



ICHEP2012 ●
Melbourne

36th International Conference on High Energy Physics

4 – 11 July 2012

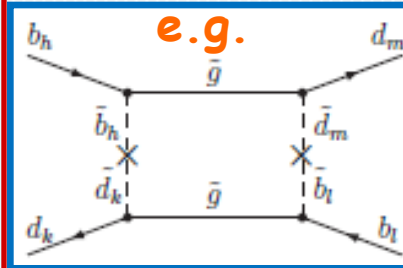
Melbourne Convention and Exhibition Centre

Flavor Physics and Lattice QCD
An emblematic study: the Unitarity Triangle Analysis

Cecilia Tarantino
Università Roma Tre¹

In order to search for New Physics and understand its nature

Flavor Physics is complementary to the direct production of NP particles



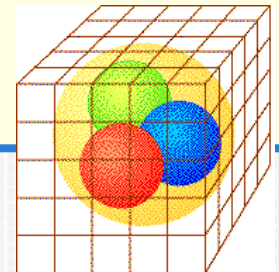
In clean and SM suppressed Flavor processes NP effects may be visible

Lattice QCD has a primary role as it allows to compute the (non-perturbative) long-distance QCD contributions from first principles

Lattice QCD:

- non-perturbative approach based on the path-integral formalism
- QCD simulated on discrete space and finite volume

→ QCD parameters only



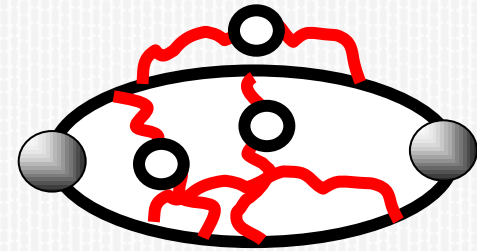
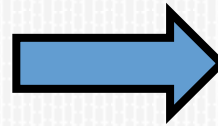
We are in the era of

"PRECISION" LATTICE QCD

1) Increasing of computational power
(Several machines of $O(0.1-10$ PetaFlops))
→ Unquenched simulations



QUENCHED



UNQUENCHED

$N_f=2$ (u, d)

$N_f=2+1$ (u, d, s)

$N_f=2+1+1$ (u, d, s, c)

2) Algorithmic improvements:

→ Light quark masses in the ChPT regime

Systematic Uncertainties:

The state of the art is evident from the color code introduced by FLAG for Pion and Kaon Physics

(Flavor Lattice Averaging Group)

Several recent lattice results have green stars

Review of lattice results concerning low energy particle physics

FLAG working group* of FLAVIANET

June 7, 2011

G. Colangelo^a, S. Dürr^{b,c}, A. Jüttner^d, L. Lellouch^e, H. Leutwyler^a, V. Lubicz^f, S. Necco^d, C. T. Sachrajda^g, S. Simula^h, A. Vladikasⁱ, U. Wenger^a, H. Wittig^j

- Continuum extrapolation:

- ★ 3 or more lattice spacings, at least 2 points below 0.1 fm
- 2 or more lattice spacings, at least 1 point below 0.1 fm
- otherwise

- Chiral extrapolation:

- ★ $M_{\pi,\min} < 250$ MeV
- $250 \text{ MeV} \leq M_{\pi,\min} \leq 400$ MeV
- $M_{\pi,\min} > 400$ MeV

- Renormalization (where applicable):

- ★ non-perturbative
- 2-loop perturbation theory
- otherwise

- Finite-volume effects:

- ★ $M_{\pi,\min}L > 4$ or at least 3 volumes
- $M_{\pi,\min}L > 3$ and at least 2 volumes
- otherwise

...

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

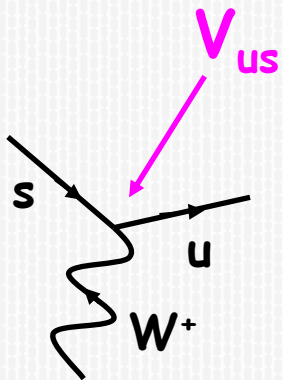
Weak eigenstates
Mass eigenstates

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

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

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

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



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

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

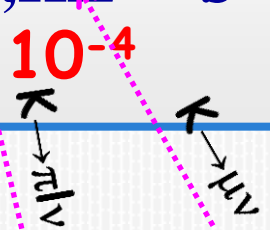
• Unitarity ($V_{CKM}^\dagger V_{CKM} = 1$) provides 9 conditions on the CKM parameters

1st row: the most stringent unitarity test

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

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

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



FLAG 1011.4408

| | |
|-------------------------|-------------|
| $ V_{us} = 0.2254(9)$ | $N_f = 2+1$ |
| $ V_{us} = 0.2251(18)$ | $N_f = 2$ |

less than 0.5% uncert. 6

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"

Last year, the strong IB corrections to f_K/f_π and to $f_+(0)$ have been calculated on the Lattice by using a strategy based on a $m_d - m_u$ 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 $\langle O \rangle_\infty \int D\phi O e^{-S_0 + \delta m \hat{S}} \stackrel{1st}{\simeq} \int D\phi O e^{-S_0} (1 + \delta m \hat{S}) \simeq \langle O \rangle_0 + \delta m \langle O \hat{S} \rangle_0$
 $dm = (\mu - md)/2$

Computation of the
(not small)
slope

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

Very promising!
(exploratory study with
modest statistics)

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

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

The Unitarity Triangle Analysis (UTA)

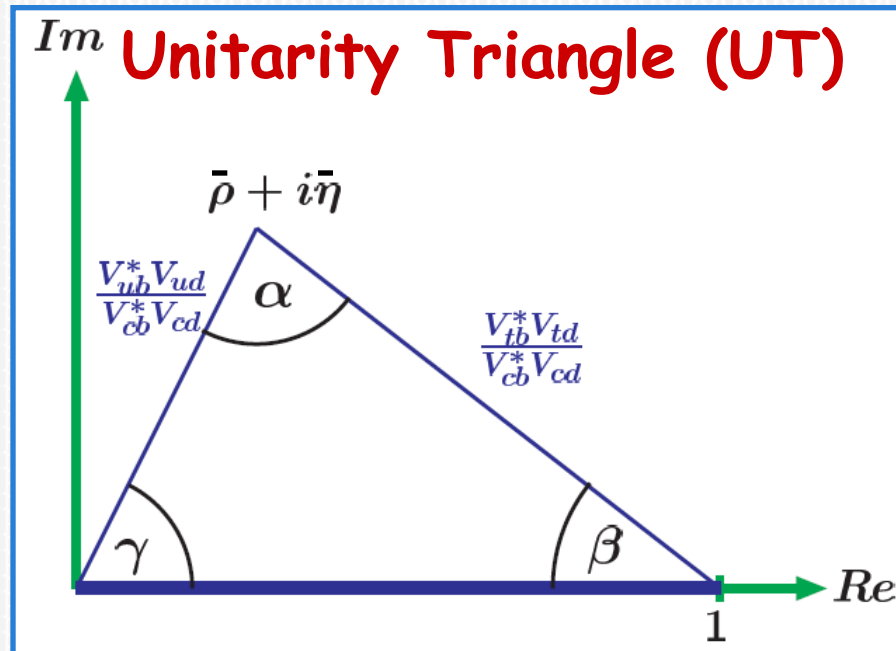
$$\bar{\rho} \equiv \rho \left(1 - \frac{\lambda^2}{2}\right), \quad \bar{\eta} \equiv \eta \left(1 - \frac{\lambda^2}{2}\right)$$

Among the 9 unitarity conditions $V_{CKM}^\dagger V_{CKM} = 1$

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

is of great phenomenological interest

It defines a triangle in the $(\bar{\rho}, \bar{\eta})$ -plane (with sides of similar size, so that CP-violation is visible)



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 |

Other UT analyses exist, by: CKMfitter (<http://ckmfitter.in2p3.fr/>),

Laiho&Lunghi&Van de Water (<http://krone.physik.unizh.ch/~lunghi/webpage/LatAves/page3/page3.htm>),

Lunghi&Soni (1010.6069), ...

Great Accuracy achieved in the UTA

Experimental Constraints

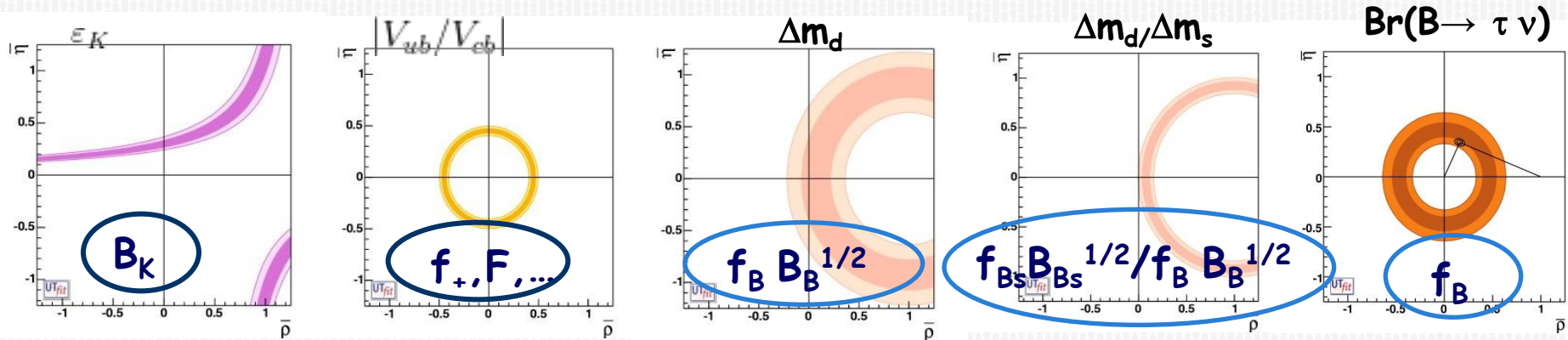
| Obs. | Accuracy |
|--|-----------------|
| ϵ_K | $\approx 0.5\%$ |
| Δm_d | $\approx 1\%$ |
| $\left \frac{\Delta m_d}{\Delta m_s} \right $ | $\approx 1\%$ |
| $\left \frac{V_{ub}}{V_{cb}} \right $ | $\approx 15\%$ |
| $\text{Br}(B \rightarrow \tau \nu)$ | $\approx 20\%$ |
| $\sin 2\beta$ | $\approx 3\%$ |
| $\cos 2\beta$ | $\approx 15\%$ |
| 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**

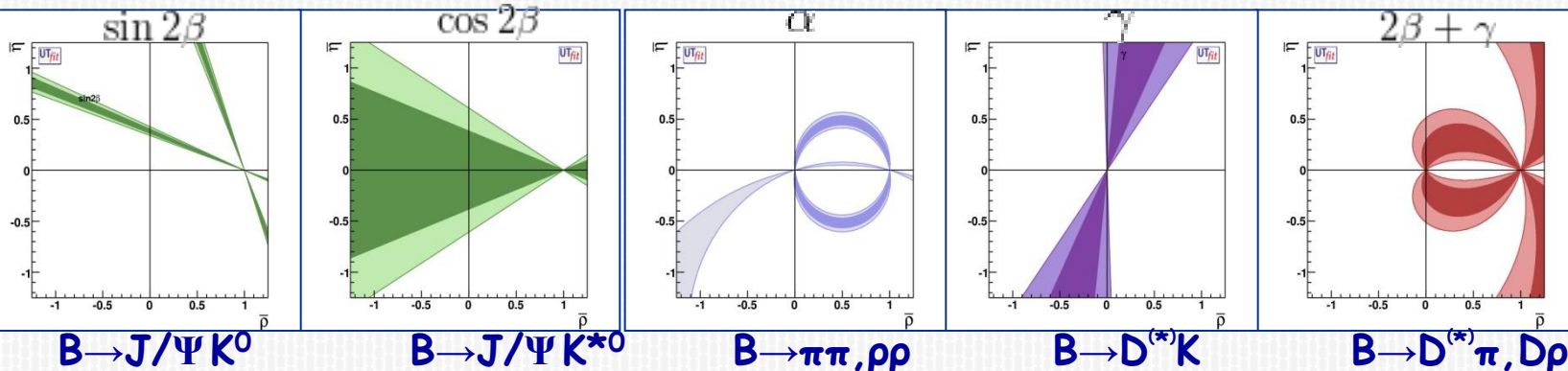
THE UTA CONSTRAINTS



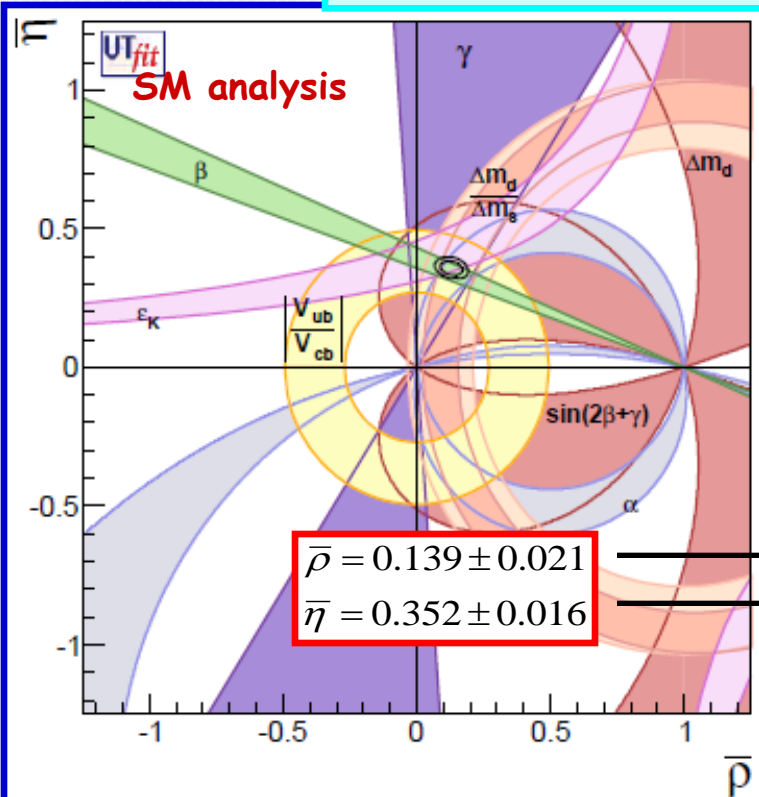
Relying on LATTICE calculations



UT-ANGLES



The UTA within the Standard Model



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

$68^\circ \pm 3^\circ$

$76^\circ \pm 11^\circ$

<1

α

$88^\circ \pm 4^\circ$

$91^\circ \pm 6^\circ$

<1

$|V_{cb}| \cdot 10^3$

42.3 ± 0.9

41.0 ± 1.0

<1

$|V_{ub}| \cdot 10^3$

3.62 ± 0.14

3.82 ± 0.56

<1

$\varepsilon_K \cdot 10^3$

1.96 ± 0.20

2.23 ± 0.01

1.4 ←

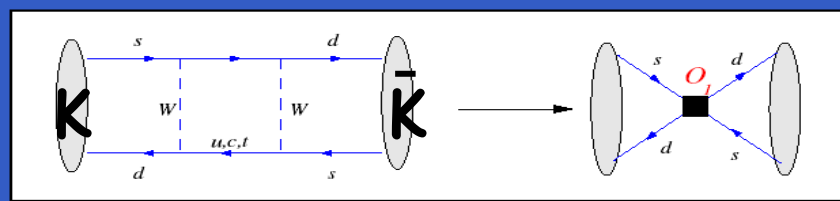
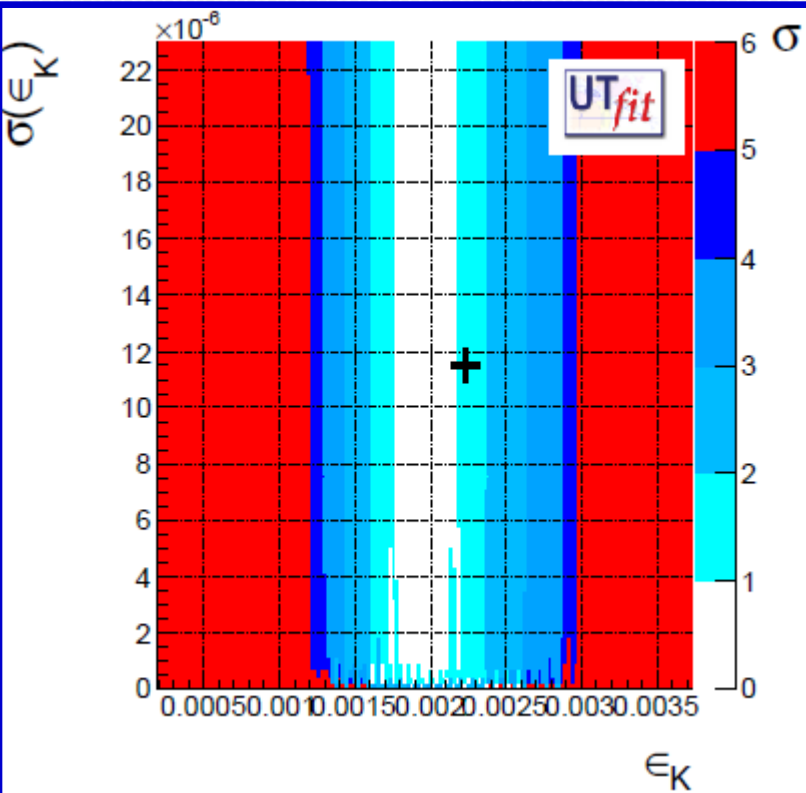
$BR(B \rightarrow \tau \nu) \cdot 10^4$

0.82 ± 0.08

1.67 ± 0.30

-2.7 ←

$$\epsilon_K (\longleftrightarrow B_K)$$



$$\langle \bar{K}^0 | Q(\mu) | K^0 \rangle = \frac{8}{3} f_K^2 m_K^2 B_K(\mu)$$

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 2011/2012 results

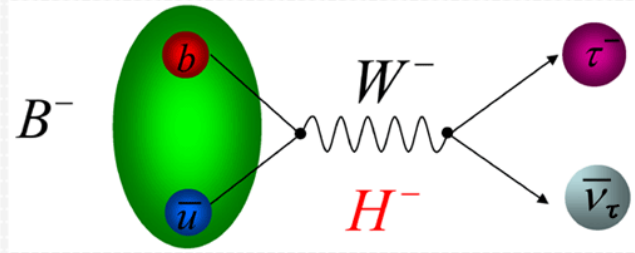
[BMW 1106.3230, Laiho&VandeWater 1112.4861,
 RBC/UKQCD 1201.0706, SWME 1111.5698]

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

$B \rightarrow \tau \nu$

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

2HDM of type II

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

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

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

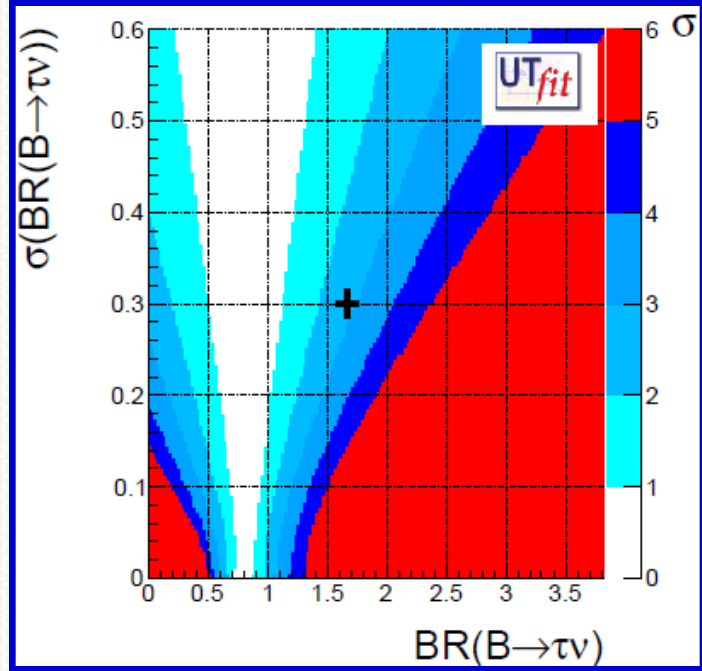
(due to other constraints, mainly $b \rightarrow s \gamma$)

$BR(B \rightarrow \tau \nu)_{SM} = (0.82 \pm 0.08) \cdot 10^{-4}$
[UTfit, update of 0908.3470]

turns out to be **smaller** by $\sim 2.7 \sigma$ than the experimental value

$BR(B \rightarrow \tau \nu)_{exp} = (1.67 \pm 0.30) \cdot 10^{-4}$

New BaBar and Belle results have been presented by G. De Nardo and Y. Yook:
BaBar confirms while Belle (with a modified hadronic tag) "reduces" the discrepancy



More recently, BaBar has obtained the new (full data) results [1205.5442] for

$$\mathcal{R}(D^{(*)}) = \mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell)$$

- They exceed the SM prediction by $2.0(2.7)\sigma$ (3.4σ when combined!)
- A charged Higgs could contribute, but in 2HDM of type II the $\tan\beta/m_{H^\pm}$ 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 $\text{Br}(B \rightarrow \tau \nu)$:

- 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]

End of June: two papers with more accurate theoretical predictions
for $\text{Br}(B \rightarrow D \tau \nu)$ No helicity suppression
→ both f_+ and f_0 are relevant

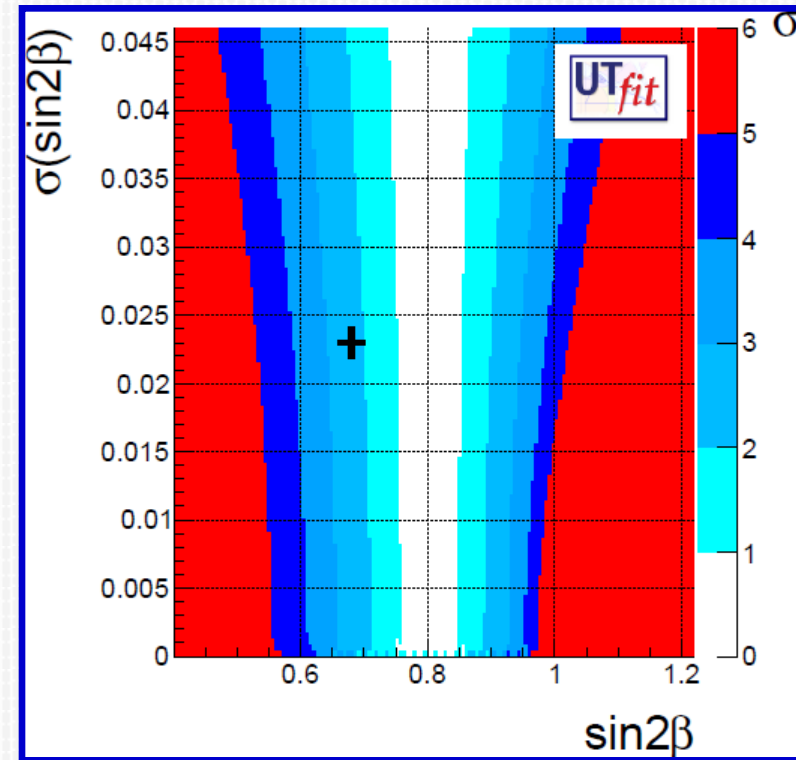
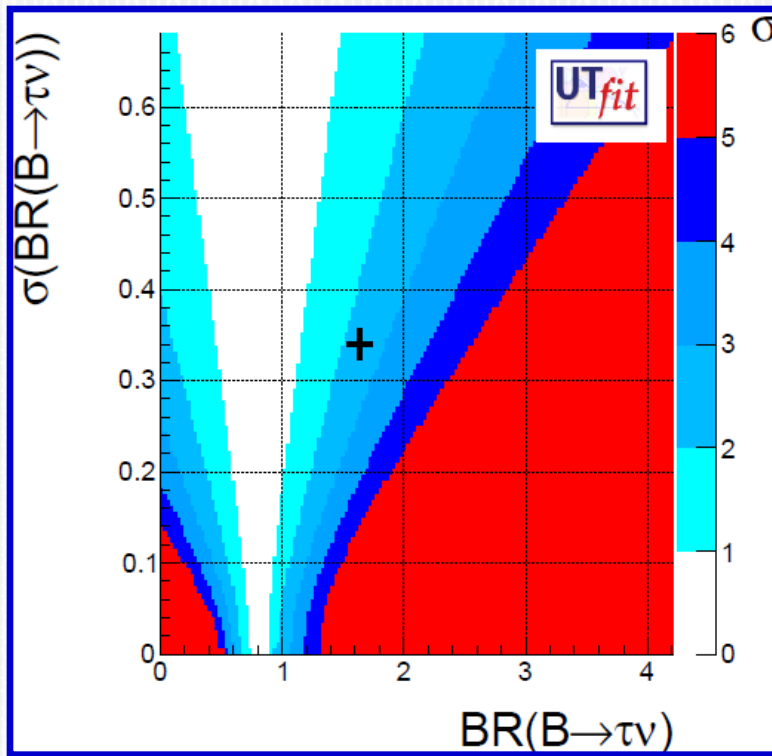
Becirevic&Kosnik&Tayduganov 1206.4977: estimate with minimal theory input
(from the Lattice (quenched and unquenched) f_+/f_0 and $f_+(q^2 > 8 \text{ GeV}^2)$) → $R(D)=0.310(20)$

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 slightly different constraint on $\tan\beta/m_{H^\pm}$

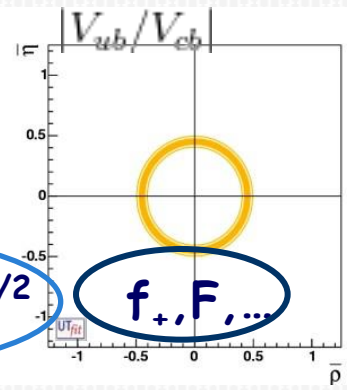
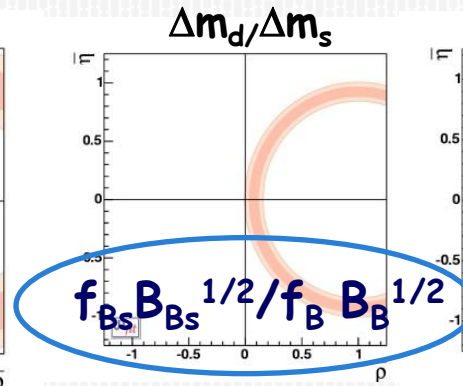
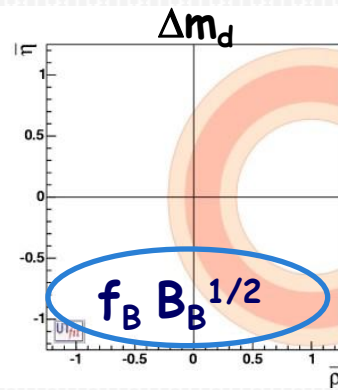
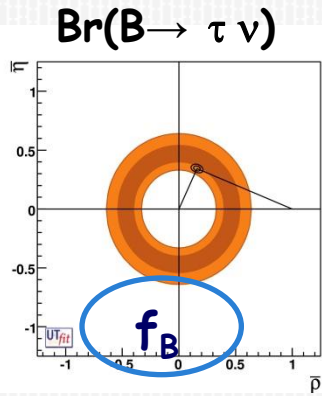
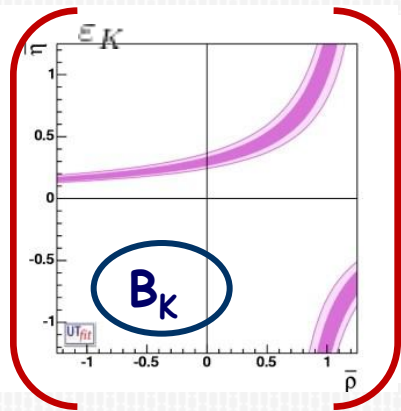
Looking for an explanation for the $B \rightarrow \tau \nu$ excess within the Standard Model

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

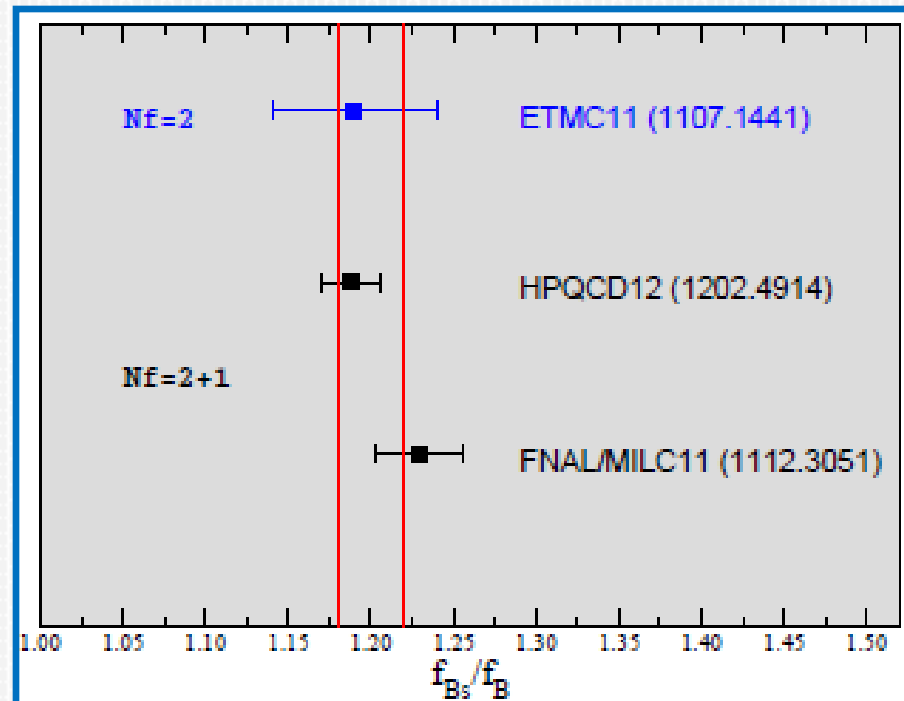
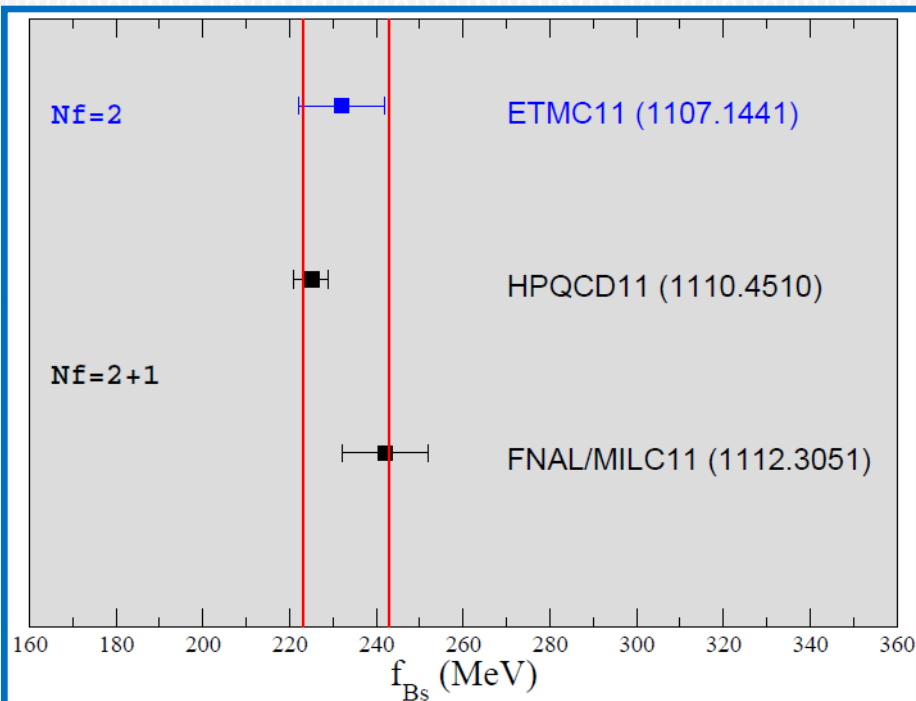


- $BR(B \rightarrow \tau \nu)_{\text{exp}}$ prefers a large value for $|V_{ub}|$ (f_B well under control)
 - But a shift in the central value of $|V_{ub}|$ would not solve the (2.4σ) β tension
- ➔ the debate on V_{ub} (exclusive vs inclusive determination) is not enough to explain all

Hadronic parameters on the Lattice, with B-Physics playing a fundamental role in the UTA



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



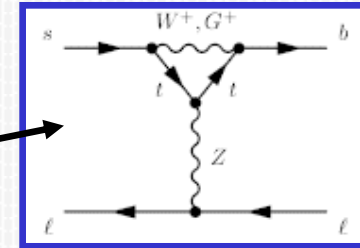
UTA Lattice inputs are (conservative)
 simple averages of unquenched ($N_f=2$ and $2+1$) results:
 $f_{B_s} = 233(10) \text{ MeV}$
 $f_{B_s}/f_B = 1.20(2)$ $\rightarrow f_B = 194(9) \text{ MeV}$

New accurate analyses (in progress by FNAL/MILC, RBC/UKQCD, ETMC, Alpha) have been presented @ Lattice 2012

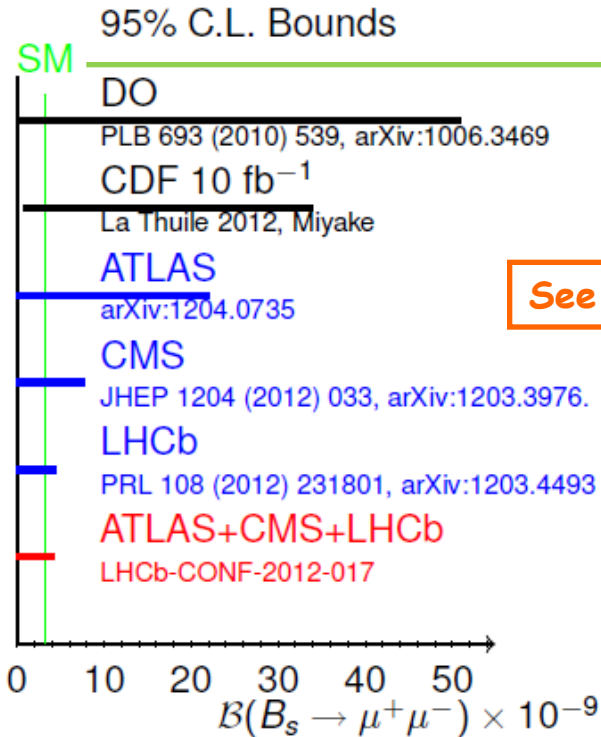
The pseudoscalar decay constant f_{B_s} also enters the important rare decays:

$$B_s \rightarrow \mu^+ \mu^-$$

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



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

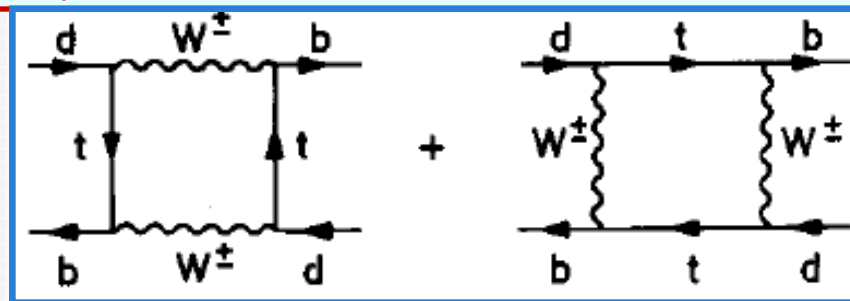


From the UTA: $Br(B_s \rightarrow \mu^+ \mu^-) = (3.5 \pm 0.3) \cdot 10^{-9}$

See talk by M.Perrin-Terrin [LHCb]

- Experimentally the fragmentation fraction f_s/f_d of $b \rightarrow B_s X$ is a fundamental ingredient
- Through factorization f_s/f_d can be related to the ratio of semileptonic form factors for $B^0 \rightarrow D^+ l^- \bar{\nu}$ and $B_s^0 \rightarrow D_s^+ l^- \bar{\nu}$
- FNAL/MILC has computed it on the Lattice (Nf=2+1, two lattice spacings), finding:
 $f_s/f_d = 0.28(4)$ [1202.6346]
 12% higher than a previous QCD sum rule estimate (P.Biasi et al.93)

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



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

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

- New Lattice analyses (by FNAL/MILC and ETMC) are in progress
- FNAL/MILC has also preliminary (first unquenched) results for the B-parameters of the complete NP basis

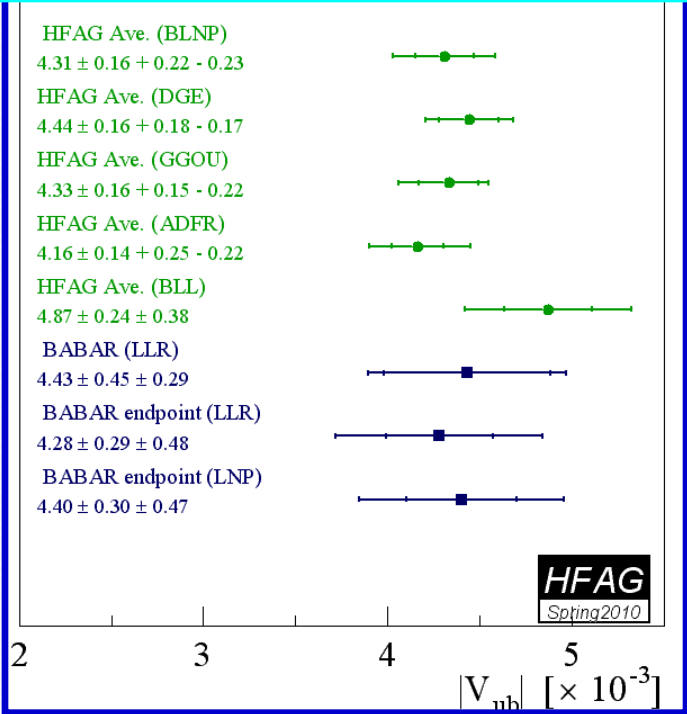
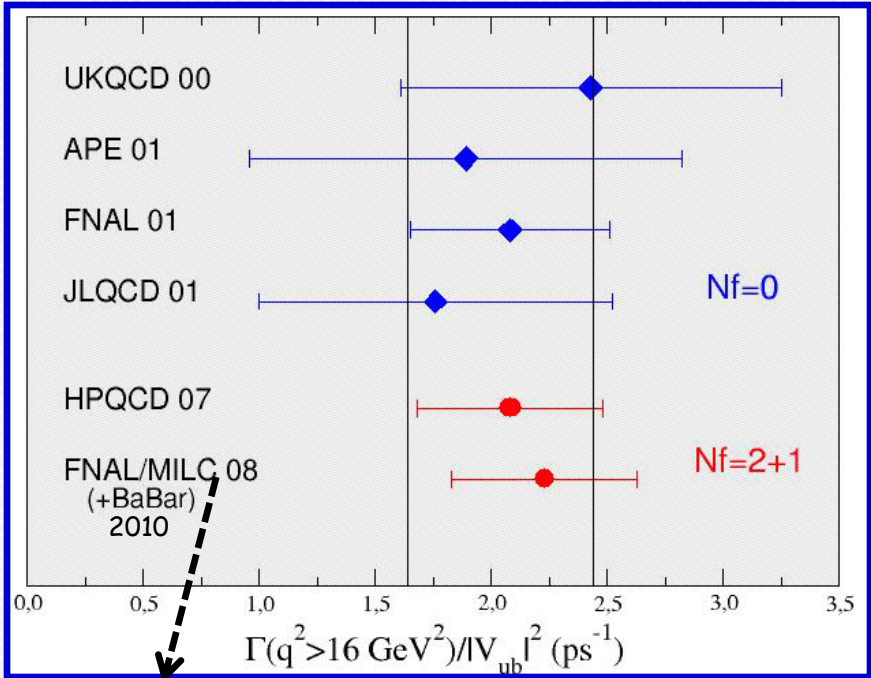
V_{ub} : exclusive (Lattice form factor) vs inclusive (OPE)

$B \rightarrow \pi l \bar{\nu}$

$B \rightarrow X_u l \bar{\nu}$

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

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



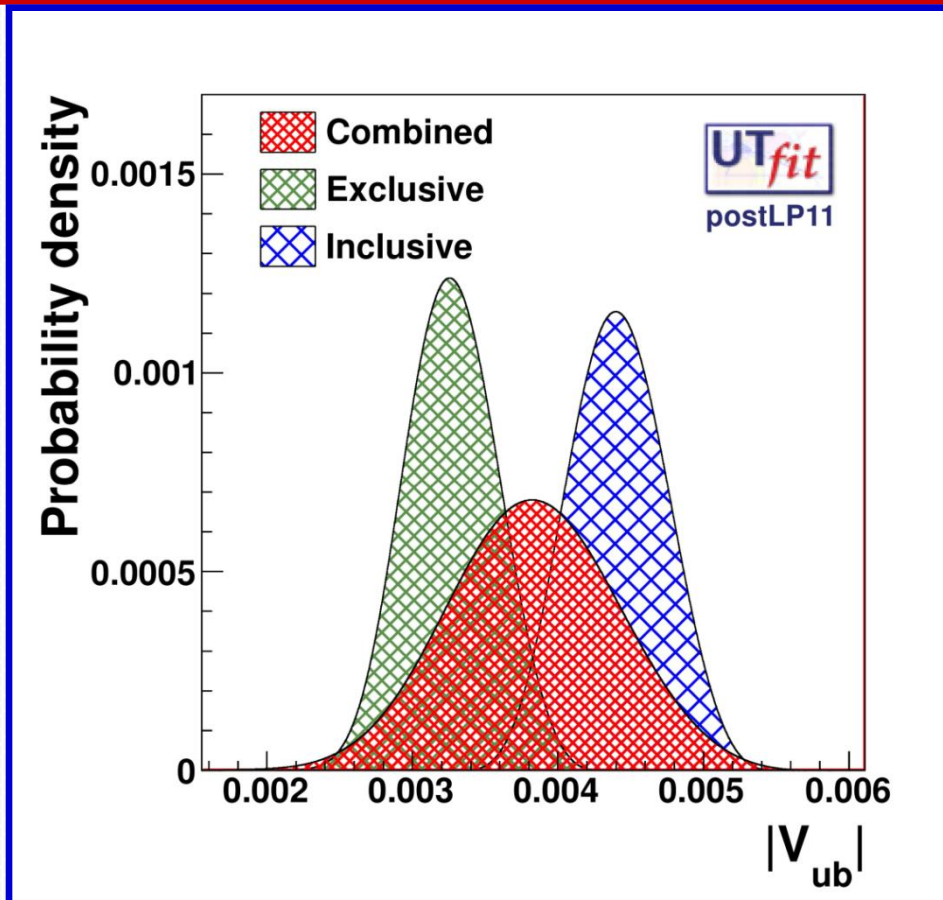
Combining it with Belle 2010 instead of Babar, V_{ub} is found to be 15% higher

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

2.6σ

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

Conservative combination for the UTA



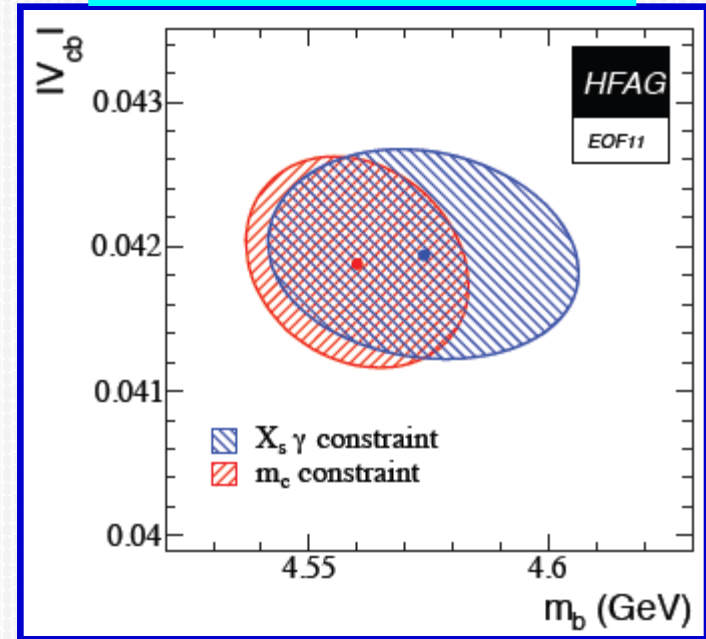
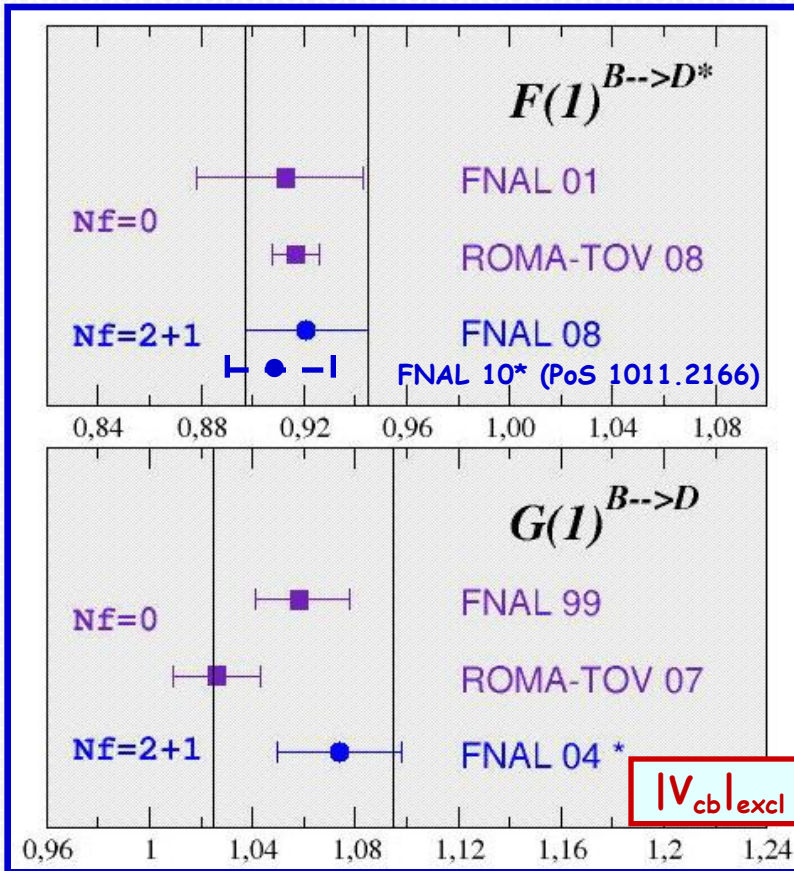
- $|V_{ub}|_{\text{input}} = (38.2 \pm 5.6) \cdot 10^{-4}$
- The UTA output is close to the (lower) exclusive result:
 $|V_{ub}|_{\text{UTA}} = (36.2 \pm 1.4) \cdot 10^{-4}$
- Further Lattice calculations are looked forward and are in progress
[by RBC/UKQCD, Alpha and HPQCD]

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



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

- **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 (by **FNAL/MILC**)

The UTA beyond the Standard Model

Bounds on the NP scale Λ

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

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

SM/MFV

Beyond SM/MFV

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

The high scale coefficients

$C_i(\Lambda)$ can be extracted from the data

(switching on one operator per time)

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

Tree/strong inter. NP: $L \sim 1$
 Perturbative NP: $L \sim \alpha_s^2, \alpha_W^2$

| MFV | next-to-MFV | generic |
|---|--|---|
| <ul style="list-style-type: none"> - $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$ - $F_{i \neq 1} = 0$ | <ul style="list-style-type: none"> - $F_i \sim F_{SM}$ - arbitrary phases | <ul style="list-style-type: none"> - $F_i \sim 1$ - arbitrary phases |

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

From (the most constraining) $K-\bar{K}$ sector,
with the new unquenched Lattice results for the NP B-parameters,
by ETMC (1207.1287, with $N_f=2$ and three lattice spacings)

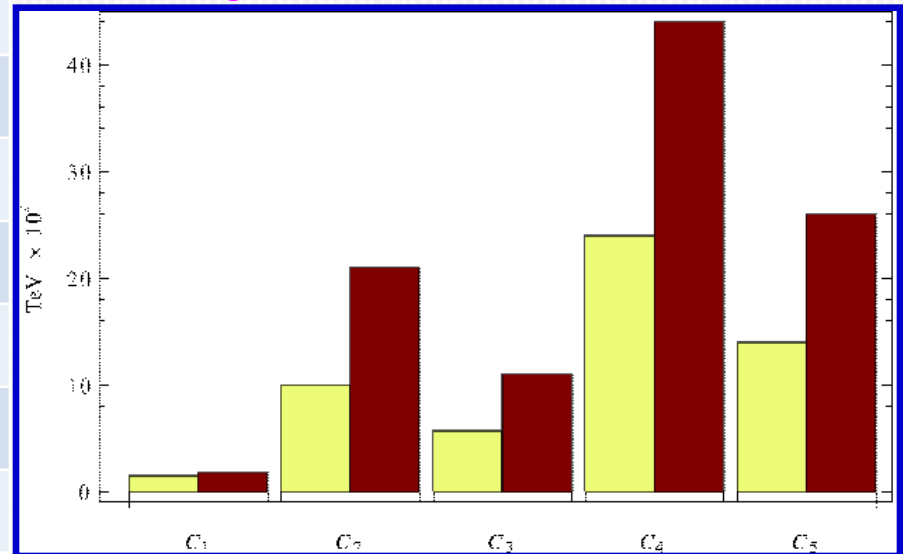
\overline{MS} at 2 GeV

| B_2 | B_3 | B_4 | B_5 |
|----------|----------|----------|----------|
| 0.54(03) | 1.13(09) | 0.82(05) | 0.63(07) |

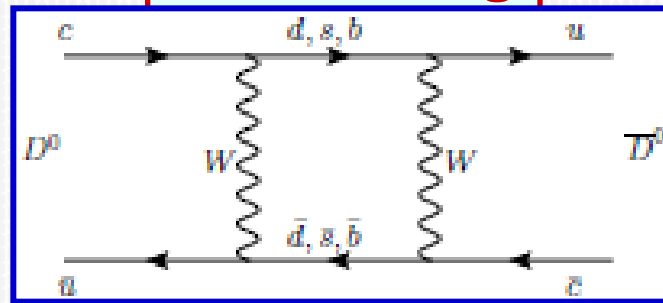
| | 95% allowed range (GeV^{-2}) | Lower limit on Λ (TeV) |
|-----------------------|----------------------------------|--------------------------------|
| NEW Im C_1^K | $[-2.8, 2.6] \cdot 10^{-15}$ | $1.9 \cdot 10^4$ |
| Im C_2^K | $[-1.6, 1.8] \cdot 10^{-17}$ | $24 \cdot 10^4$ |
| Im C_3^K | $[-6.7, 5.9] \cdot 10^{-17}$ | $12 \cdot 10^4$ |
| Im C_4^K | $[-4.1, 3.6] \cdot 10^{-18}$ | $49 \cdot 10^4$ |
| Im C_5^K | $[-1.2, 1.1] \cdot 10^{-17}$ | $29 \cdot 10^4$ |
| 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 | $[-5.2, 2.8] \cdot 10^{-17}$ | $14 \cdot 10^4$ |

- **Compatible** with NEW results by RBC/UKQCD (1206.5737, $N_f=2+1$, ONE lattice spacing)
- An analysis by SWME is in progress

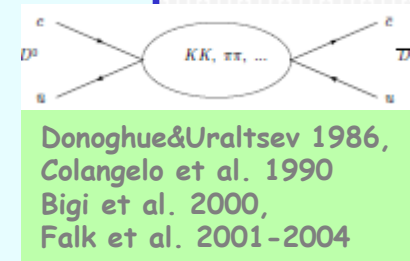
Generic Flavor Structure
Tree/strong inter. NP: $L \sim 1$



D-D̄ mixing



- It is sensitive to a different sector of New Physics (NP) with respect to K and B, being the charm an up-type quark
- It is affected by large long-distance effects (internal d and s quarks) which dominate over the short-distance contribution
- Only order of magnitude estimates exist for the long-distance contributions and are at the level of the experimental constraints, preventing from revealing an unambiguous sign of NP
- Still, barring accidental cancellations between SM and NP contributions, significant constraints can be put on the NP parameter space



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

Update of the D - \bar{D} mixing analysis of

M.Ciuchini et al. hep-ph/0703204



**By using the experimental results
(combined by UTfit in 1206.6245)**

| 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 | -0.255 α | 0.216 | [3] |
| y | $(0.309 \pm 0.281)\%$ | -0.007 | 1 | -0.019 α | -0.280 | [3] |
| $ q/p $ | $(0.95 \pm 0.22 \pm 0.10)\%$ | -0.255 α | -0.019 α | 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 | | |
| $(x'_+)'_{K\pi}$ | $(-0.024 \pm 0.052)\%$ | 0.77 | 1 | -0.94 | | |
| $(y'_+)'_{K\pi}$ | $(0.98 \pm 0.78)\%$ | -0.87 | -0.94 | 1 | | |
| A_D | $(-2.1 \pm 5.4)\%$ | 1 | 0.77 | -0.87 | | |
| $(x'_-)'_{K\pi}$ | $(-0.020 \pm 0.050)\%$ | 0.77 | 1 | -0.94 | | |
| $(y'_-)'_{K\pi}$ | $(0.96 \pm 0.75)\%$ | -0.87 | -0.94 | 1 | | |
| R_D | $(0.364 \pm 0.018)\%$ | 1 | 0.655 | -0.834 | | |
| $(x'_+)'_{K\pi}$ | $(0.032 \pm 0.037)\%$ | 0.655 | 1 | -0.909 | | |
| $(y'_+)'_{K\pi}$ | $(-0.12 \pm 0.58)\%$ | -0.834 | -0.909 | 1 | | |
| A_D | $(2.3 \pm 4.7)\%$ | 1 | 0.655 | -0.834 | | |
| $(x'_-)'_{K\pi}$ | $(0.006 \pm 0.034)\%$ | 0.655 | 1 | -0.909 | | |
| $(y'_-)'_{K\pi}$ | $(0.20 \pm 0.54)\%$ | -0.834 | -0.909 | 1 | | |
| CP asymmetry | Value | $\Delta(t)/\tau_{D^0}$ | | Reference | | |
| $A_{CP}(D^0 \rightarrow K^+ K^-)$ | $(-0.24 \pm 0.24)\%$ | | | [36, 37] | | |
| $A_{CP}(D^0 \rightarrow \pi^+ \pi^-)$ | $(0.11 \pm 0.39)\%$ | | | [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] | | |

[1] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **98**, 211802 (2007), arXiv:hep-ex/0703020.
 [2] M. Starić *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. Starić (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:1004.0771 [hep-ex].
 [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. Starić *et al.* (Belle Collaboration), Phys.Lett. **B670**, 190 (2008), arXiv:0807.0148 [hep-ex].

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

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

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

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 (first 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]

| | $\overline{MS} (2\text{GeV})$ |
|-------|-------------------------------|
| 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 Flavor Structure

Mass Insertion Approximation

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

3x3 non-diagonal flavor matrices

expanded in small off-diagonal entries:

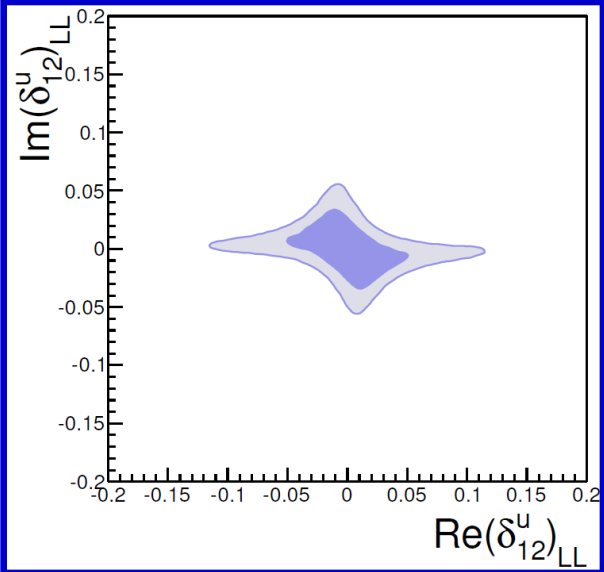
e.g., $(\delta_{LL}^U)_{ij} \equiv (m_U^2)_{LL}^{ij} / \tilde{m}^2$

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

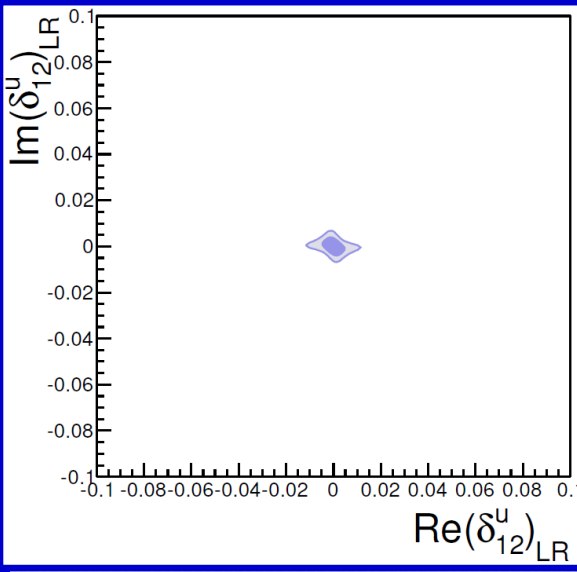
<http://www.utfit.org/UTfit/DDbarMixing>

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

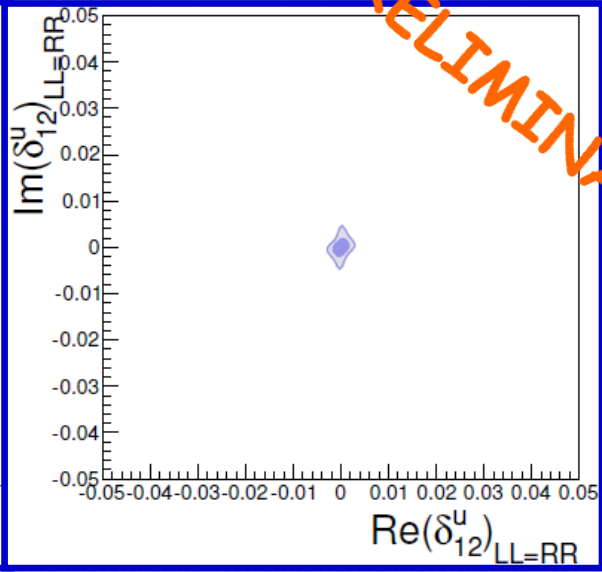
PRELIMINARY



Assuming a dominant LL mass insertion



Assuming a dominant LR mass insertion

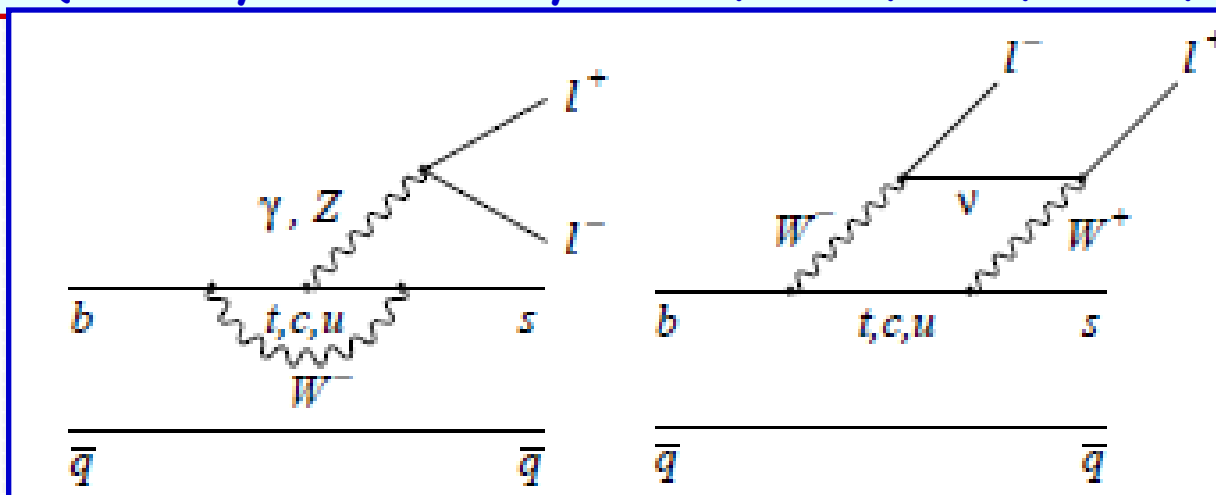


Allowing for (equal) LL and RR mass insertions

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

First unquenched Lattice results for $b \rightarrow s |^+|^-$ transitions (recently measured by BaBar, Belle, CDF, LHCb,...)



$B \rightarrow K^* |^+|^-$ \longrightarrow significant constraints on the Wilson coefficients C_7, C_9, C_{10}
of the NP effective Hamiltonian (C. Bobeth et al. 1006.5013, Hambroek & Hiller 1204.4444)
[preliminary results for the form factors by Cambridge/Edinburgh Coll.]

$\Lambda_b \rightarrow \Lambda |^+|^-$ \longrightarrow NP sensitive (baryonic analogue)
[preliminary results for the form factors by Cambridge/Edinburgh Coll.]

$B \rightarrow K |^+|^-$ \longrightarrow complementary constraints to $B_s \rightarrow \mu^+ \mu^-$
(Becirevic & Kosnik & Mescia & Schneider 1205.5811)

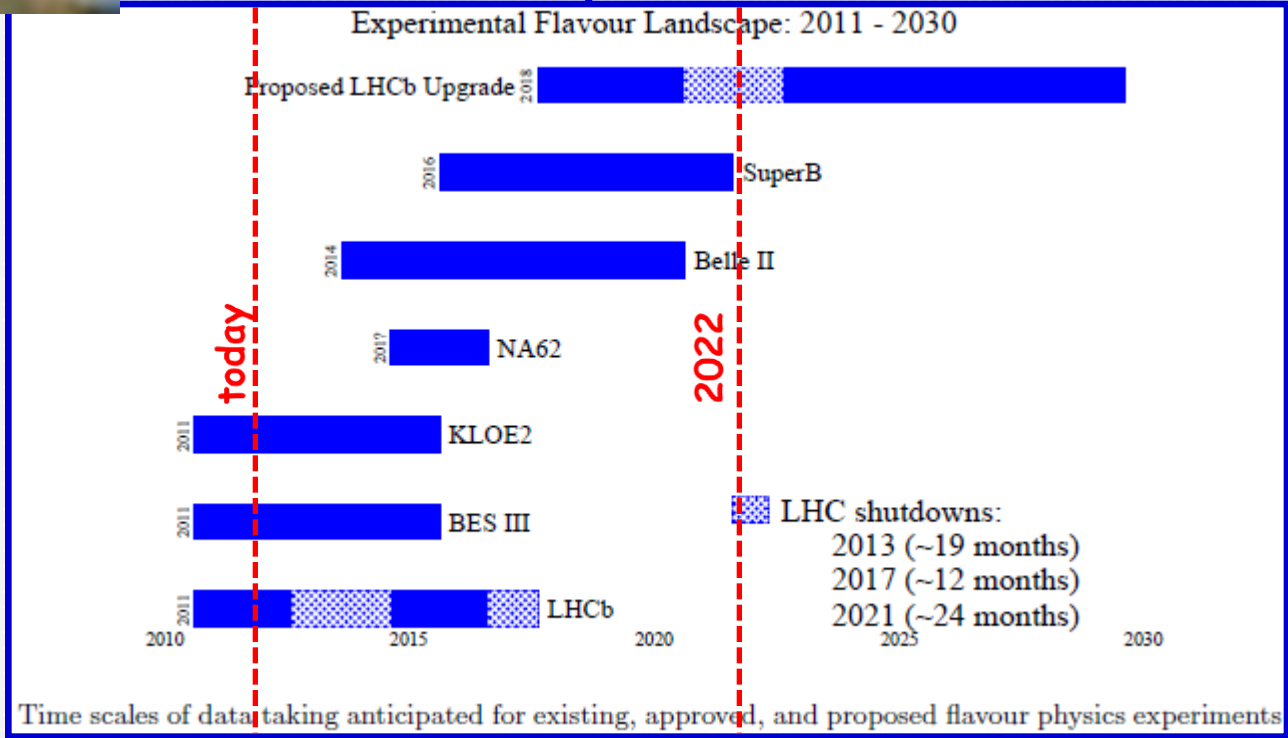
Lattice unquenched results for the three form factors f_+, f_0 and f_T are looked forward
[preliminary results by FNAL/MILC]



Looking at the next decade

In the next years there will be a great experimental activity, not only in the direct NP search at LHC, but also in the Flavor Sector

In the quark sector

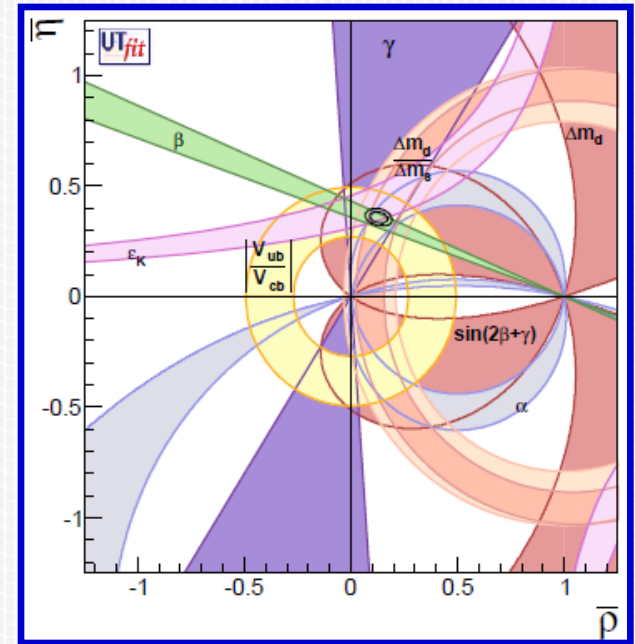
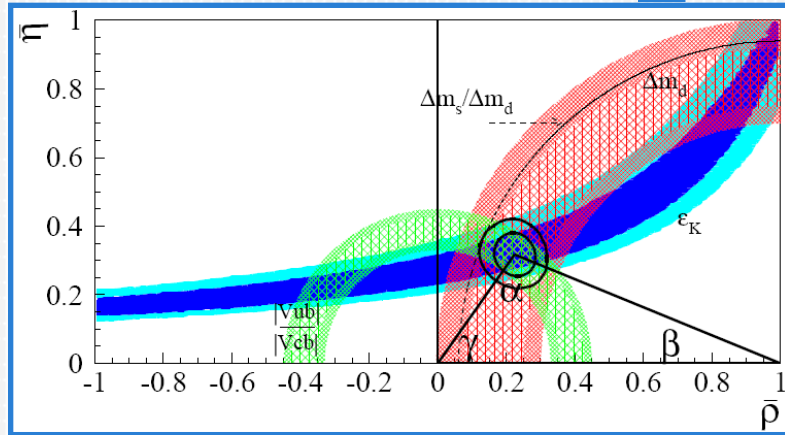


In particular, the SuperB-factories (SuperB and Belle II):

- aim at improving the accuracy of the B-factories by a factor 5-10
- will test the CKM matrix at 1% level

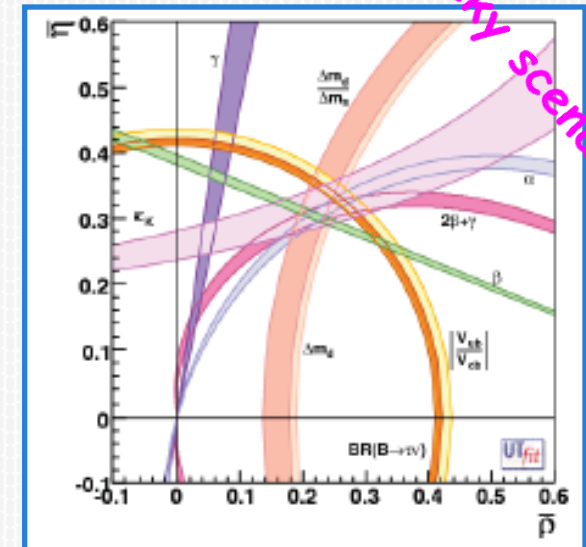
Role of B-factories in constraining the UT After B-factories

Before B-factories



After SuperB-factories?

The CKM matrix will be tested at 1% level



Lucky scenario

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_{B_s} | 238(31) MeV | [13%] | 233(10) MeV | [4%] |
| f_{B_s}/f_B | 1.24(7) | [6%] | 1.20(2) | [1.5%] |
| \hat{B}_{B_s} | 1.34(12) | [9%] | 1.33(6) | [5%] |
| B_{B_s}/B_B | 1.00(3) | [3%] (quenched, $\mu_l > m_s/2, \dots$) | 1.05(7) | [7%] |
| $F_{D^*(1)}$ | 0.91(3) | [3%] | 0.92(2) | [2%] |
| $F_+^{B \rightarrow \pi}$ | -- | [20%] | -- | [11%] |

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

Conclusion:

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



backup

FLAG is now working on the averages for Heavy Flavor Physics

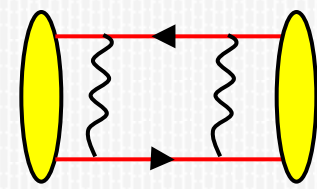
- **B-physics on the lattice** has the difficulty of large discretization effects of $O(a^*m_b)$ \longleftrightarrow the physical b-quark mass (≈ 4 GeV) cannot be directly simulated on present ($a^{-1} \leq 4$ GeV) lattices
- **Several approaches** have been investigated and adopted so far, either with:
 - **relativistic heavy quark** (simulating masses in the charm region and extrapolating to the physical b quark through step-scaling technique, ratio method, within HISQ,...)
 - **or effective theory based** (HQET, NRQCD, FermiLab or new RBC/UKQCD formulations,...)

The UTA beyond the Standard Model

Update of UTfit 0909.5065

Model-independent UTA: bounds on deviations from the SM

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



Meson-antimeson oscillations: highly sensitive to NP

For instance, in the B_s system:

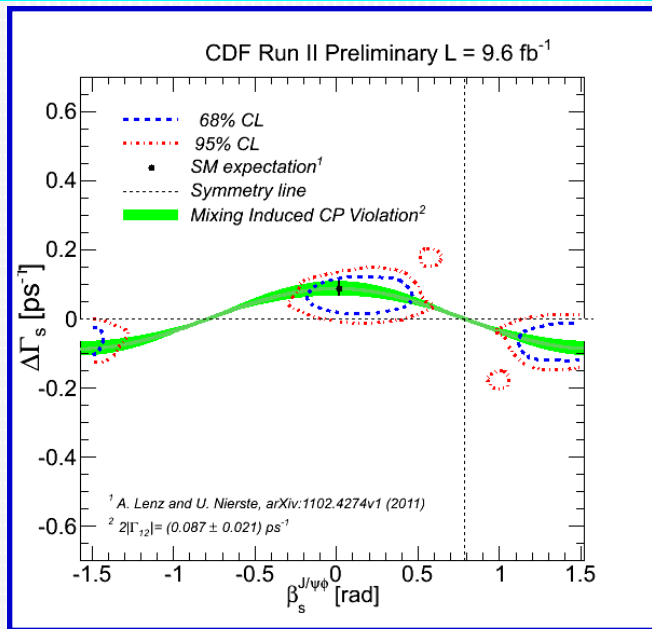
$$\Delta m_{q/K} = C_{B_q/\Delta m_K} \stackrel{=1 \text{ in SM}}{(\Delta m_{q/K})^{SM}}$$

$$A_{CP}^{B_s \rightarrow J/\psi\phi} \sim \sin 2(-\beta_s + \phi_{B_s}) \stackrel{=0 \text{ in SM}}{}$$

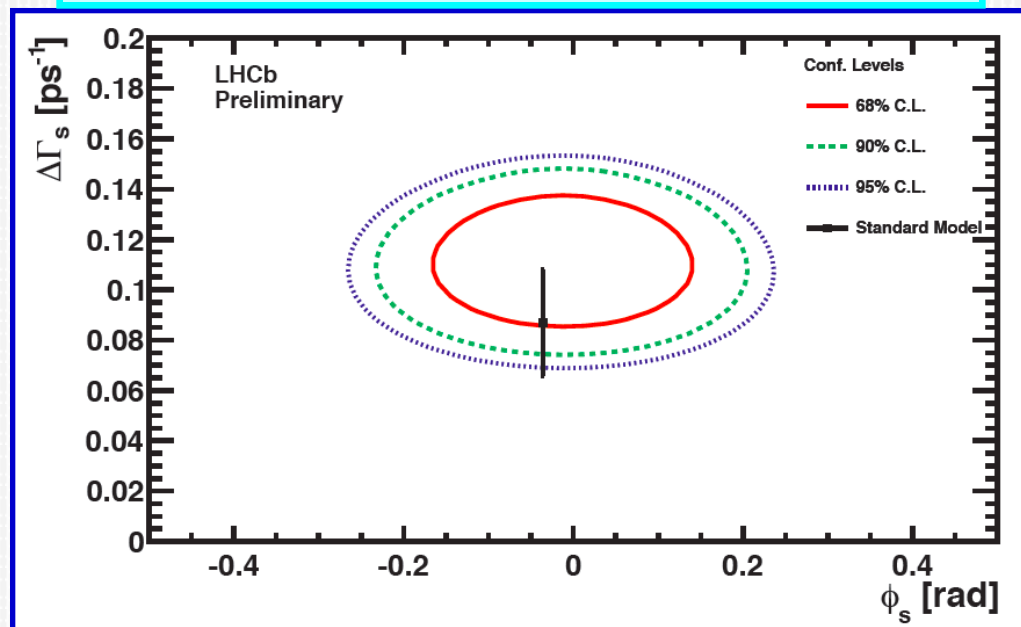
In 2009, CDF and D0 results for ϕ_{B_s} \Rightarrow More than 2.5σ deviation from the SM!

Summer 2011: Bad news for NP in B_s !

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



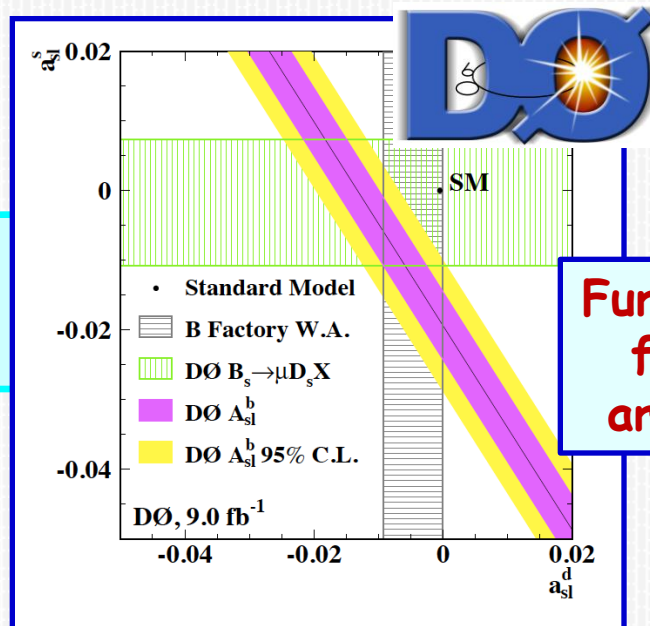
LHCb: finds compatibility as well



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

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

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

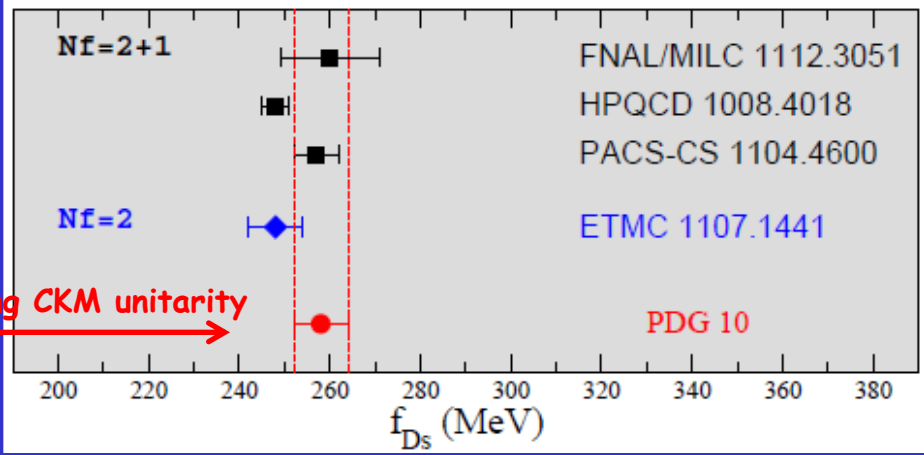
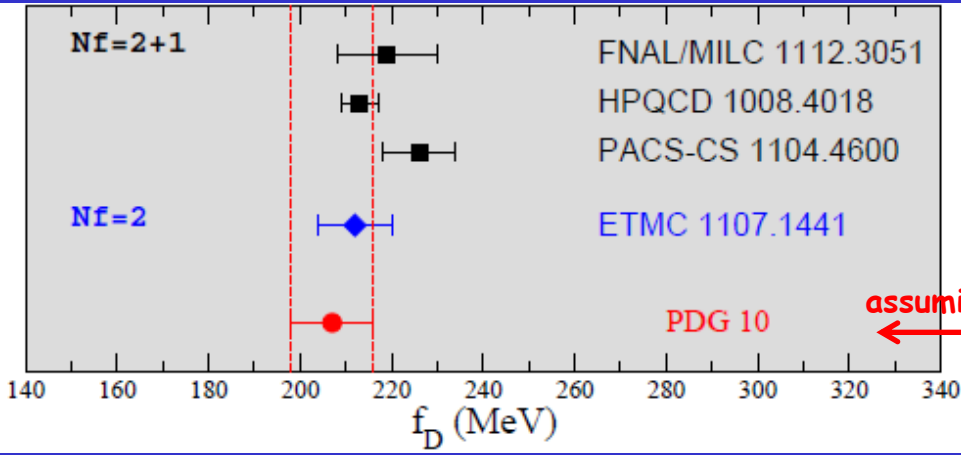
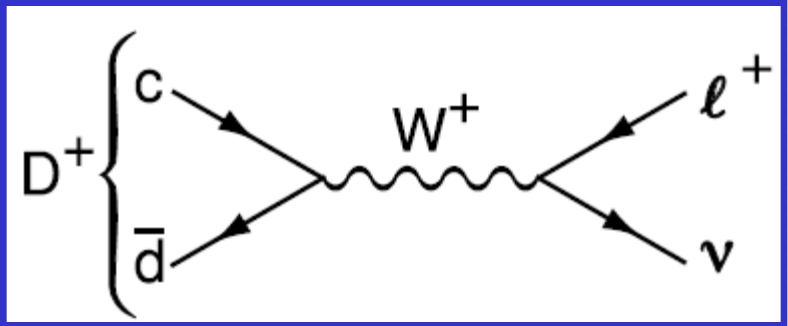


Further confirmations
from experiments
are looked forward!

...Charm Flavor Physics

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

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



Update of HPQCD10 for f_D with improved r₁
 f_D=208(3) MeV
 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_{D_s}=245(4) MeV

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

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

| | | |
|------------|---|--------------|
| HPQCD 2007 | f _{D_s} = 241 ± 3 MeV | (by 2.3 σ) ↑ |
| PDG 2008 | f _{D_s} = 273 ± 10 MeV | (by 1.5 σ) ↓ |

$D \rightarrow K/\pi \mid v \longrightarrow V_{cs}$ and V_{cd} : at present the lattice uncertainty dominates (the most accurate unquenched result is by HPQCD11)
FNAL/MILC improved analysis is in progress

Experimental Sensitivities for SuperB golden modes

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