

# Prospects of $|V_{ub}|$ measurement at Belle II

MITP Flavour at the Crossroads

27 April 2022

Tommy Martinov, on behalf of the Belle II collaboration



HELMHOLTZ

# Outline of the talk

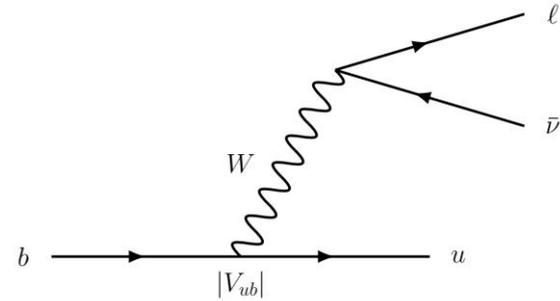


- i **Physics motivation**
- i **SuperKEKB/Belle II**
- i **Event reconstruction**
- i **Exclusive decays: theory, experiment, prospects**
- i **Inclusive decays: theory, experiment, prospects**

# Motivation

## Yet another discrepancy

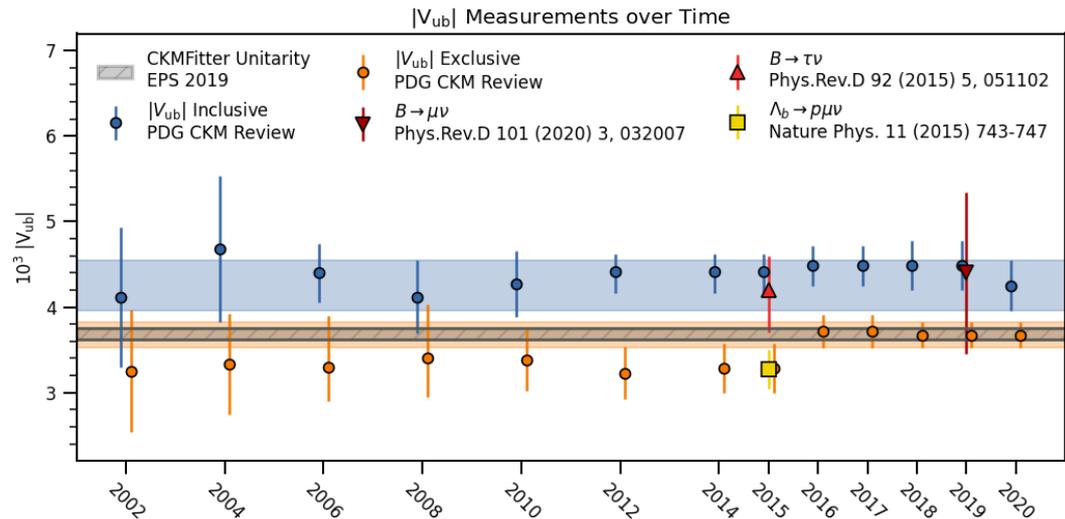
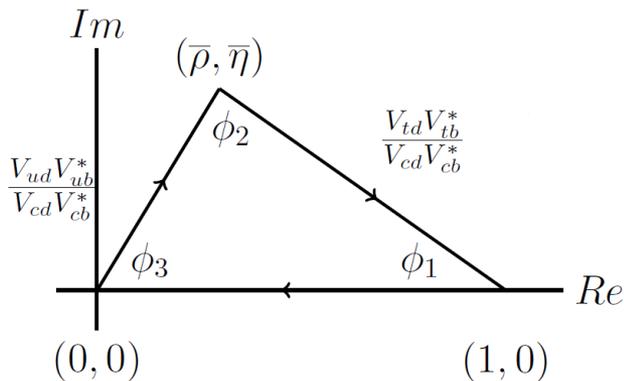
- i **Inclusive/exclusive** semi-leptonic decays:  $6 \rightarrow u \ell$
- i Results from CLEO, BaBar, Belle, LHCb
- i **~2/3 discrepancy** between the two



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

$$|V_{ub}| = (4.25 \pm 0.12_{-0.14}^{+0.15} \pm 0.23_{\Delta\text{BF}}) \times 10^{-3} \quad \text{PDG incl.}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

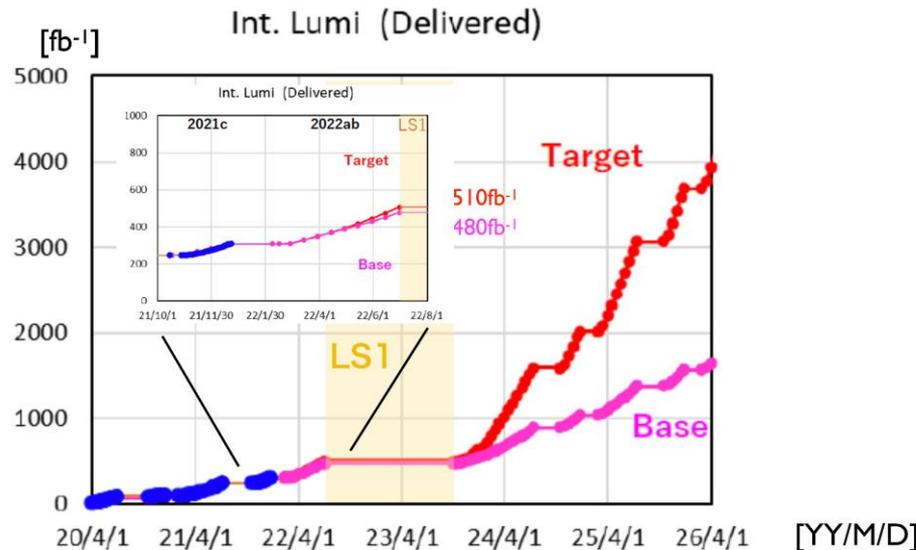
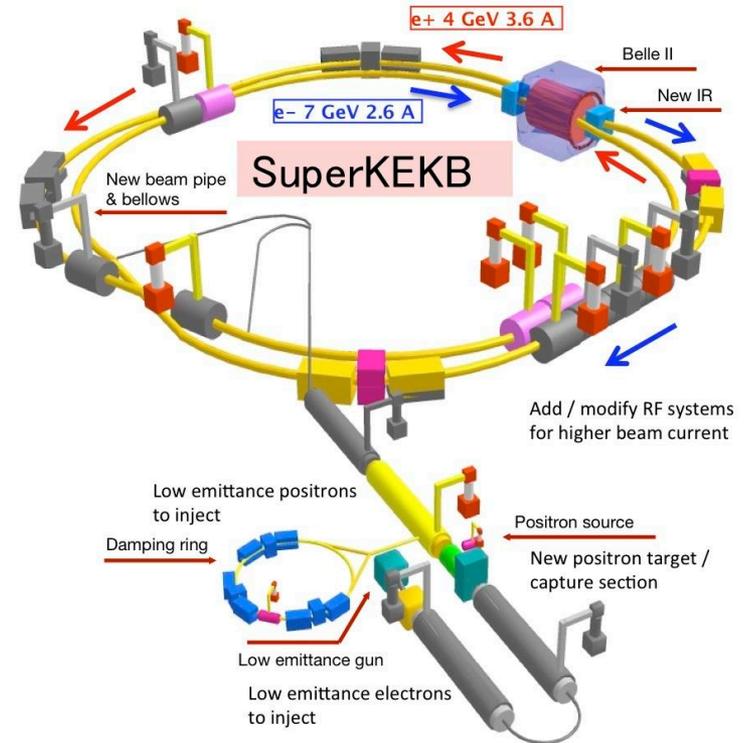
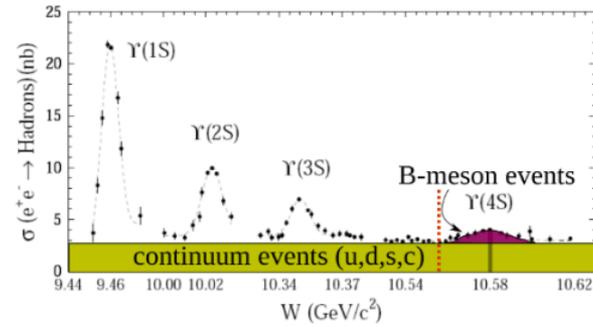


# SuperKEKB

Tsukuba, Japan

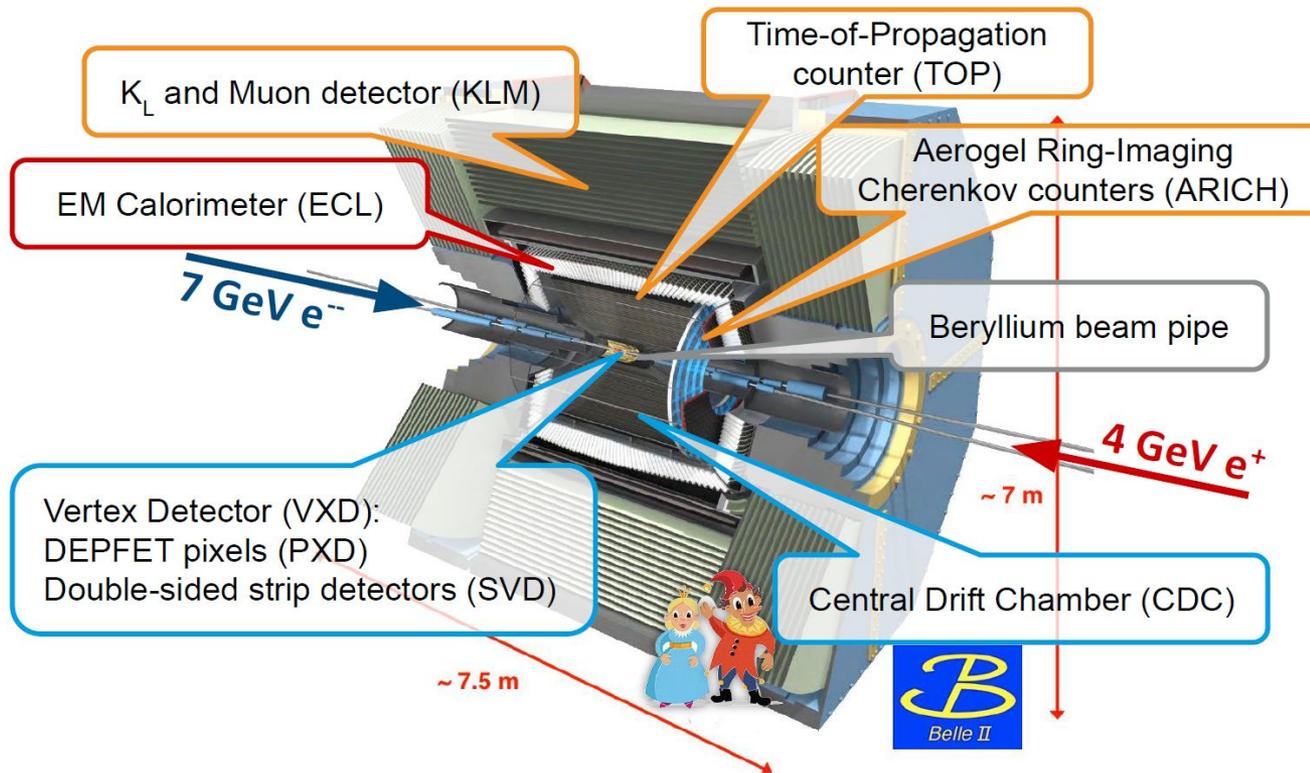


- Energy asymmetric collider at  $\sqrt{s} = 10.58 \text{ GeV}$
- with BR > 96% (B factory)
- Nano-beam + higher beam currents
- Record luminosity,  $3.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Ultimate target:  $50 \text{ ab}^{-1}$



# The Belle II Detector

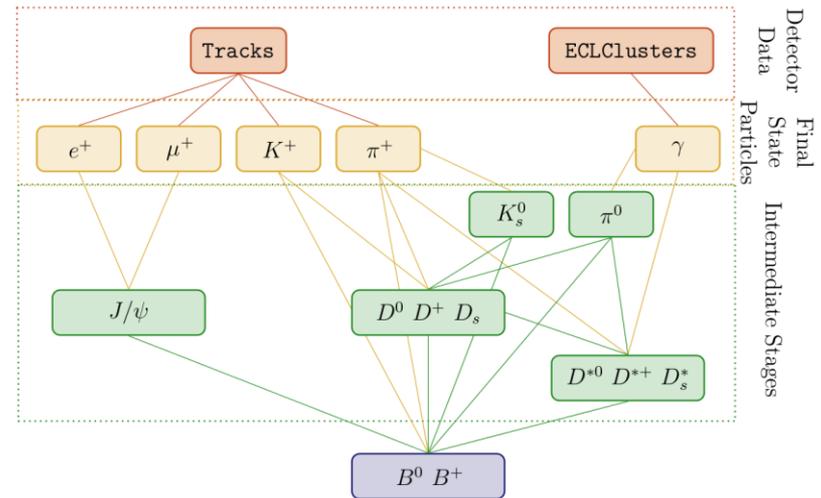
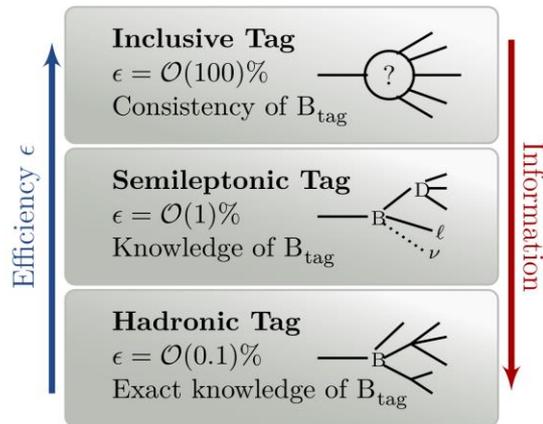
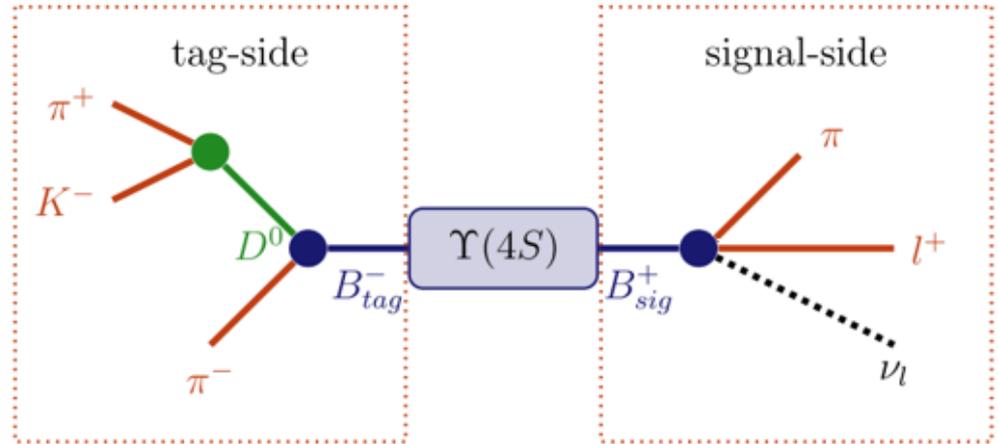
Where the magic happens



# Event reconstruction

## Full Event Interpretation

- i 3 types of tagging:
  - i Inclusive (untagged)
  - i Semi-leptonic
  - i Hadronic
  
- i **FEI**: multivariate technique to reconstruct the B-tag side ([arXiv:1807.08680](https://arxiv.org/abs/1807.08680))



MC tag-side efficiency @ 10% purity	Had. $B^+/B^0$ [%]	SL. $B^+/B^0$ [%]
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.76/0.46	1.80/2.04
N of correct $B_{tag}$ per $1 \text{ fb}^{-1}$ in Belle (FEI)	8350/5060	19800/22440

Computing and Software for Big Science (2019) 3:6

i Expect better performance

i Calibration remains a challenge

i [ @ Y U X ] b [ i b W Y f l e p t o n i c d e b a y s Z c f g Y a ]

# Exclusive decays

## A word from theory

i  $\Gamma(B \rightarrow \gamma h \text{ (exp. + theob.)})$ : fl

i General equation:

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

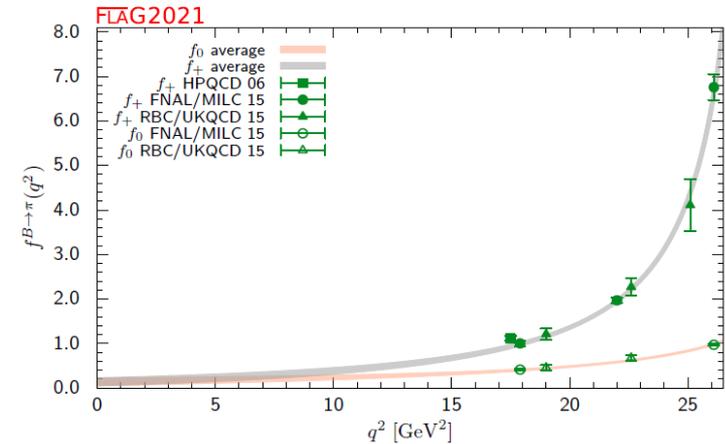
i **Form factor** extracted from:

i  $q^2 \sim q^2_{\max} = (m_B - m_\pi)^2$ : Lattice QCD

i  $q^2 \sim 0$ : QCD sum rules

i  $\rho, \omega, \phi$ : heavy, unstable, broad resonances

arXiv:2111.09849



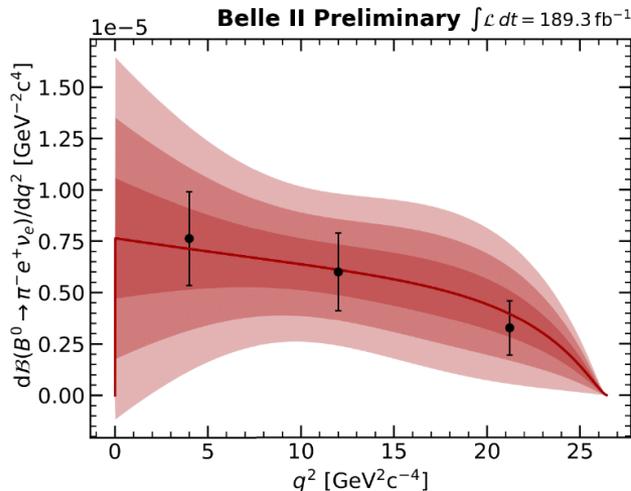
$$f_+(0) = 0.261^{+0.020}_{-0.023}$$

J. High Energ. Phys. 2012, 92

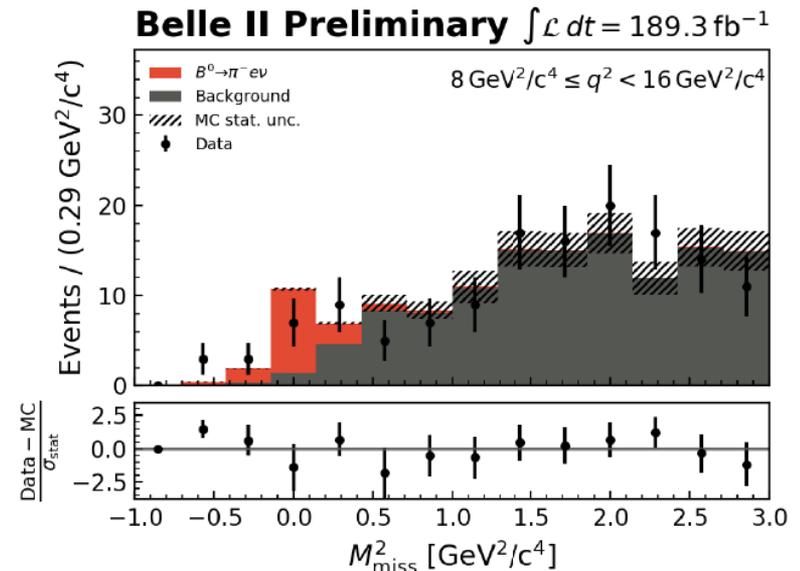
# Exclusive decays

## 6 at Belle II

- i So far: **189.3 fb<sup>-1</sup>**
- i **Hadronic tagged 6 e** ; dominant systematic uncertainty: FEI calibration
- i Distributions in **bins of q<sup>2</sup> [8;16;26.4] GeV<sup>2</sup>** |  $V_{ub}$  extraction
- i Yields are corrected by **unfolding**
- i **fit**



$$m_{miss}^2 = (p_{e^+e^-} - p_{B_{tag}} - p_{\pi} - p_{\ell})^2$$



Decay mode	Fitted $ V_{ub} $
$B^0 \rightarrow \pi^- e^+ \nu_e$	$(3.71 \pm 0.55) \times 10^{-3}$
$B^+ \rightarrow \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63) \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45) \times 10^{-3}$

# Exclusive decays

## 6 at Belle II

- i So far: **62.8 fb<sup>-1</sup>**
- i decay (almost) **exclusively to**
- i  $M$  [0.333, 1.217] GeV
- i Low signal significance: <2
- i 95% CL upper limits on BR

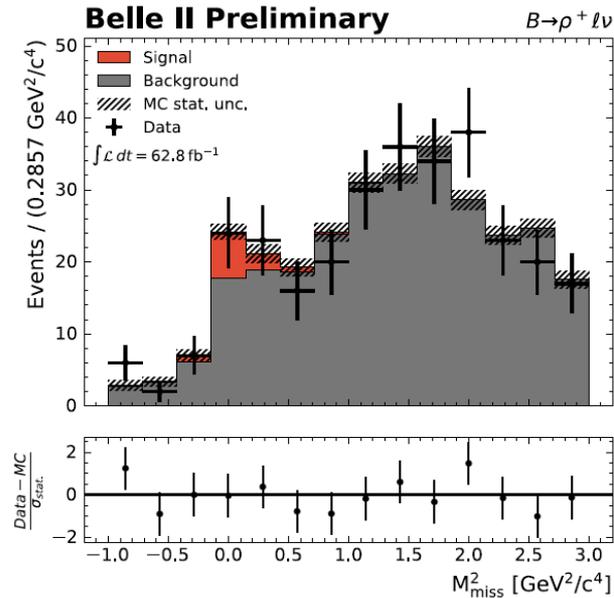
$$\mathcal{B}(B^0 \rightarrow \rho^- \ell^+ \nu_\ell) < 3.37 \times 10^{-4}$$

$$\mathcal{B}(B^+ \rightarrow \rho^0 \ell^+ \nu_\ell) < 1.97 \times 10^{-4}$$

- i PDG

$$(2.94 \pm 0.11 \pm 0.18) \times 10^{-4}$$

$$(1.58 \pm 0.11) \times 10^{-4}$$

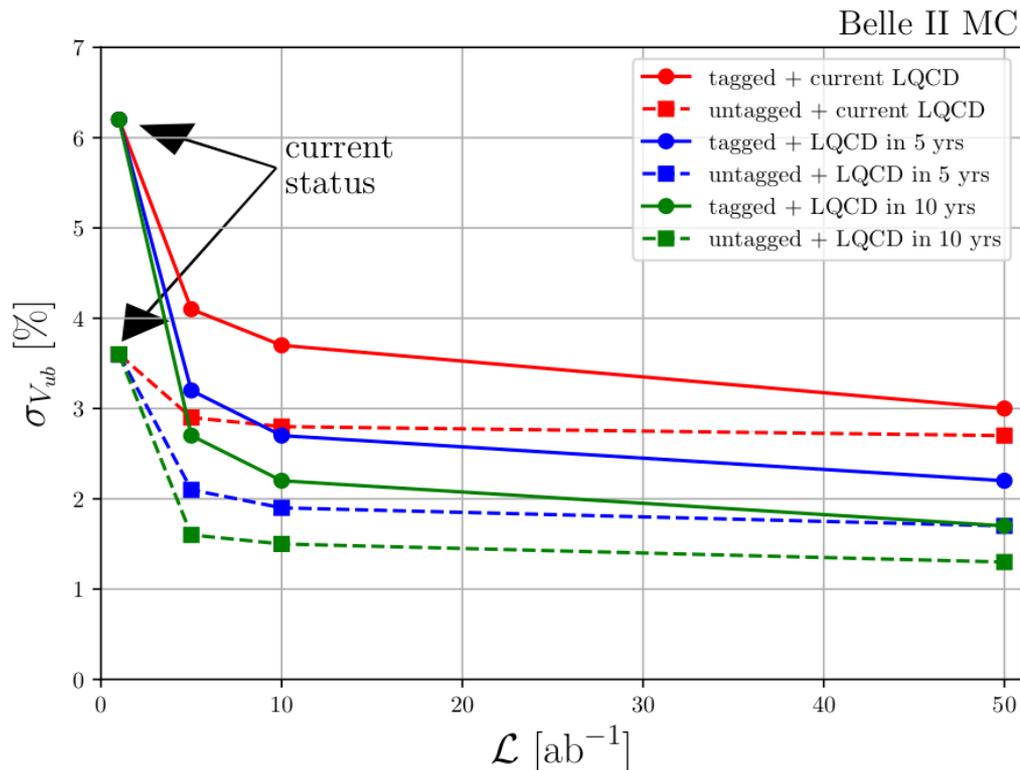


[arXiv:2111.00710](https://arxiv.org/abs/2111.00710)

# Exclusive decays

## Prospects

- i Ongoing **tagged** and **untagged** analyses with **more statistics**
- i Potential to **reduce uncertainty on  $|V_{ub}|$**  by a significant margin

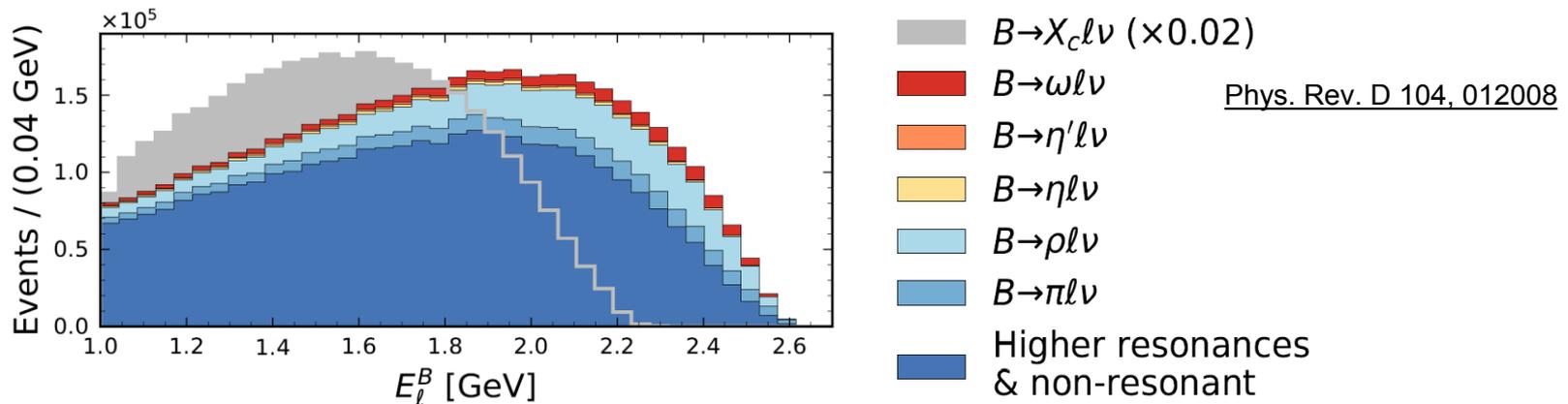


The Belle II Physics Book

# Inclusive decays

## A word from theory

- Overwhelmed by  $V_{cb}$  →  $V_{ub}$  cuts in phase space
- Kinematic regions:** lepton momentum/energy spectrum endpoint, low  $m_X$
- But **HQE breaks down** [  $b \rightarrow c$  h.c. ] [  $b \rightarrow W \rightarrow i \rightarrow g$  ] [  $j \rightarrow Y \rightarrow Y \rightarrow b \rightarrow c \rightarrow i$  ] [  $\dots$  ] [  $Y \rightarrow g \rightarrow d \rightarrow Y$  ]



- Decay rate described by (non-perturbative) **shape function**: motion of  $b$  quark inside  $B$  meson (PDFs equivalent)
- Universal for  $b$  transitions to light quarks (data-driven fits: SIMBA, NNvub)



# Inclusive decays

## How to actually measure $|V_{ub}|$

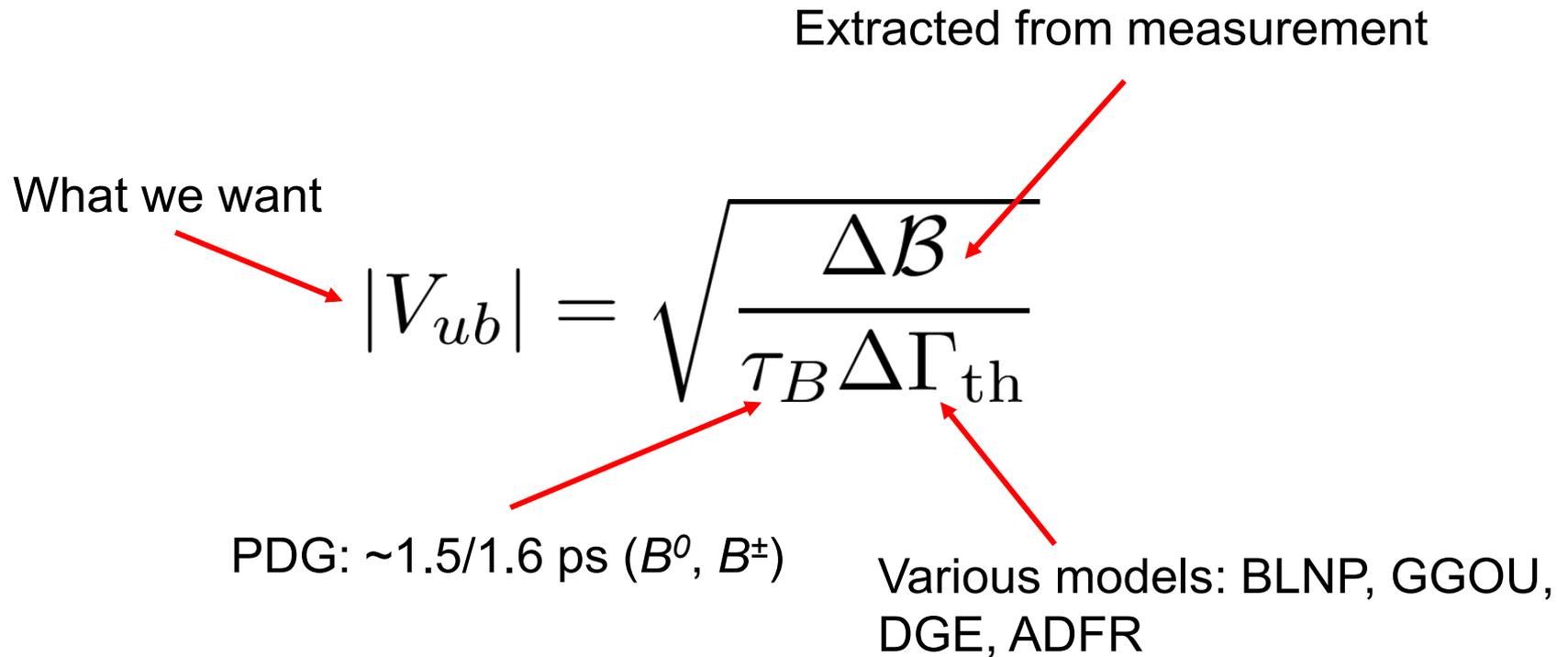
What we want

Extracted from measurement

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

PDG:  $\sim 1.5/1.6$  ps ( $B^0, B^\pm$ )

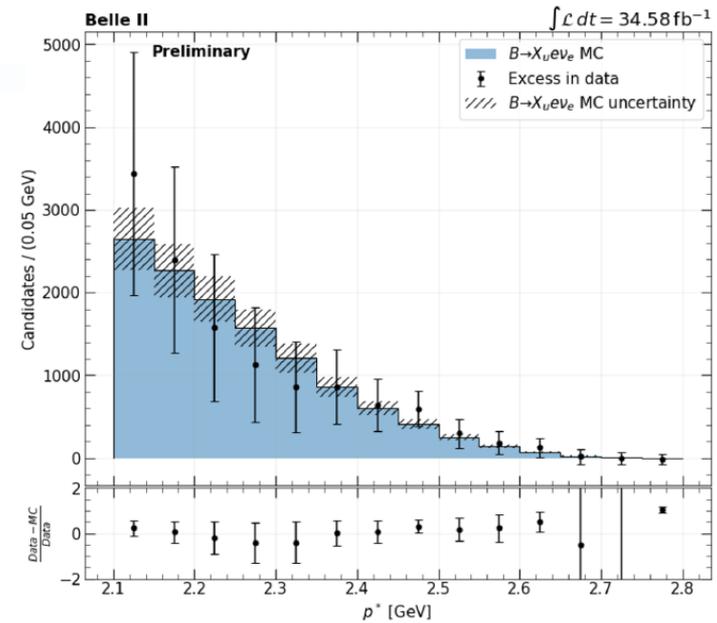
Various models: BLNP, GGOU, DGE, ADFR



# Inclusive decays

## At Belle II

- i **Untagged inclusive**  $B \rightarrow X_u e L$  with  $34.6 \text{ fb}^{-1}$
- i **Endpoint region:**  $2.1 \text{ -- } 2.8 \text{ GeV}$
- i **Significance.**



[arXiv:2103.02629](https://arxiv.org/abs/2103.02629)

# Inclusive decays

## Prospects

- i **Inclusive hadronic tagged analysis**
- i Start from **Belle strategy**: signal/background modeling, BDT/NN selection,  
Z ] h Å
- i Improved hardware/software + **larger data set** (ultimately 50 ab<sup>-1</sup>)

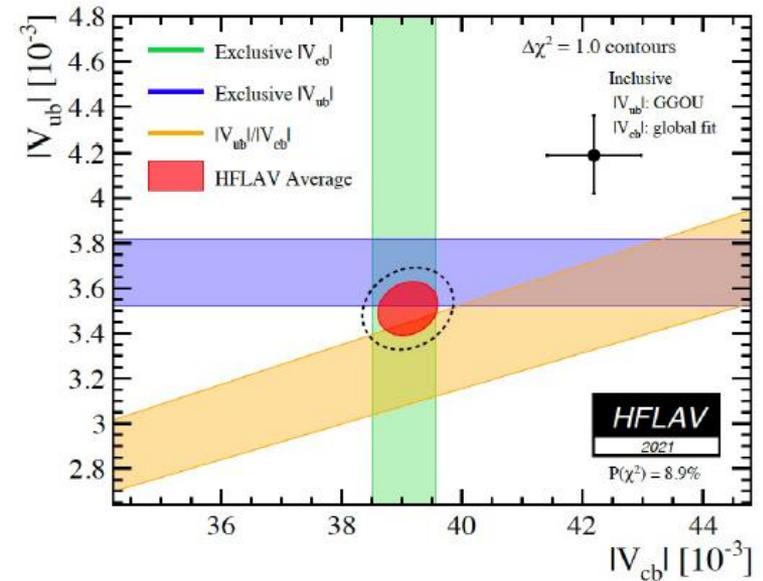
	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
5 ab <sup>-1</sup>	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab <sup>-1</sup>	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

The Belle II Physics Book

- i Model independent/global fit: **differential spectra** measurement:  $q^2, m_X, E$  Å

# Conclusions

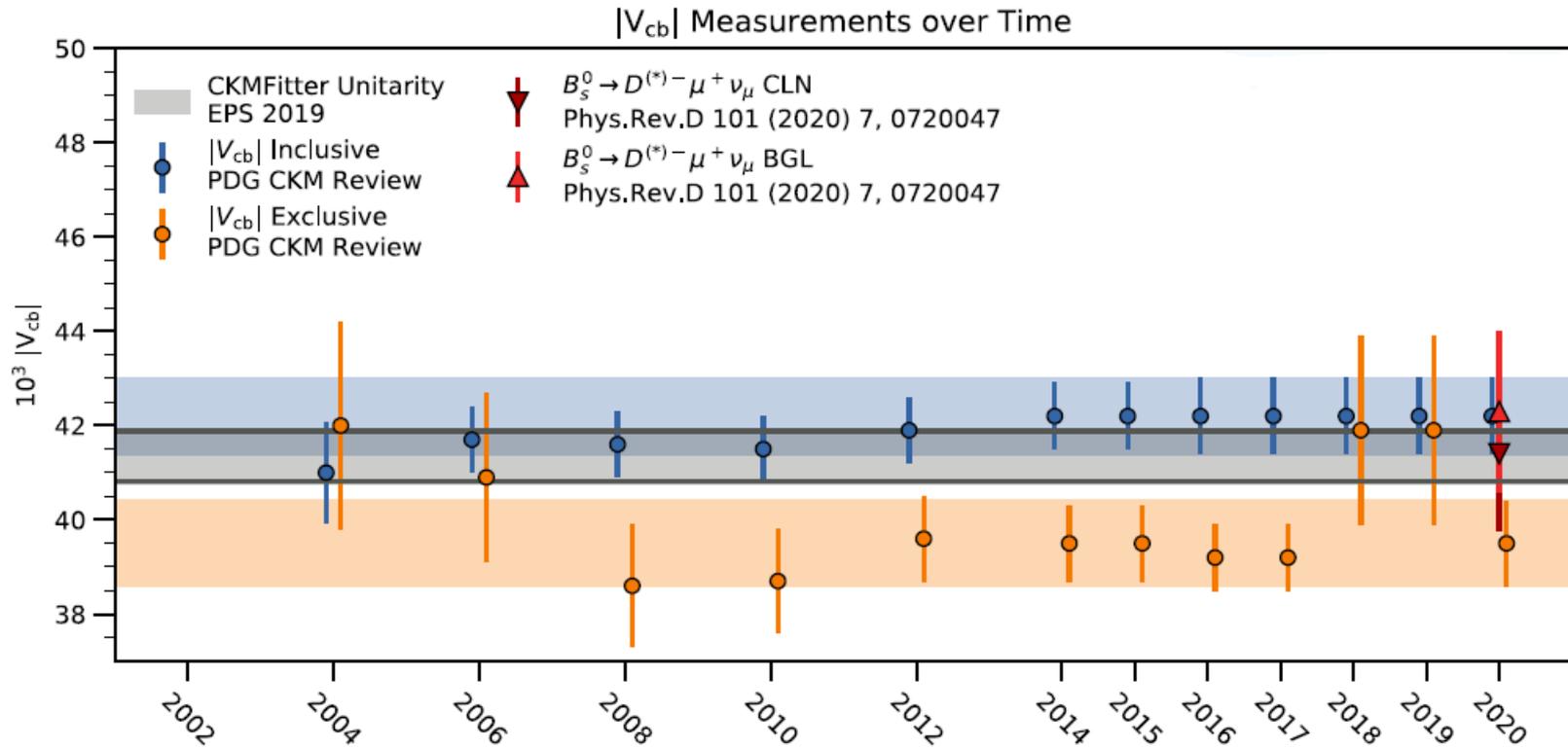
- i Tensions in CKM elements ( $V_{ub}$ ,  $V_{cb}$ )
- i Belle II
- i Better statistics but real issue is **systematics**
- i These analyses are still young
- i More model-independence ?
- i Results from LHCb ?



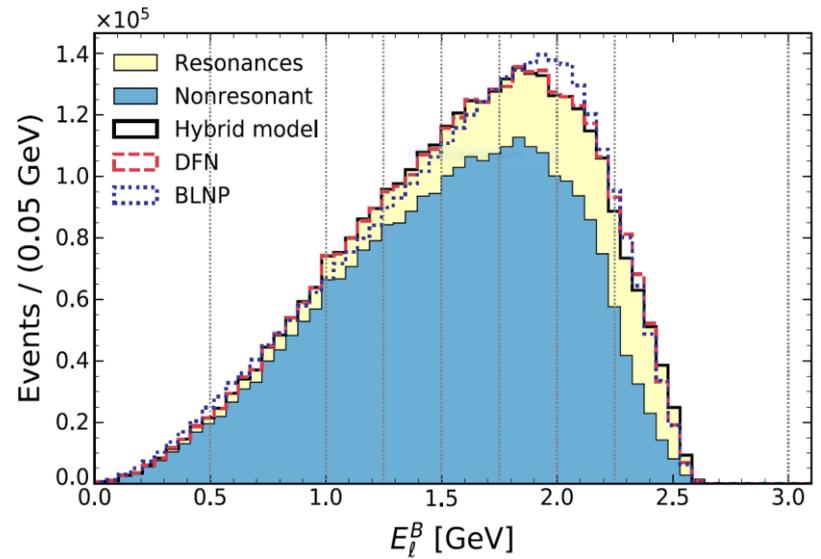
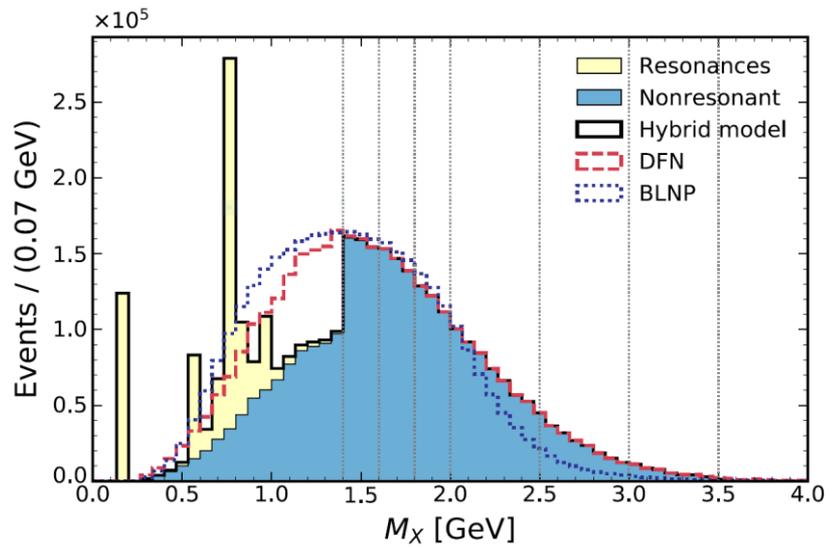
**Thank you**

**Backup**

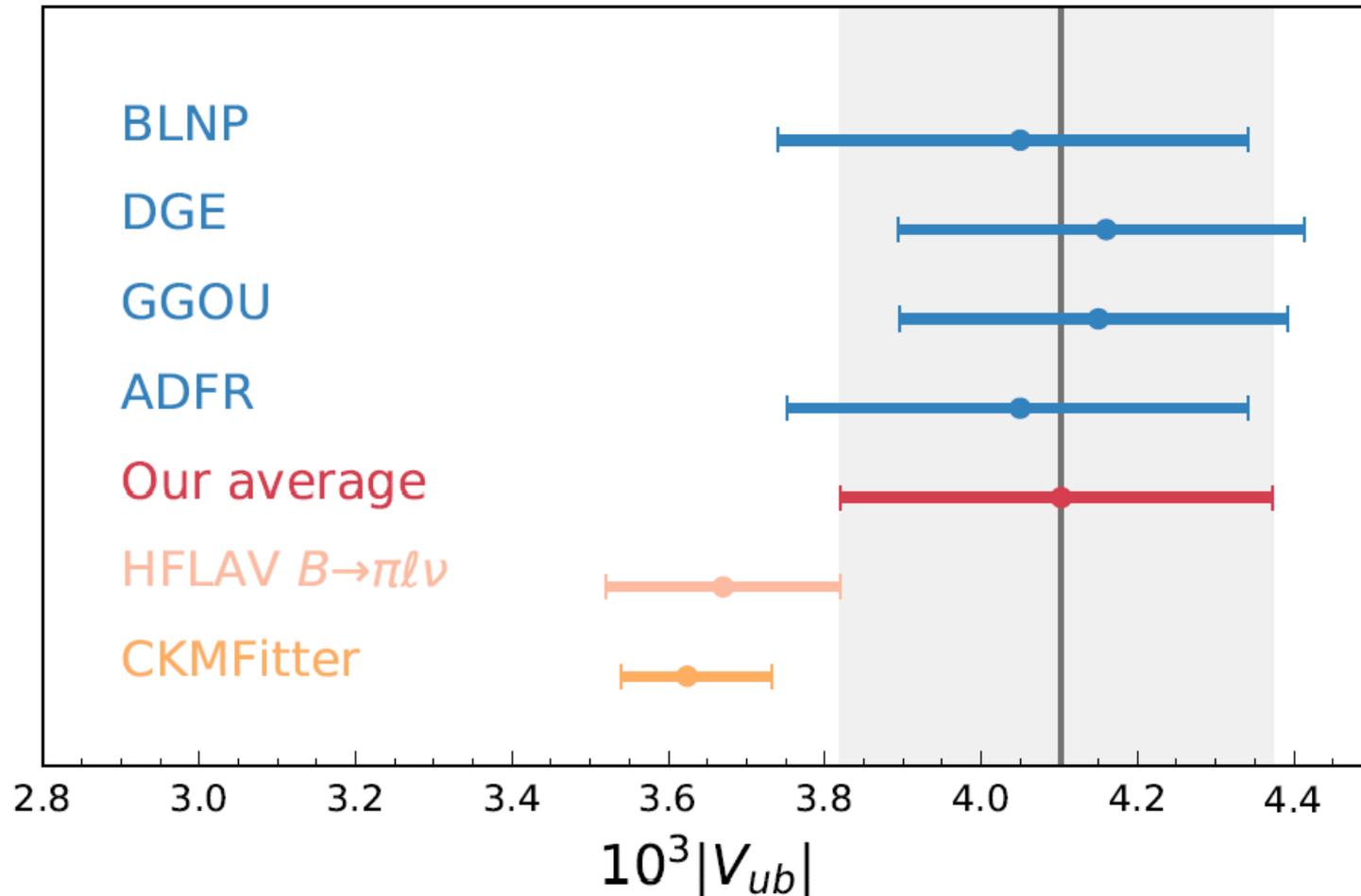
# $|V_{cb}|$ discrepancy



# Hybrid model



# Belle $|V_{ub}|$ inclusive measurement results



# theoretical predictions for $|V_{ub}|$

- i BLNP: NLO in  $\alpha_s$ , interpolation between SF and OPE region ([arXiv:hep-ph/0504071v3](#))
- i GGOU: corrections up to  $O(\alpha_s^2)$  (perturbative) and  $O(1/m_b^3)$  (non-perturbative), SF dependence via light-cone functions, kinetic scheme ([arXiv:0707.2493v2](#))
- i DGE: no direct use of SFs, predictions for hadronic observables from on-shell  $b$ -quark mass,  $\overline{\text{MS}}$  scheme ([arXiv:0806.4524v2](#))
- i ADFR: ratio of  $6 \cdot \Gamma_{\text{had}}^b$  to  $6 \cdot X_c^b$ , soft-gluon resummation at NNLO, effective QCD coupling approach,  $\overline{\text{MS}}$  scheme ([arXiv:0711.0860v2](#))

# Systematics exclusive $|V_{ub}|$ Belle II measurement

Source	% of $\mathcal{B}(B^0 \rightarrow \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \rightarrow \pi^0 e^+ \nu_e)$		
$q^2$ bin index	1	2	3	1	2	3
$N_{B\bar{B}}$				2.9		
$f_{+0}$				1.2		
FEI calibration		3.2			3.1	
Tracking		0.6			0.3	
$\pi^0$ efficiency		–			4.8	
Signal efficiency $\epsilon$	1.3	1.2	1.4	1.3	1.2	1.3
Electron ID	1.0	0.4	0.4	1.0	0.5	0.5
Pion ID	0.4	0.4	0.4		–	
Total	4.8	4.7	4.8	6.7	6.7	6.7

