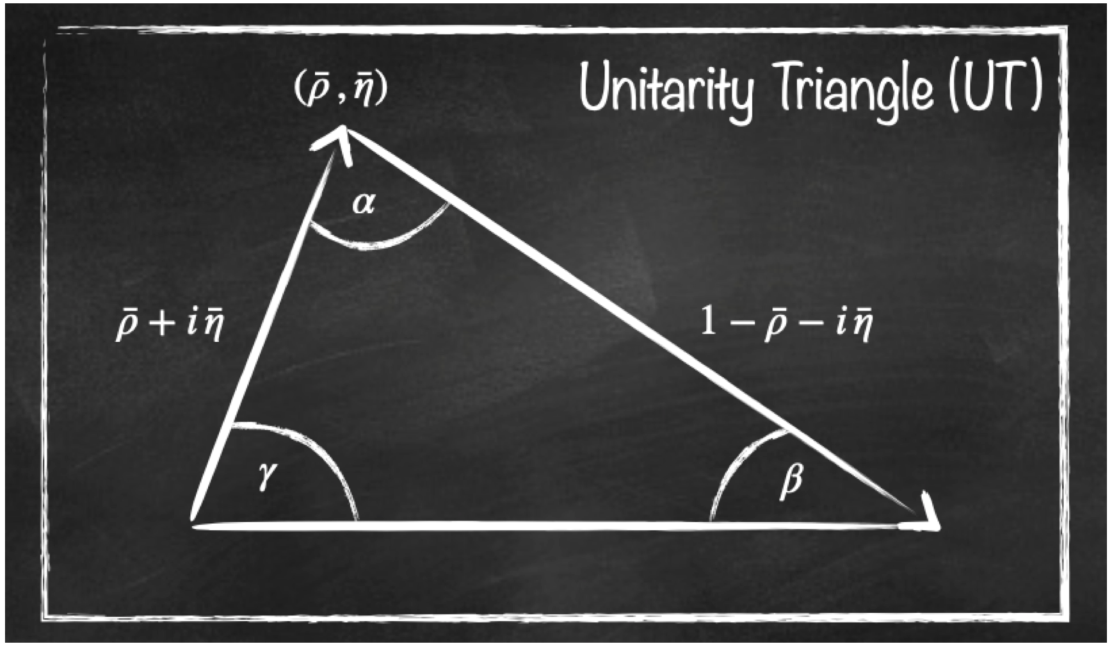
Overview on CKM matrix status and on current anomalies in flavour data

Ludovico Vittorio (Sapienza Università di Roma & INFN, Sezione di Roma)

ENP collaboration meeting – 19 May 2025



Introduction

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We can consider the SM as an Effective Field Theory (EFT) valid at low energies!

Vacuum Energy *Hierarchy* *Vacuum Stability*

$$\mathcal{L} = \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 +$$

$$(D_\mu H)^2 + \bar{\psi}\, \not{D} \psi + F_{\mu\nu}^2 + F_{\mu\nu}\tilde{F}_{\mu\nu}$$ *Strong CP*

$$Y H \bar{\psi}\psi + \frac{1}{\Lambda}(\bar{L}H)^2 + \frac{1}{\Lambda^2}\sum_i C_i O_i + \ldots$$

Flavor puzzle *Neutrino Masses*

Which is the impact of the Higgs on flavor ?

***Flavour blindness** of the SM gauge sector:*

$$\mathcal{G}_F(\mathrm{SM}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

through the Lagr. $YH\bar{\psi}\psi$ *term*

$\Rightarrow$

Effect of the Yukawas:

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Some important questions to be answered:

1. **Why three generations?**
2. **What determines the observed pattern of quark and lepton masses?**
3. **Why this *hierarchical* structure?**

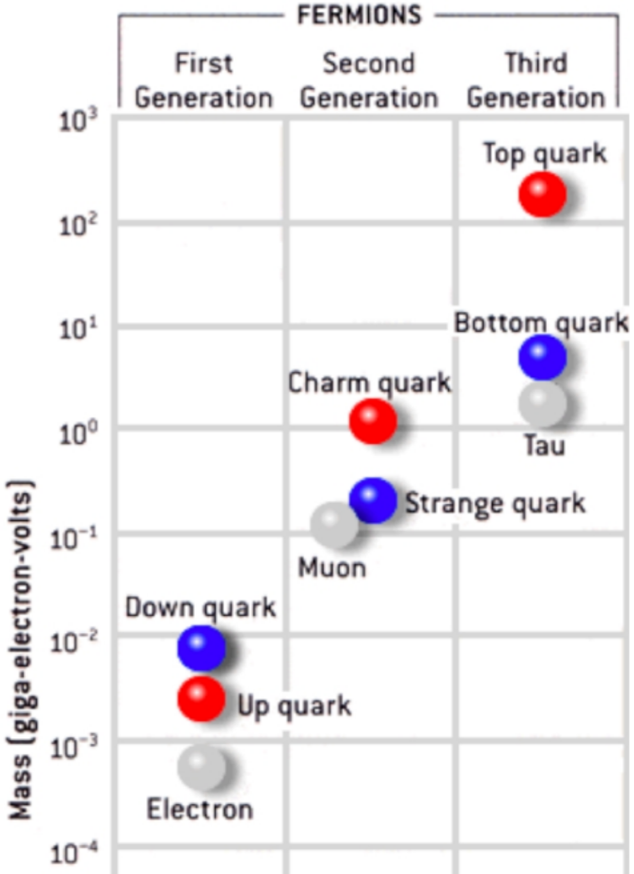

Illustration from a G. Isidori talk

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$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97431(19) & 0.22517(81) & 0.003715(93)\, e^{-i(65.1(1.3))^o} \\ -0.22503(83)\, e^{+i(0.0351(1))^o} & 0.97345(20)\, e^{-i(0.00187(5))^o} & 0.0420(5) \\ 0.00859(11)\, e^{-i(22.4(7))^o} & -0.04128(46)\, e^{+i(1.05(3))^o} & 0.999111(20) \end{pmatrix}$$

UTfit Collaboration, Rend. Lincei Sci.Fis.Nat. 34 (2023) 37-57 [arXiv:2212.03894]

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The CKM matrix describes the quark

All these questions are usually referred to as

«Flavour Problem(s)» !

Not clear answers within the SM …

UTfit Collaboration, Rend. Lincei Sci.Fis.Nat. 34 (2023) 37-57 [arXiv:2212.03894]

4. Very close to the unit matrix: where does this hierarchical structure (again) come from?

Unitarity Triangle as a (first) guide

Wolfenstein parametrization (L. Wolfenstein, PRL 51 (1983) 1945-1947):

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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We can write the unitarity of the CKM matrix as

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

$\Rightarrow$ ***Triangle in the $(\bar\rho, \bar\eta)$ plane !***

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Triangle in the $(\bar\rho, \bar\eta)$ plane !

$$\boxed{-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} - \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = R_b e^{i\gamma} + R_t e^{-i\beta} = 1 \simeq (\bar\rho + i\bar\eta) + (1-\bar\rho - i\bar\eta)}$$

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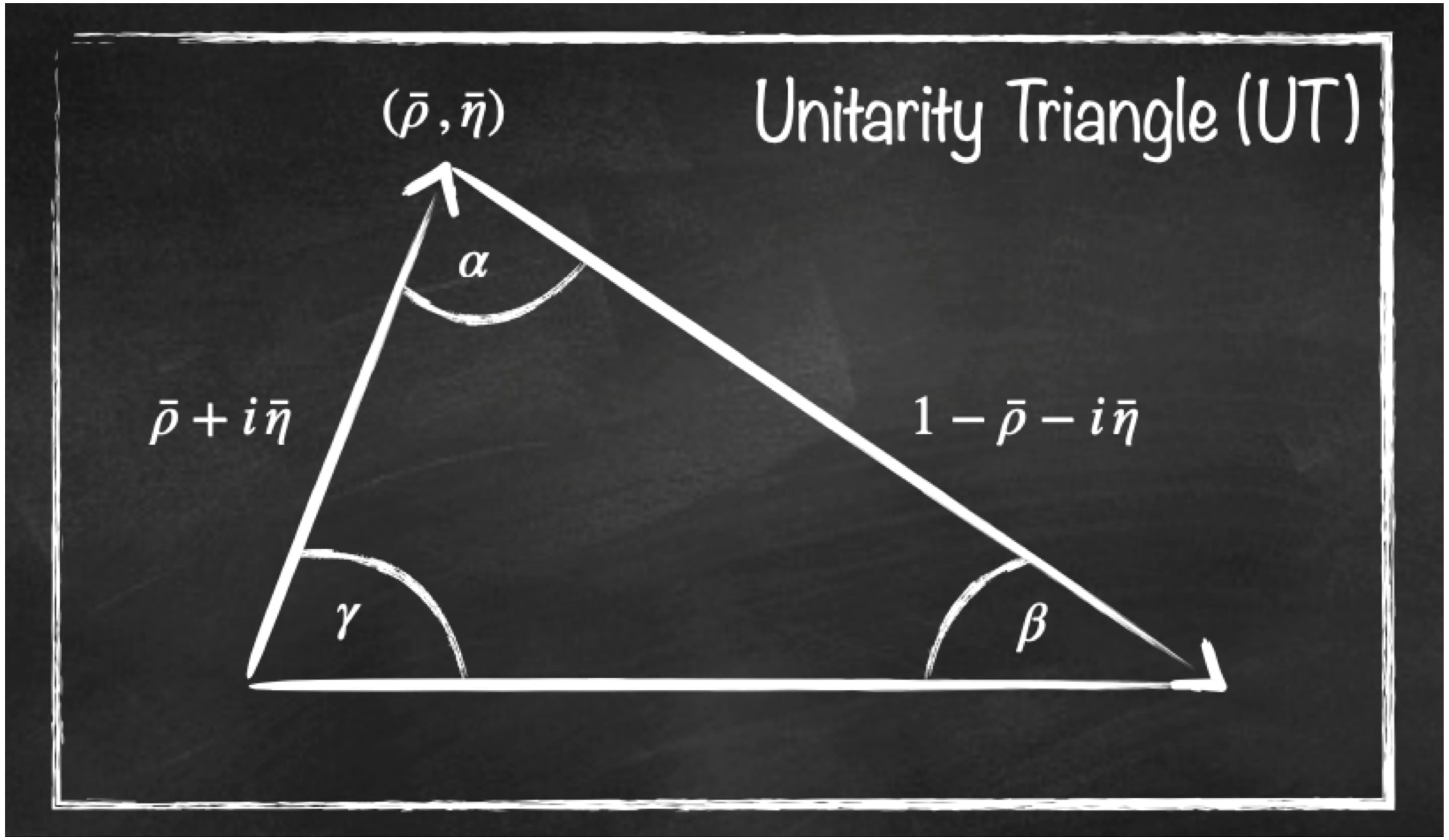

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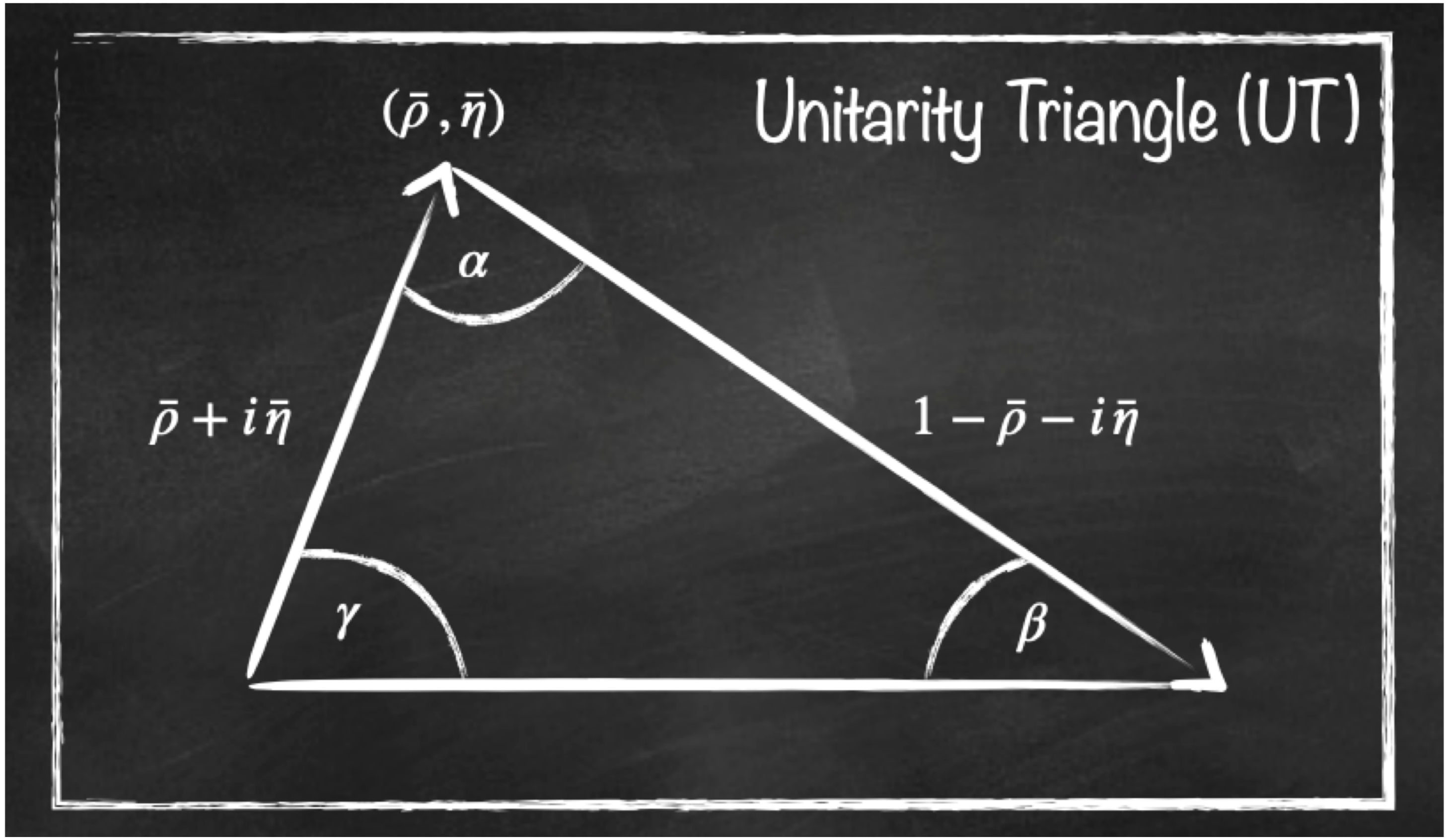

***KEY INFORMATION*:**
the sides, the angles and the area of the triangle correspond to physical quantities ! E.g.:

$$R_b \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{\bar\rho^2+\bar\eta^2}$$

$$R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}$$

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Rare decays as a (second) guide

The most apppealing places to look for possible NP effects are rare decays, since <u>rare decays are a manifestation of broken (accidental) symmetries, *e.g.* of physics beyond the Standard Model</u>

Some general examples:

1. **Proton decay** → ***Test of baryon and lepton number conservation***

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2. **Flavour Changing Neutral Currents (FCNCs): absent @ tree level & CKM-suppressed**

Of interest for this talk !

$$\boxed{\begin{array}{lcl} q_i & \to & q_j \ell^+ \ell^-, \\ q_i & \to & q_j \nu \bar{\nu}, \\ q_i & \to & q_j \gamma \end{array}}$$

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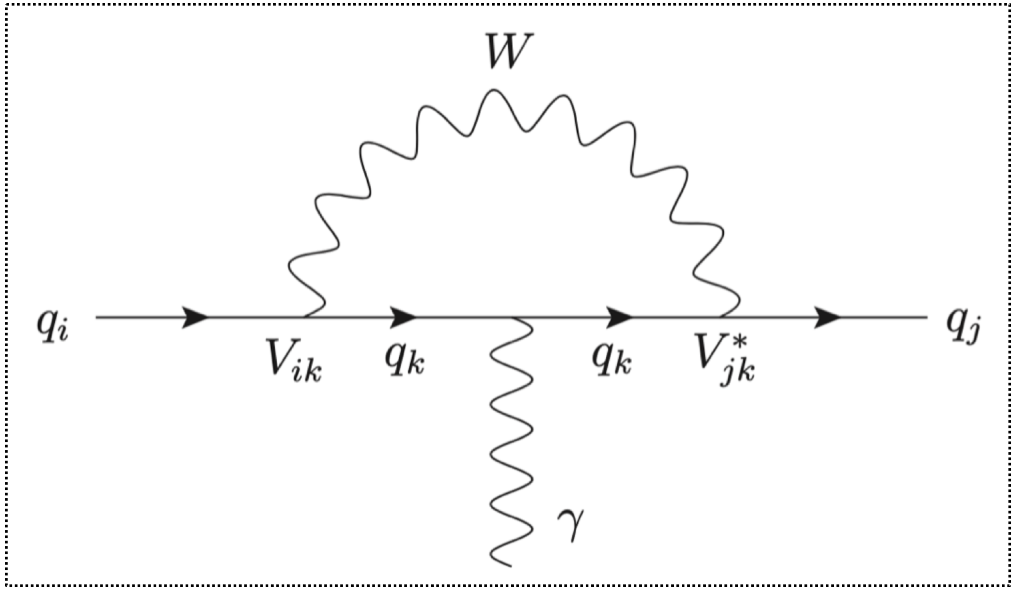

Flavour physics within and beyond the SM

Tree-level processes

FCNCs

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Tree-level processes

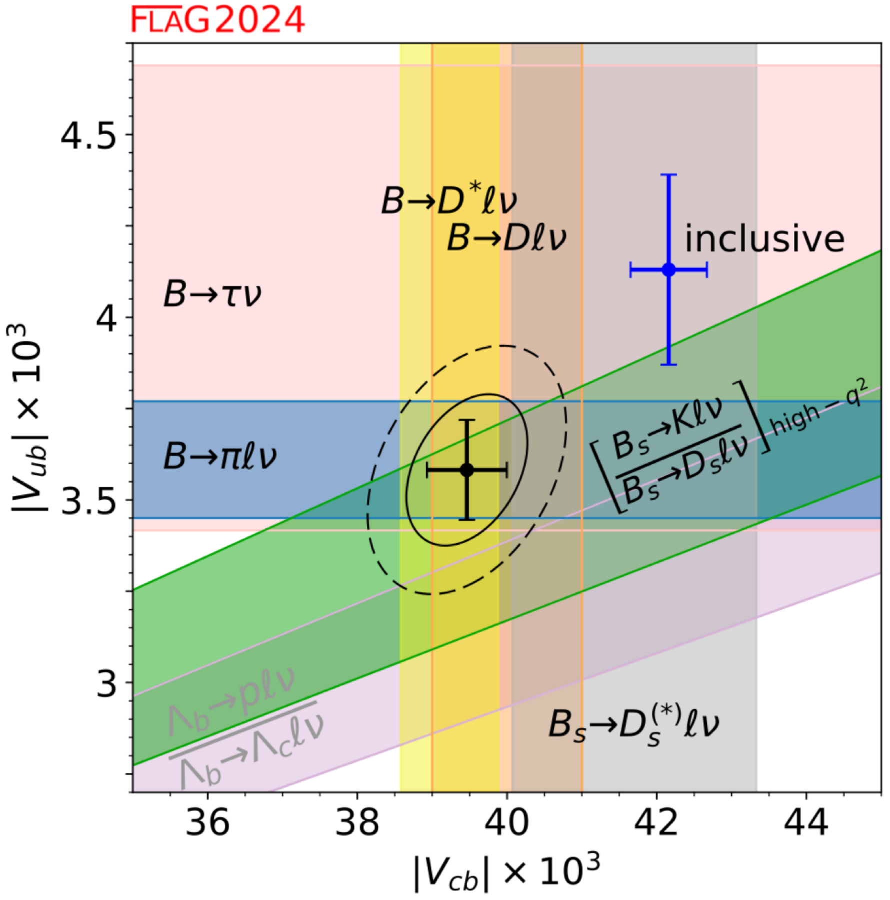
$b \to c$ transitions

FCNCs

Many challenges in $b \to c$ decays at present

Although there is *no direct evidence for New Physics from experiments*, many phenomenological puzzles need a solution:

1. |Vcb| (e |Vub|) puzzle



FLAG Review 2024 [2411.04268]

Tension:
$\sim 3\sigma$

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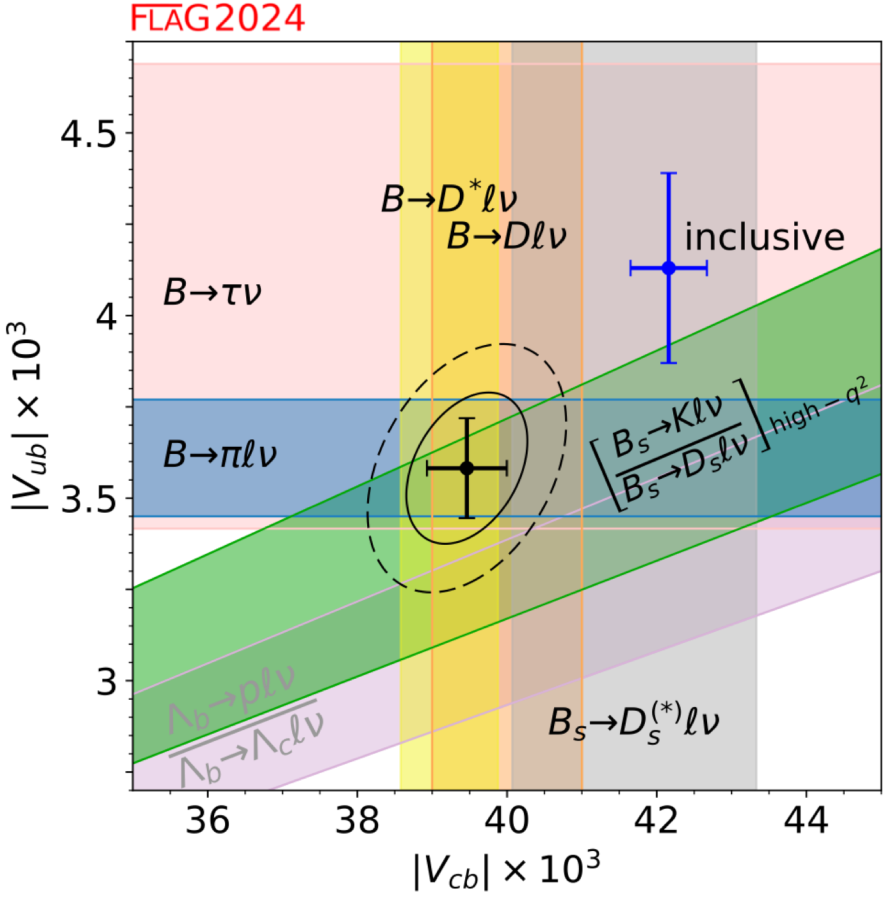

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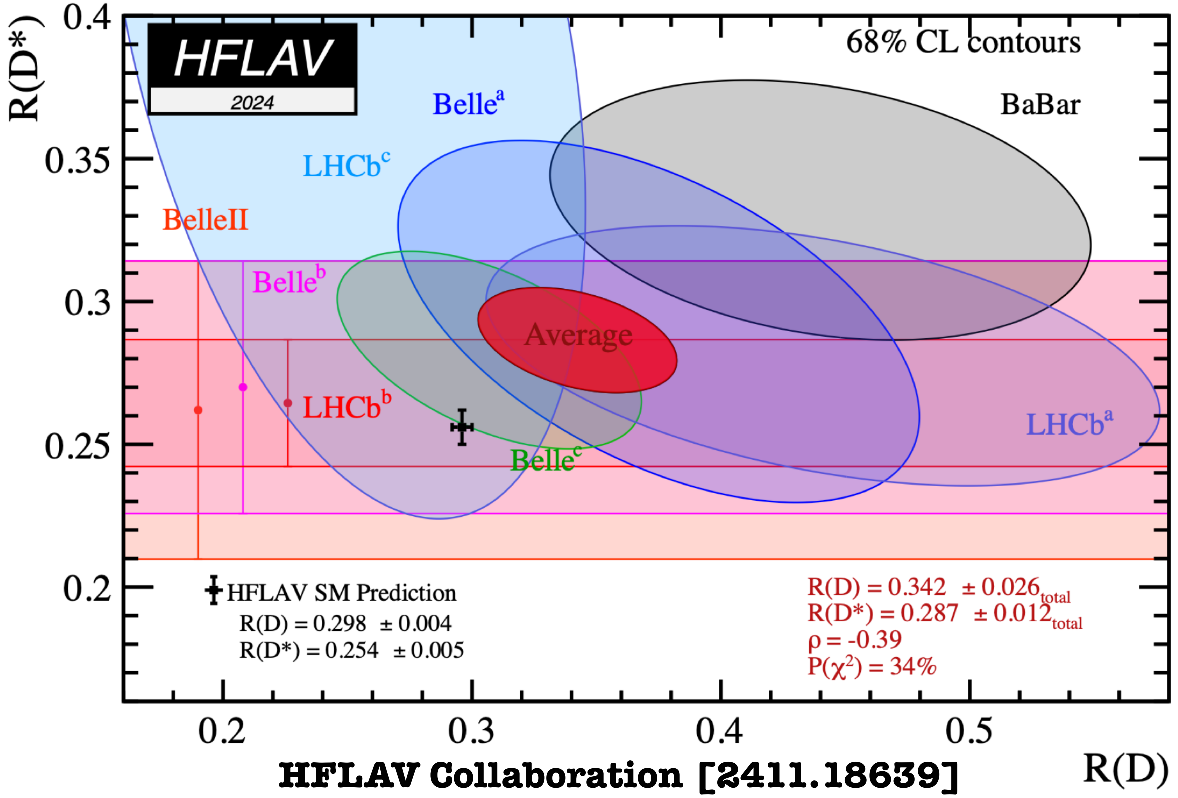
2. Lepton Flavour Universality (Violation)



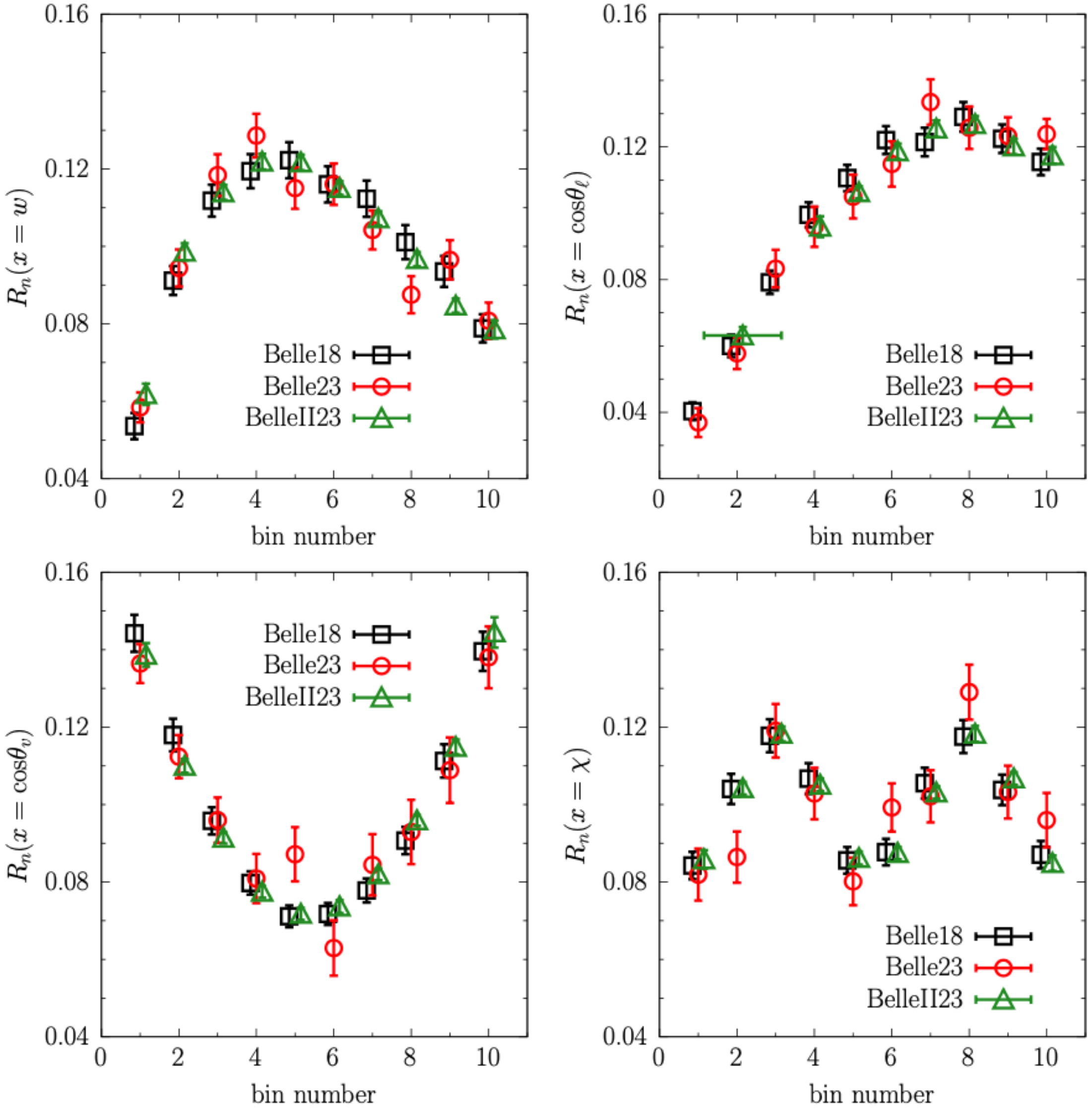
HFLAV Collaboration [2411.18639]

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

New experimental data — B → D*lν

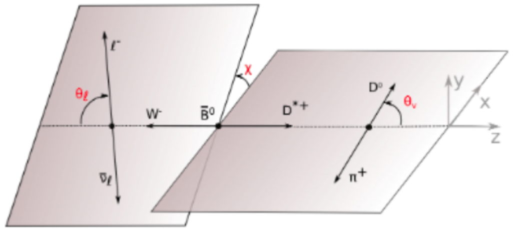
Belle Collaboration: PRD '19 [arXiv:1809.03290]
Belle Collaboration, PRD '23 [arXiv:2301.07529]
Belle-II Collaboration: PRD '23 [arXiv:2310.01170]

$$R_n(x) \equiv \Gamma^{-1} d\Gamma/dx$$



A lot of new experimental data:

- four (normalized) differential decay rates
  $\alpha = w,\ \cos\theta_\ell,\ \cos\theta_v, \chi$
- three experimental datasets by Belle/BelleII



$$\frac{d^4\Gamma}{dw d\cos\theta_v d\cos\theta_\ell d\chi} = \frac{3}{16\pi}\Gamma_0\sqrt{w^2-1}(1-2rw+r^2)\Big\{H_+^2(w)\ \sin^2\theta_v\ (1-\cos\theta_\ell)^2$$
$$+\ H_-^2(w)\ \sin^2\theta_v\ (1+\cos\theta_\ell)^2 + 4\ H_0^2(w)\ \cos^2\theta_v\ \sin^2\theta_\ell$$
$$-\ 2\ H_-(w)H_+(w)\ \sin^2\theta_v\ \sin^2\theta_\ell\ \cos 2\chi$$
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New experimental data — $B \to D^* l\nu$

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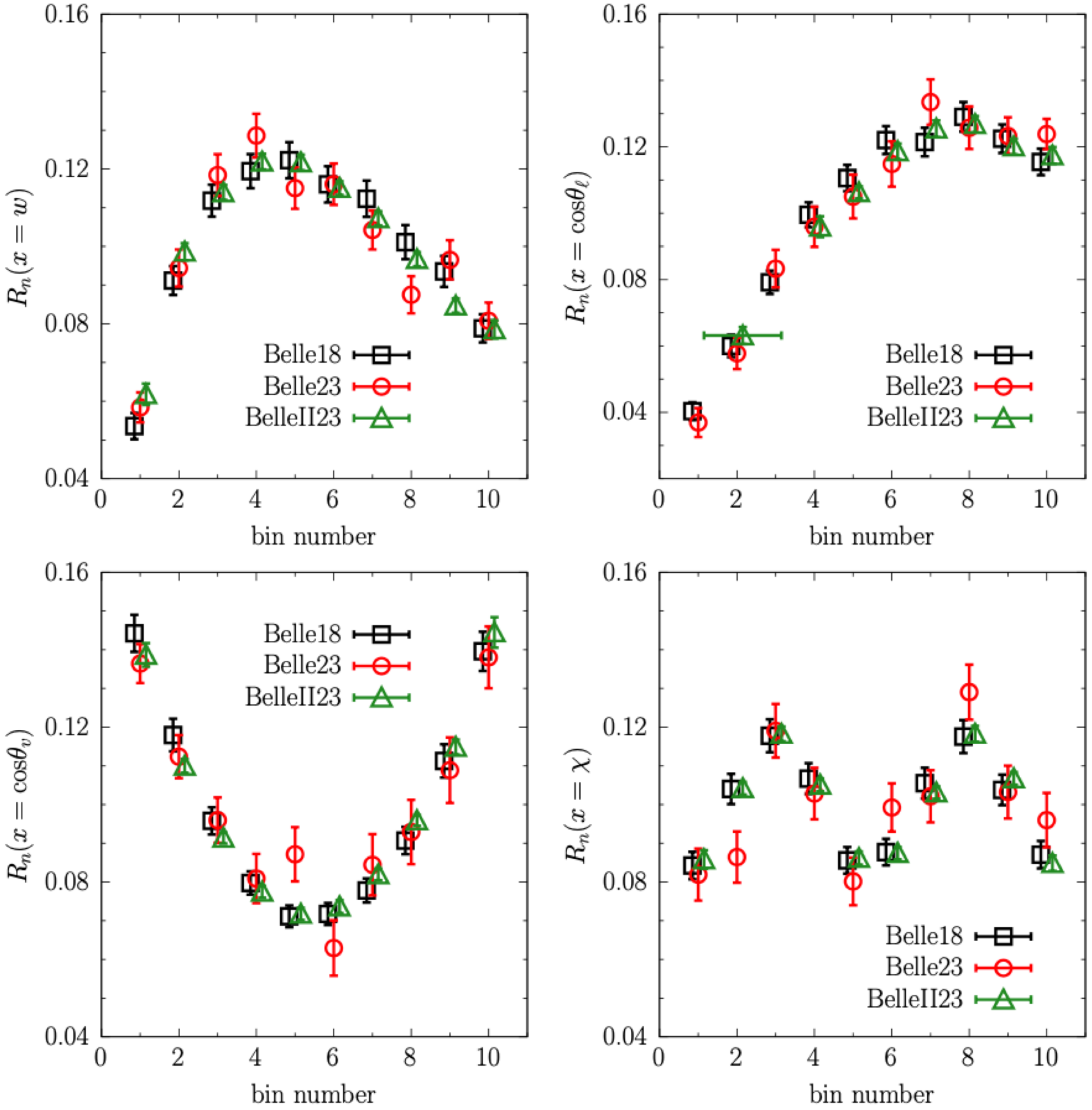

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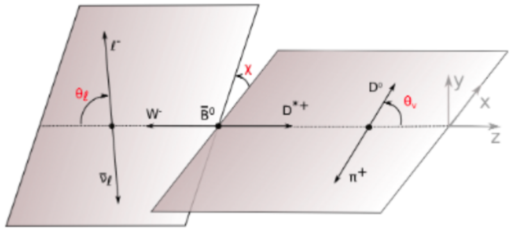

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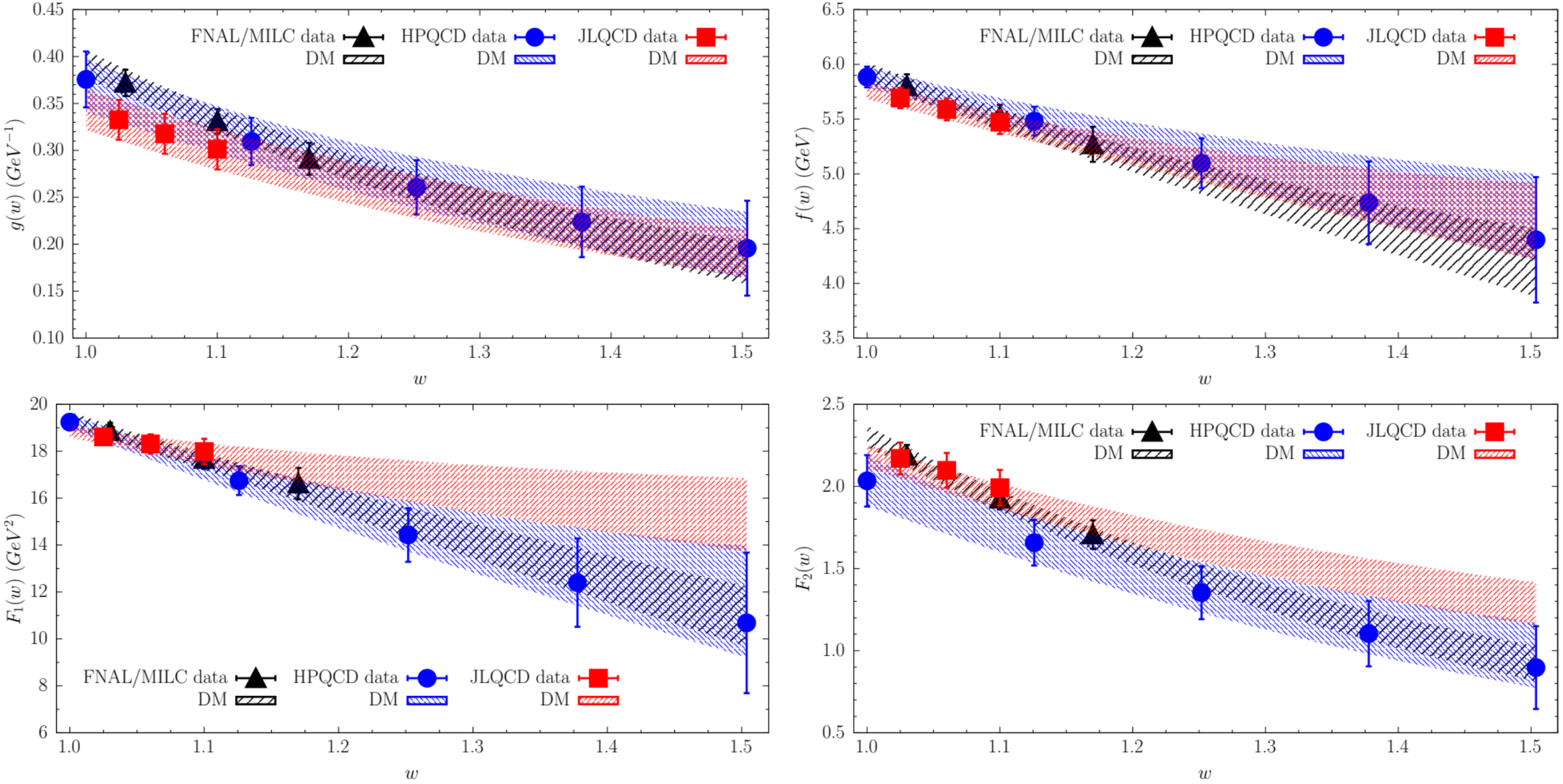
How to best analyze this new quality of data as part of a precision test of the SM ?

Shapes of the FFs starting from lattice data



Martinelli, Simula, LV, EPJC 84 (2024) 4, 400,

Similar results in **Bordone, Juettner, EPJC 85 (2025) 2, 129**

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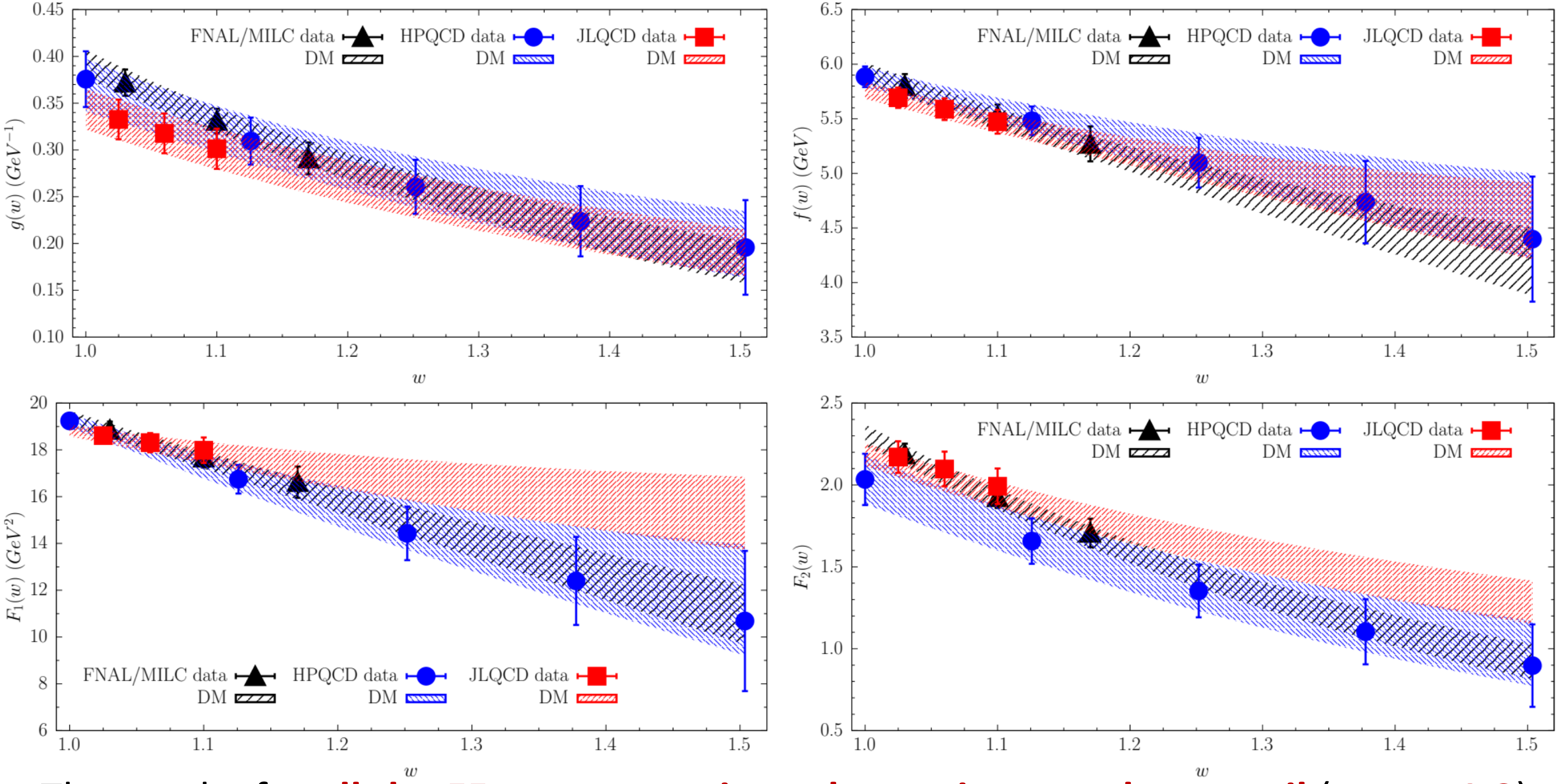

Martinelli, Simula, LV, EPJC 84 (2024) 4, 400,

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1. The results for **all the FFs are approximately consistent at low recoil** (**at w ≤ 1.2**)
2. Some differences exist among the **extrapolated values of $F_{1,2}(w)$ from JLQCD and from FNAL/MILC**

R(D*) and polarization observables

These bands alone (w/out the usage of exp. data) are sufficient for some phenomenological applications:

- **R(D*)**

Lattice FFs	$R(D^*)$
FNAL/MILC [15]	0.275(8)
HPQCD [16]	0.266(12)
JLQCD [17]	0.247(8)
Average [15]-[17] (PDG scale factor)	0.262(9) (1.8)
Combined [15]-[17]	0.259(5)
Experimental value	0.284(12) [36]

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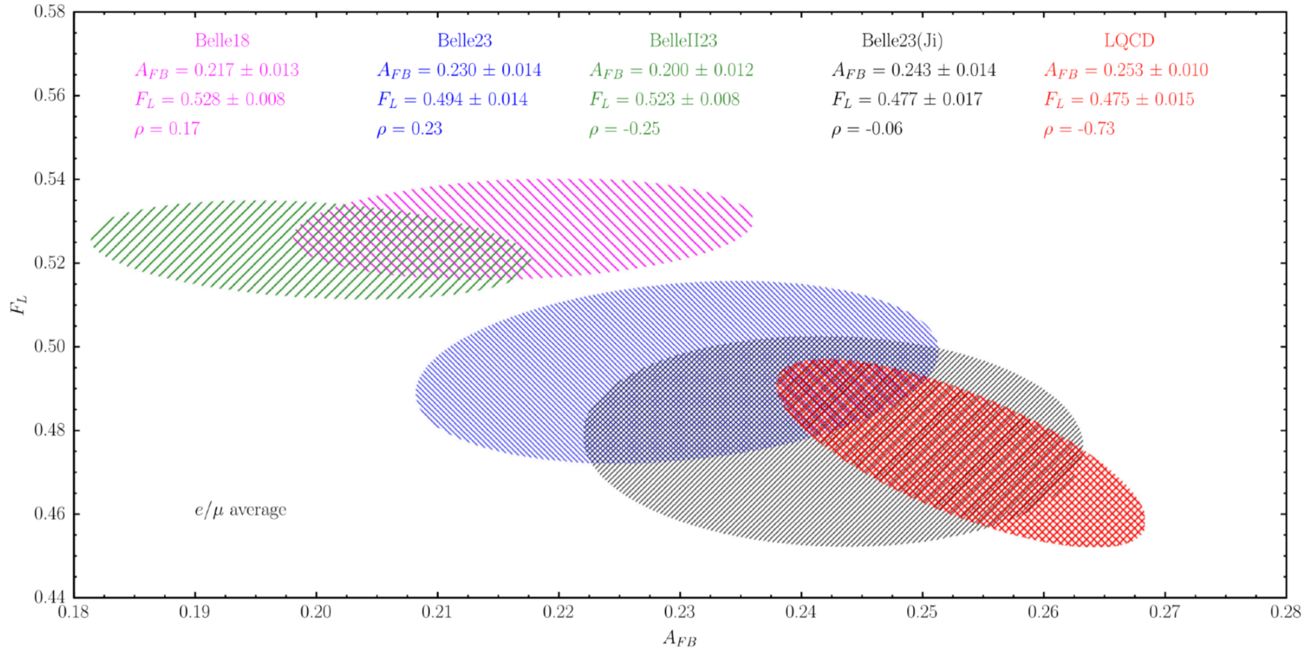
Martinelli, Simula, LV, PRD 111 (2025) 1, 013005



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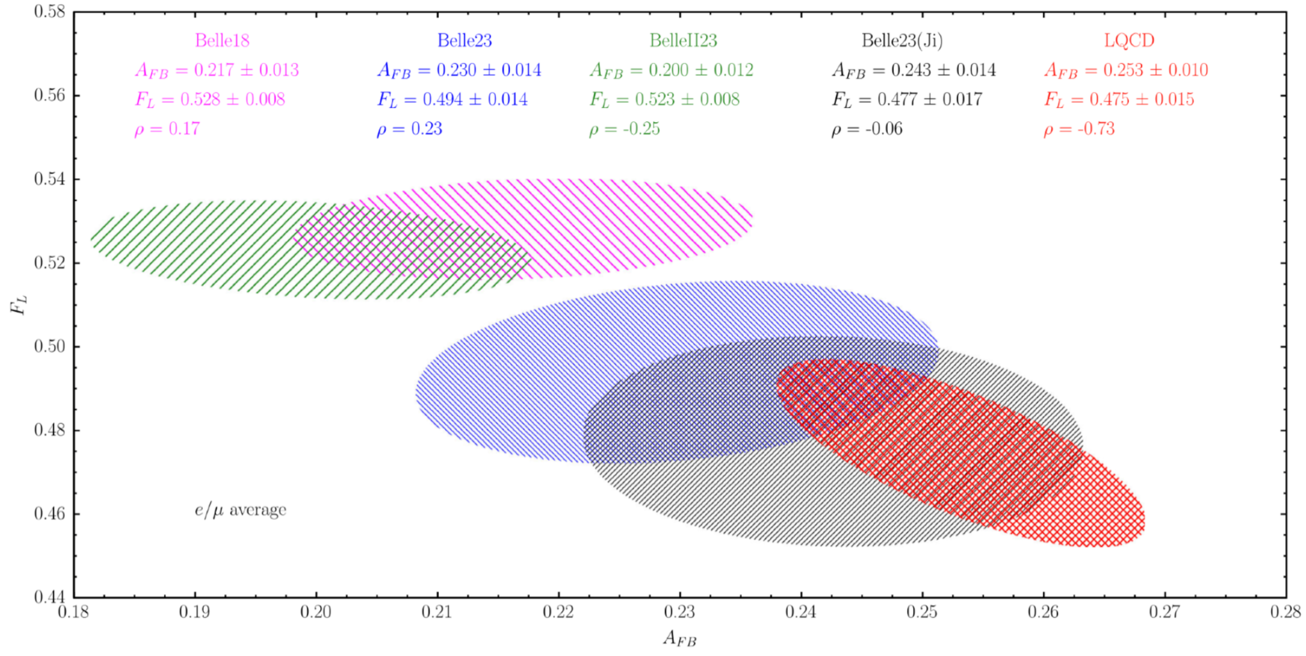

Take-home message: there are tensions amongst results from different lattice collaborations, but there are non-negligible tensions amongst experiments as well !

$|V_{cb}|$ determination

Several strategies:

A) Bin-per-bin analysis

$$|V_{cb}|_{\alpha,i} = \left(\Gamma_{\exp} \left[\frac{1}{\Gamma} \frac{d\Gamma}{d\alpha} \right]^{(i)}_{\exp} / \left[\frac{d\Gamma_0}{d\alpha}(\mathbf{a}) \right]^{(i)}_{\text{lat}} \right)^{1/2}$$

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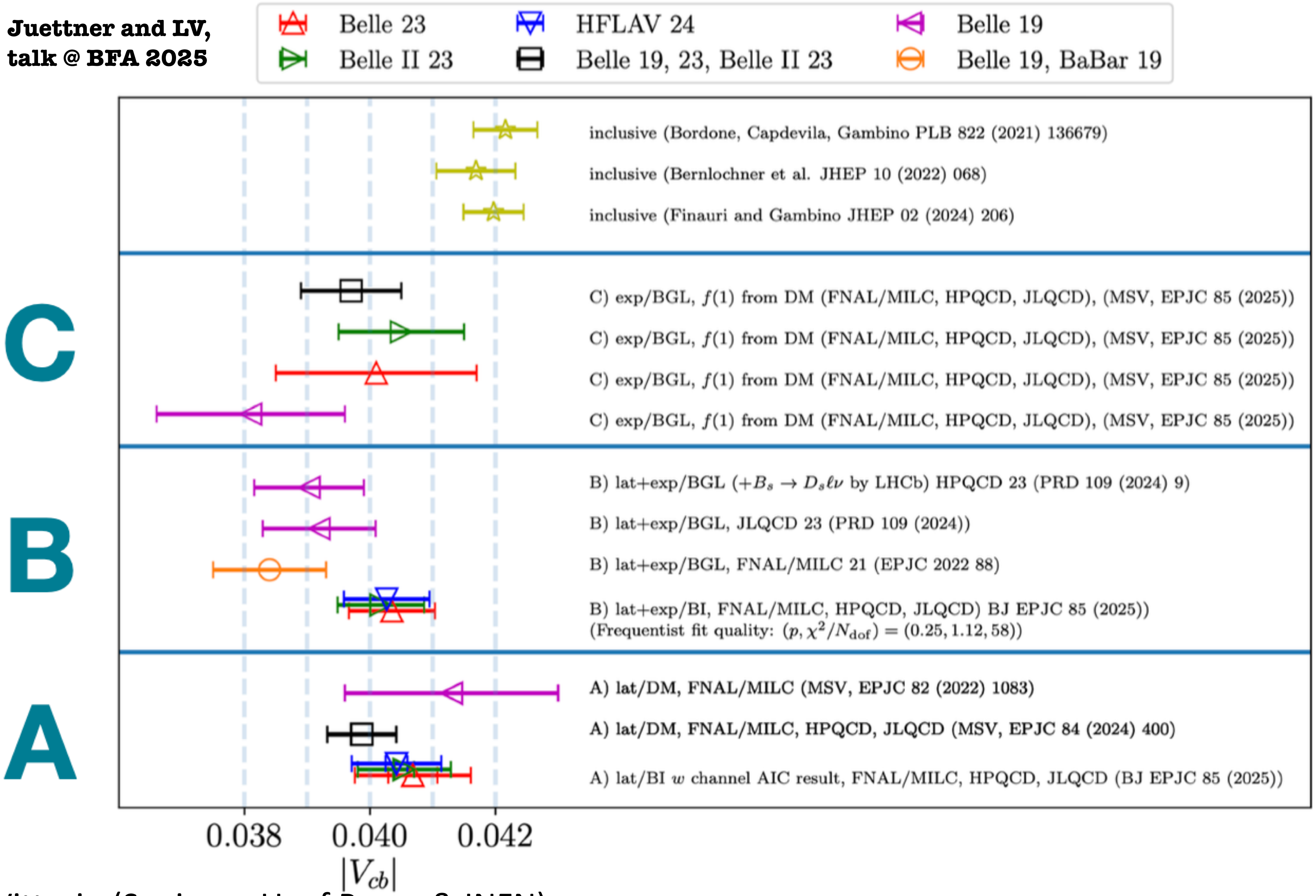
B) Latt.+exp. fits

C) Exp. fit only

(determine $|V_{cb}|$ a posteriori from the total decay width)

$|V_{cb}|$ determination

Juettner and LV, talk @ BFA 2025



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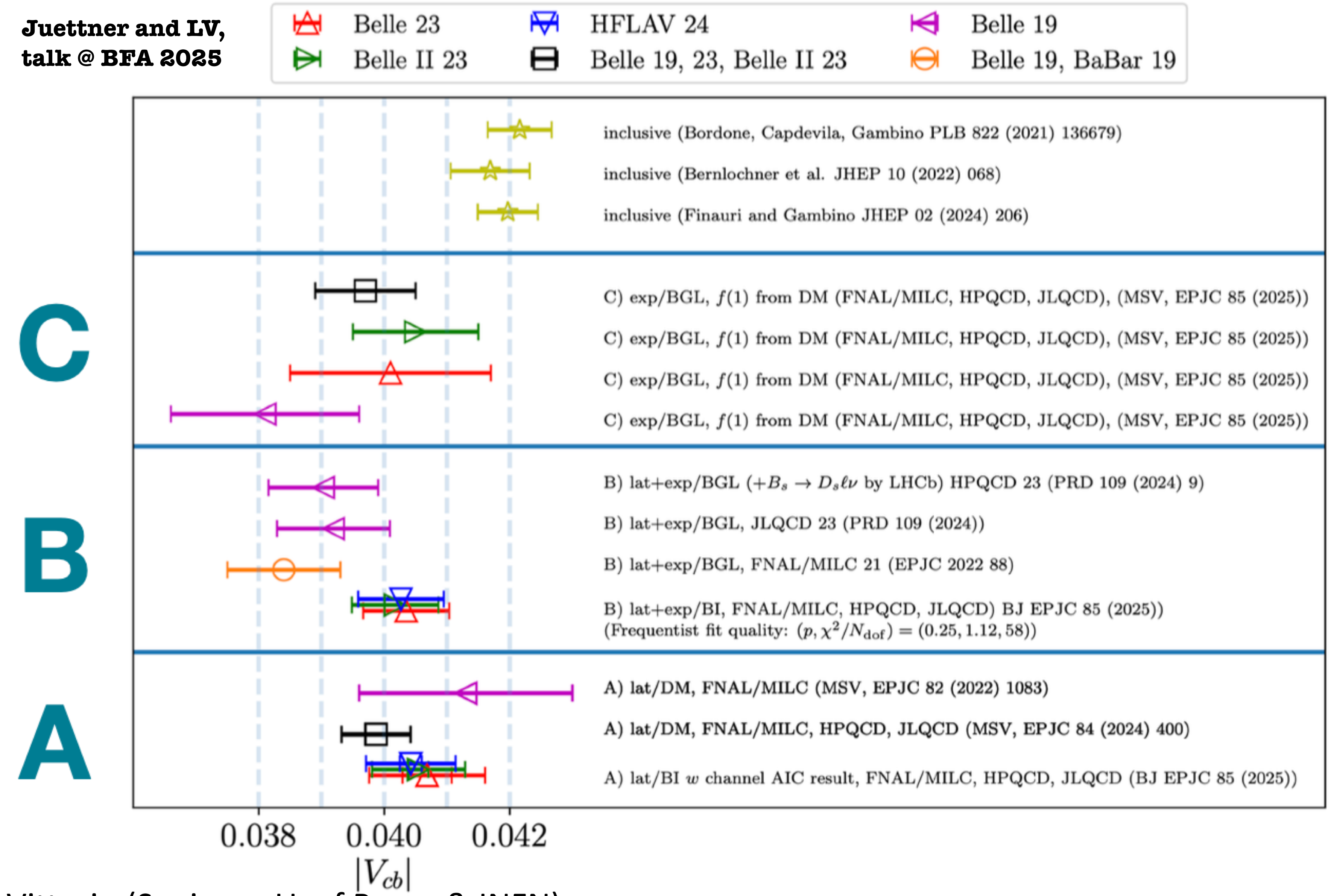


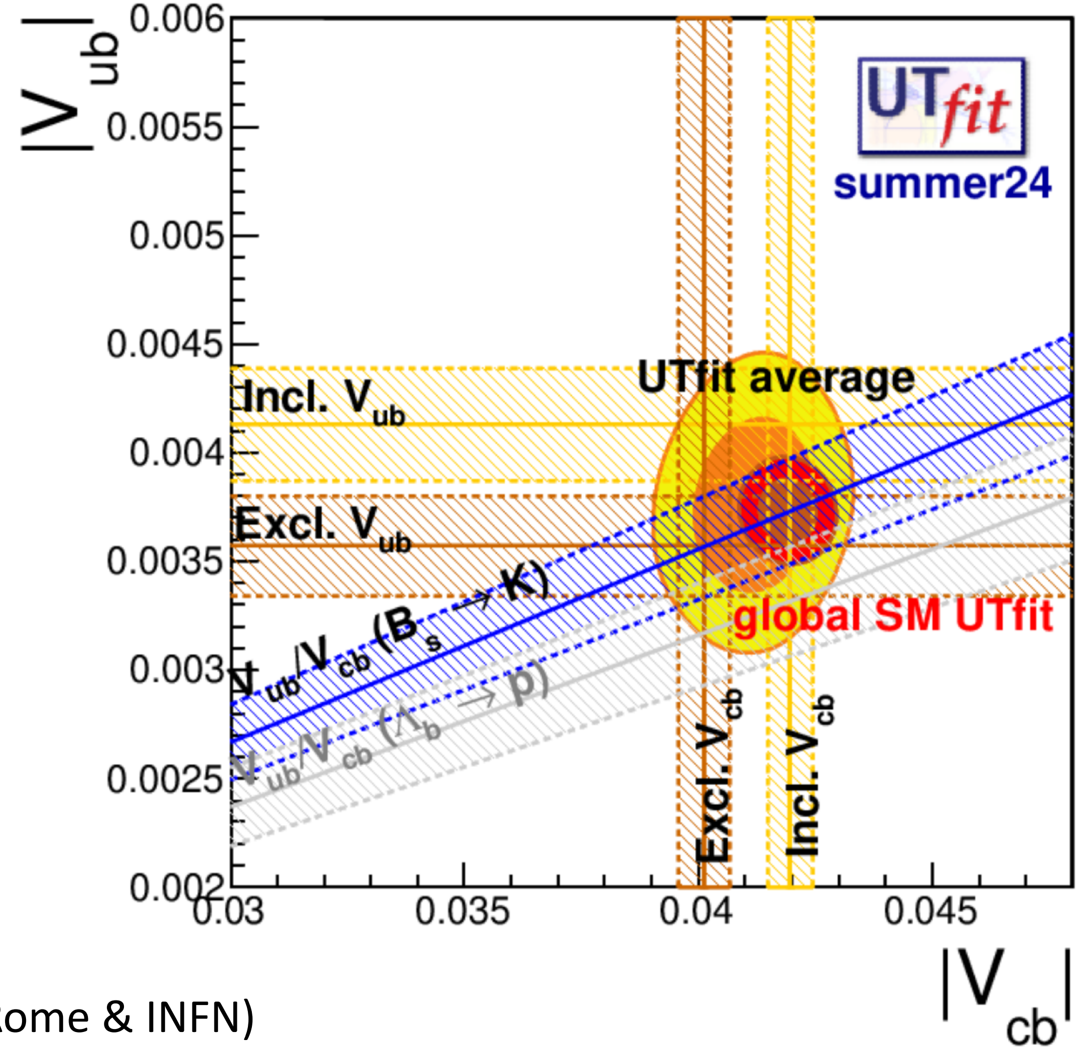
Nice consistency among strateg. A), B) and C)

Good compatibility with the inclusive determination as well

Summary of the results obtained so far: |Vcb| (and |Vub|)

Marcella Bona[1] Marco Ciuchini[2] Denis Derkach[3] Fabio Ferrari[4,5] Vittorio Lubicz[2,7] Guido Martinelli[6,8] Davide Morgante[9,10] Maurizio Pierini[11] Luca Silvestrini[6] Silvano Simula[2] Achille Stocchi[12] Cecilia Tarantino[2,7] Vincenzo Vagnoni[4] Mauro Valli[6] and Ludovico Vittorio[6,8]

www.utfit.org



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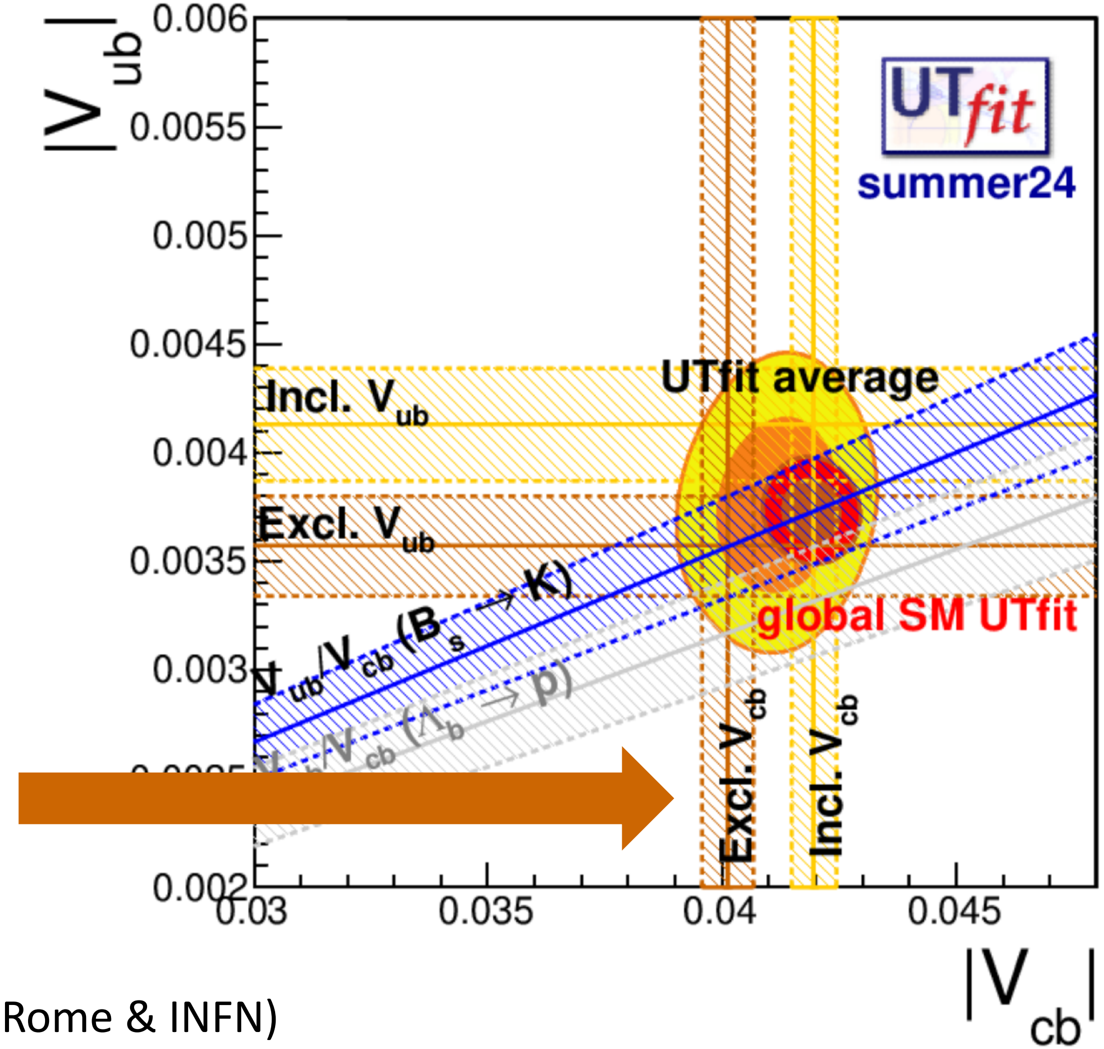

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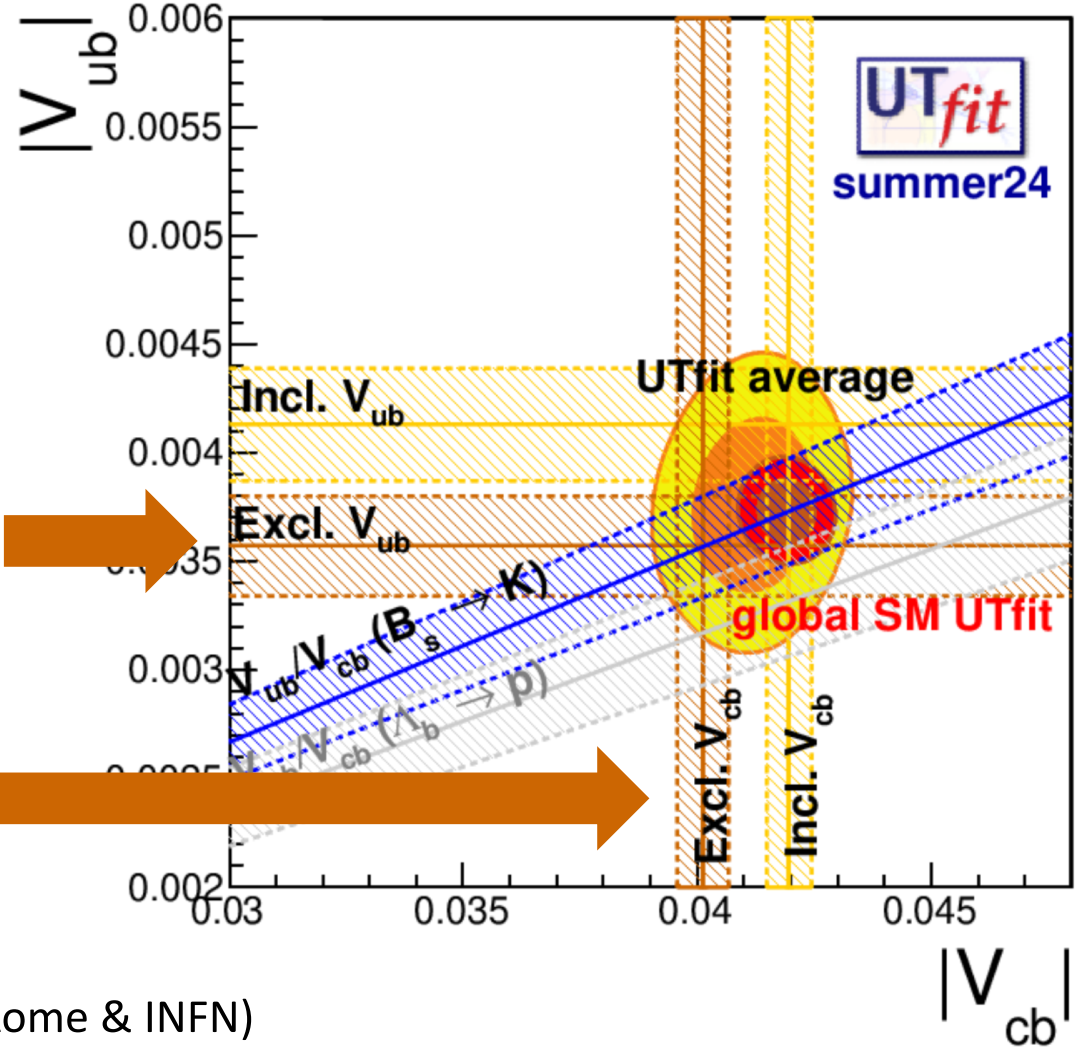

A similar analysis can be carried out for $|V_{ub}|$ ($B \to \pi$, $Bs \to K$)

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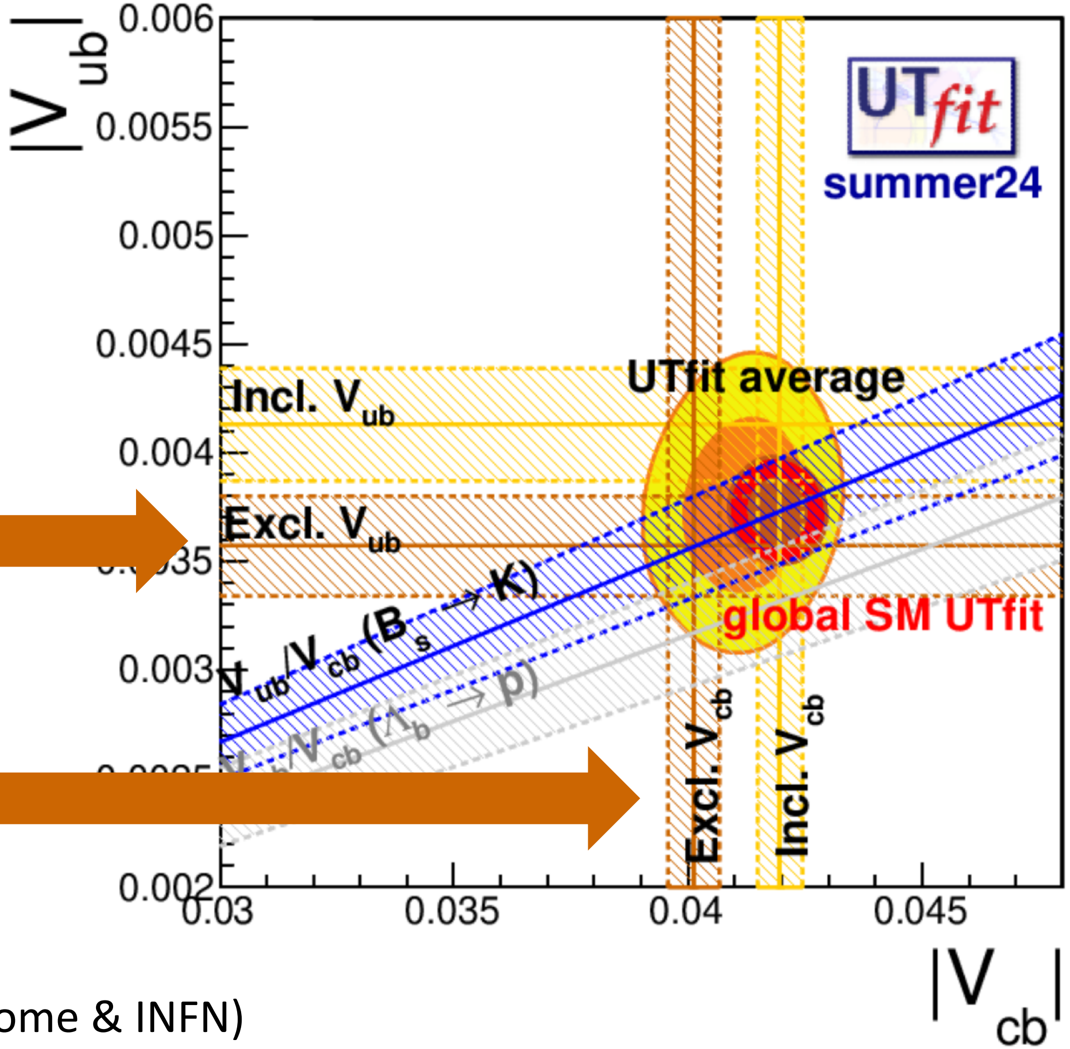

Inclusive values:

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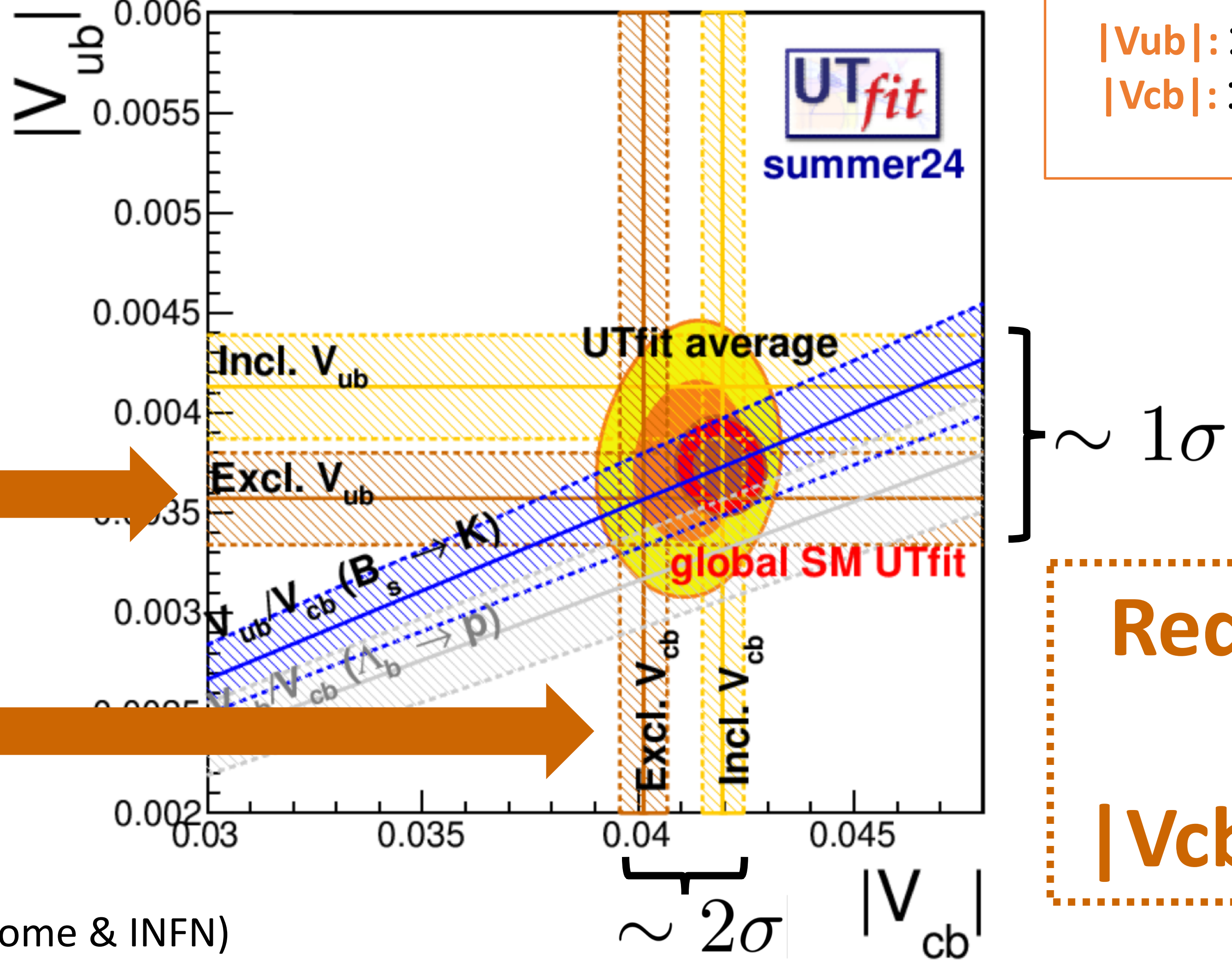


Reduced tensions in the |Vcb|-|Vub| plane

Flavour physics within and beyond the SM

Tree-level processes

FCNCs

$b \rightarrow c$ transitions

Flavour physics within and beyond the SM

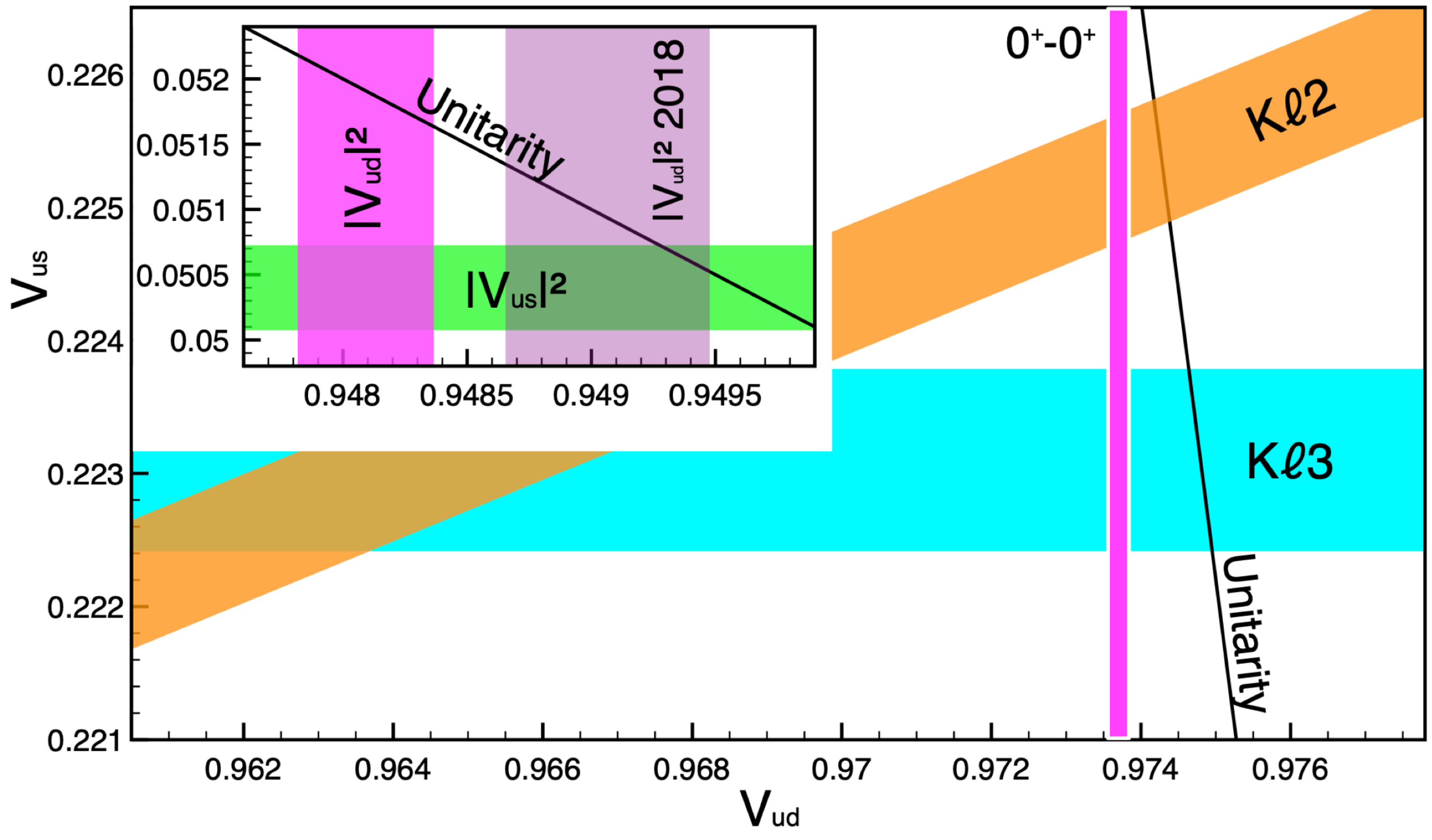
Tree-level processes

$b \rightarrow c$ transitions

|Vud| e |Vus|

FCNCs

Violation of unitarity in the 1st row ?



M. Gorshteyn, talk @ CKM23 conference

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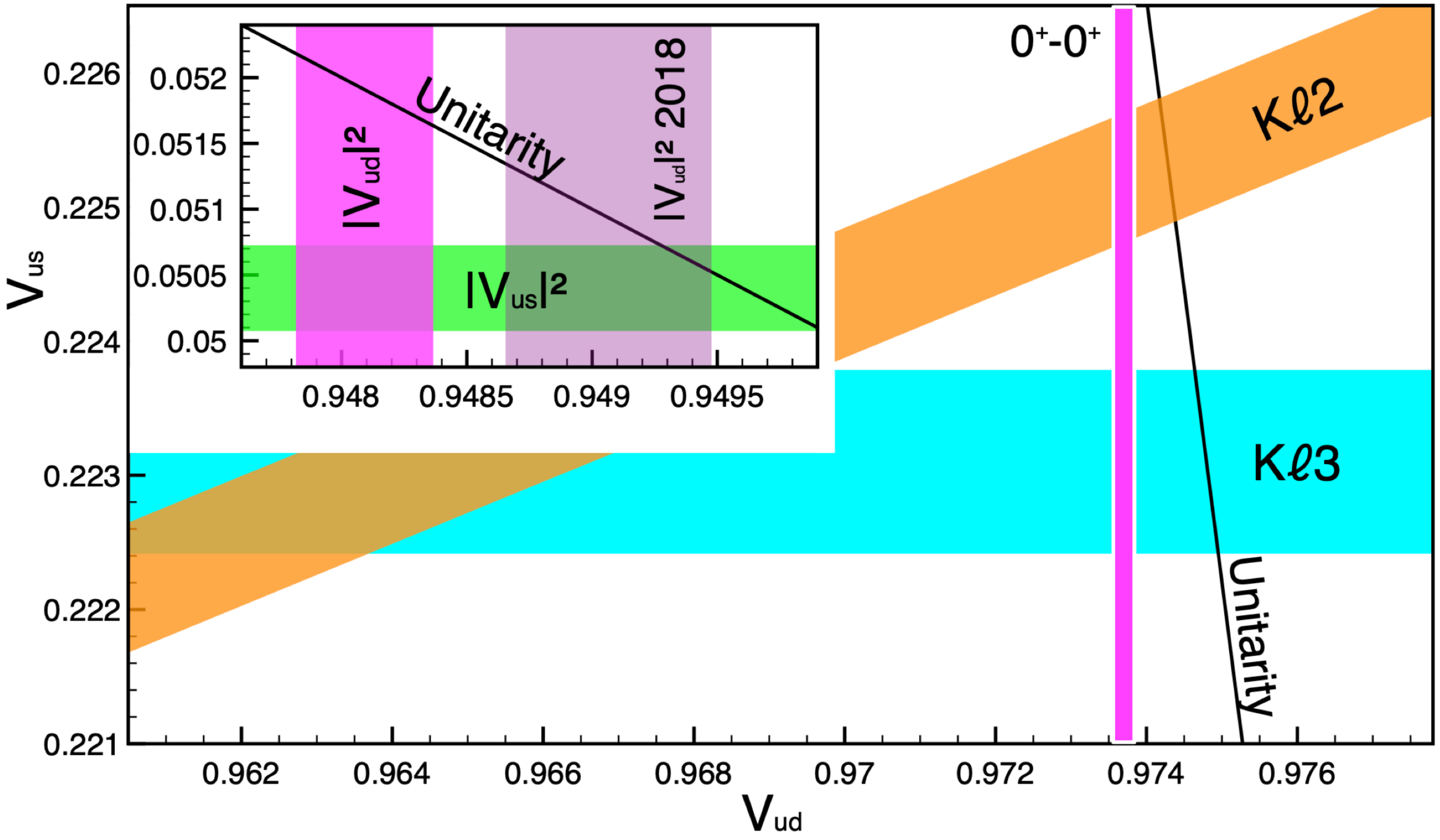

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$$\underbrace{|V_{ud}|^2}_{\sim 0.95} + \underbrace{|V_{us}|^2}_{\sim 0.05} + \underbrace{|\cancel{V_{ub}}|^2}_{\sim 10^{-5}} = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$

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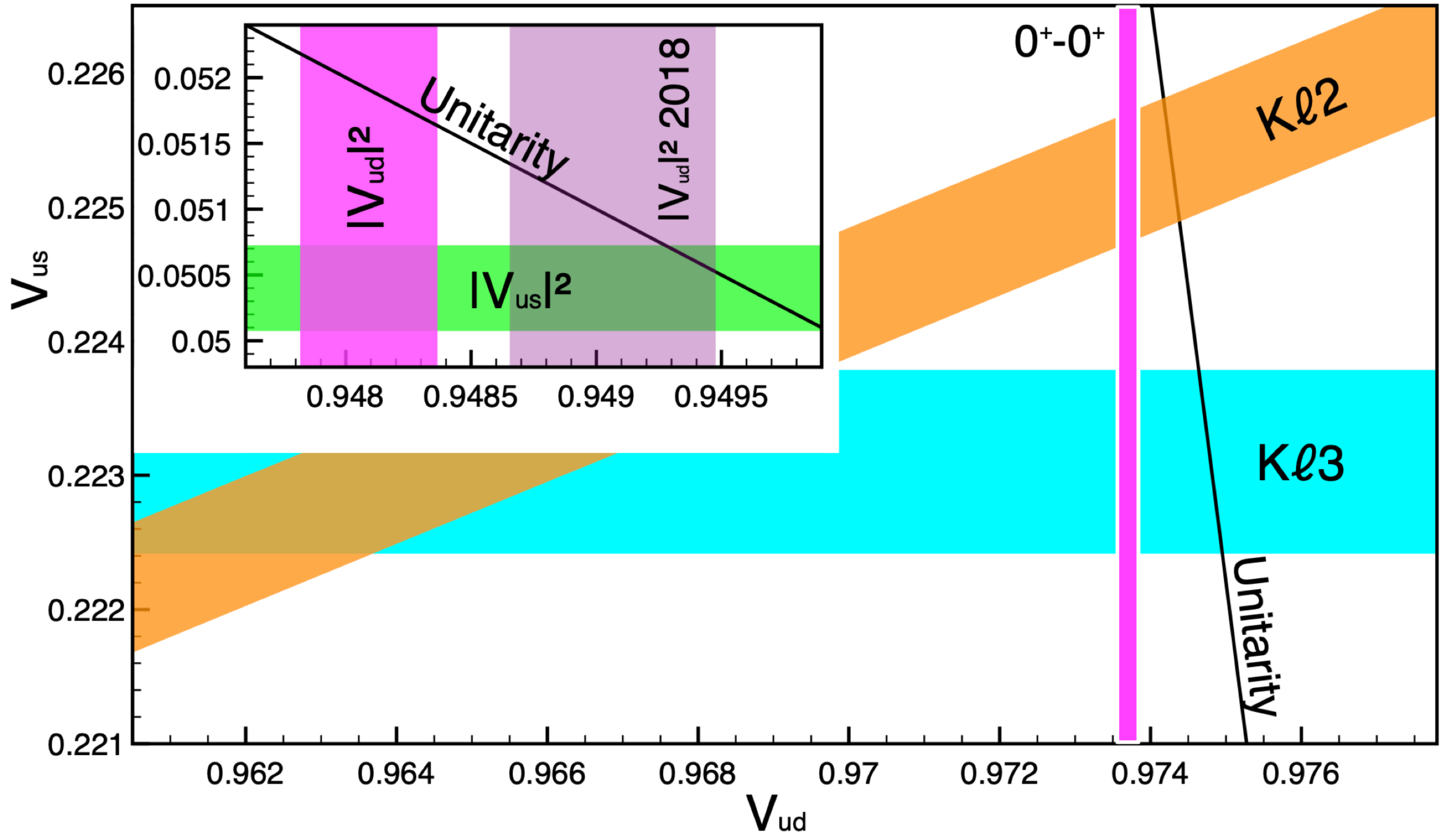

M. Gorshteyn, talk @ CKM23 conference

|Vud| e |Vus|
determinations show that:
1) there are mutual inconsistencies
2) there is an important tension with what would be the outcome of the Unitarity Triangle analysis

$$\underset{\sim 0.95}{|V_{ud}|^2} + \underset{\sim 0.05}{|V_{us}|^2} + \underset{\sim 10^{-5}}{|\cancel{V_{ub}}|^2} = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$

How to precisely determine |Vud| e |Vus|

For what concerns|Vud|:

M. Gorshteyn, talk @ CKM23 conference

- **Super allowed 0^+-0^+ decays (es.: $^{14}O \rightarrow {}^{14}N$)**

$$|V_{ud}^{0^+-0^+}| = 0.97370\,(1)_{exp,\,nucl}\,(3)_{NS}\,(1)_{RC}[3]_{total}$$

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An important improvement of exp. precision is expected at PIONEER (2203.01981)

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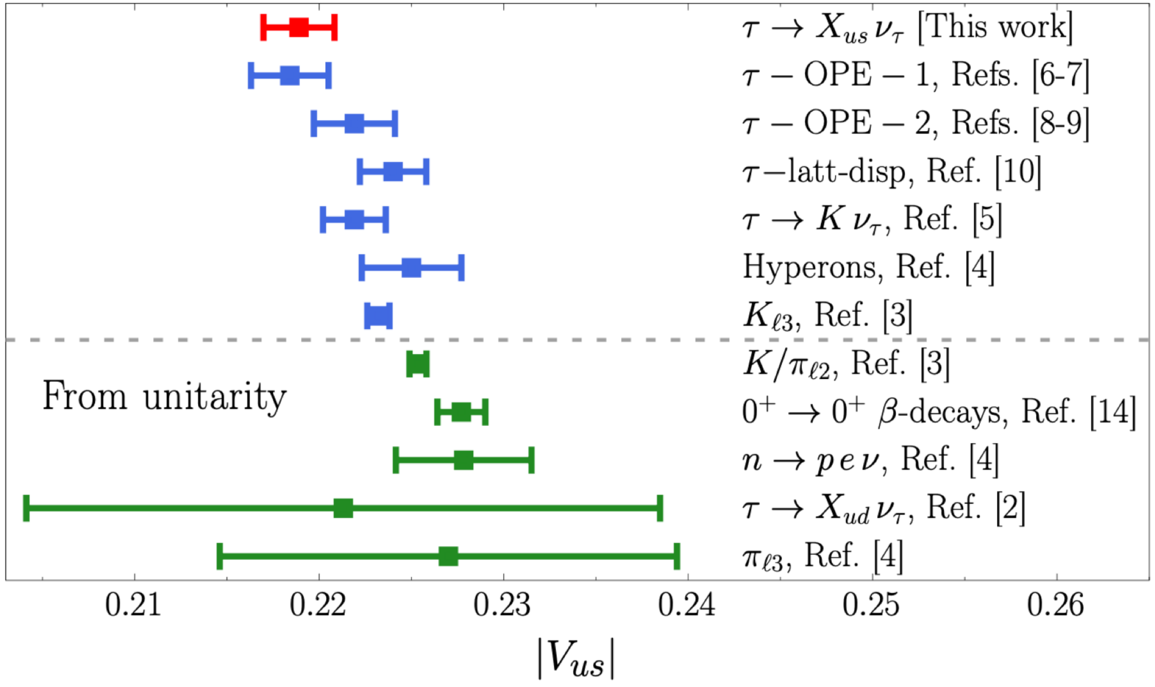

ETMC Collaboration, PRL '24 [arXiv:2403.05404]

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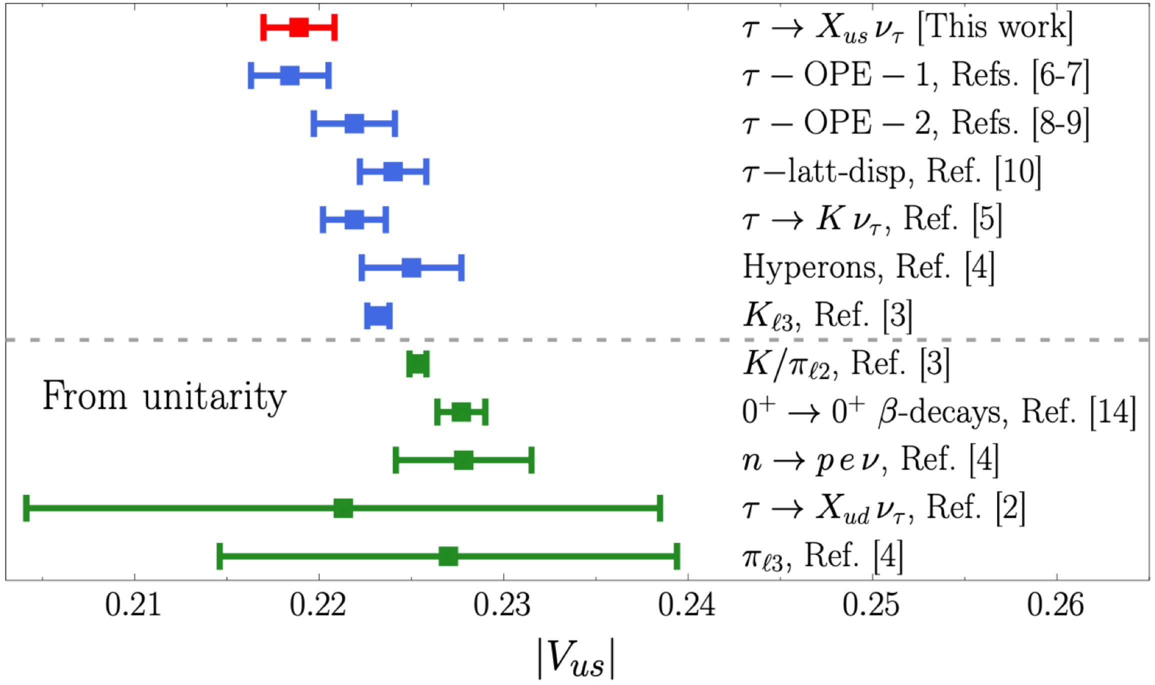

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Considering as many channels as possible will be very helpful in the future!

Flavour physics within and beyond the SM

Tree-level processes

$b \rightarrow c$ transitions

|Vud| e |Vus|

FCNCs

Flavour physics within and beyond the SM

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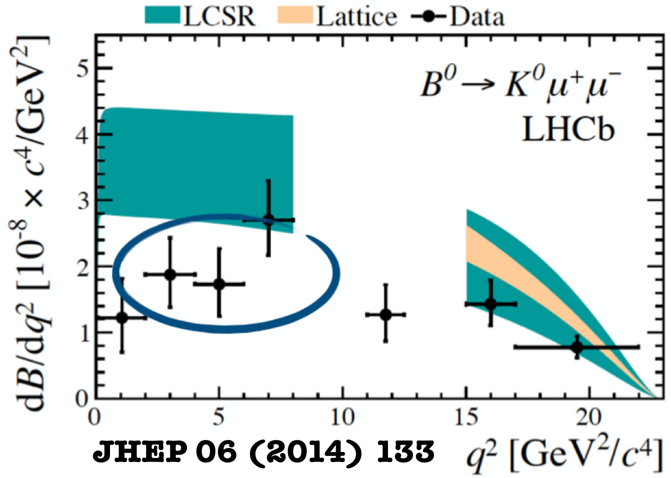
$b \to c$ transitions

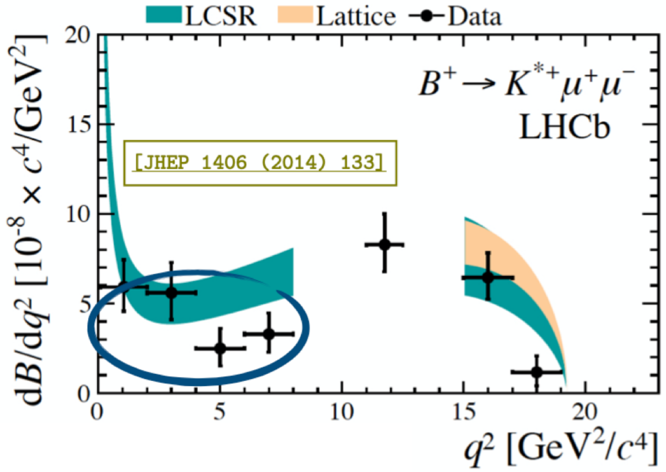
$b \to s\ell^+\ell^-$

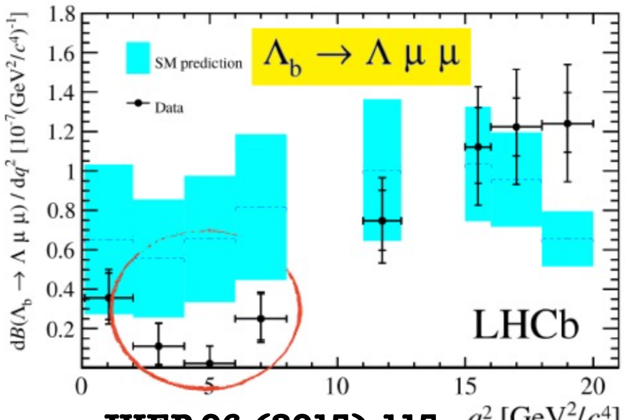
|Vud| e |Vus|

Still some tensions (?) in $b \to s$ quark transitions



JHEP 06 (2014) 133





JHEP 06 (2015) 115

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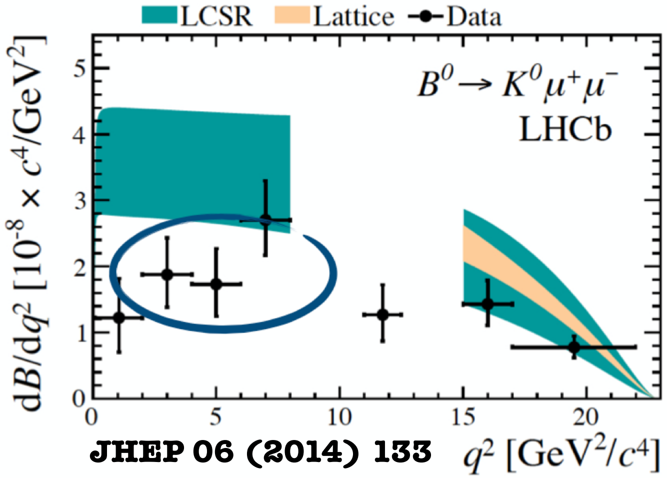
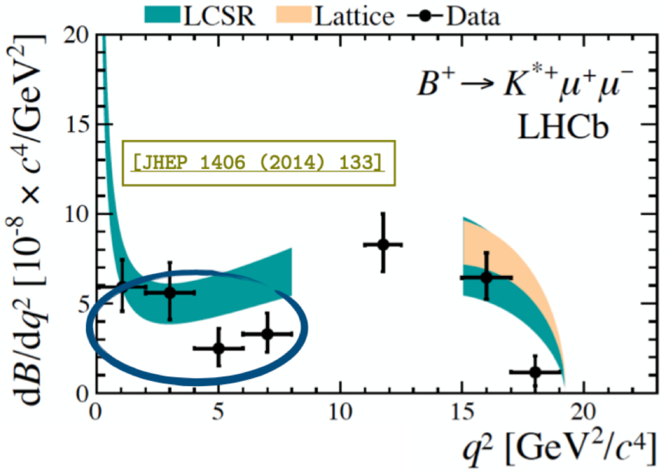
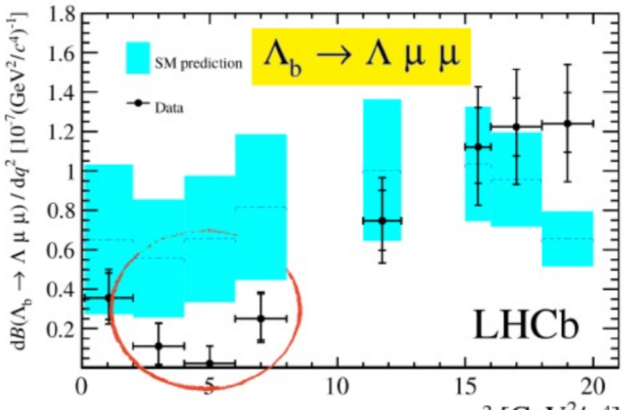


JHEP 06 (2014) 133





JHEP 06 (2015) 115

The pattern is:
TH. > EXP.
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Are we sure ?

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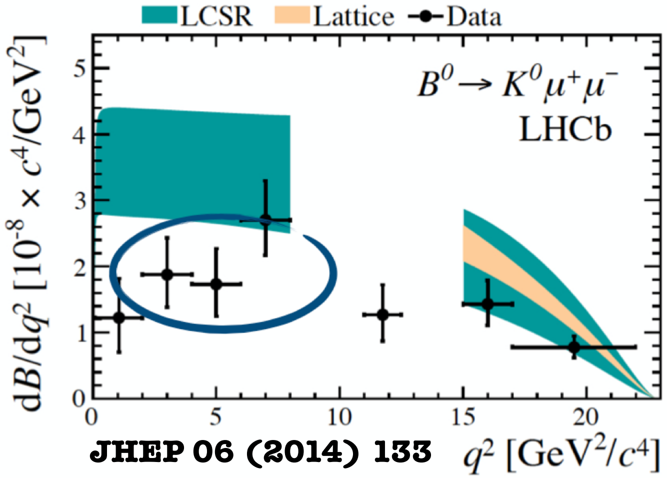
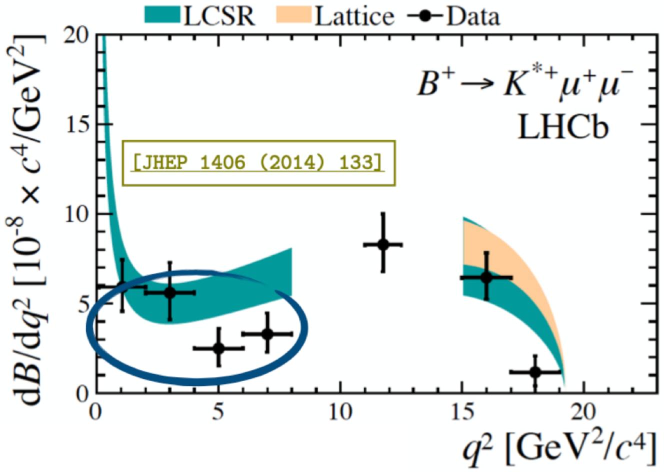
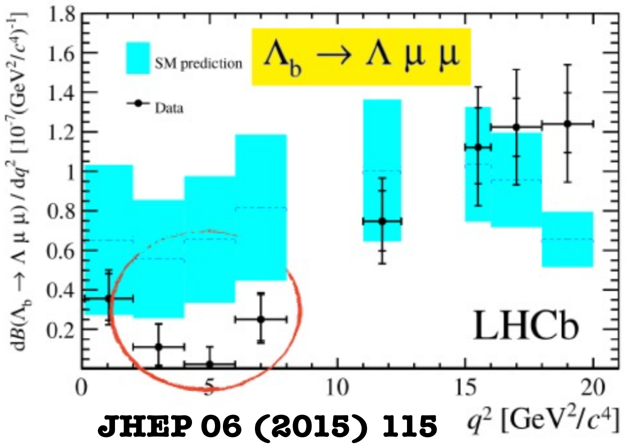


JHEP 06 (2014) 133





JHEP 06 (2015) 115

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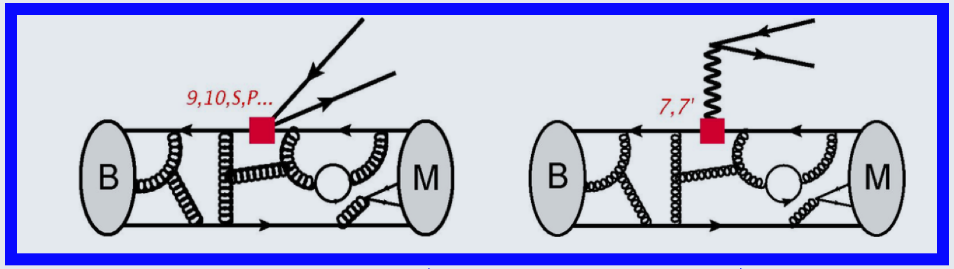
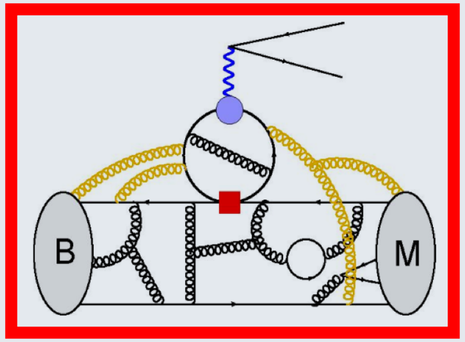
$$\mathcal{H}(b \to s\ell\ell) = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$





$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10})\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}\left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)\right]\right\}$$

local form-factors

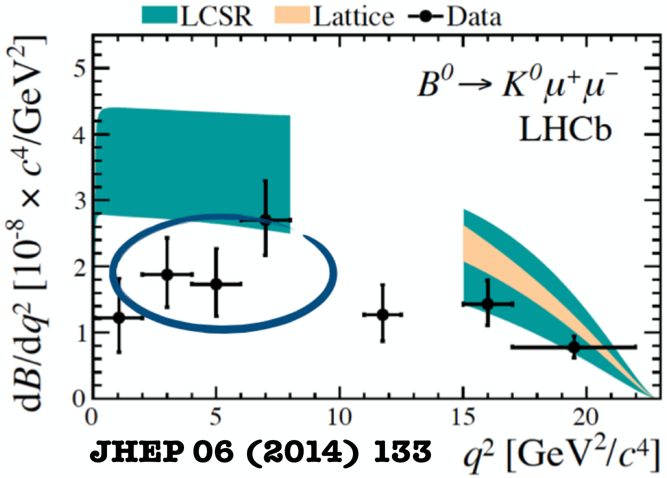
$$\mathcal{F}_\mu(k,q) = \langle \bar{M}(k)|\bar{s}\gamma_\mu b_L|\bar{B}(q+k)\rangle$$

$$\mathcal{H}_\mu(k,q) = i\int d^4x\, e^{iq\cdot x}\langle \bar{M}(k)|T\{\mathcal{J}_\mu^{\rm em}(x), \mathcal{C}_i\mathcal{O}_i\}|\bar{B}(q+k)\rangle$$

Non-local form-factors

M. Reboud's talk @ LHC Impilication Workshop 2022 @ CERN

Still some tensions (?) in $b \to s$ quark transitions



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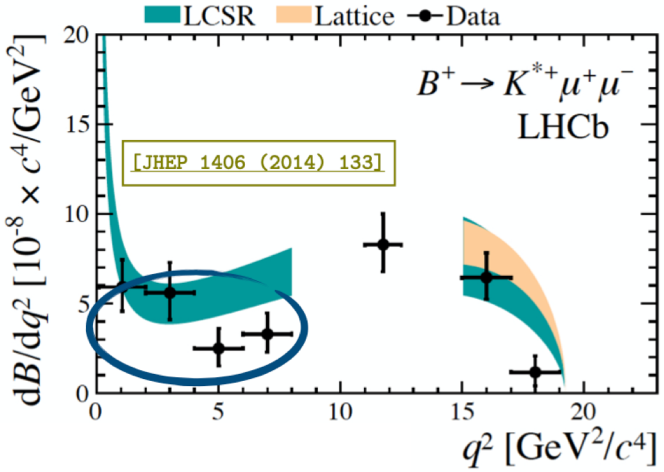

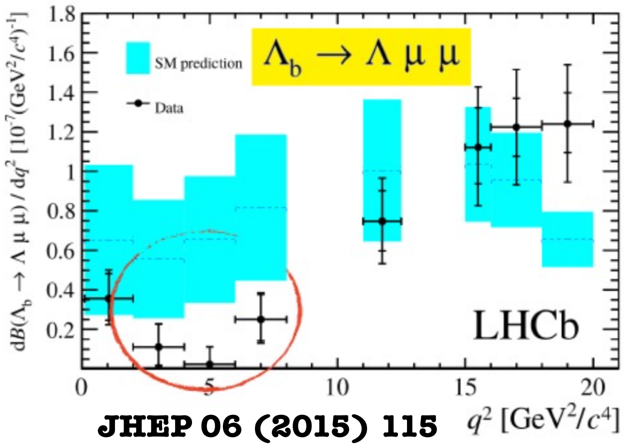

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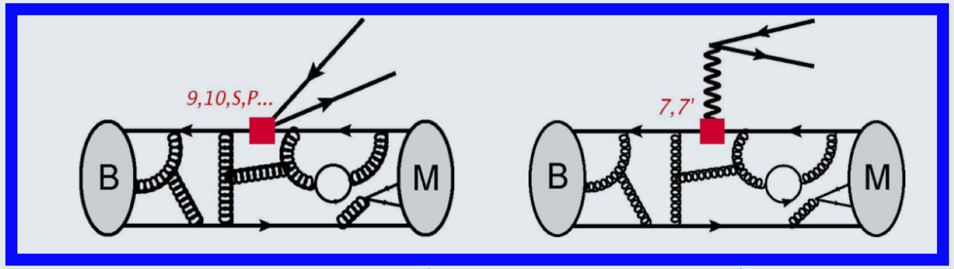

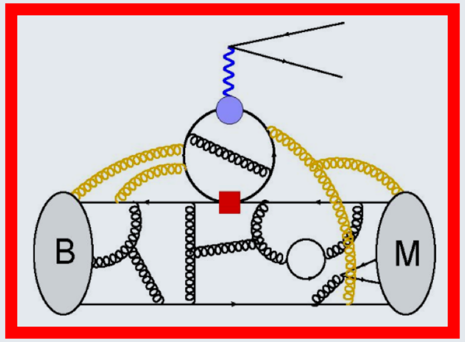

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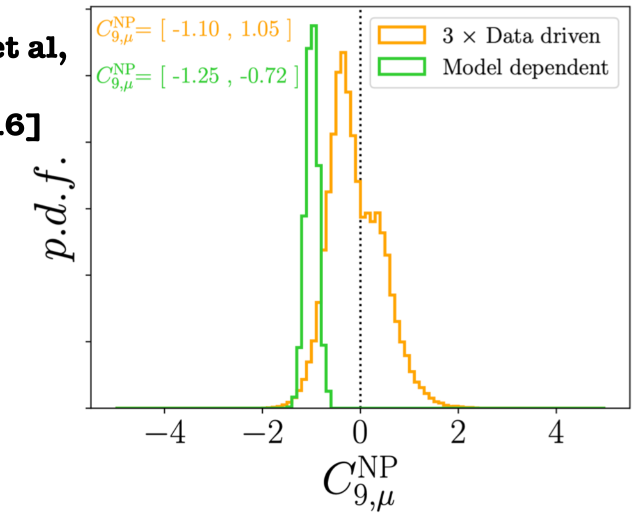
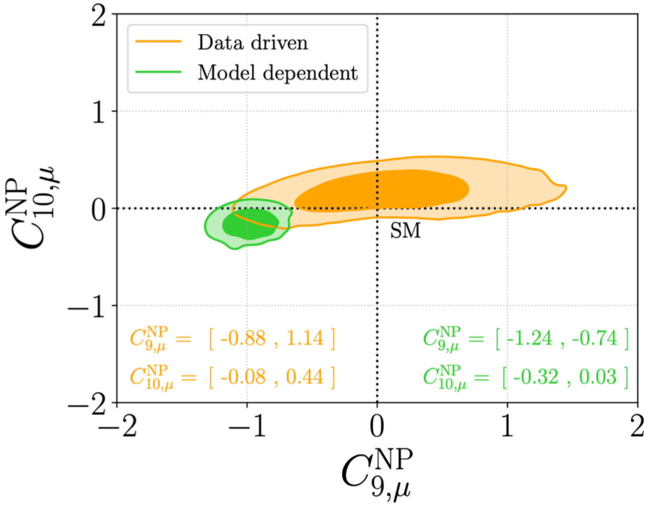
Non-local form-factors

Which is the exact contribution from non-local FFs?

No general consensus on the answer to this question:

M. Ciuchini et al, PRD '23 [2212.10516]





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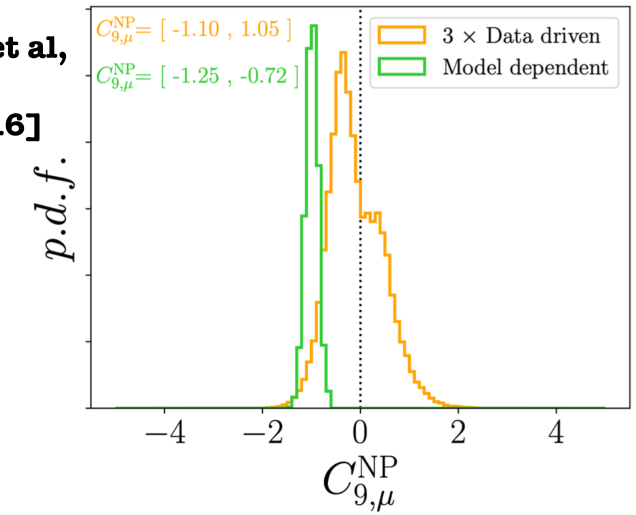

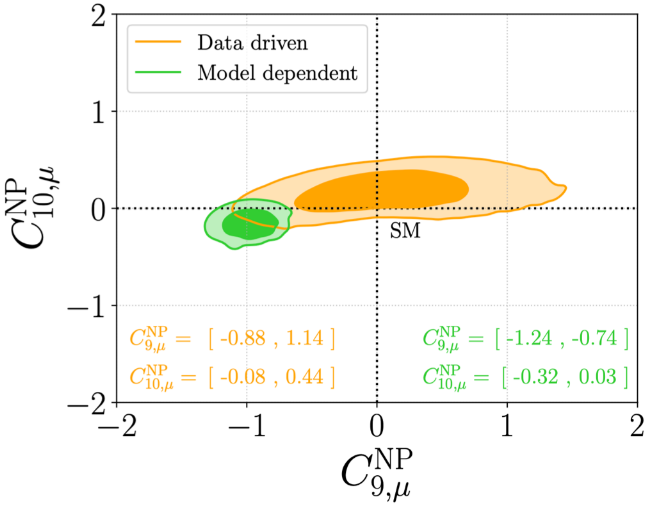

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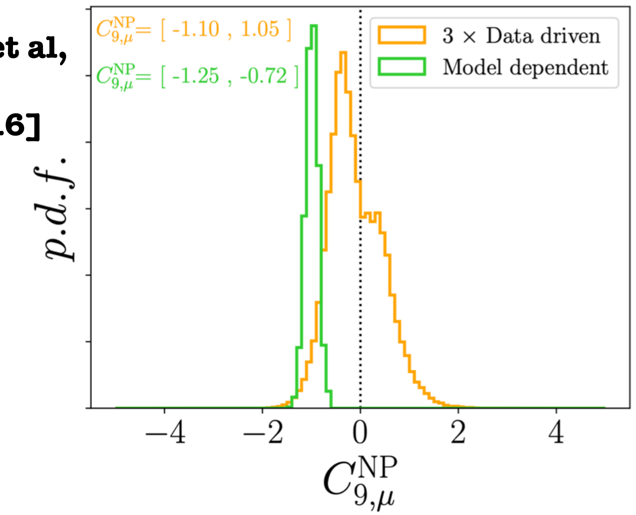

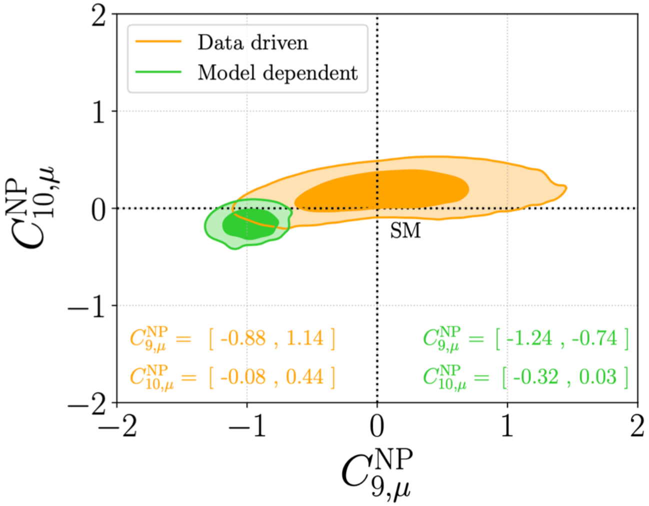

The «hypothetical» presence of NP seems to depend on the assumptions made on hadronic effects !

Data-driven: naïve expansion in q^2:

$$H_V^- \propto \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM}+h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}\, q^4\right] + \left(C_9^{\rm SM}+h_-^{(1)}\right)\widetilde{V}_{L-}\,,$$

Advantage: clear interplay among hadronic contributions and NP !

M. Ciuchini et al, JHEP '16 [1512.07157], EPJC '17 [1704.05447], EPJC '19 [1903.09632], PRD '21 [2011.01212], EPJC '23 [2110.10126], PRD '23 [2212.10516]

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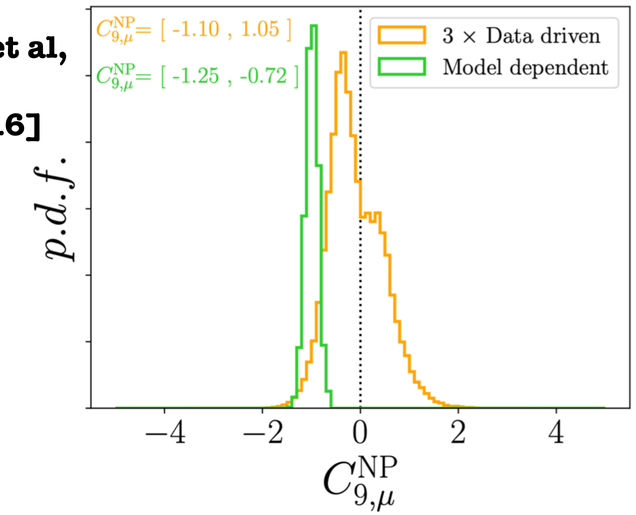

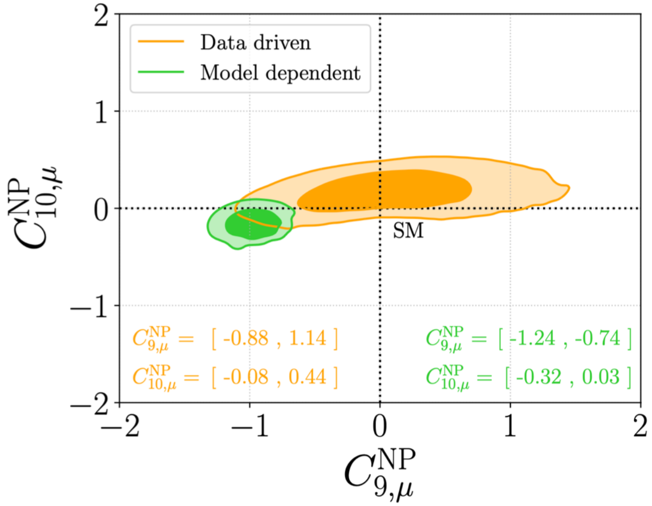

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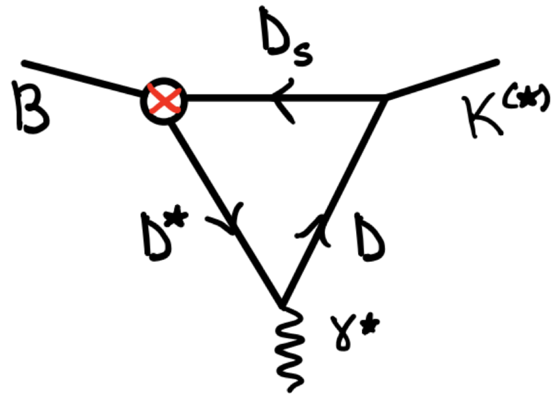
Model-depedent: the *h*-terms $[h_-^{(0)}, h_-^{(1)}, h_-^{(2)}]$ are *set to zero*.

Motivation: this assumption is supported by the results of the **application of dispersion relations, analiticity and unitarity (together with LCSR data)** to the description of non-local FFs!

C. Bobeth et al, EPJC '18 [1707.07305]
M. Chrzaszcz et al, JHEP '19 [1805.06378]
N. Gubernari et al, JHEP '21 [2011.09813], JHEP '22 [2206.03797], 2305.06301

Possible prospects for the future

i) Developments of new strategies to apply unitarity constraints on re-scattering diagrams (absent in present dispersive studies):



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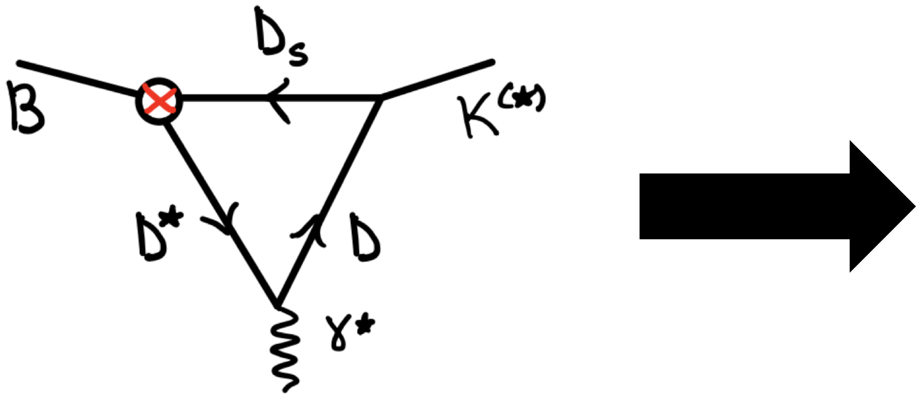
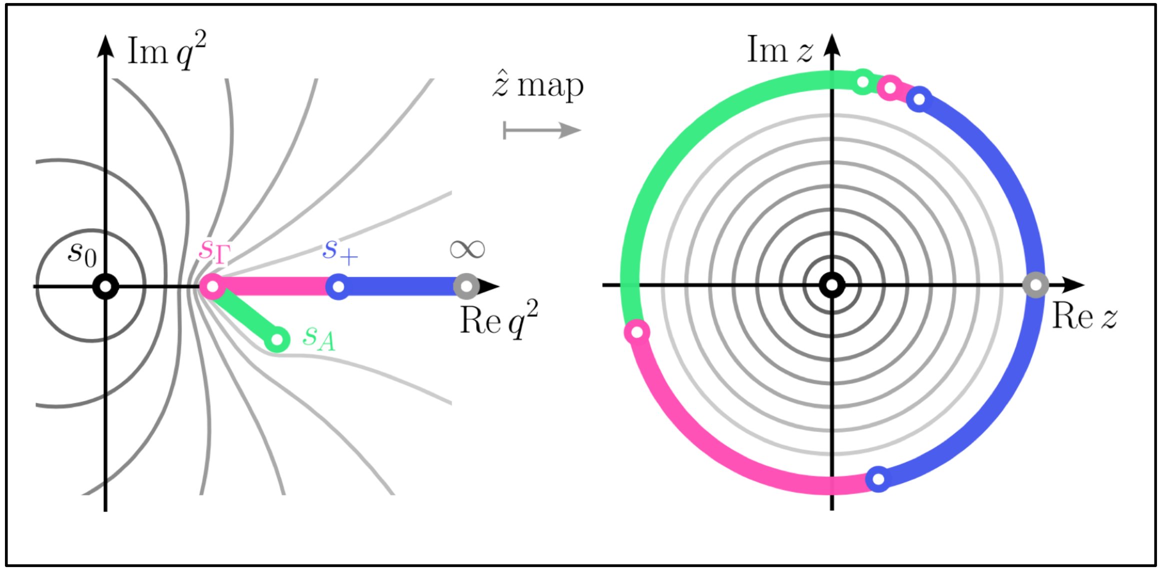
i) Developments of new strategies to apply unitarity constraints on re-scattering diagrams (absent in present dispersive studies):





Gopal, Gubernari, PRD '25 [2412.04388]
(See also **Mutke et al., JHEP '24 [2406.14608]**)

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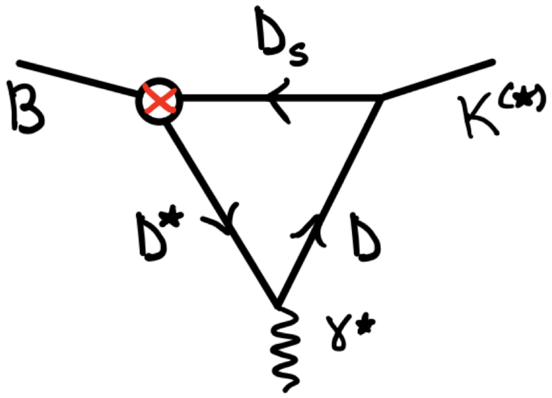

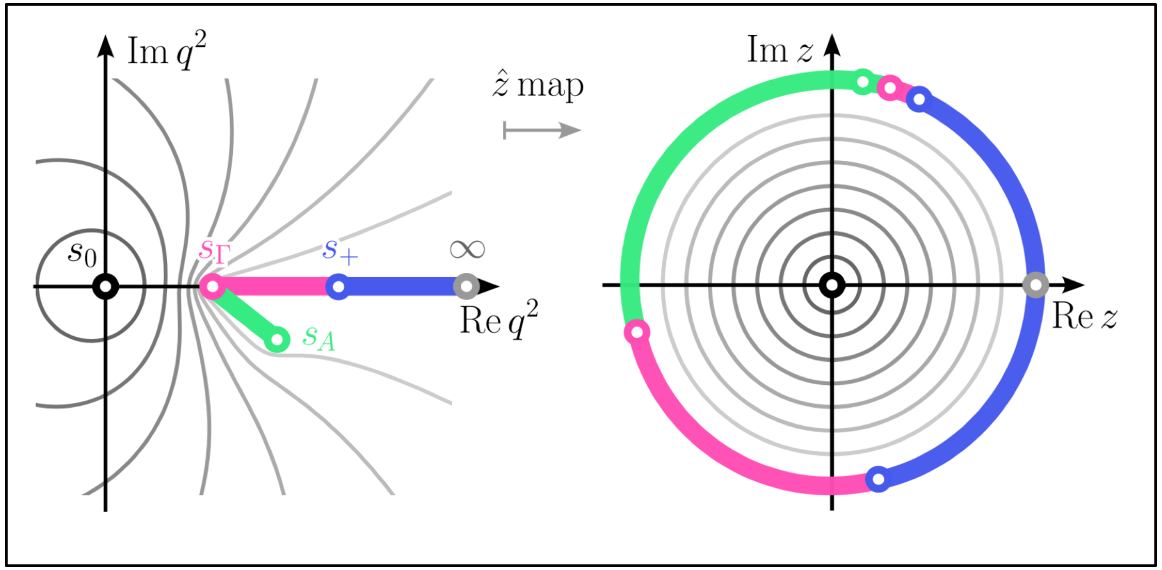

Gopal, Gubernari, PRD '25 [2412.04388]
(See also **Mutke et al., JHEP '24 [2406.14608]**)

ii) Look at novel channels which should be affected by the same (hypothetical) NP effects: Bs → $\mu\mu\gamma$ @ high-q2

Guadagnoli, et al., JHEP '23 [2303.02174, 2308.00034]
ETMC Collaboration, PRD '24 [2402.03262]
LHCb Collaboration, JHEP '24 [2404.03375]

Flavour physics within and beyond the SM

Tree-level processes

$b \rightarrow c$ transitions

|Vud| e |Vus|

FCNCs

$b \rightarrow s\ell^+\ell^-$

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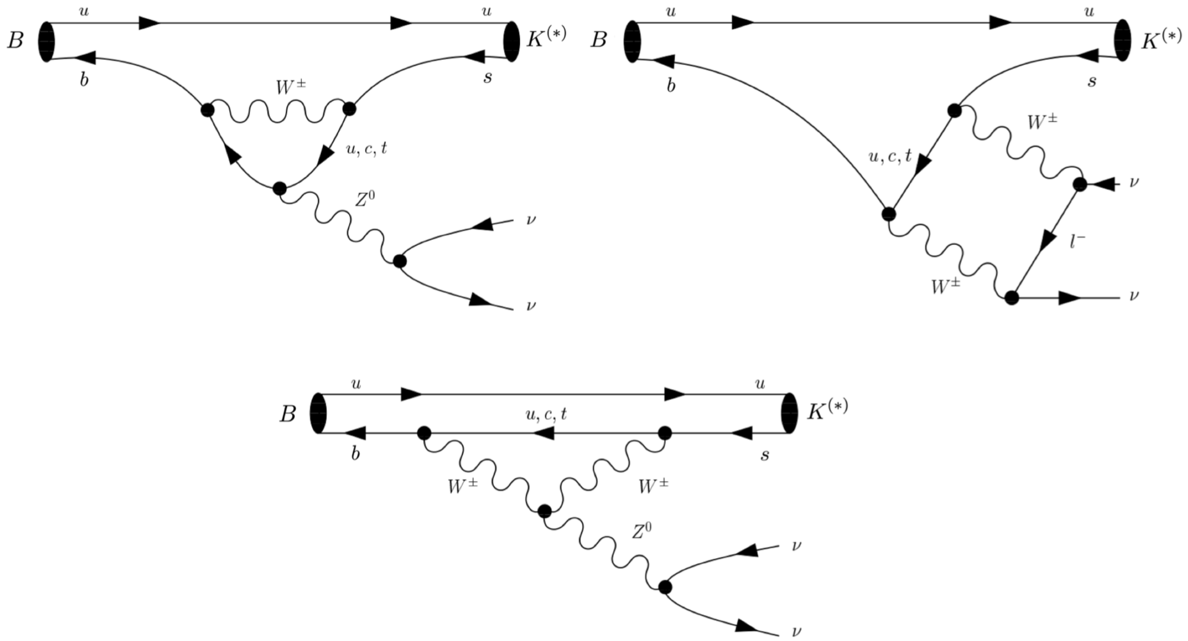
Rare semileptonic decays with di-neutrino final states

i) B → K(*)$\nu\nu$: long-distance (LD) effects are much smaller than in B → K(*)ℓ⁺ℓ⁻ !

Major sources of uncertainty:

1. **|Vcb| value (related to the |Vcb| puzzle)**
2. **Hadronic effects (i.e. FFs)**



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D. Becirevic, G. Piazza & O. Sumensari, EPJC '23 [arXiv:2301.06990]

to be compared with

$$\boxed{\mathcal{B}\left(B^{+} \to K^{+}\nu\bar{\nu}\right)\Big|_{\text{Belle-II}} = (2.4 \pm 0.7) \times 10^{-5}}$$

Belle-II Collaboration, PRD '24 [2311.14647]

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Tension in B → K$\upsilon\upsilon$: 2.8σ

→

Several NP studies:

Berezhnoy, Melikhov, EPL '24 [2309.17191]
Marzocca et al, EPJC '24 [2404.06533]
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ii) K → $\pi\nu\nu$: see Giancarlo's presentation for all the details

Flavour physics within and beyond the SM

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$|V_{ud}|$ e $|V_{us}|$

FCNCs

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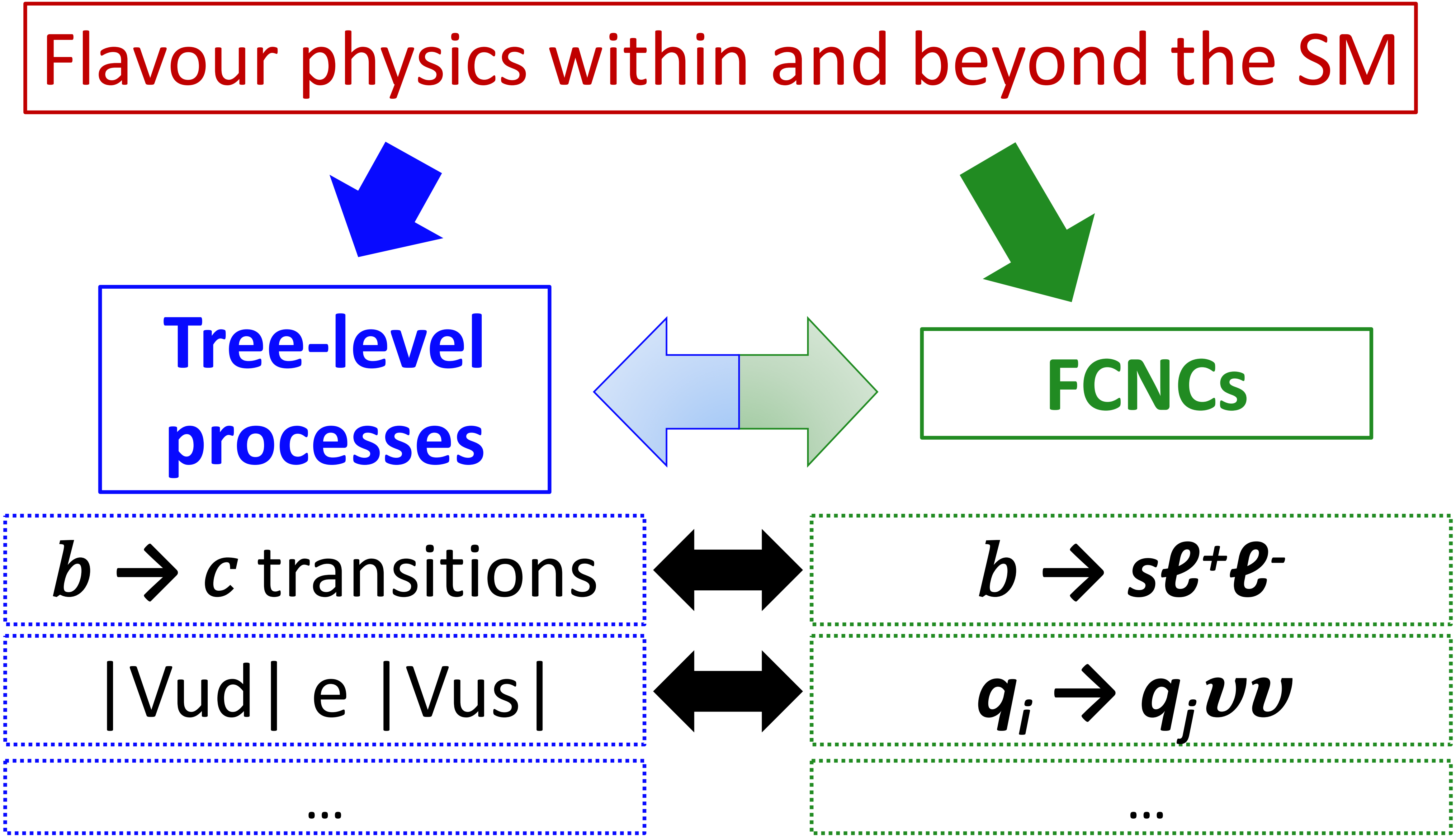

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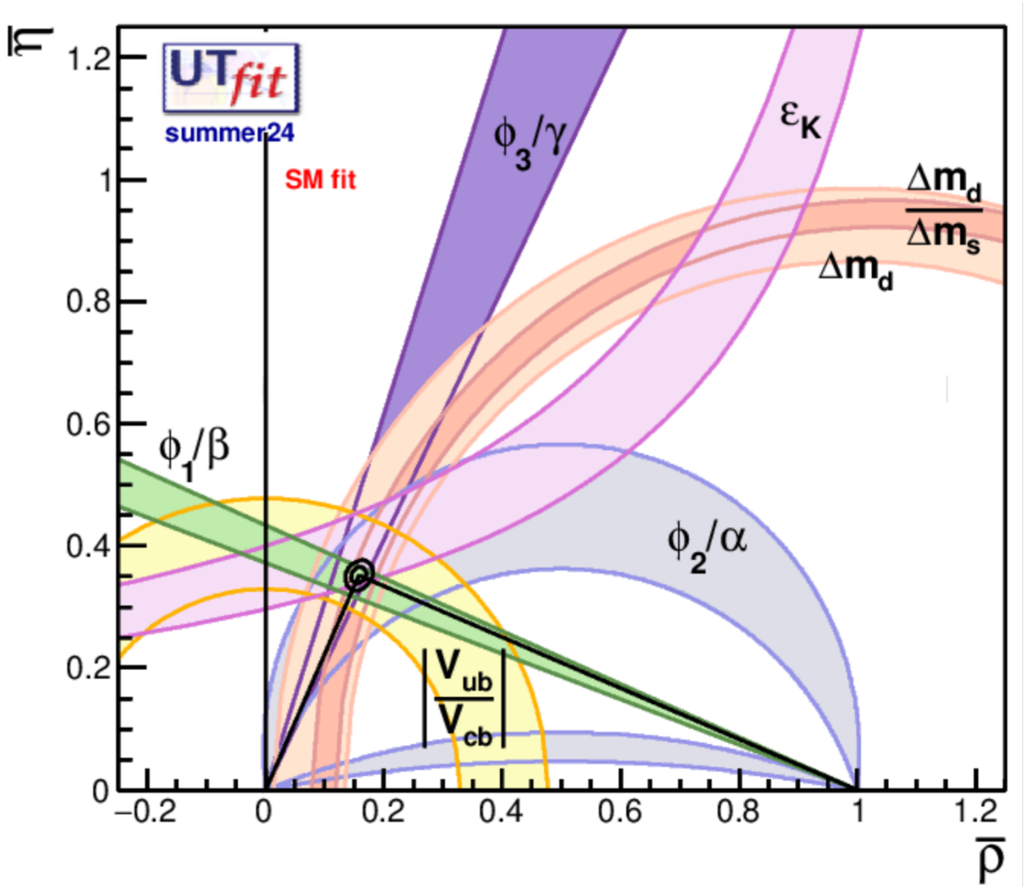
Unitarity triangle as a way to improve precision

www.utfit.org

Marcella Bona[1] Marco Ciuchini[2] Denis Derkach[3] Fabio Ferrari[4,5] Vittorio Lubicz[2,7] Guido Martinelli[6,8] Davide Morgante[9,10] Maurizio Pierini[11] Luca Silvestrini[6] Silvano Simula[2] Achille Stocchi[12] Cecilia Tarantino[2,7] Vincenzo Vagnoni[4] Mauro Valli[6] and Ludovico Vittorio[6,8]



$\bar\rho = 0.158 \pm 0.009$

$\bar\eta = 0.352 \pm 0.010$

$\lambda = 0.2250 \pm 0.0007$

$A = 0.826 \pm 0.009$

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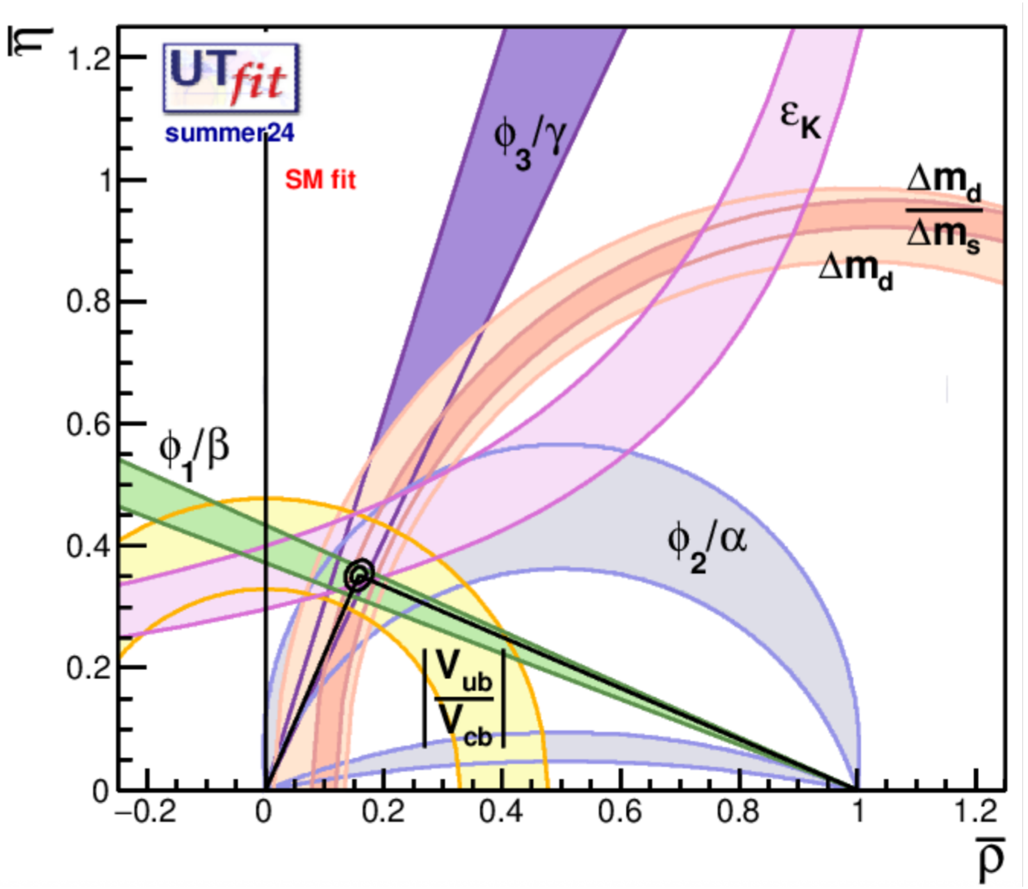

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Status of the UT analysis in the SM :

1. Overall consistency of the SM fit
2. Reached precision of 5% (3%) on $\bar{\rho}$ ($\bar{\eta}$)

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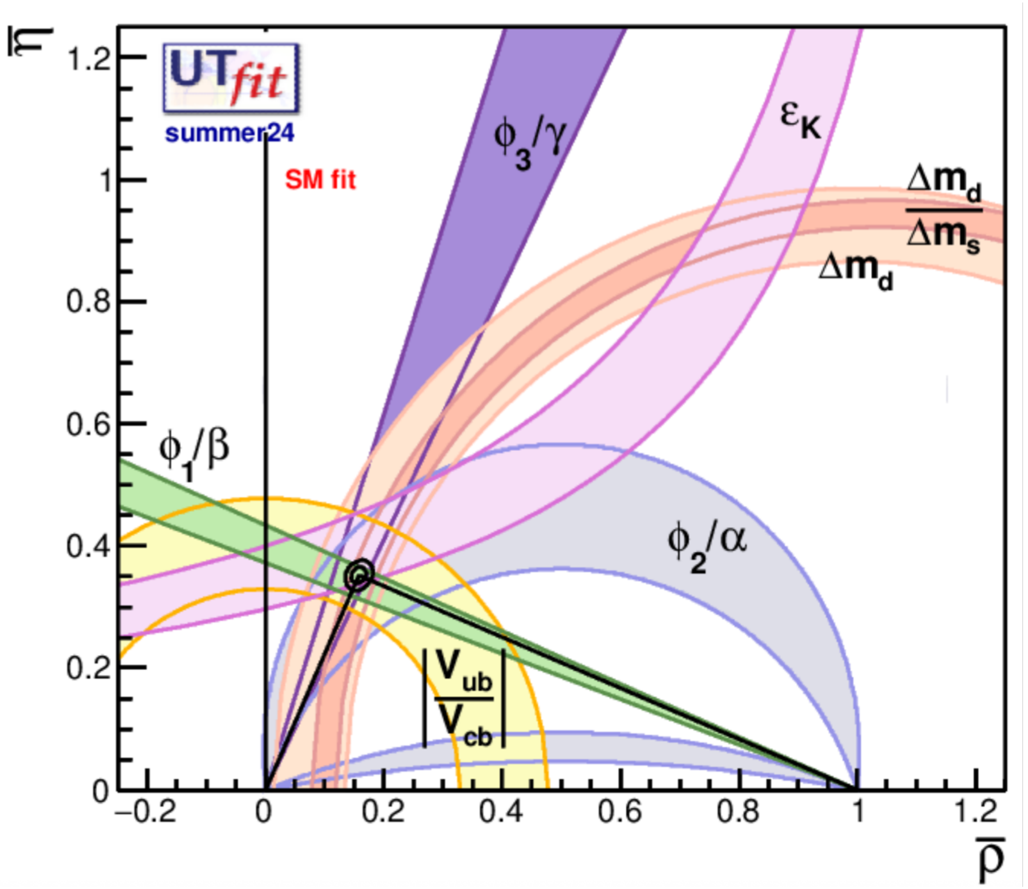
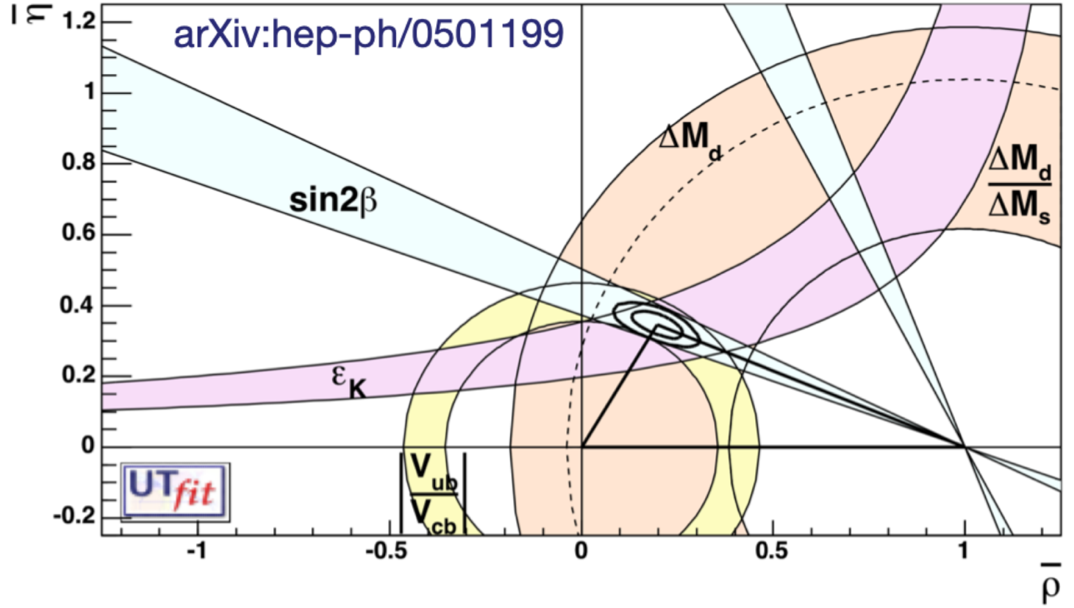


UTfit 2005:



$$\bar\rho = 0.196 \pm 0.045 \sim 23\%$$
$$\bar\eta = 0.347 \pm 0.025 \sim 7\%$$

Compatibility plots to verify consistency

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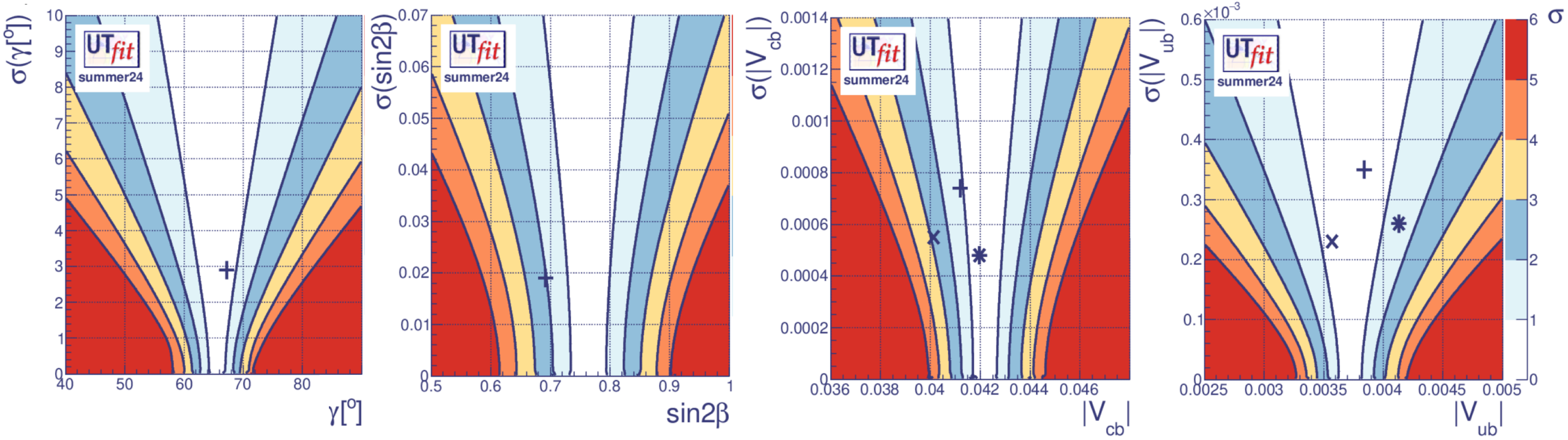
A way to "measure" the agreement of a single measurement with the indirect determination from the fit (using the other inputs):



- **Colour code:** agreement between the predicted values and the measurements at better than 1, 2, ...nσ
- The crosses have the **coordinates (x,y)=(central value, error) of the direct measurements**

x = exclusive
∗ = inclusive

Compatibility plots to verify consistency

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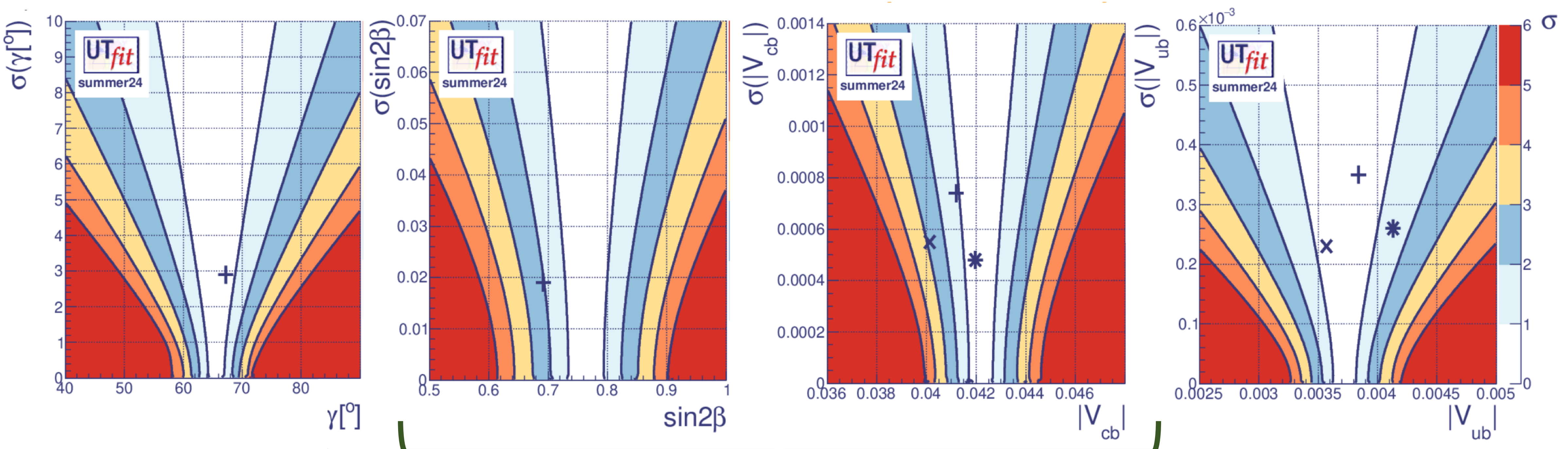

Still some tensions in these two cases …

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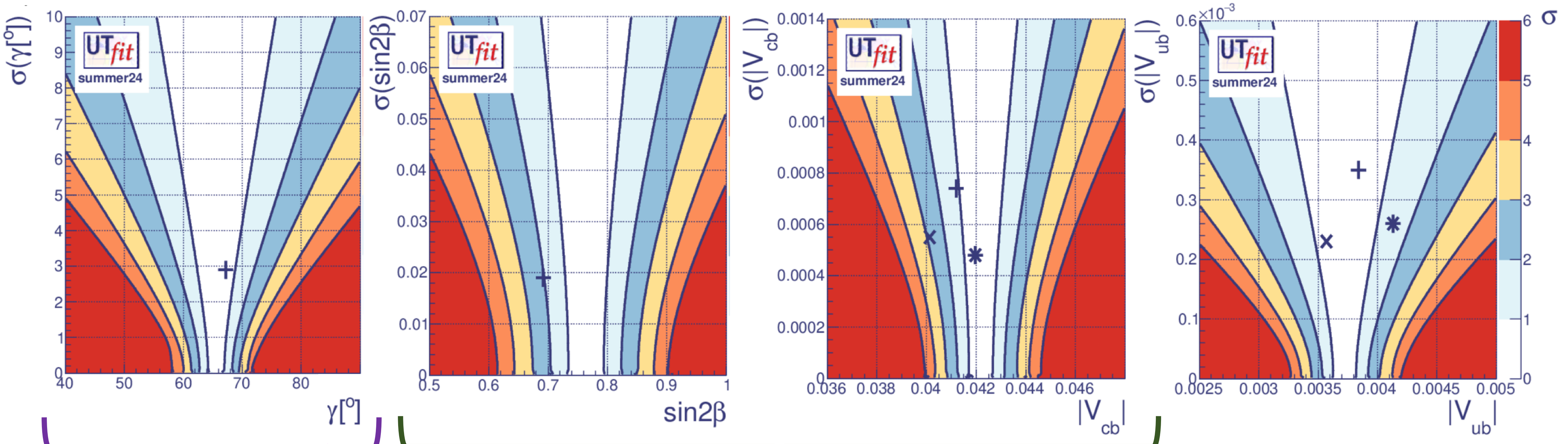

Novel analysis of beauty decays and of D-meson mixing data in 2409.06449

Still some tensions in these two cases …

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Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.692 ± 0.019	0.763 ± 0.030	~ 2
γ	67.2 ± 2.9	65.6 ± 1.4	< 1
α	95 ± 8	91.4 ± 1.4	< 1
$\|V_{cb}\| \cdot 10^3$	41.20 ± 0.74	42.19 ± 0.48	~ 1.1
$\|V_{cb}\| \cdot 10^3$ (excl)	40.13 ± 0.55		~ 2.8
$\|V_{cb}\| \cdot 10^3$ (incl)	41.97 ± 0.48		< 1
$\|V_{ub}\| \cdot 10^3$	3.84 ± 0.35	3.72 ± 0.10	< 1
$\|V_{ub}\| \cdot 10^3$ (excl)	3.57 ± 0.23	-	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.13 ± 0.26	-	~ 1.4
$BR(B \to \tau\nu)[10^4]$	1.09 ± 0.24	0.88 ± 0.05	< 1

Unitarity triangle beyond the SM

www.utfit.org

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$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i \boxed{Q_i^{bq}} + \sum_{i=1}^{3} \tilde{C}_i \boxed{\tilde{Q}_i^{bq}}$$

ΔF=2

$$\begin{aligned}
\mathcal{Q}_1 &= (\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Li}\gamma^\mu q_{Lj}), & \mathcal{Q}_1' &= (\bar{q}_{Ri}\gamma^\mu q_{Rj})(\bar{q}_{Ri}\gamma^\mu q_{Rj}) \\
\mathcal{Q}_2 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Ri} q_{Lj}), & \mathcal{Q}_2' &= (\bar{q}_{Li} q_{Rj})(\bar{q}_{Li} q_{Rj}) \\
\mathcal{Q}_3 &= (\bar{q}_{Ri}^{\alpha} q_{Lj}^{\beta})(\bar{q}_{Ri}^{\beta} q_{Lj}^{\alpha}), & \mathcal{Q}_3' &= (\bar{q}_{Li}^{\alpha} q_{Rj}^{\beta})(\bar{q}_{Li}^{\beta} q_{Rj}^{\alpha}) \\
\mathcal{Q}_4 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Li} q_{Rj}), & & \\
\mathcal{Q}_5 &= (\bar{q}_{Ri}^{\alpha} q_{Lj}^{\beta})(\bar{q}_{Li}^{\beta} q_{Rj}^{\alpha}). & &
\end{aligned}$$

Unitarity triangle beyond the SM

UTfit
www.utfit.org

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$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

NP couplings
Loop factors
NP scale

ΔF=2

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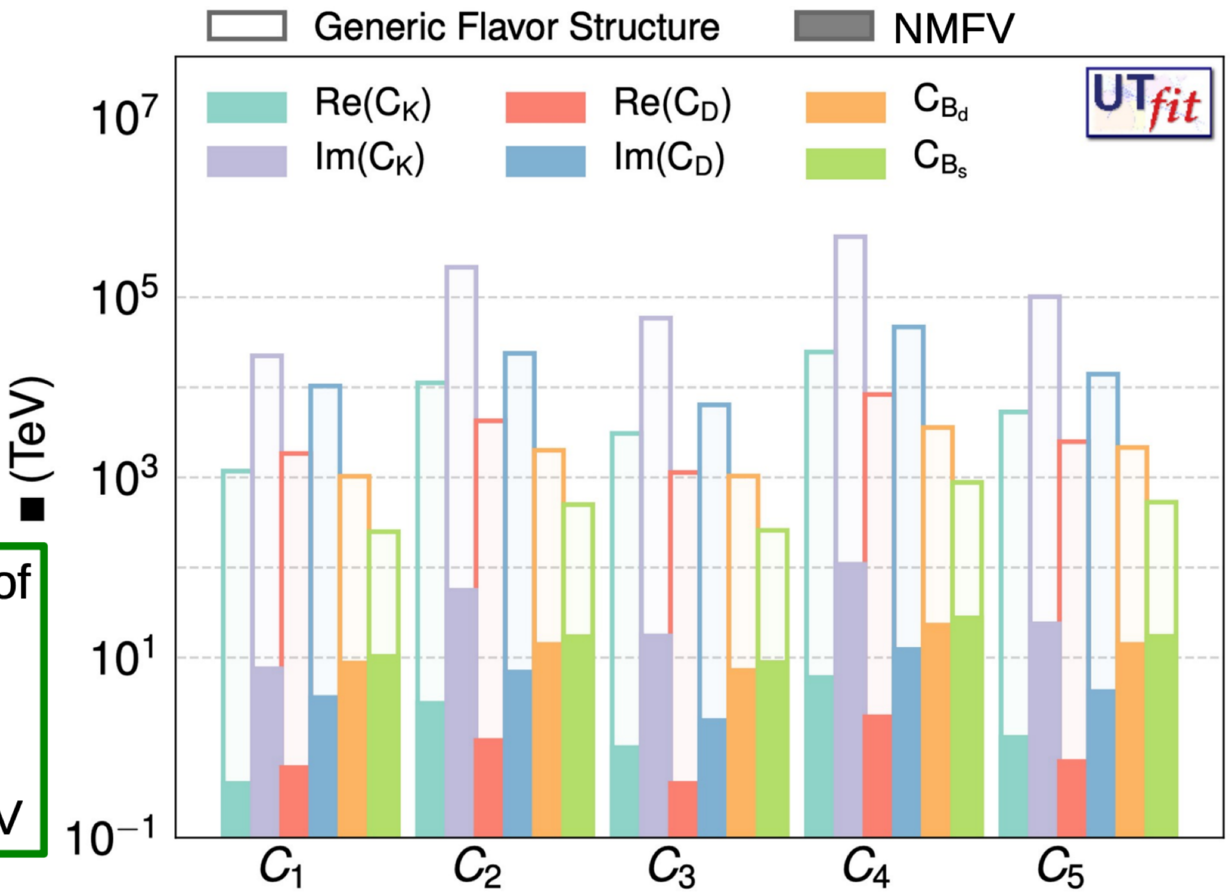
Generic:
$C(\Lambda) = \alpha/\Lambda^2$,
F_i~1, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP

$\Lambda > 4.7\ 10^5$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 1.4\ 10^4$ TeV



NMFV:
$C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$,
F_i~$|F_{SM}|$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP

$\Lambda > 108$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 3.2$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

Conclusions

Incredible moment for flavour physics: at present, a lot of new data are available and, in the next years, several new ones are going to come out !

- **Pheno studies within the SM** require precision techniques to study new data: comparison among different techniques, fundamental inputs from lattice QCD $\longrightarrow$ effort to corroborate our comprehension of EW physics

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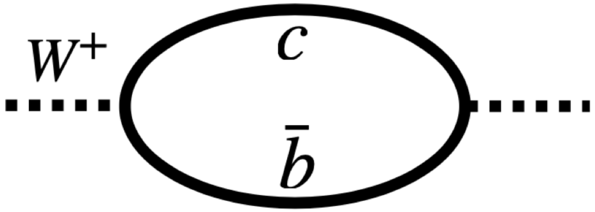
Flavour continues to be the best framework to test indirectly very high energy scales (much higher than the one presently investigated at colliders) ☺

GRAZIE PER LA VOSTRA ATTENZIONE !

BACK-UP SLIDES

Methods for data analysis – QFT constraints



Okubo, PRD 3, 2807 (1971), PRD 4, 725 (1971)
Okubo, Shih, PRD 4, 2020 (1971)
Boyd, Grinstein, Lebed, PLB 353, 306 (1995), NPB461, 493 (1996), PRD 56, 6895 (1997)

HVP tensor: $$\Pi_V^{\mu\nu}(q) = i\int d^4x e^{iqx}\langle 0|T\{V^\mu(x)V^{\nu\dagger}(0)|0\rangle = \frac{1}{q^2}(q^\mu q^\nu - q^2 g^{\mu\nu})\Pi_{1^-}(q^2) + \frac{q^\mu q^\nu}{q^2}\Pi_{0^+}(q^2)$$

Disp. relations: $$\chi_{1^-}(q^2) = \frac{1}{\pi}\int_0^\infty dt \frac{t\,\mathrm{Im}\Pi_{1^-}(t)}{(t-q^2)^3} \qquad \chi_{0^+}(q^2) = \frac{1}{\pi}\int_0^\infty dt \frac{t\,\mathrm{Im}\Pi_{0^+}(t)}{(t-q^2)^2}$$

Spectral sum: $$\mathrm{Im}\Pi_V(q^2) \sim \frac{1}{2}\sum_X (2\pi)^4\delta^4(q-p_X)\,|\langle 0|V|X\rangle|^2$$

e.g. $X = BD^*$: $|\langle 0|V|BD^*\rangle| \propto |\langle D^*|V|B\rangle|$

Unitarity constraints: $$\boxed{\frac{1}{\pi\chi_X(q^2)}\int_{t_+}^\infty dt \frac{W(t)\,|f_X(t)|^2}{(t-q^2)^n} \leq 1}$$

- dispersion relation leads to **constraint on form factors in each symmetry channel**
- χ can be evaluated in perturbation theory, e.g. at $q^2 = 0$, or lattice at whatever q^2

Martinelli, Simula, LV PRD 104 (2021) [2105.07851]

Methods for data analysis – Dispersive Matrix method

By introducing an *auxiliary function* $g_t(z) \equiv \dfrac{1}{1 - \bar{z}(t)z}$,

we can finally build up the **dispersive matrix :**

Okubo, PRD 3 (1971) 2807, PRD 4 (1971) 725
Okubo and Shih, PRD 4 (1971) 2020
Bourrely et al. NPB 189 (1981) 157
Lellouch, NPB 479 (1996) 353
Di Carlo et al., LV, PRD 104 (2021) 5, 054502

$$
\mathbf{M} = \begin{pmatrix}
\langle B_X\phi_X f_X | B_X\phi_X f_X\rangle & \langle B_X\phi_X f_X | g_t\rangle & \langle B_X\phi_X f_X | g_{t_1}\rangle & \cdots & \langle B_X\phi_X f_X | g_{t_n}\rangle \\
\langle g_t | B_X\phi_X f_X\rangle & \langle g_t | g_t\rangle & \langle g_t | g_{t_1}\rangle & \cdots & \langle g_t | g_{t_n}\rangle \\
\langle g_{t_1} | B_X\phi_X f_X\rangle & \langle g_{t_1} | g_t\rangle & \langle g_{t_1} | g_{t_1}\rangle & \cdots & \langle g_{t_1} | g_{t_n}\rangle \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\langle g_{t_n} | B_X\phi_X f_X\rangle & \langle g_{t_n} | g_t\rangle & \langle g_{t_n} | g_{t_1}\rangle & \cdots & \langle g_{t_n} | g_{t_n}\rangle
\end{pmatrix}
$$

- All the inner products are explicitly computable:

Cauchy's theorem: $\langle g_{t_i} | B_X\phi_X f_X\rangle = B_X(t_i)\phi_X(t_i)f_X(t_i)$

$$\langle g_{t_i} | g_{t_i}\rangle = \frac{1}{1 - |z(t_i)|^2} \qquad \langle g_{t_i} | g_{t_j}\rangle = \frac{1}{1 - \bar{z}(t_j)z_i}$$

Unitaritu constraint: $\langle B_X\phi_X f_X | B_X\phi_X f_X\rangle \leq \chi_X$

- Thanks to the positivity of the inner products:

$$\det \mathrm{M} \geq 0$$

$$\Downarrow$$

$$f_{X,\mathrm{lo}}(z) \leq f_X(z) \leq f_{X,\mathrm{up}}(z)$$

Model-independence: the functional form of f_X (as a function of z) is never specified !

A brief parenthesis on unitarity: the role of the susceptibilities χ

They can be computed on the lattice! Focusing again for simplicity on the 0^+, 1^- channels we have that

$$\chi_{0^+}(Q^2) \equiv \frac{\partial}{\partial Q^2}\left[Q^2 \Pi_{0^+}(Q^2)\right] = \int_0^\infty dt\, t^2 j_0(Qt)\, C_{0^+}(t)\ , \xrightarrow{W.\,I.} \frac{1}{4}\int_0^\infty dt'\, t'^4\, \frac{j_1(Qt')}{Qt'}\left[(m_b - m_c)^2 C_S(t') + Q^2 C_{0^+}(t')\right]$$

$$\chi_{1^-}(Q^2) \equiv -\frac{1}{2}\frac{\partial^2}{\partial^2 Q^2}\left[Q^2 \Pi_{1^-}(Q^2)\right] = \frac{1}{4}\int_0^\infty dt\, t^4 \frac{j_1(Qt)}{Qt}\, C_{1^-}(t)$$

$$C_{1^-}(t) = \frac{1}{3}\sum_{j=1}^{3}\int d^3x \langle 0|T\left[\bar{b}(x)\gamma_j c(x)\ \bar{c}(0)\gamma_j b(0)\right]|0\rangle\ ,$$

Fundamental advantage on the lattice:

We can choose *whatever value of Q^2* (i.e. near the region of production of the resonances)

NOT POSSIBLE IN PERTURBATION THEORY !

$$(m_b + m_c)\Lambda_{QCD} << (m_b + m_c)^2 - q^2$$

POSSIBLE IMPROVEMENT IN THE STUDY OF THE FFs through unitarity!

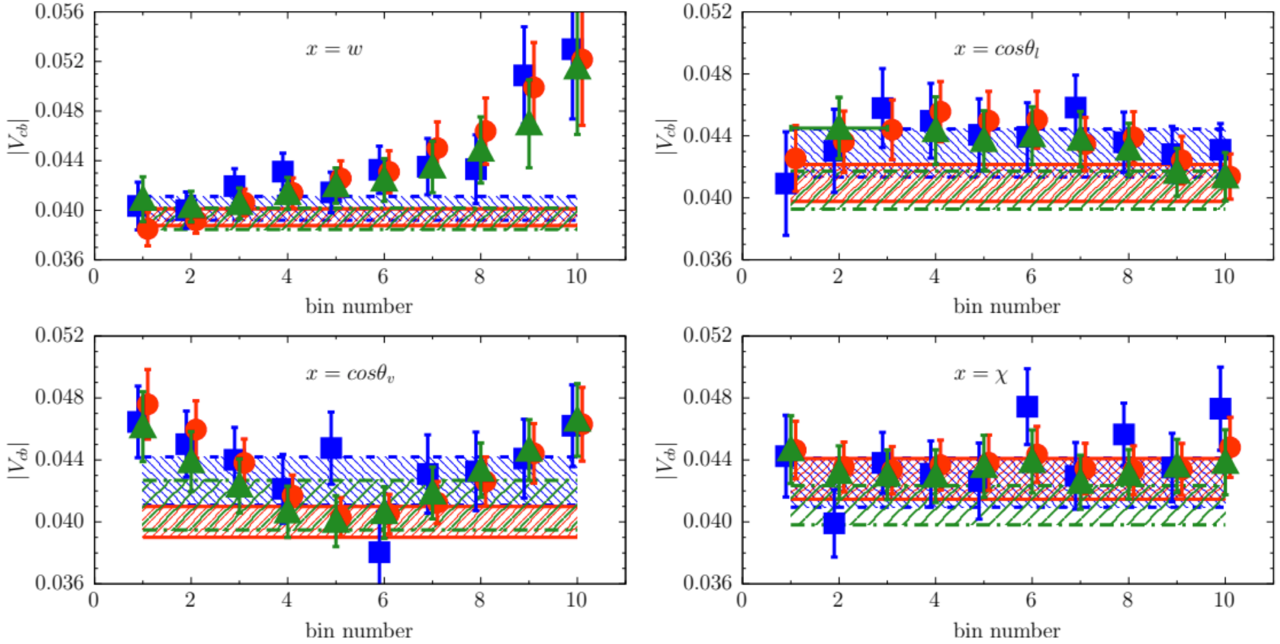
The *first lattice QCD determination* of susceptibilities of heavy-to-heavy transition current densities has been completed in **PRD '21 [arXiv:2105.07851]**, using the N_f=2+1+1 gauge ensembles generated by ETM Collaboration (*$Q^2 = 0$*) :

	Perturbative	With subtraction	Non-perturbative	With subtraction
$\chi_{V_L}\,[10^{-3}]$	6.204(81)	—	7.58(59)	—
$\chi_{A_L}\,[10^{-3}]$	24.1	19.4	25.8(1.7)	21.9(1.9)
$\chi_{V_T}\,[10^{-4}\ \mathrm{GeV}^{-2}]$	6.486(48)	5.131(48)	6.72(41)	5.88(44)
$\chi_{A_T}\,[10^{-4}\ \mathrm{GeV}^{-2}]$	3.894	—	4.69(30)	—

Differences with PT:
~4% for 1^-, ~7% for 0^-, ~20 % for 0^+ and 1^+

For PT: Bigi, Gambino PRD '16; Bigi, Gambino, Schacht PLB '17 ;Bigi, Gambino, Schacht JHEP '17

Our proposal: *bin-per-bin exclusive Vcb* determination through unitarity

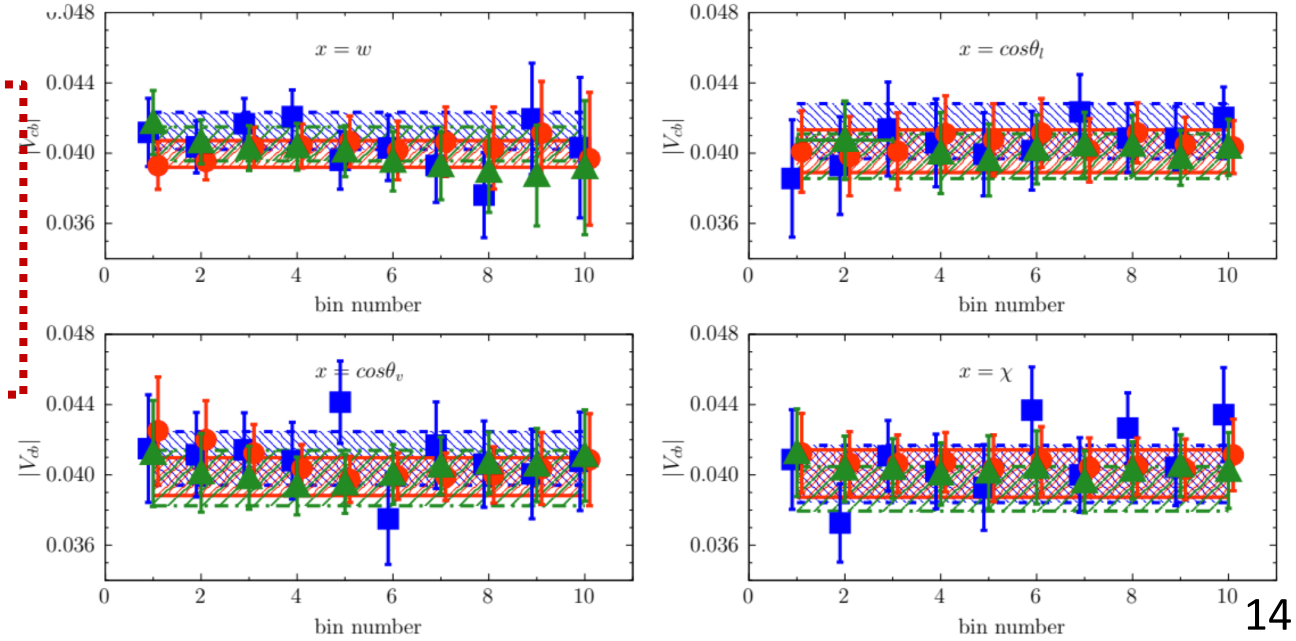


FNAL/MILC input
[HPQCD inputs give similar plots]

Belle 2018	Belle 2023	Belle-II 2023

The differences among these distributions reflect the differences among different theor. FFs results !

JLQCD inputs



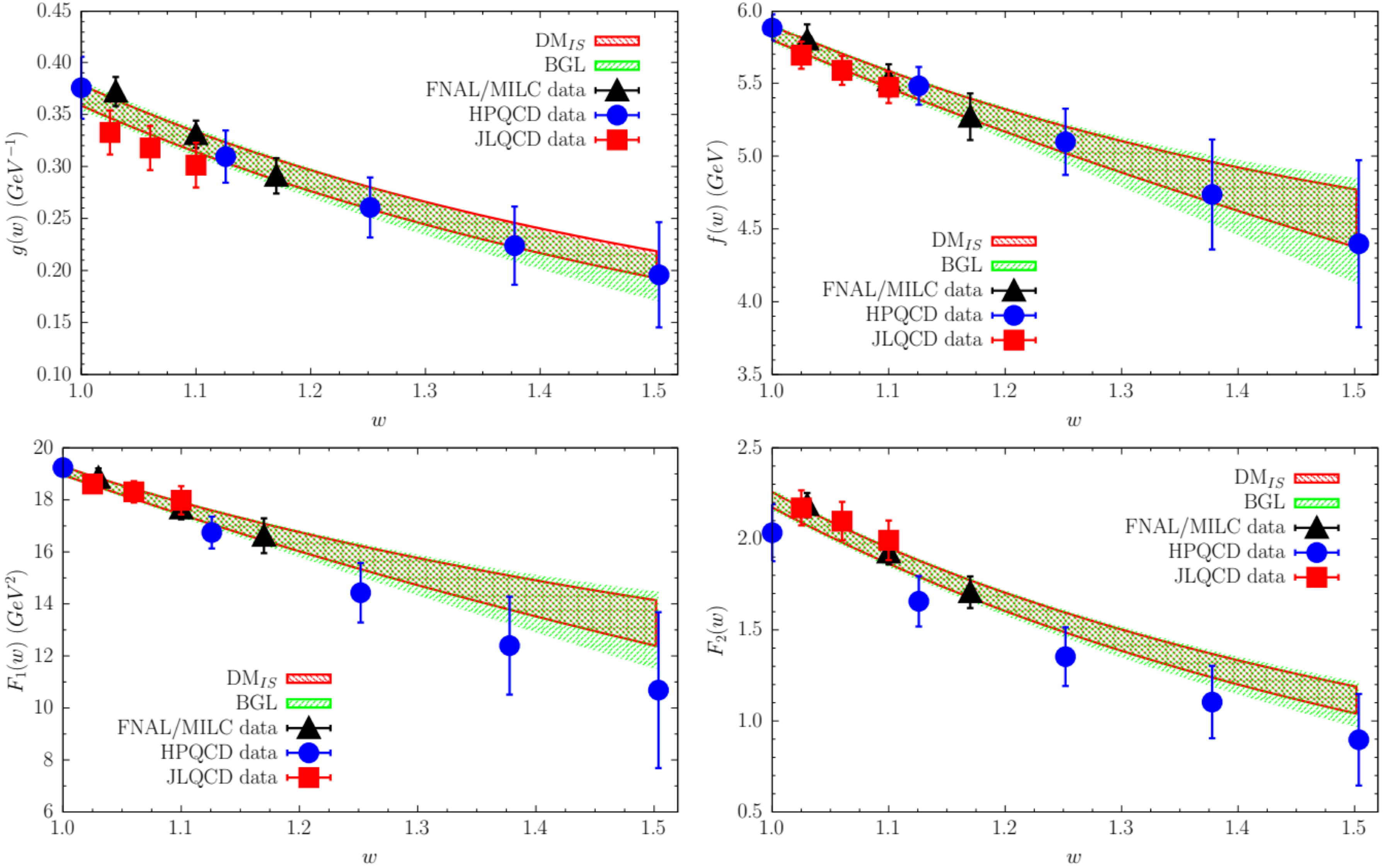


Fig. 6. *The FFs from Refs. [15–17] together with the bands (at 1 σ level) obtained by using simultaneously all the lattice inputs within the DM_{IS} method (red bands) or the BGL approach supplemented by the unitary and kinematical constraints (green bands). The BGL z-expansions are truncated after the quartic (quintic) term for the FFs g and f (F_1 and F_2). The DM bands are rigorously truncation independent.*

$|V_{cb}|$ — Strategy A: bin-by-bin analysis

Originally proposed in **Martinelli, Simula, LV, PRD 105 (2022) 3, 034503:**

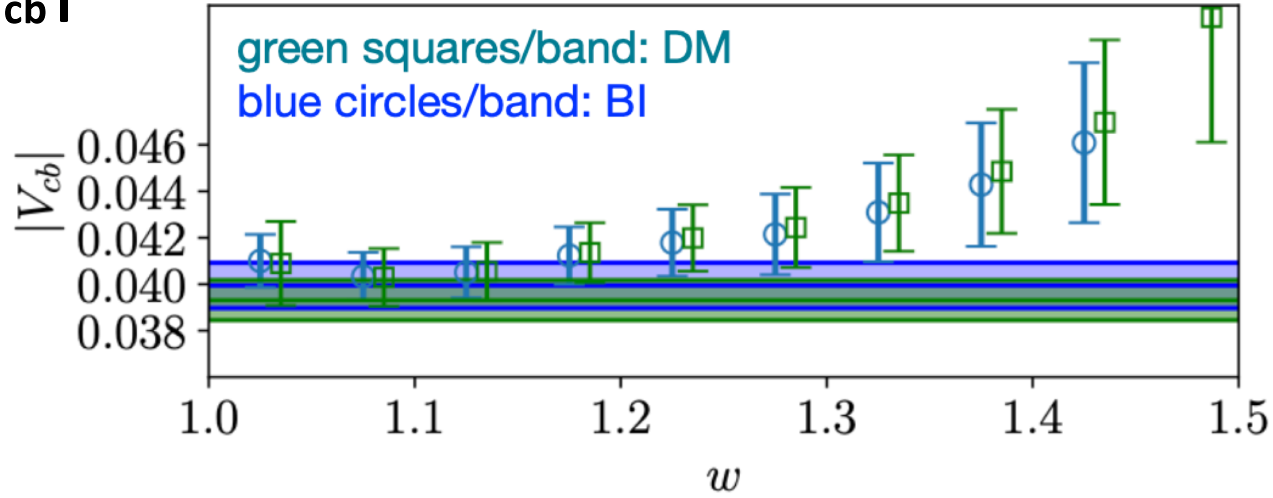
$$|V_{cb}|_{\alpha,i} = \left(\Gamma_{\text{exp}} \left[\frac{1}{\Gamma}\frac{d\Gamma}{d\alpha} \right]^{(i)}_{\text{exp}} \Big/ \left[\frac{d\Gamma_0}{d\alpha}(\mathbf{a}) \right]^{(i)}_{\text{lat}} \right)^{1/2}, \qquad \text{where} \qquad \Gamma_{\text{exp}} = \frac{\mathcal{B}(B^0 \to D^{*,-}\ell^+\nu_\ell)}{\tau(B^0)}$$

- **Each bin is *per se* a measurement of $|V_{cb}|$**
- **Per channel correlated average**

$$\left\{ w,\ \cos\theta_\ell,\ \cos\theta_v, \chi \right\}$$

- **Akaike-Information-Criterion analysis**

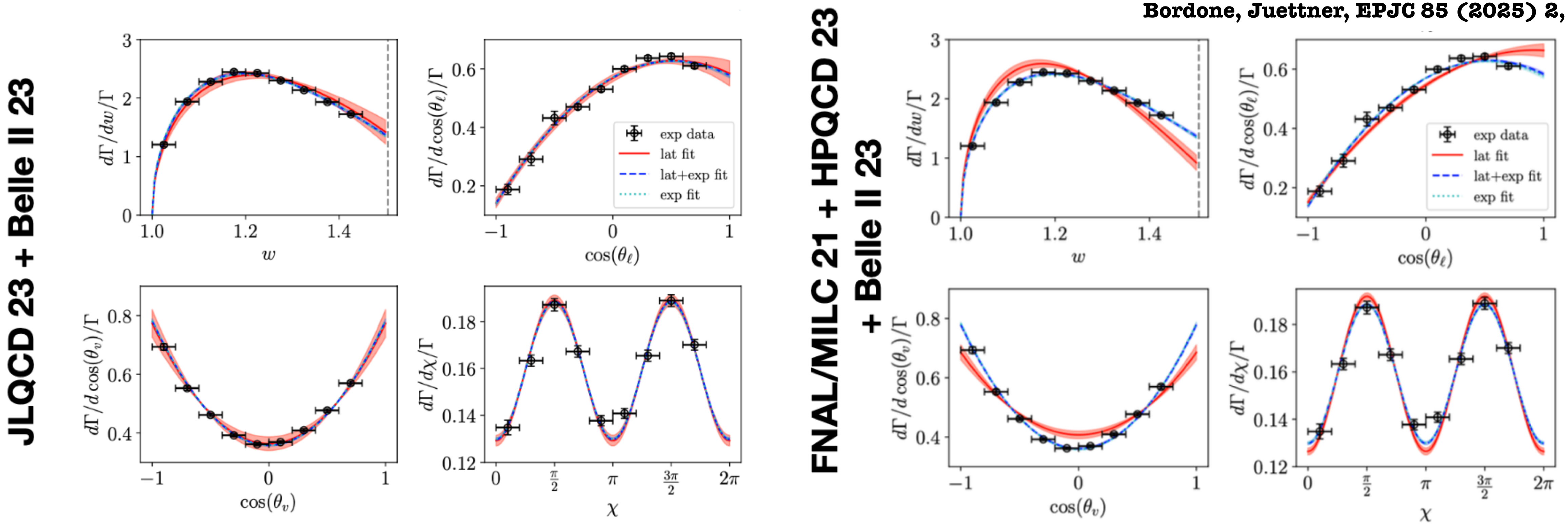
Example:
exp: Belle II 23 data / lat: FNAL/MILC 23



Martinelli, Simula, Vittorio, EPJC 84 (2024)
Bordone, Jüttner, EPJC 85 (2025)

Strategy B – fit to lattice and exp. data

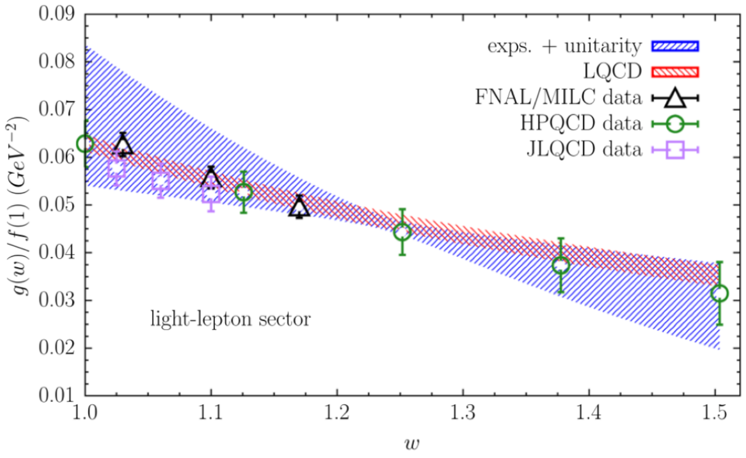
Bordone, Juettner, EPJC 85 (2025) 2, 129

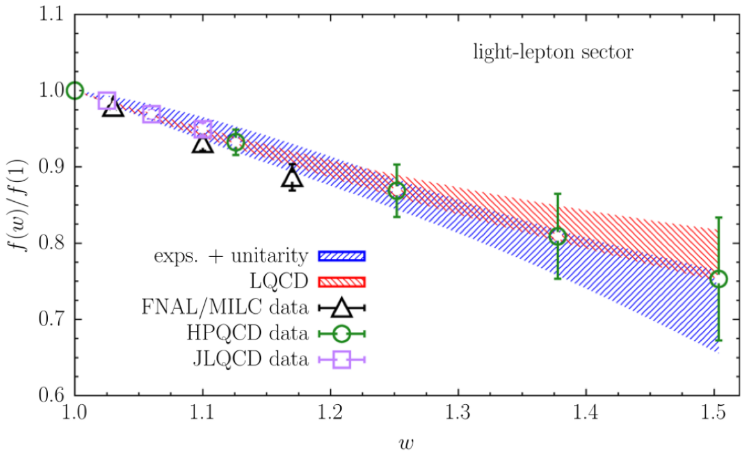


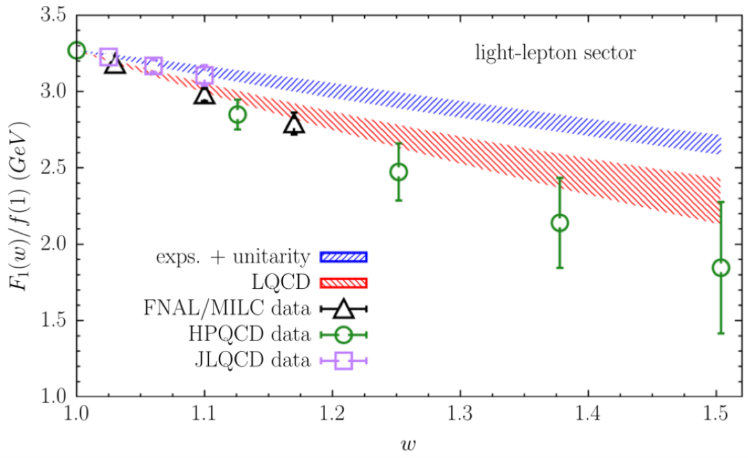
- **BGL fit to only lattice data (strategy A)** misses experimental points for two of the lattice coll.
- **BGL fit to experimental and lattice data (strategy B)** (good fit quality good): some BGL coefficients shift between strategy A) and B) by up to a few σ

Strategy C – fit to exp. data

Martinelli, Simula, LV, EPJC 85 (2025) 3, 242







BGL fit to only latt. data (strategy A)

BGL fit to exp. data (strategy C):

- **good fit quality (χ^2/N_{dof} = 1.1)**
- **unitarity imposed and higher-order coefficients regulated by unitarity** [see **Simula, LV, PRD 108 (2023) 9, 094013**]
- **only two theoretical ingredients required: susceptibilities + *f*(1)**

Other way to see the problem mentioned in strategy B:

the tension among the red and the blue bands for $F_1(w)/f(1)$ reflects the difference among two of the available lattice datasets and some experimental points

B → K$\nu\nu$ as the fundamental link among $b \to c$ and $b \to$ s

b → s$\nu\nu$ is theoretically cleaner than b → s$\mu\mu$: it is not affected by charm-loop effects !!

$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\right) \quad C_L^{\rm SM} = -6.32(7)$$

$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_R\gamma_\mu b_R\right)\left(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\right) \quad C_R^{\rm SM} = 0$$

Buchalla & Buras, NPB '93
Misiak & Urban, arXiv:hep-ph/9901278
Buchalla & Buras, arXiv:hep-ph/9901288
Brod, Gorbahn & Stamou, arXiv:1009.0947

Major sources of uncertainty:

1. Value of |Vcb| (due to CKM suppression)
2. Determination of hadronic FFs

Final prediction

$$\boxed{\mathcal{B}\left(B^\pm \to K^\pm \nu\bar{\nu}\right) = (4.44 \pm 0.30) \times 10^{-6}}$$

Final prediction

$$\boxed{\mathcal{B}\left(B^\pm \to K^{\pm *} \nu\bar{\nu}\right) = (9.8 \pm 1.4) \times 10^{-6}}$$

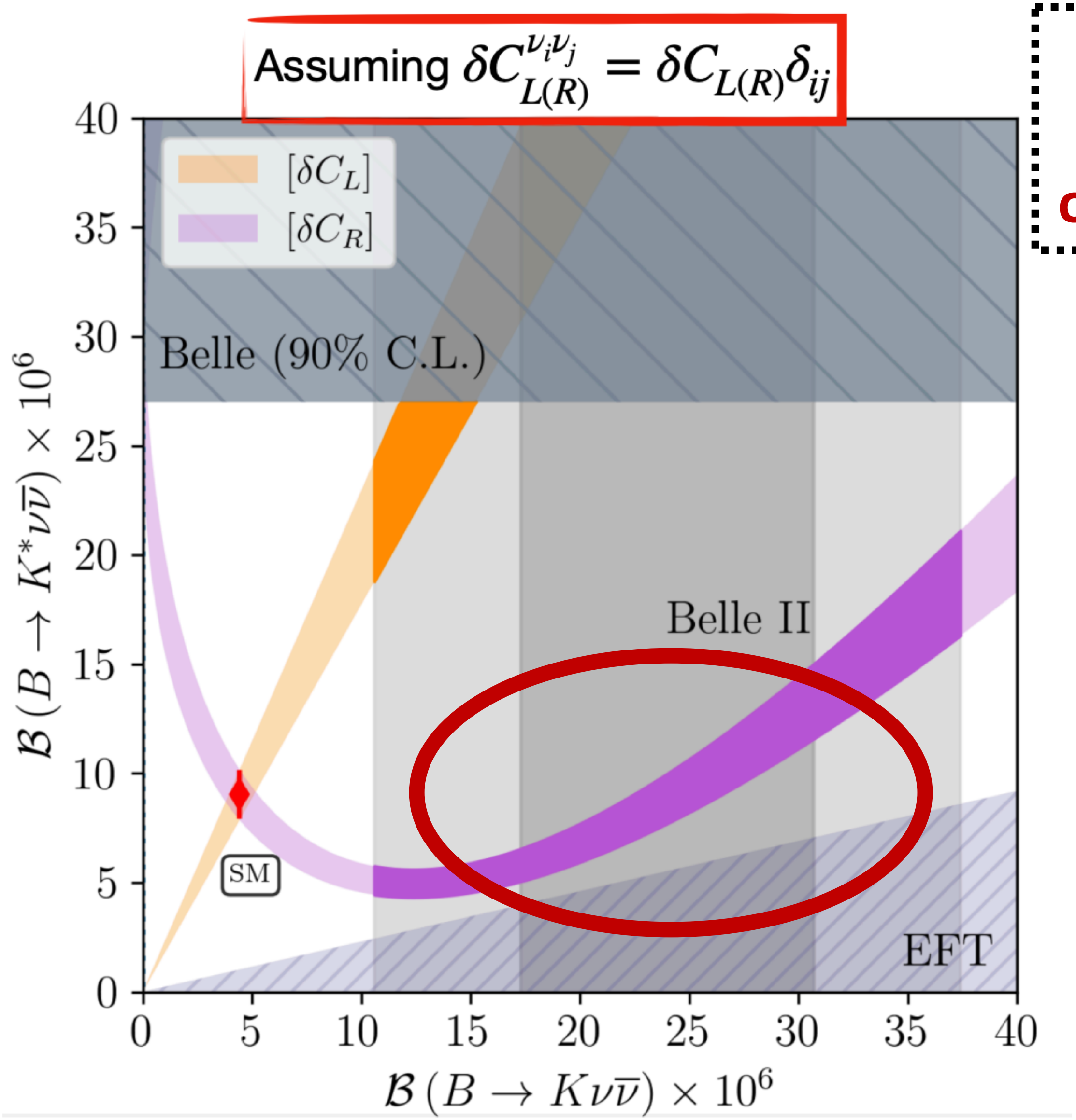
D. Becirevic, G. Piazza & O. Sumensari, EPJC '23 [arXiv:2301.06990]

to be compared with

$$\boxed{\mathcal{B}\left(B^+ \to K^+ \nu\bar{\nu}\right)\Big|_{\rm Belle-II} = (2.4 \pm 0.7) \times 10^{-5}}$$

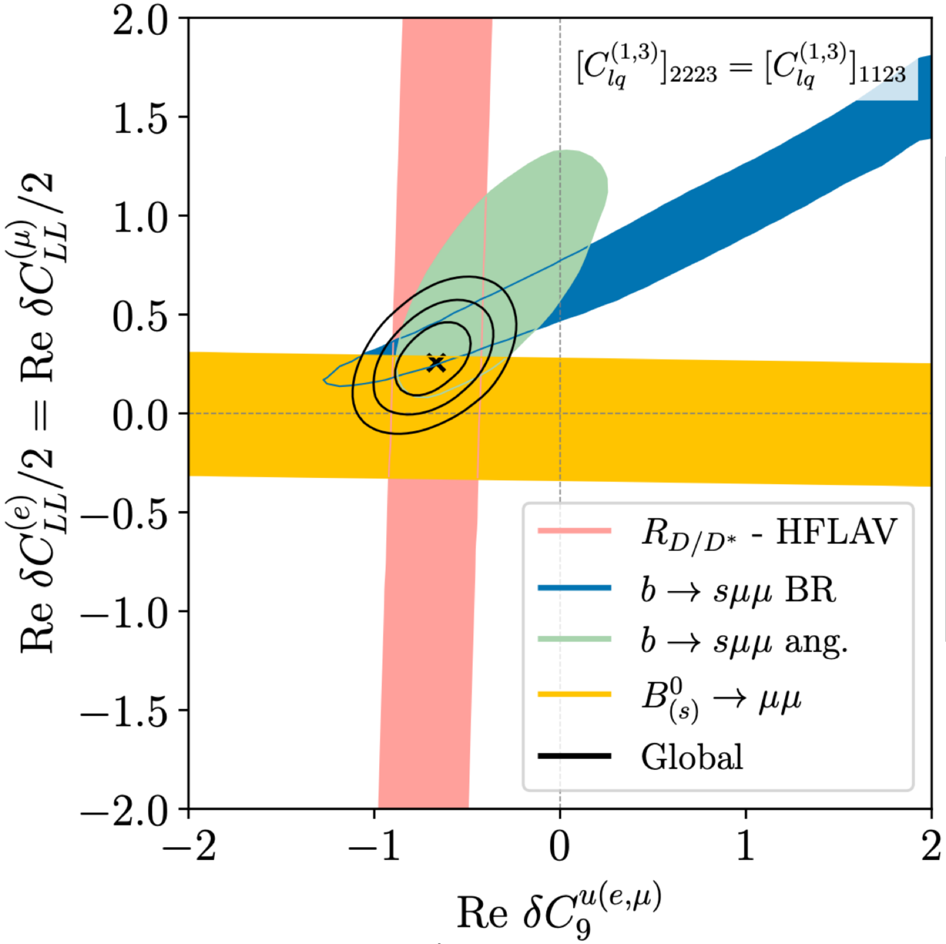
A. Glazov, plenary talk EPS-HEP2023 Conference, Aug 20-25, 2023

B → K$\nu\nu$ as the fundamental link among $b \to c$ and $b \to s$



L. Allwicher et al., arXiv:2309.02246

This kind of channels is important for SMEFT analyses, since **B → K$\nu\nu$ may influence $b \to$ s observables (with charged leptons) and $b \to c$ ones !**

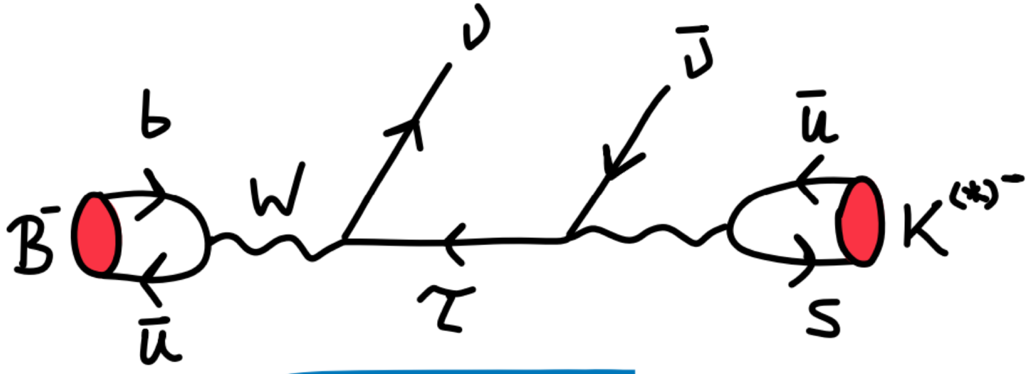


D. Guadagnoli et al, JHEP '23 [2308.00034]

Light-lepton universal NP scenario [without B → K$\nu\nu$ data]

Tree-level contribution

$B^{\pm} \to K^{\pm(*)}\nu\bar{\nu}$



$$\boxed{m_B > m_\tau > m_{K^{(*)}}}$$

J. F. Kamenik & C.Smith, arXiv:0908.1174

Charged meson decay modes have a tree-level contribution from the annihilation to an intermediate τ

Using the narrow width approximation

$$\mathscr{B}\left(B^+ \to K^{(*)+}\nu\bar{\nu}\right) \sim \mathscr{B}\left(B^+ \to \tau^+\nu\right)\mathscr{B}\left(\tau^+ \to K^{(*)+}\bar{\nu}\right)$$

$$\boxed{\frac{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{tree}}}{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{loop}}} \simeq 14\,\%\,(11\%)}$$

Non negligible contribution!

Belle-II can in principle disentangle these two contributions

Connection with b → c ?

- $C_9^{\text{univ.}}$ of the correct size can be generated through RGE effects
  [**Bobeth-Haisch, 2011**][**Crivellin *et al.*, 2018**][**Aebischer *et al.*, 2019**]

Diego Guadagnoli @ NFLF Workshop 2023, Pisa

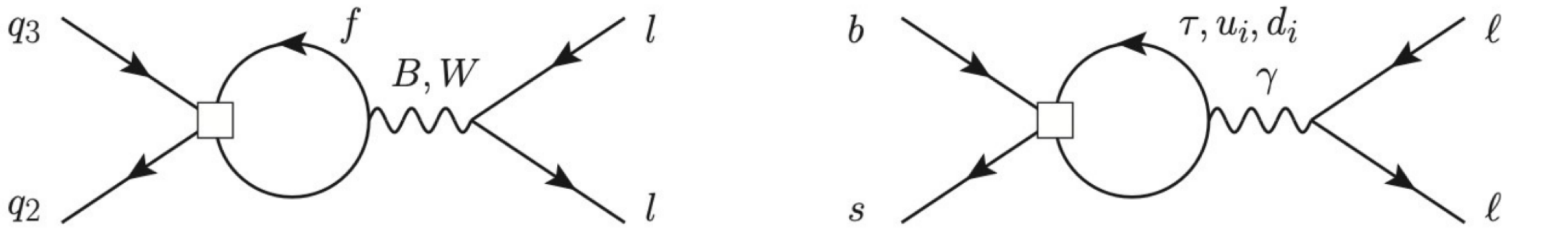


Figure 3: Diagrams inducing a contribution to C_9 through RG running above (left panel) and below (right panel) the EW scale. A sizeable contribution to C_9 is obtained when $f = u_{1,2}, d_{1,2,3}$ or l_3, see text for details.

$$2\mathcal{N}\, C_9^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} + [C_{lq}^{(1)}]_{ii23} + [C_{lq}^{(3)}]_{ii23} - \zeta c_Z \,,$$
$$2\mathcal{N}\, C_{10}^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} - [C_{lq}^{(1)}]_{ii23} - [C_{lq}^{(3)}]_{ii23} + c_Z \,,$$

$$[O_{qe}]_{23ii} = (\bar{q}_2\gamma_\mu q_3)(\bar{e}_i\gamma^\mu e_i)\,,$$
$$[O_{lq}^{(1)}]_{ii23} = (\bar{l}_i\gamma_\mu l_i)(\bar{q}_2\gamma^\mu q_3)\,,$$
$$[O_{\varphi q}^{(1)}]_{23} = (\varphi^\dagger i\overset{\leftrightarrow}{D}_\mu\varphi)(\bar{q}_2\gamma^\mu q_3)\,,$$
$$[O_{lq}^{(3)}]_{ii23} = (\bar{l}_i\gamma_\mu\tau^I l_i)(\bar{q}_2\gamma^\mu\tau^I q_3)\,,$$
$$[O_{\varphi q}^{(3)}]_{23} = (\varphi^\dagger i\overset{\leftrightarrow}{D}{}^I_\mu\varphi)(\bar{q}_2\gamma^\mu\tau^I q_3)\,,$$

Intriguingly, a large value for $[C_{lq}^{(3)}]_{3323}$, that can explain the hints for LFU violation in charged-current $b \to c$ transitions (R_D and R_{D^*}), also induces a LFU effect in C_9 that goes in the right direction to solve the $b \to s\mu\mu$ anomalies in branching ratios and angular observables.

Jason Aebischer et al., EPJC '20 [arXiv:1903.10434 [hep-ph]]

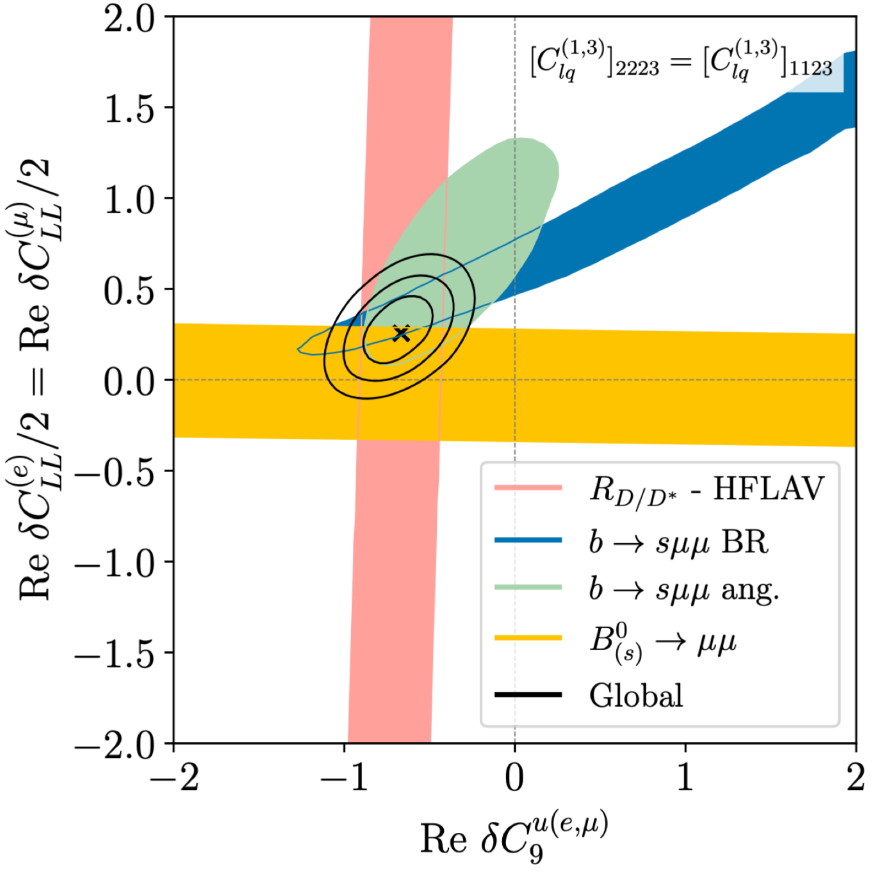
Legame tra $b \to s$ e $b \to c$: $SU(2)_L \times U(1)_Y$

Coefficienti di Wilson

$$\mathcal{L}_{\text{eff}} = -\mathcal{H}_{\text{eff}} = \sum_i \frac{1}{\boxed{\Lambda^2_{\text{UV}}}} \boxed{C_{\text{eff,i}}} \mathcal{O}_{\text{eff,i}}$$

Scala di energia della Nuova Fisica

$$\mathcal{L}^{(6)}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2}\Big\{ \left(\mathcal{C}^{(1)}_{lq} + \mathcal{C}^{(3)}_{lq}\right)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj}) + \left(\mathcal{C}^{(1)}_{lq} - \mathcal{C}^{(3)}_{lq}\right)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})$$
$$+ 2V_{cs}\left[\mathcal{C}^{(3)}_{lq}\right]_{ij} (\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj}) + [\mathcal{C}_{ld}]_{ij} (\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) + (\bar{e}_{Li}\gamma_\mu e_{Lj})\right] + \text{h.c.}\Big\}$$



Nell'ottica della fisica di precisione: analisi congiunte dei dati $b \to s$ (con leptoni carichi), $b \to c$, Bs \to $\mu\mu\gamma$ e B → K(*)$\nu\nu$ *(gli ultimi due non sono inclusi nell'esempio di sinistra)* al fine di validare (o meno) la consistenza tra tali osservabili in un dato modello di fisica oltre il MS

D. Guadagnoli et al, JHEP '23 [2308.00034]

Another possible way to describe the CKM matrix is offered by the so-called *Wolfenstein parametrization* [24]. The physical hint at the basis of this alternative formulation is that, since $S_{13} \ll S_{23} \ll S_{12} \ll 1$, it is reasonable to develop a perturbative expansion in powers of S_{12}. To be more specific, we introduce four new parameters λ, A, η and ρ, defined as

$$\begin{aligned} \lambda &\equiv S_{12} \simeq V_{us}, \\ A\lambda^2 &\equiv S_{23} \simeq V_{cb}, \\ A\lambda^3(\rho - i\eta) &\equiv S_{13} e^{-i\delta} \simeq V_{ub}, \end{aligned}$$

where the last relation holds for small δ. By putting all the ingredients together, we have the new form

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4), \tag{2.18}$$

from which it is now evident that CP non-conservation is condensed in the terms of order λ^3 or higher. In conclusion, we can also consider higher order corrections in Eq.(2.18). By way of example, including terms $O(\lambda^5)$ we obtain the expression

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda + O(\lambda^7) & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5[1-2(\rho+i\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 + O(\lambda^8) \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4[1-2(\rho+i\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} \tag{2.19}$$

where $\bar{\rho}$ and $\bar{\eta}$ are slightly modified versions of the Wolfenstein parameters ρ and η and are related to them through the relations

$$\bar{\rho} = \left(1 - \frac{1}{2}\lambda^2\right)\rho, \quad \bar{\eta} = \left(1 - \frac{1}{2}\lambda^2\right)\eta. \tag{2.20}$$