Semileptonic B Decays & $|V_{xb}|$ update

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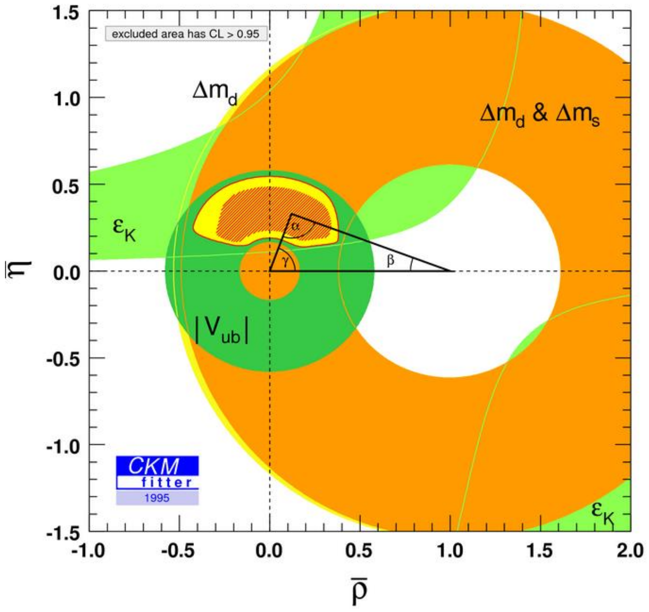
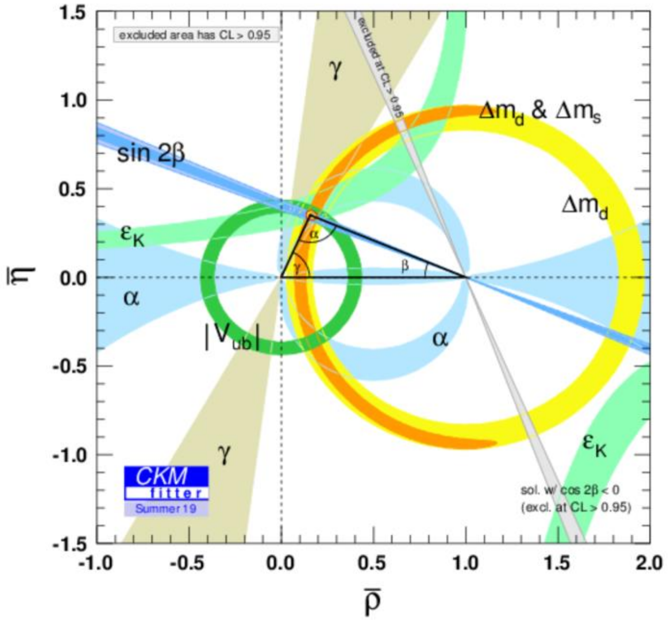
Sept, 23

Precision in flavour: the CKM matrix

1995



2019



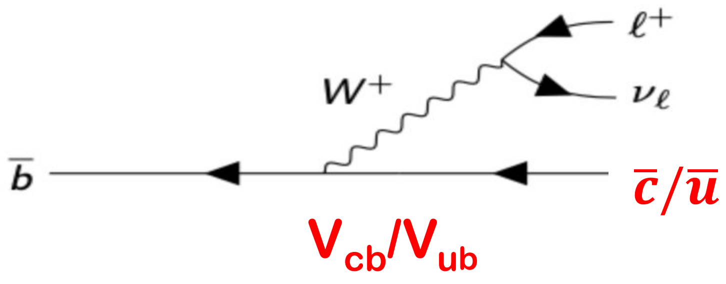
Decades of unitary triangle refinement

- **Focus on $|V_{cb}|$ & $|V_{ub}|$**

$|V_{cb}|$ normalizes the UT;
SM input e.g. $\epsilon_K \propto V_{cb}^4$

$|V_{ub}|$ constrains directly the UT

Semileptonic B decays



- Tree level: no loop suppression & assumed largely free of BSM
- Leptons + just a hadron in final state: less QCD hadronic complications
- Most precise determination of $|V_{ub}|$ & $|V_{cb}|$
- Exclusive/Inclusive determinations: different techniques:
  check of our theoretical tools for QCD

  $b \to c\ell\nu$ ($B \to D^{(*)}\ell\nu / B \to X_c\ell\nu$) $b \to u\ell\nu$ ($B \to \pi(\ldots)\ell\nu / B \to X_u\ell\nu$)

  Long standing excl/incl tension in $|V_{xb}|$--reduced, not yet clear

Inclusive decays $B \to X_c \ell \nu$

Heavy Quark Expansion for sufficiently inclusive quantities (total width, moments of kinematical distributions)
double series in α_s & Λ_{QCD}/m

$$\Gamma(B \to X_q l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{qb}|^2 \left[c_3 \langle O_3 \rangle + c_5 \frac{\langle O_5 \rangle}{m_b^2} + c_6 \frac{\langle O_6 \rangle}{m_b^3} + O\left(\frac{\Lambda_{QCD}}{m_b^4}, \frac{\Lambda_{QCD}}{m_b^3 m_c^2} + \ldots \right) \right.$$

- $c_d(d = 3, 5, \ldots)$ calculable in perturbation theory as a series in α_s
- Non perturbative matrix elements of local operators expressed in terms of HQE parameters, whose number grows with powers of Λ_{QCD}/m

Extraction of HQE parameters and $|V_{cb}|$

a simultaneous fit (global fit) based on exp measured distributions and momenta

✓ data sets & exp selections

✓ theoretical scheme employed & order of truncation of the HQE

Exp.	Hadron moments $\langle m_X^{2n} \rangle$	Lepton moments $\langle E_\ell^n \rangle$	Remarks
BaBar [154] [155]	$n=1$, $c=0.9, 1.1, 1.3, 1.5$ $n=2$, $c=0.8, 1.0, 1.2, 1.4$ $n=3$, $c=0.9, 1.3$	$n=0$, $c=0.6, 1.2, 1.5$ $n=1$, $c=0.6, 0.8, 1.0, 1.2, 1.5$ $n=2$, $c=0.6, 1.0, 1.5$ $n=3$, $c=0.8, 1.2$	Lepton momentum spectrum is obtained with an inclusive measurements. The hadronic moments are determined in hadronic tagged B meson sample.
Belle [156] [157]	$n=1$, $c=0.7, 1.1, 1.3, 1.5$ $n=2$, $c=0.7, 0.9, 1.3$	$n=0$, $c=0.6, 1.4$ $n=1$, $c=1.0, 1.4$ $n=2$, $c=0.6, 1.4$, $n=3$, $c=0.8, 1.2$	Both lepton and hadronic moments measured using the hadronic B tagged events.
CDF [158]	$n=1$, $c=0.7$ $n=2$, $c=0.7$		Hadronic mass measurement obtained from the $D^*\pi$ mass distribution in $B \to D^{(*)}\pi\ell\nu$ decays, combined with the known $B \to D^{(*)}\ell\nu$ rates.
CLEO [159]	$n=1$, $c=1.0, 1.5$ $n=2$, $c=1.0, 1.5$		The kinematics of the hadronic part is inferred from the measurement of the neutrino momentum inclusively from the global event missing momentum.
DELPHI [160]	$n=1$, $c=0.0$ $n=2$, $c=0.0$ $n=3$, $c=0.0$	$n=1$, $c=0.0$ $n=2$, $c=0.0$ $n=3$, $c=0.0$	Exploiting the large boost of the B meason produced, the moments are measured without cuts on the lepton energy.

← HFAG average

$$\langle E_\ell^n \rangle = \frac{1}{\Gamma_{E_\ell > E_{cut}}} \int_{E_\ell > E_{cut}} E_\ell^n \frac{d\Gamma}{dE_\ell} dE_\ell$$

$$\langle m_X^{2n} \rangle = \frac{1}{\Gamma_{E_\ell > E_{cut}}} \int_{E_\ell > E_{cut}} m_X^{2n} \frac{d\Gamma}{dm_X^2} dm_X^2$$

GR, M.Rotondo 1912.09562 [hep-ph]

Global HFLAV fit from the theoretical viewpoint

- ✓ includes all $O\left(\alpha_s{}^2, \frac{\Lambda_{QCD}^2 \alpha_s}{m_b^2}, \frac{\Lambda_{QCD}^3}{m_b^3}\right)$ corrections

- ✓ include 6 NP parameters $m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3$

- ✓ moments determine combinations of m_b & m_c—additional constraint from external determination of m_c (sum rules+pert)

Chetyrkin, et al. (2009) 0907.2110

- ✓ low-scale OPE-compatible masses + other assumptions: *kinetic scheme*

I.Bigi et al. hep-ph/9704245, hep-ph/940410,
Benson et al. hep-ph/0302262, Gambino & Uraltsev hep-ph/0401063

$$|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3}$$

$$\chi^2/ndf = 0.32$$

HQE status and prospects

- High order proliferation of NP parameters [also IR sensitivity to charm mass ($\log m_c$, $\frac{\Lambda_{QCD}^5}{m_b^3 m_c^2}$, ...)]

I. Bigi et al 0911.3322, Breidenbachet al 08…

- ✓ Computed/estimated up order ($\frac{\Lambda_{QCD}^5}{m_b^5}$)

Gremm et al 96, Dassinger et al 14, Mannel et al 10, Heinonen et al 14 ,Gambino et al. 16…

If included in global fit with *Lowest Lying State* Approximation
--sub-percent reduction in $|V_{cb}|$, not appreciable at the current level of precision.

Gambino et al. 1606.06174

- ✓ Part of ($\frac{\alpha_s \Lambda_{QCD}^3}{m_b^3}$) corrections completed: $\boldsymbol{\rho_D^3}$

Mannel & Pivovarov 1907. 09187

- First steps toward transition rates from lattice

Hashimoto 1703.01881, Gambino & Hashomoto 2005.13730

- Other (not equivalent) schemes (and/or different constraints) not updated

Exclusive Decays

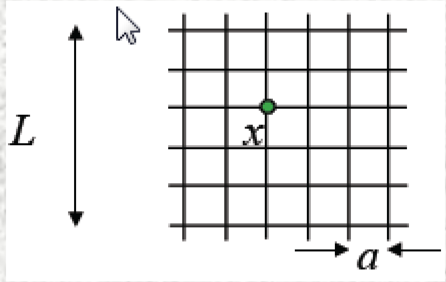
(experiment) = (known) x (**CKM elements**) x (had. matrix element)

Lattice, QCD sum rules…

Lattice

✓ $a \ll 1/m$ $m_b \sim 1/a$

effective theories (HQET, NRQCD) that eliminate high degrees of freedom (systematic expansion in $1/m_b$)



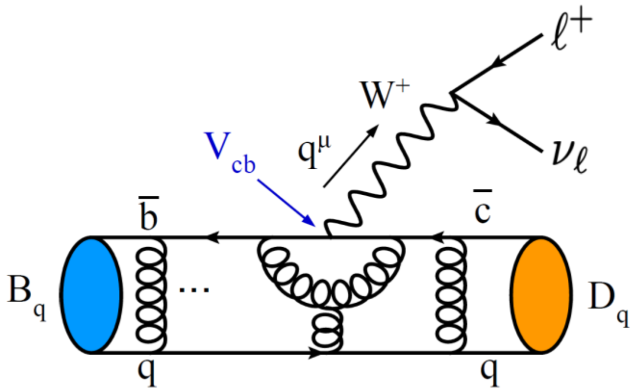
QCD sum rules

✓ Analytical approach which connects QCD Green functions, in particular their Operator Product Expansion (OPE), and their exp measurable hadronic counterparts

Exclusive $|V_{cb}|$ determination

$$\frac{d\Gamma}{d\omega}(B \to D^* l\nu) \propto G_F^2(\omega^2-1)^{\frac{1}{2}}|V_{cb}|^2\mathcal{F}(\omega)^2$$

$$\frac{d\Gamma}{d\omega}(B \to D\, l\nu) \propto G_F^2(\omega^2-1)^{\frac{3}{2}}|V_{cb}|^2\mathcal{G}(\omega)^2$$

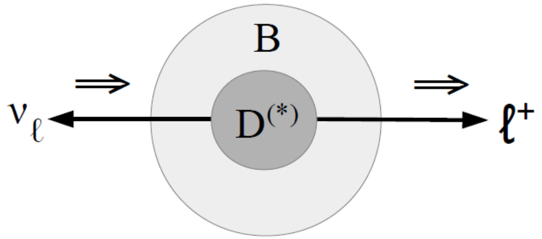


Massless leptons limit

Heavy quark symmetry

$$\mathcal{F}(\omega=1) = G\,(\omega=1) = 1 \qquad \omega = \frac{p_{D^{(*)}}\cdot p_B}{m_B\, m_{D^{(*)}}}$$

Zero recoil



$q^2 = q^2_{max}$

$w = 1$

- ✓ Non perturbative deviations of FF from unity at zero recoil ($\omega = 1$)
- ✓ Extrapolation of experimental points ($\omega \neq 1$) to zero-recoil
- ✓ Theoretical parameterization of ω dependence

Non perturbative corrections directly at non-zero recoil

$B \to D^{(*)}\ell\nu$ Form Factors

Collaboration	Refs.	$\mathcal{F}(1)$	Refs.	$\mathcal{G}(1)$
FNAL/MILC	2014	$0.906 \pm 0.004 \pm 0.012$	2015	$1.054 \pm 0.004 \pm 0.008$
HPQCD	2017	$0.895 \pm 0.010 \pm 0.024$	2015	1.035 ± 0.040
HPQCD	2019	0.914 ± 0.024		

LCSR: 2018 computed all form factors (dimension-six operators)

N. Gubernari et al. 1811.00983

Parameterizations

- Pole/sum of effective poles
  - ✓ Ball and Zwicky 2001, 2005
  - ✓ Becirevic & Kaidalov 2000
- Systematic approach exploiting dispersion relations & unitarity bounds
  - ✓ Boyd-Grinstein-Lebed 1994 (BGL)—FF expressed as a series (versions differ e.g. by order of truncation)
  - ✓ Caprini-Lelloch-Neubert 1997 (CLN)—reduce the number of parameters by HQS relations
  - ✓ Bourrely-Caprini-Lellouch 2008 (BCL)--improves the convergence of BGL series by removing an unphysical singularity at the pair production threshold and correcting the large q^2 behavior

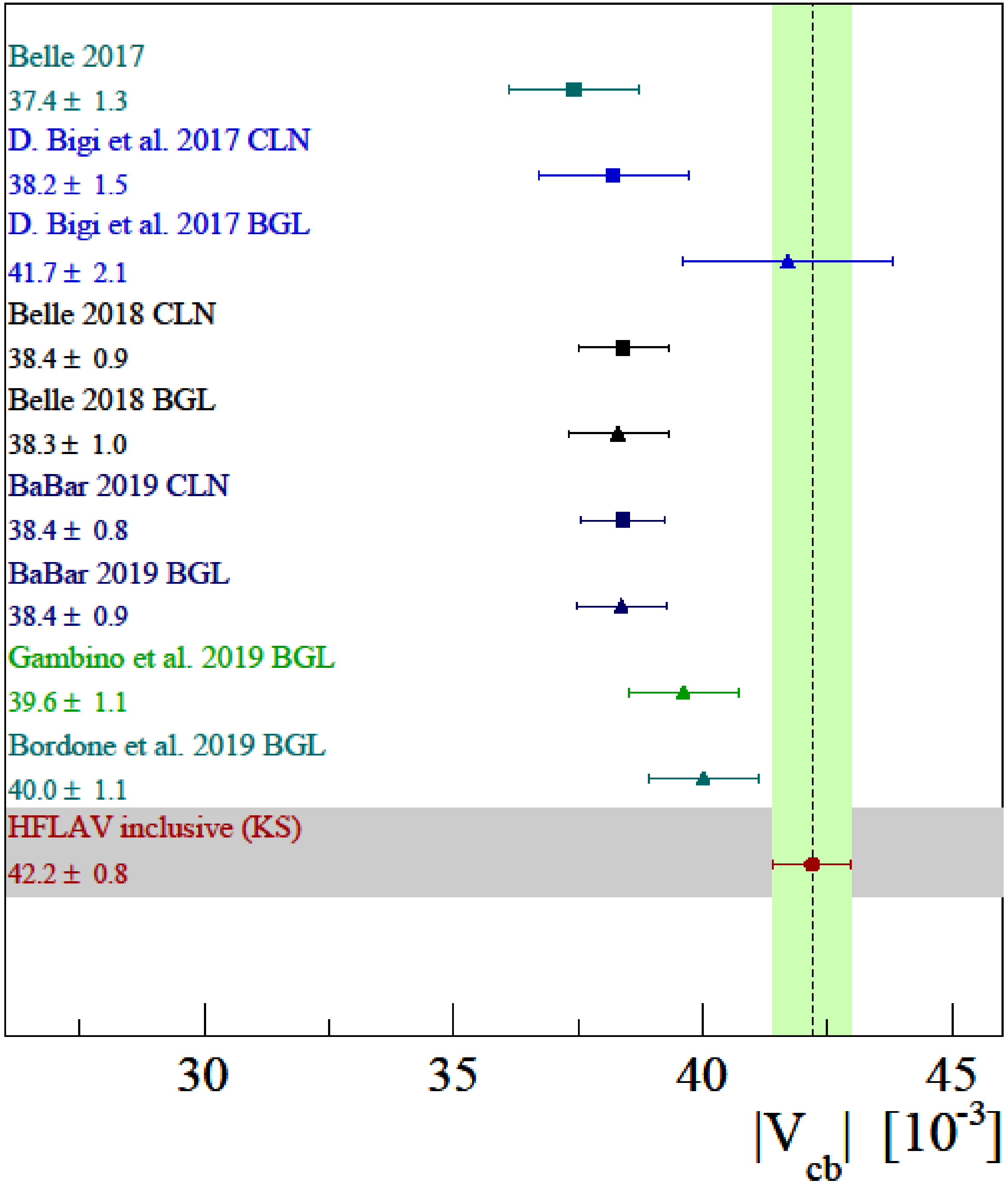
W/2017 Belle data, switching from the CLN to the BGL shifts the determination of $|V_{cb}|$ towards inclusive up to 6%; *Reliability of CLN assumptions questioned*

Bigi et al. 1703.06124, Grinstein et al. 1703.08170 (Belle 1702.01521)

W/2018 Belle & Babar data, *no significant difference CLN/BGL*

Belle 1809.03290, Gambino Jung 1905.08209, Babar 1903.10002, Gambino & Jung. 1905.08209, Bordone et al. 1908.09398

initial discrepancies useful to revisit CLN assumptions, possible systematics & subtleties, including studies on the BGL optimal number of parameters

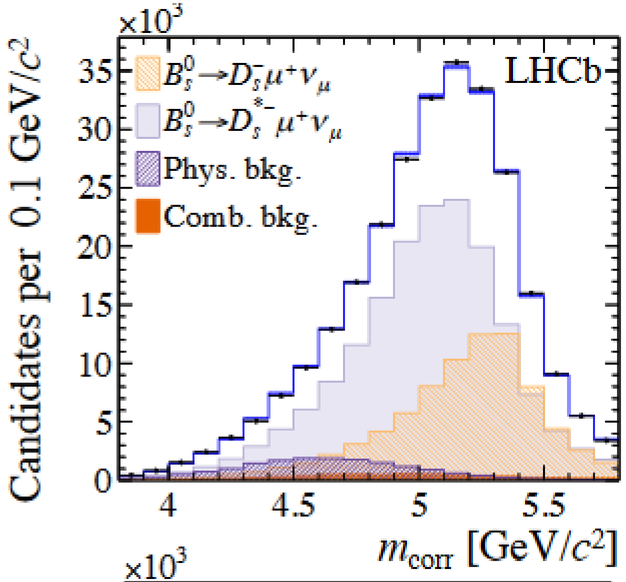


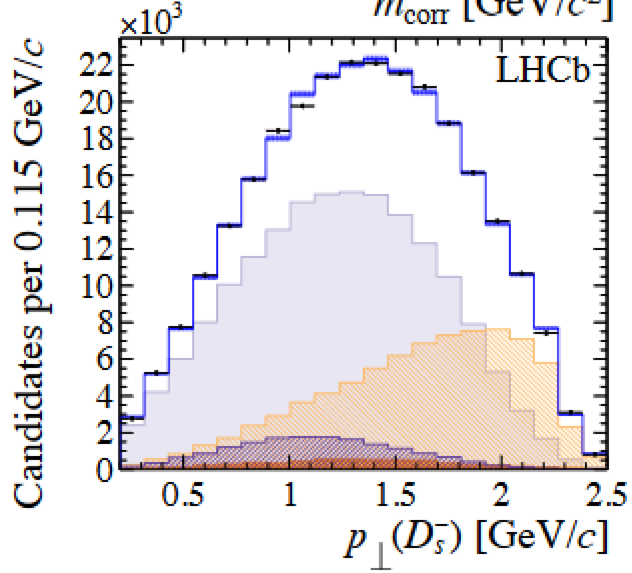
Courtesy of M. Rotondo

$B_s \to D_s^{(*)} \mu \nu_\mu$

first determination of $|V_{cb}|$ at a hadron collider and the first using B_s^0 decays

LHCb 2001.03225





Lattice FF: see C. Davies's talk yesterday
Exp analyses: see S. Brain's talk yesterday

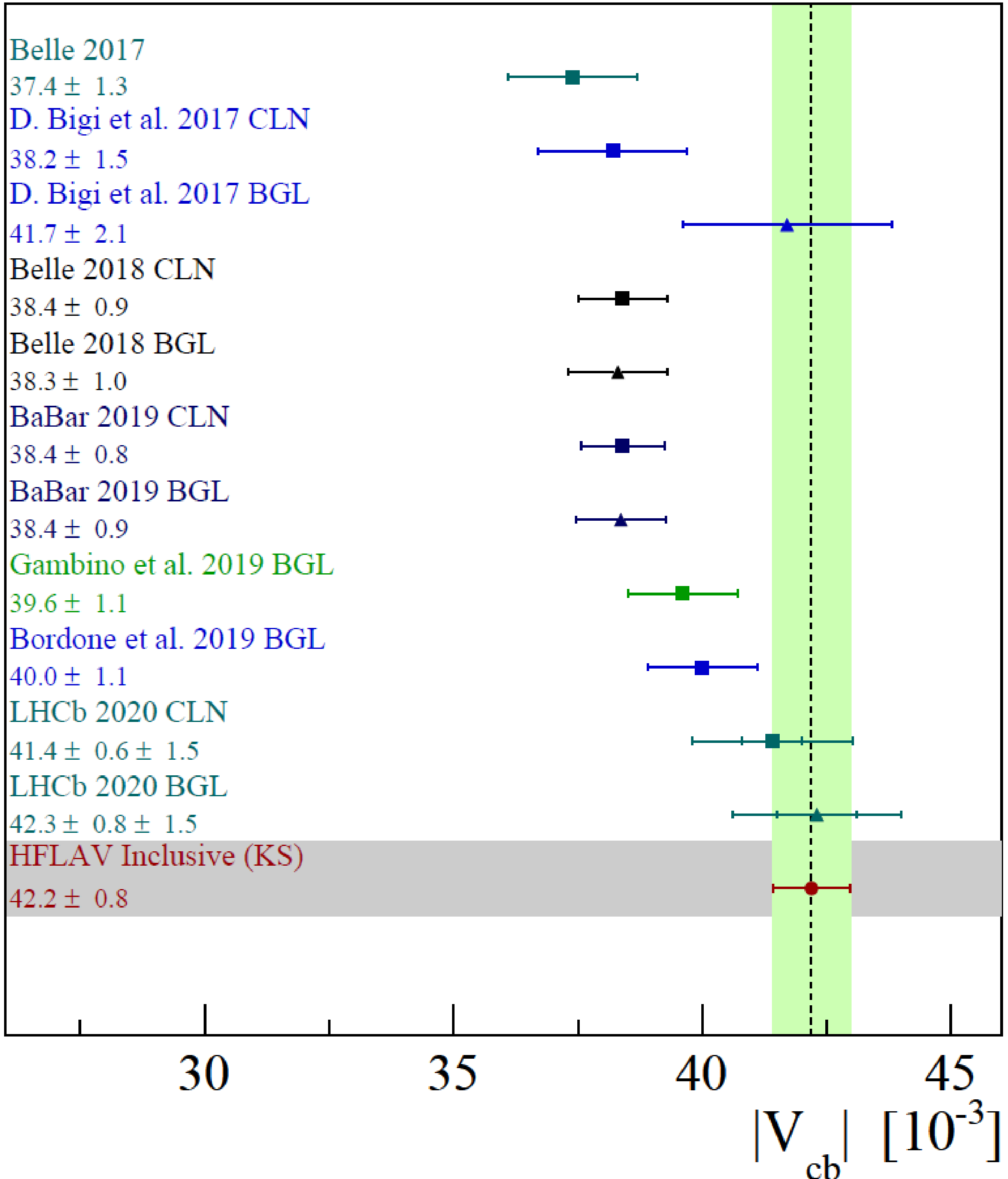
$$|V_{cb}|_{CLN} = (41.6 \pm 0.6(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$$
$$|V_{cb}|_{BGL} = (42.3 \pm 0.8(stat) \pm 0.9(syst) \pm 1.2(ext)) \times 10^{-3}$$

Compatible & in agreement with results from excl/incl B decays

- ✓ uncertainty not competitive with B factories
- ✓ dominant uncertainty due to the knowledge of the B^0_s to B^0 production ratio f_s/f_d.

New strategy for a similar measurement with B decays

At the current level of precision, it would be important to extend FF to non-zero recoil:
work in progress by JLQCD and FNAL/MILC

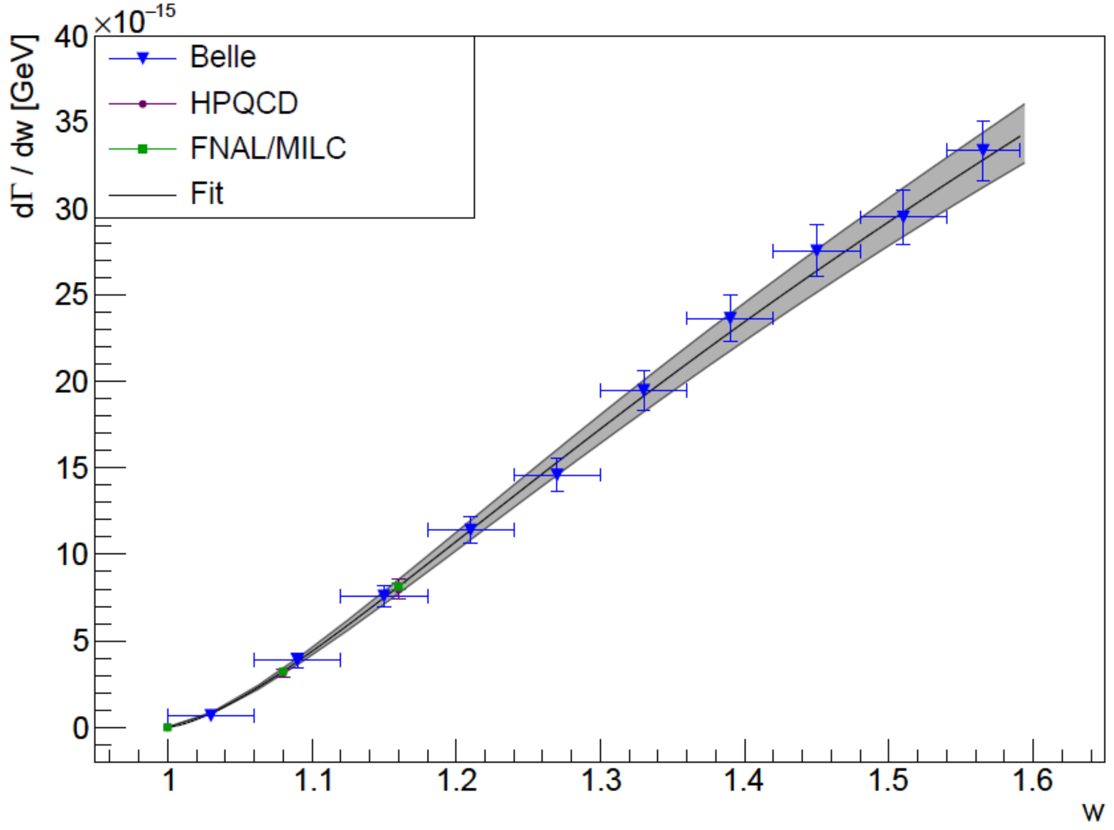


Courtesy of
M. Rotondo

$B \to D \ell \nu$

✓ Fit: lattice calculations at non-zero recoil ($\omega \neq 1$) + exp

the role of parameterization becomes less relevant: the extrapolation to zero recoil reduces to an interpolation between experimental results and different theory points.



$$|V_{cb}| = (39.58 \pm 0.94 \pm 0.37) \times 10^{-3}$$

HFLAG average

Compatible with results from $B \to D^* \ell \nu$

Comparison with baryon semileptonic decays

spin-1/2 $\Lambda_Q \rightarrow$ spin-1/2 $\Lambda_{Q'}$ in the HQET framework

$$\langle \Lambda_{Q'}(v',s')|\bar{Q}'\gamma_\mu Q|\Lambda_Q(v,s)\rangle = \bar{u}_{\Lambda'}(v',s')\left[F_1\gamma_\mu + F_2 v_\mu + F_3 v'_\mu\right] u_\Lambda(v,s)$$

$$\langle \Lambda_{Q'}(v',s')|\bar{Q}'\gamma_\mu\gamma_5 Q|\Lambda_Q(v,s)\rangle = \bar{u}_{\Lambda'}(v',s')\left[G_1\gamma_\mu + G_2 v_\mu + G_3 v'_\mu\right] \gamma_5 u_\Lambda(v,s)$$

$$w = v\cdot v' = (m_Q^2 + m_{Q'}^2 - q^2)/2m_Q m_{Q'}$$

Form factors for $\Lambda_b^0 \rightarrow \Lambda_c^+ \, \mu \, \overline{\nu_\mu}$ and $\Lambda_b^0 \rightarrow p \, \mu \, \overline{\nu_\mu}$ available in LQCD

RBC/UKQCD 1503.01421

First direct measurement (independent exclusive determination) of the ratio

LHCb 1504.01568

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu\nu)_{q^2>7\ GeV^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{R_{FF}\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu\bar{\nu}_\mu)}}$$

- ✓ baryon Λ_c^+ reconstructed in the $\Lambda_c^+ \rightarrow p\, K^- \pi^+$ decay mode
- ✓ dependence on its branching ratio, based on average of most precise measurements (Belle & BESIII) only *marginally* consistent
- ✓ more effort to be pursued, using also BaBar and LHCb data
- ✓ predicted q^2 shape for the normalization channel validated by a LHCb measurement of the q^2 spectrum

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.079 \pm 0.004_{Exp.} \pm 0.004_{F.F.}$$

using exclusive determination of the $B \rightarrow \pi\ell\nu$ decay rate from HFLAV →

$$|V_{cb}| = (46.4 \pm 3.8) \times 10^{-3}$$

compatible with inclusive

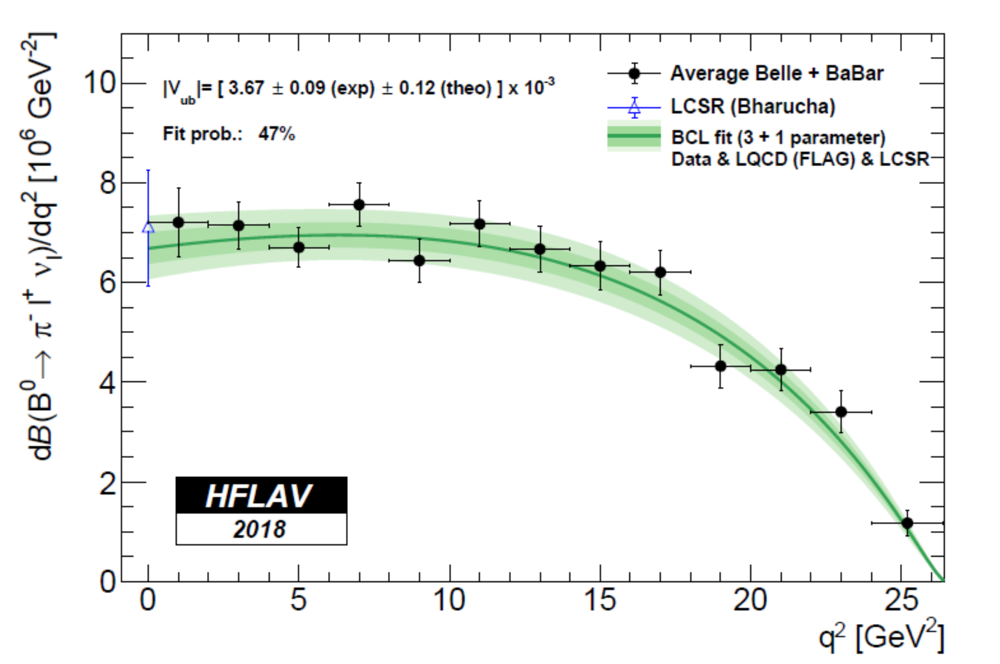
$|V_{ub}|$ exclusive determination

❑ Traditionally extracted by the decay $B \to \pi \ell \nu$ (only a single form factor in massless limit)

$$\frac{d\Gamma(\overline{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$

$$\langle \pi(p_\pi)|V^\mu|B(p_B)\rangle = f_+(q^2)\left[p_B^\mu + p_\pi^\mu - \frac{m_B^2 - m_\pi^2}{q^2} q^\mu\right] + f_0(q^2)\frac{m_B^2 - m_\pi^2}{q^2} q^\mu$$

- Since the u-quark is not heavy, HQ symmetries are not as binding as in $b \to c$
- FF from lattice (large q^2)
  Independent LQCD published determinations from RBC/UKQCD & Fermilab/MILC (2015) (WIP also by HPQCD, JLQCD, Colquhoun et al.)
  & from Light Cone Sum Rules LCSR (low q^2)
  larger uncertainties around 6-9%

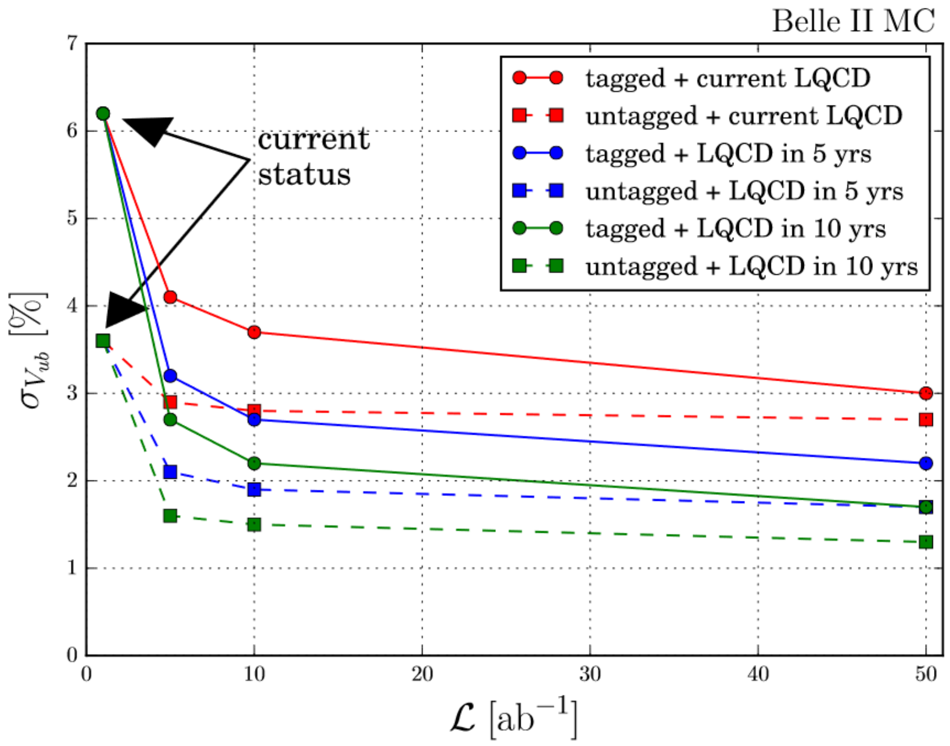


- BCL parametrization
  presence of far singularities or an incorrect asymptotic behavior more significant in the heavy-to-light kinematical range

$$|V_{ub}| = (3.70 \pm 0.10\,(\mathrm{exp}) \pm 0.12\,(\mathrm{theo})) \times 10^{-3} \;\; (\mathrm{data} + \mathrm{LQCD}),$$
$$|V_{ub}| = (3.67 \pm 0.09\,(\mathrm{exp}) \pm 0.12\,(\mathrm{theo})) \times 10^{-3} \;\; (\mathrm{data} + \mathrm{LQCD} + \mathrm{LCSR}).$$

HFLAV 1909.12524

Prospects for $B \to \pi \ell \nu$ at Belle II



M. Lubej 1705.05289

Figure 4 – $|V_{ub}|$ precision estimates for the tagged and untagged reconstruction method at 5, 10 and 50 ab^{-1} of integrated luminosity for current LQCD and LQCD forecasts in 5 and 10 years.

Expected $|V_{ub}|$ precision with Belle II dataset and LQCD forecasts for $B \to \pi \ell \nu$ channel:

- Tagged: 1.7 %
- Untagged: 1.3 %

b → u decays into vector mesons

$B \to \omega \ell \nu$, $B \to \rho \ell \nu$

$$\frac{d\mathscr{B}(B \to V\ell\nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 p_V q^2 \tau_B}{96\pi^3 m_B^2} \left[|H_0(q^2)|^2 + |H_+(q^2)|^2 + |H_-(q^2)|^2\right]$$

Form factors:

- LQCD challenging--vector mesons unstable resonances for sufficiently light quark masses

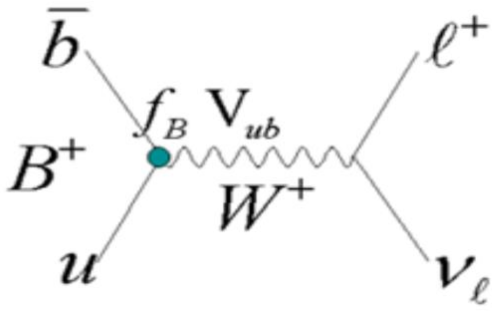
  $B \to \rho$ by UKQCD (2004) in the quenched approximation & preliminary by SPQcdR (2002)

- 2015 LCSR available-at q^2 <12 GeV

$\bar{B} \to \omega l \bar{\nu}_l$	$10^{\{-3\}}$
Bharucha et al. 2015 (LCSR)	$3.31 \pm 0.19_{exp} \pm 0.30_{th}$
$\bar{B} \to \rho l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR)	$3.29 \pm 0.09_{exp} \pm 0.20_{th}$

Results compatible w/$B \to \pi$, but consistently lower, order 10%

Leptonic decays $B \to \ell\nu$



- ✓ Theoretically clean
- ✓ CKM & helicity suppressed

$\mathcal{B}(B \to e\nu) \sim 10^{-11}$

$\mathcal{B}(B \to \mu\nu) \sim 10^{-7}$

$\mathcal{B}(B \to \tau\nu) \sim 10^{-4}$

Because of large backgrounds & systematic errors, the significances of the individual results are still below the 5σ discovery threshold

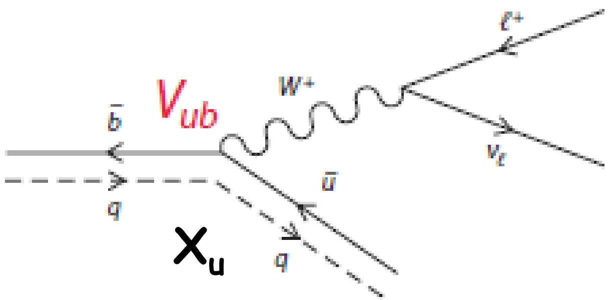
BaBar:	$B \to \tau\nu$	3.3σ & 2.3σ, for hadronic and semileptonic tags	Babar 1207.0698
Belle:	$B \to \tau\nu$	4.6σ for combined hadronic and semileptonic tags	Belle 1503.05613
	$B \to \mu\nu$	2.8σ recent improved search using the full Belle dataset	Belle 1911.03186

$$|V_{ub}| = (4.05 \pm 0.03_{th} \pm 0.64_{exp})$$

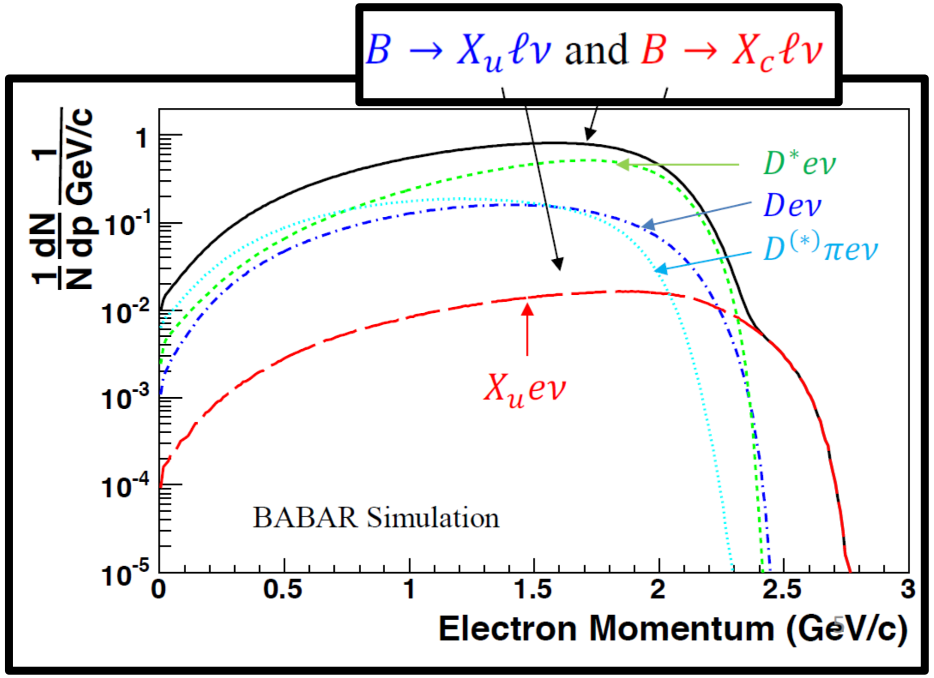
Not competitive level of precision, not used in avg.

FLAG 2019 $B \to \tau\nu$

Inclusive $|V_{ub}|$



Need experimental phase space cuts
to reduce large $b \to c$ background;



Threshold phase space region dominance

- ✓ Final gluon radiation strongly inhibited: soft and collinear singularities
- ✓ large logarithms $a_s^n \log^{2n}(2\, E_X/m_X)$ $(E_X \ll m_X)$ to be resummed at all orders in PT
- ✓ non-perturbative effects related to a small vibration of the b-quark in the B meson (Fermi motion) enhanced

Theoretical approaches

✓predictions based on parameterizations of shape function

✓*several cuts* — Bosch, Lange, Neubert, Paz (BLNP), Gambino, Giordano, Ossola, Uraltsev (GGOU), neural network fit (Gambino,Healey,Mondino)

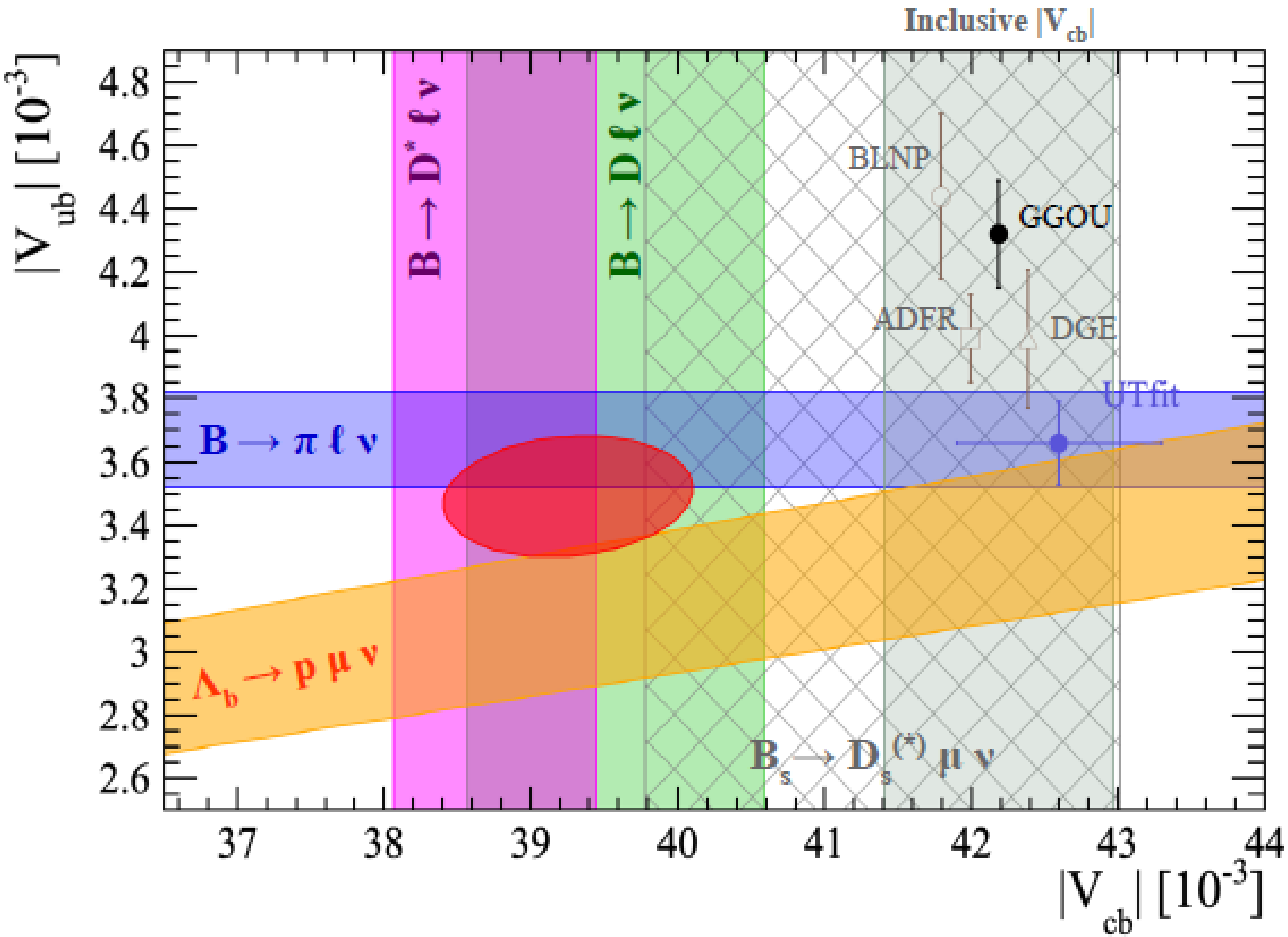
✓*m_X-q^2 cut* — Bauer, Ligeti, Luke (BLL)

✓*Lepton momentum spectrum* — Leibovich, Low, Rothstein (LLR), Lange, Neubert, Paz (LNP)

✓*global fit* — Ligeti, Stewart, Tackmann

✓predictions led by anlytical structure of resummed pQCD

Andersen, Gardi (DGE), Aglietti, Di Lodovico, Ferrera, GR (ADFR)



GR, M.Rotondo 1912.09562

New results on inclusive $B \to X_u \ell \nu_l$ decay from the Belle experiment

Preliminary results obtained with hadronic tagged analysis with full Belle dataset of 711 fb^{-1}

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

τ_B average B meson lifetime: (1.579 ± 0.004) ps

ΔΓ: Use **state-of-the-art theory**: BLNP, DGE, GGOU, ADFR to determine $|V_{ub}|$

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

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

Lu Cao, ICHEP 2020

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

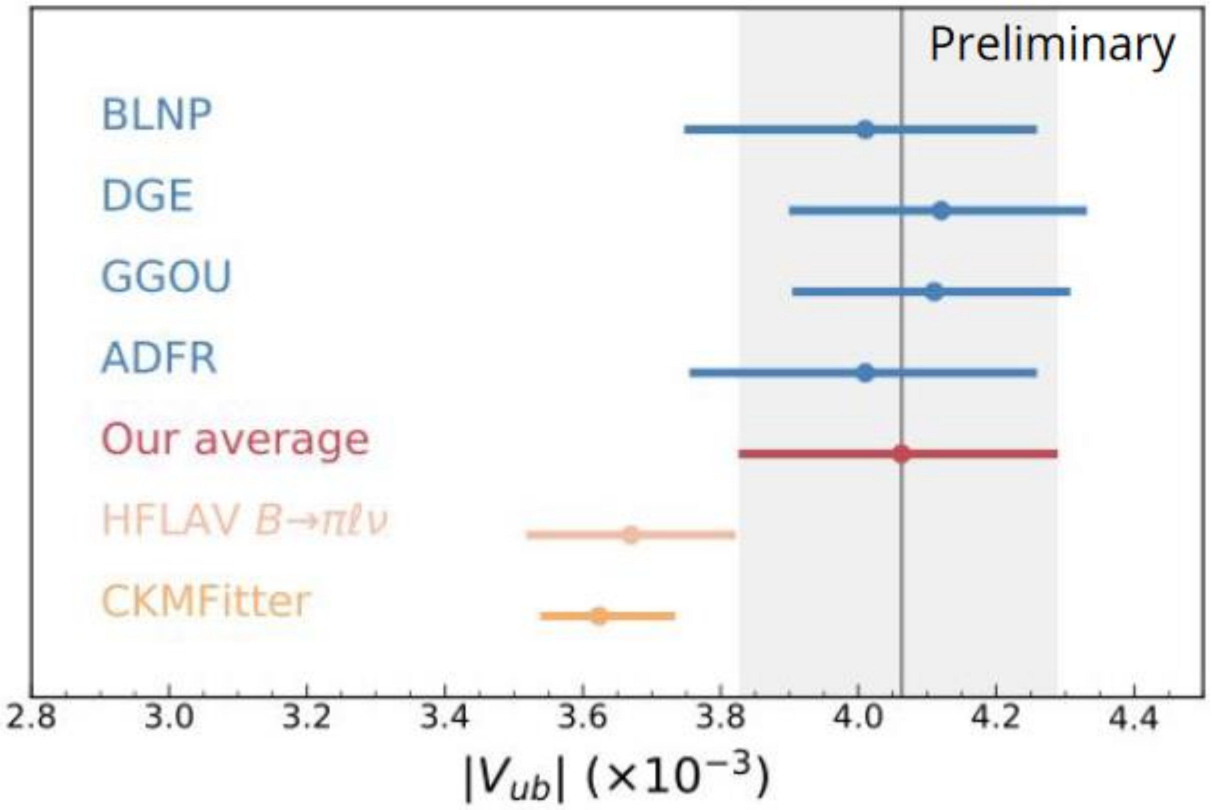
Preliminary

Fit	$\lvert V_{ub} \rvert$ (± 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)	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.19}$	$4.12^{+0.08,+0.16,+0.11}_{-0.09,-0.16,-0.12}$	$4.11^{+0.08,+0.16,+0.08}_{-0.09,-0.16,-0.09}$	$4.01^{+0.08,+0.15,+0.18}_{-0.08,-0.16,-0.18}$

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

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

Arithmetic average over results of the four theoretical calculations



$|V_{ub}|$ tension between excl. and incl. measurements is reduced to ca. 1.4σ

Lu Cao, ICHEP 2020

Belle II prospects

Observables	Expected exp. uncertainty	Facility (2025)
$\|V_{cb}\|$ incl.	1%	Belle II
$\|V_{cb}\|$ excl.	1.5%	Belle II
$\|V_{ub}\|$ incl.	3%	Belle II
$\|V_{ub}\|$ excl.	2%	Belle II/LHCb

Belle II physics book 1808.10567

In preparation for first precision measurements (see talk by T. Iijima)

- $B^0 \to D^{*+}\,\ell^-\,\nu$ & $B^- \to D^0\,\ell^-\,\nu$ (untagged, with 34.6 fb^{-1}) Belle II 2008.07198

$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = (4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_s})\,\%\,,$$

- Measurement of Hadronic Mass Moments in $B \to X_c \ell \nu$ Decays Belle II 2009.04493

- Untagged measurement of $B \to \pi\,\ell\,\nu$ Belle II ICHEP 2020

Conclusions

- ✓ $|V_{cb}|$ & $|V_{cb}|$ puzzles
  incl/excl getting closer; almost there

- ✓ Next decade: Belle II major player (& LHCb powerful ally)

- ✓ Refinements expected from theory

- ✓ Progress on lattice underway

- ✓ Exciting times ahead