Flavor Physics for Non-Experts: (a Theory) Overview

Guido Martinelli
Dipartimento di Fisica & INFN Sezione di Roma
Università La Sapienza

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

Nikhef June 8th 2018

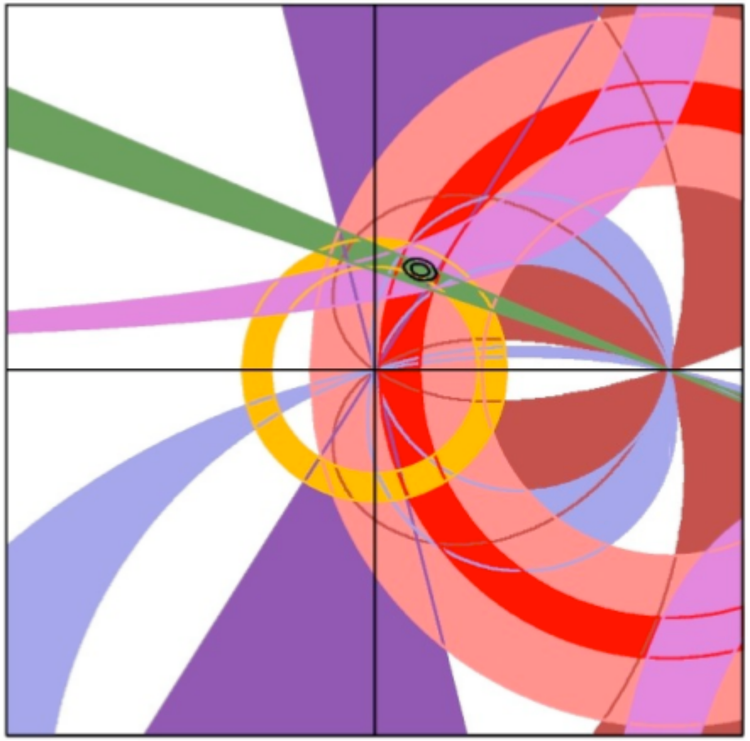
UTfit

PRACE

INFN
Istituto Nazionale di Fisica Nucleare

PLAN OF THE TALK

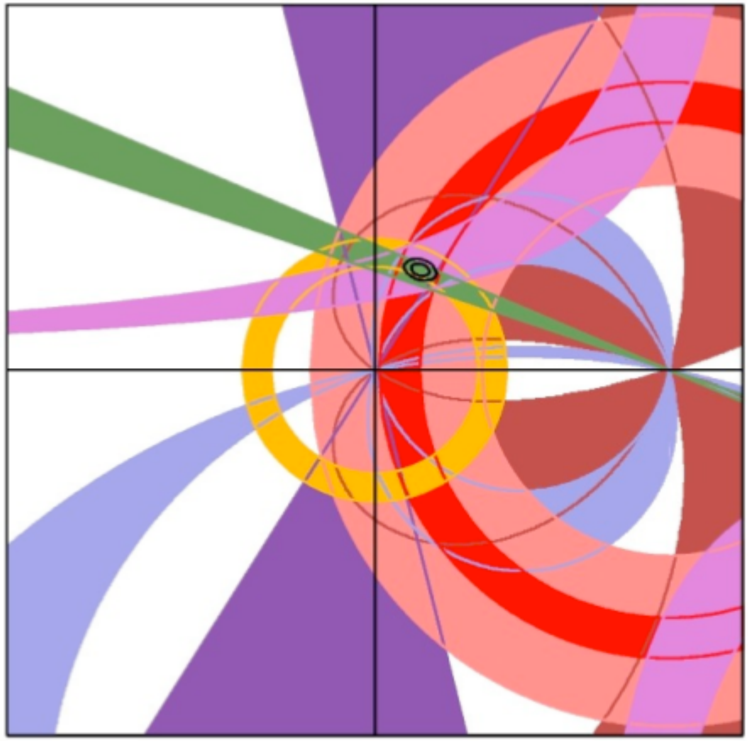
- *General introduction to the Unitary Triangle Fit*
- *SM Analysis*
- *Tensions and unknown*
- *Uncertainties in lattice calculations;*
- *From simple to complicated;*
- *Future directions, new/old ideas*
- *Beyond the SM*
- *Conclusion*



Thanks to
Bona, Ciuchini, Lubicz,
Silvestrini, Sachrajda,
Tantalo, …

Impossible to cover all recent developments – a selected list of topics – apologies for the interesting work that is not reported here

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 fundamental issue is ***to find signatures of new physics*** *and to unravel the underlying theoretical structure;*

Precision Flavor physics is a key tool*, complementary to the large energy searches at the LHC;*

If the LHC discovers new elementary particles BSM, then precision flavor physics will be necessary to constrain the underlying framework;

The discovery potential of precision flavor physics should not be underestimated.

The extraordinary progress of the experimental measurements requires accurate theoretical predictions

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

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

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

Flavor physics in the Standard Model

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

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

CP invariant

~~CP~~ 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 ?

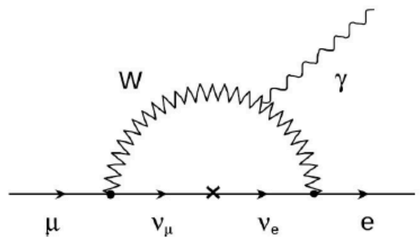
Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

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

$\mu \to e + \gamma$

lepton flavor number

$\nu_i \to \nu_k$ **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:

$q_i \;->\; q_k + \nu\,\bar{\nu}$

$q_i \;->\; q_k + l^+\,l^-$

$q_i \;->\; q_k + \gamma$

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

THUS THEY ARE SENSITIVE TO

NEW PHYSICS

CP Violation in the Standard Model

In the Standard Model the quark mass matrix, from which the CKM Matrix and $\cancel{CP}$ originate, is determined by the Yukawa Lagrangian which couples fermions and Higgs

$$\mathcal{L}^{\text{quarks}} = \mathcal{L}^{\text{kinetic}} + \mathcal{L}^{\text{weak int}} + \mathcal{L}^{\text{yukawa}}$$

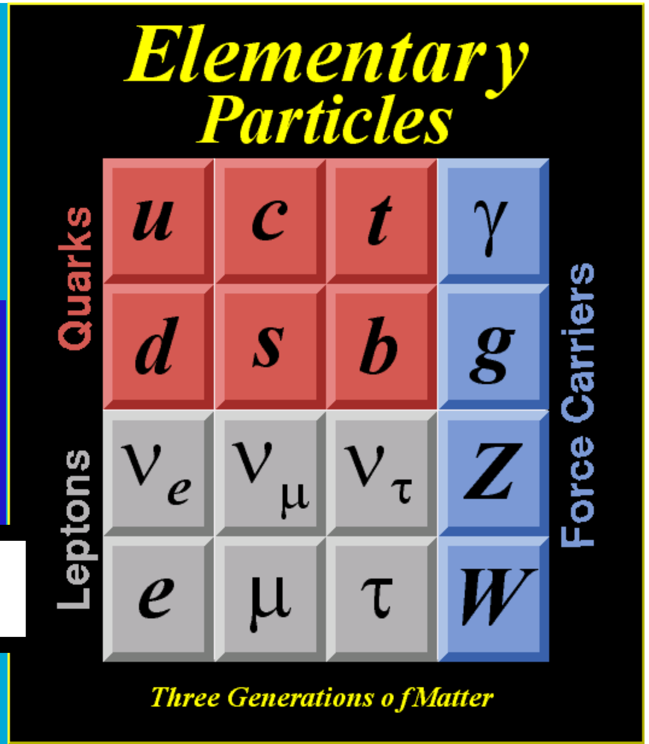
CP invariant

$\cancel{CP}$ and symmetry breaking are closely related !

QUARK MASSES ARE GENERATED BY DYNAMICAL SYMMETRY BREAKING

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad H^C = i\tau_2 H^*$$

$$\phi^+ \rightarrow 0 \qquad \phi^0 \rightarrow \frac{V}{\sqrt{2}}$$



Charge +2/3

$$\mathcal{L}^{yukawa} \equiv \sum_{i,k=1,N} [\, Y_{i,k}\,(q^i_L\, H^C)\, U^k_R + X_{i,k}\,(q^i_L\, H)\, D^k_R + \text{h.c.}\,]$$

Charge -1/3

$$\sum_{i,k=1,N} [\, m^u_{i,k}\,(\bar{u}^i_L\, u^k_R) + m^d_{i,k}\,(\bar{d}^i_L\, d^k_R) + \text{h.c.}\,]$$

Diagonalization of the Mass Matrix

Up to singular cases, the mass matrix can always be diagonalized by 2 unitary transformations

$u^i_L \rightarrow \mathbf{U}^{ik}_L\, u^k_L \qquad\qquad u^i_R \rightarrow \mathbf{U}^{ik}_R\, u^k_R$

$\mathbf{M}' = \mathbf{U}^\dagger_L\, \mathbf{M}\, \mathbf{U}_R \qquad\qquad (\mathbf{M}')^\dagger = \mathbf{U}^\dagger_R\, (\mathbf{M})^\dagger\, \mathbf{U}_L$

$$\mathcal{L}^{\mathbf{mass}} \equiv m_{\mathbf{up}}(\overline{u}_{\mathbf{L}}\, u_{\mathbf{R}} + \overline{u}_{\mathbf{R}}\, u_{\mathbf{L}}) + m_{\mathbf{ch}}(\overline{c}_{\mathbf{L}}\, c_{\mathbf{R}} + \overline{c}_{\mathbf{R}}\, c_{\mathbf{L}})$$
$$+\, m_{\mathbf{top}}(\overline{t}_{\mathbf{L}}\, t_{\mathbf{R}} + \overline{t}_{\mathbf{R}}\, t_{\mathbf{L}})$$

$$L^{weak\,int}_{CC} = \frac{g_W}{\sqrt{2}}\left(J^-_\mu W^+_\mu + h.c.\right)$$
$$\rightarrow \quad \frac{g_W}{\sqrt{2}}\left(\bar{u}_L \mathbf{V}^{CKM} \gamma_\mu d_L W^+_\mu + \ldots\right)$$

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}

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

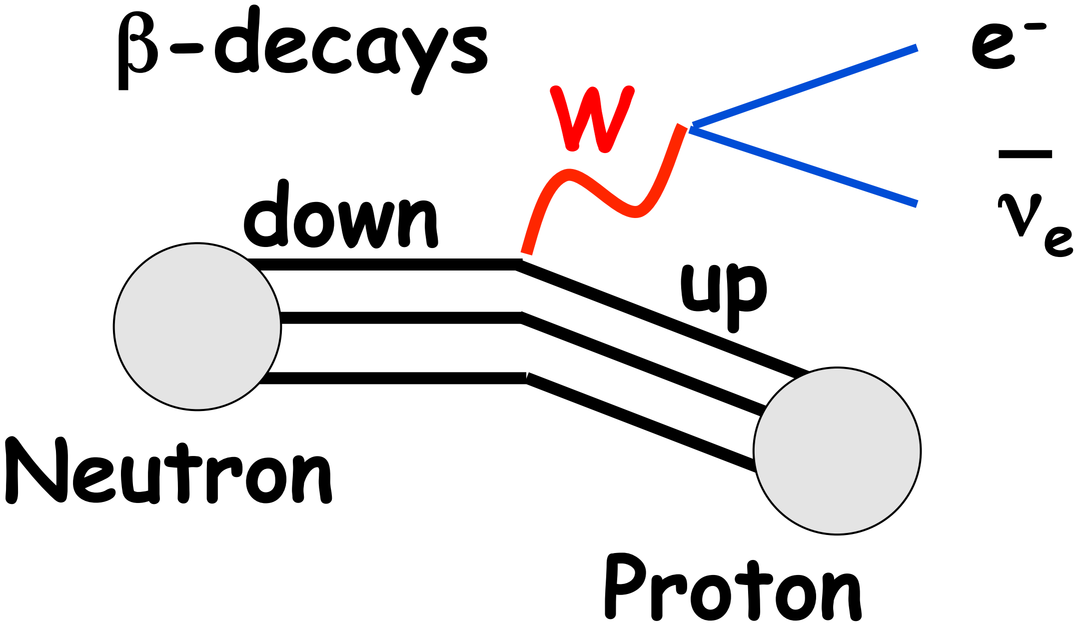
NO Flavour Changing Neutral Currents (FCNC) at Tree Level (FCNC processes are good candidates for observing NEW PHYSICS)

CP Violation is natural with three quark generations (Kobayashi-Maskawa)

With three generations all CP phenomena are related to the same unique parameter (δ)

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

Quark masses & Generation Mixing



$|V_{ud}| = 0.9735(8)$

$|V_{us}| = 0.2196(23)$

$|V_{cd}| = 0.224(16)$

$|V_{cs}| = 0.970(9)(70)$

$|V_{cb}| = 0.0406(8)$

$|V_{ub}| = 0.00409(25)$

$|V_{tb}| = 0.99(29)$

(0.999)

$|V_{ud}|$

updated values later

Textures

There is a clear correlation between mixings and masses

$m_u \sim 4$ MeV $m_c \sim 1200$ MeV $m_t \sim 170$ GeV

$m_d \sim 8$ MeV $m_s \sim 110$ MeV $m_b \sim 4.3$ GeV

Orizontal $\mathcal{U}(2)$: ψ_L $\psi_L{}^c$

$$\mathcal{L}_{higgs} = Y H \left[(\psi_L{}^a)(\psi_L{}^b)^c S^{ab} + (\psi_L{}^a)(\psi_L{}^b)^c A^{ab} \right]$$

Symmetric tensor

Antisymmetric tensor

$$\sin\theta_c \sim \sqrt{m_d / m_s}$$

R.Gatto '70

$$M^d = M \begin{pmatrix} 0 & -\sqrt{x} \\ \sqrt{x} & 1+x \end{pmatrix}$$

$$\mathrm{diag}(M) = M\,(x \;\; , 1)$$

$$x = m_d \,/\, m_s$$

$$V_1 = \begin{pmatrix} 1 \\ \sqrt{x} \end{pmatrix} \qquad \lambda_1 = M\,x$$

$$V_2 = \begin{pmatrix} -\sqrt{x} \\ 1 \end{pmatrix} \qquad \lambda_2 = M$$

Masses & Mixings (including the CP phases) are related !!

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}

$+ O(\lambda^4)$

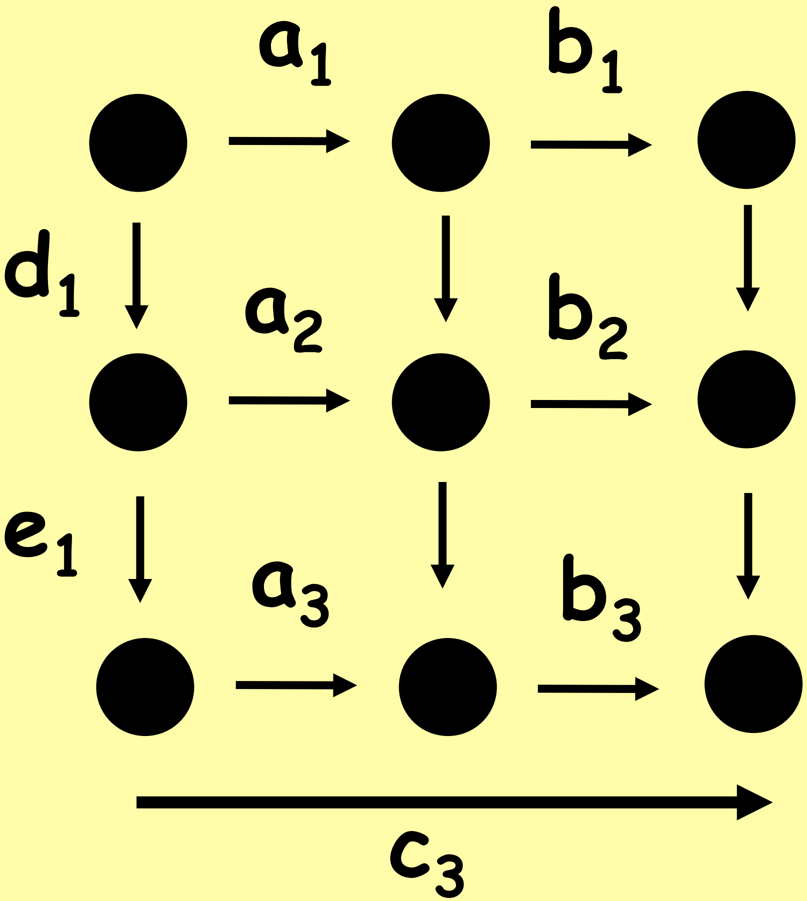
V_{td}

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

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

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

The Bjorken-Jarlskog Unitarity Triangle

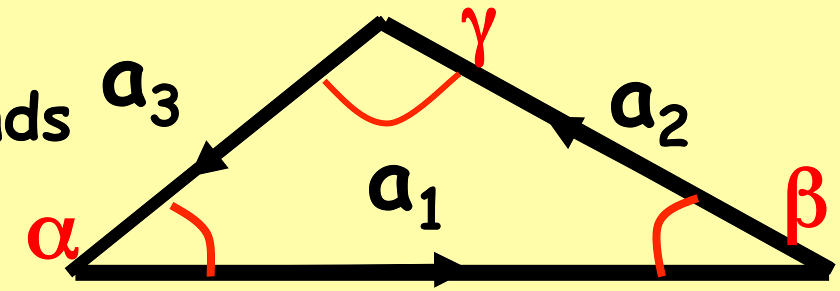


$|V_{ij}|$ is invariant under phase rotations

$$a_1 = V_{11} V_{12}^* = V_{ud} V_{us}^*$$
$$a_2 = V_{21} V_{22}^* \quad a_3 = V_{31} V_{32}^*$$

$$\boxed{\begin{array}{l} a_1 + a_2 + a_3 = 0 \\ (b_1 + b_2 + b_3 = 0 \text{ etc.}) \end{array}}$$

Only the orientation depends on the phase convention



STRONG CP VIOLATION

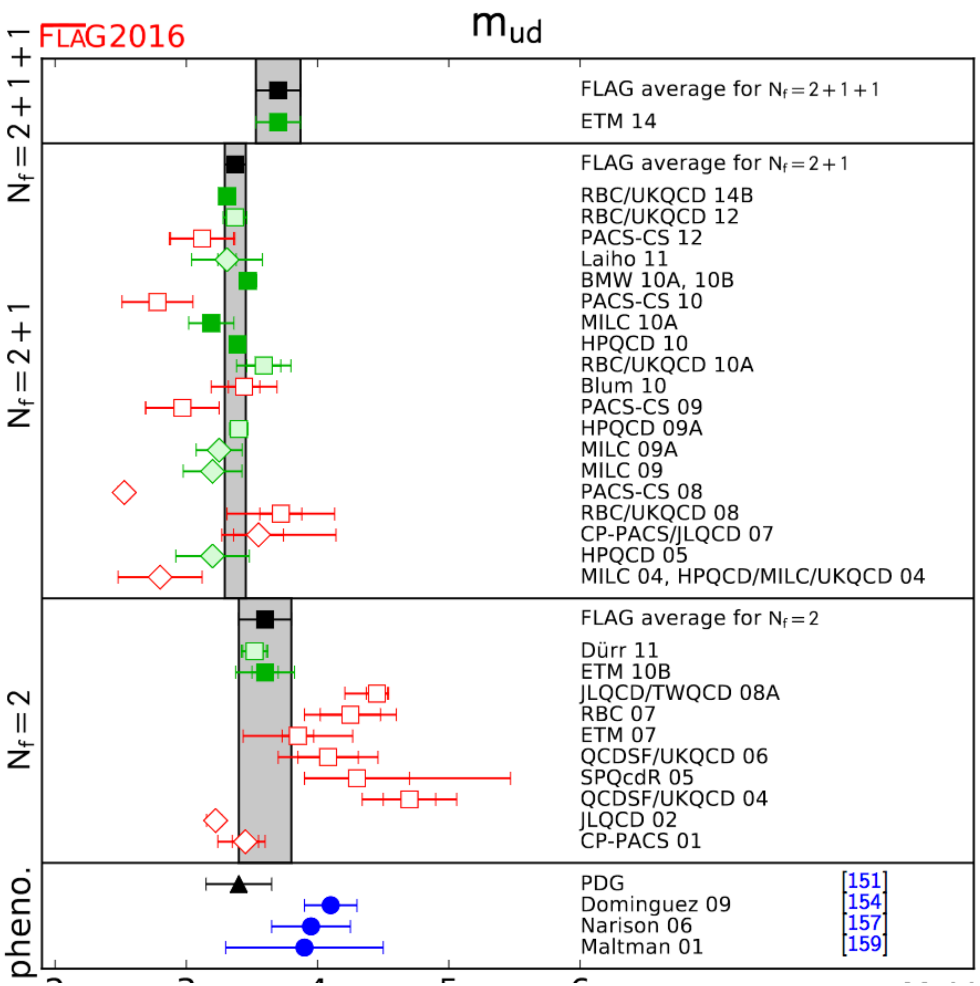
$$\mathcal{L}_\theta = \theta \, \tilde{G}^{\mu\nu a} G^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

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

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

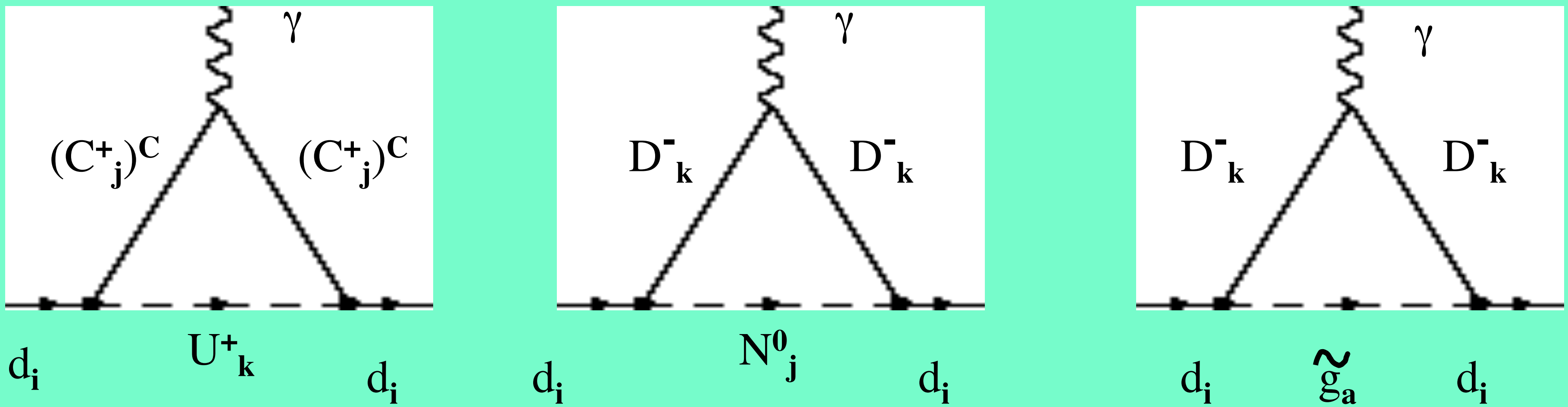
$$e_n < 3 \; 10^{-26} \text{ e cm}$$

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



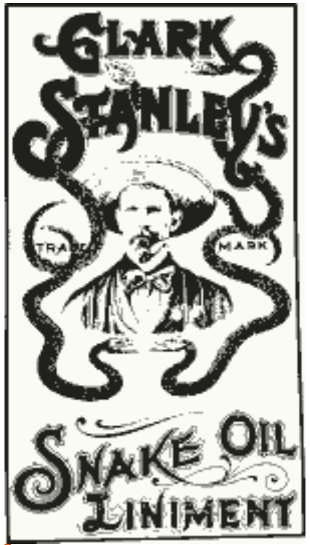
N_f	m_u	m_d	m_u/m_d	R	Q
2+1+1	2.36(24)	5.03(26)	0.470(56)	35.6(5.1)	22.2 (1.6)
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)	35.0(1.9)(1.8)	22.5(6)(6)
2	2.40(23)	4.80(23)	0.50(4)	40.7(3.7)(2.2)	24.3(1.4)(0.6)

Neutron electric dipole moment in SuperSymmetry



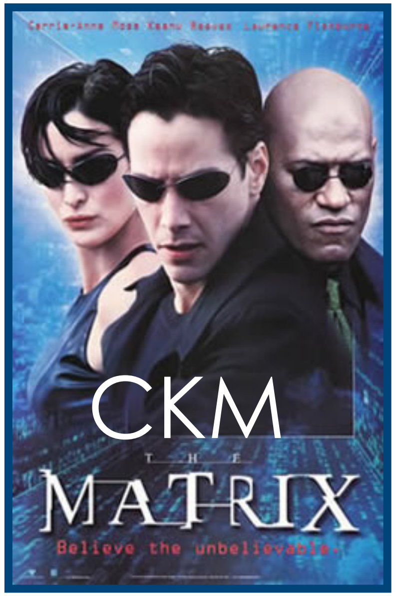
$$\mathcal{L}^{\Delta F=0} = -i/2\, C_e\, \psi \sigma_{\mu\nu}\gamma_5 \psi\, F^{\mu\nu}$$
$$-i/2\, C_C\, \psi\sigma_{\mu\nu}\gamma_5\, t^a \psi\, G^{\mu\nu a}$$
$$-1/6\, C_g\, f_{abc}\, G^a_{\mu\rho}\, G^{b\rho}{}_{\nu}\, G^c_{\lambda\sigma}\, \varepsilon^{\mu\nu\lambda\sigma}$$

$C_{e,C,g}$ can be computed perturbatively



UTfit

www.utfit.org



C. Alpigiani, A. Bevan, M.B., M. Ciuchini, D. Derkach, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, M. Pierini, C. Schiavi, L. Silvestrini, A. Stocchi, V. Sordini, C. Tarantino and V. Vagnoni

Other UT analyses exist, by:

CKMfitter (http://ckmfitter.in2p3.fr/),
Laiho&Lunghi&Van de Water (http://latticeaverages.org/)
Lunghi&Soni (1010.6069)

Measure	V_{CKM}	Other NP parameters
$\Gamma(b \to u)/\Gamma(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}, \lambda_1, F(1), \ldots$
ε_K	$\eta[(1-\bar{\rho}) + \ldots]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_{B_d}^2 B_{B_d}$
$\Delta m_d/\Delta m_1$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A_{CP}(B_d \to J/\psi K_s)$	$\sin 2\beta$	$-$

$$Q^{EXP} = V_{CKM} \times \langle H_F | \hat{O} | H_I \rangle$$

For details see:
UTfit Collaboration

http://www.utfit.org

classical UT analysis

DIFFERENT LEVELS OF THEORETICAL UNCERTAINTIES (STRONG INTERACTIONS)

1) First class quantities, with reduced or negligible theor. uncertainties

$$A_{CP}(B \to J/\psi K_s) \quad \gamma \; from \; B \to DK$$
$$K^0 \to \pi^0 \nu \bar{\nu}$$

2) Second class quantities, with theoretical errors of O(10%) or less that can be reliably estimated

$$\varepsilon_K \quad \Delta M_{d,s}$$
$$\Gamma(B \to c, u), \quad K^+ \to \pi^+ \nu \bar{\nu}$$

3) Third class quantities, for which theoretical predictions are model dependent (BBNS, charming, etc.)

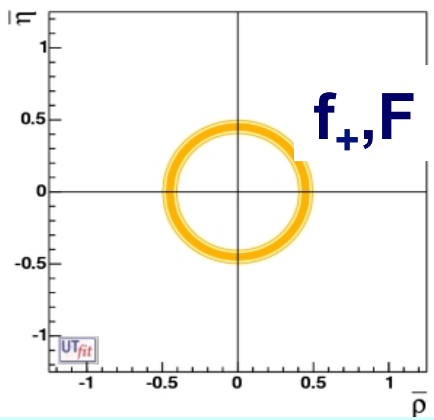
In case of discrepacies we cannot tell whether is *new physics or we must blame the model*

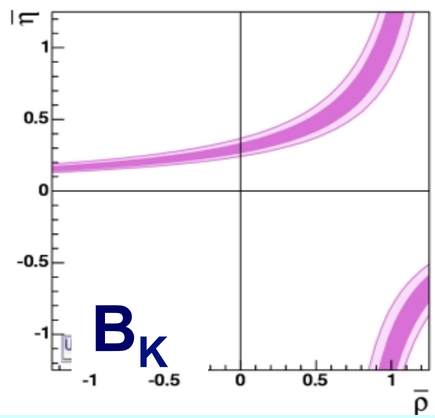
$$B \to K\pi \quad B \to \pi^0 \pi^0$$
$$B \to \phi K_s$$

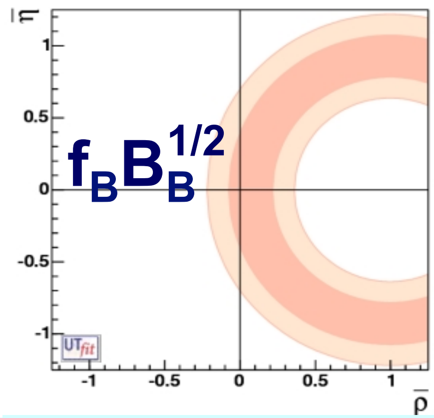
Quantities used in the Standard UT Analysis

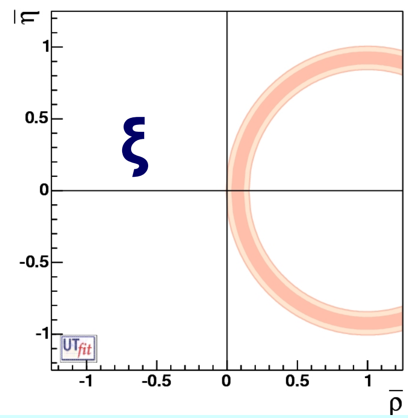
levels @
68% (95%) CL

V_{ub}/V_{cb}	ε_K	Δm_d	$\Delta m_d/\Delta m_s$





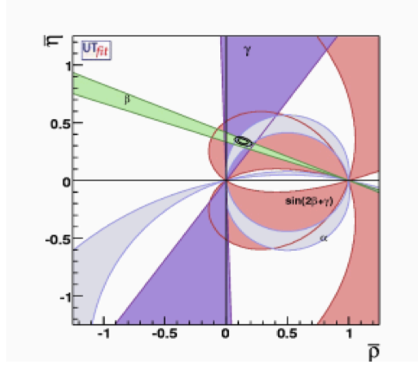




Inclusive vs Exclusive
Opportunity for lattice QCD

UT-LATTICE

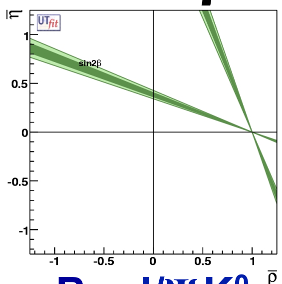
Other Quantities used in the UT Analysis



UT-ANGLES

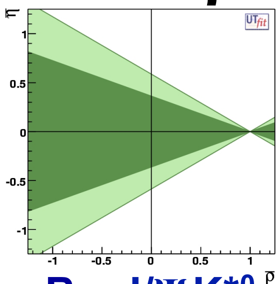
Several new determinations of UT angles are now available, thanks to the results coming from the B-Factory experiments

$\sin 2\beta$



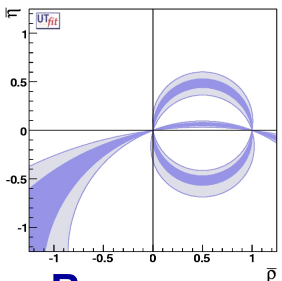
$B \to J/\Psi K^0$

$\cos 2\beta$



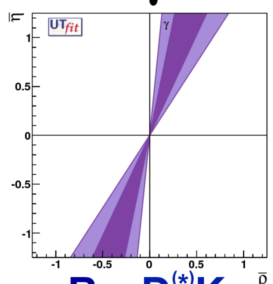
$B \to J/\Psi K^{*0}$

α



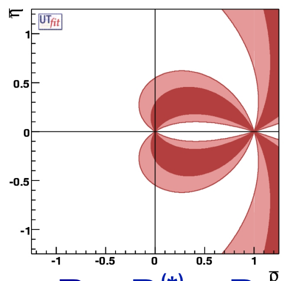
$B \to \pi\pi, \rho\rho$

γ



$B \to D^{(*)}K$

$\sin(2\beta+\gamma)$

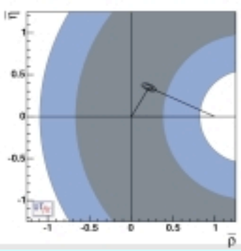


$B \to D^{(*)}\pi, D\rho$

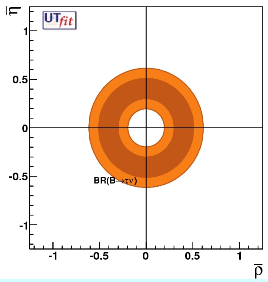
New Constraints from B and K rare decays (not used yet)

New bounds are available from rare B and K decays. They do not still have a strong impact on the global fit and they are not used at present.

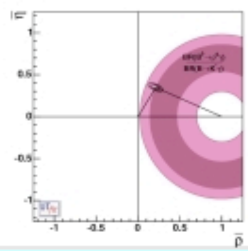
$K \to \pi \nu \bar{\nu}$

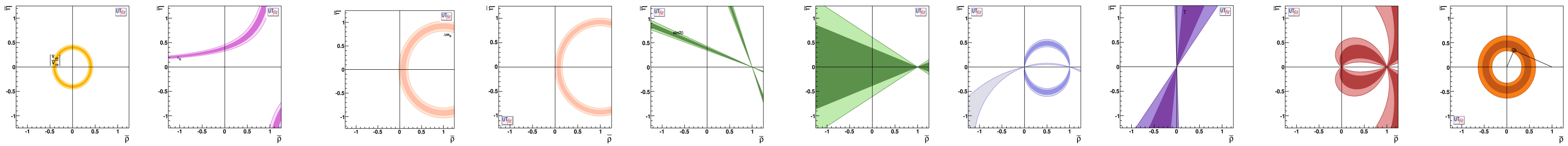


$B \to \tau \nu$



$(B \to \rho/\omega\, \gamma)/(B \to K^*\gamma)$

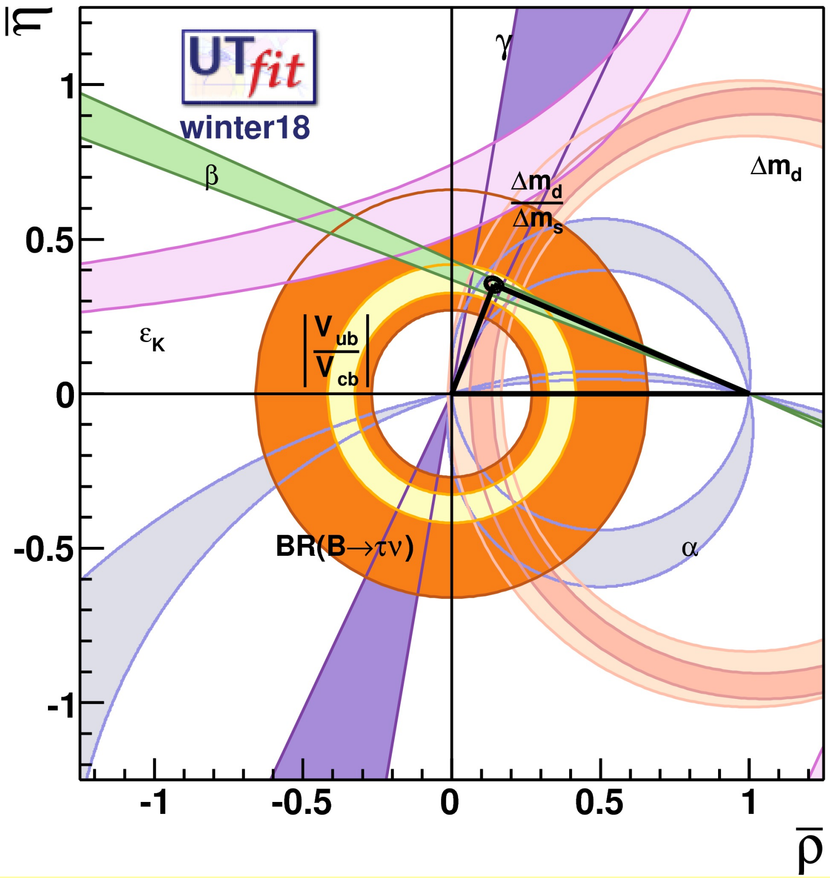




Winter 2018 results

$\bar{\rho} = 0.145 \pm 0.014$ $\bar{\eta} = 0.349 \pm 0.010$

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



$\alpha = (88.2 \pm 0.1)^0$
$\sin2\beta = 0.699 \pm 0.068$
$\beta = (22.3 \pm 0.66)^0$
$\gamma = (65.8 \pm 2.2)^0$
$A = 0.825 \pm 0.012$
$\lambda = 0.22502 \pm 0.00053$

Consistence on an over constrained fit of the CKM parameters

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

CKM Matrix in the SM
Winter 2018

$$V_{CKM} = \begin{pmatrix} (0.97431 \pm 0.00012) & (0.22517 \pm 0.00052) & (0.00365 \pm 0.00010)e^{i(-67.2\pm2.1)^\circ} \\ (-0.22504 \pm 0.00055)e^{i(0.0351\pm0.0010)^\circ} & (0.97344 \pm 0.00012)e^{i(-0.001880\pm0.000052)^\circ} & (-) \\ (0.00871 \pm 0.00014)e^{i(-22.23\pm0.63)^\circ} & (-0.04111 \pm 0.00056)e^{i(1.059\pm0.032)^\circ} & (0.999115 \pm 0.000024) \end{pmatrix}$$

Standard Parametrization (PDG)

Sin $\theta_{12} = 0.22502 \pm 0.00053$

Sin $\theta_{23} = 0.04190 \pm 0.00058$

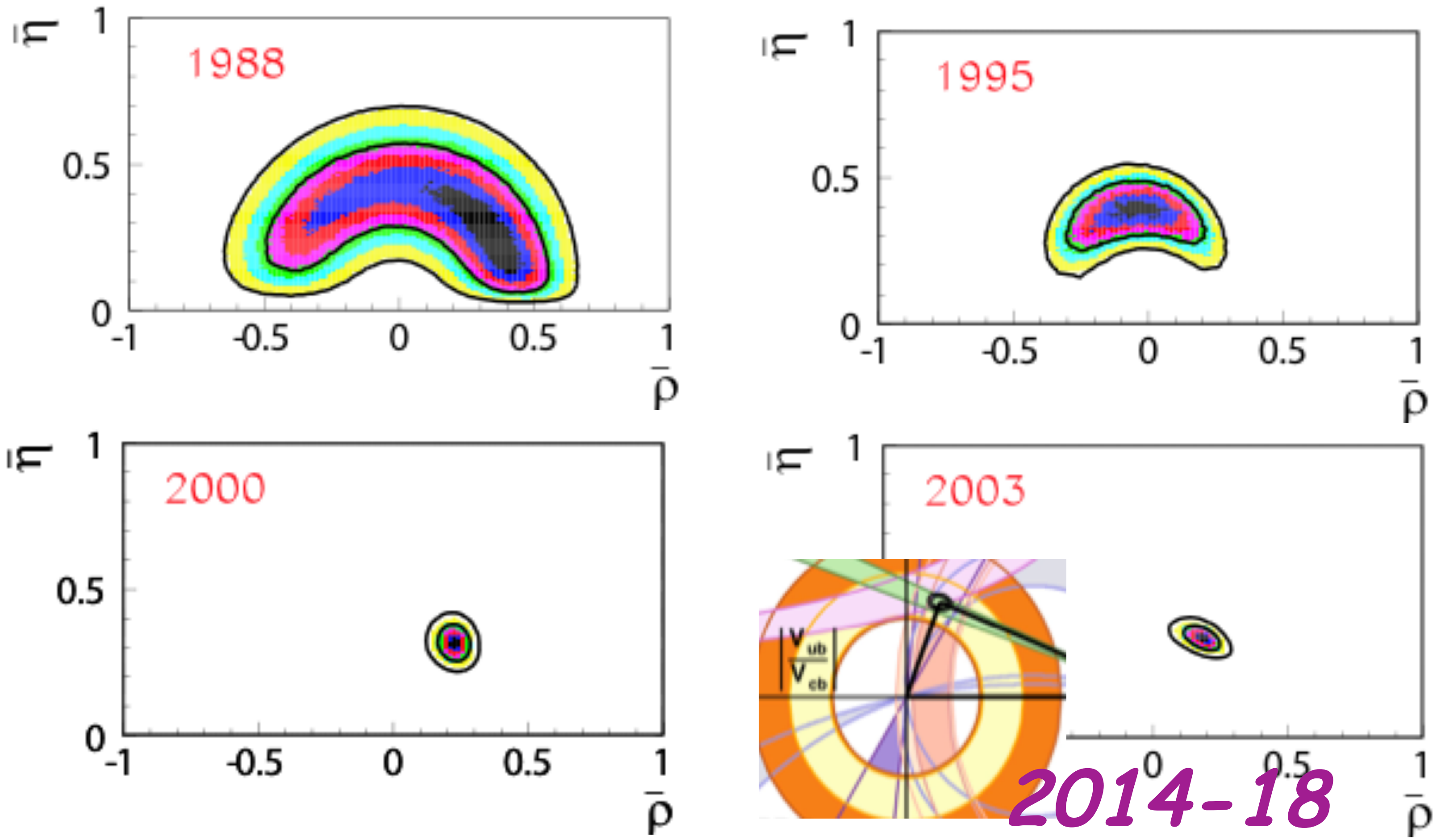
Sin $\theta_{13} = 0.003669 \pm 0.000096$ $\delta = 67.3 \pm 2.2$

Wolfenstein Parametrization (PDG)

$\lambda = 0.22502 \pm 0.00053$ $A = 0.825 \pm 0.0.12$

PROGRESS SINCE 1988

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



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

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
B_K	0.740 ± 0.029	0.81 ± 0.07	< 1
f_{Bs}	0.226 ± 0.005	0.220 ± 0.007	
f_{Bs}/f_{Bd}	1.203 ± 0.013	1.210 ± 0.030	< 1
B_{Bs}/B_{Bd}	1.032 ± 0.036	1.07 ± 0.05	< 1
B_{Bs}	1.35 ± 0.08	1.30 ± 0.07	< 1

0.843 Pull =+1.2

in general: average the Nf=2+1+1 and Nf=2+1 FLAG averages,
through eq.(28) in arXiv:1403.4504

for Bk, fBs, fBs/fBd:
FLAG Nf=2+1+1 (single result) and Nf=2+1 average

for B_{Bs}, B_{bs}/B_{bd}:
update w.r.t. the Nf=2+1 FLAG average (no Nf=2+1+1 results yet)
updating the FNAL/MILC result to FNAL/MILC 2016 (1602.03560)

Do we still care? Tensions and Unknowns

1) A ``classical'' example B -> $\tau\nu$

2) $|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive

3) $|V_{cb}|$, B mixing and ε_K

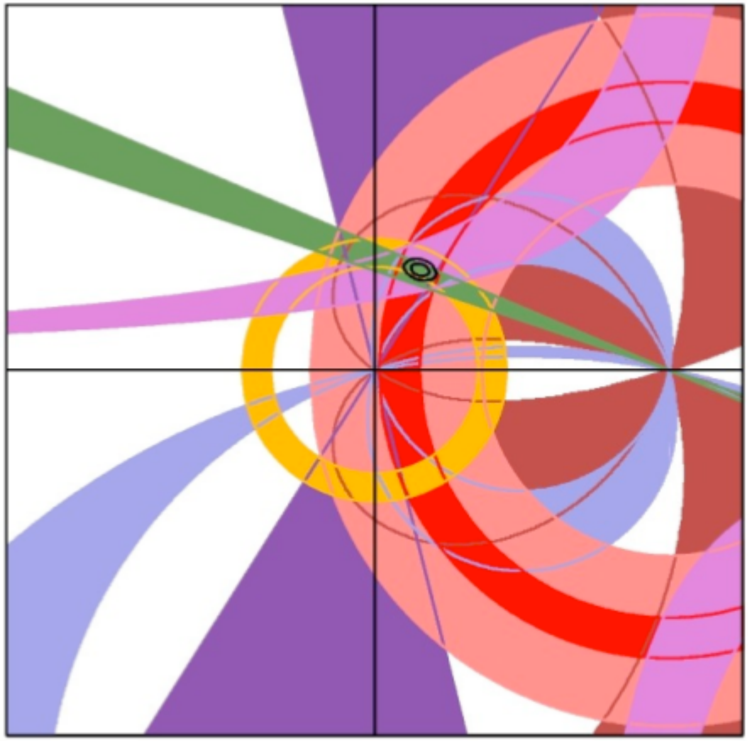
4) D-mixing

5) R(D) and R(D*)

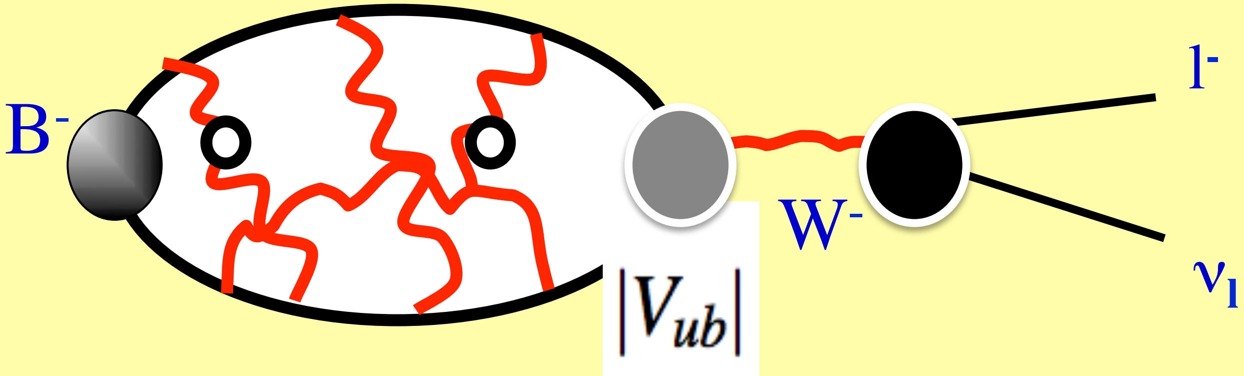
6) B -> K* ll

7) Physics BSM ?

- What can be computed and what cannot be computed



The Simplest Example

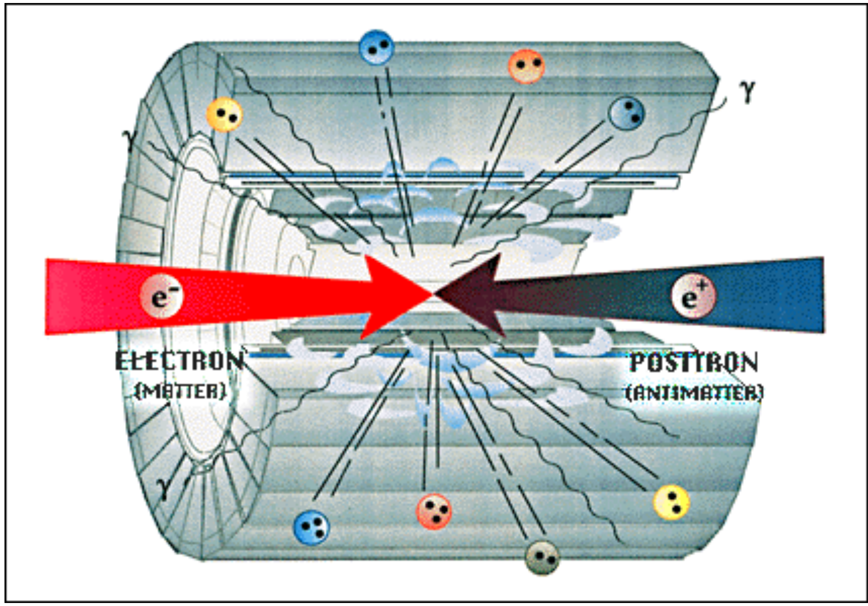


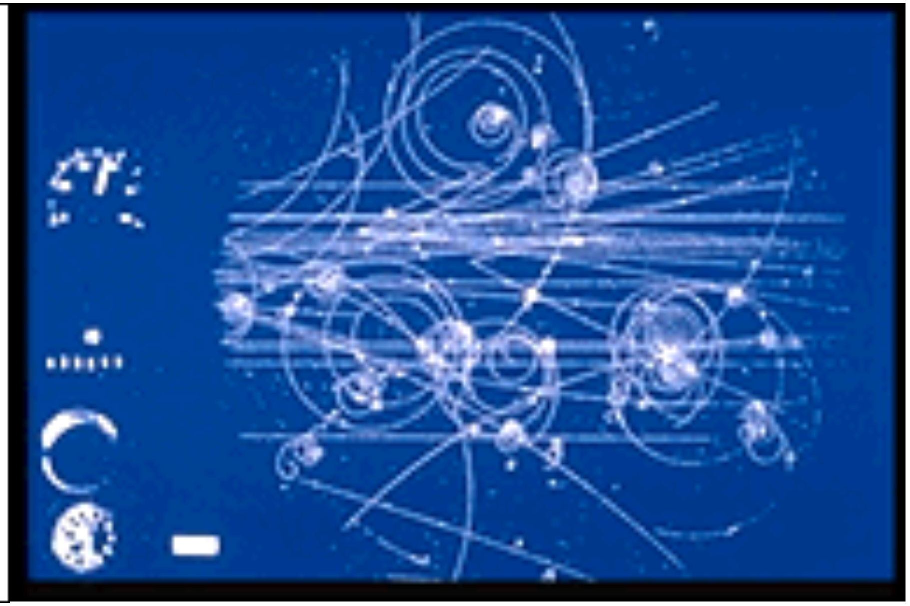
$$BR(B^- \to \tau^- \bar{\nu}_\tau) = f_B^2 |V_{ub}|^2 \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_B$$

$$\boxed{f_B^2\, |V_{ub}|^2}$$

$$\boxed{\langle 0 | \bar{b}\gamma_\mu\gamma_5 d | B^0(p)\rangle = i\, f_B\, p_\mu}$$

COULD WE COMPUTE THIS PROCESS WITH
SUFFICIENT COMPUTER POWER ?



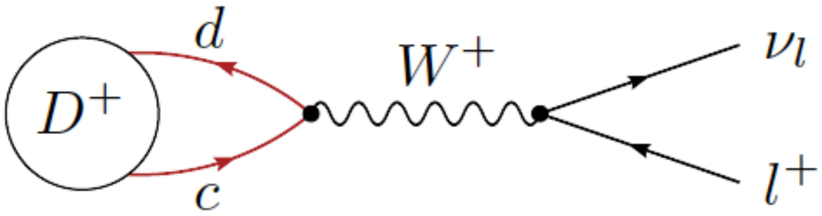


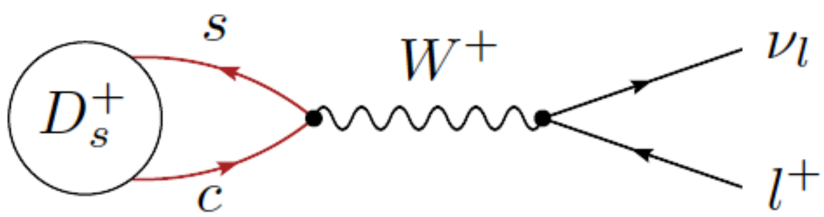
THE ANSWER IS: NO

IT IS NOT ONLY A QUESTION OF COMPUTER POWER
BECAUSE THERE ARE COMPLICATED
FIELD THEORETICAL PROBLEMS

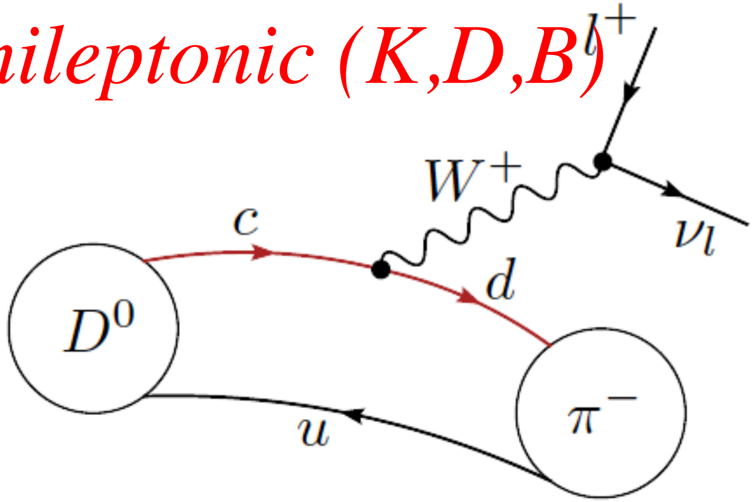
Euclide vs Minkowski

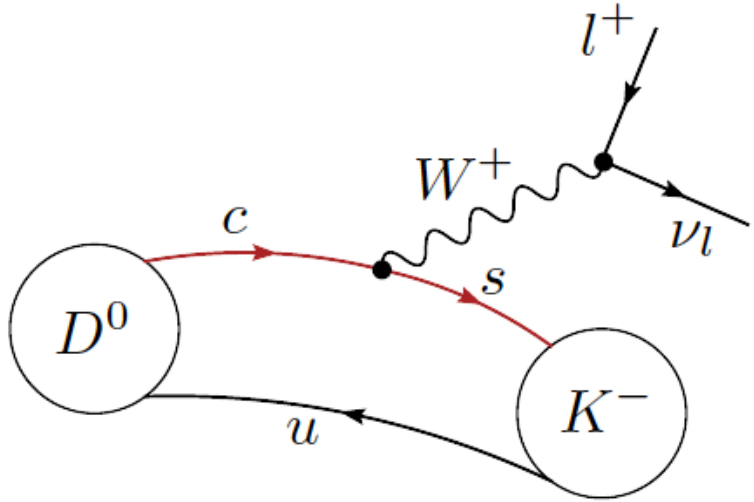
Leptonic (π,K,D,B)





Semileptonic (K,D,B)

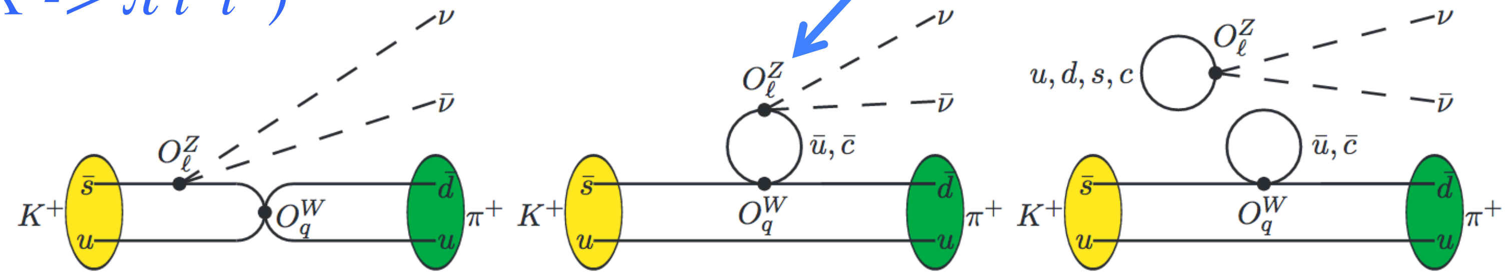




(some) Radiative and Rare

long distance effects

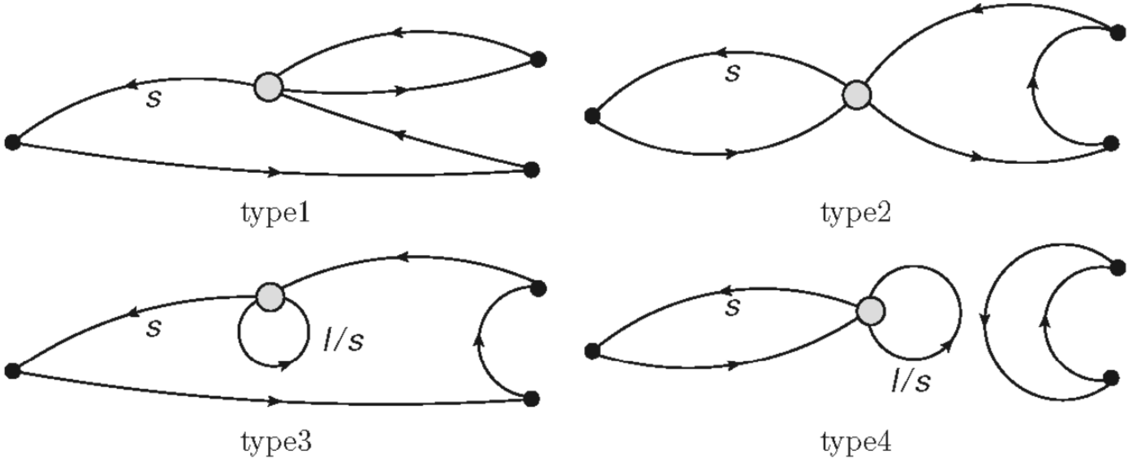
(also $K \to \pi\, l^+ l^-$)



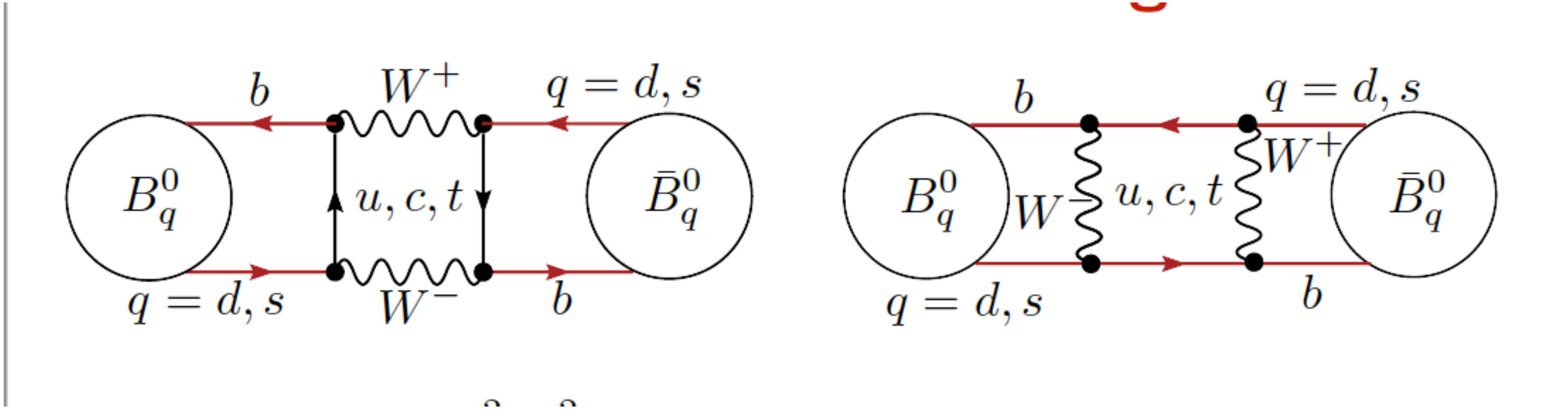
connected diag. self-loop diag. disconnected diag.

Non-leptonic *B -> ππ,Kπ, 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-> $K^{(*)}$ l^+l^-

Radiative corrections to weak amplitudes

important for hadron masses, leptonic and semileptonic decays, $|V_{us}|$, but also for D and B decays

13

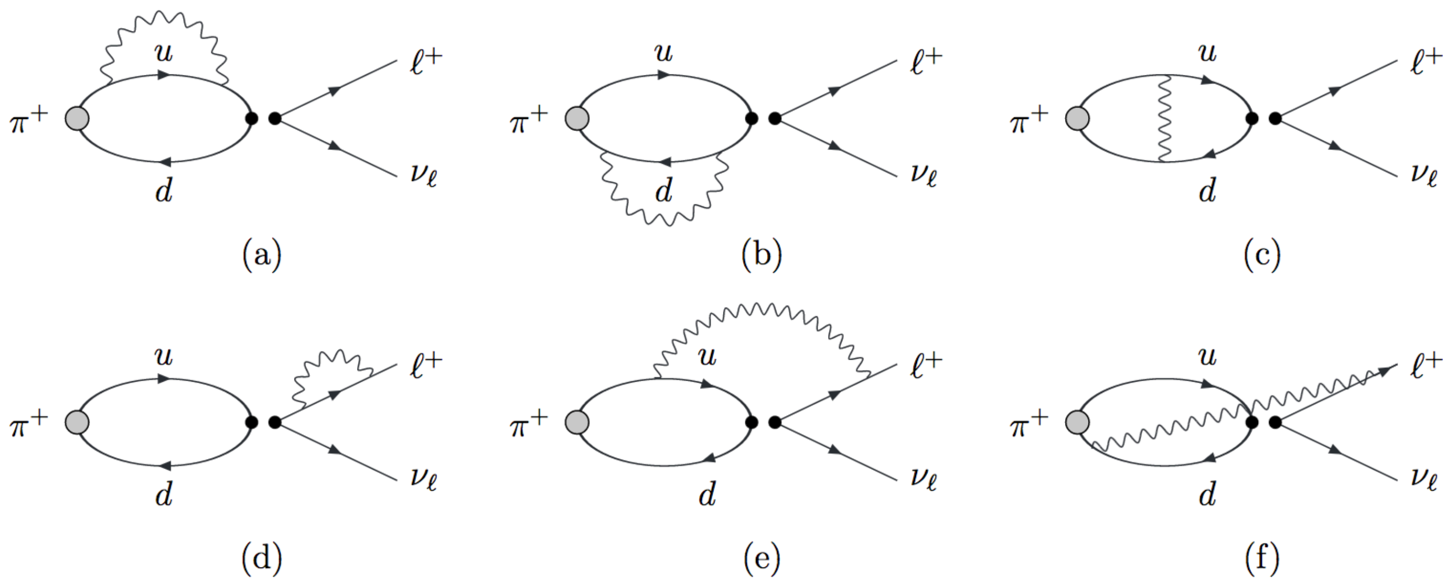


FIG. 5: Connected diagrams contributing at $O(\alpha)$ contribution to the amplitude for the decay $\pi^+ \to \ell^+ \nu_l$.

The accuracy of lattice calculations of the hadron spectrum (and hence of the quark masses) and of the decay constants and form factors is such that isospin breaking and em effects cannot be neglected anymore:

FLAG Collaboration, arXiv:1607.00299

N_f = 2+1 $m_{ud} = 3.37(8)$ MeV $m_s = 92.0(2.1)$ MeV

$m_s/m_{ud} = 27.43(31)$ ε =3%-6%

N_f = 2+1+1

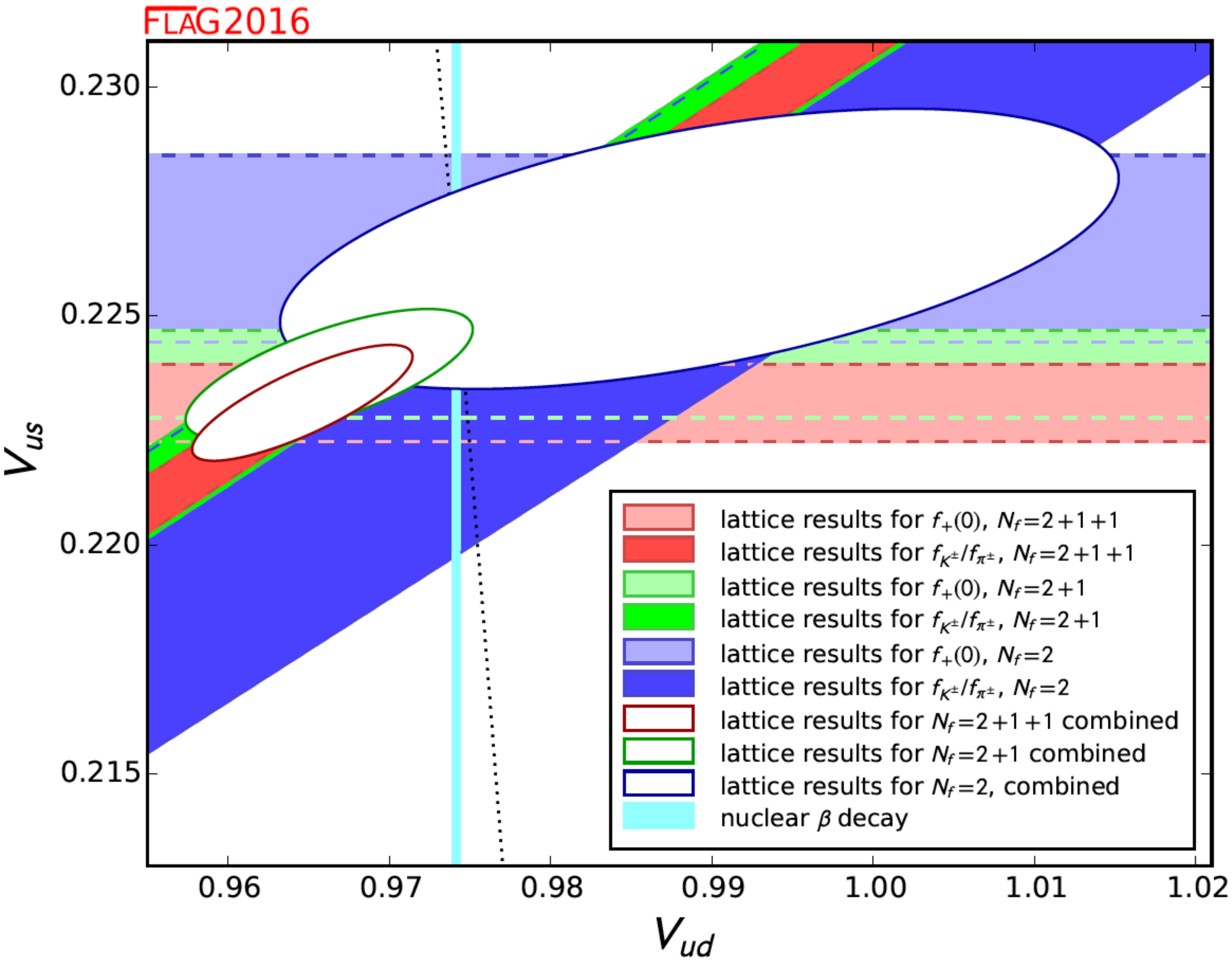
$m_{ud} = 3.70(17)$MeV $m_s = 93.9(1.1)$ MeV

$m_s/m_{ud} = 27.30(34)$

$f_\pi = 130.2(1.4)$ MeV $f_K = 155.36(0.4)$ MeV ε =0.26%

$f_K/f_\pi = 1.1933(29)$ ε =0.24% $F^{K\pi}(0) = 0.9704(32)$ ε =0.34%

STANDARD MODEL UNITARITY TRIANGLE ANALYSIS (FLAG)



- $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$ = 0.9998(5) or 0.9999(6) from semileptonic and leptonic respectively

Relevant also in D and B meson decays

ATTENTION TO THE QUOTED ERRORS

significant differences in estimates of fit and systematic uncertainties in otherwise very similar computations

well-known example from light-quark physics (both computations use MILC ensembles, relatively minor differences)

MILC 13 $$f_{K^\pm}/f_{\pi^\pm}|_{N_\mathrm{f}=2+1+1} = 1.1947\overset{\text{stat}}{(26)}\overset{\text{CL}}{(33)}\overset{\text{FV}}{(17)}\overset{\text{e.m.}}{(2)}$$

HPQCD 13 $$f_{K^\pm}/f_{\pi^\pm}|_{N_\mathrm{f}=2+1+1} = 1.1916\underset{\text{stat}}{(15)}\underset{\text{CL}}{(12)}\underset{\text{FV}}{(1)}\underset{\text{(misc).}}{(10)}$$

+ perturbative renormalization
courtesy of C. Pena

Do we still care? Tensions and Unknowns

1) A ``classical" example B -> $\tau\nu$
2) $|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive
3) $|V_{cb}|$, B mixing and ε_K
4) D-mixing
5) R(D) and R(D*)
6) B -> K* ll
7) Physics BSM ?

CKM-TRIANGLE ANALYSIS

State of The Art 2015

	Measurement	Fit	Prediction	Pull
α	$(92.7 \pm 6.2)^o$	$(90.1 \pm 2.7)^o$	$(88.3 \pm 3.4)^o$	0.6
	6.7 %	2.9 %	3.8 %	
$\sin 2\beta$	0.680 ± 0.024	0.696 ± 0.022	0.747 ± 0.039	1.8
	3.5 %	2.6 %	5.2 %	
γ	$(71.4 \pm 6.5)^o$	$(67.4 \pm 2.8)^o$	$(66.7 \pm 3.0)^o$	0.7
	9.1 %	4.2 %	4.5 %	
$\lvert V_{ub}\rvert \times 10^3$	3.81 ± 0.40	3.66 ± 0.12	3.64 ± 0.12	0.5
	10 %	3.3 %	3.3 %	
$\lvert V_{cb}\rvert \times 10^2$	4.09 ± 0.11	4.206 ± 0.053	4.240 ± 0.062	0.9
	2.6 %	1.2 %	1.4 %	
$\varepsilon_K \times 10^3$	2.228 ± 0.011	2.227 ± 0.011	2.08 ± 0.18	0.8
	0.5 %	0.5 %	8.7 %	
Δm_s (ps^{-1})	17.761 ± 0.022	17.755 ± 0.022	17.3 ± 1.0	0.2
	0.1 %	0.1 %	5.7 %	
$BR(B \to \tau\nu) \times 10^4$	1.06 ± 0.20	0.83 ± 0.07	0.81 ± 0.7	1.3
	18.9 %	7.9 %	8.2 %	
$\bar{B}R(B_s \to \mu\mu) \times 10^9$	2.9 ± 0.7	3.90 ± 0.15	3.94 ± 0.16	1.5
	24.1 %	3.8 %	4.0 %	ew corrections not included
$BR(B_d \to \mu\mu) \times 10^9$	0.39 ± 0.15	0.1098 ± 0.0057	0.1103 ± 0.0058	1.9
	38.5 %	5.2 %	5.2 %	ew corrections not included
β_s	$(0.97 \pm 0.95)^o$	$(1.056 \pm 0.039)^o$	$(1.056 \pm 0.039)^o$	0.1
	98 %	4.4 %	4.1 %	not included in the fit

$B(B \to \tau\,\nu)_{\text{Old}} = (1.67 \pm 0.30)\ 10^{-4}$

LATTICE PARAMETERS (2017)

It does not make sense to improve the precision on B_K if we do not control ***long distance effects;*** *Similarly for f_π or f_K* ***without radiative corrections***

Observables	Measurement	Prediction	Pull (#σ)
B_K	0.740 ± 0.029	0.81 ± 0.07	< 1
f_{Bs}	0.226 ± 0.005	0.220 ± 0.007	< 1
f_{Bs}/f_{Bd}	1.203 ± 0.013	1.210 ± 0.030	< 1
B_{Bs}/B_{Bd}	1.032 ± 0.036	1.07 ± 0.05	< 1
B_{Bs}	1.35 ± 0.08	1.30 ± 0.07	< 1

Long Distance Effects in Neutral Meson Mixing

N.H.Christ, T.Izubuchi, CTS, A.Soni & J.Yu (RBC-UKQCD), arXiv:1212.5931
Z.Bai, N.H.Christ, T.Izubuchi, CTS, A.Soni & J.Yu (RBC-UKQCD), arXiv:1406.0916
Z.Bai (RBC-UKQCD), arXiv:1411.3210

exp $\Delta m_K \equiv m_{K_L} - m_{K_S} = 3.483(6) \times 10^{-12}\,\mathrm{MeV}.$

3.19(41)(96) lattice unphysical masses

- Historically led to the prediction of the energy scale of the charm quark.
  Mohapatra, Rao & Marshak (1968); GIM (1970); Gaillard & Lee (1974)
- Tiny quantity $\Rightarrow$ places strong constraints on BSM Physics.
- Within the standard model, Δm_K arises from K^0–$\bar{K}^0$ mixing at second order in the weak interactions:

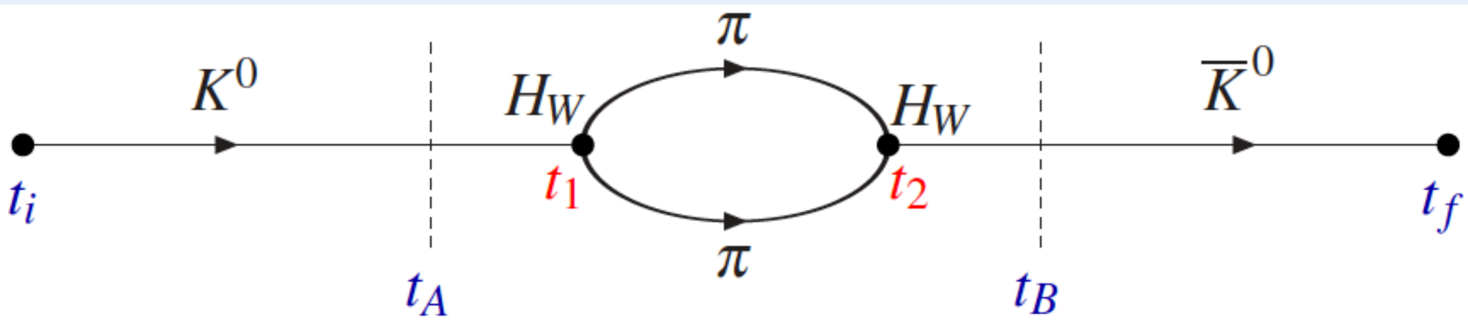
$$\Delta M_K = 2\mathcal{P} \sum_\alpha \frac{\langle \bar{K}^0 | H_W | \alpha\rangle \langle \alpha | H_W | K^0\rangle}{m_K - E_\alpha},$$

New project: $64^3 \times 128$, $a^{-1} = 2.36$ GeV, $m_c = 1.2$ GeV, $m_\pi = 136$ MeV

- Based on 59 configurations: $\Delta M_K = 5.5(1.7) \times 10^{-12}$ MeV

[C. Sachrajda's talk, Wednesday 12:30@Seminarios 6+7]

Long Distance Effects in Neutral Meson Mixing



- Δm_K is given by

$$\Delta m_K \equiv m_{K_L} - m_{K_S} = 2\mathcal{P}\sum_\alpha \frac{\langle \bar{K}^0 \,|\, \mathcal{H}_W \,|\, \alpha\rangle\, \langle \alpha \,|\, \mathcal{H}_W \,|\, K^0\rangle}{m_K - E_\alpha} = 3.483(6)\times 10^{-12}\,\text{MeV}.$$

- The above correlation function gives ($T = t_B - t_A + 1$)

$$C_4(t_A, t_B; t_i, t_f) \quad = \quad |Z_K|^2 e^{-m_K(t_f - t_i)} \sum_n \frac{\langle \bar{K}^0 \,|\, \mathcal{H}_W \,|\, n\rangle\, \langle n \,|\, \mathcal{H}_W \,|\, K^0\rangle}{(m_K - E_n)^2} \times \left\{ e^{(M_K - E_n)T} - (m_K - E_n)T - 1 \right\}.$$

- From the coefficient of T we can therefore obtain

$$\Delta m_K^{\text{FV}} \equiv 2\sum_n \frac{\langle \bar{K}^0 \,|\, \mathcal{H}_W \,|\, n\rangle\, \langle n \,|\, \mathcal{H}_W \,|\, K^0\rangle}{(m_K - E_n)}\,.$$

Long Distance Effects in Neutral Meson Mixing

- The general formula can be written: N.H.Christ, G.Martinelli & CTS, arXiv:1401.1362
  N.H.Christ, X.Feng, G.Martinelli & CTS, arXiv:1504.01170

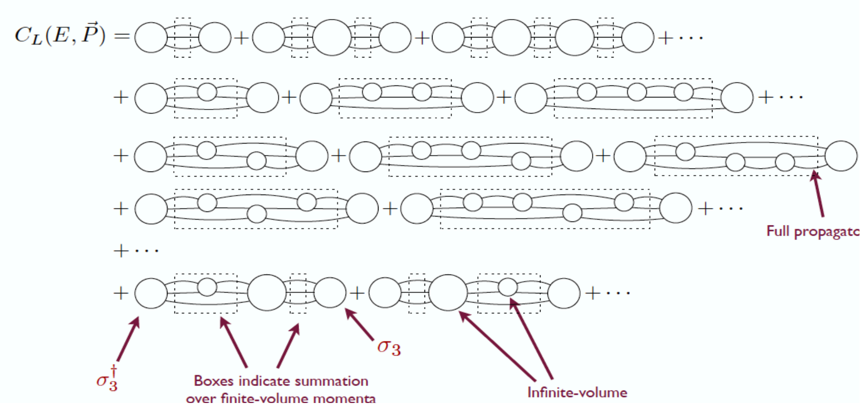
$$\Delta m_K = \Delta m_K^{\mathrm{FV}} - 2\pi \; {}_V\langle \bar{K}^0 \,|\, H \,|\, n_0 \rangle_V \; {}_V\langle n_0 \,|\, H \,|\, K^0 \rangle_V \left[\cot \pi h \, \frac{dh}{dE} \right]_{m_K} ,$$

where $h(E,L)\pi \equiv \phi(q) + \delta(k)$.

- This formula reproduces the result for the special case when the volume is such that there is a two-pion state with energy $= m_K$. N.H.Christ, arXiv:1012.6034
- Increasing the volumes keeping $h = n/2$ and thus avoiding the power corrections is an intriguing possibility.

Within reasonable approximations can be extended to D meson mixing
M. Ciuchini,V. Lubicz, L. Silvestrini, S. Simula
(progresses made by M. T. Hansen & S. Sharpe,1204.0826v4,1409.7012v,1504.04248v1)
Also CPV in D -> ππ or KK

3-particle correlator



D MIXING

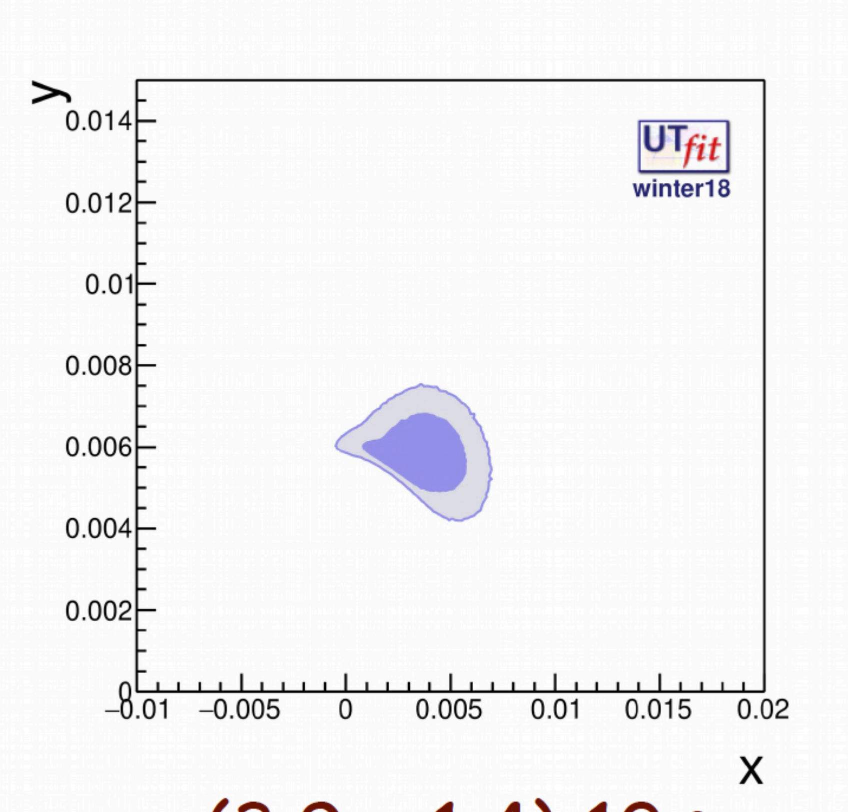
- D mixing is described by:
  - Dispersive $D \to \bar{D}$ amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive $D \to \bar{D}$ amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

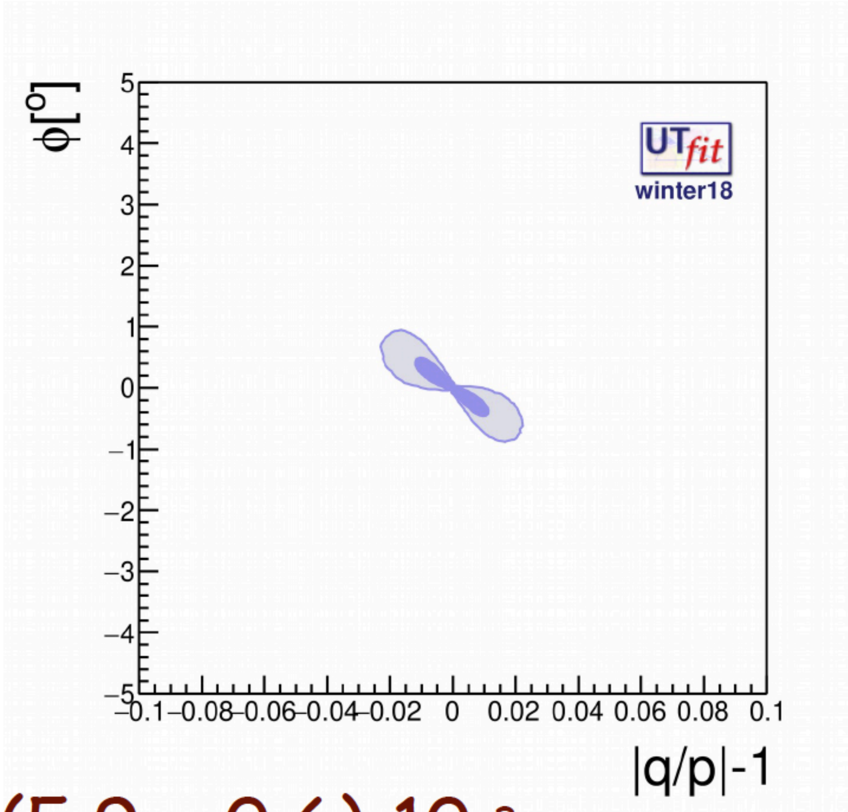
Let us assume that the Standard Model contributions to M_{12} and Γ_{12} are real

“REAL SM” APPROXIMATION

- Define $|D_{S,L}|=p|D^0|\pm q|\bar{D}^0|$ and $\delta=(1-|q/p|^2)/(1+|q/p|^2)$. All observables can be written in terms of $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$ and δ
- Introduce $\phi=\arg(q/p)=\arg(y+i\delta x)$
- $|q/p| \neq 1 \Leftrightarrow \phi \neq 0$ clear signals of NP
- Combine all available data with the assumption of real decay amplitudes and real Γ_{12}
- Preliminary winter18 combination

D mixing fit results





$x = (3.9 \pm 1.4)\ 10^{-3}$, $y = (5.9 \pm 0.6)\ 10^{-3}$,

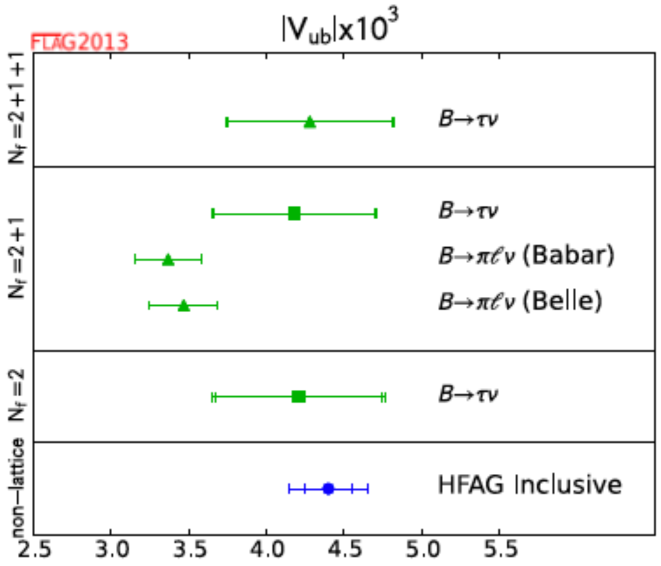
$\phi = (0.02 \pm 0.32)^\circ$, $|q/p|-1 = (0 \pm 9)\ 10^{-3}$

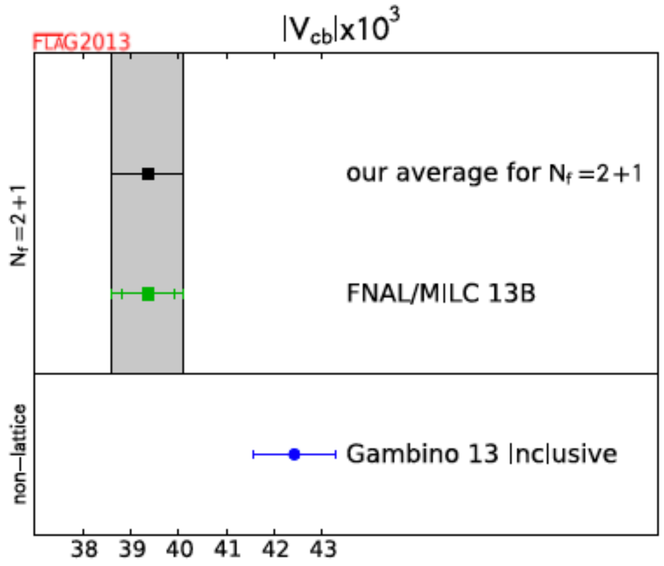
Do we still care? Tensions and Unknowns

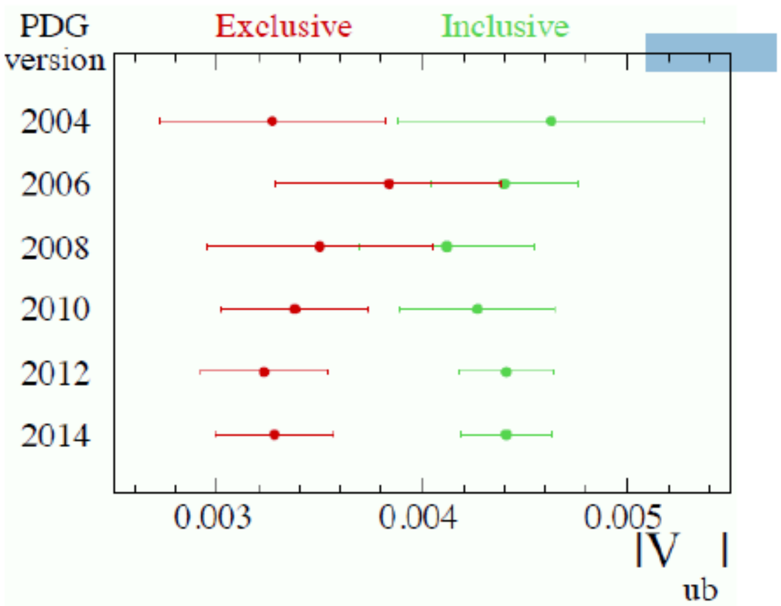
1) A ``classical" example B -> $\tau\nu$
2) $|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive
3) $|V_{cb}|$, B mixing and ε_K
4) D-mixing
5) R(D) and R(D*)
6) B -> K* ll
7) Physics BSM ?

2016

$|V_{ub}|\,,\ |V_{cb}|$







Vub Exclusive = 0.00369 ± 0.00015
Vcb Exclusive = 0.0392 ± 0.0007
Vub/Vcb Exclusive = 0.083 ± 0.006
Vub Inclusive = 0.00441 ± 0.00022
Vcb Inclusive = 0.0422 ± 0.0007
Belle = 0.04247 ± 0.00100

V_{cb} and V_{ub}

New HFAG (HFLAV) @CKM16

$|V_{cb}|$ *(excl)* = $(38.88 \pm 0.60)\ 10^{-3}$

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

New HFAG @CKM16

~3.3σ discrepancy

New HFAG @CKM16

$|V_{ub}|$ *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.50 \pm 0.20)\ 10^{-3}$

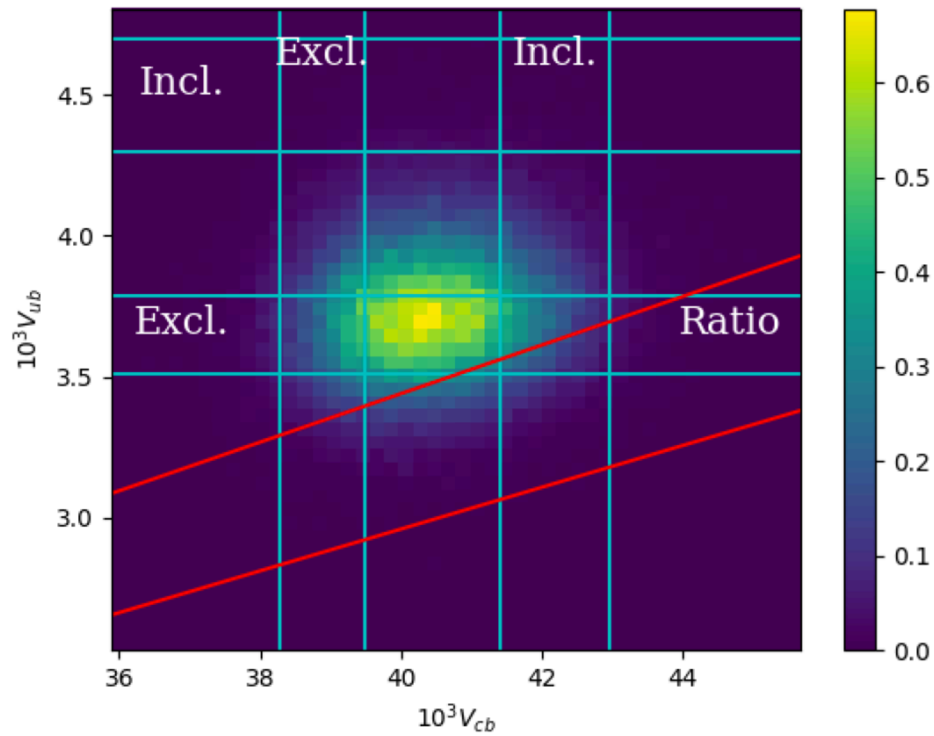
New HFAG @CKM16

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(8.0 \pm 0.6)\ 10^{-2}$

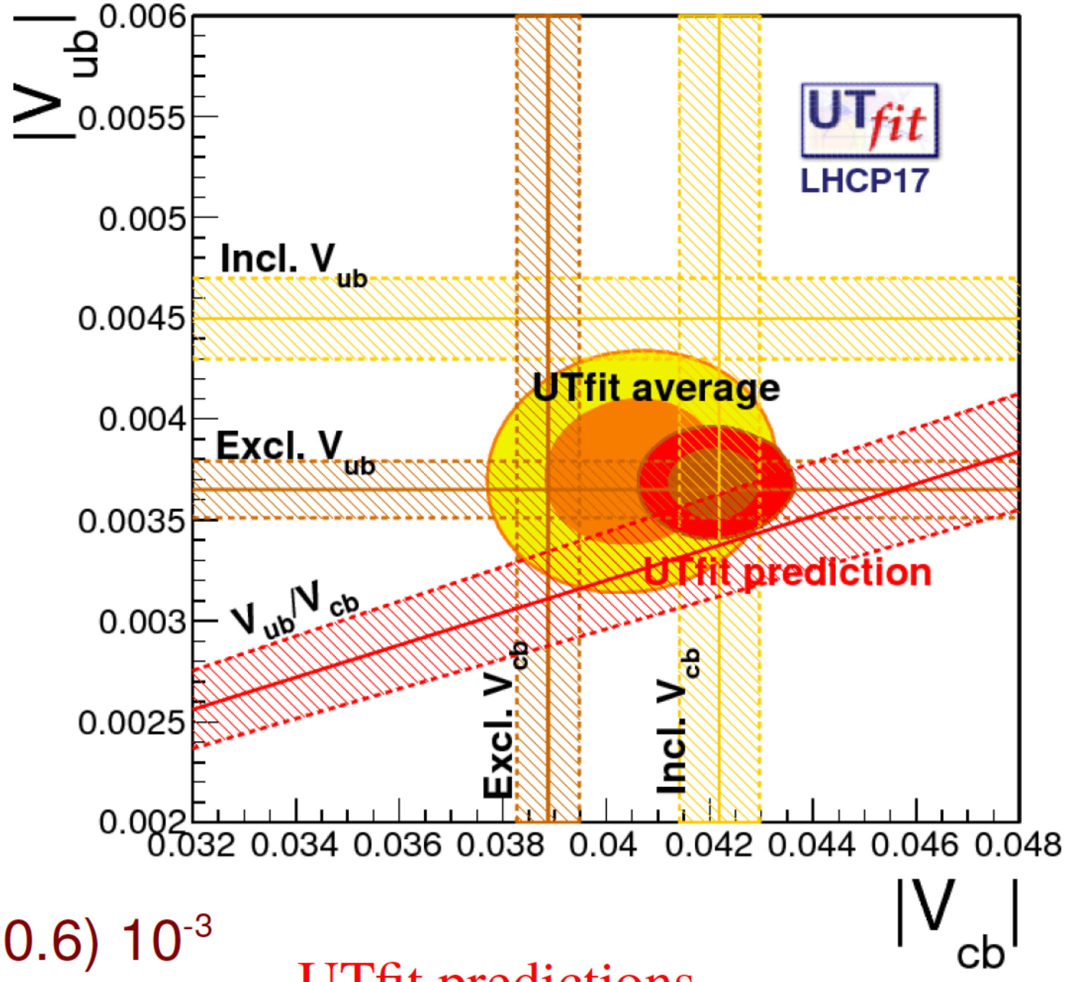
Updated value

updated for LHCP17



V_{cb} and V_{ub}

updated for LHPC17



2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with σ=1. Very similar results obtained from a 2D a la PDG procedure.

$|V_{cb}| = (40.5 \pm 1.1)\ 10^{-3}$

uncertainty ~ 2.4%

$|V_{ub}| = (3.74 \pm 0.23)\ 10^{-3}$

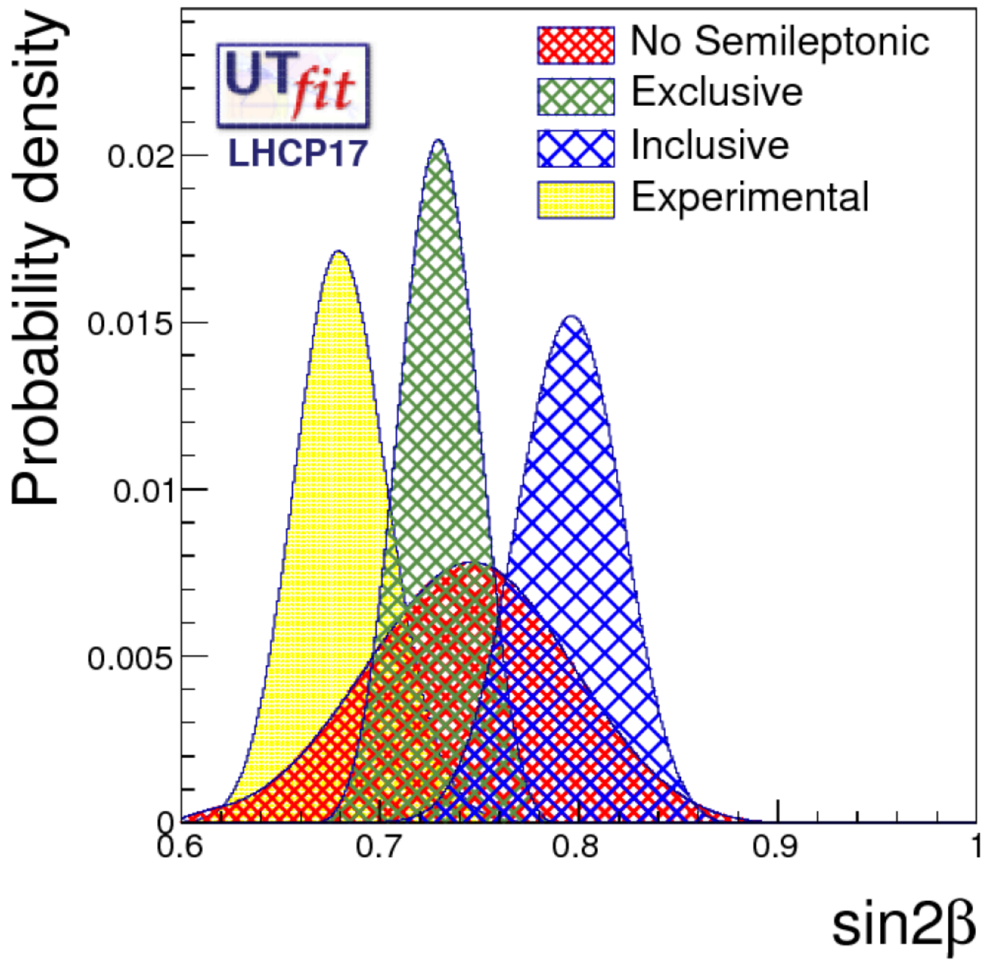
uncertainty ~ 5.6%

Incl → $|V_{cb}| = (42.1 \pm 0.6)\ 10^{-3}$

Excl → $|V_{ub}| = (3.68 \pm 0.11)\ 10^{-3}$

UTfit predictions

exclusives vs inclusives



$\sin 2\beta_{exp} = 0.745 \pm 0.050$

$\sin 2\beta_{exp} = 0.729 \pm 0.019$

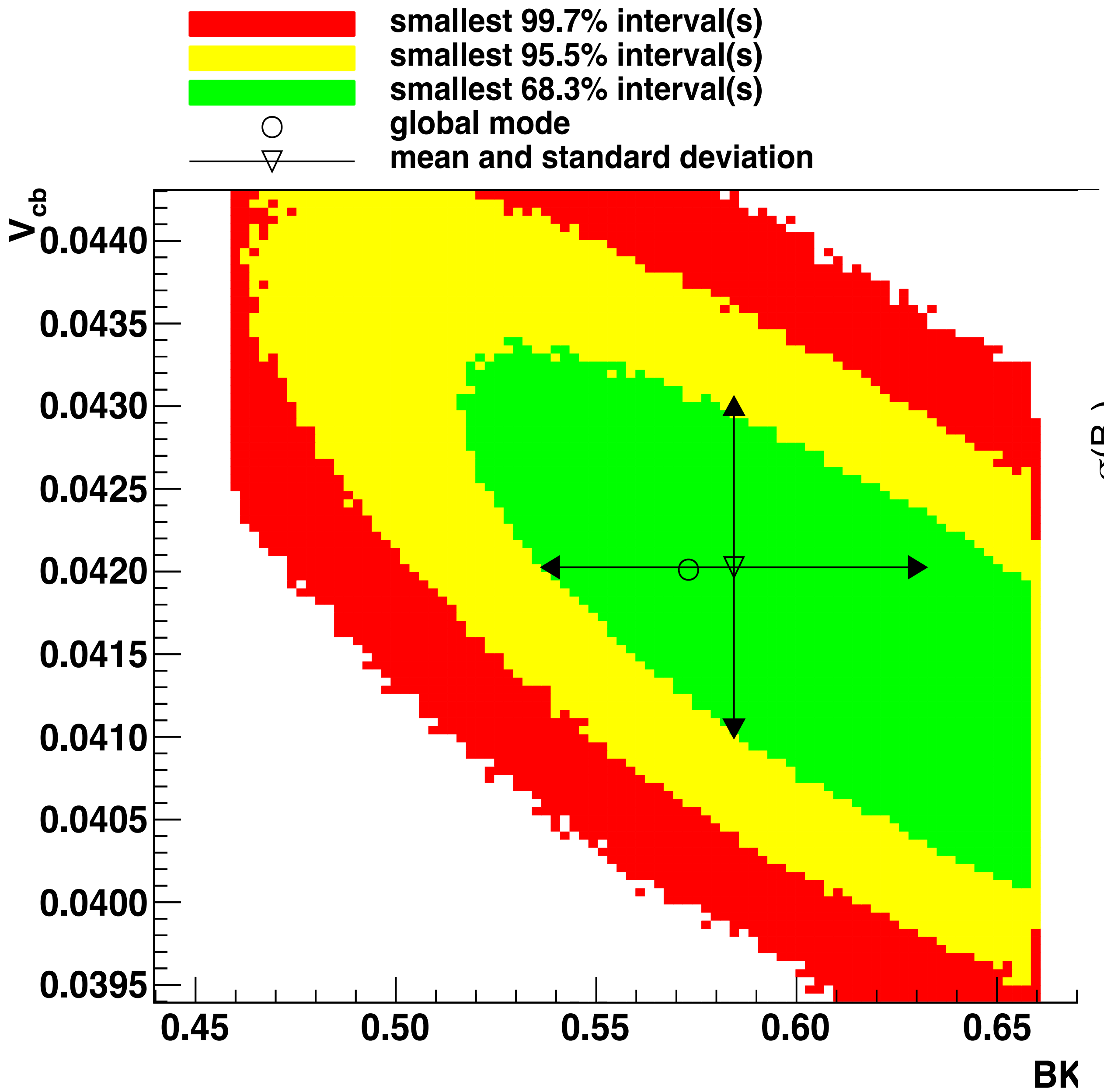
$\sin 2\beta_{exp} = 0.796 \pm 0.026$

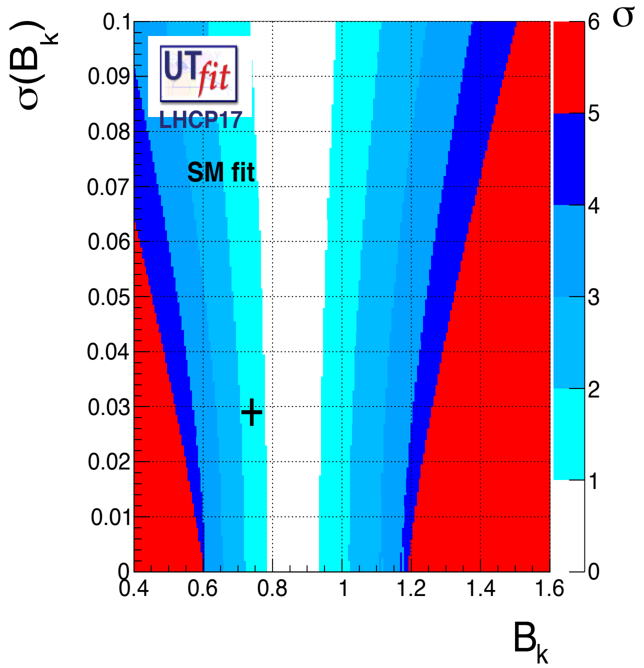
$\sin 2\beta_{exp} = 0.680 \pm 0.023$

$\sin 2\beta_{UTfit} = 0.737 \pm 0.031$

UT-fit Preliminary

- *ε_K large Vcb*
- *B mixing with large lattice matrix elements smaller Vcb*





Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$, cont'd

- New Belle analysis released: Abdesselam *et al* (Belle) 1702.01521
  - Unfolded data, full correlation matrix
  - Large dataset, energy and angular distributions
  - CLN: $|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3}$

Exclusive

- Two independent analyses using BGL:
  - Very consistent fits:

$$|V_{cb}| = (41.7\ {}^{+2.0}_{-2.1}) \times 10^{-3}$$

Bigi, Gambino & Schacht, 1703.06124

$$|V_{cb}| = (41.9\ {}^{+2.0}_{-1.9}) \times 10^{-3}$$

BG & Kobach, 1703.08170

  - Robust: different numerical inputs
  - Likely culprit: independent form factors (no HQET symmetry)

$$\begin{aligned} \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle &= ig\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu p_\alpha p'_\beta, \\ \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu\gamma^5 b|\bar{B}(p)\rangle &= f\varepsilon^{*\mu} + (\varepsilon^* \cdot p)[a_+(p+p')^\mu + a_-(p-p')^\mu], \end{aligned}$$

Recall: BGL introduced z-parametrization, eg,

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n \quad \text{with} \quad \sum_n a_n^2 \leq 1 \quad \text{and} \quad 0 \leq z \leq z_{\max} = 0.056$$

with calculable outer function ϕ and Blaschke factor P

  - CLN uses BGL technique, but imposes HQET conditions

Work ahead:

- Experiments: release unfolded data
- Experiments' next best alternative: do BGL fits
- Global analysts: do BGL fits, others (*e.g.*, polynomail in q^2)?
- Theorists: Λ/m_c effects?
- Theorists: Is BGL better than polynomial for independent form factors?
- Can this affect $B \to D^{(*)}\tau\nu$
- . ***LATTICE !!***

If I may be so bold: *problem solved*

- Retrospect: What went wrong?
  - The probelm was sociological!

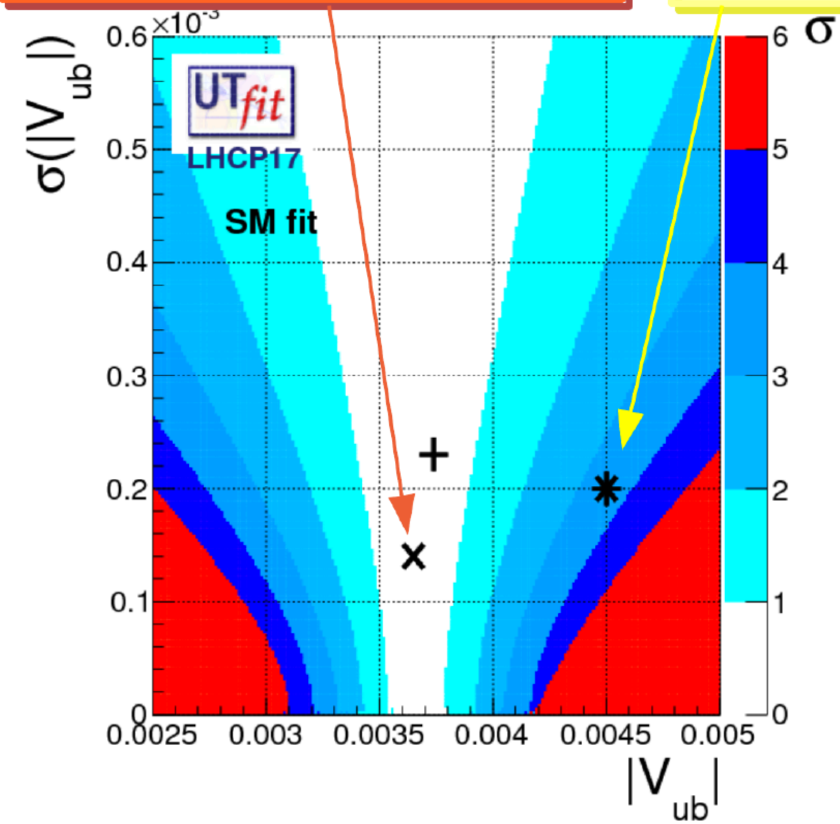
Also: FF calculations only on MILC configurations

⇒need confirmation with different methods

tensions? not really.. still that V_{ub} inclusive

V_{ub} *(excl)* = (3.65 ± 0.14) 10^{-3}

Vub (incl) = (4.50 ± 0.20) 10-3



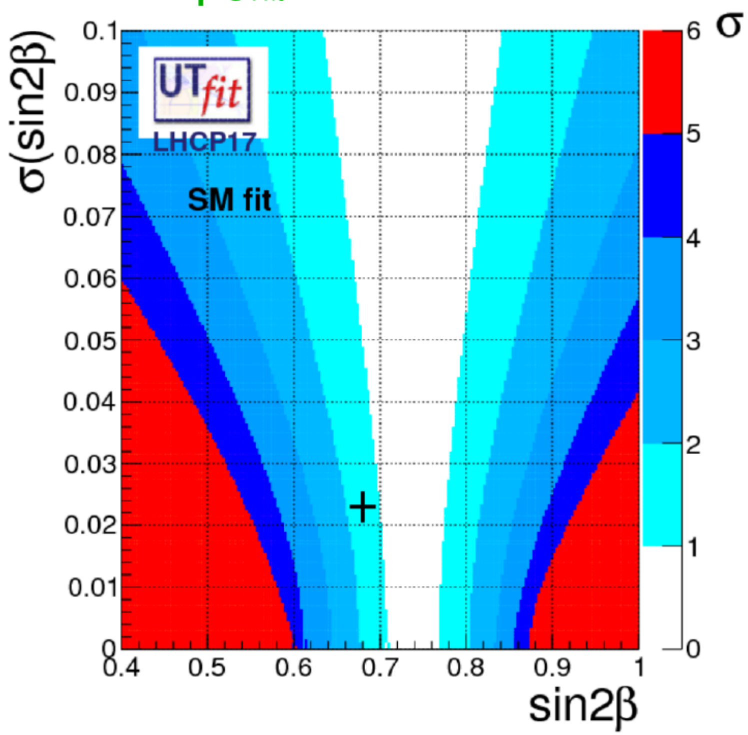
Vub_{exp} = (3.74 ± 0.23) · 10^{-3}

Vub_{UTfit} = (3.66 ± 0.13) · 10^{-3}

~1.4σ

$\sin 2\beta_{exp}$ = 0.680 ± 0.023

$\sin 2\beta_{UTfit}$ = 0.737 ± 0.031



Universal Unitarity Triangle 2016 and the Tension Between $\Delta M_{s,d}$ and ε_K in CMFV Models

Monika Blanke[a,b] and Andrzej J. Buras[c]

[a] Institut fur Kernphysik, Karlsruhe Institute of Technology,
Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

[b] Institut fur Theoretische Teilchenphysik, Karlsruhe Institute of Technology,
Engesserstraße 7, D-76128 Karlsruhe, Germany

[c] TUM-IAS, Lichtenbergstr. 2a, D-85748 Garching, Germany
Physik Department, TUM, D-85748 Garching, Germany

Abstract

Motivated by the recently improved results from the Fermilab Lattice and MILC Collaborations on the hadronic matrix elements entering $\Delta M_{s,d}$ in $B^0_{s,d}-\bar{B}^0_{s,d}$ mixing, we determine the Universal Unitarity Triangle (UUT) in models with Constrained Minimal Flavour Vi-

$$F_{B_s}\sqrt{\hat{B}_{B_s}}, \quad F_{B_d}\sqrt{\hat{B}_{B_d}}, \quad \hat{B}_K\,. \tag{2}$$

Fortunately, during the last years these uncertainties decreased significantly. In particular, concerning $F_{B_s}\sqrt{\hat{B}_{B_s}}$ and $F_{B_d}\sqrt{\hat{B}_{B_d}}$, an impressive progress has recently been made by the Fermilab Lattice and MILC Collaborations (Fermilab-MILC) that find [3]

$$F_{B_s}\sqrt{\hat{B}_{B_s}} = (274.6 \pm 8.8)\,\text{MeV}, \qquad F_{B_d}\sqrt{\hat{B}_{B_d}} = (227.7 \pm 9.8)\,\text{MeV}\,, \tag{3}$$

with uncertainties of 3% and 4%, respectively. An even higher precision is achieved for the ratio

$$\xi = \frac{F_{B_s}\sqrt{\hat{B}_{B_s}}}{F_{B_d}\sqrt{\hat{B}_{B_d}}} = 1.206 \pm 0.019\,. \tag{4}$$

CKM Uncertainties

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (8.39 \pm 0.30)\cdot 10^{-11}\left[\frac{|V_{cb}|}{0.0407}\right]^{2.8}\left[\frac{\gamma}{73.2^\circ}\right]^{0.71}$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.36 \pm 0.09)\cdot 10^{-11}\left[\frac{|V_{ub}|}{3.88\cdot 10^{-3}}\right]^{2}\left[\frac{|V_{cb}|}{0.0407}\right]^{2}\left[\frac{\sin\gamma}{\sin(73.2)}\right]^{2}$$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (65.3 \pm 3.1)\left[\overline{Br}\left(B_s \to \mu^+\mu^-\right)\right]^{1.4}\left[\frac{\gamma}{70^\circ}\right]^{0.71}\left[\frac{227\ \mathrm{MeV}}{F_{B_s}}\right]^{2.8}$$

A. Buras, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693

For $B_s \to \mu^+\mu^-$ we use the formula from [56], slightly modified in [2]

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.06) \cdot 10^{-9} \left[\frac{m_t(m_t)}{163.5\,{\rm GeV}}\right]^{3.02} \left[\frac{\alpha_s(M_Z)}{0.1184}\right]^{0.032} R_s$$

where

$$R_s = \left[\frac{F_{B_s}}{227.7\,{\rm MeV}}\right]^2 \left[\frac{\tau_{B_s}}{1.516{\rm ps}}\right] \left[\frac{0.938}{r(y_s)}\right] \left[\frac{|V_{ts}|}{41.5 \cdot 10^{-3}}\right]^2 .$$

Now,

$$|V_{td}| = |V_{us}||V_{cb}|R_t\,, \qquad |V_{ts}| = \eta_R|V_{cb}|$$

with R_t being one of the sides of the unitarity triangle (see Fig. 1) and

$$\eta_R = 1 - |V_{us}|\xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}\sqrt{\frac{m_{B_s}}{m_{B_d}}}\cos\beta + \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4) = 0.9825\,,$$

M. Blanke A. Buras 1602.040220v3

Do we still care? Tensions and Unknowns

1) A ``classical” example B -> $\tau\nu$

2) $|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive

3) $|V_{cb}|$, B mixing and ε_K

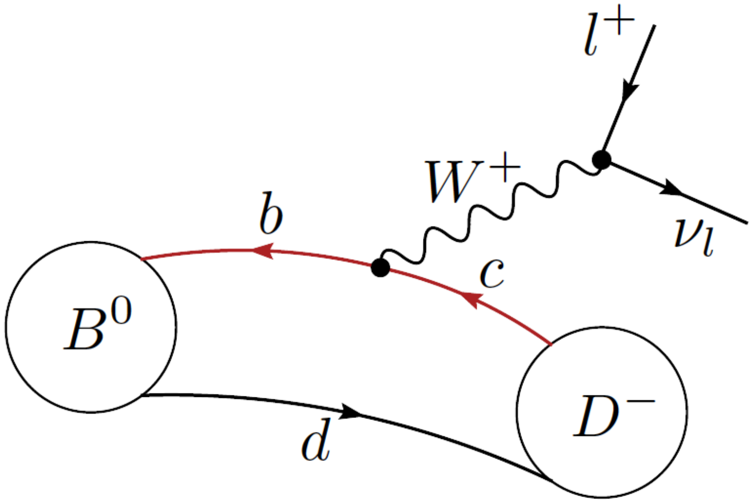
4) D-mixing (already discussed)

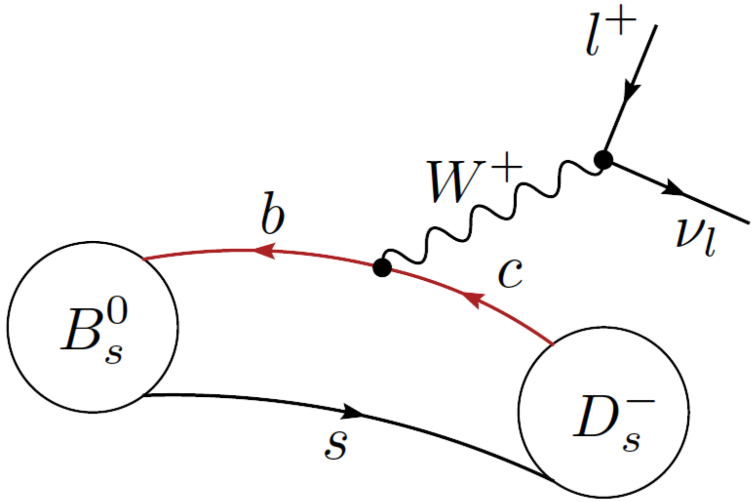
5) R(D) and R(D*) (and Vcb of course)

6) B -> $K^{(*)}$ ll

7) Physics BSM ?

B semileptonic decay: $|V_{cb}|$



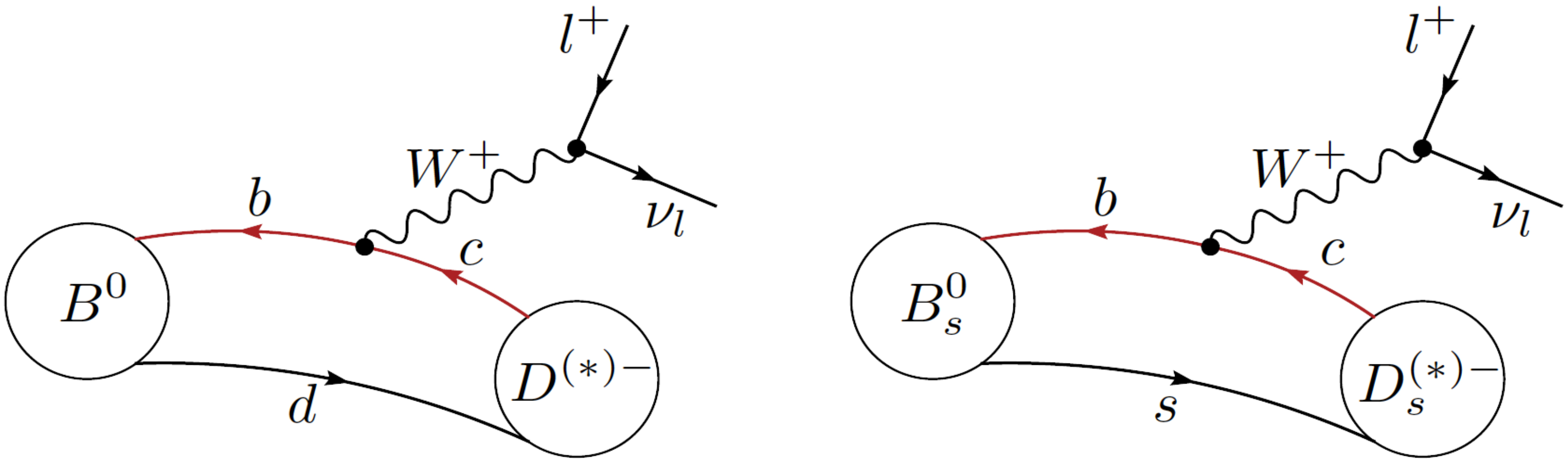


$$\frac{d\Gamma(B_{(s)} \to P l \nu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{B_{(s)}}^2} \left[\left(1 + \frac{m_l^2}{2q^2}\right) m_{B_{(s)}}^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m_{B_{(s)}}^2 - m_P^2)^2 |f_0(q^2)|^2 \right]$$

e, μ suppressed

uncertainties from kinematical factors / neglected h.o. OPE at the permille level

B semileptonic decay: $|V_{cb}|$



$$\frac{\mathrm{d}\Gamma(B \to D l \nu_l)}{\mathrm{d}w} = \frac{G_\mathrm{F}^2}{48\pi^3}(m_B + m_D)^2 (w^2-1)^{3/2} |\eta_\mathrm{EW}|^2 \, |V_{cb}|^2 \, |\mathcal{G}(w)|^2 \; + \; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$\frac{\mathrm{d}\Gamma(B \to D^* l \nu_l)}{\mathrm{d}w} = \frac{G_\mathrm{F}^2}{4\pi^3}(m_B - m_{D^*})^2 (w^2-1)^{1/2} |\eta_\mathrm{EW}|^2 \chi(w) \, |V_{cb}|^2 \, |\mathcal{F}(w)|^2 \; + \; \mathcal{O}\left(\frac{m_l^2}{q^2}\right)$$

$$w = \frac{p_B \cdot p_{D^{(*)}}}{m_B m_{D^{(*)}}} \qquad\qquad \mathcal{G}(w) = \frac{4\,\frac{m_D}{m_B}}{1 + \frac{m_D}{m_B}} f_+(q^2) \qquad \text{etc}$$

Low recoil region (w=1) accessible to lattice calculations

*B -> D-D**

same lattice configurations used $m_b\, a \approx 1.1$ in the best case

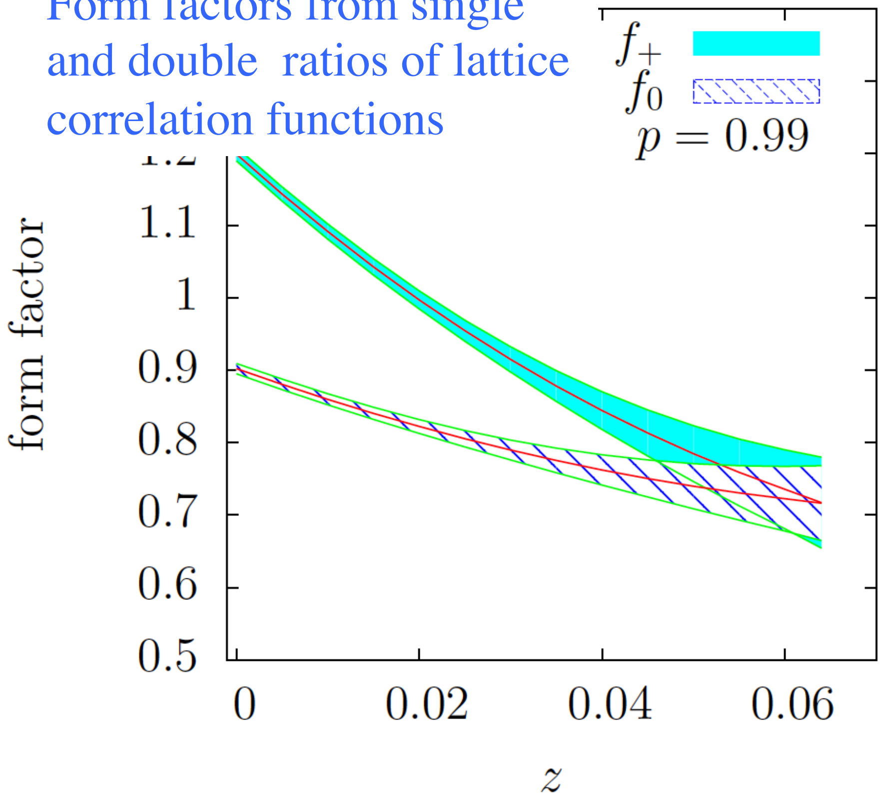
	FNAL/MILC*	FNAL/MILC	HPQCD
process	$B \to D^* \ell \nu$	$B \to D l \nu$	$B \to D l \nu$
kinematics	$w = 1$	$w \geq 1$	$w \geq 1$
ensembles	MILC	MILC	MILC
N_f	2+1	2+1	2+1
a (fm)	5/0.045 – 0.15	4/0.045 – 0.12	2/0.09, 0.12
M_π^{min} [MeV]	260	220	260
$M_\pi^{\mathrm{min}} L$	3.8	3.8	3.8
l quarks	asqtad	asqtad	asqtad
c quark	RHQ (Fermilab)	RHQ (Fermilab)	HISQ
b quark	RHQ (Fermilab)	RHQ (Fermilab)	NRQCD
reference	[1403.0635]	[1503.07237]	[1505.03925]

(* full publication of $B \to D^*$ results, no changes wrt proceedings value quoted in FLAG)

new results for $B \to Dl\nu$

[FNAL/MILC]

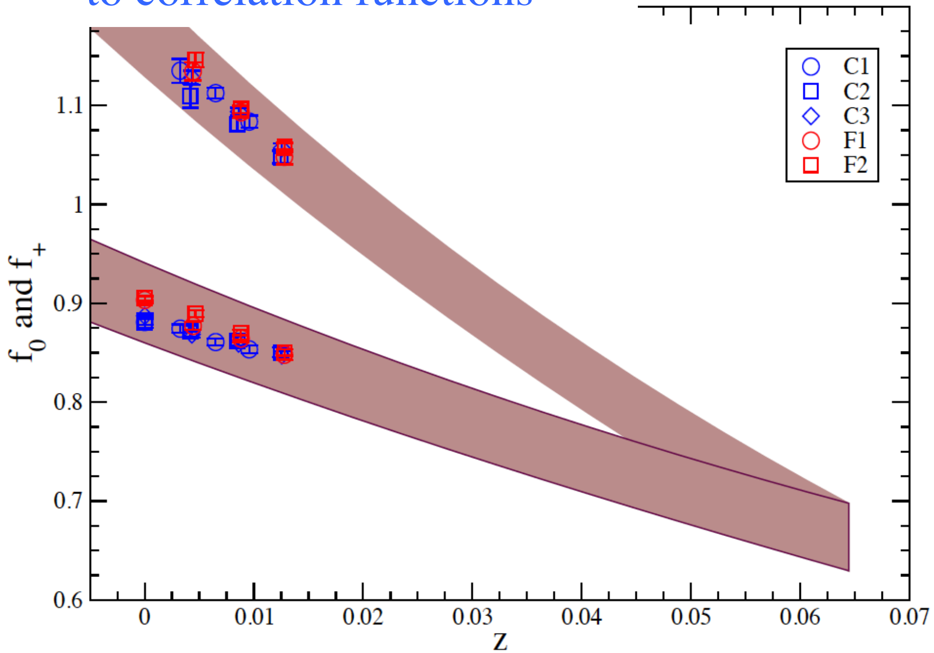
Form factors from single and double ratios of lattice correlation functions



$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)} = 0.299(11)$$

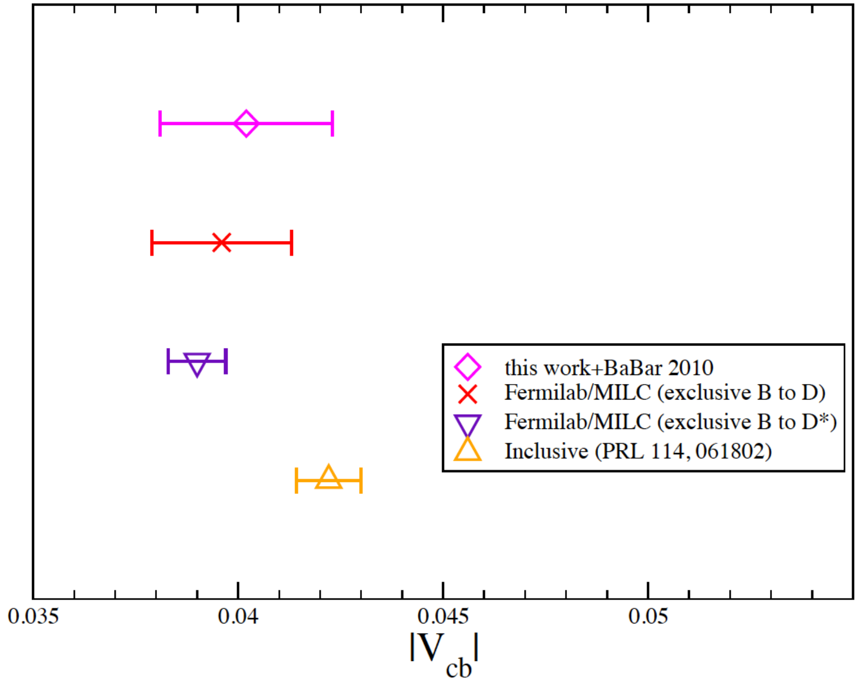
[HPQCD]

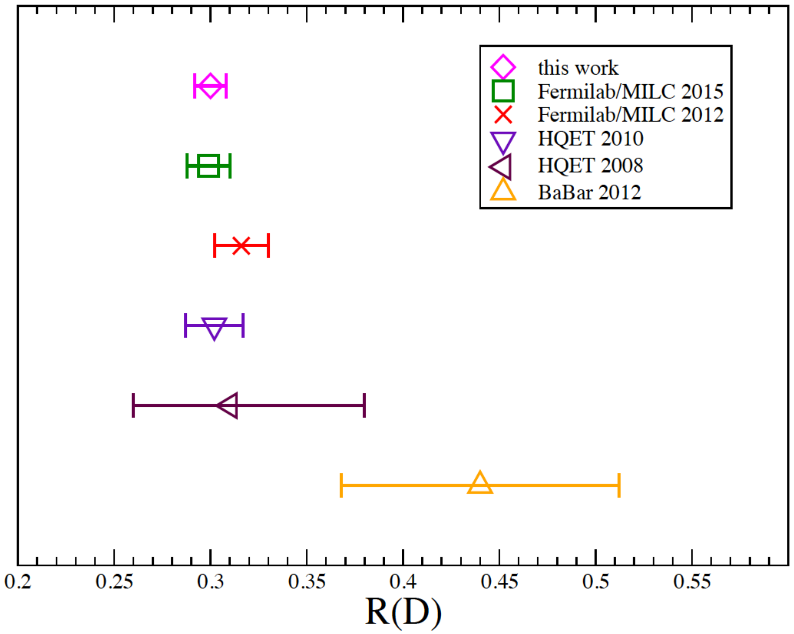
Form factors from direct fit to correlation functions

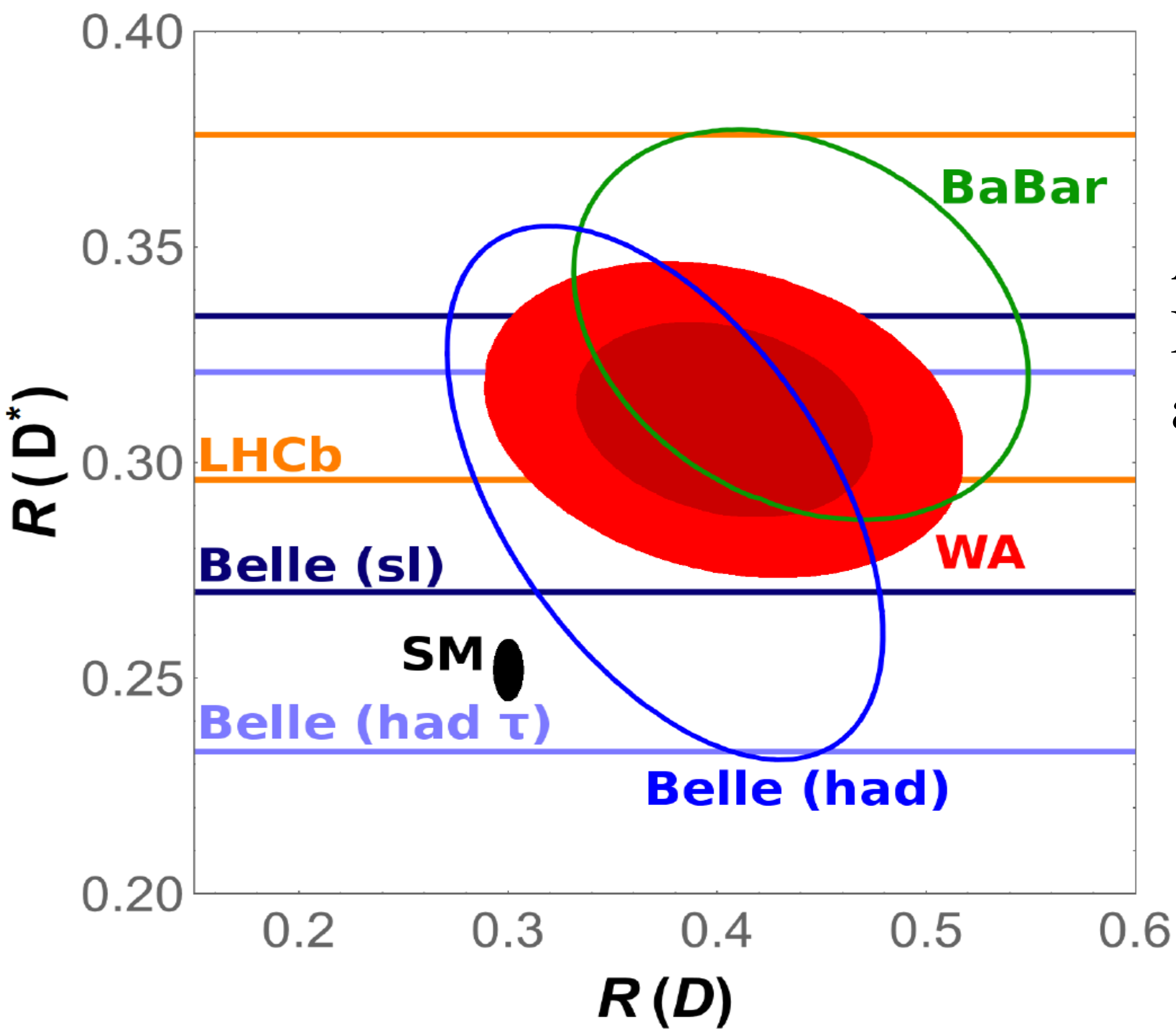


$0.300(8)$

HPQCD June 13 2016







A.Celis, M. Jung, X. Li, A. Pich arXiv:1612.07757v2

FIG. 1. *Average of $R(D^{(*)})$ measurements, displayed as red filled ellipses (68% CL and 95% CL). The SM prediction is shown as a black ellipse (95% CL), and the individual measurements as continuous contours (68% CL): Belle (blue ellipse and horizontal bands), BaBar (green ellipse), and LHCb (horizontal orange band).*

$|V_{ub}|$ & $|V_{cb}|$ inclusive vs exclusive and all that

1) On the long run exclusive decays based on non-perturbative (lattice) determination of the relevant form factors will win;
2) The precision of the theoretical predictions for inclusive decays cannot be improved (are the present quoted errors reliable?);
3) Still (much) more work is needed, and different lattice approaches to the physical B should be used and compared;
4) R(D) and R(D*) is an open problem; more lattice collaborations should work on these calculations. A comparison with Bs and Bc decays fundamental;
5) Theoretical calculations and experimental analyses should not be biased by the HQFT - after all $\Lambda_{QCD}/m_c \approx O(1)$;
6) I hope to be wrong, but the possibility of new physics in tree level b -> c decays looks to me quite remote.

Do we still care? Tensions and Unknowns

1) A ``classical" example B -> $\tau\nu$
2) $|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive
3) $|V_{cb}|$, B mixing and ε_K
4) D-mixing (already discussed)
5) R(D) and R(D*) (and Vcb of course)
6) B -> K* ll
7) Physics BSM ?

Is the present picture showing a
Model Standardissimo ?

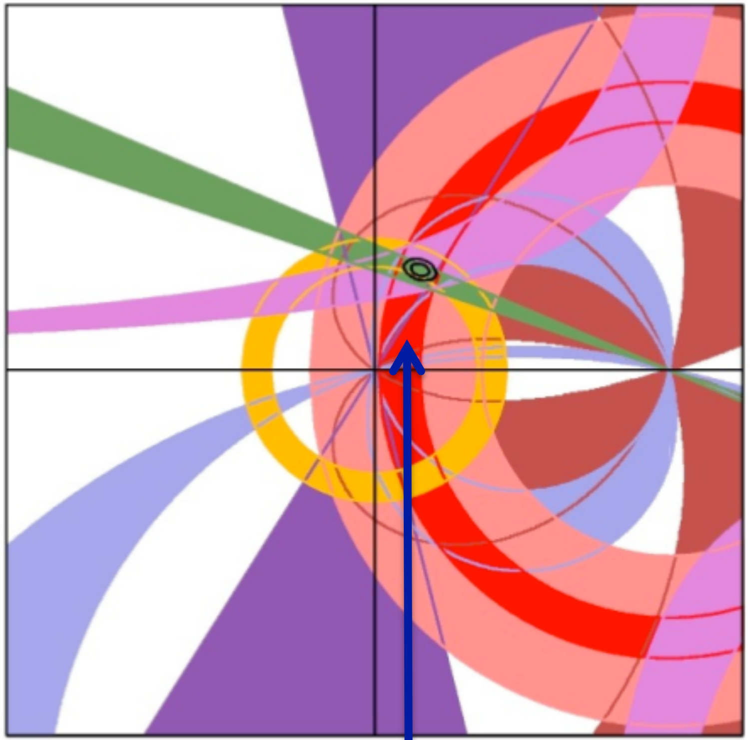
An evidence, an evidence, my kingdom for an evidence

From Shakespeare's *Richard III*
and A. Stocchi

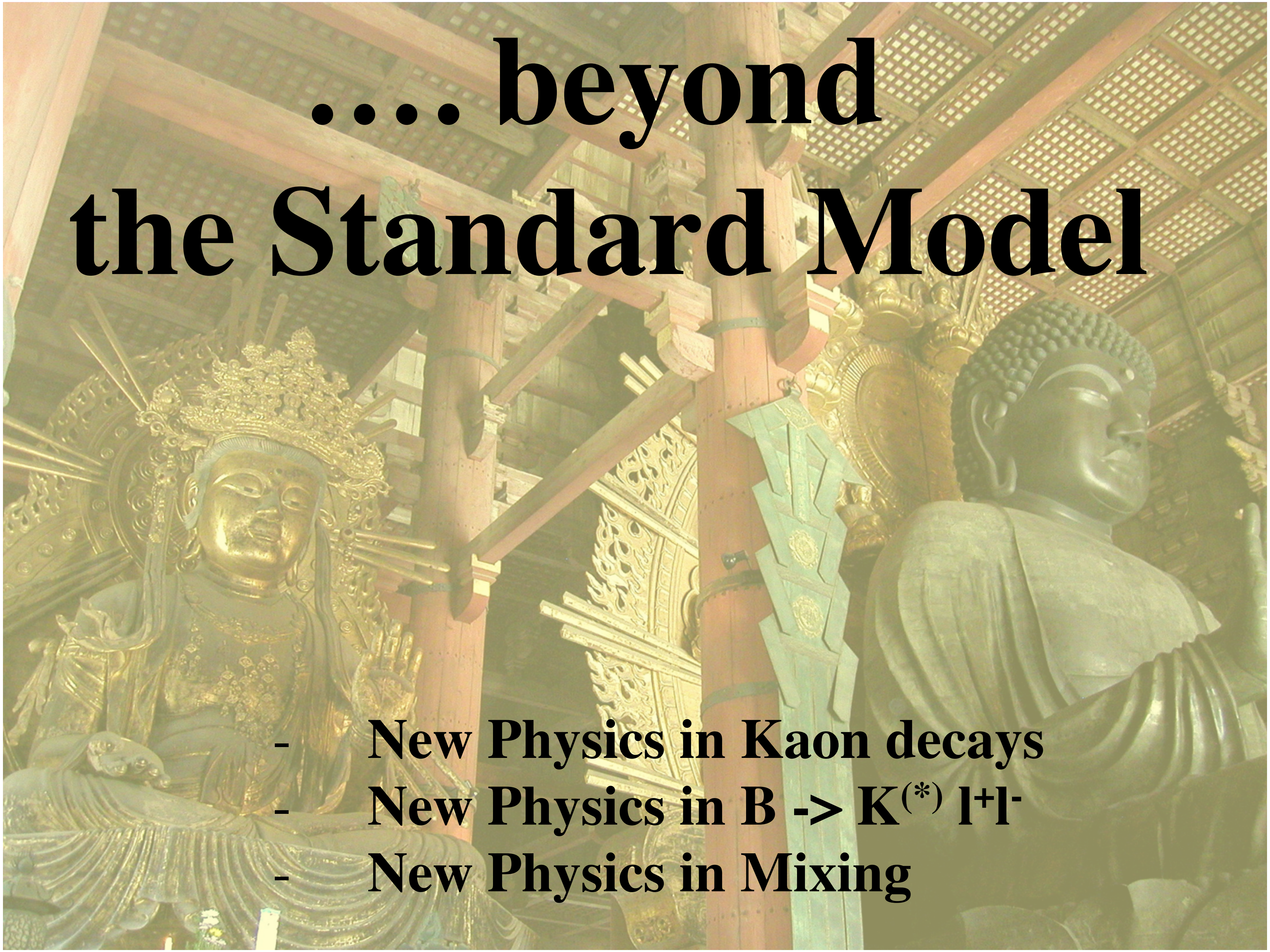
1) **Fit of NP-ΔF=2 parameters in a Model "independent" way**

2) **"Scale" analysis in ΔF=2**

BSM



VERY GOOD CONSISTENCY WITHIN THE SM !



…. beyond the Standard Model

- New Physics in Kaon decays
- New Physics in B -> $K^{(*)}\ l^+l^-$
- New Physics in Mixing

NP ANALYSIS: RESULTS

$\bar{\rho} = 0.125 \pm 0.025$

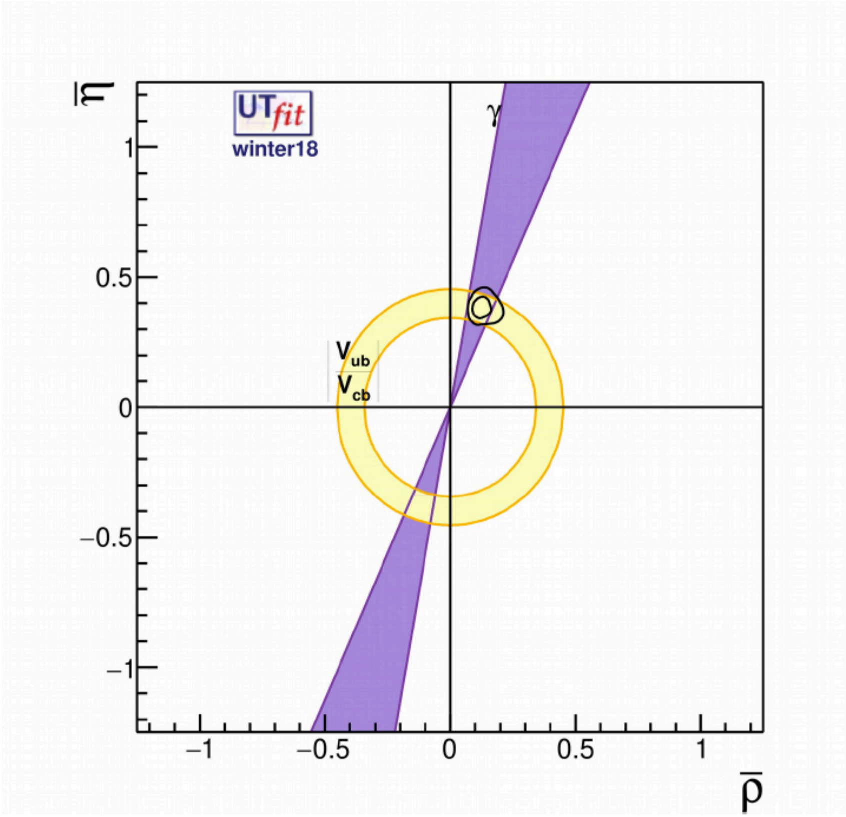
$\bar{\eta} = 0.381 \pm 0.028$

to be compared w.

$\bar{\rho} = 0.145 \pm 0.014$

$\bar{\eta} = 0.349 \pm 0.010$

in the SM



RBC-UK QCD

NEW PHYSICS IN KAON DECAYS?

$$\varepsilon'/\varepsilon = (1.4 \pm 7.0) \cdot 10^{-4}$$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right) = 31.0 \pm 6.6$$

$$(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$\left(\frac{\mathrm{Re}\,A_0}{\mathrm{Re}\,A_2}\right)_{\mathrm{exp}} = 22.4$$

Courtesy by A. Buras

Results for $\mathrm{Re}[A_0]$, $\mathrm{Im}[A_0]$ and $\mathrm{Re}[\epsilon'/\epsilon]$

Xu Feng Lattice 2017

[RBC-UKQCD, PRL115 (2015) 212001]

- Determine the $K \to \pi\pi(I = 0)$ amplitude A_0
  - Lattice results

$$\mathrm{Re}[A_0] = 4.66(1.00)_{\mathrm{stat}}(1.26)_{\mathrm{syst}} \times 10^{-7}\ \mathrm{GeV}$$
$$\mathrm{Im}[A_0] = -1.90(1.23)_{\mathrm{stat}}(1.08)_{\mathrm{syst}} \times 10^{-11}\ \mathrm{GeV}$$

  - Experimental measurement

$$\mathrm{Re}[A_0] = 3.3201(18) \times 10^{-7}\ \mathrm{GeV}$$
$\mathrm{Im}[A_0]$ is unknown

- Determine the direct CP violation $\mathrm{Re}[\epsilon'/\epsilon]$

$$\mathrm{Re}[\epsilon'/\epsilon] = 0.14(52)_{\mathrm{stat}}(46)_{\mathrm{syst}} \times 10^{-3} \quad \text{Lattice}$$
$$\mathrm{Re}[\epsilon'/\epsilon] = 1.66(23) \times 10^{-3} \quad \text{Experiment}$$

2.1 σ deviation $\Rightarrow$ require more accurate lattice results

Four dominant contributions to ε′/ε in the SM

AJB, Jamin, Lautenbacher (1993); AJB, Gorbahn, Jäger, Jamin (2015)

From $\mathrm{Re}A_0$ | From $\mathrm{Re}A_2$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \left[\frac{\mathrm{Im}(V_{td}V_{ts}^{*})}{1.4\cdot 10^{-4}}\right] 10^{-4}\left[-3.7 + 21.2\cdot B_6^{(1/2)} + 1.1 - 9.6\cdot B_8^{(3/2)}\right]$$

(Q_4)

(V-A) ⊗ (V-A) QCD Penguins	(V-A) ⊗ (V+A) QCD Penguins	(V-A) ⊗ (V-A) EW Penguins	(V-A) ⊗ (V+A) EW Penguins

Assumes that $\mathrm{Re}A_0$ and $\mathrm{Re}A_2$ (ΔI=1/2 Rule) fully described by SM (includes isospin breaking corrections)

ε′/ε from RBC-UKQCD

Calculate all contributions directly (no isospin breaking corrections)

$$\left[-(6.5\pm 3.2) + 25.3\cdot B_6^{(1/2)} + (1.2\pm 0.8) - 10.2\cdot B_8^{(3/2)}\right]$$

ε'/ε from RBC-UKQCD

Anatomy: AJB, Gorbahn, Jäger, Jamin (2015)

Calculate all contributions directly

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \left[\frac{\mathrm{Im}(V_{td}V_{ts}^*)}{1.4\cdot 10^{-4}}\right] 10^{-4}\left[-6.5 + 25.3\cdot B_6^{(1/2)} + 1.2 - 10.2\cdot B_8^{(3/2)}\right]$$

(Q_4)	(V-A) $\otimes$ (V-A) QCD Penguins	(V-A) $\otimes$ (V+A) QCD Penguins	(V-A) $\otimes$ (V-A) EW Penguins	(V-A) $\otimes$ (V+A) EW Penguins

$B_6^{(1/2)} = B_8^{(3/2)} = 1$ in the large N limit

Extracted from

RBC-UKQCD : $B_6^{(1/2)} = 0.57 \pm 0.15$ $B_8^{(3/2)} = 0.76 \pm 0.05$

EW penguins in full agreement with BGJJ but

+ third term very similar to BGJJ $(\mathrm{Re}A_2)_{\mathrm{Lattice}} \approx (\mathrm{Re}A_2)_{\mathrm{exp}}$

$$\left[\frac{(\mathrm{Re}\,A_0)}{(\mathrm{Re}\,A_0)_{\mathrm{exp}}} \approx 1.4\right] \Rightarrow$$

The negative contribution of Q_4 overestimated $\Rightarrow$

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\mathrm{Lattice}} = (1.4 \pm 7.0)\cdot 10^{-4}$$

Anatomy of ε'/ε – A new flavour anomaly?

AJB, Gorbahn, Jäger, Jamin,, 1507.xxxx

RBC-UKQCD

$$\boxed{\varepsilon'/\varepsilon = (1.4 \pm 7.0) \cdot 10^{-4}}$$

(3.2σ) $\varepsilon'/\varepsilon = (2.2 \pm 3.8) \cdot 10^{-4}$

RBC-QCD values

$$B_6^{(1/2)} = 0.57 \pm 0.15$$

$$B_8^{(3/2)} = 0.76 \pm 0.05$$

$\varepsilon'/\varepsilon = (6.3 \pm 2.5) \cdot 10^{-4}$

large N bounds (AJB, Gérard)

$$B_6^{(1/2)} = B_8^{(3/2)} = 0.76$$

$\varepsilon'/\varepsilon = (9.1 \pm 3.3) \cdot 10^{-4}$

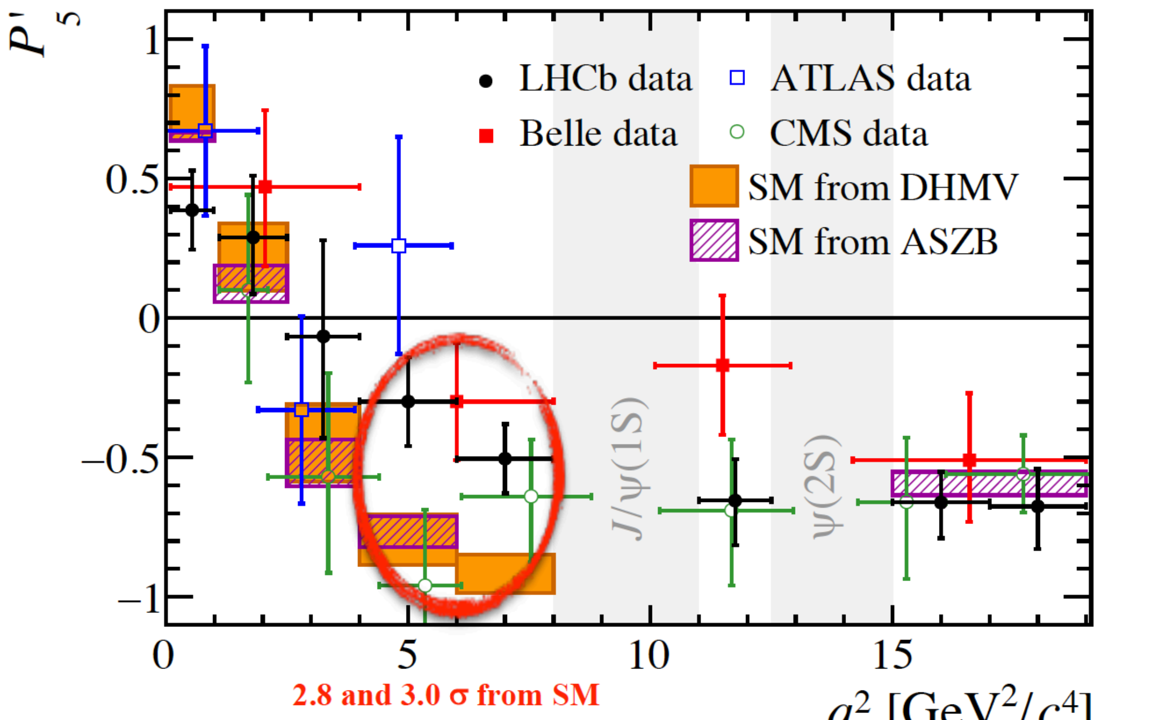
large N bounds (AJB, Gérard)

$$B_6^{(1/2)} = B_8^{(3/2)} = 1.0$$

exp: $\varepsilon'/\varepsilon = (16.6 \pm 3.3) \cdot 10^{-4}$

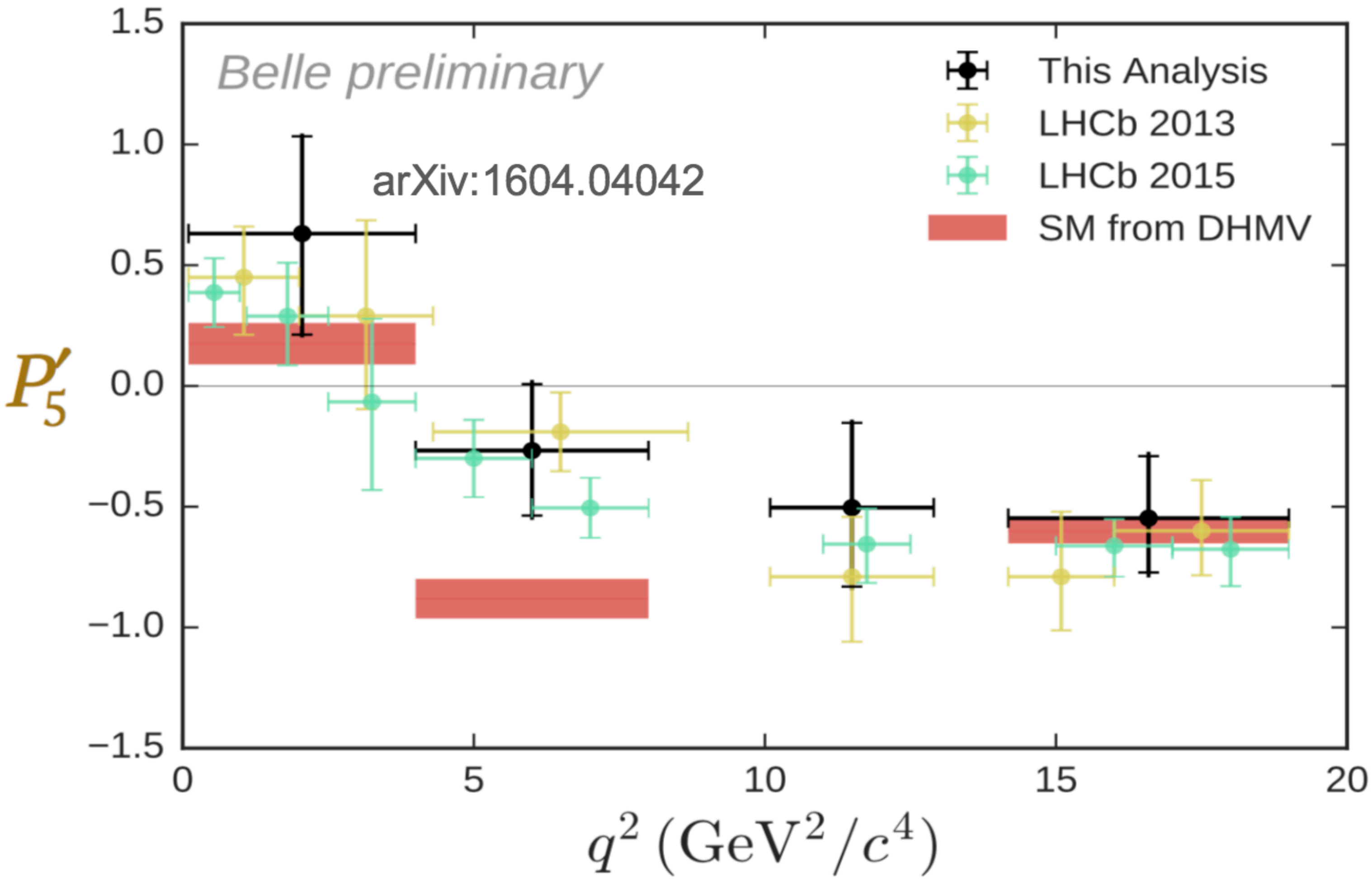
Angular Analyses

- First **full angular analysis** of $B^0 \to K^{*0}\mu\mu$: measured all CP-averaged angular terms and CP-asymmetries
- Can construct **less form-factor dependent ratios of observables**



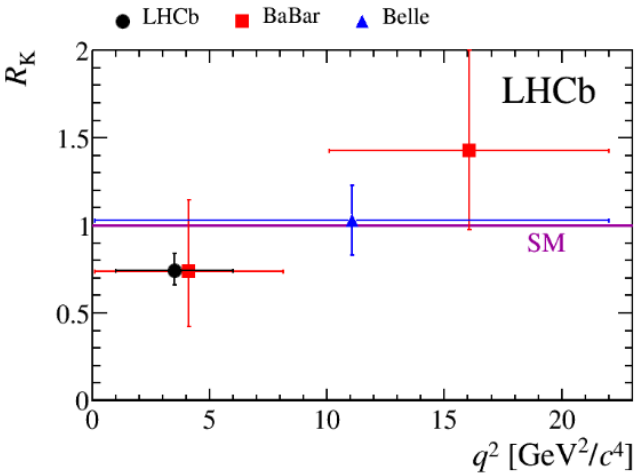
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

New analysis from Belle



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

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

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

AND NOW:

The hint that the loop induced decays $b \to s\ell\ell$ can break lepton flavor universality (1) was corroborated by the most recent LHCb results [4],

$$R_{K^*}^{\text{low}} = \frac{\mathcal{B}(B \to K^*\mu\mu)_{q^2\in[0.045,1.1]\text{GeV}^2}}{\mathcal{B}(B \to K^*ee)_{q^2\in[0.045,1.1]\text{GeV}^2}} = 0.660 \pm^{0.110}_{0.070} \pm 0.024\,,$$

$$R_{K^*}^{\text{central}} = \frac{\mathcal{B}(B \to K^*\mu\mu)_{q^2\in[1.1,6]\text{GeV}^2}}{\mathcal{B}(B \to K^*ee)_{q^2\in[1.1,6]\text{GeV}^2}} = 0.685 \pm^{0.113}_{0.069} \pm 0.047\,, \qquad (2)$$

VERY DIFFICULT TO EXPLAIN WITH HADRONIC UNCERTAINIES!!

Heavy to light semileptonic

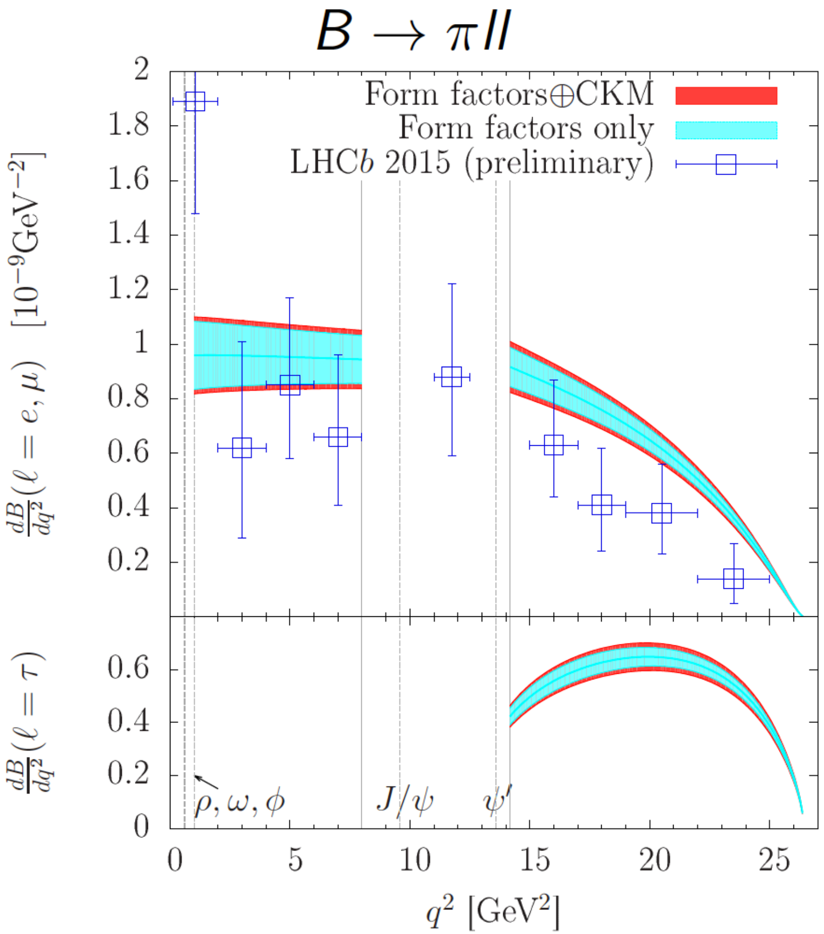
Local operator contribution only

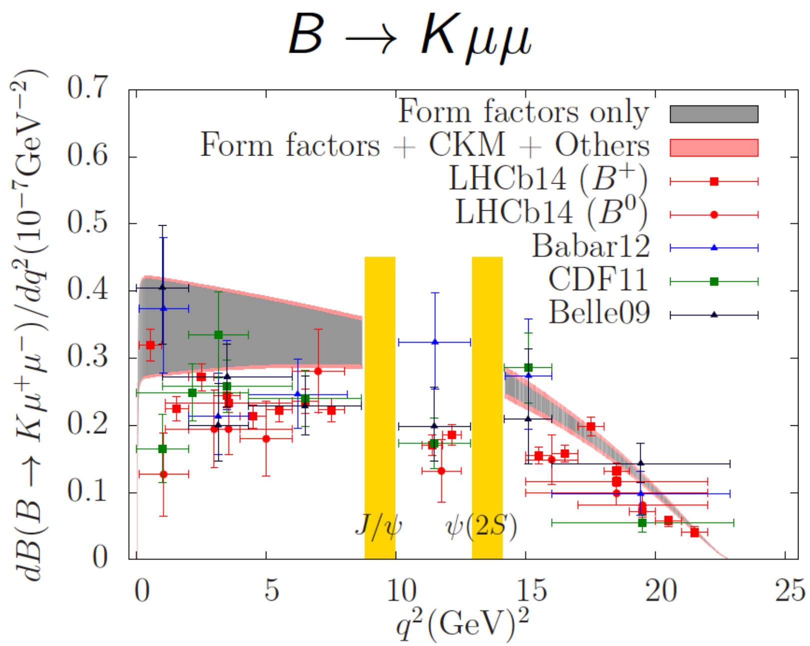
New results after Lattice 2015:

	Fermilab/MILC	Fermilab/MILC	Detmold and Meinel
process	$B \to Kll$,	$B \to \pi ll$	$\Lambda_b \to \Lambda$
kinematics	full q^2	full q^2	full q^2
ensembles	MILC asqtad	MILC asqtad	RBC/UKQCD DWF
N_f	2+1	2+1	2+1
a	4/0.045-0.12	4/0.045-0.12	2/0.09-0.12
$M_\pi^{\min}$	260	260	227
light quark	asqtad	asqtad	DWF
b quark	Fermilab	Fermilab	RHQ
Ref.	PRD.93.025026	PRL.115.152002	PRD.93.074501

- PRD.93.034005 (Fermilab/MILC, B rare decay pheno)
- PRD.94.013007 (Meinel and van Dyk, Λ_b rare decay pheno)
- PRD.88.054509, PRL.111.162002 (HPQCD, $B \to Kll$ ff and pheno), PRD.89.094501, PRL.112.212003 ($B \to K^*ll$ ff and pheno)

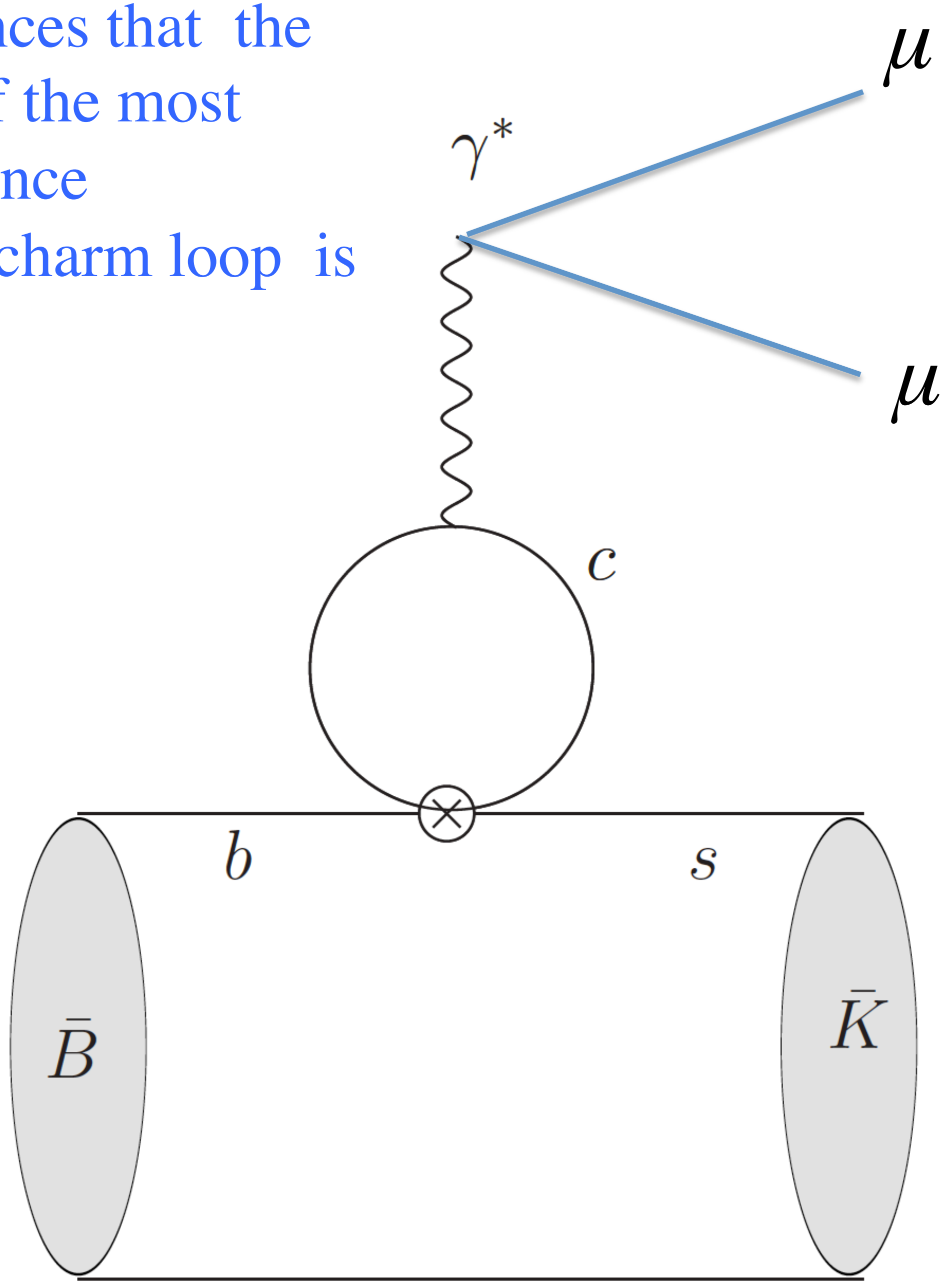
Standard Model predictions of B rare decays





- Standard-Model predictions of the differential decay rate in $B \to \pi ll$ and $B \to Kll$ process (PRL.115.152002, PRD.93.034005).

There are good chances that the lattice calculation of the most important long distance contributions via a charm loop is possible
M. Ciuchini, V.Lubicz, G.M., L. Silvestrini, S. Simula



RADIATIVE/RARE KAON DECAYS

G. Isidori, G. M., and P. Turchetti, Phys.Lett. B633, 75 (2006), arXiv:hep-lat/0506026

N.H. Christ X. Feng A. Portelli and C.T. Sachrajda *Phys.Rev. D92 (2015) no.9, 094512* [*10.1103/PhysRevD.92.094512*] *

$$K \to \pi l^+ l^- \qquad\qquad K \to \pi \nu \bar{\nu}$$

Conserved currents and GIM important

2.1 $K \to \pi \ell^+ \ell^-$ G. Isidori, G. M., and P. Turchetti

The main non-perturbative correlators relevant for these decays are those with the electromagnetic current. In particular, the relevant T-product in Minkowski space is [7, 8]

$$(\mathcal{T}_i^j)^{\mu}_{\rm em}(q^2) = -i \int d^4x\, e^{-i\,q\cdot x} \langle \pi^j(p)|T\left\{J^{\mu}_{\rm em}(x)\left[Q_i^u(0) - Q_i^c(0)\right]\right\}|K^j(k)\rangle\,, \quad (11)$$

$$J^{\mu}_{\rm em} = \frac{2}{3}\sum_{q=u,c} \bar{q}\gamma^{\mu} q - \frac{1}{3}\sum_{q=d,s} \bar{q}\gamma^{\mu} q \quad (12)$$

for $i = 1, 2$ and $j = +, 0$. Thanks to gauge invariance we can write

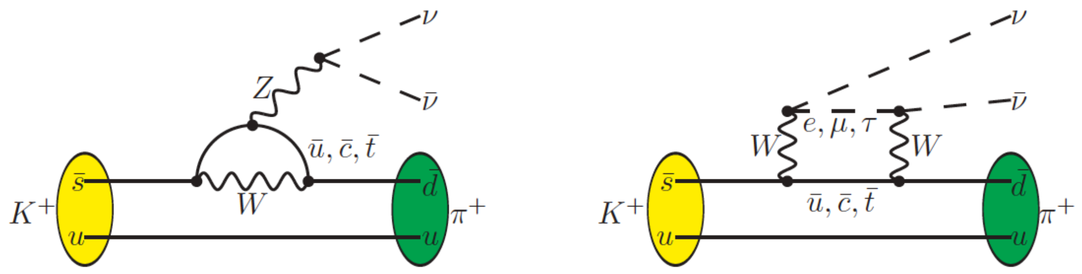
$$(\mathcal{T}_i^j)^{\mu}_{\rm em}(q^2) = \frac{w_i^j(q^2)}{(4\pi)^2}\left[q^2(k+p)^{\mu} - (m_k^2 - m_\pi^2)q^{\mu}\right]\,. \quad (13)$$

The normalization of (13) is such that the $O(1)$ scale-independent low-energy couplings $a_{+,0}$ defined in [8] can be expressed as

$$a_j = \frac{1}{\sqrt{2}} V_{us}^* V_{ud}\left[C_1 w_1^j(0) + C_2 w_2^j(0) + \frac{2N_j}{\sin^2\theta_W} f_+(0) C_{7V}\right]\,. \quad (14)$$

A detailed analysis of the extraction of the amplitude from lattice correlators by N.H. Christ X. Feng A. Portelli and C.T. Sachrajda

$K^+ \to \pi^+ \nu\bar{\nu}$: Experiment vs Standard model



Z-exchange $\quad$ W-W

$K^+ \to \pi^+ \nu\bar{\nu}$: largest contribution from top quark loop, thus theoretically clean

$$\mathcal{H}_{eff} \sim \frac{G_F}{\sqrt{2}} \cdot \underbrace{\frac{\alpha_{\rm EM}}{2\pi \sin^2\theta_W} \lambda_t X_t(x_t)}_{\mathcal{N} \sim 2\times 10^{-5}} \cdot (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

Probe the new physics at scales of $\mathcal{N}^{-\frac{1}{2}} M_W = O(10\ \text{TeV})$

Past experimental measurement is 2 times larger than SM prediction

$$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{exp}} = 1.73^{+1.15}_{-1.05} \times 10^{-10} \qquad [\text{BNL E949, '08}]$$
$$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = 9.11 \pm 0.72 \times 10^{-11} \qquad [\text{Buras et. al., '15}]$$

but still consistent with $> 60\%$ exp. error

Results for charm quark contribution

Charm quark contribution P_c

$$P_c = P_c^{\mathrm{SD}} + \delta P_{c,u}$$

NNLO QCD [Buras, Gorbahn, Haisch, Nierste, '06]:

$$P_c^{\mathrm{SD}} = 0.365(12)$$

Phenomenological ansatz [Isidori, Mescia, Smith, '05]

$$\delta P_{c,u} = 0.040(20)$$

Lattice results @$m_\pi = 420$ MeV, $m_c = 860$ MeV

[RBC-UKQCD, arXiv:1701.02858]

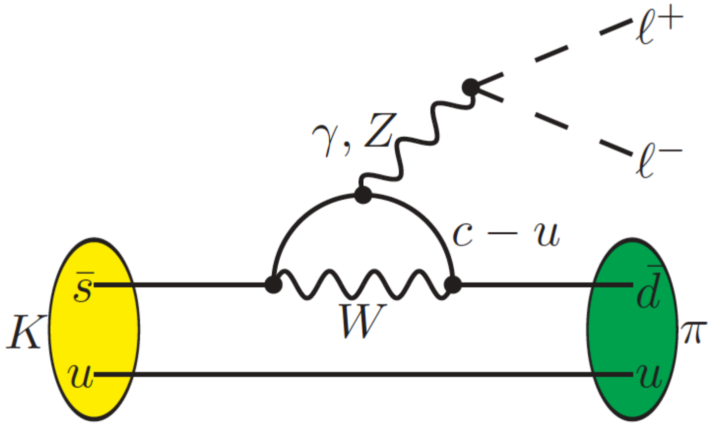
$$P_c = 0.2529(\pm 13)_{\mathrm{stat}}(\pm 32)_{\mathrm{scale}}(-45)_{\mathrm{FV}}$$
$$P_c - P_c^{\mathrm{SD}} = 0.0040(\pm 13)_{\mathrm{stat}}(\pm 32)_{\mathrm{scale}}(-45)_{\mathrm{FV}}$$

- As a smaller m_c is used, P_c is also smaller
- Cancellation in W-W and Z-exchange diag. leads to small $P_c - P_c^{\mathrm{SD}}$
- Important to perform the calculation at physical m_π and m_c

$K \to \pi\ell^+\ell^-$: CP conserving chanel

CP conserving decay: $K^+ \to \pi^+\ell^+\ell^-$ and $K_S \to \pi^0\ell^+\ell^-$

- Involve both γ- and Z-exchange diagram, but γ-exchange is much larger



- Unlike Z-exchange, the γ-exchange diagram is LD dominated
  - By power counting, loop integral is quadratically UV divergent
  - EM gauge invariance reduces divergence to logarithmic
  - $c - u$ GIM cancellation further reduces log divergence to be UV finite

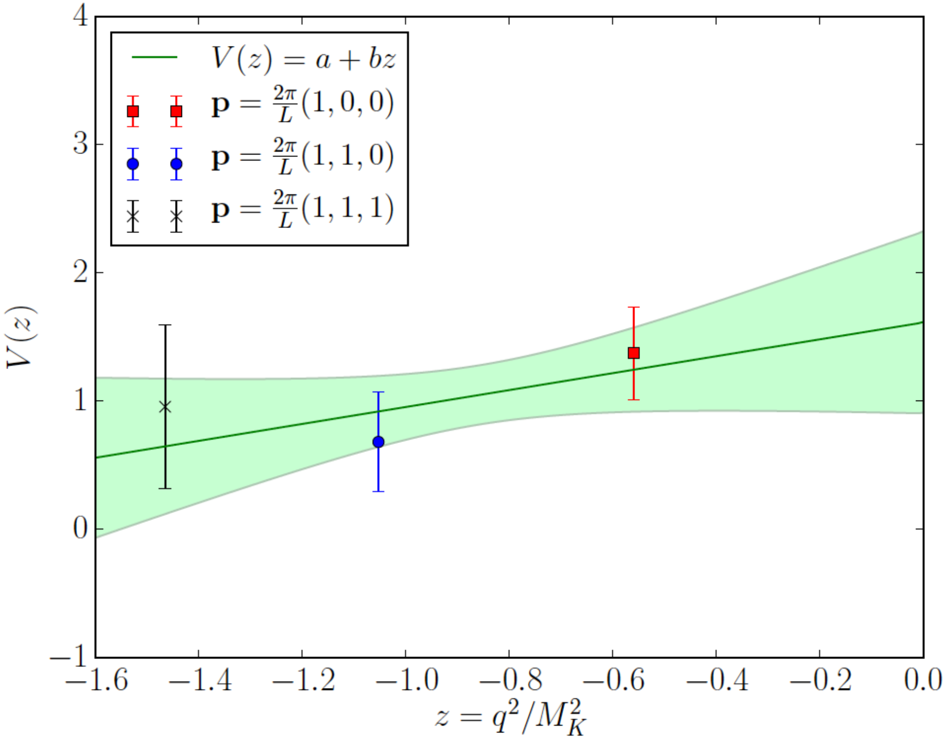
First exploratory calculation on $K^+ \to \pi^+ \ell^+ \ell^-$

Use $24^3 \times 64$ ensemble, $N_{\mathrm{conf}} = 128$
[RBC-UKQCD, PRD94 (2016) 114516]

$a^{-1} = 1.78$ GeV, $m_\pi = 430$ MeV
$m_K = 625$ MeV, $m_c = 530$ MeV

Momentum dependence of $V_+(z)$

$$V_+(z) = a_+ + b_+ z$$
$$\Rightarrow \quad a_+ = 1.6(7),\ b_+ = 0.7(8)$$



$K^+ \to \pi^+ e^+ e^-$ data + phenomenological analysis: $a_+ = -0.58(2)$, $b_+ = -0.78(7)$
[Cirigliano, et. al., Rev. Mod. Phys. 84 (2012) 399]

$$V_j(z) = a_j + b_j z + \underbrace{\frac{\alpha_j r_\pi^2 + \beta_j (z - z_0)}{G_F M_K^2 r_\pi^4}}_{K \to \pi\pi\pi} \underbrace{\left[1 + \frac{z}{r_V^2}\right]}_{F_V(z)} \underbrace{\left[\phi(z/r_\pi^2) + \frac{1}{6}\right]}_{\text{loop}}, \quad j = +, S$$

- Experimental data only provide $\frac{d\Gamma}{dz} \Rightarrow$ square of form factor $|V_+(z)|^2$
- Need phenomenological knowledge to determine the sign for a_+, b_+

TESTING THE NEW PHYSICS SCALE

Effective Theory Analysis ΔF=2

$$C_j(\Lambda) = \frac{LF_j}{\Lambda^2} \Rightarrow \Lambda = \sqrt{\frac{LF_j}{C_j(\Lambda)}}$$

Effective Hamiltonian in the mixing amplitudes

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^{\alpha} \gamma_\mu b_L^{\alpha} \, \bar{q}_L^{\beta} \gamma^\mu b_L^{\beta} \quad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^{\alpha} b_L^{\alpha} \, \bar{q}_R^{\beta} b_L^{\beta} \qquad Q_3 = \bar{q}_R^{\alpha} b_L^{\beta} \, \bar{q}_R^{\beta} b_L^{\beta}$$

$$Q_4 = \bar{q}_R^{\alpha} b_L^{\alpha} \, \bar{q}_L^{\beta} b_R^{\beta} \qquad Q_5 = \bar{q}_R^{\alpha} b_L^{\beta} \, \bar{q}_L^{\beta} b_R^{\beta}$$

$$\tilde{Q}_1 = \bar{q}_R^{\alpha} \gamma_\mu b_R^{\alpha} \, \bar{q}_R^{\beta} \gamma^\mu b_R^{\beta}$$

$$\tilde{Q}_2 = \bar{q}_L^{\alpha} b_R^{\alpha} \, \bar{q}_L^{\beta} b_R^{\beta} \qquad \tilde{Q}_3 = \bar{q}_L^{\alpha} b_R^{\beta} \, \bar{q}_L^{\beta} b_R^{\beta}$$

C(Λ) coefficients are extracted from data

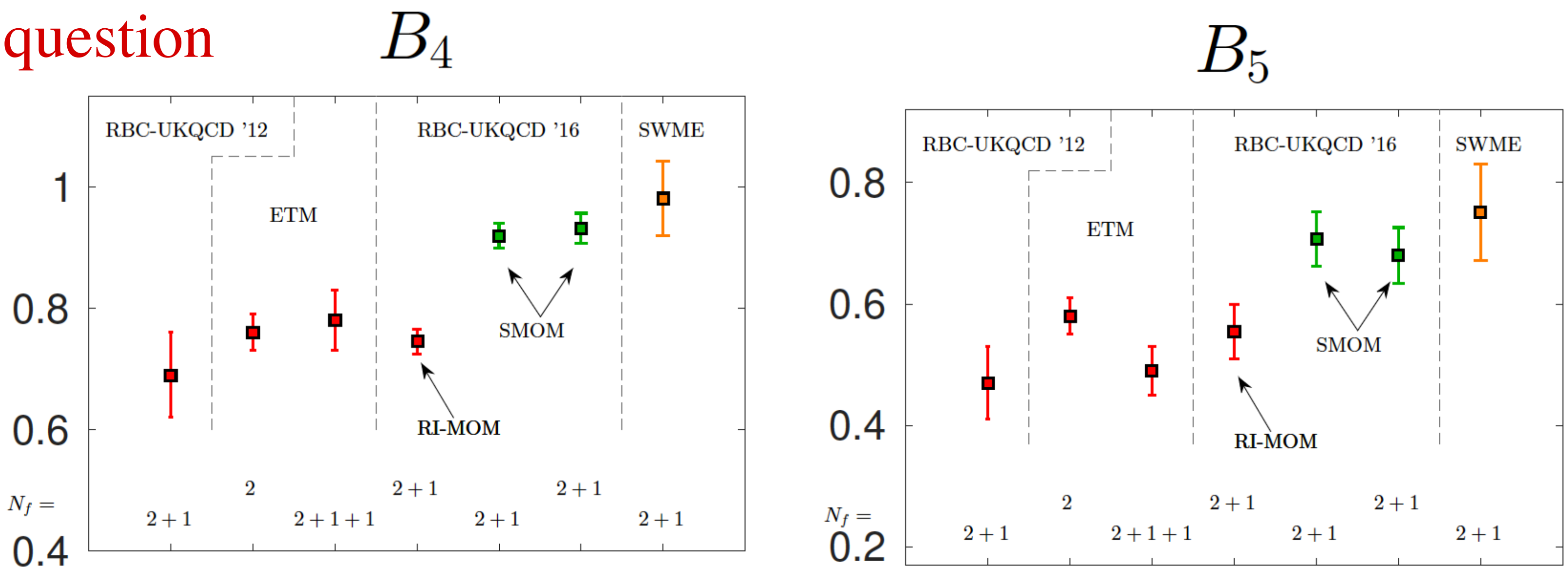
L is loop factor and should be :
L=1 tree/strong int. NP
L=α_s^2 or α_W^2 for strong/weak perturb. NP

$F_1 = F_{SM} = (V_{tq} V_{tb}^*)^2$ $F_{j=1} = 0$	**MFV**	***LATTICE CALCULATIONS ESSENTIAL IN THIS CASE !!***
$\lvert F_j \rvert = F_{SM}$ **arbitrary phases**	**NMFV**	
$\lvert F_j \rvert = 1$ **arbitrary phases**	**Flavour generic**	

Resolution of the discrepancy for B_4, B_5

$N_f = 2+1$ DWF, $a = 0.08$, 0.11 fm, $m_\pi = 300$ MeV [RBC-UKQCD, JHEP11(2016)001]

open question



Plot, courtesy of N. Garron

- Use both RI/MOM and SMOM $\Rightarrow$ the former is significantly smaller
- Use two RI/SMOM schemes, $(\not{q}, \not{q})$ and (γ_μ, γ_μ) $\Rightarrow$ consistent results
- RI/(S)MOM result compatible with previous RI/(S)MOM calculation

Study suggests RI/MOM suffers from large IR artifacts $\Rightarrow$ discrepancy

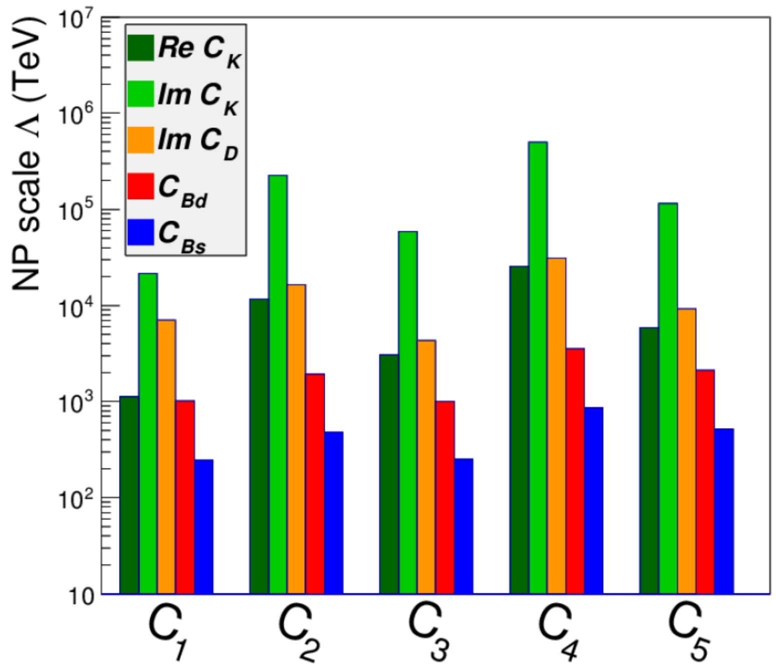
On-going project: [J. Kettle's talk, Wednesday 11:30@Seminarios 6+7]

- 64^3 and 48^3 ensembles with physical m_π and finer lattice spacing

results from the Wilson coefficients

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

$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale (in TeV at 95% prob.)

Non-perturbative NP
$\Lambda > 5.0\ 10^5$ TeV

To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s (~ 0.1) or by α_W (~ 0.03).

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

NP in α_W loops
$\Lambda > 1.5\ 10^4$ TeV

Best bound from ε_K
dominated by CKM error

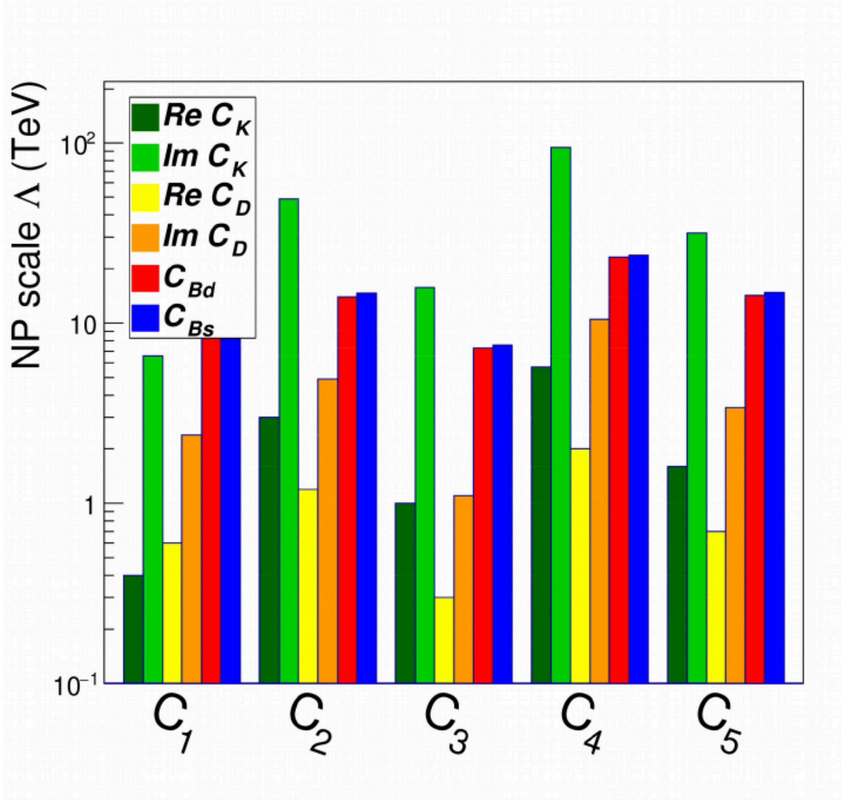
CPV in charm mixing follows,
exp error dominant

Best CP conserving from Δm_K,
dominated by long distance

B_d and B_s behind,
errors from both CKM and B-parameters

NMFV STRONGLY-INTERACTING NP

- If new chiral structures present, ε_K still gives best constraint
- B_d and B_s most powerful if no new operators arise
- Non-perturbative NMFV NP (e.g. composite Higgs)
  - $\Lambda > 94$ TeV
- Weakly interacting:
  - $\Lambda > 3$ TeV



UTfit

absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

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