Recent developments in Flavor physics, the Unitarity Fit, Anomalies and all that

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Tribute to Gauss & Kandinsky by G Martinelli

Corfù August 31 2023

UTfit

Extended Twisted Mass Collaboration

PRACE

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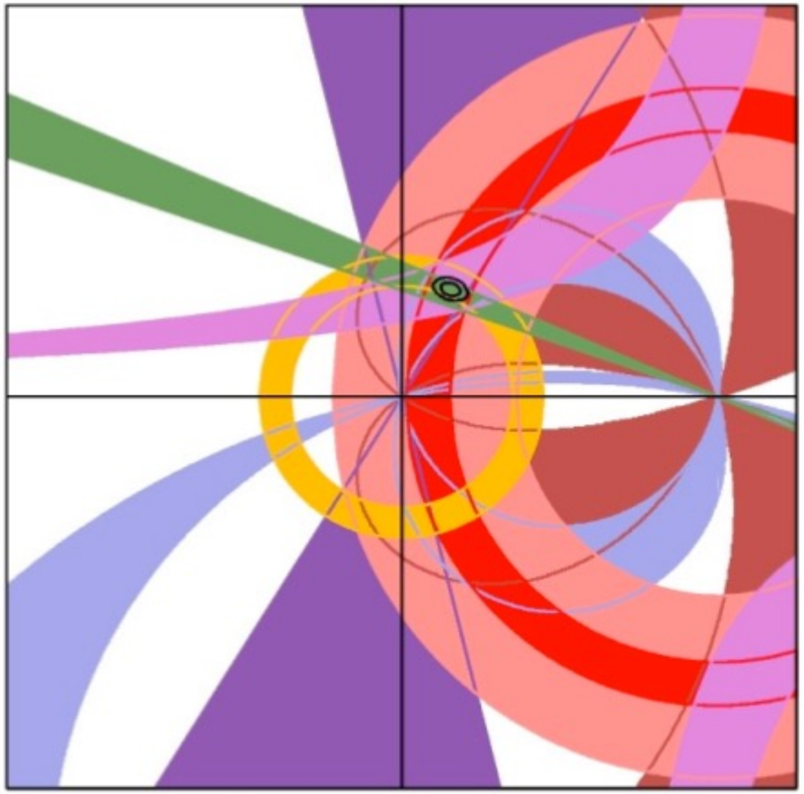
Istituto Nazionale di Fisica Nucleare

PLAN OF THE TALK

- *General introduction to the Unitary Triangle Fit*
- *SM Analysis*
- *Tensions and unknown*
- *Future directions, new/old ideas*
- *Conclusion*



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

With respect to the published paper several theoretical and experimental new unputs and updated results

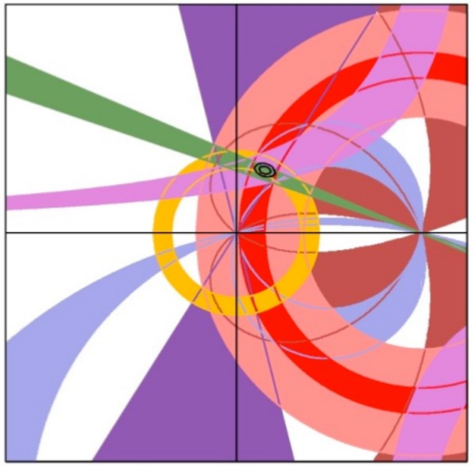
Thanks to
M. Bona, A. Di Domenico, C. Kelly, V. Lubicz, C. Sachrajda, L. Silvestrini, S. Simula, L. Vittorio

Flavour Physics

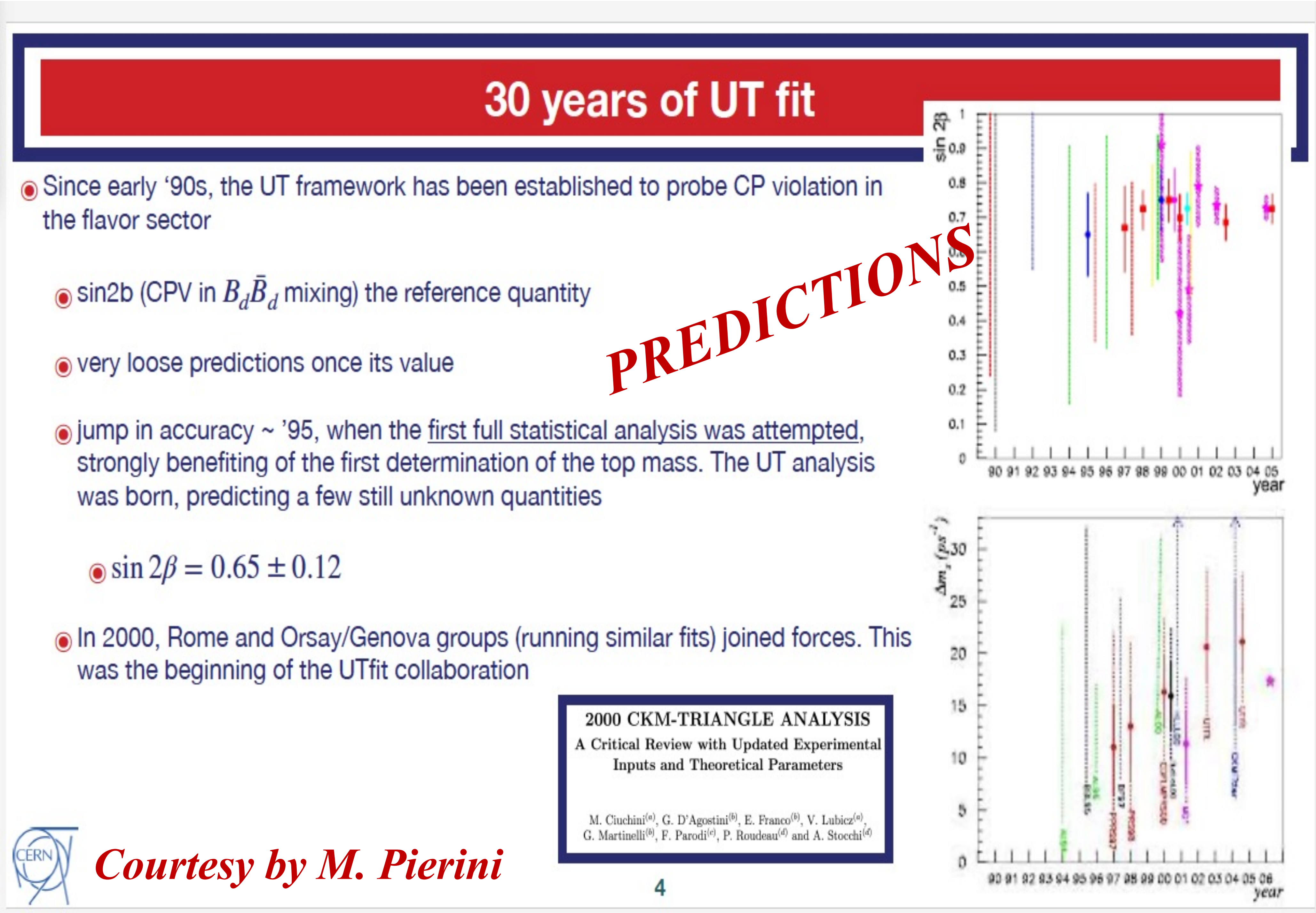
1963: Cabibbo Angle
1964: CP violation in K decays *
1970 GIM Mechanism
1973: CP Violation needs at least three quark families (CKM) *
1975: discovery of the tau lepton – 3rd lepton family *
1977: discovery of the b quark - 3rd quark family *
2003/4: CP violation in B meson decays

* Nobel Prize

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 <u>predictions</u> 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 <u>precision</u> flavor physics should not be underestimated*



30 years of UT fit

- Since early '90s, the UT framework has been established to probe CP violation in the flavor sector
  - sin2b (CPV in $B_d\bar{B}_d$ mixing) the reference quantity
  - very loose predictions once its value
  - jump in accuracy ~ '95, when the first full statistical analysis was attempted, strongly benefiting of the first determination of the top mass. The UT analysis was born, predicting a few still unknown quantities
    - $\sin 2\beta = 0.65 \pm 0.12$
  - In 2000, Rome and Orsay/Genova groups (running similar fits) joined forces. This was the beginning of the UTfit collaboration

PREDICTIONS

2000 CKM-TRIANGLE ANALYSIS
A Critical Review with Updated Experimental Inputs and Theoretical Parameters

M. Ciuchini[a], G. D'Agostini[b], E. Franco[b], V. Lubicz[a], G. Martinelli[b], F. Parodi[c], P. Roudeau[d] and A. Stocchi[d]

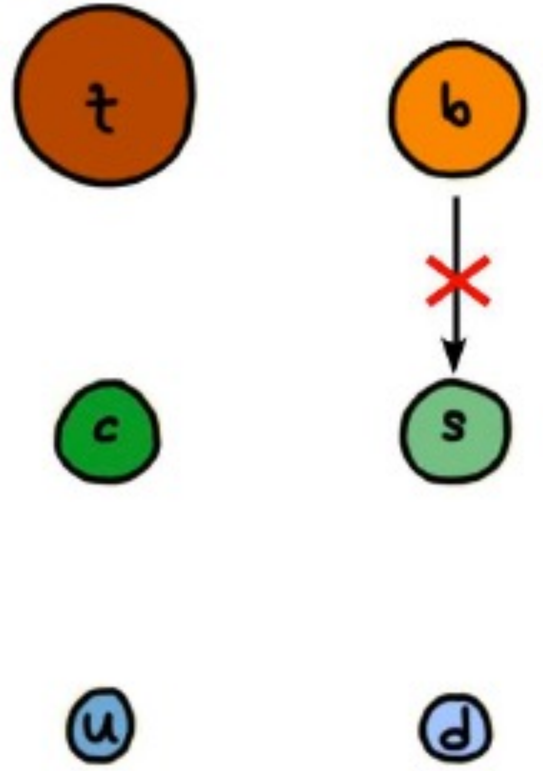
Courtesy by M. Pierini

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



RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

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

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

$q_i \rightarrow q_k + \gamma$

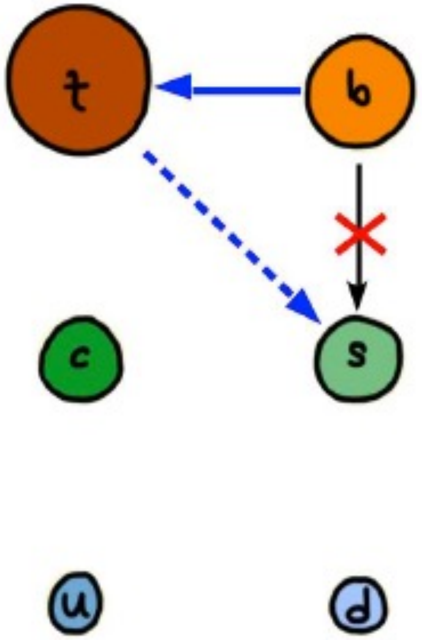
these decays occur only via loops because of GIM and are suppressed by CKM

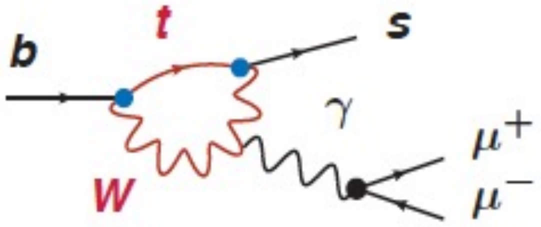
THUS THEY ARE SENSITIVE TO NEW PHYSICS

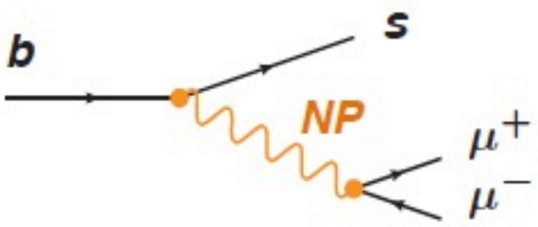
Flavor Changing Neutral Currents in the SM

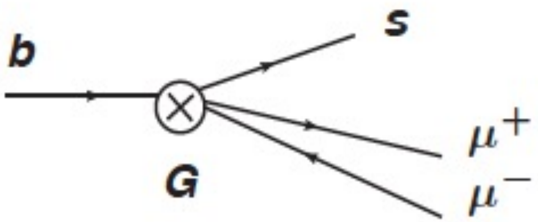
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

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









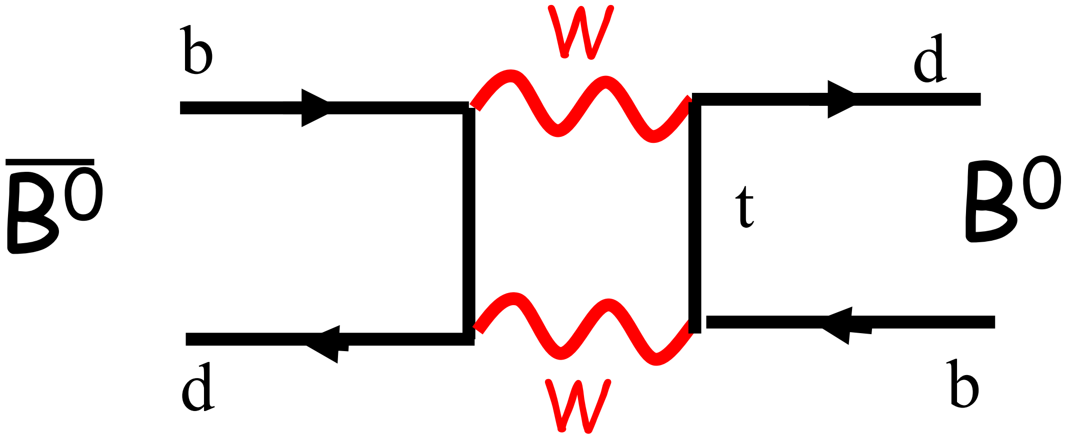
$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

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

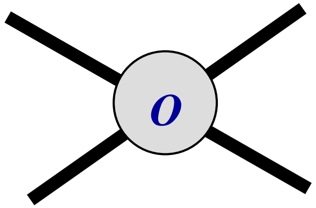
B^0 - $\overline{B^0}$ mixing

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

ΔB=2 Transitions



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



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

Hadronic matrix element

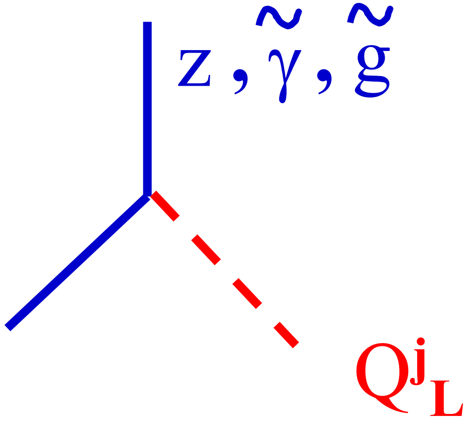
CKM

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

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

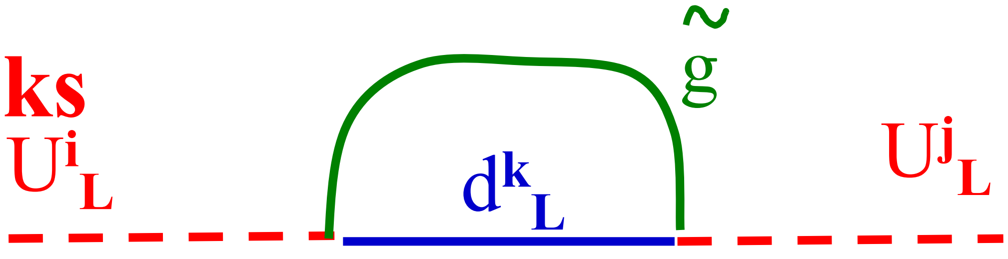
Diagonalize the SMM

FCNC

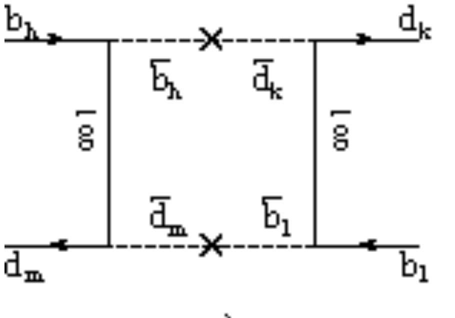


or **Rotate by the same matrices the SUSY partners of the u- and d- like quarks**

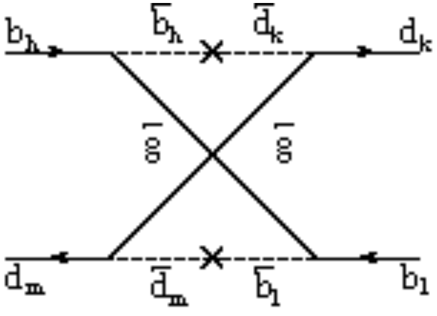
$(Q^j_L)' = U^{ij}_L \, Q^j_L$



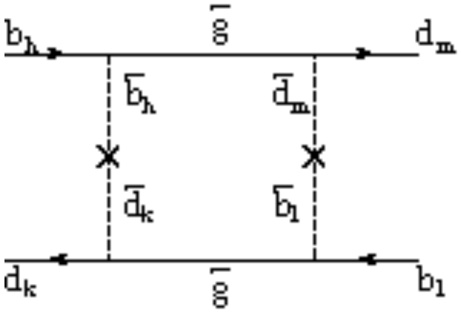
In the latter case the Squark Mass Matrix is not diagonal



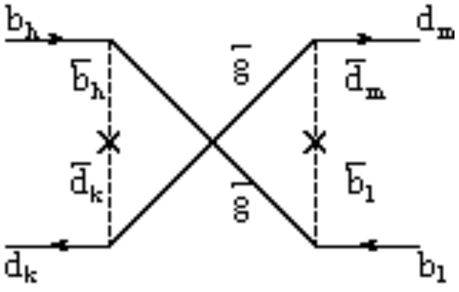
a)



c)



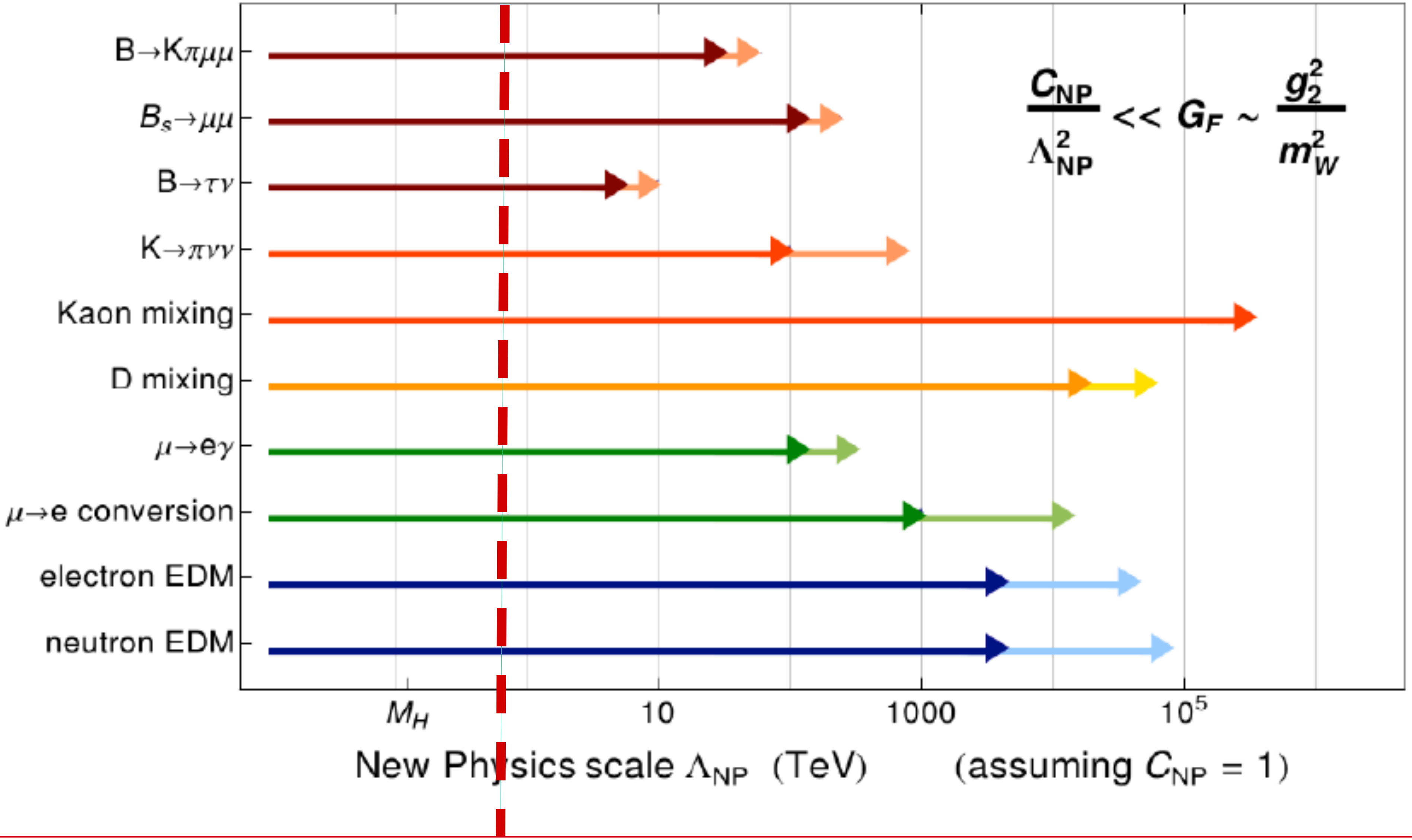
b)



d)

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

Sensitivity to New Physics from Flavor



Approximate LHC direct reach

CP Violation in the Standard Model

After the diagonalisation of the quark mass matrix

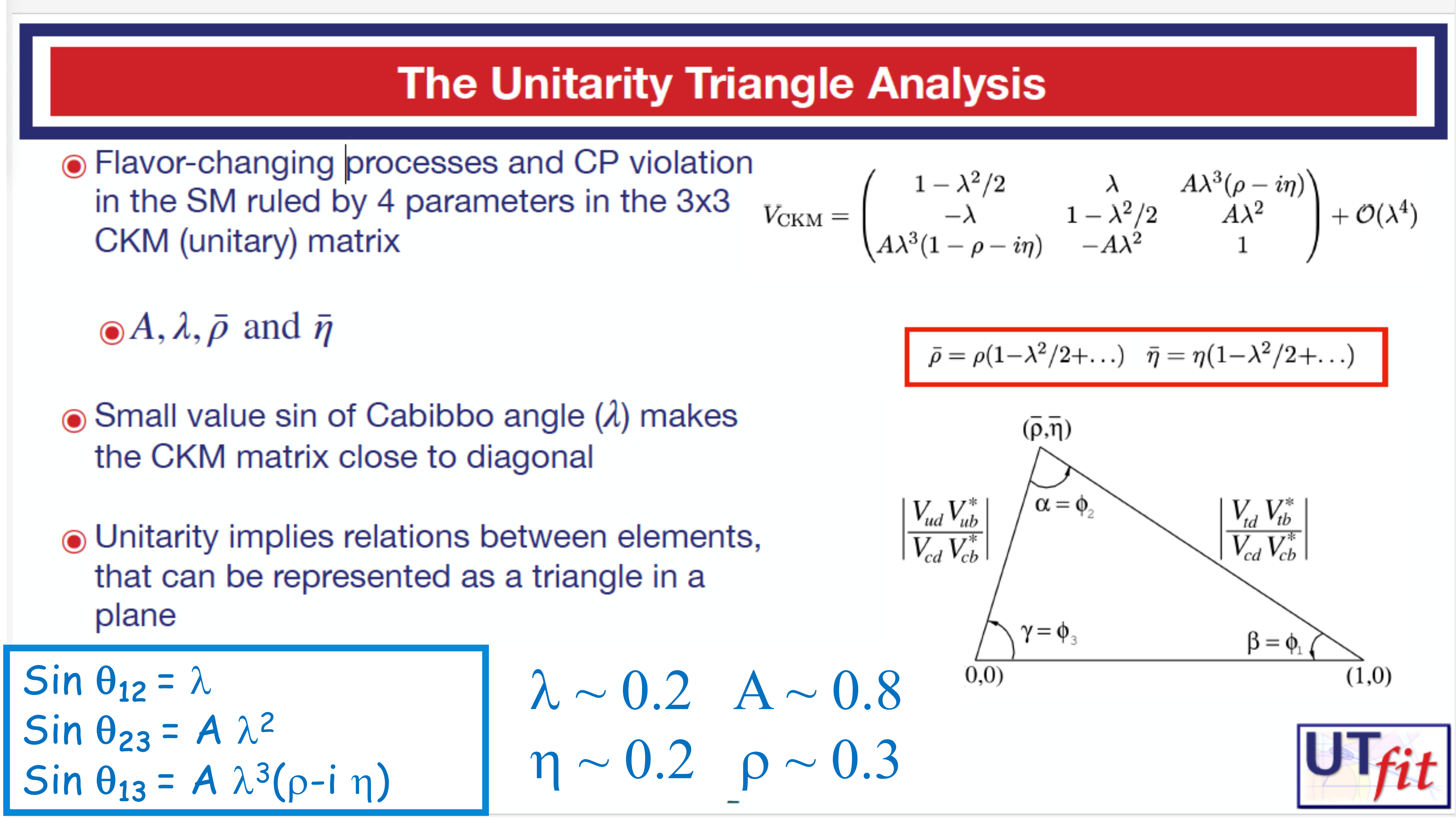
$$
\begin{aligned}
L_{CC}^{weak\,int} &= \frac{g_W}{\sqrt{2}}\left(J_\mu^- W_\mu^+ + h.c.\right) \\
\rightarrow \quad & \frac{g_W}{\sqrt{2}}\left(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W_\mu^+ + \ldots\right)
\end{aligned}
$$

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



The Unitarity Triangle Analysis

- Flavor-changing processes and CP violation in the SM ruled by 4 parameters in the 3x3 CKM (unitary) matrix

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

- $A, \lambda, \bar\rho$ and $\bar\eta$

$$\boxed{\bar\rho = \rho(1-\lambda^2/2+\ldots) \quad \bar\eta = \eta(1-\lambda^2/2+\ldots)}$$

- Small value sin of Cabibbo angle (λ) makes the CKM matrix close to diagonal

- Unitarity implies relations between elements, that can be represented as a triangle in a plane

UTfit

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

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

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

STRONG CP VIOLATION

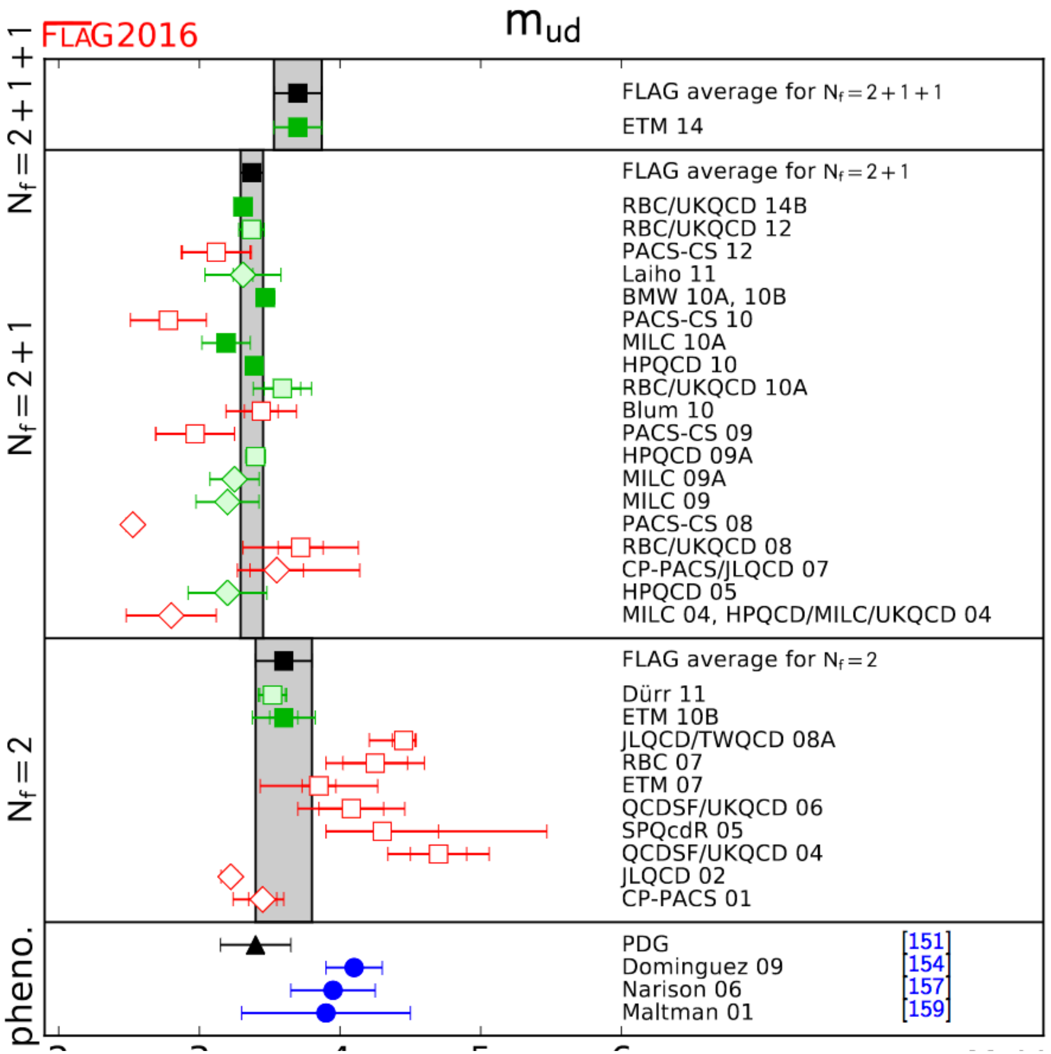
$$\mathcal{L}_\theta = \theta \, \tilde{G}^{\mu\nu a} G^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

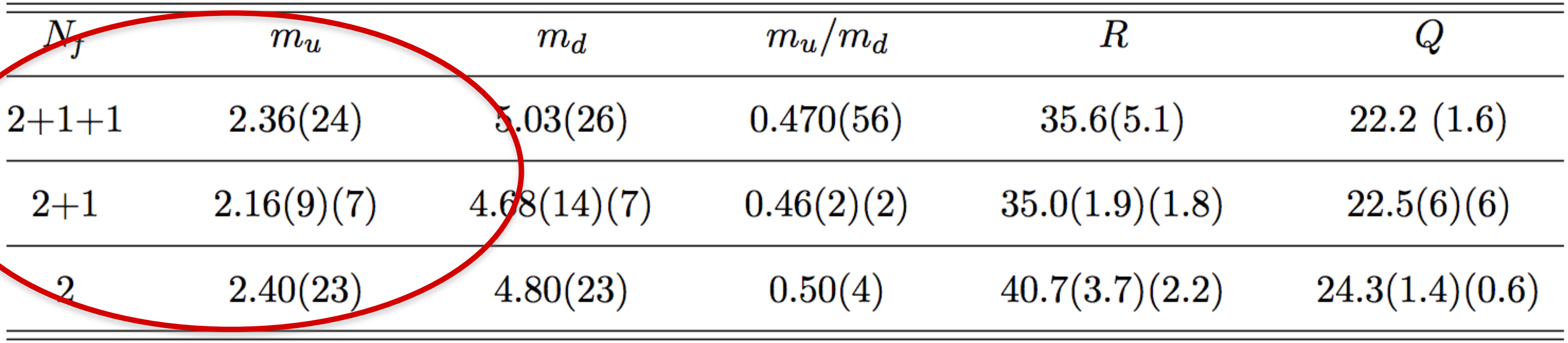
$$\mathcal{L}_\theta \sim \theta \, \vec{E}^a \cdot \vec{B}^a$$

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 !!

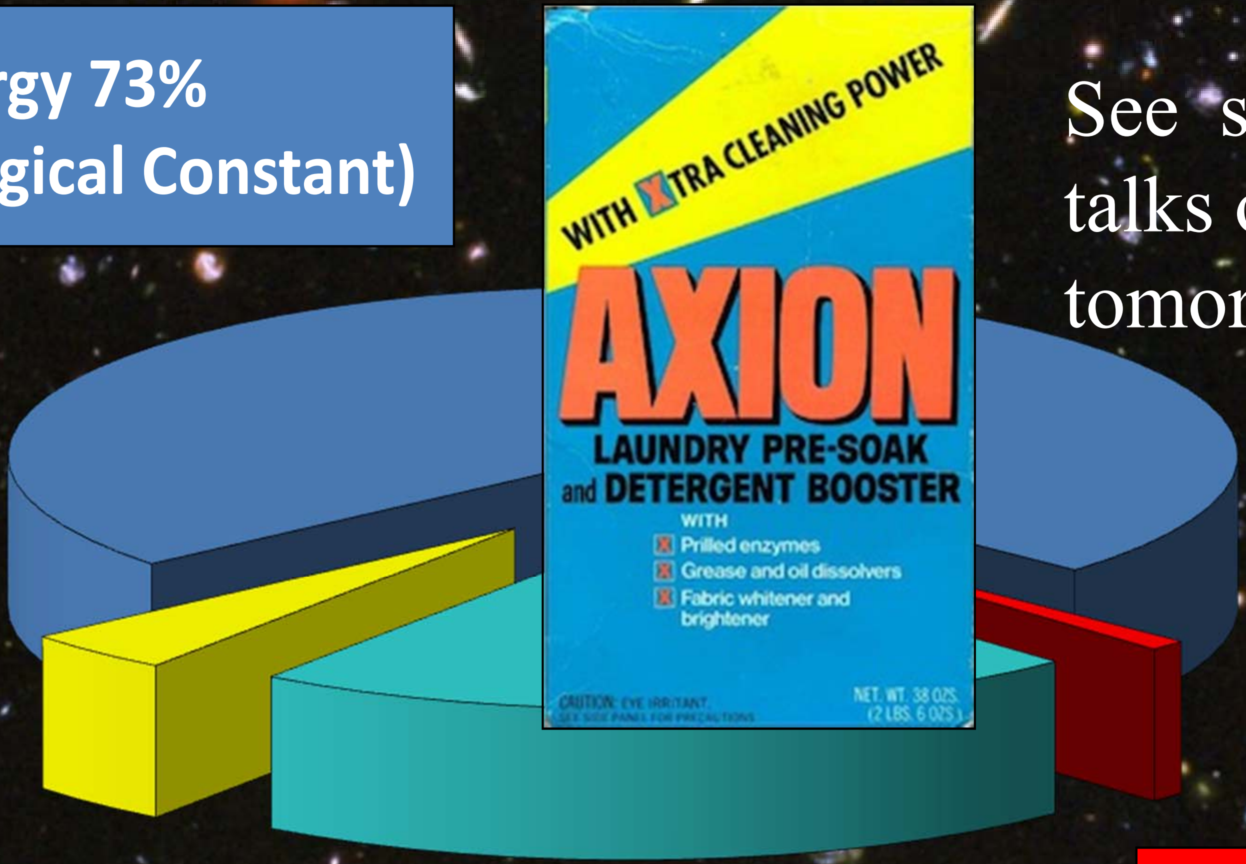




N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.36(24)	5.03(26)	0.470(56)	35.6(5.1)	22.2 (1.6)
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)	35.0(1.9)(1.8)	22.5(6)(6)
2	2.40(23)	4.80(23)	0.50(4)	40.7(3.7)(2.2)	24.3(1.4)(0.6)

Raffelt

Dark Energy 73%
(Cosmological Constant)



See several talks on axions tomorrow

Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%

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

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

SM

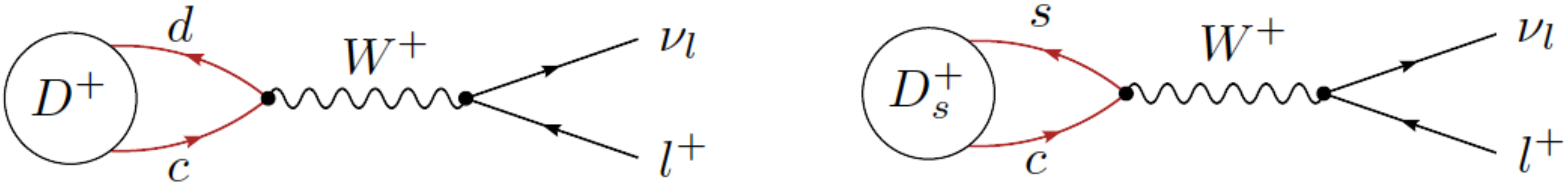
$$\boxed{Q^{EXP} = \sum_i C^i_{SM}(M_W, m_t, \alpha_s)\langle F|\hat{O}_i|I\rangle + \sum_{i'} C^{i'}_{Beyond}(\tilde{m}_\beta, \alpha_s)\langle F|\hat{O}_{i'}|I\rangle}$$

BSM

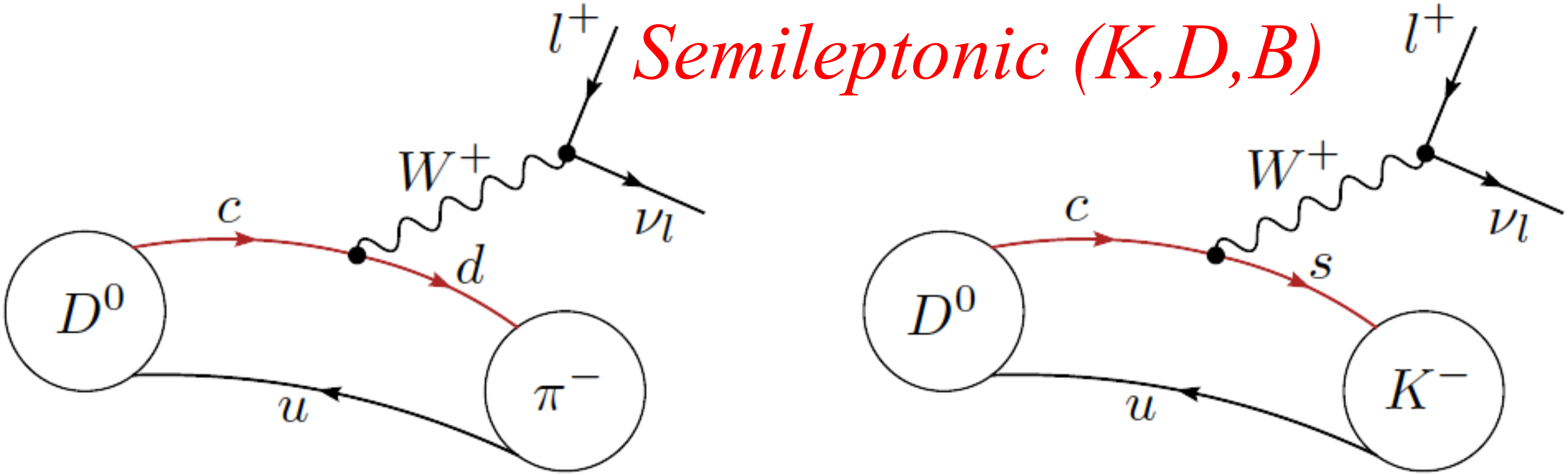
What can be computed and

What cannot be computed

Leptonic (π,K,D,B)



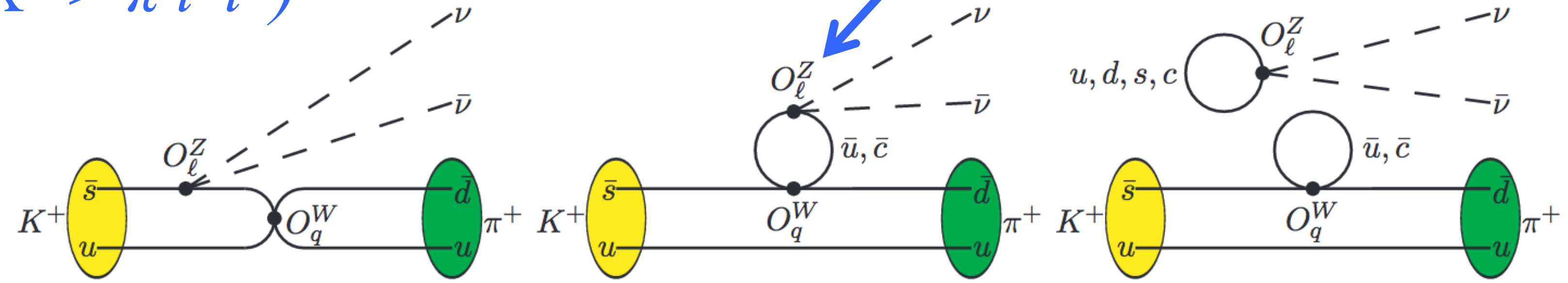
Semileptonic (K,D,B)



(some) Radiative and Rare

long distance effects

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

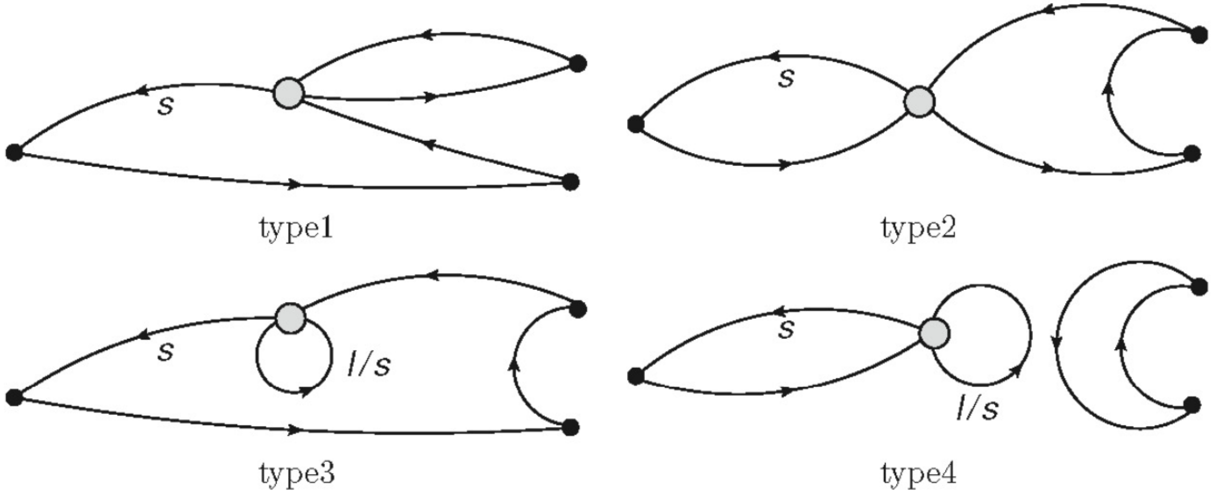


connected diag. self-loop diag. disconnected diag.

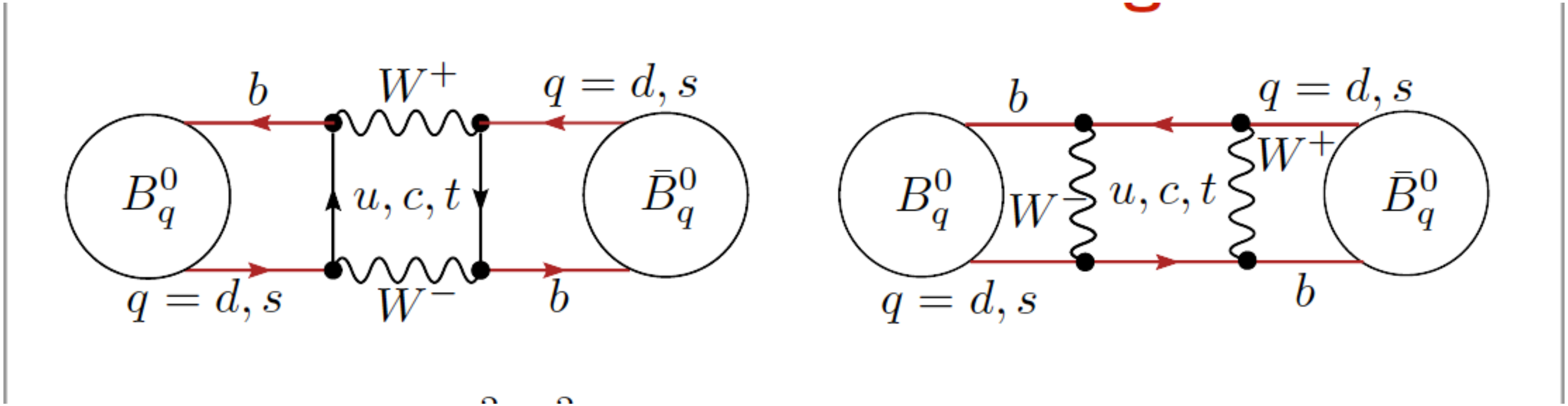
Non-leptonic

$B \to \pi\pi, K\pi$, etc. No !

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



Neutral meson mixing (local)



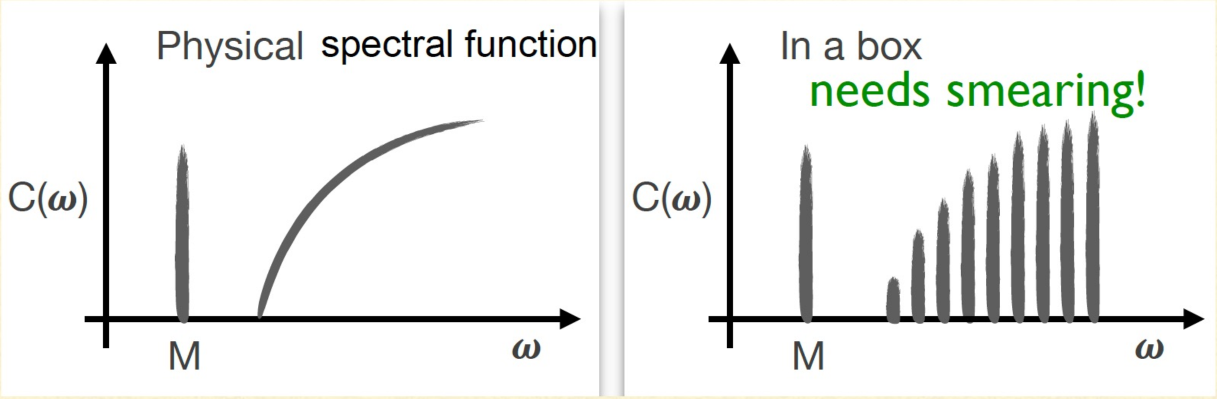
+ some long distance contributions to K and D neutral meson mixing + short distance contributions to $B \to K^{(*)} l^+ l^-$

INCLUSIVE DECAYS ON THE LATTICE

Inclusive processes impractical to treat directly on the lattice. Vacuum current correlators computed in euclidean space-time are related to $e^+e^- \to$ hadrons or τ decay via analyticity. In our case the correlators have to be computed in the *B* meson, but analytic continuation more complicated: two cuts, decay occurs only on a portion of the physical cut.

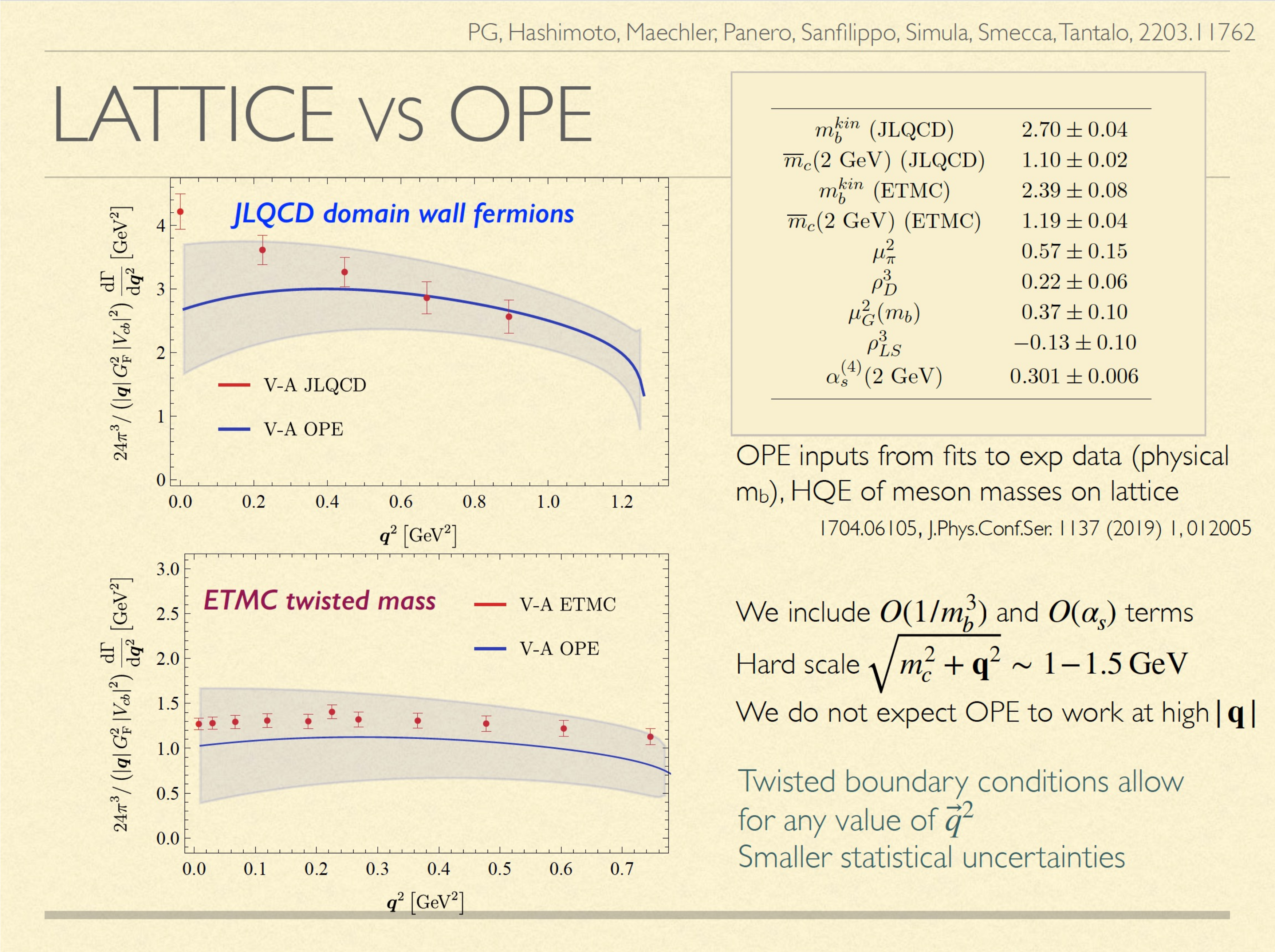
While the lattice calculation of the spectral density of hadronic correlators is an ***ill-posed problem***, the spectral density is accessible after smearing

Hansen, Meyer, Robaina, Hansen, Lupo, Tantalo, Bailas, Hashimoto, Ishikawa



W. Jay @Snowmass workshop

courtesy of P. Gambino



PG, Hashimoto, Maechler, Panero, Sanfilippo, Simula, Smecca, Tantalo, 2203.11762

LATTICE VS OPE

m_b^{kin} (JLQCD)	2.70 ± 0.04
$\overline{m}_c(2\text{ GeV})$ (JLQCD)	1.10 ± 0.02
m_b^{kin} (ETMC)	2.39 ± 0.08
$\overline{m}_c(2\text{ GeV})$ (ETMC)	1.19 ± 0.04
μ_π^2	0.57 ± 0.15
ρ_D^3	0.22 ± 0.06
$\mu_G^2(m_b)$	0.37 ± 0.10
ρ_{LS}^3	-0.13 ± 0.10
$\alpha_s^{(4)}(2\text{ GeV})$	0.301 ± 0.006

OPE inputs from fits to exp data (physical m_b), HQE of meson masses on lattice

1704.06105, J.Phys.Conf.Ser. 1137 (2019) 1, 012005

We include $O(1/m_b^3)$ and $O(\alpha_s)$ terms

Hard scale $\sqrt{m_c^2 + \mathbf{q}^2} \sim 1 - 1.5\,\text{GeV}$

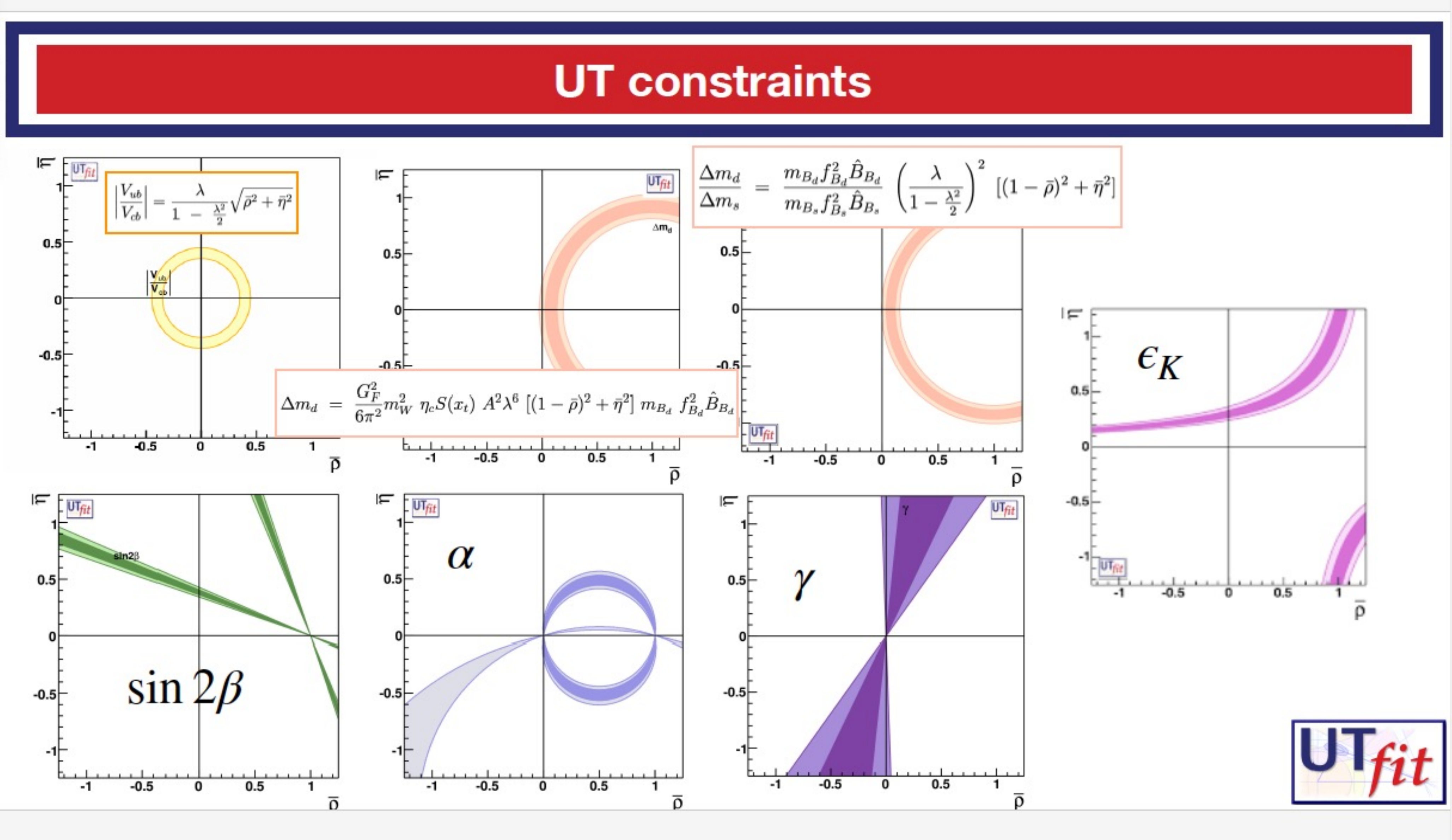
We do not expect OPE to work at high $|\mathbf{q}|$

Twisted boundary conditions allow for any value of $\vec{q}^{\,2}$

Smaller statistical uncertainties

courtesy of P. Gambino

UT constraints



$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar\rho^2+\bar\eta^2}$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f^2_{B_d} \hat{B}_{B_d}}{m_{B_s} f^2_{B_s} \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 \left[(1-\bar\rho)^2+\bar\eta^2\right]$$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6 \left[(1-\bar\rho)^2+\bar\eta^2\right] m_{B_d}\ f^2_{B_d} \hat{B}_{B_d}$$

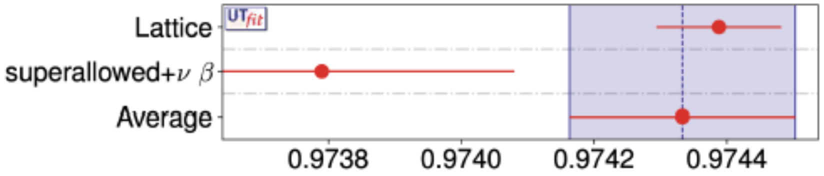
redundancy is the big strength of the UT analysis

one can remove a subset of inputs and still determine the CKM

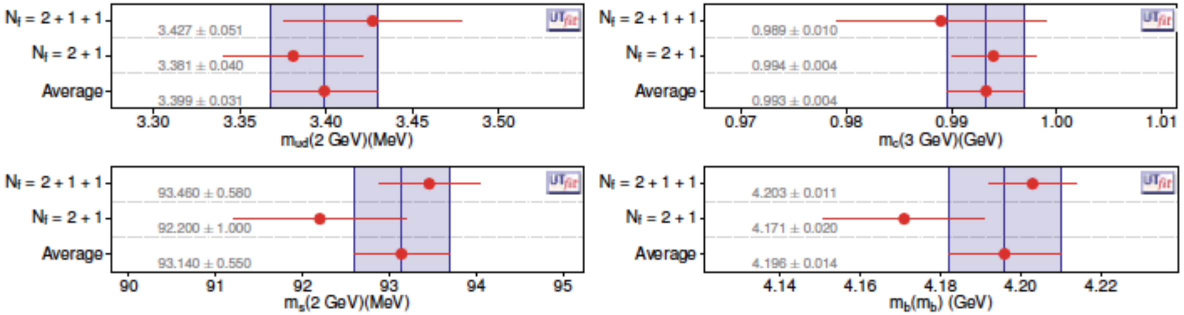
one can exclude η=0 using only CP conserving processes

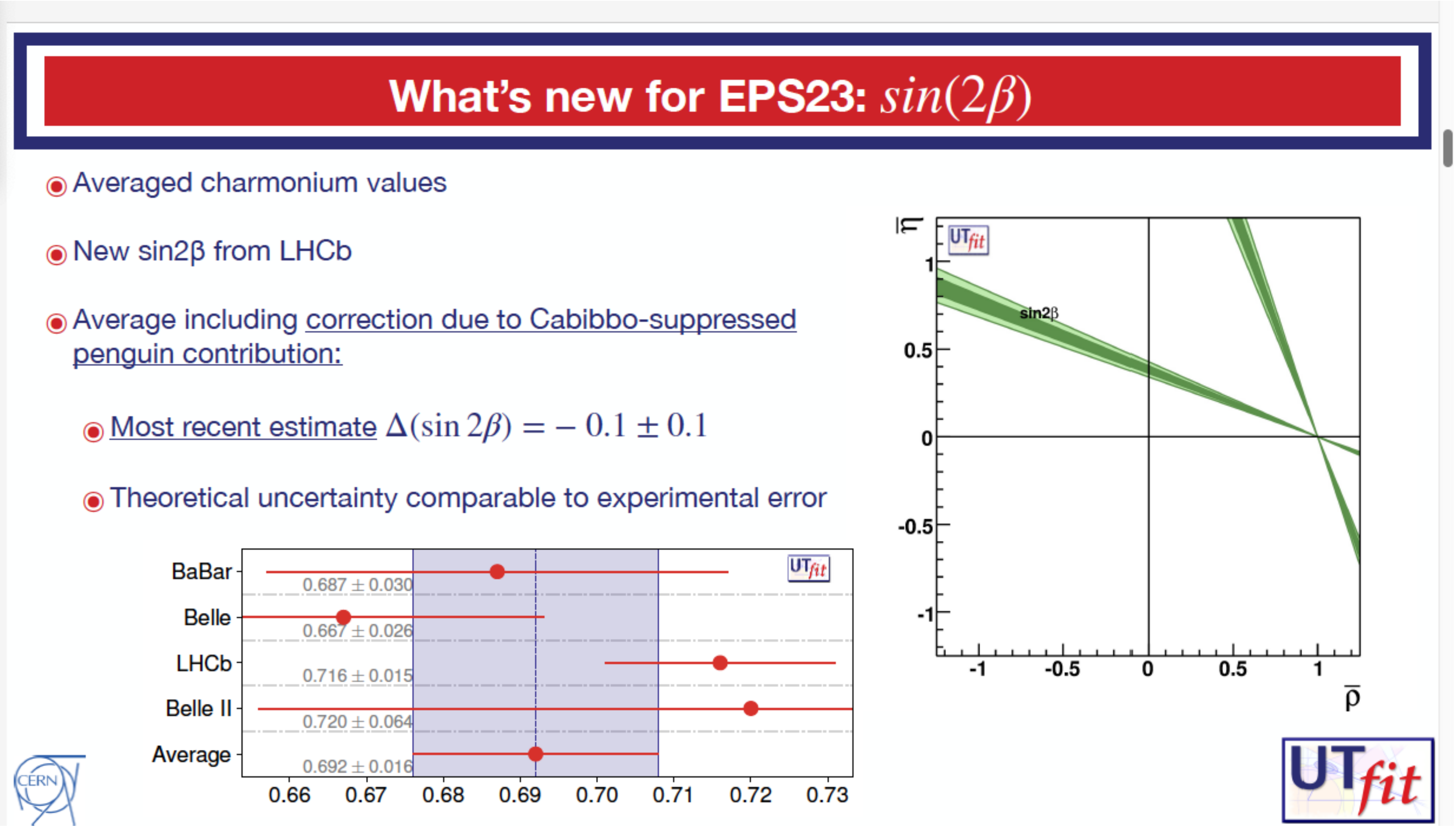
What's new for EPS23

- Theory updates:
  - New V_{ud} extraction from neutron decays, following V. Cirigliano et al. arXiv:2306.03138
  - New lattice values for masses
  - New lattice form factors for exclusive $b \to q\ell\nu$
- Experiment updates:
  - New sin2β by LHCb
  - New γ by LHCb
  - New α
- …



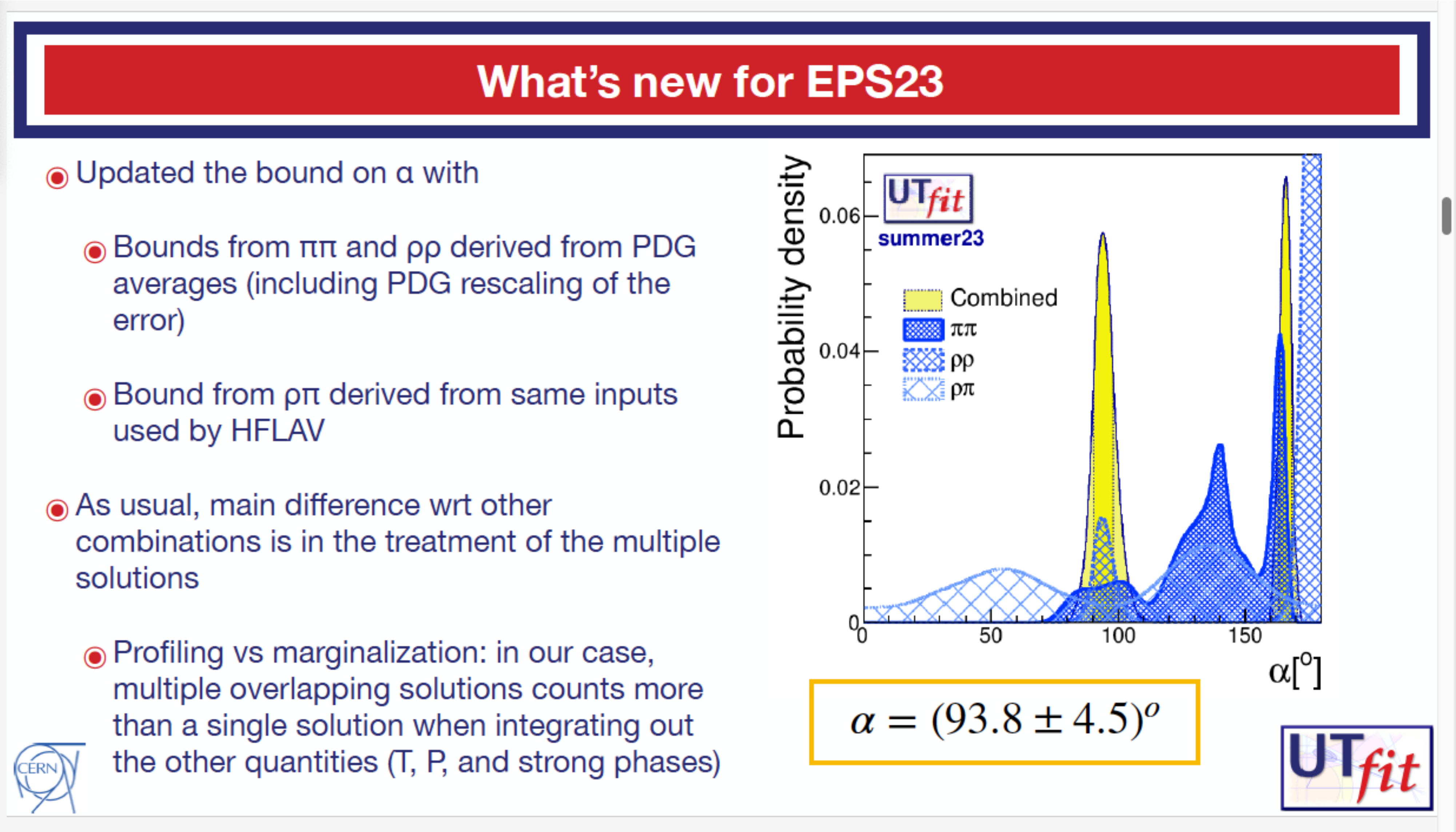
All masses computed in $\overline{\mathrm{MS}}$ and averaged with PDG scale factors





What's new for EPS23: $sin(2\beta)$

- Averaged charmonium values
- New sin2β from LHCb
- Average including correction due to Cabibbo-suppressed penguin contribution:
  - Most recent estimate $\Delta(\sin 2\beta) = -0.1 \pm 0.1$
  - Theoretical uncertainty comparable to experimental error

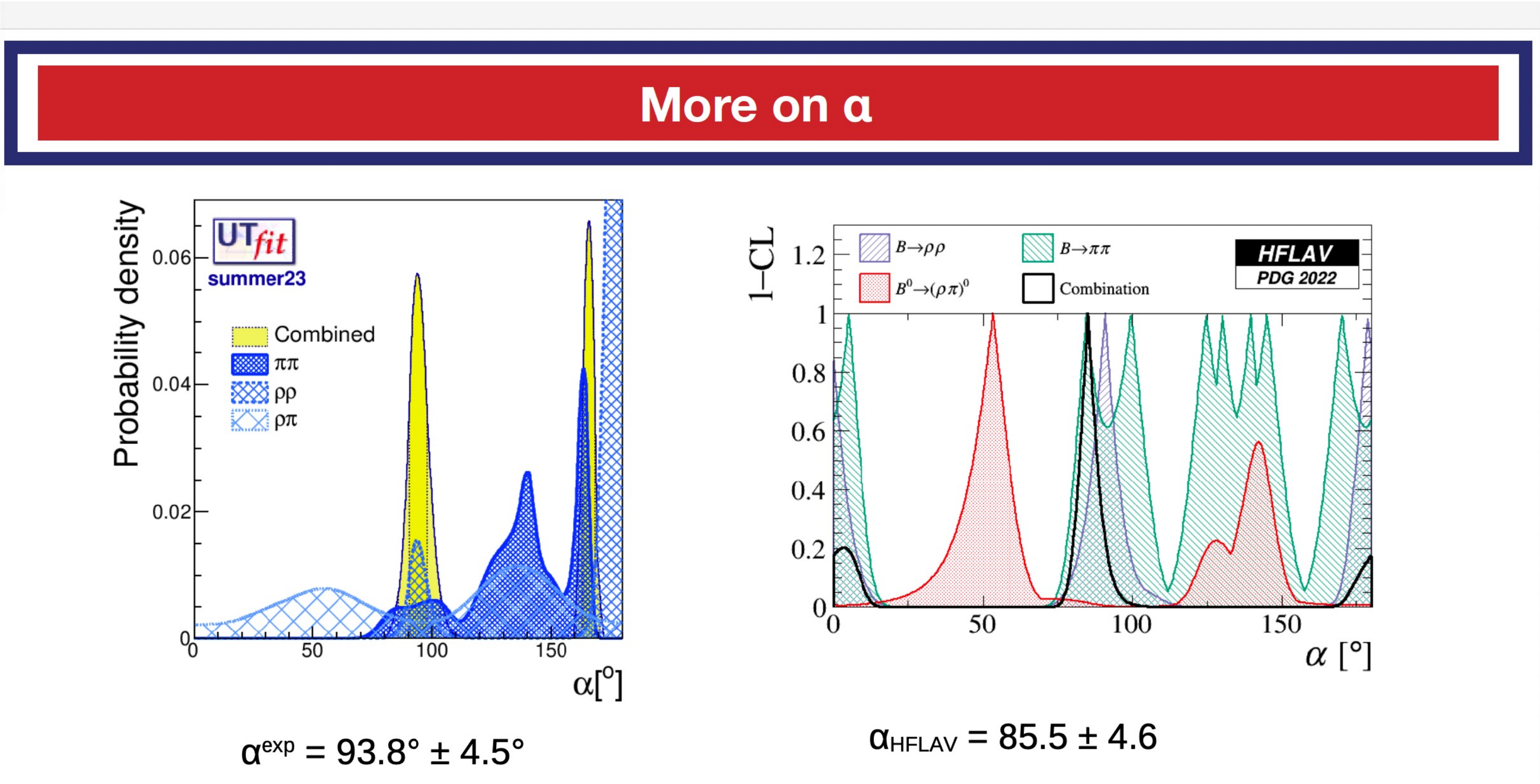


What's new for EPS23

- Updated the bound on α with
  - Bounds from ππ and ρρ derived from PDG averages (including PDG rescaling of the error)
  - Bound from ρπ derived from same inputs used by HFLAV
- As usual, main difference wrt other combinations is in the treatment of the multiple solutions
  - Profiling vs marginalization: in our case, multiple overlapping solutions counts more than a single solution when integrating out the other quantities (T, P, and strong phases)

$$\alpha = (93.8 \pm 4.5)^o$$

More on α

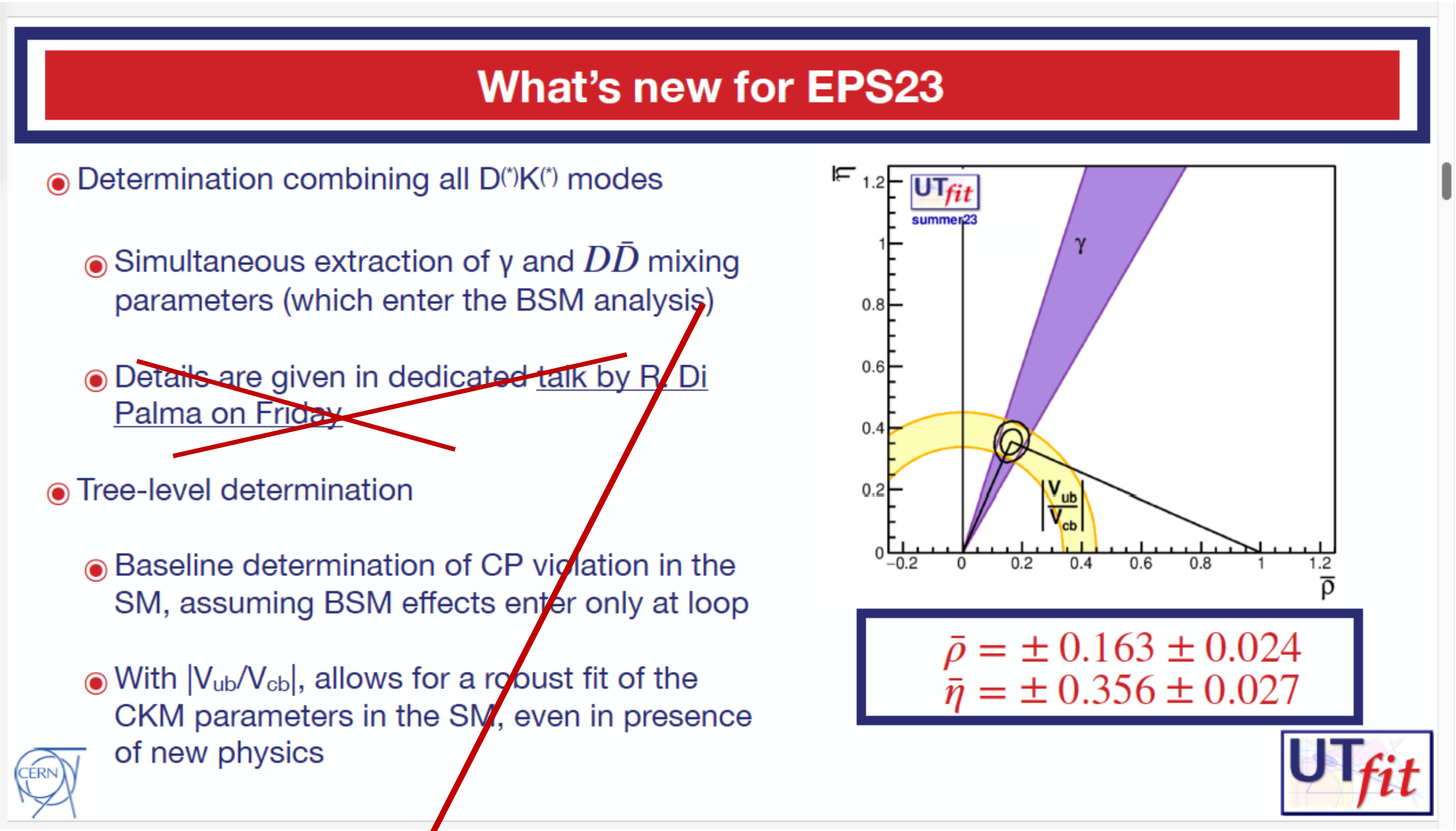


$\alpha^{exp} = 93.8° \pm 4.5°$

$\alpha_{HFLAV} = 85.5 \pm 4.6$

Inputs are slighly different from what HFLAV because for the BR averages we use the PDG (with the error inflation if there is a tension), while HFLAV would use their averages without error inflation.
So the pipi BR inputs are slightly different. We also use the updated rhopi.

HFLAV
It seems that the reason why the combination falls on the pipi solution on the left of the rhorho peak (while the right solution would be just as probable and even not distinguishable) is due to the small bump from the rhopi distribution which instead goes to zero for the pipi solution on the right.



What’s new for EPS23

- Determination combining all $D^{(*)}K^{(*)}$ modes
  - Simultaneous extraction of γ and $D\bar{D}$ mixing parameters (which enter the BSM analysis)
  - ~~Details are given in dedicated talk by R. Di Palma on Friday~~
- Tree-level determination
  - Baseline determination of CP violation in the SM, assuming BSM effects enter only at loop
  - With $|V_{ub}/V_{cb}|$, allows for a robust fit of the CKM parameters in the SM, even in presence of new physics

$$\bar{\rho} = \pm 0.163 \pm 0.024$$
$$\bar{\eta} = \pm 0.356 \pm 0.027$$

See talk by G. D’Ambrosio

V_{cb} and V_{ub}

from FLAG 2021

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

NEW (40.55 ± 0.46) 10^{-3}

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

from Bordone et al.
arXiv:2107.00604

~ 3.2σ discrepancy

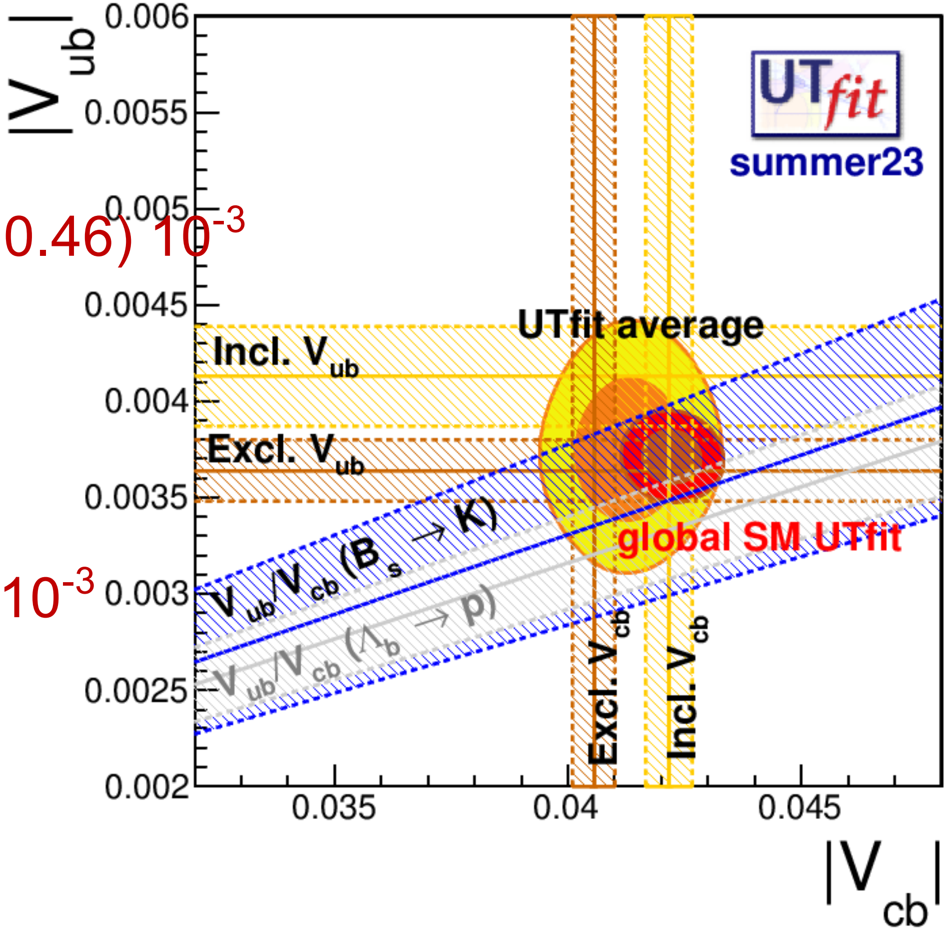
NEW (3.64 ± 0.16) 10^{-3}

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

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

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

~1.6σ discrepancy



From B_s to K at high q^2

$|V_{ub}$ / $V_{cb}|$ *(LHCb)* = (9.46 ± 0.79) 10^{-2}

NEW (8.27 ± 1.17) 10^{-2}

$|V_{ub}$ / $V_{cb}|$ *(LHCb)* = (7.9 ± 0.6) 10^{-2}

From Λ_b, excluded following FLAG guidelines

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

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

WORK IN PROGRESS (G.M., S.Simula, L.Vittorio)

NEW Vcb= $(40.55 \pm 0.54)\ 10^{-3}$
EXCLUSIVE from B-> D*

INCLUSIVE $(42.16 \pm 0.50)\ 10^{-3}$

NEW Vub/Vcb = $(8.27 \pm 1.17)\ 10^{-2}$
FLAG UNDERESTIMATES OF THE UNCERTAINTY
The larger error reduces the correlation between Vub nd Vcb

G.Martinelli et al.: Updates on the determination of $|V_{cb}|$, $R(D^*)$ and $|V_{ub}|/|V_{cb}|$ 13

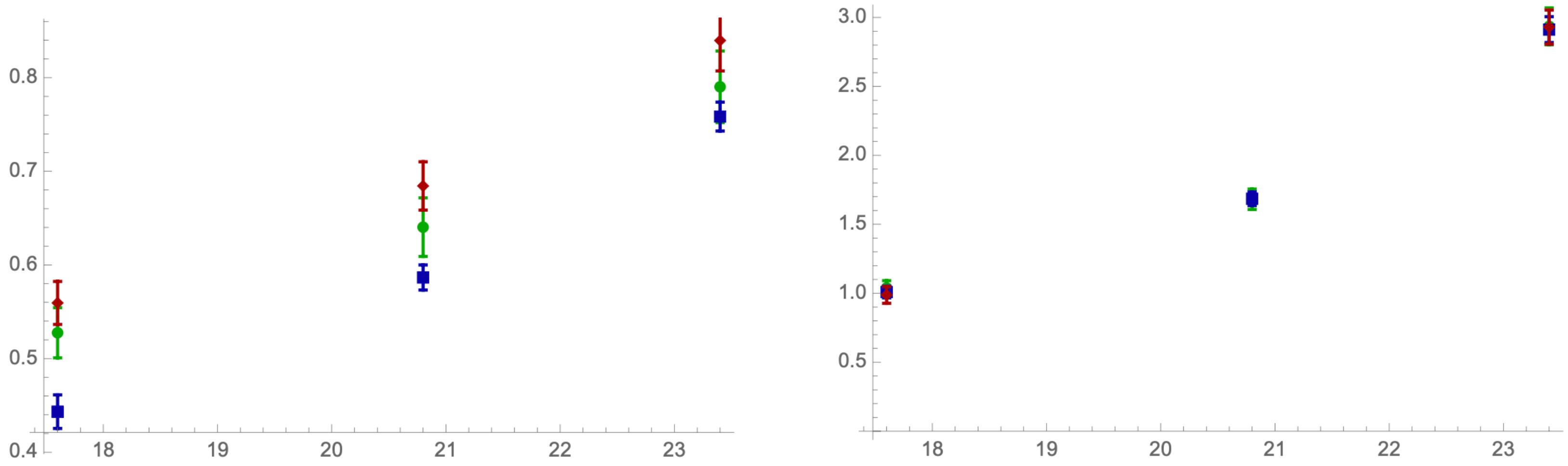
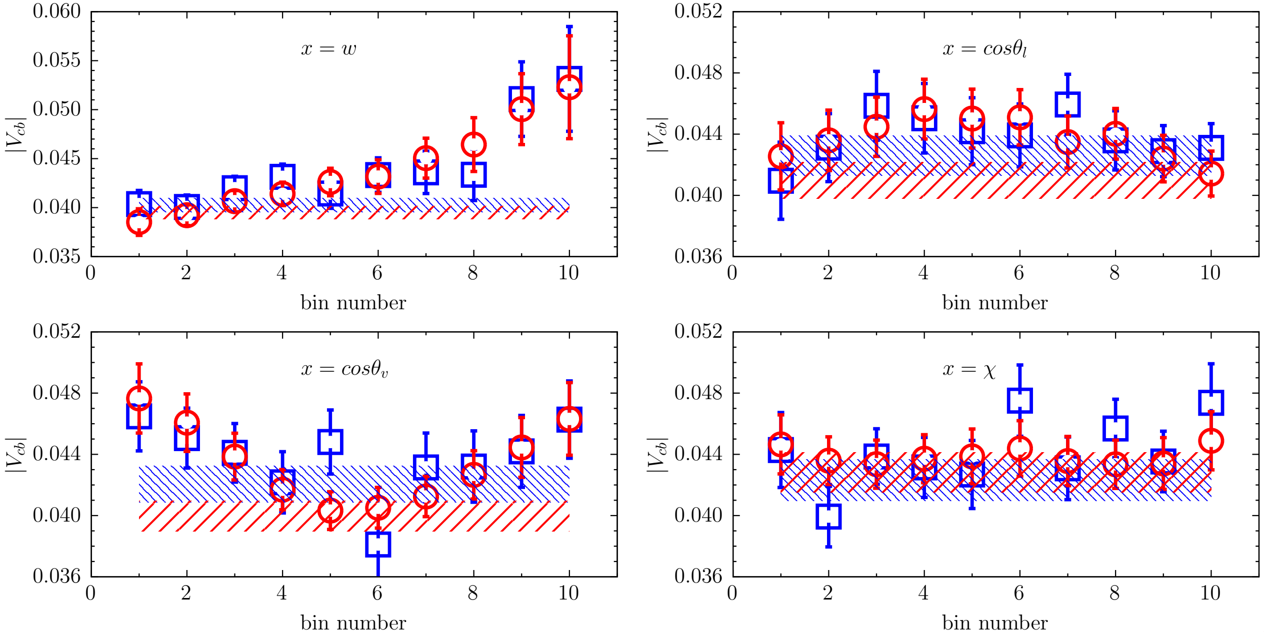


Fig. 8. *Available lattice results for the FFs $f_0(q^2)$ (left panel) and $f_+(q^2)$ (right panel) relevant for $B_s \to K\ell\nu_\ell$ decays. The RBC/UKQCD [6] (diamond), FNAL/MILC [31] (squares) and HPQCD [32, 33] (circles).*

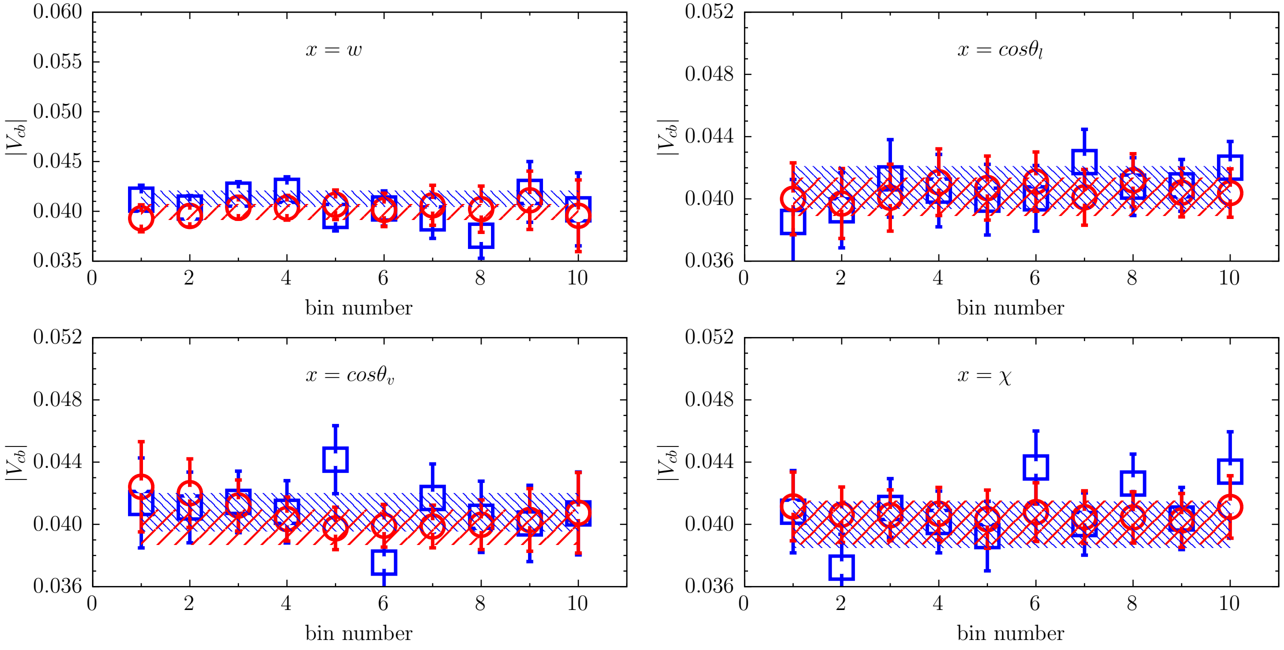
Utfit Prediction Vcb= $(42.21 \pm 0.51)\ 10^{-3}$

Vub= $(3.70 \pm 0.09)\ 10^{-3}$



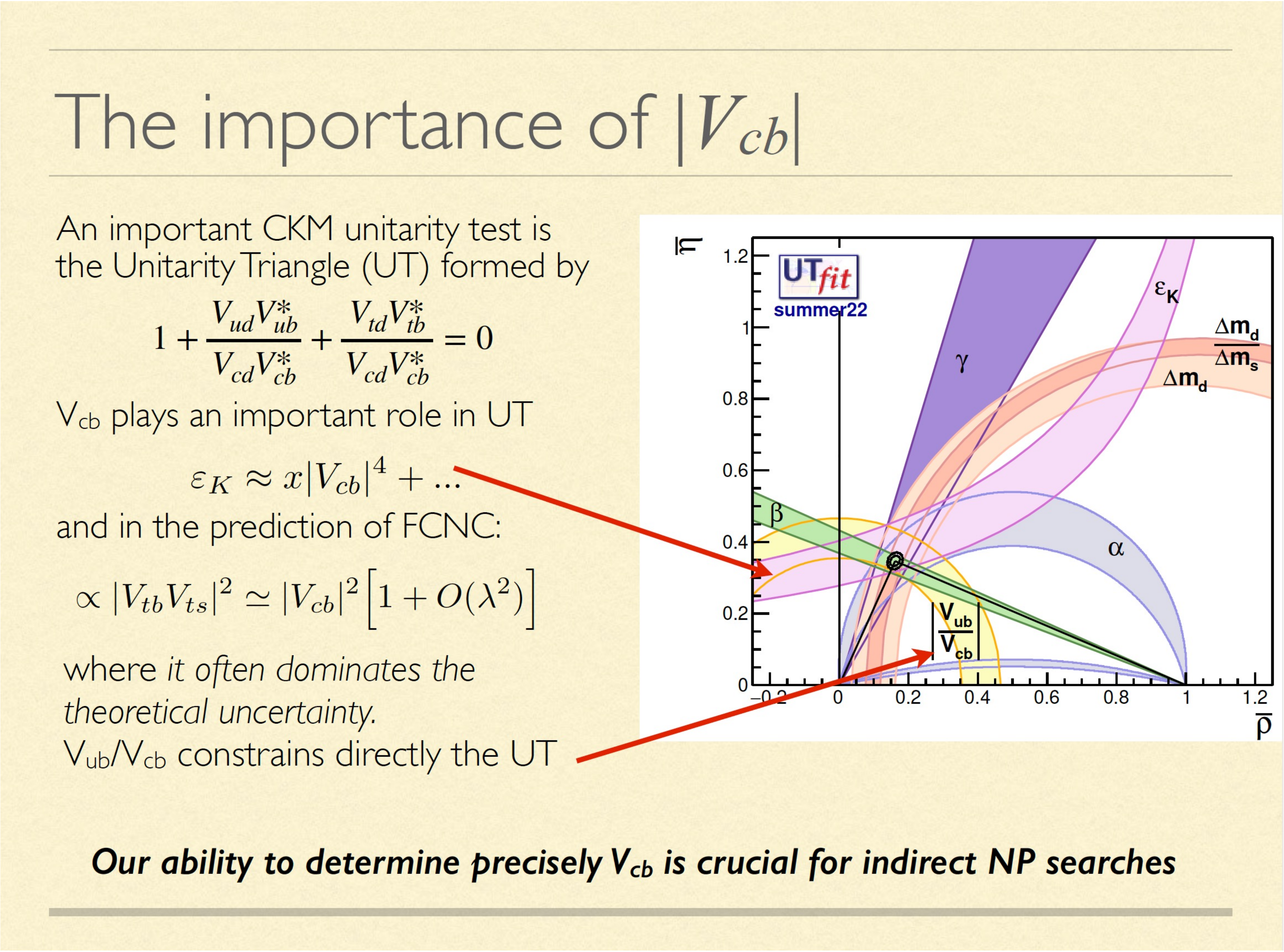
FNAL/MILC

Mainly due to $F_1(w)$



JLQCD

GM,S. Simula,L.Vittorio



The importance of $|V_{cb}|$

An important CKM unitarity test is the Unitarity Triangle (UT) formed by

$$1 + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

V_{cb} plays an important role in UT

$$\varepsilon_K \approx x|V_{cb}|^4 + \dots$$

and in the prediction of FCNC:

$$\propto |V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2 \left[1 + O(\lambda^2)\right]$$

where *it often dominates the theoretical uncertainty.*

V_{ub}/V_{cb} constrains directly the UT

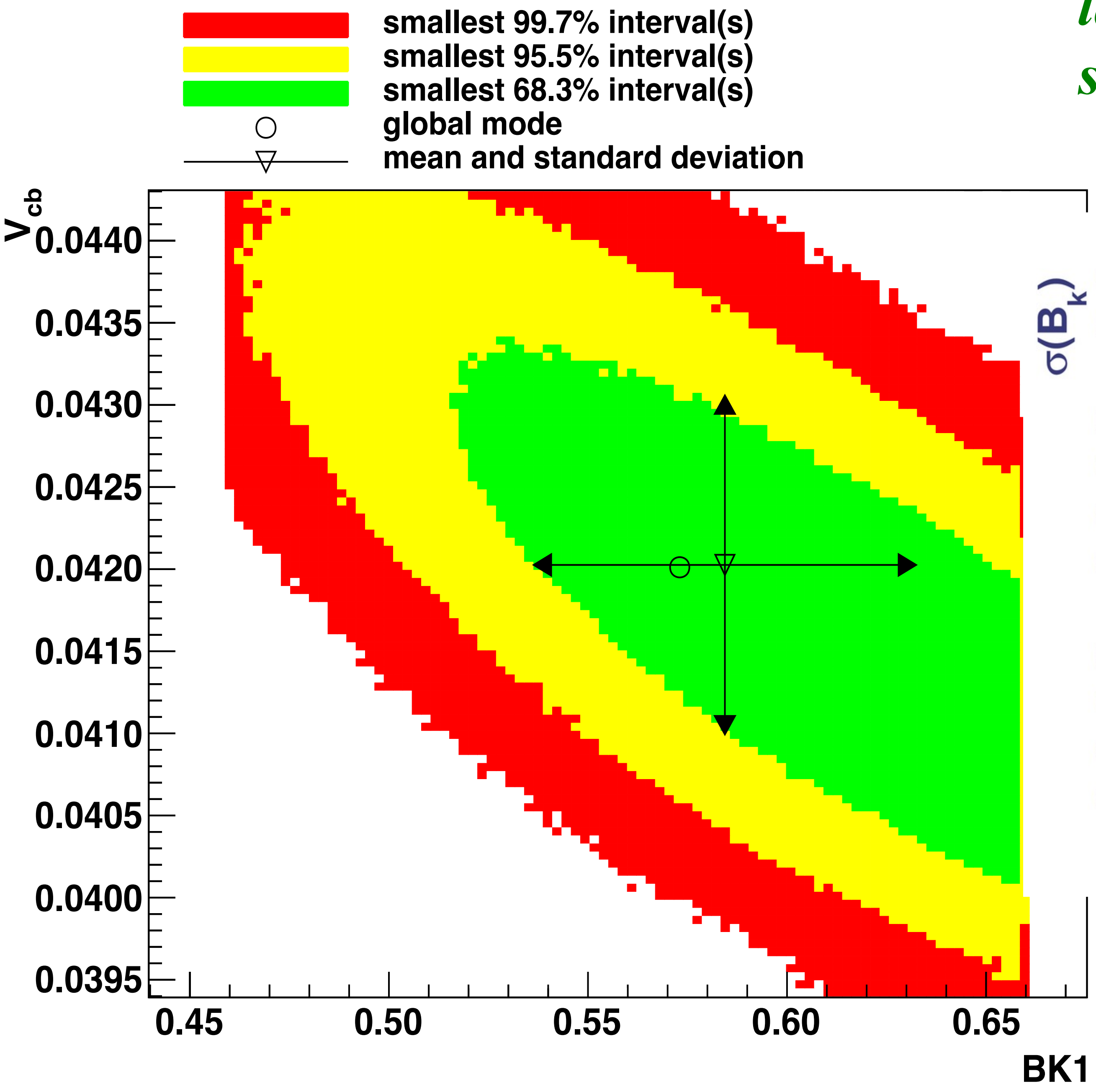
Our ability to determine precisely V_{cb} is crucial for indirect NP searches

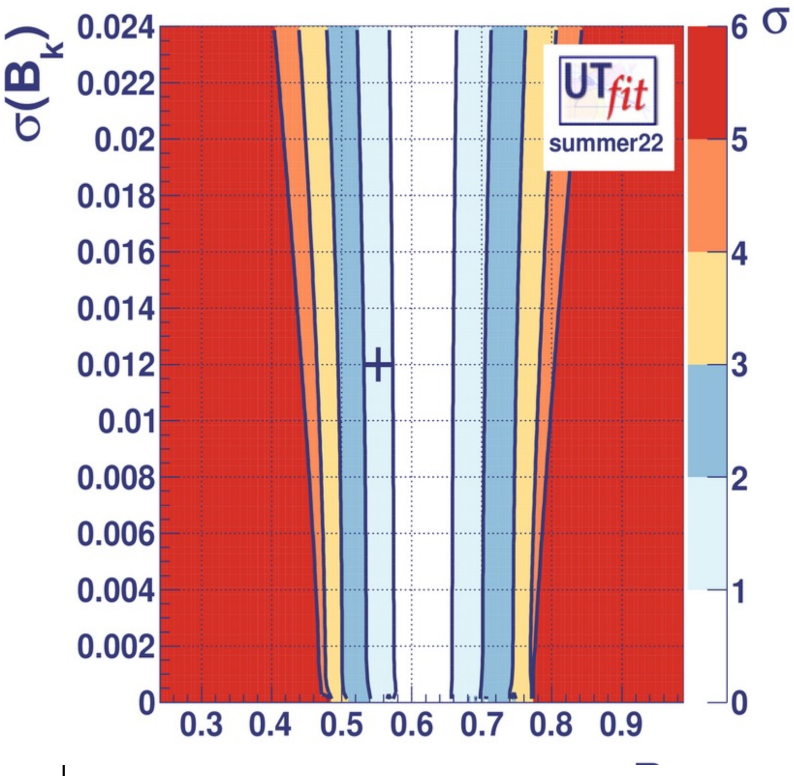
Courtesy by Gambino

UT-fit Preliminary

- ε_K large Vcb

-B mixing with large lattice matrix elements smaller Vcb





2022

Power corrections to the CP-violation parameter ε_K

M. Ciuchini$^{(a)}$, E. Franco$^{(b)}$, V. Lubicz$^{(c,a)}$,
G. Martinelli$^{(d,b)}$, L. Silvestrini$^{(b)}$, C. Tarantino$^{(c,a)}$

$$\varepsilon_K^{exp} = 2.228 \pm 0.011) \cdot 10^{-3}$$

2021: an estimate from the 1/mc expansion of the effective Hamiltonian + UTfit

$$\varepsilon_K = 2.00\ (15)\ x\ 10^{-3}$$

Computing the long-distance contributions to ε_K

Ziyuan Bai
Columbia University, USA
bzyhty@gmail.com

Norman Christ[*] [†]
Columbia University, USA
E-mail: nhc@phys.columbia.edu

RBC and UKQCD Collaborations

2015: a real exploratory calculation

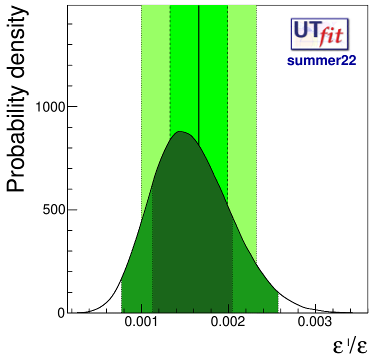
no physical masses, no extrapolation to the continuum

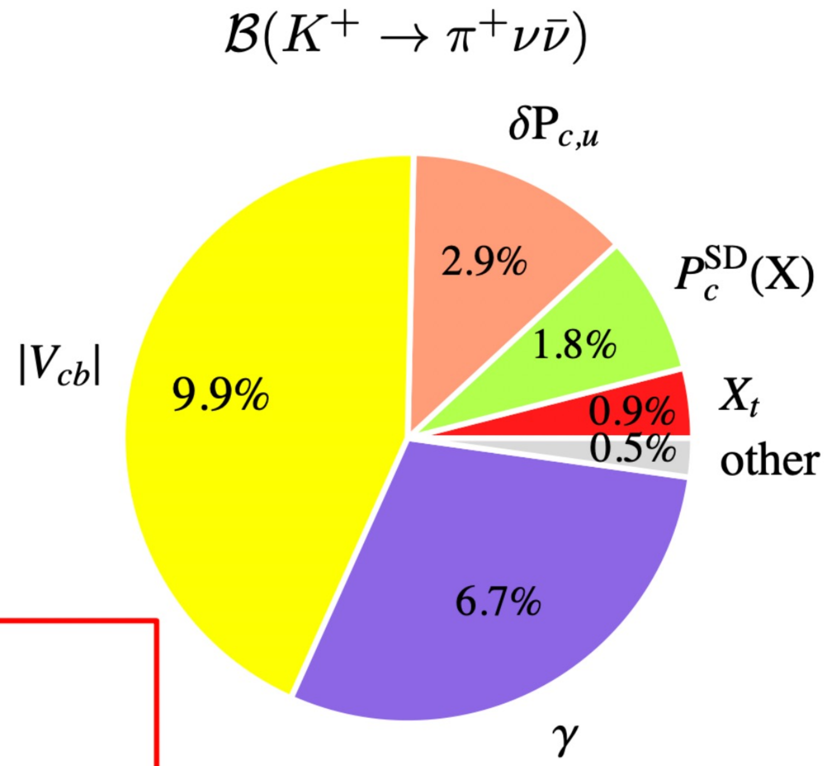
$$|\varepsilon| = (1.806(41) + 0.891(11) + 0.209(6) + 0.112(13)) \times 10^{-3} = 3.019(45) \times 10^{-3}$$

$$tt \qquad ut_{SD} \qquad ut_{LD} \qquad \mathrm{Im}(A_0),$$

e'/e from RBC now in Utfit:

e'/ e= 15.2(4.7) x10^{-4}



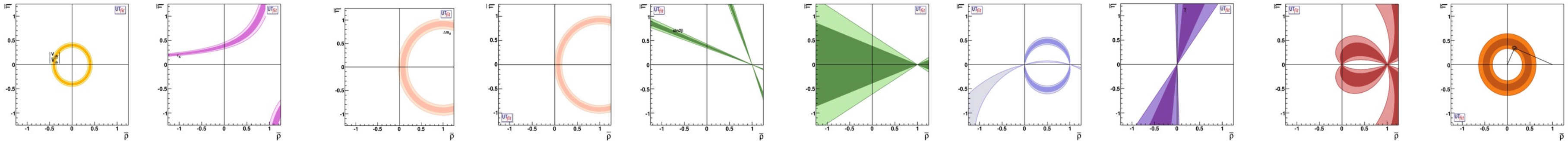


SM branching ratios:
[arXiv:2109.11032]

$K^+ \to \pi^+\nu\nu(\gamma) = (8.62 \pm 0.42) \times 10^{-11}$

$K_L \to \pi^0\nu\nu = (2.94 \pm 0.15) \times 10^{-11}$

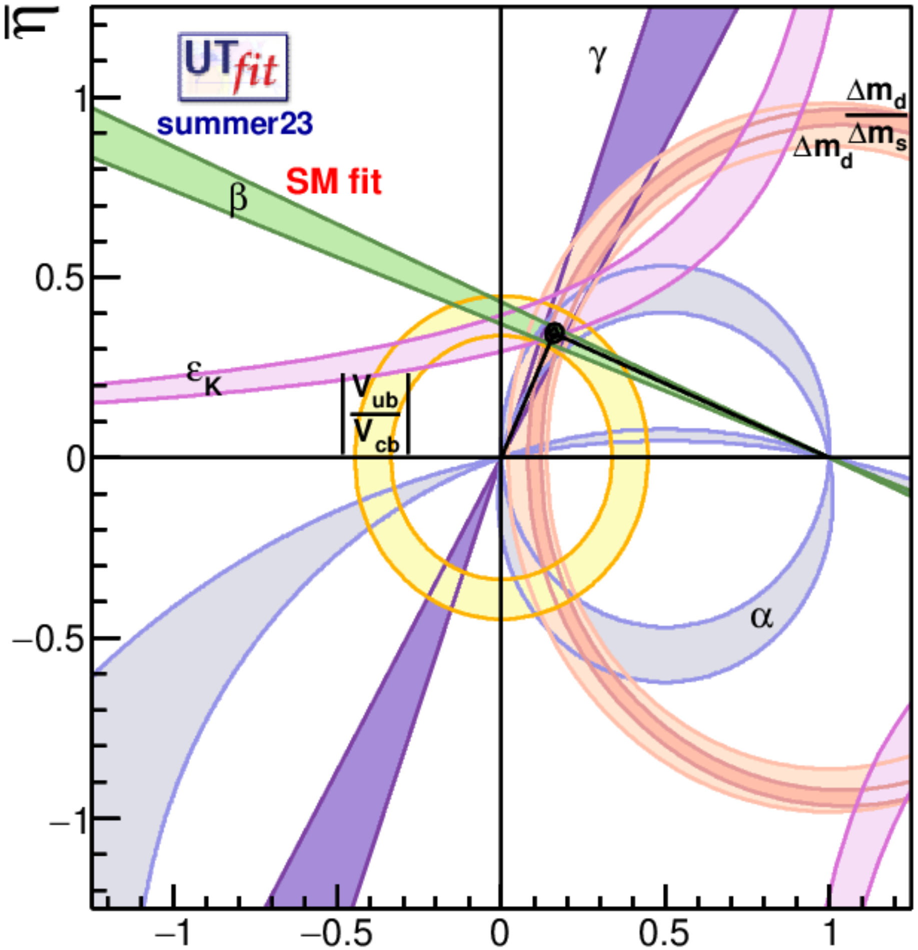
Courtesy by G. D'Ambrosio



2023 results

$\bar{\rho} = 0.160 \pm 0.009 \quad \bar{\eta} = 0.345 \pm 0.011$

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



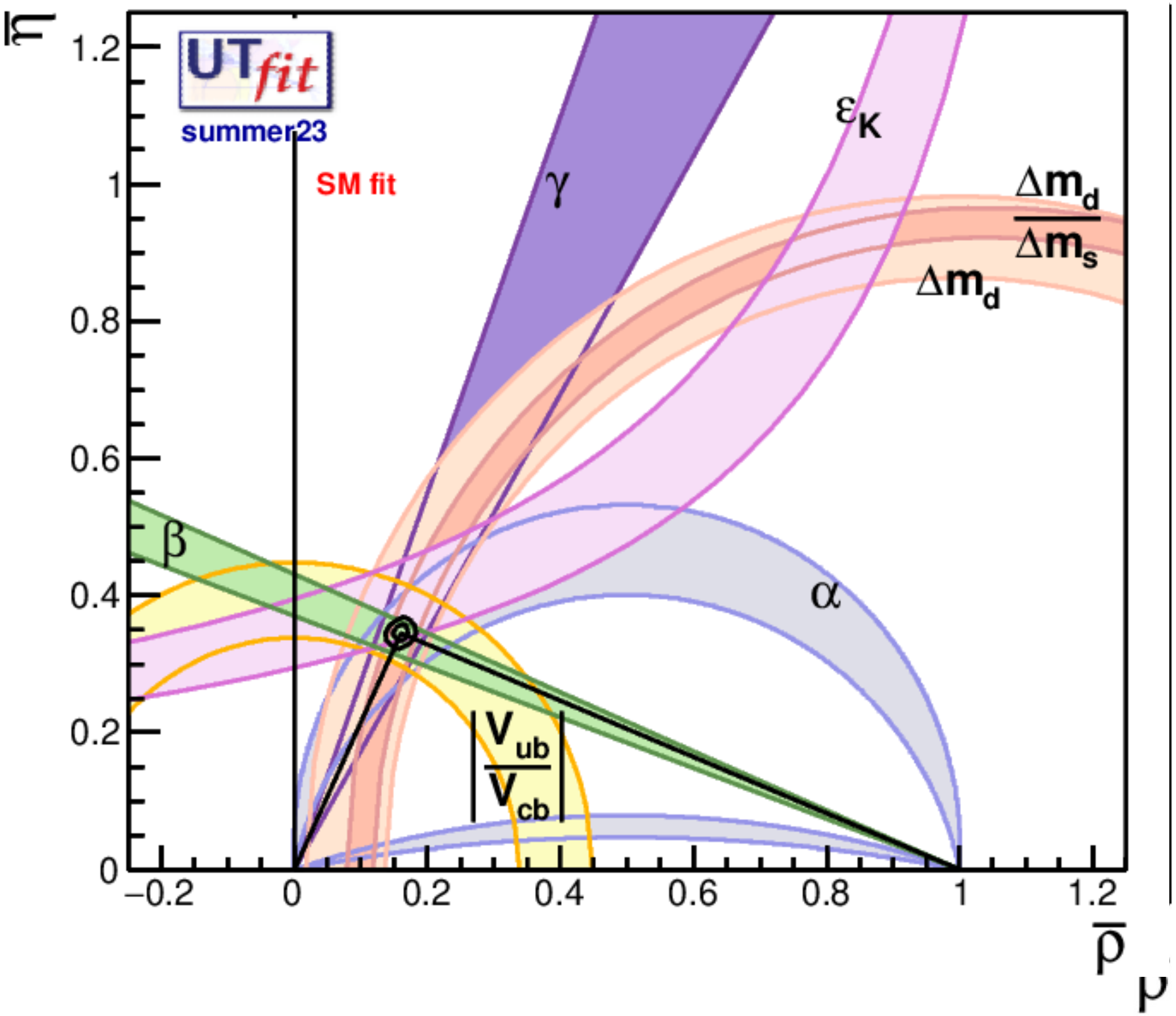
$\alpha = (92.4 \pm 1.4)^0$
$\sin 2\beta = 0.703 \pm 0.014$
$\beta = (22.46 \pm 0.68)^0$
$\gamma = (65.1 \pm 1.3)^0$
$A = 0.828 \pm 0.011$
$\lambda = 0.22519 \pm 0.00083$
2022

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%

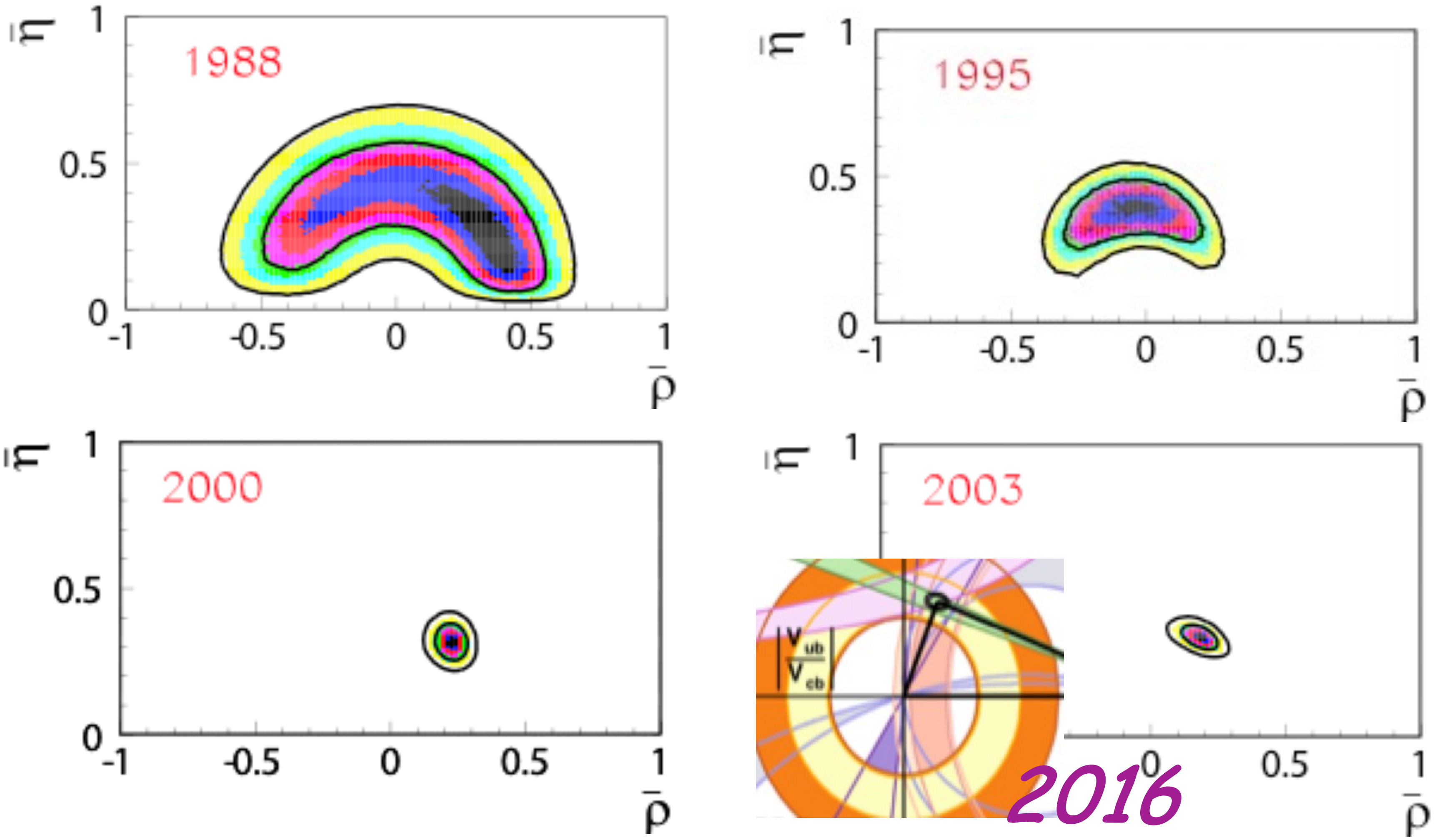
$\rho = 0.160 \pm 0.009$

$\eta = 0.345 \pm 0.011$

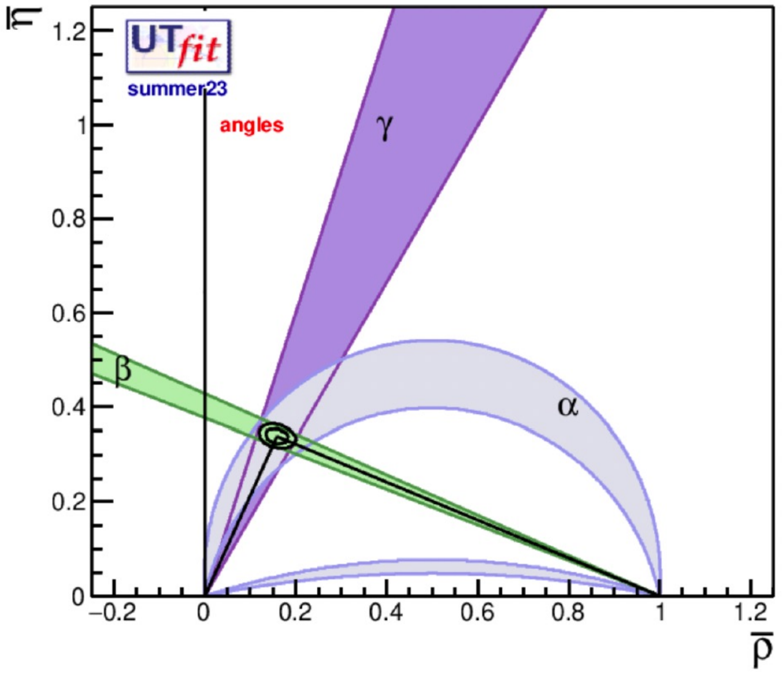
~3%

PROGRESS SINCE 1988

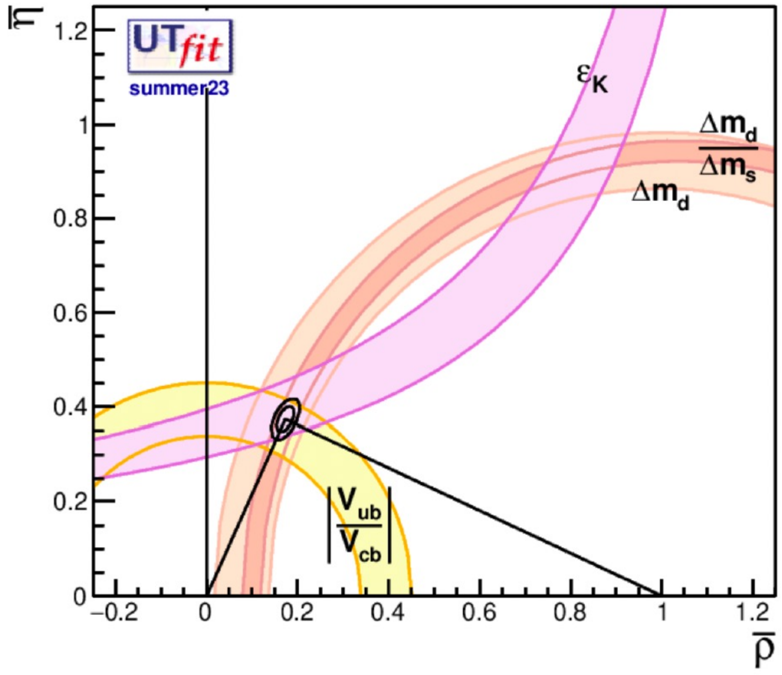
Experimental progress so impressive that we can fit the hadronic matrix elements (in the SM)



Standard Model Fit result



$$\bar{\rho} = 0.159 \pm 0.016$$
$$\bar{\eta} = 0.339 \pm 0.010$$



$$\bar{\rho} = 0.173 \pm 0.012$$
$$\bar{\eta} = 0.374 \pm 0.019$$

compatibility plots

A way to “measure” the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavour physics

2022

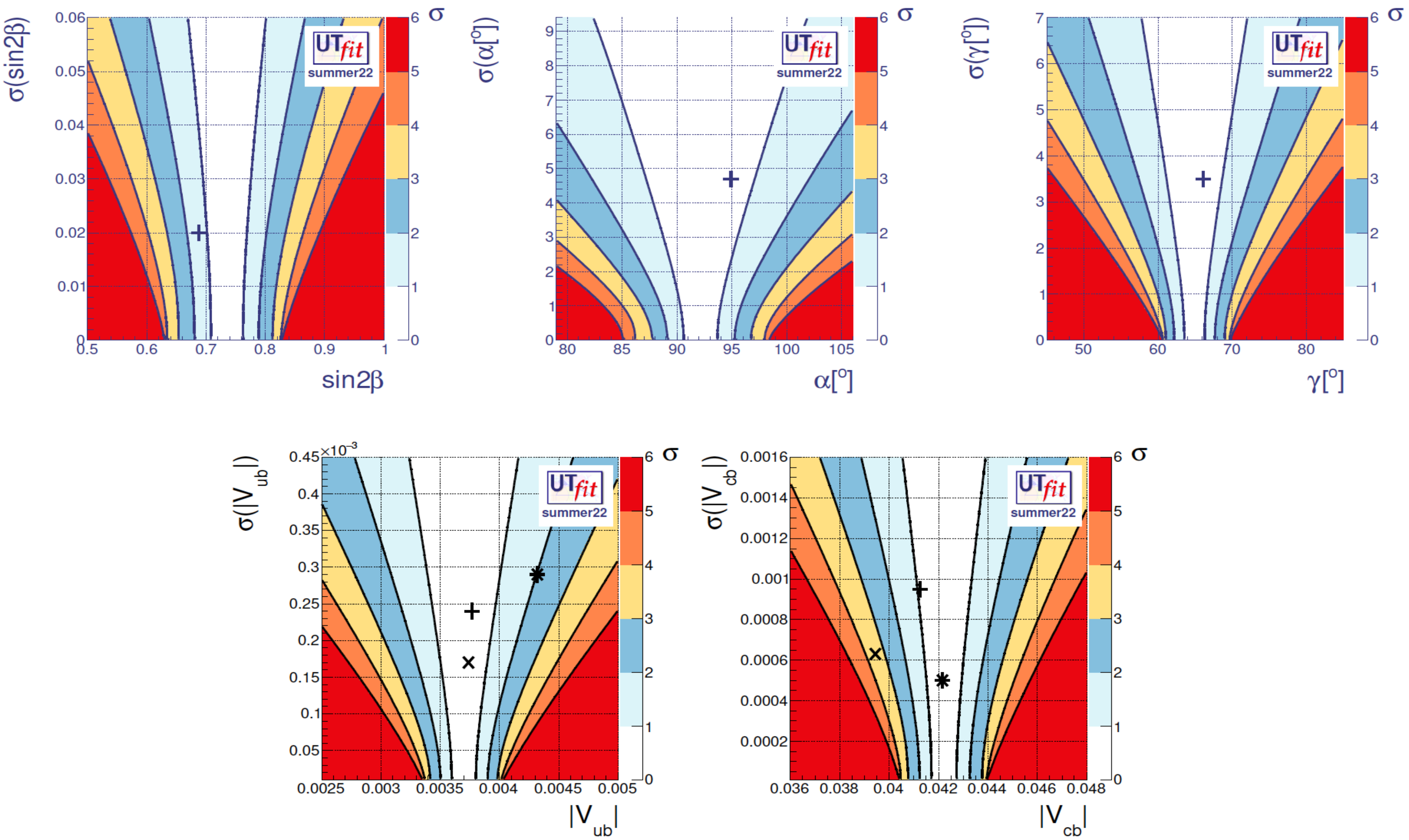
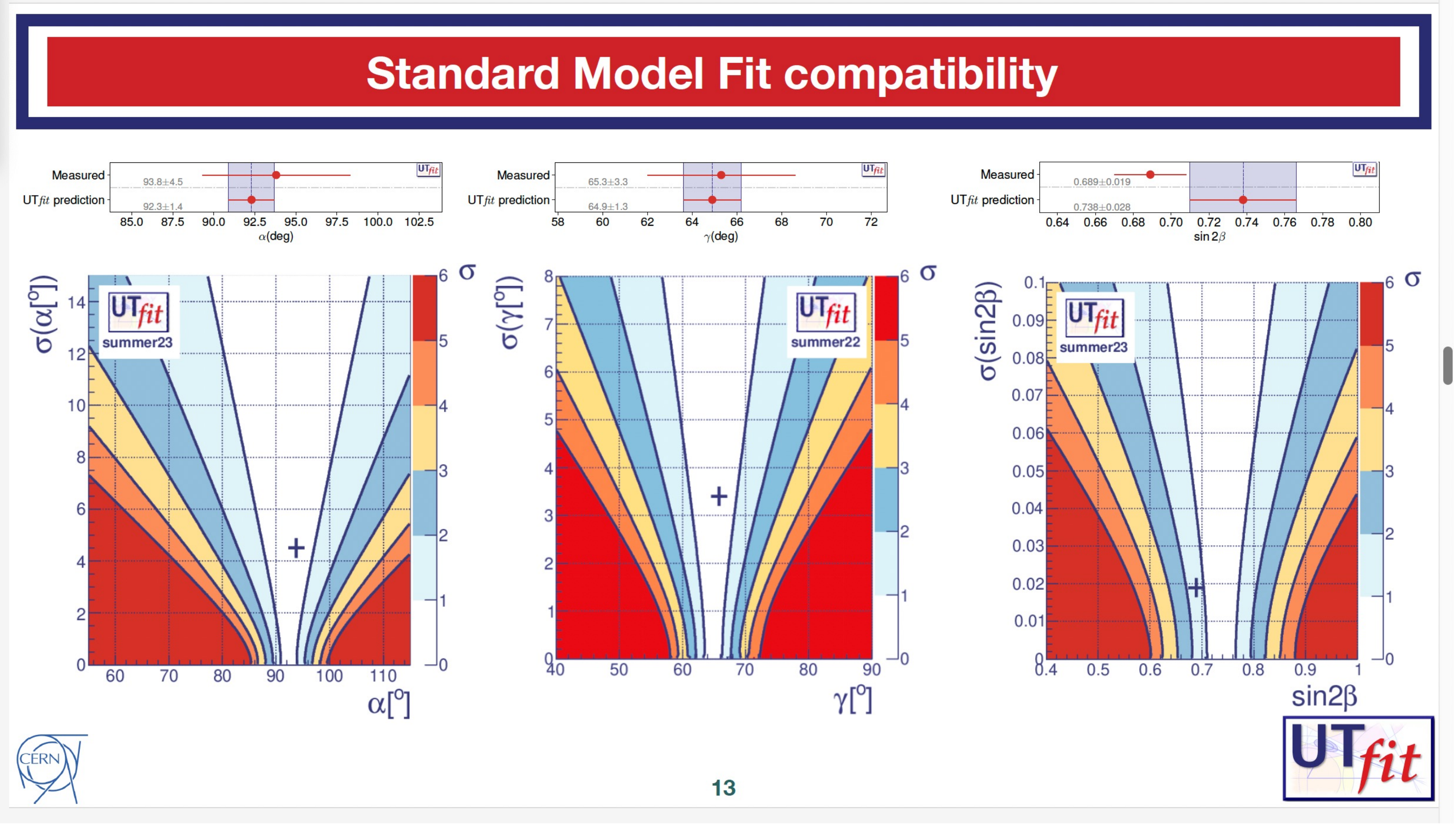


FIG. 5. *Pull plots (see text) for* $\sin 2\beta$ *(top-left),* α *(top-centre),* γ *(top-right),* $|V_{ub}|$ *(bottom-left) and* $|V_{cb}|$ *(bottom-right) inputs. The crosses represent the input values reported in Table I. In the case of* $|V_{ub}|$ *and* $|V_{cb}|$ *the* x *and the* * *represent the values extracted from exclusive and inclusive semileptonic decays respectively.*

2023



Standard Model Fit compatibility

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

Two critical issues

- $\boxed{V_{cb}}$

  - 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

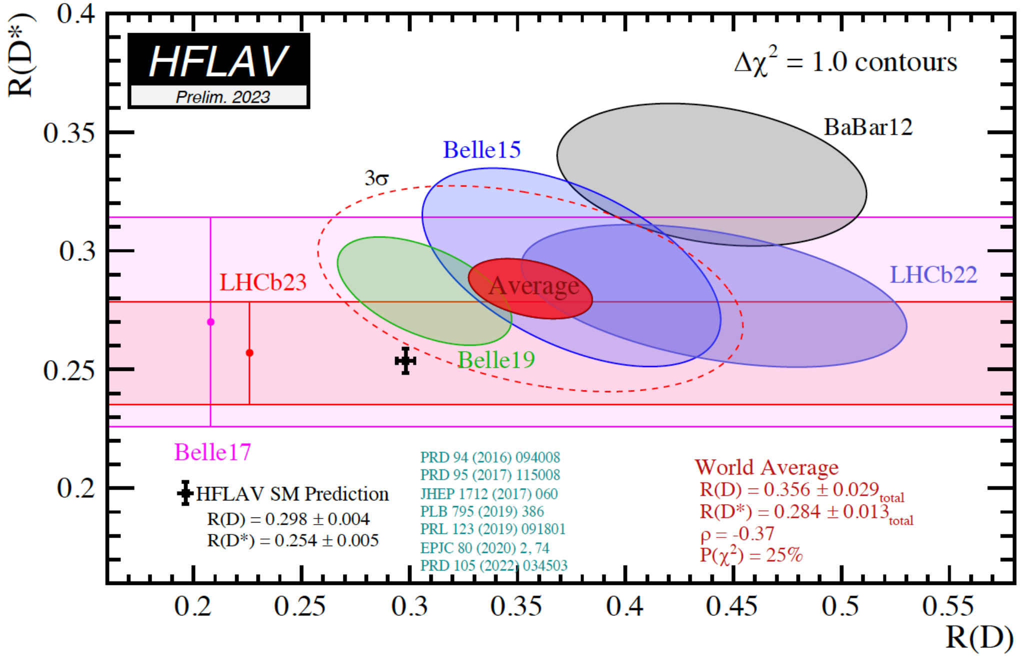
  $|V_{cb}| \cdot 10^3 = 42.16\ (50)$

  (Bordone et al. 2107.00604)

- $\boxed{R_{D(*)}}$

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

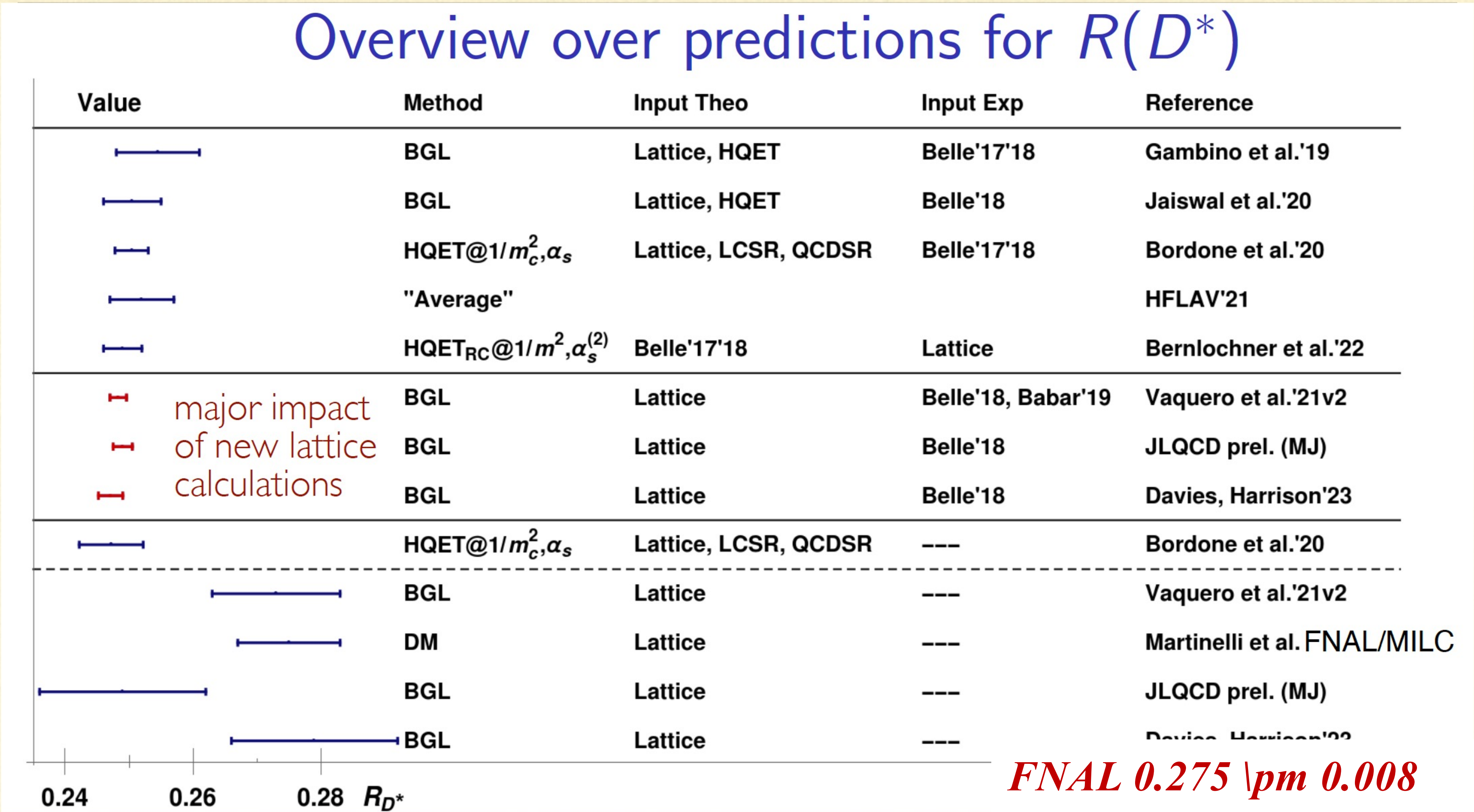
$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$



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

2022

$\boxed{3.2\sigma \quad \text{tension}}$



Overview over predictions for $R(D^*)$

Value	Method	Input Theo	Input Exp	Reference
	BGL	**Lattice, HQET**	**Belle'17'18**	**Gambino et al.'19**
	BGL	**Lattice, HQET**	**Belle'18**	**Jaiswal et al.'20**
	HQET@$1/m_c^2,\alpha_s$	**Lattice, LCSR, QCDSR**	**Belle'17'18**	**Bordone et al.'20**
	"Average"			**HFLAV'21**
	HQET$_{RC}$@$1/m^2,\alpha_s^{(2)}$	**Belle'17'18**	**Lattice**	**Bernlochner et al.'22**
	BGL	**Lattice**	**Belle'18, Babar'19**	**Vaquero et al.'21v2**
	BGL	**Lattice**	**Belle'18**	**JLQCD prel. (MJ)**
	BGL	**Lattice**	**Belle'18**	**Davies, Harrison'23**
	HQET@$1/m_c^2,\alpha_s$	**Lattice, LCSR, QCDSR**	**---**	**Bordone et al.'20**
	BGL	**Lattice**	**---**	**Vaquero et al.'21v2**
	DM	**Lattice**	**---**	**Martinelli et al.** FNAL/MILC
	BGL	**Lattice**	**---**	**JLQCD prel. (MJ)**
	BGL	**Lattice**	**---**	**Davies, Harrison'23**

major impact of new lattice calculations

FNAL 0.275 \pm 0.008
JLQCD 0.248 \pm 0.008
HPQCD 0.276 \pm 0.009

Predictions based only on Fermilab & HPQCD lead to larg agreement with exp, mostly because of the suppression at high w of the denominator. *I see no reason not to use experimental data for a SM test*, especially in presence of tensions in lattice data.

Courtesy by Gambino

EXP 0.284 \pm 0.013

…. beyond the Standard Model

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

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

UT generalization Beyond the Standard Model

- fit simultaneously for the CKM and the NP parameters (generalized UT analysis)
  - parameterize BSM effects in $\Delta F = 2$ Hamiltonian in model-independent
  - use all available experimental information
- find out NP contributions to ΔF=2 transitions

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$
$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$
$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$
$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

New local four-fermion operators are generated

$Q_1 = (\bar{b}_L{}^A \gamma_\mu d_L{}^A)(\bar{b}_L{}^B \gamma_\mu d_L{}^B)$ SM

$Q_2 = (\bar{b}_R{}^A d_L{}^A)(\bar{b}_R{}^B d_L{}^B)$

$Q_3 = (\bar{b}_R{}^A d_L{}^B)(\bar{b}_R{}^B d_L{}^A)$

$Q_4 = (\bar{b}_R{}^A d_L{}^A)(\bar{b}_L{}^B d_R{}^B)$

$Q_5 = (\bar{b}_R{}^A d_L{}^B)(\bar{b}_L{}^B d_R{}^A)$

+ those obtained by L ↔ R

Similarly for the s quark e.g.
$(\bar{s}_R{}^A d_L{}^A)(s_R{}^B d_L{}^B)$

$$\langle \bar{K}^0|O_1(\mu)|K^0\rangle = \frac{8}{3} M_K^2 f_K^2\, B_1(\mu)\,,$$

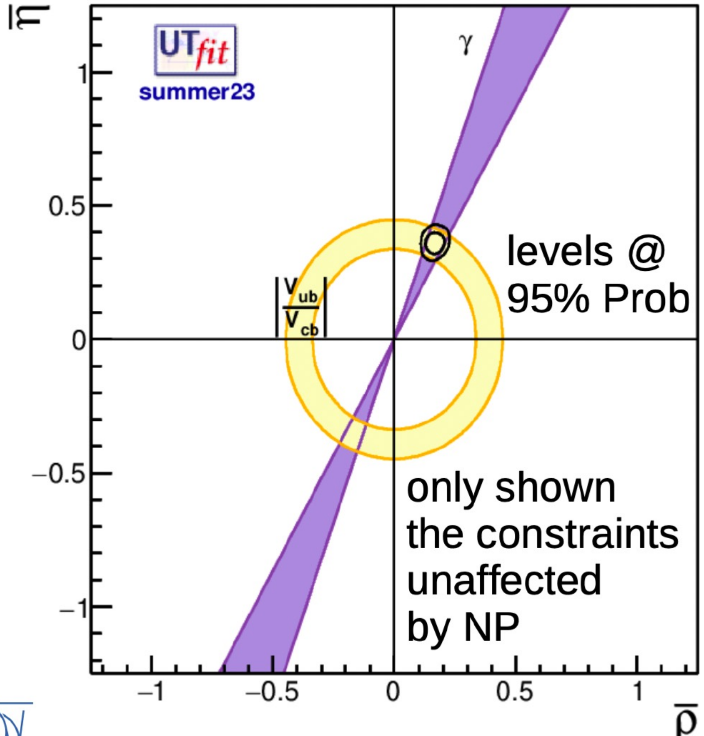
$$\langle \bar{K}^0|O_2(\mu)|K^0\rangle = -\frac{5}{3}\left(\frac{M_K}{m_s(\mu)+m_d(\mu)}\right)^2 M_K^2 f_K^2\, B_2(\mu)\,,$$

$$\langle \bar{K}^0|O_3(\mu)|K^0\rangle = \frac{1}{3}\left(\frac{M_K}{m_s(\mu)+m_d(\mu)}\right)^2 M_K^2 f_K^2\, B_3(\mu)\,,$$

$$\langle \bar{K}^0|O_4(\mu)|K^0\rangle = 2\left(\frac{M_K}{m_s(\mu)+m_d(\mu)}\right)^2 M_K^2 f_K^2\, B_4(\mu)\,,$$

$$\langle \bar{K}^0|O_5(\mu)|K^0\rangle = \frac{2}{3}\left(\frac{M_K}{m_s(\mu)+m_d(\mu)}\right)^2 M_K^2 f_K^2\, B_5(\mu)\,,$$

Results of BSM analysis: CKM parameters



levels @ 95% Prob

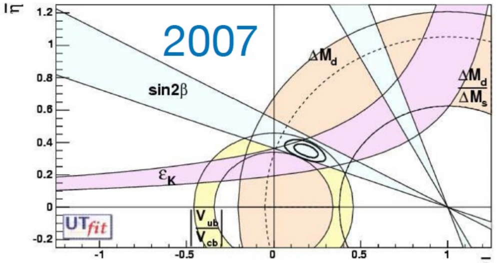
only shown the constraints unaffected by NP

CKM parameters from BSM analysis

$$\bar{\rho} = 0.167 \pm 0.025$$
$$\bar{\eta} = 0.361 \pm 0.027$$

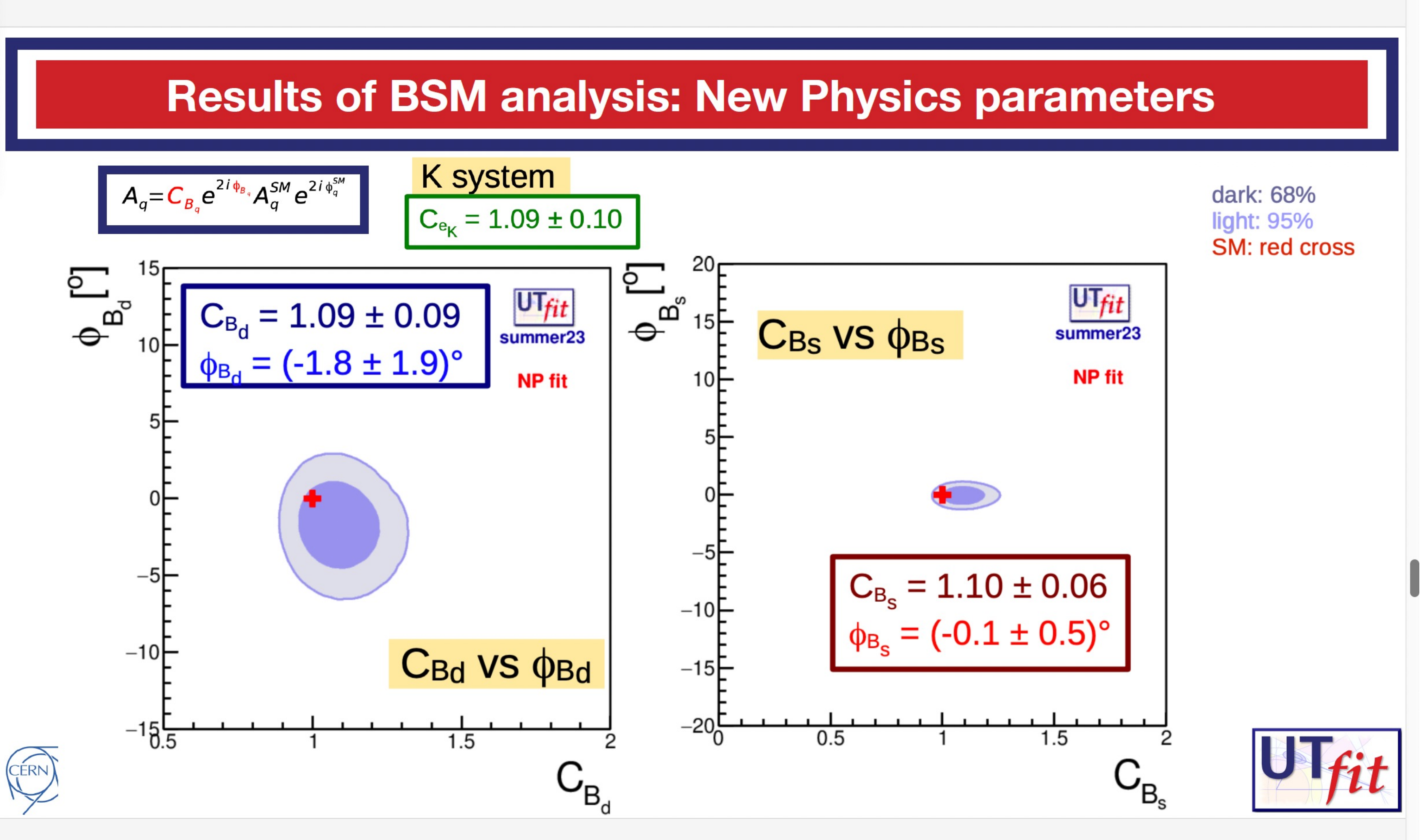
CKM parameters known (even in presence of NP effects) with similar precision of pre-LHC SM analysis

2004



$$\bar{\rho} = 0.164 \pm 0.028$$
$$\bar{\eta} = 0.340 \pm 0.016$$

Results of BSM analysis: New Physics parameters



$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$

K system

$C_{\epsilon_K} = 1.09 \pm 0.10$

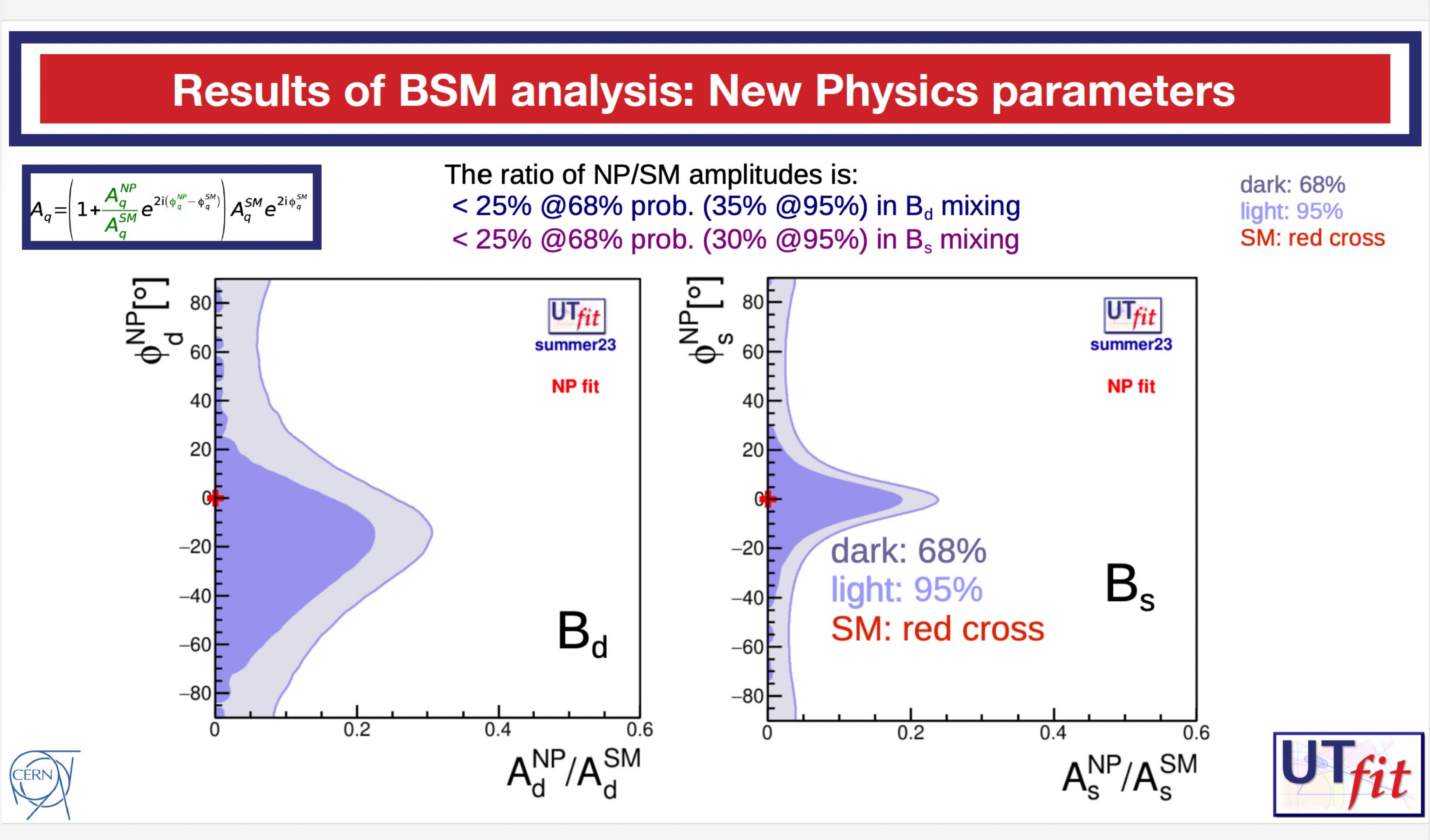
dark: 68%
light: 95%
SM: red cross

$C_{B_d} = 1.09 \pm 0.09$
$\phi_{B_d} = (-1.8 \pm 1.9)°$

C_{Bd} vs ϕ_{Bd}

C_{Bs} vs ϕ_{Bs}

$C_{B_s} = 1.10 \pm 0.06$
$\phi_{B_s} = (-0.1 \pm 0.5)°$



Results of BSM analysis: New Physics parameters

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

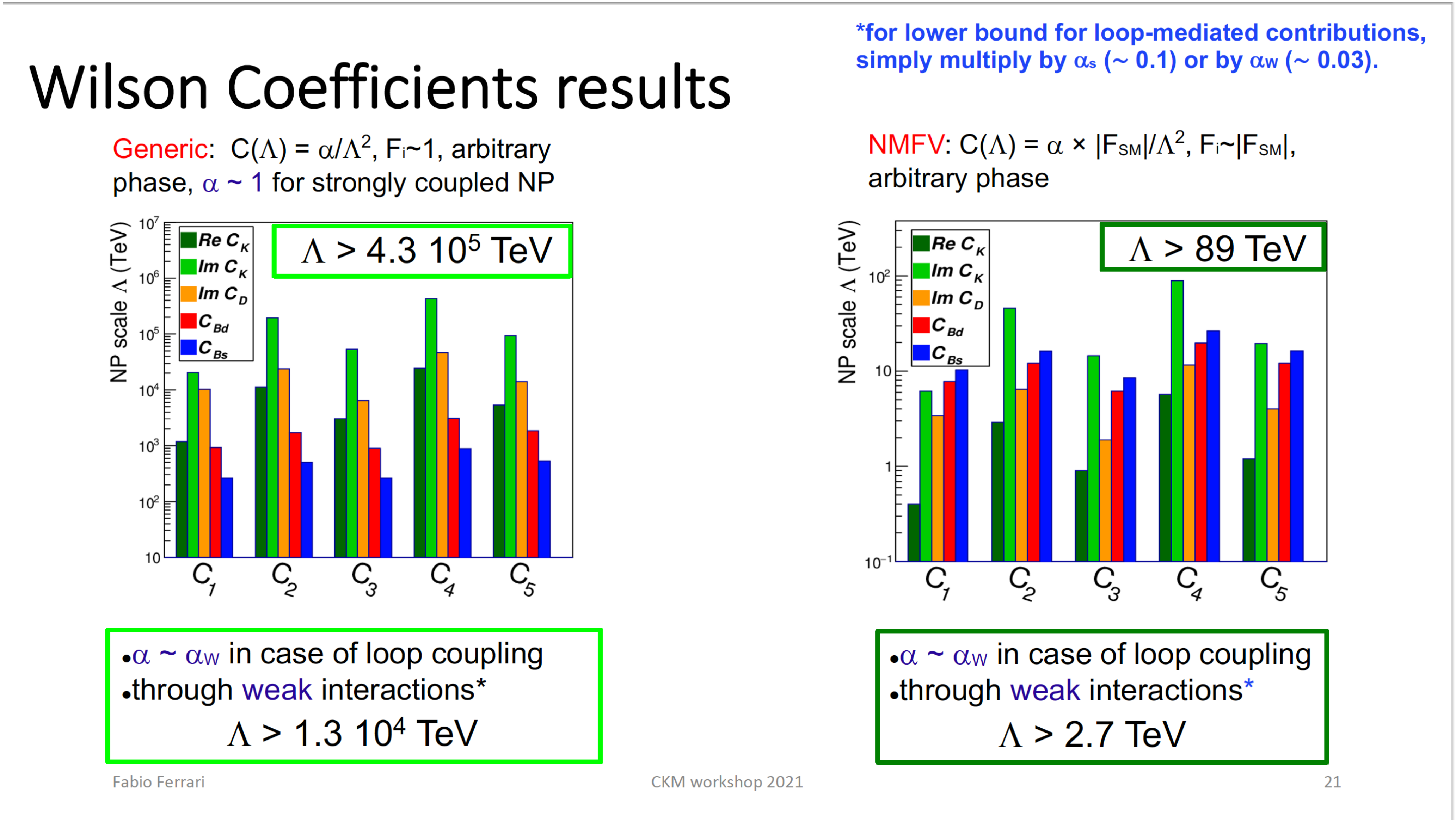
The ratio of NP/SM amplitudes is:

< 25% @68% prob. (35% @95%) in B_d mixing

< 25% @68% prob. (30% @95%) in B_s mixing

dark: 68%
light: 95%
SM: red cross

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

$\Lambda > 4.3\ 10^5$ TeV

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

$\Lambda > 1.3\ 10^4$ TeV

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

$\Lambda > 89$ TeV

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

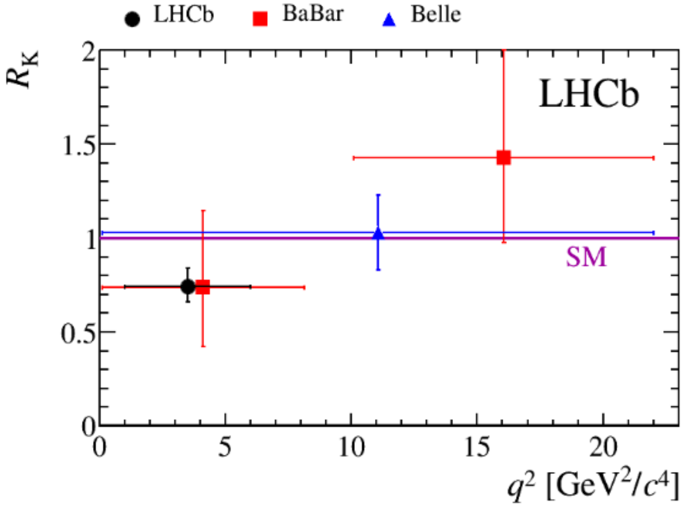
$\Lambda > 2.7$ TeV

Fabio Ferrari CKM workshop 2021 21

2022

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

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



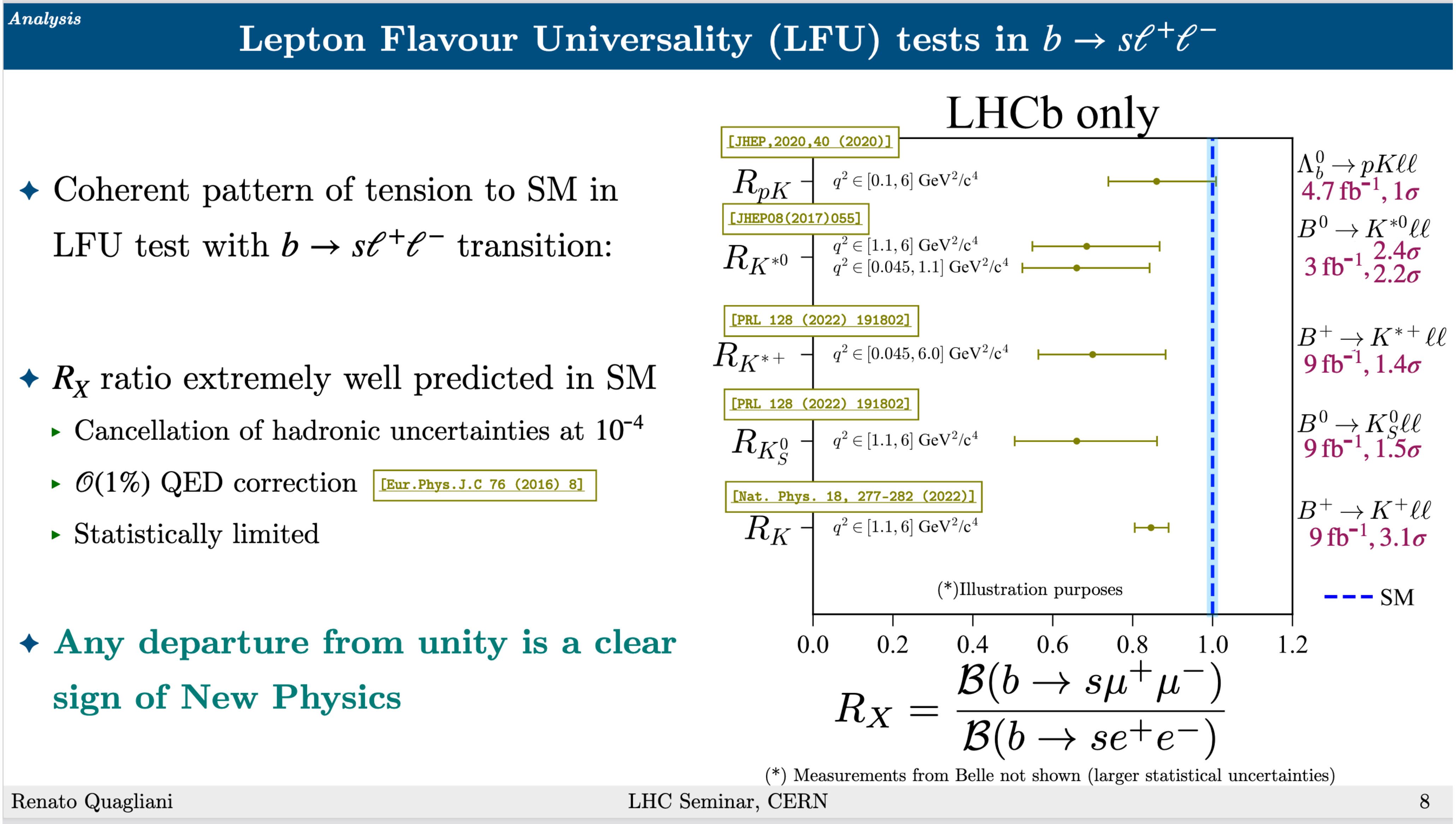
LHCb, PRL 113 151601
Belle, PRL 103 171801
BaBar, PRD 86 032012

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

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: $B^0\rightarrow K^{*0}\,l^+l^-$, $B_s\rightarrow\phi\,l^+l^-$, $\Lambda_B\rightarrow\Lambda\,l^+l^-$

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)

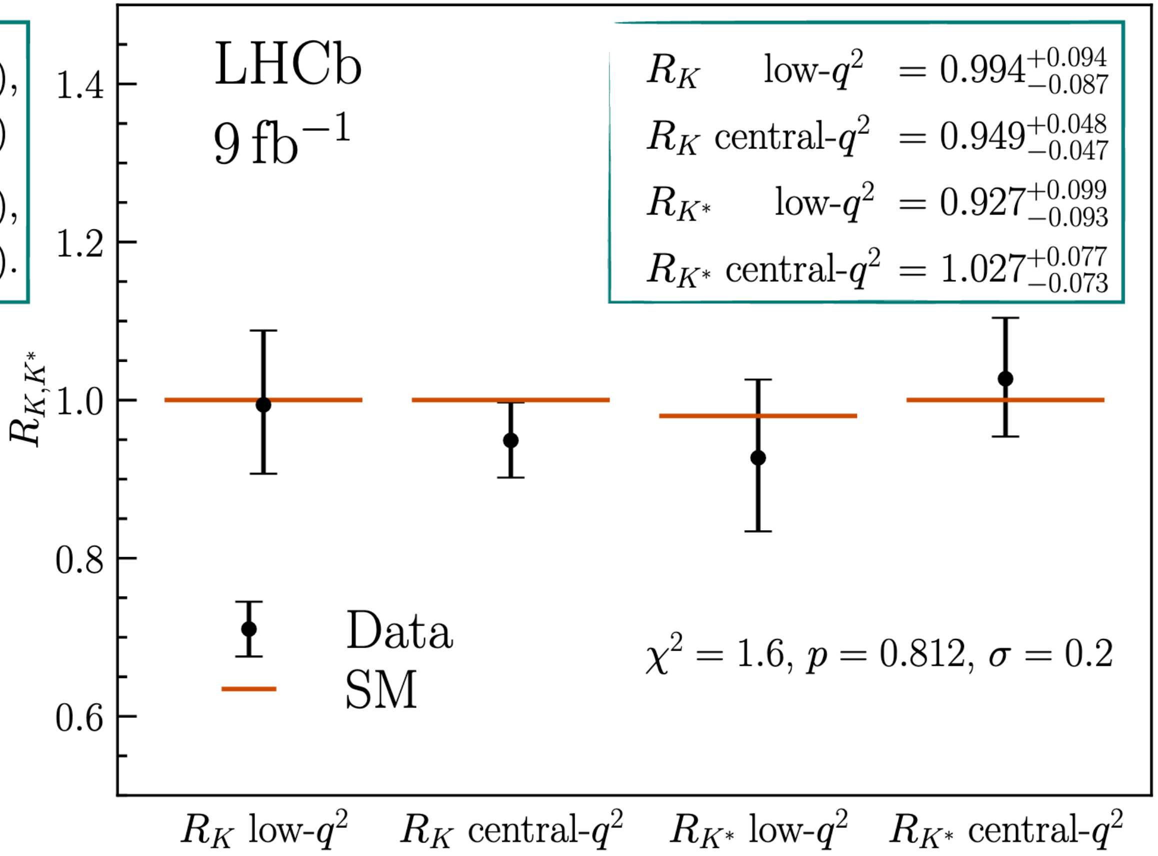
Harakiri!

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

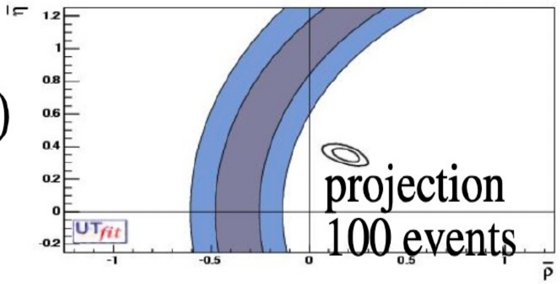


some old plots coming back to fashion:

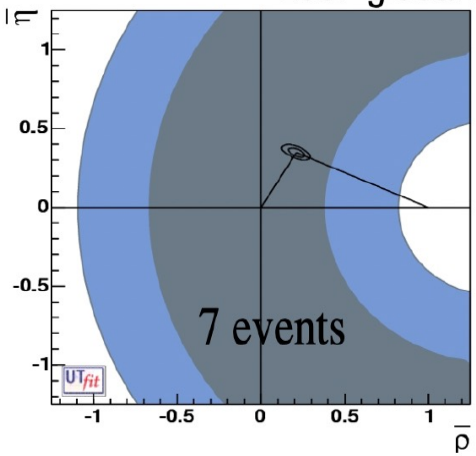
As NA62 and KOTO are analysing data:

BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)

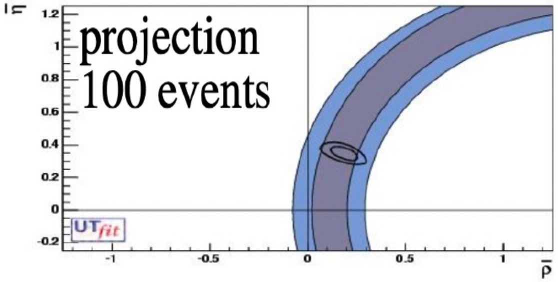
E949 central value

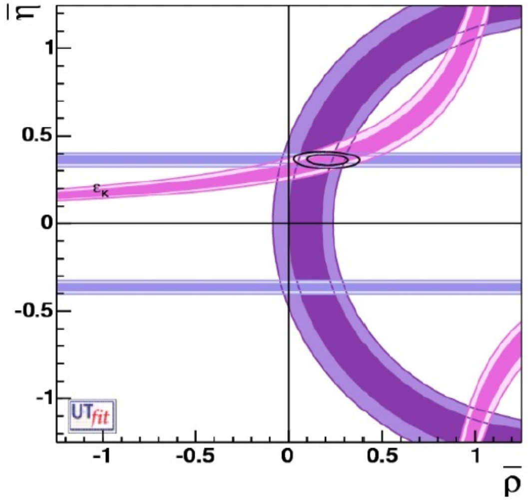


2007 global fit a



SM central value





including
BR($K^0 \rightarrow \pi^0\nu\bar{\nu}$
SM central va

◉We updated the UT analysis to Summer 23 inputs

◉New experimental determinations of the UT angles

◉New theory inputs (lattice, Vud)

◉Overall consistency of the fit ◉Reached precision of ~5% (~3%) on ( )

◉Extended the analysis to include new physics in DF=2 Hamiltonians

◉new inputs for D-\bar D mixing

◉probed new physics effects up to ◉ (1000) PeV for new physics with generic flavor structure

◉ (100–1000) GeV in MFV scenarios

absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

Tribute to Gauss & Kandinsky by G. Martinelli

Istituto Nazionale di Fisica Nucleare