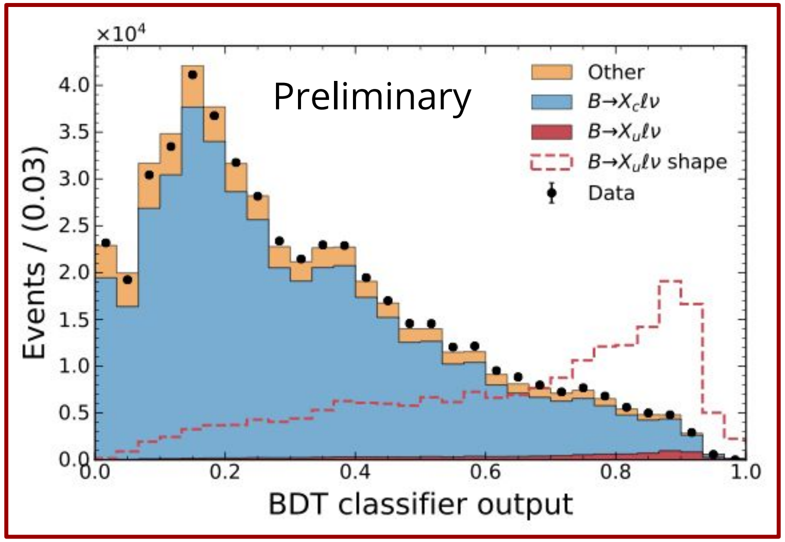
$$MM^2 = \left(P_{\Upsilon(4S)} - P_{\mathrm{tag}} - P_X - P_\ell\right)^2$$

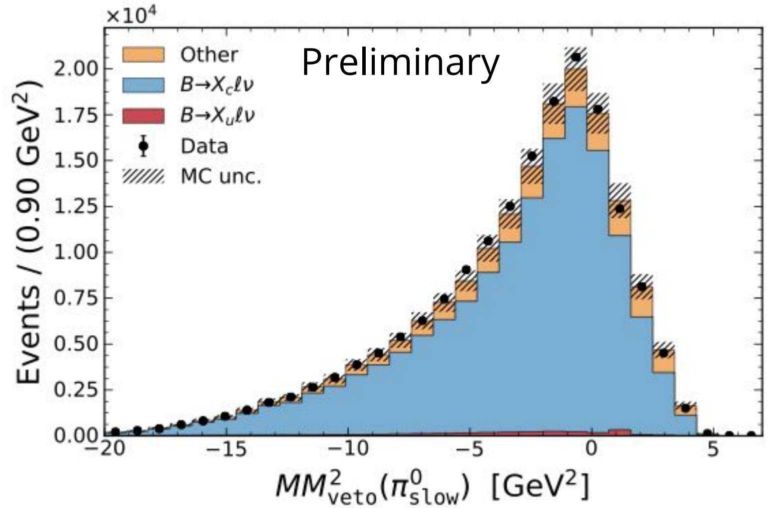
- Leptonic system:

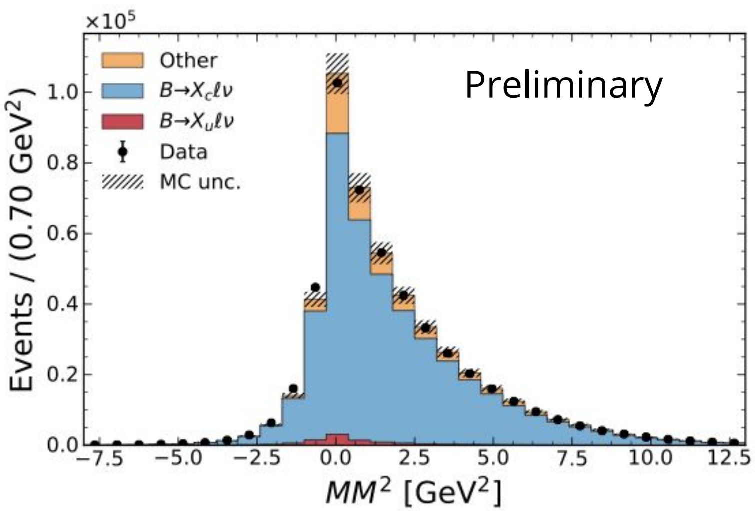
$$q^2 = (P_B - P_X)^2 = (P_l + P_\nu)^2$$

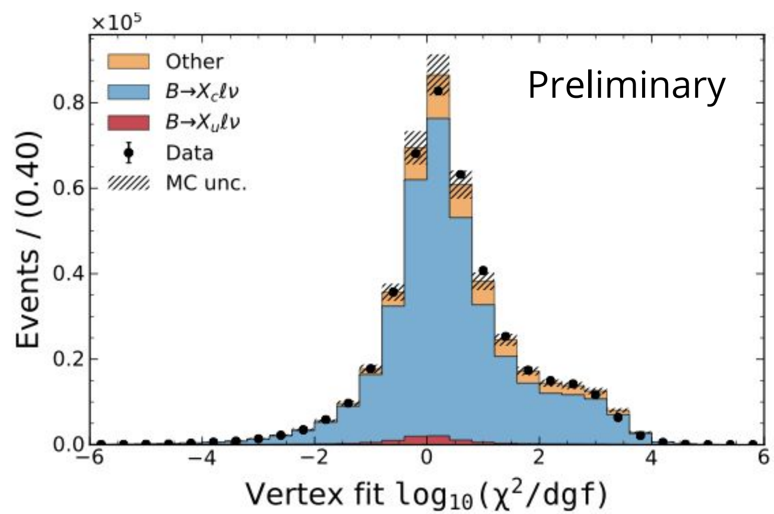
Background Suppression BDT

- Use **machine learning (BDT)** to suppress backgrounds
- BDT output and top ranking input feature vaiables are shown

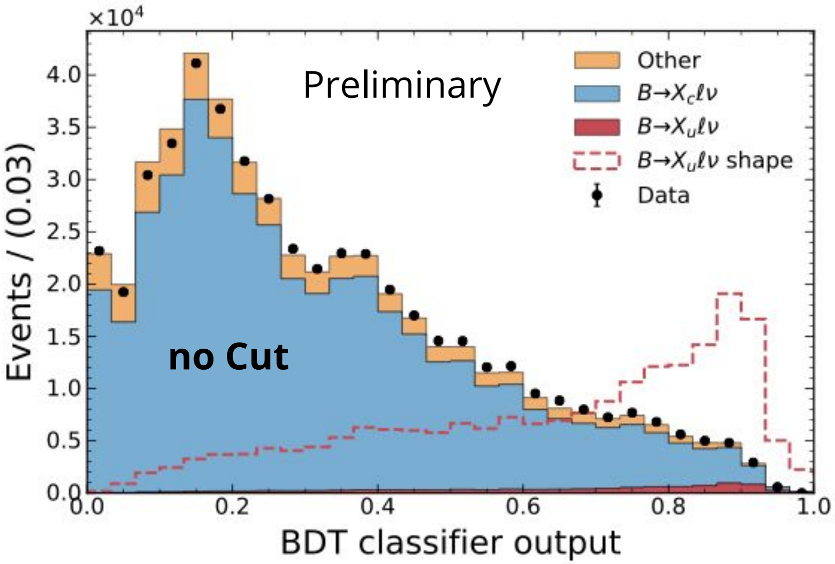


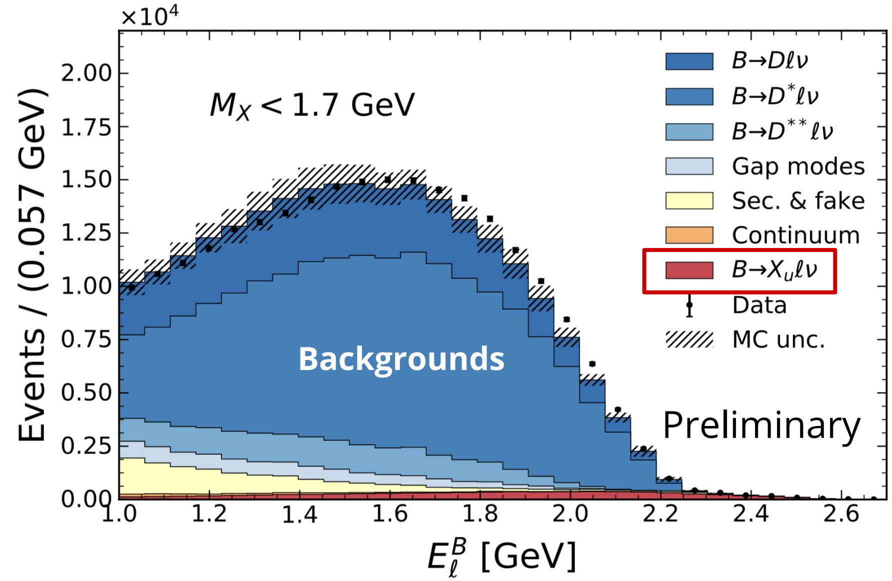


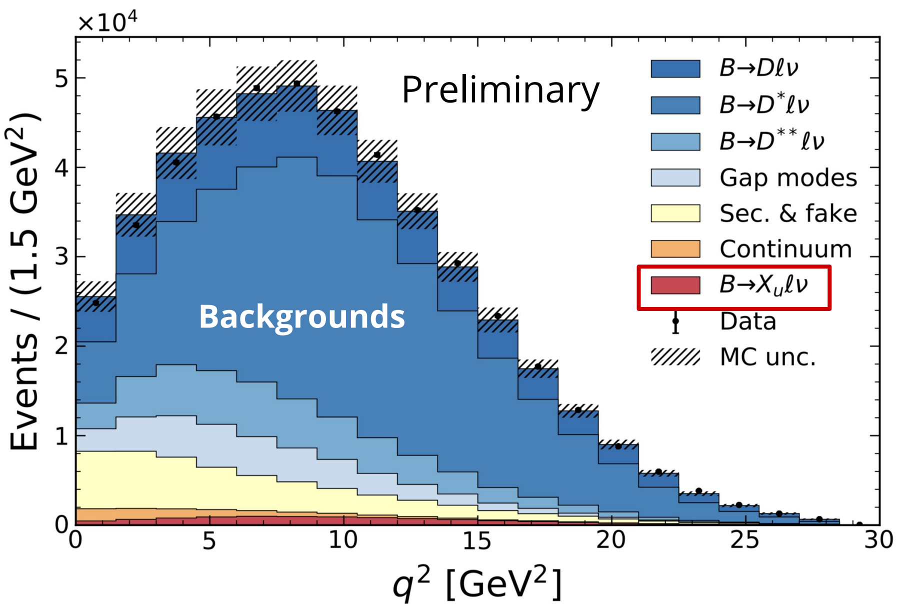


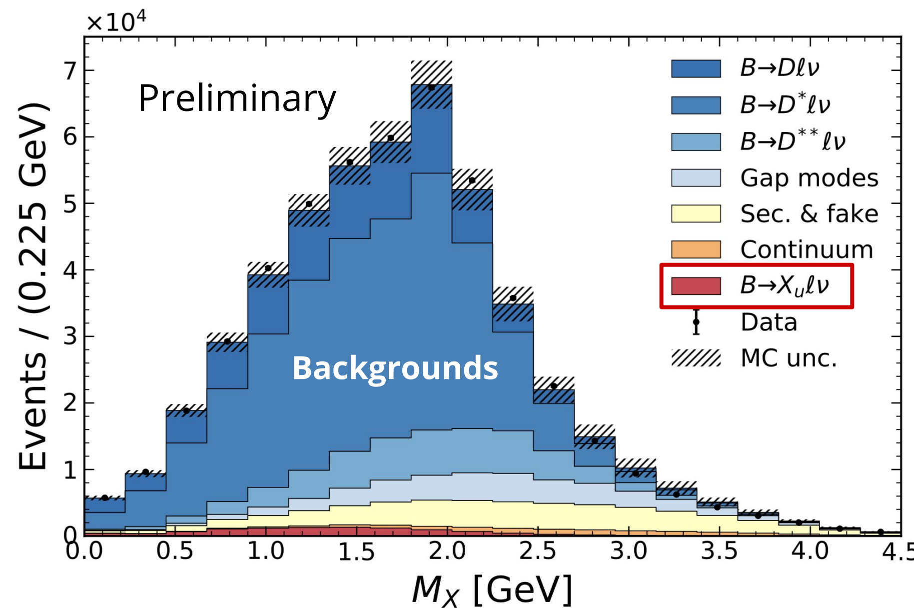


Inclusive Events

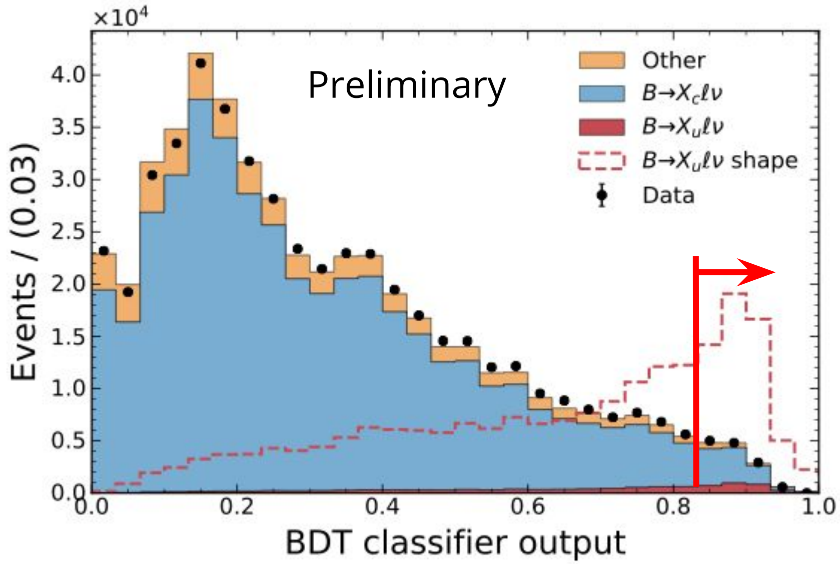


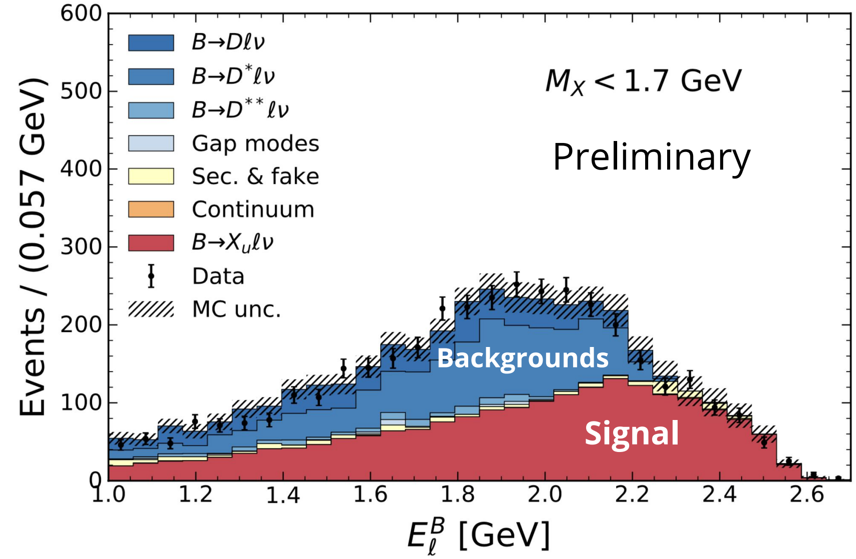


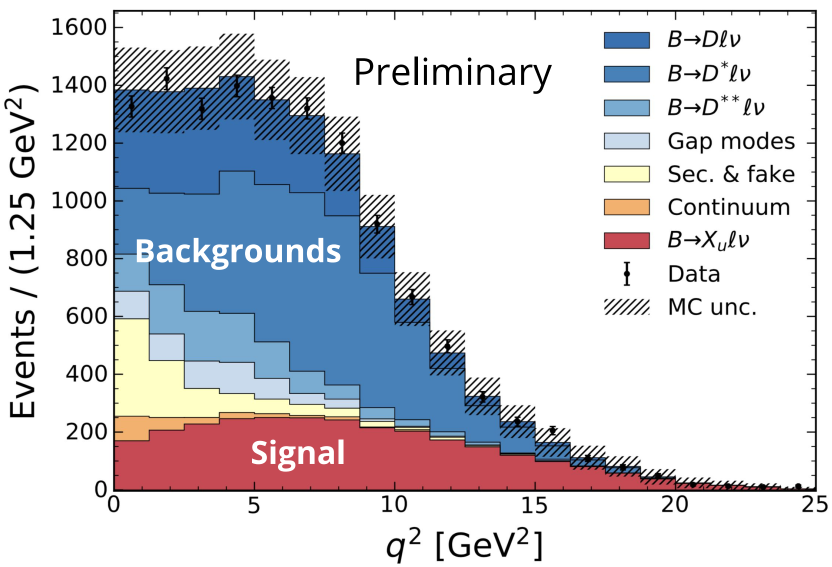


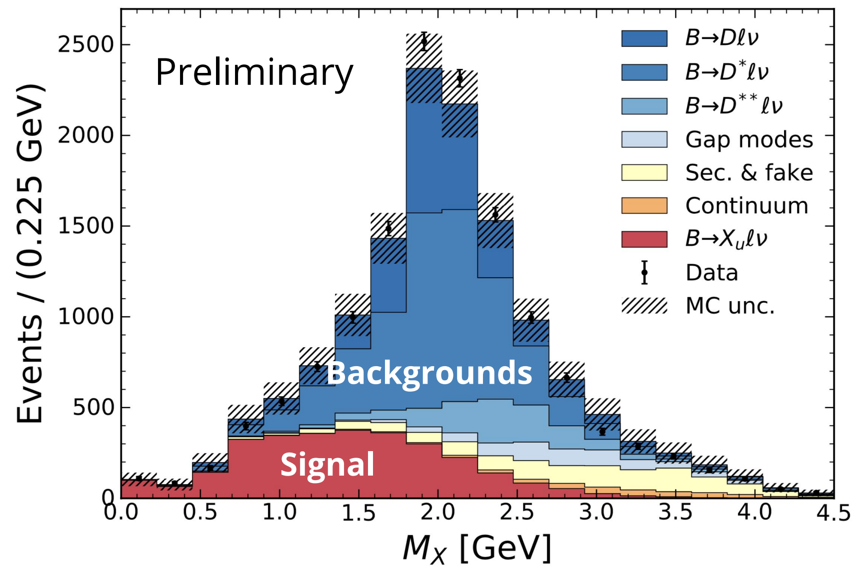


After BDT Selection









Signal Extraction

- Extract signal using binned likelihood in **3 phase space (PS) regions**
  - $E_\ell^B > 1$ GeV (covers 86% of available signal PS)
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV (56%)
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2 (31%)

→ Fit either E_ℓ^B ,M_X, q^2 or M_X:q^2

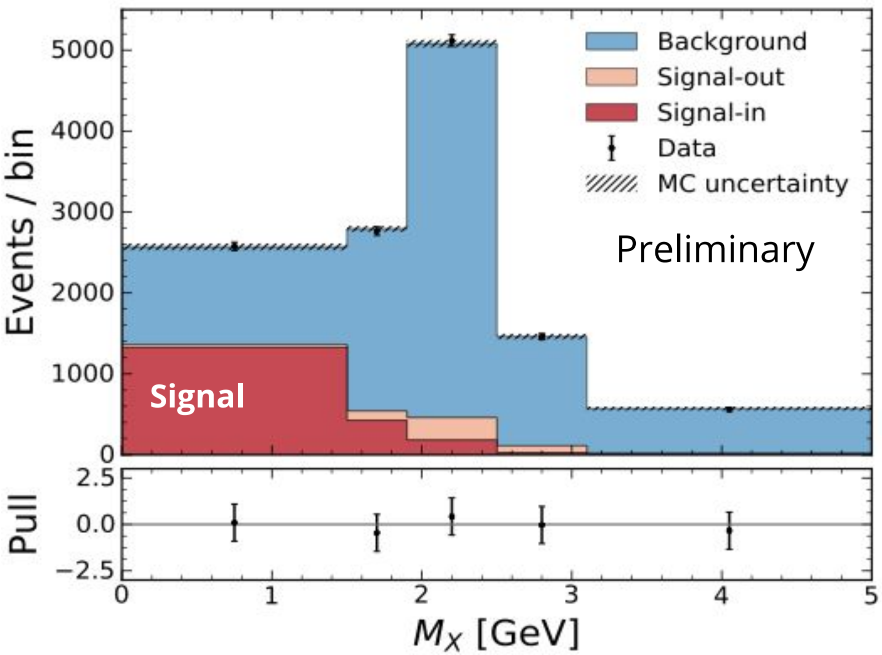
→ MC templates for **signal**, **signal-out** (outside PS) & **background**

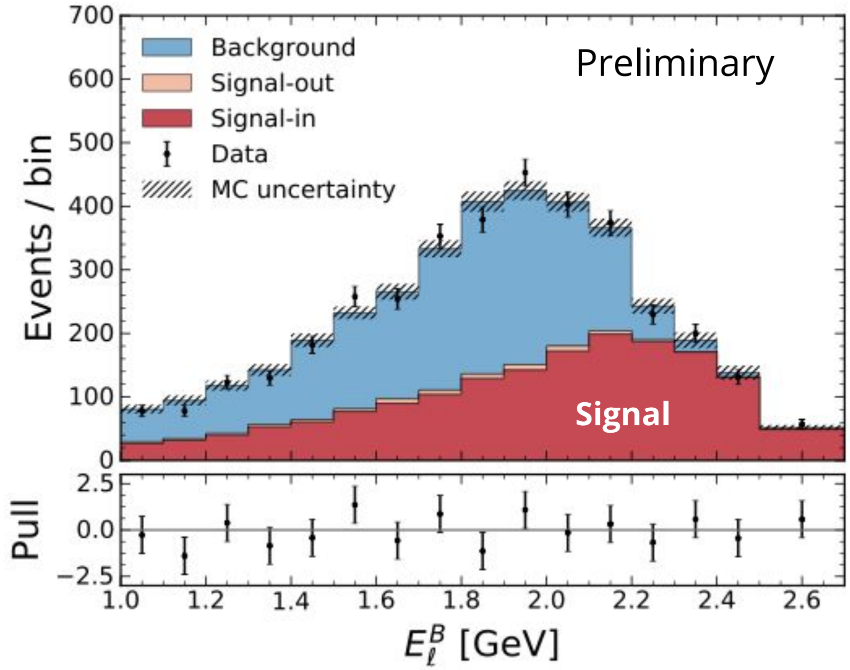
In total carry out **five fits:**

Apply additional **kinematic cuts** for E_ℓ^B and q^2 fits to reduce *$B \rightarrow X_c l\nu$ modelling*

	Test	Fit var	Phase space	Additional cut
1D fit	(a)	M_X	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV	
1D fit	(b)	q^2	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$M_X^{\mathtt{reco}} < 1.7$ GeV
1D fit	(c1)	E_ℓ^B	$E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV	$M_X^{\mathtt{reco}} < 1.7$ GeV
1D fit	(c2)	E_ℓ^B	$E_\ell^B > 1$ GeV	$M_X^{\mathtt{reco}} < 1.7$ GeV
2D fit	(d)	$M_X - q^2$	$E_\ell^B > 1$ GeV	

Fits for $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV





ΔB = **$(1.04 \pm 0.04_{stat} \pm 0.07_{sys}) \times 10^{-3}$**

Preliminary

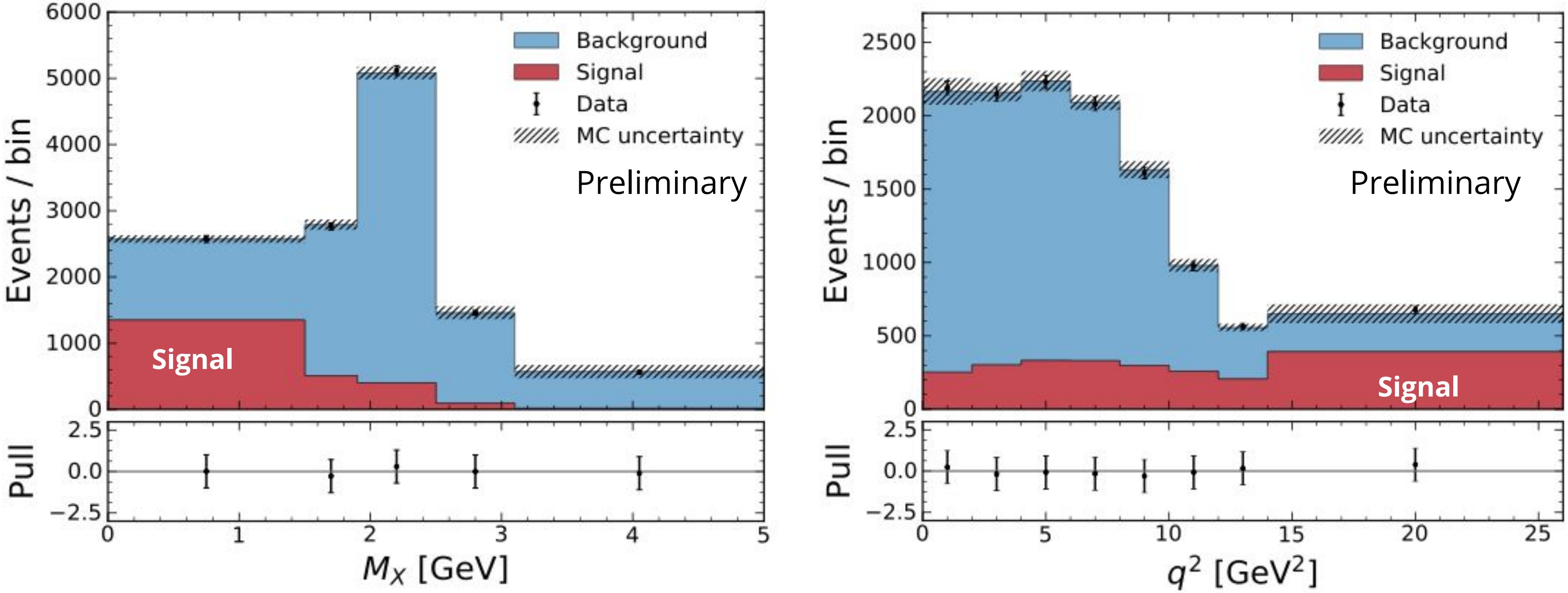
ΔB = **$(1.09 \pm 0.05_{stat} \pm 0.10_{sys}) \times 10^{-3}$**

Preliminary

BaBar (2012): ΔB = **$(1.15 \pm 0.13) \times 10^{-3}$**

Fit for $E_\ell^B > 1$ GeV

Projections of 2D fit resut:



$\Delta\mathcal{B} = (1.56 \pm 0.06_{stat} \pm 0.12_{sys}) \times 10^{-3}$

Preliminary

BaBar (2017): $\Delta\mathcal{B} = (1.55 \pm 0.12) \times 10^{-3}$

BaBar (2012): $\Delta\mathcal{B} = (1.82 \pm 0.19) \times 10^{-3}$

Belle (2010): $\Delta\mathcal{B} = (1.96 \pm 0.23) \times 10^{-3}$

Theoretical Decay Rates & $|V_{ub}|$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\,\ell^+\,\nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u\,\ell^+\,\nu_\ell)}}\,.$$

- τ_B average B meson lifetime: (1.579 ± 0.004) ps
- ΔΓ: Use **state-of-the-art theory**: BLNP, DGE, GGOU, ADFR to determine $|V_{ub}|$

Phase-space region	BLNP	DGE	GGOU	ADFR
$M_X < 1.7$ GeV	$45.2^{+5.4}_{-4.6}$	$42.3^{+5.8}_{-3.8}$	$43.7^{+3.9}_{-3.2}$	$52.3^{+5.4}_{-4.7}$
$M_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$23.4^{+3.4}_{-2.6}$	$24.3^{+2.6}_{-1.9}$	$23.3^{+3.2}_{-2.4}$	$31.1^{+3.0}_{-2.6}$
$E_\ell^B > 1$ GeV	$61.5^{+6.4}_{-5.1}$	$58.2^{+3.6}_{-3.0}$	$58.5^{+2.7}_{-2.3}$	$61.5^{+5.8}_{-5.1}$

[in unit of ps^{-1}]

Preliminary Results on $|V_{ub}|$

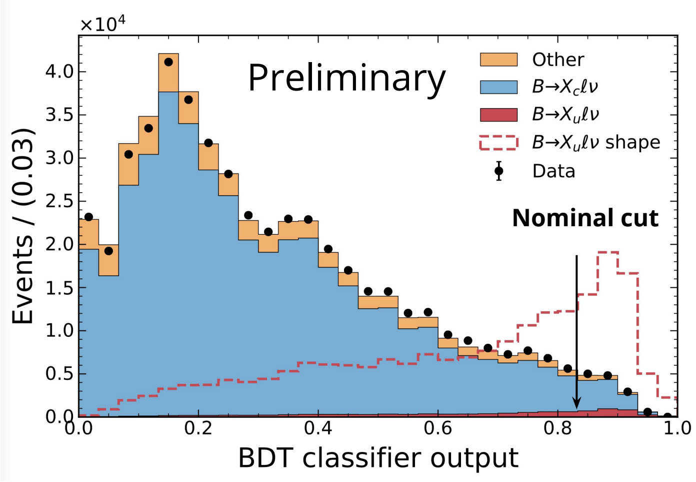
- M_X:q^2 **fit** **most precise** & covers largest phase-space **(~86%)**

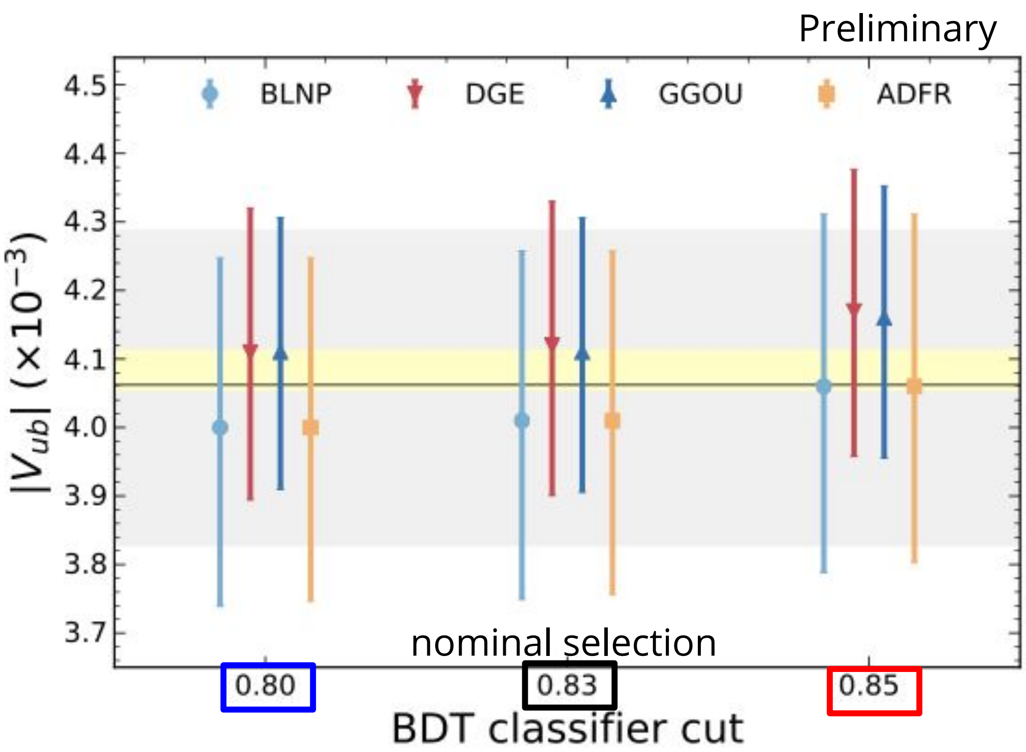
Preliminary

Fit	$\|V_{ub}\|$ (± stat ± sys ± theo.)			
	BLNP	DGE	GGOU	ADFR
(a)	$3.81^{+0.08,+0.13,+0.21}_{-0.08,-0.13,-0.21}$	$3.99^{+0.08,+0.14,+0.20}_{-0.08,-0.14,-0.26}$	$3.88^{+0.08,+0.13,+0.15}_{-0.08,-0.14,-0.16}$	$3.55^{+0.07,+0.12,+0.17}_{-0.07,-0.12,-0.17}$
(b)	$4.35^{+0.18,+0.26,+0.26}_{-0.18,-0.28,-0.28}$	$4.27^{+0.17,+0.26,+0.18}_{-0.18,-0.28,-0.21}$	$4.36^{+0.18,+0.27,+0.24}_{-0.18,-0.28,-0.27}$	$3.77^{+0.15,+0.23,+0.17}_{-0.16,-0.24,-0.17}$
(c1)	$3.90^{+0.09,+0.17,+0.21}_{-0.10,-0.18,-0.21}$	$4.08^{+0.10,+0.18,+0.20}_{-0.10,-0.19,-0.26}$	$3.97^{+0.09,+0.18,+0.15}_{-0.10,-0.19,-0.16}$	$3.63^{+0.09,+0.16,+0.17}_{-0.09,-0.17,-0.17}$
(c2)	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.20}$	$4.25^{+0.10,+0.21,+0.11}_{-0.10,-0.22,-0.12}$	$4.24^{+0.10,+0.21,+0.09}_{-0.10,-0.22,-0.10}$	$4.14^{+0.10,+0.20,+0.18}_{-0.10,-0.22,-0.18}$
(d)	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.19}$	$4.12^{+0.08,+0.16,+0.11}_{-0.09,-0.16,-0.12}$	$4.11^{+0.08,+0.16,+0.08}_{-0.09,-0.16,-0.09}$	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.18}$

Stability over Bkg Contamination

Change of result if background is **increased (+37%)** or **decreased (-26%)**





Extracted $|V_{ub}|$ remains stable:

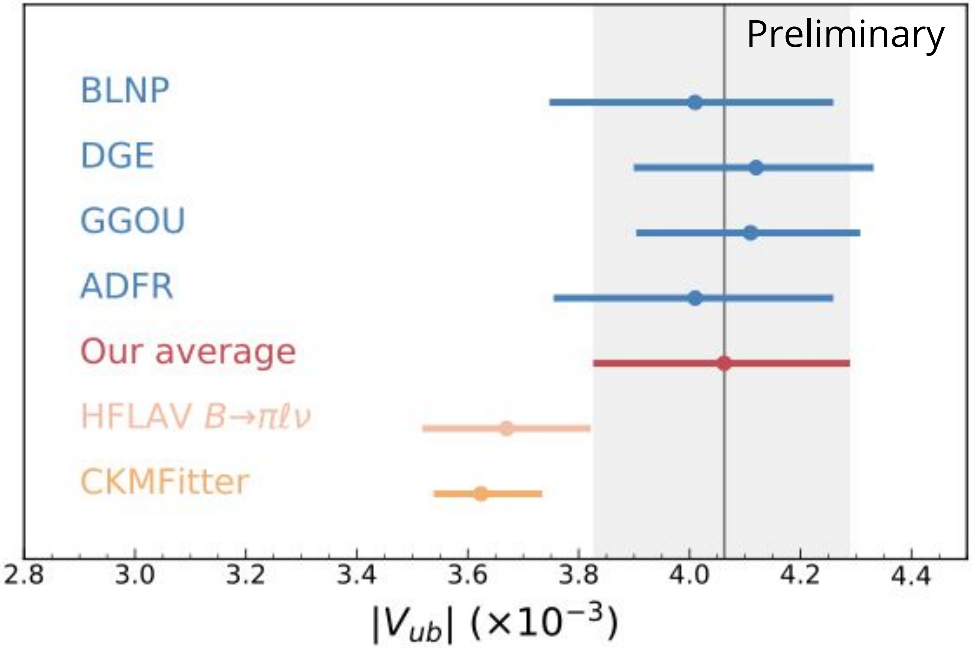
$\rightarrow$ **-0.2%** and **+1.2%**

Average Result on $|V_{ub}|$

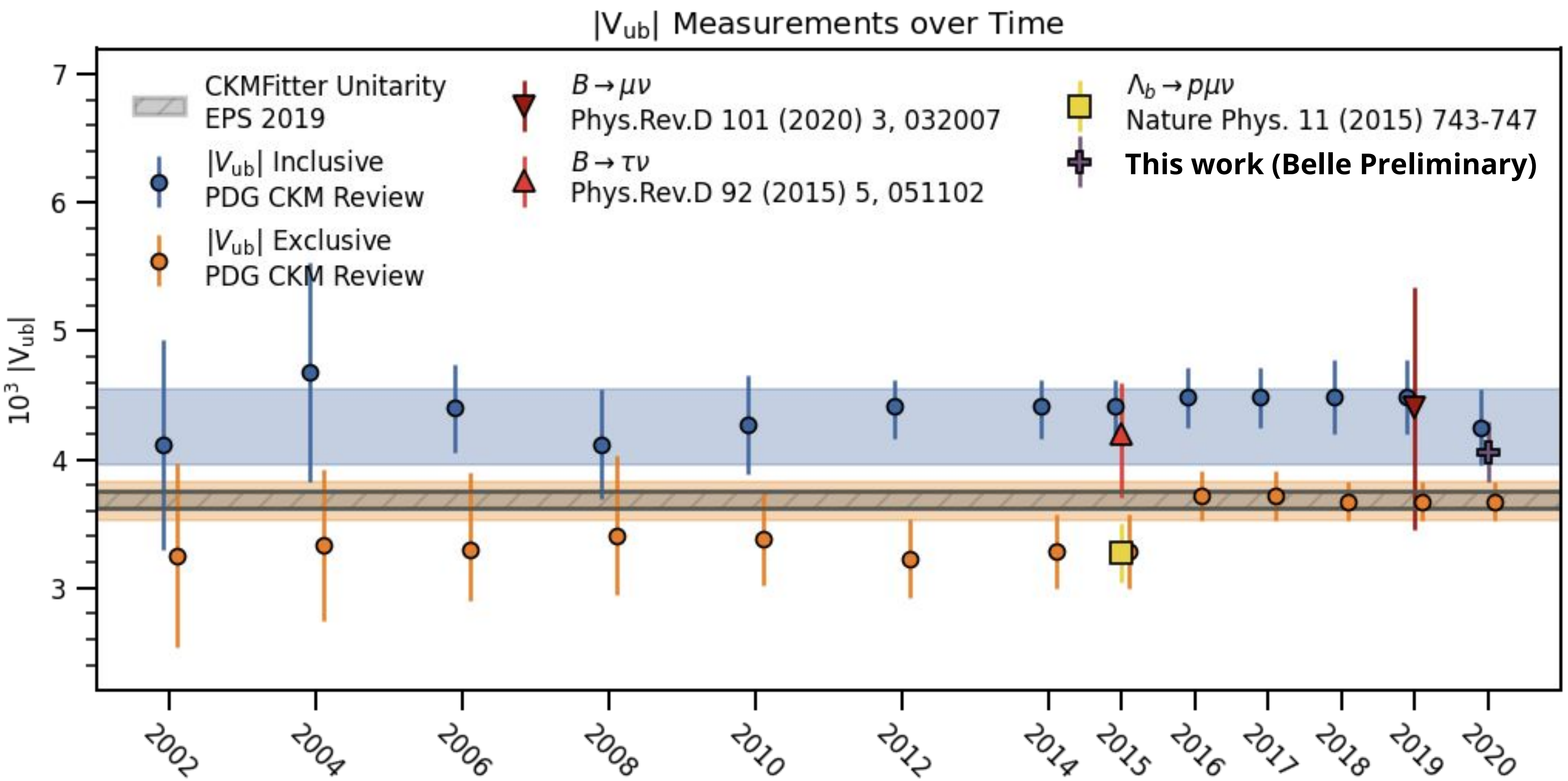
Arithmetic average over results of four theory calculations:

$$|V_{ub}| \text{ (avg)} = \mathbf{(4.06 \pm 0.09_{stat} \pm 0.16_{sys} \pm 0.15_{theo}) \times 10^{-3}}$$

Value is compatible with excl. and CKM expectation within **1.4 σ** and **1.6 σ**



Summary on $|V_{ub}|$ over Time



Summary

- Preliminary resluts are obtatined with hadronic tagged analysis with full Belle dataset:

  $\Delta\mathcal{B}(B \to X_u l\nu, E^B_l > 1\ \mathrm{GeV}) = \mathbf{(1.56 \pm 0.06_{stat} \pm 0.12_{sys}) \times 10^{-3}}$

  $\to |V_{ub}|\ (\mathrm{avg}) = \mathbf{(4.06 \pm 0.09_{stat} \pm 0.16_{sys} \pm 0.15_{theo}) \times 10^{-3}}$

- The measured partial branching fractions for various PS are compatible with the previous Belle and BaBar results.

- $|V_{ub}|$ tension between excl. and incl. measurements is found to be ca. **1.4 standard deviations**.

Thank you

Backup

Background $B \to X_c l\nu$ MC

- Update excl. BR to PDG2019 and the masses and widths of D**.
- To fill the **gap** between the inclusive and exclusive measurement, additional MC samples were generated. (100% uncertainty on BR in systematics covariance matrix)

	BR	B^+	B^0
	$B \to X_c \ell^+ \nu_\ell$		
D, D*	$B \to D \ell^+ \nu_\ell$	$(2.5 \pm 0.1) \times 10^{-2}$	$(2.3 \pm 0.1) \times 10^{-2}$
D, D*	$B \to D^* \ell^+ \nu_\ell$	$(5.4 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
D**	$B \to D_0^* \ell^+ \nu_\ell$ $(\hookrightarrow D\pi)$	$(0.420 \pm 0.075) \times 10^{-2}$	$(0.390 \pm 0.069) \times 10^{-2}$
D**	$B \to D_1^* \ell^+ \nu_\ell$ $(\hookrightarrow D^*\pi)$	$(0.423 \pm 0.083) \times 10^{-2}$	$(0.394 \pm 0.077) \times 10^{-2}$
D**	$B \to D_1 \ell^+ \nu_\ell$ $(\hookrightarrow D^*\pi)$	$(0.422 \pm 0.027) \times 10^{-2}$	$(0.392 \pm 0.025) \times 10^{-2}$
D**	$B \to D_2^* \ell^+ \nu_\ell$ $(\hookrightarrow D^*\pi)$	$(0.116 \pm 0.011) \times 10^{-2}$	$(0.107 \pm 0.010) \times 10^{-2}$
D**	$B \to D_2^* \ell^+ \nu_\ell$ $(\hookrightarrow D\pi)$	$(0.178 \pm 0.024) \times 10^{-2}$	$(0.165 \pm 0.022) \times 10^{-2}$
D**	$\rho(D_2^* \to D^*\pi, D_2^* \to D\pi) = 0.693$		
Gap	$B \to D_1 \ell^+ \nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.242 \pm 0.100) \times 10^{-2}$	$(0.225 \pm 0.093) \times 10^{-2}$
Gap	$B \to D\pi\pi \ell^+ \nu_\ell$	$(0.06 \pm 0.06) \times 10^{-2}$	$(0.06 \pm 0.06) \times 10^{-2}$
Gap	$B \to D^*\pi\pi \ell^+ \nu_\ell$	$(0.216 \pm 0.102) \times 10^{-2}$	$(0.201 \pm 0.095) \times 10^{-2}$
Gap	$B \to D\eta \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
Gap	$B \to D^*\eta \ell^+ \nu_\ell$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
	$B \to X_c \ell^+ \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

Systematics on Partical BF

Preliminary

Phase-space region	Fractional uncertainties: $M_X < 1.7\,\mathrm{GeV}$, $E_\ell^B > 1\,\mathrm{GeV}$	$M_X < 1.7\,\mathrm{GeV}$, $E_\ell^B > 1\,\mathrm{GeV}$	$M_X < 1.7\,\mathrm{GeV}$, $q^2 > 8\,\mathrm{GeV}^2$, $E_\ell^B > 1\,\mathrm{GeV}$	$E_\ell^B > 1\,\mathrm{GeV}$	$E_\ell^B > 1\,\mathrm{GeV}$
Fit variable(s)	(M_X fit)	(E_ℓ^B fit)	(q^2 fit)	(E_ℓ^B fit)	($M_X : q^2$ fit)
Source of uncertainty					
Additive uncertainties	small due to coarse mX binning		large due to direct dependence on q^2 shape & **separation of $q^2 > 8$ GeV^2**		
$B \to X_u\,\ell^+\,\nu_\ell$ modelling	1.4 %	4.7 %	6.1 %	4.8 %	2.3 %
$B \to X_c\,\ell^+\,\nu_\ell$ modelling	1.5 %	1.5 %	0.9 %	1.5 %	1.5 %
$\mathcal{L}_{\mathrm{LID}}$,$\mathcal{L}_{\mathrm{KID}}$, Tracking, π_s eff.	1.4 %	0.4 %	1.1 %	0.5 %	1.4 %
MC statistics	2.8 %	4.8 %	6.4 %	4.8 %	3.0 %
Multiplicative uncertainties					
$B \to X_u\,\ell^+\,\nu_\ell$ modeling					
$B \to \pi\,\ell^+\,\nu_\ell$ FFs	0.1 %	0.1 %	1.6 %	0.1 %	0.1 %
$B \to \rho\,\ell^+\,\nu_\ell$ FFs	0.4 %	0.4 %	3.0 %	0.4 %	0.4 %
$B \to \omega\,\ell^+\,\nu_\ell$ FFs	1.0 %	1.2 %	5.0 %	1.2 %	0.8 %
$B \to \eta\,\ell^+\,\nu_\ell$ FFs	0.2 %	0.1 %	1.4 %	0.2 %	0.1 %
$B \to \eta'\,\ell^+\,\nu_\ell$ FFs	0.1 %	0.1 %	1.4 %	0.1 %	0.1 %
$\mathcal{B}(B \to \pi\,\ell^+\,\nu_\ell)$	0.2 %	0.3 %	0.3 %	0.3 %	0.2 %
$\mathcal{B}(B \to \rho\,\ell^+\,\nu_\ell)$	0.3 %	0.5 %	0.5 %	0.5 %	0.3 %
$\mathcal{B}(B \to \omega\,\ell^+\,\nu_\ell)$	0.1 %	0.1 %	0.1 %	0.1 %	0.1 %
$\mathcal{B}(B \to \eta\,\ell^+\,\nu_\ell)$	0.1 %	0.1 %	0.1 %	0.1 %	0.1 %
$\mathcal{B}(B \to \eta'\,\ell^+\,\nu_\ell)$	0.1 %	0.1 %	0.1 %	0.1 %	0.1 %
$\mathcal{B}(B \to X_u\,\ell^+\,\nu)$ (sizeable due to impact on eff.)	3.0 %	3.4 %	3.2 %	4.9 %	3.8 %
DFN parameters	2.1 %	2.3 %	2.8 %	3.4 %	2.6 %
Hybrid model	0.2 %	0.2 %	0.3 %	0.6 %	0.5 %
MC statistics	< 0.1 %	< 0.1 %	< 0.1 %	< 0.1 %	< 0.1 %
$\mathcal{L}_{\mathrm{LID}}$ efficiency	1.5 %	1.6 %	1.6 %	1.6 %	1.5 %
$\mathcal{L}_{\mathrm{KID}}$ efficiency	0.7 %	0.7 %	0.6 %	0.8 %	0.8 %
$N_{B\bar{B}}$	1.3 %	1.3 %	1.3 %	1.3 %	1.3 %
Slow pion efficiency	< 0.1 %	< 0.1 %	< 0.1 %	< 0.1 %	< 0.1 %
Tracking efficiency	0.9 %	0.4 %	0.8 %	0.4 %	0.9 %
Tagging calibration	3.6 %	3.6 %	3.6 %	3.6 %	3.6 %
Total syst. uncertainty	**6.7 %**	**13 %**	**9.3 %**	**10.4 %**	**7.7 %**

Shape uncertainties

Effect on normalization

Total X_u model errors: ca. 4 - 7.6%

Most inclusive meas (2D fit): **5.3%**

Previous Belle result with same same phase space: **6.3%**

Details on Theory Rates

The theory rates $\Delta\Gamma(B \to X_u \ell^+ \nu_\ell)$ from various theory calculations are listed. The rates are in units of ps^{-1}.

Phase-space region	BLNP [51]	DGE [52, 53]	GGOU [54]	ADFR [55, 56]
$M_X < 1.7\,\mathrm{GeV}$	$45.2^{+5.4}_{-4.6}$	$42.3^{+5.8}_{-3.8}$	$43.7^{+3.9}_{-3.2}$	$52.3^{+5.4}_{-4.7}$
$M_X < 1.7\,\mathrm{GeV},\ q^2 > 8\,\mathrm{GeV}^2$	$23.4^{+3.4}_{-2.6}$	$24.3^{+2.6}_{-1.9}$	$23.3^{+3.2}_{-2.4}$	$31.1^{+3.0}_{-2.6}$
$p_\ell > 1\,\mathrm{GeV}$	$61.5^{+6.4}_{-5.1}$	$58.2^{+3.6}_{-3.0}$	$58.5^{+2.7}_{-2.3}$	$61.5^{+5.8}_{-5.1}$

- **BLNP**: The prediction of Bosch, Lange, Neubert and Paz (short BLNP) of Ref. [51] provides a prediction at NLO accuracy and incorporate all known corrections. Predictions are interpolated between the shape-function dominated region (endpoint of the lepton spectrum, small hadronic mass) to the region of phase space, that can be described via teh operator product expansion (OPE). As input we use $m_b^{\mathrm{SF}} = 4.58 \pm 0.03\,\mathrm{GeV}$ and $\mu_\pi^{2\,\mathrm{SF}} = 0.20^{+0.09}_{-0.10}\,\mathrm{GeV}^2$.

- **DGE**: The dressed gluon approximation (short DGE) from Andersen and Gardi [52, 53] makes predictions avoiding the direct use of shape functions, but produces predictions for hadronic observables using the on-shell b-quark mass. The calculation is carried out in the $\overline{\mathrm{MS}}$ scheme and we use $m_b(\overline{\mathrm{MS}}) = 4.19 \pm 0.04\,\mathrm{GeV}$.

- **GGOU**: The prediction from Gambino, Giordano, Ossola and Uraltsev [54] (short GGOU) incorporate all known perturbative and non-perturbative effects up to the order $\mathcal{O}(\alpha_s^2\,\beta_0)$ and $\mathcal{O}(1/m_b^3)$, respectively. The shape function dependence is incorporated by parametrizing its effects in each structure function with a single light-cone function. The calculation is carried out in the kinetic scheme and we use as inputs $m_b^{\mathrm{kin}} = 4.55 \pm 0.02$ GeV and $\mu_\pi^{2\,\mathrm{kin}} = 0.46 \pm 0.08\,\mathrm{GeV}^2$.

- **ADFR**: The calculation of Aglietti, Di Lodovico, Ferrera, and Ricciardi [55, 56] makes use of the ratio of $B \to X_u \ell^+ \nu_\ell$ to $B \to X_c \ell^+ \nu_\ell$ rates and soft-gluon resummation at NNLO and an effective QCD coupling approach. The calculation uses the $\overline{\mathrm{MS}}$ scheme and we use $m_b(\overline{\mathrm{MS}}) = 4.19 \pm 0.04\,\mathrm{GeV}$.