XVth Quark Confinement and the Hadron Spectrum Conference

2022 - University of Stavanger

TENSIONS IN THE HEAVY SECTOR

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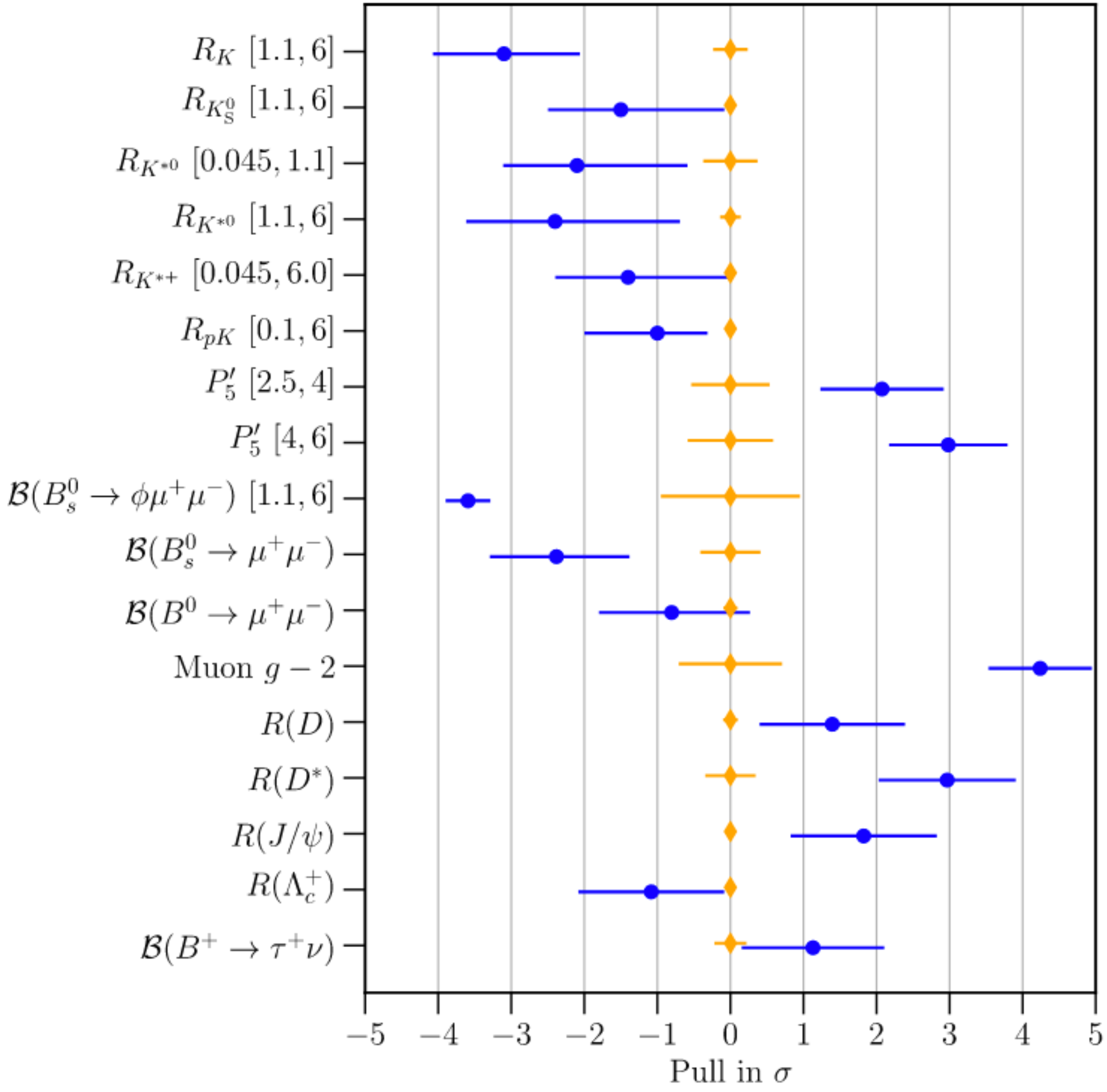
Aug 2nd, 2022



Selection of flavor anomalies shown as pulls of (blue points) experiment versus (orange diamonds) theory expectation.

For each measurement the quadratic sum of the experimental and heory uncertainties is normalised to unity and the deviation of the experimental value is displayed in this unit.

D. Guadagnoli, P. Koppenburg, arXive 2207.01851

ASSIGNMENT

Explain differences between observables and SM predictions in the heavy flavour sector

Observables in $b \to s\, \ell^+\ell^-$ driven decays (from 2013 at LHCb)

Observables in $b \to c\, \ell\nu$ driven decays (from 2012 at Belle)

V_{ub}/V_{cb} exclusive/inclusive puzzle (decades of CKM fits)

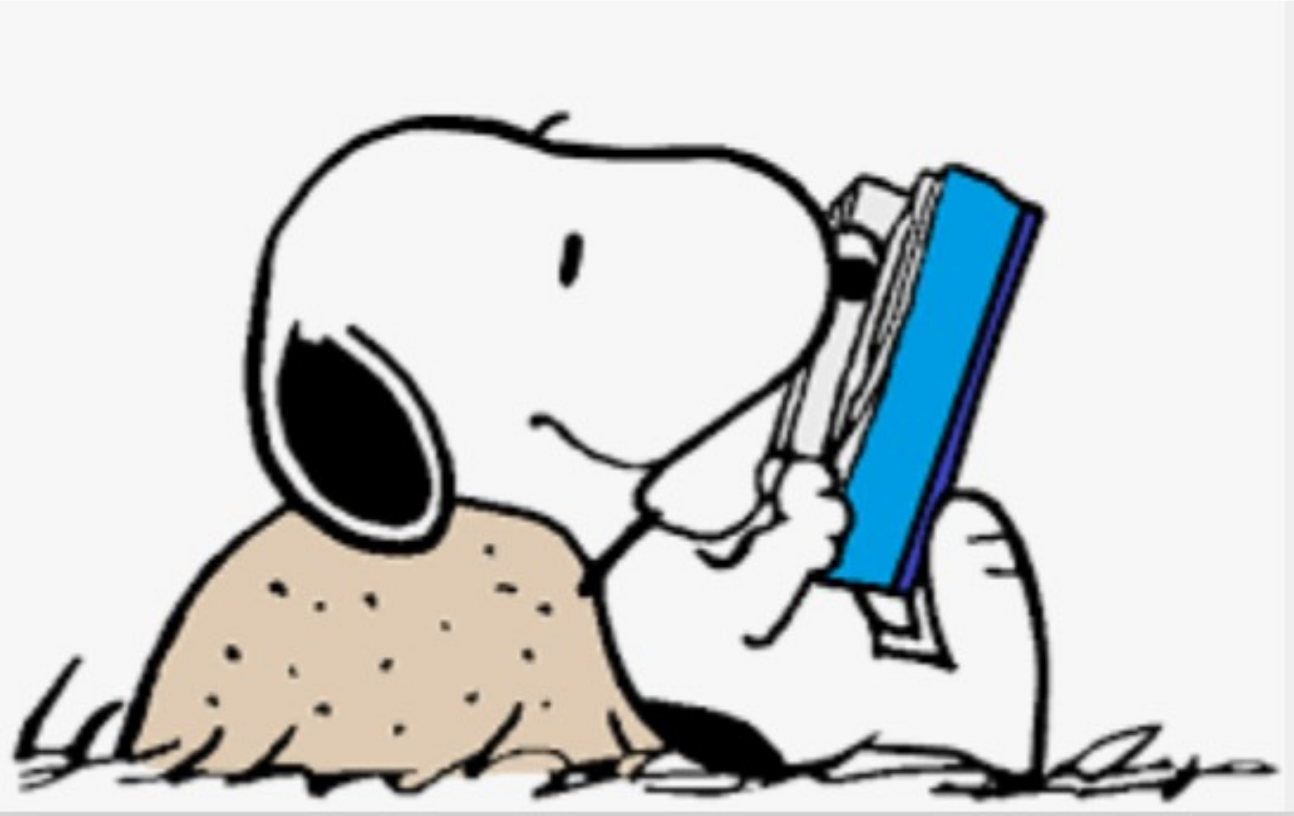
EXECUTION

Effective Field Theories and/or Model building

RESULTS

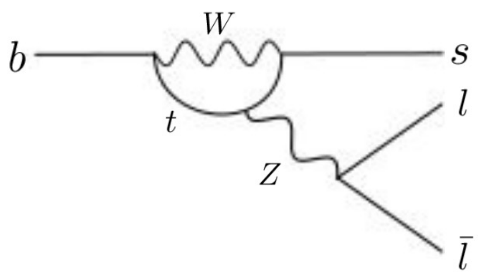
Not (yet) conclusive

Reading the assignment: Experimental situation



Semileptonic B decays

$b \to s$ anomalies



1 loop (and CKM suppressed) in the SM   BR $\sim \mathcal{O}(10^{-6})$ or lower

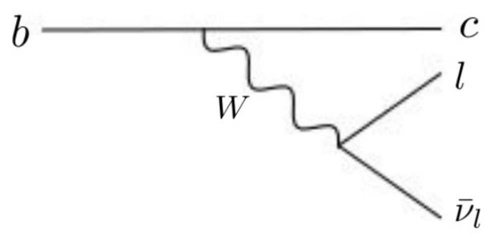
Neutral current

Discrepancy in

- R(K) and R(K*), R(ϕ) testing LFU
  (FF large hadronic cancellation in SM)
- observables related to $b \to s\,\mu^+\mu^-$
  - Branching ratios
  - angular observable
    - Optimized (as P_5') and not

Expected heavy NP $\sim 4\; 10^{-5}\, G_F \to \dfrac{1}{(40\;Tev)^2}$

$b \to c$ anomalies



Tree level in the SM. Br a few %

Charged current

Discrepancy in

- R(D) R(D*) R(J/Ψ) testing LFU
  (FF large hadronic cancellation in SM)

Expected light NP$\sim$ $10^{-2}\, G_F \to \dfrac{1}{(few\;Tev)^2}$

Lepton Flavour Universality violation (LFUV)

$$R_X \equiv \frac{BR(B \to Xll/l\nu)}{BR(B \to Xl'l'/l'\nu')}$$

CKM factors and hadronic (in SM) cancellations

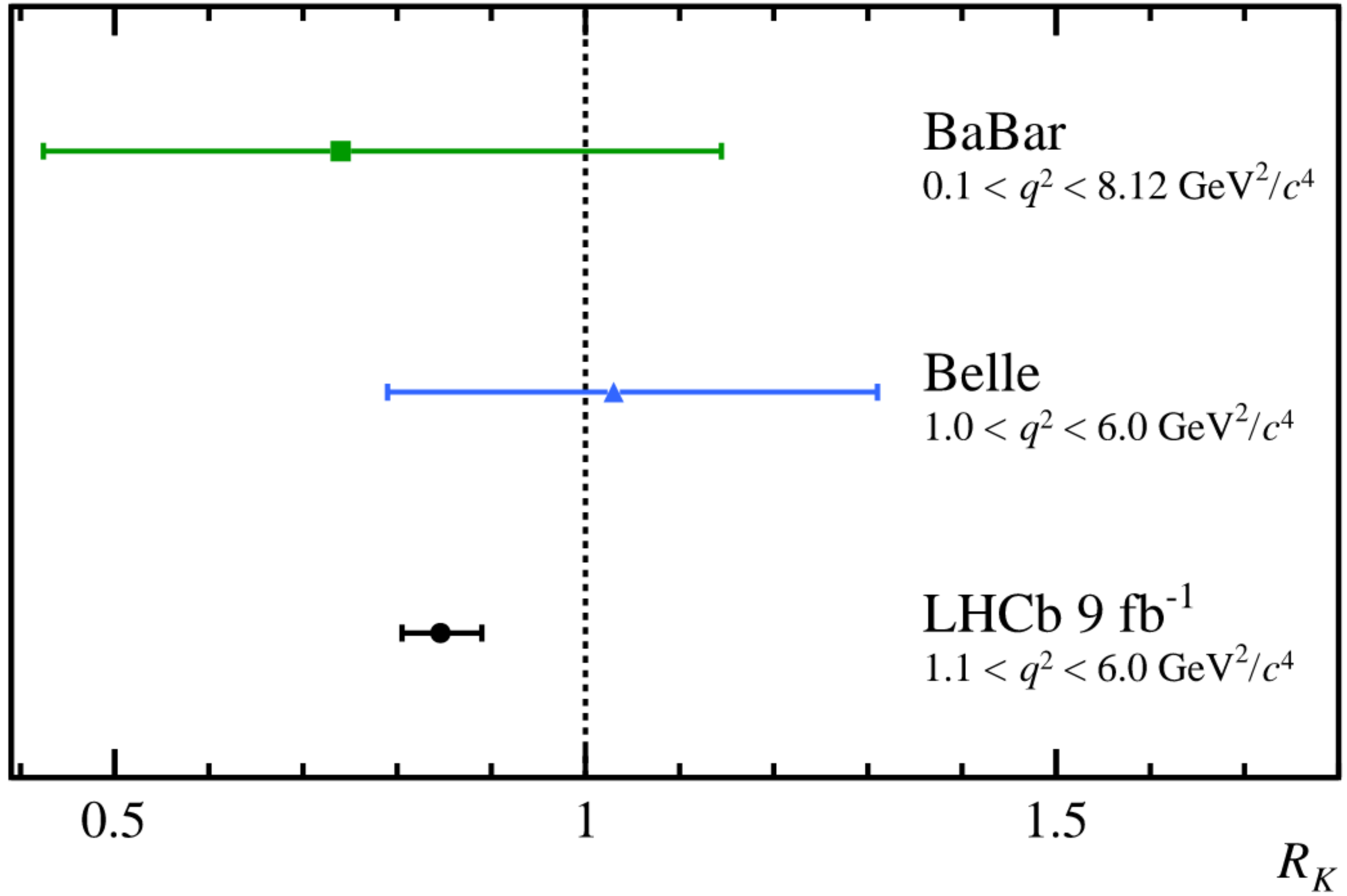
$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]}$$

$q^2 \in [1, 6]\,\mathrm{GeV}^2$ to stay away from $\bar{c}c$ resonances

$$R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

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

$$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$



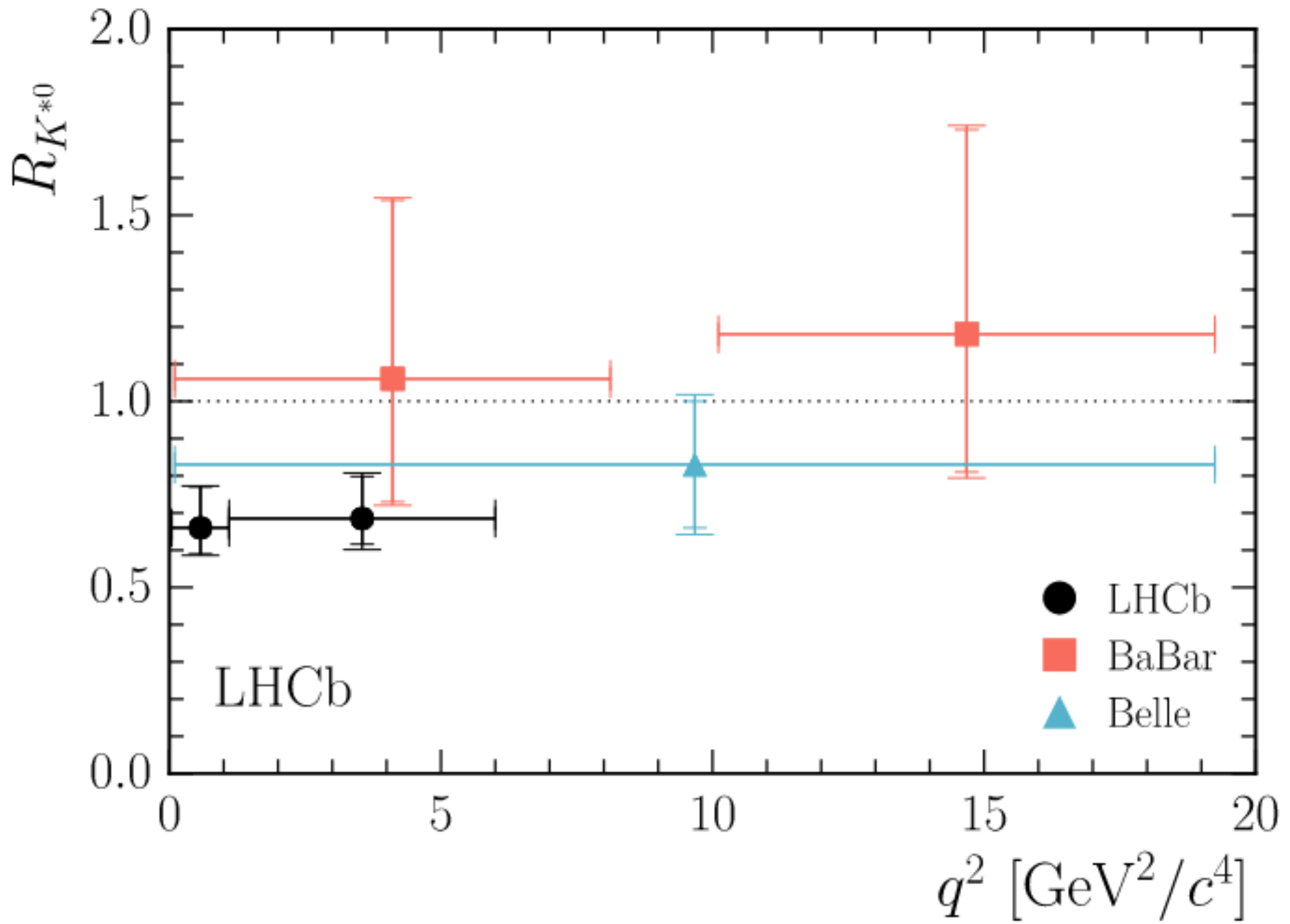
Phys. Rev. **D86** (2012) 032012.

JHEP **03** (2021) 105,

Nature Phys. 18 (2022) 3

$$R_K^{[1.1,6]} = 0.847(42)^{\text{LHCb}} \quad \text{vs} \quad R_K^{[1,6]} = 1.00(1)^{\text{SM}}$$

3.1 σ



JHEP 08 (2017) 055

Phys. Rev. **D86** (2012) 032012;

Phys. Rev. Lett. **103** (2009)

LHCB

$$R_{K^{*0}} = \begin{cases} 0.66\ ^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.69\ ^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$

SM compatible
2.1-2.3 σ
2.4-2.5 σ
depending on the th prediction

LFU test in $b \to s\ell\ell$ decays

Deviation O(20%) on SM **loop-order** processes

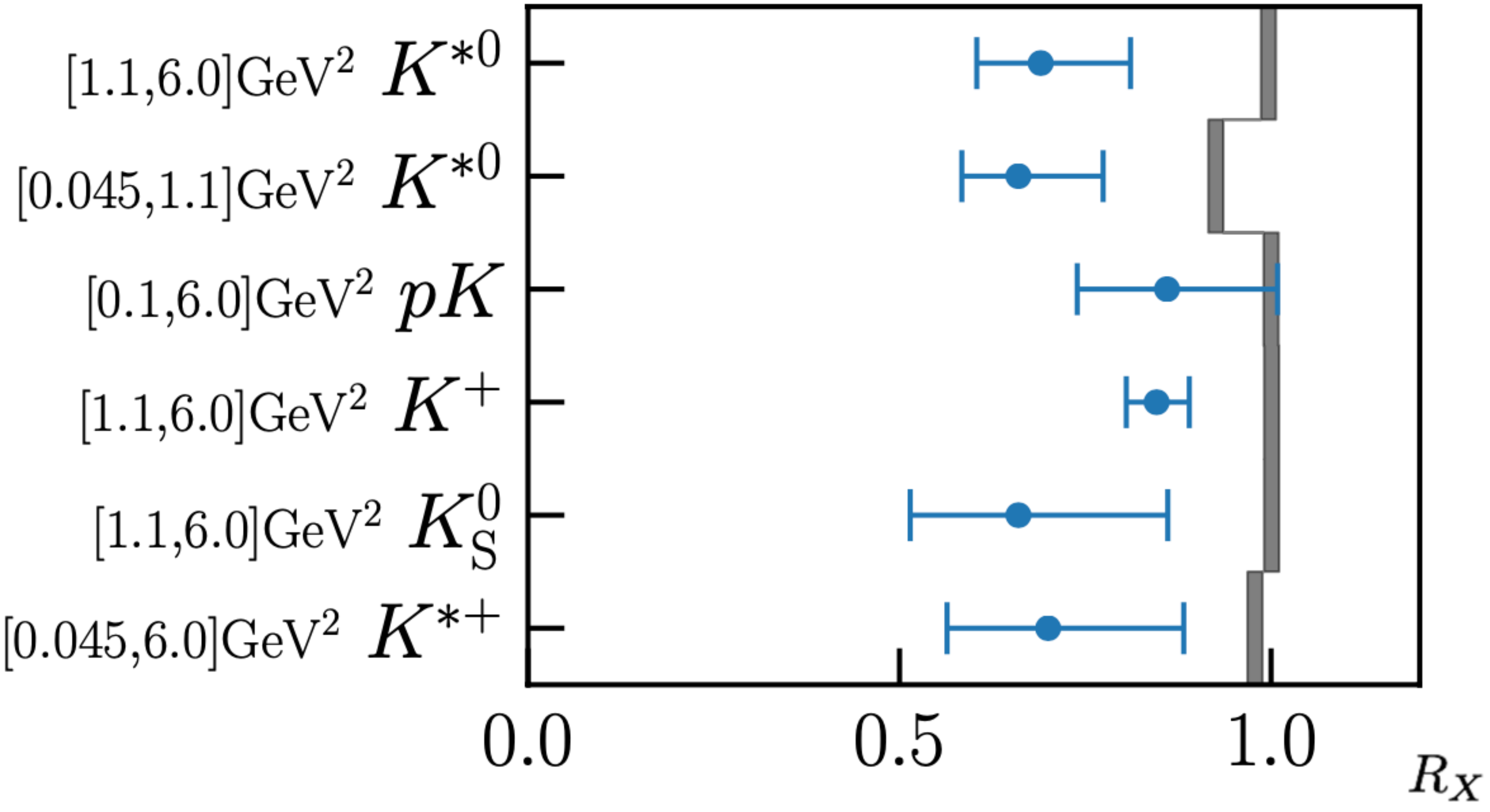
$B^0 \to K^{*0}\ell\ell$

$\Lambda_b \to pK\ell\ell$

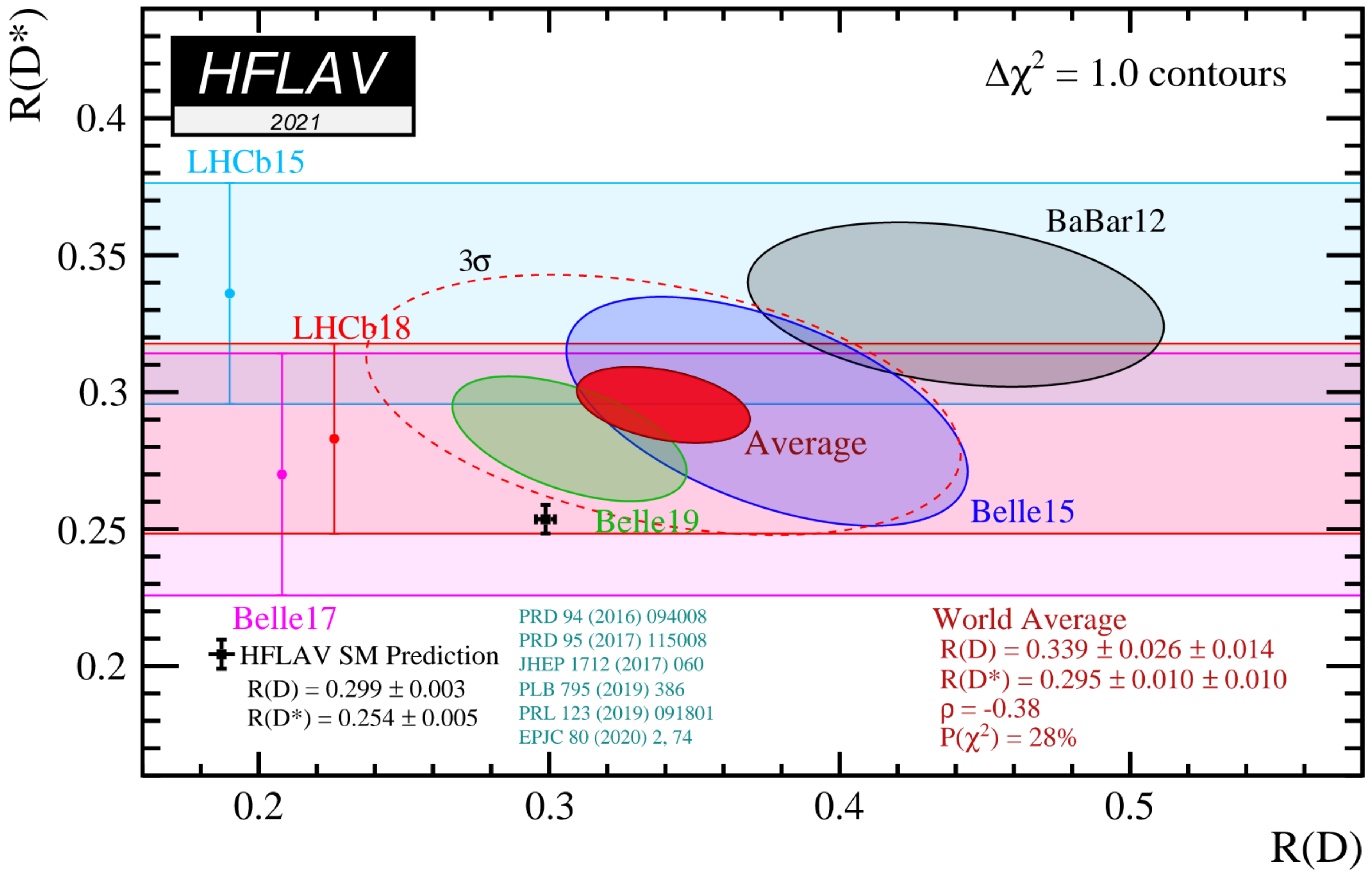
$B^+ \to K^+\ell\ell$

$B^0 \to K^0_S\ell\ell$

$B^+ \to K^{*+}\ell\ell$



Mauri LHCb

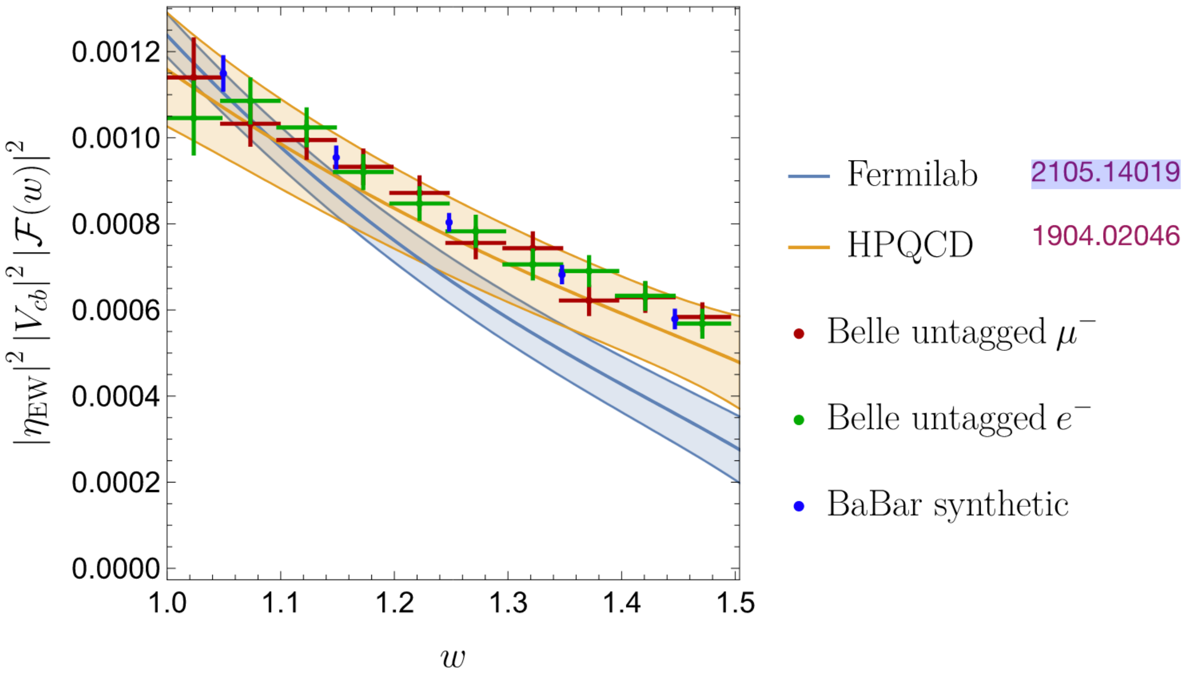


R(D) and R(D^*) exceed the SM predictions by 1.4σ and 2.8σ respectively

combined tension with SM is 3.3σ [HFLAV, 2206.07501]

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 $\mathcal{F}(w)^{B_s\to D_s^*} = \mathcal{F}(w)^{B\to D^*}$

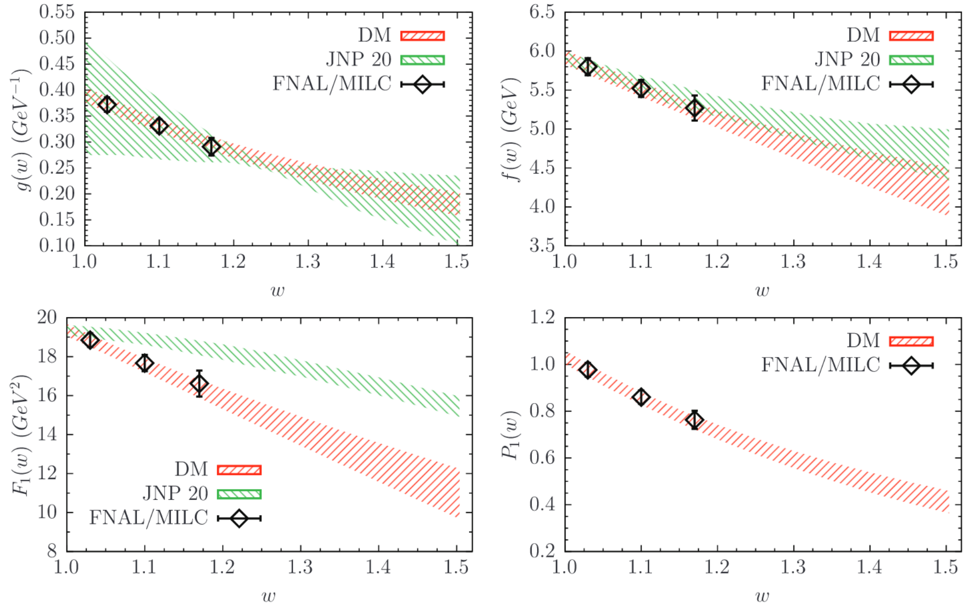
Bečirević Moriond 22

$$\frac{d\Gamma_\tau}{dw} = \frac{d\Gamma_{\tau,1}}{dw} + \frac{d\Gamma_{\tau,2}}{dw}$$

$$\frac{d\Gamma_{\tau,1}}{dw} = \left(1-\frac{m_\tau^2}{q(w)^2}\right)^2\left(1+\frac{m_\tau^2}{2q(w)^2}\right)\times\frac{d\Gamma}{dw} \qquad [r = m_{D^*}/m_B]$$

$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2 m_{D^*}^2 |V_{cb}|^2}{48\pi^3 m_B}\sqrt{w^2-1}\,[2q^2(w)\,(f(w)^2 + m_B^2 m_{D^*}^2\,(w^2-1)\,g(w)^2) + \mathcal{F}_1(w)^2]$$

$$\frac{d\Gamma_{\tau,2}}{dw} = \frac{\eta_{EW}^2|V_{cb}|^2 G_F^2 m_B^5}{32\pi^3}\,\frac{m_\tau^2(m_\tau^2-q(w)^2)^2 r^3(1+r)^2(w^2-1)^{3/2}P_1(w)^2}{q(w)^6}$$



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

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

1.3σ compatibility

LHCB

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

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

2.1σ from SM central values ~ 0.25. LQCD $R(J/\Psi) = 0.2582 \pm 0.0038$

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

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

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

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

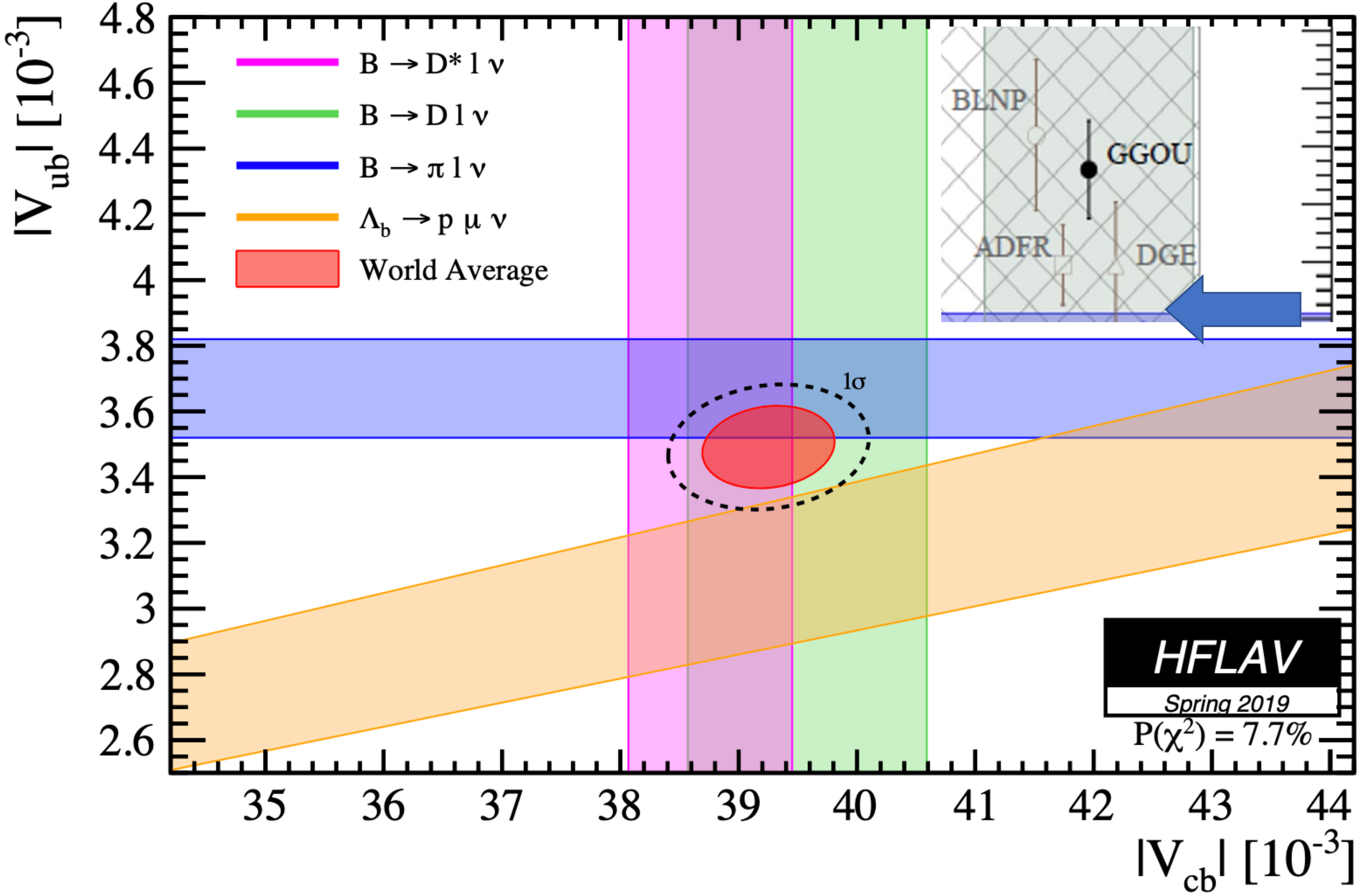
1σ from SM central values (agreement)

Approximate sum rule

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

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

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



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

interpretation

EFFECTIVE FIELD THEORY:

BSM at a higher kinematic range

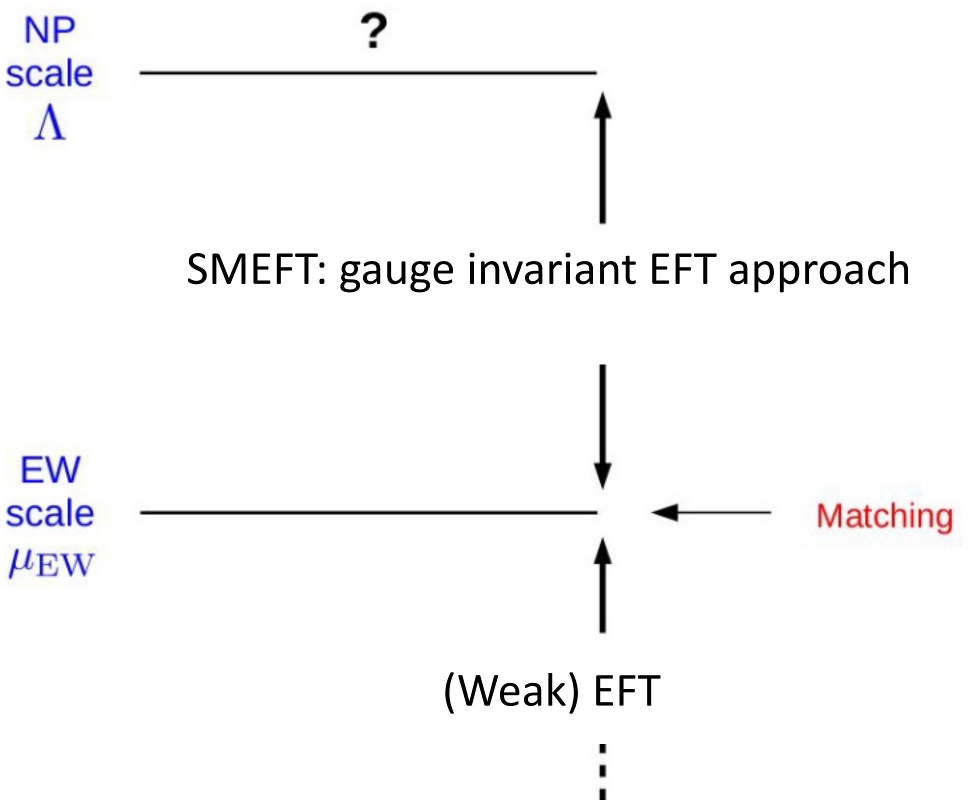
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

interpretation of the EFT bounds (i.e. their applicability to NP models)

global fits



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

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

NP generally assumed in semitauonic B decays

Effective Hamiltonian for b → cτ ν

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

O_V^R excluded by SMEFT match

Charged current process: simple (tree level) model interpretation

$$O_S^R = (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau)$$
$$O_S^L = (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau)$$

$$O_V^L = (\bar{c} \gamma^\mu P_L b)\,(\bar{\tau} \gamma_\mu P_L \nu_\tau)$$
$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)\,(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

GLOBAL FITS

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

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

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

$C_S^L = 4C_T \neq 0$; $C_V^L, C_S^L = -4C_T$; $C_V^L, C_S^R \neq 0$ (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

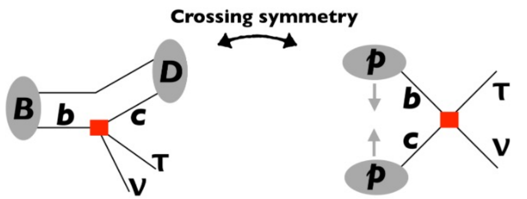
Charged W ′ bosons:

simplified models (spin-1 colorless weak triplet, a 2HDM, a spin-0 or spin-1 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

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

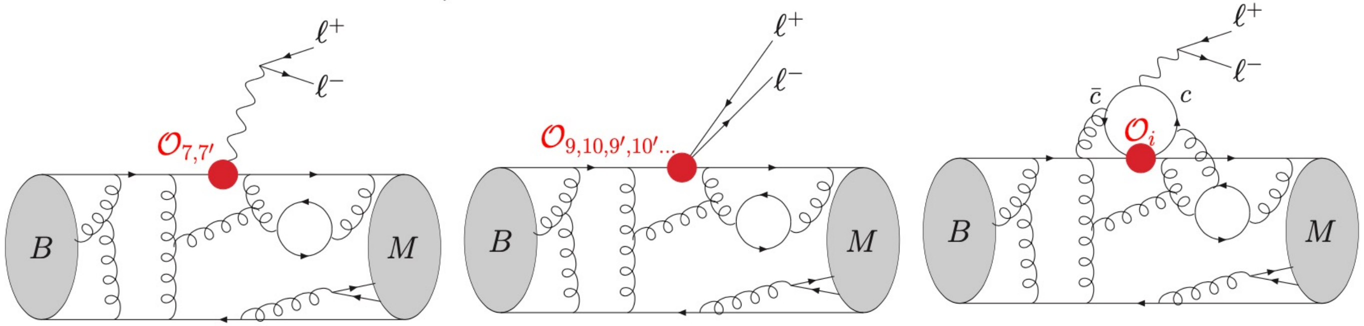
$\ell = \mu,\ e$

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

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

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

Two sources of hadronic uncertainties for exclusive



Form factors (local)

Charm loop (non-local)

J. Matias

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

About 250 obs All, 25 LFUV

1D Scenarios for $C_{i\mu}$

$$\mathcal{C}_{i\ell} = \mathcal{C}_{i\ell}^{\rm SM} + \mathcal{C}_{i\ell}^{\rm NP}$$

	All				LFUV			
1D Hyp.	Best fit	1 σ/2 σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	1 σ/ 2 σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.01	$[-1.15,-0.87]$ $[-1.29,-0.72]$	7.0	24.0 %	-0.87	$[-1.11,-0.65]$ $[-1.37,-0.45]$	4.4	40.7 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.45	$[-0.52,-0.37]$ $[-0.59,-0.30]$	6.5	16.9 %	-0.39	$[-0.48,-0.31]$ $[-0.56,-0.23]$	5.0	73.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-0.92	$[-1.07,-0.75]$ $[-1.22,-0.59]$	5.7	8.2 %	-1.60	$[-2.10,-0.98]$ $[-2.49,-0.46]$	3.2	8.4 %

$\mathrm{Pull}_{\mathrm{SM}}$ is quoted in units of standard deviation.
The p-value of the SM hypothesis is 0.44% for the fit “All” and 0.91% for quantities assessing LFUV

M. Algueró et al. EPJC 82 (2022)

Global fits: general agreement

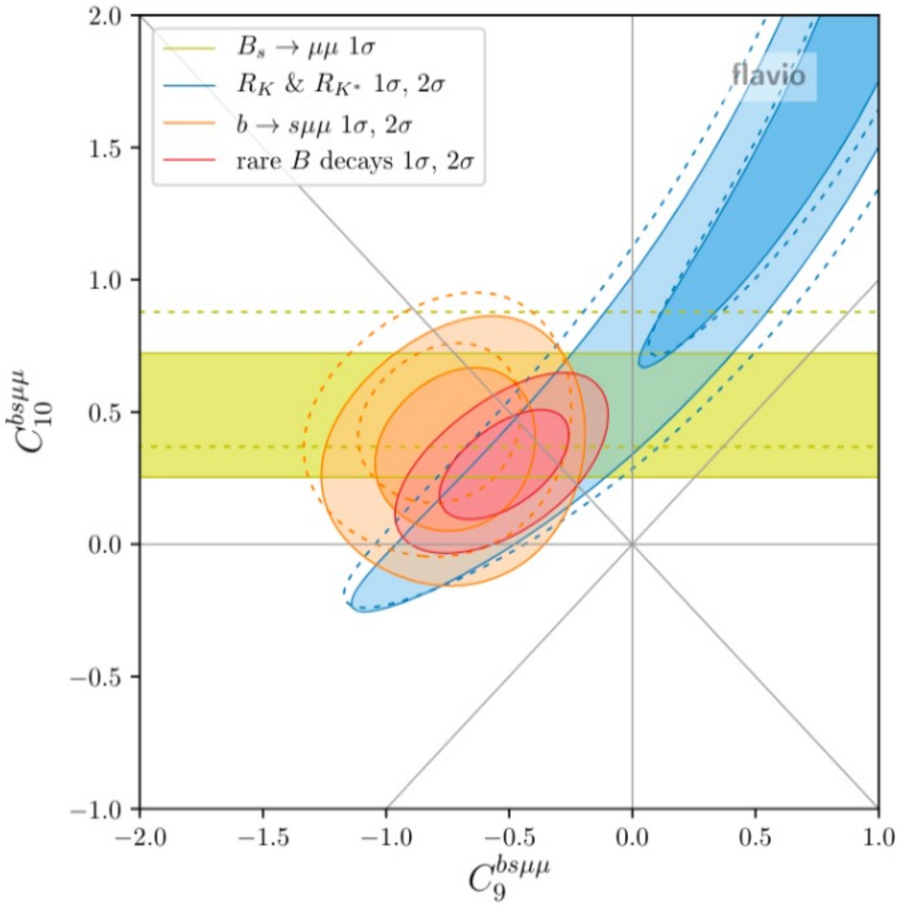
Alguero 21, Geng 21, Cornella 21, Angelescu 21, Hurth 21…

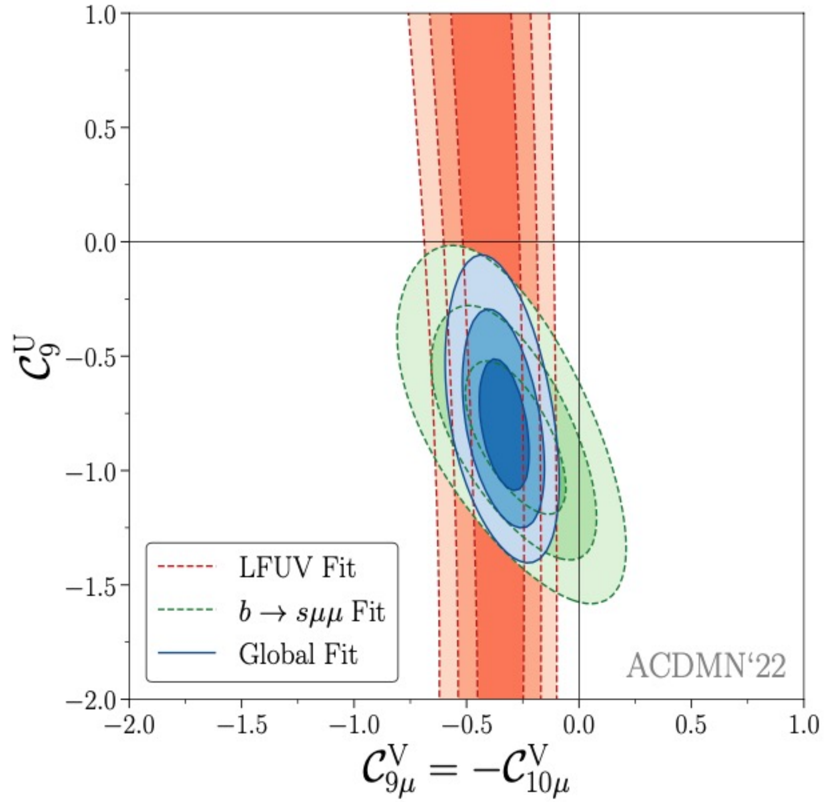
$\delta C_9 \neq 0$, and $\delta C_9 = -\delta C_{10} < 0$ in particular

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

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

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





Combination of LFU ratios, combination of $b \to s\mu\mu$ observables, BR($B_s \to \mu^+\mu^-$), and the global fit.

Altmannshofer 21

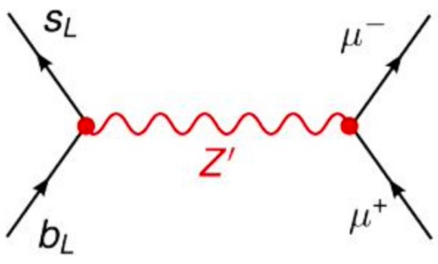
J. Matias

Mainstream models:

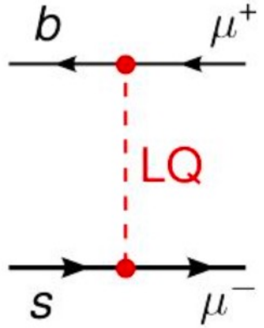
- loop-induced NP

- tree-level NP contributions

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



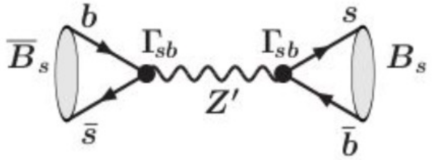
Leptoquarks
scalar or vectors



- ❑ $\Lambda_{NP} \sim$ 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

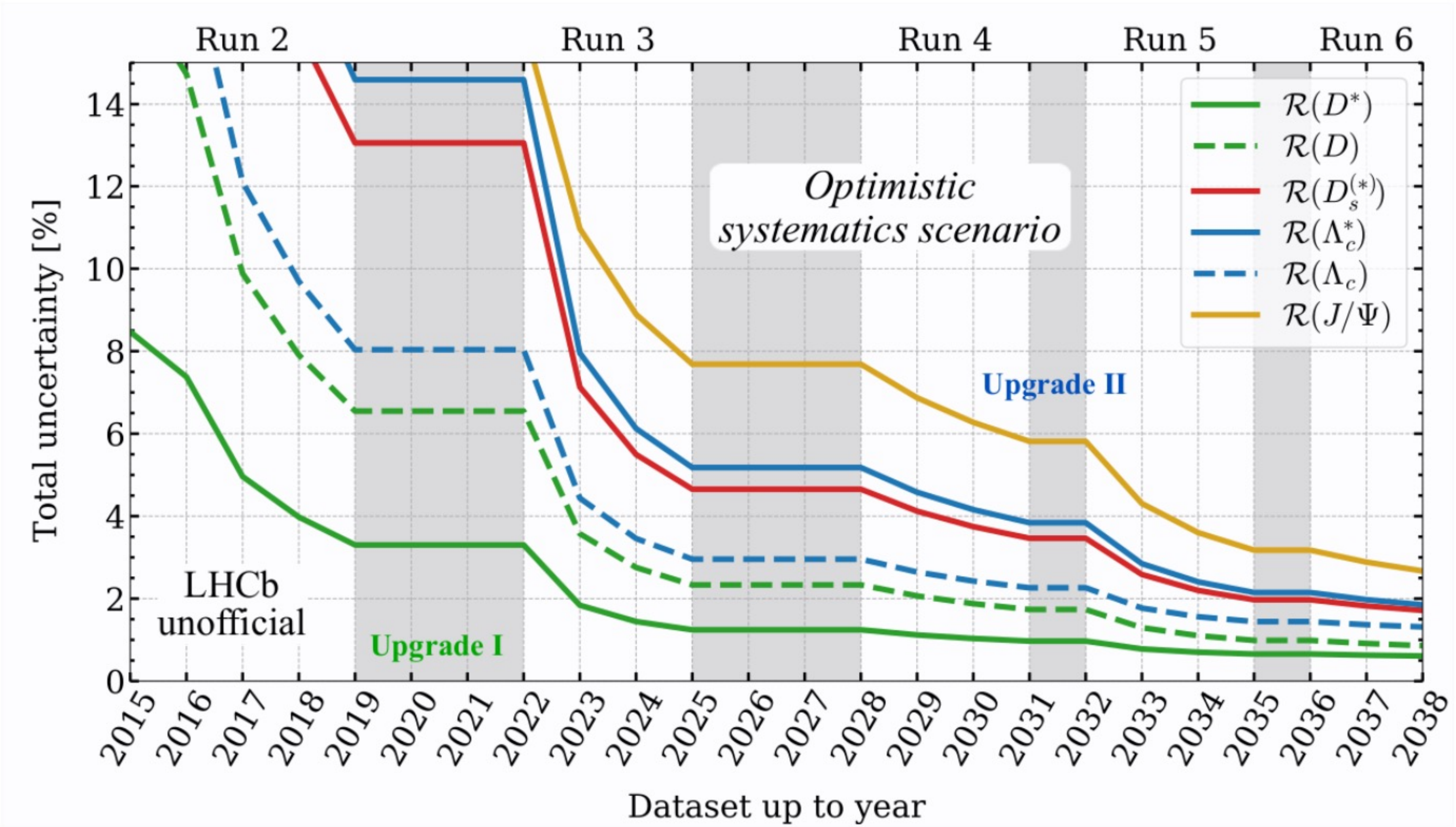
- ❑ bsZ' coupling stringently constrained by B_s–$\bar{B}_s$ mixing data



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

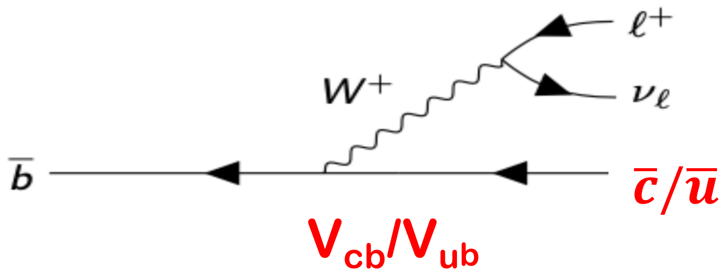
Cornella 21

LHCb prospects



[arXiv:2101.08326, arXiv:1808.08865]

$|V_{xb}|$ puzzle



- Semileptonic decays most precise determination of $|V_{ub}|$ & $|V_{cb}|$
- Tree level: no loop suppression & assumed largely free of BSM
- 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 $|V_{xb}|$

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

HQE status and prospects

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

I. Bigi et al 0911.3322, Breidenbachet al 08…

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

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 ($\frac{\alpha_s \Lambda^3_{QCD}}{m_b^3}$) corrections completed: $\boldsymbol{\rho_D^3}$

Mannel & Pivovarov 1907. 09187

- First steps toward transition rates from lattice

Hashimoto 1703.01881, Gambino & Hashomoto 2005.13730
Gambino et al. 2203.11762

- Using moments of the dilepton moment q2 spectrum recently been measured for the first time by both Belle (2021) and Belle II (2022)

Fael et al JHEP 02 (2019) 177,
Bernlochner et al 2022

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

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

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

Exclusive $|V_{cb}|$ determination

- 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[10]

✓ 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.

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

FLAG Review 2021 [arXiv:2111.09849]

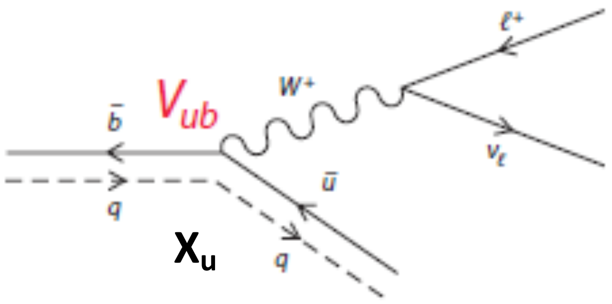
INCLUSIVE:

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

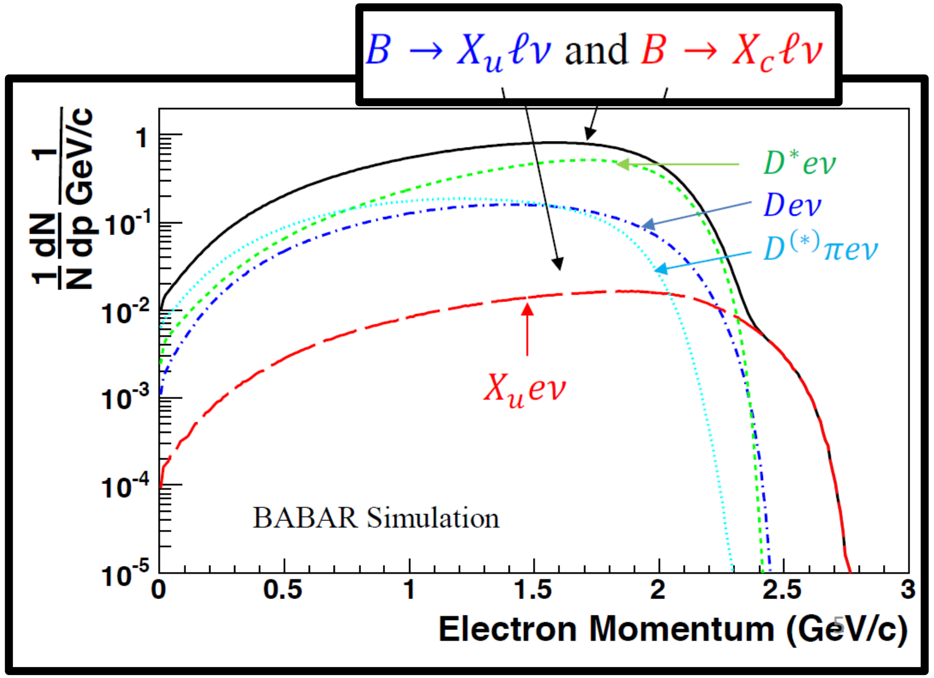
Bordone et al., Phys.Lett.B [2107.00604]

$\sim 2.7\sigma$ 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

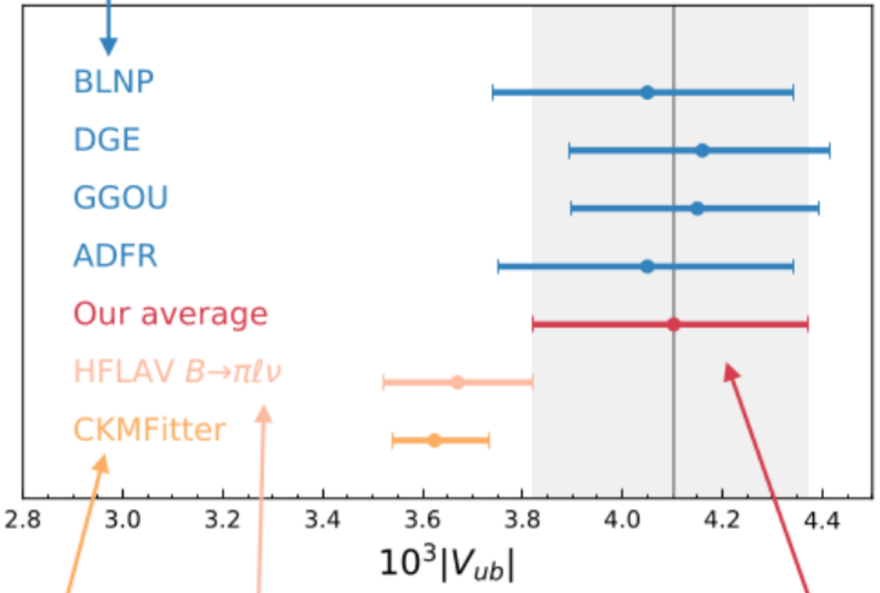
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

3 phase-space regions

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

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

M. T. Prim Belle ICHEP 2022

Inclusive decays

Prospects

Inclusive hadronic tagged analysis

Start from **Belle strategy**: signal/background modeling, BDT/NN selection,

Improved hardware/software + **larger data set** (ultimately 50 ab^{-1})

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

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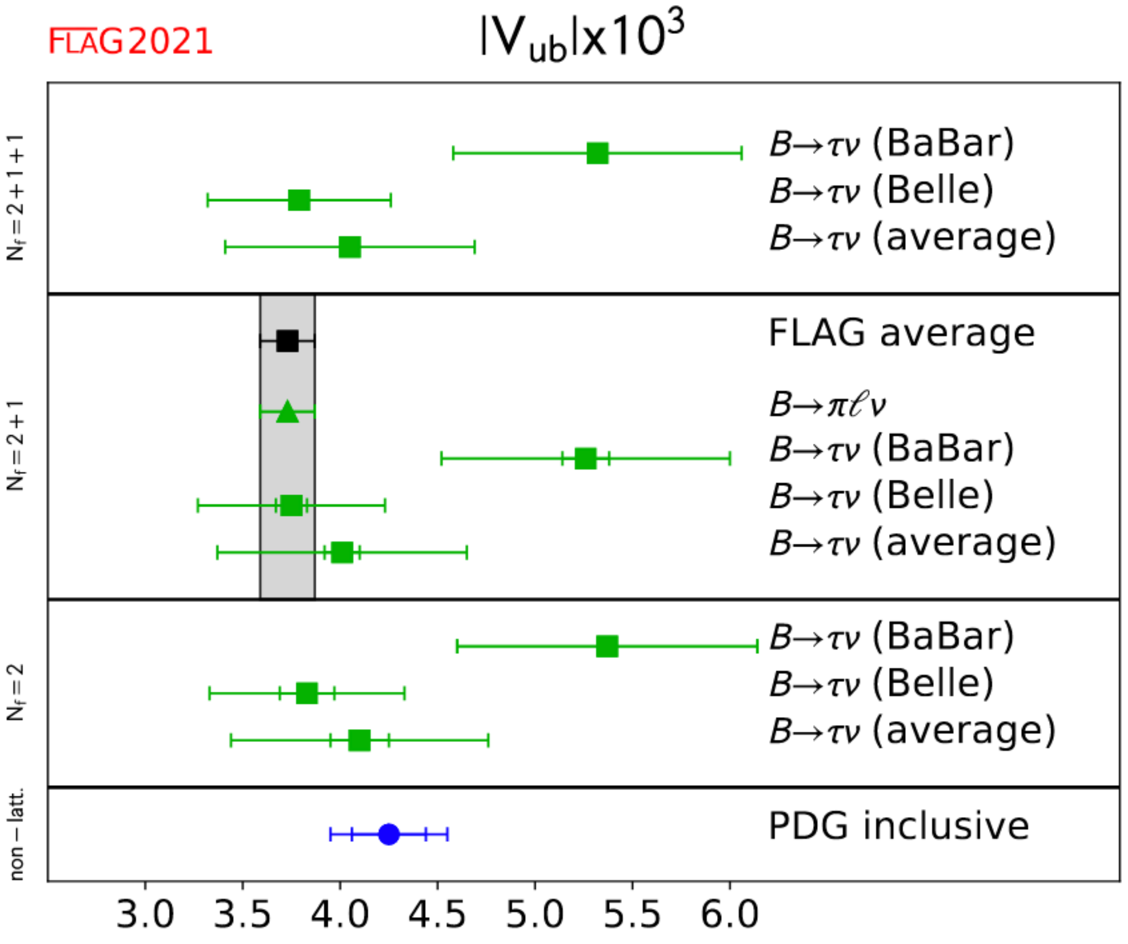
Model independent/global fit: **differential spectra** measurement: q^2, m_X, E

$|V_{ub}|$ exclusive determination

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



$$|V_{ub}| = 3.63(14) \times 10^{-3}$$

1.5-2σ difference, still reduced with DM approach

Source	$10^{-3} \times \lvert V_{ub}\rvert$ EXCLUSIVE
LQCD	
Fermilab/MILC [33, 34]	3.72 ± 0.16
RBC/UKQCD [35]	3.61 ± 0.32
combination w/ Pade approx. [51]	$3.53 \pm 0.08_{\text{stat}} \pm 0.06_{\text{syst}}$
HFLAV [8]	$3.70 \pm 0.10_{\text{stat}} \pm 0.12_{\text{syst}}$
LCSR	
Duplancic et al. [16]	$3.5 \pm 0.4 \pm 0.2 \pm 0.1$
Imsong et al. [21]	$3.32^{+0.26}_{-0.22}$
this work	$3.28^{+0.33}_{-0.28}$
LCSR + LQCD	
HFLAV [8]	$3.67 \pm 0.09_{\text{stat}} \pm 0.12_{\text{syst}}$
this work	3.77 ± 0.15

- from the semileptonic $B \to \pi$ decays

$$|V_{ub}| \cdot 10^3 = 3.62 \pm 0.47 \ ,$$

- from the semileptonic $B_s \to K$ processes

$$|V_{ub}| \cdot 10^3 = 3.77 \pm 0.48 \ .$$

by averaging

$$|V_{ub}| \cdot 10^3 = 3.69 \pm 0.34$$

Only 1σ from the most recent Belle result on inclusive |Vub| determination

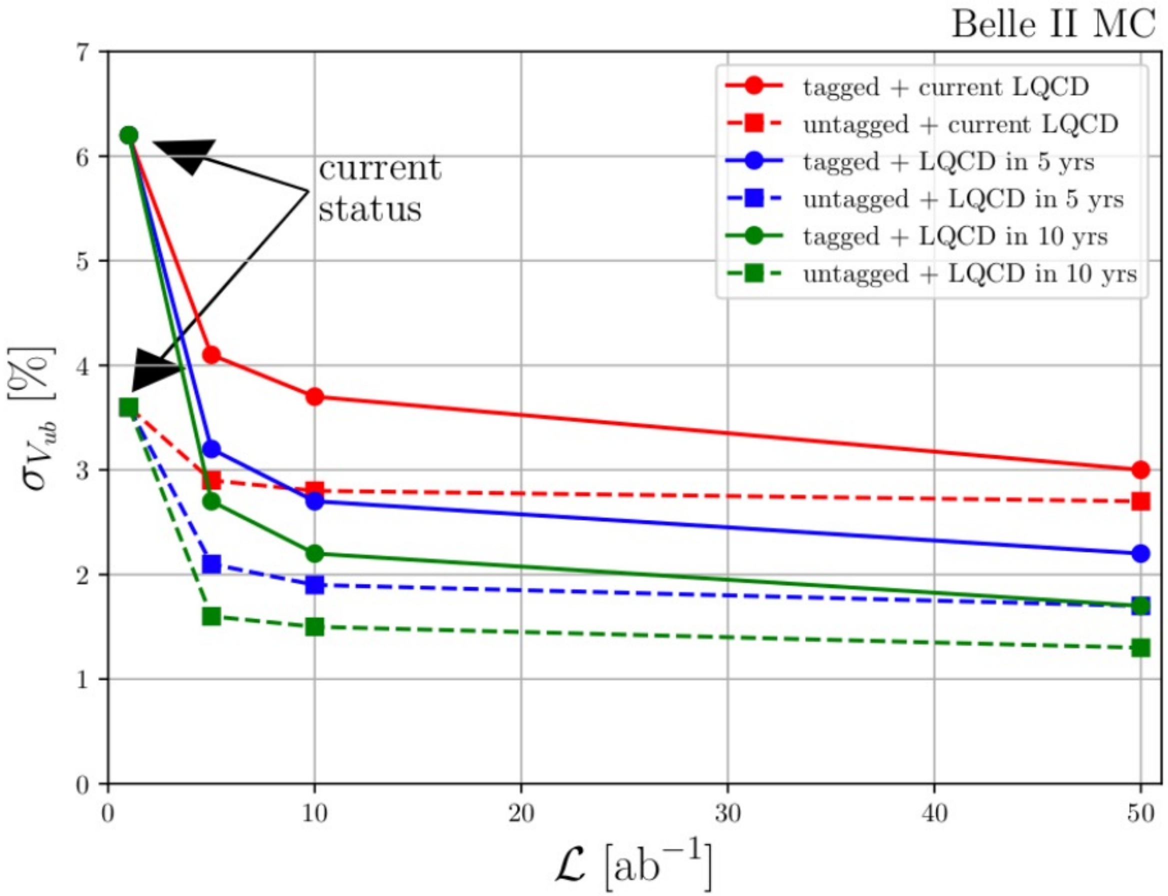
D.Leljak et al JHEP 07 (2021)
07 B. Melik Portorose 2021

Martinelli et al.
2202.10285

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

Ongoing **tagged** and **untagged** analyses with **more statistics**

Potential to **reduce uncertainty on $|V_{ub}|$** by a significant margin



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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; almost there (?)
- ✓ Next decade: Belle II major player (& LHCb powerful ally)