Lattice Flavor Physics with an eye to SuperB

An emblematic study showing the important role of Lattice QCD: the Unitarity Triangle Analysis

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The SM turns out to be very successful
in describing essentially all processes
But
It is expected to be an effective theory valid up to a cutoff scale
as it has some important limits

- The SM is a quantum theory for strong and electroweak interactions but NOT for gravitation

- There is cosmological evidence of Dark Matter (not made up of SM particles) in the Universe

- The SM CP-violation due to the phase in the Cabibbo-Kobayashi-Maskawa matrix is not enough to explain the required amount for baryogenesis

- In order to have a Higgs mass of O(100 GeV) as expected, an innatural fine-tuning is required (hierarchy problem)

- …

Moreover, the solution doesn't seem to be trivial:
the FLAVOR PROBLEM

"NP is expected at the TeV scale
(in order to solve the hierarchy problem)

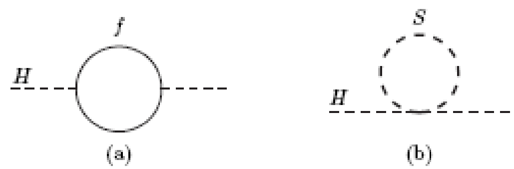


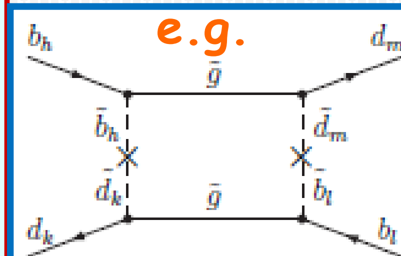
Figure 1.1: One-loop quantum corrections to the Higgs squared mass parameter m_H^2, due to (a) a Dirac fermion f, and (b) a scalar S.

but in flavor processes NP effects are not observed
(hinting for NP at higher scales)"

The flavor structure of the NP model cannot be generic

In order to reveal NP
and understand its nature
Flavor Physics has a fundamental role,
which is complementary to
the direct production of NP particles

e.g.



The study of clean
and SM suppressed
Flavor processes may
reveal NP effects

It is crucial to have hadronic uncertainties well under control

→ **Lattice QCD has a primary role**

An emblematic study showing the important role of Lattice QCD is the determination of the parameters of the **Cabibbo-Kobayashi-Maskawa mixing matrix**

Weak eigenstates Mass eigenstates

The CKM Matrix

$$\overline{U}_L \gamma^\mu V_{CKM} D_L W^+_\mu$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 3x3 unitary matrix
- 4 parameters: 3 angles and 1 phase
- The phase is responsible for CP-violation

The Wolfenstein parameterization
(A, λ, ρ, η)

up to $O(\lambda^3)$ with $\lambda \equiv \sin\theta_{Cabibbo} \approx 0.2$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

($\eta \neq 0 \leftrightarrow$ CP-violation)

($O(\lambda^5)$ corrections are required by the present accuracy)

The expansion parameter $\lambda = V_{us}$ from Lattice QCD

- Unitarity ($V_{CKM}^{\dagger} V_{CKM} = 1$) provides 9 conditions on the CKM parameters

1^{st} row: the most stringent unitarity test

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Source:	Nuclear β-dec.	Kl3,Kl2	b→u semil.
Abs. error:	$4 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$\sim 10^{-6}$

$K \to \pi l \nu$, $K \to \mu \nu$

Pseudoscalar decay constant f_K and vector form factor $f_+(q^2=0)$ from Lattice QCD

See Gilberto Colangelo's FLAG review (tomorrow)

FLAG 1011.4408

$\lvert V_{us} \rvert = 0.2254(9)$	$N_f = 2+1$
$\lvert V_{us} \rvert = 0.2251(18)$	$N_f = 2$

less than 0.5% uncert.

Isospin Breaking Effects

The lattice determinations are usually obtained in the limit of exact ISOSPIN SYMMETRY, i.e. $m_u = m_d$ and $Q_u = Q_d = 0$

Though small, isospin breaking effects are becoming important at the current level of precision in flavor physics. Their typical size is:

$Q_u \neq Q_d$: $O(\alpha_{e.m.}) \approx 1/100$ "electromagnetic"

$m_u \neq m_d$: $O[(m_d - m_u)/\Lambda_{QCD}] \approx 1/100$ "strong"

Recently, Lattice studies of (em and strong) isospin breaking effects have been performed (mainly for estimating mass splittings)

→See Taku Izubuchi's review

Last year, the strong IB corrections to f_K/f_π and to $f_+(0)$ have been calculated on the Lattice for the first time

A strategy for Lattice QCD: the $(m_d - m_u)$ expansion

Roma123 Collaboration 1110.6294 [hep-lat]
P. Dimopoulos, G. de Divitiis, R. Frezzotti, V. Lubicz, G. Martinelli, R. Petronzio, G. Rossi, F.Sanfilippo, S. Simula, N.Tantalo, C. T.

Expand the functional integral in powers of
dm =(mu-md)/2

$$\langle O \rangle \propto \int D\phi\, O\, e^{-S_0 + \delta m \hat{S}} \overset{1st}{\simeq} \int D\phi\, O\, e^{-S_0}\left(1 + \delta m\, \hat{S}\right) \simeq \langle O \rangle_0 + \delta m \langle O\, \hat{S} \rangle_0$$

Computation of the (not small) slope

$$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{QCD} = -0.0039(3)(2) \times \frac{\left[M^2_{K^0} - M^2_{K^+}\right]^{QCD}}{6.05 \times 10^3\ \mathrm{MeV}^2}$$

Very promising!
(exploratory study with modest statistics)

$$\left[\frac{f_+^{K^0\pi^-}(0) - f_+^{K\pi}(0)}{f_+^{K\pi}(0)}\right]^{QCD} = 0.85(18)(1) \times 10^{-4} \times \frac{\left[M^2_{K^0} - M^2_{K^+}\right]^{QCD}}{6.05 \times 10^3\ \mathrm{MeV}^2}$$

Preliminary,
to be extrapolated to the chiral and continuum limit,
disconnected contributions to be included

The Unitarity Triangle Analysis (UTA)

- Unitarity ($V_{CKM}^{\dagger} V_{CKM} = 1$) provides 9 conditions on the CKM parameters

- Among these it is of great phenomenological interest

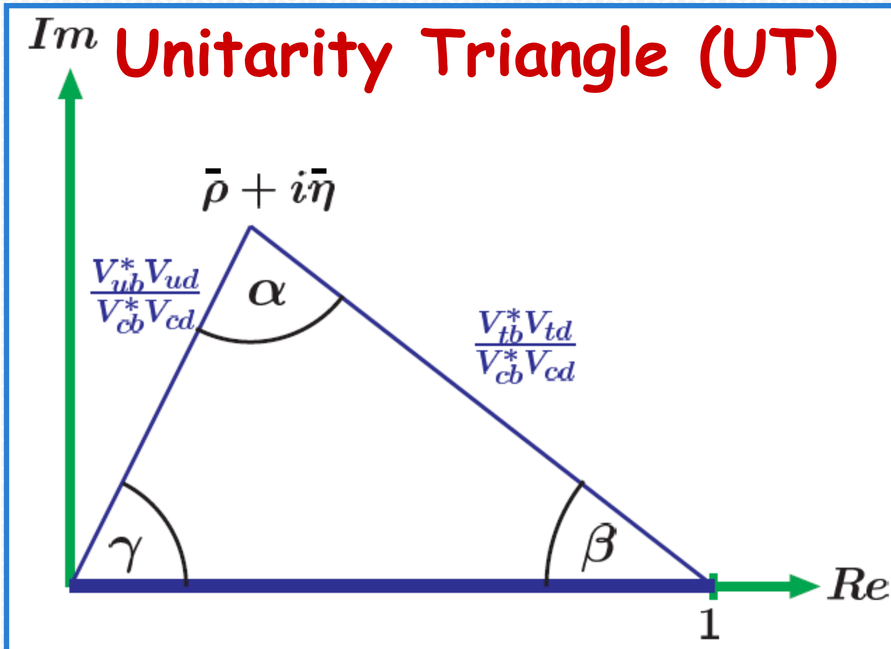
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

$$\bar{\rho} \equiv \rho\left(1 - \frac{\lambda^2}{2}\right), \qquad \bar{\eta} \equiv \eta\left(1 - \frac{\lambda^2}{2}\right)$$

It defines a triangle in the $(\bar{\rho},\bar{\eta})$-plane

(with sides of similar size, so that CP-violation is visible)

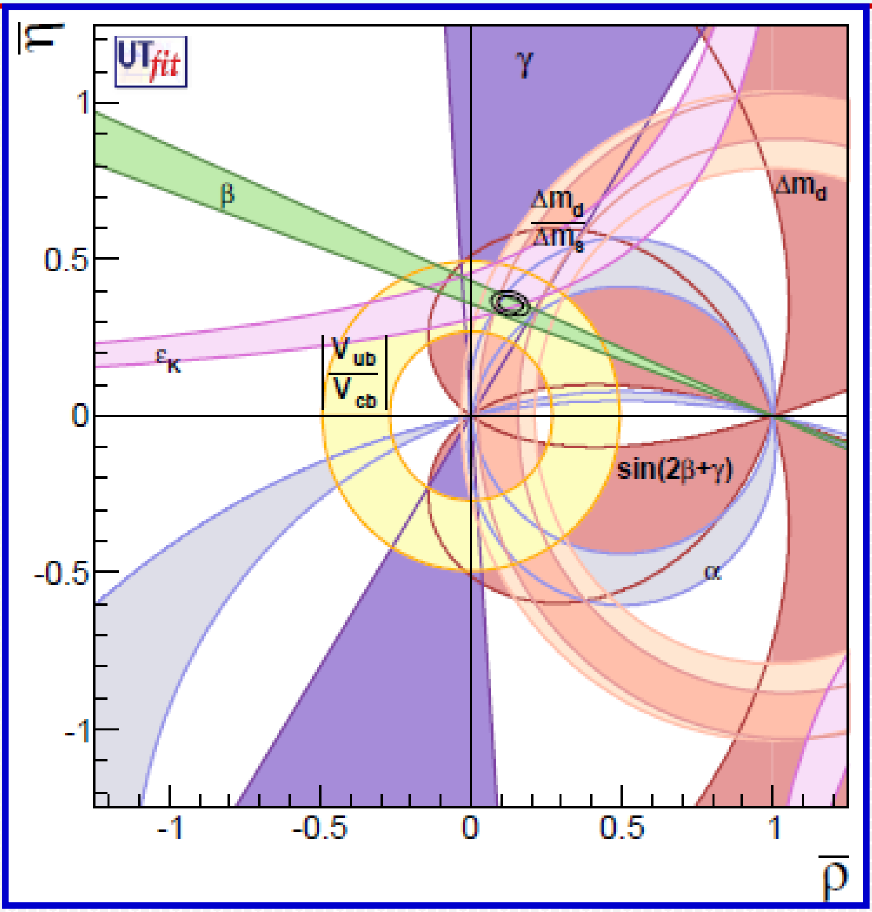
Unitarity Triangle (UT)



UTA by UTfit

www.utfit.org : Summer2012 (post-Moriond12) fit

(conservative averages for the Lattice inputs: simple (not-weighted) averages with the error representing present typical uncertainties)



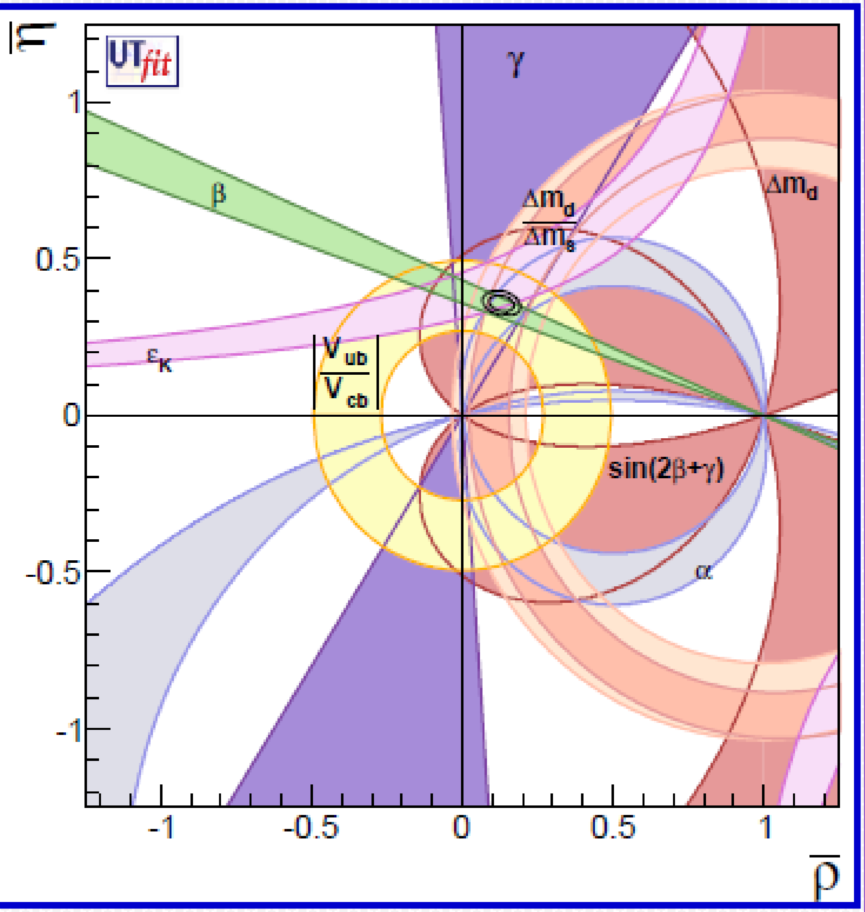
Other UT analyses exist, by: CKMfitter (http://ckmfitter.in2p3.fr/), **Laiho&Lunhgi&Van de Water** (http://krone.physik.unizh.ch/~lunghi/webpage/LatAves/page3/page3.htm), **Lunghi&Soni** (1010.6069),…

www.utfit.org

Collaboration of Theorists and Experimentalists

Adrian Bevan	Queen Mary, University of London
Marcella Bona	Queen Mary, University of London
Marco Ciuchini	INFN Sezione di Roma Tre
Denis Derkach	LAL-IN2P3 Orsay
Enrico Franco	University of Roma "La Sapienza"
Vittorio Lubicz	University of Roma Tre
Guido Martinelli	SISSA, Trieste
Fabrizio Parodi	University of Genova
Maurizio Pierini	CERN
Carlo Schiavi	University of Genova
Luca Silvestrini	INFN Sezione of Roma
Viola Sordini	IPNL-IN2P3 Lyon
Achille Stocchi	LAL-IN2P3 Orsay
Cecilia Tarantino	University of Roma Tre
Vincenzo Vagnoni	INFN Sezione of Bologna

Great Accuracy achieved in the UTA



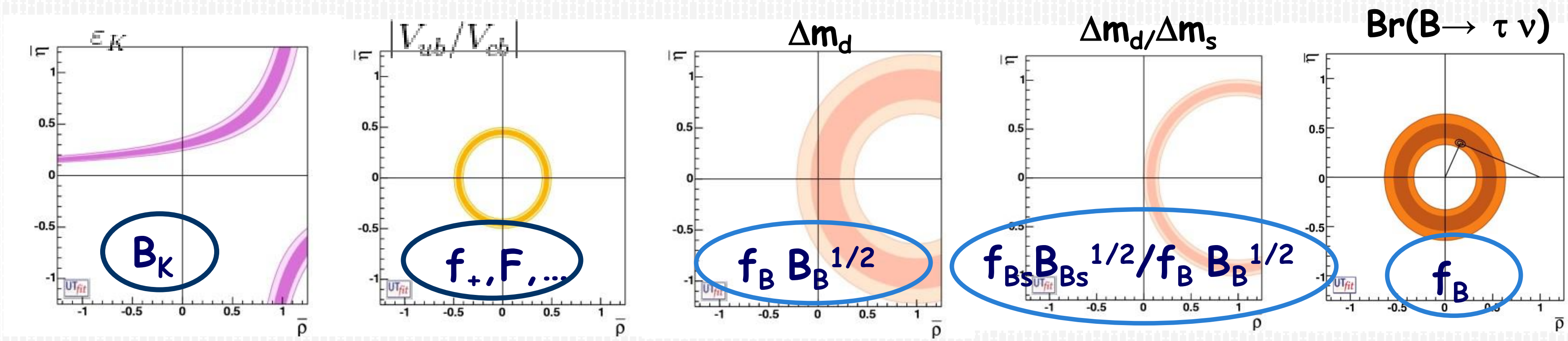
Experimental Constraints

Obs.	Accuracy
ε_K	$\approx 0.5\%$
Δm_d	$\approx 1\%$
$\left\lvert \frac{\Delta m_d}{\Delta m_s} \right\rvert$	$\approx 1\%$
$\left\lvert \frac{V_{ub}}{V_{cb}} \right\rvert$	$\approx 15\%$
$Br(B \to \tau\nu)$	$\approx 20\%$
$\sin 2\beta$	$\approx 3\%$
$\cos 2\beta$	$\approx 15\%$
α	$\approx 7\%$
γ	$\approx 14\%$
$(2\beta + \gamma)$	$\approx 50\%$

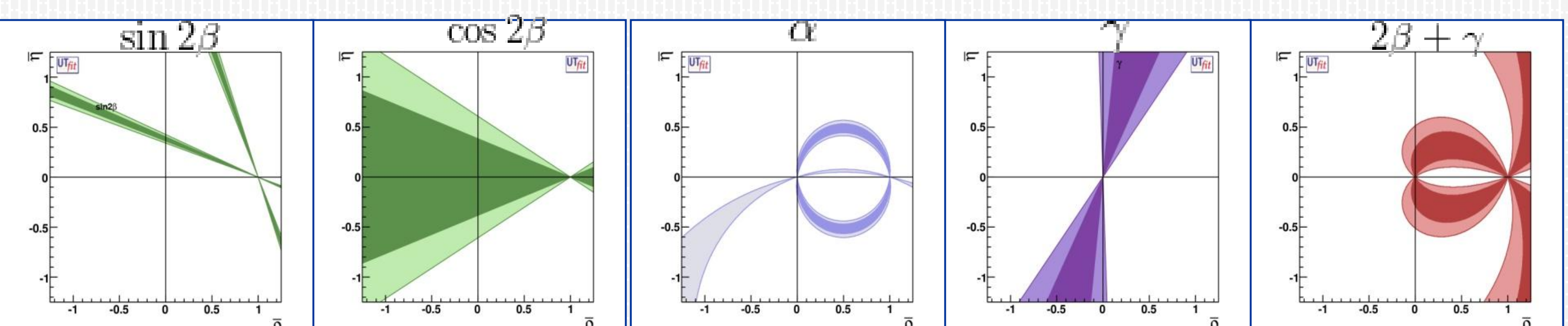
For a **significant comparison** between exp. measurements and theor. predictions, **hadronic uncertainties** must be **well under control**

THE UTA CONSTRAINTS

Relying on LATTICE calculations

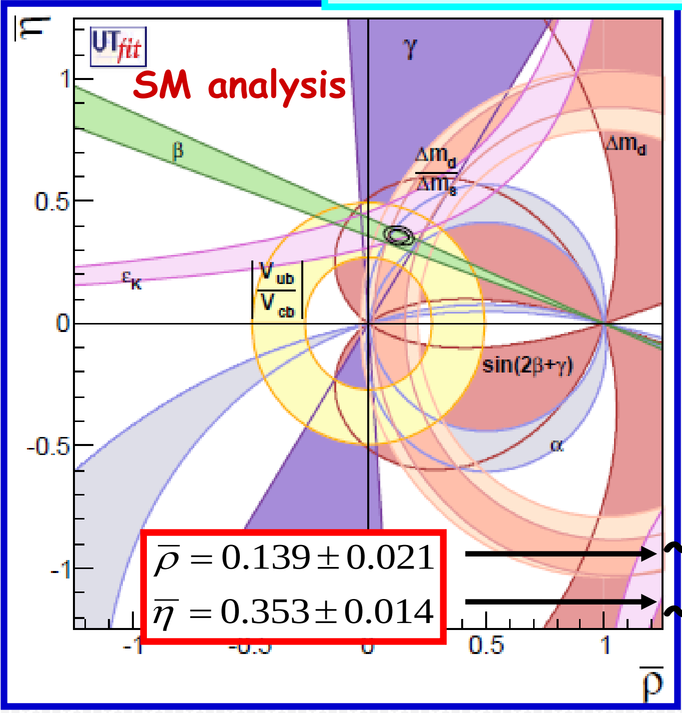


UT-ANGLES



B→J/Ψ K^0 | B→J/Ψ K^{*0} | B→ππ, ρρ | B→$D^{(*)}$K | B→$D^{(*)}$π, Dρ

The UTA within the Standard Model



$\bar\rho = 0.139 \pm 0.021$ → ~15%

$\bar\eta = 0.353 \pm 0.014$ → ~ 4%

The experimental constraints overconstrain the CKM parameters consistently

The UTA has established that the CKM matrix is the dominant source of flavor mixing and CP violation

From a closer look

From the UTA (excluding its exp. constraint)

	Prediction	Measurement	Pull
$\sin 2\beta$	0.81±0.05	0.680±0.023	2.4 ←
γ	68°±3°	76°±11°	<1
α	88°±4°	91°±6°	<1
$\lvert V_{cb}\rvert \cdot 10^3$	42.3±0.9	41.0±1.0	<1
$\lvert V_{ub}\rvert \cdot 10^3$	3.62±0.14	3.82±0.56	<1
$\hat{B}_K$	0.85±0.09	0.75±0.02	1.1 ←
$BR(B \to \tau\nu) \cdot 10^4$	0.82±0.08	1.67±0.30	-2.7 ←

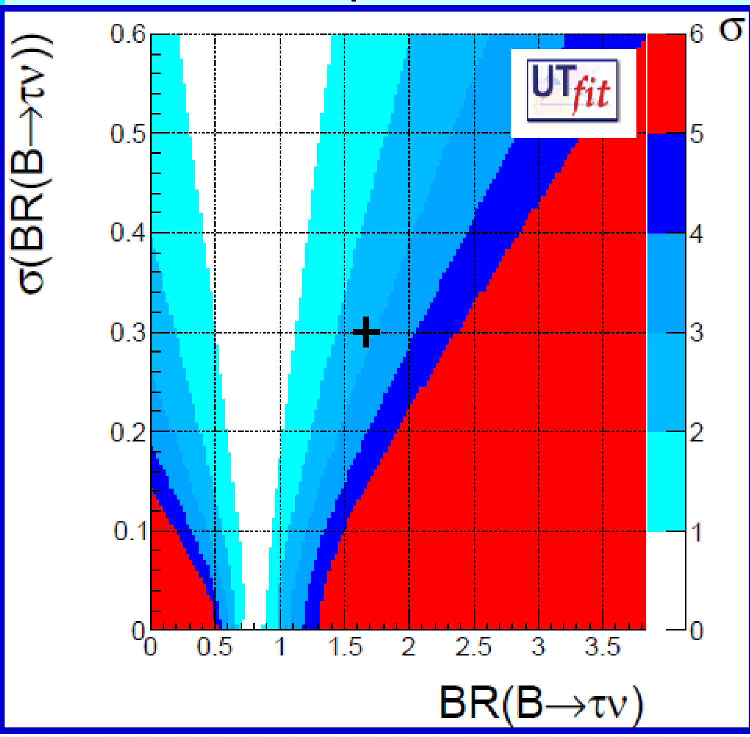
$BR(B\to\tau\nu)_{SM} = (0.82\pm0.08)\cdot10^{-4}$

[UTfit, update of 0908.3470]

turns out to be smaller by ~2.7 σ than the experimental value

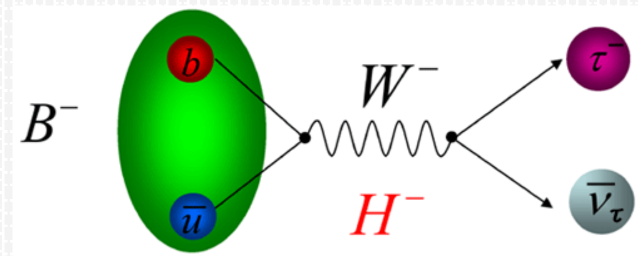
$BR(B\to\tau\nu)_{exp} = (1.67\pm0.30)\cdot10^{-4}$

$B\to\tau\nu$



Can NP explain the enhancement?

- The NP contribution, for being visible, should be at tree-level too
- It could come from a charged Higgs, as it couples significantly only to the τ



BUT

The charged Higgs can not explain the enhancement in *simple* models (due to other constraints, mainly $b\to s\gamma$)

2HDM of type II

(H_u couples to up-quarks H_d couples to down-quarks)

$$\frac{BR(B\to\tau\nu)_{2HDM}}{BR(B\to\tau\nu)_{SM}} = \left(1-\tan^2\beta\,\frac{m_B^2}{m_{H^+}^2}\right)^2$$

Suppression factor for allowed $\tan\beta/m_{H^+}$ values

More recent NP analyses have been motivated by the new (full data) BaBar results [1205.5442] for $\mathcal{R}(D^{(*)}) = \mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)$

- They exceed the SM prediction by 2.0(2.7)σ (3.4 σ when combined!)
- A charged Higgs could contribute, but in 2HDM of type II the $\tan\beta/m_{H+}$ value which is able to explain the D enhancement cannot explain the D* measurement [based on Heavy Quark Symmetry + quenched form factors Kamenik&Mescia08 and Fajfer&Kamenik&Nisandzic12]

More elaborated NP models could provide an explanation for the BaBar results and for Br($B \to \tau \nu$):

- 2HDM of type III (with H_u and H_d coupling to both up- and down-quarks) with flavor violation in the up sector [A.Crivellin, C.Greub, A.Kokulu, 1206.2634]

- Right-right vector and right-left scalar currents (effective field theory approach) that could exist in some 2HDM, leptoquarks or composite quarks and leptons Models (with non trivial flavor structure) [S.Fajfer, J.Kamenik, I.Nisandzic, J.Zupan, 1206.1872]

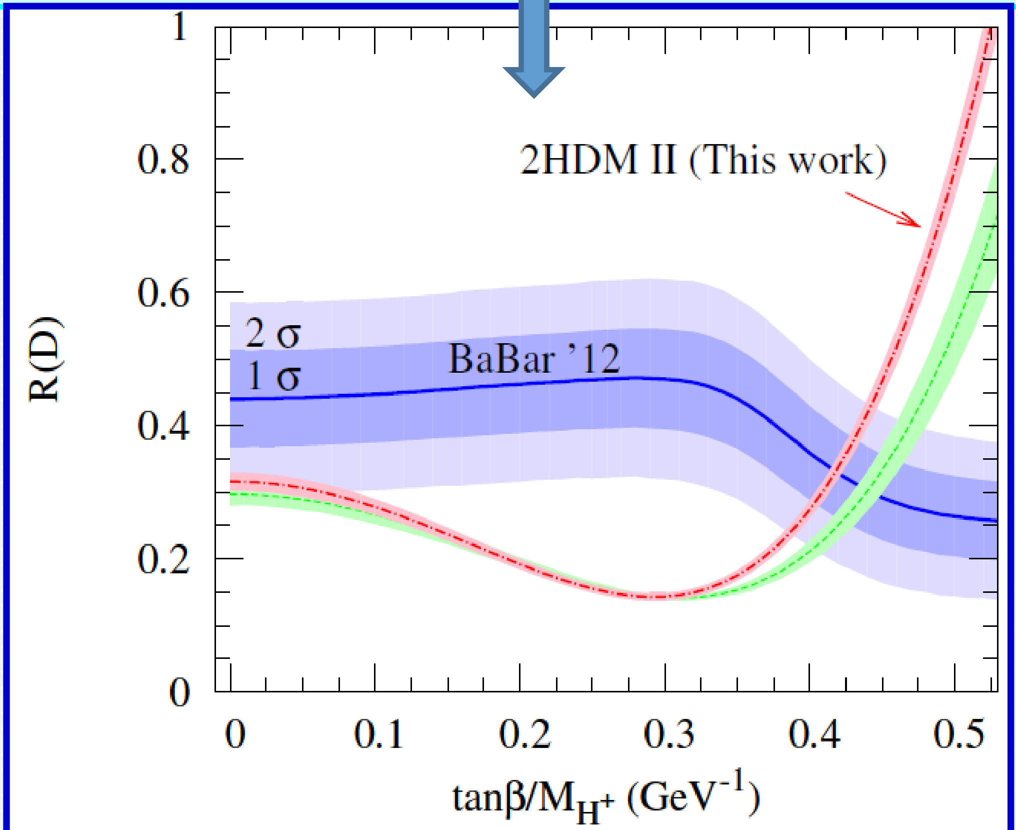
Last Friday: two papers with more accurate theoretical predictions for $Br(B \to D\,\tau\,\nu)$

No helicity suppression
both f_+ and f_0 are relevant

Becirevic&Kosnik&Tayduganov 1206.4977: estimate with minimal theory input (from the Lattice (quenched and unquenched) f_+/f_0 and $f_+(q^2 > 8\ GeV^2)$) ⟹ R(D)=0.310(20)

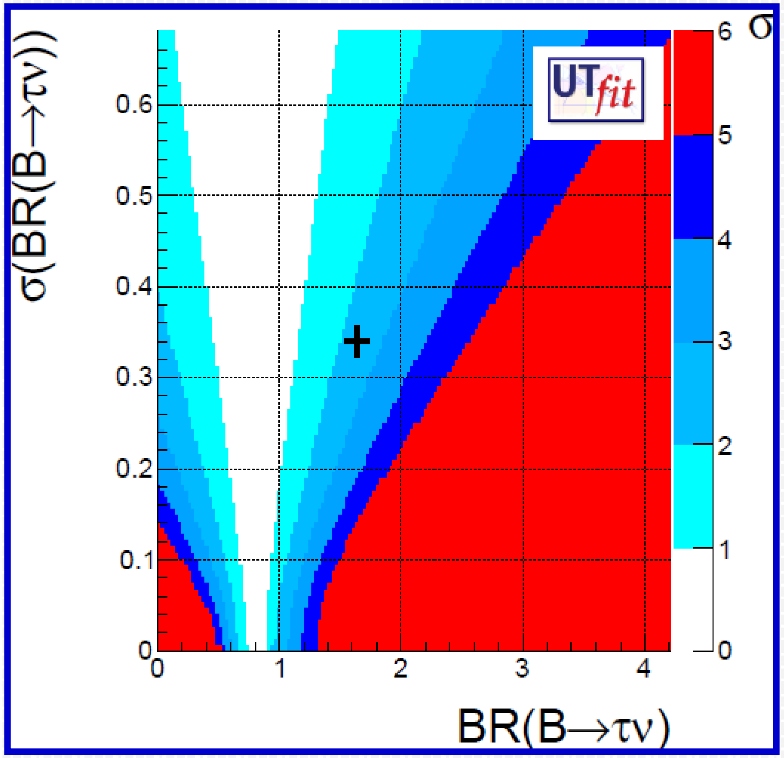
1.8 and 1.7σ from BaBar

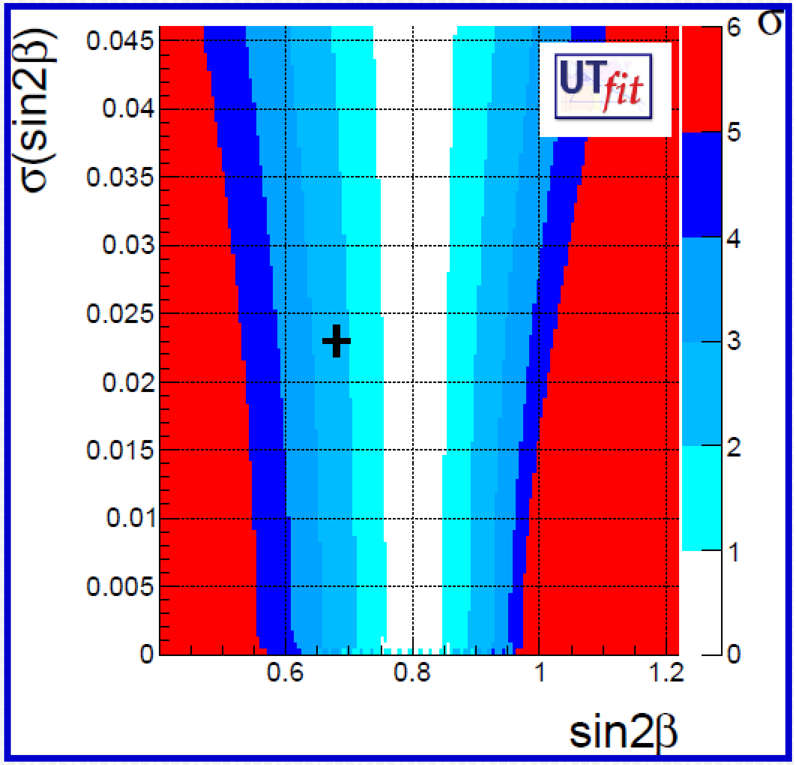
FNAL/MILC 1206.4992: using $f_0(q^2)$ from Lattice (unquenched FNAL/MILC 1202.6346)
⟹ R(D)=0.316(14), and a different constraint on $\tan\beta/m_{H+}$ (see A.Kronfeld's talk)



Looking for an explanation for the B→ τ ν excess within the Standard Model

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

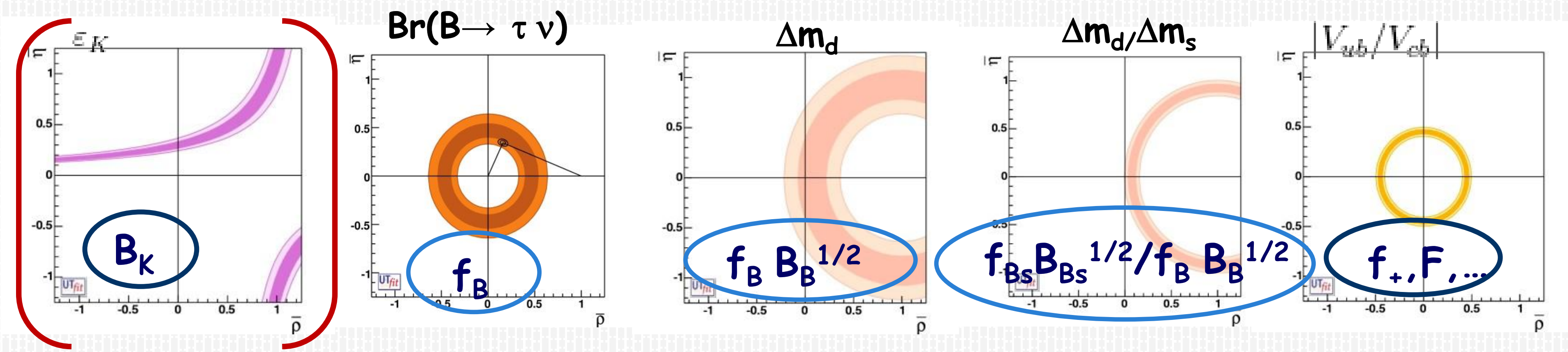




- $BR(B\to \tau\nu)_{exp}$ prefers a large value for $|V_{ub}|$ (f_B well under control)
- But a shift in the central value of $|V_{ub}|$ would not solve the (2.4σ) β tension

⇒ the debate on V_{ub} (exclusive vs inclusive determination) is not enough to explain all

B-physics hadronic parameters on the Lattice: fundamental ingredient in the UTA and more in general for Flavor Physics



- B-physics on the lattice has the difficulty of large discretization effects of $O(a^*m_b)$ ⟺ the physical b-quark mass (≈4 GeV) cannot be directly simulated on present (a^{-1} ≤4 GeV) lattices

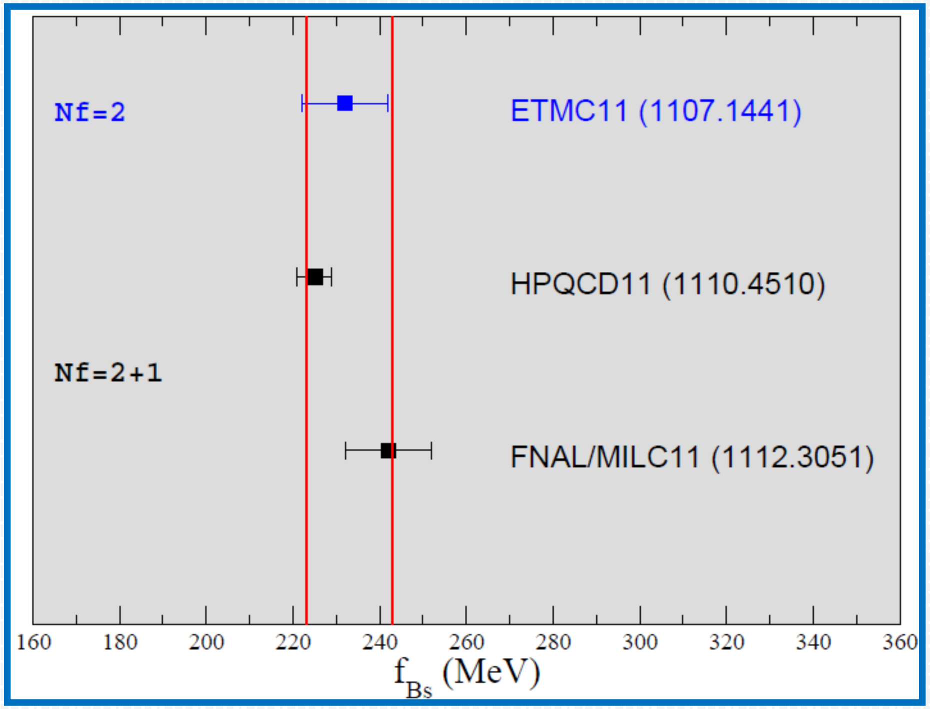
- Several approaches have been investigated and used so far, either with relativistic heavy quark or effective theory based

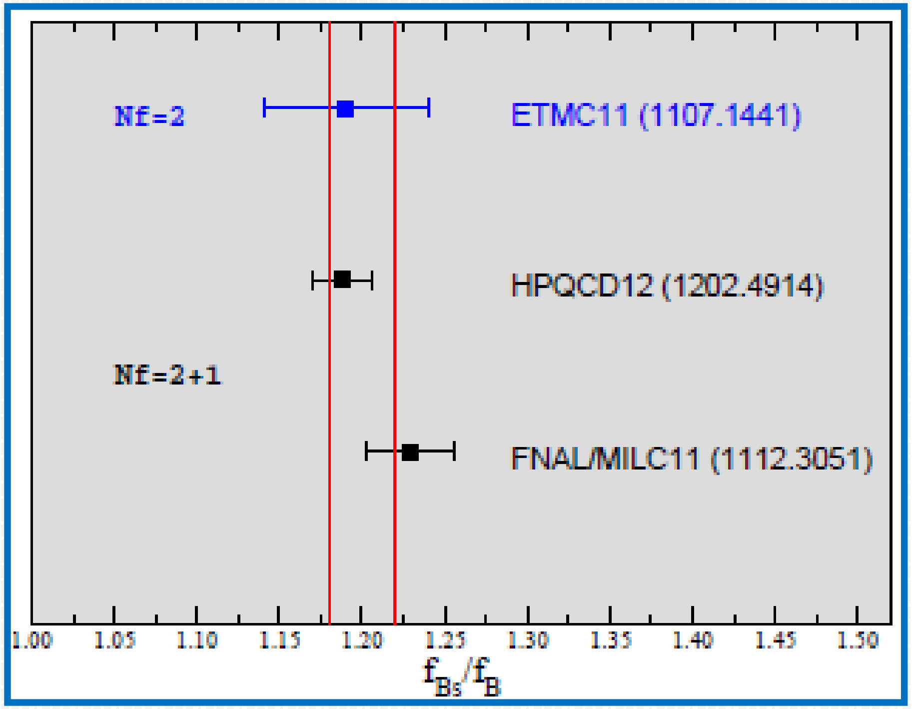
- RELATIVISTIC QCD with simulated quark masses in the charm region (and higher)+some suitable *technique:*
  - Step-scaling [Tor Vergata], matching several lattice simulations at different volumes and up to physical b-quark mass (at small volume)
  - Ratio method [ETMC], suitable ratios with exactly known static limit
  - HISQ [HPQCD], leading discretization terms of $O(\alpha_s a^2 m_h^2)$, $O(a^4 m_h^4)$ + small taste changing

- EFFECTIVE THEORY BASED:
  - HQET [Alpha], static quark limit (expansion in Λ_{QCD}/m_h)
  - NRQCD [HPQCD], expansion in the velocity v
  - FermiLab [FNAL/MILC], removing key discretization errors by tuning 3 parameters (from exp. input + pert. theory)
  - Non-perturbatively tuned relativistic heavy-quark action [RBC/UKQCD], (NEW! 1206.2554,see C.Lehner's talk), a variant of the FermiLab approach with fully non-pert. tuning of the 3 parameters from the *clean* $B_s^{(*)}$ system (exp. values of m_{Bs} and m_{Bs^*} and continuum energy-momentum relation for B_s)

Decay constants: f_{Bs} and f_{Bs}/f_B

(f_{Bs} has a smooth chiral limit, in the ratio some uncertainties cancel)





UTA Lattice inputs are (conservative) simple averages of unquenched (N_f=2 and 2+1) results:

f_{Bs}= 233(10) MeV

f_{Bs}/f_B= 1.20(2)

→ f_B=194(9) MeV

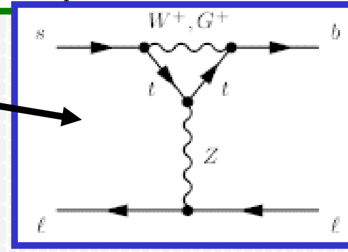
The HPQCD11 result for f_{Bs} is very accurate (2%), thanks to heavy HISQ quark
[see H.Na's talk]

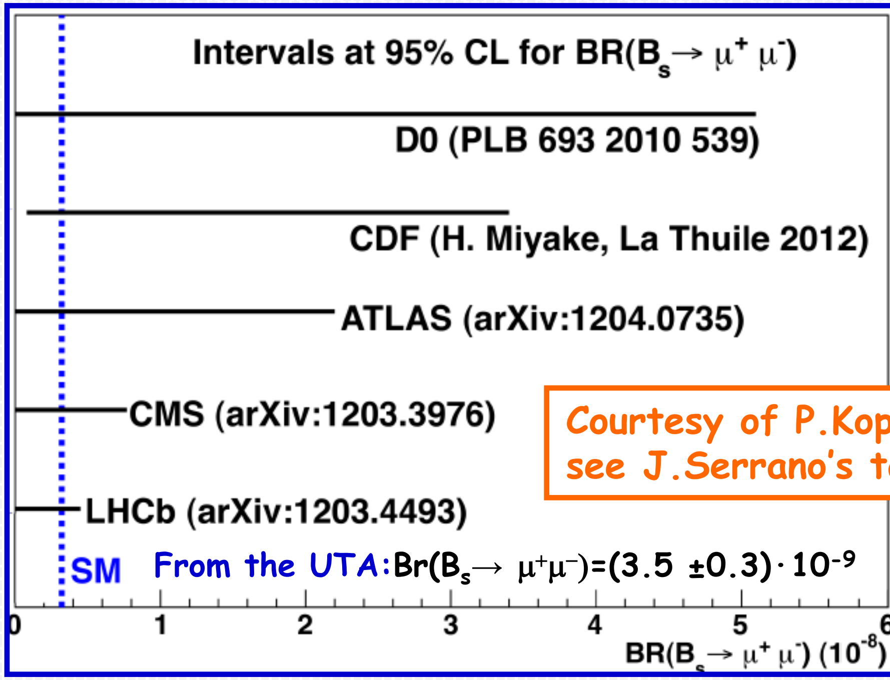
New accurate analyses are in progress
[see E.Neil's(FNAL/MILC), O.Witzel's(RBC/UKQCD) and A.Shindler's(ETMC) talks and F.Bernardoni's(Alpha) poster]

The pseudoscalar decay constant f_{B_s} also enters the important rare decays: $B_s \to \mu^+\mu^-$

$$Br(B_s \to l^+l^-) = \tau(B_s)\frac{G_F^2}{\pi}\left(\frac{\alpha}{4\pi \sin^2 \Theta_W}\right)^2 F_{B_s}^2 m_l^2 m_{B_s}\sqrt{1-4\frac{m_l^2}{m_{B_s}^2}}|V_{tb}^* V_{ts}|^2 Y^2(x_t)$$

- Highly sensitive to NP (loop FCNC: Z-penguin dominated)
- Theoretically clean (purely leptonic)





Courtesy of P.Koppenburg [LHCb], see J.Serrano's talk for LHCb updates

- Experimentally the fragmentation fraction f_s/f_d of $b \to B_s X$ is a fundamental ingredient
- Through factorization f_s/f_d can be related to the ratio of semileptonic form factors for $B^0 \to D^+ l^- \bar{\nu}$ and $B_s^0 \to D_s^+ l^- \bar{\nu}$
- FNAL/MILC has computed it (Nf=2+1, two lattice spacings), finding:

  f_s/f_d=0.28(4) [1202.6346] (see A.Kronfeld's talk)

  in good agreement with LHCb 1111.2357 (0.27(2)) and PDG (0.29(2)) and 12% higher than a previous QCD sum rule estimate (P.Blasi et al.93)

B-parameters: B_{Bs} and B_{Bs}/B_B

UTA Lattice inputs coincide with the N_f=2+1 HPQCD09 results [0902.1815]:

$$\hat{B}_{Bs} = 1.33(6)$$
$$B_{Bs}/B_B = 1.05(7)$$

Very recently FNAL/MILC12 has obtained a very well compatible result [1205.7013]:

$B_{Bs}/B_B = 1.06(11)$ [combining ξ and $f_{Bs}/f_B \rightarrow$ overestimated error]

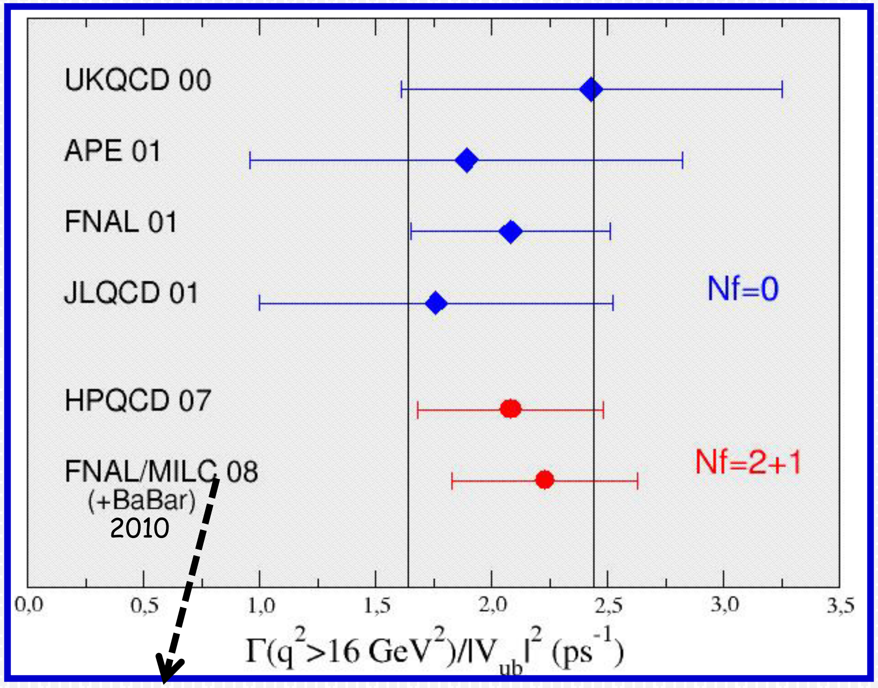
New Lattice analyses are in progress:
ETMC, with Nf=2, see N.Carrasco Vela's talk

FNAL/MILC, see E.Freeland's talk
(direct computation of B_{Bs}/B and first unquenched results for the B-parameters of the complete NP basis)

V_{ub}: exclusive (Lattice form factor) vs inclusive (OPE)

$B \to \pi l \nu$

Theoretically clean Lattice calculations but only two *modern* results exist so far



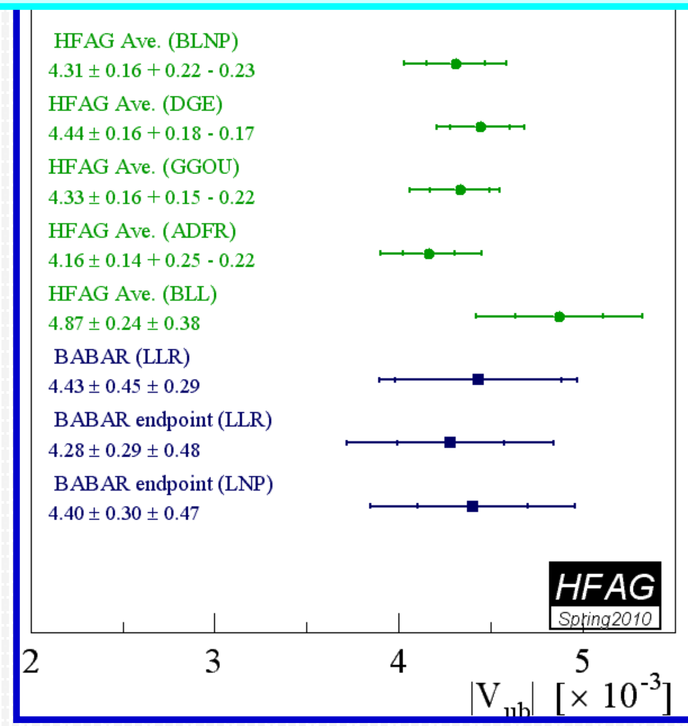
Combining it with Belle 2010 instead of Babar, V_{ub} is found to be 15% higher

$|V_{ub}|_{excl}$ = $(32.8 \pm 3.1) \cdot 10^{-4}$

2.6 σ

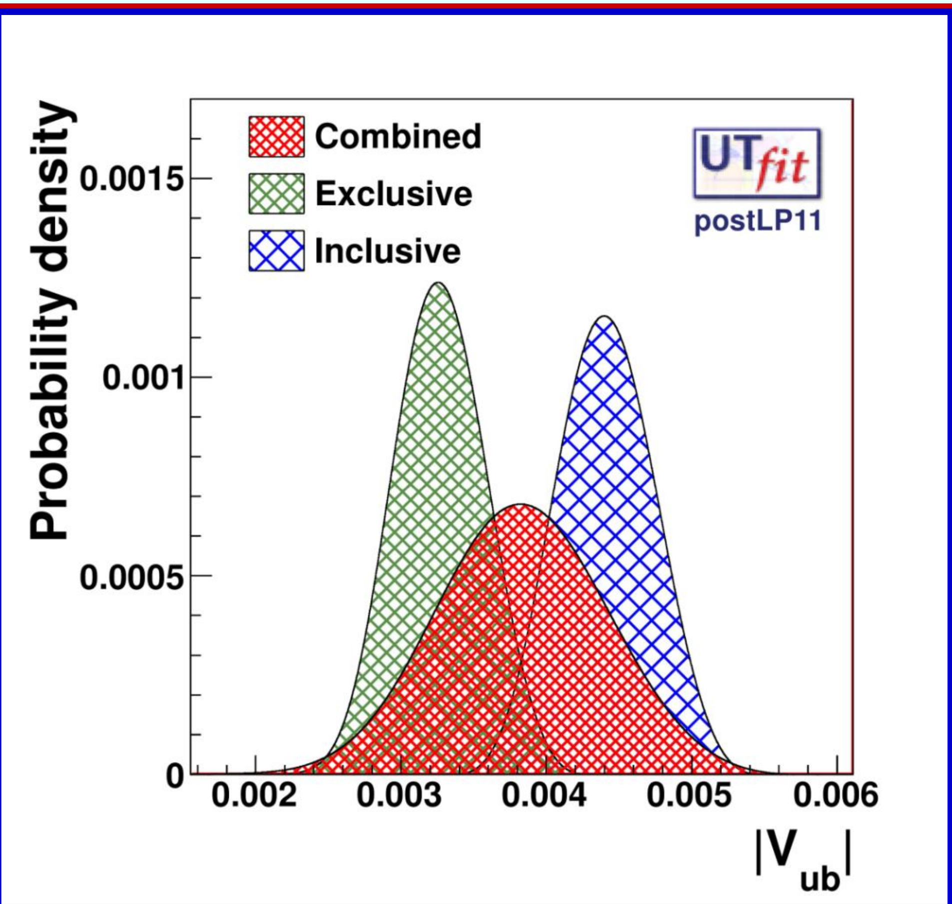
$B \to X_u l \nu$

Experimental cuts introduce some model dependence in treating long-distance contributions at threshold



$|V_{ub}|_{incl}$ = $(44.1 \pm 2.8) \cdot 10^{-4}$

Conservative combination for the UTA



- $|V_{ub}|_{input}$ = $(38.2 \pm 5.6)\cdot 10^{-4}$
- The UTA output is close to the (lower) exclusive result:

$$|V_{ub}|_{UTA} = (36.2 \pm 1.4)\cdot 10^{-4}$$

- Further Lattice calculations are looked forward and are in progress

[see talks by T.Kawanai(RBC/UKQCD),F.Bernardoni(Alpha) and C.Bouchard(HPQCD)]

or under investigation

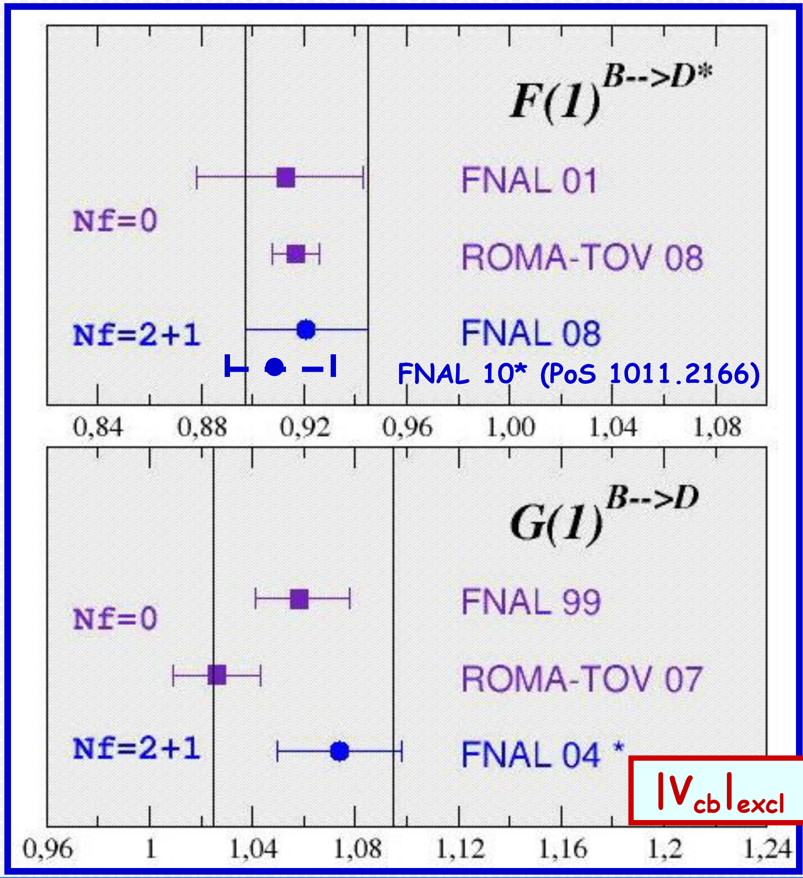
[see Steven Gottlieb's talk (FNAL/MILC)]

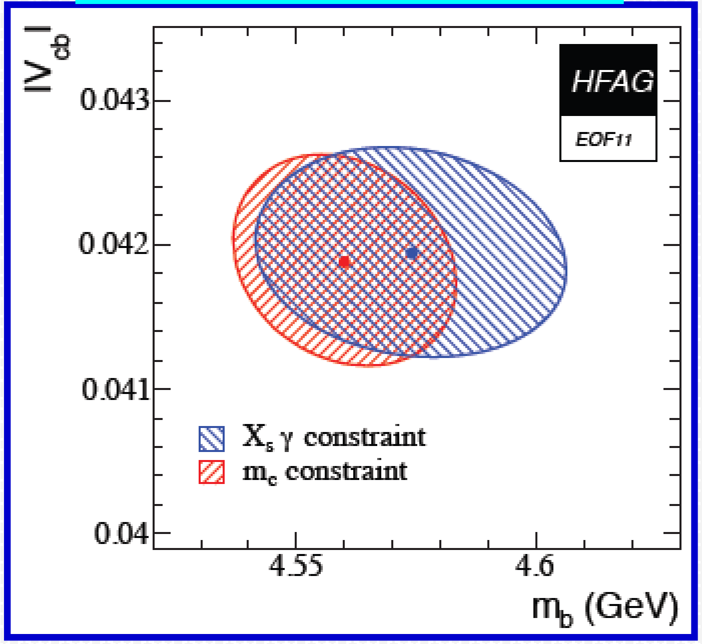
V_{cb}:

exclusive (Lattice form factors) vs inclusive (OPE based global fit)

Theoretically clean Lattice calculations but only one *modern* result exists so far

Some model dependence affects the global fit





$|V_{cb}|_{excl} = (39.0 \pm 0.9)\cdot 10^{-3}$ ⟺ 2.4 σ ⟺ $|V_{cb}|_{incl} = (41.9 \pm 0.8)\cdot 10^{-3}$

- Conservative combination for the UTA: $|V_{cb}|_{input} = (41.0 \pm 1.0)\cdot 10^{-3}$
- The UTA output is close to the (higher) inclusive result: $|V_{cb}|_{UTA} = (42.3 \pm 0.9)\cdot 10^{-3}$
- Further Lattice calculations are looked forward and are in progress

  [see C.De Tar's talk (FNAL/MILC)]

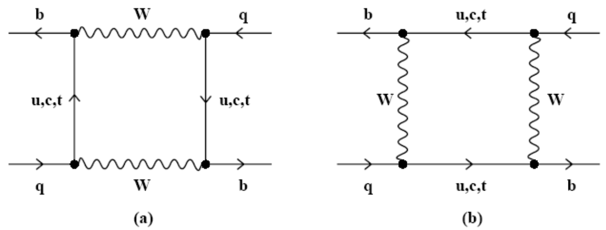
The UTA beyond the Standard Model

Update of UTfit 0909.5065

Model-independent UTA: bounds on deviations from the SM (+CKM)

- Parametrize generic NP in DF=2 processes
- Use all available experimental info
- Fit simultaneously the CKM and NP parameters

Neutral mesons are not eigenstates of the Weak Interactions:



⇒ "particle-antiparticle oscillations":

highly sensitive to NP

Results for the B_s mixing amplitude:

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} \left(\Delta m_{q/K}\right)^{SM}$$

$C_{B_q/\Delta m_K}$ =1 in SM

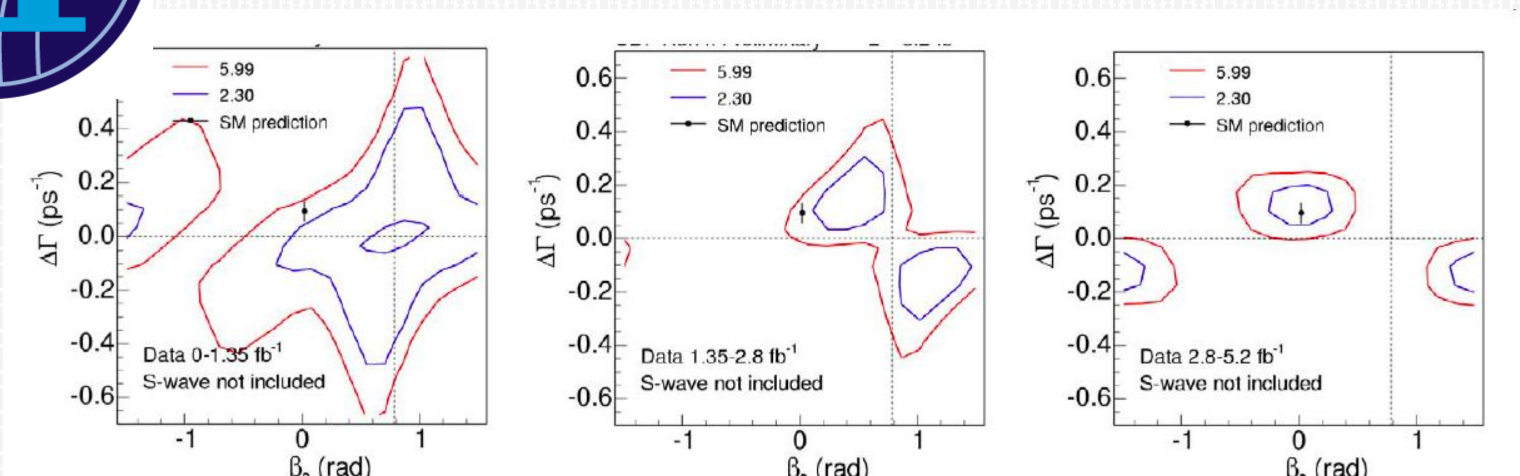
$$A_{CP}^{B_s \to J/\psi\phi} \sim \sin 2\left(-\beta_s + \phi_{B_s}\right)$$

ϕ_{B_s} =0 in SM

In 2009, CDF and D0 results for ϕ_{Bs}

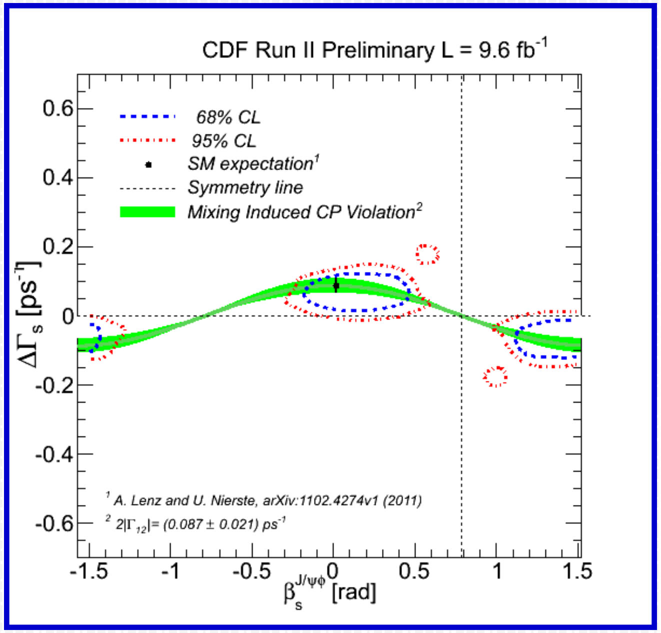
More than 2.5σ deviation from the SM!

Summer 2011: Bad news for NP in B_s!
New CDF data do not show any deviation

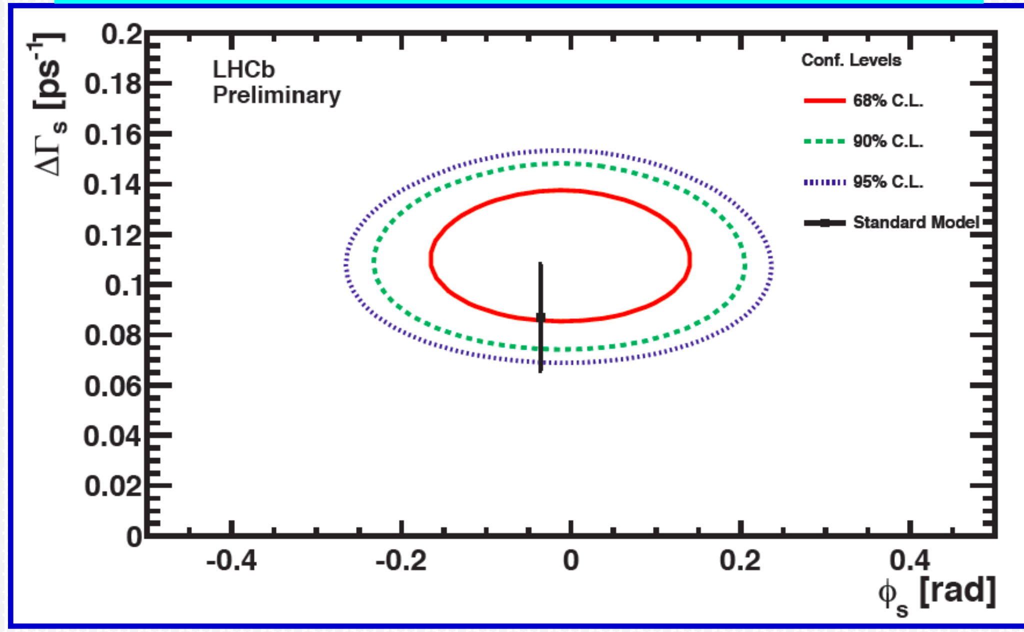


2007 | added in 2008 | added in 2010

CDF: full data analysis (compatibility with the SM within less than 1 σ)



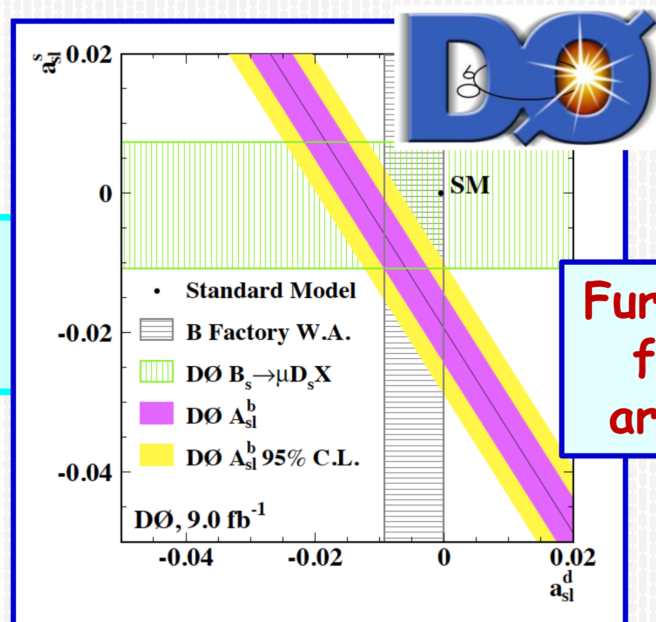
LHCb: finds compatibility as well



Still, the dimuon charge asymmetry (measured by D0) $a_{\mu\mu}$ points to a large value of ϕ_{Bs}

$$a_{sl}^b \equiv \frac{\Gamma(\overline{B}_q \to B_q \to \mu^+ X) - \Gamma(B_q \to \overline{B}_q \to \mu^- X)}{\Gamma(\overline{B}_q \to B_q \to \mu^+ X) + \Gamma(B_q \to \overline{B}_q \to \mu^- X)}$$

$$A_{sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = a_{sl}^b$$



Further confirmations from experiments are looked forward!

Flavour Physics is highly sensitive to NP: Bounds on the NP scale Λ

e.g. for K-$\bar{K}$

$$\mathcal{H}_{\rm eff}^{\Delta S=2} = \sum_{i=1}^{5} C_i \mathcal{O}_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{\mathcal{O}}_i$$

SM/MFV →

$$\mathcal{O}_1 = [\bar{s}^\alpha \gamma_\mu (1-\gamma_5) d^\alpha][\bar{s}^\beta \gamma_\mu (1-\gamma_5) d^\beta]$$

Beyond SM/MFV:

$$\mathcal{O}_2 = [\bar{s}^\alpha (1-\gamma_5) d^\alpha][\bar{s}^\beta (1-\gamma_5) d^\beta]$$
$$\mathcal{O}_3 = [\bar{s}^\alpha (1-\gamma_5) d^\beta][\bar{s}^\beta (1-\gamma_5) d^\alpha]$$
$$\mathcal{O}_4 = [\bar{s}^\alpha (1-\gamma_5) d^\alpha][\bar{s}^\beta (1+\gamma_5) d^\beta]$$
$$\mathcal{O}_5 = [\bar{s}^\alpha (1-\gamma_5) d^\beta][\bar{s}^\beta (1+\gamma_5) d^\alpha]$$
$$\tilde{\mathcal{O}}_1 = [\bar{s}^\alpha \gamma_\mu (1+\gamma_5) d^\alpha][\bar{s}^\beta \gamma_\mu (1+\gamma_5) d^\beta]$$
$$\tilde{\mathcal{O}}_2 = [\bar{s}^\alpha (1+\gamma_5) d^\alpha][\bar{s}^\beta (1+\gamma_5) d^\beta]$$
$$\tilde{\mathcal{O}}_3 = [\bar{s}^\alpha (1+\gamma_5) d^\beta][\bar{s}^\beta (1+\gamma_5) d^\alpha]$$

The high scale coefficients $C_i(\Lambda)$ can be extracted from the data (switching on one operator per time)

$$C_i(\Lambda) = \frac{L F_i}{\Lambda^2} \Rightarrow \Lambda = \sqrt{\frac{L F_i}{C_i(\Lambda)}}$$

Tree/strong inter. NP: $L \sim 1$

Perturbative NP: $L \sim \alpha_s^2, \alpha_W^2$

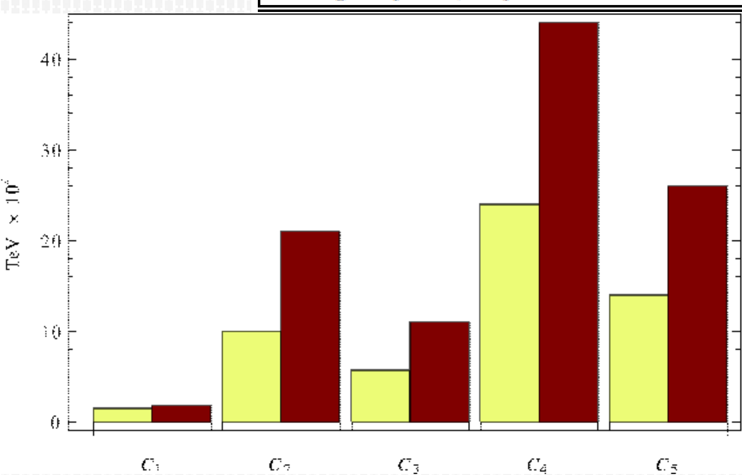
MFV	next-to-MFV	generic
- $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$	- $\lvert F_i \rvert \sim F_{SM}$	- $\lvert F_i \rvert \sim 1$
- $F_{i \neq 1} = 0$	- arbitrary phases	- arbitrary phases

Updated lower bound on the NP scale w.r.t. 0707.0636

From (the most constraining) $K-\bar{K}$ sector,
with the unquenched Lattice results for the NP B-parameters,
by P. Dimopoulos et al. [ETMC, with N_f=2, three lattice spacings]
(forthcoming paper, see N.Carrasco Vela's talk)

Generic Flavor Structure
Tree/strong inter. NP: L~1

		95% allowed range (GeV^{-2})	Lower limit on Λ (TeV)
NEW	Im C_1^K	$[-2.7, 3.0] \cdot 10^{-15}$	$1.8 \cdot 10^4$
	Im C_2^K	$[-2.3, 2.2] \cdot 10^{-17}$	$21 \cdot 10^4$
	Im C_3^K	$[-8.0, 8.4] \cdot 10^{-17}$	$11 \cdot 10^4$
	Im C_4^K	$[-5.0, 5.1] \cdot 10^{-18}$	$44 \cdot 10^4$
	Im C_5^K	$[-1.5, 1.5] \cdot 10^{-17}$	$26 \cdot 10^4$
OLD	Im C_1^K	$[-4.4, 2.8] \cdot 10^{-15}$	$1.5 \cdot 10^4$
	Im C_2^K	$[-5.1, 9.3] \cdot 10^{-17}$	$10 \cdot 10^4$
	Im C_3^K	$[-3.1, 1.7] \cdot 10^{-16}$	$5.7 \cdot 10^4$
	Im C_4^K	$[-1.8, 0.9] \cdot 10^{-17}$	$24 \cdot 10^4$
	Im C_5^K	$[-5.2, 2.8] \cdot 10^{-17}$	$14 \cdot 10^4$



$$R_i = \frac{\langle \bar{K}^0 | O_i | K^0 \rangle}{\langle \bar{K}^0 | O_1 | K^0 \rangle}, \quad i = 2,\ldots,5 \quad (\overline{MS} \text{ at } 2\,\text{GeV})$$

ETMC

R_2	R_3	R_4	R_5
-14.7(06)	6.2(04)	25.7(11)	6.8(05)

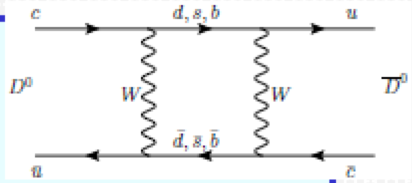
NEW (this week) results by RBC/UKQCD exist
(N_f=2+1 domain-wall and ONE lattice spacing)
1206.5737 (see N.Garron's talk)

RBC/UKQCD

R_2	R_3	R_4	R_5
-16.1(17)	7.7(08)	28.0(29)	9.0(09)

Preliminary results have been also obtained by SWME
(see H.J Kim's talk and S.Sharpe's talk on staggered ChPT)

$D-\bar{D}$ mixing: B_D parameters



- At variance with K and B systems, the first evidence for $D-\bar{D}$ mixing is quite recent, 2007 (BaBar & Belle)

- It is sensitive to a different sector of New Physics (NP) with respect to K and B, being the charm an up-type quark

- $D-\bar{D}$ mixing is affected by large long-distance effects (internal d and s quarks) which dominate over the short-distance contribution

Donoghue&Uraltsev 1986,
Colangelo et al. 1990
Bigi et al. 2000,
Falk et al. 2001-2004

- Only order of magnitude estimates exist for the long-distance contributions and are at the level of the experimental constraints, preventing from revealing and unambiguous sign of NP

- Still, barring accidental cancellations between SM and NP contributions, significant constraints can be put on the NP parameter space

Update of the D-$\bar{\text{D}}$ mixing analysis of M.Ciuchini et al. hep-ph/0703204

PRELIMINARY

http://www.utfit.org/UTfit/DDbarMixing

$$A = A_{SM} + A_{NP} e^{i\phi_{NP}}$$

With A_{SM}, due to large long-distance uncertainties, taken as flatly distributed in [-0.01,0.01] ps^{-1}

By using the experimental results

Observable	Value	Correlation Coeff.					Reference
y_{CP}	$(0.866 \pm 0.155)\%$						[2, 17–25]
A_Γ	$(0.022 \pm 0.161)\%$						[2, 20, 23–26]
x	$(0.811 \pm 0.334)\%$	1	-0.007	-0.255α	0.216		[3]
y	$(0.309 \pm 0.281)\%$	-0.007	1	-0.019α	-0.280		[3]
$\lvert q/p\rvert$	$(0.95 \pm 0.22 \pm 0.10)\%$	-0.255α	-0.019α	1	-0.128 α		[3]
ϕ	$(-0.035 \pm 0.19 \pm 0.09)$	0.216	-0.280	-0.128 α	1		[3]
x	$(0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$	1	0.0615				[27]
y	$(0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$	0.0615	1				[27]
R_M	$(0.0130 \pm 0.0269)\%$						[28–32]
$(x'_+)_{K\pi\pi^0}$	$(2.48 \pm 0.59 \pm 0.39)\%$	1	-0.69				[33]
$(y'_+)_{K\pi\pi^0}$	$(-0.07 \pm 0.65 \pm 0.50)\%$	-0.69	1				[33]
$(x'_-)_{K\pi\pi^0}$	$(3.50 \pm 0.78 \pm 0.65)\%$	1	-0.66				[33]
$(y'_-)_{K\pi\pi^0}$	$(-0.82 \pm 0.68 \pm 0.41)\%$	-0.66	1				[33]
x^2	$(0.1549 \pm 0.2223)\%$	1	-0.6217	-0.00224	0.3698	0.01567	[34]
y	$(2.997 \pm 2.293)\%$	-0.6217	1	0.00414	-0.5756	-0.0243	[34]
R_D	$(0.4118 \pm 0.0948)\%$	-0.00224	0.00414	1	0.0035	0.00978	[34]
$2\sqrt{R_D}\cos\delta_{K\pi}$	$(12.64 \pm 2.86)\%$	0.3698	-0.5756	0.0035	1	0.0471	[34]
$2\sqrt{R_D}\sin\delta_{K\pi}$	$(-0.5242 \pm 6.426)\%$	0.01567	-0.0243	0.00978	0.0471	1	[34]
R_D	$(0.3030 \pm 0.0189)\%$	1	0.77	-0.87			[1]
$(x'_+)^2_{K\pi}$	$(-0.024 \pm 0.052)\%$	0.77	1	-0.94			[1]
$(y'_+)_{K\pi}$	$(0.98 \pm 0.78)\%$	-0.87	-0.94	1			[1]
A_D	$(-2.1 \pm 5.4)\%$	1	0.77	-0.87			[1]
$(x'_-)^2_{K\pi}$	$(-0.020 \pm 0.050)\%$	0.77	1	-0.94			[1]
$(y'_-)_{K\pi}$	$(0.96 \pm 0.75)\%$	-0.87	-0.94	1			[1]
R_D	$(0.364 \pm 0.018)\%$	1	0.655	-0.834			[35]
$(x'_+)^2_{K\pi}$	$(0.032 \pm 0.037)\%$	0.655	1	-0.909			[35]
$(y'_+)_{K\pi}$	$(-0.12 \pm 0.58)\%$	-0.834	-0.909	1			[35]
A_D	$(2.3 \pm 4.7)\%$	1	0.655	-0.834			[35]
$(x'_-)^2_{K\pi}$	$(0.006 \pm 0.034)\%$	0.655	1	-0.909			[35]
$(y'_-)_{K\pi}$	$(0.20 \pm 0.54)\%$	-0.834	-0.909	1			[35]
CP asymmetry	Value			$\Delta\langle t\rangle/\tau_{D^0}$			Reference
$A_{CP}(D^0 \to K^+K^-)$	$(-0.24 \pm 0.24)\%$						[36, 37]
$A_{CP}(D^0 \to \pi^+\pi^-)$	$(0.11 \pm 0.39)\%$						[36, 37]
ΔA_{CP}	$(-0.82 \pm 0.21 \pm 0.11)\%$			$(9.83 \pm 0.22 \pm 0.19)\%$			[9]
ΔA_{CP}	$(-0.62 \pm 0.21 \pm 0.10)\%$			$(26 \pm 1)\%$			[10]

TABLE I. Experimental data used in the analysis of D mixing, from ref. [38]. $\alpha = (1 + |q/p|)^2/2$ and $\Delta A_{CP} = A_{C}$[…] $K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$. Asymmetric errors have been symmetrized. We do not use measurements that do not […] CP violation in mixing, except for ref. [27].[a]

[1] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 98, 211802 (2007), arXiv:hep-ex/0703020.
[2] M. Staric et al. (Belle Collaboration), Phys.Rev.Lett. 98, 211803 (2007), arXiv:hep-ex/0703036 [hep-ex].
[3] K. Abe et al. (BELLE), Phys. Rev. Lett. 99, 131803 (2007), arXiv:0704.1000 [hep-ex].
[9] R. Aaij et al. (LHCb Collaboration), (2011), arXiv:1112.0938 [hep-ex].
[10] CDF public note 10784 (2012).
[17] J. Link et al. (FOCUS Collaboration), Phys.Lett. B485, 62 (2000), arXiv:hep-ex/0004034 [hep-ex].
[18] S. Csorna et al. (CLEO Collaboration), Phys.Rev. D65, 092001 (2002), arXiv:hep-ex/0111024 [hep-ex]
[19] K. Abe et al. (Belle Collaboration), Phys.Rev.Lett. 88, 162001 (2002), arXiv:hep-ex/0111026 [hep-ex].
[20] B. Aubert et al. (BABAR Collaboration), Phys.Rev. D78, 011105 (2008), arXiv:0712.2249 [hep-ex].
[21] B. Aubert et al. (BABAR Collaboration), Phys.Rev. D80, 071103 (2009), arXiv:0908.0761 [hep-ex].
[22] A. Zupanc et al. (Belle Collaboration), Phys.Rev. D80, 052006 (2009), arXiv:0905.4185 [hep-ex].
[23] R. Aaij et al. (LHCb Collaboration), (2011), arXiv:1112.4698 [hep-ex].
[24] M. Staric (Belle Collaboration), talk presented at Charm 2012 (2012).
[25] N. Neri (BaBar Collaboration), talk presented at Charm 2012 (2012).
[26] E. Aitala et al. (E791 Collaboration), Phys.Rev.Lett. 83, 32 (1999), arXiv:hep-ex/9903012 [hep-ex].
[27] P. del Amo Sanchez et al. (The BABAR Collaboration), Phys. Rev. Lett. 105, 081803 (2010), arXiv:1[…]
[28] E. Aitala et al. (E791 Collaboration), Phys.Rev.Lett. 77, 2384 (1996), arXiv:hep-ex/9606016 [hep-ex].
[32] U. Bitenc et al. (BELLE Collaboration), Phys.Rev. D77, 112003 (2008), arXiv:0802.2952 [hep-ex].
[33] B. Aubert et al. (BABAR Collaboration), Phys.Rev.Lett. 103, 211801 (2009), arXiv:0807.4544 [hep-ex].
[34] W. Sun (CLEO-C Collaboration), talk presented at Physics in Collision 2010 (2010).
[35] L. Zhang et al. (BELLE Collaboration), Phys.Rev.Lett. 96, 151801 (2006), arXiv:hep-ex/0601029 [hep-ex].
[36] B. Aubert et al. (BaBar Collaboration), Phys.Rev.Lett. 100, 061803 (2008), arXiv:0709.2715 [hep-ex].
[37] M. Staric et al. (Belle Collaboration), Phys.Lett. B670, 190 (2008), arXiv:0807.0148 [hep-ex].

By using the Lattice results for the B_D-parameters strong constraints can be put on the parameter space of some NP models

NEW Preliminary unquenched (N_f=2) results by ETMC

[N. Carrasco, P. Dimopoulos, R. Frezzotti, V. Gimenez, V. Lubicz, G. Martinelli, F. Mescia, M. Papinutto, G.C. Rossi, S. Simula, C. T., A. Vladikas]

(see N.Carrasco Vela's talk)

First accurate results:
unquenched, improved operators, non-perturbative renormalization, continuum limit, chiral extrapolation with $m_\pi \geq 260$ MeV

	$\overline{MS}$ (2GeV)
B_1	0.77(04)
B_2	0.73(05)
B_3	1.37(12)
B_4	0.96(05)
B_5	1.22(14)

In the MSSM with a generic Flavour Structure

It is useful to work in the SuperCKM basis where gluino couplings are flavour diagonal and to expand (non-diagonal) sfermion mass matrices

Mass Insertion Approximation

$$M^2_{\tilde{u}} = \begin{pmatrix} (m^2_U)_{LL} & (m^2_U)_{LR} \\ (m^2_U)^{\dagger}_{LR} & (m^2_U)_{RR} \end{pmatrix}$$

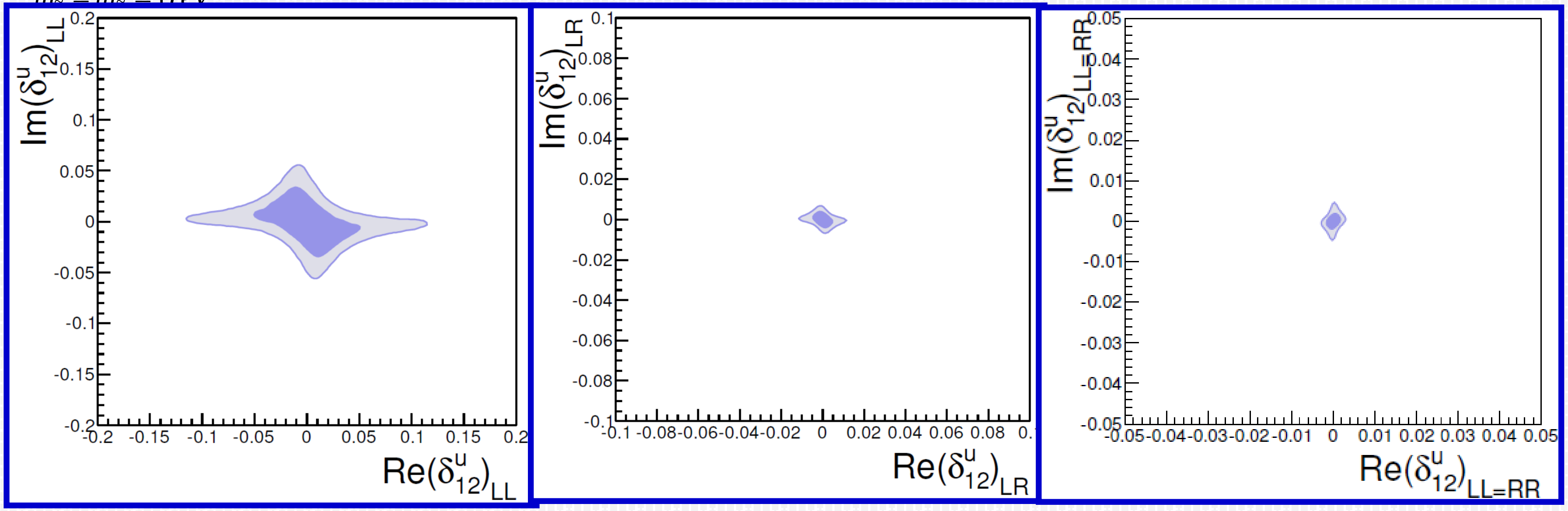
3x3 non-diagonal flavour matrices

expanded in small off-diagonal entries:

e.g., $(\delta^U_{LL})_{ij} \equiv (m^2_U)^{ij}_{LL} / \tilde{m}^2$

Constraints on the δs from D-$\bar{D}$ mixing

e.g. $m_{\tilde{q}} = m_{\tilde{g}} = 1 TeV$



Assuming a dominant LL mass insertion

Assuming a dominant LR mass insertion

Allowing for (equal) LL and RR mass insertions

strongly constrained as chirality-flipping operators are generated

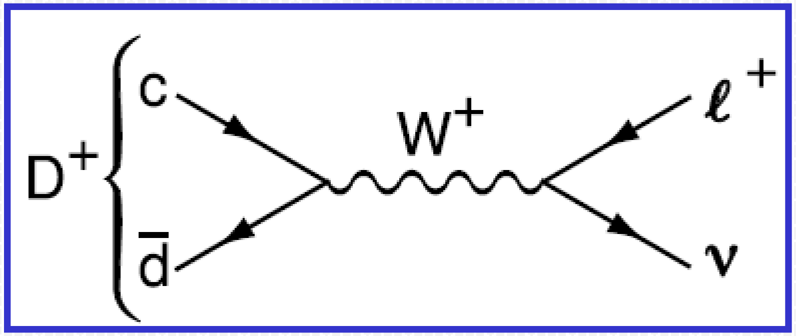
Mass insertions turn out to be more constrained than in hep-ph/0703204 by a factor ≈5 due to the increased lattice accuracy

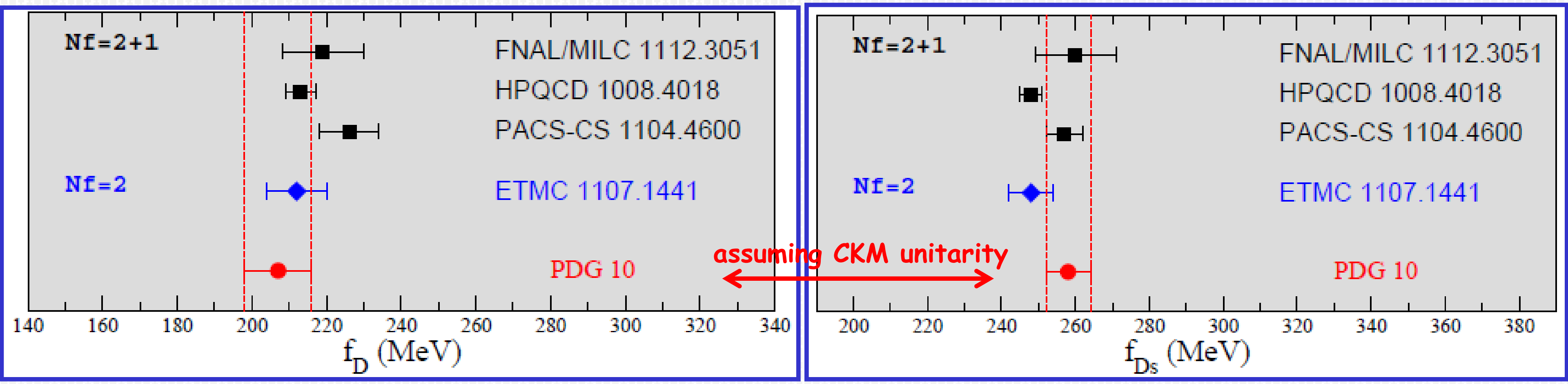
Further Lattice results for the B_D-parameters are looked forward

...Charm Flavor Physics

$D_{(s)}$ leptonic decays: f_D and f_{Ds}

$$\Gamma(P \to \ell\nu) = \frac{G_F^2}{8\pi} f_P^2\, m_\ell^2 m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 |V_{q_1 q_2}|^2$$





Update of HPQCD10 for f_D with improved r_1
f_D=208(3) MeV, see H.Na's talk (HPQCD)

New preliminary N_f=2+1+1 result (HISQ on HISQ) by FNAL/MILC with accuracy similar to HPQCD

f_D=210(5) MeV f_{Ds}=245(4) MeV
(see D.Toussaint's talk)

+E.Neil's talk (FNAL/MILC)

The past (2008) f_{Ds} puzzle has been solved!

Tension between lattice determination and experimental measurement, mainly due to the 3 σ deviation between:

HPQCD 2007 f_{Ds} = 241± 3 MeV (by 2.3 σ) ↑

PDG 2008 f_{Ds} = 273 ±10 MeV (by 1.5 σ) ↓

Other interesting B and D semileptonic form factors

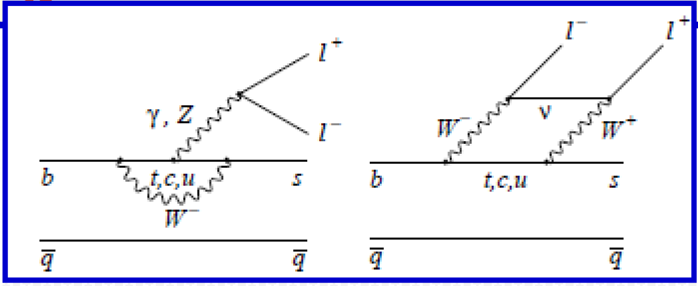
$D \to K/\pi\ l\ \nu$ ⇒ V_{cs} and V_{cd}: at present the lattice uncertainty dominates (the most accurate unquenched result is by HPQCD11)
FNAL/MILC improved analysis is in progress [see J.Bailey's poster]

First unquenched results for:

$B \to K^* l^+ l^-$ (BaBar, Belle, CDF, LHCb) ⇒ significant constraints on the Wilson coefficients C_7, C_9, C_{10} of the NP effective Hamiltonian (C.Bobeth et al.1006.5013, Hambrock&Hiller1204.4444)
[M.Wingate's talk (Horgan&Liu&Meinel&Wingate on MILC confs.)]

$\Lambda_b \to \Lambda l^+ l^-$ ⇒ NP sensitive (baryonic analogue) first observation by CDF (1107.3753)
[S.Meinel's talk (Detmold&Lin&Meinel on RBC/UKQCD 2+1 flavor domain-wall ensembles)]

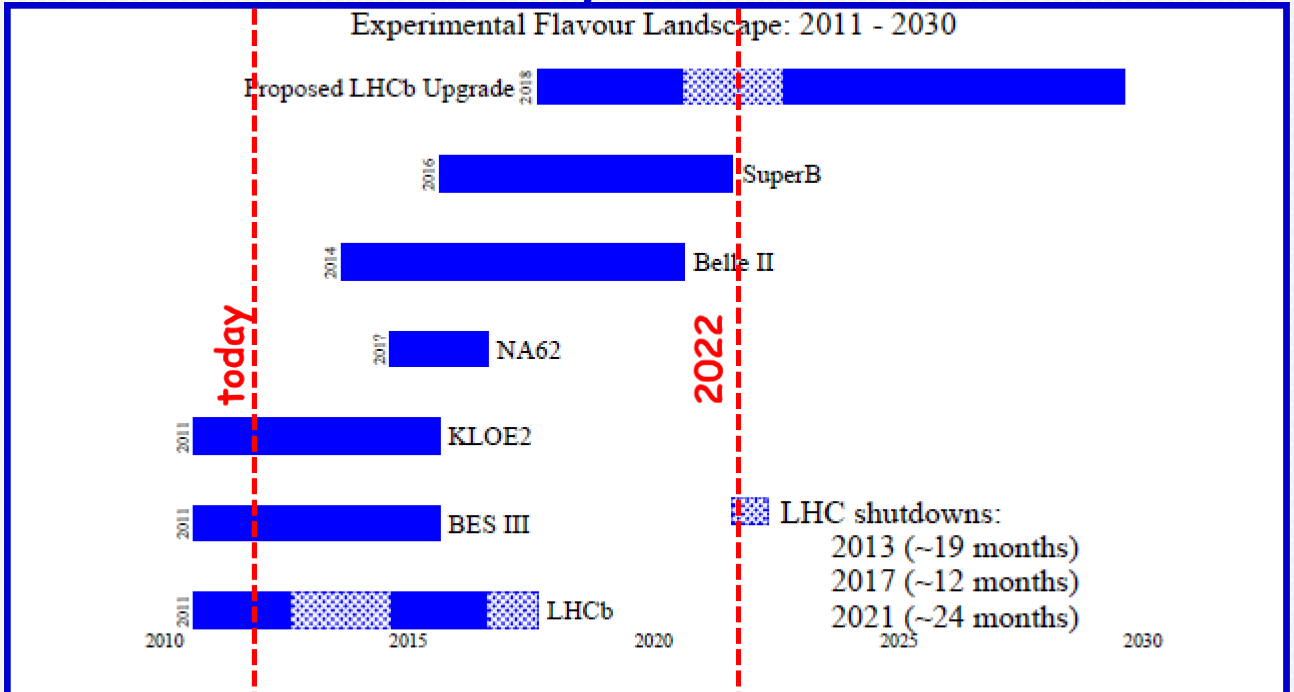
$B \to K l^+ l^-$, recently measured by BaBar (1204.3933)
⇒ complementary constraints to $B_s \to \mu^+\mu^-$ (Becirevic&Kosnik&Mescia&Schneider 1205.5811)
Lattice unquenched results for the three form factors f_+, f_0 and f_T are looked forward
[S.Gottlieb's talk (FNAL/MILC)]



An eye to the SuperB Era

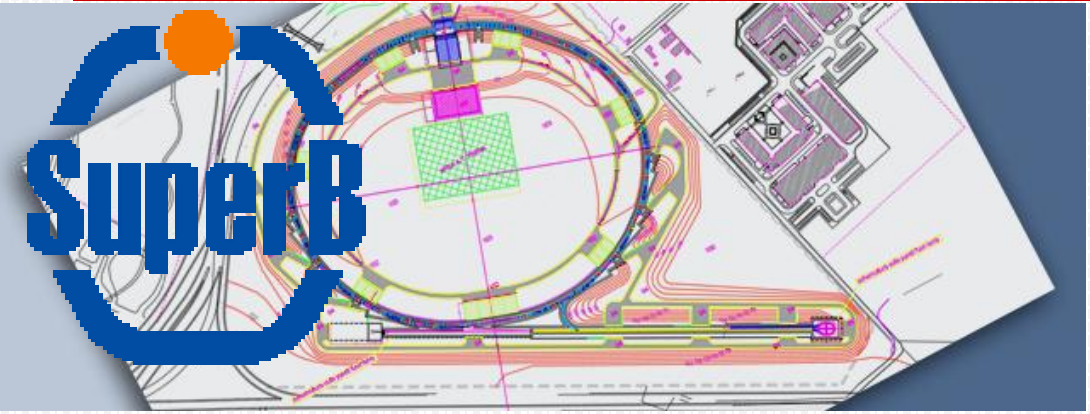
Present and next decades will see a great experimental activity,
not only in the direct NP search at LHC,
but also in the Flavor Sector

In the quark sector



Time scales of data taking anticipated for existing, approved, and proposed flavour physics experiments

The SuperB and Belle II projects have been approved!
(Italy and Japan)



Belle II

http://www.cabibbolab.it/

http://belle2.kek.jp/

- e^+-e^- collider with the appropriate energy to **produce couples of B and anti-B mesons, in a clean environment** (like BaBar and Belle,but with ~100 times higher luminosity)

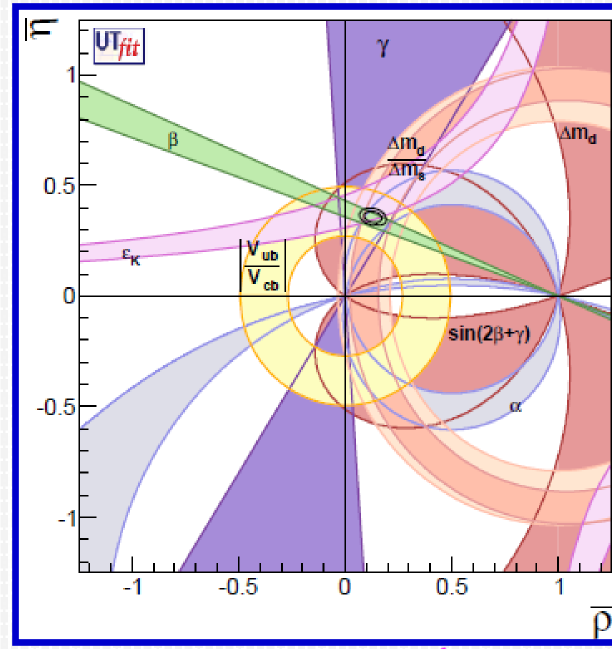
- it aims at **improving** the **accuracy** of the **B-factories** by a factor **5-10**

- It will **test** the **CKM** matrix at **1%** level

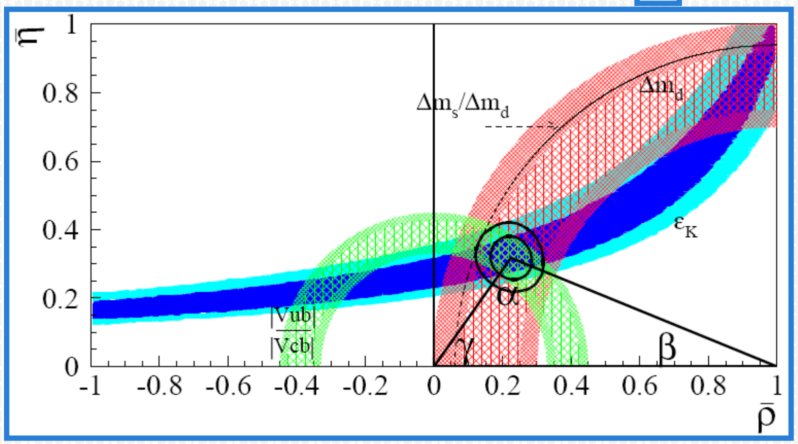
- It will **increase** the **sensitivity** for several channels sensitive to **NP** by one order of magnitude (e.g. $B \to \tau\nu$, but **also beyond B-physics**: τ decays which violate lepton flavor, CP-violation in the D-sector,…)

Role of B-factories in constraining the UT

After B-factories



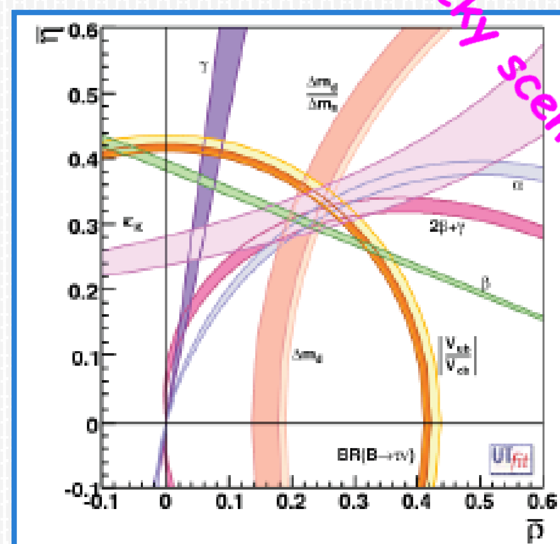
Before B-factories



lucky scenario

After SuperB-factories?

The CKM matrix will be tested at 1% level



On the Lattice side:
Ten Years Ago → Today

Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]		UTA Lattice inputs 2012 [www.utfit.org]	
$\hat{B}_K$	0.86(15)	[17%]	0.75(2)	[3%]
f_{Bs}	238(31) MeV	[13%]	233(10) MeV	[4%]
f_{Bs}/f_B	1.24(7)	[6%]	1.20(2)	[1.5%]
$\hat{B}_{Bs}$	1.34(12)	[9%]	1.33(6)	[5%]
B_{Bs}/B_B	1.00(3) (quenched, $\mu_l > m_s/2$,…)	[3%]	1.05(7)	[7%]
$F_{D*}(1)$	0.91(3)	[3%]	0.92(2)	[2%]
$F_+^{B\to\pi}$	--	[20%]	--	[11%]

- The last 10 years teach us that Lattice QCD has made important progresses (higher computational power, better algorithms, quenched->unquenched)
- More recently further improvements are being realized:
  simulations at the physical point, discretization effects well under control (in the light and heavy sectors), N_f=2+1+1, …

Conclusion:

Flavor Lattice QCD is on the right way to the 1% accuracy target

backup

ε_K

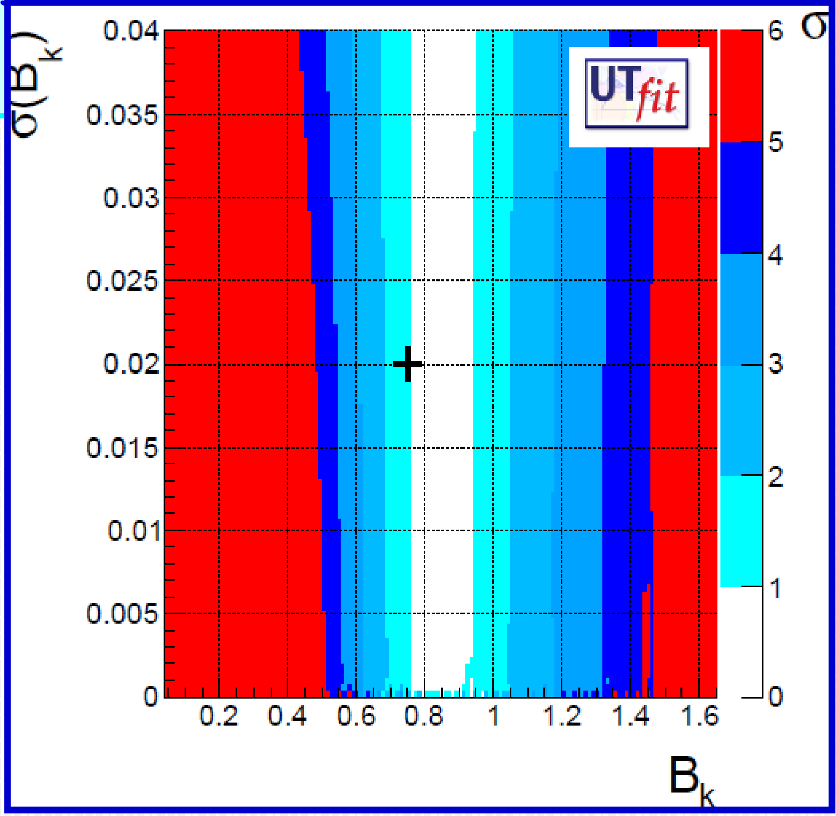
Buras&Guadagnoli (0805.3887)+**Buras&Guadagnoli&Isidori** (1002.3612):
decrease of the SM prediction of ε_K by ~6%

$$\epsilon_K = \sin\phi_\epsilon e^{i\phi_\epsilon}\left[\frac{\mathrm{Im}M_{12}^{(6)}}{\Delta m_K} + \rho\xi\right]$$

Long-distance

More recently:
Brod&Gorbahn (1007.0684, 1108.2036): NNLO QCD analysis of the charm-top and charm-charm contributions in box diagrams (further 2% suppression of ε_K)

Improved accuracy in B_K from Lattice QCD, thanks to the continuum limit in unquenched studies (smaller though compatible values w.r.t ~5 years ago)



B_K

UTfit Lattice input: $\hat{B}_K$=0.750(20)

- very well compatible with FLAG10: $\hat{B}_K^{Nf=2+1}$=0.738(20) and $\hat{B}_K^{Nf=2}$=0.729(30),

- a bit higher than FLAG10, to take into account 2011 results [BMW 1106.3230, Laiho&VandeWater 1112.4861, RBC/UKQCD 1201.0706, SWME 1111.5698] (see Gilberto Colangelo's talk)

Simulation with pion masses down to the physical value (and more) thanks to the 2-step HEX smeared clover-improved Wilson action

Experimental Sensitivities for SuperB golden modes

Observable/mode	Current now	LHCb (2017) 5 fb^{-1}	Super$B$ (2021) 75 ab^{-1}	Belle II (2021) 50 ab^{-1}	LHCb upgrade (10 years of running) 50 fb^{-1}	theory now
τ Decays						
$\tau \to \mu\gamma$ $(\times 10^{-9})$	< 44		< 2.4	< 5.0		
$\tau \to e\gamma$ $(\times 10^{-9})$	< 33		< 3.0	< 3.7 (est.)		
$\tau \to \ell\ell\ell$ $(\times 10^{-10})$	$< 150 - 270$	< 244 [a]	$< 2.3 - 8.2$	< 10	< 24 [b]	
$B_{u,d}$ Decays						
$\mathrm{BR}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34		0.05	0.04		1.1 ± 0.2
$\mathrm{BR}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0		0.02	0.03		0.47 ± 0.08
$\mathrm{BR}(B \to K^{*+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 80		1.1	2.0		6.8 ± 1.1
$\mathrm{BR}(B \to K^{+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 160		0.7	1.6		3.6 ± 0.5
$\mathrm{BR}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26		0.11	0.13	0.23	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060		0.02	0.02		$\sim 10^{-6}$
$B \to K^*\mu^+\mu^-$ (events)	250 [c]	8000	10-15k [d]	7-10k	100,000	-
$\mathrm{BR}(B \to K^*\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16		0.06	0.07		1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	400	10-15k	7-10k	5,000	-
$\mathrm{BR}(B \to K^*e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17		0.05	0.07		1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14 [e]	[f]	0.040	0.03		-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280		8,600	7,000		-
$\mathrm{BR}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})$ [g]	3.66 ± 0.77 [h]		0.08	0.10		1.59 ± 0.11
S in $B \to K_S^0\pi^0\gamma$	-0.15 ± 0.20		0.03	0.03		-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07		0.01	0.02		± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.15	0.02	0.03	0.03	± 0.02
B_s^0 Decays						
$\mathrm{BR}(B_s^0 \to \gamma\gamma)$ $(\times 10^{-6})$	< 8.7		0.3	$0.2 - 0.3$		0.4 - 1.0
A_{SL}^s $(\times 10^{-3})$	-7.87 ± 1.96 [i]	[j]	4.	5. (est.)		0.02 ± 0.01
D Decays						
x	$(0.63 \pm 0.20\%$	0.06%	0.02%	0.04%	0.02%	$\sim 10^{-2}$ [k]
y	$(0.75 \pm 0.12)\%$	0.03%	0.01%	0.03%	0.01%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.02%	0.03%	0.05%	0.01%	$\sim 10^{-2}$ (see above).
$\|q/p\|$	$(0.91 \pm 0.17)\%$	8.5%	2.7%	3.0%	3%	$\sim 10^{-3}$ (see above).
$\arg\{q/p\}$ $(^\circ)$	-10.2 ± 9.2	4.4	1.4	1.4	2.0	$\sim 10^{-3}$ (see above).

For several golden modes the sensitivity will be improved from 2 to 10 times

The theoretical predictions, for a significant comparison, should improve by 2-5 times