Anomalies in semileptonic B decays

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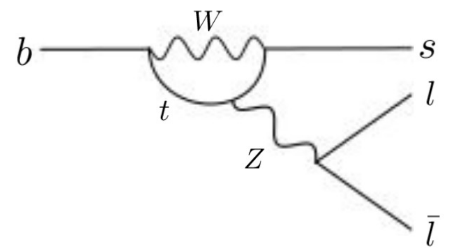
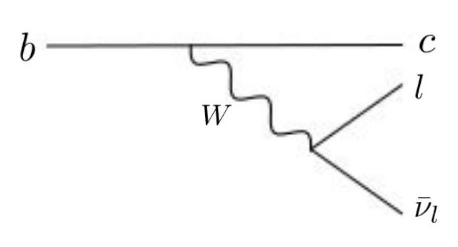
differences between data based results and SM predictions in observables:

$b \to s\, \ell^+ \ell^-$ driven (from 2013@LHCb)

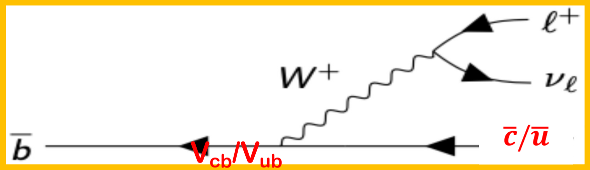


$b \to c\, \ell\, \nu$ driven (from 2012@Belle)



differences in:

$|V_{ub}/V_{cb}|$ exclusive/inclusive determinations (decades of CKM fits)



Analyses: Effective Field Theories, BSM Model building, data reinterpretation

Results: not (yet) conclusive

$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q\to X_s\mu^+\mu^-)}{dq^2}dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B_q\to X_s e^+e^-)}{dq^2}dq^2} = 1 \pm \mathcal{O}(1\,\%)^{1}$$

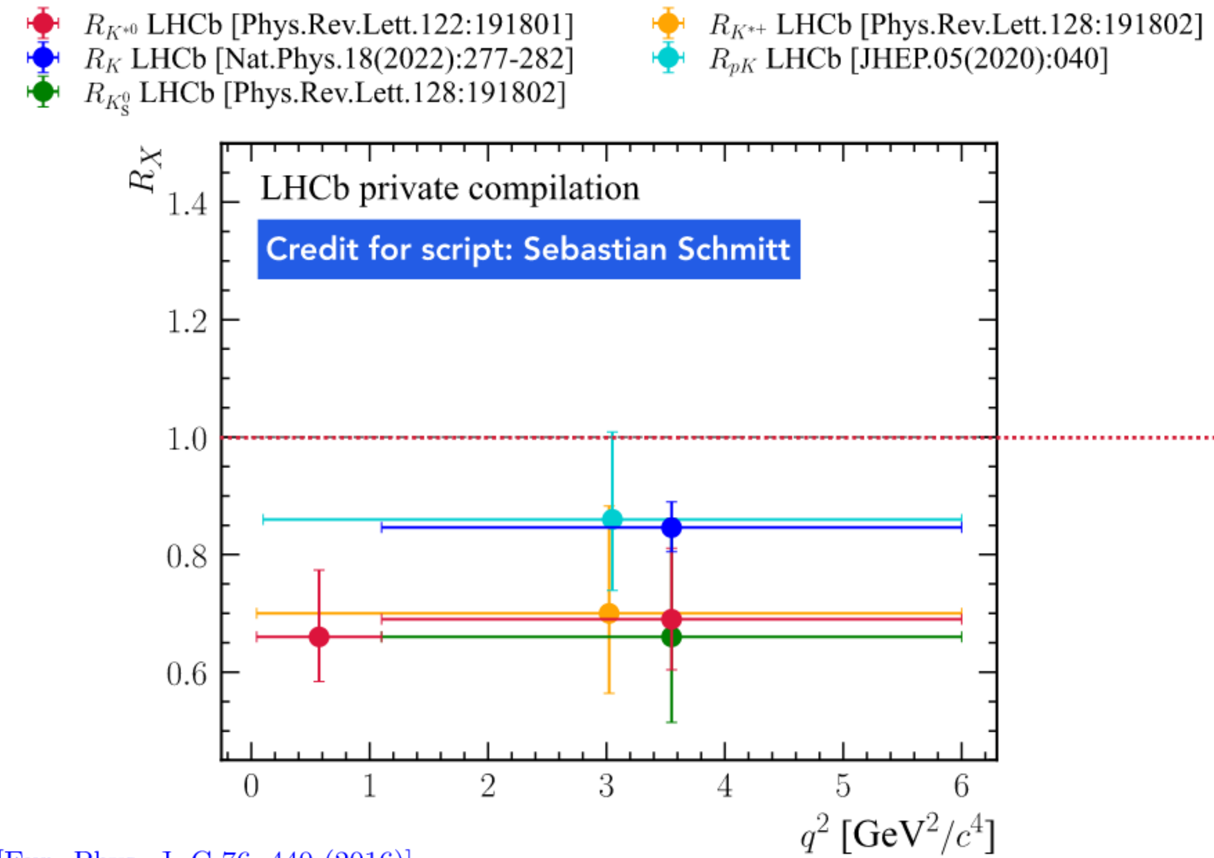
- testing LFU
  (FF large hadronic cancellation in SM)
- q^2 intervals to avoid resonances

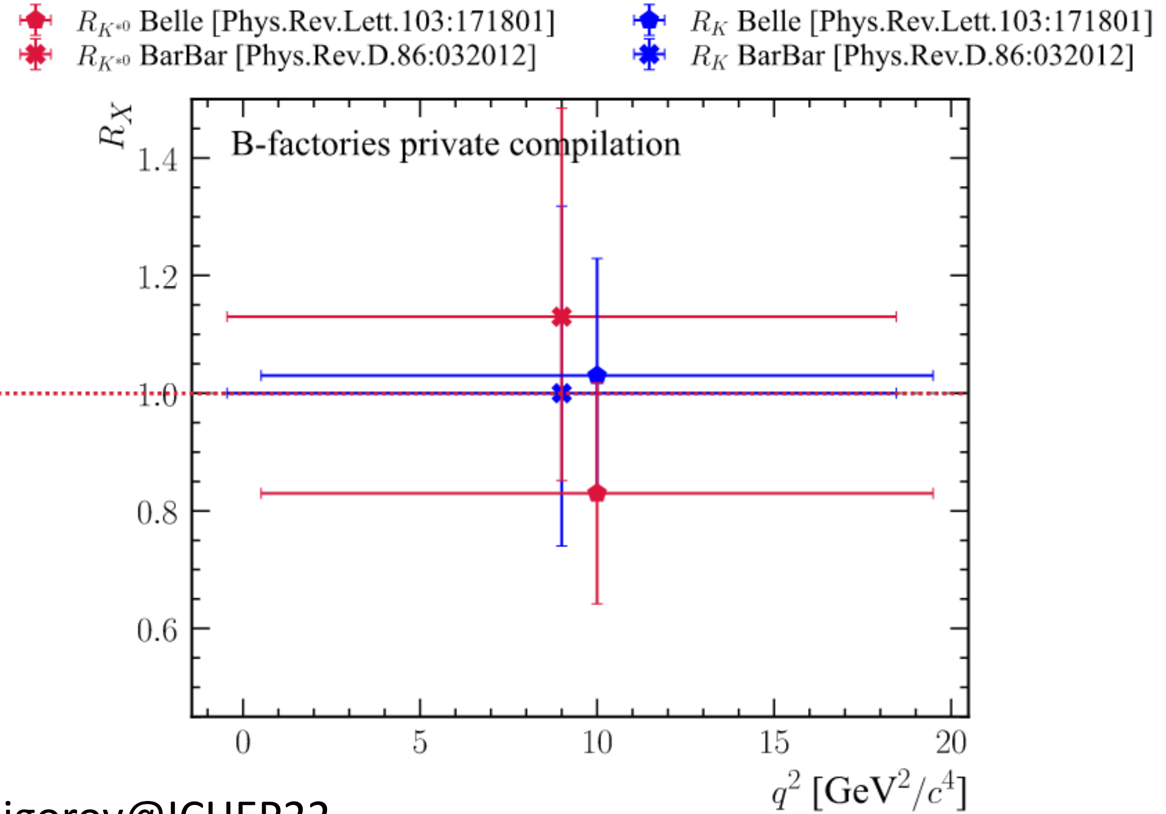
- $R_K = 0.846^{+0.042}_{-0.039}\,(\text{stat.})\,^{+0.013}_{-0.012}\,(\text{syst.})$, central
- Tension of $3.1\,\sigma$ with the SM

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.}), \text{low} \\ 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst.}), \text{central} \end{cases}$$

- Compatible with SM at 2.1 and $2.4\,\sigma$

"low"-q^2: $[0.045, 1.1]\,\text{GeV}^2/c^4$
"central"-q^2: $[1.1, \quad 6.0]\,\text{GeV}^2/c^4$





[1] [Eur. Phys. J. C 76, 440 (2016)]

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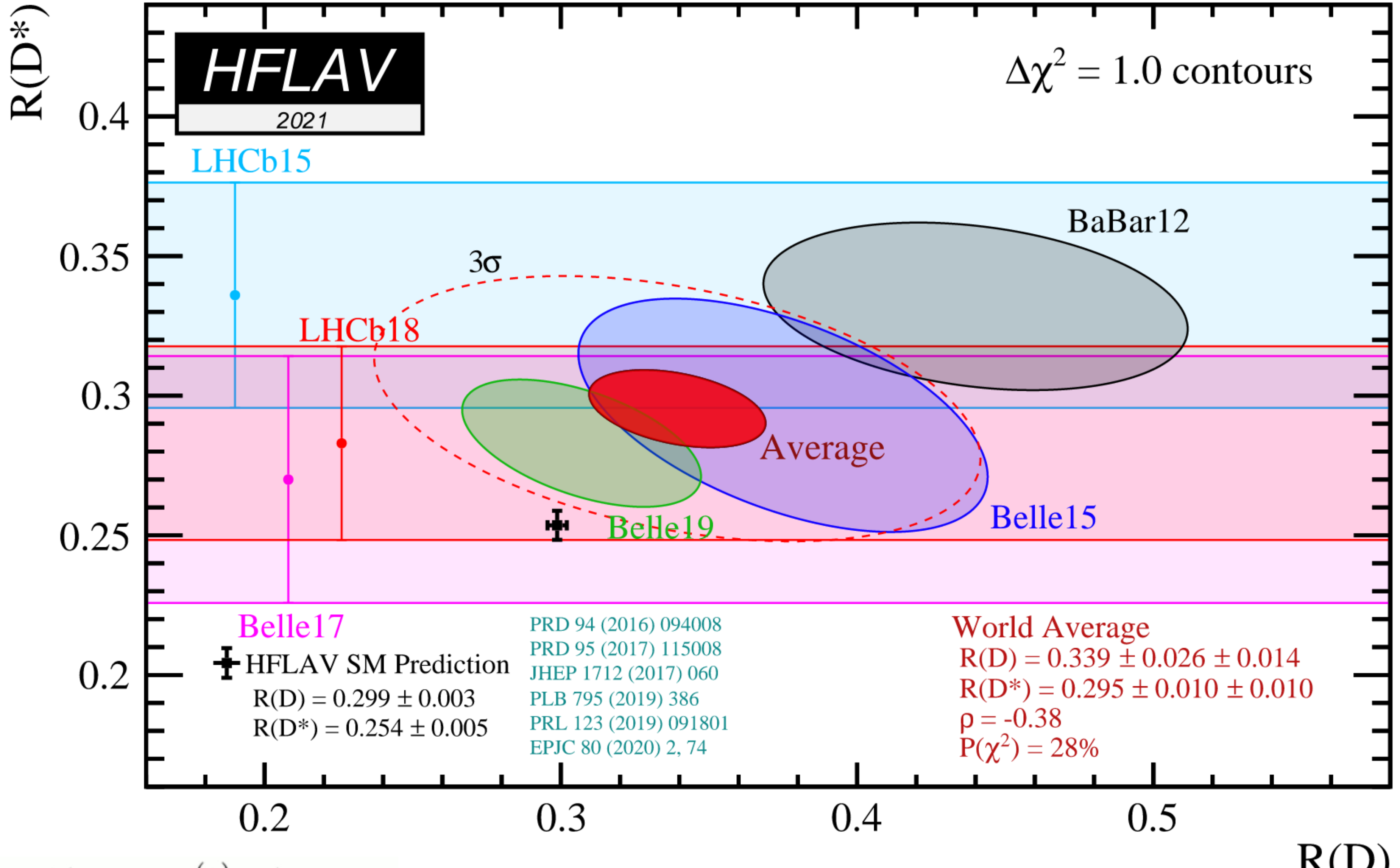


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)}$$

- R(D) and R(D^*) exceed the SM predictions by 1.4σ and 2.8σ respectively
- combined tension with SM is 3.3σ

[HFLAV, 2206.07501]

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst}).$$

LHCb *Phys.Rev.Lett.* 120 (2018) 12

$R(J/\psi)_{SM} = 0.2582 \pm 0.0038$

HPQCD Phys. Rev. Lett. 125, 222003 (2020)

2σ from SM central values

First LFU test in a baryonic $b \to c\ell\nu$ decay

$$R(\Lambda_c) = \frac{B(\Lambda_b \to \Lambda_c \tau^- \bar{\nu})}{B(\Lambda_b \to \Lambda_c \mu^- \bar{\nu})} = 0.242 \pm 0.026\,(\text{stat.}) \pm 0.040(\text{syst.}) \pm 0.059(\text{ext.BR.}meas.)$$

LHCb, *Phys.Rev.Lett.* 128 (2022) 19

$R(\Lambda_c)_{SM} = 0.33 \pm 0.01$

1σ from SM central values

Approximate sum rule

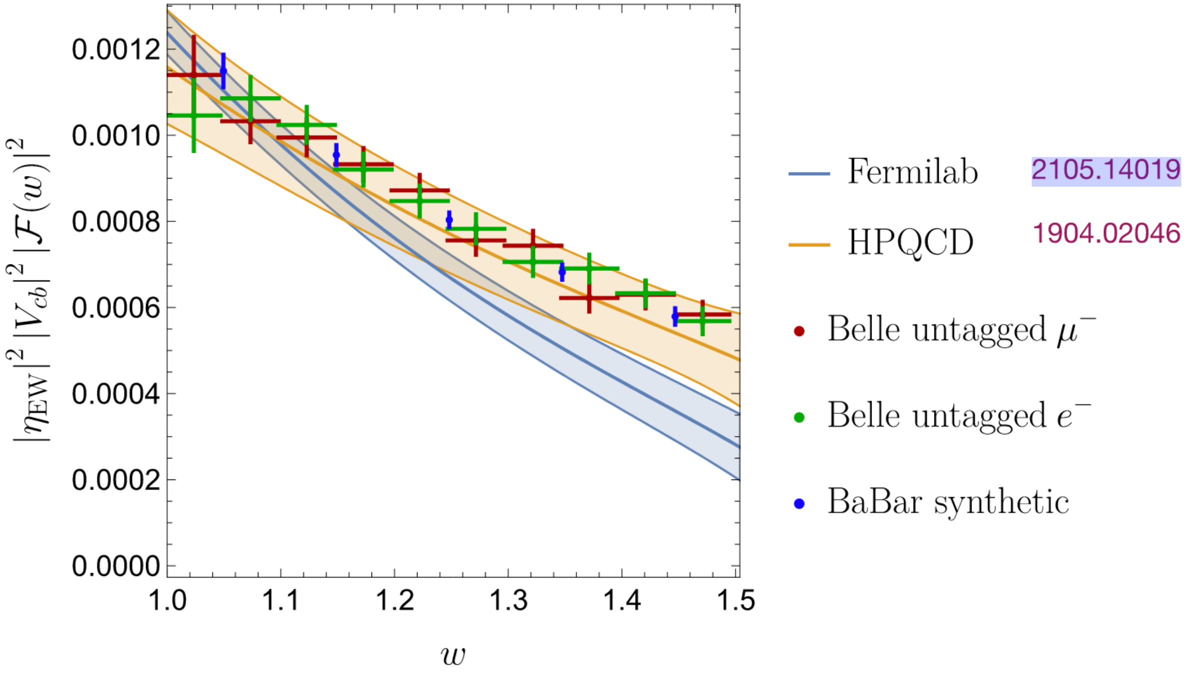
$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{SM}} \simeq 0.262 \frac{R(D)}{R(D)_{SM}} + 0.738 \frac{R(D^*)}{R(D^*)_{SM}} = 1.15 \pm 0.04$$

enhancement of $R(\Lambda_c)$ if the anomaly in $R(D^{(*)})$ holds true

Blanke et al. *Phys Rev D 99 (2019) 075006*

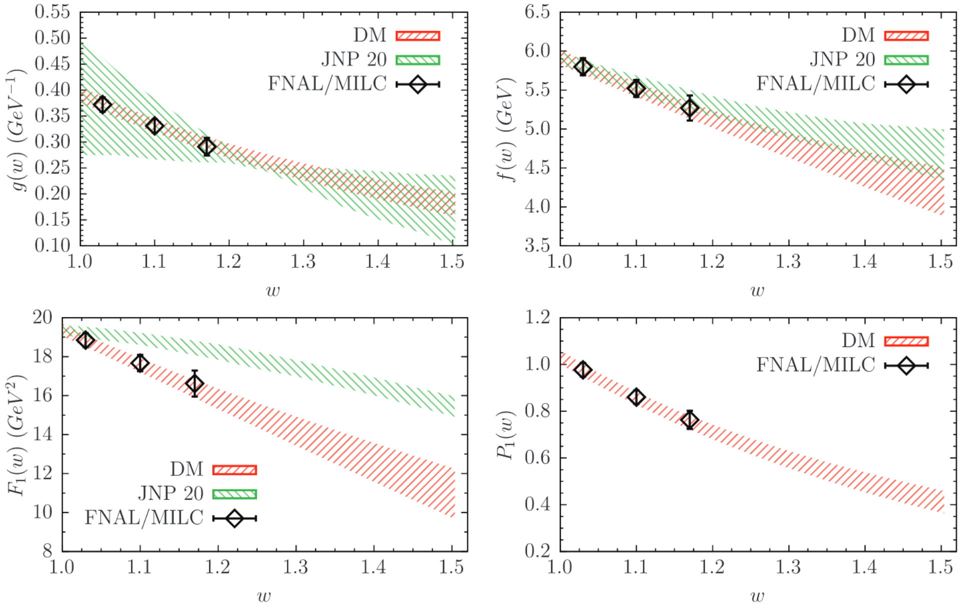
CAUTION

$$\frac{d\mathcal{B}(B\to D^*\ell\bar\nu)}{dq^2} = \frac{1}{2m_B m_{D^*}}\frac{d\mathcal{B}(B\to D^*\ell\bar\nu)}{dw} \propto |V_{cb}|^2 |\mathcal{F}(w)|^2$$



- Assuming with HPQCD that $\mathcal{F}(w)^{B_s\to D_s^*} = \mathcal{F}(w)^{B\to D^*}$

$$\frac{d\Gamma_\tau}{dw} = \frac{d\Gamma_{\tau,1}}{dw} + \frac{d\Gamma_{\tau,2}}{dw} \quad \begin{cases} \dfrac{d\Gamma_{\tau,1}}{dw} = \left(1-\dfrac{m_\tau^2}{q(w)^2}\right)^2\left(1+\dfrac{m_\tau^2}{2q(w)^2}\right)\times\dfrac{d\Gamma}{dw} \qquad [r = m_{D^*}/m_B] \\ \dfrac{d\Gamma}{dw} = \dfrac{\eta_{EW}^2 G_F^2 m_{D^*}^2 |V_{cb}|^2}{48\pi^3 m_B}\sqrt{w^2-1}\left[2\,q^2(w)\left(\boxed{f(w)}^2 + m_B^2 m_{D^*}^2\,(w^2-1)\boxed{g(w)}^2\right) + \boxed{\mathcal{F}_1(w)}^2\right] \\ \dfrac{d\Gamma_{\tau,2}}{dw} = \dfrac{\eta_{EW}^2|V_{cb}|^2 G_F^2 m_B^5}{32\pi^3}\dfrac{m_\tau^2(m_\tau^2-q(w)^2)^2 r^3(1+r)^2(w^2-1)^{3/2}\boxed{P_1(w)}^2}{q(w)^6} \end{cases}$$



JNP:Jaiswal et al. JHEP, 06 (2020) 165

DM: Dispersive Matrix method $\quad R(D^*) = 0.275 \pm 0.008$

1.3σ compatibility

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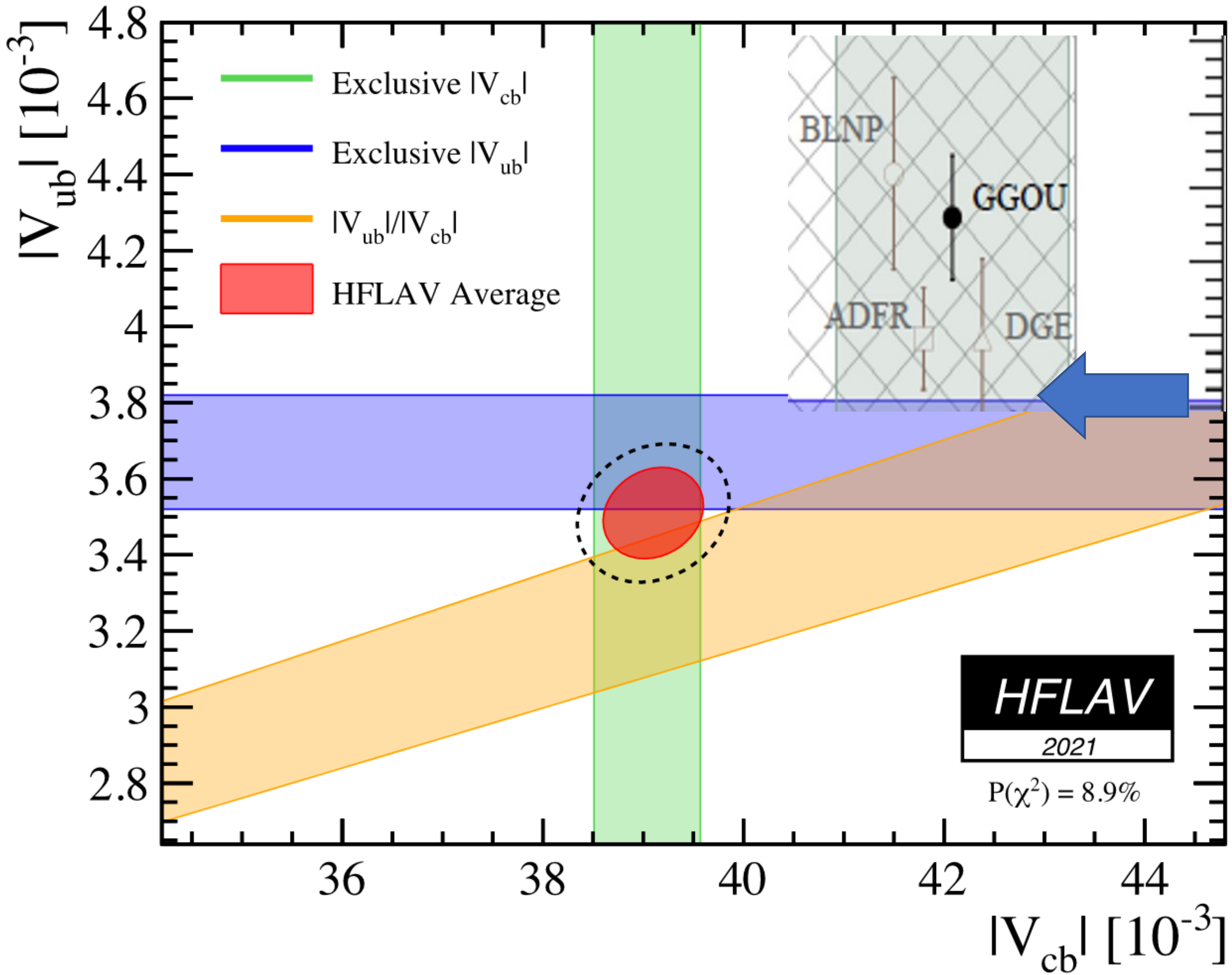


GR, M.Rotondo
J.Phys.G 47 (2020) 113001

$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03$$

Belle *Phys.Rev.D* 100 (2019) 5, 052007,

NP generally assumed in semitauonic B decays

Effective Hamiltonian for b → c τ ν

$$\boxed{H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_V^L) O_V^L + C_V^R O_V^R + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]}$$

O_V^R excluded by SMEFT match

Charged current process: simple (tree level) model interpretation

$$\boxed{\begin{aligned} O_S^R &= (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) \\ O_S^L &= (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) \end{aligned}}$$

$$\boxed{\begin{aligned} O_V^L &= (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma_\mu P_L \nu_\tau) \\ O_T &= (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau) \end{aligned}}$$

GLOBAL FITS

Aebischer et al. 2020, Blanke et al. 2019, Murgui et al. 2019,Shi et al 2019,…

$\boxed{C_S^{L,R} \neq 0}$ charged Higgs

$\boxed{C_V^L \neq 0}$ charged vector boson W ′

$\boxed{C_S^L = 4C_T \neq 0}$ $\boxed{C_V^L, C_S^L = -4C_T}$ $\boxed{C_V^L, C_S^R \neq 0}$ (scalar or vector) leptoquark

new charged states with masses at or below the TeV and with significant couplings to the third generation SM fermions → potential targets for direct searches at the LHC

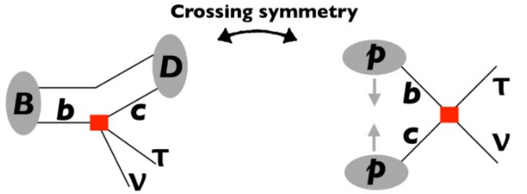
Charged W ′ bosons:

simplified models (spin-1 colorless weak triplet, a 2HDM, a spin-0 leptoquark,…) in tension with existing τ +τ − LHC results.
Not applies to the low mass region in the W ′ and vector leptoquark models

Faroughy et al.2016

Charged Higgs boson $H^{\pm}$:

tension with the LHC mono-τ data



large BR(Bc → τ ν) > 50% induced
no direct experimental bound but upper limits of 30%, and even 10%
But as large as 60% not excluded

Greljo et al. 2019

Alonso 2019, Akeroydet 2017, Blanke. 2019, Aebischer 2021,…

Leptoquarks:

Generally evade the mono-τ test (can induce CP-violating couplings)
LHC constraints from their pair-production and t-channel mediated dilepton processes
LHC searches for colour-octet resonances, often introduced together in UV-complete models

Angelescu 2018, Babu e2021, Buttazzo 2017, Diaz 2017, Baker 2019,…

Warning: more severe constraints in concrete UV completions
e.g.. including light RH neutrinos

Iguro 2017, Greljo 2018, Robinson 2019, Azatov 2018, Mandal 2020,…

$b \to s\,\ell^+\ell^-$ effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

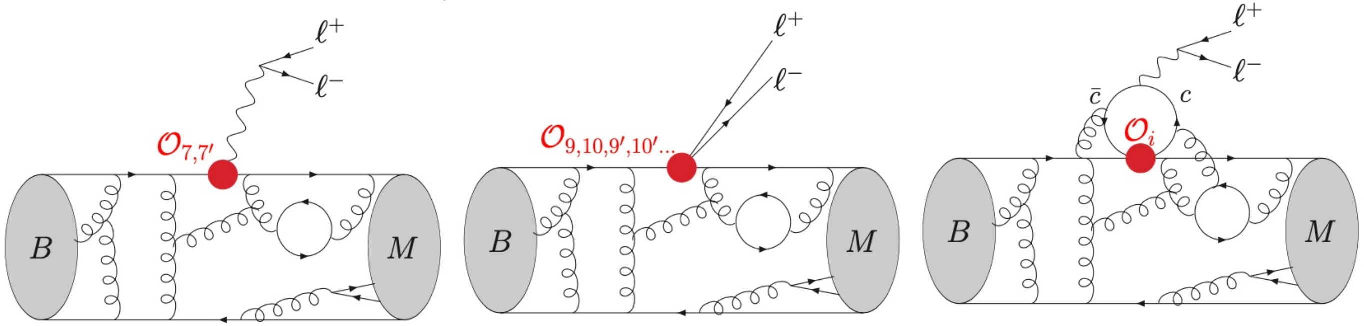
$$\ell = \mu,\ e$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{9'\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \qquad \mathcal{O}_{10'\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

Two sources of hadronic uncertainties for exclusive



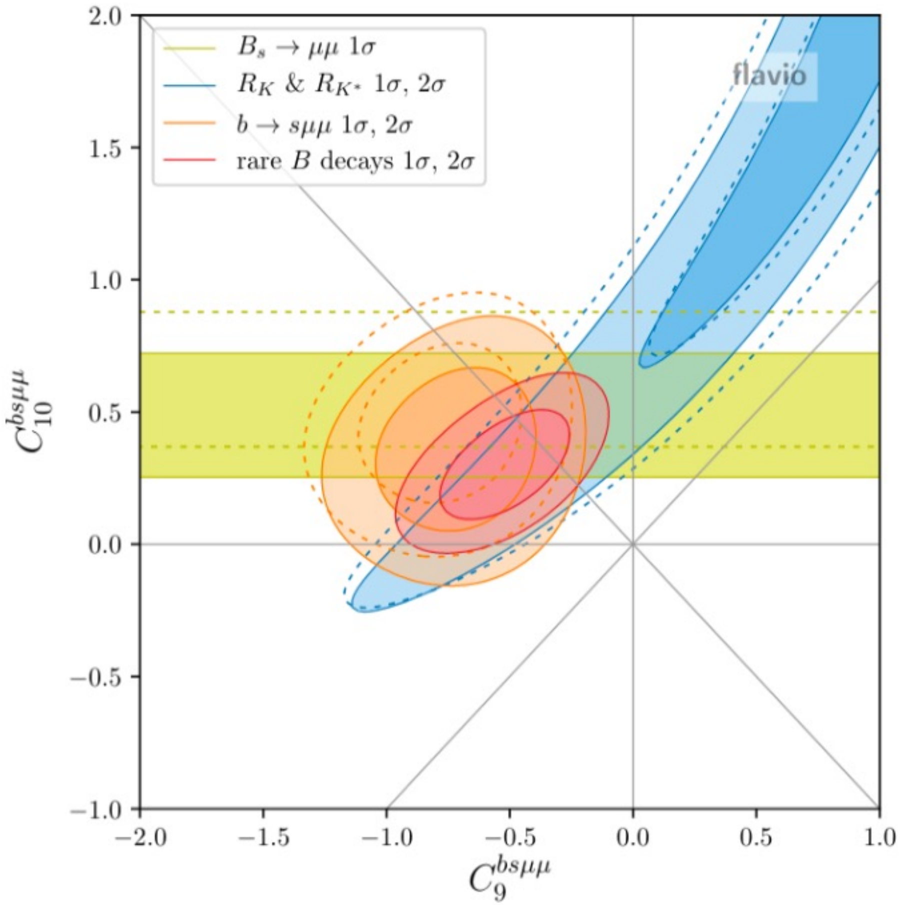
Form factors (local) Charm loop (non-local)

Global fits
- Fully Data Driven: no assumption about charming penguins
- Partly or fully Model Dependent: assume LCSR result for charming penguins

Global fits: general agreement

$\delta C_9 \neq 0$, and $\delta C_9 = -\delta C_{10} < 0$ in particular

$C_9^{bs\mu\mu} \simeq -0.73 \qquad C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} \simeq -0.39.$

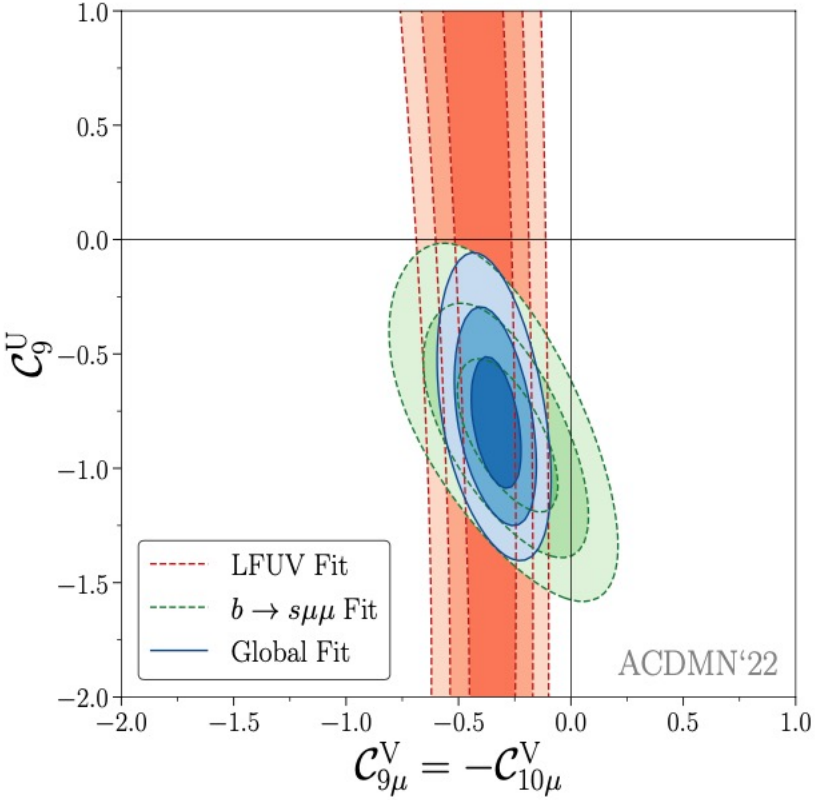


Combination of LFU ratios, combination of b → sμμ observables, BR(Bs → μ+μ−), and the global fit.

Altmannshofer et al. 21

Allowing for the presence of lepton flavour universal NP in addition to LFUV contributions to muons only.

$$\begin{aligned} C_{ie}^{\rm NP} &= C_i^{\rm U} \\ C_{i\mu}^{\rm NP} &= C_{i\mu}^{\rm V} + C_i^{\rm U} \end{aligned}$$

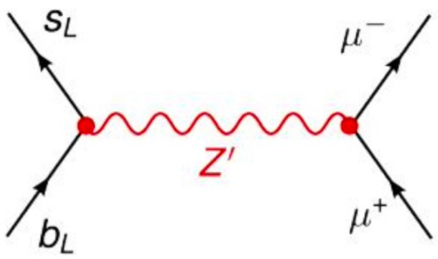


Mainstream models:

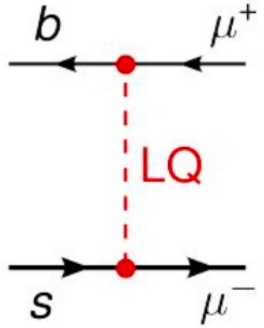
- loop-induced NP

- tree-level NP contributions

Z' gauge bosons
changing coupling to LH quarks
VL couplings to leptons
FV or FNU in lepton sector



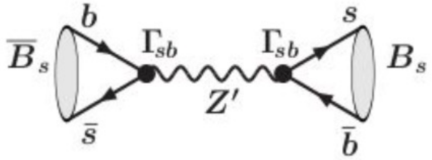
Leptoquarks
scalar or vectors



❑ $\Lambda_{NP} \sim$ 40 TeV no direct production of new particles at the (HL-)LHC
Limited reach for searches for deviations from the SM in high-p_T di-muon tails

greljo 2017

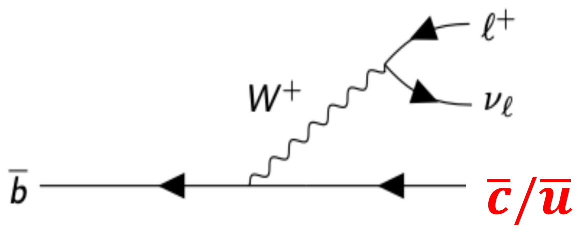
❑ bsZ' coupling stringently constrained by B_s–$\bar{B}_s$ mixing data



❑ vector leptoquark. Solution to b-> c and b-> s anomalies
[cons UV completion, possible large number of parameters and assumptions]

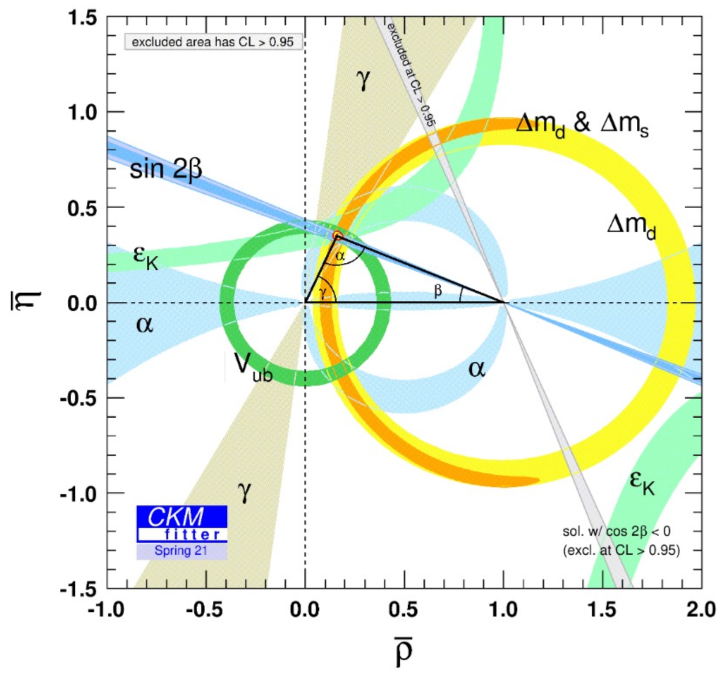
Cornella 21

$|V_{xb}|$ puzzle



V_{cb}/V_{ub}

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



Exclusive/Inclusive determinations: different techniques:
check of our theoretical tools for QCD

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

Long standing excl/incl tension in $|V_{xb}|$

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

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

- $c_d(d = 3, 5, \dots)$ calculable in perturbation theory as a series in α_s
- Non perturbative matrix elements of local operators expressed in terms of HQE parameters
  - High order parameters proliferation from $\frac{1}{m_b^4}$
- First steps toward transition rates from lattice

S. Hashimoto, 2017 Gambino Hashimoto 2020

Exclusive decays $b \to c\,\ell\,\nu$

- ✓ Systematic approach using dispersion relation & unitarity bounds with different extrapolations (BGL, CLN, BCL) to zero recoil

- ✓ Fit: lattice calculation at non zero recoil & different data
  The role of parameterization becomes less relevant: extrapolation reduces to interpolation among exp results **and th points**

$$
|V_{cb}|^{\text{excl.}} = \begin{cases}
(38.40 \pm 0.74)\cdot 10^{-3} & \text{FNAL/MILC, BaBar, Belle} & B \to D^*\ell\nu\,, \\
(40.3 \pm 0.8)\cdot 10^{-3} & \text{LCSR2 and lattice, BaBar, Belle} & B \to D^{(*)}\ell\nu \\
(40.3 \pm 1.7)\cdot 10^{-3} & \text{LCSR1, BaBar} & B \to D\ell\nu\,, \\
(41.0 \pm 1.3)\cdot 10^{-3} & \text{LCSR1, Belle} & B \to D\ell\nu\,, \\
(41.0 \pm 1.2)\cdot 10^{-3} & \text{lattice + unitarity, Belle} & B \to D\ell\nu\,, \\
(42.2 \pm 2.3)\cdot 10^{-3} & \text{HPQCD, LHCb} & B_s \to D_s^*\ell\nu
\end{cases}
$$

$$|V_{cb}| \times 10^3 = 39.36(68)$$

FLAG Review 2021 [arXiv:2111.09849]

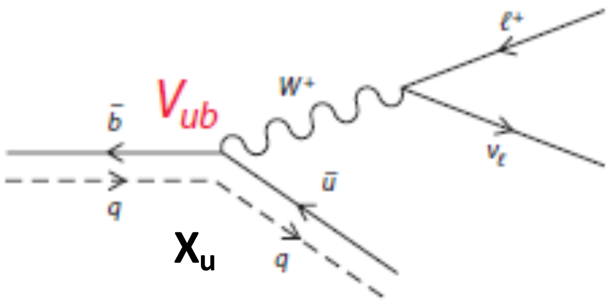
INCLUSIVE:

$$|V_{cb}| \times 10^3 = 42.16(50)$$

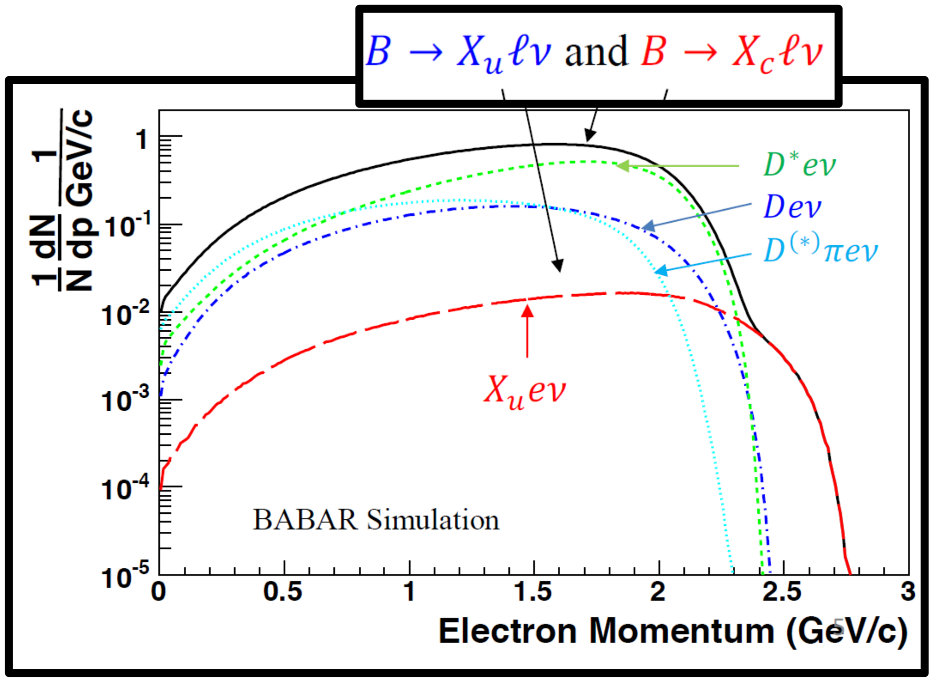
Bordone et al., Phys.Lett.B [2107.00604]

~ 2.7σ difference excl./incl.

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)

Fit kinematic distributions and measure partial BF

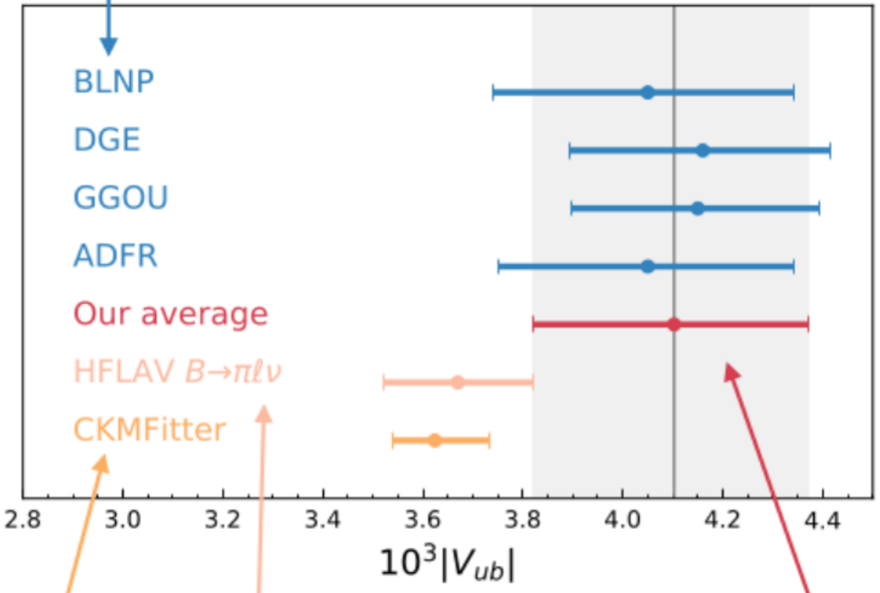
3 phase-space regions

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

Phase-space region
$M_X < 1.7\,\mathrm{GeV}$
$M_X < 1.7\,\mathrm{GeV},\ q^2 > 8\,\mathrm{GeV}^2$
$E_\ell^B > 1\,\mathrm{GeV}$

4 predictions of the partial rate

Result for most inclusive region with $E_\ell^B > 1\,\mathrm{GeV}$



Exclusive Average for $B \to \pi\ell\bar{\nu}_\ell$:
$|V_{ub}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$

CKM Unitarity:
$|V_{ub}| = \left(3.62^{+0.11}_{-0.08}\right) \times 10^{-3}$

Arithmetic average:
$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$

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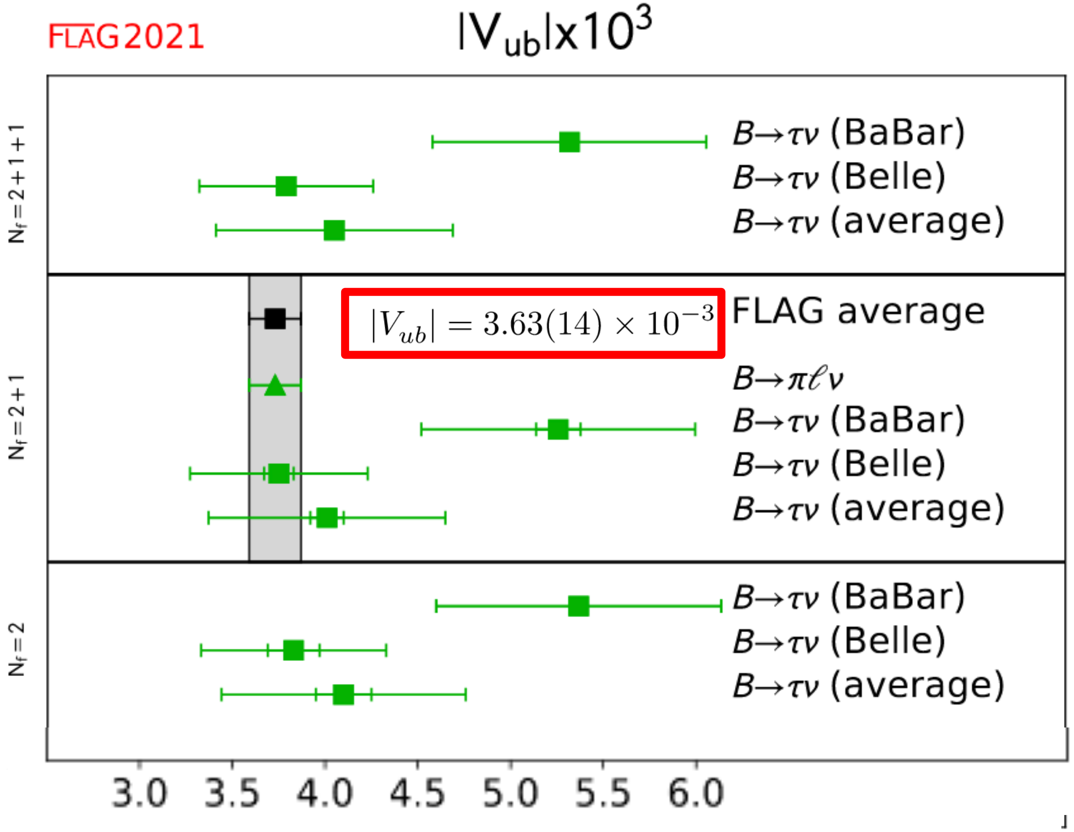
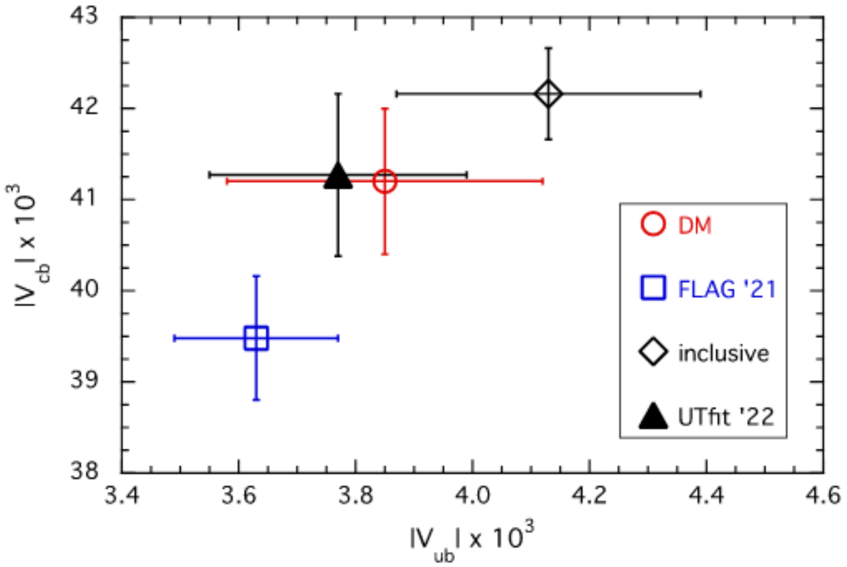
$|V_{ub}|$ exclusive determination

LCSR	
Duplancic et al.	$3.5 \pm 0.4 \pm 0.2 \pm 0.1$
Imsong et al.	$3.32^{+0.26}_{-0.22}$
Leljak et al.	$3.28^{+0.33}_{-0.28}$

LCSR + LQCD	
HFLAV	$3.67 \pm 0.09_{stat} \pm 0.12_{syst}$
Leljak et al.	3.77 ± 0.15





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COMPARE WITH INCL

$$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$$

Belle@ICHEP 2022

Down to about 3 to 1-2σ difference

Conclusions

- ✓ LFNU: progress in lattice and global fits
  - ✓ Patterns emerge in EFT but no definite BSM yet
  - ✓ Surviving exp scrutiny, but no measurement alone claim discovery

- ✓ $|V_{cb}|$ & $|V_{ub}|$ puzzles incl/excl getting closer

  $|V_{ub}|$ most recent Belle result reduce tension, increase uncertainty

- ✓ Prospects:

  LHCb focused on completing a combined analysis of $R(K^*)$ & $R(K)$ with the Run 1+2 dataset

  Belle II results for $R(K^*)$, $|V_{cb}|$ & $|V_{ub}|$ expected, (looking forward to inclusive ratios $R(X_{\{\frac{\tau}{\ell}\}})$)