Mixing and CP violation: General Introduction and Lattice Perspectives

Charm 2016:

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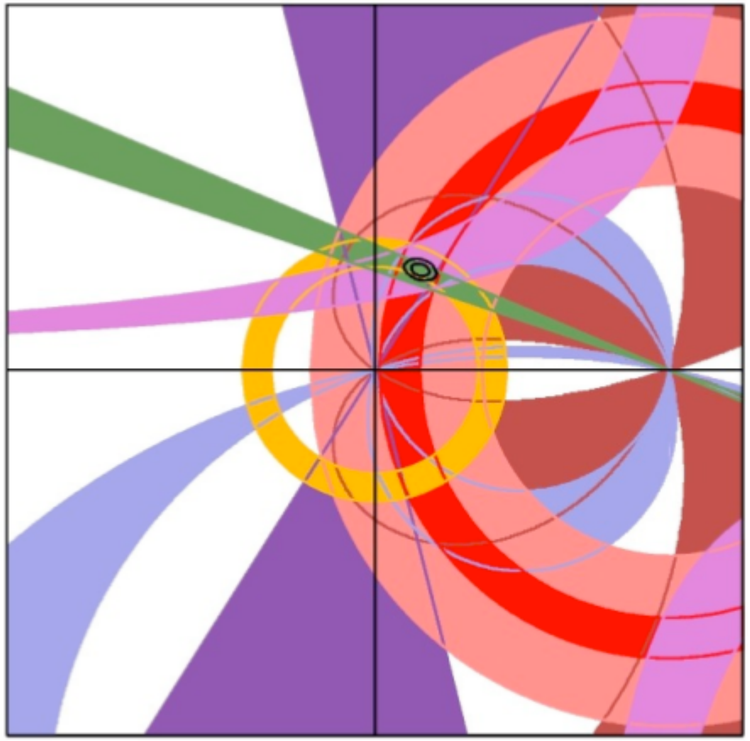
PLAN OF THE TALK

- *General introduction to the Unitary Triangle Fit*
- *SM Analysis*
- *Tensions and unknown*
- *New/old ideas from Lattice QCD vs Charm Physics*
- *Conclusion*

- *New Physics -> M. Ciuchini*
- *More on Charm D. Derkach*



Thanks to Bona, Lubicz and Silvestrini,

Flavor physics in the Standard Model

In the SM, the quark mass matrix, from which the CKM matrix and $\not{CP}$ violation originate, is determined by the coupling of the Higgs boson to fermions.

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

CP invariant

$\not{CP}$ and symmetry breaking are stricIty correlated

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

EWSB

has many accidental simmetries

may violate accidental simmetries

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

Almost no CP violation at tree level

Flavour Physics is extremely sensitive to New Physics (NP)

In competition with Electroweak Precision Measurements

WHY RARE DECAYS ?

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

Proton decay	baryon and lepton number conservation
$\mu \rightarrow e + \gamma$ $\nu_i \rightarrow \nu_k$ found !	lepton flavor number

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

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

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

$q_i \ -> \ q_k + \gamma$

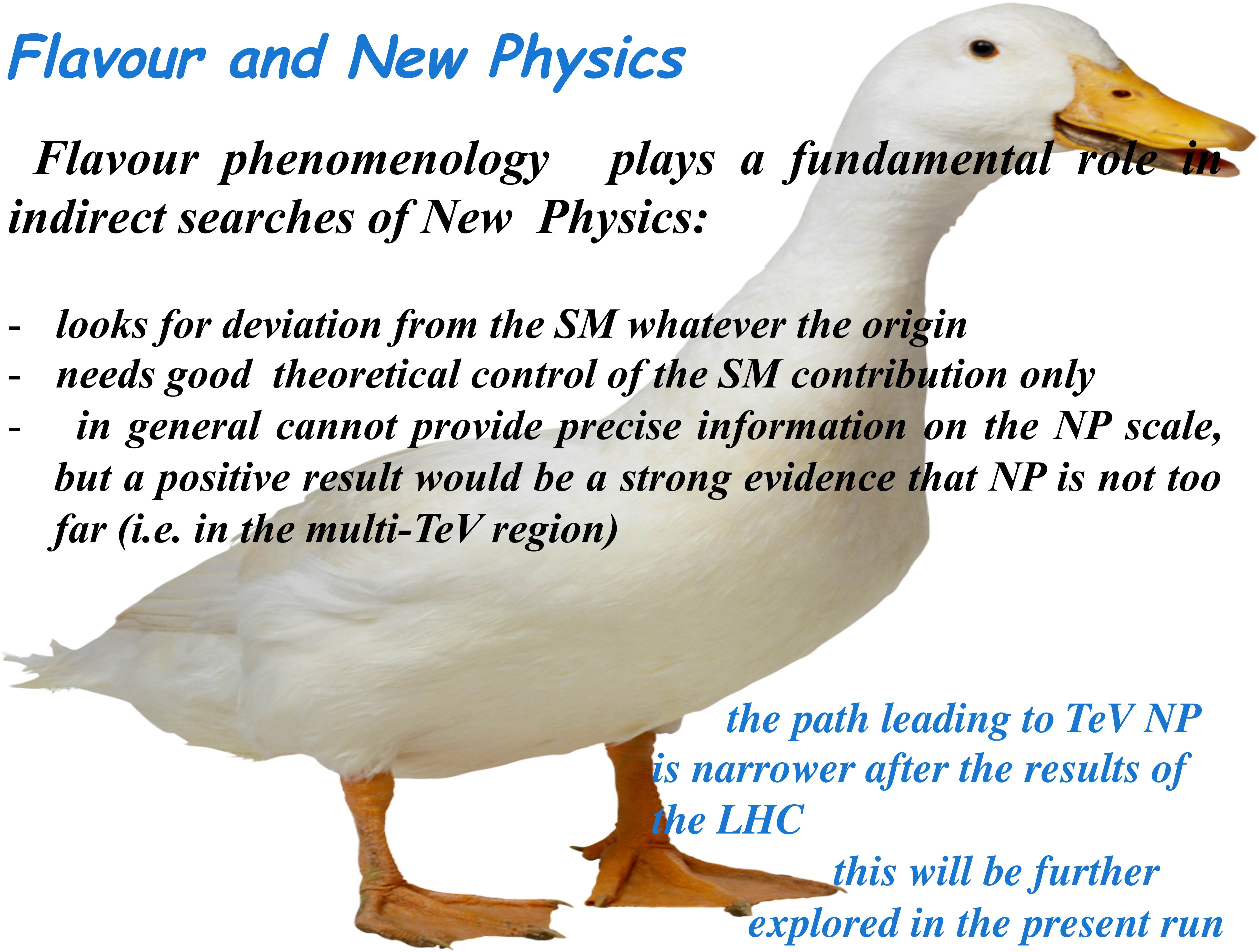
these decays occur only via loops because of GIM and are suppressed by CKM

THUS THEY ARE SENSITIVE TO NEW PHYSICS

Flavour and New Physics

Flavour phenomenology plays a fundamental role in indirect searches of New Physics:

- ***looks for deviation from the SM whatever the origin***
- ***needs good theoretical control of the SM contribution only***
- ***in general cannot provide precise information on the NP scale, but a positive result would be a strong evidence that NP is not too far (i.e. in the multi-TeV region)***



the path leading to TeV NP is narrower after the results of the LHC

this will be further explored in the present run

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

2) Precision Flavor physics is a key tool, complementary to the large energy searches at the LHC, in this endeavour;

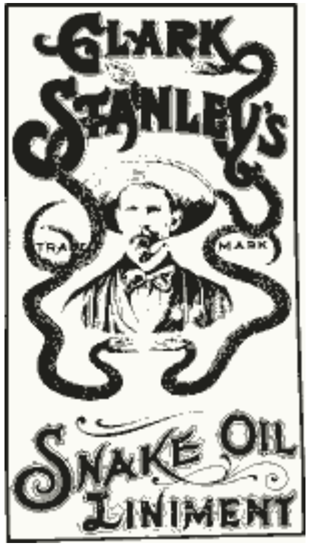
3) If the LHC discovers new elementary particles BSM, then precision flavor physics will be necessary to understand the underlying framework;

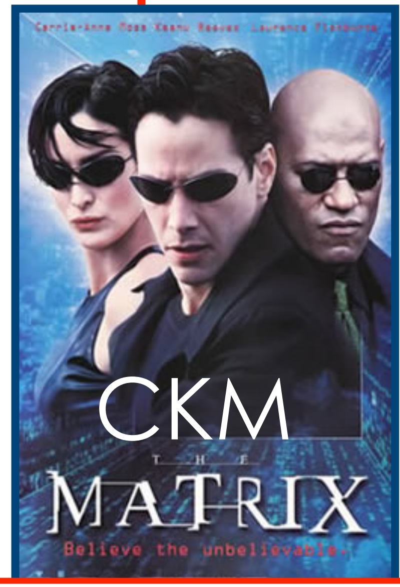
4) The discovery potential of precision flavor physics should also not be underestimate;

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

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

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





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)

CP Violation in the Standard Model

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. <u>CP violation;</u>

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)

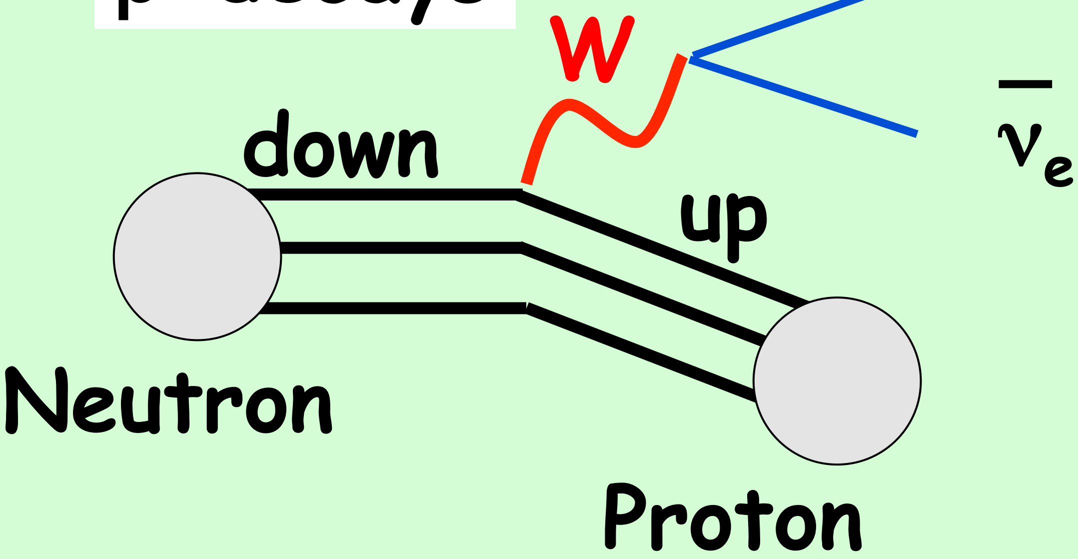
CP Violation is natural with three quark generations (Kobayashi-Maskawa)

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

β-decays



$|V_{ud}|$

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

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

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

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

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

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

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

(0.999)

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}

$\sin\theta_{12} = \lambda$

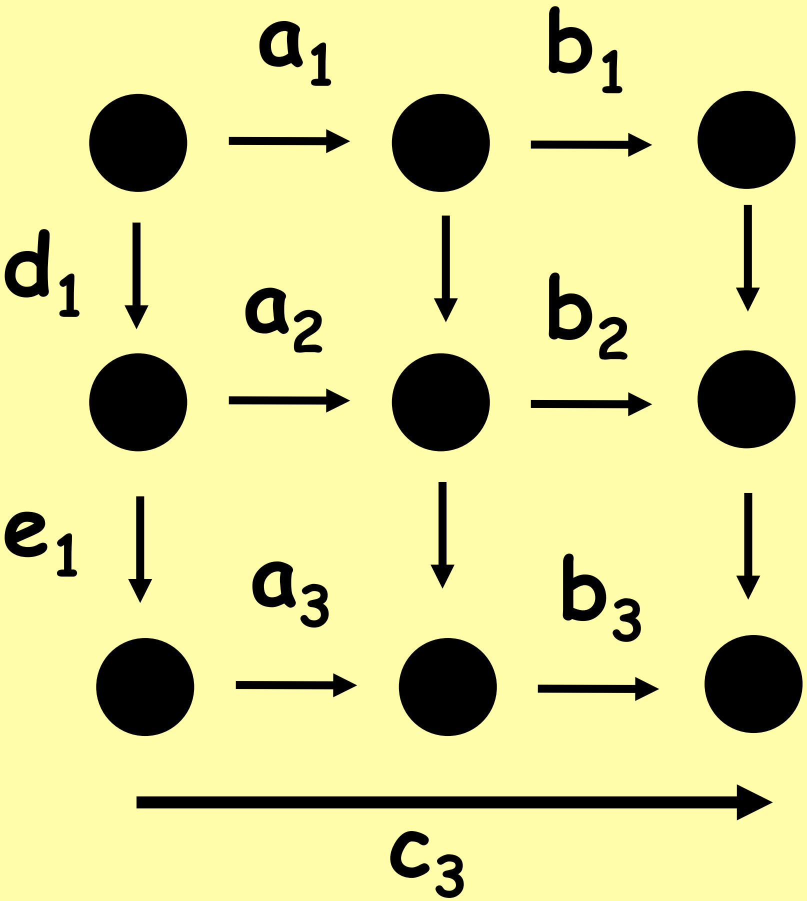
$\sin\theta_{23} = A\,\lambda^2$

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

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

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

The Bjorken-Jarlskog Unitarity Triangle



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

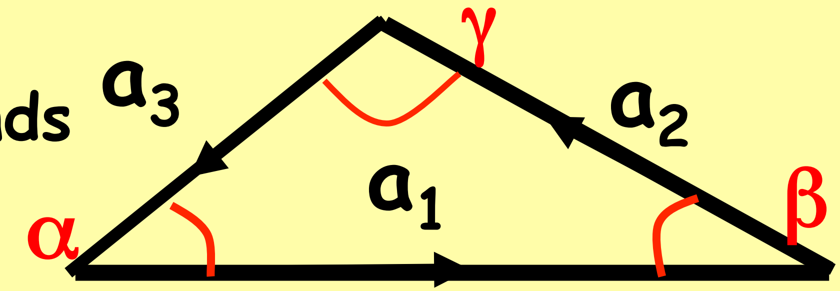
$$a_1 = V_{11} V_{12}^* = V_{ud} V_{us}^*$$

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

$$a_1 + a_2 + a_3 = 0$$

$$(b_1 + b_2 + b_3 = 0 \text{ etc.})$$

Only the orientation depends on the phase convention



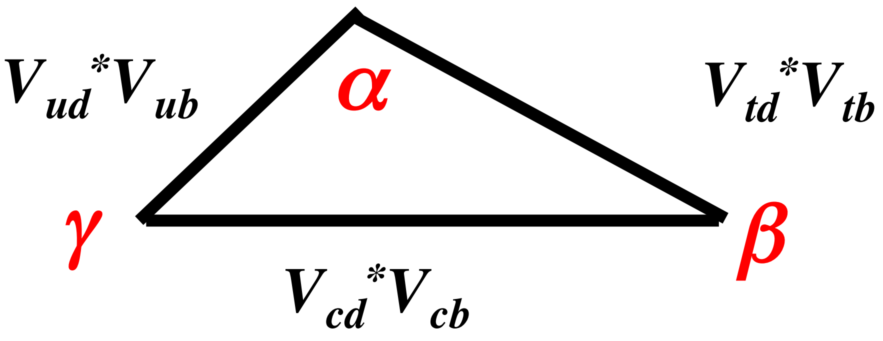
Physical quantities correspond to invariants under phase reparametrization i.e. $|a_1|, |a_2|, \ldots, |e_3|$ and the area of the Unitary Triangles

$$J = \mathrm{Im}\,(a_1 a_2^{*}) = |a_1 \; a_2| \,\mathrm{Sin}\,\beta$$

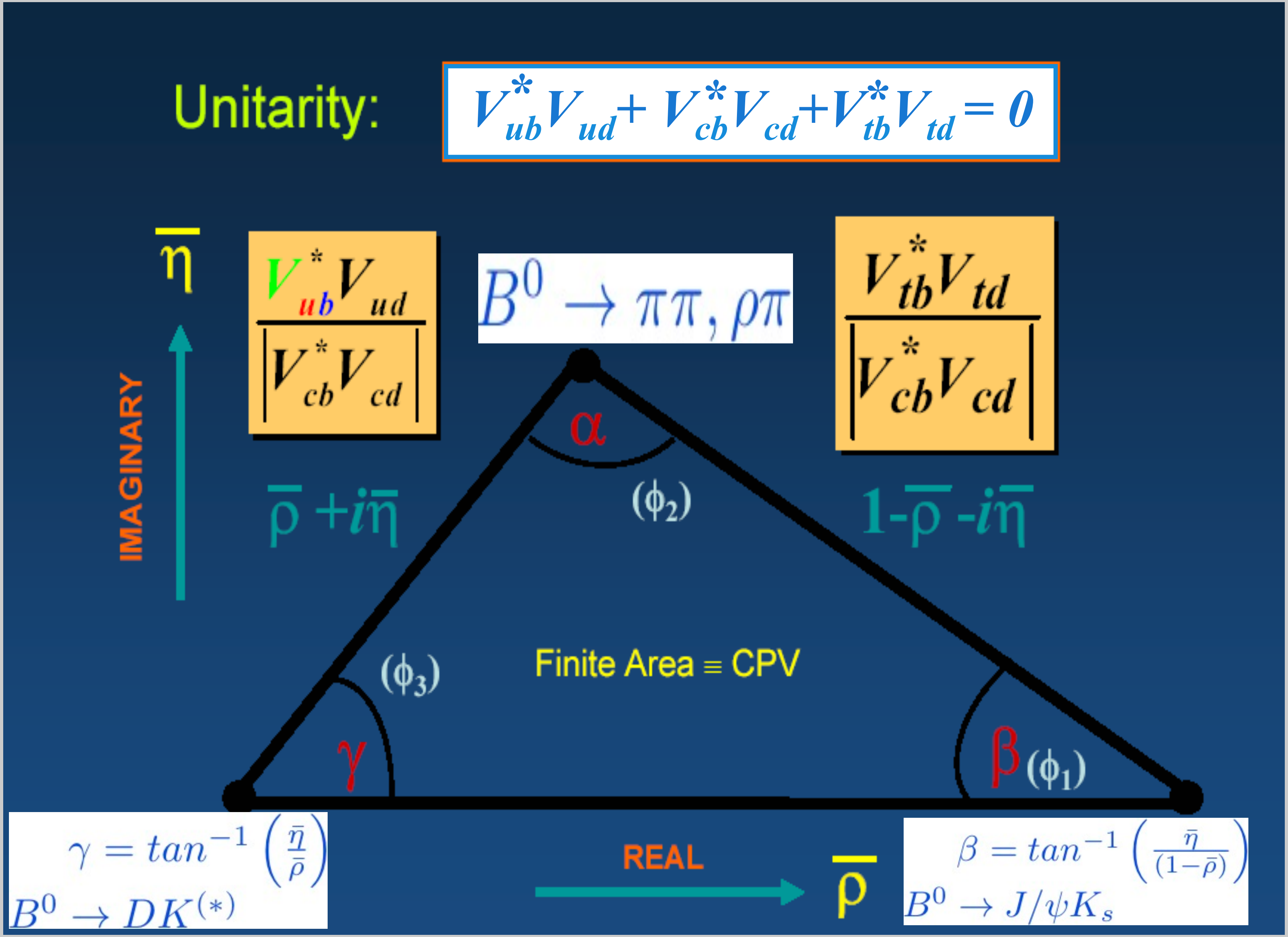
a precise knowledge of the moduli (angles) would fix J

$\not{CP} \propto J$

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

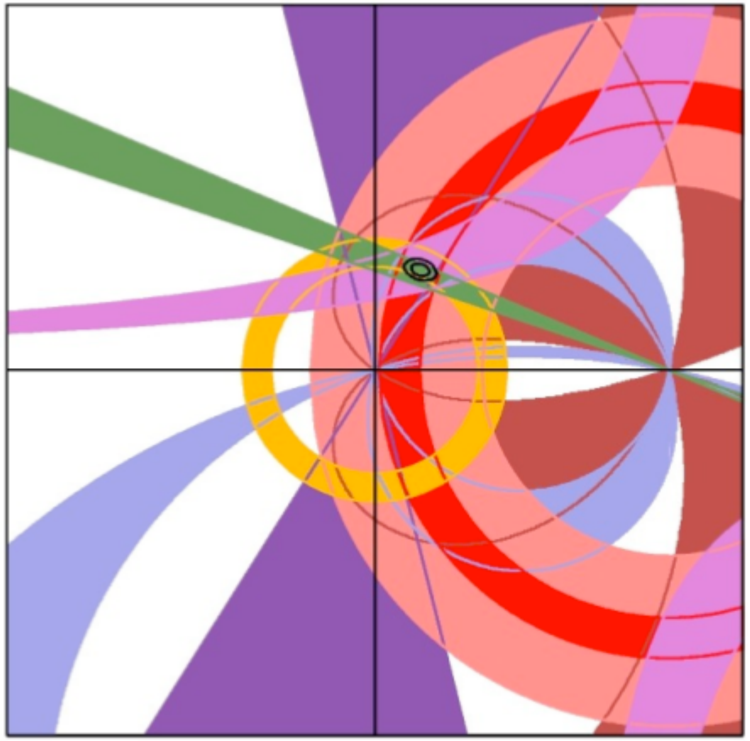


$\gamma = \delta_{CKM}$



Unitarity:
$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$
$\bar{\eta}$
IMAGINARY
$\frac{V^*_{ub}V_{ud}}{|V^*_{cb}V_{cd}|}$
$B^0 \to \pi\pi, \rho\pi$
$\frac{V^*_{tb}V_{td}}{|V^*_{cb}V_{cd}|}$
α
(ϕ_2)
$\bar{\rho} + i\bar{\eta}$
$1-\bar{\rho} - i\bar{\eta}$
(ϕ_3)
Finite Area ≡ CPV
γ
β (ϕ_1)
$\gamma = tan^{-1}\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$
$B^0 \to DK^{(*)}$
REAL
$\bar{\rho}$
$\beta = tan^{-1}\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$
$B^0 \to J/\psi K_s$

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, !?)*

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

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

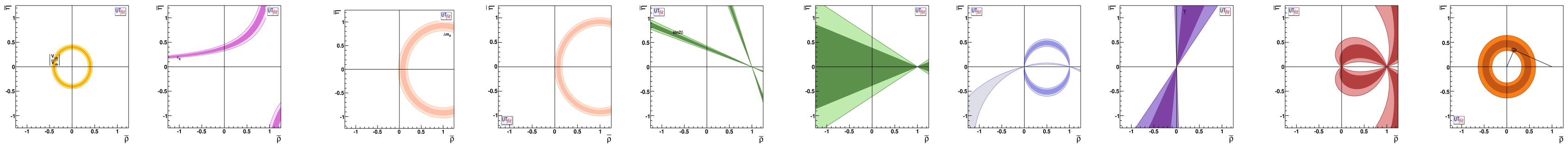
2) Second class quantities, with theoretical errors of O(10%) or less that can be reliably estimated

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

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*

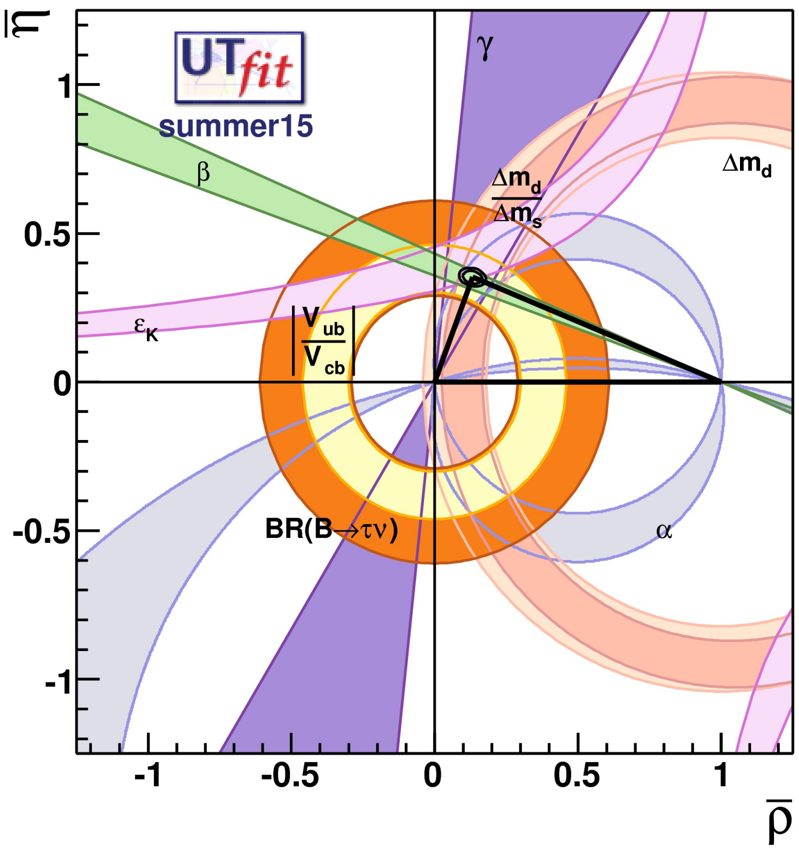
$B \to K \pi$ $B \to \pi^0 \pi^0$
$B \to \phi K_s$



2016 results

$\overline{\rho} = 0.153 \pm 0.013$ $\overline{\eta} = 0.343 \pm 0.011$

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



$\alpha = (92.0 \pm 2.0)^0$

$\sin 2\beta = 0.696 \pm 0.018$

$\beta = (21.82 \pm 0.72)^0$

$\gamma = (65.8 \pm 1.9)^0$

$A = 0.833 \pm 0.012$

$\lambda = 0.22497 \pm 0.00069$

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 2016

CKM matrix thus looks like

$$V_{CKM} = \begin{pmatrix} (0.97431 \pm 0.00015) & (0.22512 \pm 0.00067) & (0.00365 \pm 0.00012) e^{i(-65.88 \pm 1.88)^\circ} \\ (-0.22497 \pm 0.00067) e^{i(0.0352 \pm 0.0010)^\circ} & (0.97344 \pm 0.00015) e^{i(-0.001877 \pm 0.000055)^\circ} & (0.04255 \pm 0.00069) \\ (0.00869 \pm 0.00014) e^{i(-22.00 \pm 0.73)^\circ} & (-0.04156 \pm 0.00056) e^{i(1.040 \pm 0.035)^\circ} & (0.999097 \pm 0.000024) \end{pmatrix}$$

Standard Parametrization (PDG)

Sin θ_{12} = 0.22497 ± 0.00069

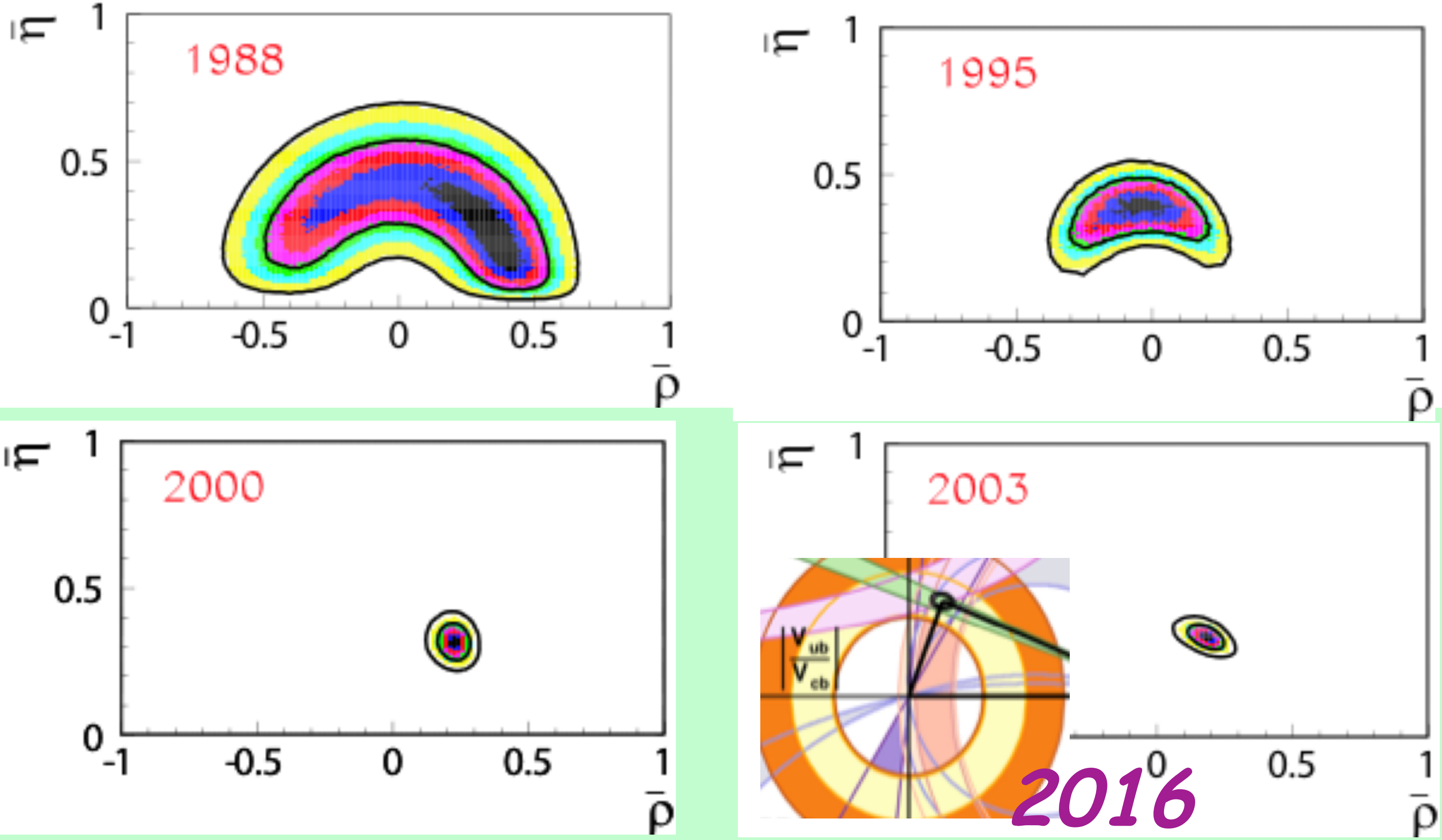
Sin θ_{23} = 0.04229 ± 0.00057

Sin θ_{13} = 0.00368 ± 0.00002 δ = 65.9 ± 2.0

Wolfenstein Parametrization (PDG)

λ= 0.22497 ± 0.00069 A = 0.833 ± 0.0.12

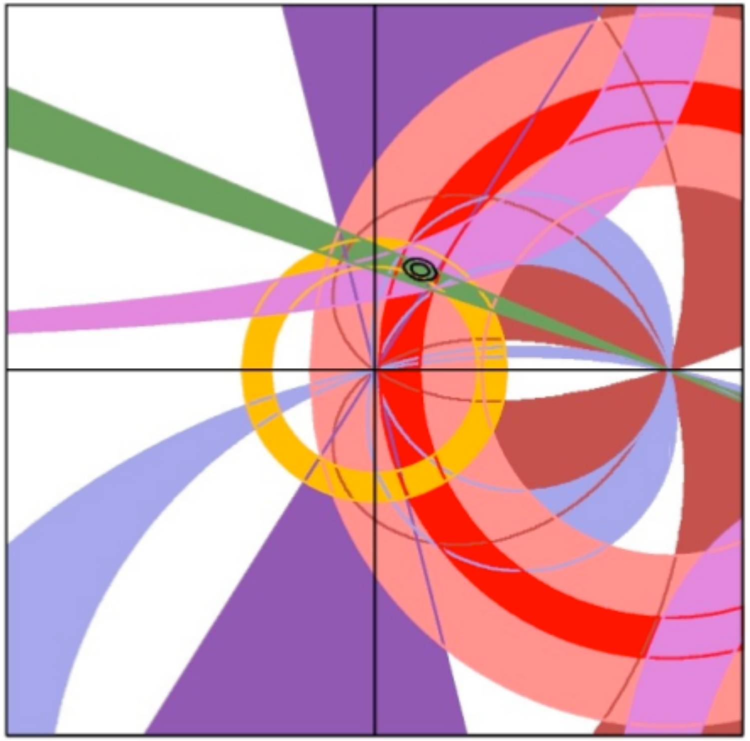
PROGRESS SINCE 1988



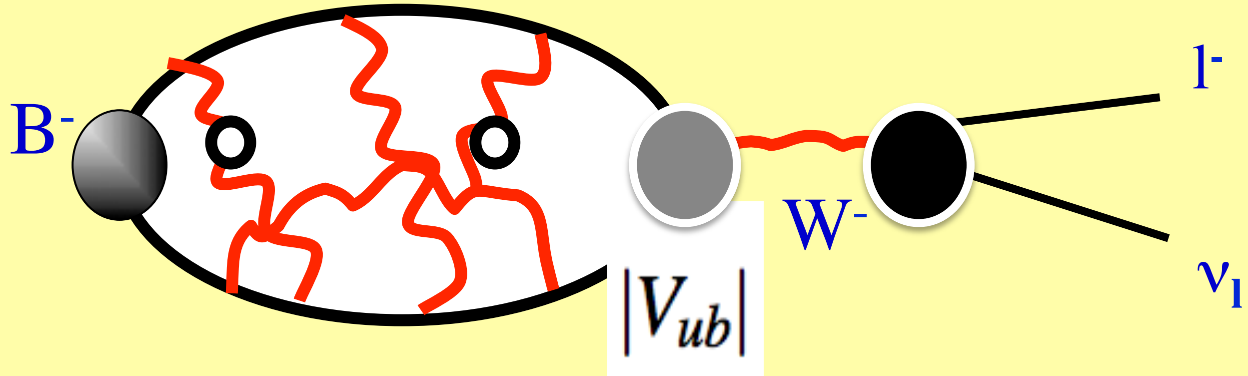
Do we still care? Tensions and Unknowns

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

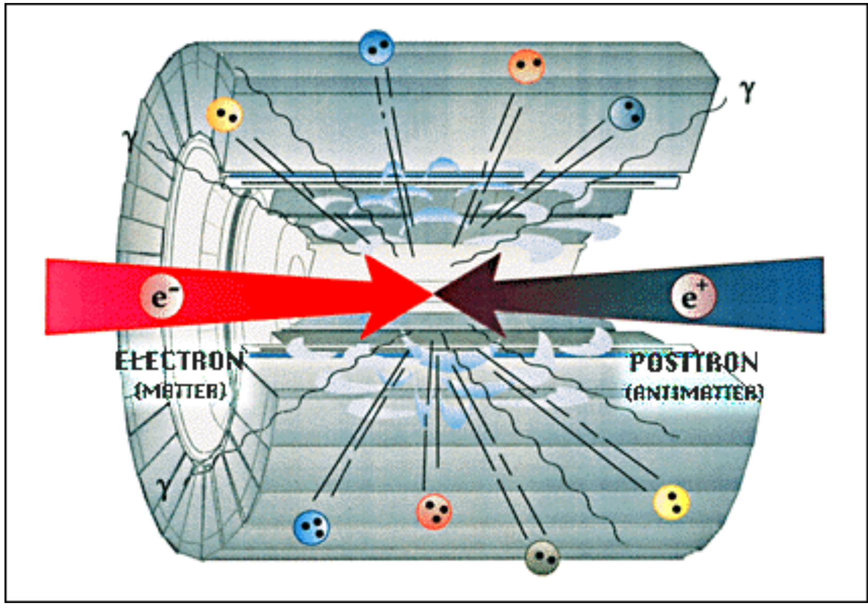


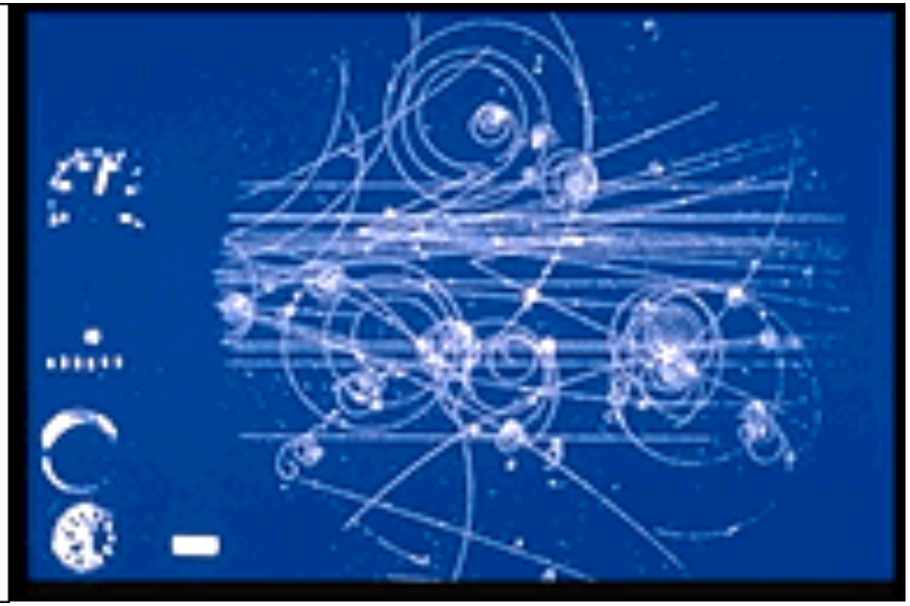
$$BR(B^- \to \tau^- \bar{\nu}_\tau) = f_B^2 |V_{ub}|^2 \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_B$$

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

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

COULD WE COMPUTE THIS PROCESS WITH
SUFFICIENT COMPUTER POWER ?



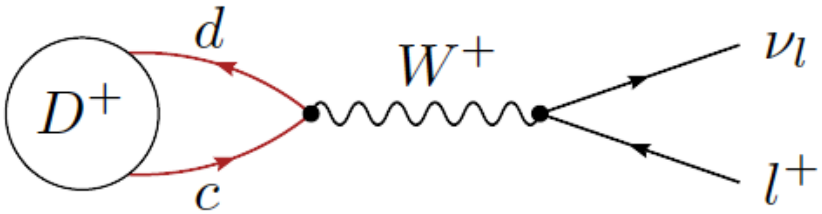


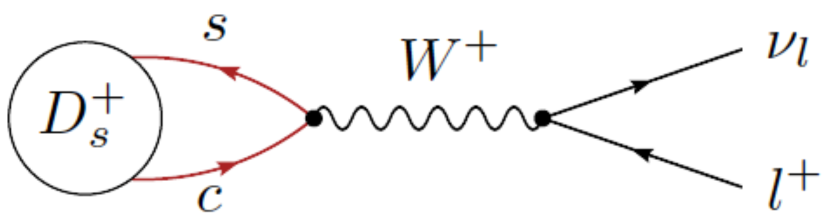
THE ANSWER IS: NO

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

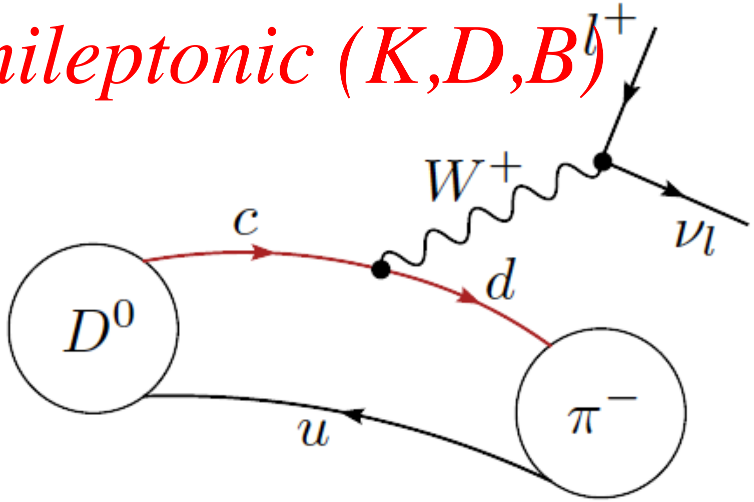
Euclide vs Minkowski

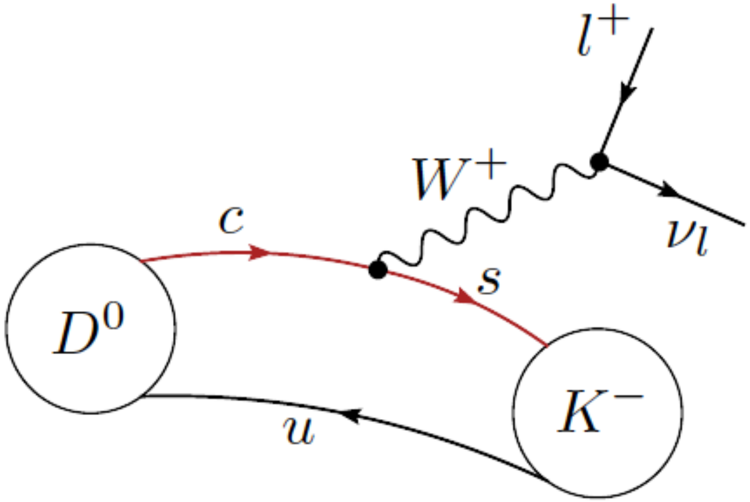
Leptonic (π,K,D,B)





Semileptonic (K,D,B)

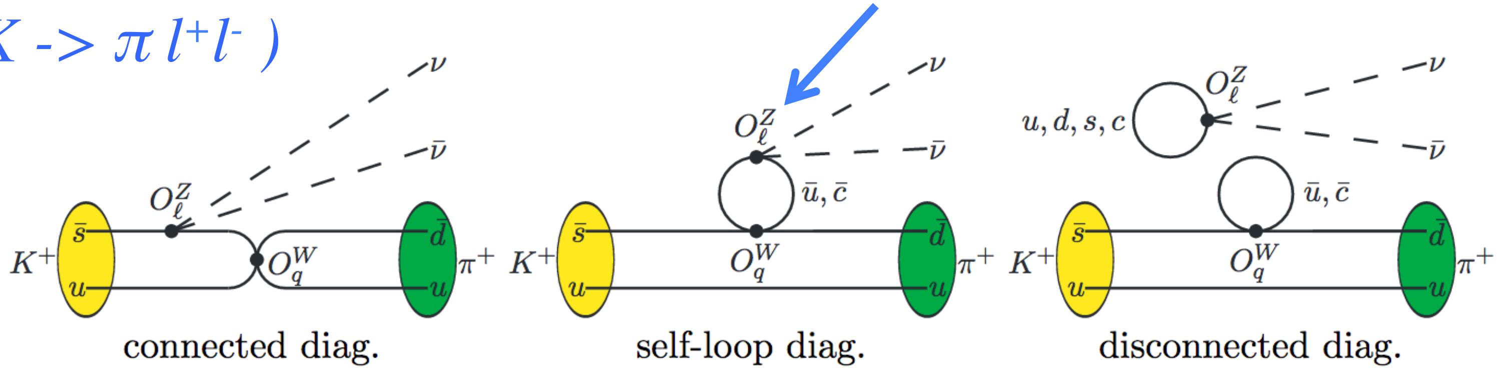




(some) Radiative and Rare

long distance effects

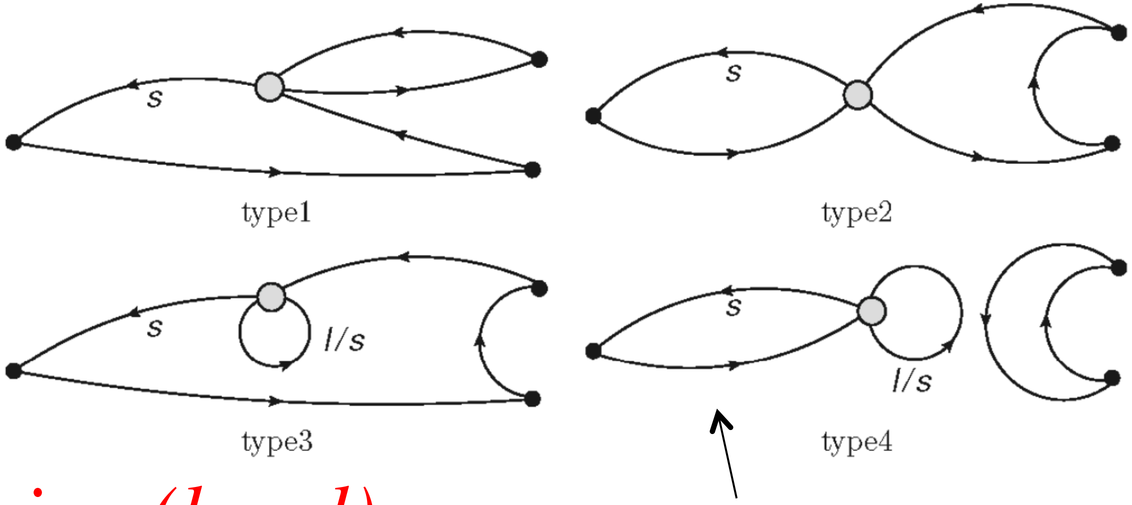
(also K -> π l⁺l⁻)



Non-leptonic

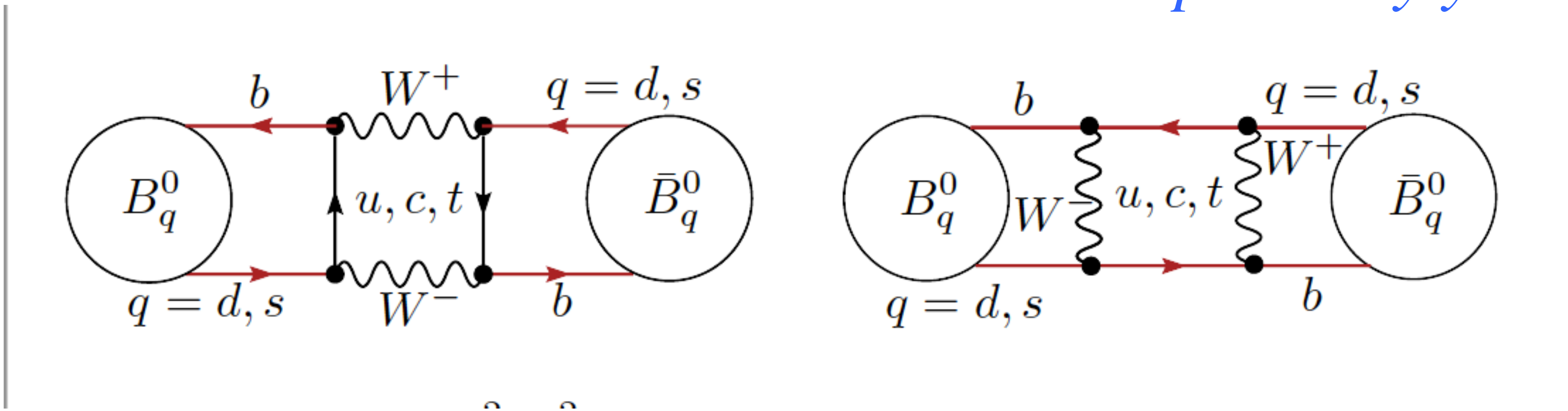
but only below the inelastic threshold (may be also 3 body decays)

B -> ππ,Kπ, etc. No ! (Not yet)



D -> Kπ probably yes

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

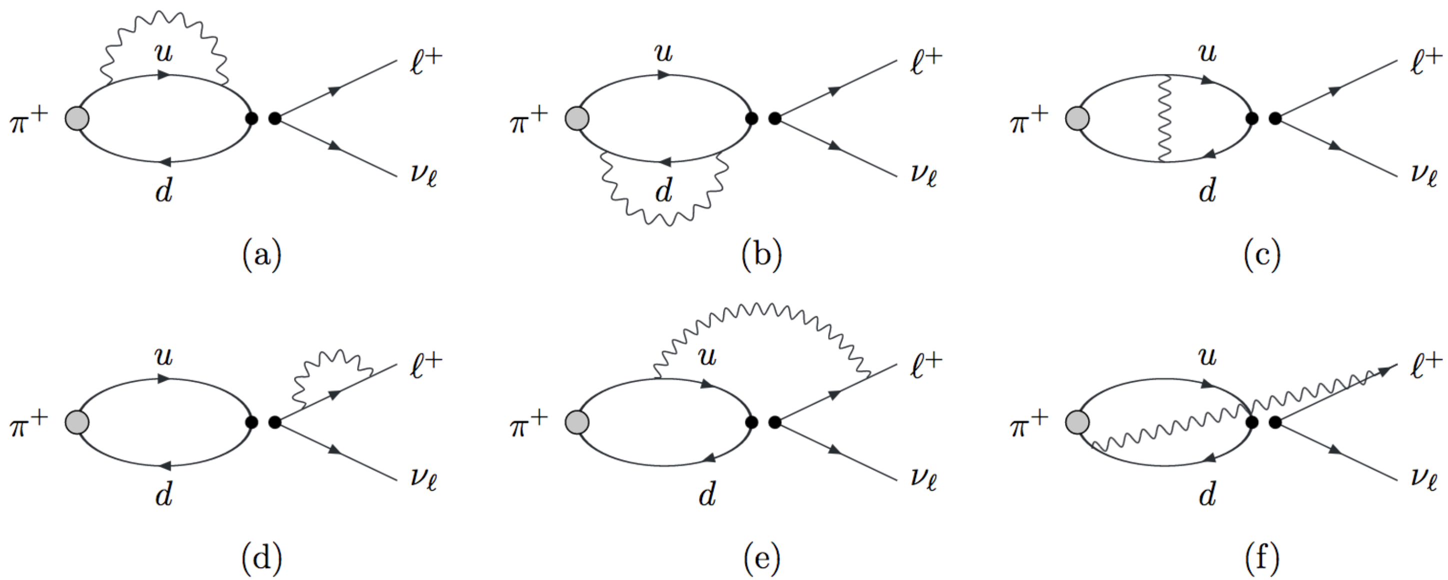
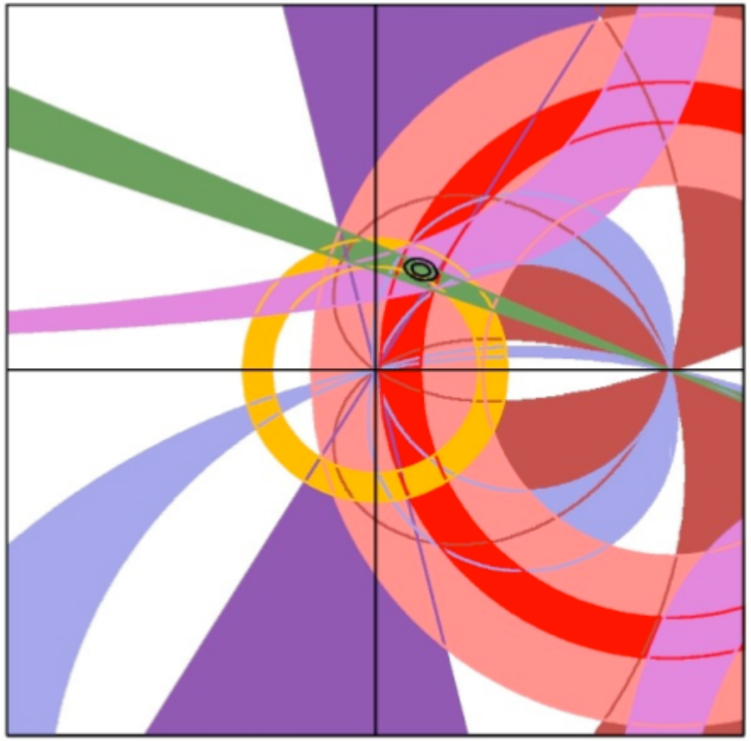


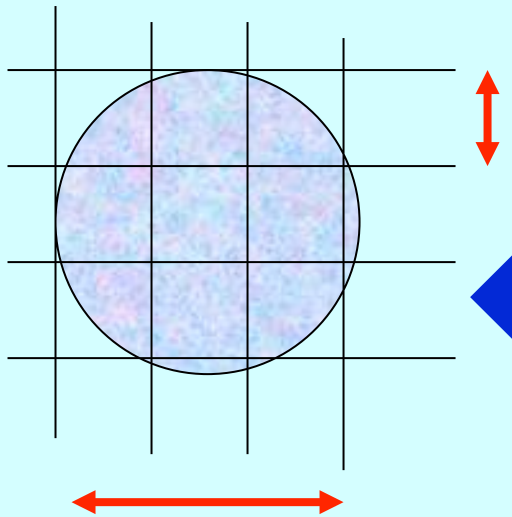
FIG. 5: Connected diagrams contributing at $O(\alpha)$ contribution to the amplitude for the decay $\pi^+ \to \ell^+ \nu_l$.

- *Uncertainties in lattice QCD calculations*

Not in this talk



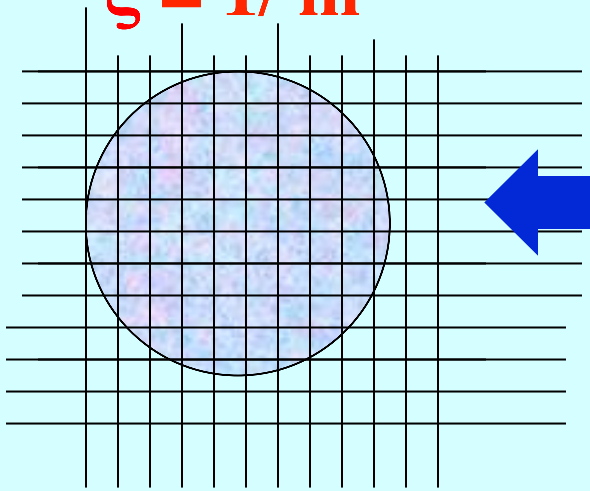
Continuum limit, discretization and finite volume errors



a Formal $\lim_{a \to 0} S_{Lattice}(\phi) \to S_{Continuum}(\phi)$

$\xi = 1/m$

$a/\xi = m\,a \sim 1$ The size of the object is comparable to the lattice spacing



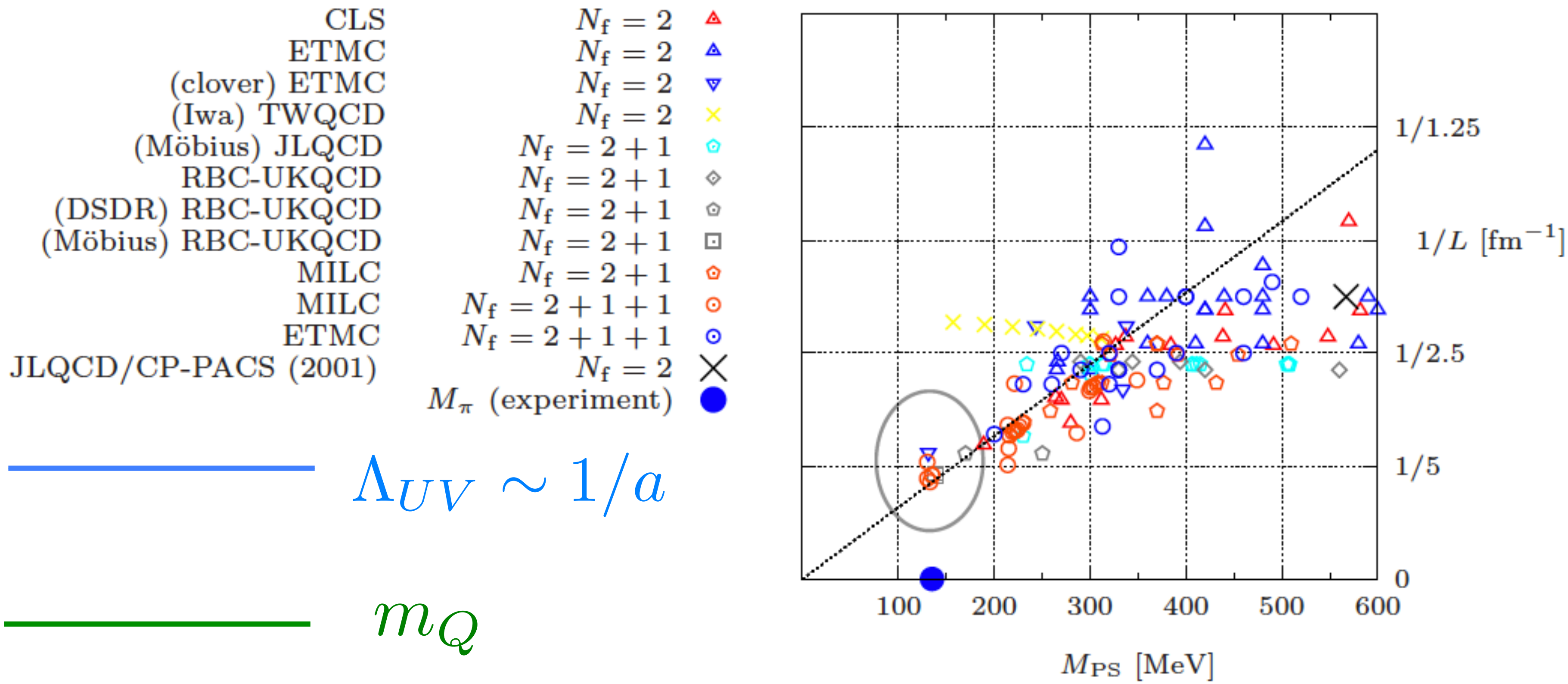
$a/\xi \ll 1$ i.e. $m\,a \to 0$ The size of the object is much larger than the lattice spacing

Similar to $a \sum_n \to \int dx$

Physics Reach (Mainly Heavy Flavor Physics)

many slides from lattice 2015 particularly from C. Pena

- charm physics directly accessible for some time now
- fraction of available ensembles used for HQ physics still limited



$\Lambda_{UV} \sim 1/a$

m_Q

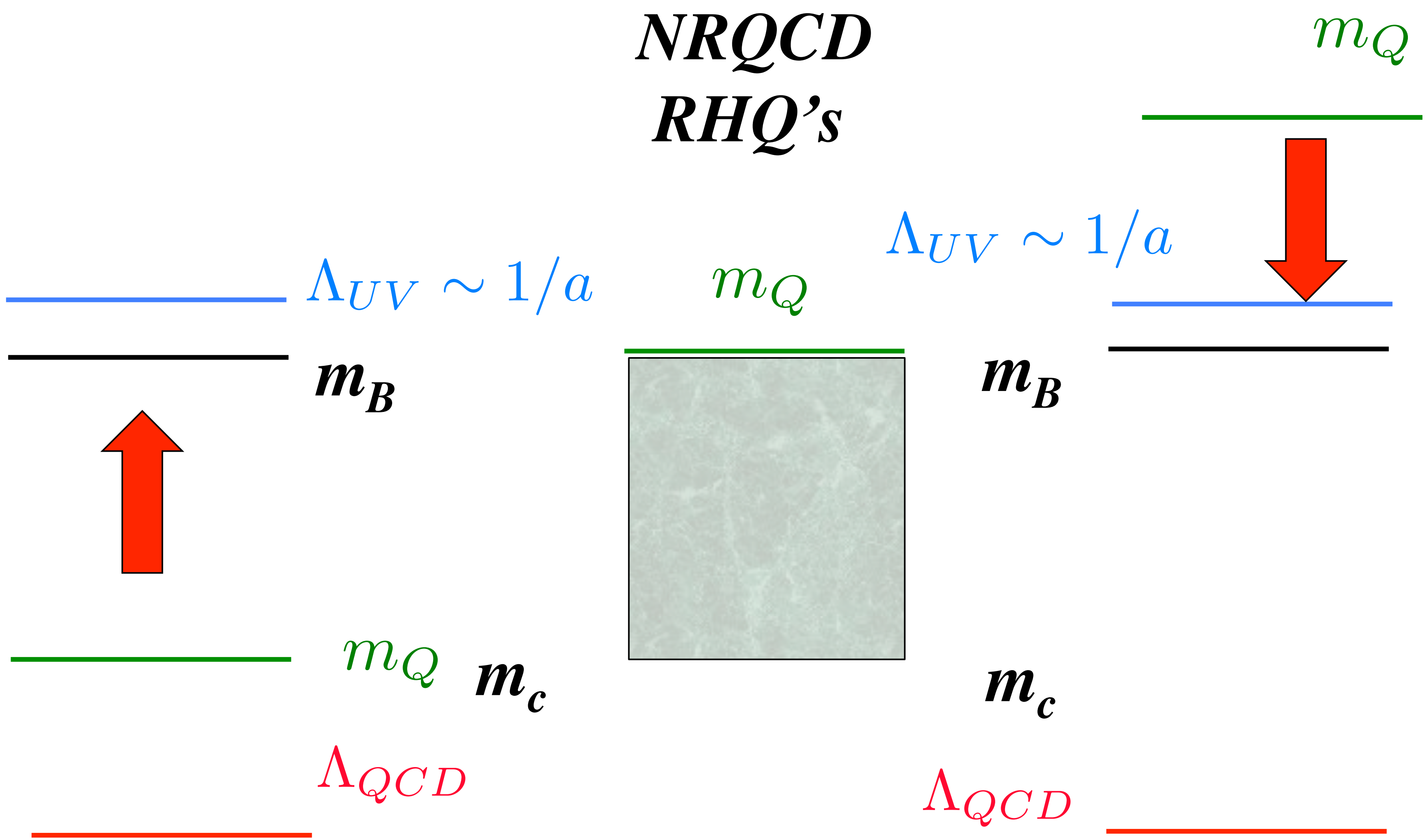
Λ_{QCD}

[G Herdoíza]

a crosscheck of different approaches is fundamental

Extrapolation in $1/m_Q$
Ratio Method

npHQET



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)

stat CL FV e.m.

MILC 13 $f_{K^\pm}/f_{\pi^\pm}|_{N_f=2+1+1} = 1.1947(26)(33)(17)(2)$

HPQCD 13 $f_{K^\pm}/f_{\pi^\pm}|_{N_f=2+1+1} = 1.1916(15)(12)(1)(10)$

stat CL FV (misc).

+ perturbative renormalization
courtesy of C. Pena

$\Lambda_b \to p\,\ell^- \bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c\,\ell^- \bar{\nu}_\ell$ form factors from lattice QCD with relativistic heavy quarks

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[2] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[3] Department of Physics, University of Arizona, Tucson, AZ 85721, USA
[4] RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

Very nice paper – interesting for LHCb

Parameter	coarse	fine
$am_Q^{(b)}$	8.45	3.99
$\xi^{(b)}$	3.1	1.93
$c_{E,\,B}^{(b)}$	5.8	3.57
$am_Q^{(c)}$	0.1214	−0.0045
$\xi^{(c)}$	1.2362	1.1281
$c_E^{(c)}$	1.6650	1.5311
$c_B^{(c)}$	1.8409	1.6232

TABLE II. Parameters of the bottom and charm quark actions [51, 52].

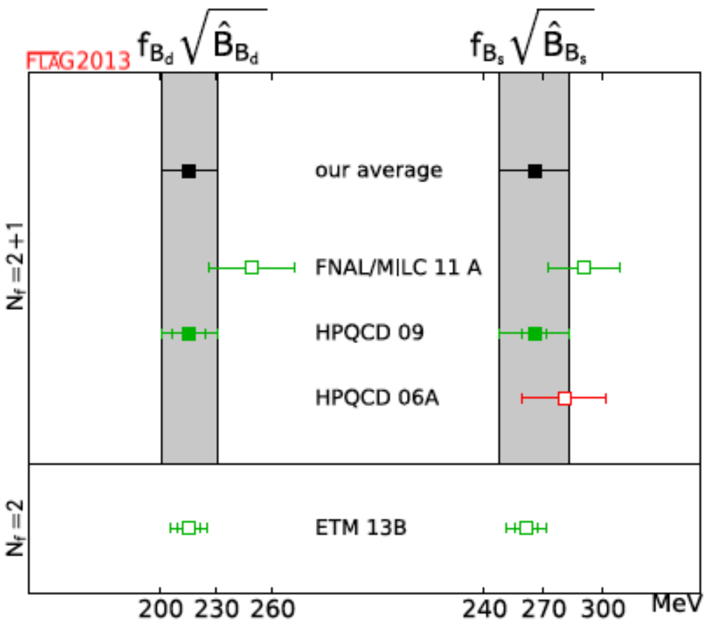
the parameters ν, c_E, c_B as functions of am_Q, heavy-quark discretization errors proportional to powers of am_Q can be removed to all orders. The remaining discretization errors are of order $a^2|\mathbf{p}|^2$, where $|\mathbf{p}|$ is the typical magnitude of the spatial momentum of the heavy quark inside the hadron. As the continuum limit $a \to 0$ is approached, the

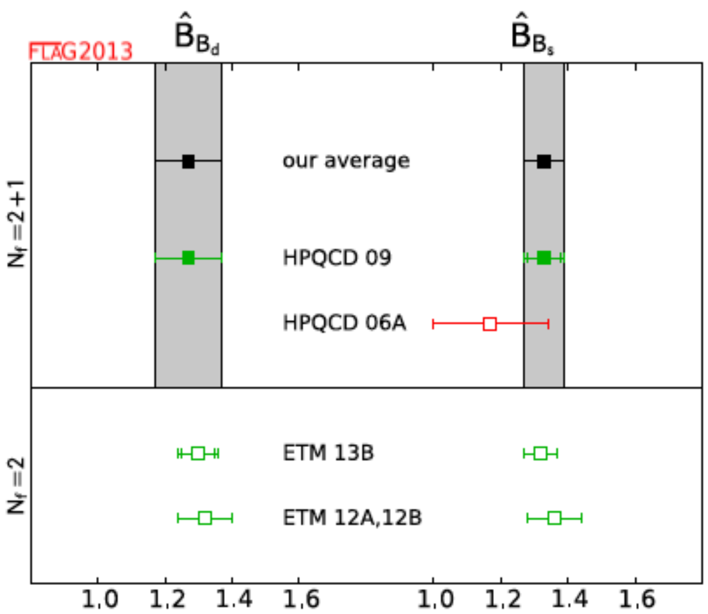
FLAG-2 on B mixing

BBs = 1.32(5) Nf=2, ETMC
BBs = 1.33(6) Nf=2+1 HPQCD
BBs = 1.492(92)Nf=2+1, NEW FNAL/MILC
UTFIT AV. BBs = 1.38(11)

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	$f_{B_d}\sqrt{\hat{B}_{B_d}}$	$f_{B_d}\sqrt{\hat{B}_{B_s}}$	$\hat{B}_{B_d}$	$\hat{B}_{B_s}$
FNAL/MILC 11A	[411]	2+1	C	★	○	★	○	✓	$250(23)^{\dagger}$	$291(18)^{\dagger}$	–	–
HPQCD 09	[402]	2+1	A	○	$○^{\nabla}$	★	○	✓	$216(15)^{*}$	$266(18)^{*}$	$1.27(10)^{*}$	$1.33(6)^{*}$
HPQCD 06A	[412]	2+1	A	■	■	★	○	✓	–	281(21)	–	1.17(17)
ETM 13B	[334]	2	P	★	○	★	★	✓	216(6)(8)	262(6)(8)	1.30(5)(3)	1.32(5)(2)
ETM 12A, 12B	[392, 413]	2	C	★	○	★	★	✓	–	–	$1.32(8)^{\diamond}$	$1.36(8)^{\diamond}$

now published (ETM 13B)



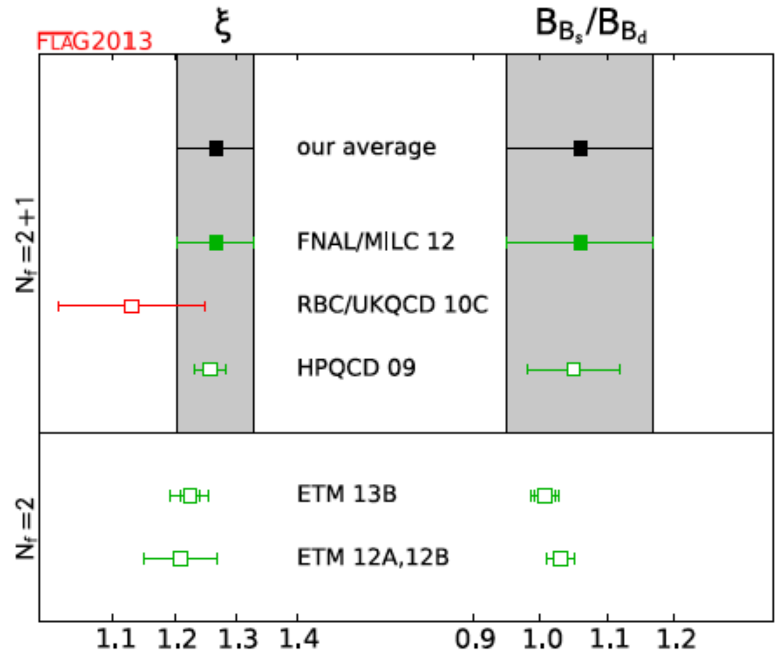


FLAG-2 on B mixing

FLAG2 BBs/BBd = 1.06(11)
UTFIT BBs/BBd = 1.012(27)

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization/matching	heavy quark treatment	ξ	B_{B_s}/B_{B_d}
FNAL/MILC 12	[414]	2+1	A	○	○	★	○	✓	1.268(63)	1.06(11)
RBC/UKQCD 10C	[405]	2+1	A	■	■	★	○	✓	1.13(12)	–
HPQCD 09	[402]	2+1	A	○	○▽	★	○	✓	1.258(33)	1.05(7)
ETM 13B	[334]	2	P	★	○	★	★	✓	1.225(16)(14)(22)	1.007(15)(14)
ETM 12A, 12B	[392, 413]	2	C	★	○	★	★	✓	1.21(6)	1.03(2)

now published



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

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

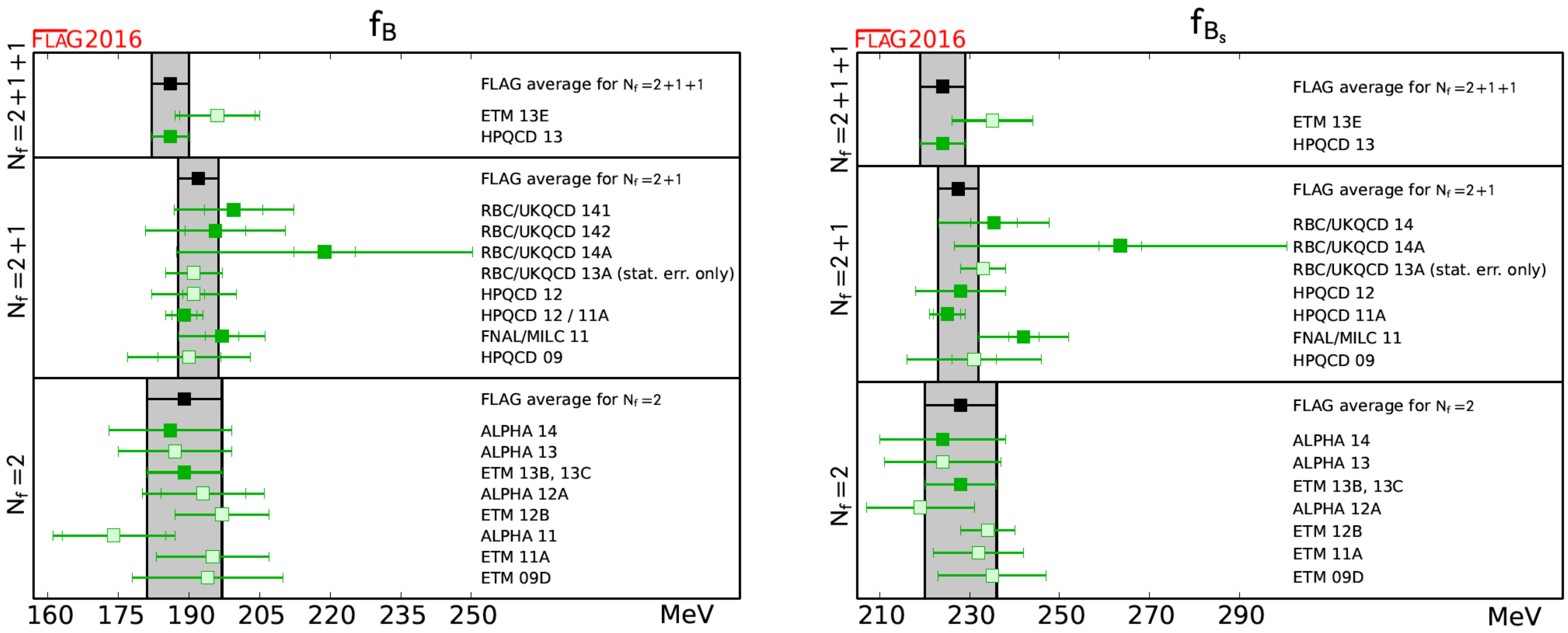


Figure 20: Decay constants of the B and B_s mesons. The values are taken from Tab. 32 (the

$$f_B = 192.0(4.3)\ \text{MeV} \quad \textit{(186)} \quad \text{Refs. [48, 53–56]},$$

$N_f = 2+1:$

$$f_{B_s} = 228.4(3.7)\ \text{MeV} \quad \textit{(224)} \quad \text{Refs. [48, 53–56]},$$

N_f=2+1+1

$$f_{B_s}/f_B = 1.201(16) \quad \textit{(1.205)} \quad \text{Refs. [48, 53–56]}.$$

LATTICE PARAMETERS (2016)

*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***

obtained excluding the given constraint from the fit

			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

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:

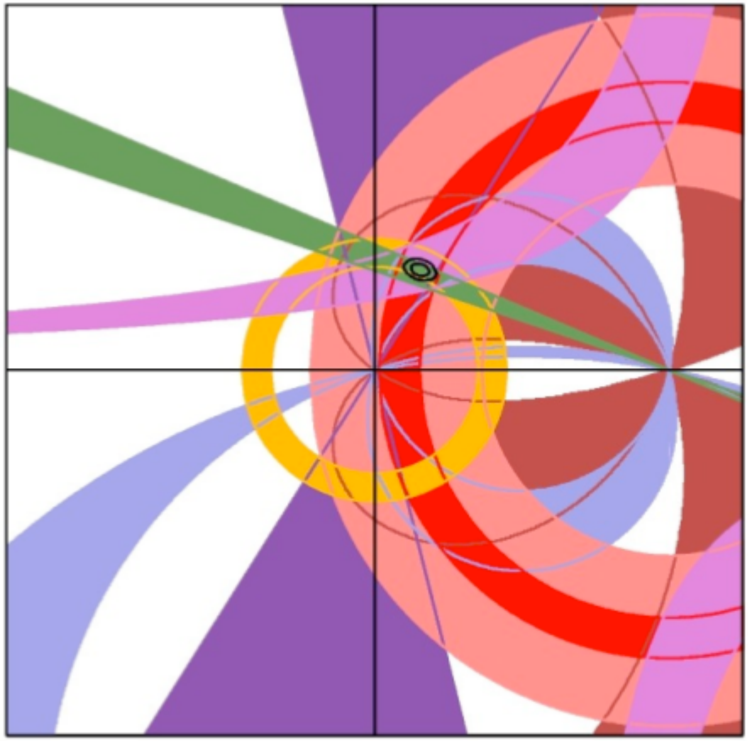
FLAG Nf=2+1+1 (single result) and Nf=2+1 average

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 (1602.13560)

- ***Future directions***



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

3.19(41)(96) lattice unphysical masses

- Historically led to the prediction of the energy scale of the charm quark.

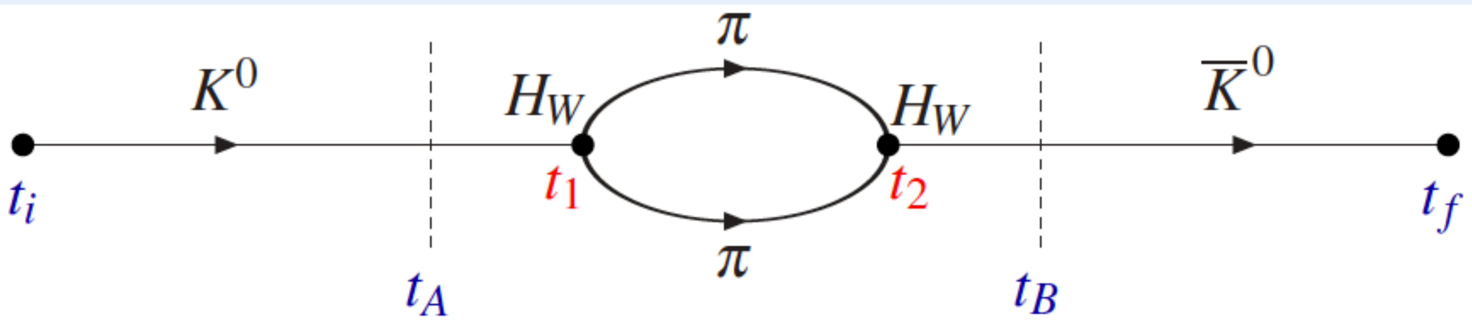
  Mohapatra, Rao & Marshak (1968); GIM (1970); Gaillard & Lee (1974)

- 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:

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

where the sum over $|\alpha\rangle$ includes an energy-momentum integral.

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 ($T = t_B - t_A + 1$)

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

- 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

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

  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.

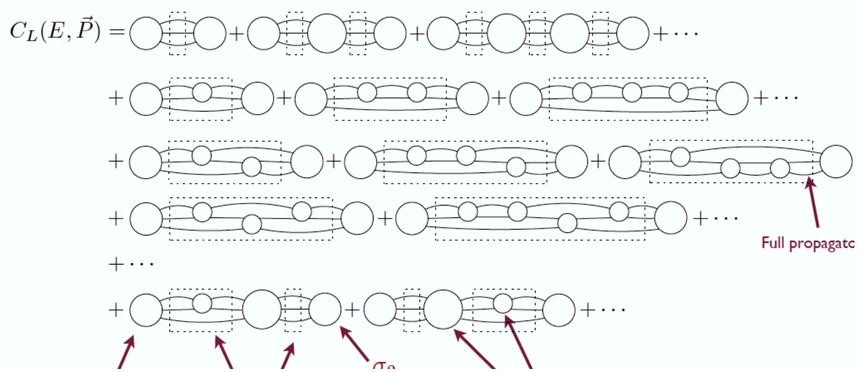
Within reasonable approximations can be extended to D meson mixing

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 -> $\pi\pi$ 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 II

- 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, with

$$\sqrt{2}\,\Delta m = \mathrm{sign}(\cos\Phi_{12})\sqrt{4|M_{12}|^2-|\Gamma_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\sqrt{2}\,\Delta\Gamma = 2\sqrt{|\Gamma_{12}|^2-4|M_{12}|^2+\sqrt{(4|M_{12}|^2+|\Gamma_{12}|^2)^2-16|M_{12}|^2|\Gamma_{12}|^2\sin^2\Phi_{12}}}\,,$$

$$\delta = \frac{2|M_{12}||\Gamma_{12}|\sin\Phi_{12}}{(\Delta m)^2+|\Gamma_{12}|^2}\,, \qquad (7)$$

- Notice that $\phi=\arg(q/p)=\arg(y+i\delta x)$ - ~~$\arg\Gamma_{12}$~~
- $|q/p|\neq 1 \Leftrightarrow \phi\neq 0$ clear signals of NP

Ciuchini et al; Kagan & Sokoloff

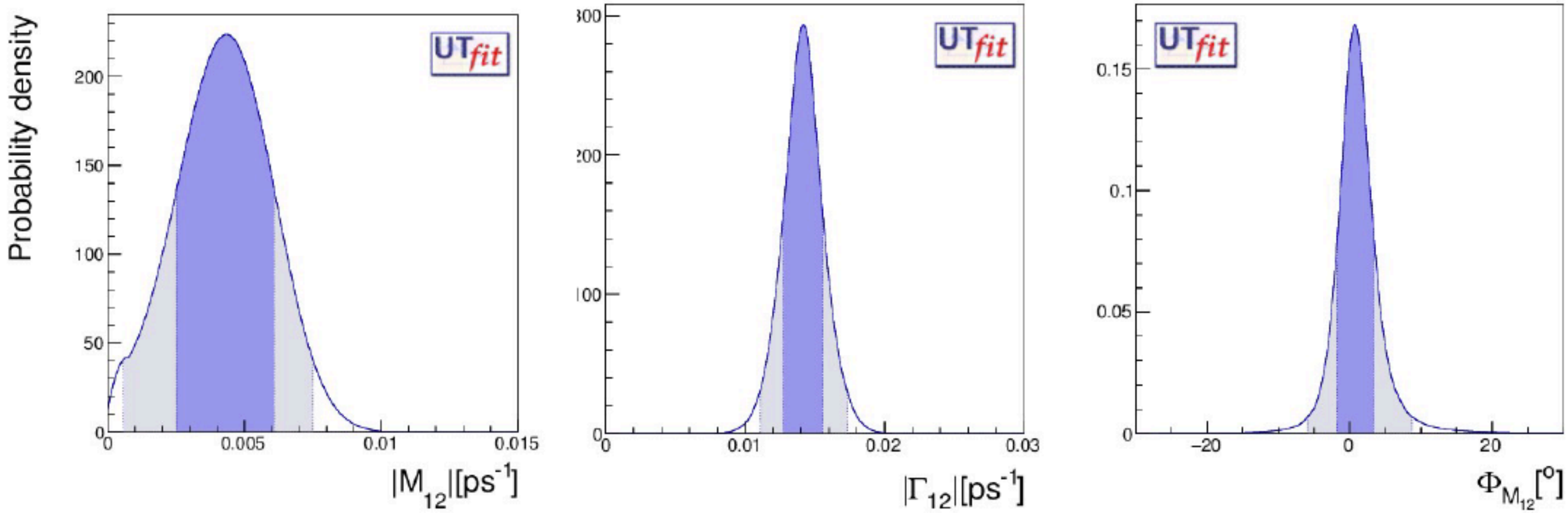
CPV IN CHARM MIXING

- Latest UTfit average (HFAG very similar):

  $x = (3.5 \pm 1.5)\ 10^{-3}$, $y = (5.8 \pm 0.6)\ 10^{-3}$,

  $|q/p|-1 = (0.7 \pm 1.8)\ 10^{-2}$, $\phi = \arg(q/p) = (0.20 \pm 0.56)^\circ$

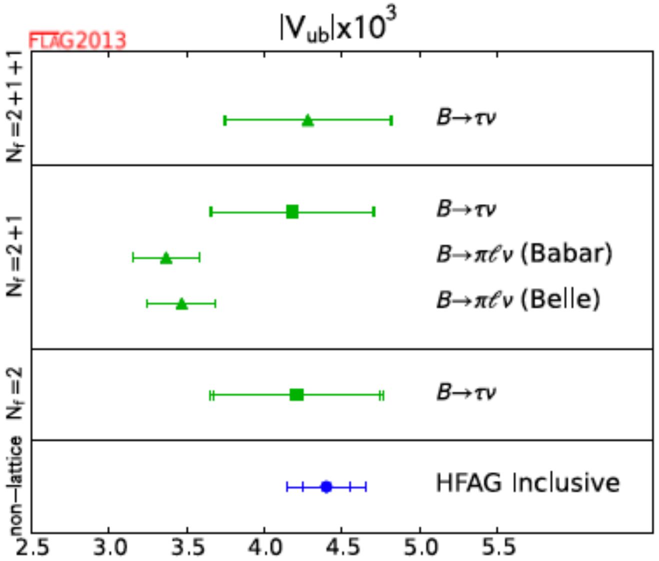
  $|M_{12}| = (4 \pm 2)/\text{fs}$, $|\Gamma_{12}| = (14 \pm 1)/\text{fs}$, $\Phi_{12} = (0 \pm 3)^\circ$

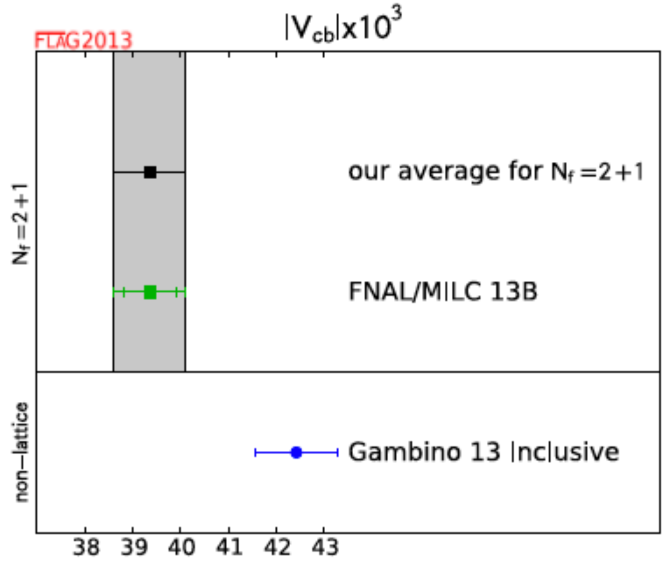


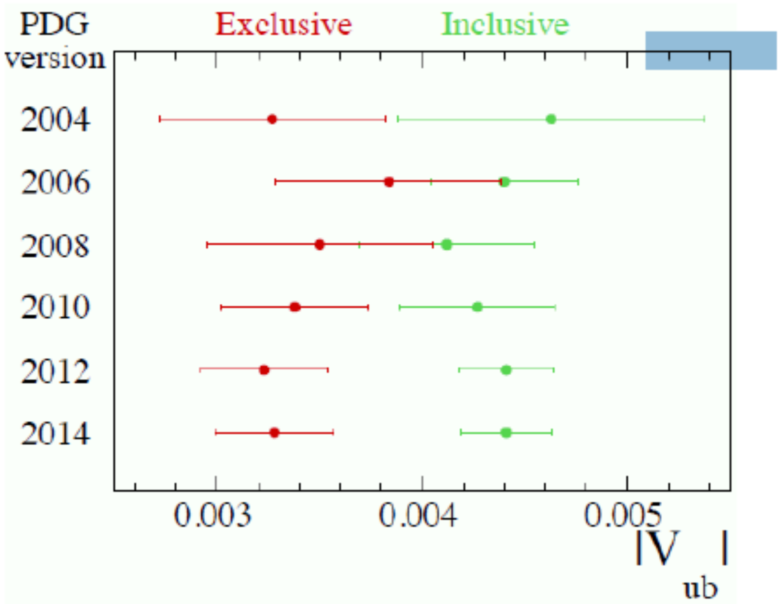
Do we still care? Tensions and Unknowns

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 ?

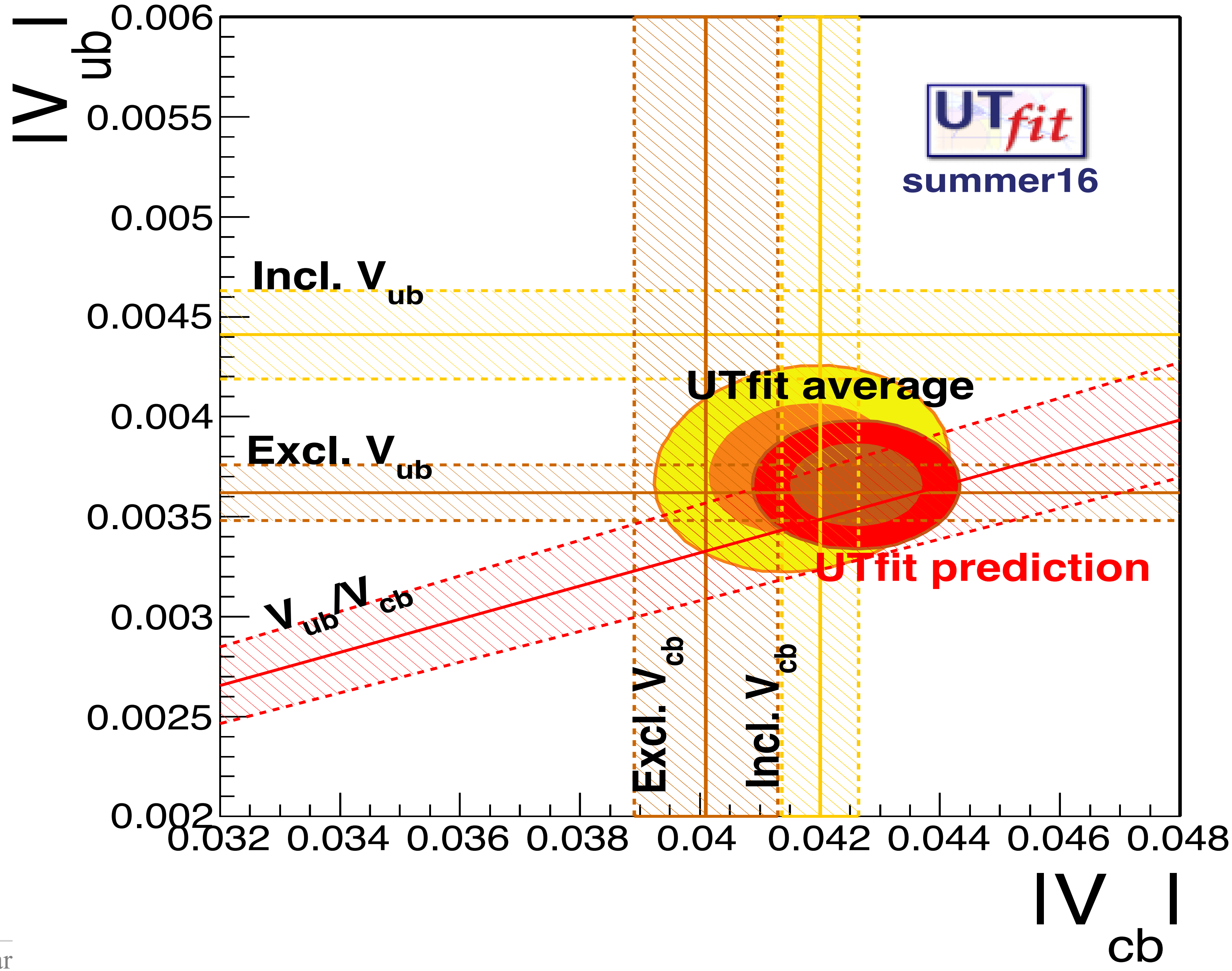
$|V_{ub}|$, $|V_{cb}|$





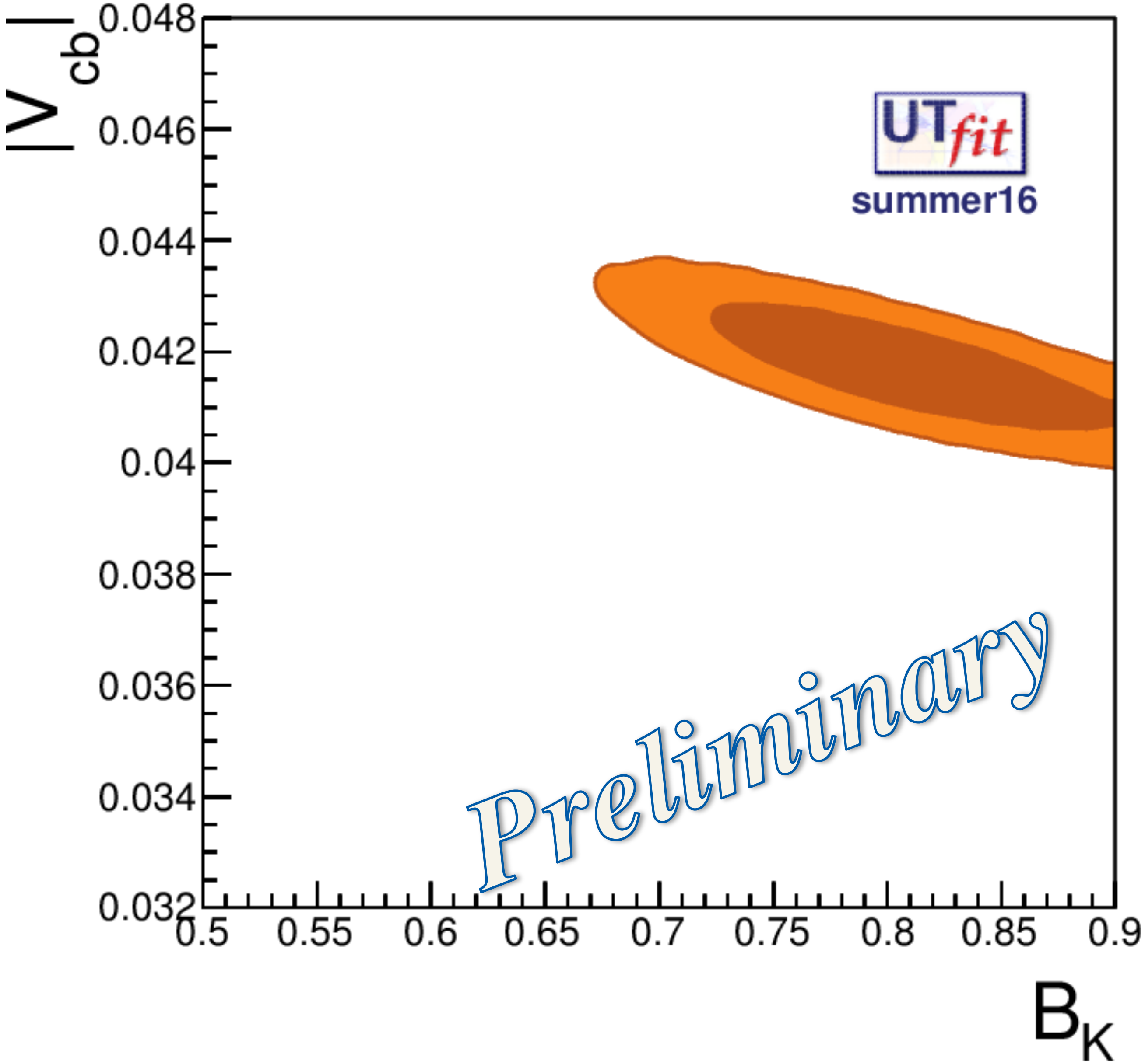


Vub Exclusive = 0.00361 ± 0.00013
Vcb Exclusive = 0.0400 ± 0.0011
Vub/Vcb Exclusive = 0.083 ± 0.006
Vub Inclusive = 0.00440 ± 0.00022
Vcb Inclusive = 0.0420 ± 0.0006



UTfit
summer16
Incl. V_{ub}
Excl. V_{ub}
UTfit average
UTfit prediction
V_{ub}/V_{cb}
Excl. V_{cb}
Incl. V_{cb}
$|V_{ub}|$
$|V_{cb}|$
0.006
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.032
0.034
0.036
0.038
0.04
0.042
0.044
0.046
0.048

UT-fit 2016 Correlation Bk vs Vcb
in quest for theoretical improvement



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

2015 **inclusives** **vs** **exclusives**

	inclusives	exclusives
V_{ub}	$(4.40 \pm 0.22) \times 10^{-3}$	$(3.61 \pm 0.13) \times 10^{-3}$
V_{cb}	$(4.20 \pm 0.06) \times 10^{-2}$	$(4.00 \pm 0.11) \times 10^{-2}$

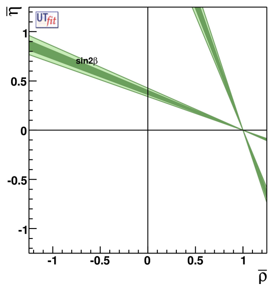
V_{ub} $(3.73 \pm 0.21) \times 10^{-3}$
V_{cb} $(4.17 \pm 0.10) \times 10^{-2}$

$\sin 2\beta_{exp} =$
0.680 ± 0.023

$\sin 2\beta_{UTfit} =$
0.740 ± 0.037
$B_K = 0.81 \pm 0.07$

$\sin 2\beta_{incl} =$
0.784 ± 0.027
$B_K = 0.74 \pm 0.05$
(2015)

$\sin 2\beta_{excl} =$
0.703 ± 0.021
$B_K = 0.93 \pm 0.07$
(2015)

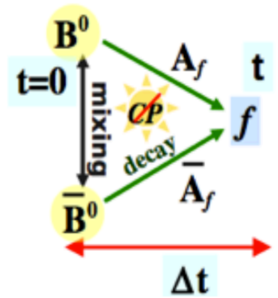


Courtesy of D. Derkach

Beta results

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

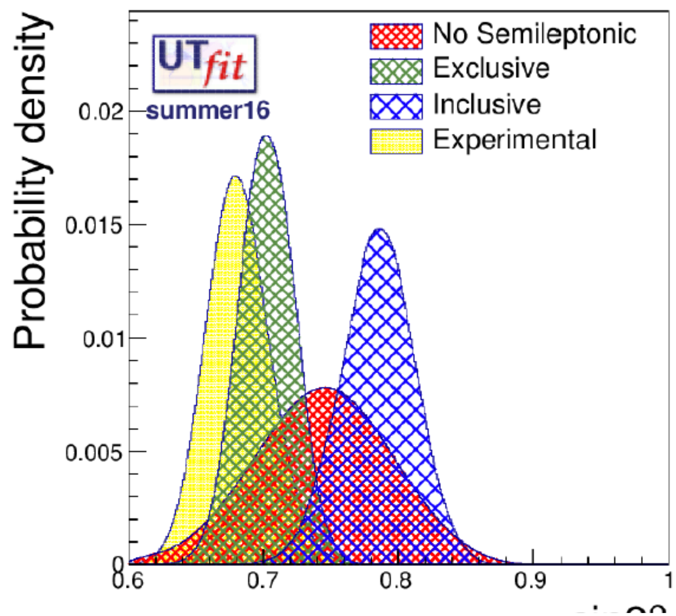
sin2β from time-dependent A_{CP} in $B \to J/\psi K$



$$a_{f_{CP}}(t) = \frac{\mathrm{Prob}(B^0(t) \to f_{CP}) - \mathrm{Prob}(\overline{B^0}(t) \to f_{CP})}{\mathrm{Prob}(\overline{B^0}(t) \to f_{CP}) + \mathrm{Prob}(B^0(t) \to f_{CP})} = C_f \cos\Delta m_d t \; + \; S_f \sin\Delta m_d t$$

The decay is dominated by a single (tree level) amplitude, thus a can be simplified:

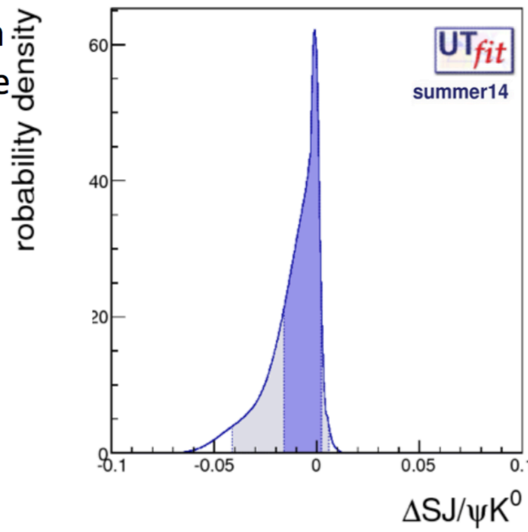
$$a_{f_{CP}}(t) = -\eta_{CP} \sin(\Delta m_d t) \sin 2\beta$$



We also analise $\bar{B}^0 \to J/\psi\pi^0$ to obtain the theoretical uncertainty related to the penguin polution in data-driven way. This gives us an additional correction:

data-driven theoretical uncertainty

$\Delta S \in [-0.02, 0.00]$ at 68% prob.



$$\sin(2\beta) = (0.680 \pm 0.023)$$

CKM Uncertainties

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

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

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

A. Buras

AJB, Buttazzo,
Girrbach-Noe,
Knegjens
1503.02693

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

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

where

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

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

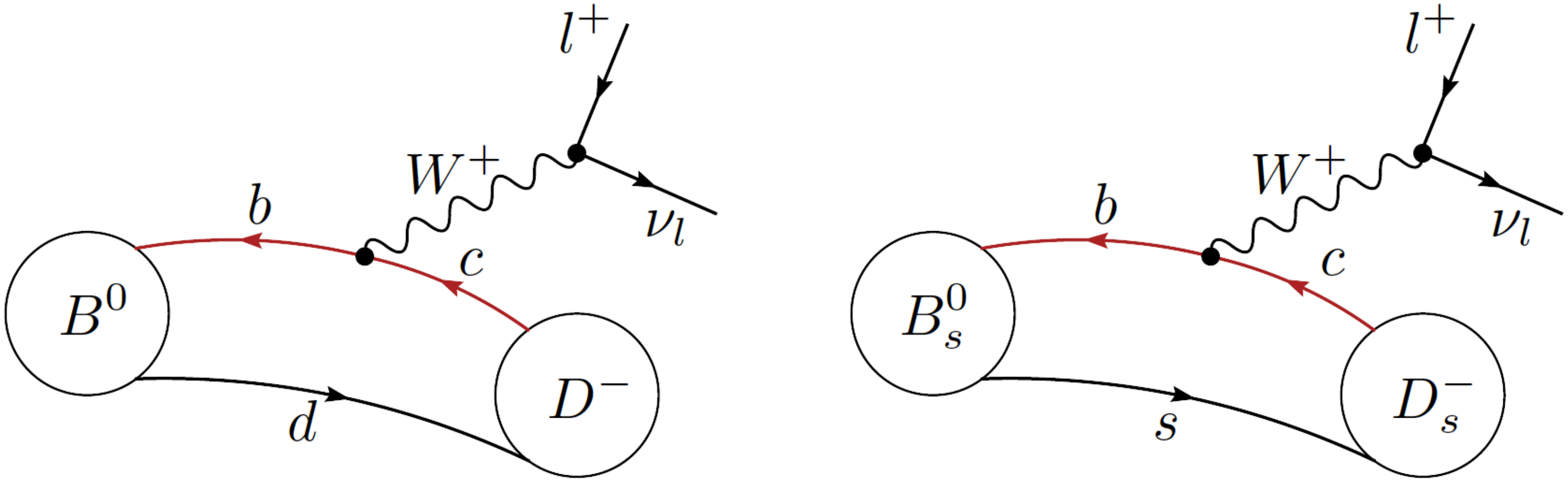
$$\eta_R = 1 - |V_{us}|\xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}\sqrt{\frac{m_{B_s}}{m_{B_d}}}\cos\beta + \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4) = 0.9825\,,$$

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: $|V_{cb}|$

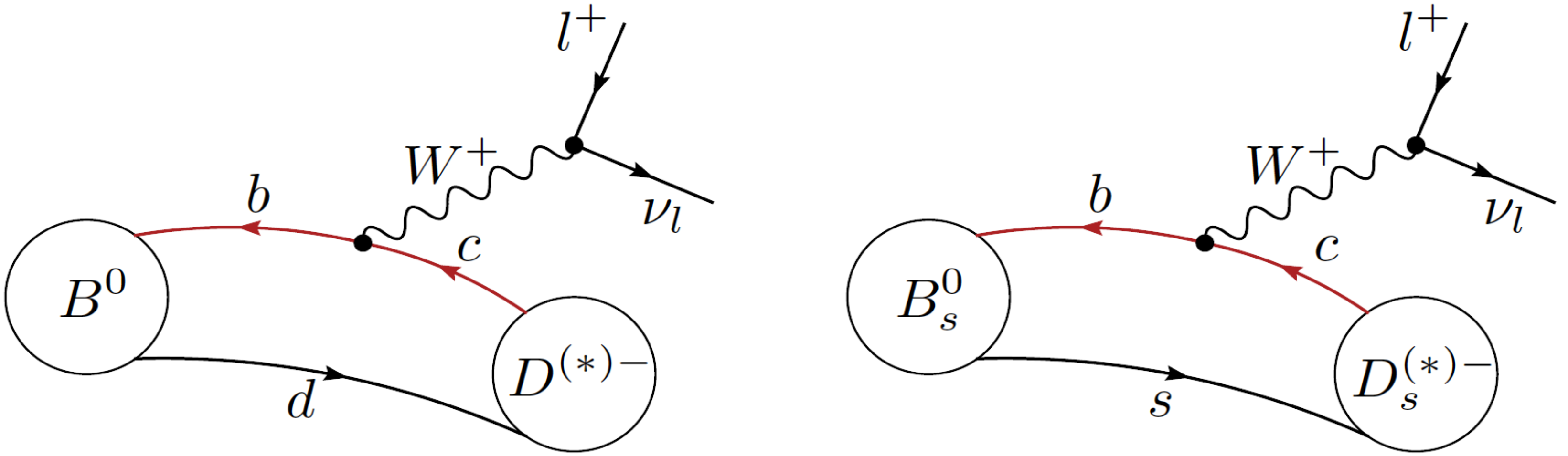


$$\frac{d\Gamma(B_{(s)} \to Pl\nu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{24\pi^3} \frac{(q^2 - m_l^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_{B_{(s)}}^2} \left[\left(1 + \frac{m_l^2}{2q^2}\right) m_{B_{(s)}}^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_l^2}{8q^2} (m_{B_{(s)}}^2 - m_P^2)^2 |f_0(q^2)|^2 \right]$$

e,μ suppressed

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

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



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

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

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

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

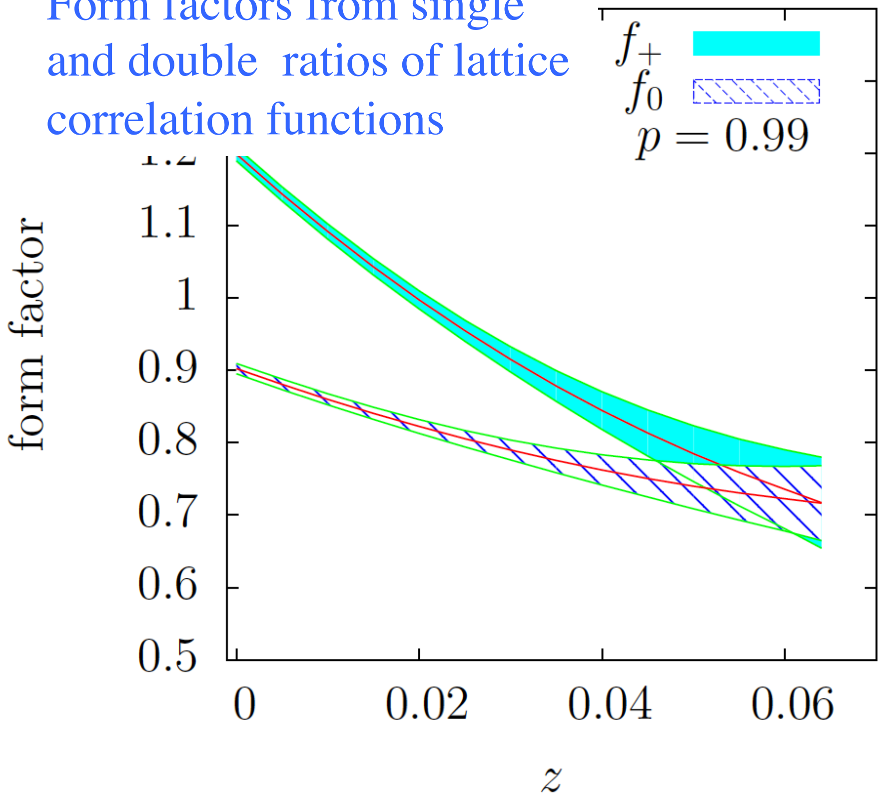
	FNAL/MILC*	FNAL/MILC	HPQCD
process	$B \to D^* \ell \nu$	$B \to D l \nu$	$B \to D l \nu$
kinematics	$w = 1$	$w \geq 1$	$w \geq 1$
ensembles	MILC	MILC	MILC
N_f	2+1	2+1	2+1
a (fm)	5/0.045 – 0.15	4/0.045 – 0.12	2/0.09, 0.12
$M_\pi^{\min}$ [MeV]	260	220	260
$M_\pi^{\min} L$	3.8	3.8	3.8
l quarks	asqtad	asqtad	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]

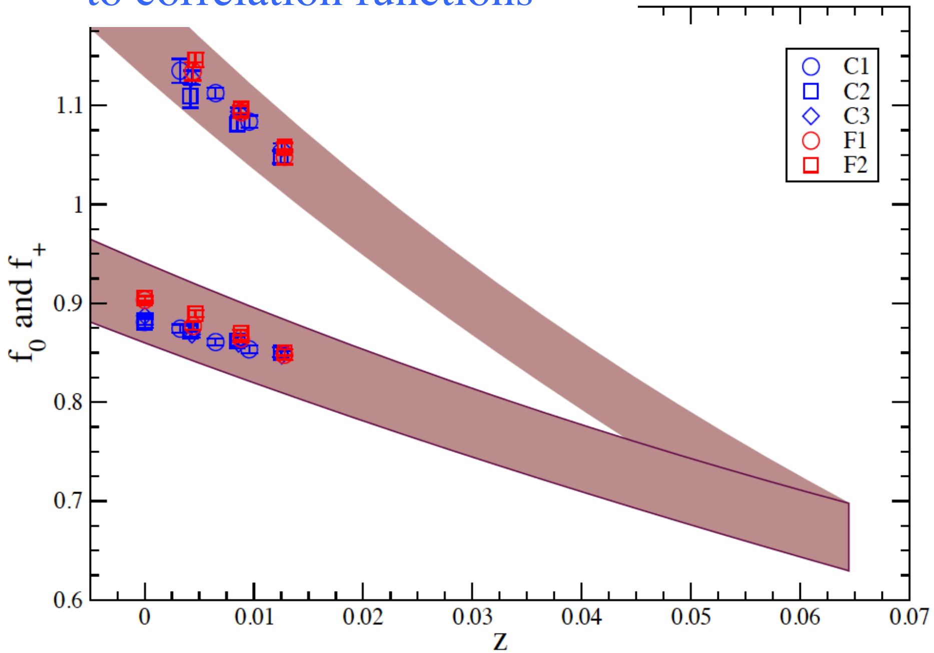
Form factors from single and double ratios of lattice correlation functions



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

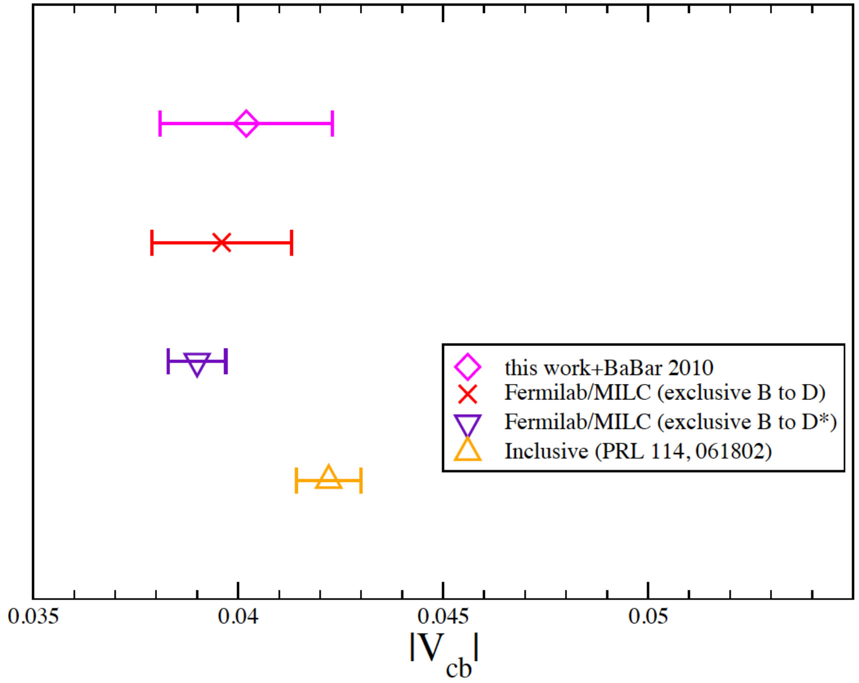
[HPQCD]

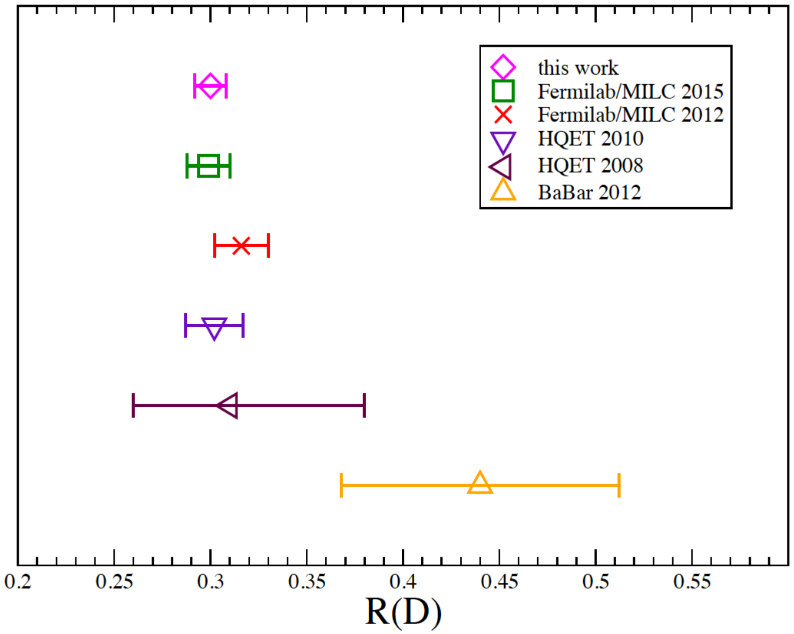
Form factors from direct fit to correlation functions



0.300(8)

HPQCD June 13 2016



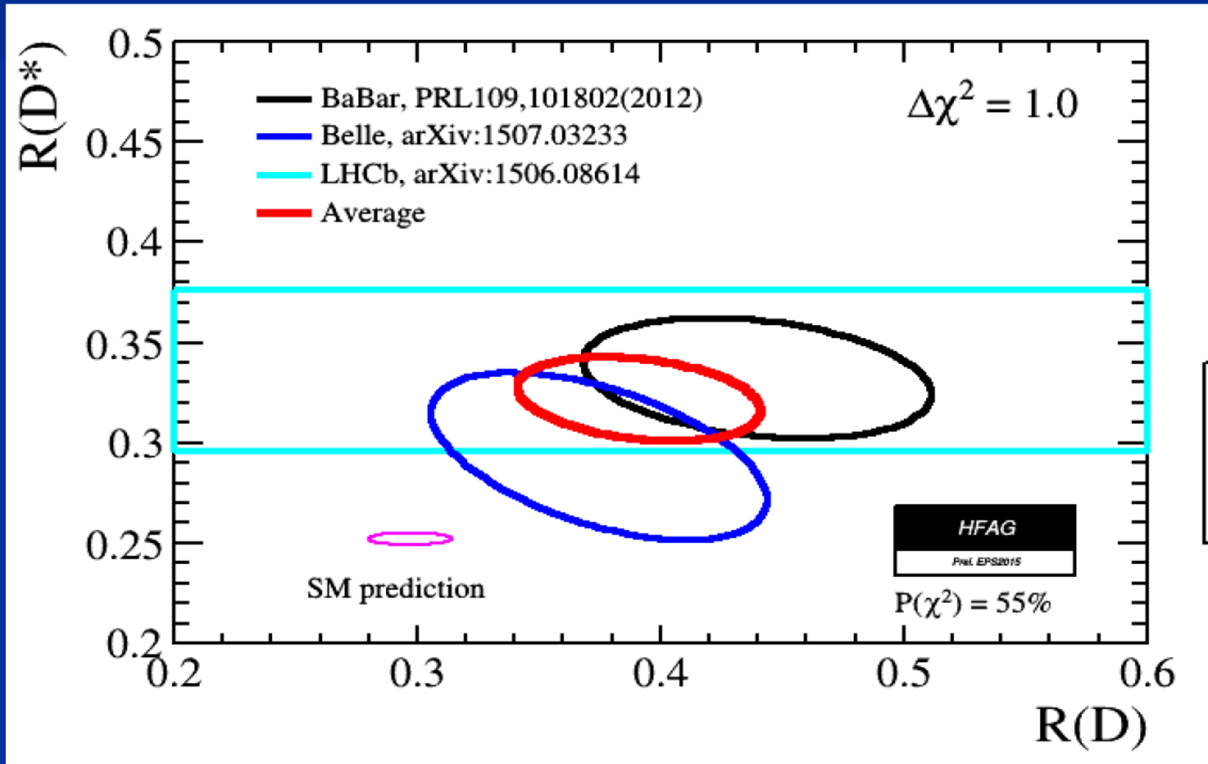


Tauonic B decays

Crivellin 2016

- Tree-level decays in the SM via W-boson

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu \big/ B \to D^{(*)}\ell\,\nu$$



➡ Combined ≈4 σ deviation

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

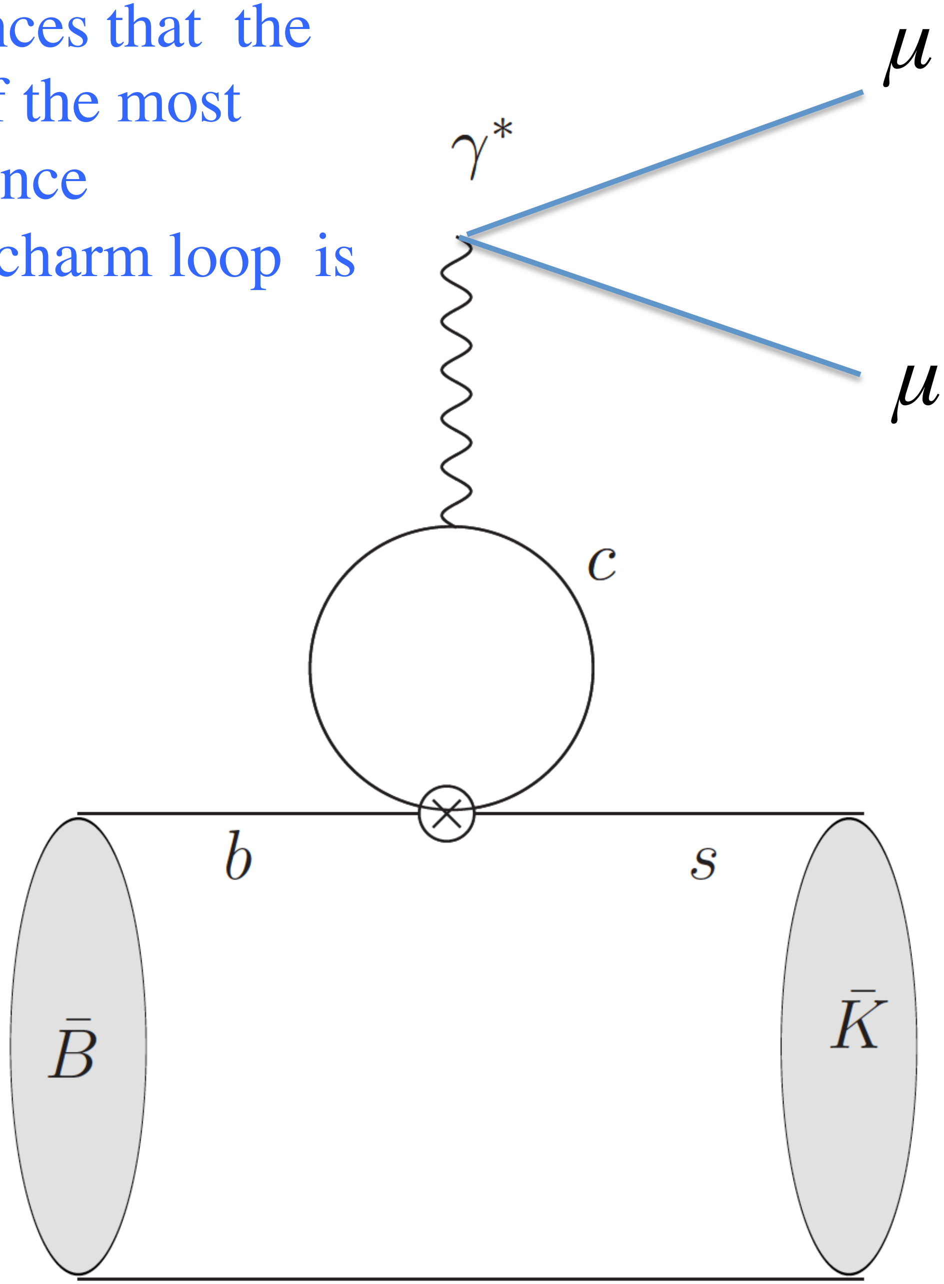
1) On the long run exclusive decays based on non-perturbative (lattice) determination of the relevant form factors will win;
2) The precision of the theoretical predictions for inclusive decays cannot be improved (are the present quoted errors reliable?);
3) Still (much) more work is needed, and different 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;
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 ?

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]

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

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

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

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***

****Not today for lack of time see talk by M. Ciuchini***

CONCLUSIONS

1) The high precision of the SM UT Analysis allows to test the SM and to search for NP at a level which is competitive with direct searches
2) CKM matrix is the dominant source of flavour mixing and CP violation $\sigma(\rho)\sim 8\ \%$ & $\sigma(\eta) \sim 3$
3) %. SM analysis shows a very good overall consistency
4) The main tensions disappeared
5) Inclusive vs exclusive semileptonic decays still need theoretical improvement and BK/Kkbar mixing !!

Thus for the time being we have to remain with a STANDARDISSIMO STANDARD MODEL but …

erc

UTfit

absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION

SISSA

International School for Advanced Studies

INFN

Istituto Nazionale di Fisica Nucleare