Il Flavor di Nando

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UTfit

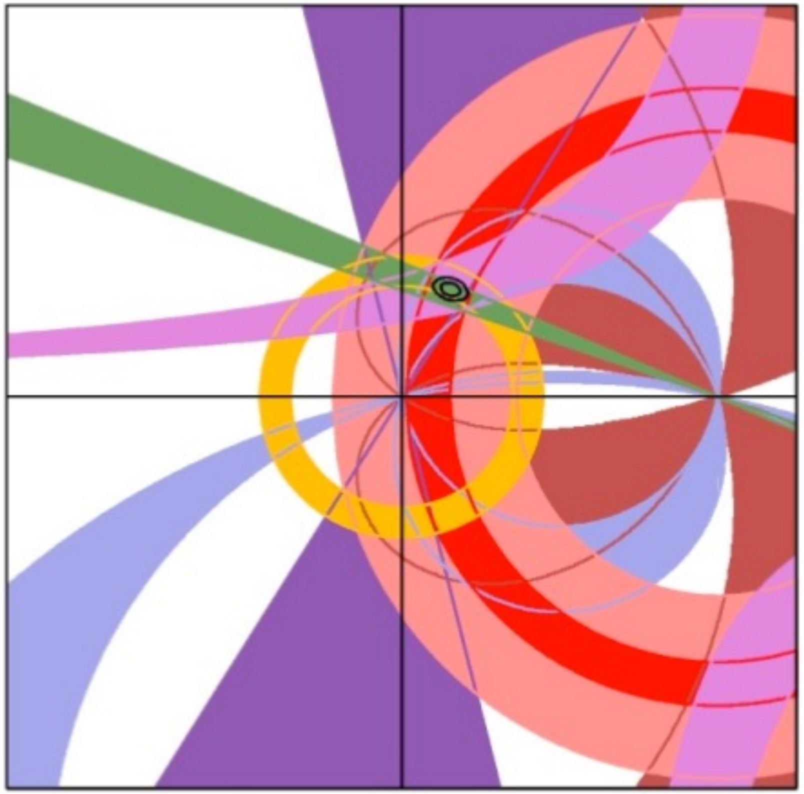
Extended Twisted Mass Collaboration

PRACE

INFN Istituto Nazionale di Fisica Nucleare

PLAN OF THE TALK

- *Synthetic (pre-)history of Nando & Guido*
- *Flavor & Babar*
- *The Unitary Triangle Fit*
- *SM Analysis*
- *Tensions and unknown*
- *BSM, Future directions, new/old ideas*
- *Conclusion*

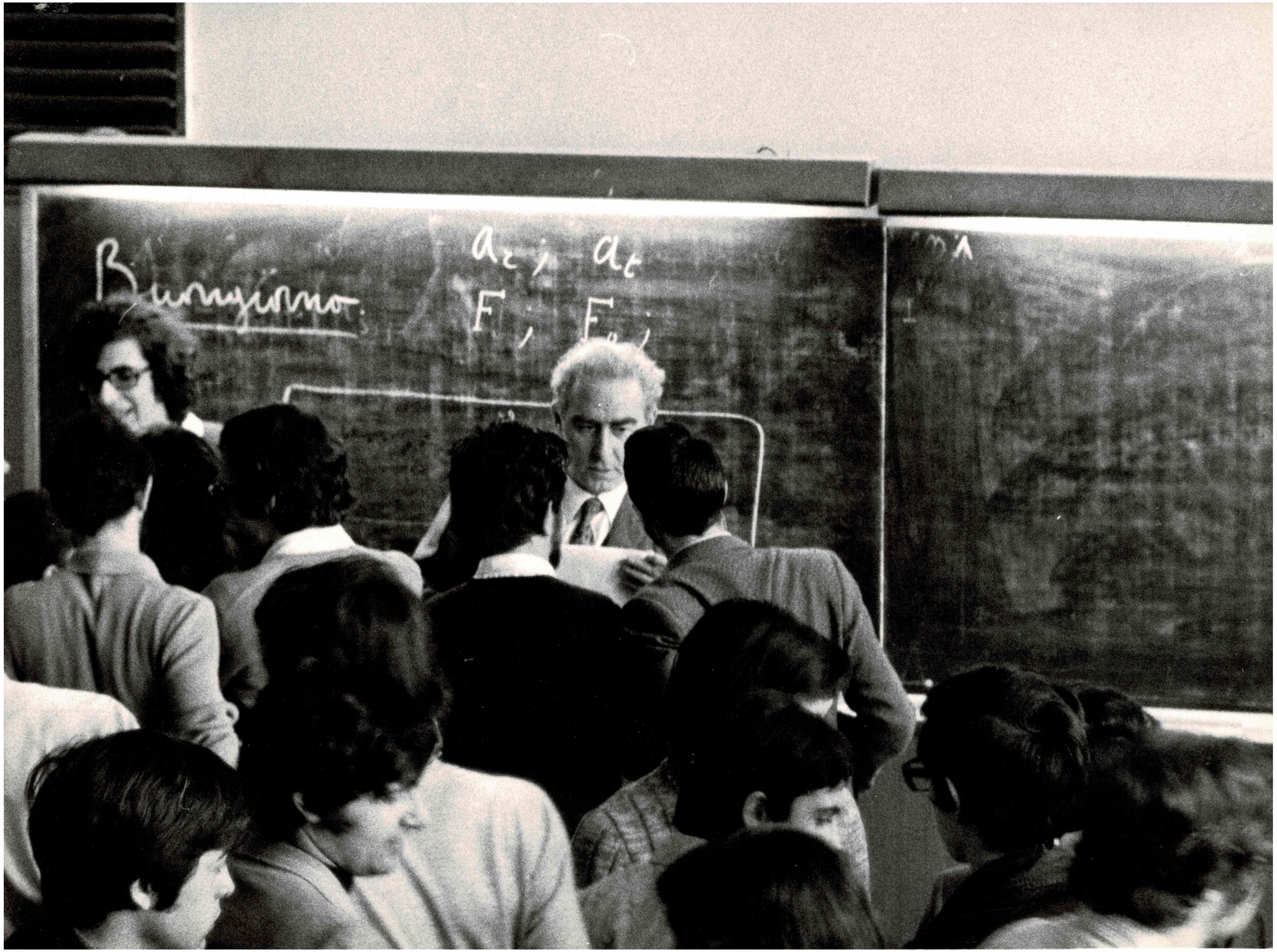


Thanks to
M. Bona, A. Di Domenico, C. Kelly, V. Lubicz, C. Sachrajda, L. Silvestrini, S. Simula, L. Vittorio,

New UTfit Analysis of the Unitarity Triangle in the Cabibbo-Kobayashi-Maskawa scheme

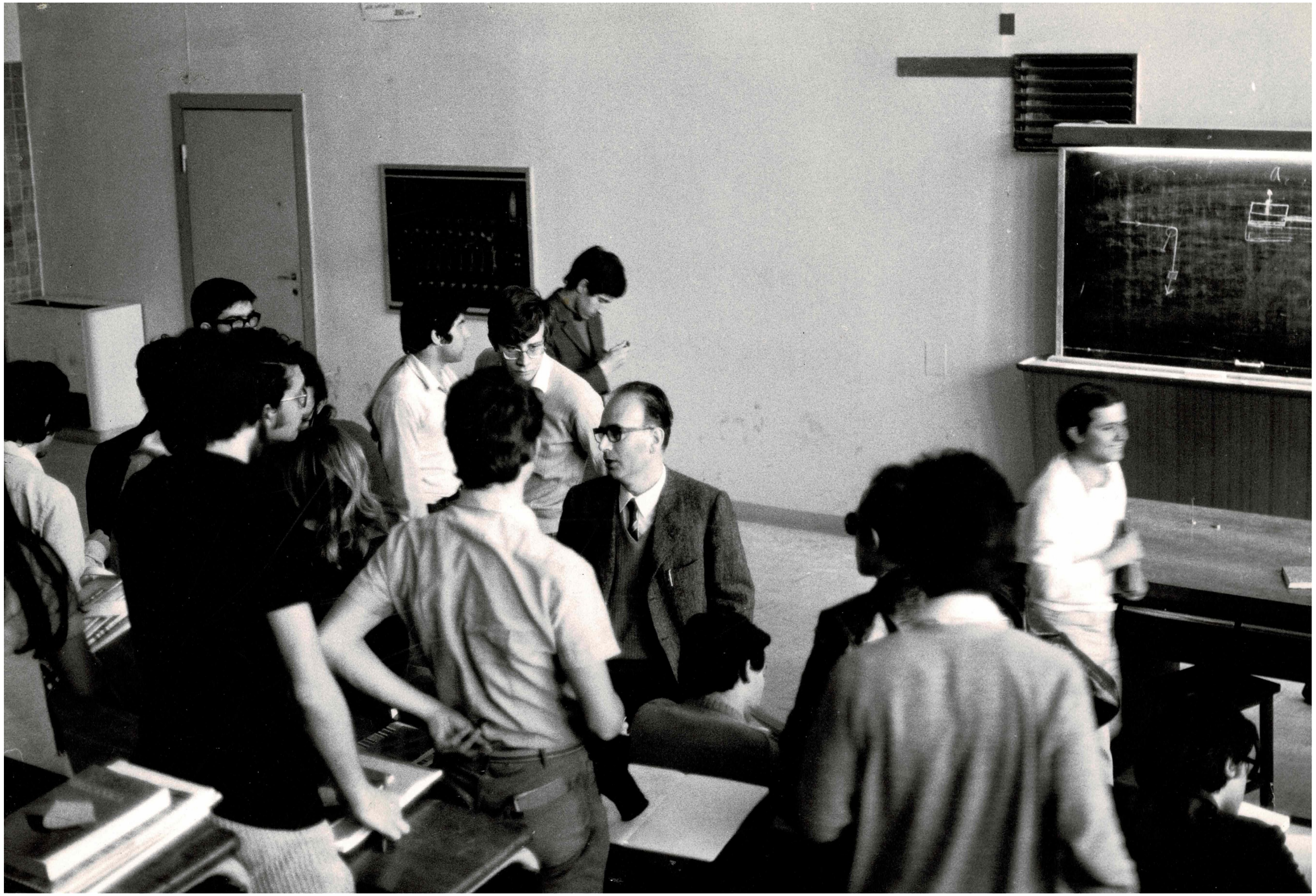
Rend.Lincei Sci.Fis.Nat. 34 (2023) 37-57
arXiv:2212.03894

Non avendolo mai mozzicato – anche se a volte ne avrei avuto voglia - non conosco il sapore di Nando, ma ricordo quando ci siamo incontrati



Aula Amaldi, allora Aula di Fisica Generale, Maggio 1971
Lezioni di Fisica 1 del prof. Salvini

A-L prof. Salvini *M-Z prof. Chiarotti*



Aula Amaldi, allora Aula di Fisica Generale, Maggio 1971
Lezioni di Fisica 1 del prof. Chiarotti
Collettivo di Fisica & Massimo Pieri

Poi abbiamo preso strade diverse
entrambi fisica delle particelle, uno sperimentale l'altro teorico
Ci siamo ritrovati qualche anno più tardi con un lavoro sulle PdF al NLO

Parametrization of Proton Structure Functions #5

CHARM Collaboration • J.V. Allaby (CERN) et al. (Aug, 1987)

Published in: *Phys.Lett.B* 197 (1987) 281-284

DOI cite claim reference search 55 citations

Parton Densities from Deep Inelastic Scattering to Hadronic Processes at Super Collider Energies #6

M. Diemoz (Rome U. and INFN, Rome), F. Ferroni (Rome U. and INFN, Rome), E. Longo (Rome U. and INFN, Rome), G. Martinelli (CERN) (Jun, 1987)

Published in: *Z.Phys.C* 39 (1988) 21

DOI cite claim reference search 455 citations

con un breve ma importante seguito ....

NEUTRINO INTERACTIONS: STUDY OF NUCLEON STRUCTURE BY NEUTRINOS #4

M. Diemoz (Rome U.), E. Longo (Rome U.), G. Martinelli (Rome U.), F. Ferroni (Ancona U.) (1989)

Published in: *Camb.Monogr.Part.Phys.Nucl.Phys.Cosmol.* 1 (1991) 496-584

al ristorante la Pergola dello Chef Heinz Beck

Evoluzione verso il Flavor (anche in senso culinario)

Indipendentemente Nando e collaboratori con Babar (vedi talk di Livio Lanceri) e Enrico, Marco, Laura ed io (+ Luca+Utfit) ci siamo tuffati nella Fisica del Flavor: Nagoya 2006

Col sapore si mangia bene e Nando ama la buona cucina

Evoluzione verso il Flavor non solo in senso culinario

Un periodo di intensa collaborazione con il gruppo Babar di Roma, tra i giovani Sharham, Gianluca, Federico (Mescia), ...

1)

3)

2)

Seminari con cadenza più o meno regolare per discutere insieme violazione di CP per mesoni B, decadimenti leptonici, decadimenti non-leptonici, fisica oltre il Modello Standard

3) Arriva un mutante: lo studente in comune Nando-Guido, ovvero Maurizio Pierini

Università degli Studi di Roma "La Sapienza"
Facoltà di Scienze Matematiche, Fisiche e Naturali
Corso di Laurea in Fisica

Decadimenti a due corpi del mesone B senza charm nello stato finale

Tesi di Laurea
di Maurizio Pierini
matricola: 11108048

Relatore:
Prof. Fernando Ferroni
Corelatore:
Prof. Guido Martinelli

Anno Accademico 2000-2001

Università degli Studi di Roma "La Sapienza"
Facoltà di Scienze Matematiche, Fisiche e Naturali
Corso di Laurea in Fisica

Time dependent Asymmetries in $b \to s$ decays in the Standard Model and beyond

Tesi presentata da
Maurizio Pierini
per il conseguimento del titolo di Dottore di Ricerca

Relatore:
Prof. Fernando Ferroni
Corelatore:
Prof. Guido Martinelli

Anno Accademico 2000-2001

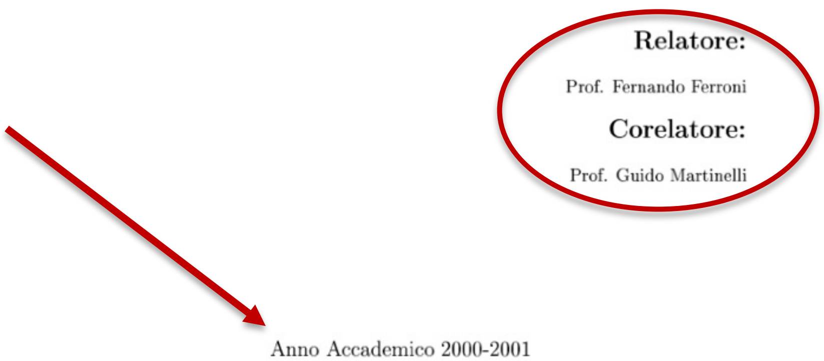
3) Arriva un mutante: lo studente in comune Nando-Guido, ovvero Maurizio Pierini

Correlatore, Corelatore o Co-relattore

RR.1) tutti i vocabolari o dizionari della lingua italiana riportano"correlatore", ed anzi in molti il termine a singola R (e così pure co-relatore) non è neppure minimamente citato come possibile anche se più rara alternativa;

RR.2) si tratta di un caso di raddoppio sintattico (es.: correligionario, corresponsabile, ecc.) che viene spontaneo nel parlare, e quindi entrato definitivamente nell'uso comune della nostra lingua;

RR.3) la maggior parte di quelli che si ostinano a dire "corelatore"sono di Roma o di origine laziale; come risaputo, in quel vernacolo la riduzione di "RR" a "R" è molto comune nel linguaggio parlato   MAURIZIO MANCO È DE ROMA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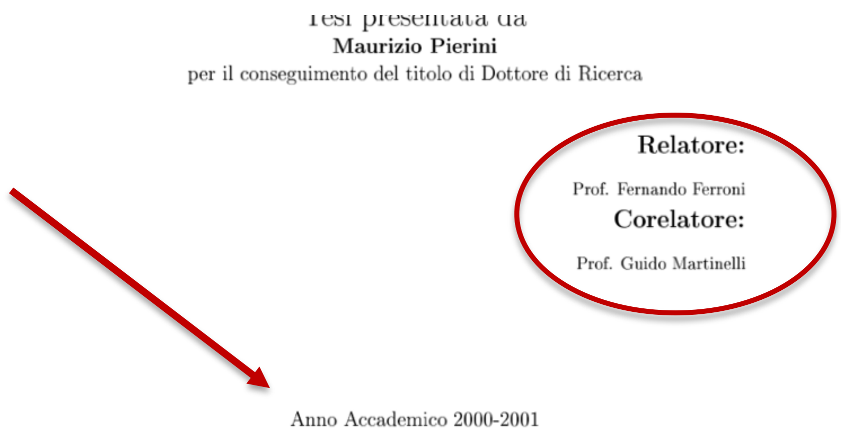
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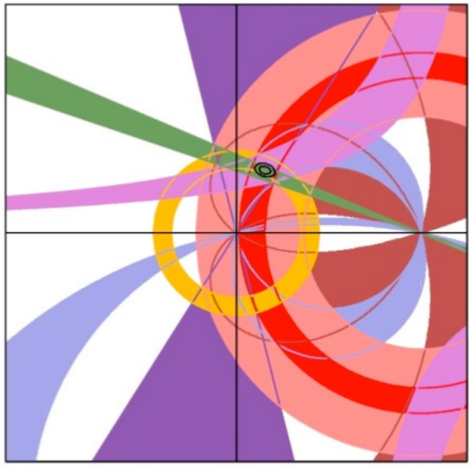
Prof. Guido Martinelli
Anno Accademico 2000-2001

Oltre il flavor

Con Nando Presidente dell'INFN
accordo con la SISSA per far nascere il GSSI
(e non posso non menzionare Eugenio Coccia
e i nostri surreali incontri col ministro Profumo)

non resta tanto tempo per parlare di Fisica,
ovvero della fisica del sapore 20 anni dopo

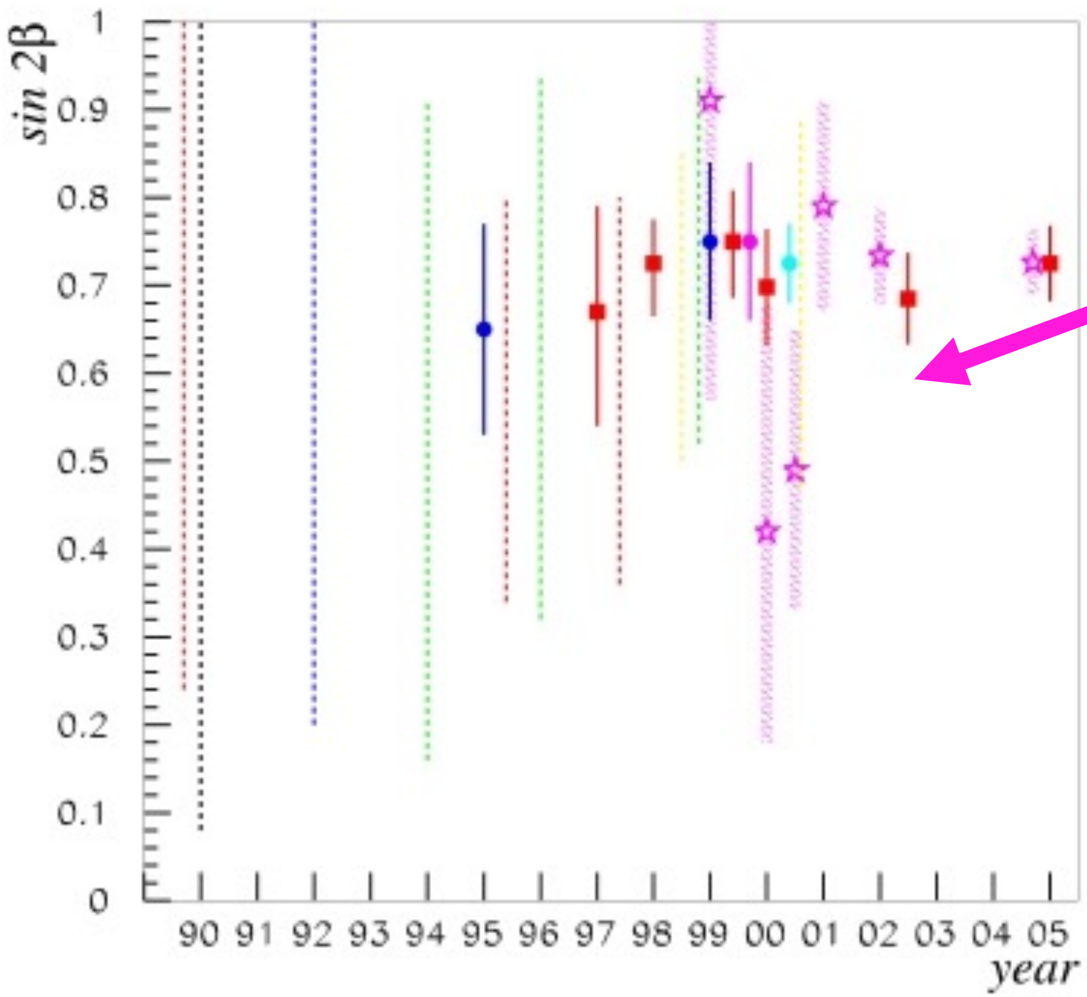
STANDARD MODEL
UNITARITY TRIANGLE ANALYSIS
(Flavor Physics)



- *Provides the best determination of the CKM parameters;*
- *Tests the consistency of the SM (``direct'' vs ``indirect'' determinations) @ the quantum level;*
- *Provides predictions for SM observables (in the past for example sin 2β and Δm_s)*
- *It could lead to new discoveries (CP violation, Charm, !?)*
- *The discovery potential of precision flavor physics should not be underestimated*

Theoretical predictions of Sin 2 β in the years

2004



predictions exist since '95

experiments

$\sin 2\beta_{UTA} = 0.65 \pm 0.12$

Prediction 1995 from

Ciuchini,Franco,G.M.,Reina,Silvestrini

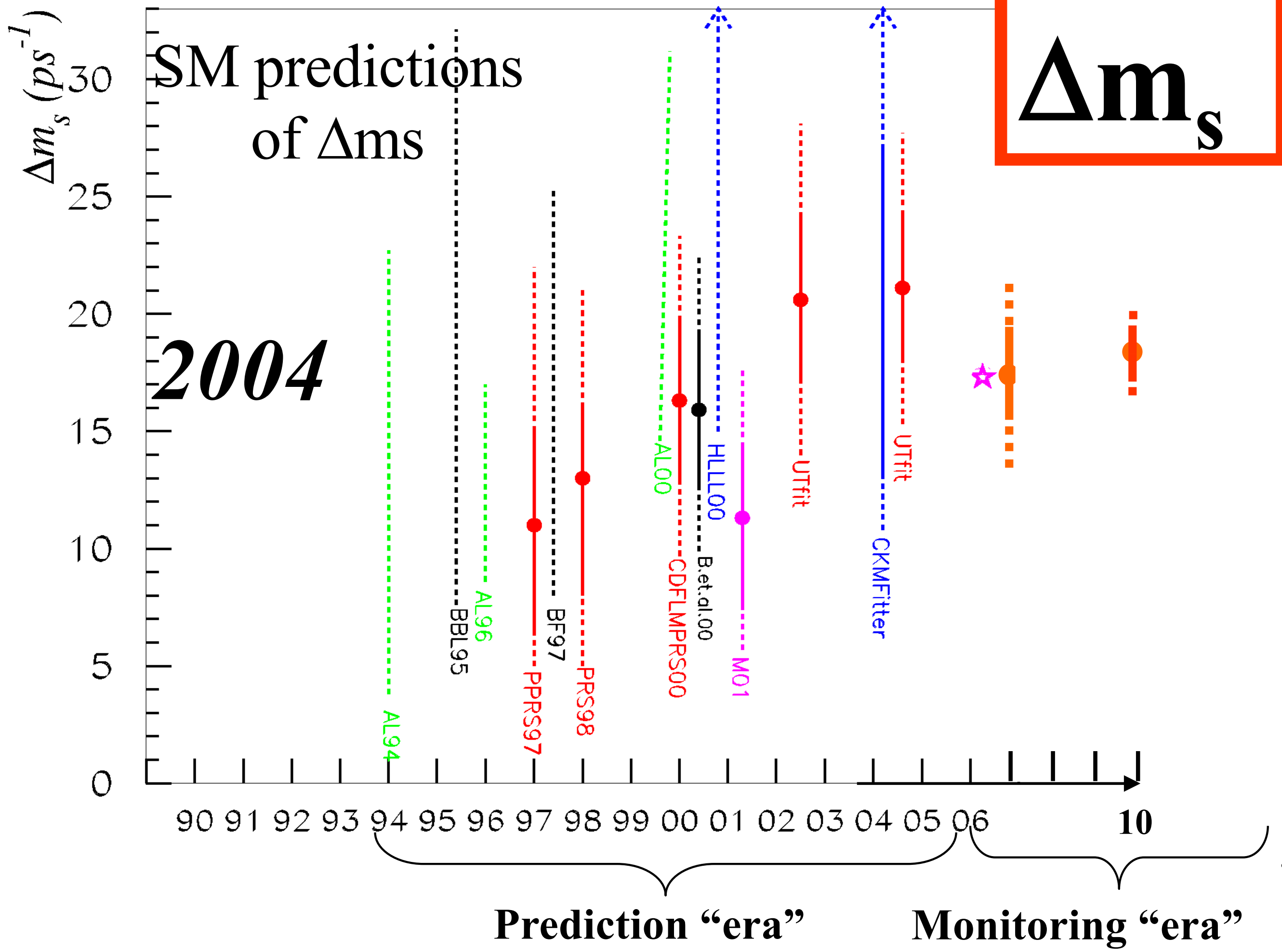
$\sin 2\beta_{UTfit} = 0.736 \pm 0.028$

2023

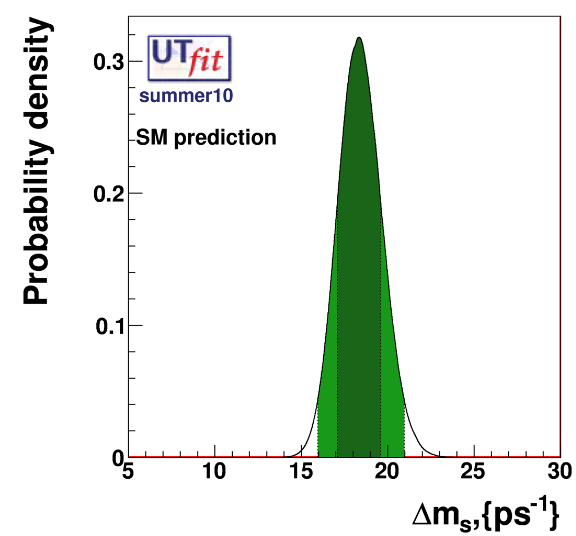
$\sin 2\beta_{exp} = 0.688 \pm 0.020$

2023 pull=-1.4

Δm_s

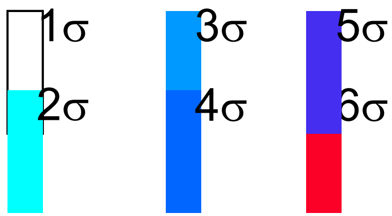


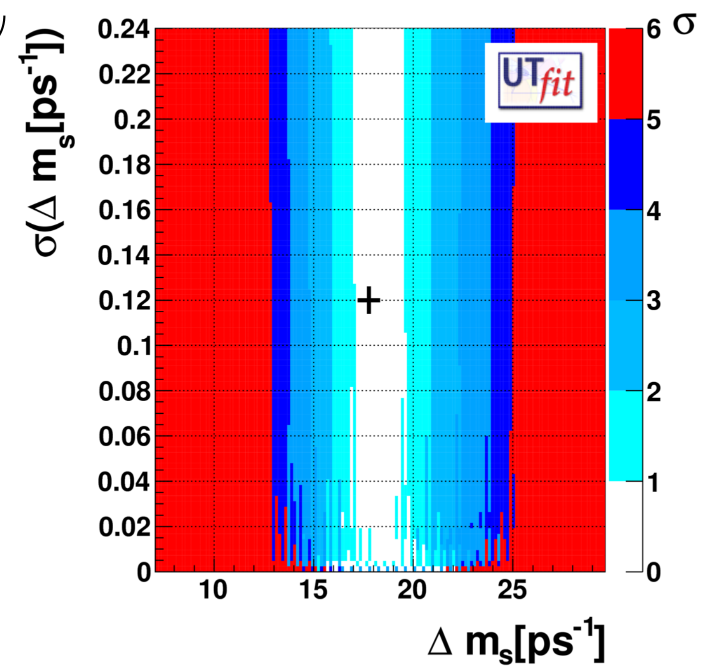
SM expectation
$\Delta m_s = (16.92 \pm 0.99)\ ps^{-1}$



Exp
$\Delta m_s = (17.72 \pm 0.04)\ ps^{-1}$

SM expectation 2023
$\Delta m_s = (17.94 \pm 0.69)\ ps^{-1}$
Exp
$\Delta m_s = (17.741 \pm 0.020)\ ps^{-1}$





Flavour Physics (on the Lattice)

1963: Cabibbo Angle
1964: CP violation in K decays *
1970 GIM Mechanism
1973: CP Violation needs at least three quark families (CKM) *
1975: discovery of the tau lepton – 3rd lepton family *
1977: discovery of the b quark - 3rd quark family *
2003/4: CP violation in B meson decays

* *Nobel Prize*

Flavor physics in the Standard Model

In the SM, the quark mass matrix, from which the CKM matrix and CP̸ violation originate, is determined by the coupling of the Higgs boson to fermions.

$$\mathcal{L}^{\mathbf{quarks}} = \mathcal{L}^{\mathbf{kinetic}} + \mathcal{L}^{\mathbf{gauge}} + \mathcal{L}^{Yukawa}$$

CP invariant

CP̸ and symmetry breaking are striclty correlated

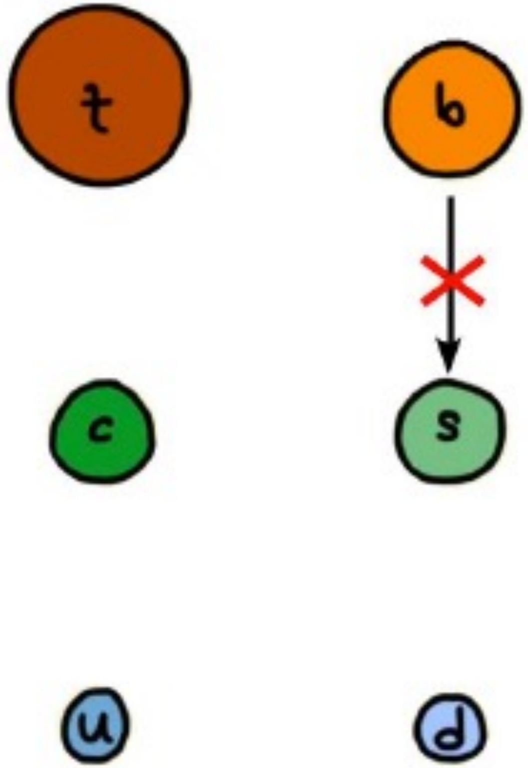
$$\mathcal{L}(\Lambda_{Fermi}) = \mathcal{L}(\Lambda, H, H^{\dagger}) + \mathcal{L}^{kin} + \mathcal{L}^{gauge}_{SM} + \mathcal{L}^{Yukawa}_{SM} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \ldots$$

EWSB

has many accidental simmetries

may violate accidental simmetries

Absence of FCNC at tree level (& GIM suppression of FCNC @loop level)



Almost no CP violation at tree level

Flavour Physics is extremely sensitive to New Physics (NP)

In competition with Electroweak Precision Measurements

WHY RARE DECAYS ?

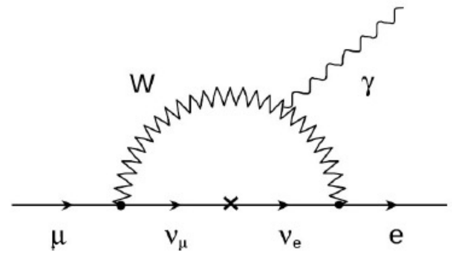
Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

Proton decay — **baryon and lepton number conservation**

$\mu \rightarrow e + \gamma$

lepton flavor number

$\nu_i \rightarrow \nu_k$ **found !**



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

$q_i \rightarrow q_k + \nu \bar{\nu}$

$q_i \rightarrow q_k + l^+ l^-$

$q_i \rightarrow q_k + \gamma$

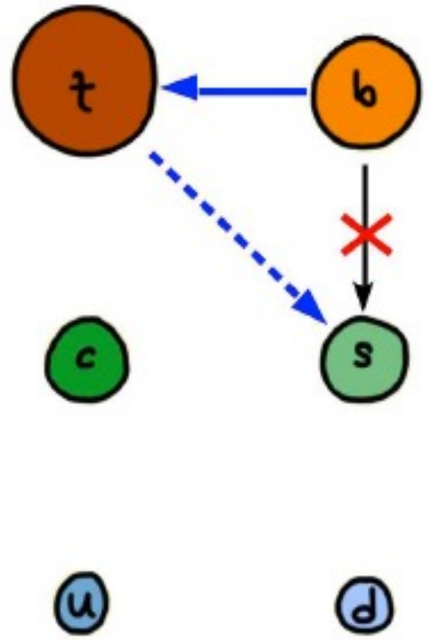
these decays occur only via loops because of GIM and are suppressed by CKM

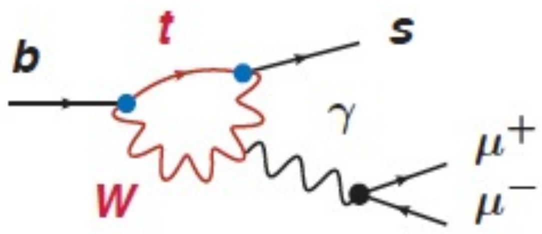
THUS THEY ARE SENSITIVE TO NEW PHYSICS

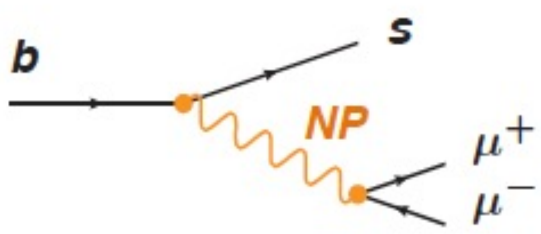
Flavor Changing Neutral Currents in the SM

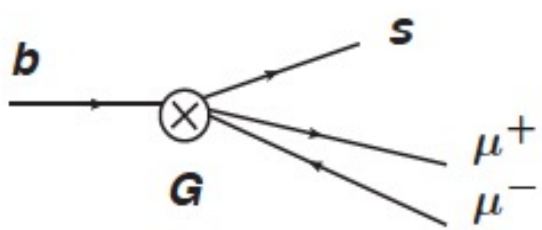
In the SM, flavor changing neutral currents (FCNCs)
are absent at the tree level

FCNCs can arise at the loop level
they are suppressed by loop factors
and small CKM elements









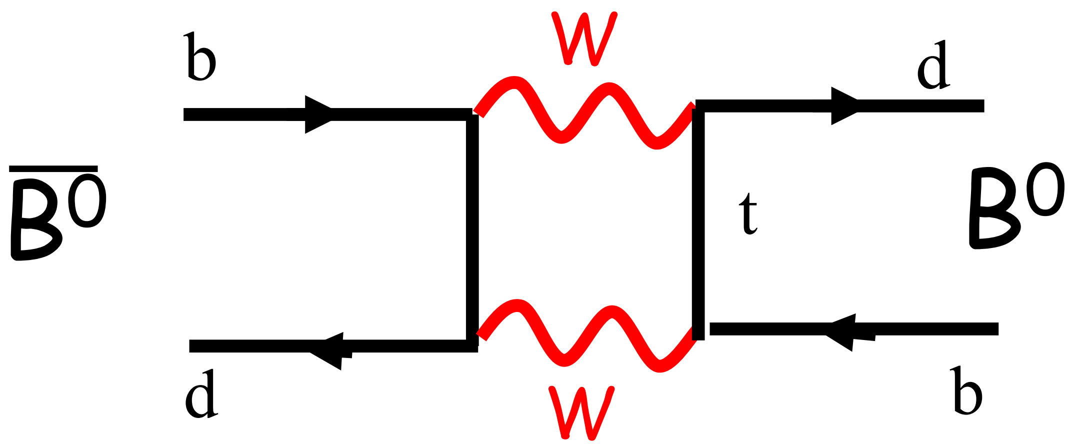
$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

→ measuring low energy flavor observables gives information
on new physics flavor couplings and the new physics mass scale

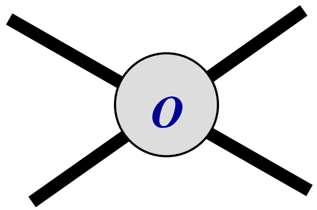
B^0 - $\overline{B^0}$ mixing

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$$

ΔB=2 Transitions



$$\mathcal{H}_{eff}^{\Delta B=2} =$$



$$\propto \left(\bar{d}\, \gamma_\mu (1 - \gamma_5)\, b \right)^2$$

Hadronic matrix element

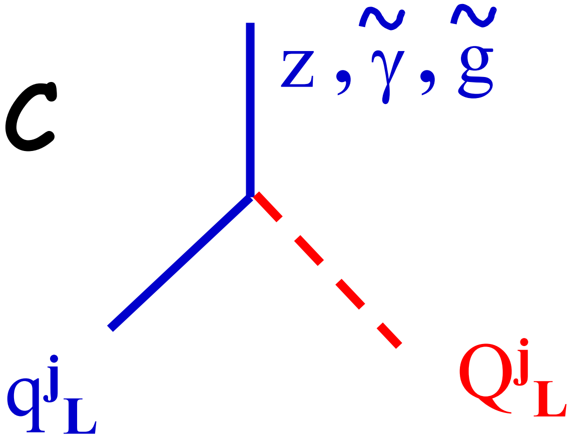
CKM

$$\Delta m_{d,s} = \frac{G_F^2 M_W^2}{16\pi^2} A^2 \lambda^6 F_{tt}\left(\frac{m_t^2}{M_W^2}\right) \langle O \rangle$$

In general the mixing mass matrix of the SQuarks (SMM) is not diagonal in flavour space analogously to the quark case We may either

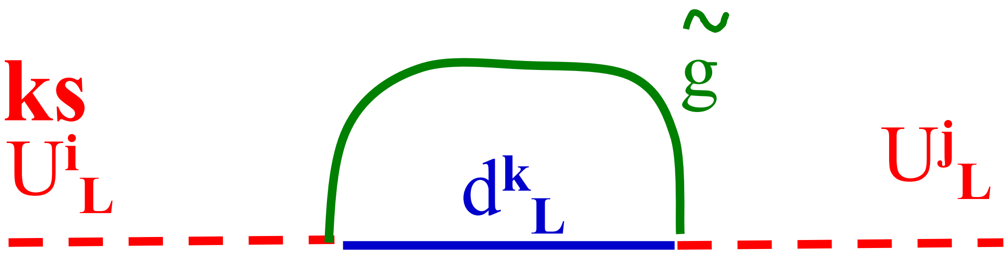
Diagonalize the SMM

FCNC

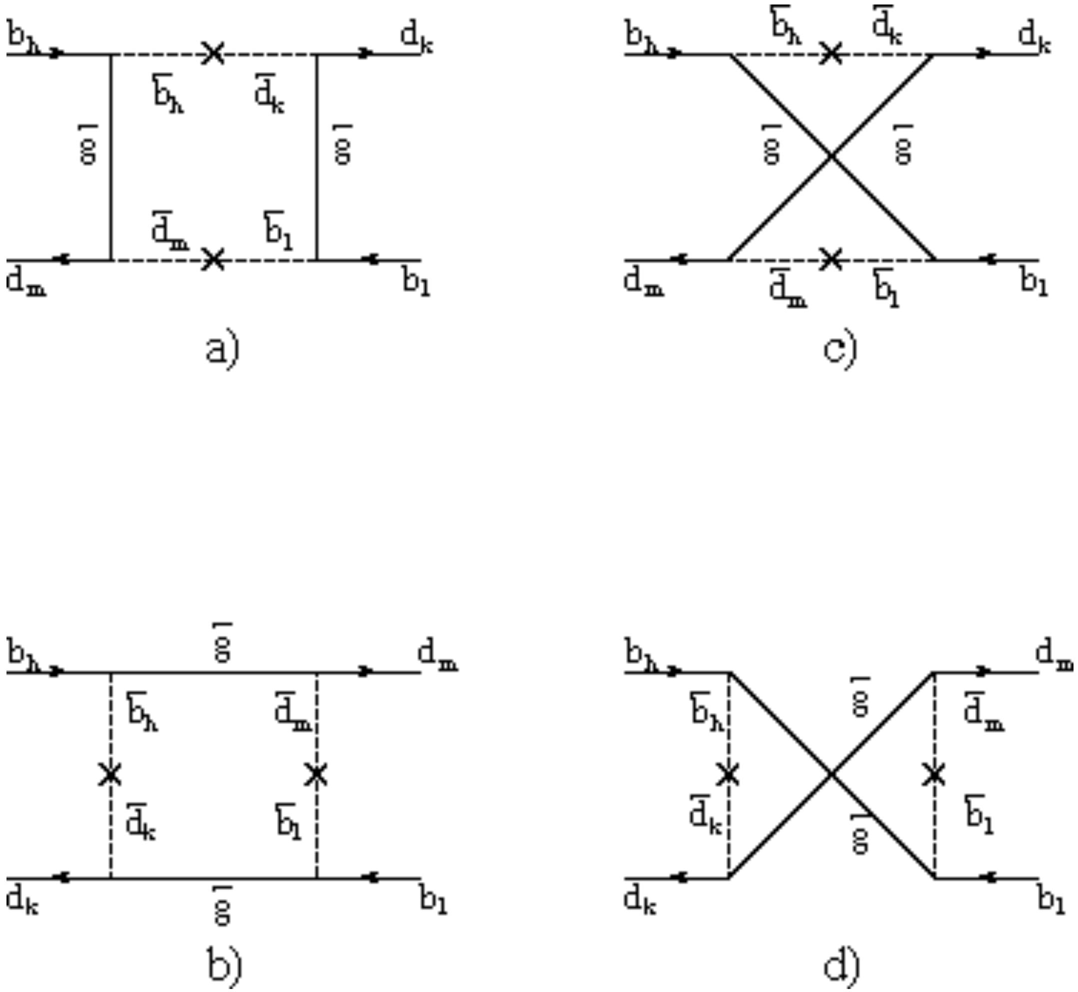


or **Rotate by the same matrices the SUSY partners of the u- and d- like quarks**

$(Q^j_L)' = U^{ij}_L \, Q^j_L$



In the latter case the Squark Mass Matrix is not diagonal



$$(m^2{}_Q)_{ij} = m^2{}_{average}\, \mathbf{1}_{ij} + \Delta m_{ij}{}^2 \qquad \delta_{ij} = \Delta m_{ij}{}^2 / m^2{}_{average}$$

CP Violation in the Standard Model

After the diagonalisation of the quark mass matrix

$$L_{CC}^{weak\,int} = \frac{g_W}{\sqrt{2}} \left(J_\mu^- W_\mu^+ + h.c. \right)$$

$$\rightarrow \quad \frac{g_W}{\sqrt{2}} \left(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W_\mu^+ + \ldots \right)$$

N(N-1)/2 angles and (N-1)(N-2) /2 phases

N=3 3 angles + 1 phase KM

the phase generates complex couplings i.e. CP violation;

6 masses +3 angles +1 phase = 10 parameters

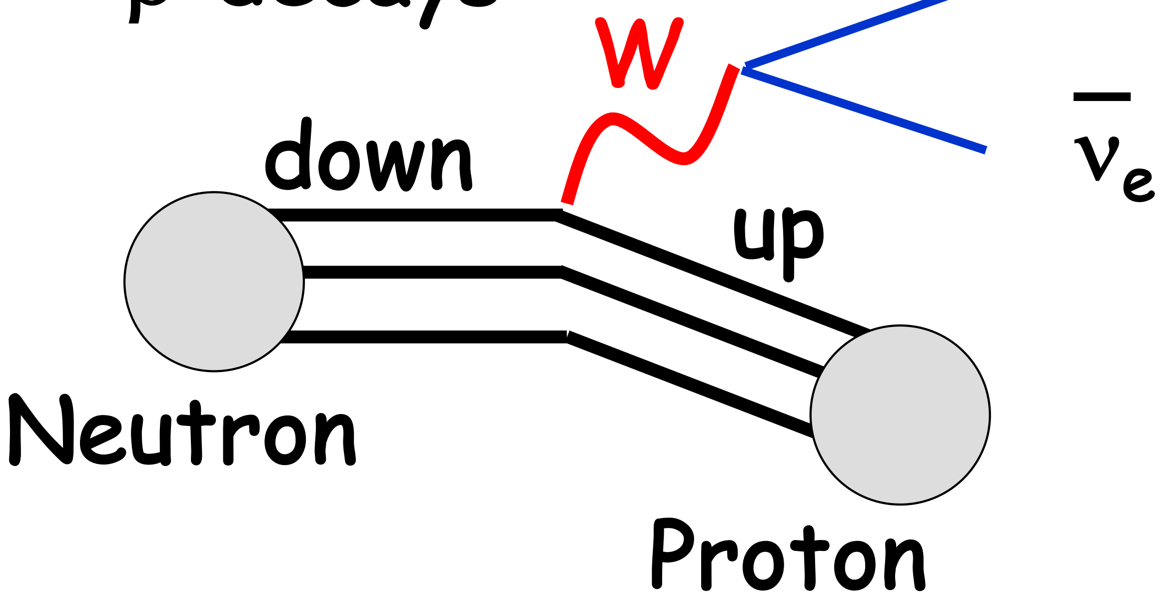
V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{tb}	V_{ts}	V_{tb}

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}

Quark masses & Generation Mixing

β-decays



$|V_{ud}|$

$|V_{ud}| = 0.9735(8)$
$|V_{us}| = 0.2196(23)$
$|V_{cd}| = 0.224(16)$
$|V_{cs}| = 0.970(9)(70)$
$|V_{cb}| = 0.0406(8)$
$|V_{ub}| = 0.00409(25)$
$|V_{tb}| = 0.99(29)$
(0.999)

updated values later

The Wolfenstein Parametrization

$1 - 1/2\,\lambda^2$	λ	$A\,\lambda^3(\rho - i\,\eta)$
$-\lambda$	$1 - 1/2\,\lambda^2$	$A\,\lambda^2$
$A\,\lambda^3 \times (1 - \rho - i\,\eta)$	$-A\,\lambda^2$	1

V_{ub}

$+ O(\lambda^4)$

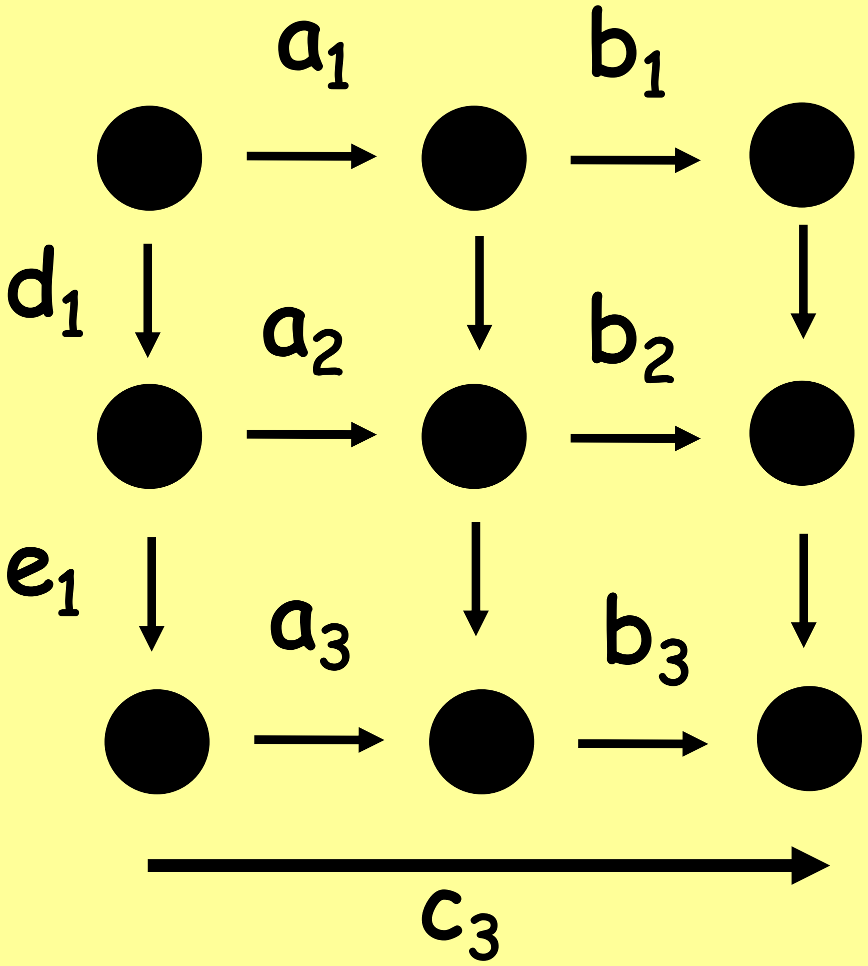
V_{td}

$\sin\theta_{12} = \lambda$
$\sin\theta_{23} = A\,\lambda^2$
$\sin\theta_{13} = A\,\lambda^3(\rho - i\,\eta)$

$\lambda \sim 0.2 \quad A \sim 0.8$

$\eta \sim 0.2 \quad \rho \sim 0.3$

The Bjorken-Jarlskog Unitarity Triangle



$|V_{ij}|$ is invariant under phase rotations

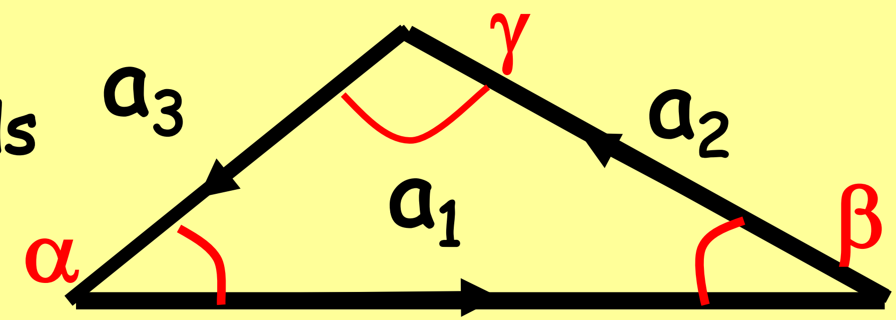
$a_1 = V_{11} V_{12}^* = V_{ud} V_{us}^*$

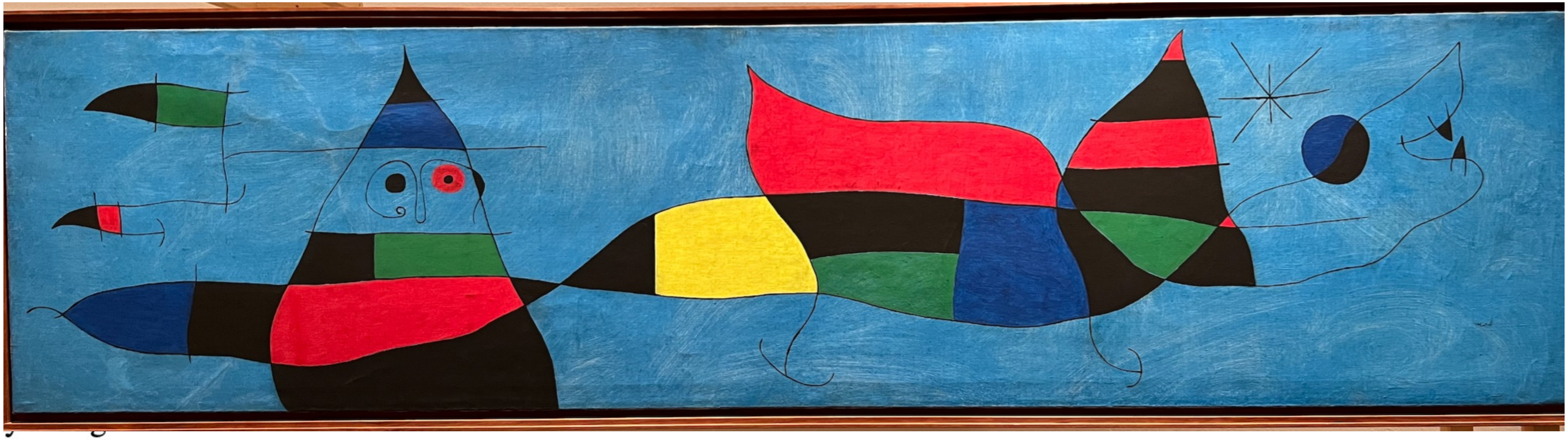
$a_2 = V_{21} V_{22}^*$ $a_3 = V_{31} V_{32}^*$

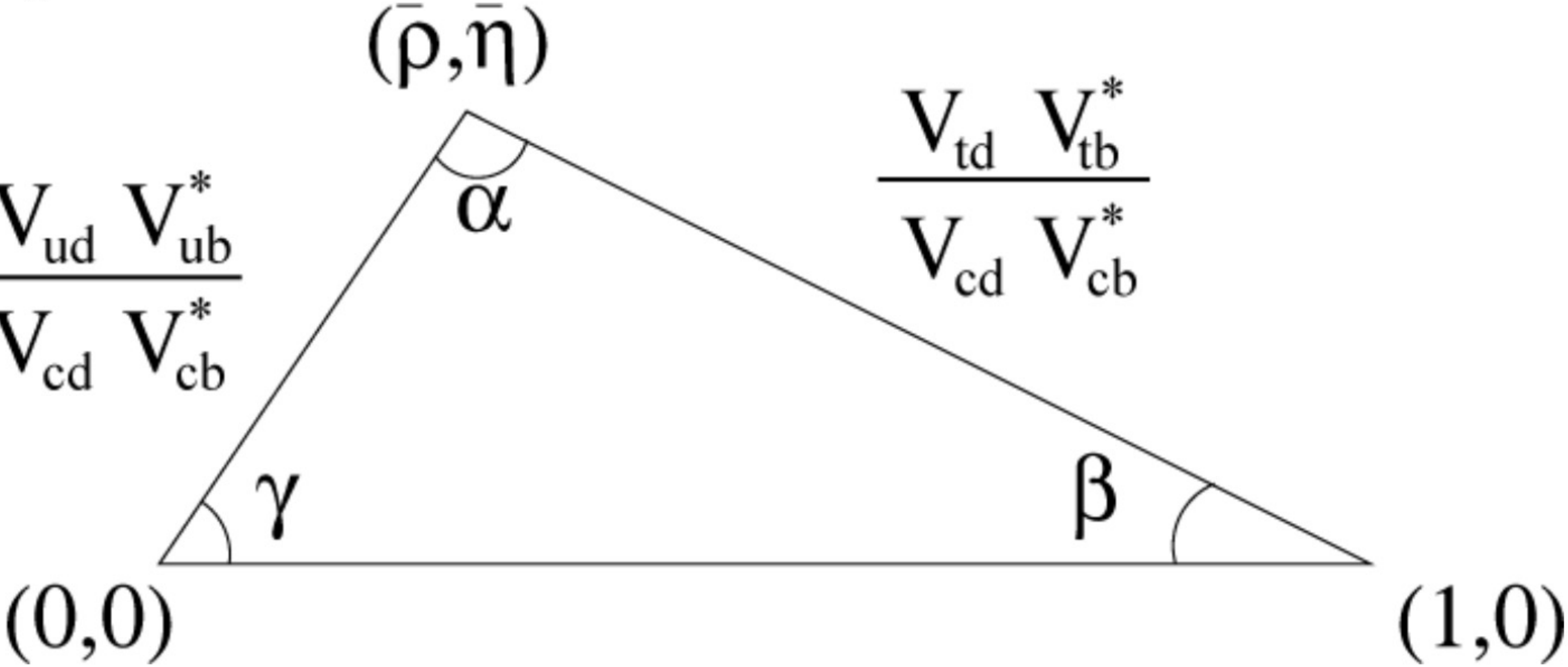
$a_1 + a_2 + a_3 = 0$

$(b_1 + b_2 + b_3 = 0$ etc.$)$

Only the orientation depends on the phase convention







The Standard Triangle of the Standard Model

STRONG CP VIOLATION

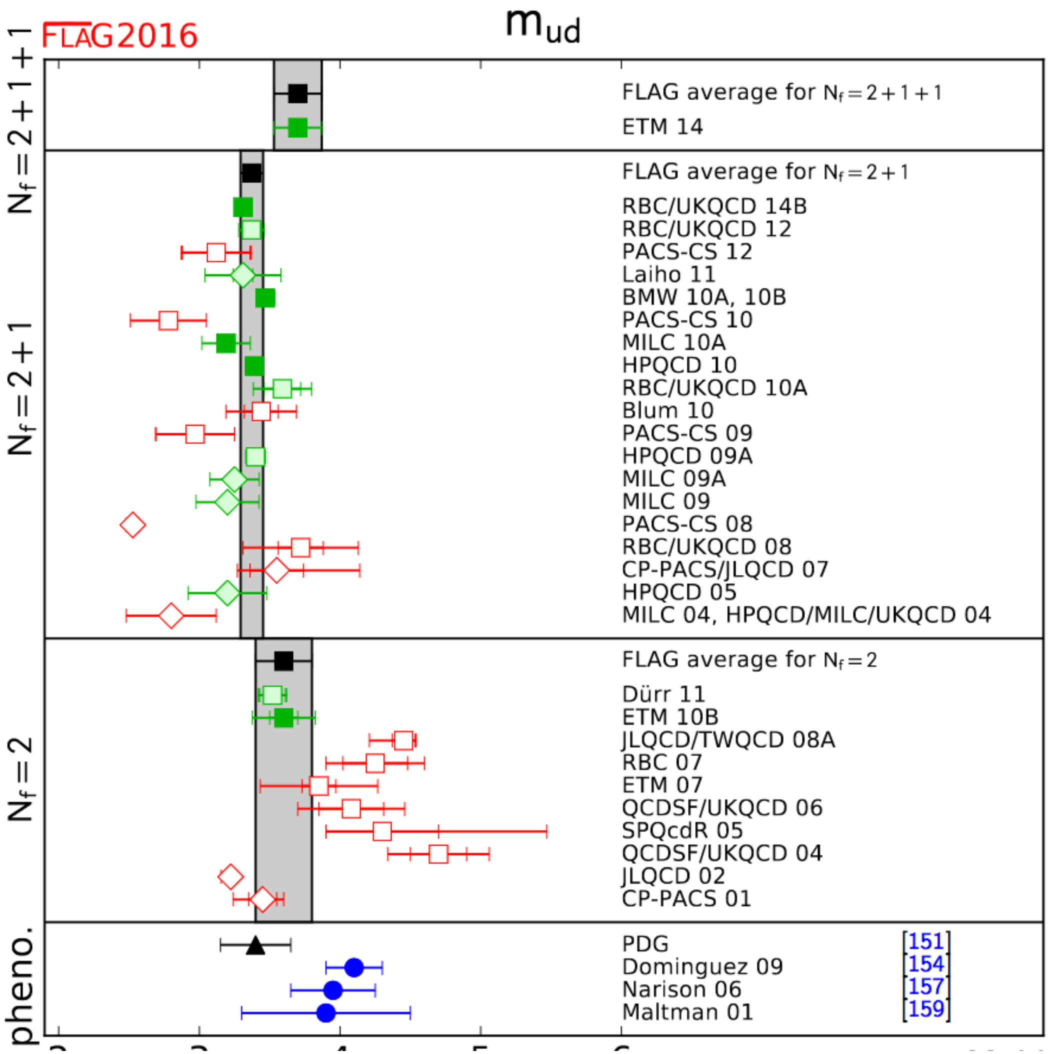
$$\mathcal{L}_\theta = \theta\, \tilde{G}^{\mu\nu a} G^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

$$\mathcal{L}_\theta \sim \theta\, \vec{E}^a \cdot \vec{B}^a$$

This term violates CP and gives a contribution to the electric dipole moment of the neutron

$$e_n < 3\ 10^{-26}\ e\ cm$$

$\theta < 10^{-10}$ which is quite unnatural !!



N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.36(24)	5.03(26)	0.470(56)	35.6(5.1)	22.2 (1.6)
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)	35.0(1.9)(1.8)	22.5(6)(6)
2	2.40(23)	4.80(23)	0.50(4)	40.7(3.7)(2.2)	24.3(1.4)(0.6)

The extraordinary progress of the experimental measurements requires accurate theoretical predictions

Precision flavor physics requires the control of hadronic effects for which lattice QCD simulations are essential

$$Q^{EXP} = V_{CKM} \langle F | \hat{O} | I \rangle$$

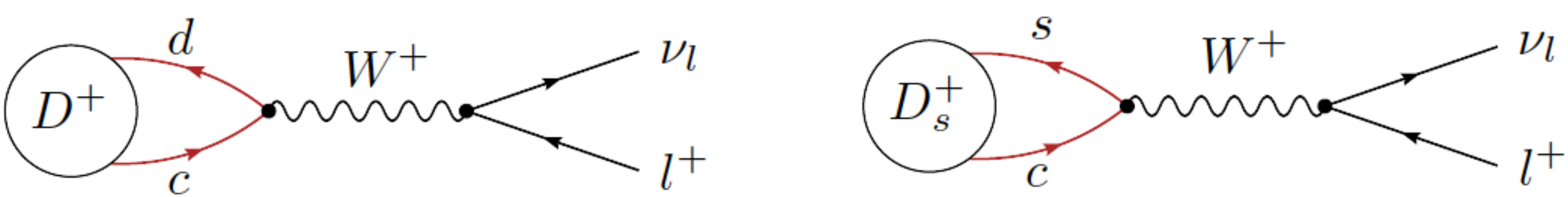
SM

$$Q^{EXP} = \sum_i C^i_{SM}(M_W, m_t, \alpha_s) \langle F | \hat{O}_i | I \rangle + \sum_{i'} C^{i'}_{Beyond}(\tilde{m}_\beta, \alpha_s) \langle F | \hat{O}_{i'} | I \rangle$$

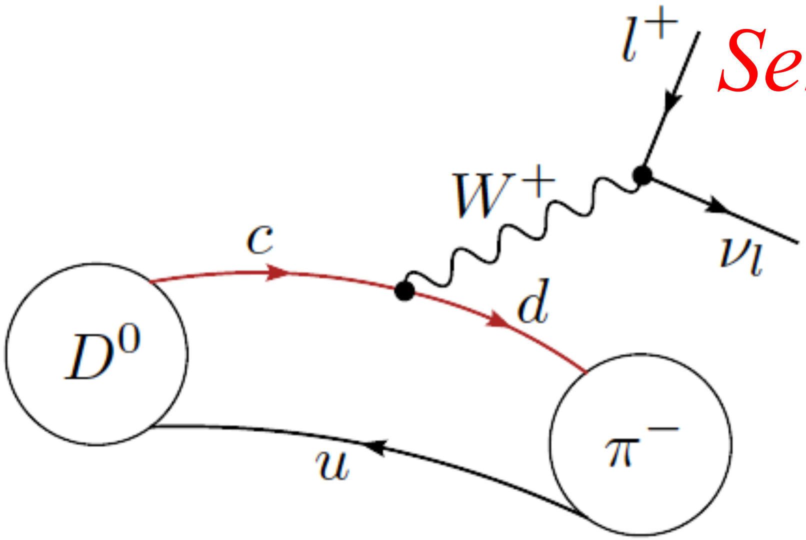
BSM

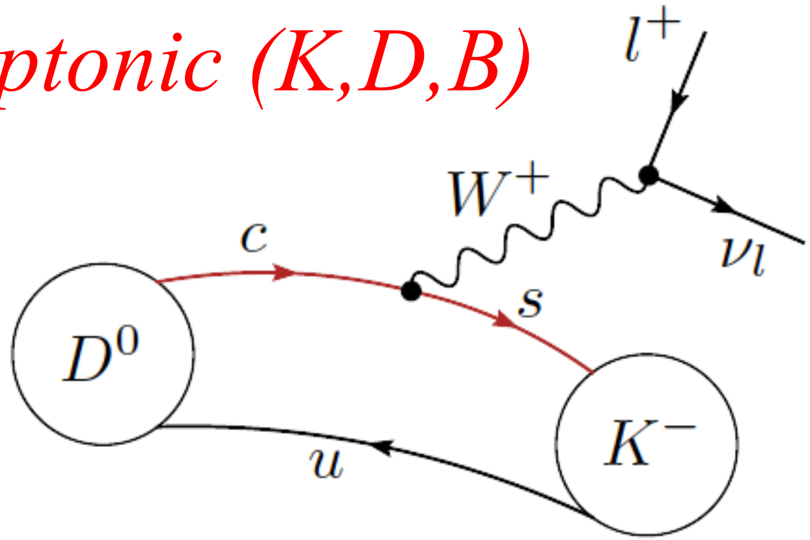
What can be computed and what cannot be computed

Leptonic (π,K,D,B)



Semileptonic (K,D,B)

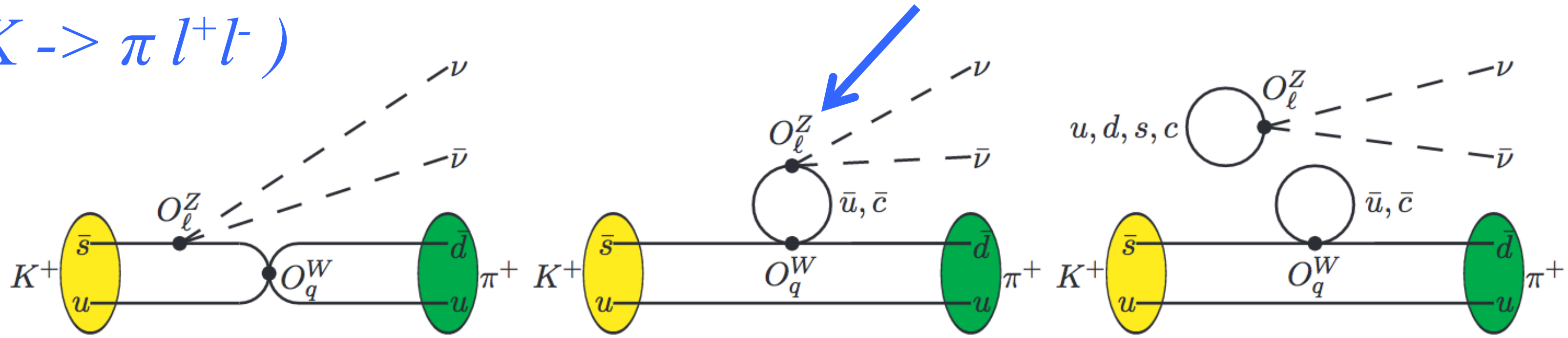




(some) Radiative and Rare

long distance effects

(also $K \to \pi\, l^+ l^-$)

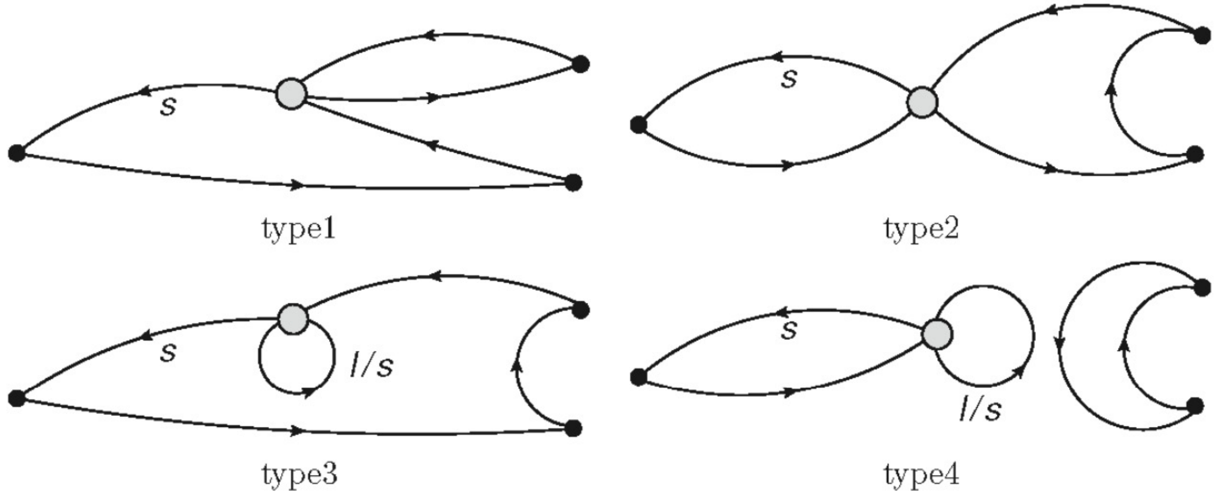


connected diag. self-loop diag. disconnected diag.

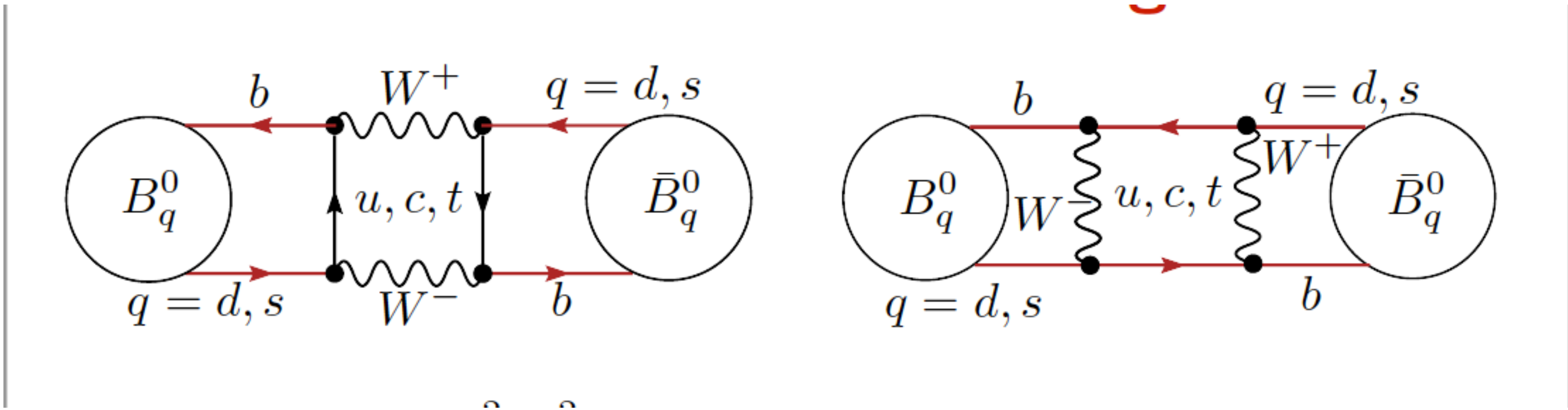
Non-leptonic

but only below the inelastic threshold (may be also 3 body decays)

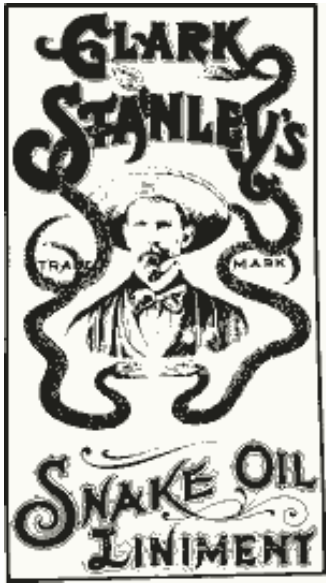
B -> ππ,Kπ, etc. No !



Neutral meson mixing (local)



+ some long distance contributions to K and D neutral meson mixing + short distance contributions to $B \to K^{(*)} l^+ l^-$



UTfit

www.utfit.org

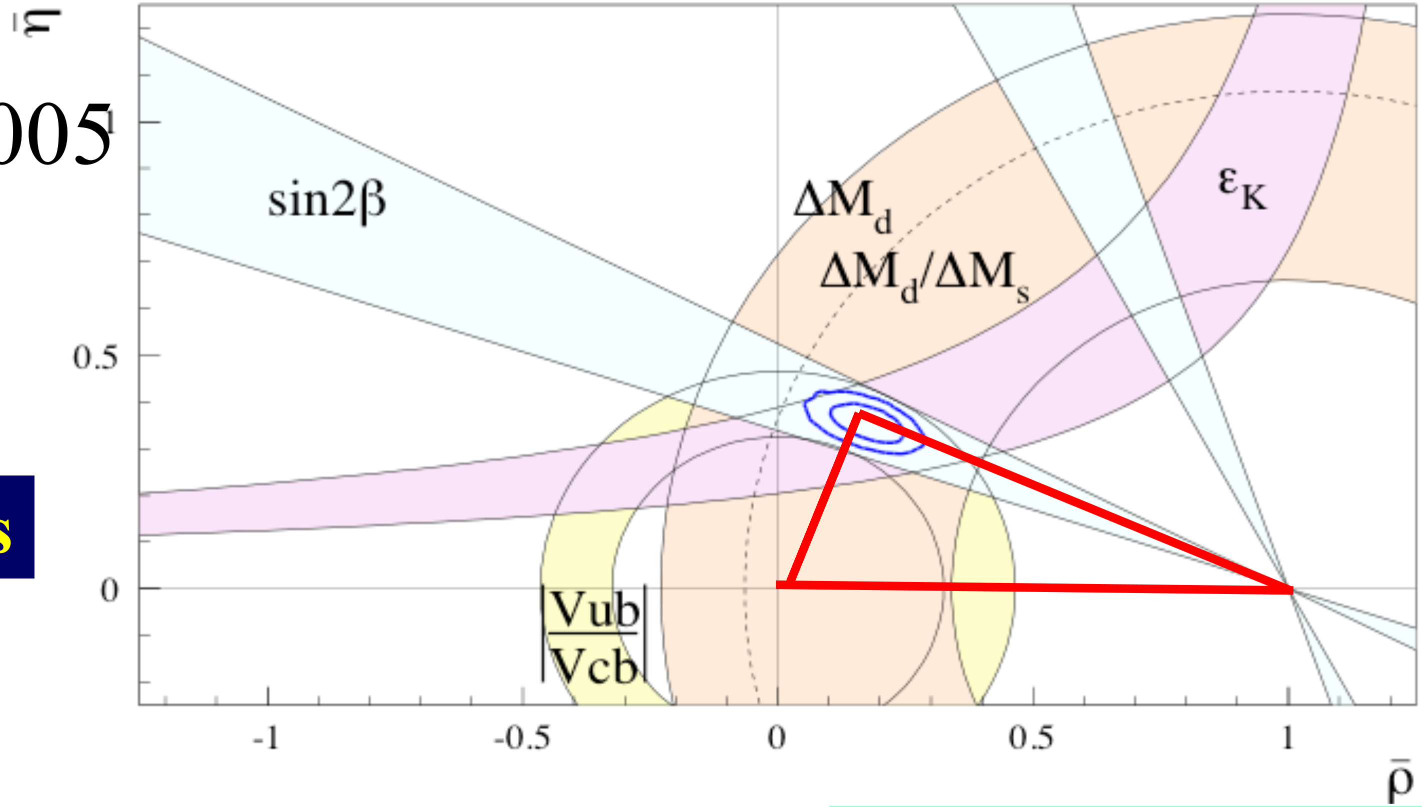
RELOADED

M.Bona, M. Ciuchini, D. Derkach, F. Ferrari, E. Franco,
V. Lubicz, G. Martinelli, D. Morgante, M. Pierini,
L. Silvestrini, S. Simula, C. Tarantino, V. Vagnoni,
M. Valli, and L.Vittorio

2023

Unitary Triangle SM

2005



semileptonic decays

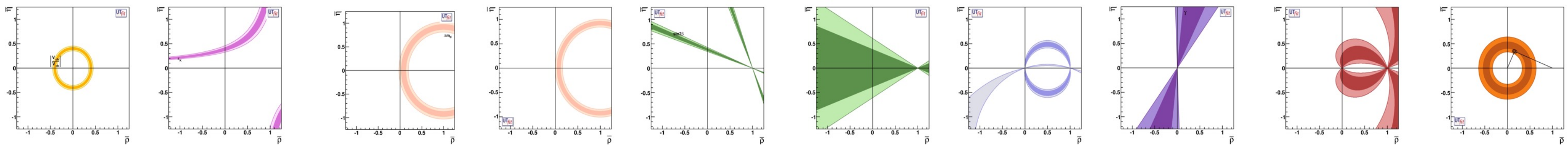
Experimental co

Meas.	$V_{CKM}\times$other	$(\bar{\rho},\bar{\eta})$
$\frac{b\to u}{b\to c}$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar{\rho}^2+\bar{\eta}^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d}$	$(1-\bar{\rho})^2+\bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \xi^2$	$(1-\bar{\rho})^2+\bar{\eta}^2$
ϵ_K	$f(A,\bar{\eta},\bar{\rho},B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$
$A(J/\psi K^0)$	$sin2\beta$	$\frac{2\bar{\eta}(1-\bar{\rho})}{\sqrt{\bar{\eta}^2+(1-\bar{\rho})^2}}$

$K^0 - \overline{K^0}$ mixing

$B^0_{d,s} - \overline{B^0}_{d,s}$ mixing

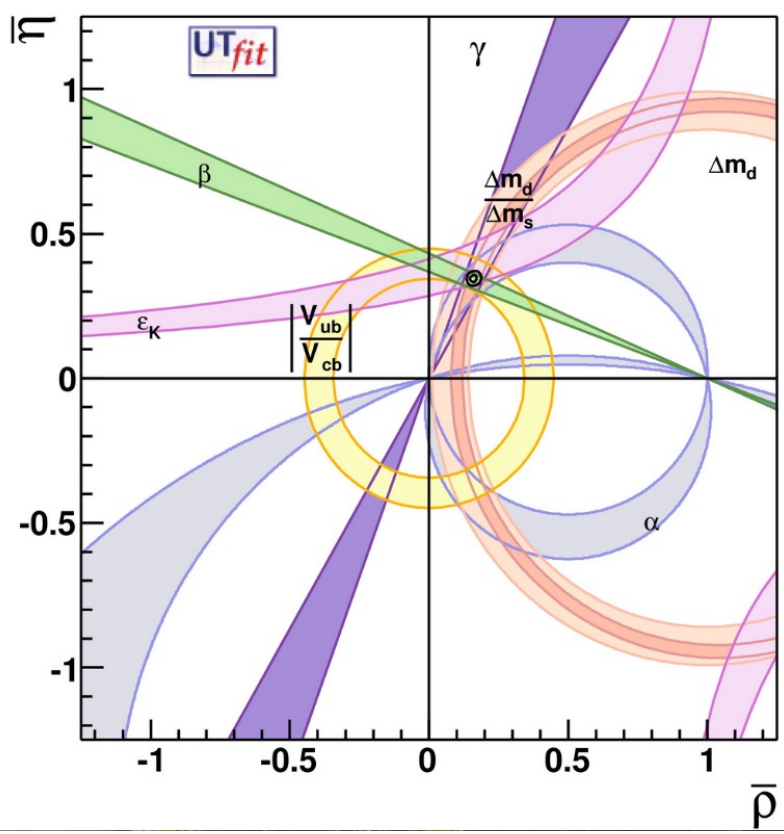
B_d



2023 results

$\bar{\rho} = 0.1609 \pm 0.0095$ $\bar{\eta} = 0.347 \pm 0.010$

In the hadronic sector, the SM CKM pattern represents the principal part of the flavor structure and of CP violation



$\alpha = (94.9 \pm 4.7)^0$

$\sin 2\beta = 0.688 \pm 0.0206$

$\beta = (22.46 \pm 0.68)^0$

$\gamma = (66.1 \pm 3.5)^0$

$A = 0.828 \pm 0.011$

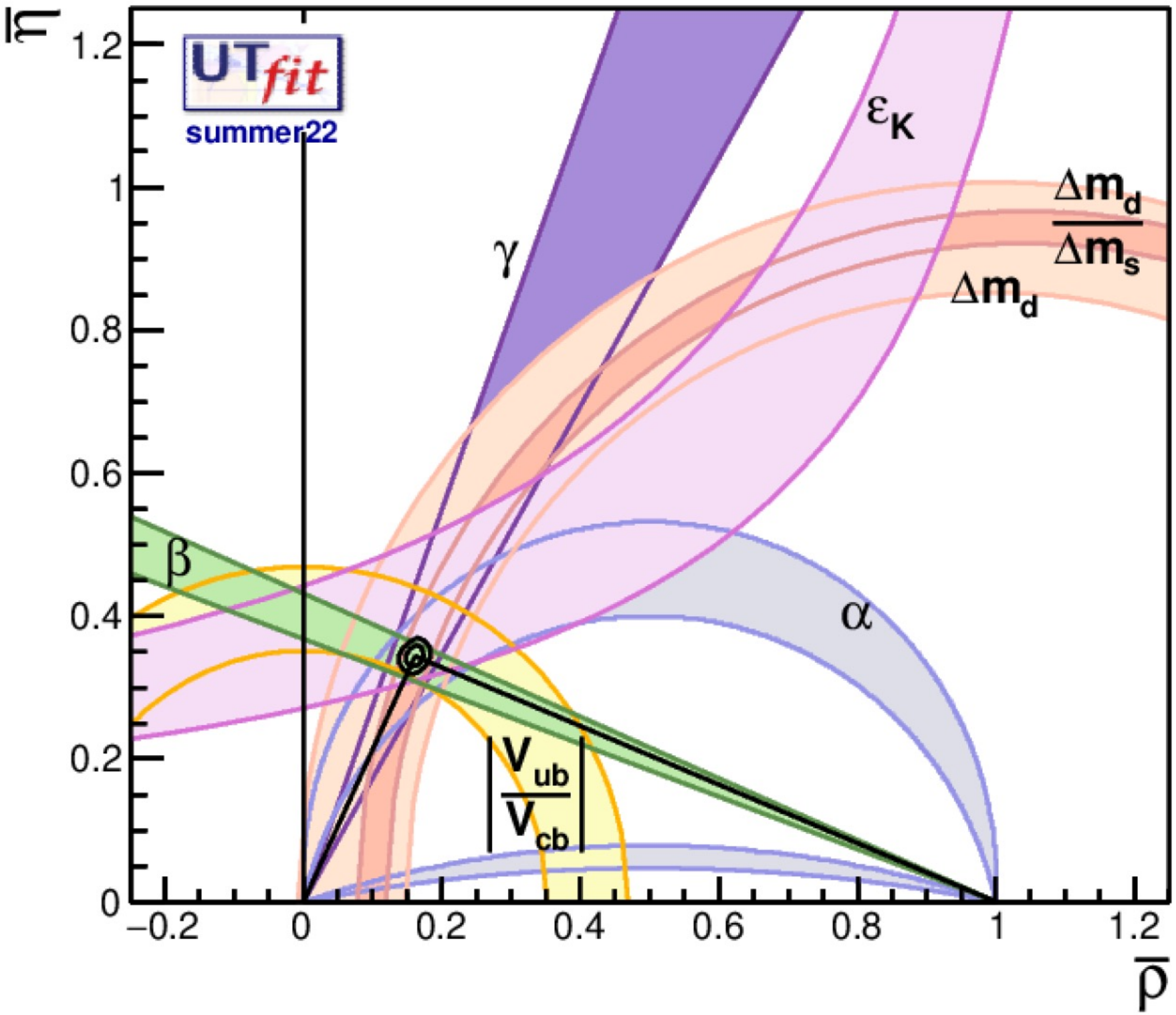
$\lambda = 0.22519 \pm 0.00083$

Consistence on an over constrained fit of the CKM parameters

CKM matrix is the dominant source of flavour mixing and CP violation

Unitarity Triangle analysis in the SM:

zoomed in..



levels @
95% Prob

~6%

$\rho = 0.1609 \pm 0.0095$

$\eta = 0.347 \pm 0.010$

~3%

Progressi dall'epoca della tesi di Pierini

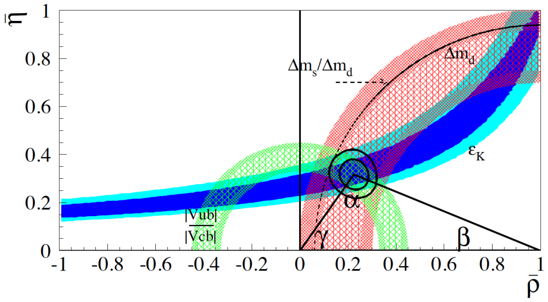
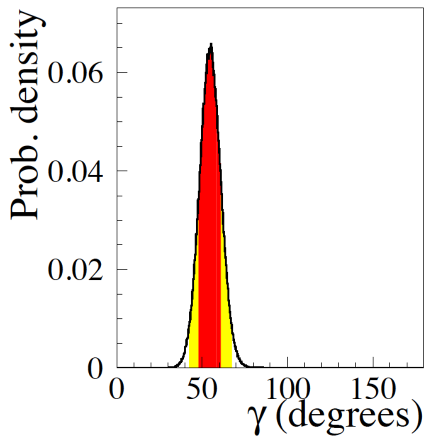
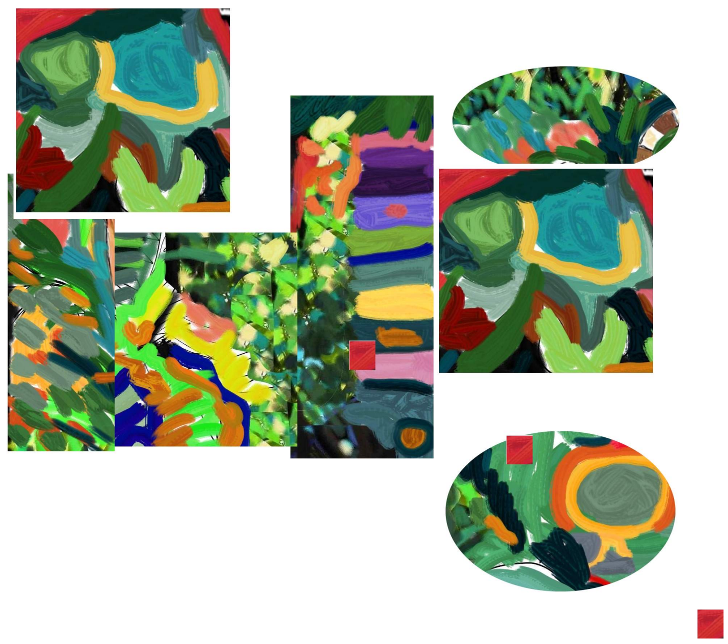


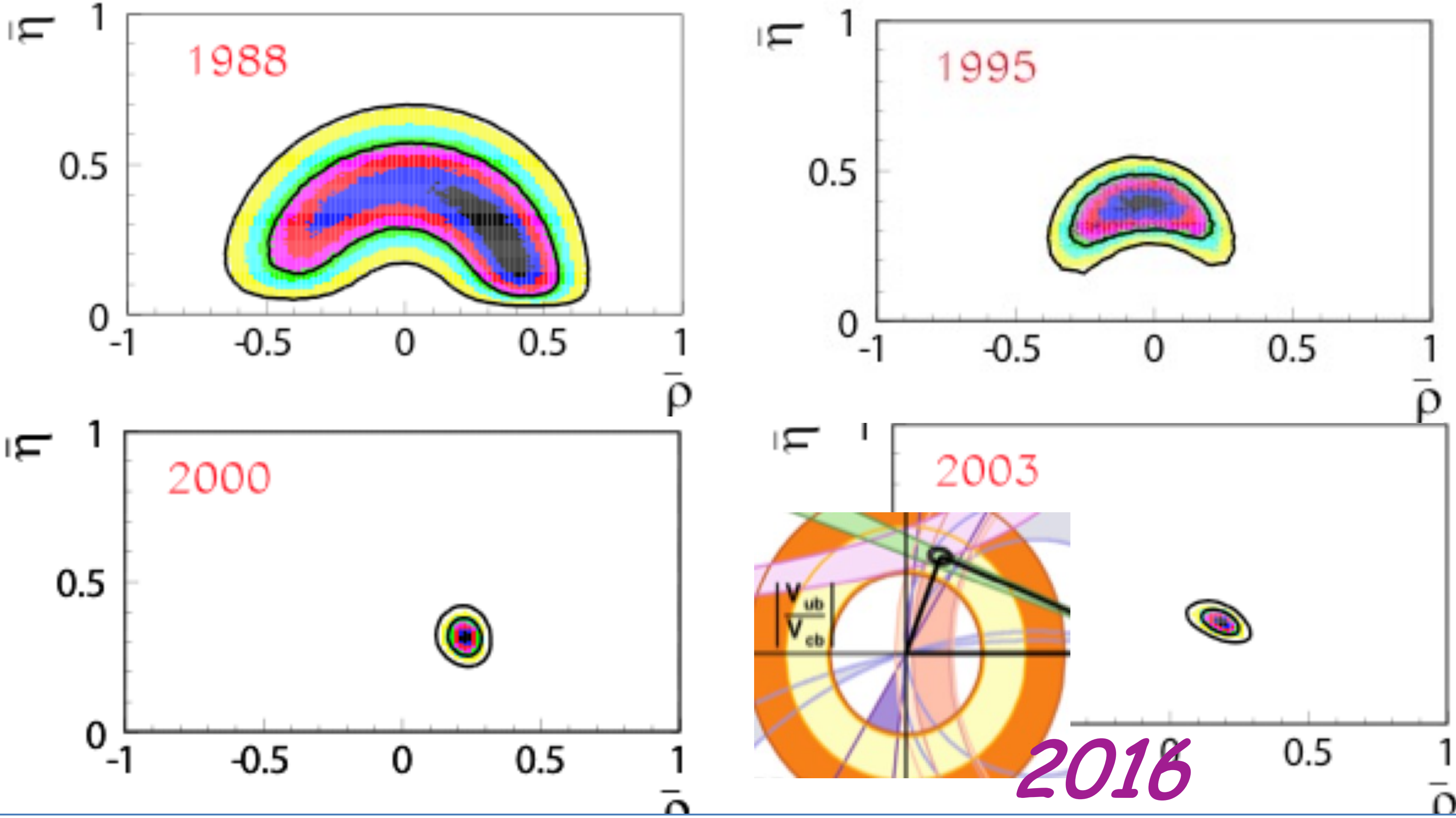
Figura 1.4: *Limiti imposti al valore di $(\bar{\rho}, \bar{\eta})$ dalle misure indirette. Ogni banda rappresenta l'indeterminazione sul limite imposto, dovuto alle incertezze con cui sono note le varie quantità.'*





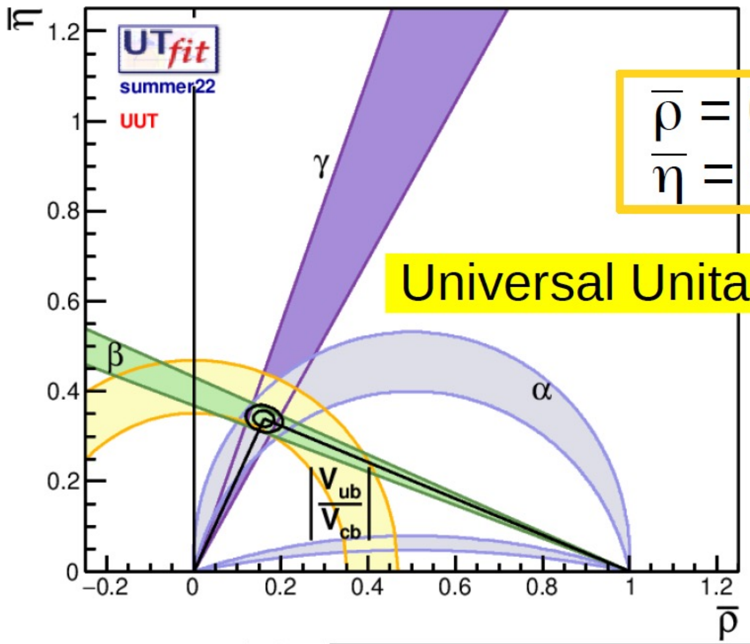
PROGRESS SINCE 1988

Experimental progress so impressive that we can fit the hadronic matrix elements (in the SM)



BABAR played a fundamental role in this Progress

Some interesting configurations

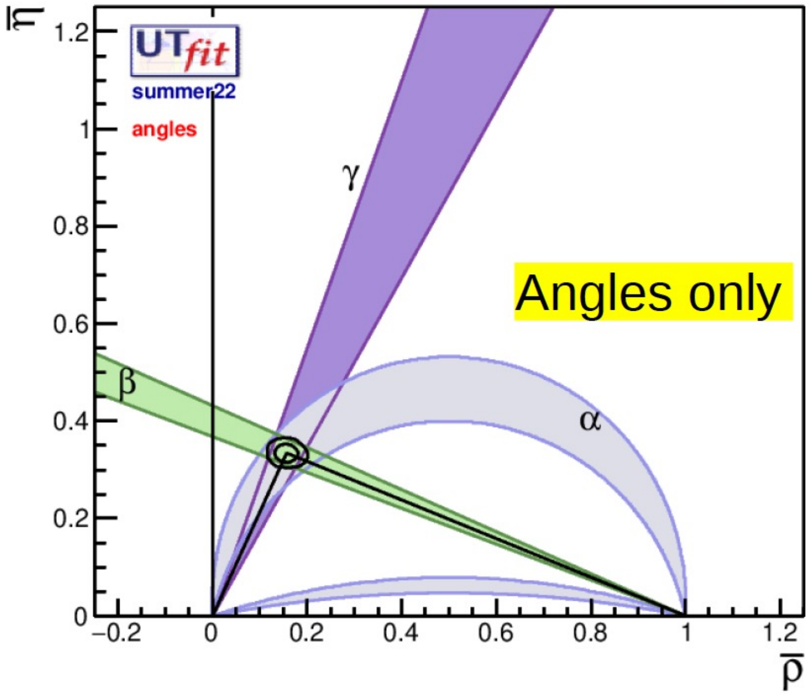


~10%

$\bar{\rho}$ = 0.161 ± 0.017
$\bar{\eta}$ = 0.339 ± 0.011

~3%

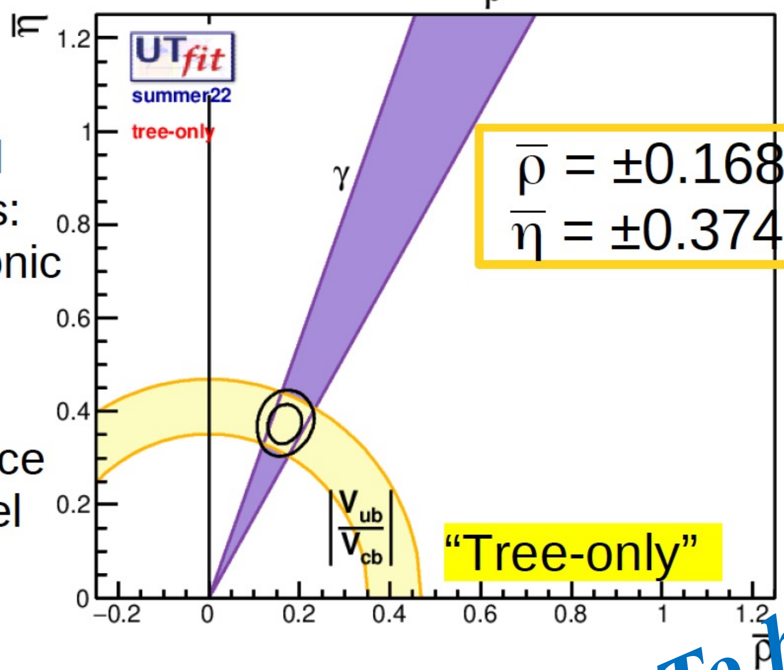
Universal Unitary Triangle



Angles only

Tree-level processes: Semileptonic and DK B decays

→ reference for model building

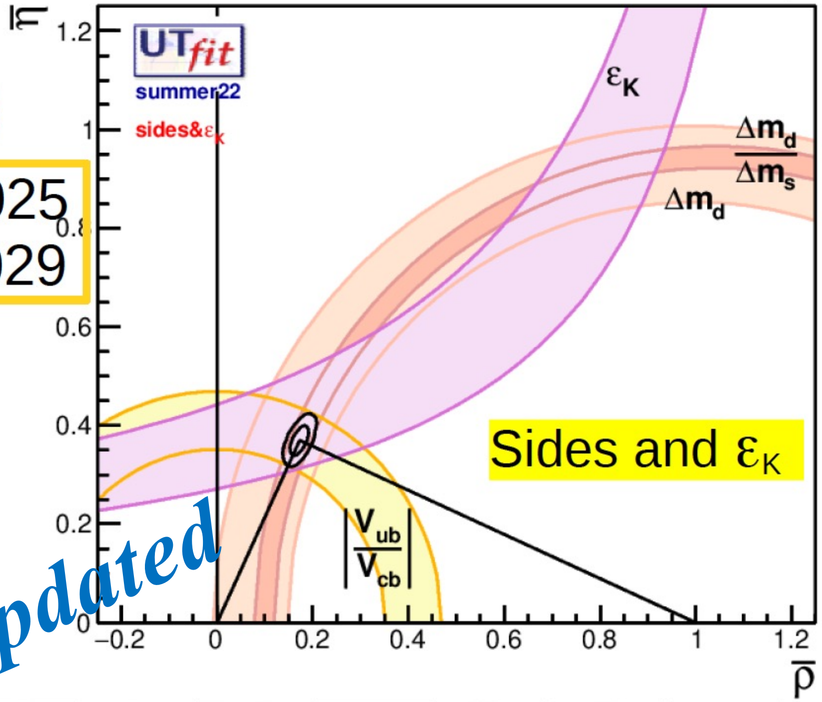


~15%

$\bar{\rho}$ = ±0.168 ± 0.025
$\bar{\eta}$ = ±0.374 ± 0.029

~8%

"Tree-only"

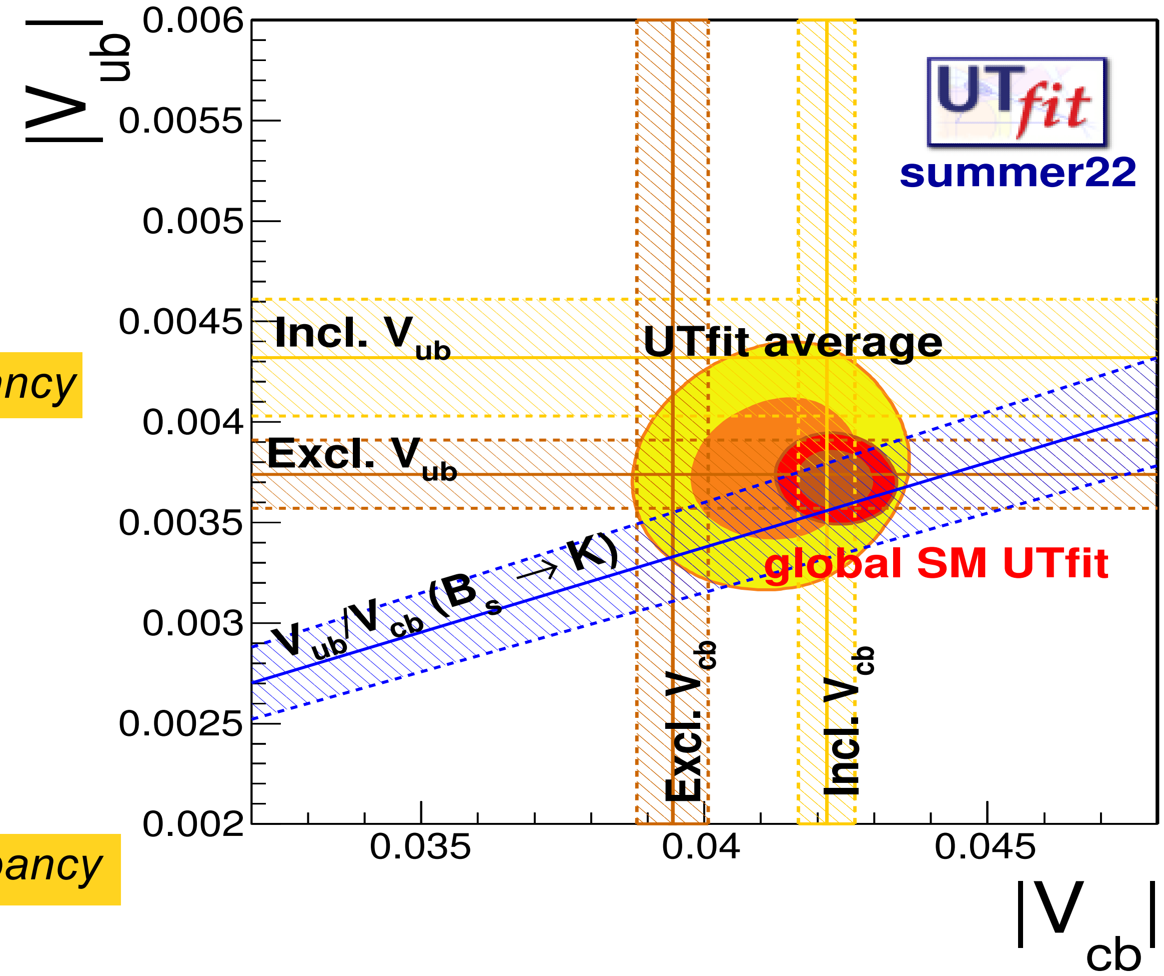


Sides and ε_K

To be updated

V_{cb} and V_{ub}

TENSIONS



from FLAG 2021

$|V_{cb}|$ *(excl)* = $(39.44 \pm 0.63)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.16 \pm 0.50)\ 10^{-3}$

from Bordone et al.
arXiv:2107.00604

~ 3.2σ discrepancy

$|V_{ub}|$ *(excl)* = $(3.74 \pm 0.17)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.32 \pm 0.29)\ 10^{-3}$

from GGOU HFLAV 2021
adding a flat uncertainty
covering the spread
of central values

~1.6σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(9.46 \pm 0.79)\ 10^{-2}$ — From B_s to K at high q^2

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(7.9 \pm 0.6)\ 10^{-2}$ — From Λ_b, excluded following FLAG guidelines

From global SM fit $|V_{cb}| = (42.00 \pm 0.47)\ 10^{-3}$ $|V_{ub}| = (3.715 \pm 0.093)\ 10^{-3}$

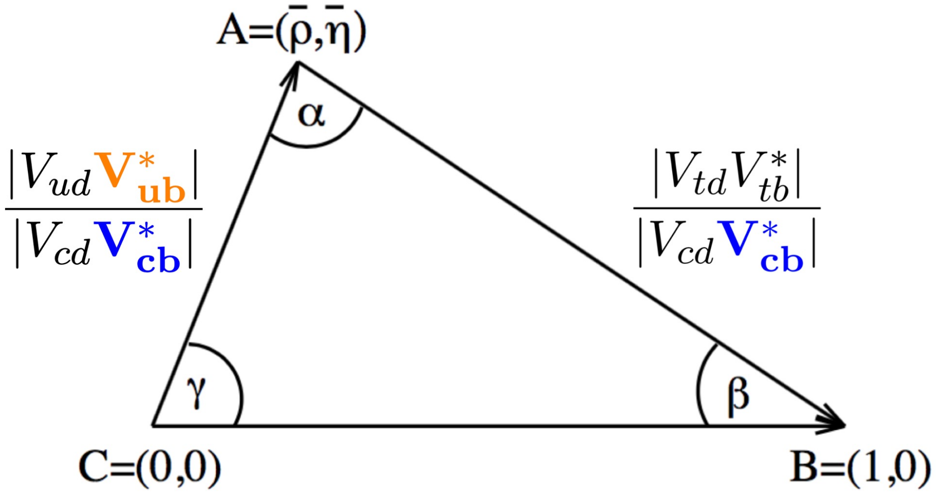
Utfit Prediction Vcb= $(42.22 \pm 0.51)\ 10^{-3}$ *Vub*= $(3.70 \pm 0.11)\ 10^{-3}$

Exclusive semileptonic $B \to \{D(*),\pi\}$ decays through unitarity (and other developments)

Work in collaboration with M. Naviglio. S. Simula and L. Vittorio

(PRD '21 (2105.02497), PRD '21 (2105.07851), PRD '22 (2105.08674), 2109.15248, 2204.05925, 2202.10285)

See talk by A. Vaquero



Mr. Nosferatu from Transylvania

State-of-the-art of the semileptonic B → {D(*),π} decays

Two critical issues

- V_{cb}

- exclusive/inclusive $|V_{cb}|$ puzzle:

exclusive (FLAG '21): $|V_{cb}|(BGL) \cdot 10^3 = 39.36\ (68)$

inclusive (HFLAV '21): $|V_{cb}| \cdot 10^3 = 42.19\ (78)$

difference of ~ 2.7 σ

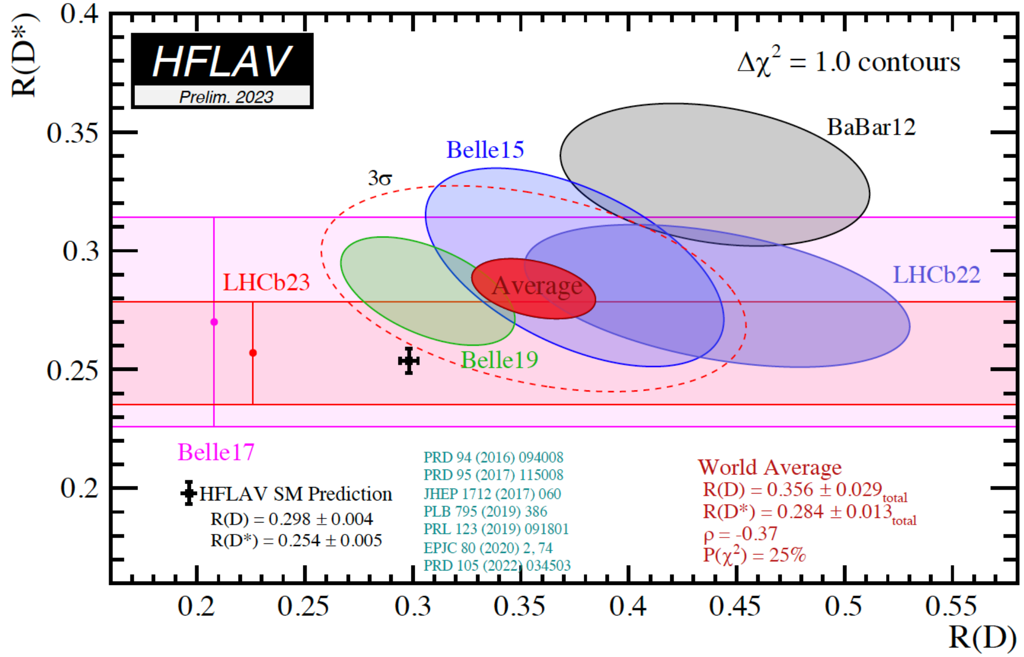
$|V_{cb}| \cdot 10^3 = 42.16\ (50)$

(Bordone et al. 2107.00604)

- $R_{D(*)}$

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

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



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

3.2σ tension

Main Results from the Dispersive Matrix Method

to show the relevant, attractive features of the Dispersion Matrix (DM) approach [arXiv:2105.02497], which is a rigorously model-independent tool for describing the hadronic form factors (FFs) in their whole kinematical range

- entirely based on first principles (i.e. lattice QCD simulations of 2- and 3-point Euclidean correlators)
- independent on any assumption about the momentum dependence of the FFs
- unitarization of the input theoretical data (including also kinematical constraints)
- **no mixing among theoretical calculations and experimental data to describe the shape of the FFs**

* results for $B_{(s)} \to D_{(s)}^{(*)} \ell \nu_\ell$ decays: extraction of $|V_{cb}|$ and theoretical determination of $R(D_{(s)}^{(*)})$ using LQCD results for the FFs (from FNAL/MILC and HPQCD) [2105.08674, 2109.15248, 2204.05925]

decay	$\lvert V_{cb}\rvert^{DM} \cdot 10^3$	inclusive [2107.00604]	exclusive [FLAG 21]
$B \to D$	41.0 ± 1.2		
$B \to D^*$	41.3 ± 1.7		
$B_s \to D_s$	42.4 ± 2.0		
$B_s \to D_s^*$	41.4 ± 2.6		
average	41.4 ± 0.8	42.16 ± 0.50	39.36 ± 0.68
difference		$\simeq 0.8\,\sigma$	$\simeq 1.9\,\sigma$

observable	DM	experiment	difference
$R(D)$	0.296 (8)	0.340 (27) (13)	$\simeq 1.4\,\sigma$
$R(D^*)$	0.275 (8)	0.295 (11) (8)	$\simeq 1.3\,\sigma$
$R(D_s)$	0.298 (5)		
$R(D_s^*)$	0.250 (6)		

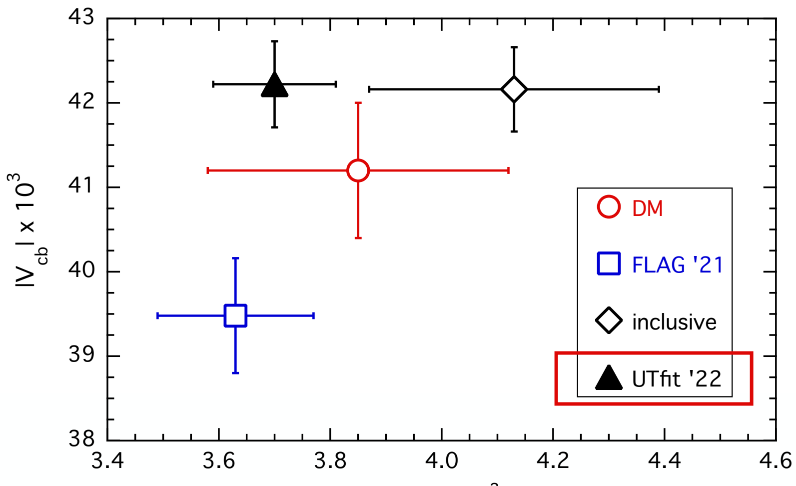
Utfit 42.22 (0.51)

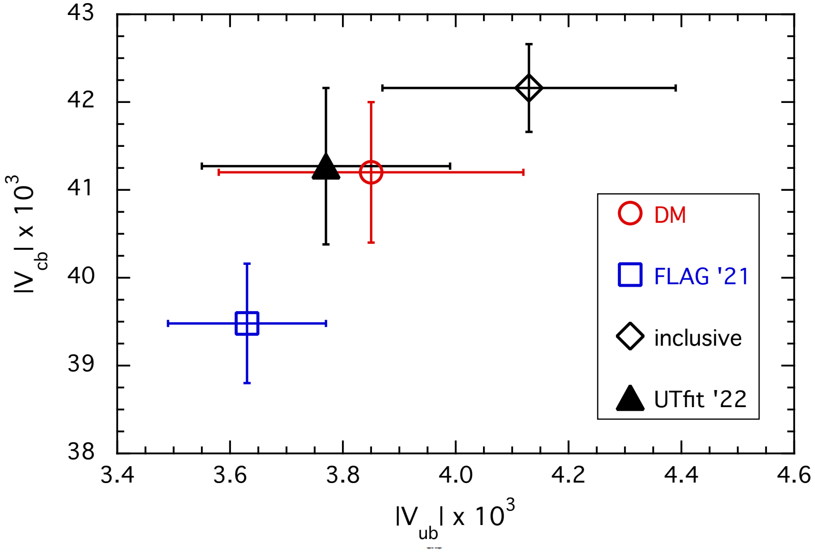
*** reduced tensions in both $|V_{cb}|$ and $R(D^{(*)})$ ***

From S. Simula

- *universal: it can be applied to any exclusive semileptonic decays of mesons and baryons*

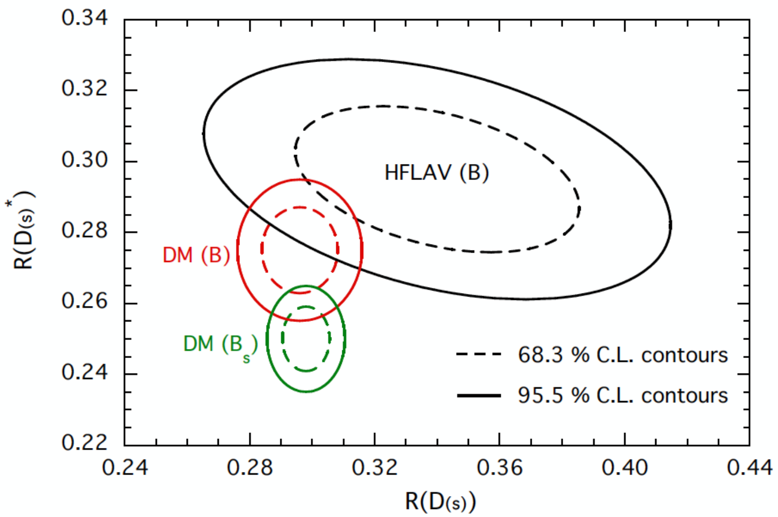
Summary





	decays	DM	FLAG '21	inclusive
$\lvert V_{cb}\rvert \cdot 10^3$	$B_{(s)} \to D_{(s)}^{(*)}$	41.4 (8)	39.48 (68)	42.16 (50)
$\lvert V_{ub}\rvert \cdot 10^3$	$B_{(s)} \to \pi, K$	3.85 (27)	3.63 (14)	4.13 (26)

SU(3) breaking effects need further investigation



	DM	HFLAV '19
R(D)	0.296 (8)	0.340 (27) (13)
R(D*)	0.275 (8)	0.295 (11) (8)
$R(D_s)$	0.298 (5)	
$R(D_s^*)$	0.250 (6)	

reduced tensions in both $|V_{cb}|$, $|V_{ub}|$ and $R(D^{(*)})$ when theory and experiments are not fitted simultaneously

$$
\begin{aligned}
H_W^{\mu\nu}(k,\boldsymbol{p}) &= H_{\mathrm{SD}}^{\mu\nu}(k,\boldsymbol{p}) + H_{\mathrm{pt}}^{\mu\nu}(k,\boldsymbol{p}) \\
H_{\mathrm{SD}}^{\mu\nu}(k,\boldsymbol{p}) &= \frac{H_1(p\cdot k,k^2)}{M_{D_s}}\left[k^2 g^{\mu\nu} - k^\mu k^\nu\right] + \frac{H_2(p\cdot k,k^2)}{M_{D_s}}\frac{\left[(p\cdot k-k^2)k^\mu - k^2(p-k)^\mu\right]}{(p-k)^2-M_{D_s}^2}(p-k)^\nu \\
&\quad - i\frac{F_V(p\cdot k,k^2)}{M_{D_s}}\varepsilon^{\mu\nu\gamma\beta}k_\gamma p_\beta + \frac{F_A(p\cdot k,k^2)}{M_{D_s}}\left[(p\cdot k-k^2)g^{\mu\nu} - (p-k)^\mu k^\nu\right] \\
H_{\mathrm{pt}}^{\mu\nu}(k,\boldsymbol{p}) &= f_{D_s}\left[g^{\mu\nu} + \frac{(2p-k)^\mu(p-k)^\nu}{2p\cdot k-k^2}\right],
\end{aligned}
$$

real photon

16

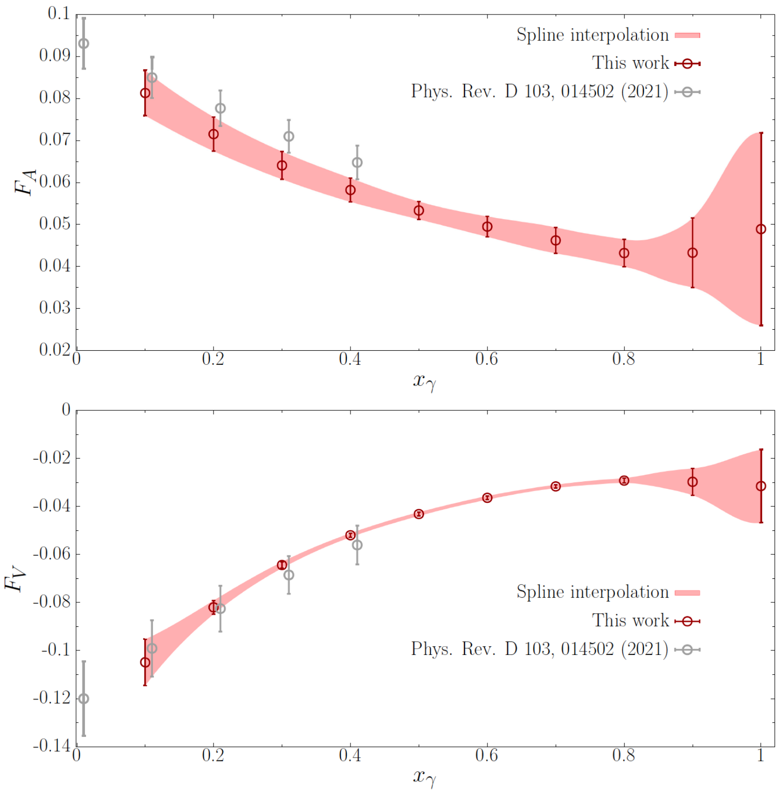


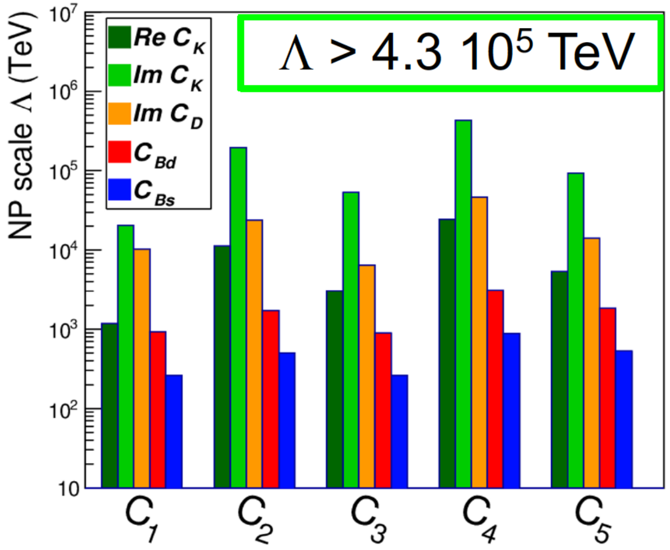
FIG. 8: The form factors F_A (top figure) and F_V (bottom figure), obtained after the extrapolation to the continuum limit, shown as a function of the dimensionless variable x_γ. In each of the two figures, the red band is the result of a smooth cubic spline interpolation to our data, while the gray data points correspond to the results from Ref. [15] which have been slightly shifted horizontally for visualization purposes.

Beyond the SM

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

Wilson Coefficients results

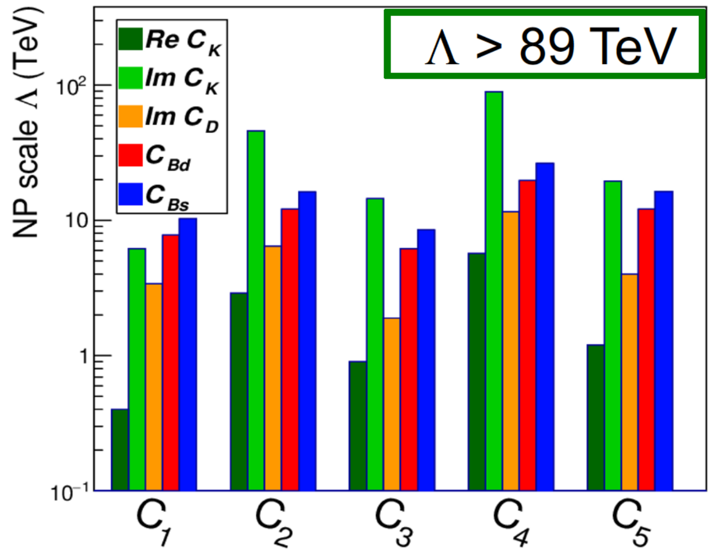
Generic: $C(\Lambda) = \alpha/\Lambda^2$, F_i~1, arbitrary phase, α ~ 1 for strongly coupled NP



- α ~ α_W in case of loop coupling
- through weak interactions*

$\Lambda > 1.3\ 10^4$ TeV

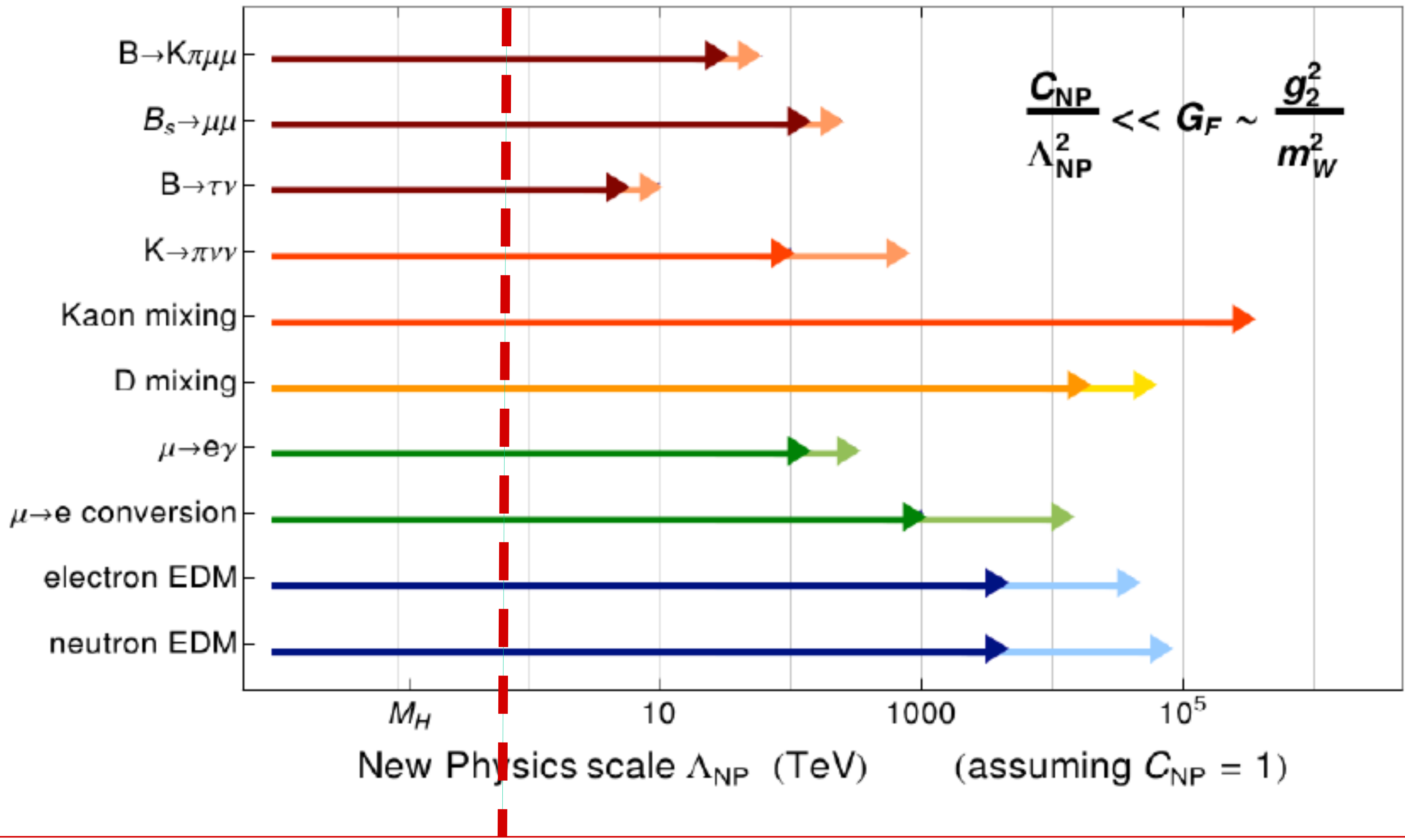
NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, F_i~$|F_{SM}|$, arbitrary phase



- α ~ α_W in case of loop coupling
- through weak interactions*

$\Lambda > 2.7$ TeV

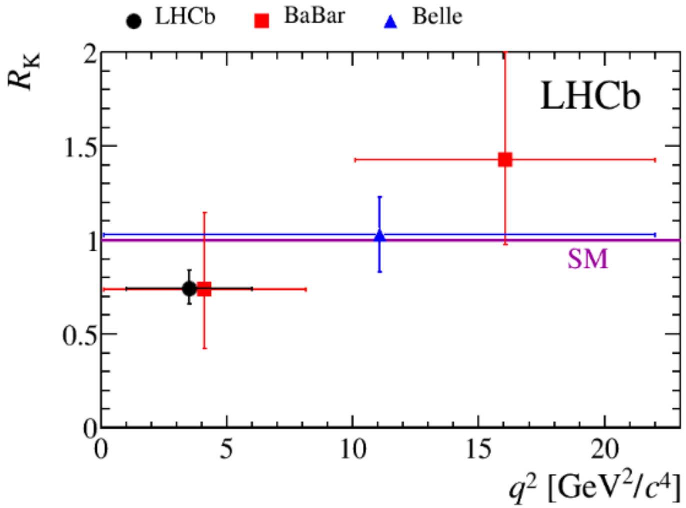
Sensitivity to New Physics from Flavor



Approximate LHC direct reach

Reminder:
$R_K = B(B^+ \to K^+\mu^+\mu^-)/B(B^+ \to K^+e^+e^-)$

- Test of lepton universality : $R_K \sim 1$ in SM, with negligible theoretical uncertainties



LHCb, PRL 113 151601
Belle, PRL 103 171801
BaBar, PRD 86 032012

$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

Old slide

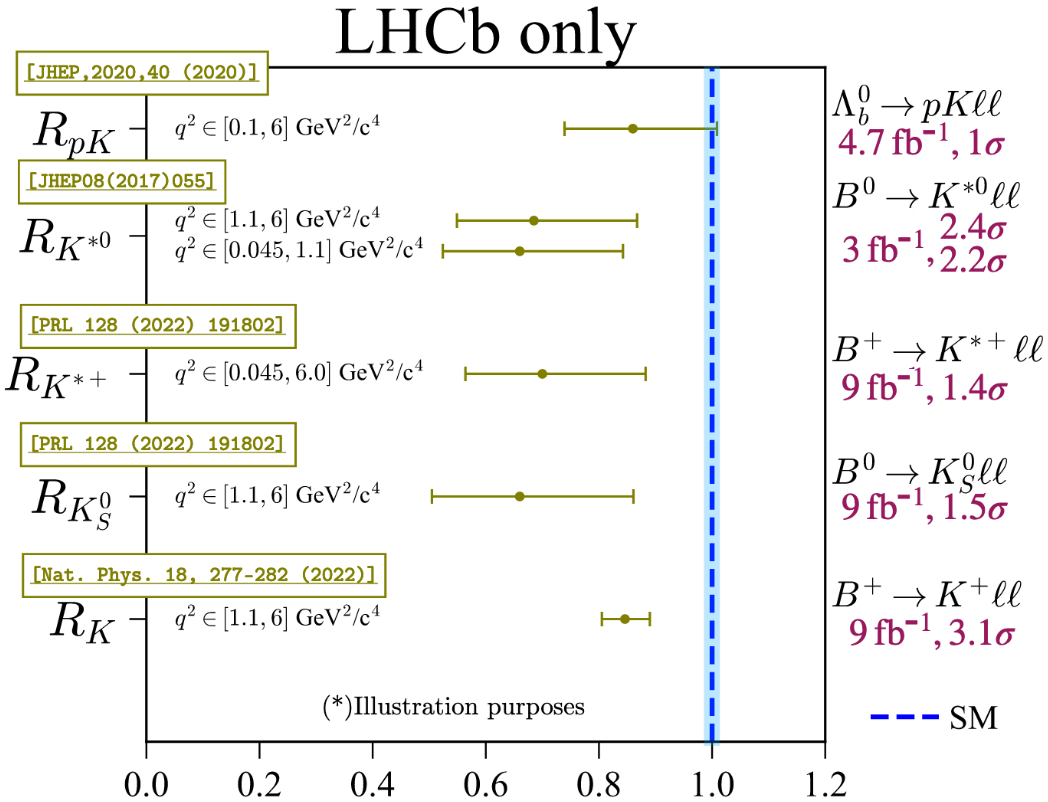
- Compatible with SM at 2.6σ
- Experimentally challenging
  - lower trigger efficiency for electrons, resolution deteriorated by bremsstrahlung
- Other modes suitable for same test: $B^0 \to K^{*0} l^+ l^-$, $B_s \to \phi\, l^+ l^-$, $\Lambda_B \to \Lambda\, l^+ l^-$

Excitement

Analysis

Lepton Flavour Universality (LFU) tests in $b \to s\ell^+\ell^-$

- Coherent pattern of tension to SM in LFU test with $b \to s\ell^+\ell^-$ transition:
- R_X ratio extremely well predicted in SM
  - Cancellation of hadronic uncertainties at 10^{-4}
  - $\mathcal{O}(1\%)$ QED correction [Eur.Phys.J.C 76 (2016) 8]
  - Statistically limited
- **Any departure from unity is a clear sign of New Physics**



$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to se^+e^-)}$$

(*) Measurements from Belle not shown (larger statistical uncertainties)

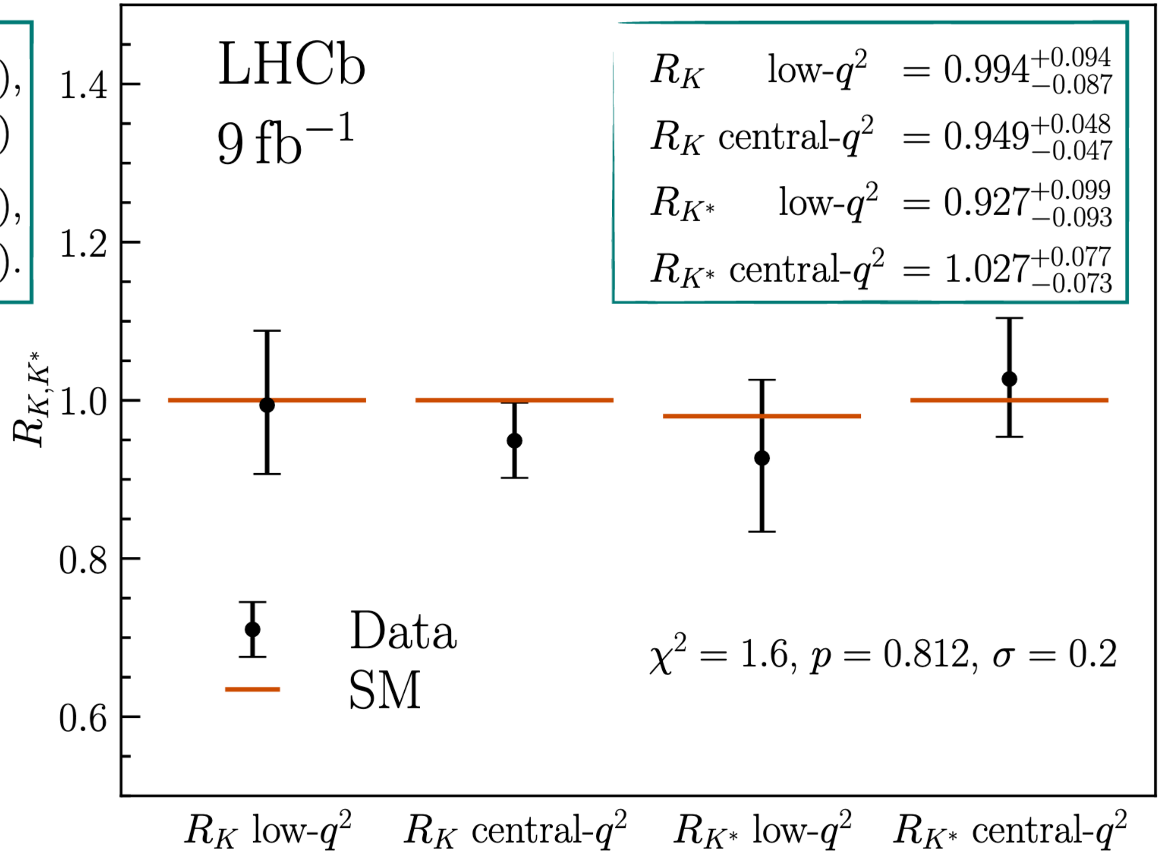
Harakiri!

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



Caro Nando,

la nostra conoscenza e amicizia è > 50 anni, abbiamo fatto insieme cose di cui possiamo andare orgogliosi (e tu anche di più senza di me), spero che continueremo a profittare di questa nostra amicizia ancora per molto…

THANKS FOR YOUR ATTENTION

INFN
Istituto Nazionale di Fisica Nucleare

UTfit

Back up Slides

The Dispersive Matrix (DM) method $B \to D$

$t \equiv q^2$

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

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

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

The conformal variable z is related to the momentum transfer as:

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

$[0, t_{max} = t_-] \Rightarrow [z_{max}, 0]$

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

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

The DM method

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

We also have to define the kinematical functions

$$\phi_0(z, Q^2) = \sqrt{\frac{2n_I}{3}} \sqrt{\frac{3t_+ t_-}{4\pi}} \frac{1}{t_+ - t_-} \frac{1+z}{(1-z)^{5/2}} \left(\beta(0) + \frac{1+z}{1-z}\right)^{-2} \left(\beta(-Q^2) + \frac{1+z}{1-z}\right)^{-2},$$

$$\phi_+(z, Q^2) = \sqrt{\frac{2n_I}{3}} \sqrt{\frac{1}{\pi(t_+ - t_-)}} \frac{(1+z)^2}{(1-z)^{9/2}} \left(\beta(0) + \frac{1+z}{1-z}\right)^{-2} \left(\beta(-Q^2) + \frac{1+z}{1-z}\right)^{-3}, \quad \beta(t) \equiv \sqrt{\frac{t_+ - t}{t_+ - t_-}}$$

Thus, we need **these external inputs** to implement our method:

- estimates of the FFs, computed on the lattice, *@ $\{t_1, \ldots, t_n\}$*: from Cauchy's theorem (for generic *m*)

$$\langle g_{t_m} | \phi f \rangle = \phi(t_m, Q^2) f(t_m)$$

LQCD data!

$$\langle g_{t_m} | g_{t_l} \rangle = \frac{1}{1 - \bar{z}(t_l) z(t_m)}$$

Q^2

- non-perturbative values of the susceptibilities, since from the dispersion relations (calling the Euclidean quadratic momentum)

$$\chi(Q^2) \geq \langle \phi f | \phi f \rangle$$

Since the susceptibilities are computed on the lattice, we can in principle use whatever value of $Q^2 \equiv -q^2$

The DM method

The positivity of the original inner products guarantees that $\det \mathbf{M} \geq 0$ namely

LOWER bound

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

UPPER bound

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

UNITARITY FILTER: unitarity is satisfied if γ is semipositive definite, namely if

$$\chi \geq \sum_{i,j=1}^{N} f_i f_j \phi_i \phi_j d_i d_j \frac{(1 - z_i^2)(1 - z_j^2)}{1 - z_i z_j}$$

This is a parametrization-independent unitarity test of the LQCD input data

A detailed discussion of the treatment of statistical errors and constraints was also presented (simplified with respect to L. Lellouch NPB, 479 (1996))

Non-perturbative computation of the susceptibilities

The possibility to compute the χs on the lattice allows us to 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 our method

Work in progress...

To compute the susceptibilities on the lattice, we start from the Euclidean correlators:

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

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

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

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

Non-perturbative computation of the susceptibilities

Let us choose for the moment zero Q^2:

$$\boxed{\chi_{0^+}(Q^2=0)} = \int_0^\infty dt\; t^2\; C_{0^+}(t)\;,$$

$$\boxed{\chi_{1^-}(Q^2=0)} = \frac{1}{12}\int_0^\infty dt\; t^4\; C_{1^-}(t)\;,$$

$$\chi_{0^-}(Q^2=0) = \int_0^\infty dt\; t^2\; C_{0^-}(t)\;,$$

$$\chi_{1^+}(Q^2=0) = \frac{1}{12}\int_0^\infty dt\; t^4\; C_{1^+}(t)\;.$$

$$\chi_{0^+}(Q^2=0) = \frac{1}{12}(m_b-m_c)^2\int_0^\infty dt\; t^4\; C_S(t)$$

$$\chi_{0^-}(Q^2=0) = \frac{1}{12}(m_b+m_c)^2\int_0^\infty dt\; t^4\; C_P(t)$$

$$C_{0^+}(t) = \boxed{\widetilde{Z}_V^2}\int d^3x\langle 0|T\left[\bar{q}_1(x)\gamma_0 q_2(x)\;\bar{q}_2(0)\gamma_0 q_1(0)\right]|0\rangle\;,$$

$$C_{1^-}(t) = \boxed{\widetilde{Z}_V^2}\frac{1}{3}\sum_{j=1}^{3}\int d^3x\langle 0|T\left[\bar{q}_1(x)\gamma_j q_2(x)\;\bar{q}_2(0)\gamma_j q_1(0)\right]|0\rangle\;,$$

$$C_{0^-}(t) = \boxed{\widetilde{Z}_A^2}\int d^3x\langle 0|T\left[\bar{q}_1(x)\gamma_0\gamma_5 q_2(x)\;\bar{q}_2(0)\gamma_0\gamma_5 q_1(0)\right]|0\rangle\;,$$

$$C_{1^+}(t) = \boxed{\widetilde{Z}_A^2}\frac{1}{3}\sum_{j=1}^{3}\int d^3x\langle 0|T\left[\bar{q}_1(x)\gamma_j\gamma_5 q_2(x)\;\bar{q}_2(0)\gamma_j\gamma_5 q_1(0)\right]|0\rangle\;,$$

$$C_S(t) = \boxed{\widetilde{Z}_S^2}\int d^3x\langle 0|T\left[\bar{q}_1(x) q_2(x)\;\bar{q}_2(0) q_1(0)\right]|0\rangle\;,$$

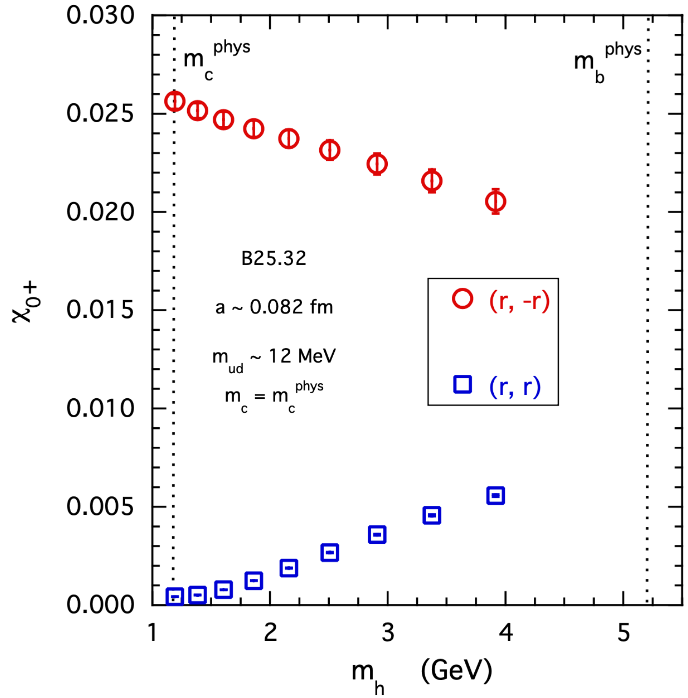
$$C_P(t) = \boxed{\widetilde{Z}_P^2}\int d^3x\langle 0|T\left[\bar{q}_1(x)\gamma_5 q_2(x)\;\bar{q}_2(0)\gamma_5 q_1(0)\right]|0\rangle\;,$$

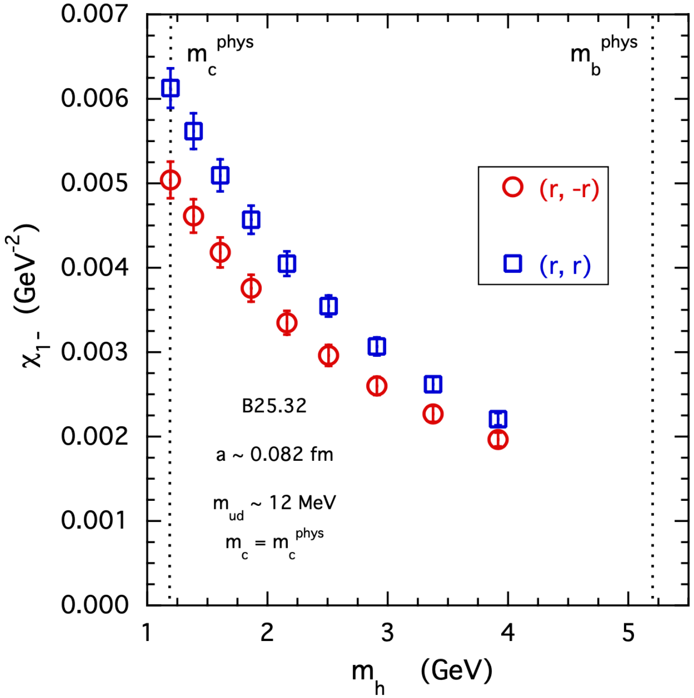
Z: appropriate renormalization constants

N. Carrasco et al. [ETM Coll.], NPB 887 (2014) [arXiv:1403.4504]

Non-perturbative computation of the susceptibilities

***r*: (unphysical) Wilson parameter**





Following set of nine quark masses:

$$m_h(n) = \lambda^{n-1}\, m_c^{phys} \qquad \text{for } n = 1, 2, \ldots$$

$$m_h(1) = m_c^{phys}$$

$$\lambda \equiv [m_b^{phys}/m_c^{phys}]^{1/10} = [5.198/1.176]^{1/10} \simeq 1.1602$$

$$m_h(9) \simeq 3.9 \text{ GeV} \simeq 0.75\, m_b^{phys}$$

$$m_h = a\mu_h/(Z_P a)$$

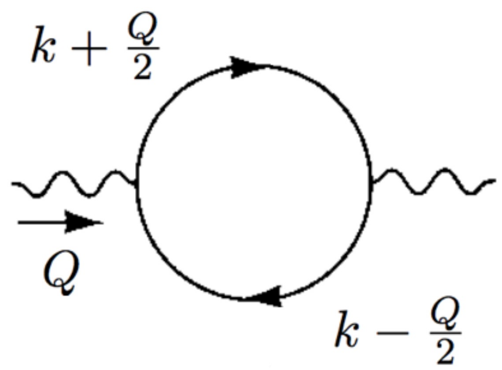
Contact terms &

Large discretisation effects

Contact terms & perturbative subtraction

In **twisted mass LQCD** (tmLQCD):

$$\Pi_V^{\alpha\beta} = \int_{-\pi/a}^{+\pi/a} \frac{d^4k}{(2\pi)^4} \,\mathrm{Tr}\Big[\gamma^\alpha G_1(k+\frac{Q}{2})\gamma^\beta G_2(k-\frac{Q}{2})\Big],$$



$$G_i(p) = \frac{-i\gamma_\mu \mathring{p}_\mu + \mathcal{M}_i(p) - i\mu_{q,i}\gamma_5\tau^3}{\mathring{p}^2 + \mathcal{M}_i^2(p) + \mu_{q,i}^2}, \qquad i=1,2$$

$$\mathring{p}_\mu \equiv \frac{1}{a}\sin(ap_\mu), \qquad \mathcal{M}_i(p) \equiv m_i + \frac{r_i}{2}a\hat{p}_\mu^2, \qquad \hat{p} \equiv \frac{2}{a}\sin\Big(\frac{ap_\mu}{2}\Big).$$

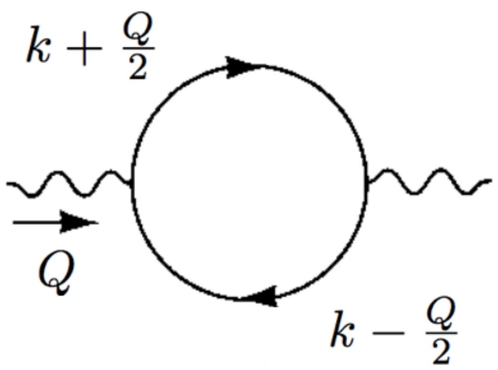
$$\begin{aligned}\Pi_V^{\alpha\beta} &= a^{-2}(Z_1^I + (r_1^2-r_2^2)Z_2^I + (r_1^2-r_2^2)(r_1^2+r_2^2)Z_3^I)g^{\alpha\beta} \\ &+ (\mu_1^2 Z^{\mu_1^2} + \mu_2^2 Z^{\mu_2^2} + \mu_1\mu_2 Z^{\mu_1\mu_2})g^{\alpha\beta} + (Z_1^{Q^2} + (r_1^2-r_2^2)Z_2^{Q^2})Q\cdot Q g^{\alpha\beta} \\ &+ (Z_1^{Q^\alpha Q^\beta} + (r_1^2-r_2^2)Z_2^{Q^\alpha Q^\beta})Q^\alpha Q^\beta + r_1 r_2(a^{-2}Z_1^{r_1r_2}g^{\alpha\beta} + (Z_2^{r_1r_2} + (r_1^2+r_2^2)Z_3^{r_1r_2} \\ &+ (r_1^4+r_2^4)Z_4^{r_1r_2})Q\cdot Q g^{\alpha\beta} + (\mu_1^2 Z_5^{r_1r_2} + \mu_2^2 Z_6^{r_1r_2})g^{\alpha\beta}) + O(a^2),\end{aligned}$$

CONTACT TERMS!!!

Contact terms & perturbative subtraction

In **twisted mass LQCD** (tmLQCD):

$$\Pi_V^{\alpha\beta} = \int_{-\pi/a}^{+\pi/a} \frac{d^4k}{(2\pi)^4}\, \mathrm{Tr}\Big[\gamma^\alpha G_1(k+\frac{Q}{2})\gamma^\beta G_2(k-\frac{Q}{2})\Big],$$



Thus, by separating the *longitudinal* and the *transverse* contributions, we can compute the susceptibilities for all the spin-parity quantum numbers **in the free theory on the lattice**, *i.e.* at order $\mathcal{O}(\alpha_s^0)$ using twisted-mass fermions!

$$\chi_j^{free} = \boxed{\chi_j^{LO}} + \boxed{\chi_j^{discr}}$$

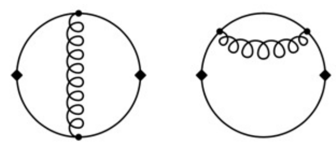
LO term of PT @ $\mathcal{O}(\alpha_s^0)$

contact terms and discretization effects @ $\mathcal{O}(\alpha_s^0 a^m)$ with $m \geq 0$

Perturbative subtraction:

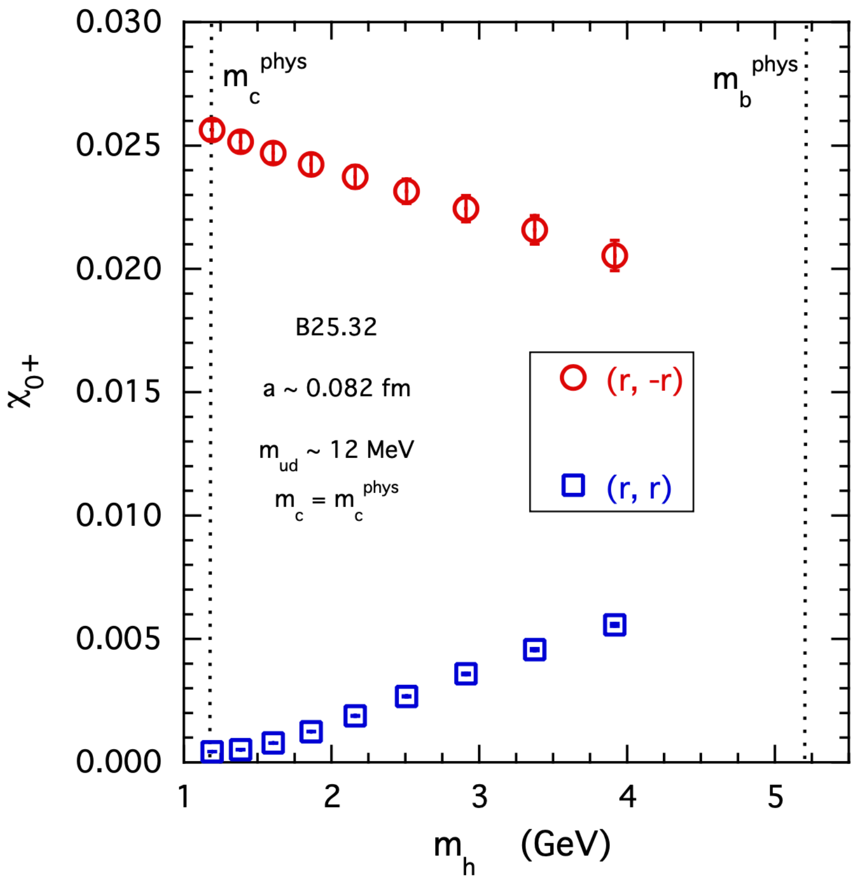
$$\chi_j \to \chi_j - \left[\chi_j^{free} - \chi_j^{LO}\right]$$

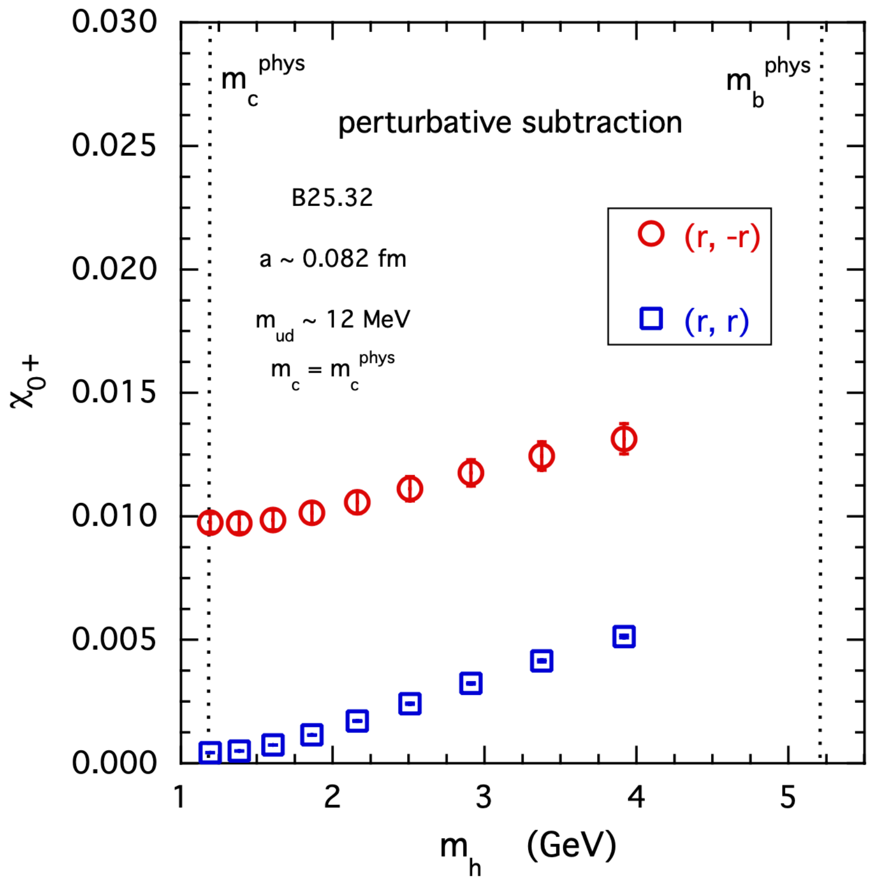
Higher order corrections?



Work in progress...

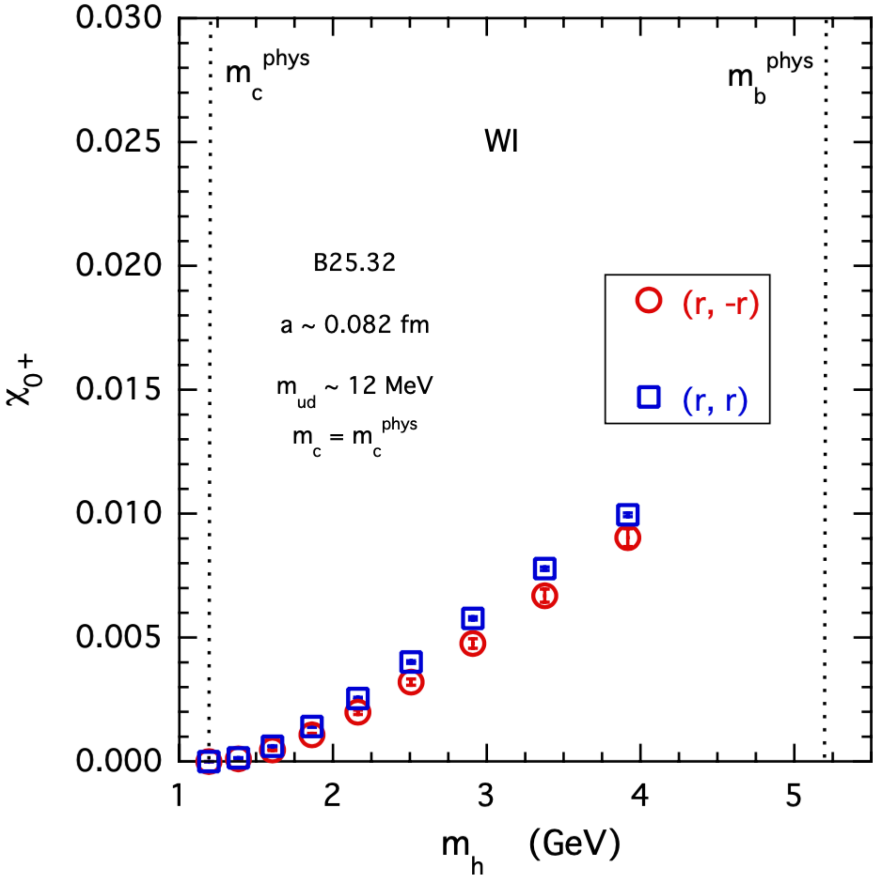
Contact terms & perturbative subtraction

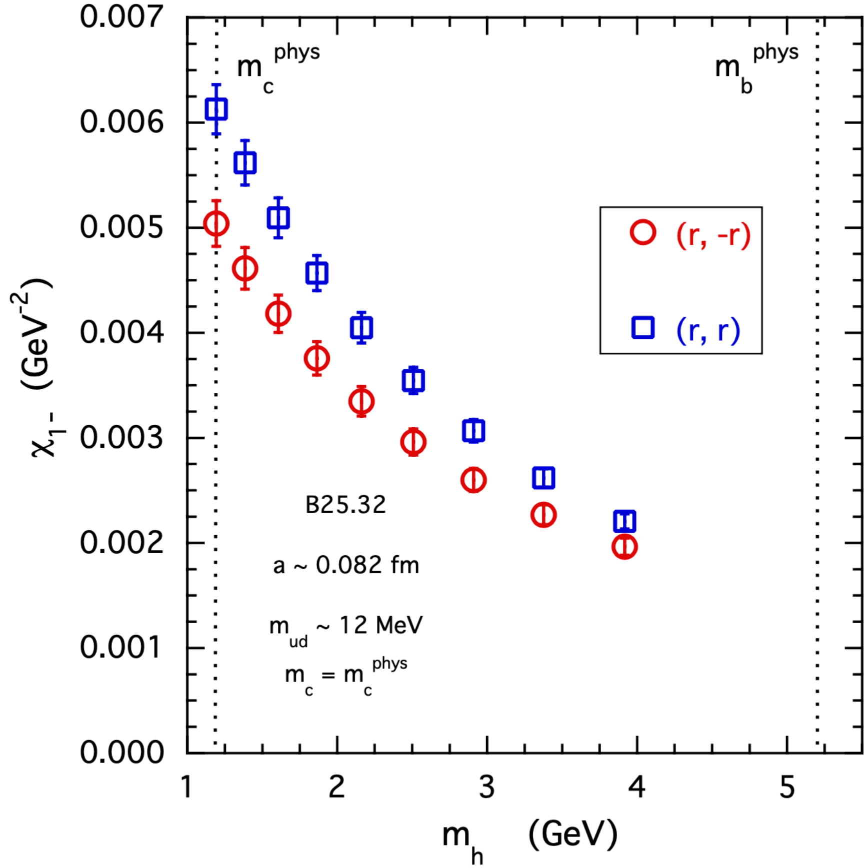




NOT ENOUGH…

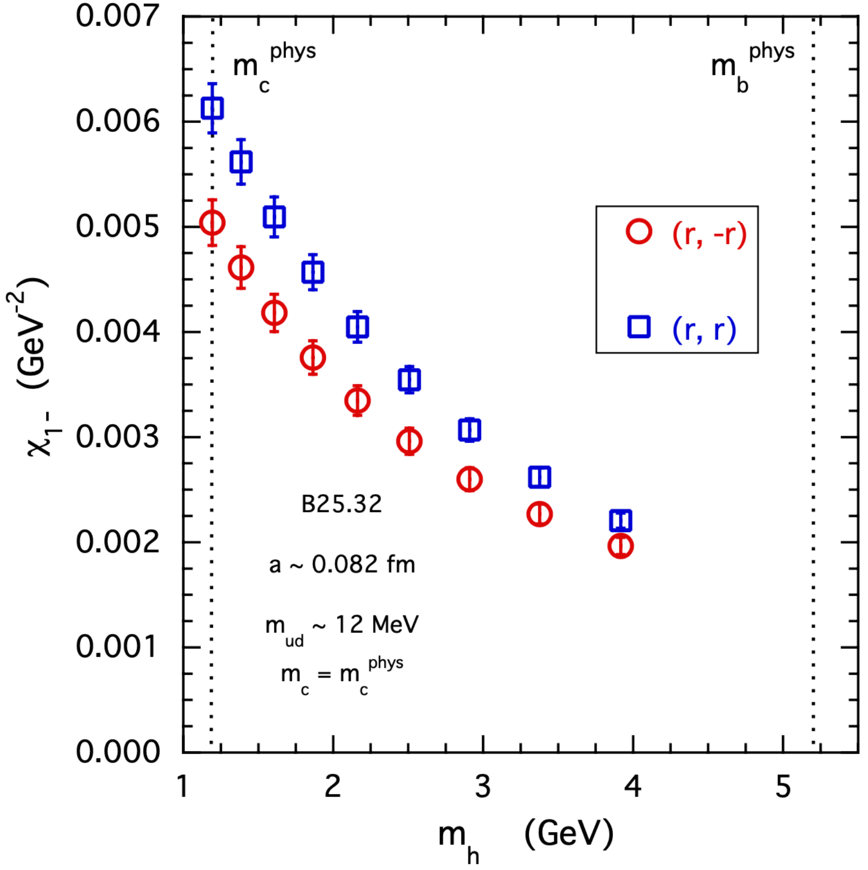
Non-perturbative computation of the susceptibilities

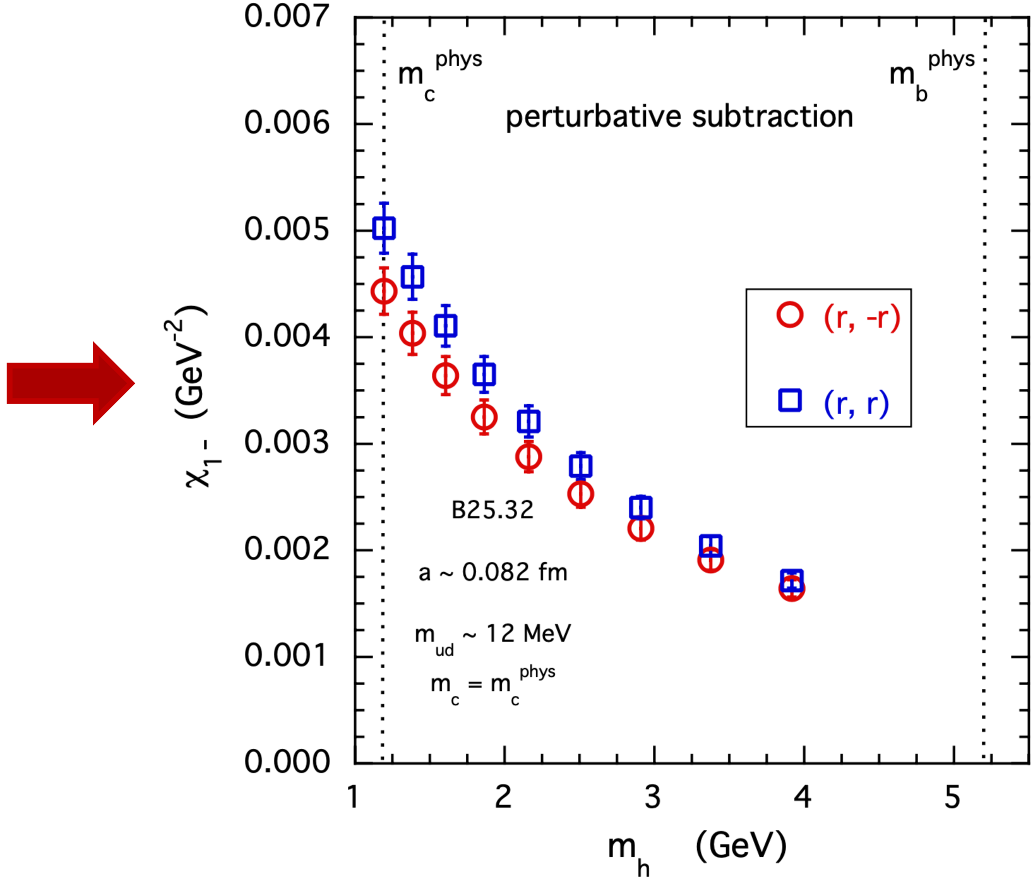




Much better using the Ward Identity

Contact terms & perturbative subtraction





OK

An extrapolation to the continuum limit was implemented

ETMC ratio method & final results

For the extrapolation to the physical *b*-quark point we have used the ETMC ratio method:

$$R_j(n; a^2, m_{ud}) \equiv \frac{\chi_j[m_h(n); a^2, m_{ud}]}{\chi_j[m_h(n-1); a^2, m_{ud}]} \boxed{\frac{\rho_j[m_h(n)]}{\rho_j[m_h(n-1)]}}$$

to ensure that

$$\lim_{n\to\infty} R_j(n) = 1$$

$$\rho_{0^+}(m_h) = \rho_{0^-}(m_h) = 1 \; ,$$

$$\rho_{1^-}(m_h) = \rho_{1^+}(m_h) = (m_h^{pole})^2$$

All the details are deeply discussed in *arXiv:2105.07851*. In this way, we have obtained **the first lattice QCD determination of susceptibilities of heavy-to-heavy (and heavy-to-light, *in prep.*) transition current densities:**

$b \to c$

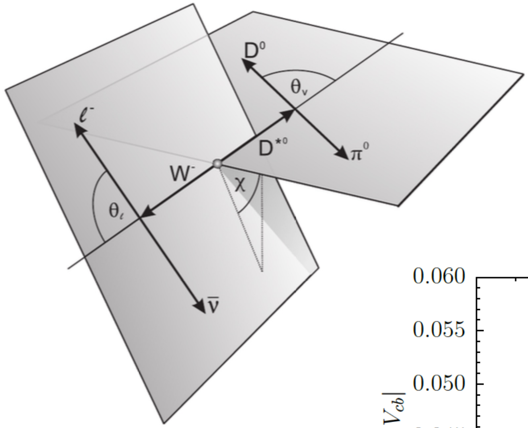
	Perturbative	With subtraction	Non-perturbative	With subtraction
$\chi_{V_L}[10^{-3}]$	6.204(81)	—	7.58(59)	—
$\chi_{A_L}[10^{-3}]$	24.1	19.4	25.8(1.7)	21.9(1.9)
$\chi_{V_T}[10^{-4}\ \text{GeV}^{-2}]$	6.486(48)	5.131(48)	6.72(41)	5.88(44)
$\chi_{A_T}[10^{-4}\ \text{GeV}^{-2}]$	3.894	—	4.69(30)	—

$b \to u$

Non-perturbative	With subtraction
2.04(20)	—
2.34(13)	—
4.88(1.16)	4.45(1.16)
4.65(1.02)	—

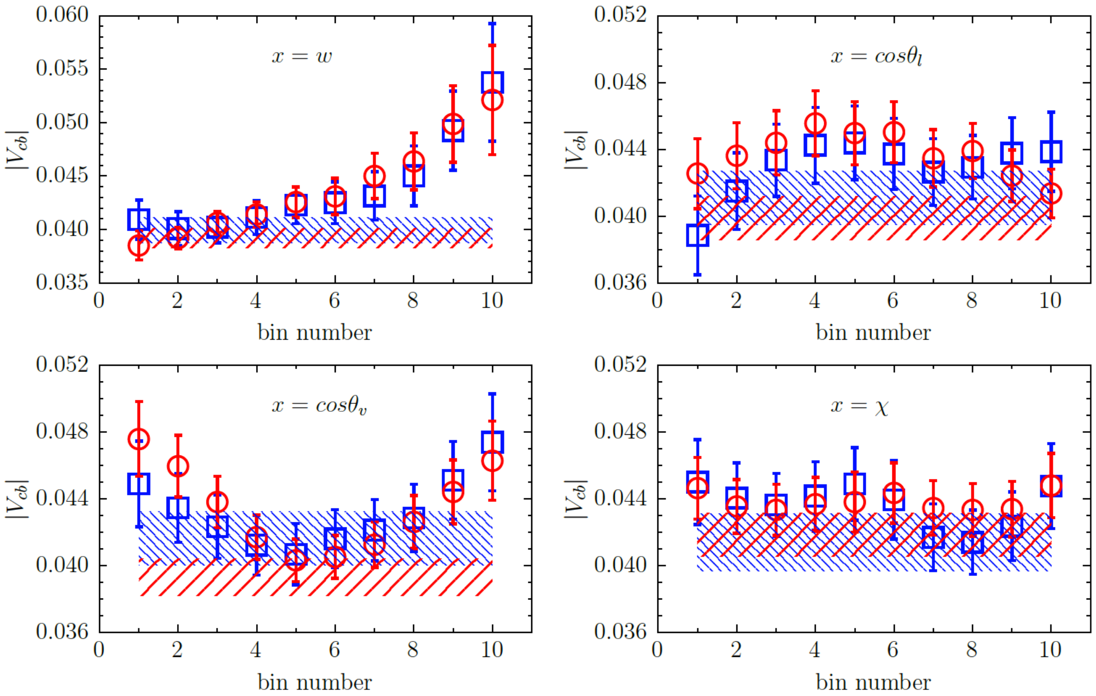
Differences with PT? **~4% for 1^-, ~7% for 0^-, ~20 % for 0^+ and 1^+**

Bigi, Gambino PRD '16
Bigi, Gambino, Schacht PLB '17
Bigi, Gambino, Schacht JHEP '17



Exclusive Vcb determination from B -> D*

$$d\Gamma/dx\ , \qquad x = w, \cos\theta_l, \cos\theta_v, \chi$$



Blue squares: arXiv:1702.01521

Red points: arXiv:1809.03290

In the w differential decay rate data systematically above the result of the fit

This problem is known and has been studied, for example, in Nucl. Instrum. Meth. A346 (1994) 306-311

Our interpretation is that there is a problem related to the experimental calibration and to the covariance matrix

experimental data for $B \to D^* \ell \nu_\ell$ decays

- two sets of data from Belle collaboration arXiv:1702.01521 and arXiv:1809.03290
- four different differential decay rates $d\Gamma/dx$ where $x = \{w, \cos\theta_v, \cos\theta_\ell, \chi\}$: 10 bins for each variable

total of 80 data points

*** we do not mix theoretical calculations with experimental data to describe the shape of the FFs ***

$$|V_{cb}|_i \equiv \sqrt{\frac{(d\Gamma/dx)_i^{exp.}}{(d\Gamma/dx)_i^{th.}}} \qquad i = 1, \ldots, N_{bins}$$

* issue with the covariance matrix $C_{ij}^{exp.}$ of the Belle data: $\Gamma^{exp.} \equiv \sum_{i=1}^{10} \left(\frac{d\Gamma}{dx}\right)_i^{exp.}$ should be the same for all the variables x

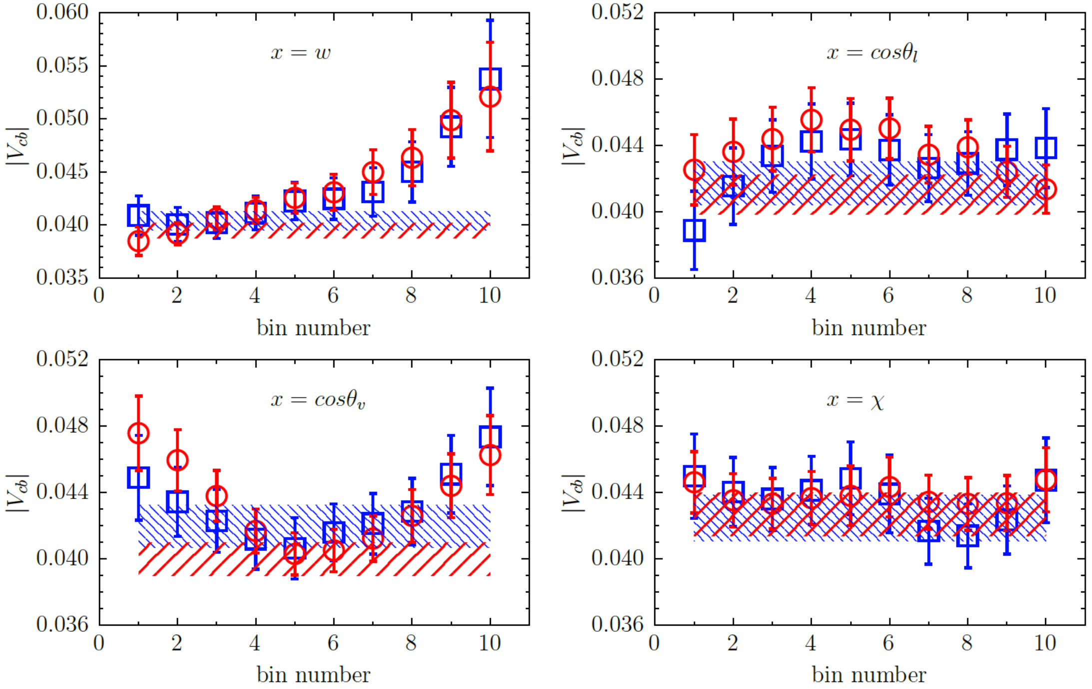
(see D'Agostini, arXiv: 2001.07562)

- we recover the above property by evaluating the correlation matrix of the experimental ratios

$$\frac{1}{\Gamma^{exp.}} \left(\frac{d\Gamma}{dx}\right)_i^{exp.}$$

and by considering the new covariance matrix of the experimental data given by (see arXiv:2105.08674)

$$\widetilde{C}_{ij}^{exp.} \to \rho_{ij}^{ratios} \sqrt{C_{ii}^{exp.} C_{jj}^{exp.}}$$



blue data: Belle 1702.01521

red data: Belle 1809.03290

significative improvement of the $\chi^2/(\mathrm{d.o.f.})$

bands are (correlated) weighted averages

$$|V_{cb}| = \frac{\sum_{i,j=1}^{10} (\mathbf{C}^{-1})_{ij} |V_{cb}|_j}{\sum_{i,j=1}^{10} (\mathbf{C}^{-1})_{ij}} ,$$

$$\sigma^2_{|V_{cb}|} = \frac{1}{\sum_{i,j=1}^{10} (\mathbf{C}^{-1})_{ij}} ,$$

Exclusive Vcb determination from B → D*

Belle 1702.01521

Belle 1809.03290

experiment	$\|V_{cb}\|(x=w)$	$\|V_{cb}\|(x=\cos\theta_l)$	$\|V_{cb}\|(x=\cos\theta_v)$	$\|V_{cb}\|(x=\chi)$
Ref. [11]	0.0404 (9)	0.0417 (13)	0.0420 (13)	0.0425 (14)
χ^2/(d.o.f.)	1.05	0.89	0.69	0.73
Ref. [12]	0.0395 (7)	0.0410 (12)	0.0400 (10)	0.0427 (13)
χ^2/(d.o.f.)	1.22	1.36	2.02	0.41

averaging procedure

$$\mu_x = \frac{1}{N}\sum_{k=1}^{N} x_k \ ,$$

$$\sigma_x^2 = \frac{1}{N}\sum_{k=1}^{N}\sigma_k^2 + \frac{1}{N}\sum_{k=1}^{N}(x_k-\mu_x)^2,$$

$$|V_{cb}| = (41.2 \pm 1.6)\cdot 10^{-3}$$

with the original covariance of Belle data

$$|V_{cb}| = (40.5 \pm 1.7)\cdot 10^{-3}$$

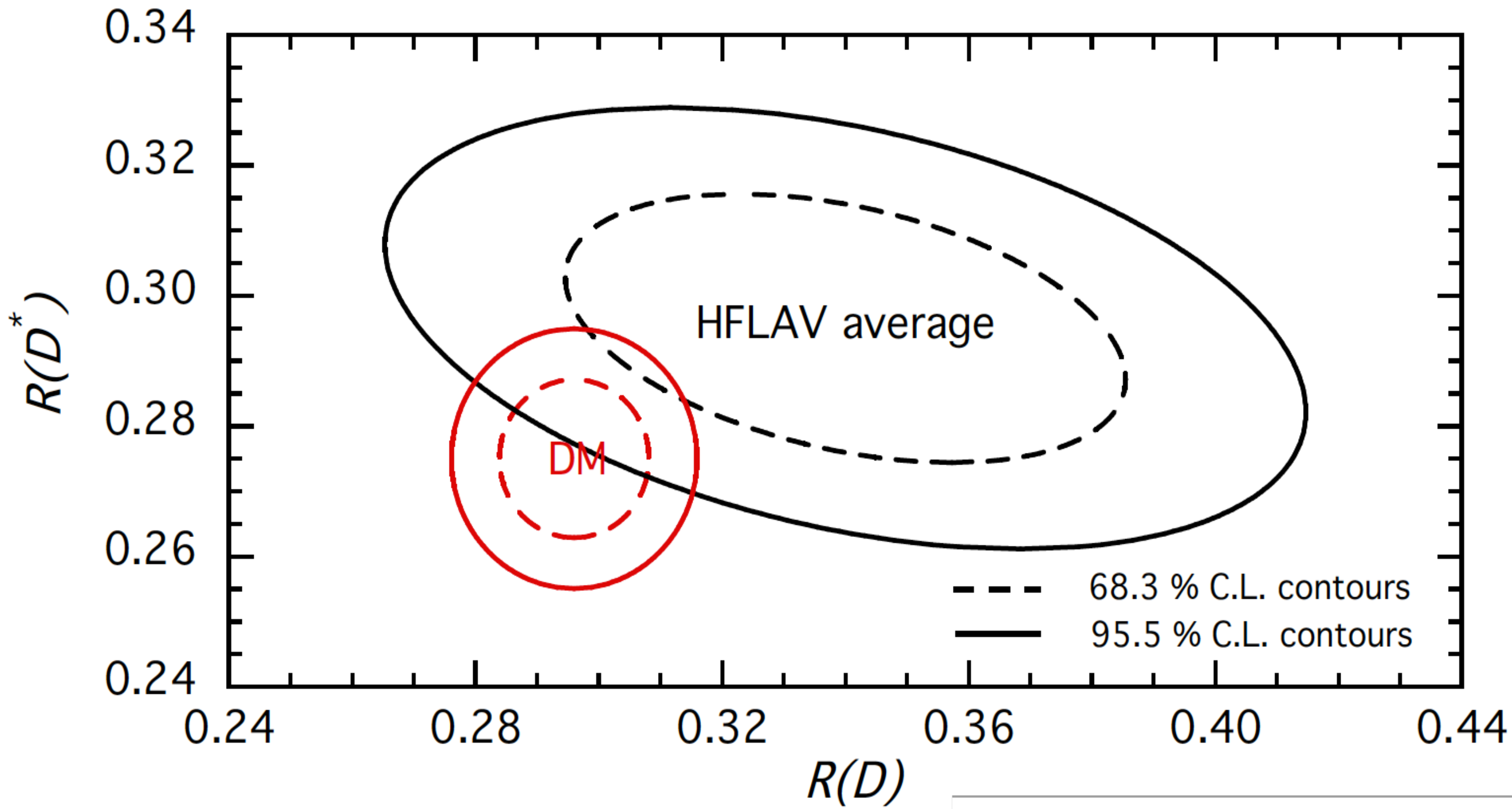
$|V_{cb}|_{excl.} \cdot 10^3 = 39.6^{+1.1}_{-1.0}$ Gambino et al., arXiv:1905.08209

$|V_{cb}|_{excl.} \cdot 10^3 = 39.56^{+1.04}_{-1.06}$ Jaiswal et al., arXiv:2002.05726

$|V_{cb}|_{excl.} \cdot 10^3 = 38.86 \pm 0.88$ FLAG '21, arXiv:2111.09849

the use of exp. data to describe the shape of the FFs leads to smaller errors, but the use of truncated BGL fits does not guarantee that the final error is not underestimated

$|V_{cb}|_{incl.} \cdot 10^3 = 42.16 \pm 0.50$ (Bordone et al: arXiv:2107.00604)

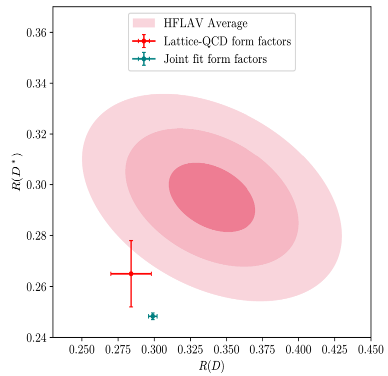


Is there really a problem with Lepton Flavor Universality in $B \to D^{(*)}$ decays ?

or

Much ado about nothing

$R(D^{(*)})$



Lattice-QCD-only SM predictions:

$$R(D^*)_{\text{FNAL/MILC 2021}} = 0.265 \pm 0.013$$
$$R(D)_{\text{FNAL/MILC 2015}} = 0.284 \pm 0.014$$
$$R(D)_{\text{FLAG 2021}} = 0.2934 \pm 0.0053$$

[FNAL/MILC, arXiv:2105.14019; HFLAV, arXiv:1909.12524/EPJC 2021]

See the talks by Judd Harrison, Shoji Hashimoto, Takashi Kaneko, Gumaro Rendon, and Silvano Simula for more lattice results on heavy→heavy decays!

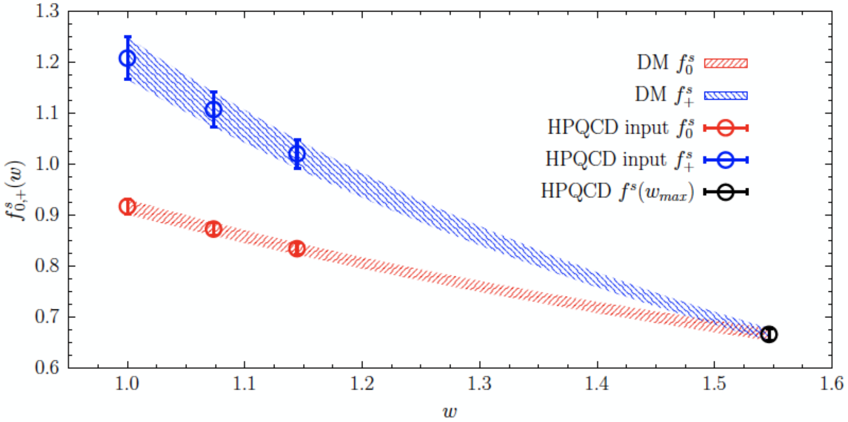
S. Meinel CKM21

form factors for $B_s \to D_s^{(*)} \ell \nu_\ell$ decays

[arXiv:2204.05925]

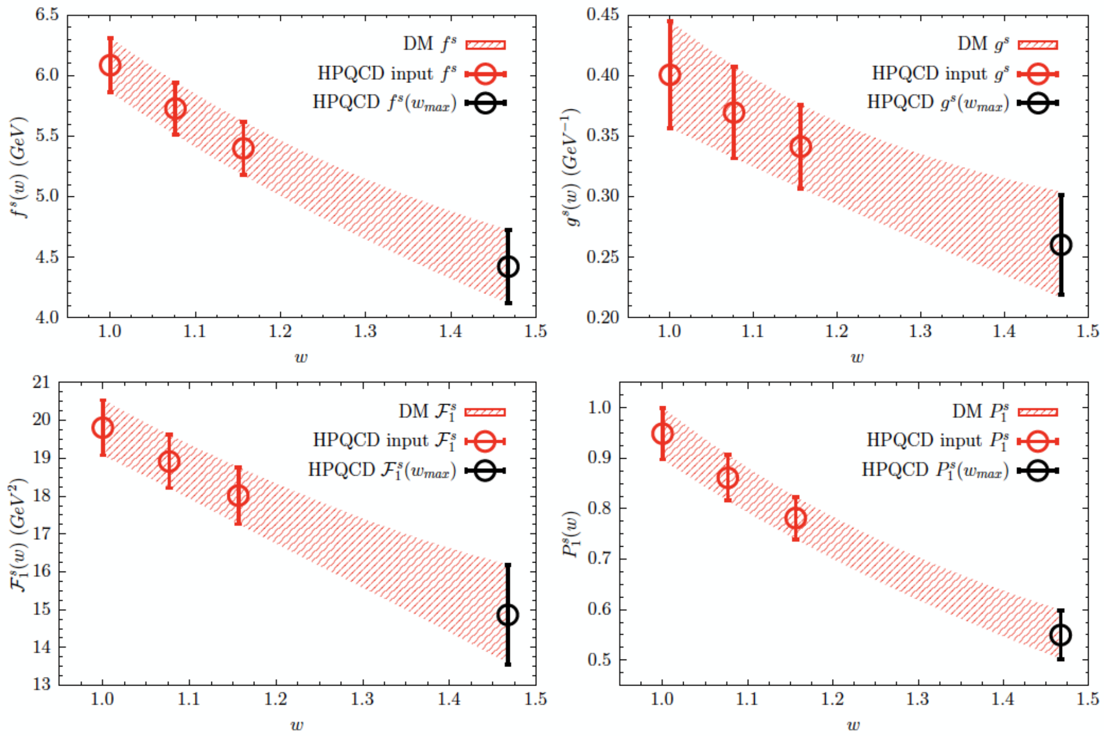
* lattice QCD form factors from **HPQCD arXiv:1906.00701**($B_s \to D_s$) and **arXiv:2105.11433** ($B_s \to D_s^*$) in the form of BCL fits in the whole kinematical range
* we extract 3 data points for the FFs at small values of the recoil and we apply the DM approach

$B_s \to D_s \ell \nu_\ell$



* nice agreement in the whole kinematical range

$B_s \to D_s^* \ell \nu_\ell$



DM confronts BGL

two important differences in the DM method with respect to BGL parametrization

- No series expansion to describe the FFs → ***NO TRUNCATION ERRORS***

particularly relevant for semileptonic decays characterized by a very large q^2 range

$B \to \pi \ell \nu$ Maximum $q^2 = 26.46$ GeV^2

$\Lambda_b \to p \ell \nu$ Maximum $q^2 = 21.9$ GeV^2

- Unitarity check of FFs data completely independent of the parameterization

The DM approach

i) reproduces exactly the known data

ii) allows to extrapolate the form factor in the whole kinematical range

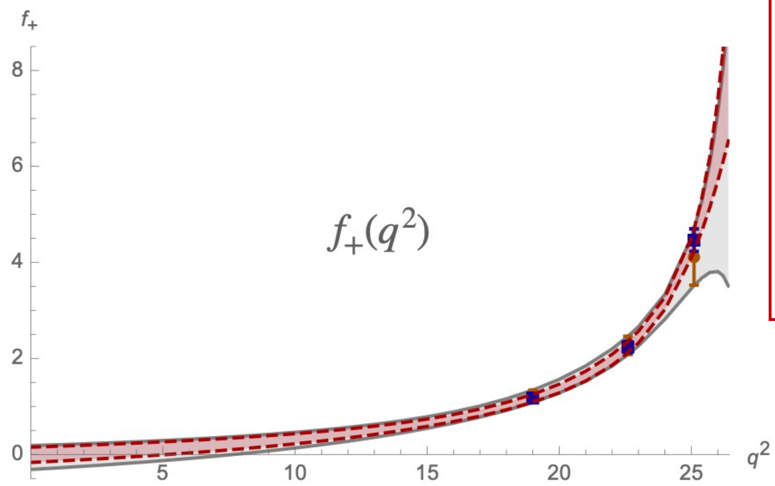
iii) in a parameterization-independent way

iv) providing a band of values representing the results of all possible BGL fits satisfying unitarity and passing through the known points (important for estimating uncertainties)

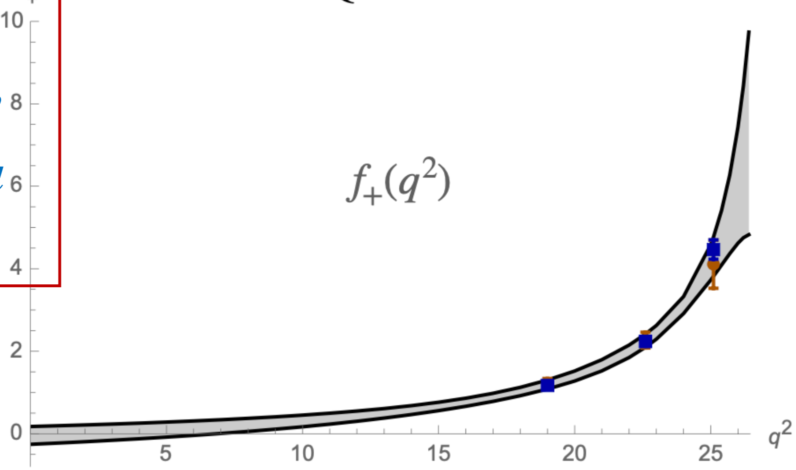
Semileptonic B → π decays *(in prep.)*

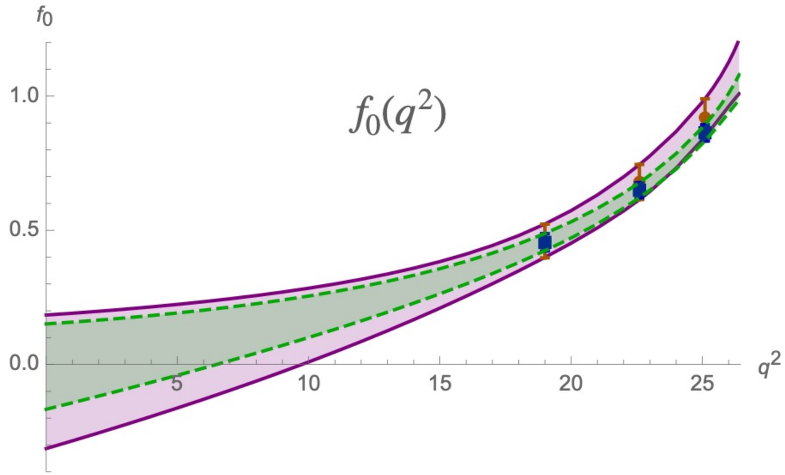
Solid: RBC/UKQCD
Dashed: FNAL/MILC

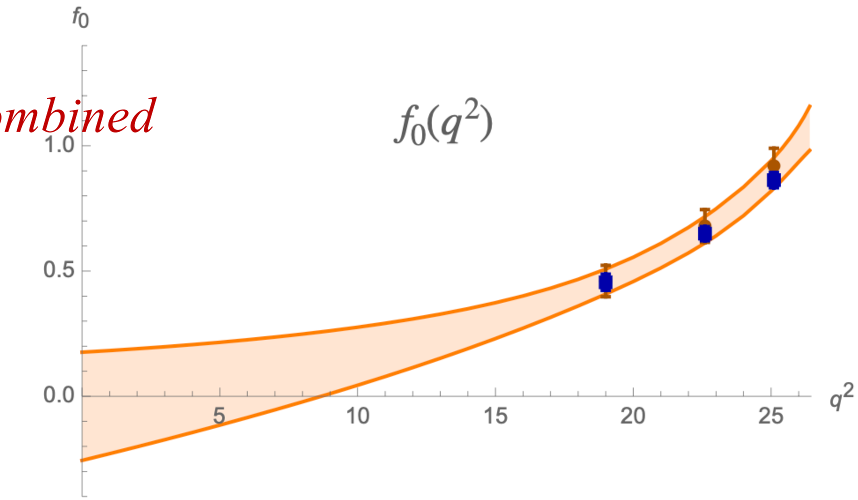
Non-perturbative susceptibility for the $b \to u$ current



RBC/UKQCD + FNAL/MILC



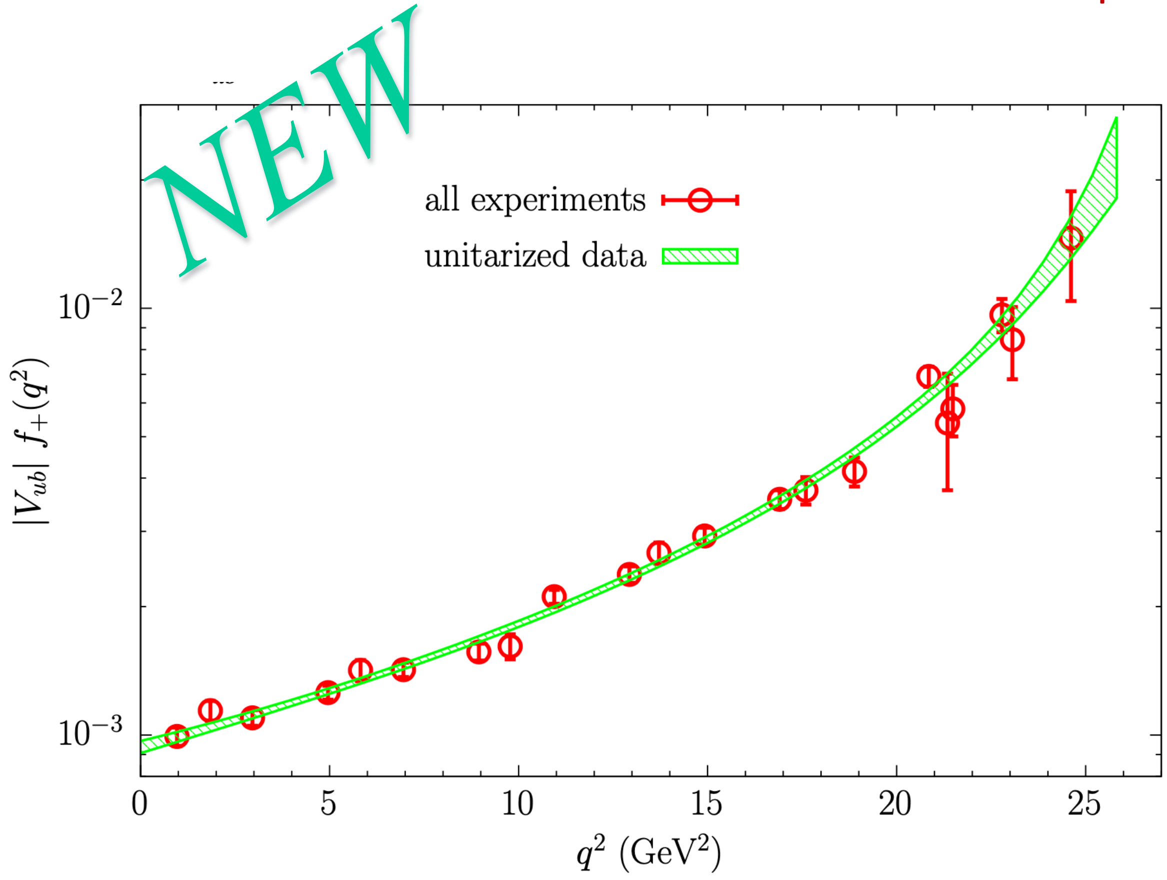




	$f_+(0) = f_0(0)$
RBC/UKQCD	-0.06 ± 0.25
FNAL/MILC	-0.01 ± 0.16
Combined	-0.04 ± 0.22
LCSR	0.28 ± 0.03

- **3 RBC/UKQCD data (points) for each FF [arXiv:1501.05363]**
- **3 FNAL/MILC data (squares) for each FF [arXiv:1503.07839]**

Unitarization of the experimental data



$$|\mathbf{V_{ub}}|_{\mathbf{DM}} \times \mathbf{10^3} = \mathbf{3.88 \pm 0.32}$$

Reference	$\|V_{ub}\| \times 10^3$
FLAG '21	3.74 ± 0.17
HFLAV '18 & PDG '20	4.32 ± 0.29
Belle Coll. '21	4.10 ± 0.28

Exclusive and the inclusive values are compatible at the 1σ level

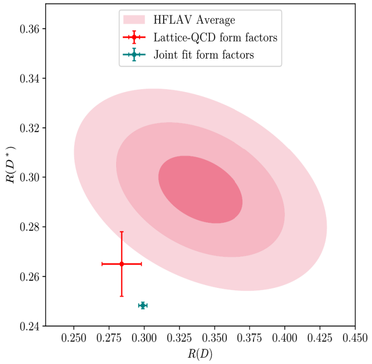
* construct the experimental values of $|V_{ub} f_+(q_i^2)| = \sqrt{\Delta\Gamma_i / z_i}$ (z_i = kinematical coefficient in the i-th bin)

* apply the DM method on the data points $|V_{ub} f_+(q_i^2)|$ using the unitarity bound $|V_{ub}|^2 \chi_{1^-}(0)$ with an initial guess for $|V_{ub}|$

* determine $|V_{ub}|$ using the theoretical DM bands and iterate the procedure until consistency for $|V_{ub}|$ is reached

S. Meinel CKM21

$R(D^{(*)})$



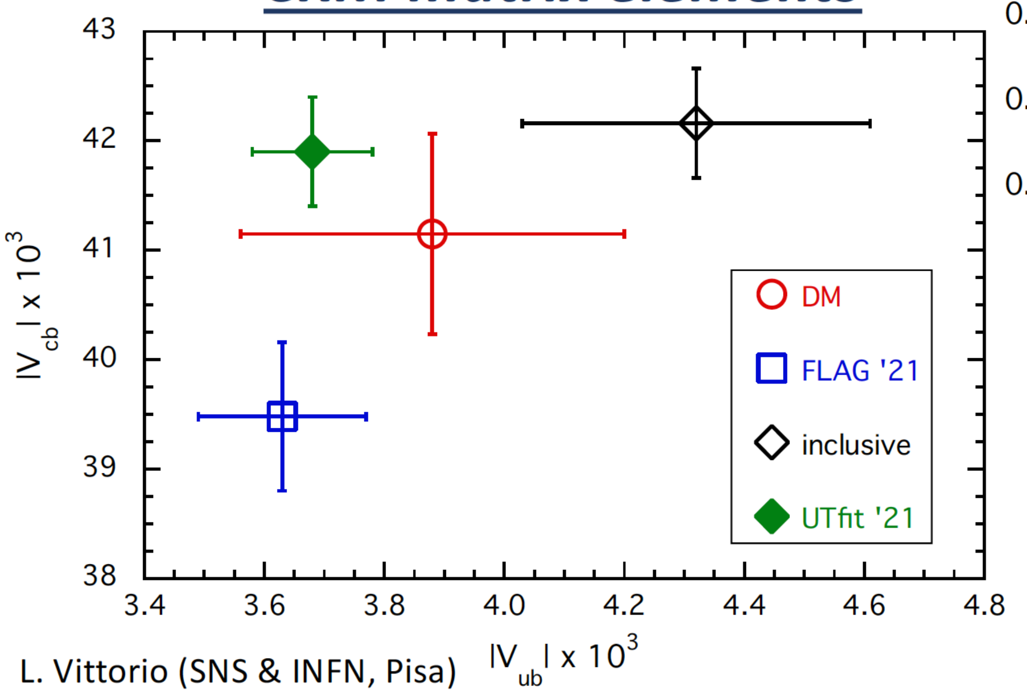
Lattice-QCD-only SM predictions:

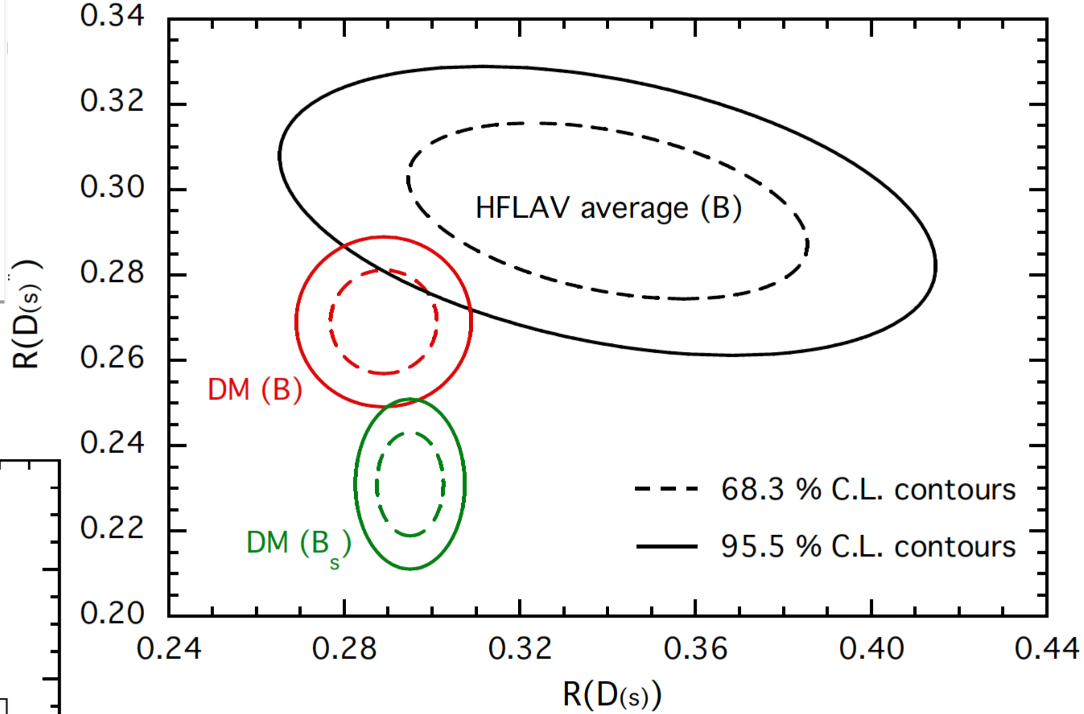
$$R(D^*)_{\text{FNAL/MILC 2021}} = 0.265 \pm 0.013$$
$$R(D)_{\text{FNAL/MILC 2015}} = 0.284 \pm 0.014$$
$$R(D)_{\text{FLAG 2021}} = 0.2934 \pm 0.0053$$

[FNAL/MILC, arXiv:2105.14019; HFLAV, arXiv:1909.12524/EPJC 2021]

See the talks by Judd Harrison, Shoji Hashimoto, Takashi Kaneko, Gumaro Rendon, and Silvano Simula for more lattice results on heavy→heavy decays!

CKM matrix elements





LFU observables

IMPORTANT: *the difference between* the red and the green area *comes from the difference in the LQCD computations by FNAL/MILC and HPQCD Collaborations*

Conclusions

*The **Dispersion Matrix approach** is a powerful tool to implement unitarity in the analysis of exclusive semileptonic decays of mesons and baryons*

- it does not rely on any assumption about the momentum dependence of the hadronic form factors

- it can be based entirely on first principles *(i.e*. unitarity and analiticity) using non-perturbative lattice determinations of both the relevant form factors and the dispersive bounds (the susceptibilities) from appropriate 2-point and 3-point (Euclidean) correlation functions

- it predicts band of values that are equivalent to all possible BGL fits satisfying unitarity and reproducing exactly a given set of data points. Larger but more reliable uncertainties

- It is not biased by the fit of the experimental data

- it is universal, namely it can be applied to any exclusive semileptonic decay e.g. baryon decays

Conclusions 2

New insight on both:

- *the |Vcb|, |Vub| puzzles (exclusive and inclusive determinations compatible @ the 1σ level)*

We found problems with the Belle covariance matrix

- *the R(D(*)) anomalies (theoretical values and measurements compatible @ the 1.6σ level)*

- *No apparent deviation in the down sector, what about the up one?*