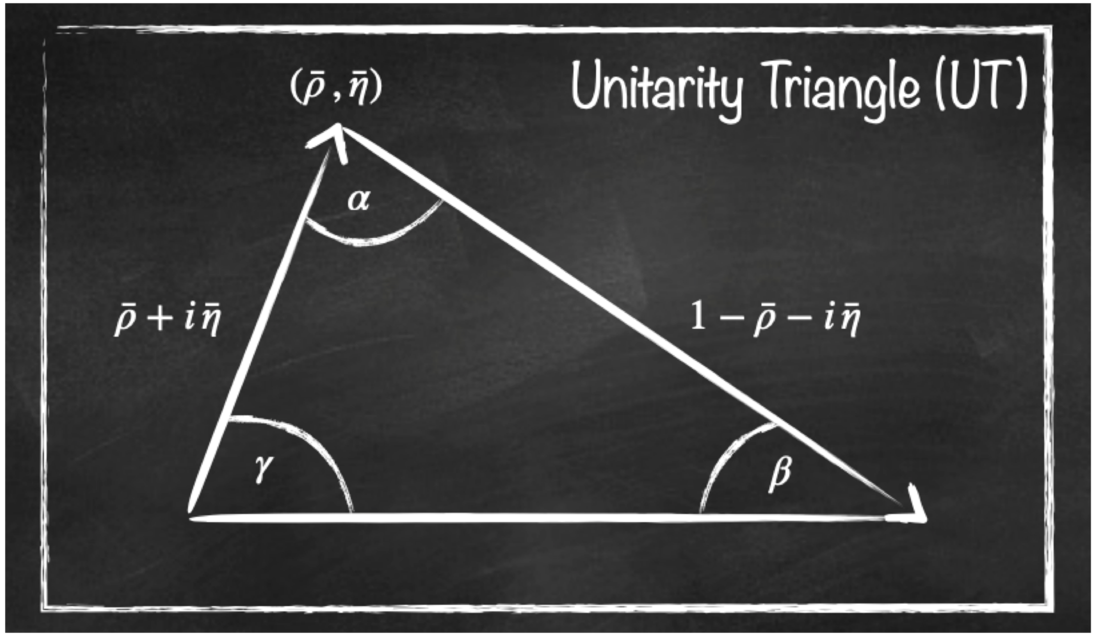
Fenomenologia della fisica del sapore in prospettiva degli esperimenti futuri

Ludovico Vittorio (LAPTh & CNRS, Annecy, France)

IFAE 2024, Firenze – 4 Aprile 2024



Many thanks to D. Guadagnoli, G. Martinelli, S. Simula and M. Valli for discussions and suggestions

Introduzione

Il Modello Standard (MS) descrive accuratamente molteplici fenomeni microscopici che osserviamo in Natura:
tantissime previsioni teoriche dei parametri e degli osservabili dello MS sono in accordo con le misure sperimentali !

MS come una Teoria di Campo Efficace valida alle basse energie!

Energia del vuoto

Gerarchia

Stabilità del vuoto

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

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

CP forte

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

"Flavor puzzle"

Massa del neutrino

Qual è l'impatto dell'Higgs sulla fisica del sapore ?

Simmetria del settore di gauge del MS:

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

Attraverso il termine $Y H\bar{\psi}\psi$ $\Longrightarrow$

Effetto dei termini di Yukawa:

$$\mathcal{G}_F(\text{SM}) = U(1)_B \times U(1)_L$$

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Alcune importanti domande necessitano una risposta:

1. **Perché tre generazioni?**
2. **Cosa determina la gerarchia che osserviamo nelle masse dei quark e dei leptoni?**

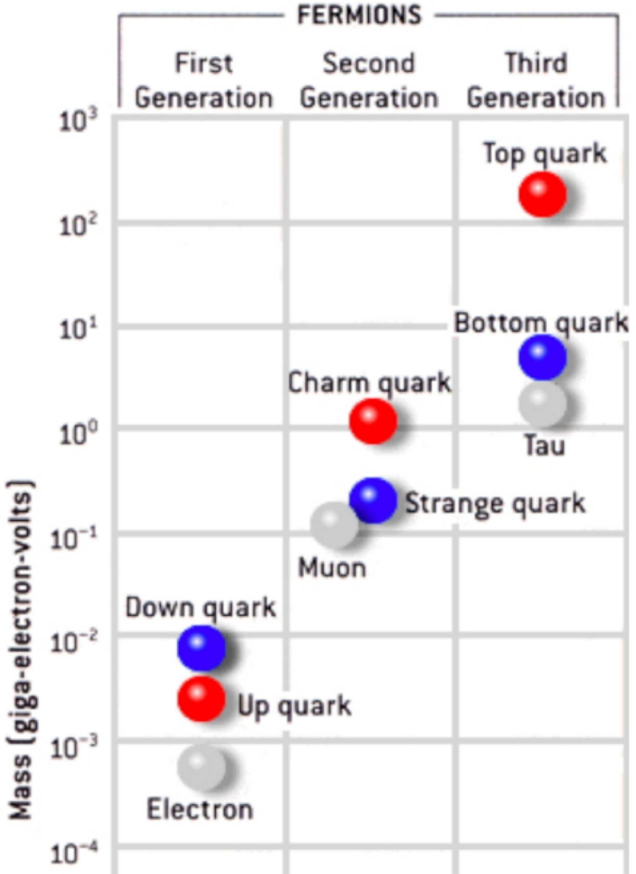

Illustrazione da una presentazione di G. Isidori

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

La matrice CKM descrive le interazioni tra quark di diversa carica elettrica, i suoi elementi possono esser determinati <u>solo</u> tramite un paragone diretto con i dati sperimentali

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

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

3. Simile alla matrice identità: perché (di nuovo) questa gerarchia?

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Alcune importanti domande necessitano una risposta:

La matrice CKM descrive le interazioni

Tutte queste domande costituiscono il cosiddetto «*Flavor Puzzle*» !

Nessuna risposta chiara nel MS ad oggi …

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Il Triangolo di Unitarietà come (prima) guida

Parametrizzazione di Wolfenstein (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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L'unitarietà della matrice CKM può esser scritta come:

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

$\Rightarrow$ ***Triangolo nel piano*** $(\bar\rho, \bar\eta)$ ***!***

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Triangolo nel piano $(\bar\rho, \bar\eta)$!

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

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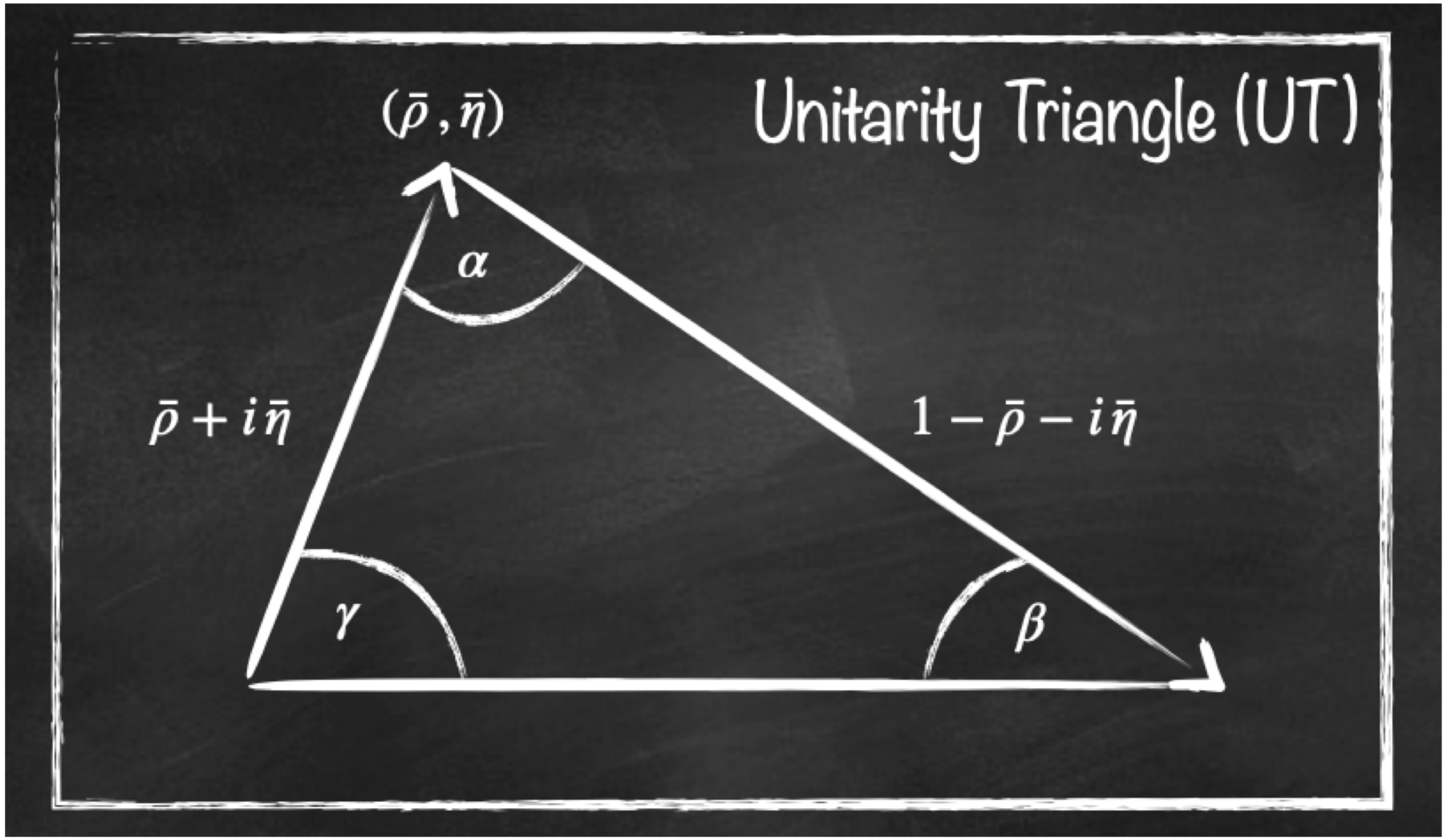

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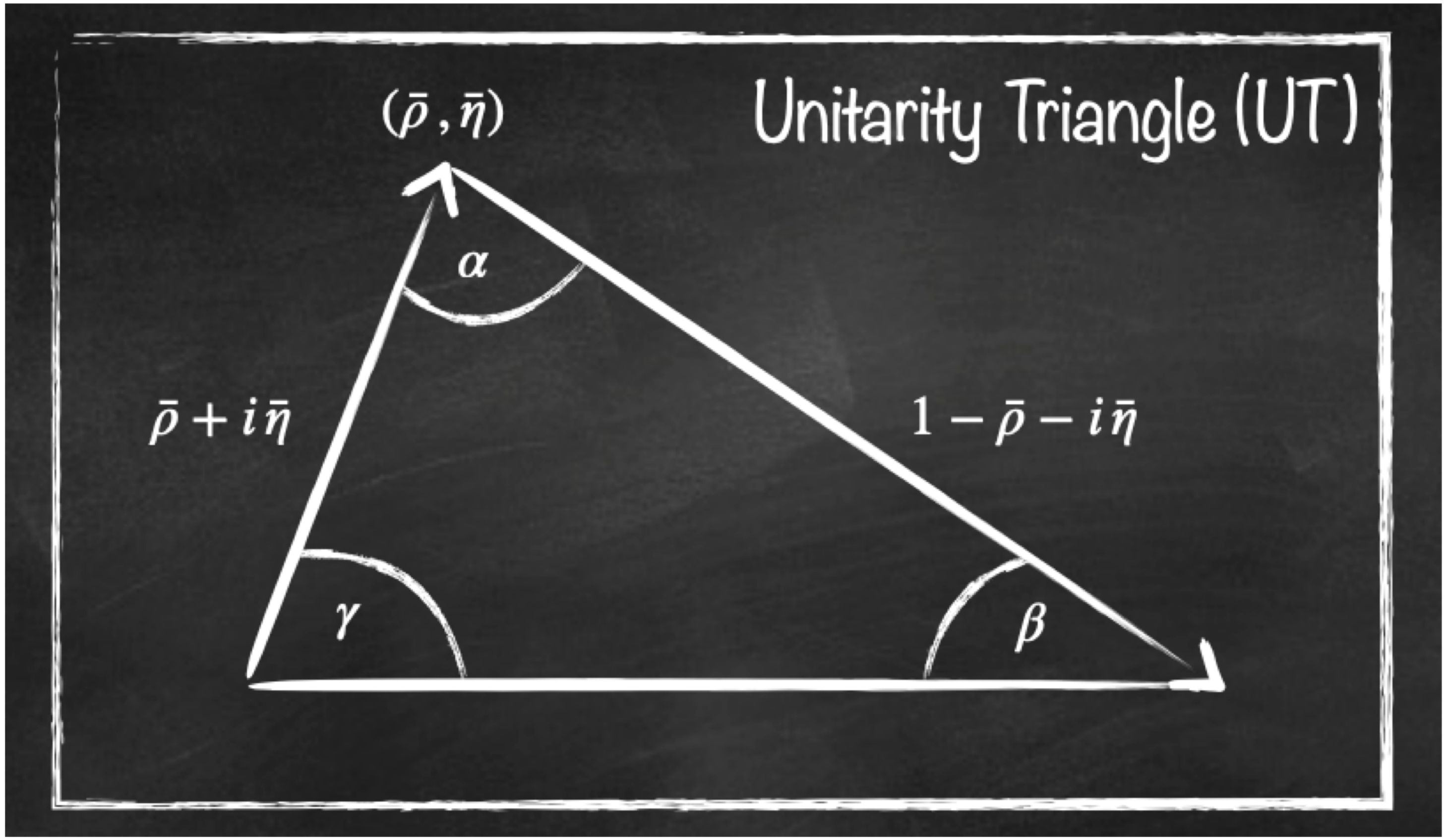

<u>*INFO CHIAVE*</u>: i lati, gli angoli e l'area del triangolo sono quantità fisiche! Ad esempio:

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

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

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I decadimenti rari come (seconda) guida

I luoghi più promettenti in cui cercare possibili effetti di Nuova Fisica sono i *decadimenti rari*,
in quanto manifestazione di simmetrie rotte (accidentali), ad es. di fisica oltre il MS

Due esempi generici:

1. ***Decadimento del protone*** → ***Test della conservazione dei numeri leptonico e barionico***

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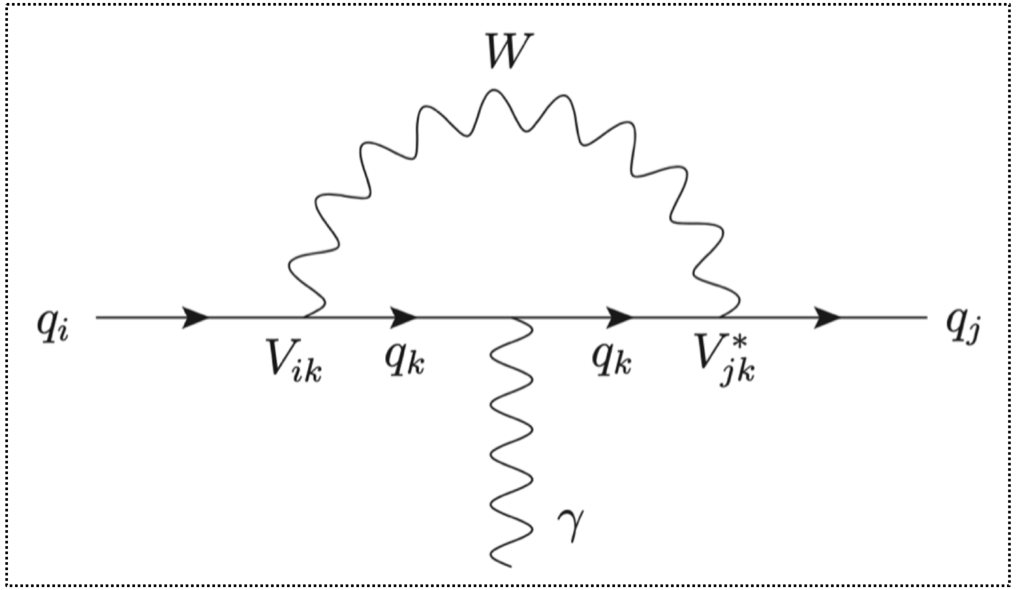
Due esempi generici:

1. ***Decadimento del protone*** → ***Test della conservazione dei numeri leptonico e barionico***
2. ***Correnti neutre con cambiamento di sapore (FCNCs):*** **processi a loop, CKM-soppressi**

Di interesse per questo talk!

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



Fisica del sapore nel ed oltre il MS

Processi Tree-level

FCNCs

Fisica del sapore nel ed oltre il MS

Processi Tree-level

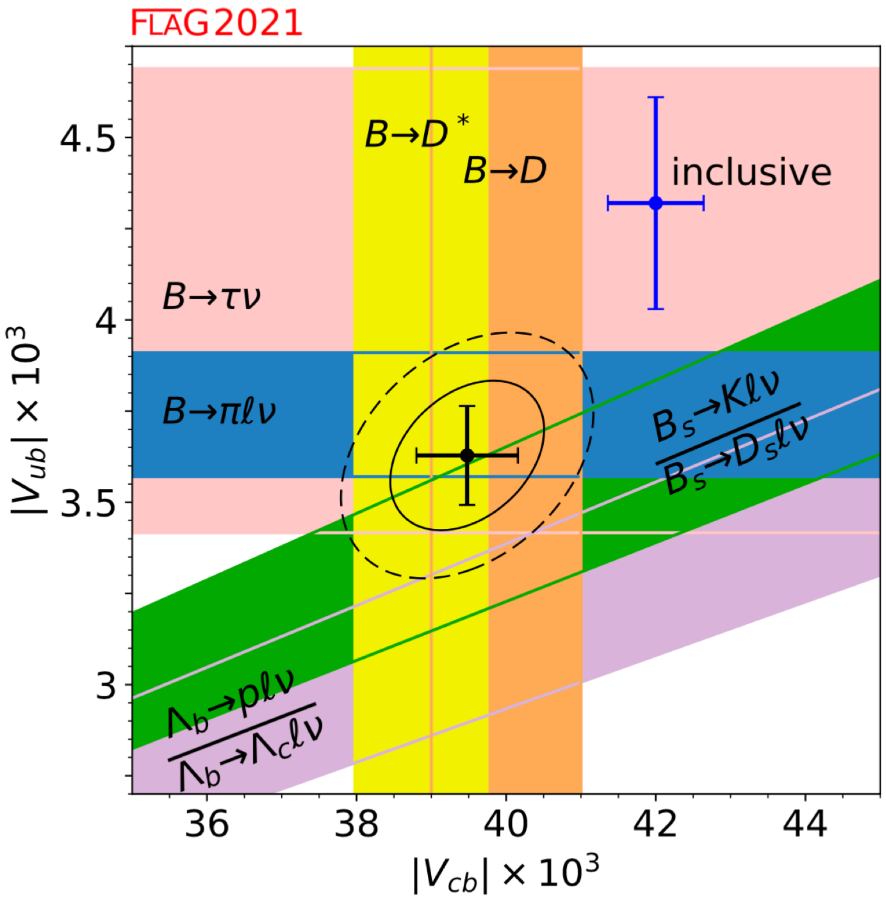
FCNCs

Transizioni $b \to c$

Motivazioni fenomenologiche: decadimenti $b \to c$

Sebbene *non ci sia evidenza diretta di Nuova Fisica dagli esperimenti*, alcuni problemi richiedono una soluzione (nel MS?):

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



Tensione: $\sim 3\sigma$

FLAG Review 2021 [EPJC '22 (2111.09849)]

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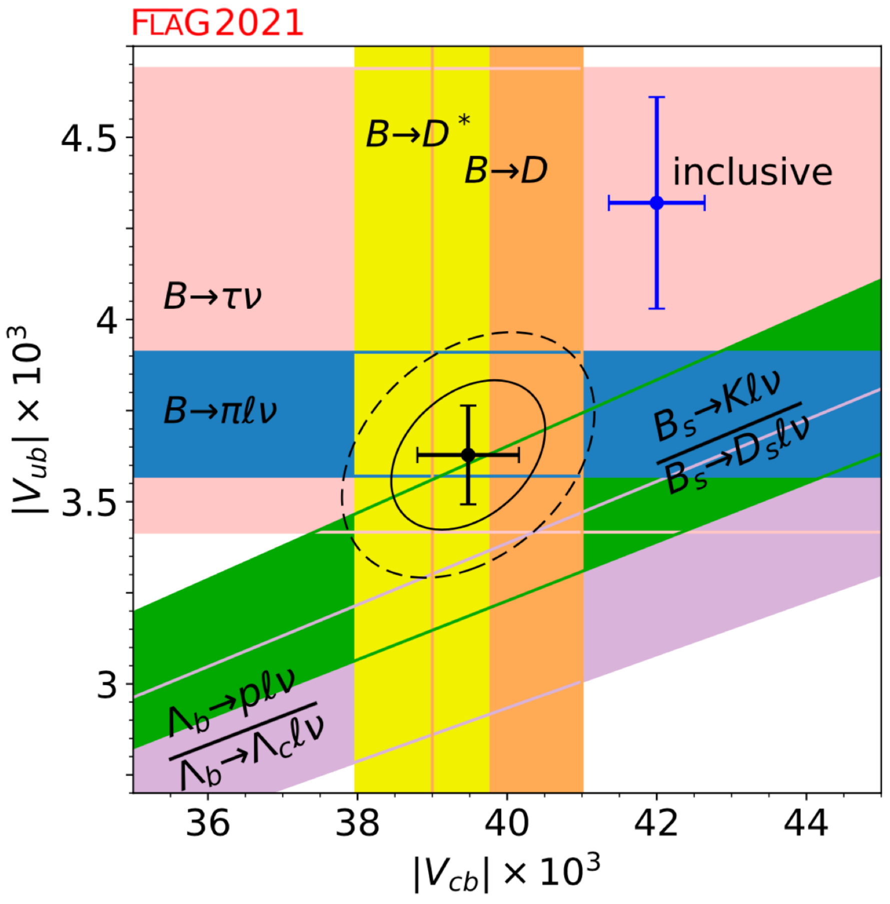

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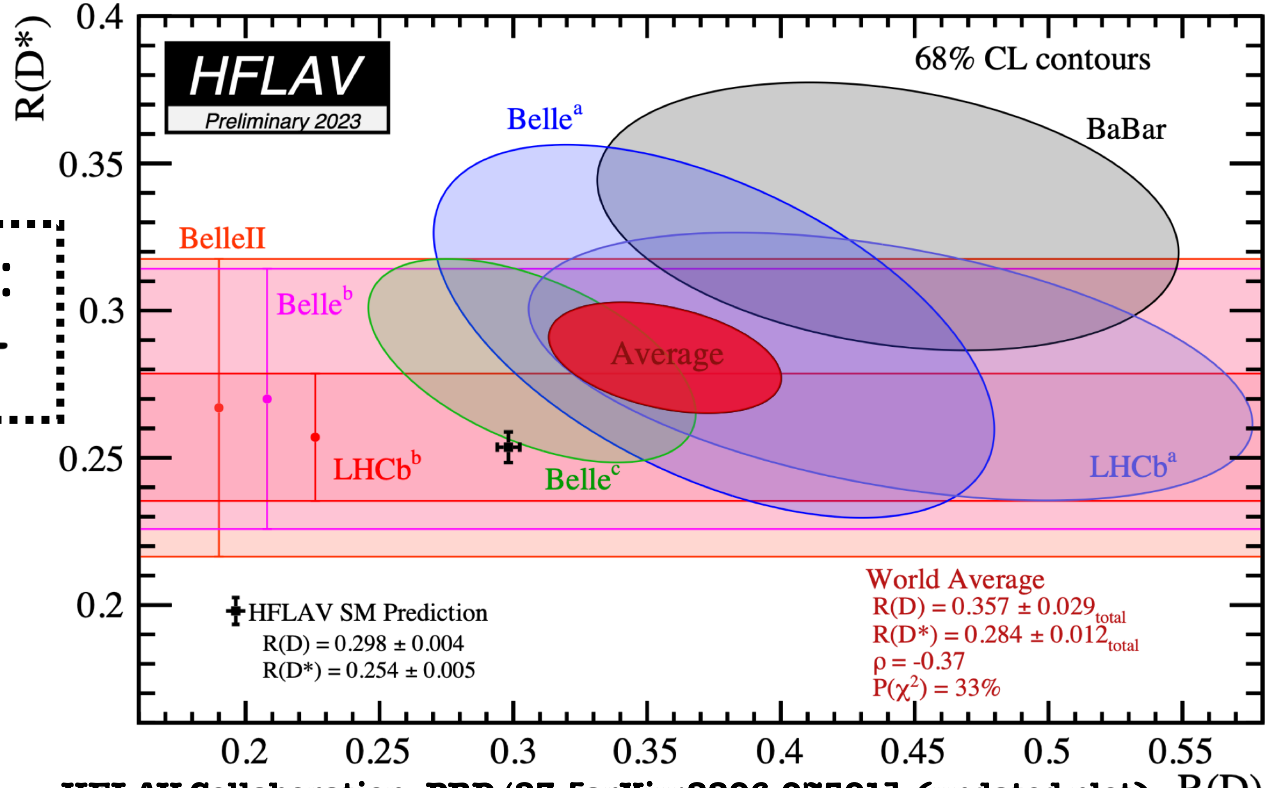
2. (Violazione di) Universalità del Sapore Leptonico



HFLAV Collaboration, PRD '23 [arXiv:2206.07501] (updated plot)

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

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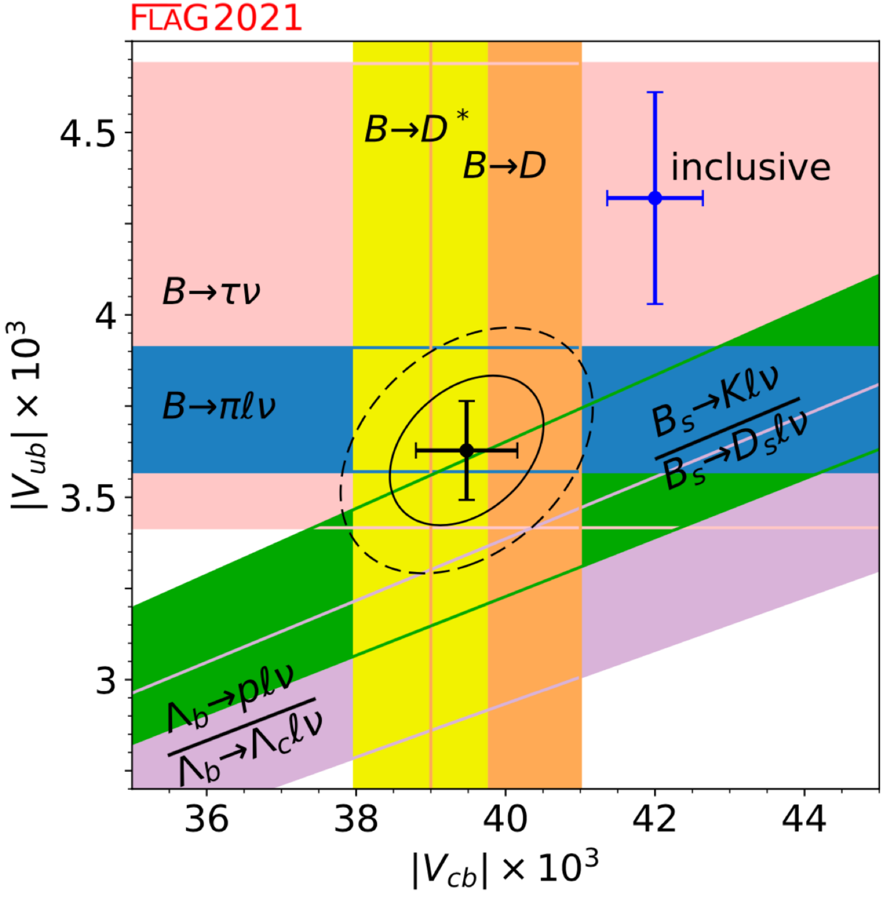

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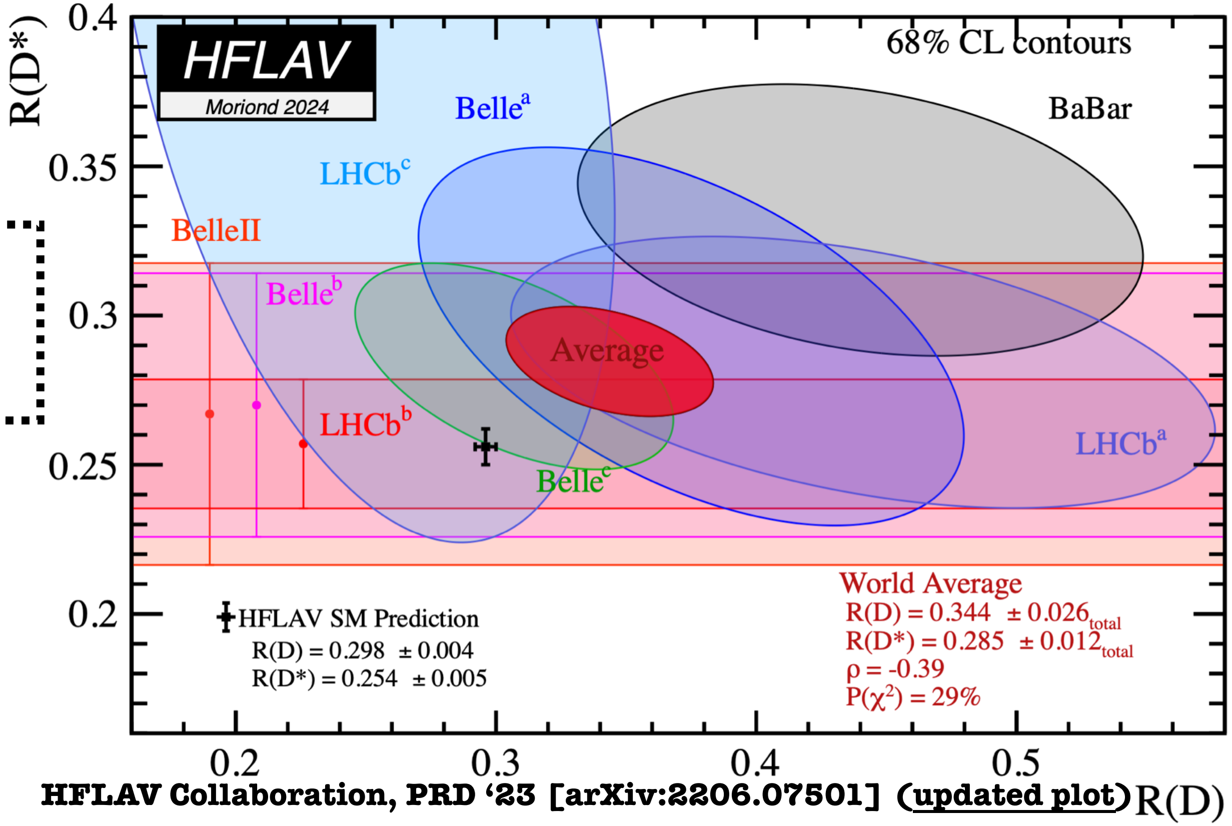

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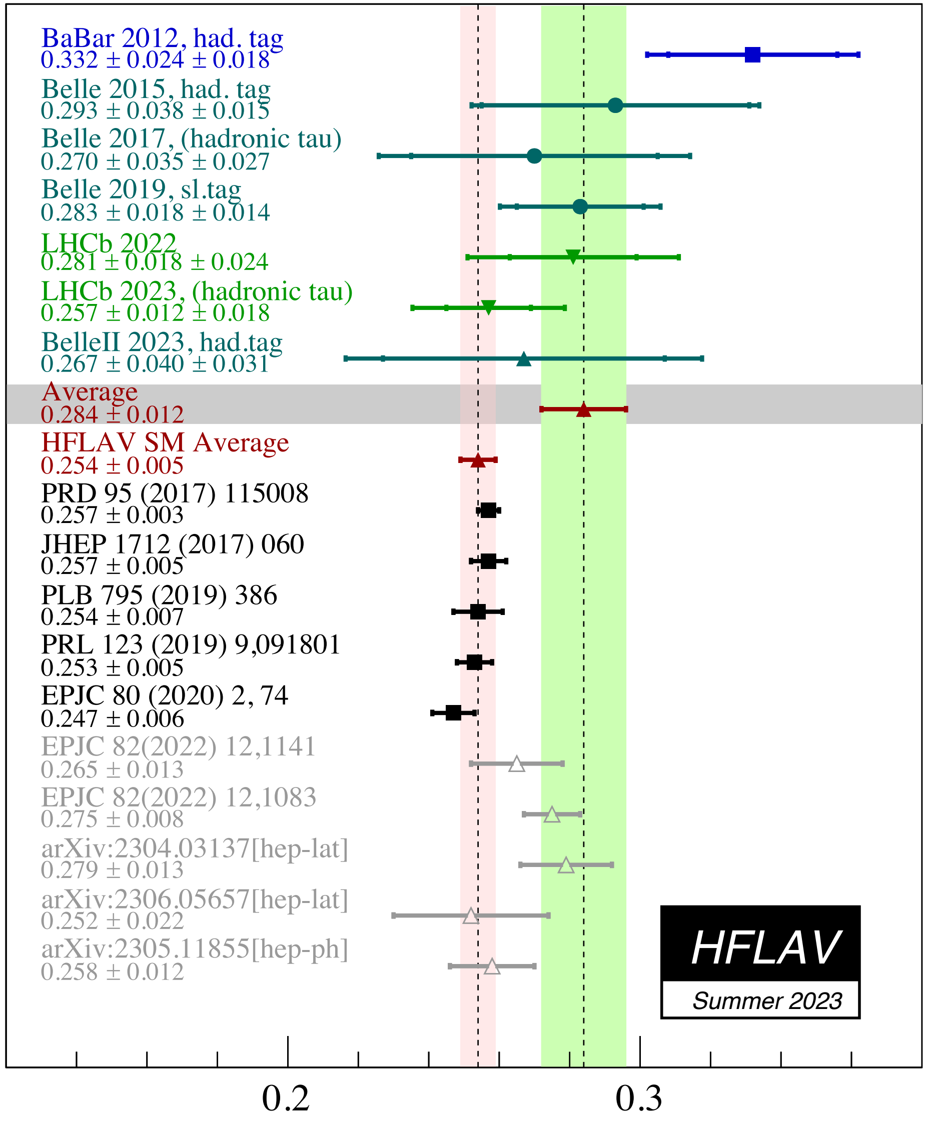

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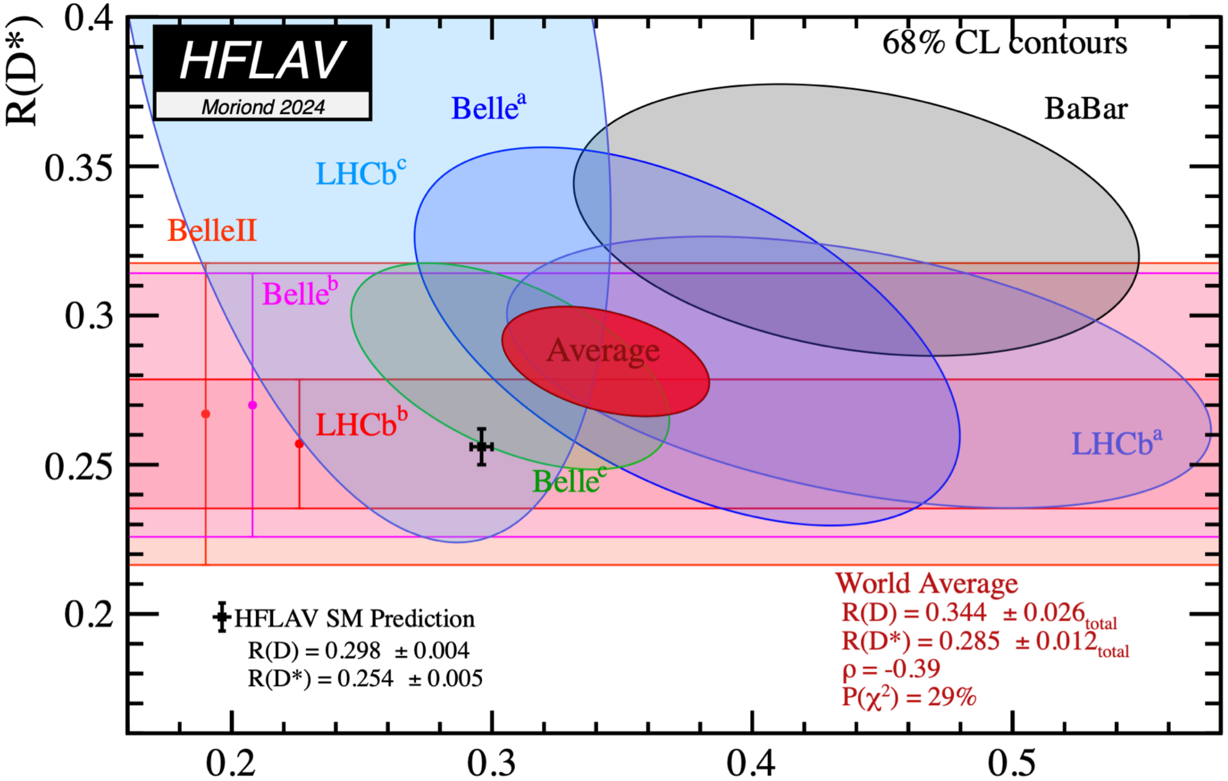

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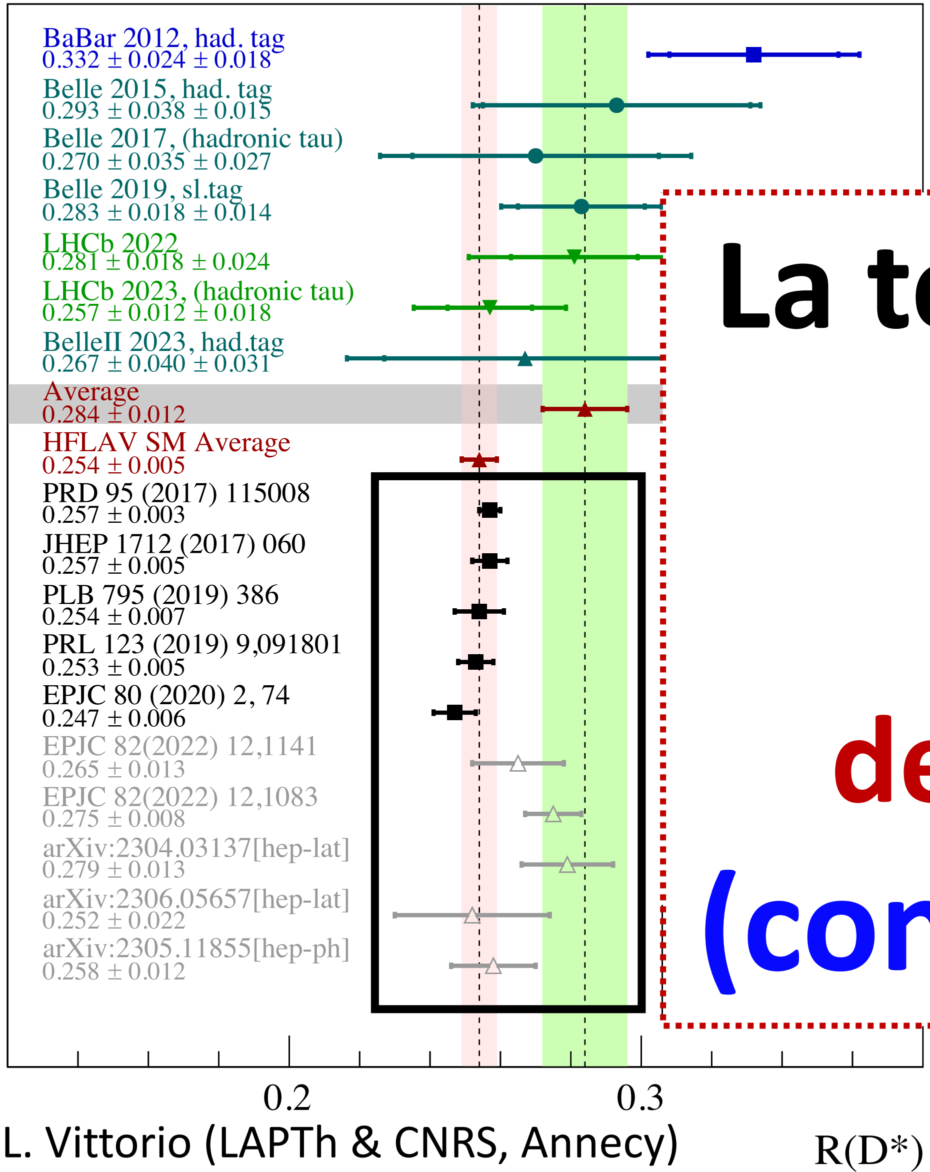

2. (Violazione di) Universalità del Sapore

La tensione dipende dall'analisi teorica considerata …

Peculiarità *solo* dei decadimenti semil. B → D* !

(consenso generale su B → D)

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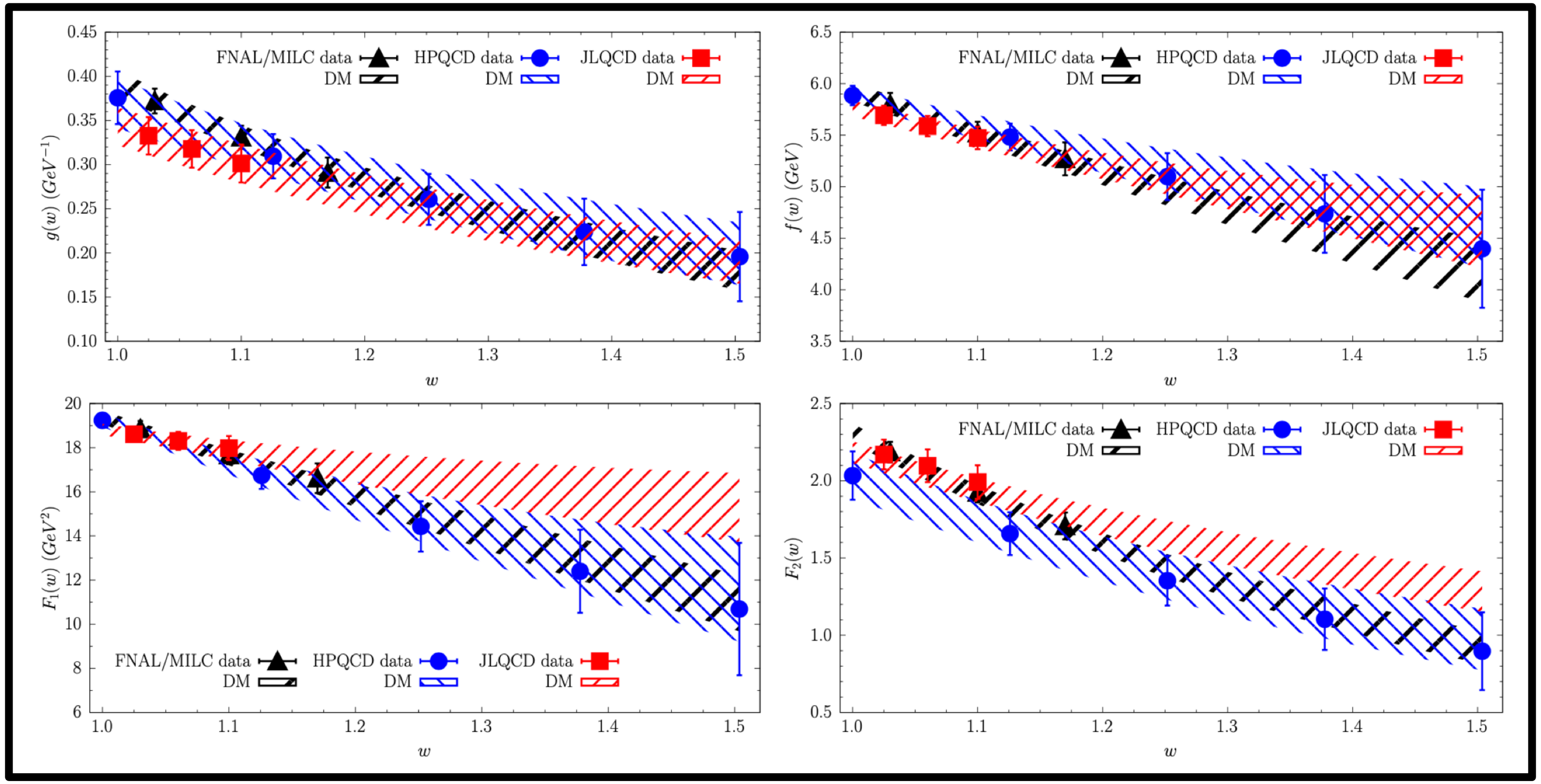
L'importanza dei fattori di forma per i decadimenti B → D*$\ell\upsilon$



G. Martinelli, S. Simula, LV, arXiv:2310.03680

FNAL/MILC:
EPJC '22
(arXiv:2105.14019)

HPQCD:
arXiv:2304.03137

JLQCD:
PRD '24
arXiv:2306.05657

Punti da tenere a mente:

i) I risultati dei conti di reticolo sono compatibili tra di loro a basso rinculo (w ≤ 1.2);

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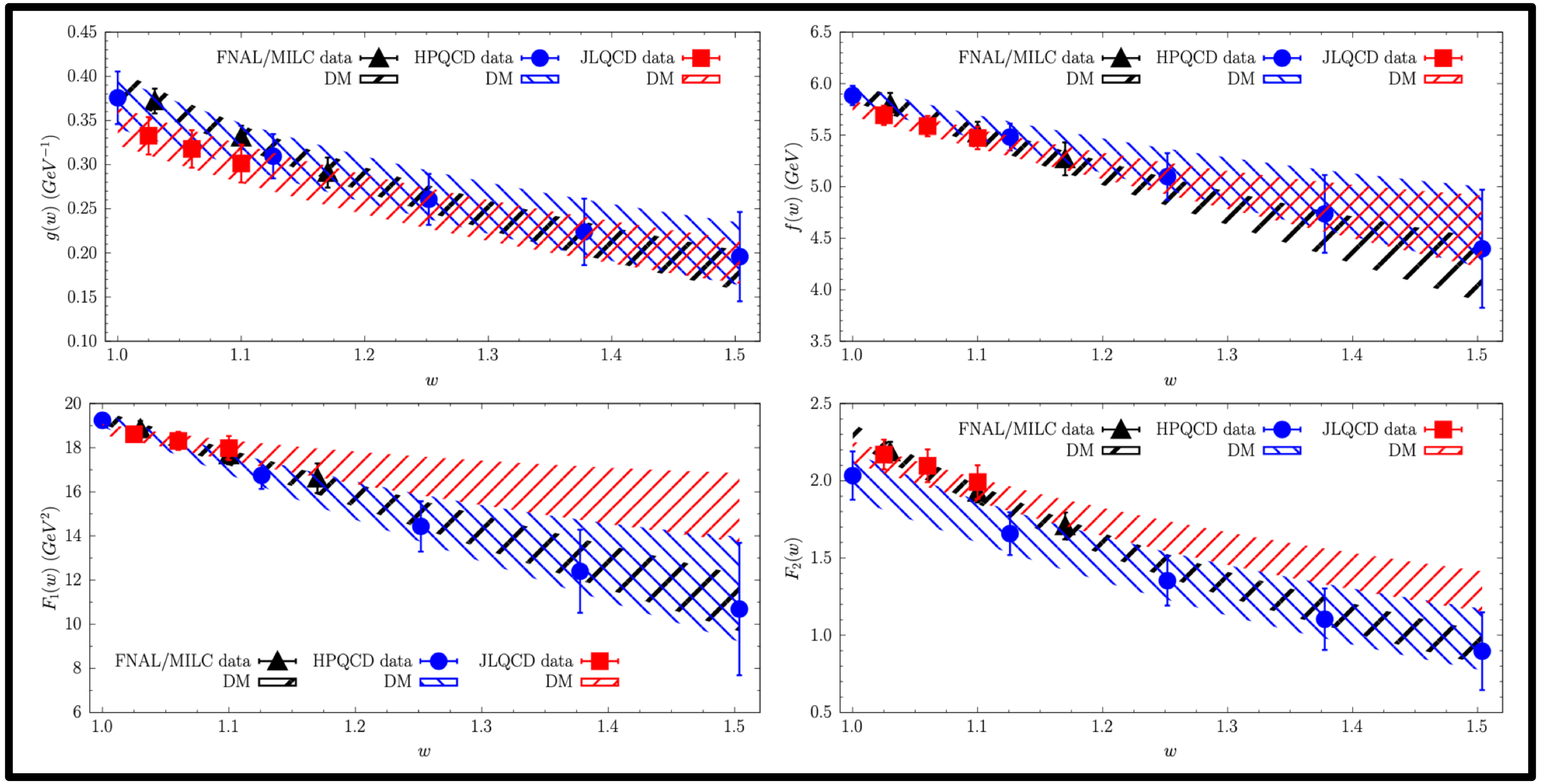

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Teor.:	***Esp.:***
0.262(9)	**0.284(12)**

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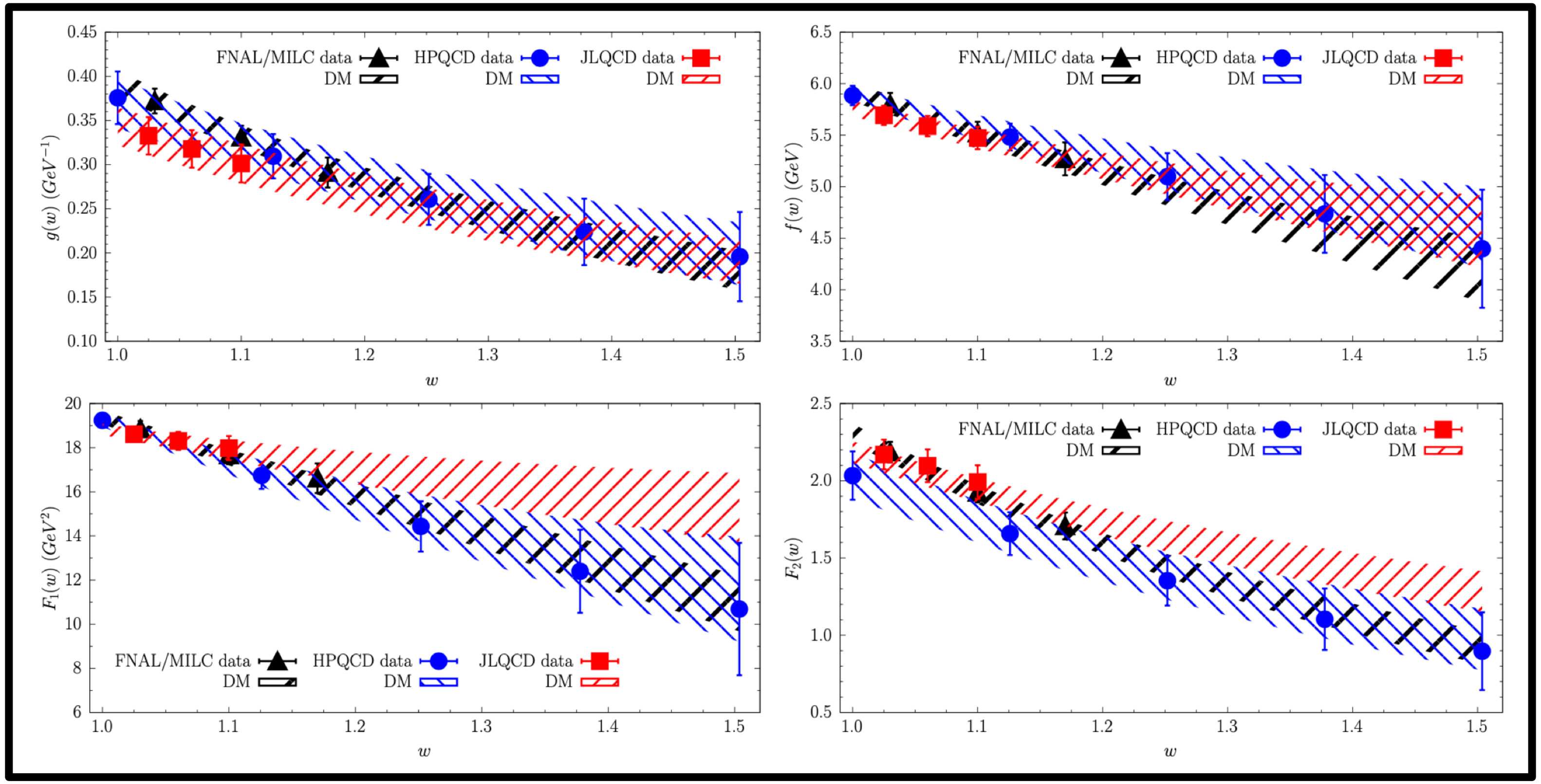

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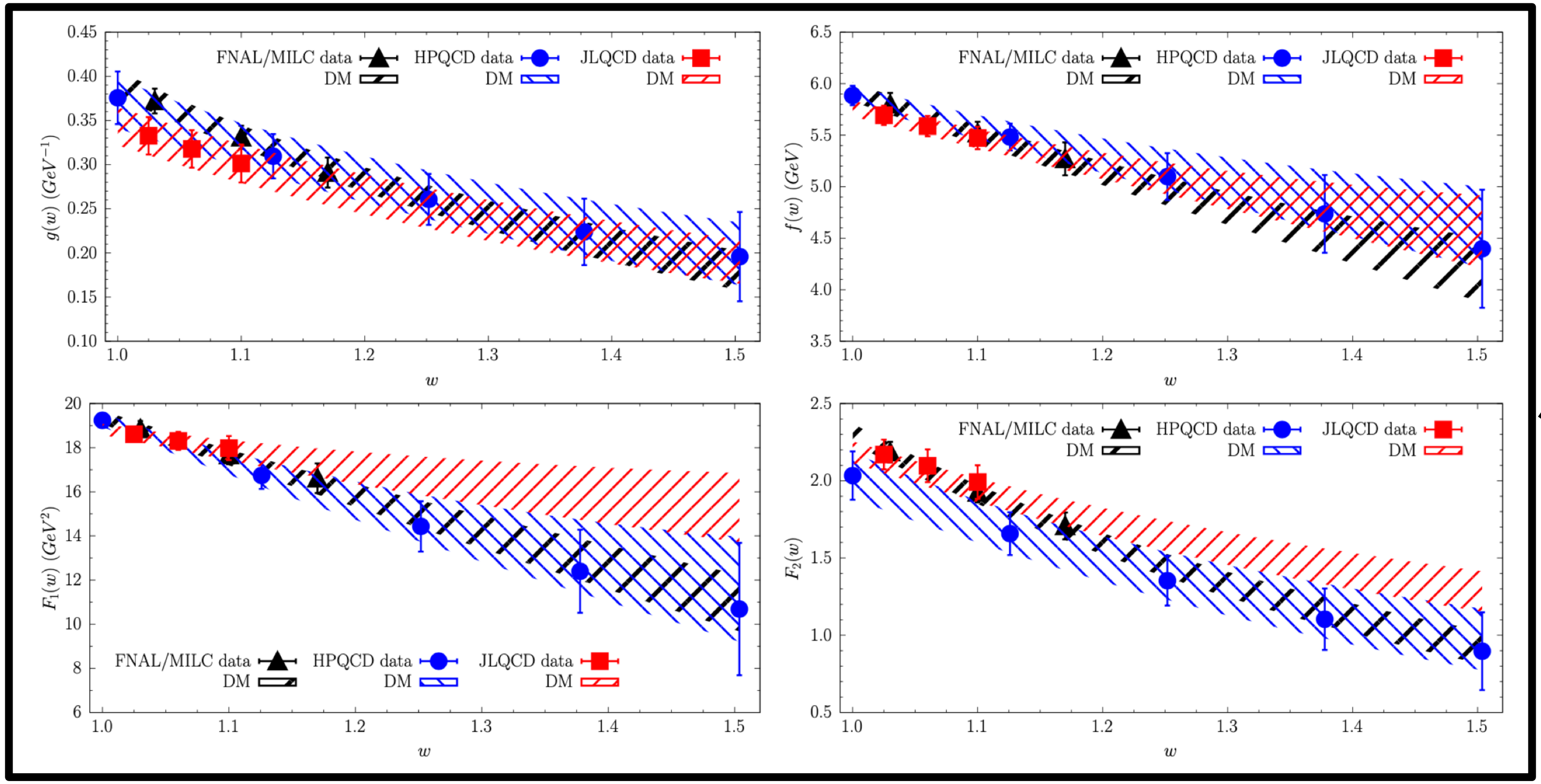

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Belle and Belle-II Coll. [2301.07529, 2310.01170]

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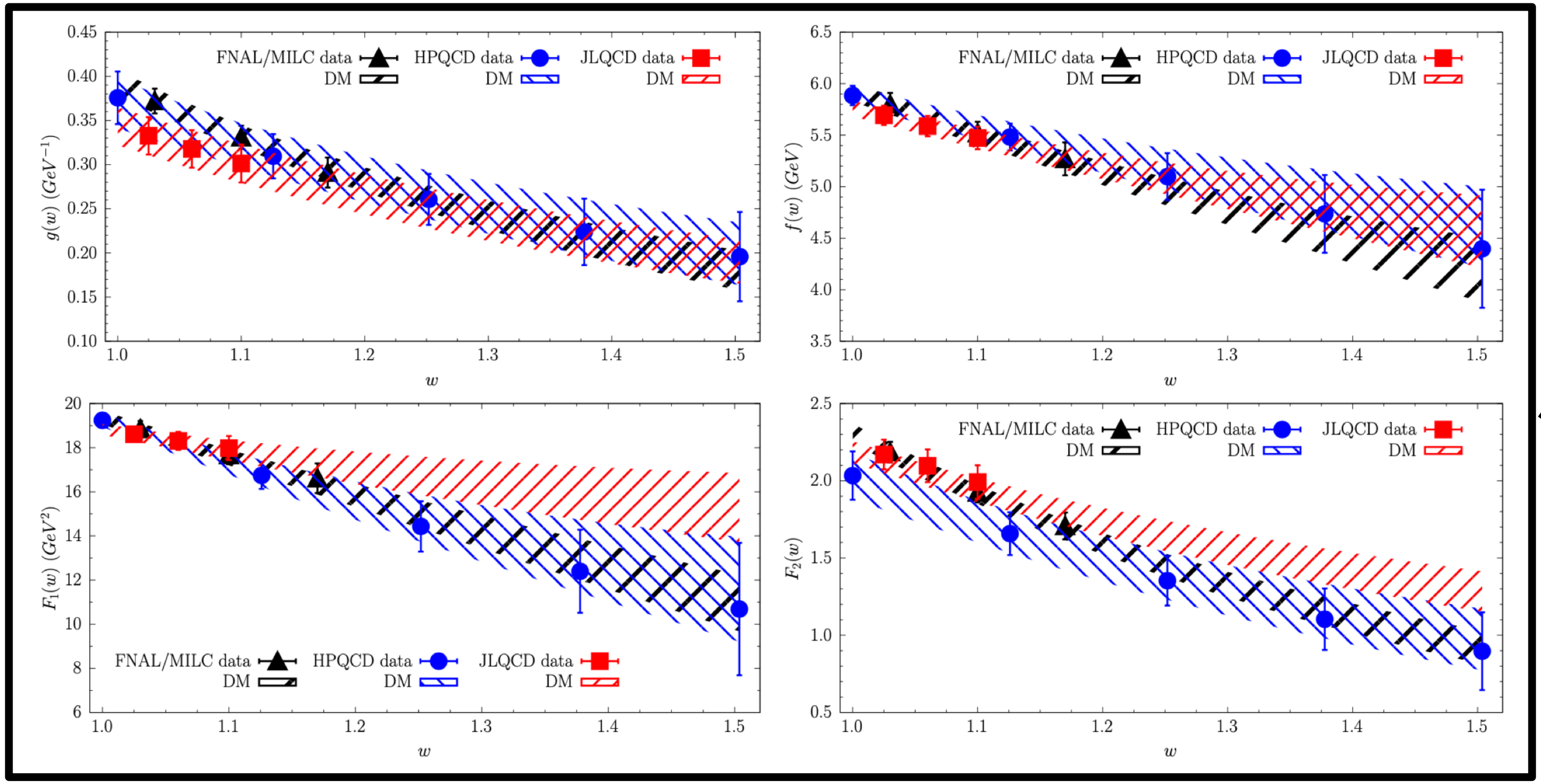

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Nuova Fisica accoppiata ai leptoni leggeri ?

M. Fedele et al., PRD '23 (2305.15457)
P. Colangelo et al., 2401.12304

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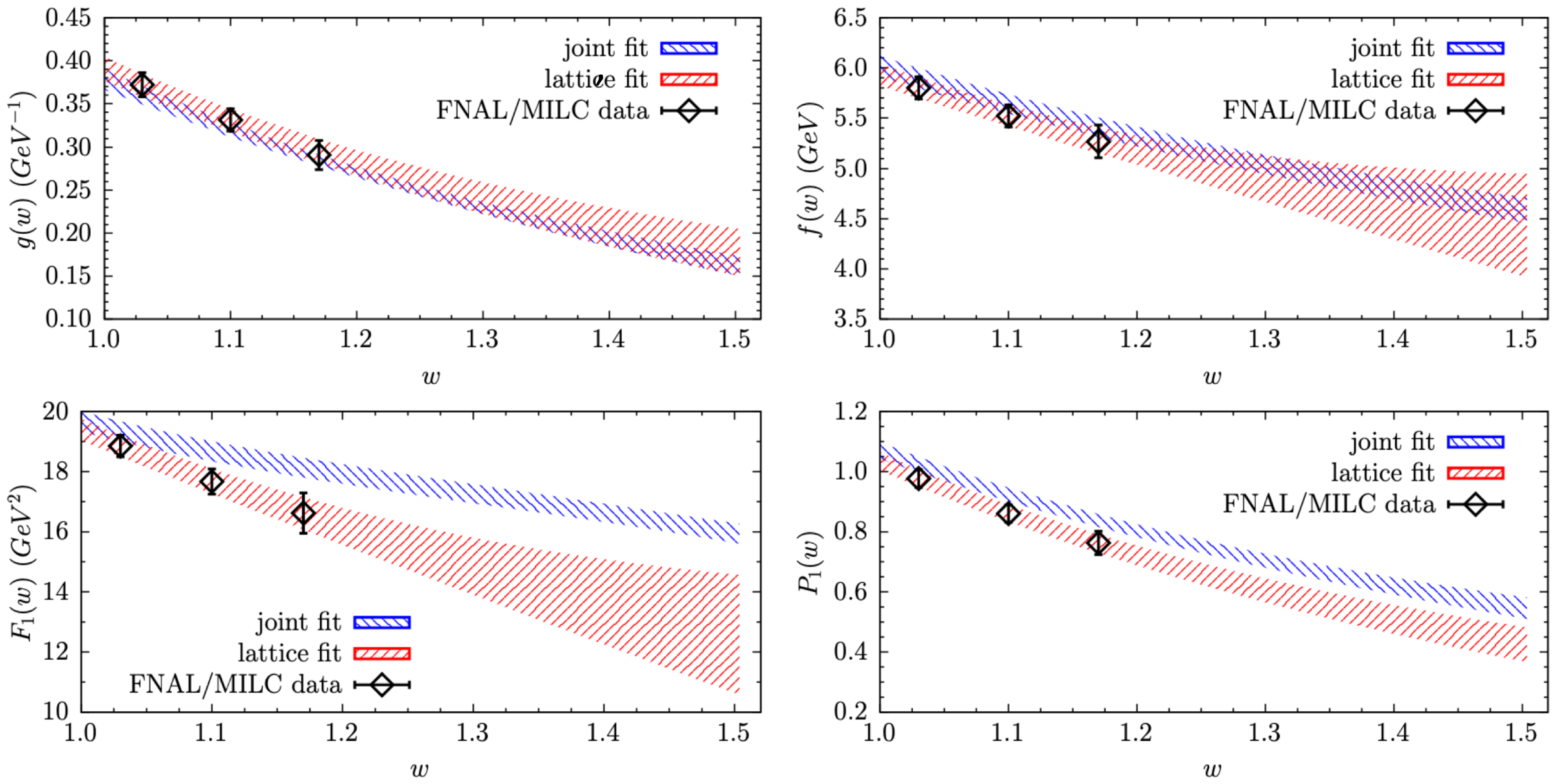
Perché non fare un fit globale dei dati di reticolo ed exp.

Consideriamo i fits implementati dalla collaborazione FNAL/MILC in EPJC ‘22 [arXiv:2105.14019]:



joint fit:
BGL fit of LQCD points + Belle + BaBar exp. data

$|V_{cb}| \cdot 10^3 = 38.40 \pm 0.74$

$R(D^*) = 0.2483 \pm 0.0013$

lattice fit:
quadratic BGL fit of LQCD points only

$|V_{cb}| > |V_{cb}|^{\text{joint fit}}$?

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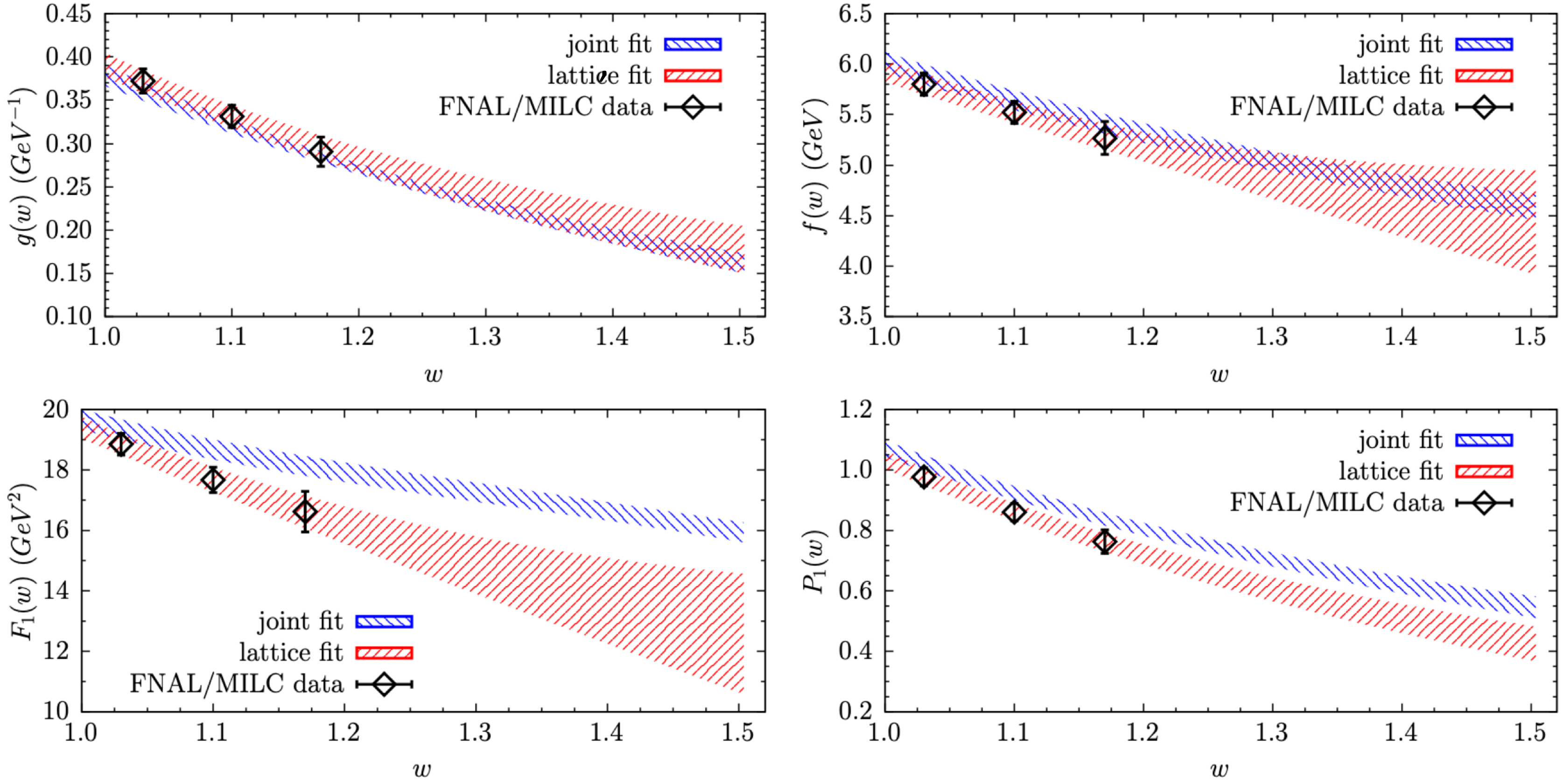

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Per evitare effetti di bias, *prima* si studino i dati di reticolo (per fissare i FF con la teoria) e *dopo* si comparino teoria ed exp.!

Perché non fare un fit globale dei dati di reticolo ed exp.

Consideriamo i fits implementati dalla collaborazione FNAL/MILC in EPJC '22 [arXiv:2105.14019] (basati sui dati Belle 2018)

0.45 6.5

METODOLOGIA GENERALE: questa strategia per l'analisi dei dati di reticolo e delle misure sperimentali va adoperata sempre, in particolare in presenza di molti FF dalla teoria. **Esempi per $b \to c$ e $b \to u$:**

- Decadimenti di part. pseudoscalare in part. vettoriale:

$$B \to \rho \ell \nu,\ \ B \to \omega \ell \nu,\ \ B_s \to K^* \ell \nu,\ \ \ldots$$

- Decadimenti di barioni:

$$\Lambda_p \to \Lambda_c \ell \nu,\ \ \Lambda_b \to p \ell \nu,\ \ \ldots$$

Novità sull'estrazione di |Vcb|

- Belle 2018/Belle-II 2023: $d\Gamma/dx$

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

- Belle 2023: $(d\Gamma/dx)/\Gamma$

Belle Collaboration, PRD '23 [arXiv:2301.07529]

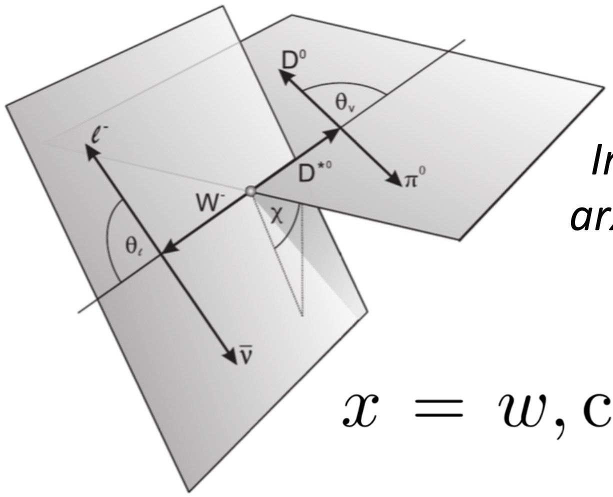

Image taken from arXiv:1702.01521v2

$$x = w, \cos\theta_l, \cos\theta_v, \chi$$

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BIN-PER-BIN |Vcb|:

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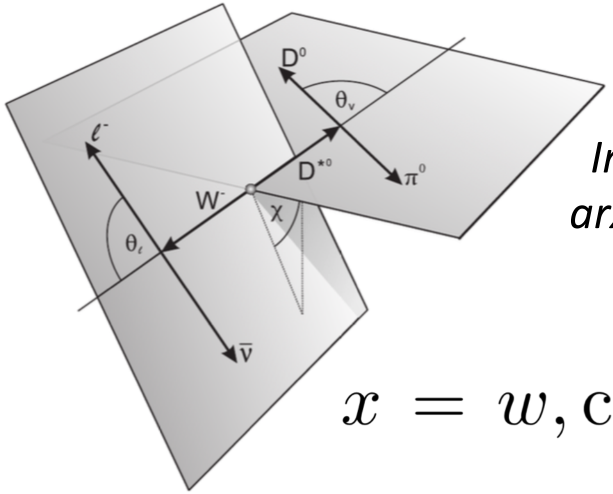
[alcuni plots nelle slides di back-up]



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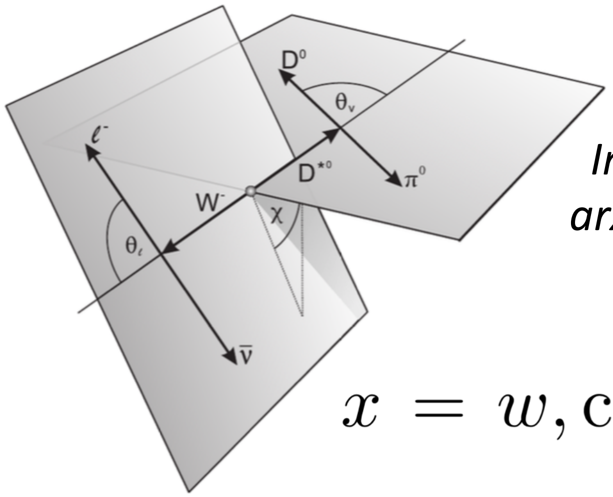

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$\lvert V_{cb}\rvert \cdot 10^3$			
experiment	FNAL/MILC	HPQCD	JLQCD
Belle 2018	39.64 (74)	39.11 (81)	39.92 (74)
$\chi^2/(\text{d.o.f.})$	3.71	1.14	0.04
Belle 2023	40.87 (115)	41.03 (125)	41.38 (134)
$\chi^2/(\text{d.o.f.})$	1.80	0.11	0.31
Belle-II 2023	39.35 (77)	39.98 (102)	40.20 (85)
$\chi^2/(\text{d.o.f.})$	0.63	0.09	0.42

$$|V_{cb}| = (39.92 \pm 0.64) \cdot 10^{-3}$$

(scaling factor à la PDG of 1.0)

G. Martinelli, S. Simula, LV, arXiv:2310.03680

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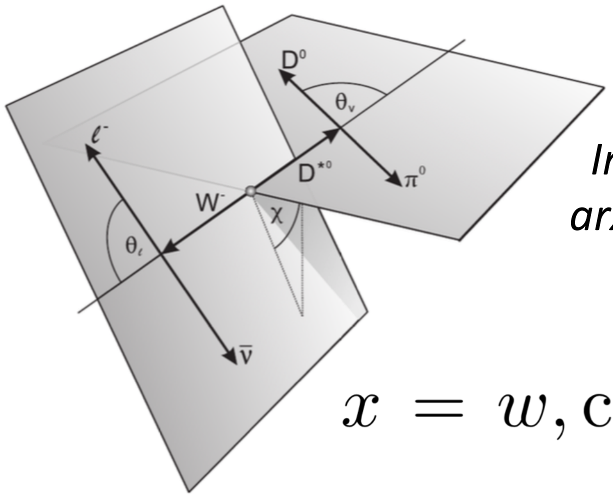

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Se la teoria fosse data da uno studio combinato dei 3 datasets di reticolo (piuttosto che dall'analisi separata di ciascuno di essi), si otterrebbero risultati simili.

Stima conservativa e affidabile dell'incertezza!

Fisica del sapore nel ed oltre il MS

Processi Tree-level

FCNCs

Transizioni $b \to c$

Fisica del sapore nel ed oltre il MS

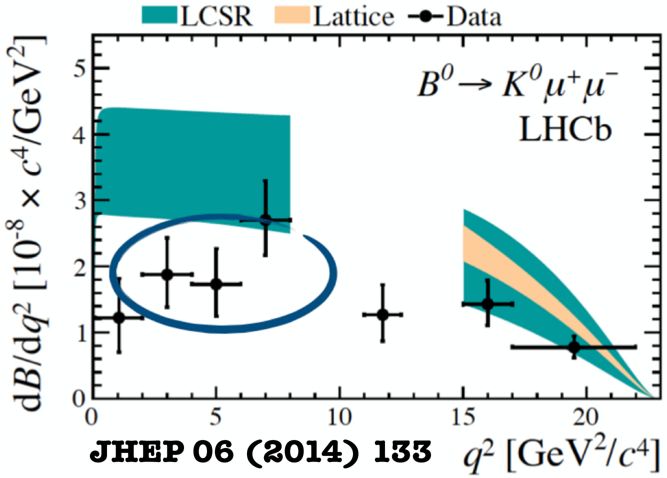
Processi Tree-level

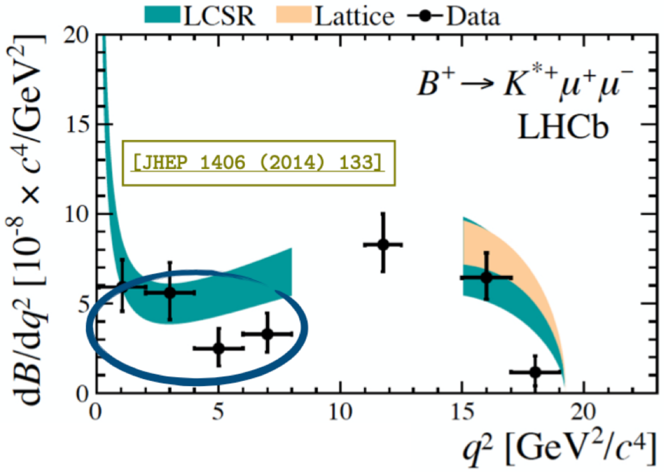
FCNCs

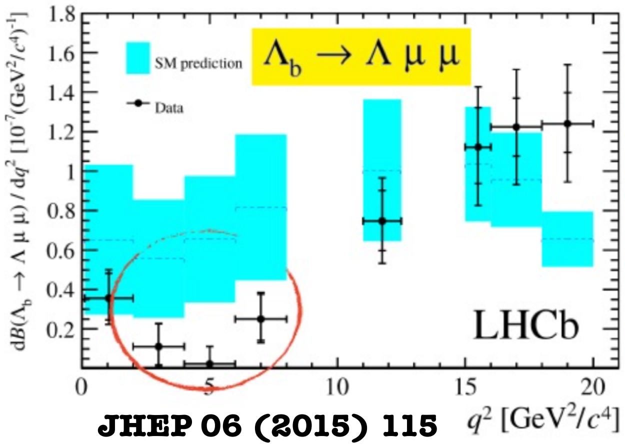
Transizioni $b \to c$

Transizioni $b \to s$

Tensioni persistenti (?) nei processi $b \to s$







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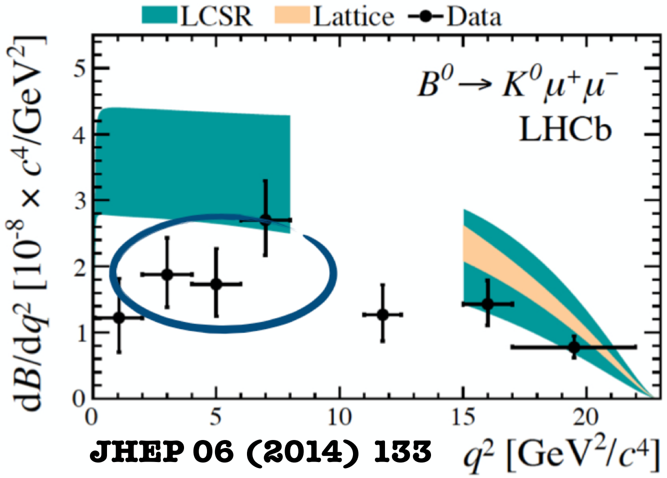

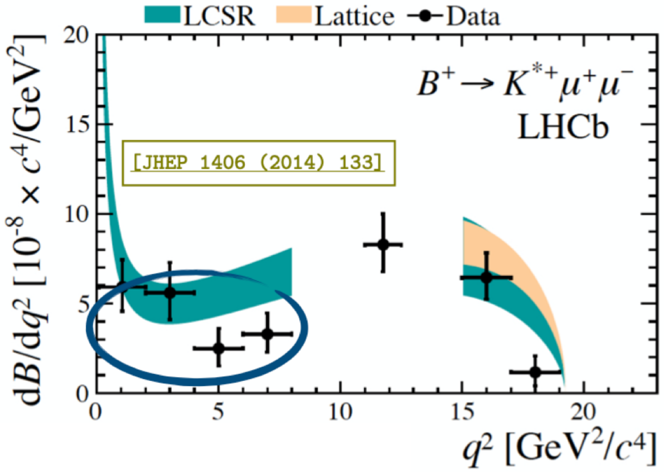

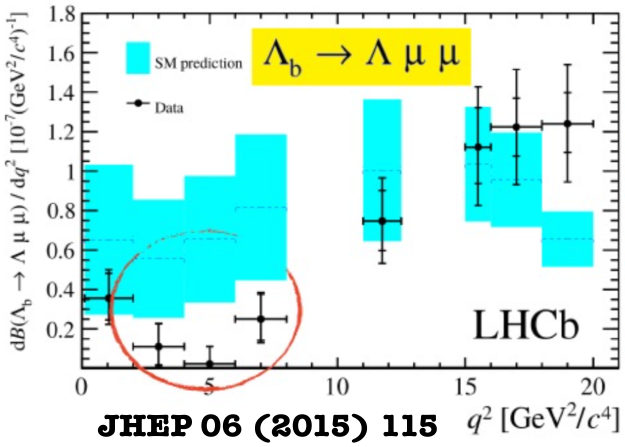

Quadro stabile:
TH. > EXP.
…
Ne siamo sicuri ?

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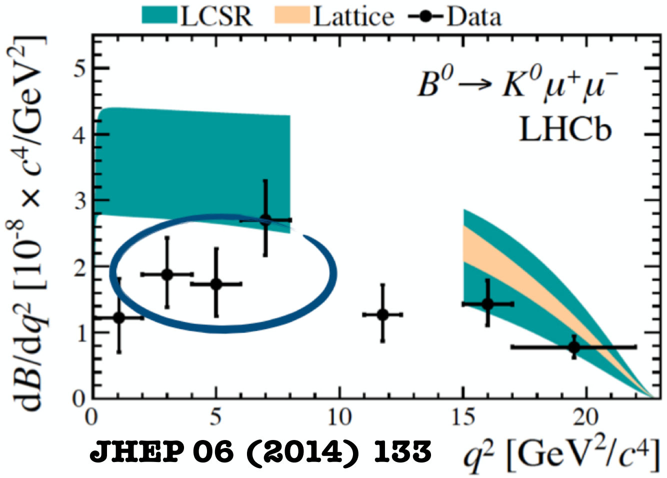
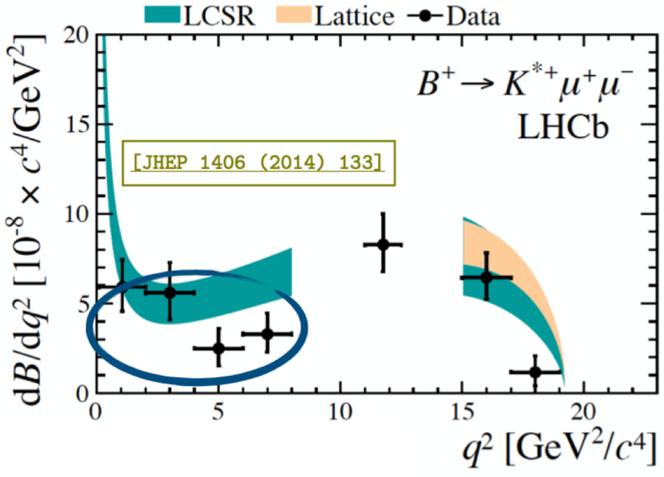
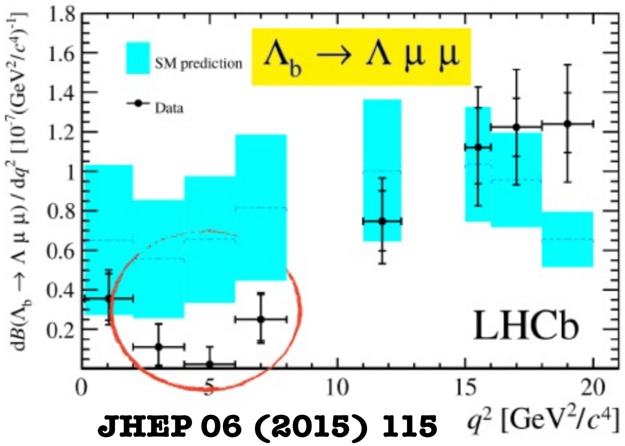


JHEP 06 (2014) 133





JHEP 06 (2015) 115

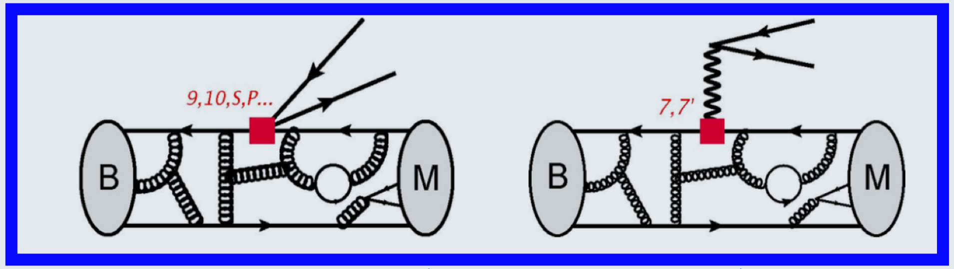
Quadro stabile:

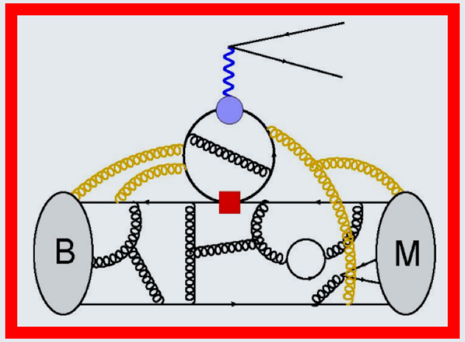
TH. > EXP.

…

Ne siamo sicuri ?

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





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

local form-factors

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

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Non-local form-factors

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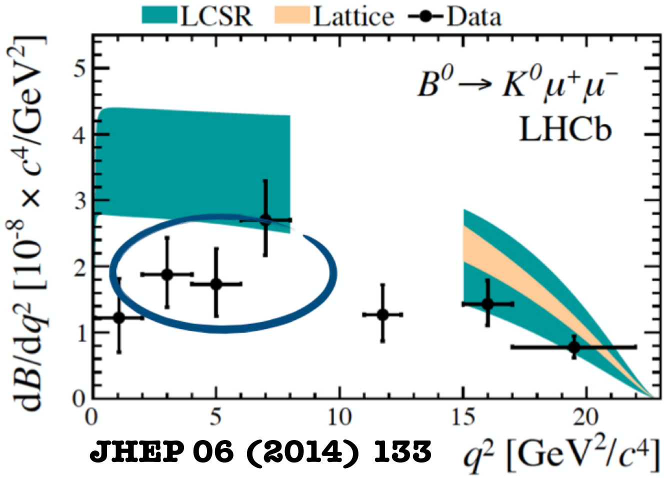
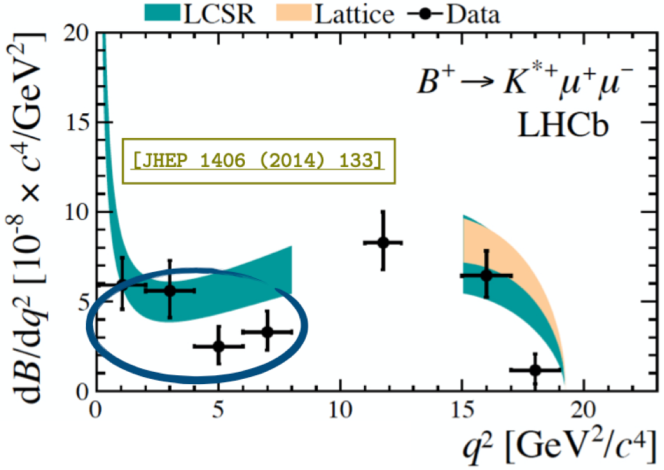
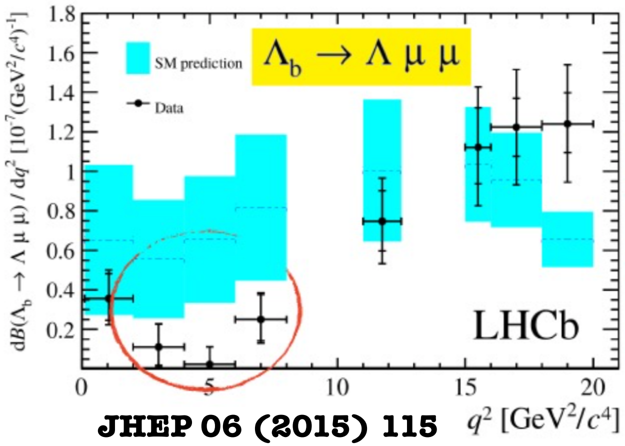


JHEP 06 (2014) 133





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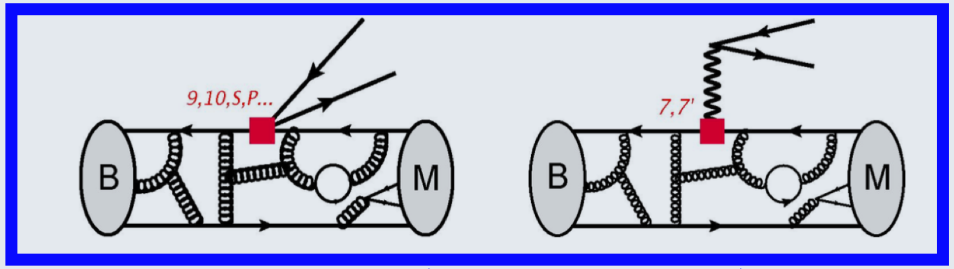

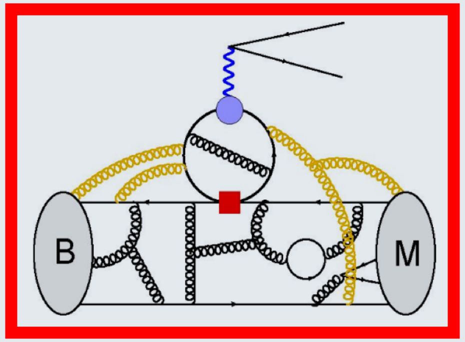

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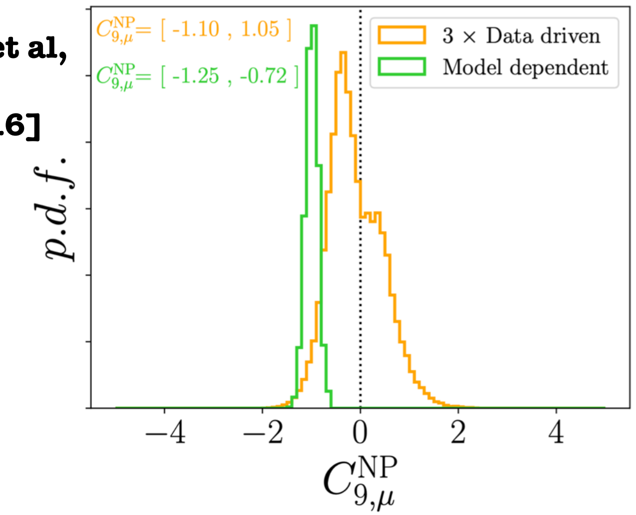
Non-local form-factors

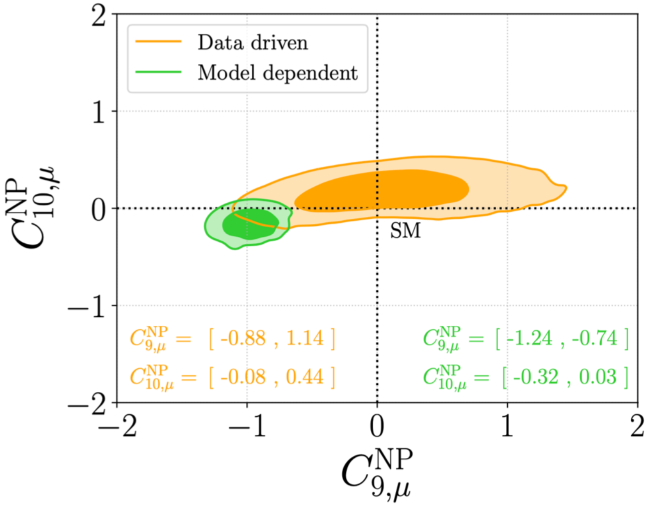
 M. Reboud's talk @ LHC Impilication Workshop 2022 @ CERN

Qual è il contributo dei FF non locali?

Non c'è consenso generale sulla risposta a questa domanda:

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





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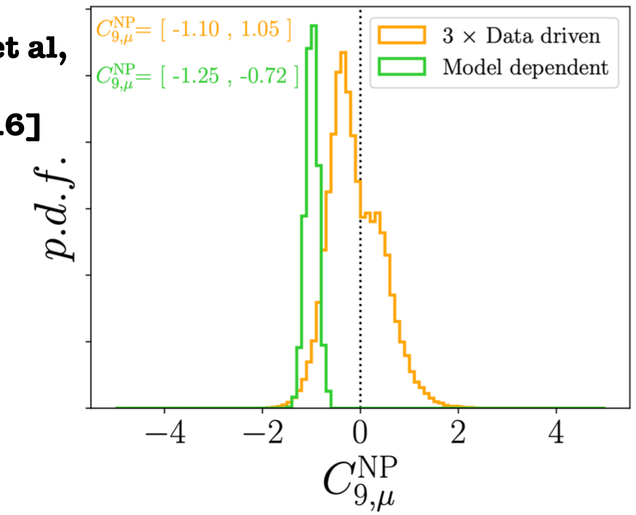

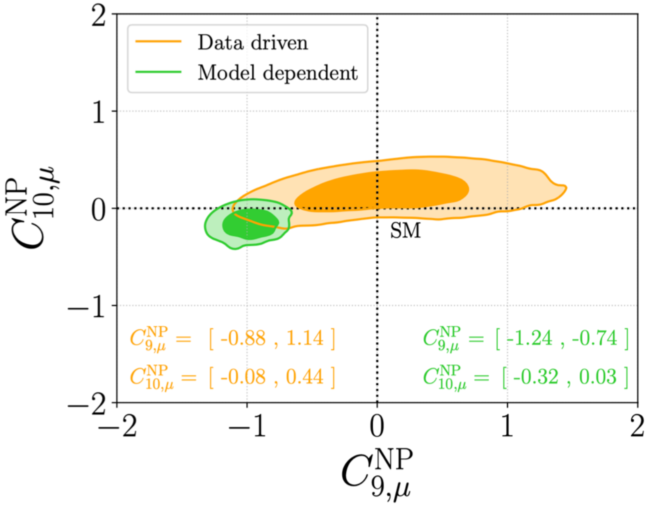

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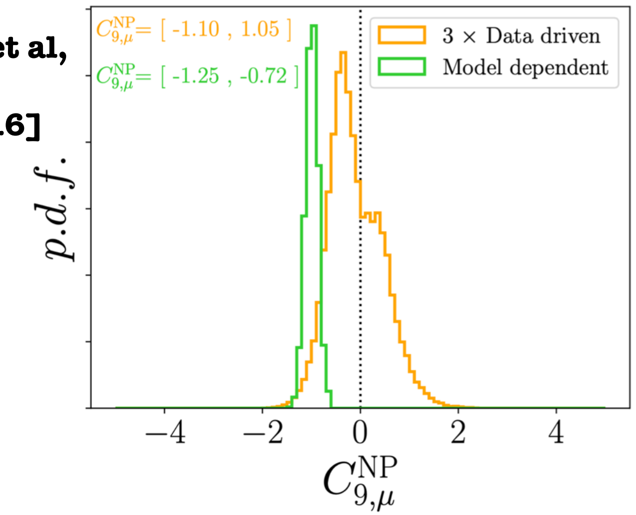

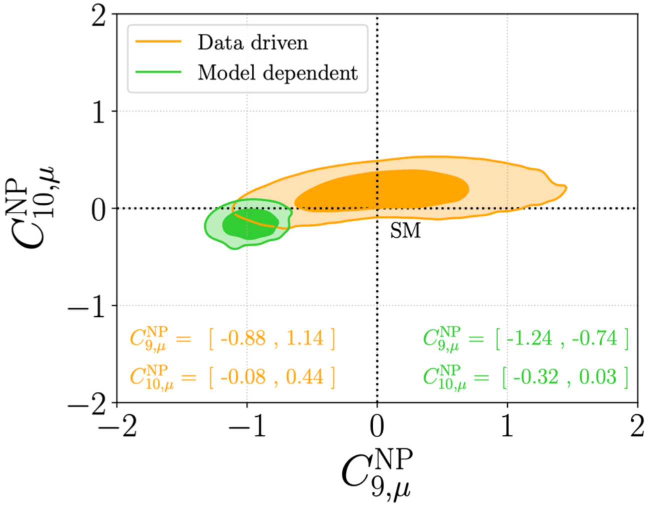

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Vantaggio: è trasparente la sinergia tra contributi adronici e Nuova Fisica!

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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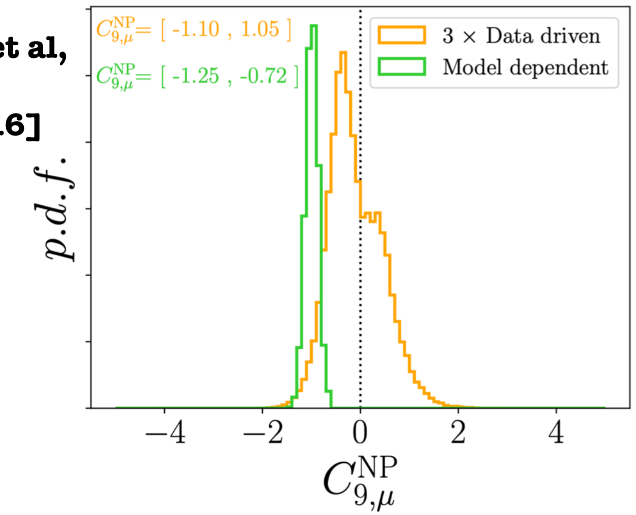

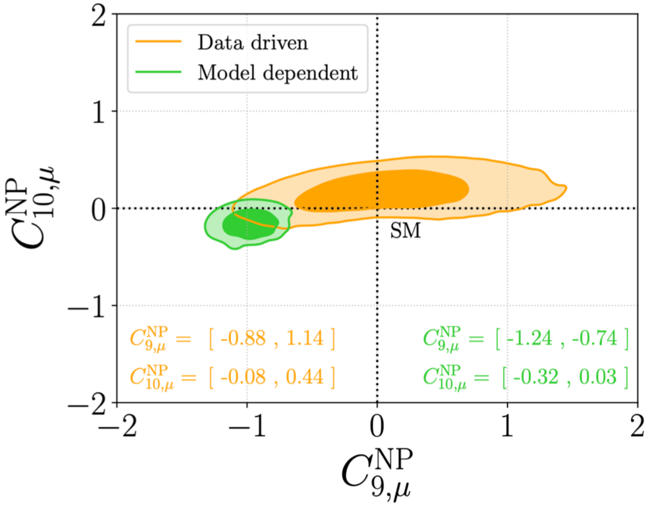

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Model-depedent: gli *h*-termini $[h_-^{(0)}, h_-^{(1)}, h_-^{(2)}]$ sono considerati *trascurabili*.

Motivazione: questa assunzione è supportata dall'**applicazione di relazioni di dispersione, analiticità e unitarietà (insieme ai dati LCSR)** alla descrizione dei fattori di forma non locali!

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

La necessità di trovare osservabili $b \to$ s complementari

i) Bs \to $\mu\mu\gamma$ @ alto-q2: le osservabili ad alto q^2 dipendono dagli stessi effetti di corta distanza presenti in B \to K(*), ***ma sono libere dai prima citati effetti di lunga distanza*****!**

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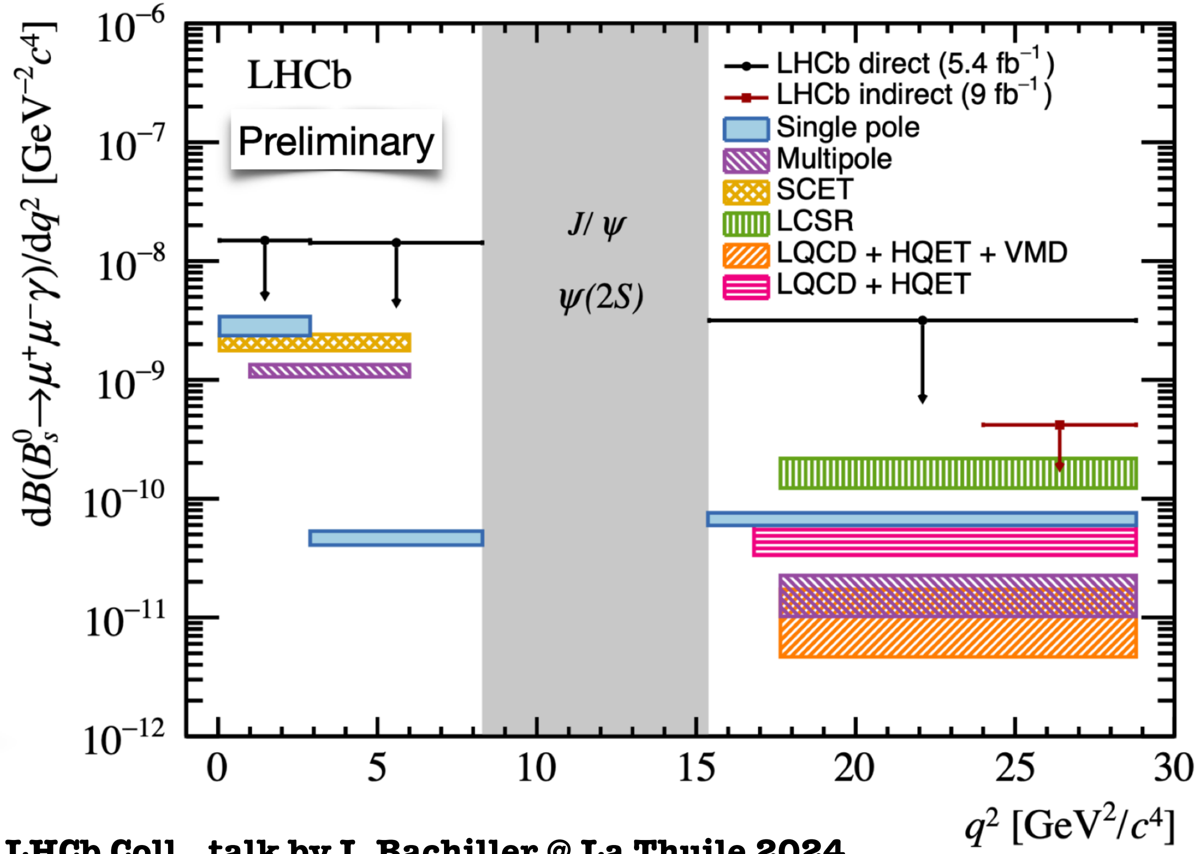

LHCb Coll., talk by I. Bachiller @ La Thuile 2024

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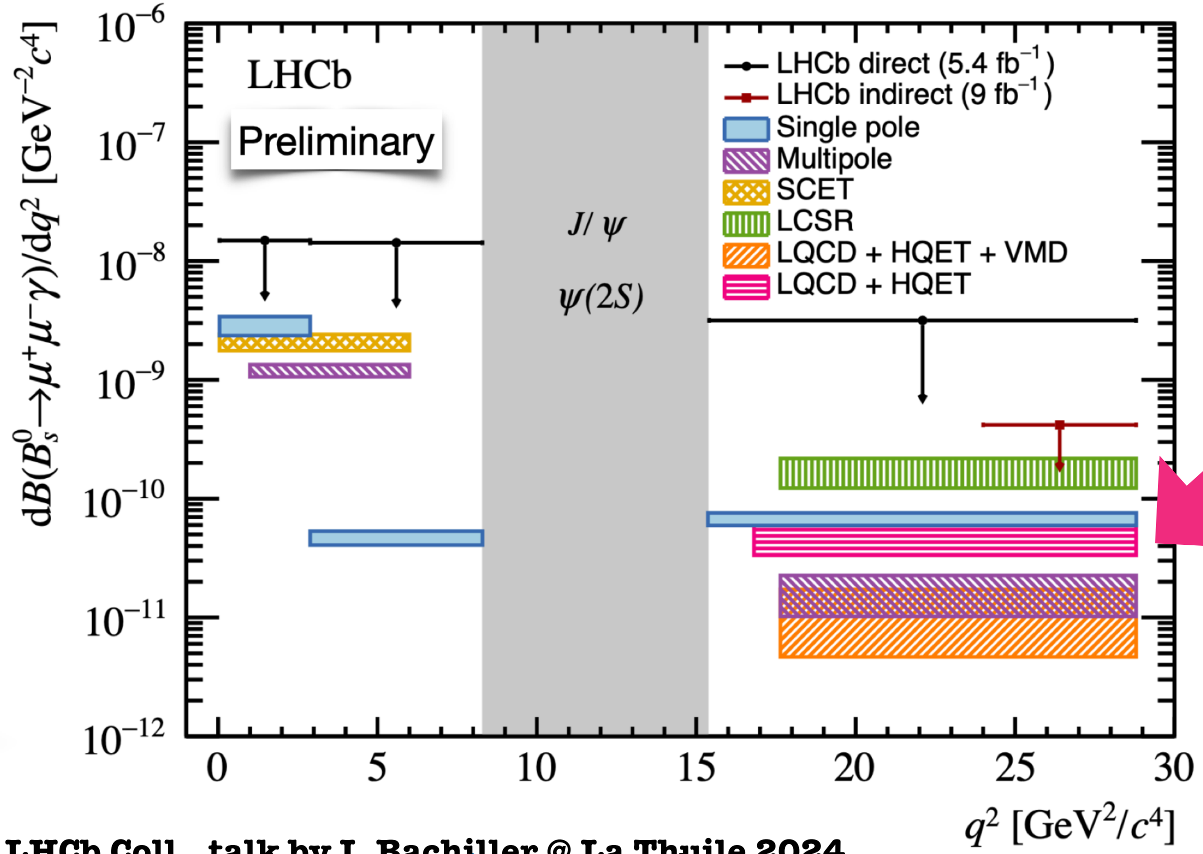

LHCb Coll., talk by I. Bachiller @ La Thuile 2024

Importanti progressi anche a livello teorico:
primo studio di reticolo da parte della Collaborazione ETMC
(2402.03262)

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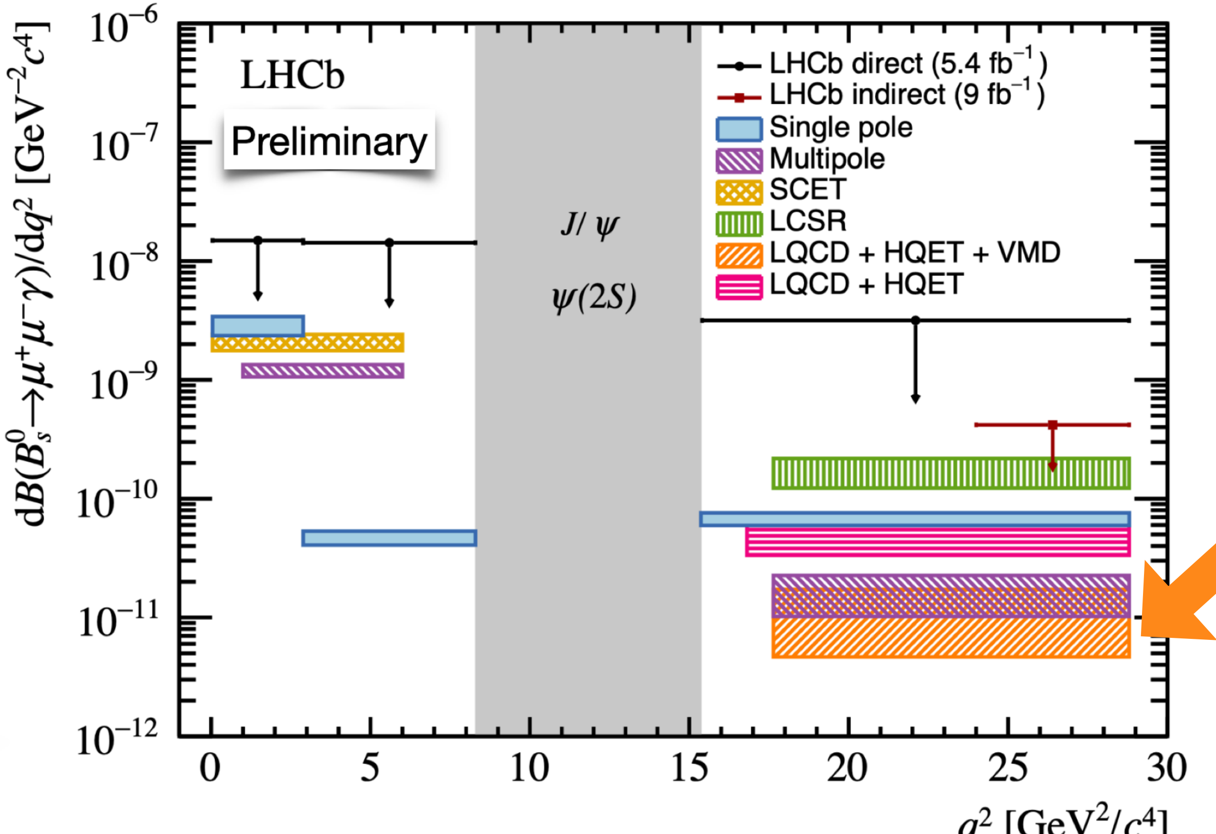
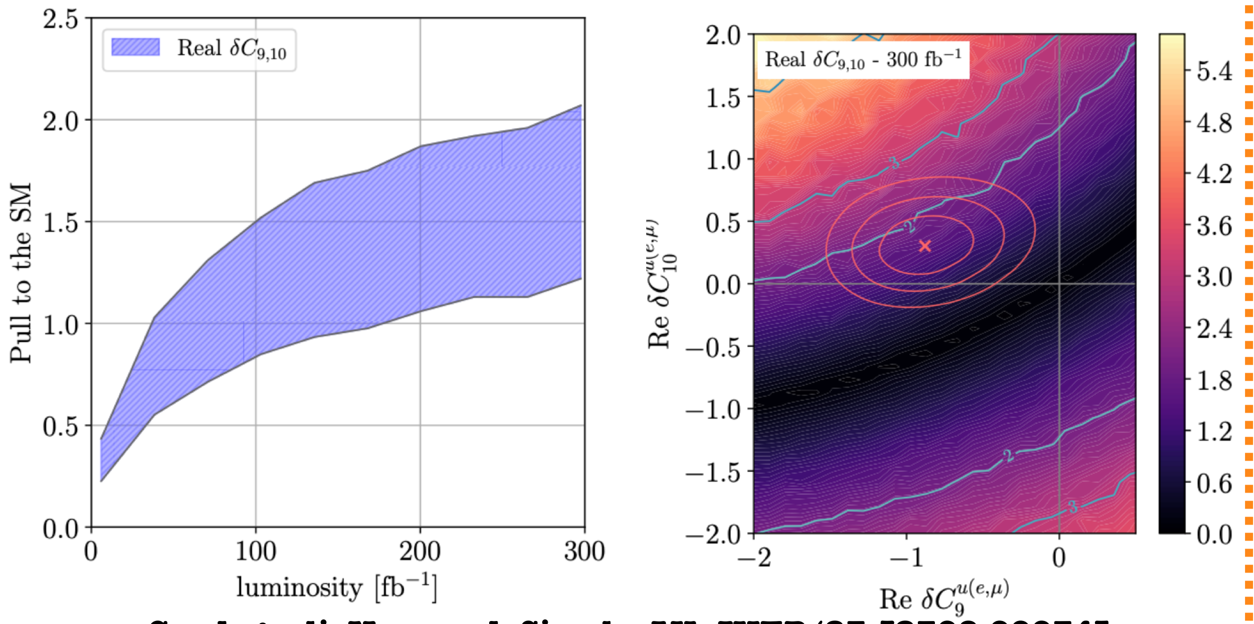


LHCb Coll., talk by I. Bachiller @ La Thuile 2024

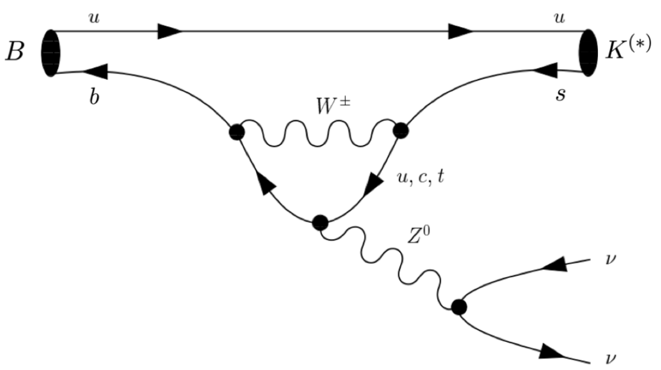
Approccio fenom. adoperato per uno studio di sensitività oltre il Modello Standard:

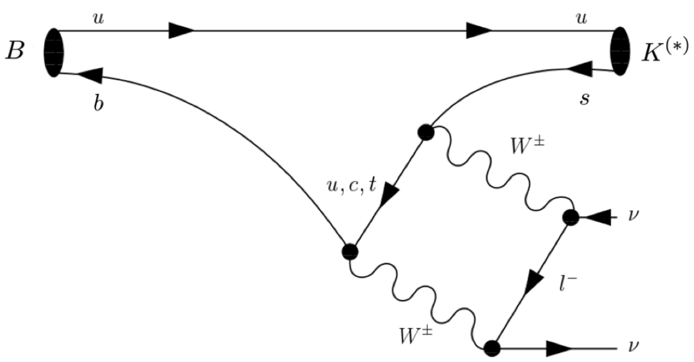


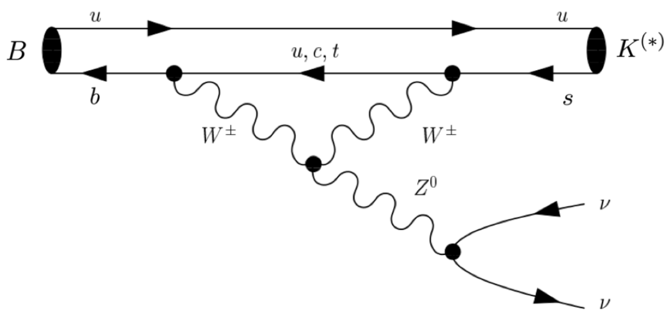
Guadagnoli, Normand, Simula, LV, JHEP '23 [2308.00034]

La necessità di trovare osservabili $b \to s$ complementari

ii) B → K(*)$\upsilon\upsilon$: non afflitto per nulla dagli effetti di lunga distanza !







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Maggiori sorgenti di incertezza:

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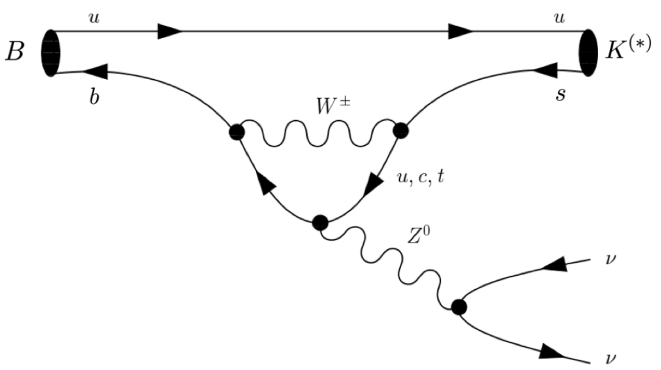
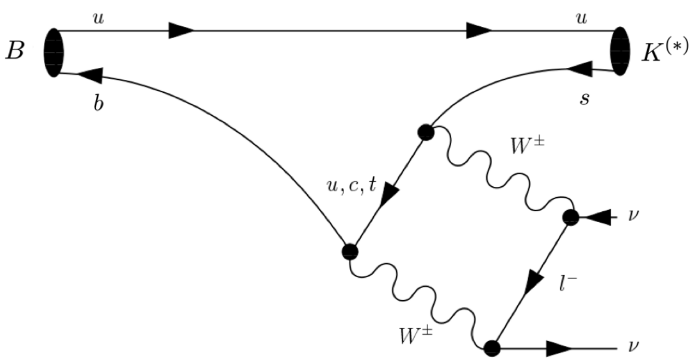
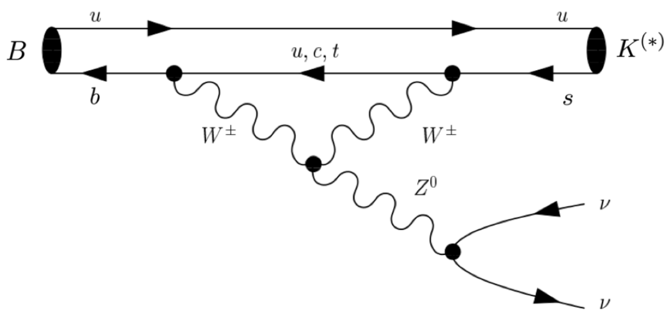
2. **Fisica adronica**







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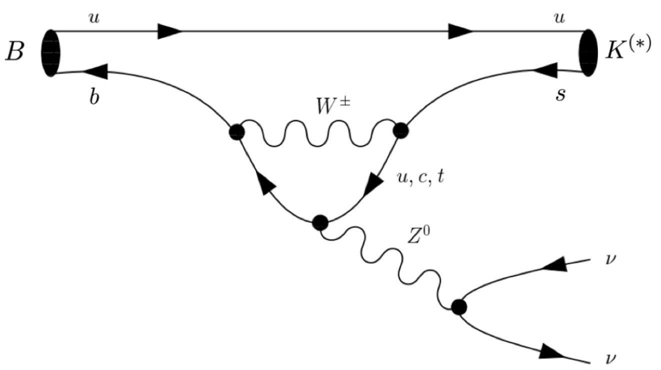
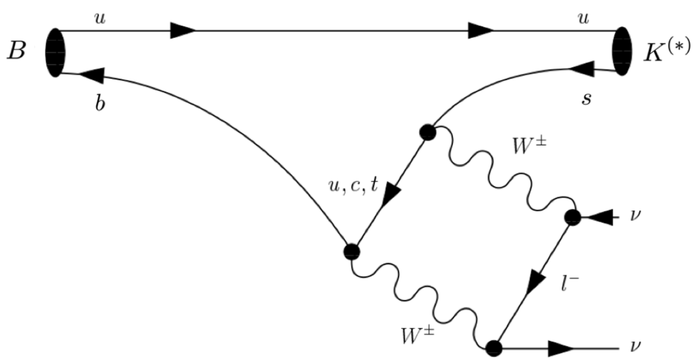
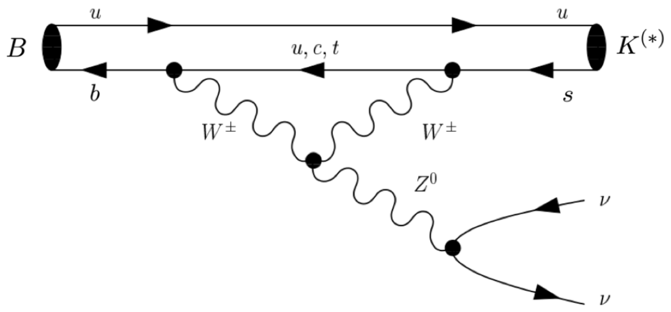






Final prediction MS:

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

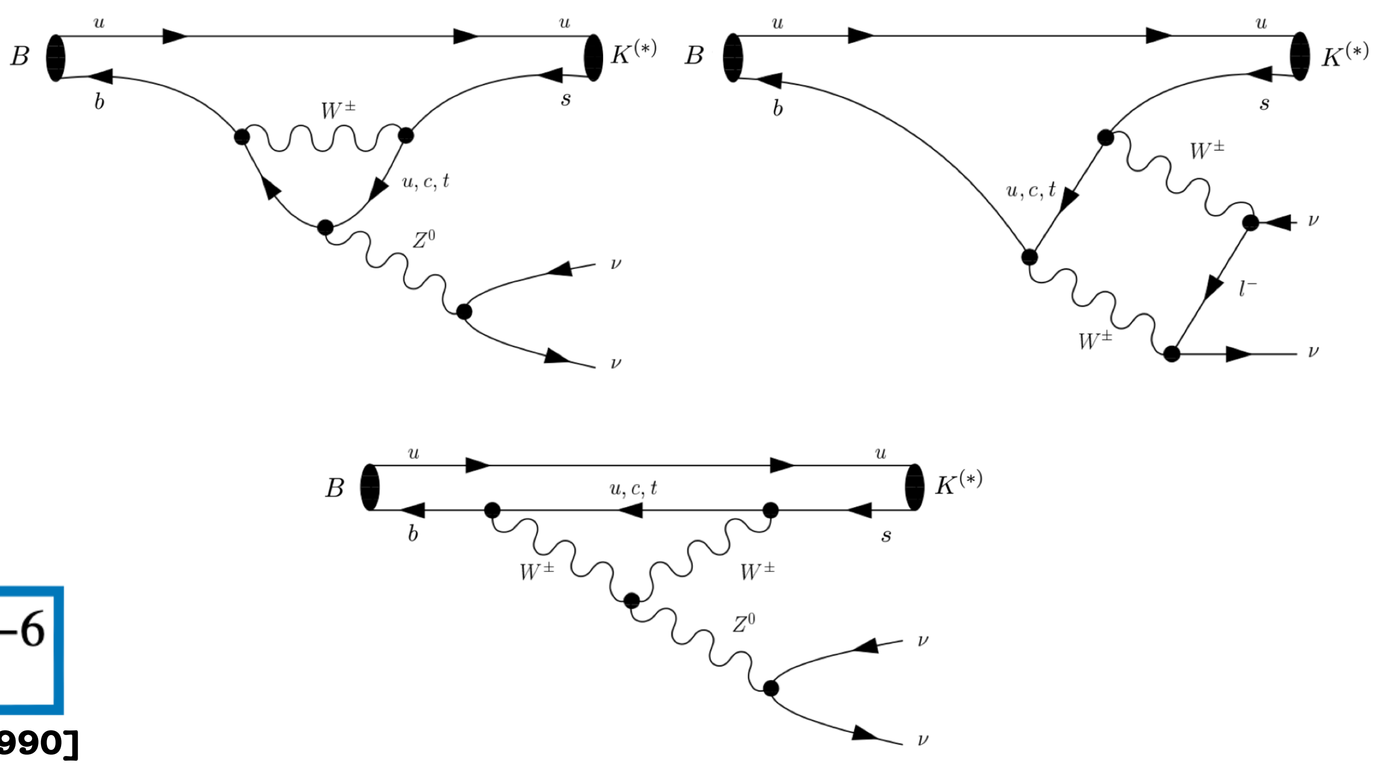
D. Becirevic, G. Piazza & O. Sumensari, EPJC '23 [arXiv:2301.06990]

La necessità di trovare osservabili $b \to s$ complementari

ii) B → K(*)$\nu\nu$: non afflitto per nulla dagli effetti di lunga distanza !

Maggiori sorgenti di incertezza:

1. **Valore di |Vcb| (soppressione CKM)**
2. **Fisica adronica**



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da comparare con

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

Belle-II Collaboration, arXiv:2311.14647

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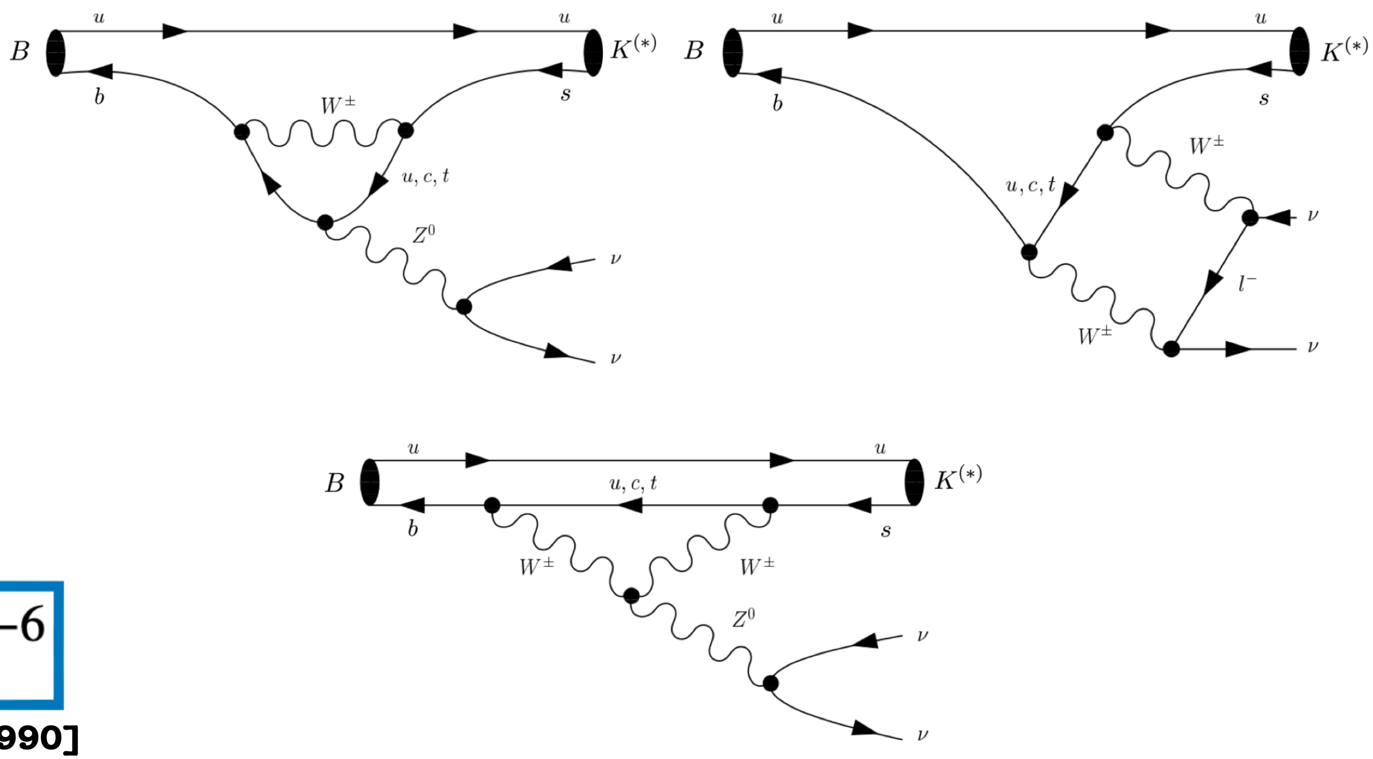

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Belle-II Collaboration, arXiv:2311.14647

Tensione in B → K$\nu\nu$: 2.8σ

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

Coefficienti di Wilson

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

Scala di energia della Nuova Fisica

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Scala di energia della Nuova Fisica

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

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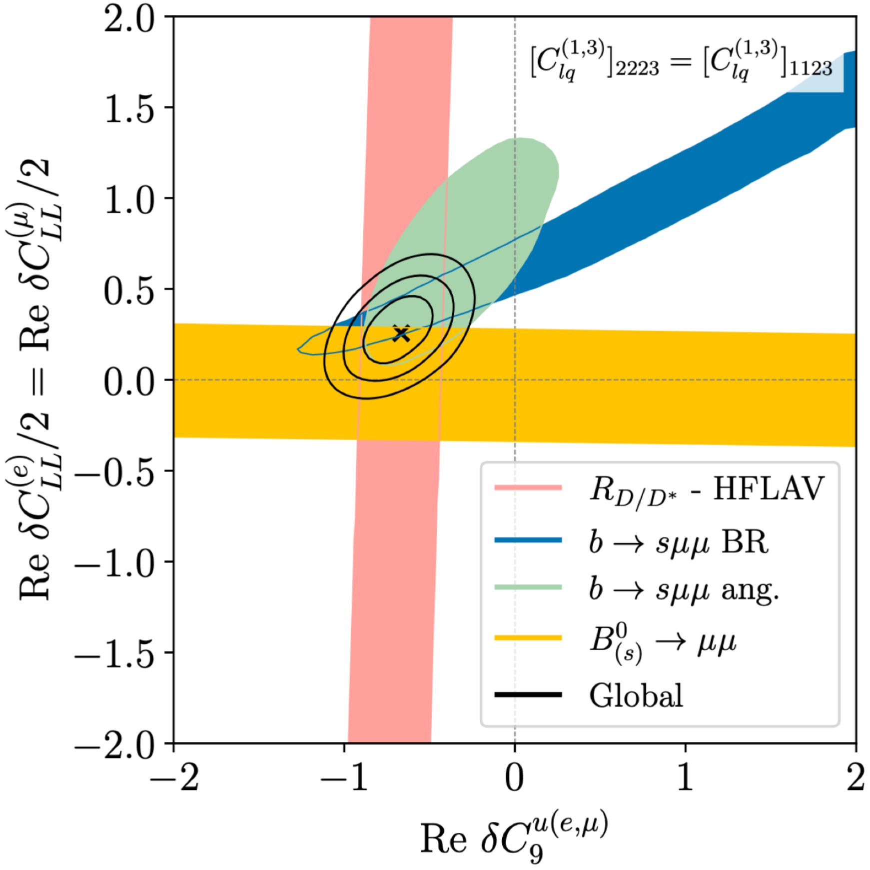

D. Guadagnoli et al, JHEP '23 [2308.00034]

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

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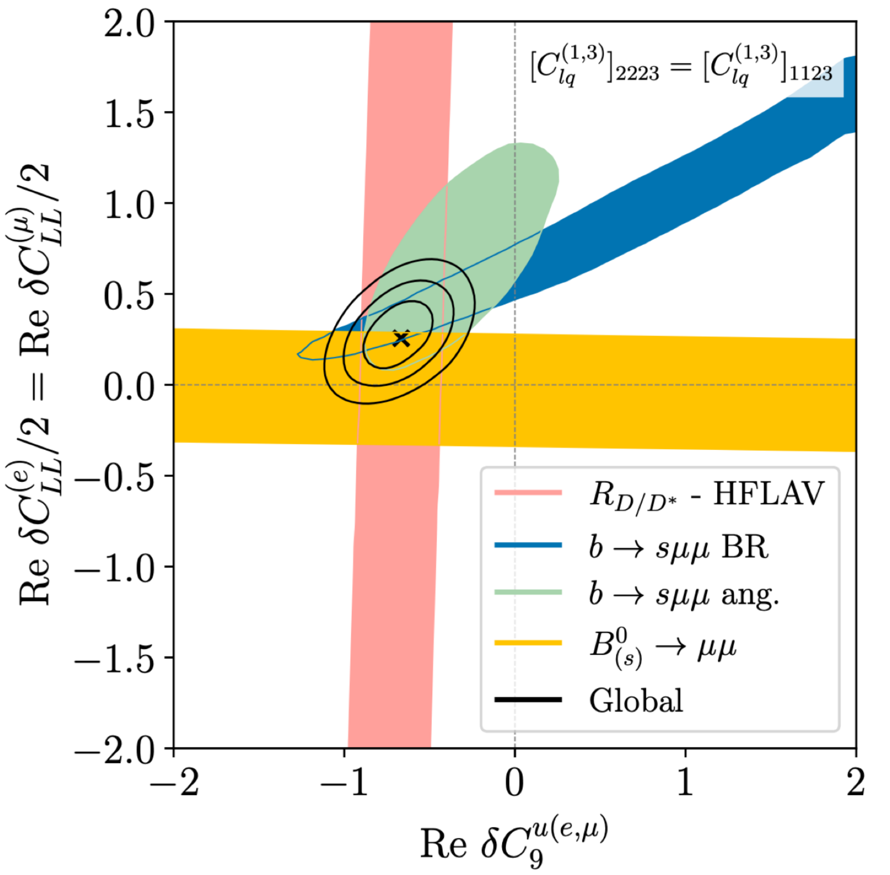

<u>Nell'ottica della fisica di precisione:</u> **analisi congiunte dei dati $b \to s$ (con leptoni carichi), $b \to c$, Bs \to $\mu\mu\gamma$ e B → K(*)$\nu\nu$ (*gli ultimi due non sono inclusi nell'esempio di sinistra*) al fine di validare (o meno) la consistenza tra tali osservabili in un dato modello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

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

Fisica del sapore nel ed oltre il MS

Processi Tree-level

Transizioni $b \to c$

FCNCs

Transizioni $b \to s$

Fisica del sapore nel ed oltre il MS

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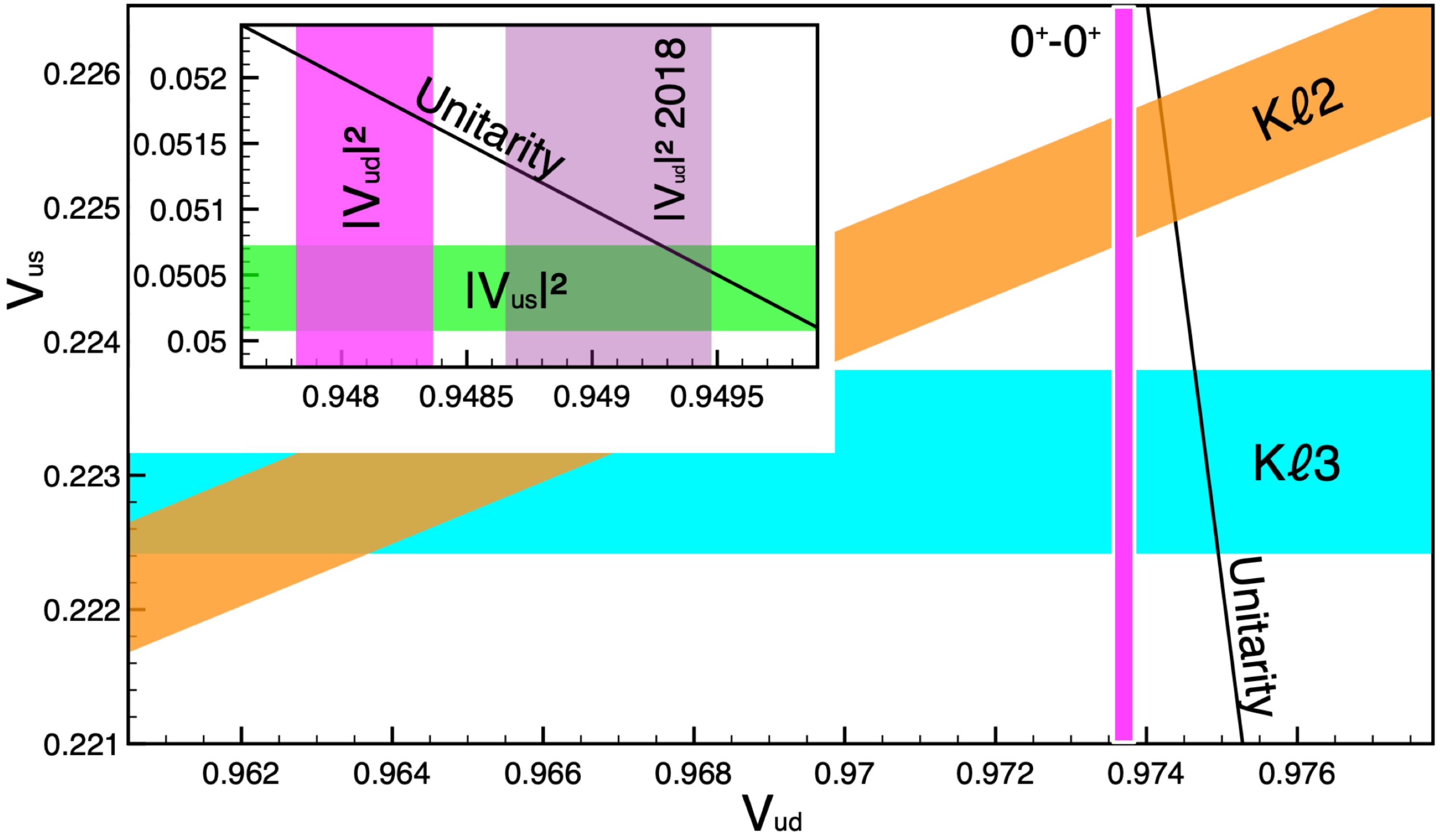
Transizioni $b \to c$ ⟷ Transizioni $b \to s$

|Vud| e |Vus|

Violazione dell'unitarietà nella 1ª riga ?



M. Gorshteyn, talk @ CKM23 conference

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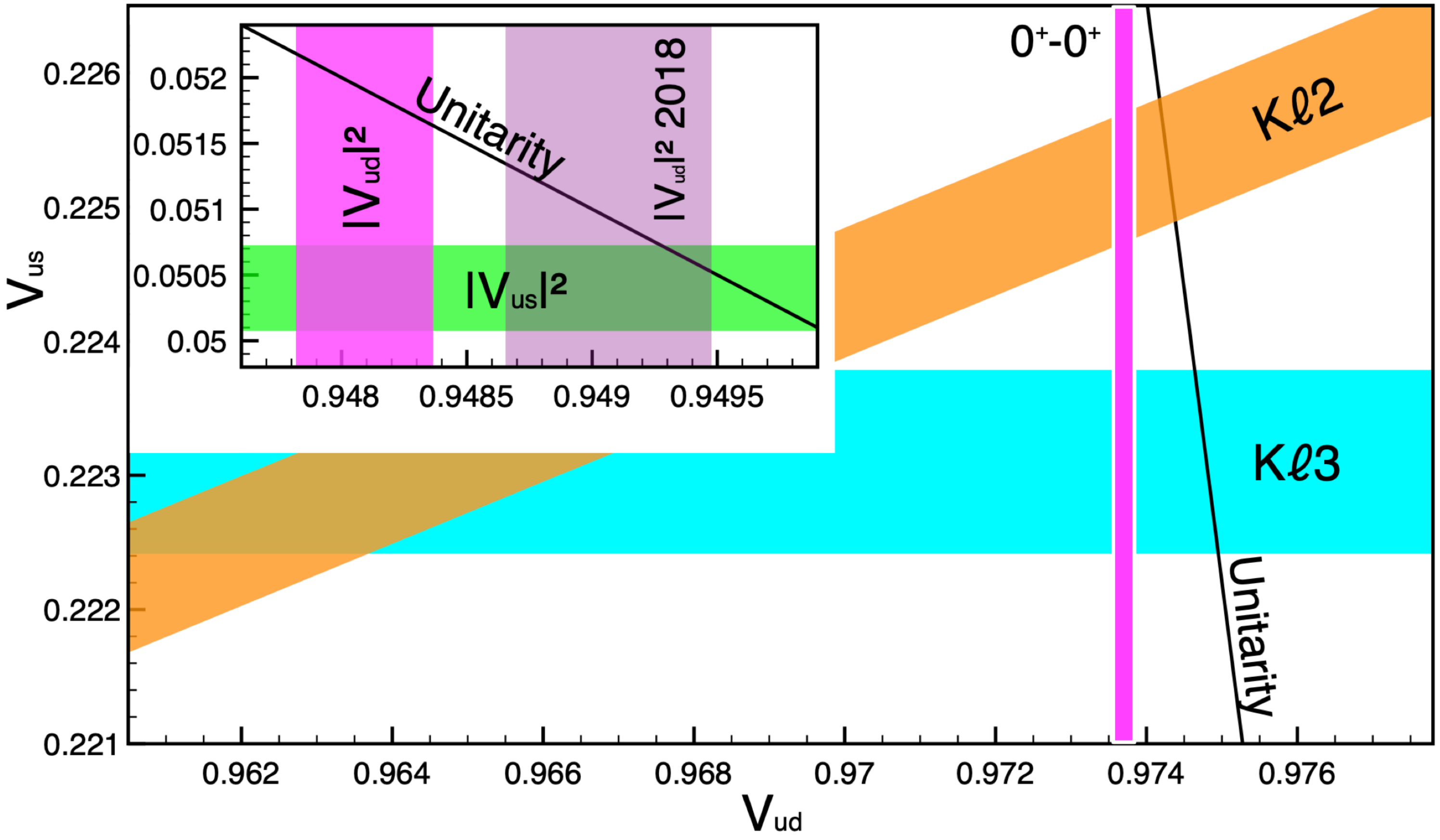

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$$\underset{\sim 0.95}{|V_{ud}|^2} + \underset{\sim 0.05}{|V_{us}|^2} + \underset{\sim 10^{-5}}{|\cancel{V_{ub}}|^2} = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$

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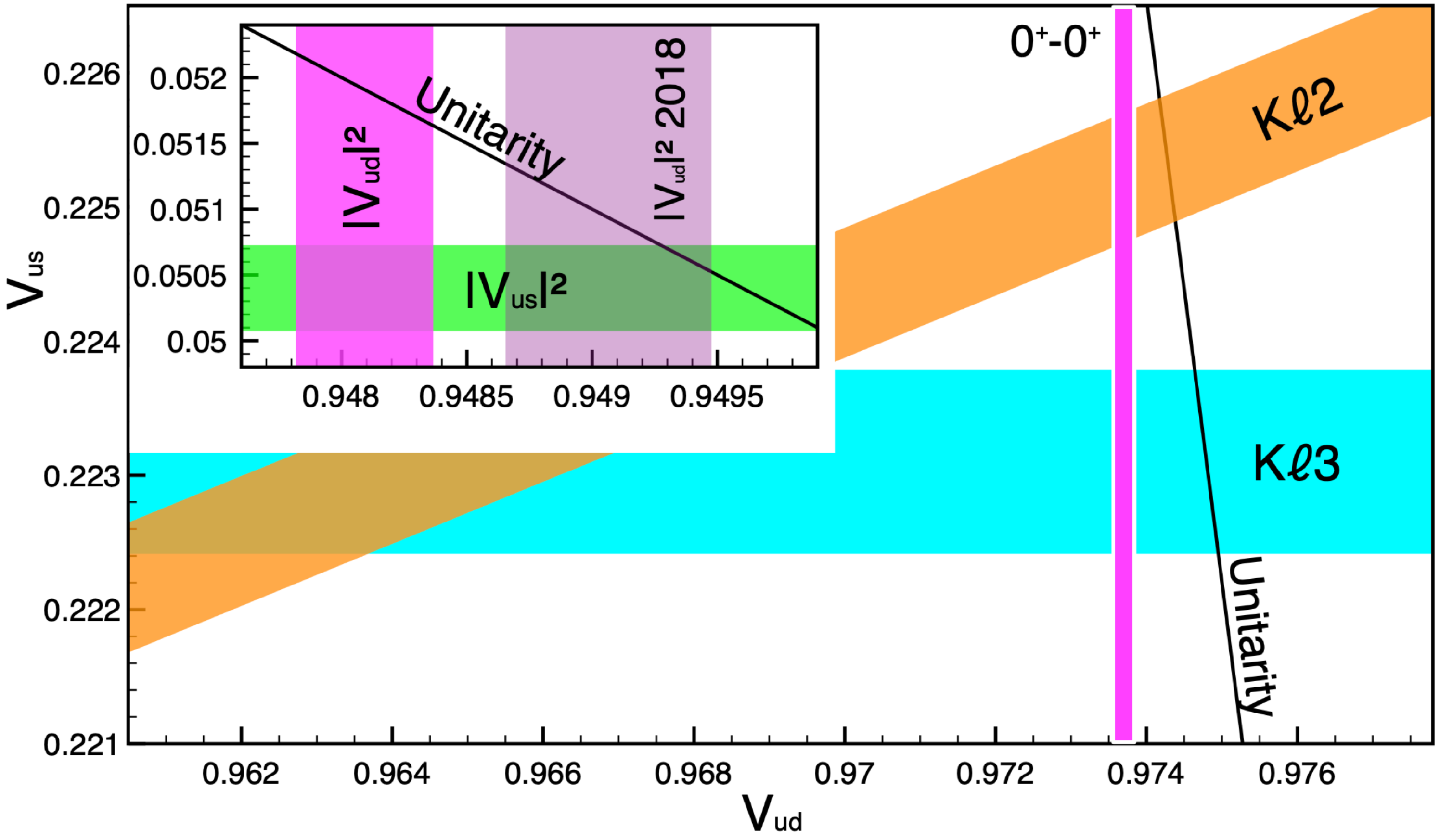

M. Gorshteyn, talk @ CKM23 conference

Le varie determinazioni di |Vud| e |Vus| mostrano:

1) varie reciproche inconsistenze

2) una tensione con l'unitarietà nella 1ª riga della matrice CKM

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

Sintesi delle varie determinazioni di |Vud| e |Vus|

Per quanto concerne |Vud|:

M. Gorshteyn, talk @ CKM23 conference

- Decadimenti nucleari 0^+-0^+ (es.: $^{14}O \rightarrow {}^{14}N$)

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

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E' la determinazione teoricamente più precisa !
Atteso un importante miglioramento della precisione exp. da parte di PIONEER (2203.01981)

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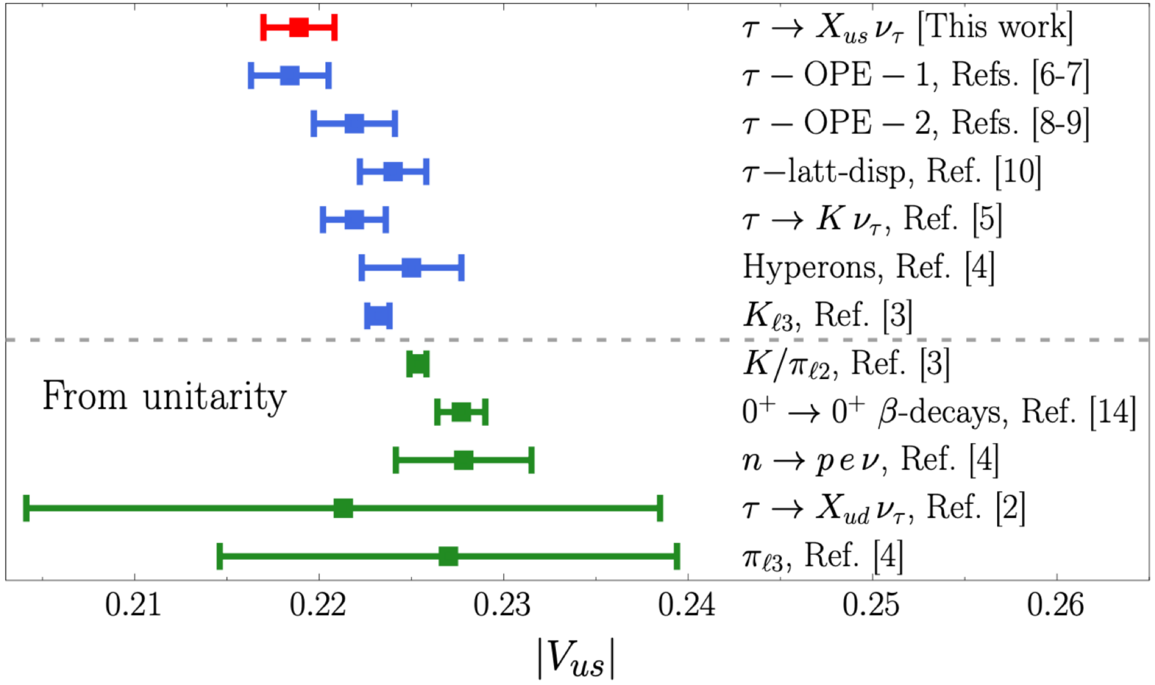

ETMC Collaboration [arXiv:2403.05404]

Sintesi delle varie determinazioni di |Vud| e |Vus|

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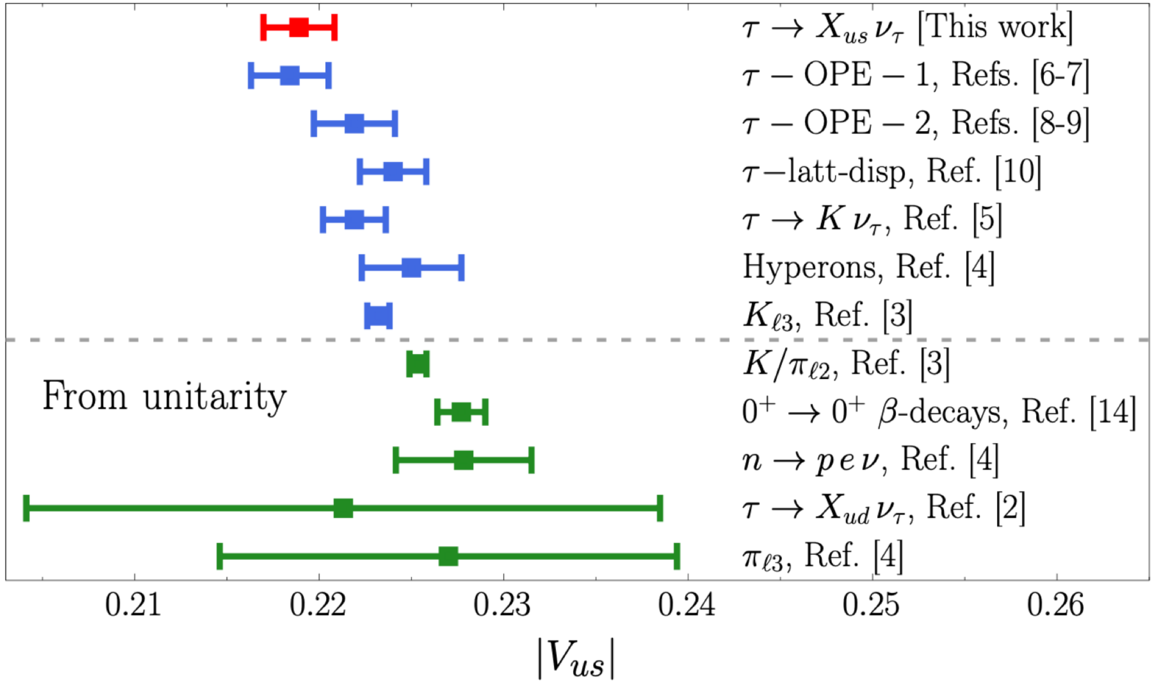

ETMC Collaboration [arXiv:2403.05404]

Strategia: aumentare il più possibile il numero di canali da studiare !

Fisica del sapore nel ed oltre il MS

Processi Tree-level

FCNCs

Transizioni $b \to c$

$|$Vud$|$ e $|$Vus$|$

Transizioni $b \to s$

K $\to \pi \upsilon \upsilon$

Decadimenti rari del mesone K

Tre maggiori esperimenti in questa direzione: **NA62** **(K^+)**, **KOTO** **(K_L) e** **LHCb** **(K_S + iperoni). Focalizzandoci sui decadimenti rari del K^+: nel MS**

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_w} \sum_{\ell=e,\mu,\tau} \left(\lambda_c X^\ell + \lambda_t X_t\right) (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell L} \gamma^\mu \nu_{\ell L}) + \text{h.c.}\,,$$

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$$\boxed{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \ = \kappa_+ (1+\Delta_{\rm EM}) \left[\left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_t\right)^2 + \left(\frac{{\rm Re}\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{{\rm Re}\lambda_t}{\lambda^5} X_t\right)^2 \right],}$$

Buchalla, Buras e Lautenbacher, Rev. Mod. Phys. '96 [hep-ph/9512380]

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A livello numerico:

Buchalla, Buras e Lautenbacher, Rev. Mod. Phys. '96 [hep-ph/9512380]

$$10^{11} \times \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 8.38 \pm 0.14_{X_t^{\rm QCD}} \pm 0.01_{X_t^{\rm EW}} \pm 0.11_{P_c} \pm 0.25_{\delta P_{cu}}$$

Incertezze dal Triangolo Unitario

$$\pm 0.04_{\kappa_+} \pm 0.14_\lambda \pm 0.31_A \pm 0.12_{\bar{\rho}} \pm 0.03_{\bar{\eta}} \pm 0.05_{m_t} \pm 0.15_{m_c} \pm 0.06_{\alpha_s}$$

Anzivino et al., arXiv:2311.02923 [Kaons@CERN23]

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Anzivino et al., arXiv:2311.02923 [Kaons@CERN23]

EXP. (NA62): $\text{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-11}$

NA62 Coll., JHEP '21 [2103.15389]

Decadimenti rari del mesone K

Buchalla, Buras e Lautenbacher, Rev. Mod. Phys. '96 [hep-ph/9512380]

Focalizzandoci sui decadimenti rari del K_L: nel MS

$$\boxed{\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \kappa_L r_{\epsilon_K}\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X_t\right)^2}$$

$$10^{11} \times \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = 2.87 \pm 0.07_{X_t^{\mathrm{QCD}}} \pm 0.01_{X_t^{\mathrm{EW}}} \pm 0.02_{\kappa_L}$$

Incertezze dal Triangolo Unitario

$$\pm 0.15_{\bar{\eta}} \pm 0.15_{A} \pm 0.07_{\lambda} \pm 0.03_{m_t}\,.$$

Anzivino et al., arXiv:2311.02923 [Kaons@CERN23]

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Anzivino et al., arXiv:2311.02923 [Kaons@CERN23]

EXP. (KOTO): $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$ at 90% C.L.

KOTO Coll., K. Shiomi's talk at Kaon2023@CERN

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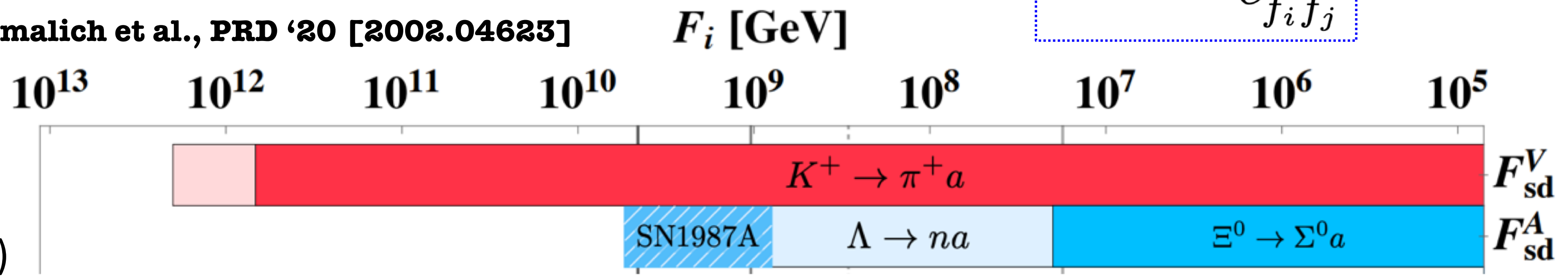
Questi decadimenti rimangono uno strumento chiave per porre limiti a modelli oltre il MS! Ad es.

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left(c^V_{f_i f_j} + c^A_{f_i f_j} \gamma_5\right) f_j$$

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{c^{V,A}_{f_i f_j}}$$

Martin Camalich et al., PRD '20 [2002.04623]



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Transizioni $b \to c$ ⟷ Transizioni $b \to s$

|Vud| e |Vus|

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Processi Tree-level

FCNCs

Transizioni $b \to c$ ⟷ Transizioni $b \to s$

|Vud| e |Vus| ⟷ $K \to \pi \upsilon \upsilon$

Fisica del sapore nel ed oltre il MS

Processi Tree-level

FCNCs

Transizioni $b \to c$	⟷	Transizioni $b \to s$
|Vud| e |Vus|	⟷	K $\to \pi\upsilon\upsilon$
…		…

Fisica del sapore nel ed oltre il MS

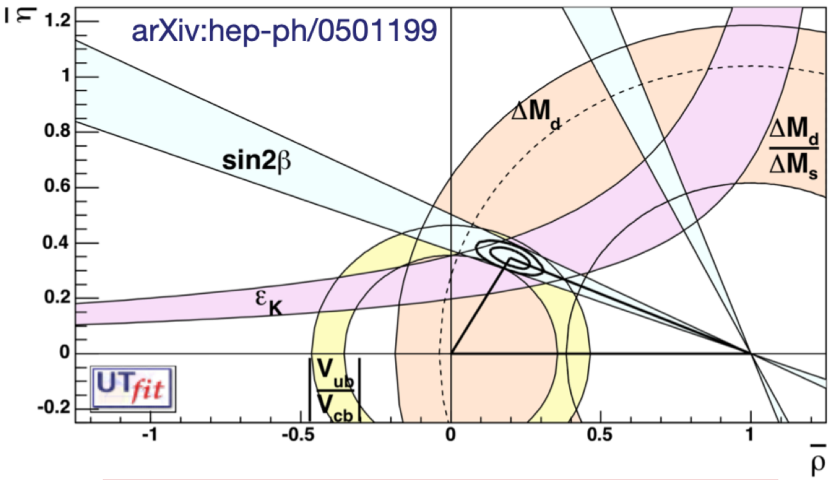
Processi Tree-level ↔ **FCNCs**

Processi Tree-level		FCNCs
Transizioni $b \to c$	⟷	Transizioni $b \to s$
|Vud| e |Vus|	⟷	K $\to \pi\upsilon\upsilon$
…		…

Passato, presente e future del triangolo di unitarietà

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[14]



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

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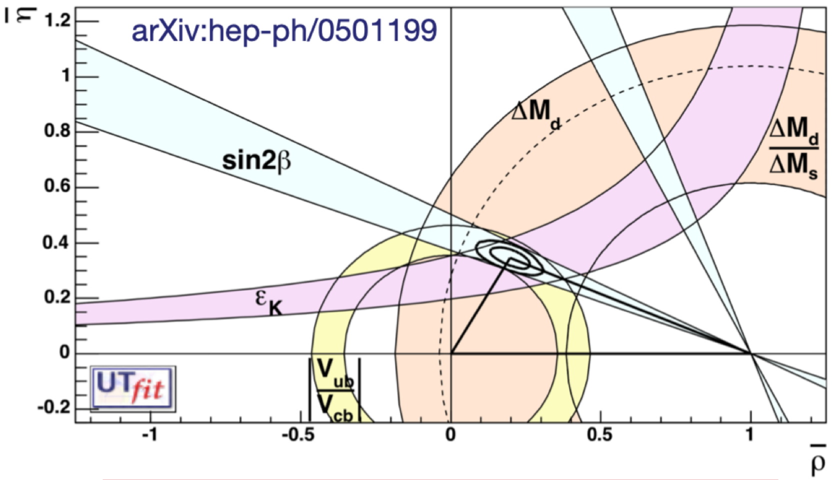

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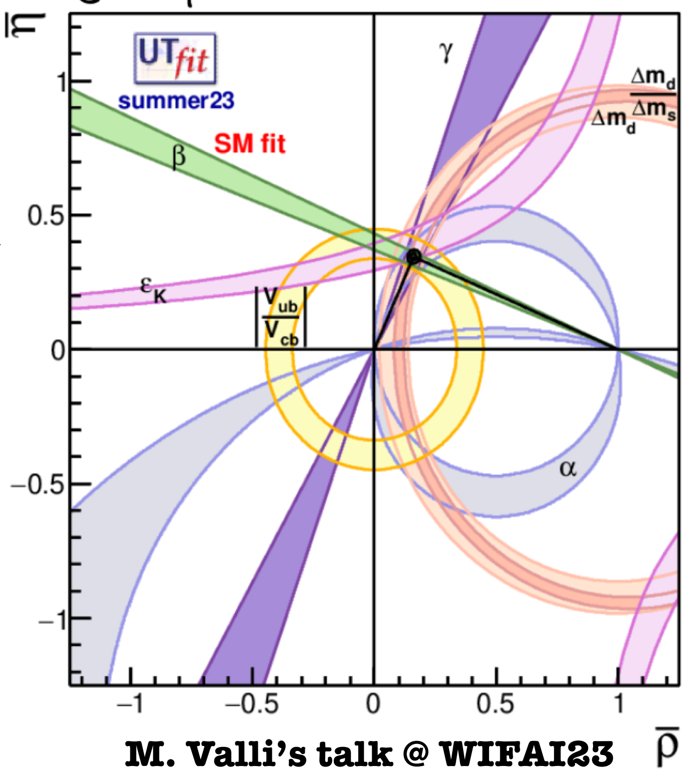
@ 95% prob



M. Valli's talk @ WIFAI23

$$\bar{\rho} = 0.160 \pm 0.009 \sim 6\%$$
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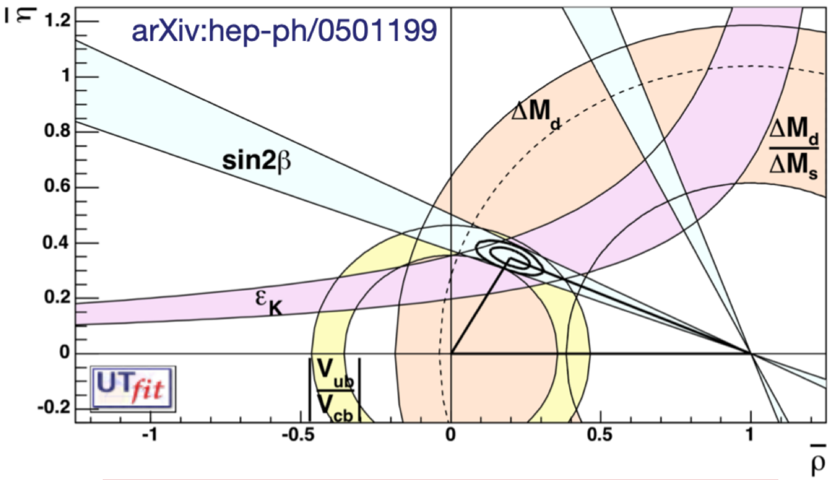

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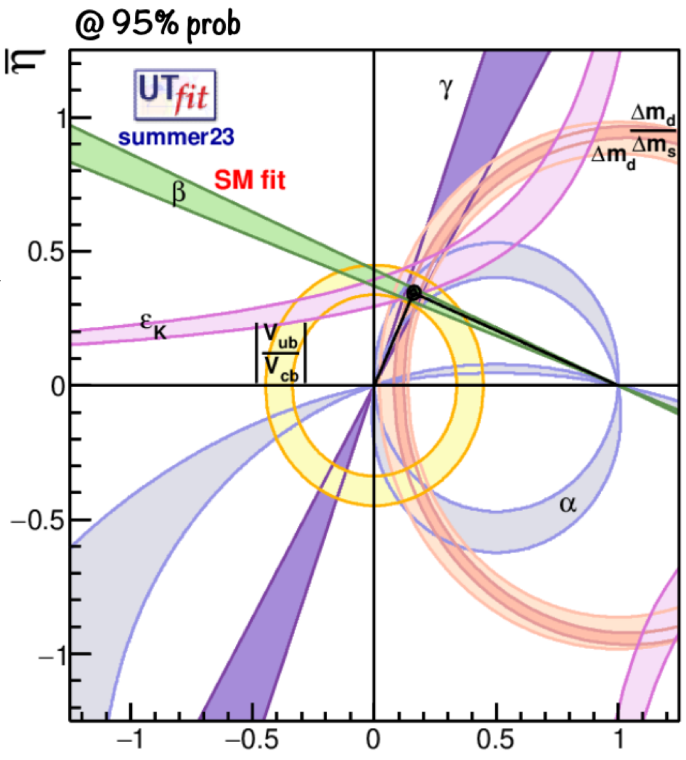

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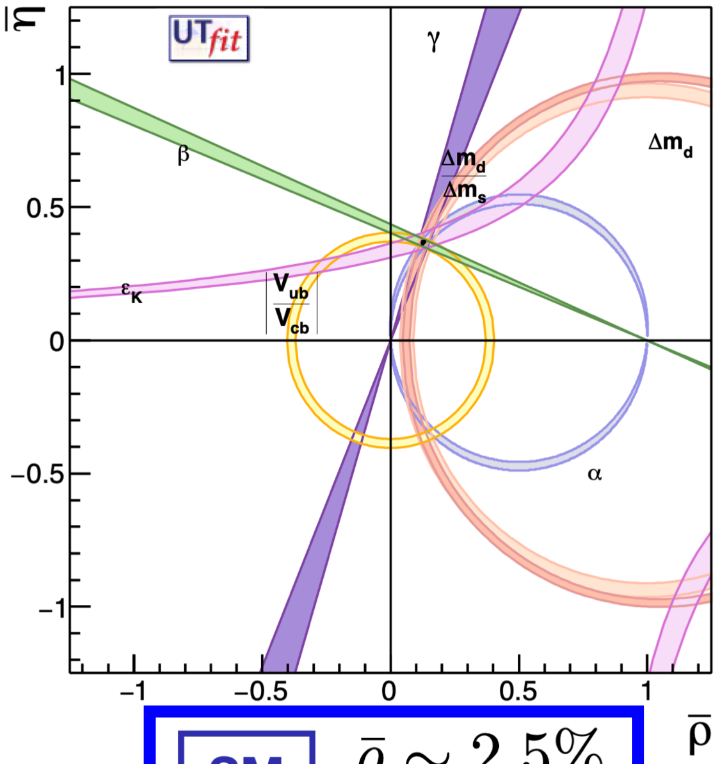

SM fit

$$\bar{\rho} \sim 2.5\%$$
$$\bar{\eta} \sim 1\%$$

Passato, presente e future del triangolo di unitarietà

www.utfit.org

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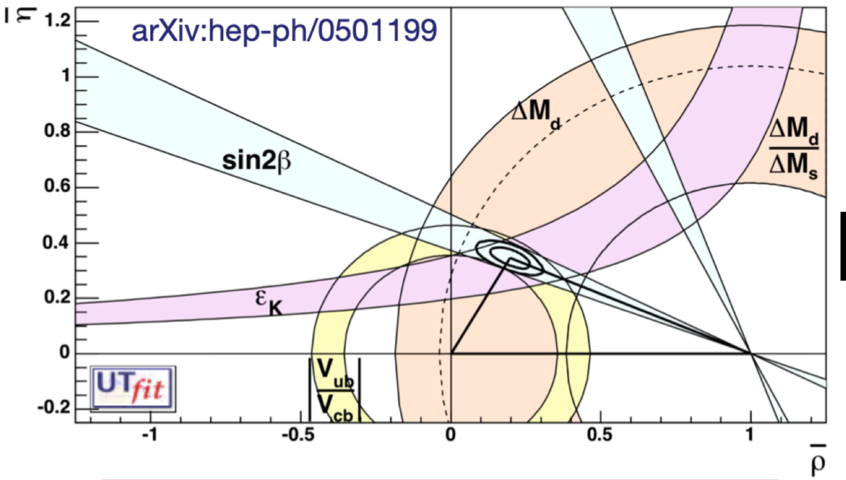

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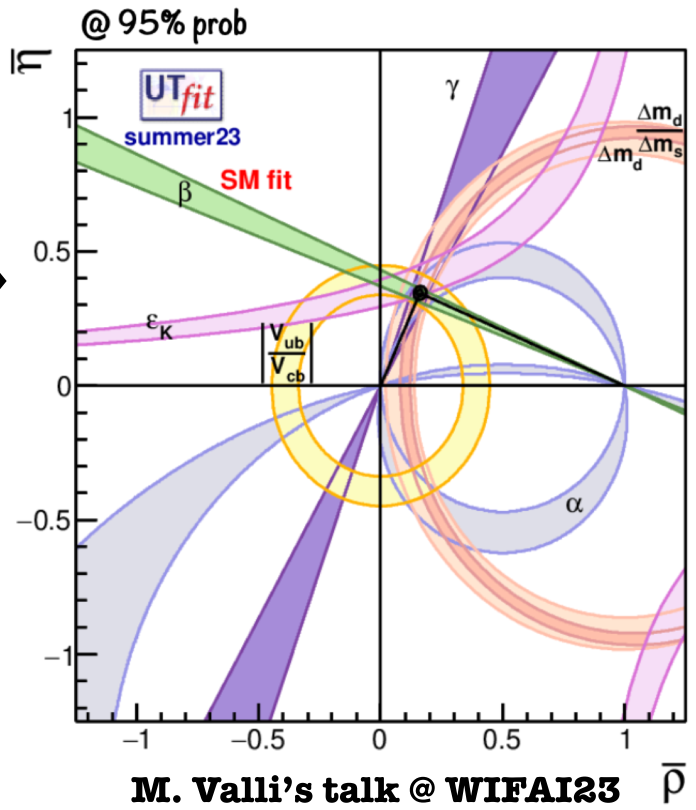

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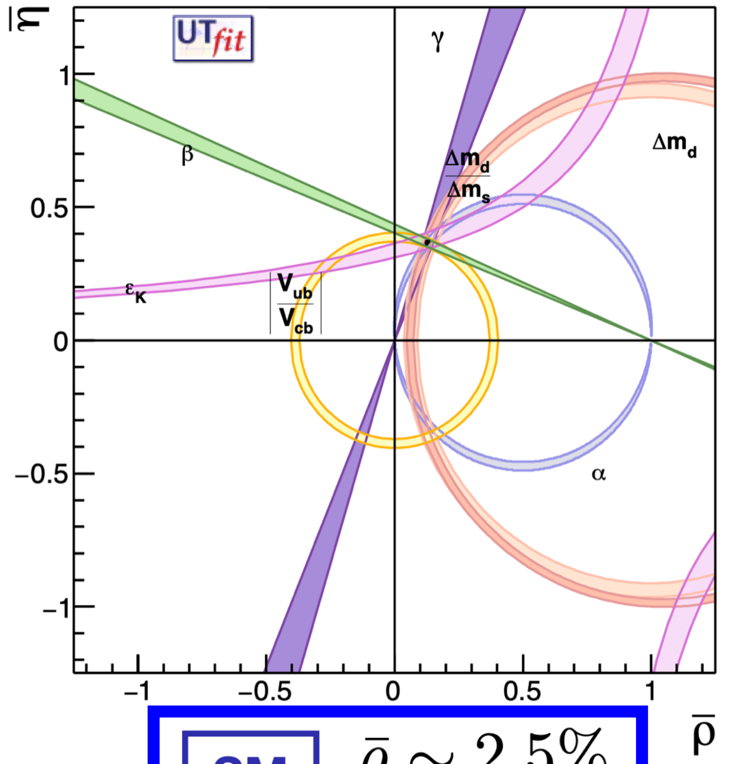

SM fit $\bar\rho \sim 2.5\%$ $\bar\eta \sim 1\%$

A tal fine: fondamentale ogni aumento di precisione sia sul lato th. sia sul lato exp. !

Conclusioni

La fisica del sapore si trova nell'era della fisica di precisione! Necessità di aumentare la precisione di molte osservabili e di misurare per la prima volta nuovi canali… Due principi guida: triangolo di unitarietà e decadimenti rari !

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Alcuni messaggi chiave:

- $b \rightarrow c$: **fissare una strategia precisa di analisi dei dati di reticolo e sperimentali**
- $b \rightarrow s$: **comprendere l'importanza dei fattori di forma non locali, anche con l'aiuto di nuove osservabili (alto q^2, …)**
- $d \rightarrow u$ e $s \rightarrow u$: **consolidare (o meno) i presenti segnali di violazione dell'unitarietà nella 1a riga della matrice CKM**
- $s \rightarrow d$: **informazione centrale per la fisica oltre il MS e connessa con studi dall'ambito astrofisico**

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Alcuni messaggi chiave:

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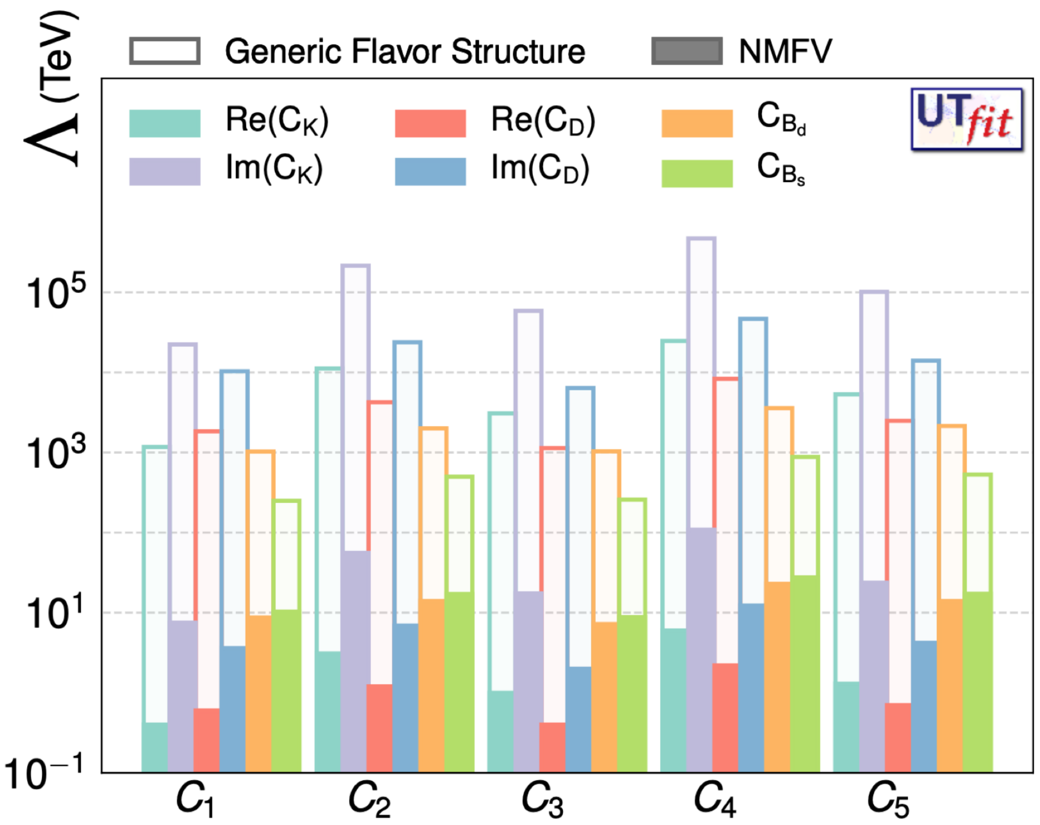
Possibilità di porre dei limiti sempre più precisi sulla nuova fisica (e sulla sua scala) !



GRAZIE PER LA VOSTRA ATTENZIONE !

BACK-UP SLIDES

How to constrain the magnitude of the WCs

Example: Strong bounds can be obtained from a Beyond-the-SM study of the Unitarity Triangle!

(at low energy scale [WEFT])

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

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

NP couplings

Loop factors

NP scale

ΔF=2

$$\begin{aligned}
Q_1 &= (\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Li}\gamma^\mu q_{Lj}), & Q_1' &= (\bar{q}_{Ri}\gamma^\mu q_{Rj})(\bar{q}_{Ri}\gamma^\mu q_{Rj}) \\
Q_2 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Ri} q_{Lj}), & Q_2' &= (\bar{q}_{Li} q_{Rj})(\bar{q}_{Li} q_{Rj}) \\
Q_3 &= (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Ri} q^\alpha_{Lj}), & Q_3' &= (\bar{q}^\alpha_{Li} q^\beta_{Rj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}) \\
Q_4 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Li} q_{Rj}), & & \\
Q_5 &= (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}). & &
\end{aligned}$$

Effective Field Theory & New Physics

Specific example: Strong bounds on **ΔF = 2 processes** from a NP study of the Unitarity Triangle!

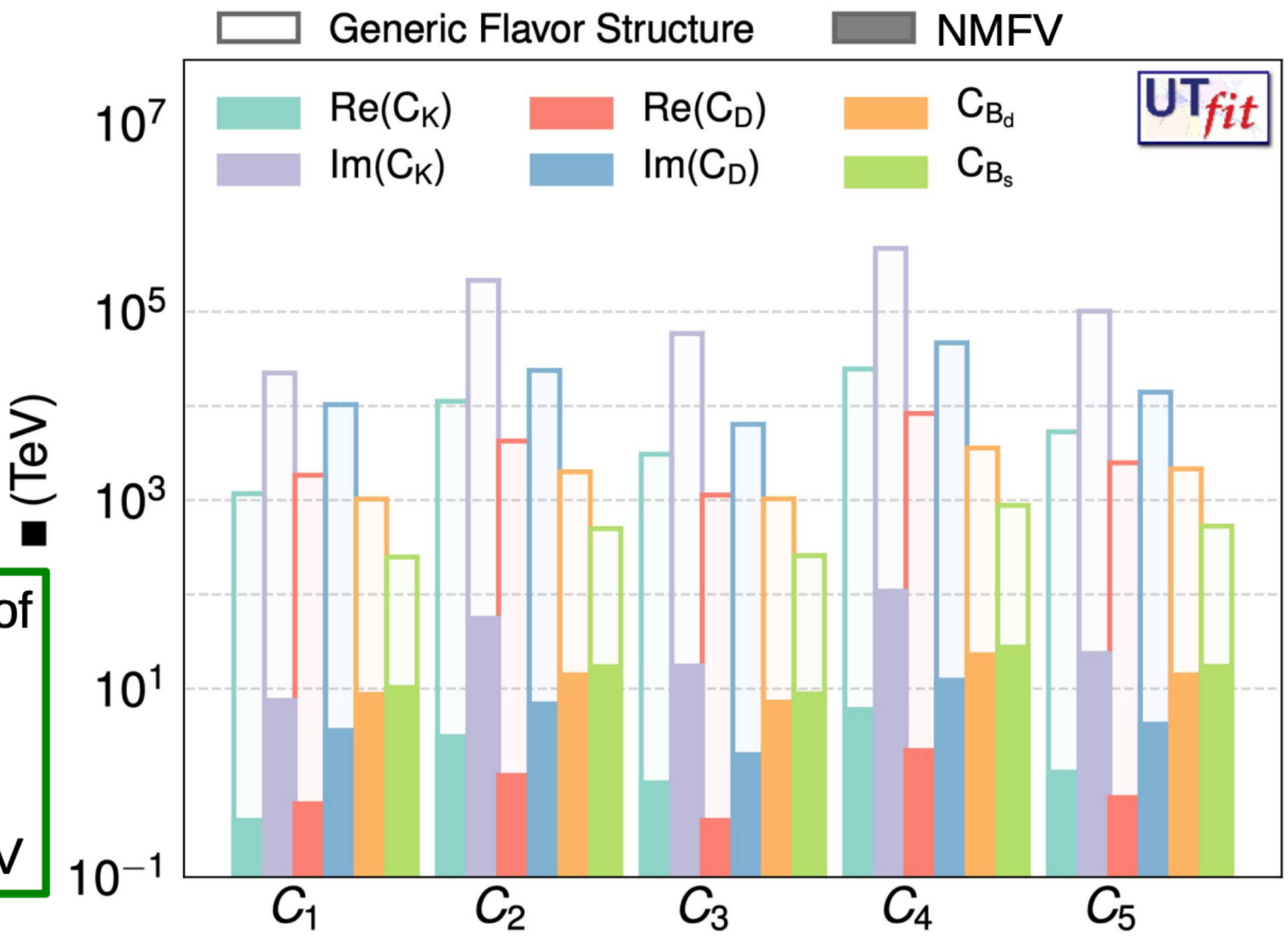
Generic:
$C(\Lambda) = \alpha/\Lambda^2$,
F_i~1, arbitrary phase

$\alpha \sim 1$ 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

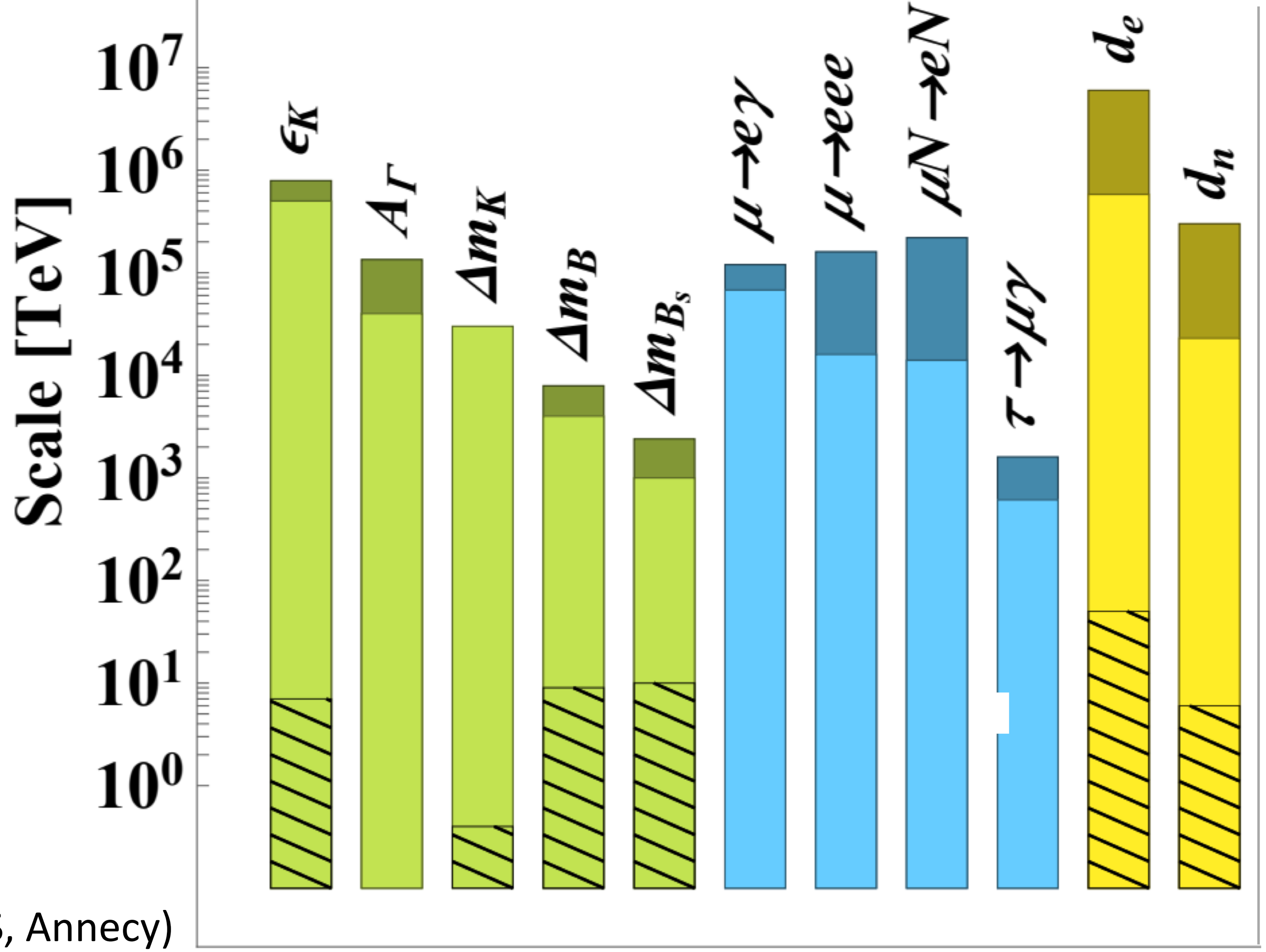
$\Lambda > 3.2$ TeV

Effective Field Theory & New Physics

Wilson coefficients (WCs)

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

Energy scale of New Physics



***Physics Briefing Book*, European Strategy for Particle Physics Preparatory Group [arXiv:1910.11775]**

Parametrization of the hadronic form factors

Different approaches exist in literature in order to describe the hadronic Form Factors (FFs) in the whole kinem. region:

- **HQET-based parametrizations: they employ HQET** and sistematically expand the FFs in inverse powers of the heavy quark masses. Exp., lattice and/or LCSR data are then used to contrain free parameters. Some applications are contained here:

  Bordone, Jung, van Dyk, EPJC '20 [1908.09398] **Bernlochner et al., PRD '17 [1703.05330] & PRD '22 [2206.11281]**
  Iguro and Watanabe, JHEP '20 [2004.10208]

- **Boyd-Grinstein-Lebed (BGL) parametrization: it employs first principles of the theory, namely unitarity, analiticity and crossing symmetry**. The FFs are then expanded in series, the coefficients of the series can be determined through exp., lattice and/or LCSR data. Some applications are contained here:

  Gambino et al., PRD '16 [1606.08030], PLB '17 [1703.06124], JHEP '17 [1707.09509], PLB '19 [1905.08209]
  Grienstein and Kobach, PLB '17 [1703.08170]
  Nandi et al, JHEP '17 [1707.09977], JHEP '20 [2002.05726 [hep-ph]], JHEP '23 [2212.02528], arXiv:2305.11855

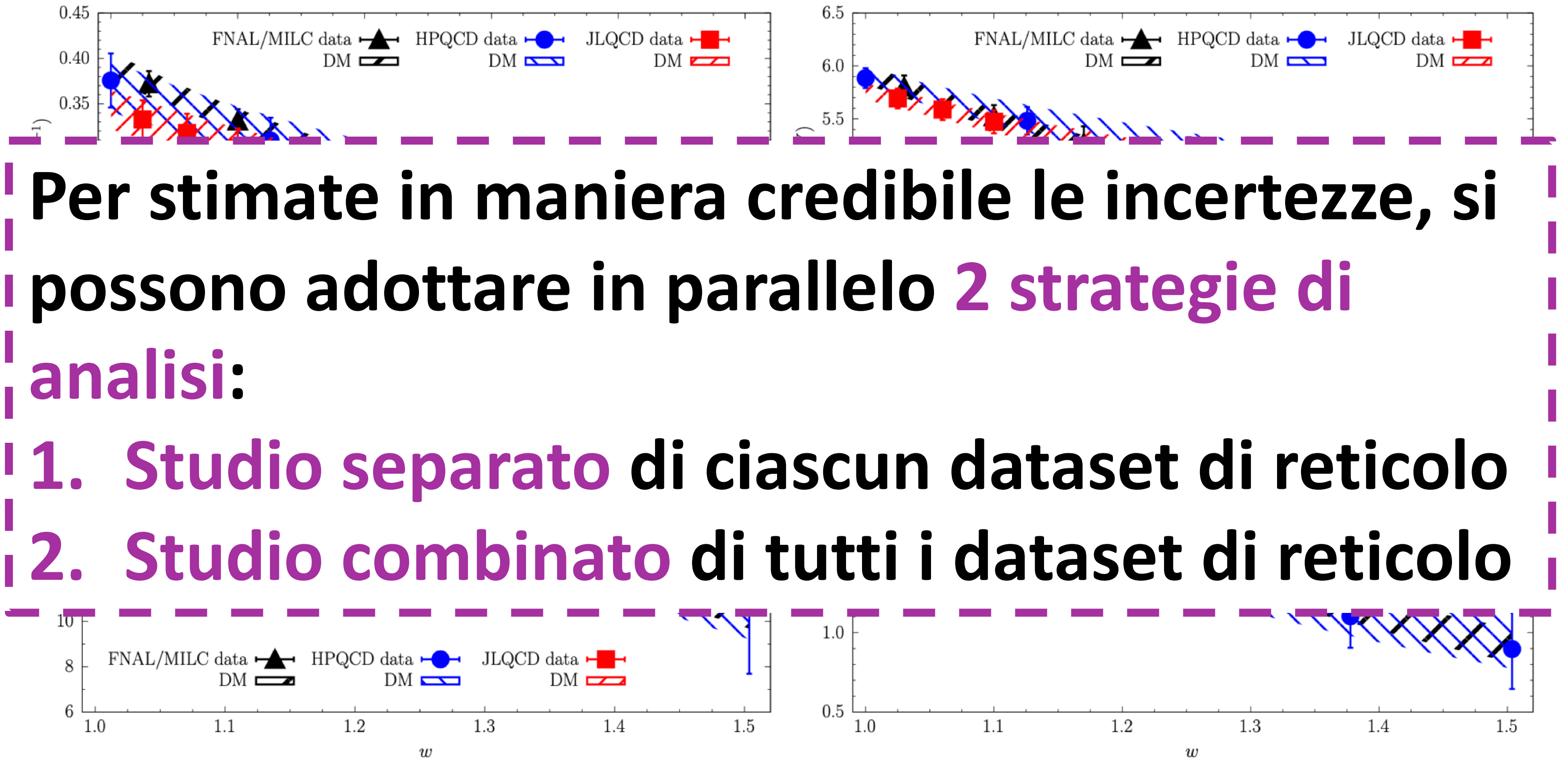
- **Dispersive Matrix (DM) method (not parametrization): it employs the same first principles of BGL**. No expansion needed, it is completely model-independent and avoids all the issues related to truncation errors. Unitarity is also built-in. See:

  S. Okubo [PRD, 3 (1971); PRD, 4 (1971)], Bourrely et al [NPB, 189 (1981)] and L. Lellouch [NPB, 479 (1996)]
  G. Martinelli et al., PRD '21 (2105.02497), PRD '21 (2105.07851), PRD '22 (2105.08674), EPJC '22 (2109.15248), PRD '22 (2204.05925), 2310.03680
  M. Fedele et al, PRD '23 (2305.15457)

- **Bayesian Inference (BI) parametrization: it employs the same first principles of BGL**. The FFs are then expanded in series with unitarity built-in. The Bayesian theorem allows them to avoid any issue with truncation errors. The coefficients of the series can be determined through exp., lattice and/or LCSR data (applications available only for Bs \to K\ell\nu). See:

  Flynn, Jüttner and Tsang, arXiv:2303.11285

L'importanza dei fattori di forma per i decadimenti B → D*$\ell\upsilon$



Per stimate in maniera credibile le incertezze, si possono adottare in parallelo 2 strategie di analisi:

1. **Studio separato di ciascun dataset di reticolo**
2. **Studio combinato di tutti i dataset di reticolo**

Lattice FFs	$R(D^*)$	
FNAL/MILC	0.275(8)	
HPQCD	0.266(12)	
JLQCD	0.247(8)	
Average (PDG scale factor)	0.262(9) (1.8)	1
Combined	0.259(5)	2
Experimental value	0.284(12)	

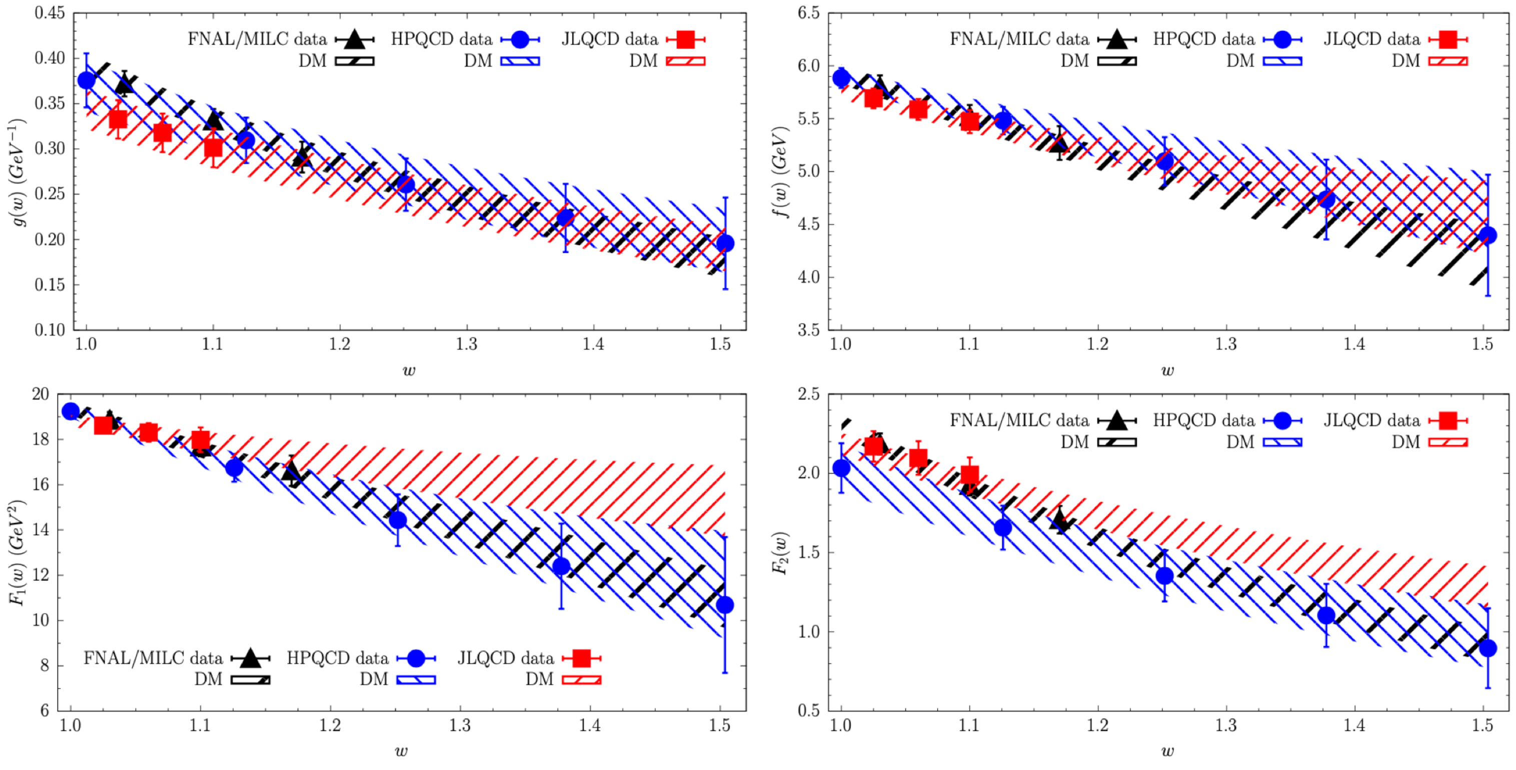
G. Martinelli, S. Simula, LV, arXiv:2310.03680

<u>Punti da tenere a mente</u>:

i) I risultati dei conti di reticolo sono compatibili tra di loro a basso rinculo (w ≤ 1.2);

ii) La banda dei **valori estrapolati di F1(w) da JLQCD**, tuttavia, è **molto differente da quella ottenuta usando i valori di FNAL/MILC** e **un po' diversa da quella ricavata tramite i punti di HPQCD**

L’importanza dei fattori di forma per i decadimenti B → D*$\ell\upsilon$



G. Martinelli, S. Simula, LV, arXiv:2310.03680

Nuova Fisica «leggera» ?

M. Fedele et al., PRD ‘23 (2305.15457)
P. Colangelo et al., 2401.12304

Lattice FFs	$R(D^*)$	$F_{L,\ell}$
FNAL/MILC	0.275(8)	0.450(19)
HPQCD	0.266(12)	0.435(42)
JLQCD	0.247(8)	0.516(29)
Average (PDG scale factor)	0.262(9) (1.8)	0.465(22) (1.5)
Combined	0.259(5)	0.473(14)
Experimental value	0.284(12)	0.520(6)

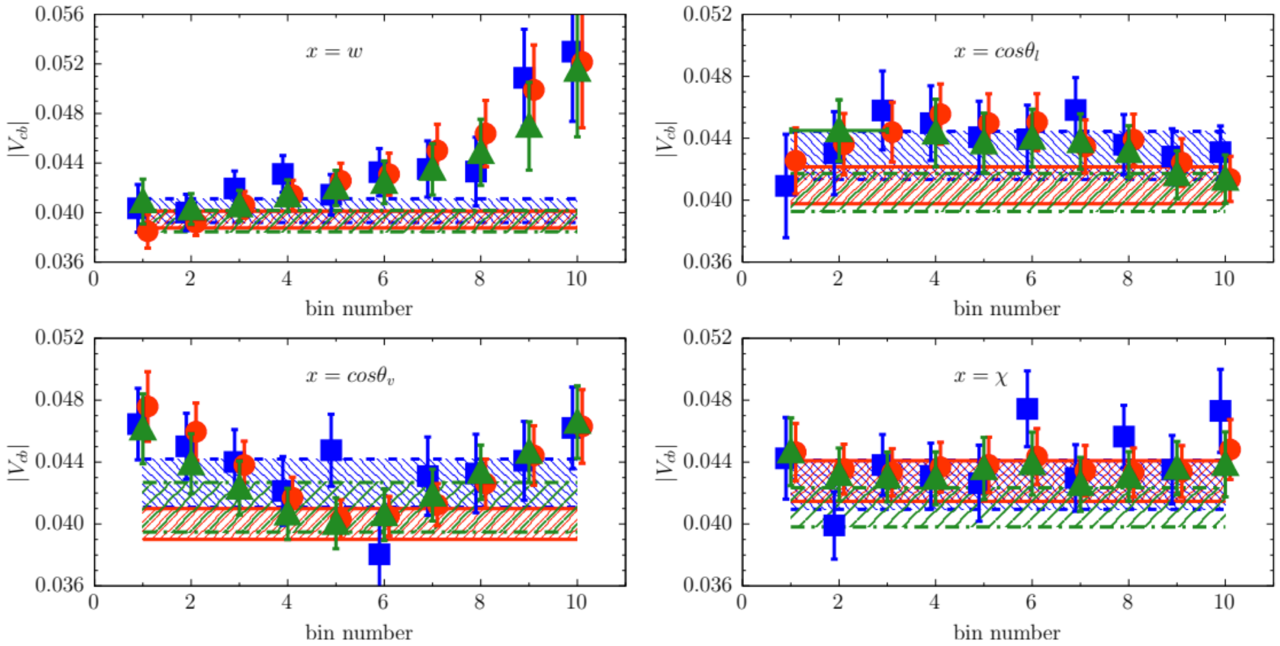
Compatibili a 1.5σ !!

<u>Punti da tenere a mente</u>:

i) I risultati dei conti di reticolo sono compatibili tra di loro a basso rinculo (**w ≤ 1.2**);

ii) La banda dei **valori estrapolati di F1(w) da JLQCD**, tuttavia, è **molto differente da quella ottenuta usando i valori di FNAL/MILC** e **un po’ diversa da quella ricavata tramite i punti di HPQCD**

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

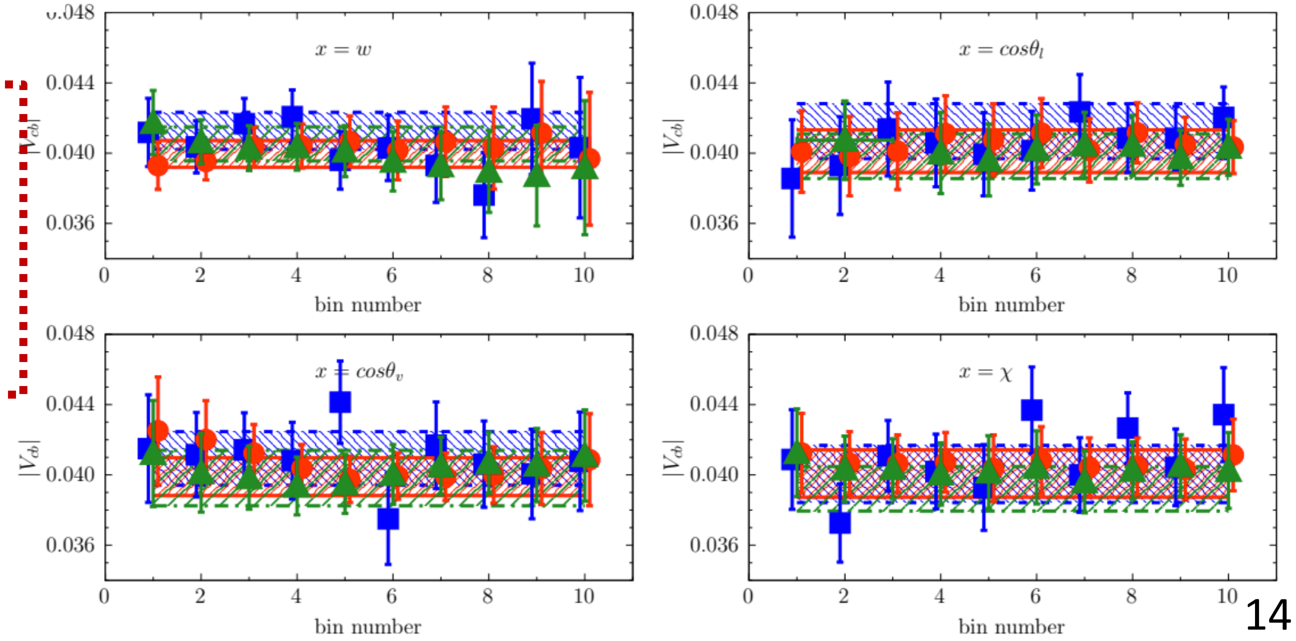


FNAL/MILC input
[HPQCD inputs give similar plots]

Belle 2018 Belle 2023 Belle-II 2023

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

JLQCD inputs



Novità sull'estrazione di |Vcb|

BIN-PER-BIN |Vcb|:

$$|V_{cb}|_i \equiv \sqrt{\frac{(d\Gamma/dx)_i^{exp.}}{(d\Gamma/dx)_i^{th.}}}$$

[alcuni plots nelle slides di back-up]

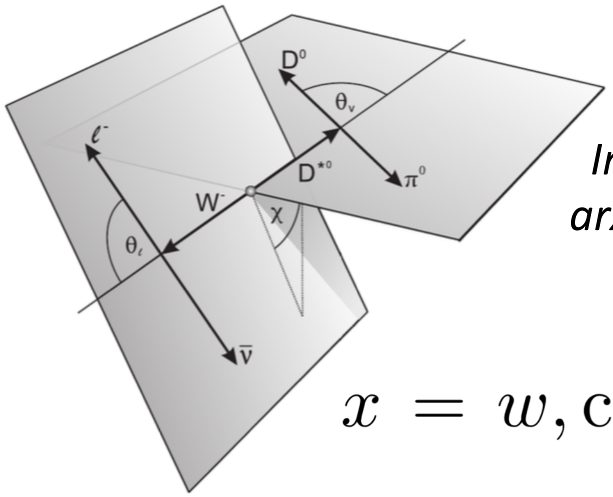


Image taken from arXiv:1702.01521v2

$$x = w, \cos\theta_l, \cos\theta_v, \chi$$

1. STUDI SEPARATI di ciascuno dei 3 set di dati di

$\lvert V_{cb}\rvert \cdot 10^3$			
experiment	FNAL/MILC	HPQCD	JLQCD
Belle 2018	39.64 (74)	39.11 (81)	39.92 (74)
χ^2/(d.o.f.)	3.71	1.14	0.04
Belle 2023	40.87 (115)	41.03 (125)	41.38 (134)
χ^2/(d.o.f.)	1.80	0.11	0.31
Belle-II 2023	39.35 (77)	39.98 (102)	40.20 (85)
χ^2/(d.o.f.)	0.63	0.09	0.42

$$|V_{cb}| = (39.92 \pm 0.64) \cdot 10^{-3}$$

(scaling factor à la PDG of 1.0)

G. Martinelli, S. Simula, LV, arXiv:2310.03680

2. STUDIO COMBINATO dei 3 set di dati di reticolo:

$$|V_{cb}| \cdot 10^3 = 39.87 \pm 0.55$$

(scaling factor à la PDG of 1.2)

input FNAL/MILC				
experiment	$\lvert V_{cb}\rvert_{x=w} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_l} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_v} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\chi} \cdot 10^3$
Belle '18 [19]	39.4 (7)	40.9 (12)	40.0 (10)	42.7 (14)
$\chi^2/(\text{d.o.f.})$	1.21	1.36	1.99	0.38
Belle '23 [13]	40.2 (10)	42.9 (16)	42.6 (16)	42.5 (16)
$\chi^2/(\text{d.o.f.})$	1.72	0.83	1.14	1.94
BelleII '23 [14]	39.3 (9)	40.5 (12)	41.1 (16)	41.1 (13)
$\chi^2/(\text{d.o.f.})$	0.81	2.55	2.46	1.36

input HPQCD				
experiment	$\lvert V_{cb}\rvert_{x=w} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_l} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_v} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\chi} \cdot 10^3$
Belle '18 [19]	39.4 (9)	40.3 (15)	39.7 (13)	41.5 (17)
$\chi^2/(\text{d.o.f.})$	0.53	0.59	0.96	0.32
Belle '23 [13]	41.0 (12)	41.5 (18)	41.1 (17)	41.0 (19)
$\chi^2/(\text{d.o.f.})$	1.21	0.63	0.86	1.65
BelleII '23 [14]	39.8 (11)	39.9 (15)	39.4 (18)	40.2 (16)
$\chi^2/(\text{d.o.f.})$	0.37	1.63	1.52	1.15

input JLQCD				
experiment	$\lvert V_{cb}\rvert_{x=w} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_l} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_v} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\chi} \cdot 10^3$
Belle '18 [19]	40.0 (8)	40.1 (12)	39.9 (11)	40.1 (13)
$\chi^2/(\text{d.o.f.})$	0.24	0.24	0.38	0.10
Belle '23 [13]	41.3 (11)	41.3 (16)	40.9 (15)	40.0 (16)
$\chi^2/(\text{d.o.f.})$	1.72	0.50	0.60	1.69
BelleII '23 [14]	40.5 (10)	39.8 (13)	39.8 (16)	39.2 (13)
$\chi^2/(\text{d.o.f.})$	0.62	1.47	1.41	0.99

Table 1. *Mean values and uncertainties of the CKM element $|V_{cb}|$ obtained by the correlated average procedure given by Eqs. (7)-(8) for each of the four kinematical variables x and for each of the three experimental data sets [13, 14, 19] and of the lattice inputs. The corresponding values of the reduced (correlated) $\chi^2/(d.o.f.)$ variable are also shown.*

DM Importance Sampling case

input FNAL/MILC + HPQCD + JLQCD					
experiment	$\lvert V_{cb}\rvert_{x=w} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_l} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\cos\theta_v} \cdot 10^3$	$\lvert V_{cb}\rvert_{x=\chi} \cdot 10^3$	Average
Belle '18 [19]	39.66 (51)	40.46 (78)	39.72 (68)	41.52 (88)	39.81 (50)
χ^2/(d.o.f.)	0.76	1.10	1.99	0.33	3.48
Belle '23 [13]	40.36 (84)	41.69 (106)	41.72 (121)	41.69 (118)	41.13 (91)
χ^2/(d.o.f.)	1.90	0.62	1.07	1.84	1.00
BelleII '23 [14]	39.47 (72)	39.87 (87)	40.93 (129)	40.16 (95)	39.38 (64)
χ^2/(d.o.f.)	0.75	2.52	2.54	1.39	0.29

Table 3. *Mean values and uncertainties of the CKM element $|V_{cb}|$ obtained by the correlated average procedure for each of the four kinematical variables x and for each experiment [13, 14, 19], using simultaneously the three lattice calculations of the FFs extrapolated by the DM_{IS} approach (see text and Fig. 7). In the last column for each experiment we give the correlated average of the four determinations, including in the individual uncertainties the corresponding PDG scale factor.*

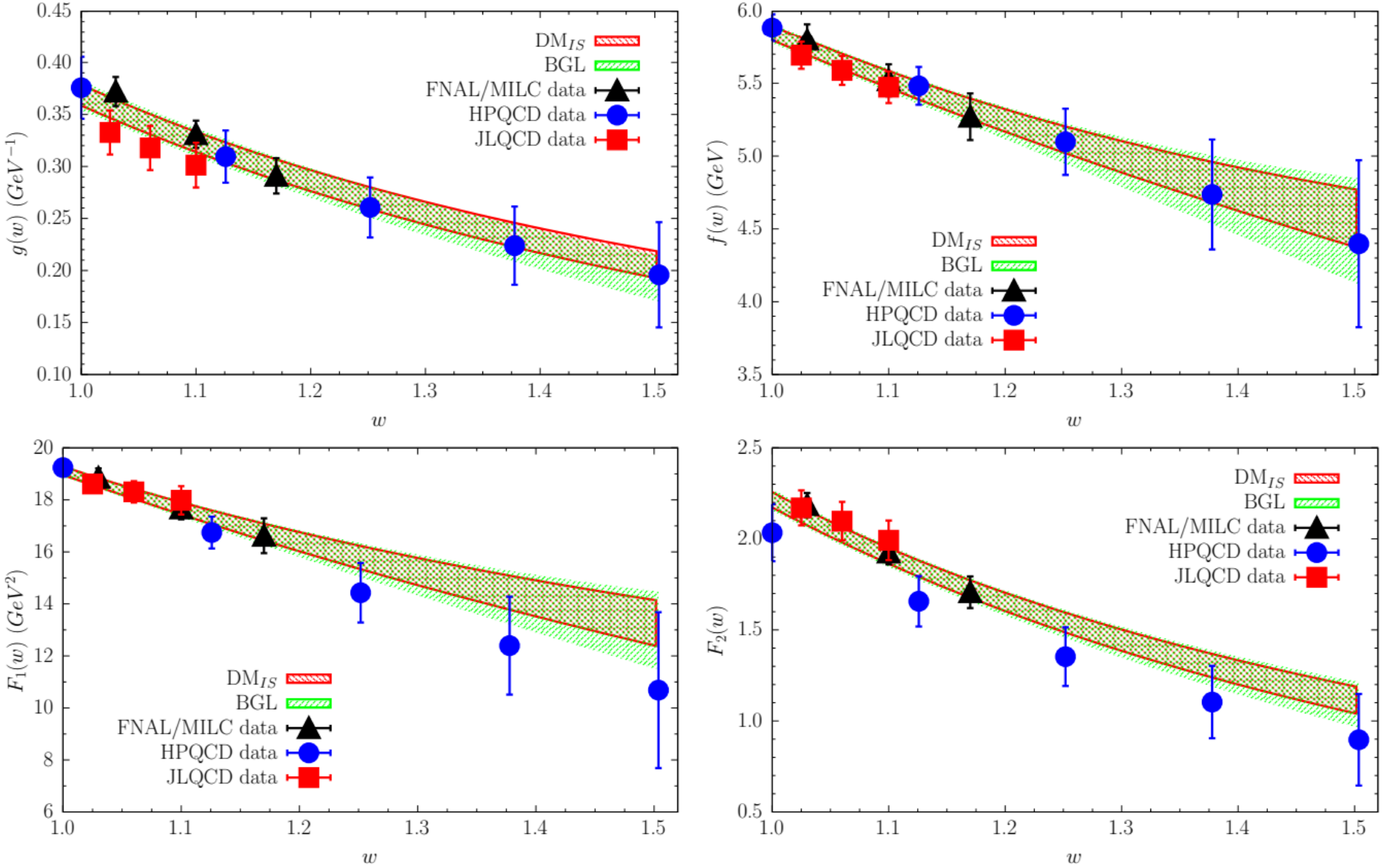


Fig. 6. *The FFs from Refs. [15–17] together with the bands (at $1\,\sigma$ level) obtained by using simultaneously all the lattice inputs within the DM_{IS} method (red bands) or the BGL approach supplemented by the unitary and kinematical constraints (green bands). The BGL z-expansions are truncated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

R(D*) and the polarization observables

Zoom on F_L^{τ} in different q2-bins:

Lattice FFs	low-q^2 bin	high-q^2 bin
FNAL/MILC [15]	0.486(15)	0.381(5)
HPQCD [16]	0.459(38)	0.367(14)
JLQCD [17]	0.534(25)	0.398(10)
Average [15]-[17] (PDG scale factor)	0.495(17) (1.4)	0.383(6) (1.4)
Combined [15]-[17]	0.498(12)	0.384(4)
Experimental value [40]	0.51(7)(3)	0.35(8)(2)

Table 5. *Longitudinal D^*-polarization fraction $F_{L,\tau}$ measured by LHCb [40] in two different q^2-bins: $q^2 < 7$ GeV^2 (low-q^2) and $q^2 > 7$ GeV^2 (high-q^2). The theoretical predictions correspond to the use of the FFs from the three lattice Collaborations [15–17]. We also give the average of the three separate results according to the PDG procedure [31] (Average), including the scale factor for the uncertainty, and the results obtained by combining the FFs of the three lattice Collaborations as they were the results of a single calculation using the DM_{IS} approach (Combined).*

For the experimental numbers see LHCb-PAPER-2023-020
(also https://indico.cern.ch/event/1184945/contributions/5435450/attachments/ 2716717/4718735/LFU_MCalvi.pdf)

Implicazioni sul triangolo di unitarietà: |Vcb| e |Vub|

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[14]

$|V_{cb}|_{excl} \times 10^3 = 40.55 \pm 0.46$

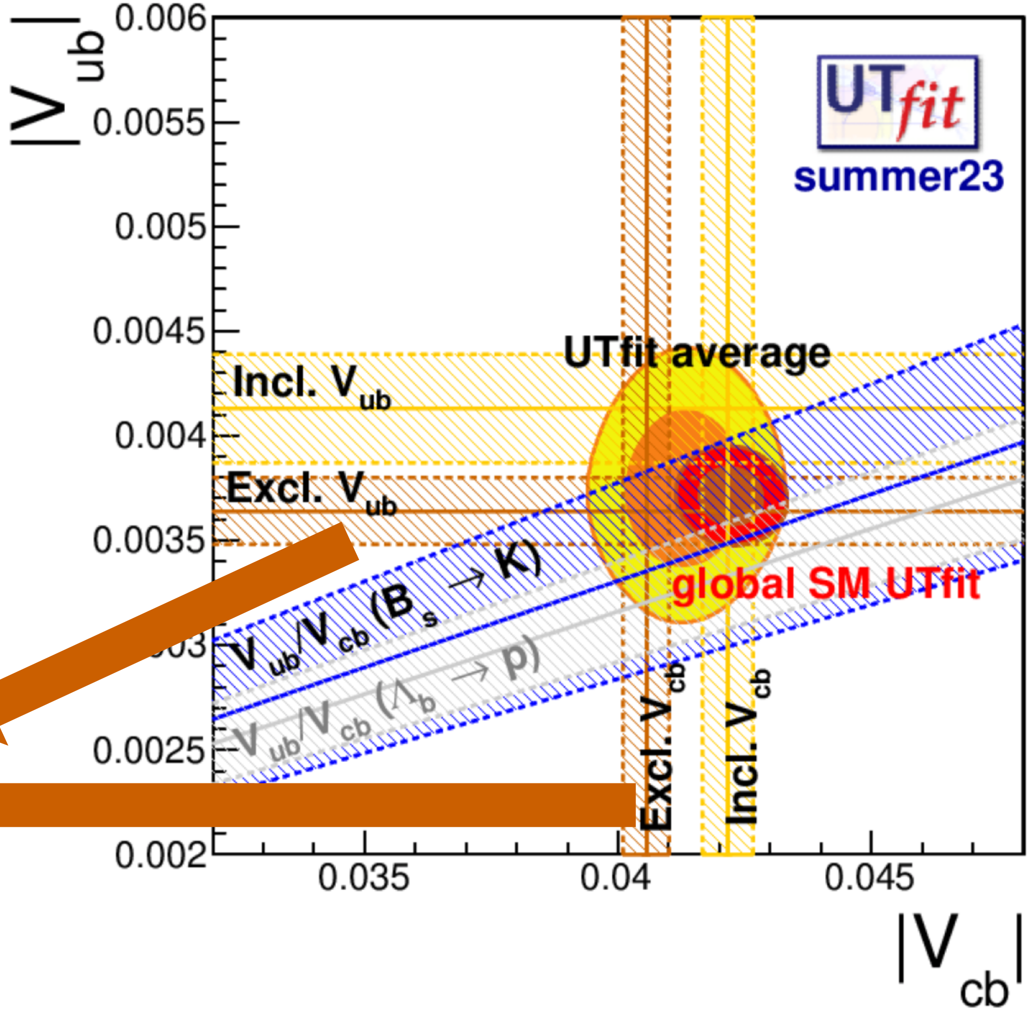
$|V_{cb}|_{incl} \times 10^3 = 42.16 \pm 0.50$

$|V_{cb}|_{ave} \times 10^3 = 41.1 \pm 1.3$

$|V_{ub}|_{excl} \times 10^3 = 3.64 \pm 0.16$

$|V_{ub}|_{incl} \times 10^3 = 4.13 \pm 0.26$

$|V_{ub}|_{ave} \times 10^3 = 3.75 \pm 0.26$



In sintesi, **per quanto concerne le determinazioni esclusive, *la strategia di analisi dati è fondamentale*** !

***Il messaggio principale è*: evitare ogni studio fenomenologico che mischi dati di reticolo e dati sperimentali (specialmente in presenza di qualche discrepanza tra questi …)**

Disappearance of R(K) and R(K*) anomalies

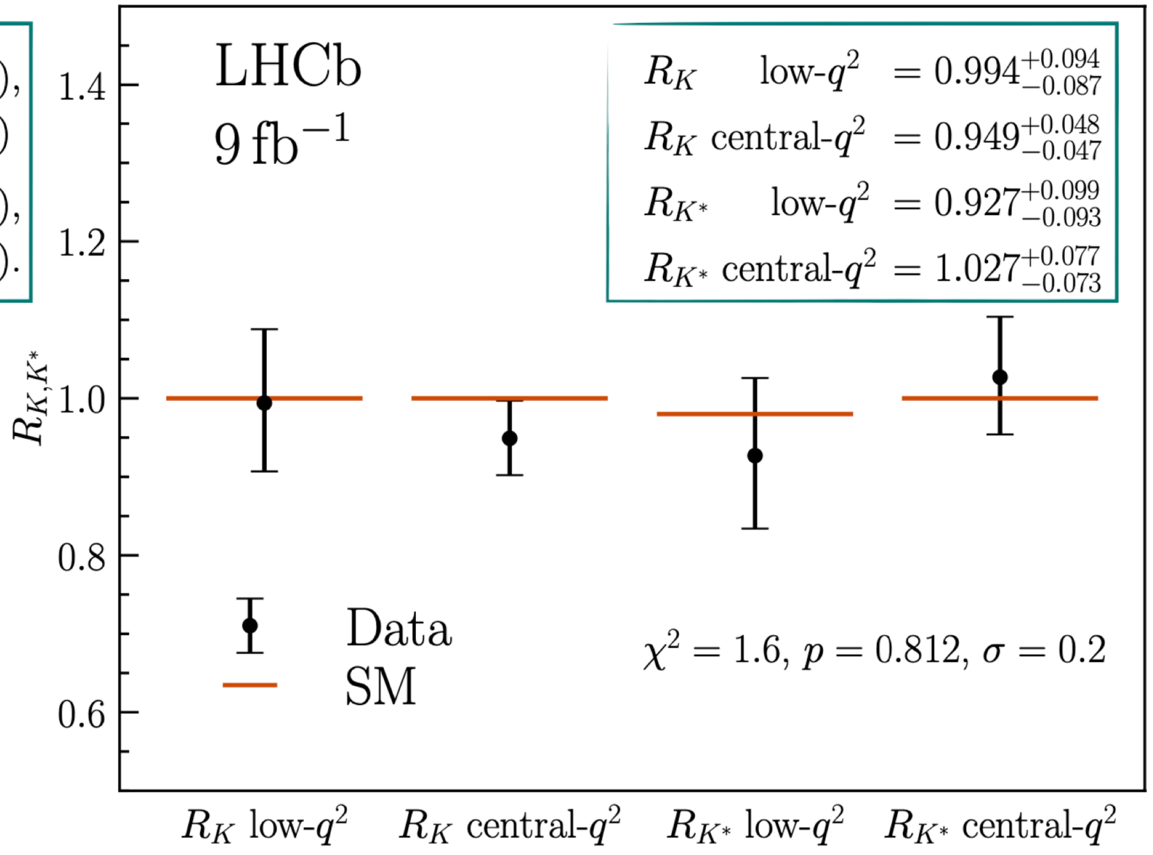
Analysis: results

Results

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\ (\text{stat})\ ^{+0.027}_{-0.029}\ (\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\ (\text{stat})\ ^{+0.034}_{-0.033}\ (\text{syst}) \end{cases}$$

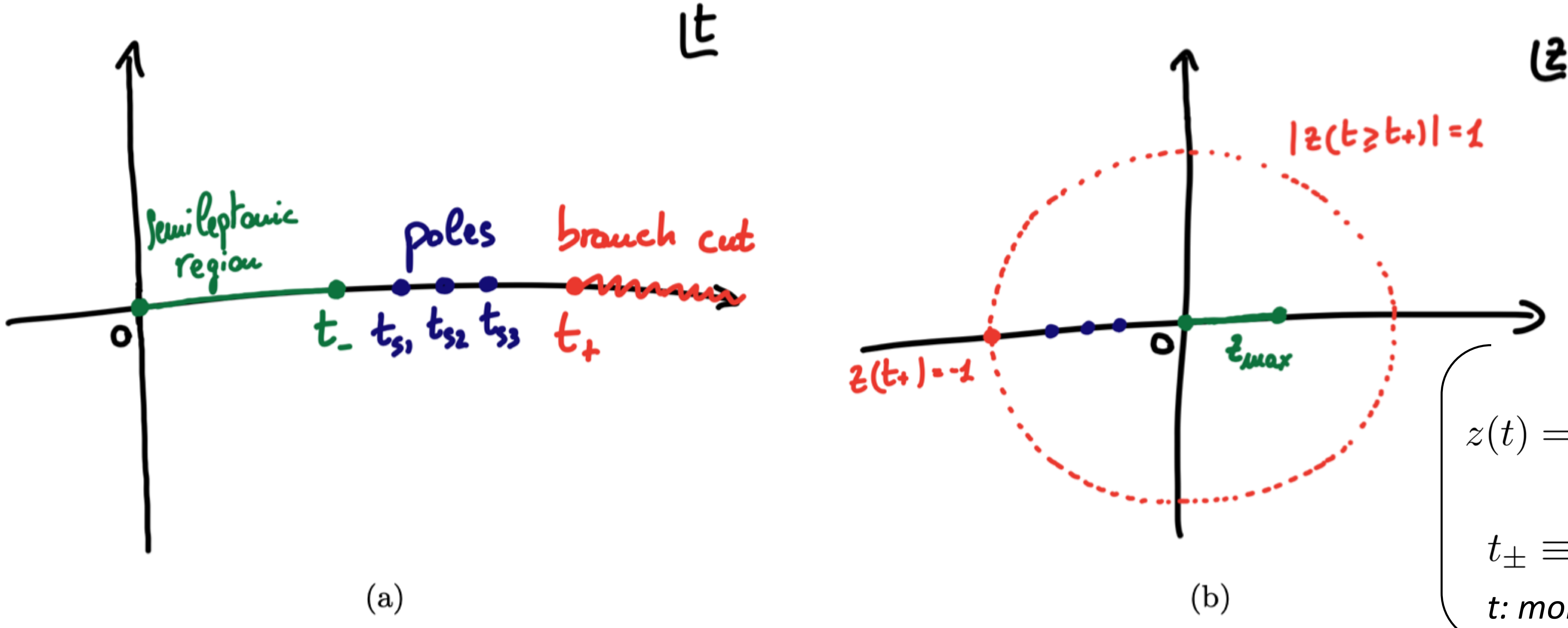
$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\ (\text{stat})\ ^{+0.023}_{-0.023}\ (\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\ (\text{stat})\ ^{+0.027}_{-0.027}\ (\text{syst}). \end{cases}$$

- ✦ Most precise and accurate LFU test in $b \to s\ell\ell$ transition
- ✦ Compatible with SM with a simple χ^2 test on 4 measurement at 0.2 σ



R. Quagliani's talk @ CERN, December the 20th

The conformal variable



$$z(t) = \frac{\sqrt{\frac{t_+ - t}{t_+ - t_-}} - 1}{\sqrt{\frac{t_+ - t}{t_+ - t_-}} + 1}$$

$$t_\pm \equiv (m_B \pm m_D)^2$$

t: momentum transfer

Figure 3.3: Sketch of the analytic structure of the hadronic form factors as function of t (left panel) or as function of z (right panel). The green line represents the region relevant for semileptonic decays. The blue points are the isolated poles coming from one-particle states. In conclusion, the red branch cut in the left panel is caused by multi-particle states, *i.e.* states of two or more particles. This branch cut translates in the unit circle $|z| = 1$ in the right panel.

The Dispersive Matrix (DM) method

Our goal is to describe the FFs using a novel, non-perturbative and model independent approach *in the whole kinematical region*!

- Pioneering works from S. Okubo [PRD, 3 (1971); PRD, 4 (1971)], C. Bourrely et al [NPB, 189 (1981)] and L. Lellouch [NPB, 479 (1996)]
- New developments in M. di Carlo et al, PRD '21 (2105.02497)

Let us focus on a generic FF *f*: **we will determine f(t) with f(t_i) known at positions t_i (i=1, ..., N)**

$$z(t) = \frac{\sqrt{\frac{t_+ - t}{t_+ - t_-}} - 1}{\sqrt{\frac{t_+ - t}{t_+ - t_-}} + 1}$$

$$t_\pm \equiv (m_B \pm m_D)^2$$

t: momentum transfer

How? Through: - An inner product

$$\langle h_1 | h_2 \rangle = \int_{|z|=1} \frac{dz}{2\pi i z} \bar{h}_1(z) h_2(z)$$

- An auxialiary function

$$g_t(z) \equiv \frac{1}{1 - \bar{z}(t) z}$$

We build up the matrix M of the scalar products of ϕf, g_t, g_{t1}, ..., g_{tN} :

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

The Dispersive Matrix (DM) method

CENTRAL ISSUE: since **M** contains only inner products, by construction its determinant is semipositive definite

$$\det \mathbf{M} \geq 0 \;\Rightarrow\; f_{\rm lo}(z) \leq f(z) \leq f_{\rm up}(z)$$

DISPERSION RELATIONS:

$$0 \leq \langle \phi f | \phi f \rangle \leq \chi(q^2)$$

$$\mathbf{M} = \begin{pmatrix} \boxed{\langle \phi f | \phi f \rangle} & \langle \phi f | g_t \rangle & \langle \phi f | g_{t_1} \rangle & \cdots & \langle \phi f | g_{t_n} \rangle \\ \langle g_t | \phi f \rangle & \langle g_t | g_t \rangle & \langle g_t | g_{t_1} \rangle & \cdots & \langle g_t | g_{t_n} \rangle \\ \langle g_{t_1} | \phi f \rangle & \langle g_{t_1} | g_t \rangle & \langle g_{t_1} | g_{t_1} \rangle & \cdots & \langle g_{t_1} | g_{t_n} \rangle \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \langle g_{t_n} | \phi f \rangle & \langle g_{t_n} | g_t \rangle & \langle g_{t_n} | g_{t_1} \rangle & \cdots & \langle g_{t_n} | g_{t_n} \rangle \end{pmatrix}$$

Basics of IS DM

The basic idea is a substitution of the usual probability density function (PDF) adopted in our analyses:

$$PDF(f_i) \propto e^{-\frac{1}{2}\sum_{i,j=0}^{N}(f_i - F_i)C_{ij}^{-1}(f_j - F_j)}$$

All the details are contained also in **arXiv: 2309.02135**

$$PDF_{IS}(f_i) \propto PDF(f_i) \cdot \exp\left[-\frac{s}{\chi(q_0^2)}\chi_{\{f\}}^{DM}(q_0^2)\right]$$

In short: a new set of input data $\{\widetilde{F}_i, \widetilde{C}_{ij}\}$ is introduced in order to increase the likelihood of small values of χDM !

$$\beta - \sqrt{\gamma} \leq f(z) \leq \beta + \sqrt{\gamma}$$

χDM

$$\beta = \frac{1}{d(z)\phi(z)}\sum_{j=1}^{N} f_j \phi_j d_j \frac{1 - z_j^2}{z - z_f} \qquad \gamma = \frac{1}{d^2(z)\phi^2(z)}\frac{1}{1 - z^2}\left[\chi - \boxed{\sum_{i,j=1}^{N} f_i f_j \phi_i \phi_j d_i d_j \frac{(1 - z_i^2)(1 - z_j^2)}{1 - z_i z_j}}\right]$$

Relevant quantities for monitoring the results of IS DM

Recall that the **DM** remains a **fitting procedure with a vanishing value of the χ2-variable in a frequentist language**!
Then, we have to monitorate the deviation of the new input data from the initial ones thorugh the quantities

$$\Delta \equiv \left\{ \frac{1}{N+1} \sum_{i,j=0}^{N} (\widetilde{F}_i - F_i) C_{ij}^{-1} (\widetilde{F}_j - F_j) \right\}^{1/2}$$

Δ < 1 means that on average the new data deviate from the original ones by less than one standard deviation

$$\eta \equiv \left\{ \frac{1}{N+1} \sum_{i=0}^{N} \frac{\widetilde{F}_i^2}{F_i^2} \right\}^{1/2}$$

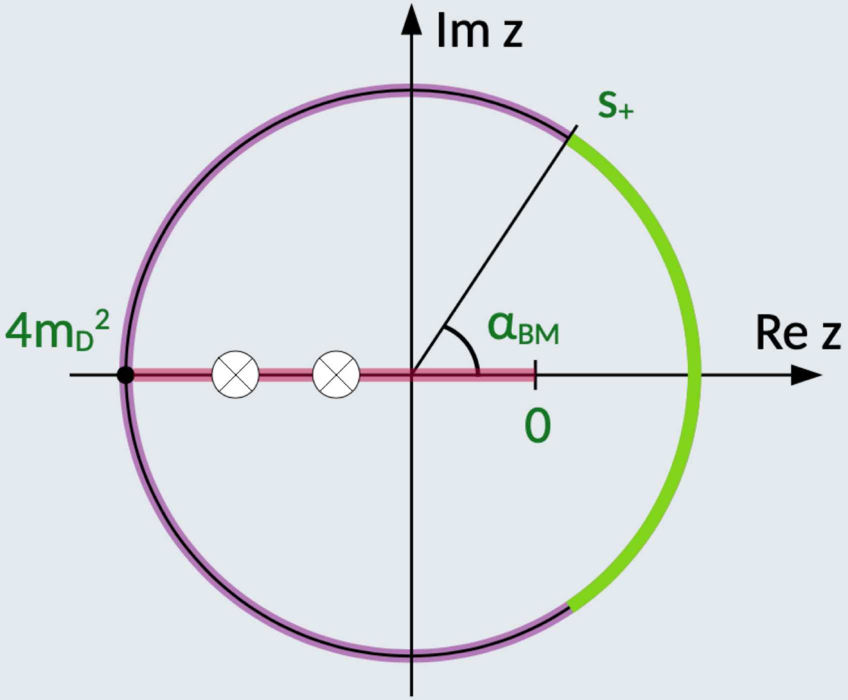
The value of η can be less or larger than unity depending on whether the new data are (on average) less or larger than original ones

$$\epsilon \equiv \left\{ \frac{1}{N+1} \sum_{i=0}^{N} \frac{\widetilde{C}_{ii}}{C_{ii}} \right\}^{1/2} = \left\{ \frac{1}{N+1} \sum_{i=0}^{N} \frac{\widetilde{\sigma}_i^2}{\sigma_i^2} \right\}^{1/2}$$

Same physical meaning of η, but now referred to the uncertaintities of the new data in comparison to the original ones

Parametrization #3

$$1 > 2\int_{-\alpha_{BK}}^{+\alpha_{BK}} d\alpha \left|\hat{\mathcal{H}}_0^{B\to K}(e^{i\alpha})\right|^2 + \sum_\lambda \left[2\int_{-\alpha_{BK^*}}^{+\alpha_{BK^*}} d\alpha \left|\hat{\mathcal{H}}_\lambda^{B\to K^*}(e^{i\alpha})\right|^2 + \int_{-\alpha_{B_s\phi}}^{+\alpha_{B_s\phi}} d\alpha \left|\hat{\mathcal{H}}_\lambda^{B_s\to \phi}(e^{i\alpha})\right|^2\right]$$



- The bound can be "**diagonalized**" with **orthonormal polynomials** of the arc of the unit circle [Gubernari, van Dyk, Virto '20]

$$\mathcal{H}_\lambda(z) = \frac{1}{\phi(z)\mathcal{P}(z)} \sum_{k=0}^{N} a_{\lambda,k}\, p_k(z)$$

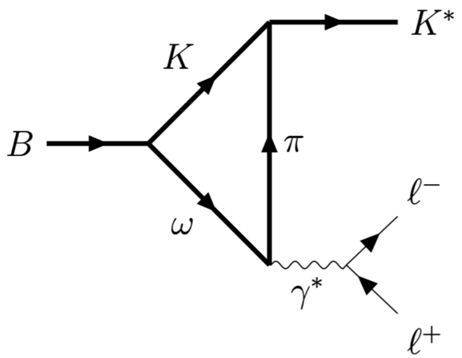
- The new coefficients respect the **simple bound**:

$$\sum_{n=0}^{\infty} \left\{ 2\left|a_{0,n}^{B\to K}\right|^2 + \sum_{\lambda=\perp,\|,0} \left[2\left|a_{\lambda,n}^{B\to K^*}\right|^2 + \left|a_{\lambda,n}^{B_s\to\phi}\right|^2\right]\right\} < 1$$

Two possible paths to solve this issue

i) Compute re-scattering diagrams using model-dependent schemes:

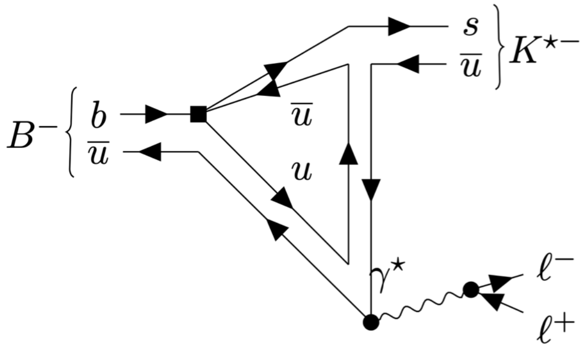
$$\boxed{\begin{aligned} A_{LD}(\lambda_{K^*},\sigma_{\ell^+},\sigma_{\ell^-}) \;=\; \frac{1}{q^2}\sum_{\lambda_\omega,\lambda_\gamma} \mathcal{A}(B\to K\omega(\lambda_\omega))\times \\ \mathcal{A}(K\omega(\lambda_\omega)\to K^*(\lambda_{K^*})\gamma^*(\lambda_\gamma))\;\mathcal{A}(\gamma^*(\lambda_\gamma)\to \ell^+(\sigma_{\ell^+})\ell^-(\sigma_{\ell^-})),\end{aligned}}$$



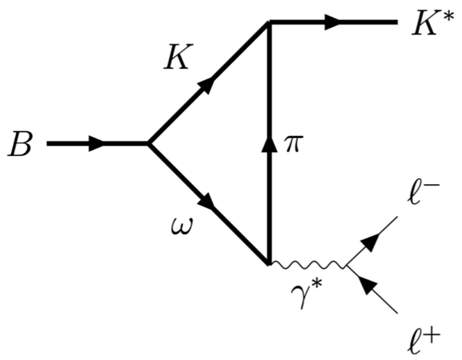
$$\left\{\begin{aligned}
&\mathcal{A}(B\to K\omega(\lambda_\omega)) = g_{BK\omega}\,(p_K+p_\omega)\cdot\epsilon^*(\lambda_\omega),\\
&\mathcal{A}(K\omega(\lambda_\omega)\to K^*(\lambda_{K^*})\gamma^*(\lambda_\gamma)) = \frac{1}{4\pi}\int_0^{2\pi} d\phi\,\int_{t_{min}}^{t_{max}}\frac{dt}{2|\vec{p}_\omega||\vec{q}|}\times\\
&\qquad\left\{\frac{i\,e\,g_{KK^*\pi}\,f_{\omega\pi^0}}{t-m_\pi^2}\,p_K\cdot\epsilon^*(\lambda_K)\epsilon^{\mu\nu\alpha\beta}p_{\omega\mu}q_\nu\epsilon_\alpha(\lambda_\omega)\epsilon^*_\beta(\lambda_\gamma)\right\},\\
&\mathcal{A}(\gamma^*(\lambda_\gamma)\to\ell^+(\sigma_{\ell^+})\ell^-(\sigma_{\ell^-})) = e\,\bar{u}_{\ell^-}(\sigma_{\ell^-})\,(\gamma\cdot\epsilon_\gamma(\lambda_\gamma))\,v_{\ell^+}(\sigma_{\ell^+}),
\end{aligned}\right.$$

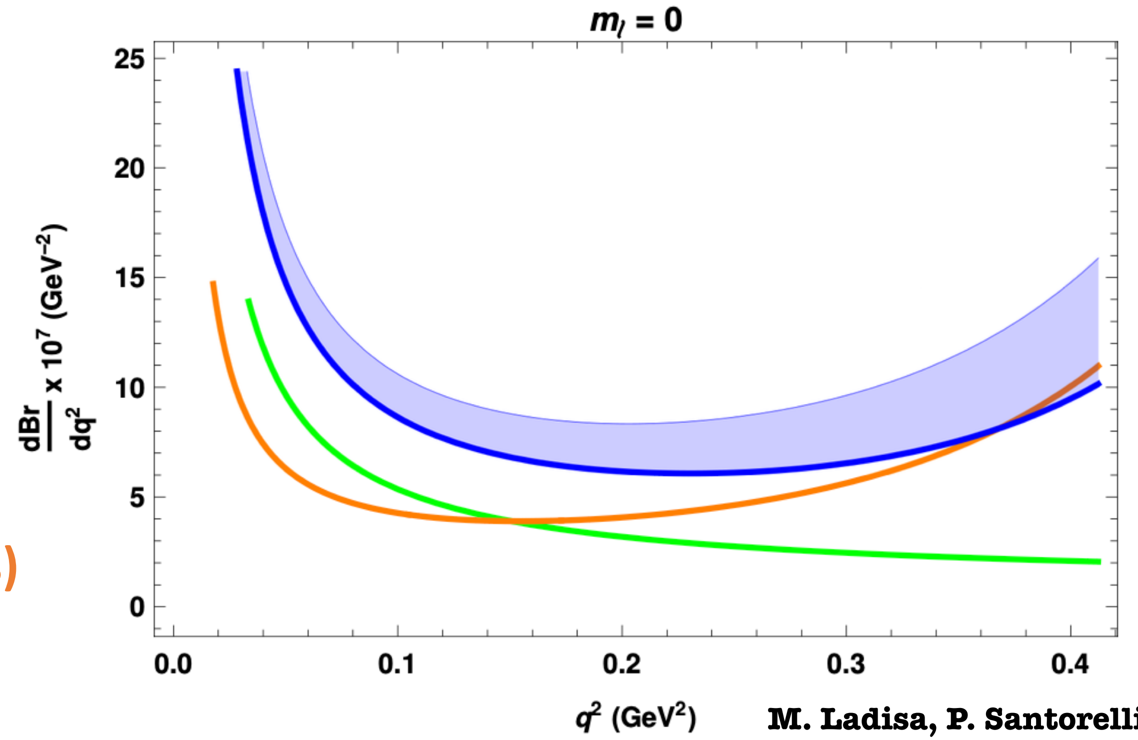
Two possible paths to solve this issue

i) Compute re-scattering diagrams using different (model-dependent) schemes:



one possible mesonic realization



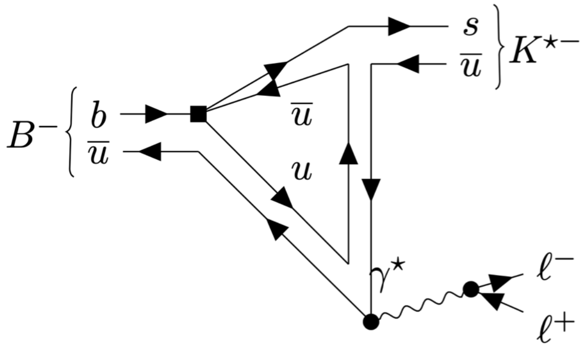


Short Distance (local FFs)
Long Distance (non-local FFs)
SD+LD combination

M. Ladisa, P. Santorelli, PLB '23 [2208.00080]

Two possible paths to solve this issue

i) Compute re-scattering diagrams using different (model-dependent) schemes:



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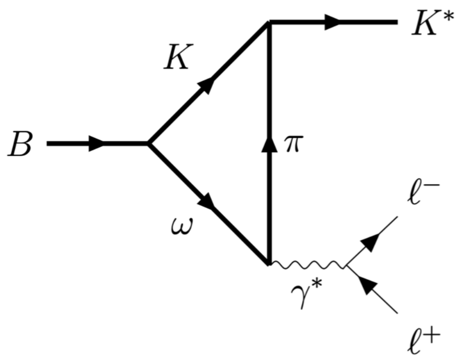
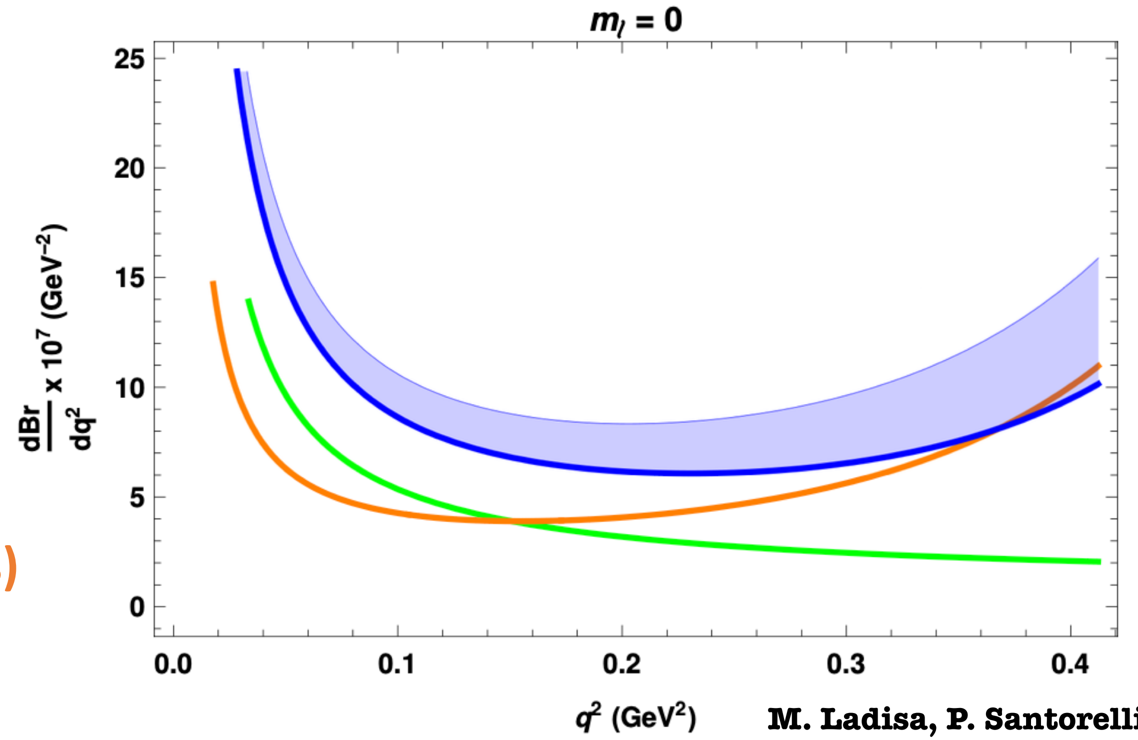




Short Distance (local FFs)
Long Distance (non-local FFs)
SD+LD combination

Non-negligible contribution from non-local FFs

M. Ladisa, P. Santorelli, PLB '23 [2208.00080]

Programma estendibile per i canali $b \to d$!!

Questa strategia «multi-percorso» può esser estesa alle transizioni *b* \to *d*:

Canali semileptonici:

$$B \to \pi \ell^+ \ell^-$$

$$B \to \rho \ell^+ \ell^-$$

Canali inclusivi:

$$B \to X_d \ell^+ \ell^-$$

Canali radiativi:

$$B_{(d)} \to \gamma \ell^+ \ell^-$$

i) **Avendo qui una maggiore soppressione CKM (prop. a $|V_{td}V_{tb}|$^2), qualsiasi incremento del BR può esser interpretato come un chiaro segnale di Nuova Fisica;**

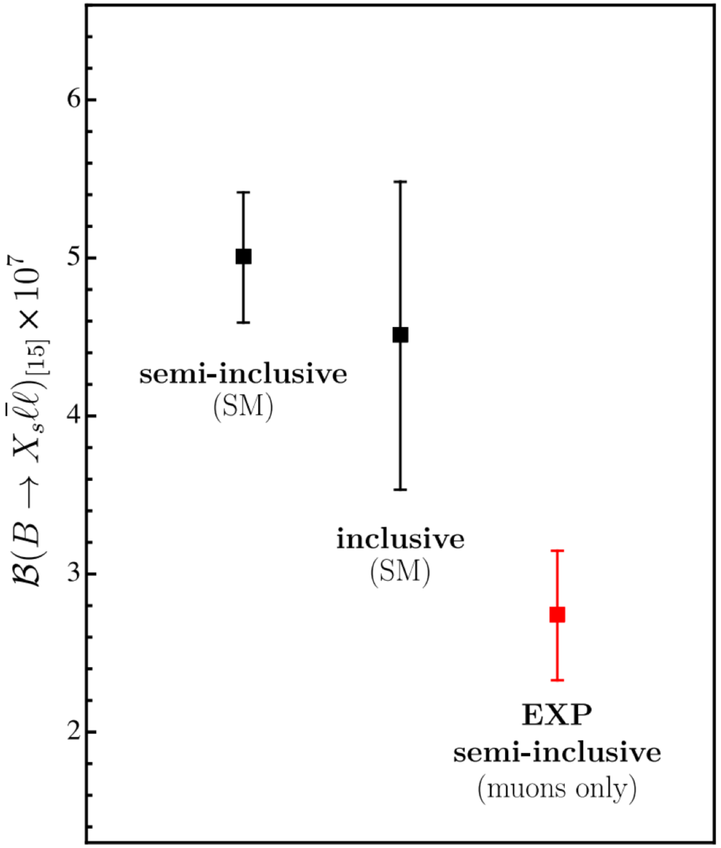
ii) **Se i) è vero, importante conseguenze per la nostra comprensione teorica della struttura di sapore della teoria completa**

JHEP '23 [2208.14463] , EPJC '23 [2209.04457], JHEP '23 [2212.10497], PLB '23 [2303.15384], 2310.06734 ...

Two possible paths to solve this issue

ii) Focus on **complementary observables** !!

- **Semi-inclusive decays @ high-q2**:



Isidori, Polonsky, Tinari, PRD '23 [2305.03076]

- «Inclusive»:

$$R^{(\ell)}_{\rm incl}(q_0^2) = \frac{\displaystyle\int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_s\bar{\ell}\ell)}{dq^2}}{\displaystyle\int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_u\bar{\ell}\nu)}{dq^2}},$$

$$\mathcal{O}_7 = \frac{m_b}{e}(\bar{s}_L\sigma_{\mu\nu}b_R)F^{\mu\nu}$$

$$\mathcal{O}_V = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_L = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\ell_L)\,,$$

$$R_{\rm incl}(q_0^2) = \frac{|V_{tb}V_{ts}^*|^2}{|V_{ub}|^2}\left[\mathcal{R}_L + \Delta\mathcal{R}_{[q_0^2]}\right]$$

$$\boxed{\mathcal{R}_L = \frac{\alpha_e^2 C_L^2}{16\pi^2} = \frac{\mathcal{C}_L^2}{8G_F^2}}$$

limit of purely left-handed interactions and identical hadronic distributions

$$\Delta\mathcal{R}_{[15]} = \frac{\alpha_e^2}{8\pi^2}\Big[C_V^2 + C_V C_L + 0.485C_L + 0.97C_V + 0.93 + \Delta_{\rm n.p.} + C_7(1.91 + 2.05C_L + 4.27C_7 + 4.1C_V)\Big]$$

$$\mathcal{B}(B \to X_s\bar{\ell}\ell)^{\rm SM}_{[15]} = (4.5 \pm 1.0) \times 10^{-7}$$
$$= 4.5 \times 10^{-7}\,[1 \pm 0.16_{\rm exp} \pm 0.11_{\rm CKM} \pm 0.09_{\Delta\mathcal{R}}]\,.$$

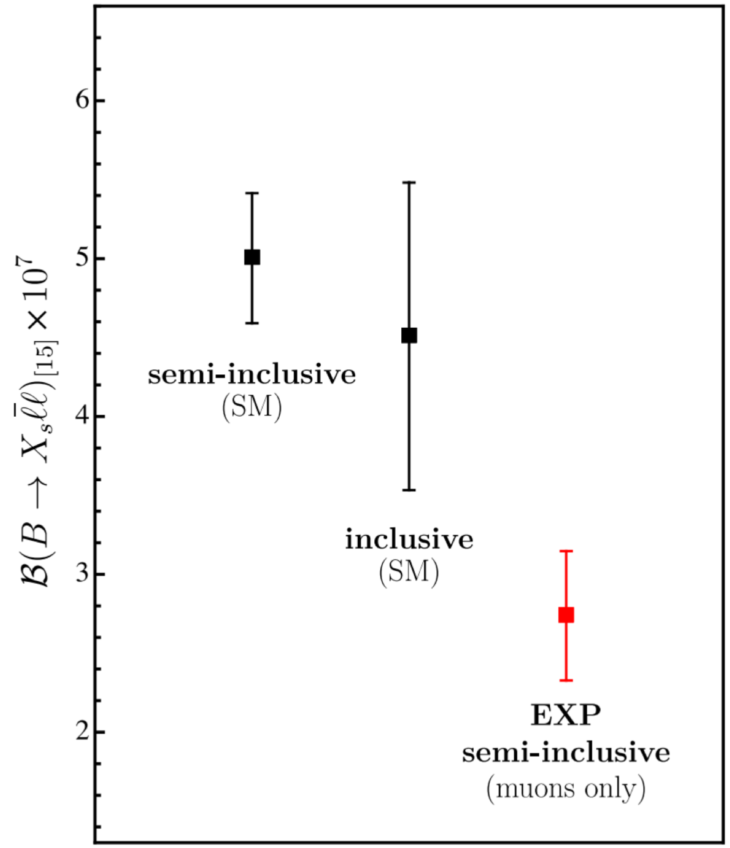
- «Semi-inclusive»:

$$\sum_i \mathcal{B}(B \to X_s^i\bar{\ell}\ell)_{[15]} = \left(1 + \Delta^{[15]}_{K\pi}\right) \times \left[\mathcal{B}(B \to K\bar{\ell}\ell)_{[15]} + \mathcal{B}(B \to K^*\bar{\ell}\ell)_{[15]}\right],$$

Two possible paths to solve this issue

ii) Focus on **complementary observables** !!

- Semi-inclusive decays @ high-q2:



Isidori, Polonsky, Tinari, PRD '23 [2305.03076]

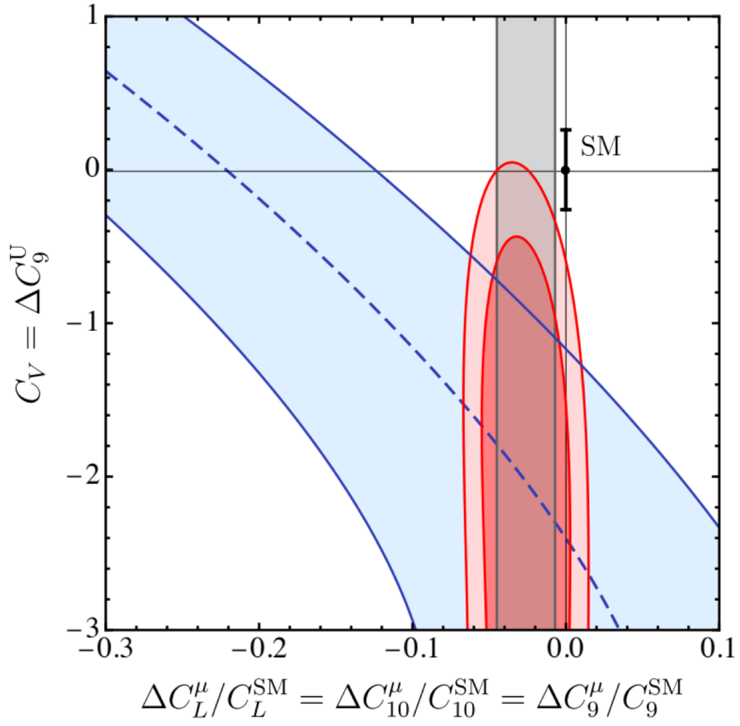


FIG. 2. Regions for the Wilson coefficients favored by experimental data. Here, $\Delta C_L^\mu = C_L^\mu - C_L^{\rm SM}$ is the correction to the SM value of C_L for the muon modes. The blue area is the 1σ compatibility region between the inclusive computation of $\mathcal{B}(B \to X_s \bar{\ell}\ell)$ and the experimental sum of exclusive modes (the dashed line indicates the best fit). The vertical grey band shows the 1σ value of C_L^μ determined by $\mathcal{B}(B_s \to \bar{\mu}\mu)$ and the LFU ratios (assuming a lepton-universal C_V). The dark and light red regions give the combined compatibility at 68% and 90% confidence level, respectively. To ease the comparison with previous studies, we also show on both axes the notation in the standard operator basis.

Radiative-and-leptonic Bs decays

A novel possibility is the study of rare radiative-and-leptonic Bs decays. This is experimentally challenging, and yet LHCb has recently set a limit (very close to the SM signal):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$

LHCb Collaboration, LHCb-PAPER-2021-007 & LHCb-PAPER-2021-008

This is the first world limit on these decays!

Several advantages from the theoretical point of view:

1. No chirality suppression (thanks to the additional photon): **enhancement w.r.t. the leptonic counterpart**!
2. Sensitivity to a **larger set of WCs**: not only O_{10}(‘), also O_7(‘) and O_9(‘) (O_9(‘) and O_{10}(‘) are relevant at high-$q2$)
3. Smart way to detect it experimentally: **«indirect» method** **(Dettori, Guadagnoli, Reboud, Phys.Lett.B 768 (2017) 163-167)**

Three key issues in what follows:

1. How does the «indirect» method work?
2. How to deal with these decays in the SM?
3. Which is the SM prediction for the BR?

The "indirect" method to detect radiative-and-leptonic decays

The basic idea is to reconstruct the radiative signal from the non-radiative counterpart, namely

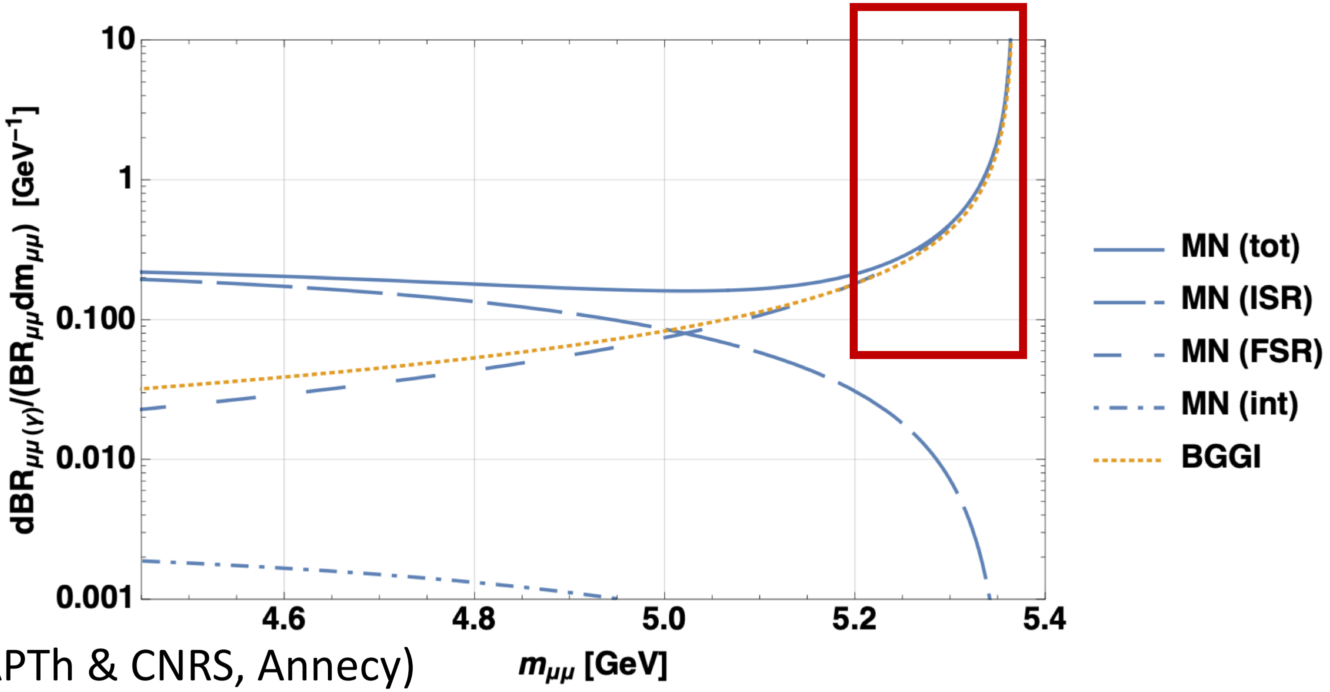
$$B_s^0 \to \mu^+\mu^-\gamma \text{ from } B_s^0 \to \mu^+\mu^-$$

Dettori, Guadagnoli, Reboud, Phys.Lett.B 768 (2017) 163-167

How? Enlarging the dilepton invariant mass below the Bs-peak (it works IF the bkgs are well under control!)

The problem is in other words

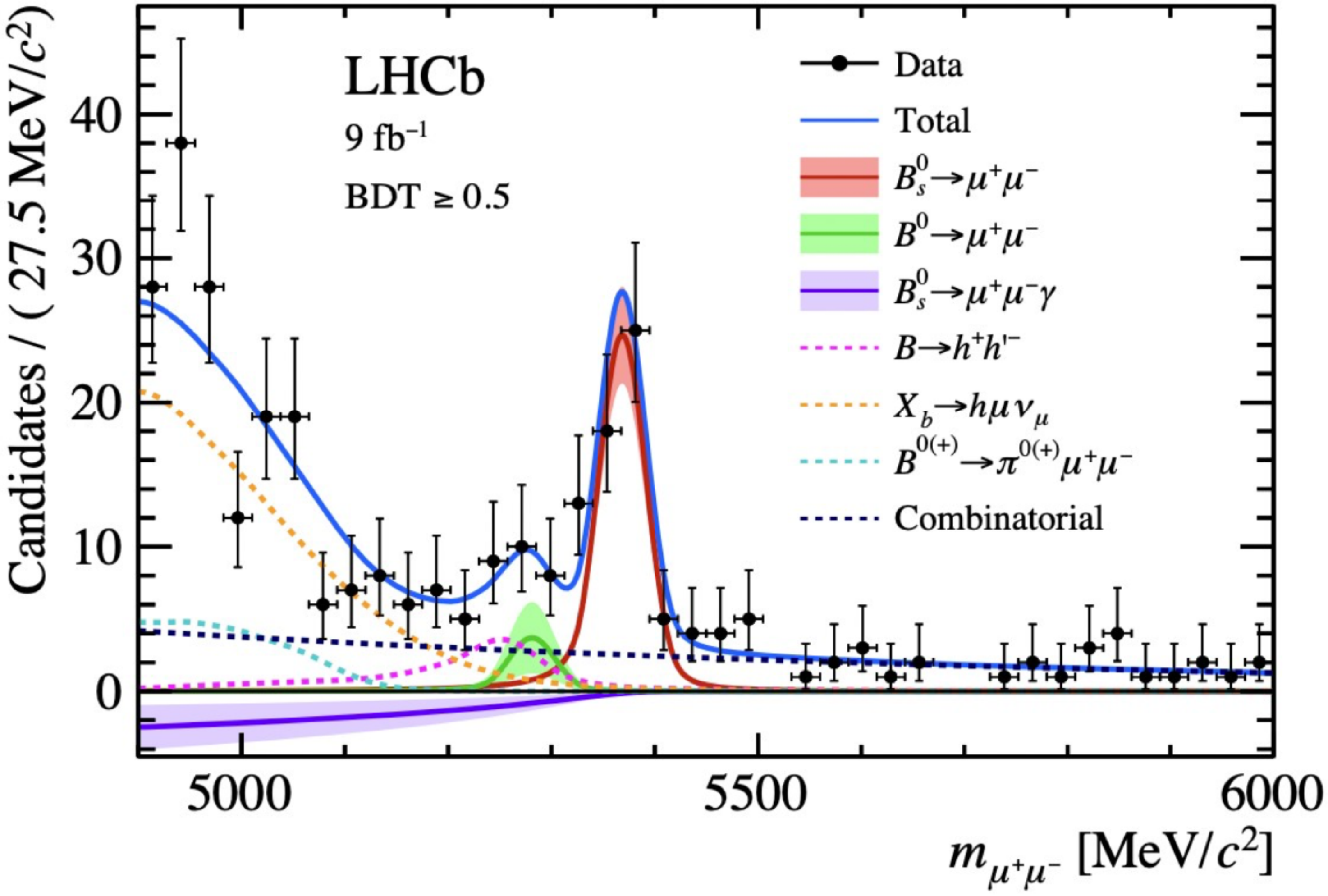
$$\mathcal{B}(B_s^0 \to \mu^+\mu^- + n\gamma) \text{ VS } \mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$$



For very soft photons, the single-photon component of the former should be equal to the latter!

The “indirect” method to detect radiative-and-leptonic decays

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$



(from LHCb-PAPER-2021-007, LHCb-PAPER-2021-008)

Some pros:

i) No recontruction of the photon, whose efficieny is inherently small

ii) Measur. at high-q2, which is the best region for Lattice QCD and is also the region least affected by resonances

iii) Sensitivity to C9, C10

Some cons:

i) Signal as a «shoulder», i.e. requires reliable estimation of all other «shoulders»

ii) Difficult below (4.2 GeV)^2

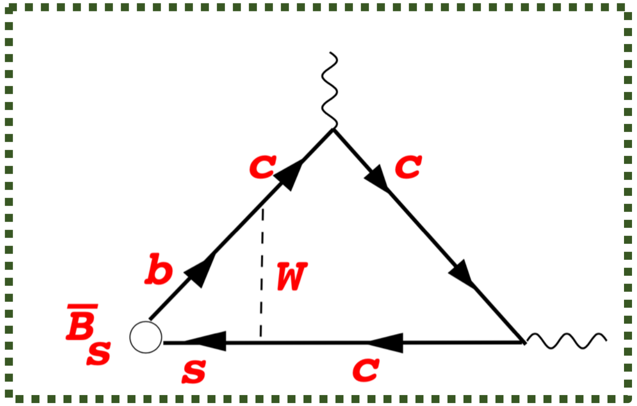
iii) Mass resolution crucial !!

Radiative-and-leptonic decays in the SM

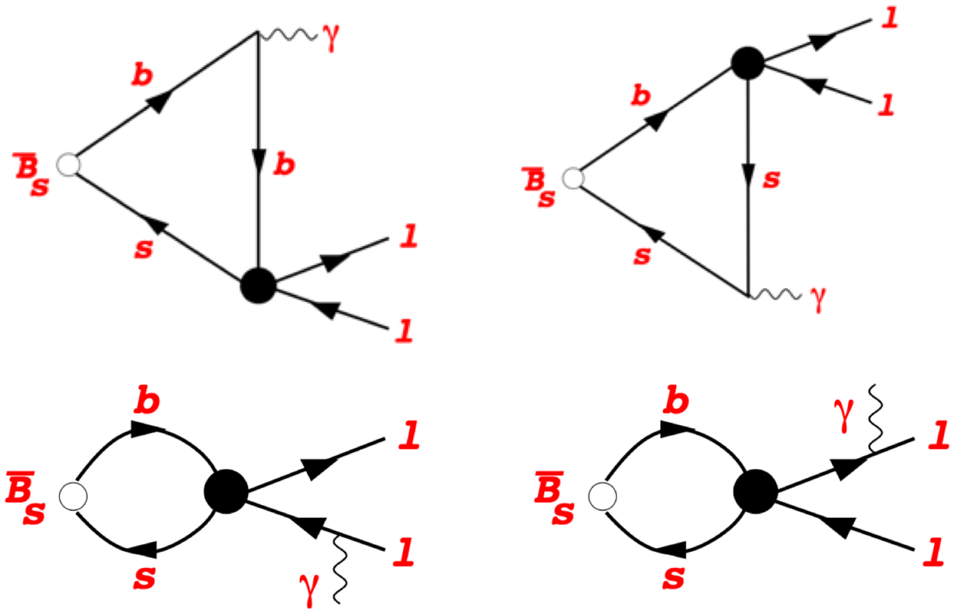
5 different classes of diagrams:

1. DE of the photon from valence quarks
2. DE of the virtual photon from valence quarks
3. Bremsstrahlung
4. Charm loops diagrams
5. Weak annihilation diagram

Example:



Important issue: **<u>only 4 diagrams</u> give a relevant contribution at high-q2, *i.e.***



● = $O_{9,10}$

A new approach to the hadronic FFs

D. Guadagnoli, C. Normand S. Simula, LV, JHEP 07 (2023) 112

Phenomenological approach: we want some data at HIGH-q2 to be extrapolated to the Bs-sector, since at present we have no direct lattice computations of the form factors in this sector!

$$\langle \gamma(k,\epsilon)|O_\mu^V|\bar{B}_q(p_B)\rangle = s_e(P_\mu^\perp V_\perp(q^2) - P_\mu^\parallel (V_\parallel(q^2) + Q_{\bar{B}_q} f_{B_q}^{(pt)}) - P_\mu^{\mathrm{Low}} Q_{\bar{B}_q} f_{B_q}^{(pt)})$$

Janowski, Pullin and Zwicky, JHEP 12 (2021) 008

GNSV PLAN: analysis of the data for Ds \to \gamma in A. Desiderio et al., PRD 103 (2021) 014502 and, then, extrapolation to the Bs sector!

$$V_{\perp[\|]}^{D_s}(q^2) = \frac{1}{\pi}\int_0^\infty dt \frac{\mathrm{Im}[V_{\perp[\|]}^{D_s}(t)]}{t-q^2} = \frac{r_{\perp[\|]}^{D_s^*[D_{s1}]}}{1-q^2/m^2_{D_s^*[D_{s1}]}} + \dots$$

$$\left[\; r_\perp^{D_s^*} = \frac{m_{D_s} f_{D_s^*}}{m_{D_s^*}} g_{D_s^* D_s \gamma}, \qquad r_\|^{D_{s1}} = \frac{m_{D_s} f_{D_{s1}}}{m_{D_{s1}}} g_{D_{s1} D_s \gamma} \;\right]$$

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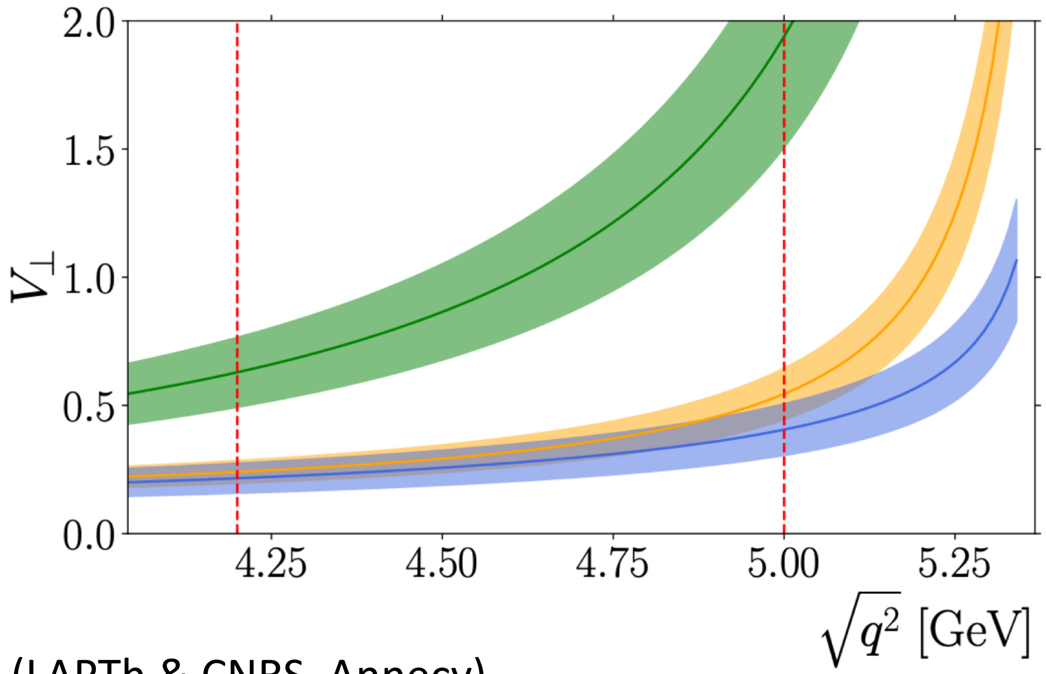
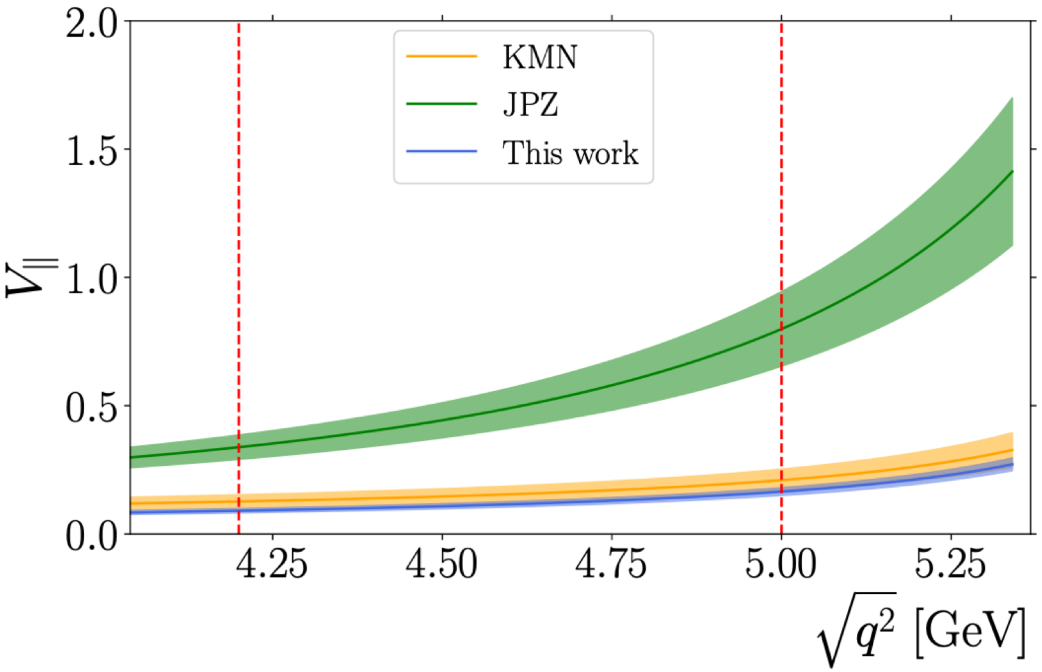
Once we inferred the residues and the tri-couplings in the Ds sector:

$$
\begin{aligned}
g_{D_s^* D_s \gamma} &= Q_s \mu_s^{\perp 1} + Q_c \mu_c^{\perp 1} \,, \\
g_{D_{s1}^* D_s \gamma} &= Q_s \mu_s^{\perp 2} + Q_c \mu_c^{\perp 2} \,, \\
g_{B_s^* B_s \gamma} &= Q_s \mu_s^{\perp 1} + Q_b \mu_b^{\perp 1} \,, \\
g_{B_{s1}^* B_s \gamma} &= Q_s \mu_s^{\perp 2} + Q_b \mu_b^{\perp 2} \,.
\end{aligned}
$$

$$
\begin{aligned}
g_{D_{s1} D_s \gamma} &= -Q_s \mu_s^{\parallel} + Q_c \mu_c^{\parallel} \,, \\
g_{B_{s1} B_s \gamma} &= -Q_s \mu_s^{\parallel} + Q_b \mu_b^{\parallel} \,,
\end{aligned}
$$

$$
\left[\mu_c^{\parallel} = \frac{m_s}{m_c} \mu_s^{\parallel} \,, \qquad \mu_b^{\parallel} = \frac{m_s}{m_b} \mu_s^{\parallel} \,. \right]
$$





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 → sμμ: 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

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

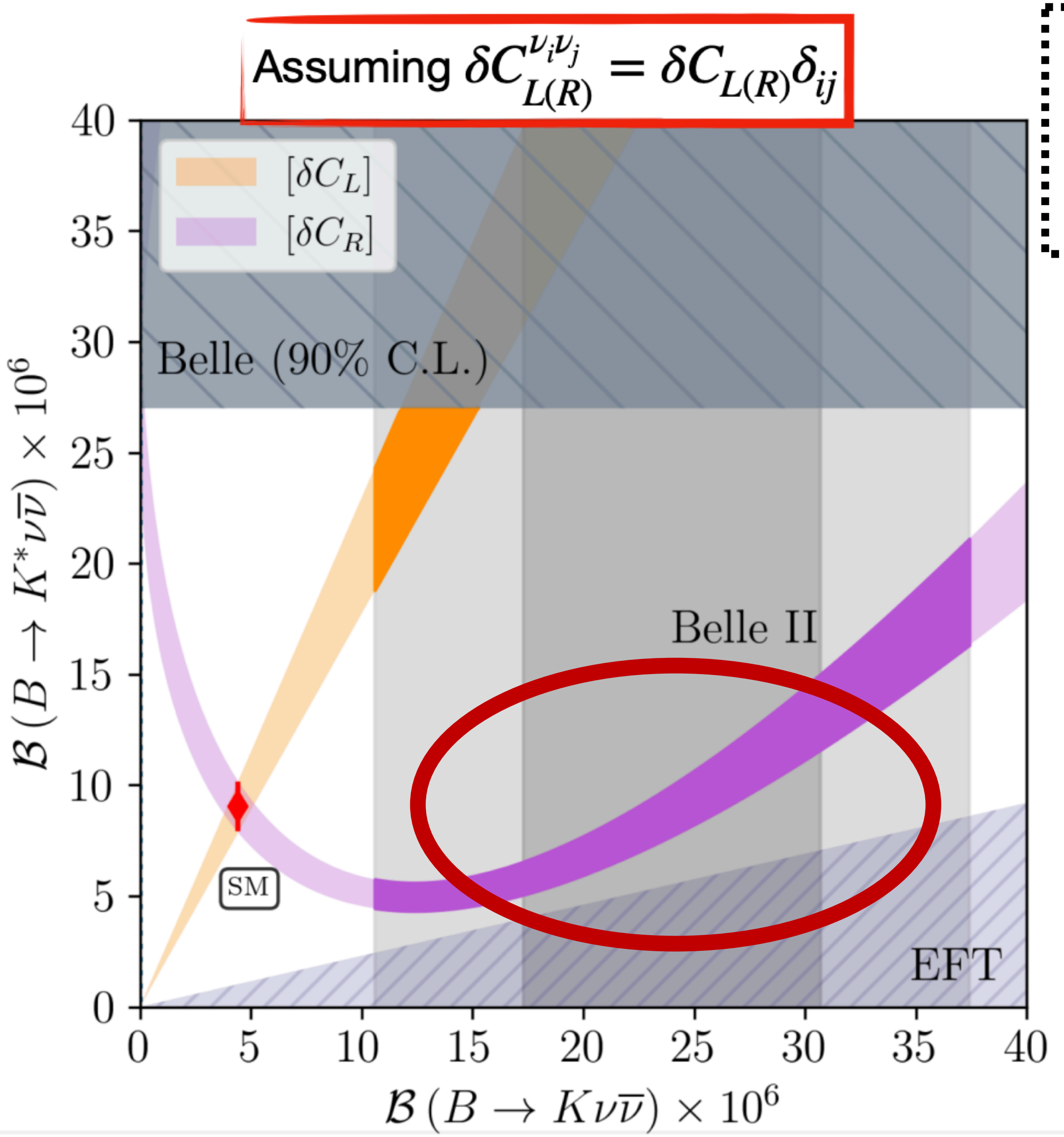
D. Becirevic, G. Piazza & O. Sumensari, EPJC ‘23 [arXiv:2301.06990]

to be compared with

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

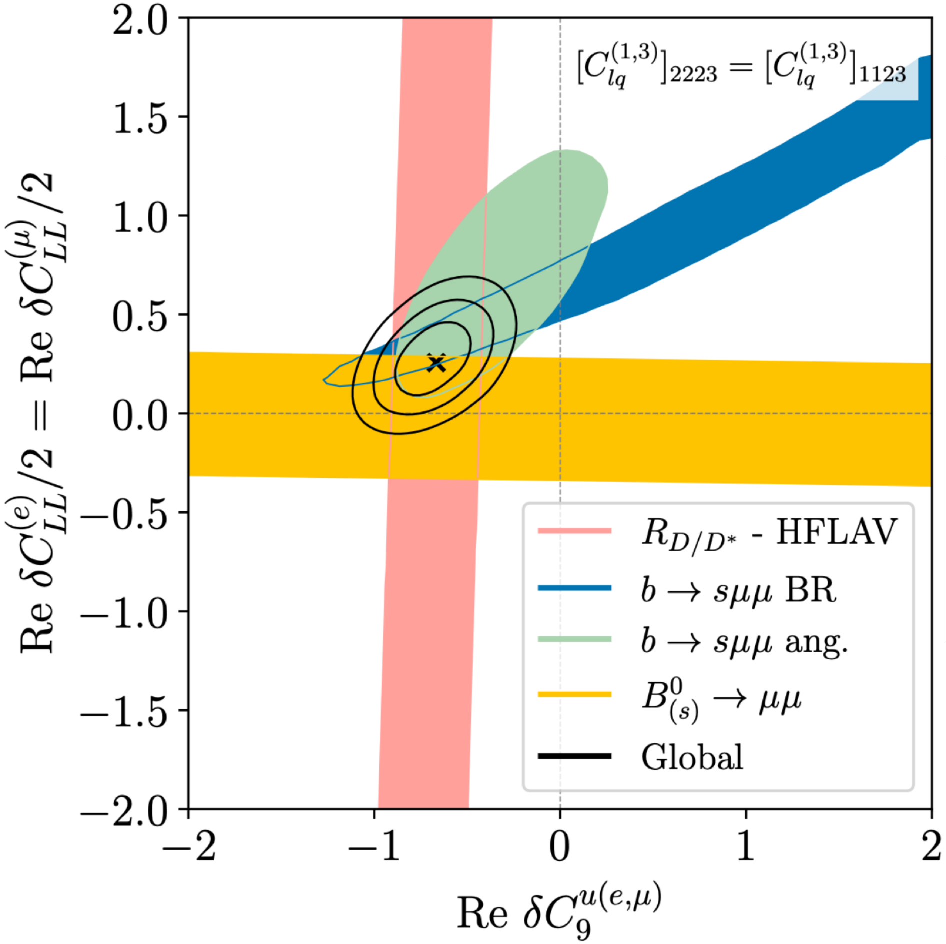
A. Glazov, plenary talk EPS-HEP2023 Conference, Aug 20-25, 2023

B → Kνν 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 → Kνν may influence $b \to$ s observables (with charged leptons) and $b \to c$ ones !**



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

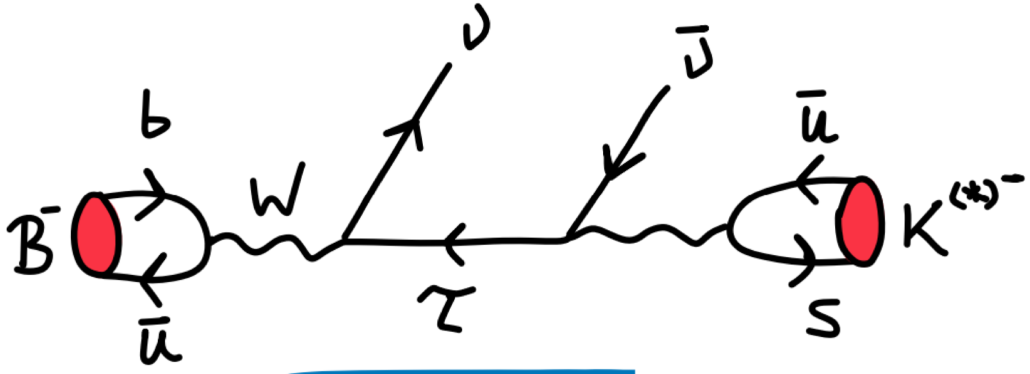
Light-lepton universal NP scenario [without B → Kνν data]

Tree-level contribution

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

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

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



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

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 $b \to c$?

- $C_9^{\text{univ.}}$ 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

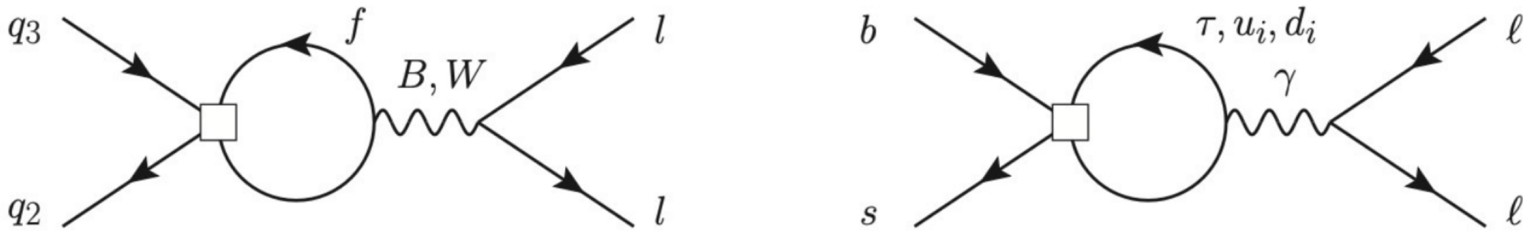


Figure 3: Diagrams inducing a contribution to C_9 through RG running above (left panel) and below (right panel) the EW scale. A sizeable contribution to C_9 is obtained when $f = u_{1,2}, d_{1,2,3}$ or l_3, see text for details.

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

$$\Longleftrightarrow$$

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

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]]

Decadimenti rari del mesone K

Questi decadimenti possono provare, per la prima volta, effetti di corta distanza nelle ampiezze FCNC *s* → *d*: essi sono privi di effetti di lunga distanza. Importante impatto per la fisica oltre il Modello Standard !

Un esempio pratico è offerto dall'assione. Interazioni dell'assione con fermioni del MS:

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left(c^V_{f_i f_j} + c^A_{f_i f_j} \gamma_5 \right) f_j$$

Martin Camalich et al., PRD '20 [2002.04623]

$$\left[m_a = 5.691(51)\,\mu\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a} \right) \right]$$

Gorghetto and Villadoro, JHEP '19 [1812.01008]

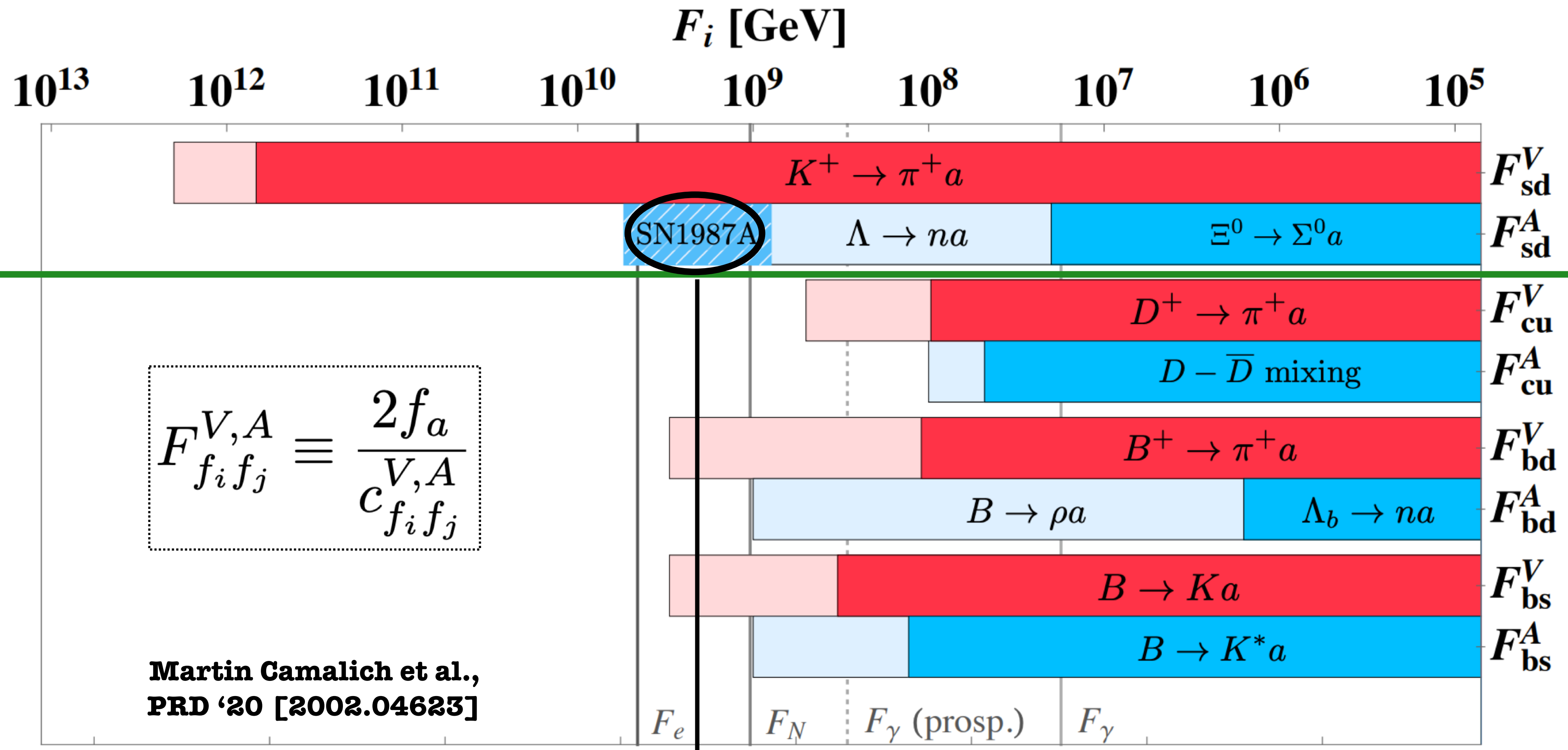
Gli accoppiamenti possono sia essere universali in sapore sia violare il sapore ! In particolare:

$\Gamma(K^+ \to \pi^+ a)$ ⟷ Limite su cV_{23}

$\Gamma(B_1 \to B_2 a)$ ⟷ Limite su cV_{23} e cA_{23}

… …

Decadimenti rari del K (e non solo): il caso dell'assione



Recente aggiornamento in **Cavan Piton et al., 2401.10979**

I decadimenti rari del K e degli iperoni nel settore *s* → *d* sono fondamentali per porre dei limiti agli accoppiamenti tra assione e quarks. Importante interconnessione con l'astrofisica (SN1987A = limite dallo studio di supernove) !