CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$

Guglielmo De Nardo, on behalf of the Belle II Collaboration (representing all B-factories)
University of Napoli Federico II and INFN Napoli

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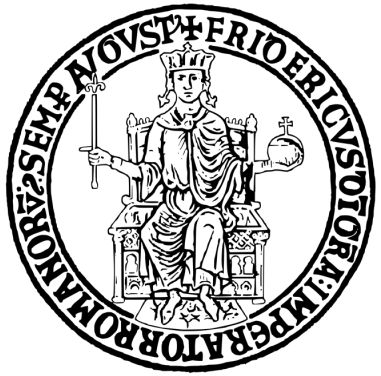
Flavor Physics and CP Violation
27-31 May 2024, Chulalongkorn University, Bangkok



Introduction

- $|V_{ub}|$ and $|V_{cb}|$ important to constrain CKM Unitarity
- Extracted from BF measurement of beauty hadron semi-leptonic decays

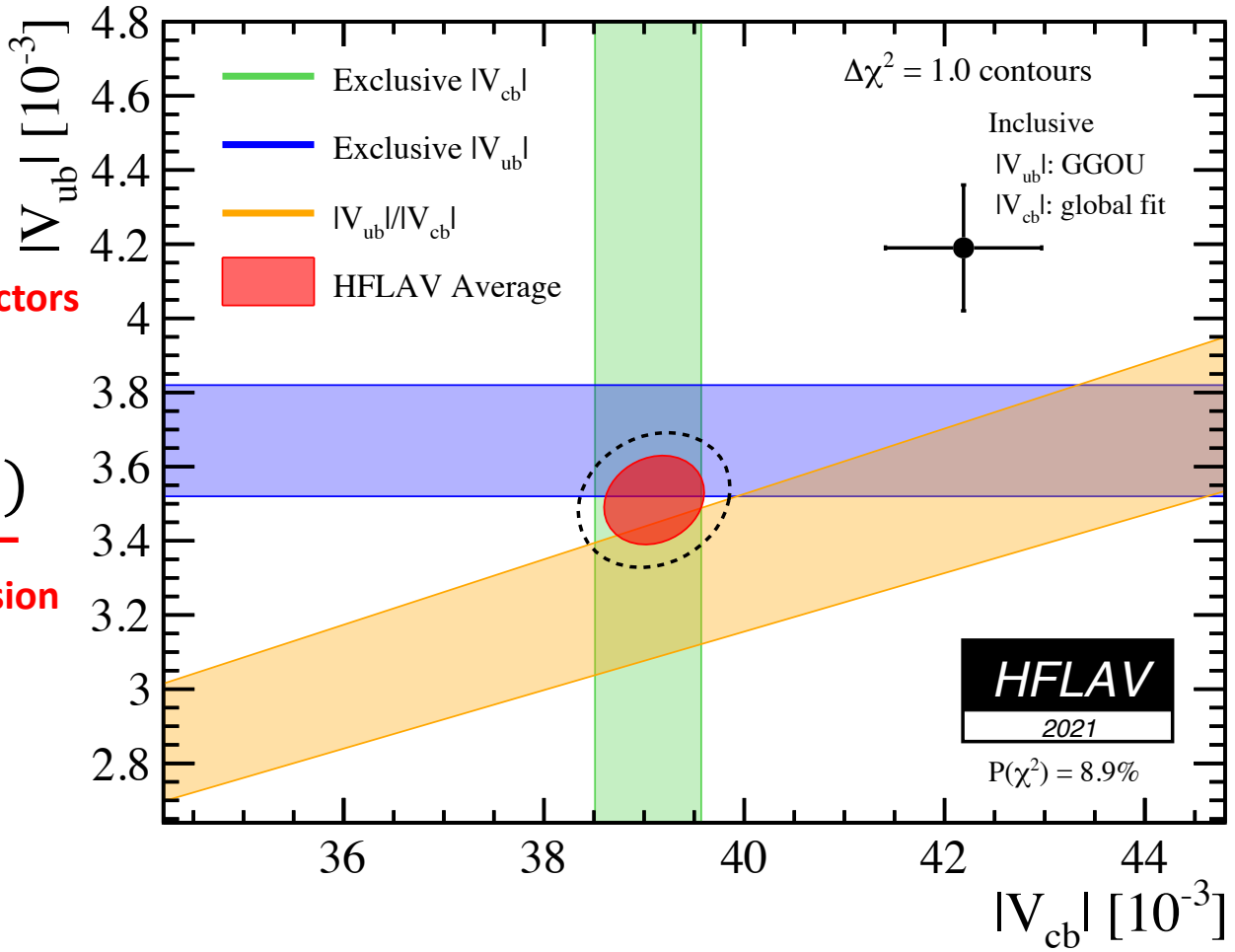
- With exclusive decays:
- $BF(B \to H_q l \nu) \leftarrow |V_{qb}|^2 FF(q^2)$

THEORY INPUT: Form factors

- or inclusive decays
- $BF(B \to X_q l \nu) \leftarrow |V_{qb}|^2 \ (1 + \ldots)$

THEORY INPUT: OPE expansion

Longstanding tension among exclusive and inclusive determinations



Recent results to be shown today

$|V_{cb}|$

- $|V_{cb}|$ from angular coefficients of $B \rightarrow D^* l\nu$
  Belle, arXiv:2310.20286 *submitted to* PRL
- $|V_{cb}|$ from $B \rightarrow Dl\nu$
  BaBar, arXiv:2311.15071 → shown by S. Robertson
- $|V_{cb}|$from $B_s^0 \rightarrow D_s^{(*)-}\mu^+\nu$
  LHCb PRD 101,072004 (2020)

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  Belle, PRL 131, 211801 (2023)

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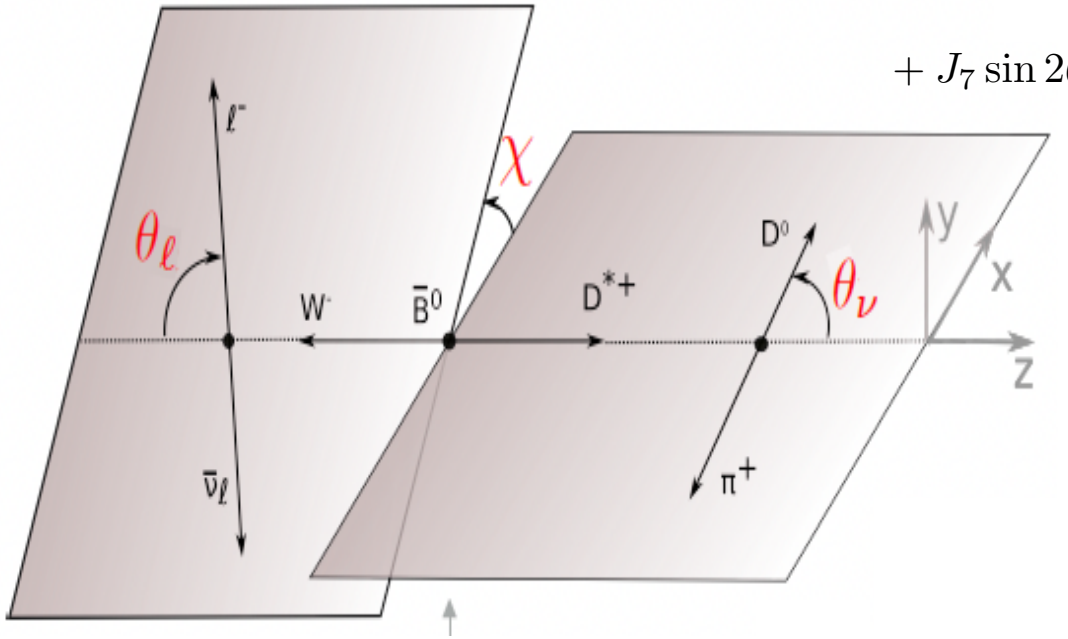
$|V_{cb}|$ from angular coefficients of $B \to D^* l\nu$

Belle preliminary
arXiv:2310.20286

- Full Belle dataset 711 fb^{-1} - Hadronic B tagging
- reconstruction of $B^+ \to D^{*0} l\nu$ and $B^0 \to D^{*+} l\nu$ with $D^{*+} \to D^0\pi^+, D^+\pi^0$
- Continuum background suppressed by BDT exploiting different BB vs qq topologies

$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\, \mathrm{d}\cos\theta_\ell\, \mathrm{d}\cos\theta_\mathrm{V}\, \mathrm{d}\chi} = \frac{2G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2 m_B^4 m_{\mathrm{D}^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_\mathrm{V} + J_{1c} \cos^2\theta_\mathrm{V}$$
$$+ (J_{2s} \sin^2\theta_\mathrm{V} + J_{2c} \cos^2\theta_\mathrm{V}) \cos 2\theta_\ell + J_3 \sin^2\theta_\mathrm{V} \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_\mathrm{V} + J_{6c} \cos^2\theta_\mathrm{V}) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_\mathrm{V} \sin^2\theta_\ell \sin 2\chi \Big) .$$

- 4D differential rate



$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

12 $\overline{J_i} = \int_{\Delta w} J_i(w) dw$ are estimated in 4 bins from data

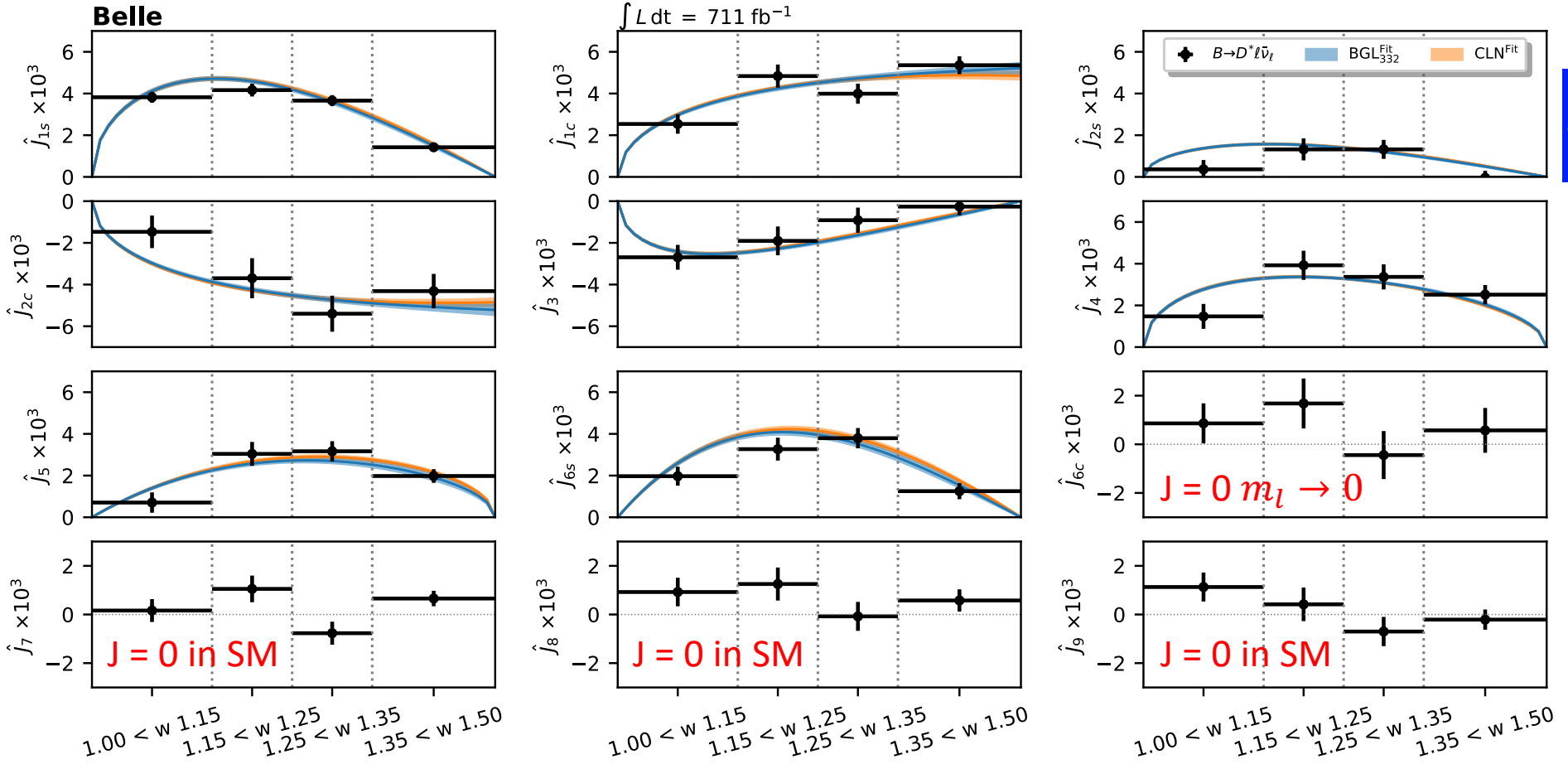
Get maximal information from full angular distributions
SM test possibile (some J = 0 in SM) and LFU test comparing e vs μ

$|V_{cb}|$ from angular coefficients of $B \rightarrow D^* l\nu$

Fit results with BGL and CLN parameterizations

$$|V_{cb}| = (41.0 \pm 0.3_{stat} \pm 0.4_{syst} \pm 0.5_{theo})\ \text{BGL}$$

$$|V_{cb}| = (40.9 \pm 0.3_{stat} \pm 0.4_{syst} \pm 0.4_{theo})\ \text{CLN}$$



Belle preliminary
arXiv:2310.20286

$|V_{cb}|$ from angular coefficients of $B \rightarrow D^* l\nu$

|Vcb| in agreement with previous analysis on same dataset [PRD 108(2023) 012002]
Better agreement with latest inclusive results and HFLAV inclusive average

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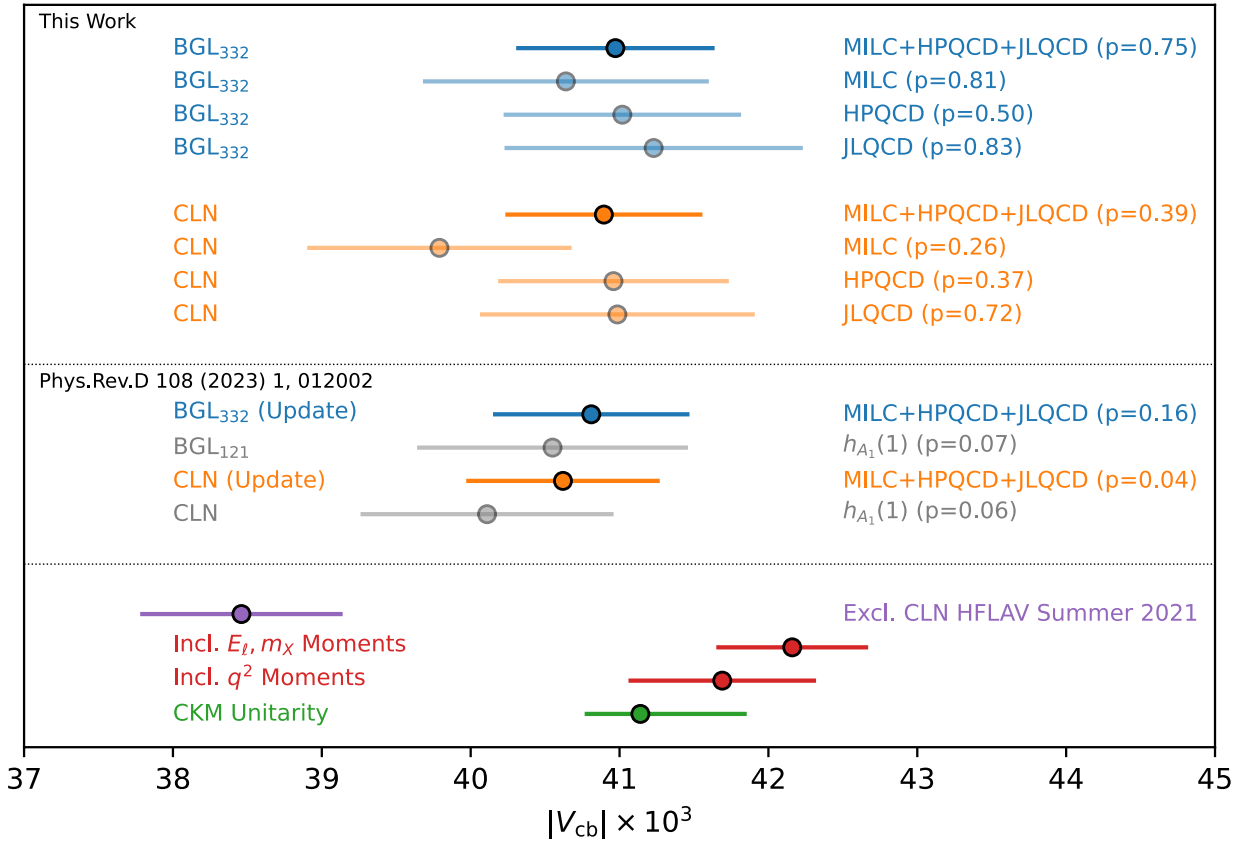
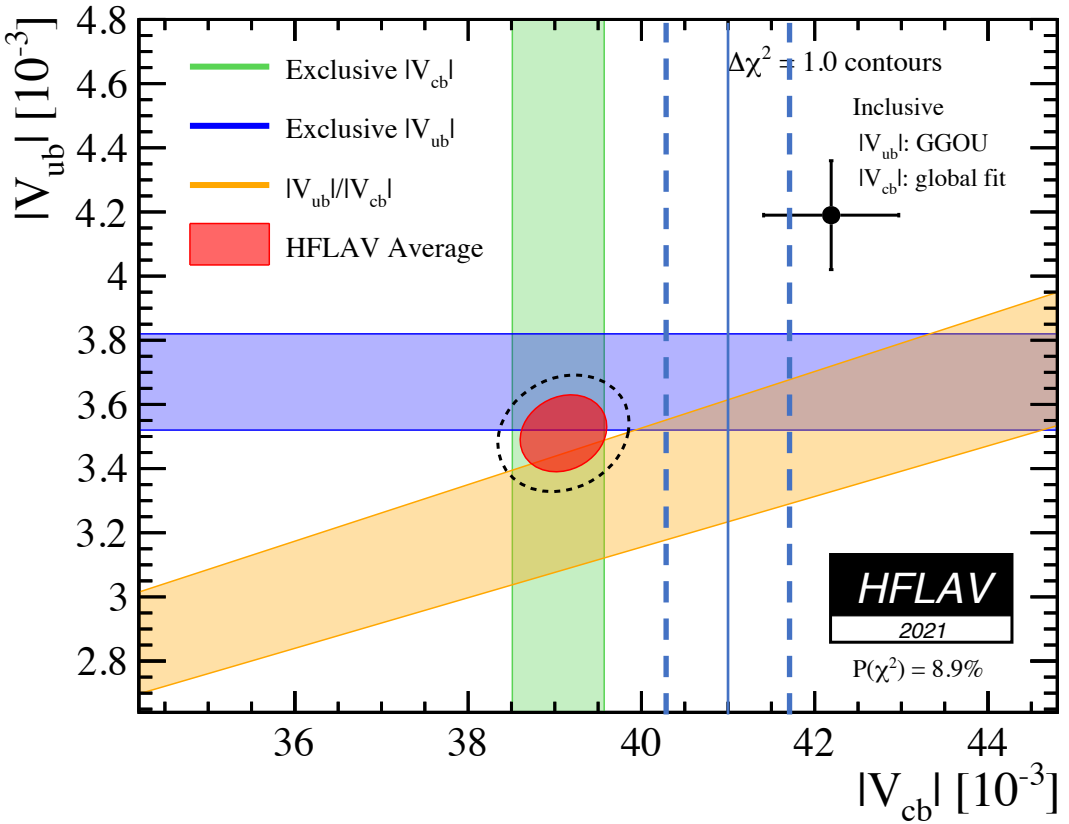


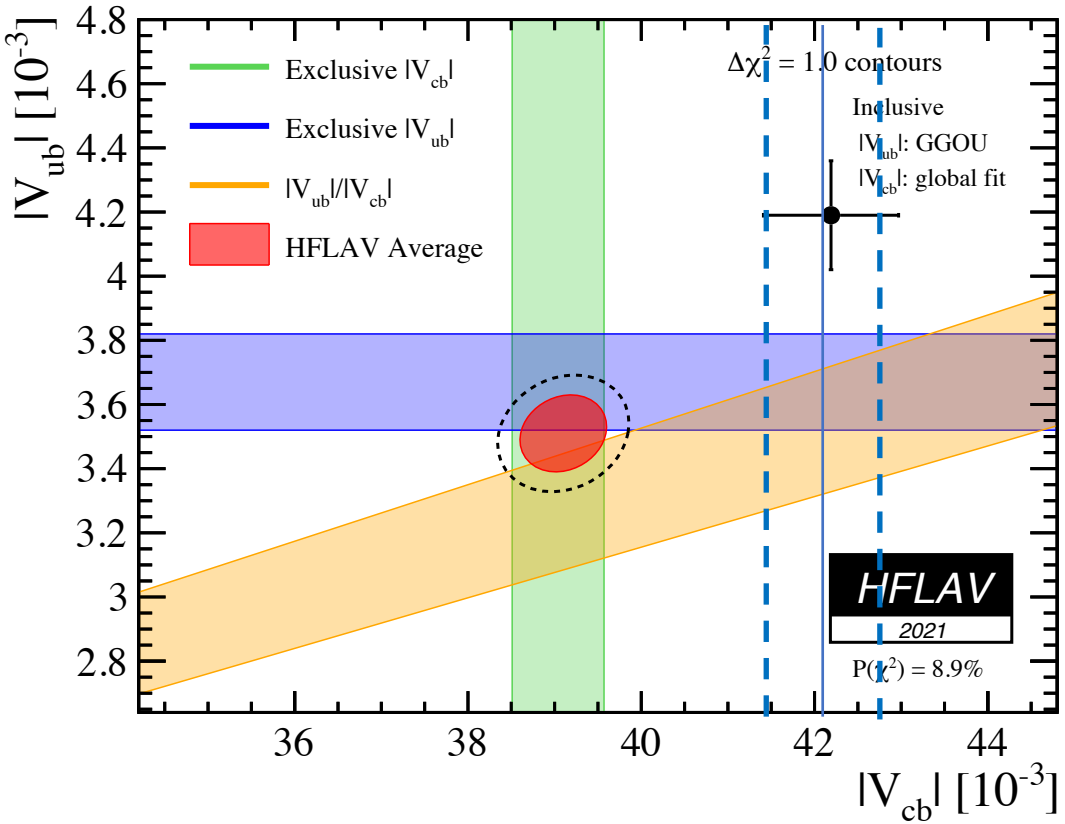
This work
$(41.0 \pm 0.7)\times 10^{-3}$



Adding BaBar result

Belle $B \rightarrow D^{*} l\nu$ (2023)

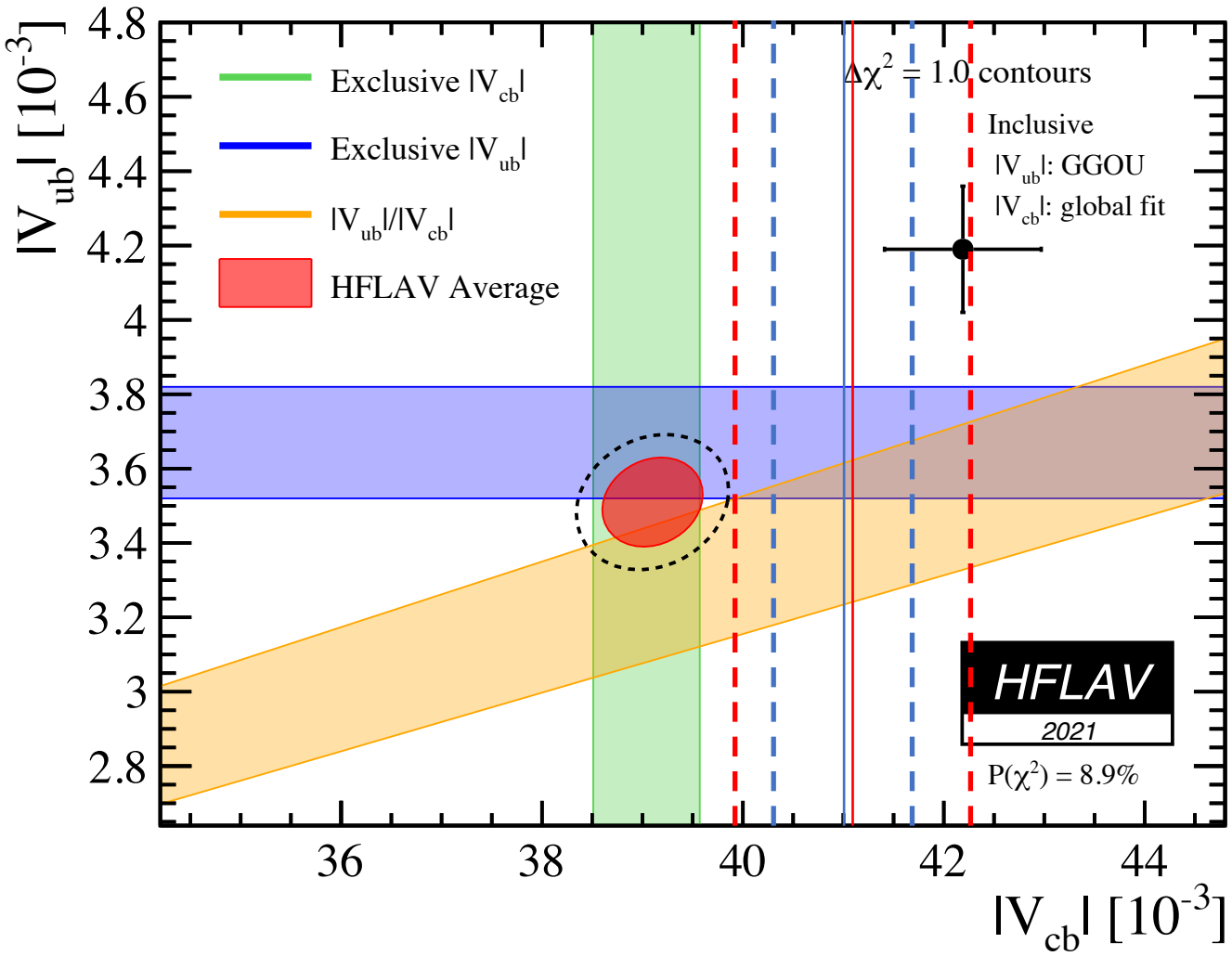
$(41.0 \pm 0.7)\times 10^{-3}$



BaBar preliminary
arXiv:2311.15071

+ BaBar $B \rightarrow D l\nu$ (2023)

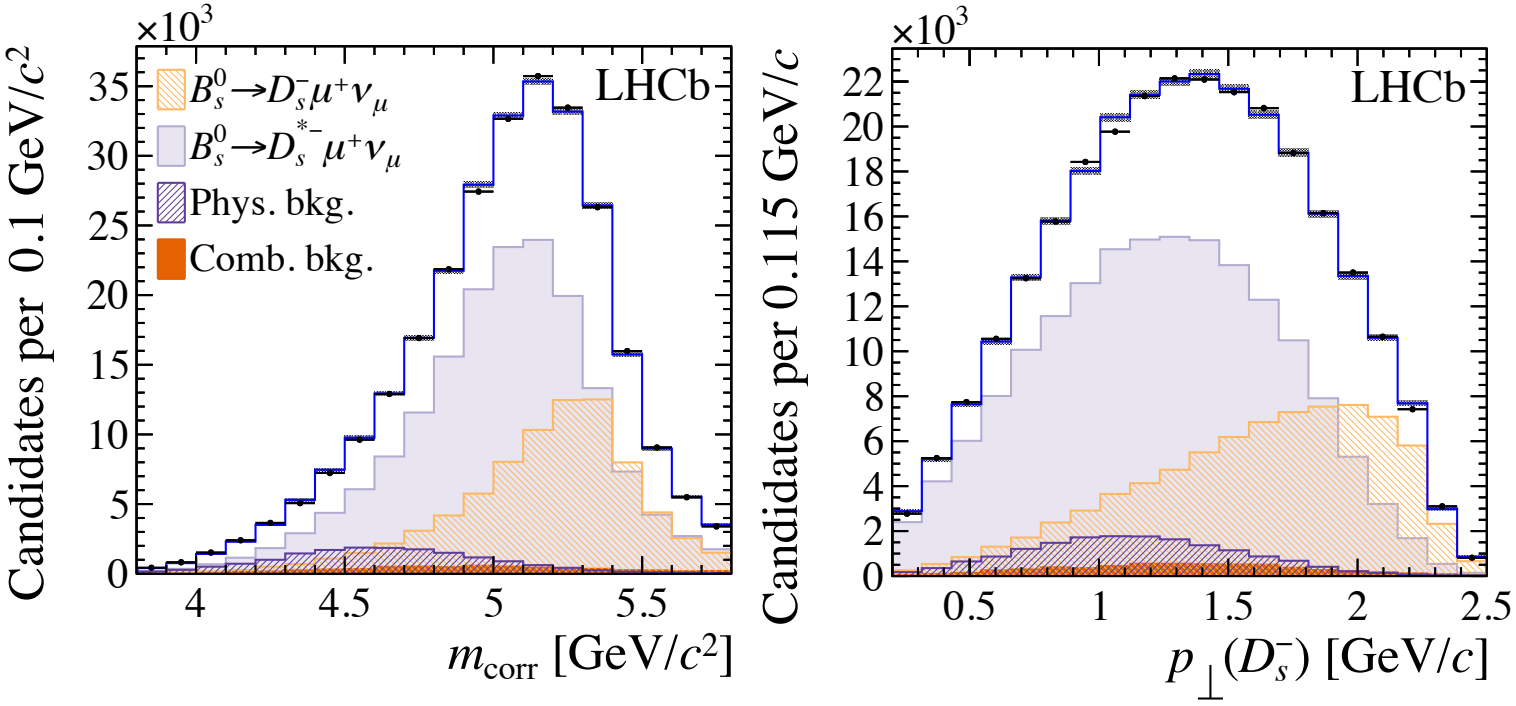
$(41.09 \pm 1.16)\times 10^{-3}$



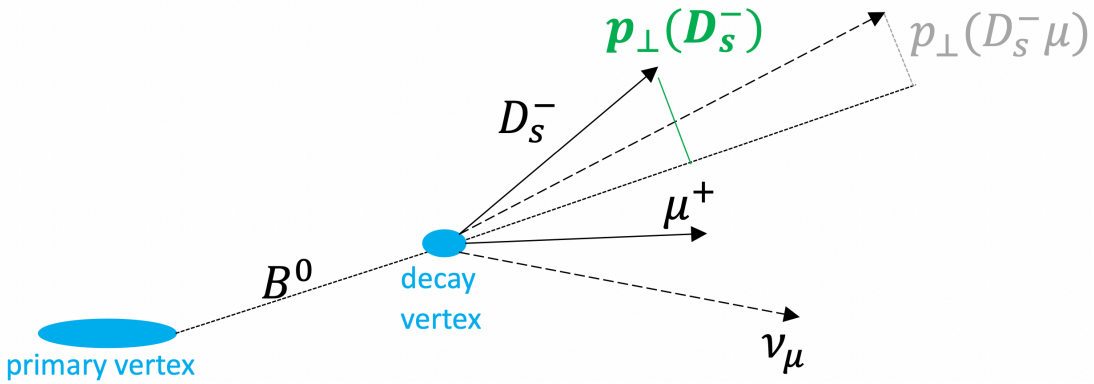
$|V_{cb}|$ from $B_s^0 \to D_s^{(*)-}\mu^+\nu$

PRD 101, 072004 (2020)

- Run 1 data set (1 fb^{-1} + 2fb^{-1})
- High momentum muon trigger
- Reconstruction strategy
  - Signal mode: $B_s^0 \to D_s^{(*)-}\mu^+\nu$
  - Normalization mode: $B^0 \to D^{(*)-}\mu^+\nu$
  - Minimize systematics using same final state $[K^+K^-]_\phi\,\pi^+$
- Exp. Challenge: signal peak with unreconstructed neutrino



$$m_{\rm corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$$



Vcb and FF parameters extracted from 2D fit to m_{corr} and $p_\perp(D_s^-)$

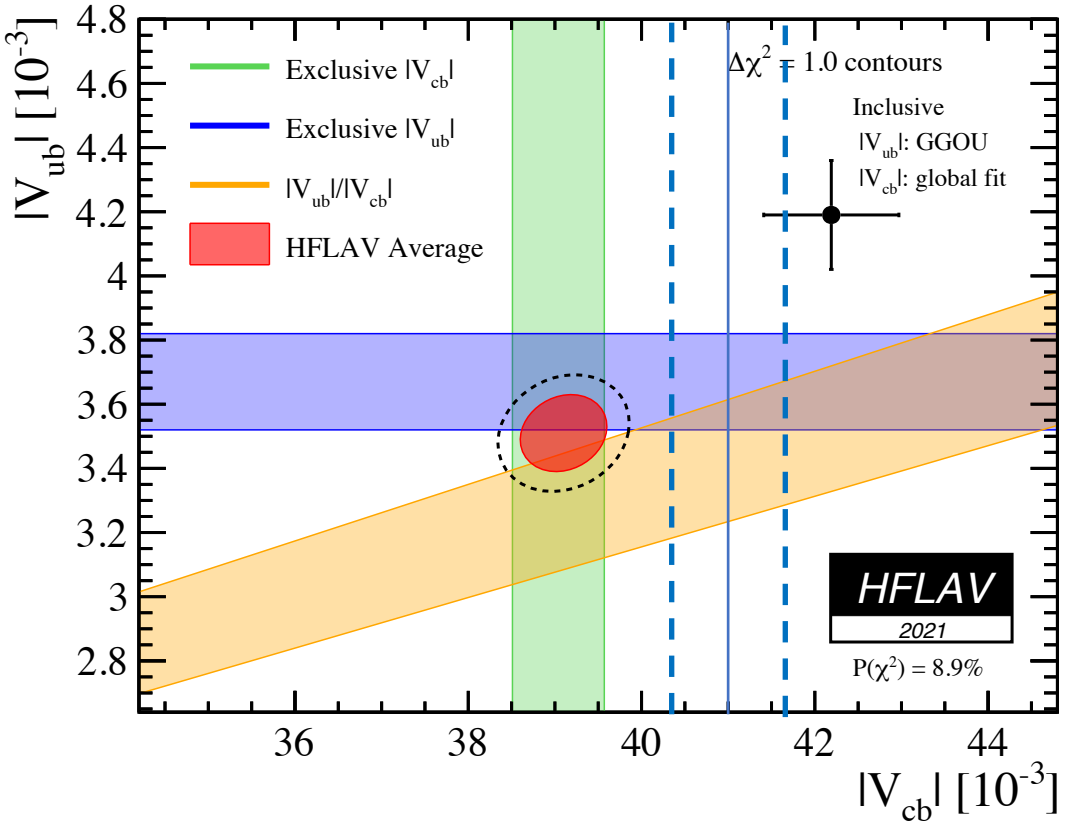
$$|V_{cb}|_{\rm CLN} = (41.6 \pm 0.6(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$

$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$

$|V_{cb}|$

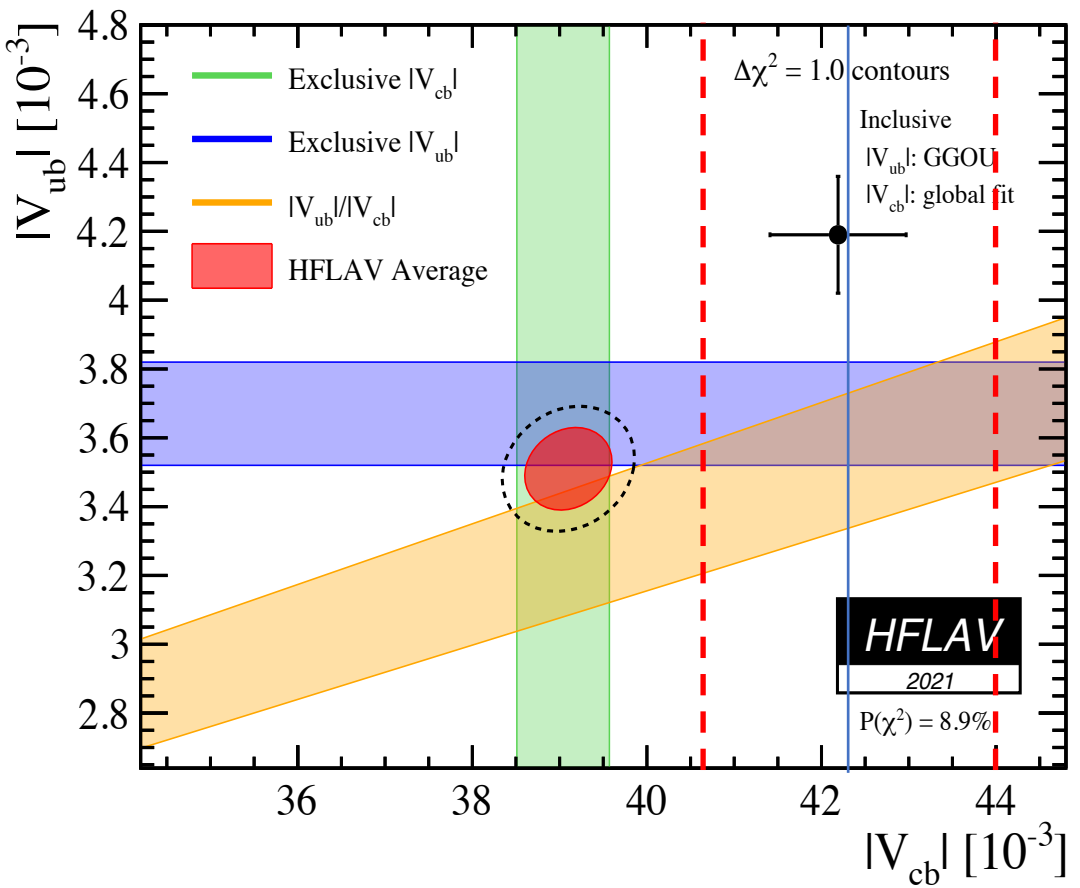
Belle $B \rightarrow D^* l\nu$ (2023)

$(41.0 \pm 0.7)\times10^{-3}$



LHCb $B_s^0 \rightarrow D_s^{(*)-}\mu^+\nu$ (2020)

$(42.3 \pm 1.7)\times10^{-3}$



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$|V_{ub}|$ from $B^0 \to \pi^+ l\nu$ and $B^+ \to \rho^0 l\nu$

Preliminary new result shown at Moriond 2024

- Untagged reconstruction of $B^0 \to \pi^+ l\nu$ and $B^+ \to \rho^0 l\nu$
- Large backgrounds of $B \to X_c l\nu$ and continuum
  - Suppressed with BDT discriminator
  - Require consistency of the rest of the event with B decay kinematics
  - Extract signal yields in bins of q^2 simultaneously for $\pi^+ l\nu$ mode and $\rho^0 l\nu$ mode

$\mathcal{L} = 364\ \mathrm{fb}^{-1}$

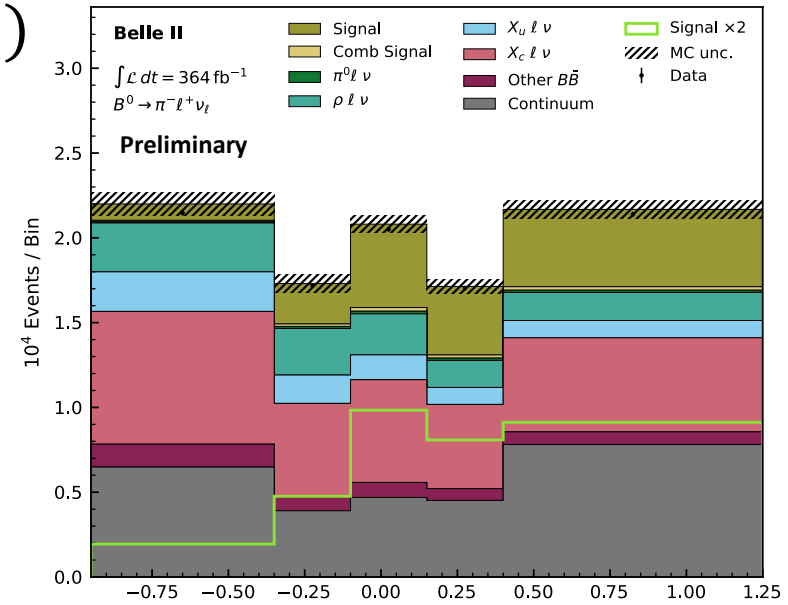
$p_l^* > 1\ GeV\ (\pi), 1.4\ GeV (\rho)$

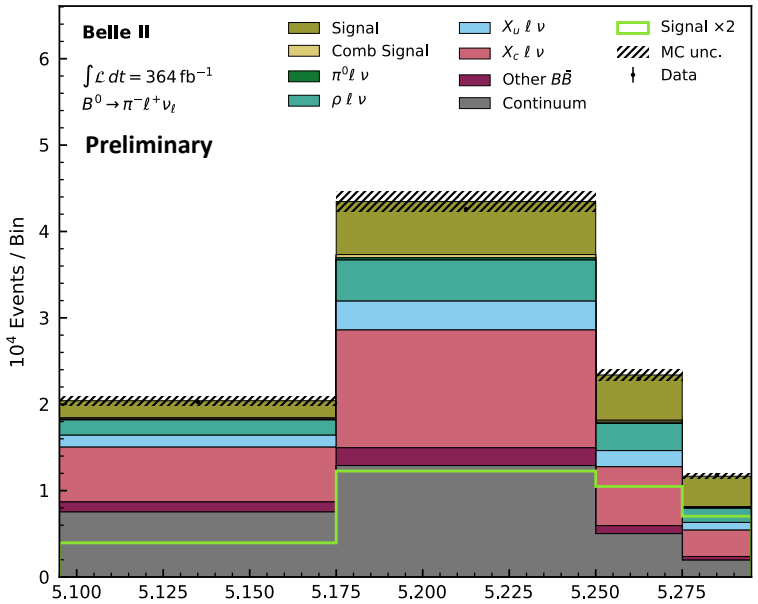
$$\cos\theta_{\mathrm{BY}} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$

$$M_{bc} = \sqrt{E_{\mathrm{beam}}^{*2} - |\vec{p}_B^*|^2}$$

$$\Delta E = E_B^* - E_{\mathrm{beam}}^*$$

N.B. B momentum determined by a neutrino reconstruction technique optimized for best resolution



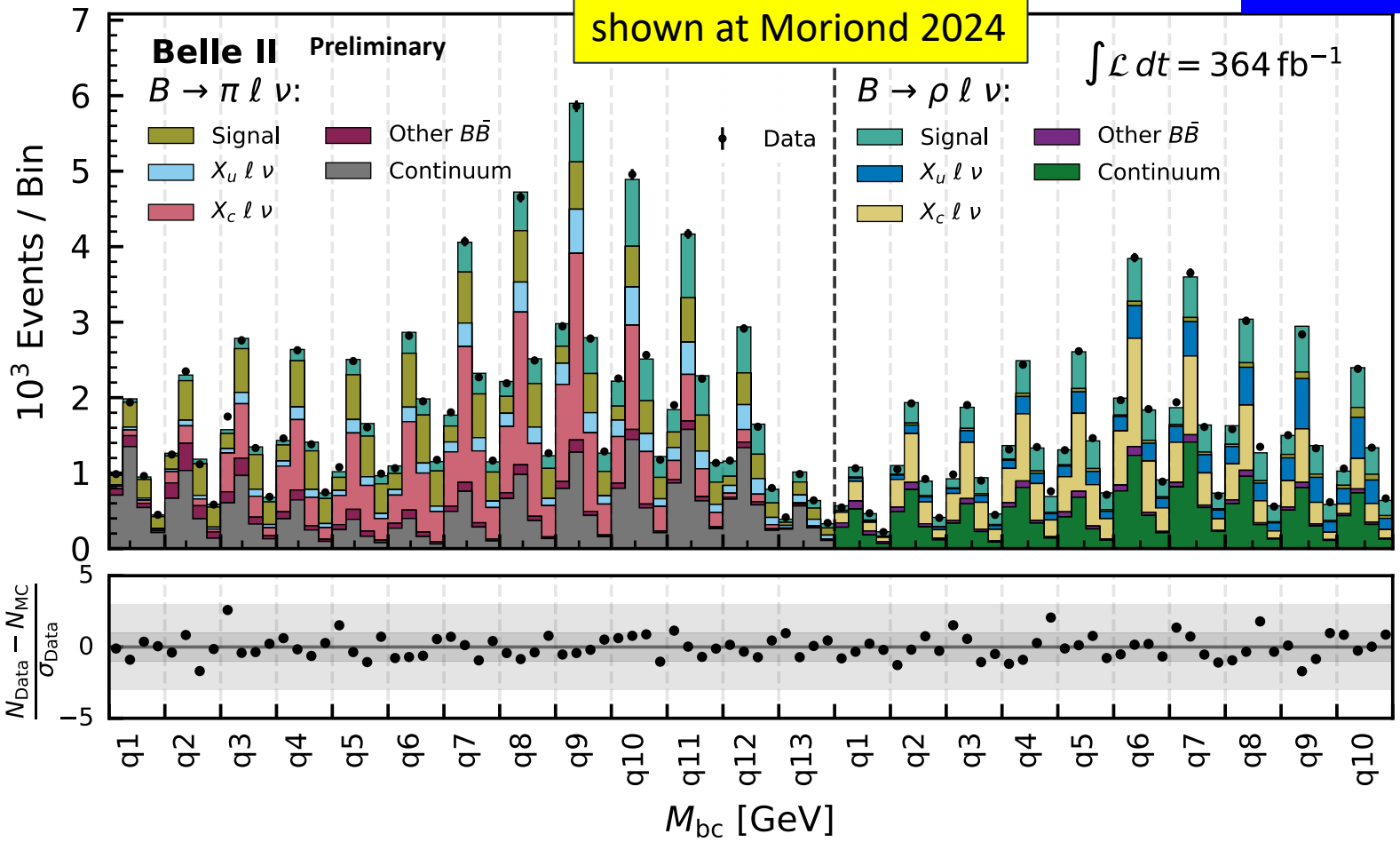


$|V_{ub}|$ from $B^0 \to \pi^+ l\nu$ and $B^+ \to \rho^0 l\nu$

Preliminary new result shown at Moriond 2024

Simultaneous 3D fit in $(13 + 10) \times 4 \times 6$ bins of $q^2 \times M_{bc} \times \Delta E$

Take into account cross-feeds and correlations with backgrounds



- Partial branching ratios ΔB_i obtained from fitted yield in each q bin and reconstruction efficiency
- Total branching ratio is the sum of all the partial ΔB_i

$$\mathcal{B}(B^0 \to \pi^+ l\nu) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \rho^0 l\nu) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

Consistent with PDG

$|V_{ub}|$ from $B^0 \to \pi^+ l\nu$ and $B^+ \to \rho^0 l\nu$

Estimate $|V_{ub}|$ minimising $\chi^2 = \sum_{i,j=1}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \chi^2_{theo}$

Belle II

Preliminary new result shown at Moriond 2024

	$B^0 \to \pi^+ l^- \bar{\nu}_l$	$B^- \to \rho^0 l^- \bar{\nu}_l$
Form factor param.	Bourrely-Caprini-Lellouch (BCL) Phys. Rev. D **82**, 099902	Bharucha-Straub-Zwicky (BSZ) JHEP (2016) 98
Theory prediction	LQCD Eur. Phys. J. C **82** (2022) 869 LQCD + LCSR JHEP (2021) 36	LCSR JHEP (2016) 98

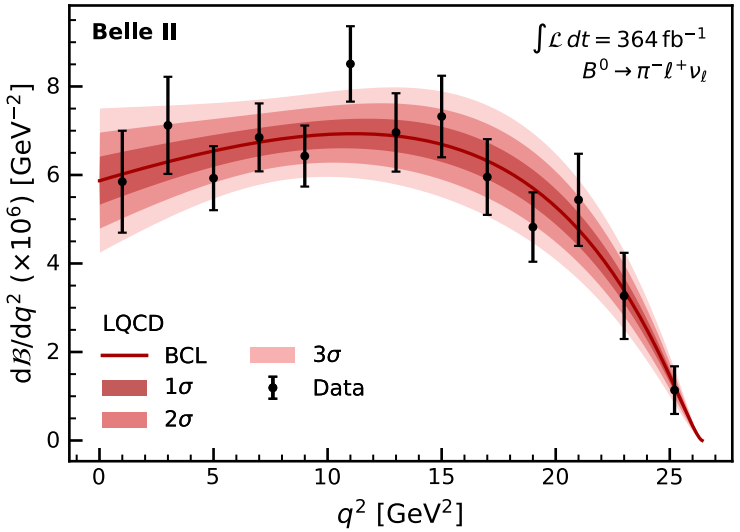
$$B^0 \to \pi^+ l\nu : |V_{ub}|_{LQCD} = (3.93 \pm 0.09_{stat} \pm 0.13_{syst} \pm 0.19_{theo}) \times 10^{-4}$$

$$|V_{ub}|_{+LCSR} = (3.73 \pm 0.07_{stat} \pm 0.07_{syst} \pm 0.16_{theo}) \times 10^{-4}$$

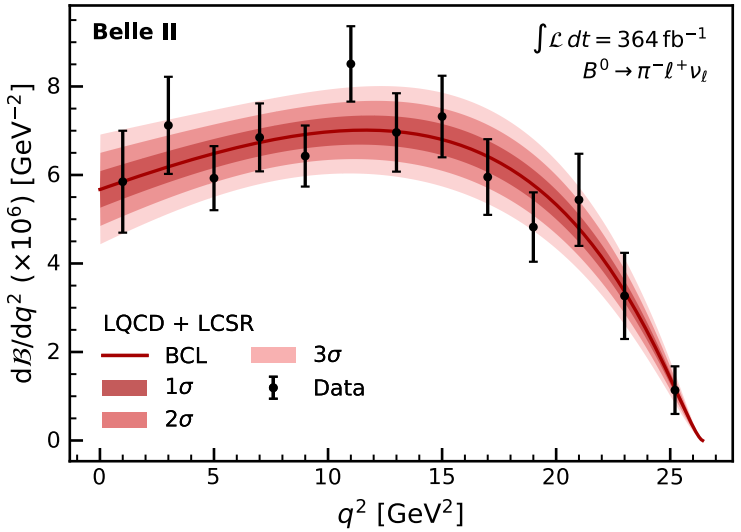
$$B^+ \to \rho^0 l\nu : |V_{ub}|_{LCSR} = (3.19 \pm 0.12_{stat} \pm 0.17_{syst} \pm 0.26_{theo}) \times 10^{-4}$$

Largest contributions to syst.: estimation of continuum background and B → π π l ν non resonant uncertainty

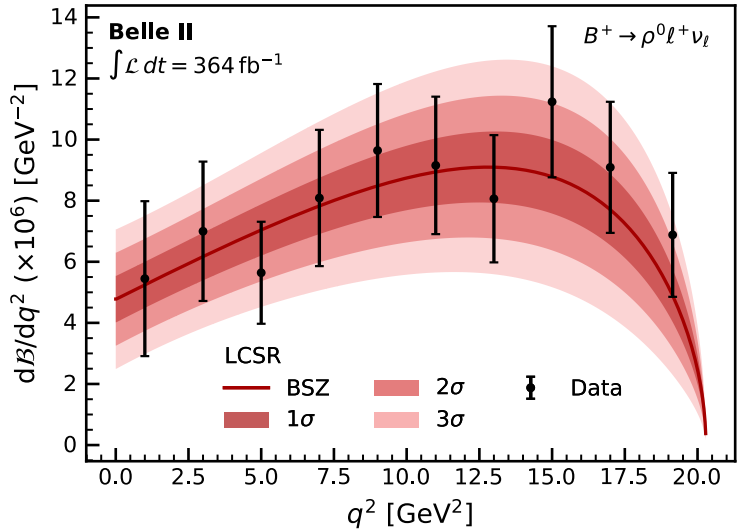
$B^0 \to \pi^+ l\nu$ $d\mathcal{B}/dq^2$ with LCQD



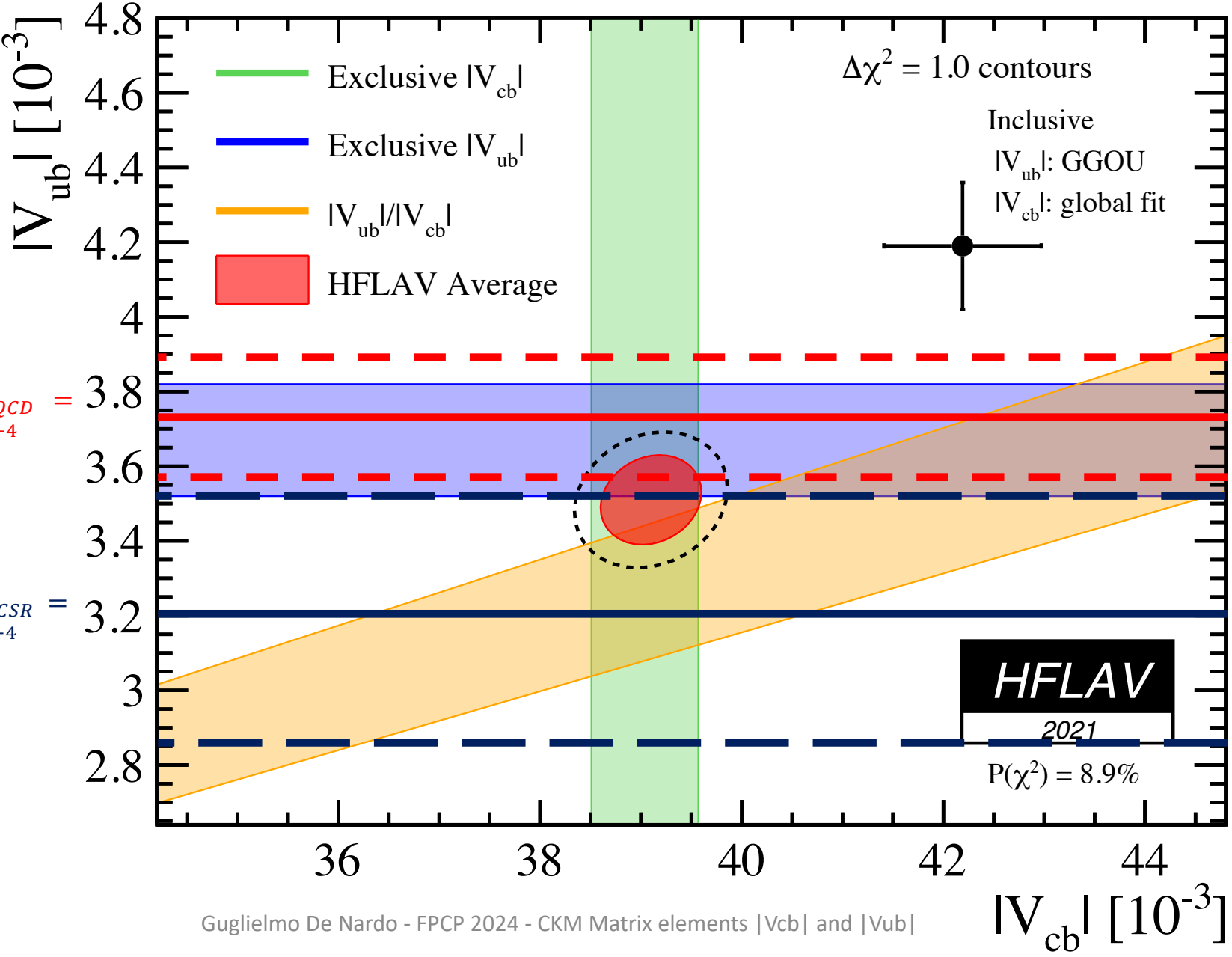
$B^0 \to \pi^+ l\nu$ $d\mathcal{B}/dq^2$ with LCQD+LCSR



$B^+ \to \rho^0 l\nu$ $d\mathcal{B}/dq^2$ with LCSR



|Vub| from $B^0 \to \pi^+ l\nu$ and $B^+ \to \rho^0 l\nu$



Preliminary new result shown at Moriond 2024

$|V_{ub}|$ excl. HFLAV = $(3.67 \pm 0.15) \times 10^{-3}$

$B^0 \to \pi^+ l\nu : |V_{ub}|_{LQCD} = (3.73 \pm 0.16) \times 10^{-4}$

$B^0 \to \rho^0 l\nu : |V_{ub}|_{LCSR} = (3.19 \pm 0.33) \times 10^{-4}$

Reducing the tension with V_{ub} inclusive

Still large (10%) uncertainty

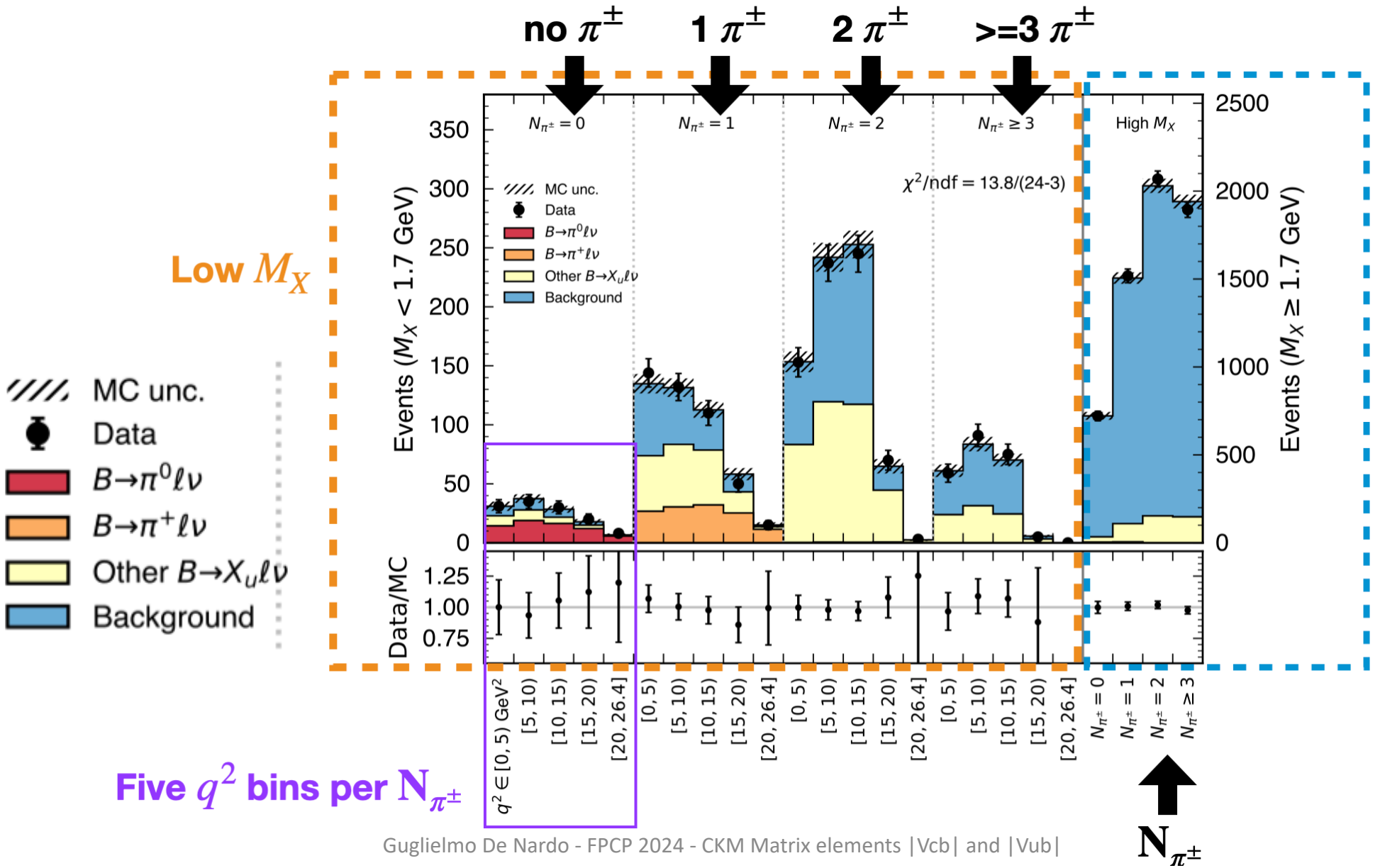
$|V_{ub}|$ from exclusive and inclusive B decays

PRL 131, 211801 (2023)

- Extends previous Belle analysis of $B \rightarrow X_u l \nu$ inclusive decays with hadronic tags [PRD 104, 012008(2021)]
- Reconstruction flow
  - Full reconstruction of the tag B (hadronic)
  - require an e or μ with $p_l > 1$ GeV
  - assign the remaining reconstruction objects to X system
- Fit Normalizations (signal and background yields) and $B \rightarrow \pi l \nu$ form factors from q^2 shape
- Data divided into bins of charged pion multiplicity ($N_{\pi^\pm}$=0,1,2, ≥ 3) to separate $B^+ \rightarrow \pi^0 l \nu$, $B^0 \rightarrow \pi^+ l \nu$, and other $B \rightarrow X_u \, l \, \nu$
- $M_X > 1.7\ GeV$ defines b → c dominated background region
- b → u enhanced region with $M_X < 1.7\ GeV$ is divided in 5 q^2 bins

$|V_{ub}|$ from exclusive and inclusive B decays

PRL 131, 211801 (2023)



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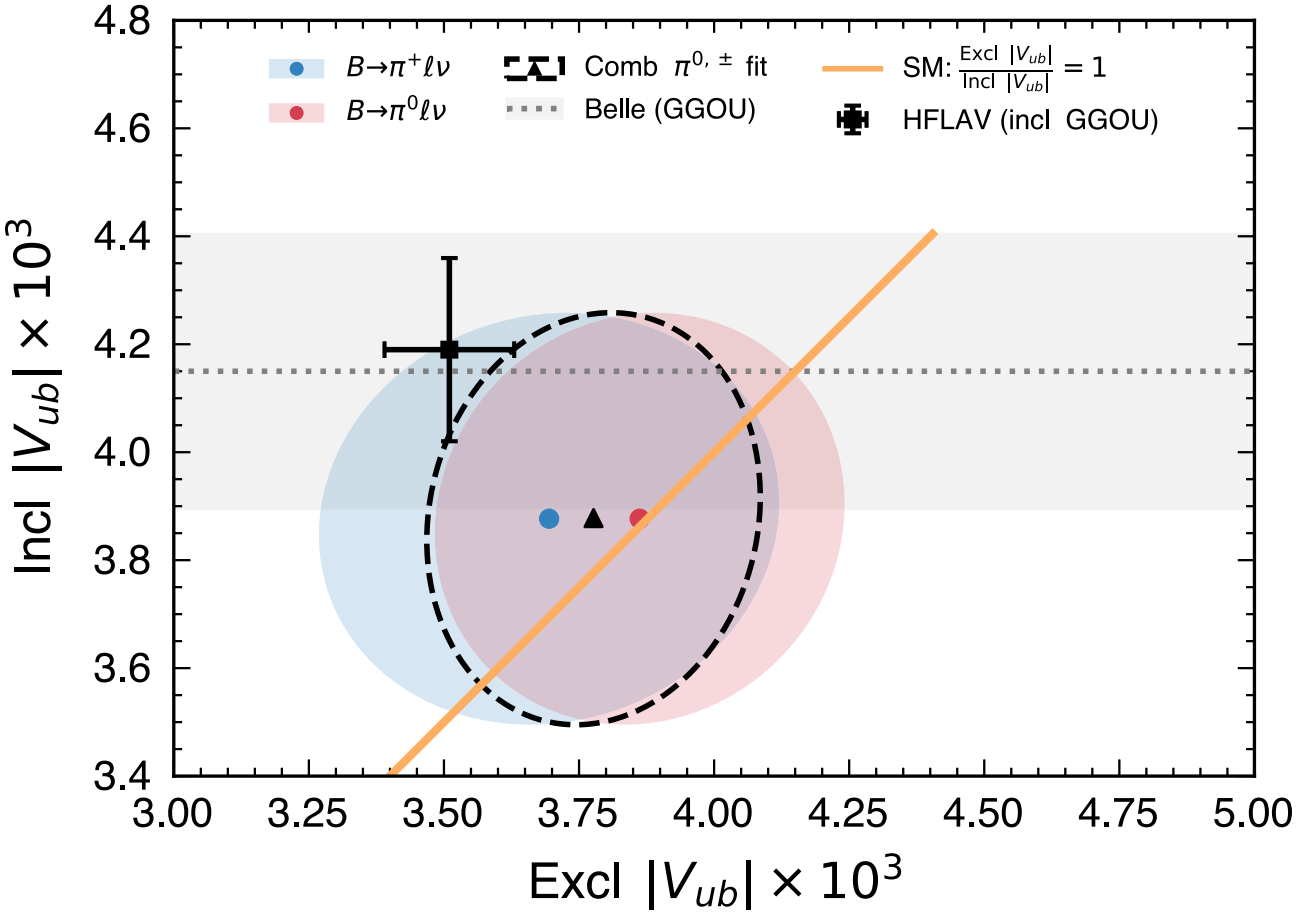
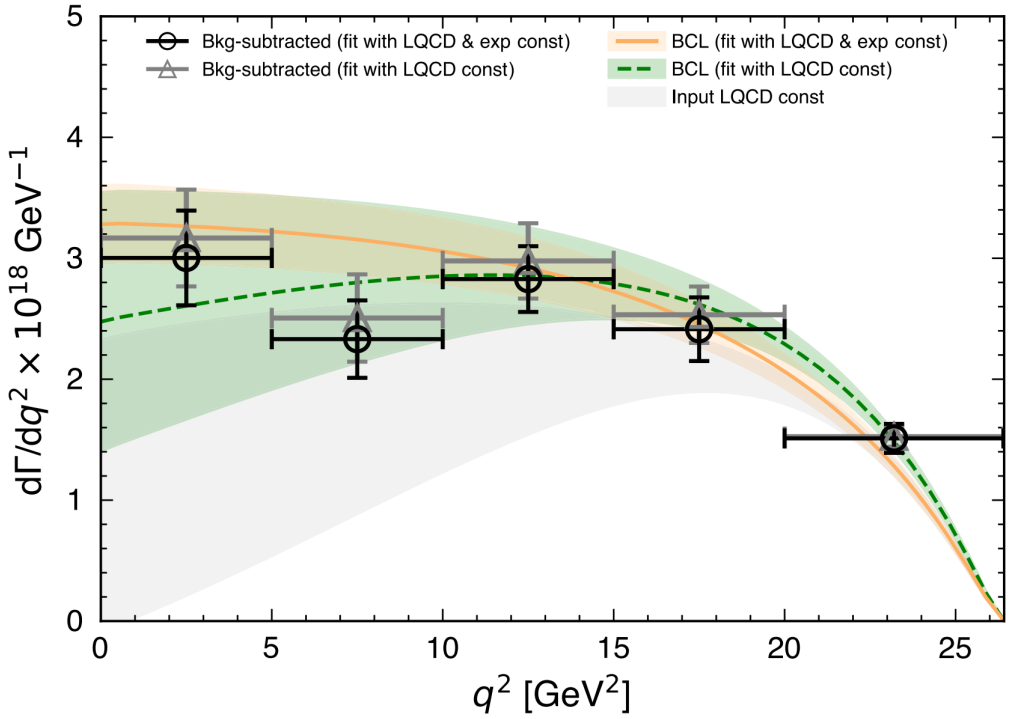
PRL 131, 211801 (2023)

Extracted with several theory constraints/assumptions





$$|V_{ub}|_{excl} = (3.78 \pm 0.23_{stat} \pm 0.16_{syst} \pm 0.14_{theo})\times10^{-3}$$
$$|V_{ub}|_{incl} = (3.88 \pm 0.20_{stat} \pm 0.31_{syst} \pm 0.09_{theo})\times10^{-3}$$

ratio 0.97 ± 0.12 compatible with w.a. within 1.2σ

Weighted average $|V_{ub}|_{avg} = (3.84 \pm 0.26)\times10^{-3}$

Consistent with CKMFitter (3.64 ± 0.07) within 0.8σ

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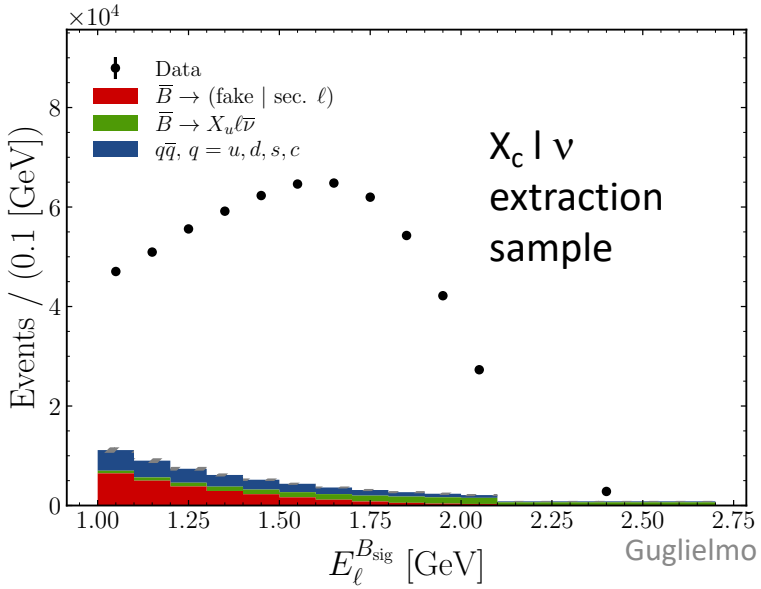
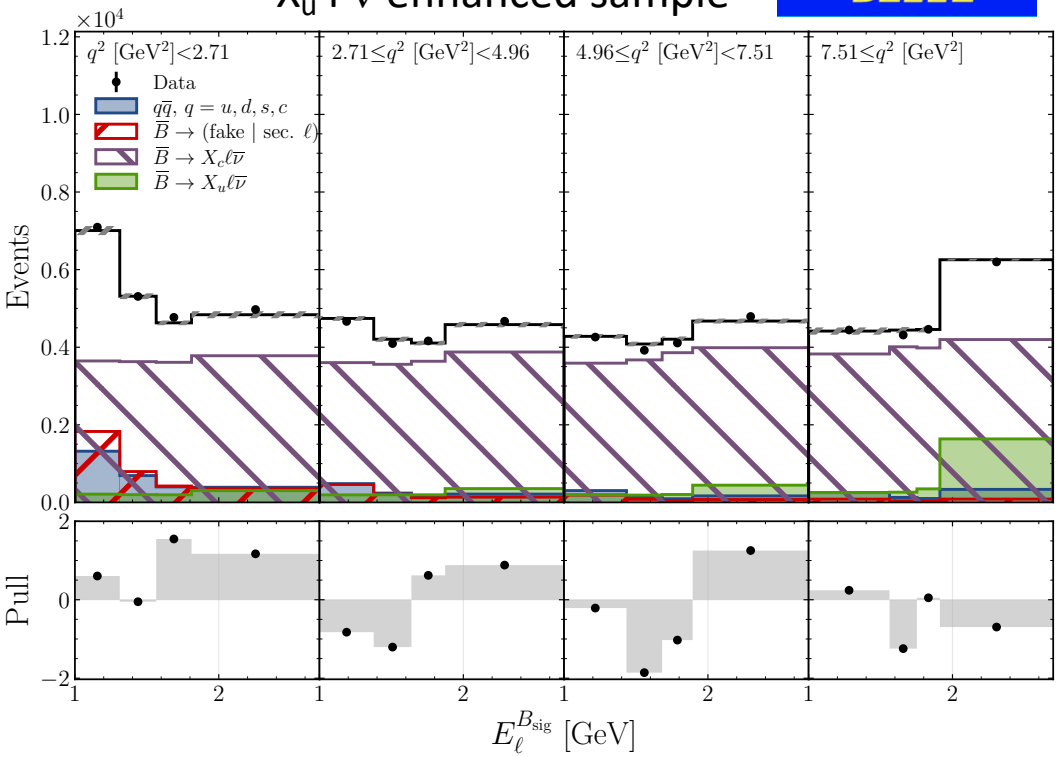
$|V_{ub}|/|V_{cb}|$ from inclusive decays (Belle)

- Full 711 fb^{-1} Belle dataset analysed with Belle II reconstruction hadronic tag software
- K^+ or K_S reconstruction to tag a b→ c decay
  - N(K) > 0 signal depleted sample for of X_c l ν decays
  - N(K) =0 signal enhanced sample to extract signal yields
- Inclusive D* reco to veto b→ c
  - reconstructing soft pion and high M^2_{miss}
- 1D fit to E_l in u-depleted sample to get $N^{X_c l\,\nu}$
- 2D fit to $E_l \times q^2$ in u-enhanced sample to get $N^{X_u l\,\nu}$



X_u l ν enhanced sample



$$\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \overline{\nu})}{\Delta\mathcal{B}(\overline{B} \to X_c \ell \overline{\nu})} = \frac{\epsilon^{X_c \ell \overline{\nu}} N^{X_u \ell \overline{\nu}}}{\epsilon^{X_u \ell \overline{\nu}} N^{X_c \ell \overline{\nu}}}, \quad = 1.96\,(\,1\,\pm 8.4\%\,\pm 7.9\%) \times 10^{-2}$$

Belle preliminary
arXiv:2311.00458

$|V_{ub}|/|V_{cb}|$ from inclusive decays (Belle)

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u l\nu)}{\Delta\mathcal{B}(B \to X_c l\nu)} \frac{\Delta\Gamma(B \to X_c l\nu)}{\Delta\Gamma(B \to X_u l\nu)}}$$

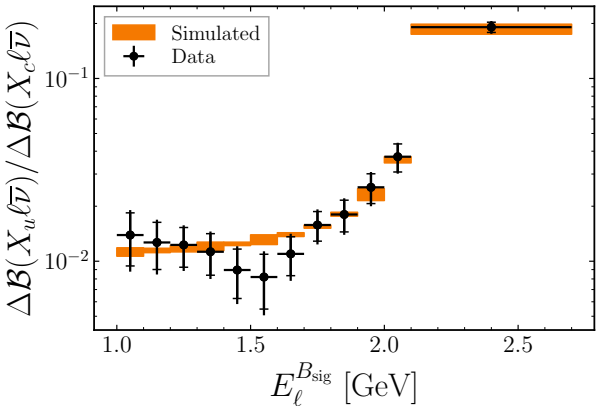
→ KIN Eur. Phys. J. C **81**, 226

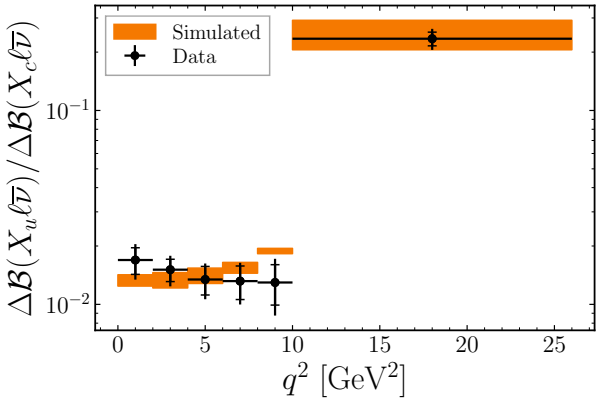
→ BLNP Phys. Rev. D **72**, 073006

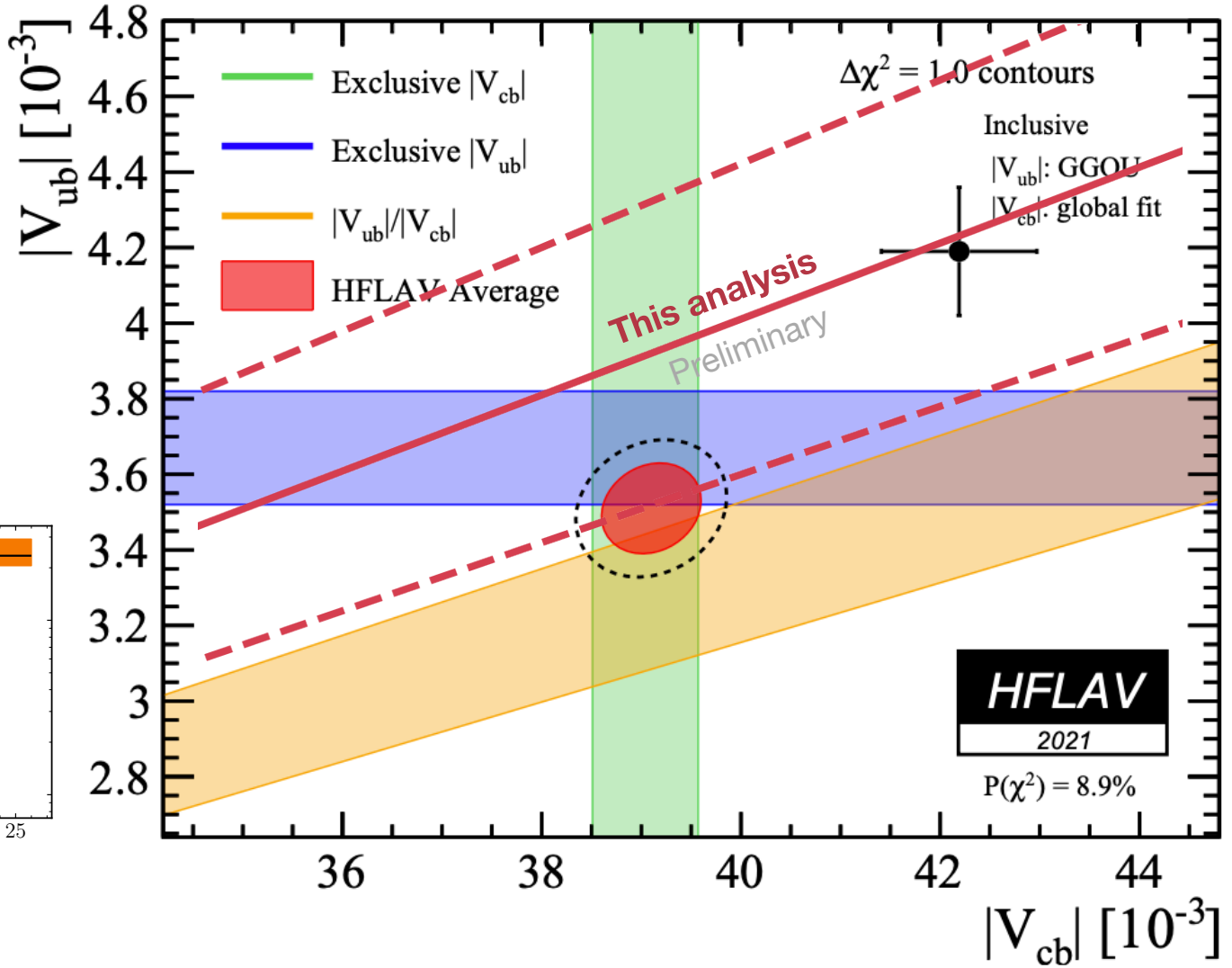
GGOU JHEP 10 (2007) 58

$$\frac{|V_{ub}|}{|V_{cb}|}^{\text{BLNP}} = 0.0972\left(1 \pm 4.2\%_{\text{stat}} \pm 3.9\%_{\text{syst}} \pm 5.6\%_{\text{theo}}\right)$$

$$\frac{|V_{ub}|}{|V_{cb}|}^{\text{GGOU}} = 0.0996\left(1 \pm 4.2\%_{\text{stat}} \pm 3.9\%_{\text{syst}} \pm 3.0\%_{\text{theo}}\right)$$







$|V_{ub}|/|V_{cb}|$ and observation of $B_s^0 \to K^-\mu^+\nu$

PRL 126, 081804 (2021)

- Dataset: 2012 data 2 fb^{-1} @ 8TeV
- Signal mode: $B_s^0 \to K^-\mu^+\nu$
- Normalization mode: $B_s^0 \to D_s^-\mu^+\nu$, $D_s^- \to K^+K^-\pi^-$

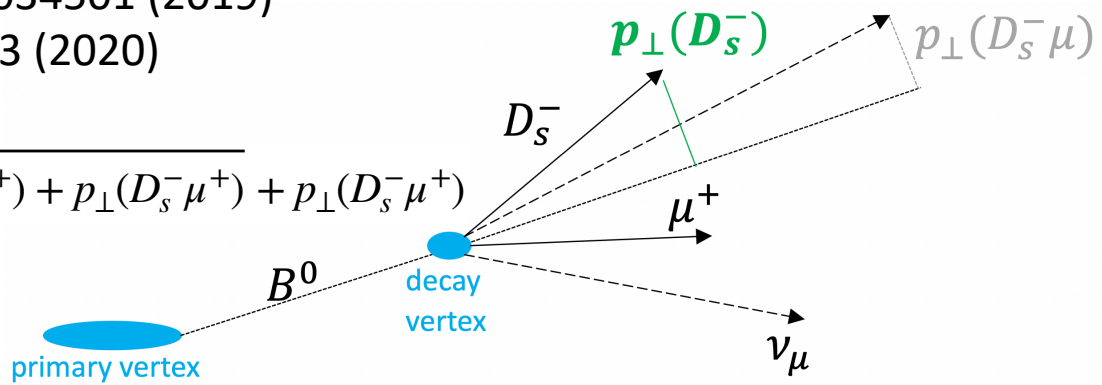
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF(B_s^0 \to K^-\mu^+\nu)}{FF(B_s^0 \to D_s^-\mu^+\nu)} = \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu)} = \frac{N_K}{N_D} \times \frac{\varepsilon_D}{\varepsilon_K} \times \mathcal{B}(D_s^- \to K^+K^-\pi^-)$$

PDG

Parameter of interest — Theory input — Exp data — MC

LCSR for $B_s^0 \to K^-\mu^+\nu$ $q^2 < 7$ GeV^2 JHEP 2017, 112 (2017)
LQCD for $B_s^0 \to K^-\mu^+\nu$ $q^2 < 7$ GeV^2 PRD 100, 034501 (2019)
LQCD for $B_s^0 \to D_s^-\mu^+\nu$ all q^2 PRD 101, 074513 (2020)

Extract $|V_{ub}|/|V_{cb}|$ in two regions of q^2 fitting $m_{corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$



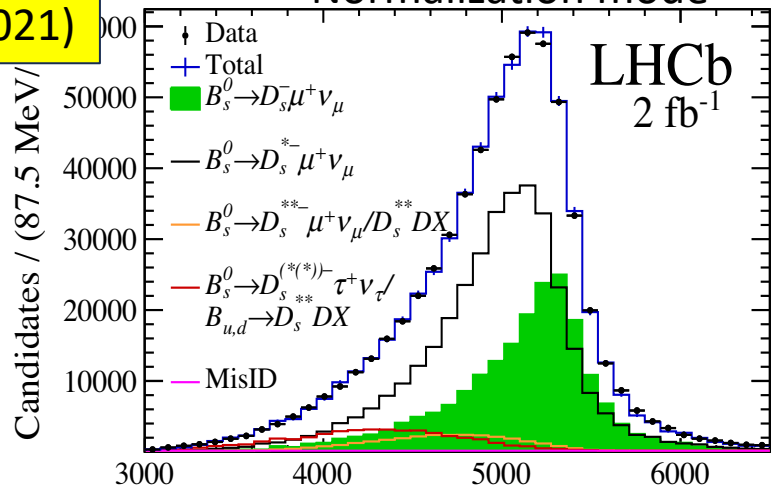
$|V_{ub}|/|V_{cb}|$ and observation of $B_s^0 \to K^-\mu^+\nu$

PRL 126, 081804 (2021)

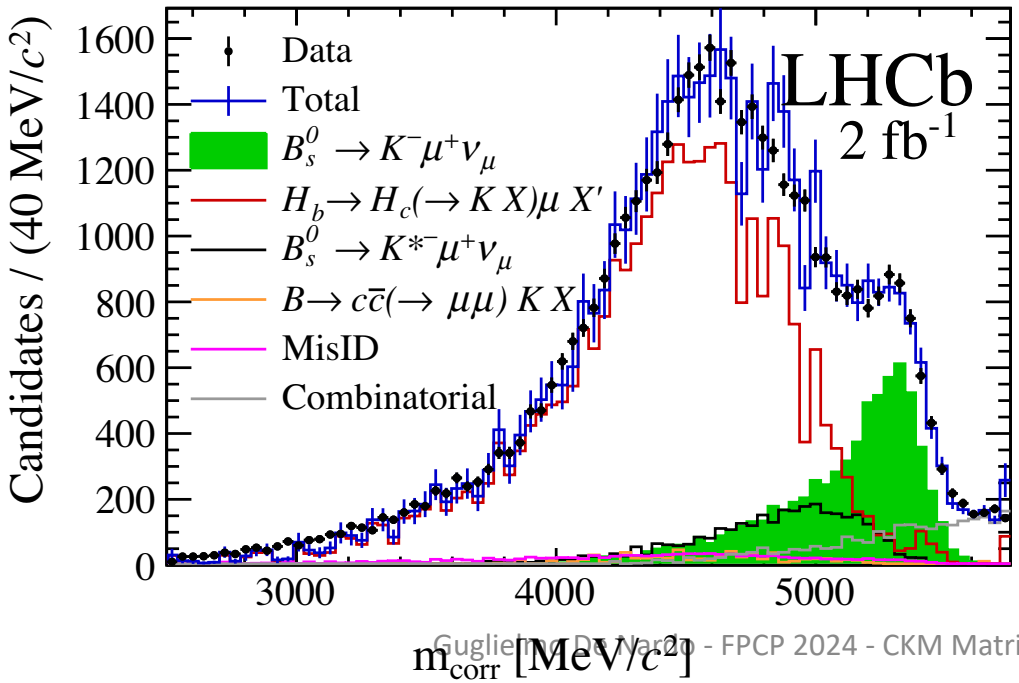
$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008\,(D_s) \pm 0.0030\,(\text{FF}),$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013\,(D_s) \pm 0.0068\,(\text{FF}),$$

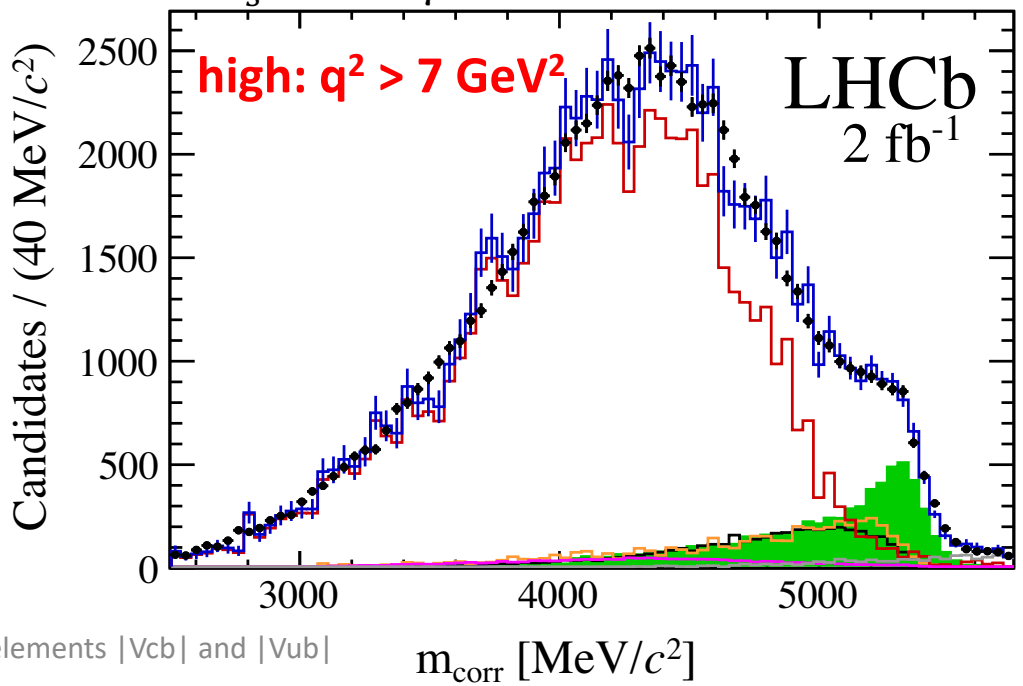
Normalization mode



$B_s^0 \to K^-\mu^+\nu$ **low : q^2 < 7 GeV^2**



$B_s^0 \to K^-\mu^+\nu$ **high: q^2 > 7 GeV^2**



Conclusions

- BaBar, Belle and Belle II producing recently many updated and improved measurements of $|V_{cb}|$ and $|V_{ub}|$, with both inclusive and exclusive decays
  - Decided to restrict in this talk to the latest and had to neglect many others slightly older

- LHCb results less recent but bringing unique observations like Bs S.L. decays
  - Keeps demonstrating competitive results in S.L. decays

- Future: huge improvements in statistics expected from both LHCb and Belle II
  - Will permit to reach ultimate sensitivities and exploit maximal information from differential distributions