Lattice QCD and flavour physics

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OUTLINE:

- Motivations for flavour physics
- Accuracy of lattice QCD:
  1. the quenched era (<2006)
  2. the precision era
- The first row unitarity test
  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- The Unitarity Triangle Analysis
  $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$
  1. Lattice inputs
  2. Deviations from the SM
- Accuracy of LQCD: 3. the future

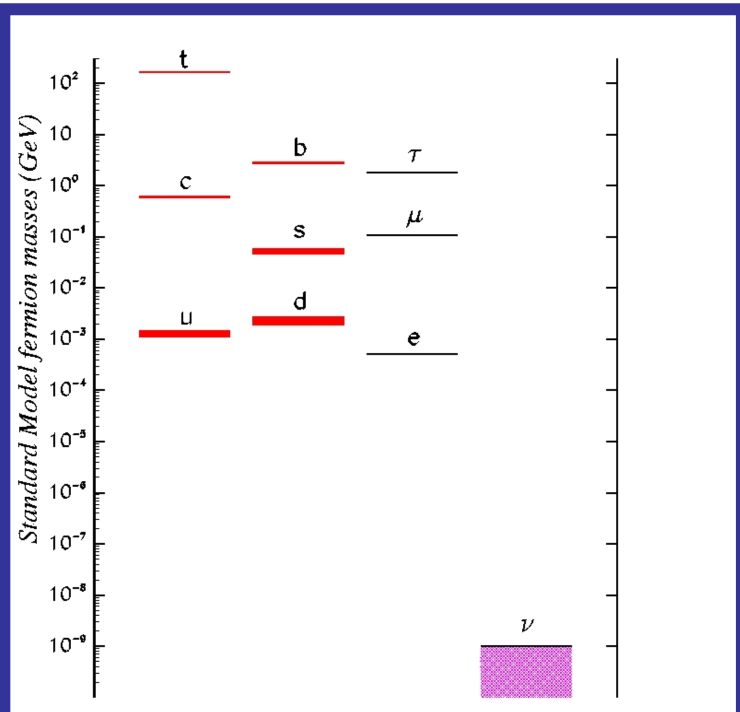
Motivations for flavour physics

1) Flavour physics is (well) described but not explained in the Standard Model

A large number of free parameters in the flavor sector:
10 parameters in the quark sector (6 m_q + 4 CKM),
12 in the lepton sector (with massive neutrinos)

Open questions

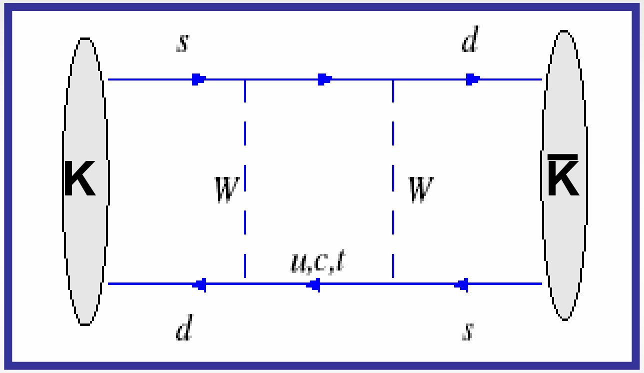
- Why 3 families with their observed particle content?
- Why the spectrum of quarks and charged leptons covers 5 orders of magnitude? ($m_q \sim Y v \sim G_F^{-1/2}$...)
- What give rise to the pattern of quark mixing and the magnitude of CP violation?



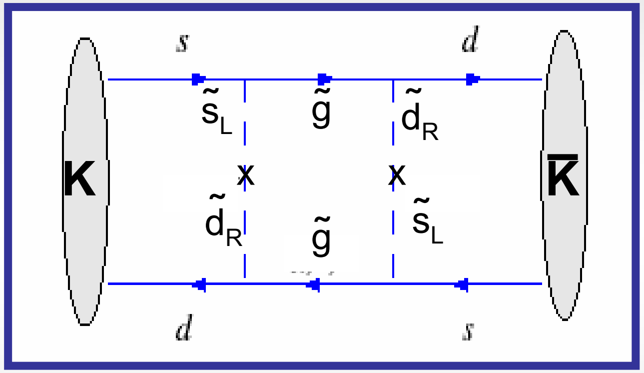
2) Flavour physics plays a crucial role in the indirect searches of new physics

New Physics enters the low-energy processes through quantum loops

→ Flavor Physics could allow us to discriminate among different New Physics scenarios



Standard Model

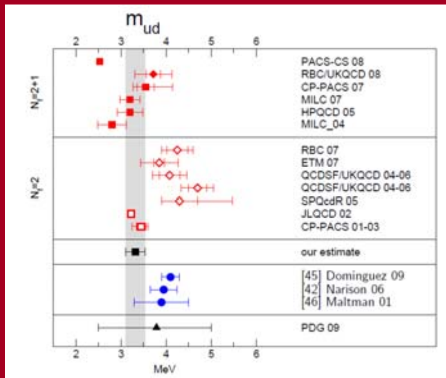


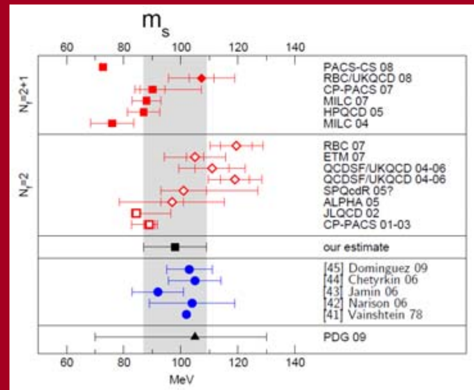
New Physics

In the past, the existence of the charm quark or the heaviness of the top quark have been predicted from the study of virtual effects long before their experimental observation

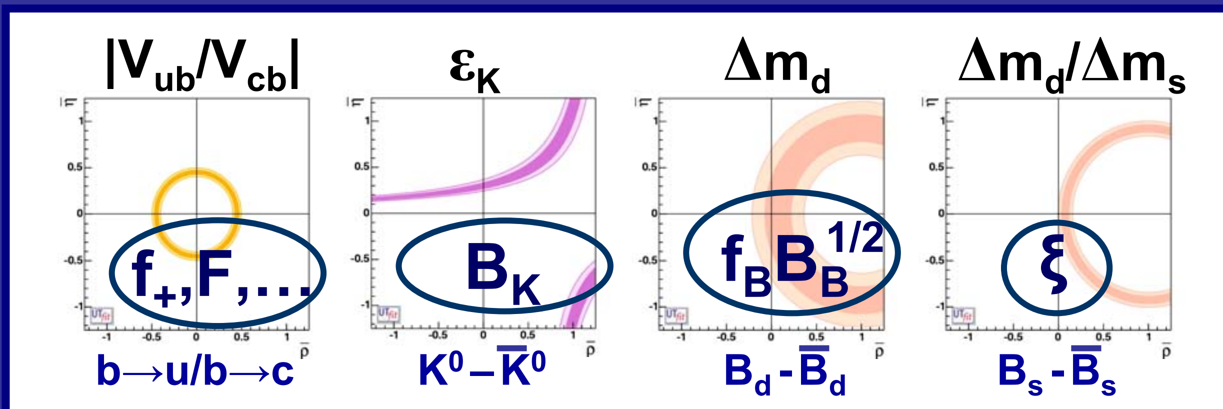
No evidence of New Physics from indirect searches has been observed yet: the Standard Model works too well (the "flavour problem")

Lattice QCD and flavour physics





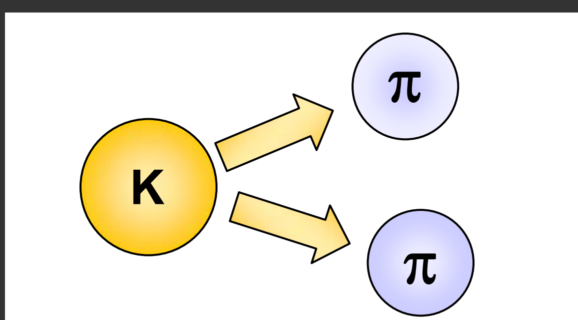
Quark masses



CKM matrix elements

UTA

Beyond SM physics



More difficult problems

Covered in this talk

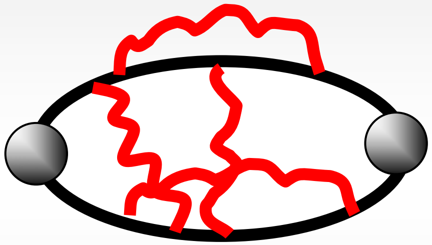
Accuracy of Lattice QCD

1. The "quenched" era

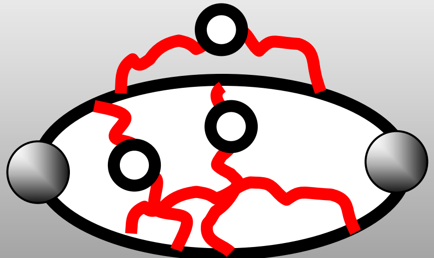
For many years, uncertainties in lattice calculations have been dominated by the quenched approximation

History of lattice errors (before 2006)

	f_B [MeV]	$f_{Bs}\sqrt{B_s}$ [MeV]	ξ
J.Flynn Latt'96	175(25) 14%	----	----
C.Bernard Latt'00	200(30) 15%	267(46) 17%	1.16(5) 4%
L.Lellouch Ichep'02	193(27)(10) 15%	276(38) 14%	1.24(4)(6) 6%
Hashimoto Ichep'04	189(27) 14%	262(35) 13%	1.23(6) 5%
N.Tantalo CKM'06	223(15)(19) 11%	246(16)(20) 10%	1.21(2)(5) 4%



QUENCHED



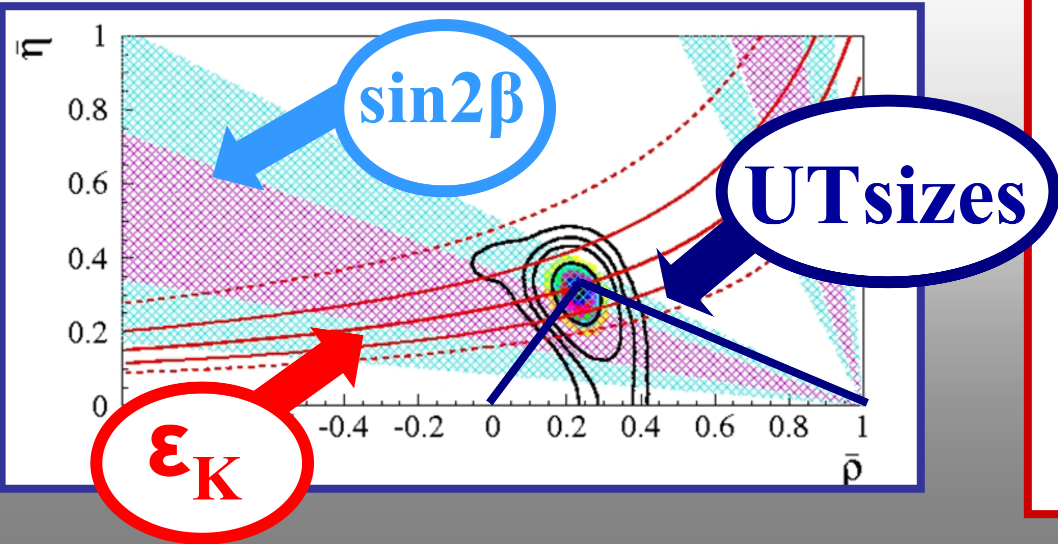
UNQUENCHED

In spite of the relatively large lattice uncertainties, important results for flavour physics have been achieved

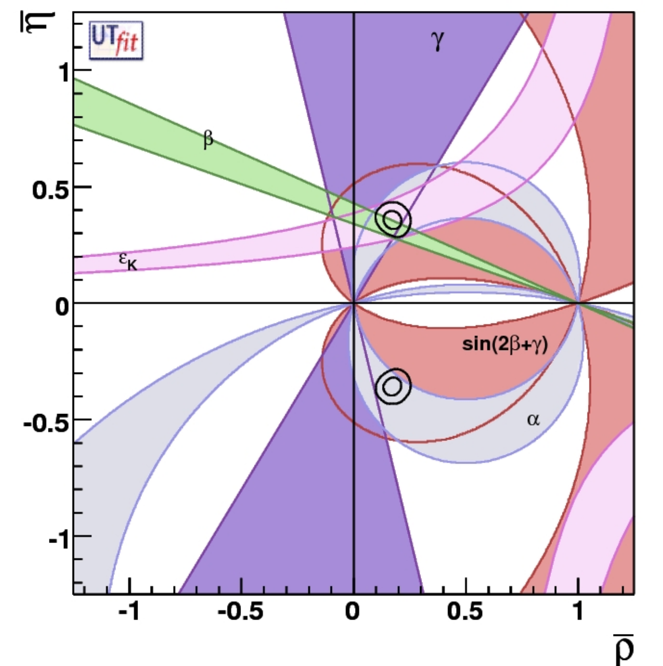
CKM PARADIGM OF ~~CP~~

CP-conserving and CP-violating processes determine the same CKM phase

Ciuchini et al.,2000



UTfit, today



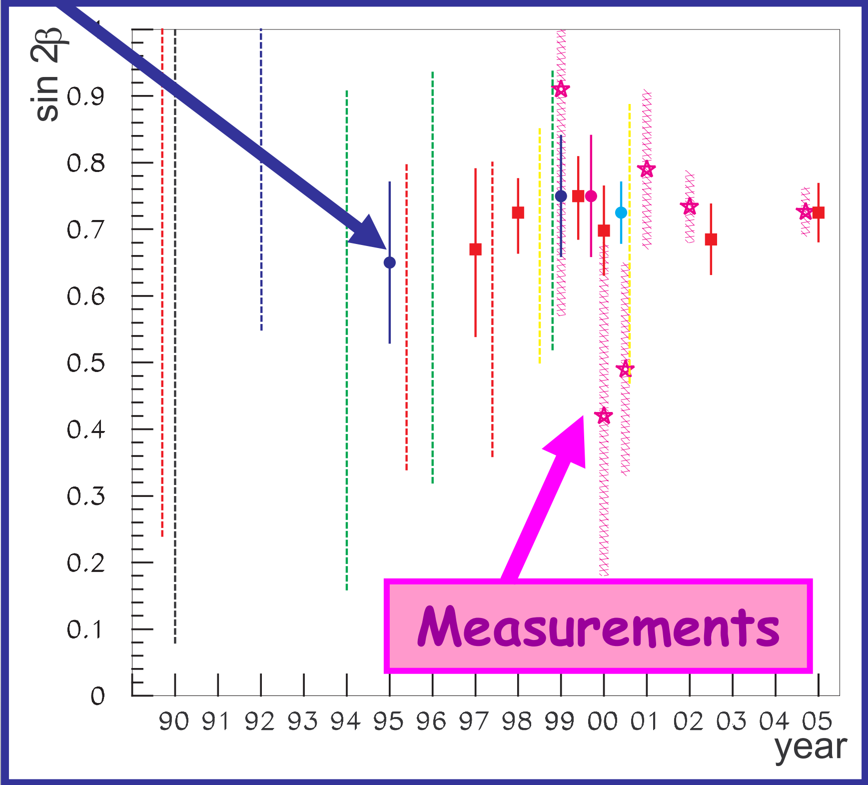
PREDICTION OF Sin2β

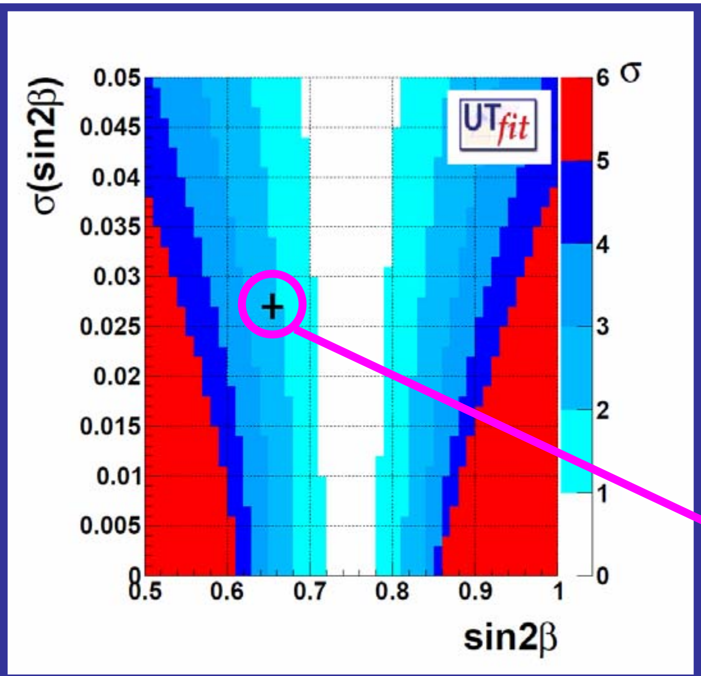
Ciuchini et al.,1995:
$\sin 2\beta_{UTA} = 0.65 \pm 0.12$

Ciuchini et al.,2000:
$\sin 2\beta_{UTA} = 0.698 \pm 0.066$

UTfit today:
$\sin 2\beta_{UTA} = 0.751 \pm 0.035$

Predictions exist since 1995





Direct measurement today:
$\sin 2\beta_{J/\psi K0} = 0.655 \pm 0.027$

SM PREDICTION OF Δm_s

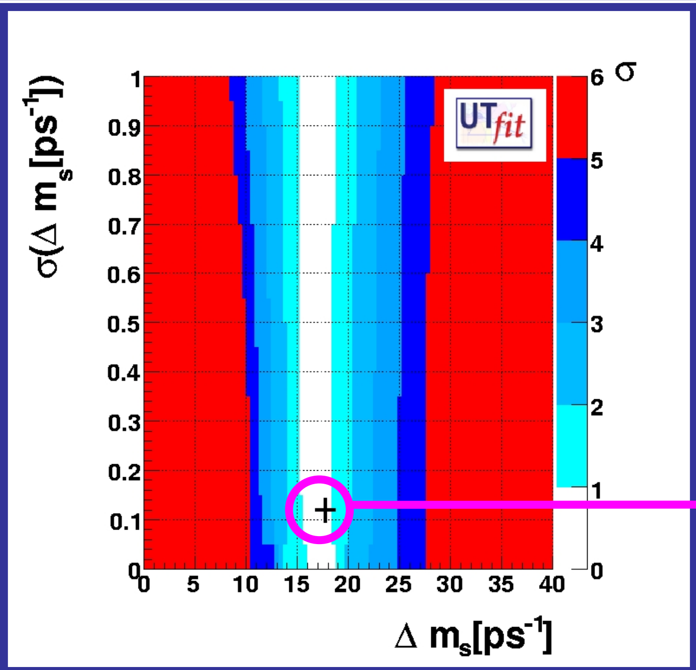
LOOKING FOR NEW PHYSICS EFFECTS

Ciuchini et al.,2000:

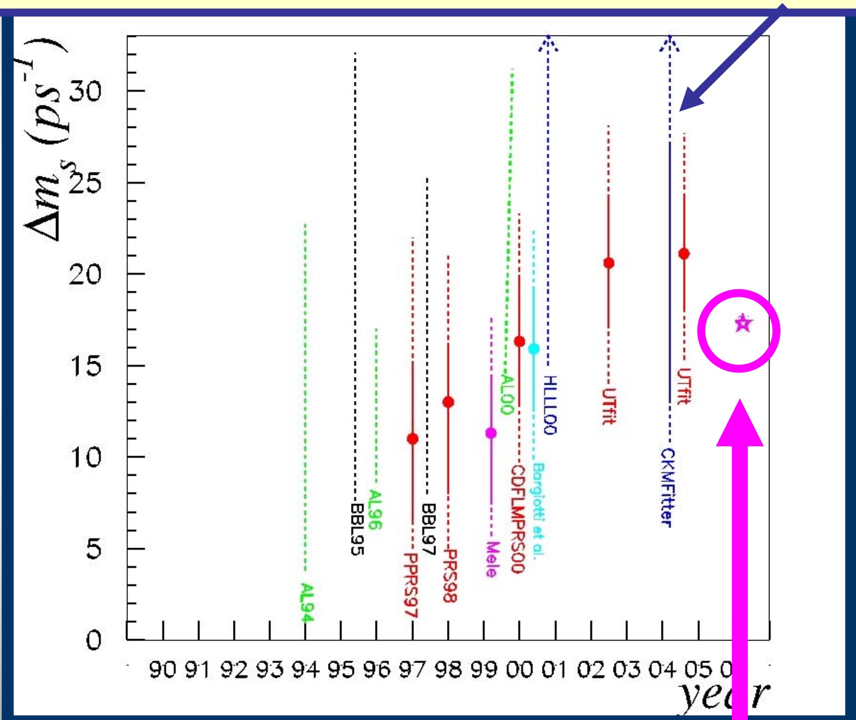
$\Delta m_s = (16.3 \pm 3.4)\ ps^{-1}$

UTfit today:

$\Delta m_s = (16.8 \pm 1.6)\ ps^{-1}$



The predicted range was very large in the frequentistic CKMFitter approach



Direct measurement today

$\Delta m_s = (17.77 \pm 0.12)\ ps^{-1}$

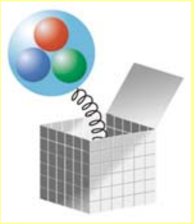
Accuracy of Lattice QCD

2. The “precision” era

PRECISION FLAVOUR PHYSICS

Experiments 2010		
$\|V_{us}\| f_+(0)$	0.21661 ± 0.00047	0.2%
$\frac{\|V_{us}\| F_K}{\|V_{ud}\| F_\pi}$	0.27599 ± 0.00059	0.2%
ε_K	(2.228 ± 0.011) × 10^{-3}	0.5%
Δm_d	(0.507 ± 0.005) ps^{-1}	1%
Δm_s	(17.77 ± 0.12) ps^{-1}	0.7%
Sin2β	0.655 ± 0.027	4%

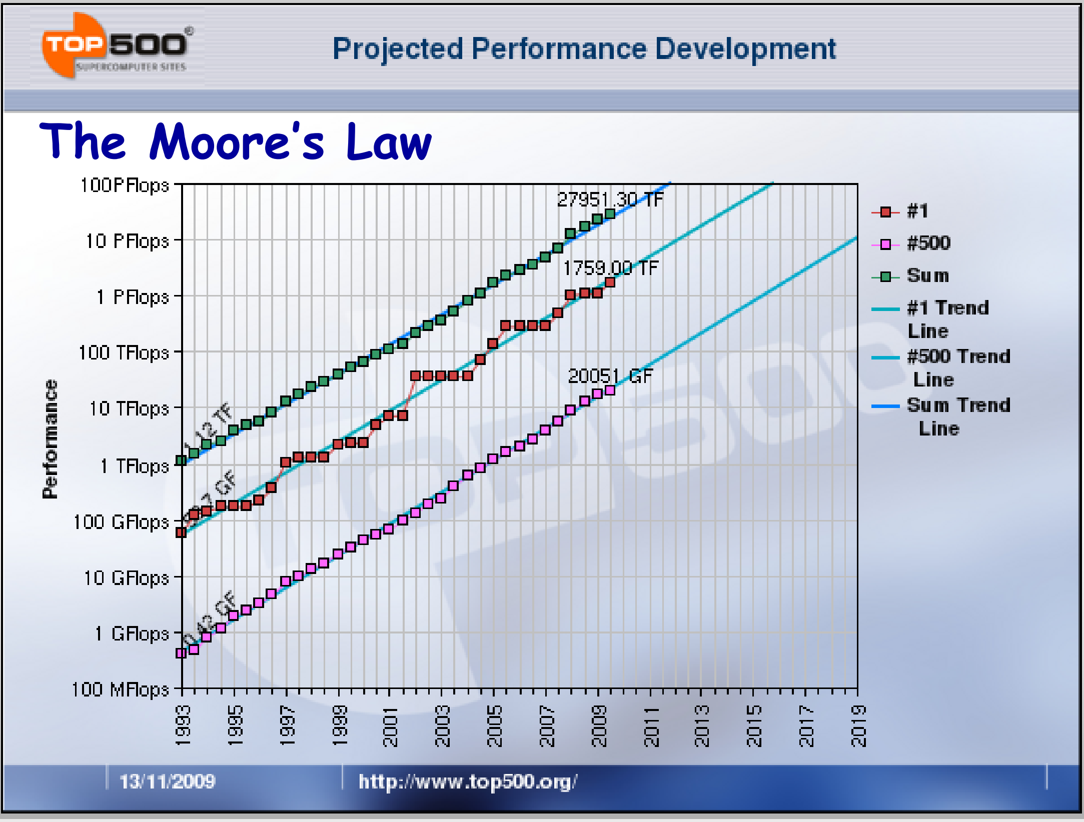
Lattice 2010		2006
$f_+(0)$	0.5%	0.9%
F_K/F_π	0.9%	1.1%
B_K	5%	11%
$f_B\sqrt{B_B}$	5%	13%
$f_{Bs}\sqrt{B_{Bs}}$	5%	13%
—	—	—



THE "PRECISION ERA" OF LATTICE QCD: WHY NOW

1) Increasing of computational power

→ Unquenched simulations



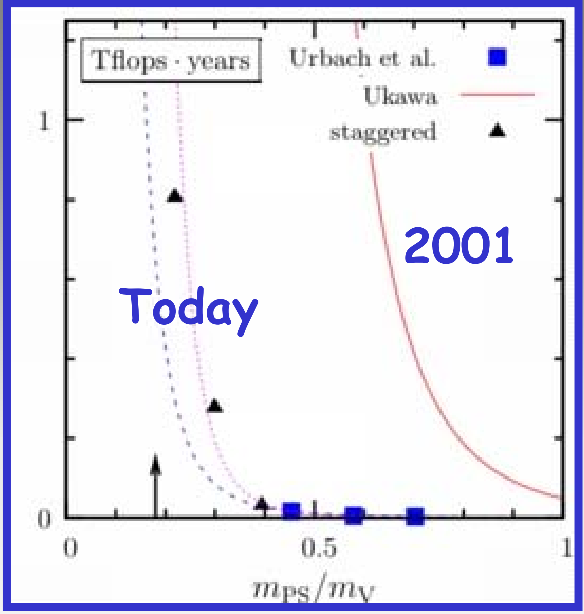
For Lattice QCD today: ~ 5–30TFlops (like the # 500 in the TOP500 list)

TeraFlops machines are required to perform unquenched simulations. Available only since few years.

CPU cost for Nf=2 Wilson fermions: [Del Debbio et al. 2006]

$$\text{TFlops-years} \simeq 0.15 \left(\frac{N_{conf}}{100}\right)\left(\frac{L_s}{3\ \text{fm}}\right)^5\left(\frac{L_t}{2L_s}\right)\left(\frac{0.15}{\hat{m}/m_s}\right)\left(\frac{0.08\ \text{fm}}{a}\right)^6$$

2) Algorithmic improvements:
➡ Light quark masses in the ChPT regime



CPU cost (for Nf=2 Wilson fermions):

Ukawa 2001 (The Berlin wall):

$$\text{TFlops-years} \simeq 3.1 \left(\frac{N_{conf}}{100}\right)\left(\frac{L_s}{3\text{ fm}}\right)^5\left(\frac{L_t}{2L_s}\right)\left(\frac{0.2}{\hat{m}/m_s}\right)^3\left(\frac{0.1\text{ fm}}{a}\right)^7$$

Del Debbio et al. 2006:

$$\text{TFlops-years} \simeq 0.03 \left(\frac{N_{conf}}{100}\right)\left(\frac{L_s}{3\text{ fm}}\right)^5\left(\frac{L_t}{2L_s}\right)\left(\frac{0.2}{\hat{m}/m_s}\right)\left(\frac{0.1\text{ fm}}{a}\right)^6$$

Today: $M_\pi^{latt} \approx 200-300\text{ MeV} \quad \left(\hat{m}_{ud}^{latt}/m_s \approx 1/6-1/12\right)$ ChPT

Few years ago: $M_\pi^{latt} \approx 500\text{ MeV} \quad \left(\hat{m}_{ud}^{latt}/m_s \approx 1/2\right)$

KAON AND B PHYSICS ON THE LATTICE

Collaboration	Quark action	Nf	a [fm]	$(M_\pi)^{min}$ [MeV]	Observables
MILC + FNAL, HPQCD,…	Improved staggered	2+1	≥ 0.045	230	f_K, B_K, f_B, B_B, $B \to D/\pi\, l\nu$
PACS-CS	Clover (NP)	2+1	0.09	156	f_K
RBC/UKQCD	DWF	2+1	≥ 0.08	290	$f_+(0)$, f_K, B_K, $K \to \pi\pi$
BMW	Clover smeared	2+1	≥ 0.07	190	f_K
JLQCD	Overlap	2 [2+1]	0.12	290	B_K
ETMC	Twisted mass	2 [2+1+1]	≥ 0.07	260	$f_+(0)$, f_K, B_K, f_B
QCDSF	Clover (NP)	2	≥ 0.06	300	$f_+(0)$, f_K

THE FIRST ROW UNITARITY TEST

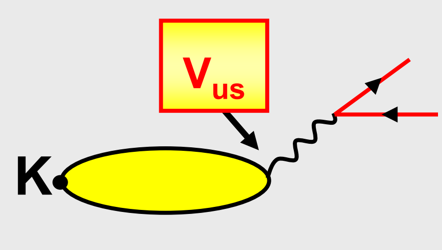
$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

The most stringent unitarity test

Vus/Vud from Kμ2/πμ2 decays

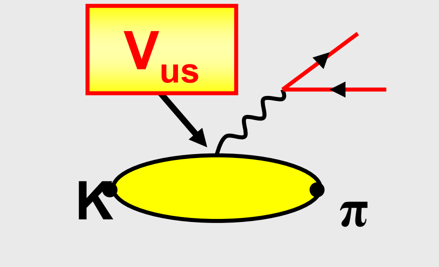
$$\frac{\Gamma(K\to\mu\bar{\nu}_\mu(\gamma))}{\Gamma(\pi\to\mu\bar{\nu}_\mu(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2}\left(\frac{f_K}{f_\pi}\right)^2 \frac{m_K(1-\frac{m_\mu^2}{m_K^2})}{m_\pi(1-\frac{m_\mu^2}{m_\pi^2})} \times 0.9930(35)$$

[Marciano 04]



Vus from Kl3 decays

$$\Gamma_{K\to\pi l\nu} = C_K^2 \frac{G_F^2 m_K^5}{192\pi^2} I\, S_{EW}[1+\Delta_{SU(2)}+2\Delta_{EM}] \times |V_{us}|^2 |f_+^{K\pi}(0)|^2$$

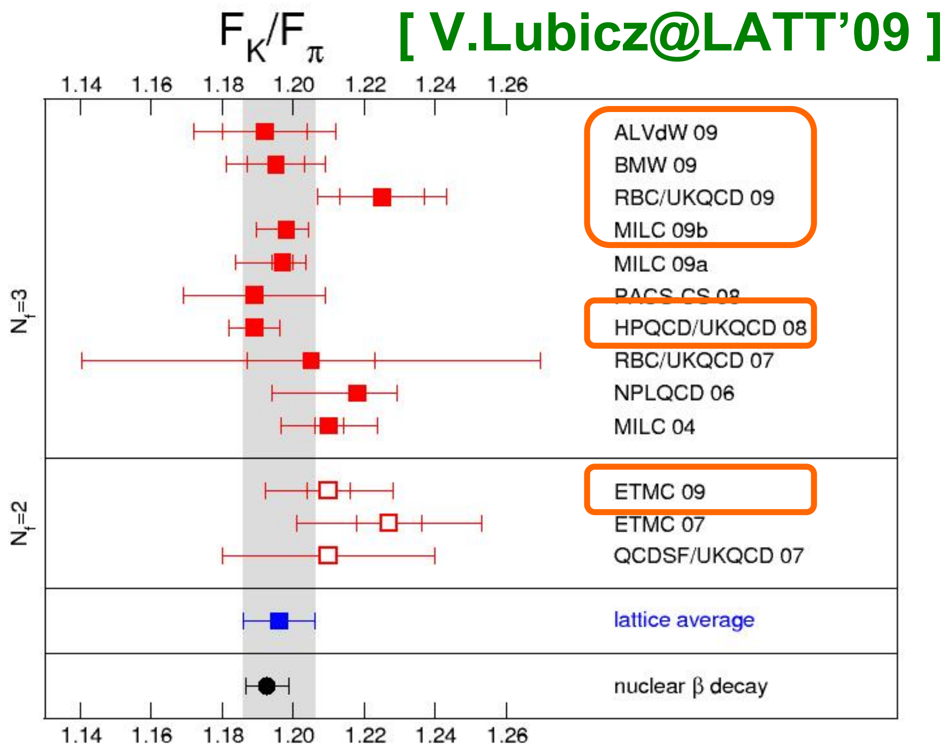


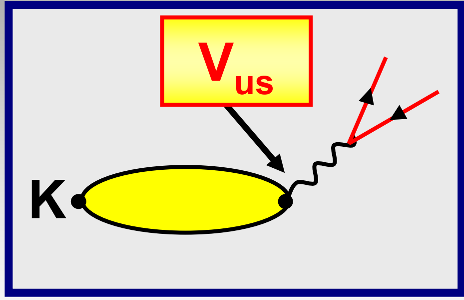
$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_k}{f_\pi} = 0.27599(59)$$

FlaviA net Kaon WG

$$|V_{us}|\, f_+(0) = 0.21661(47)$$

V_{us}/V_{ud} from leptonic K decays: f_K/f_π





$$\frac{\Gamma(K \to \mu\bar{\nu}_\mu(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2}\left(\frac{f_K}{f_\pi}\right)^2 \frac{m_K\left(1-\frac{m_\mu^2}{m_K^2}\right)}{m_\pi\left(1-\frac{m_\mu^2}{m_\pi^2}\right)} \times 0.9930(35)$$

[Marciano 04]

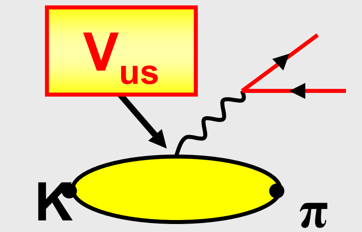
$f_K/f_\pi = 1.196\,(1)\,(10)$ **0.8%**

The accuracy is comparable to the one reached on $f_+(0)$ [0.5%]

- $|V_{us}|_{Kl2} = 0.2248(19)$
- $|V_{us}| = 0.2255(10)$
  Using unitarity and $|V_{ud}|$ from nuclear β decays

V_{us} from semileptonic K decays: $f_+^{K\pi}(0)$

$$\Gamma_{K\to\pi l\nu} = C_K^2 \frac{G_F^2 m_K^5}{192\pi^2} I\, S_{EW}[1 + \Delta_{SU(2)} + 2\Delta_{EM}] \times |V_{us}|^2 |f_+^{K\pi}(0)|^2$$



Ademollo-Gatto: $f_+(0) = 1 - O(m_s - m_u)^2$ ← $O(1\%)$. But represents the largest theoret. uncertainty

SU(3)-ChPT

$$f_+(0) = 1 + f_2 + f_4 + O(p^8)$$

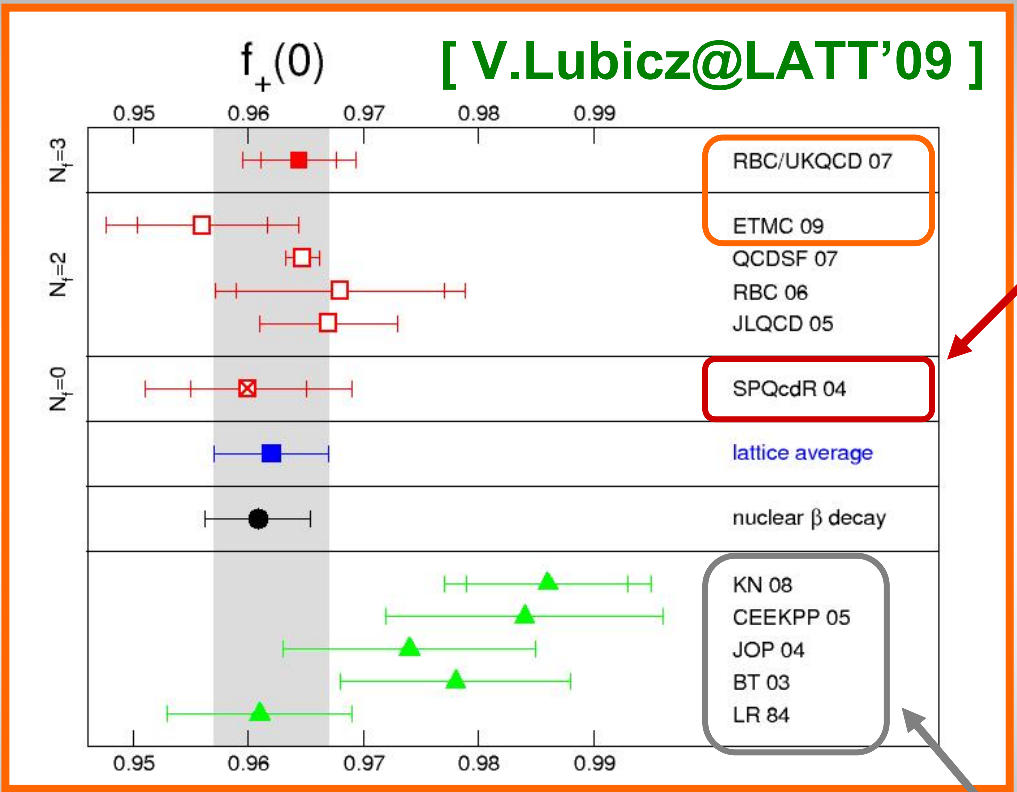
- Vector Current Conservation (→ 1)
- $f_2 = -0.023$ Independent of L_i (Ademollo-Gatto)
- THE LARGEST UNCERTAINTY (→ f_4)

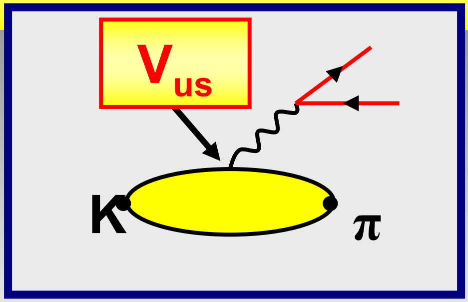
Old standard estimate:

Leutwyler, Roos (1984) (QUARK MODEL)

$f_4 = -0.016 \pm 0.008$

V_{us} from semileptonic K decays: $f_+^{K\pi}(0)$





The first lattice calculation, 2004

Double ratio method: the achieved accuracy is $O(1\%)$

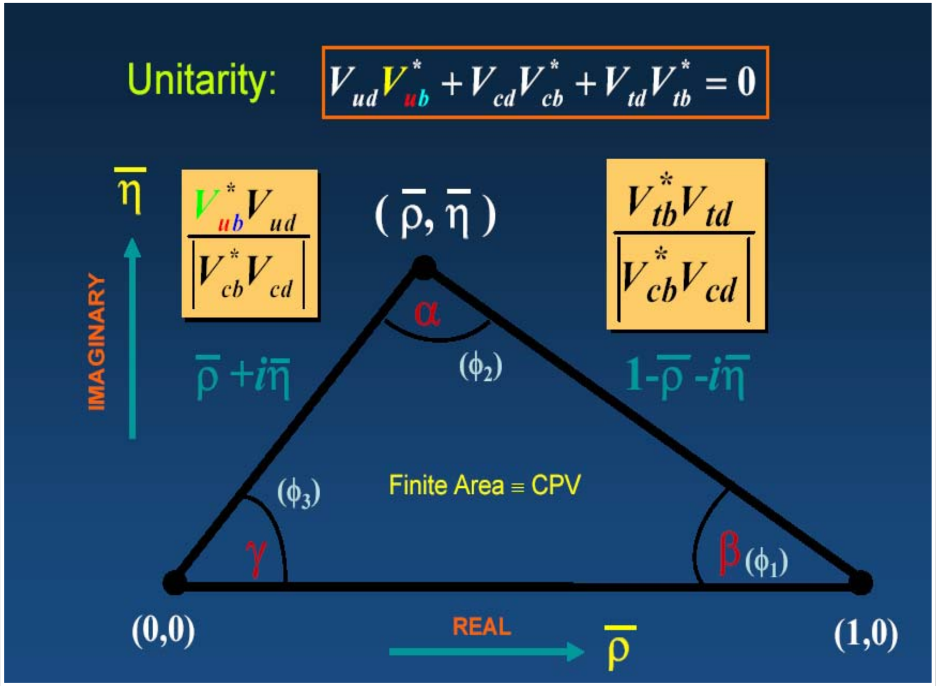
- $|V_{us}|_{Kl3} = 0.2252(13)$
- $|V_{us}|_{Kl2} = 0.2248(19)$
- $|V_{us}| = 0.2255(10)$
  Using unitarity and $|V_{ud}|$ from nuclear β decays

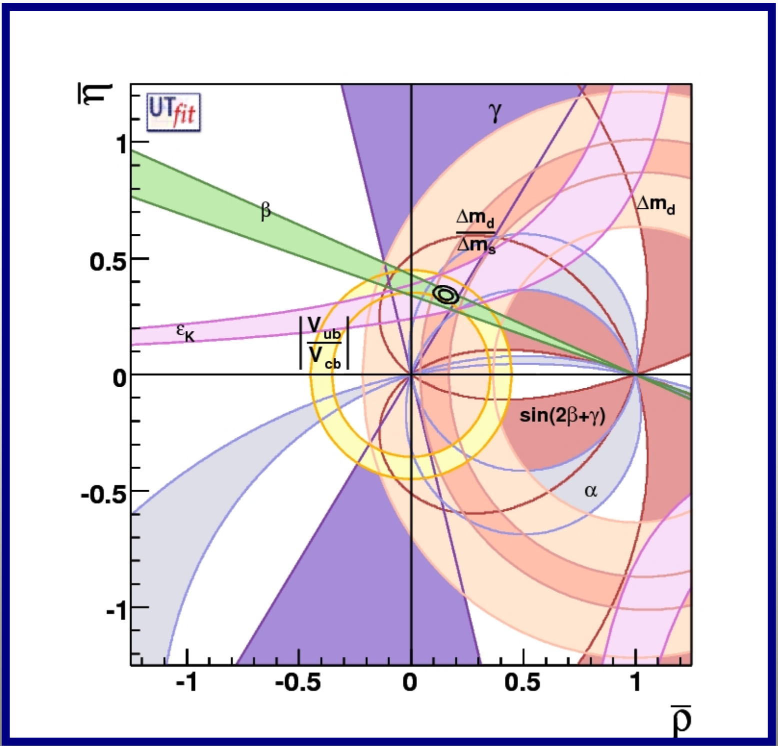
$f_+(0) = 0.962\,(3)\,(4)$ **0.5%**

Analytical model calculations tends to give larger predictions than lattice results

THE UNITARITY TRIANGLE ANALYSIS

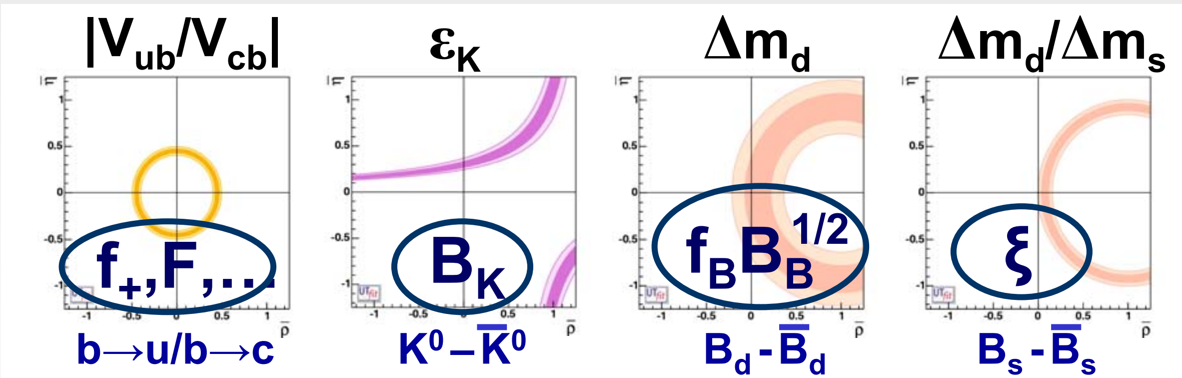
1. Lattice inputs

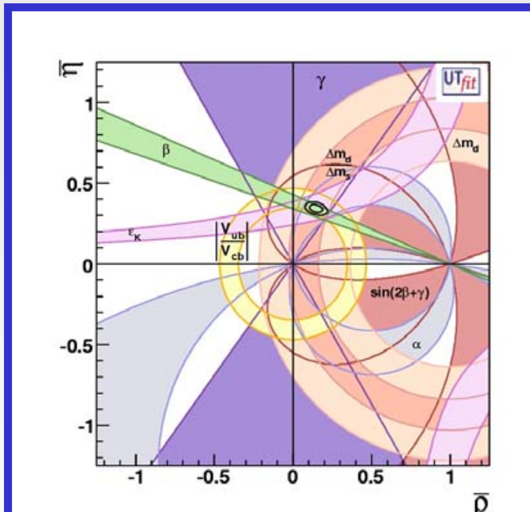




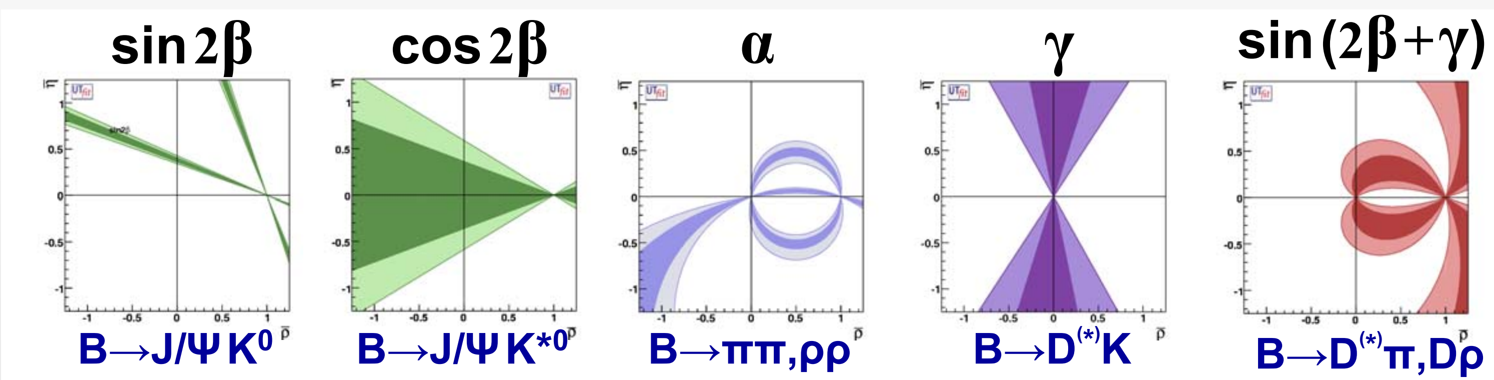
THE UTA CONSTRAINTS

UT-LATTICE

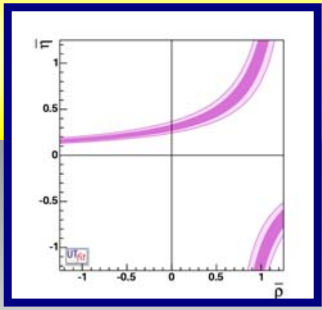


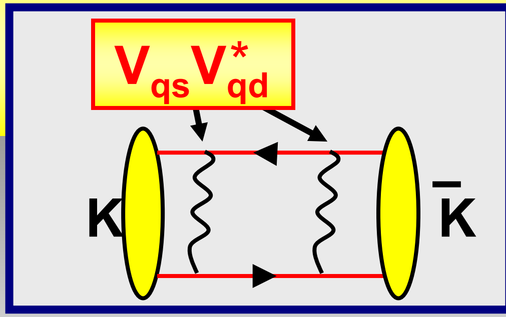


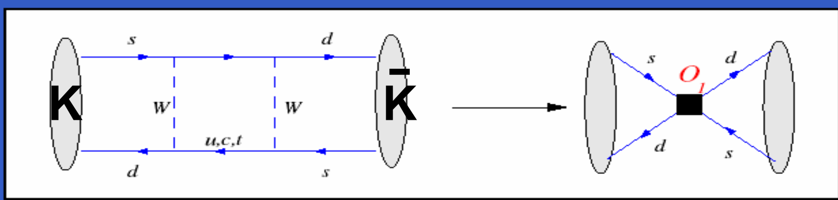
UT-ANGLES



K^0–$\bar{K}^0$ mixing: B_K







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

Pre-history

QCD SR, Pich, De Rafael, **1985**:

$\hat{B}_K = 0.33 \pm 0.09$

LQCD, Gavela et al., **1987**:

$\hat{B}_K = 0.90 \pm 0.20$

History

Quench. error

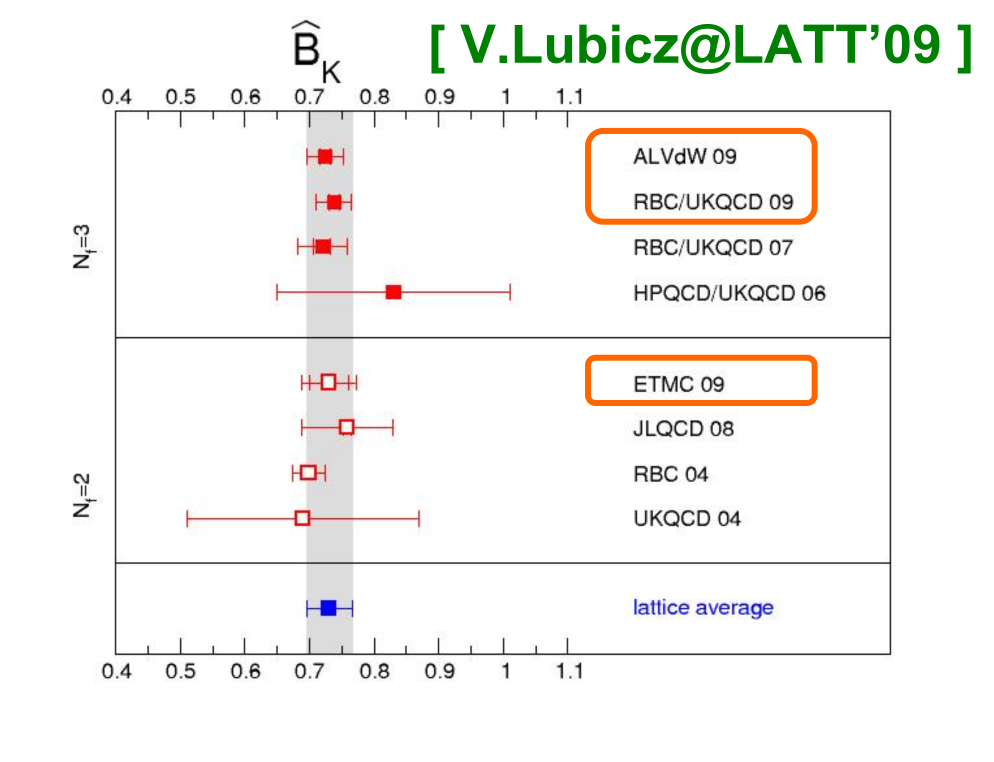
$\hat{B}_K = 0.90 \pm 0.03 \pm 0.15$ — S.Sharpe@Latt'96 — 17%

$\hat{B}_K = 0.86 \pm 0.05 \pm 0.14$ — L.Lellouch@Latt'00 — 17%

$\hat{B}_K = 0.79 \pm 0.04 \pm 0.08$ — C.Dawson@Latt'05 — 11%

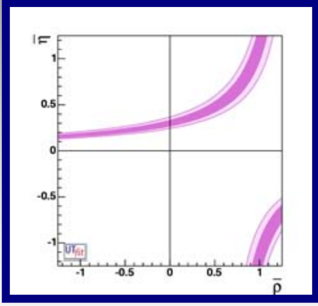
$\hat{B}_K = 0.731 \pm 0.036$ — V.Lubicz@Latt'09 — 5%

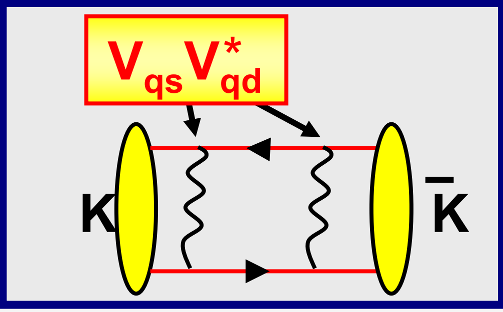
K^0–$\bar{K}^0$ mixing: B_K



$\hat{B}_K = 0.731\,(7)\,(35)$ 5%

Error in 2006: 11%





From the UT fit, assuming the Standard Model

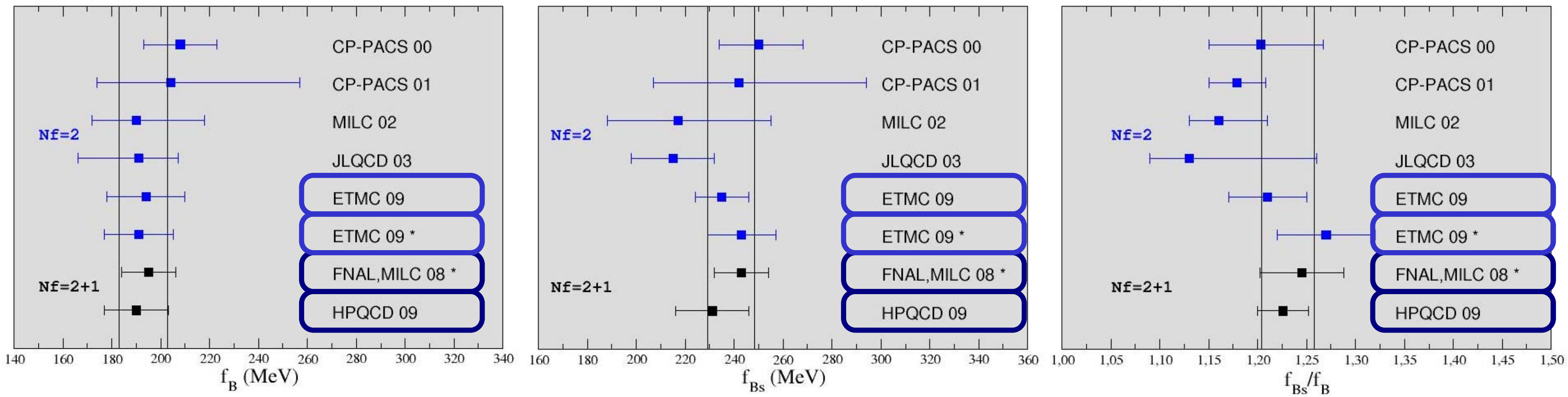
$\hat{B}_K = 0.87\,(8)$

with $K_\varepsilon = 0.94(2)$,

A.Buras, D.Guadagnoli, G.Isidori, arXiv:1002.3612

B-mesons decay constants: f_B, f_{Bs}

Lattice inputs for $\Delta m_{d/s}$ and $B \to \tau\nu$



Averages from J.Laiho, E.Lunghi, R.Van de Water, 0910.2928

f_{Bs} = 238.8 ± 9.5 MeV

f_B = 192.8 ± 9.9 MeV

4-5%

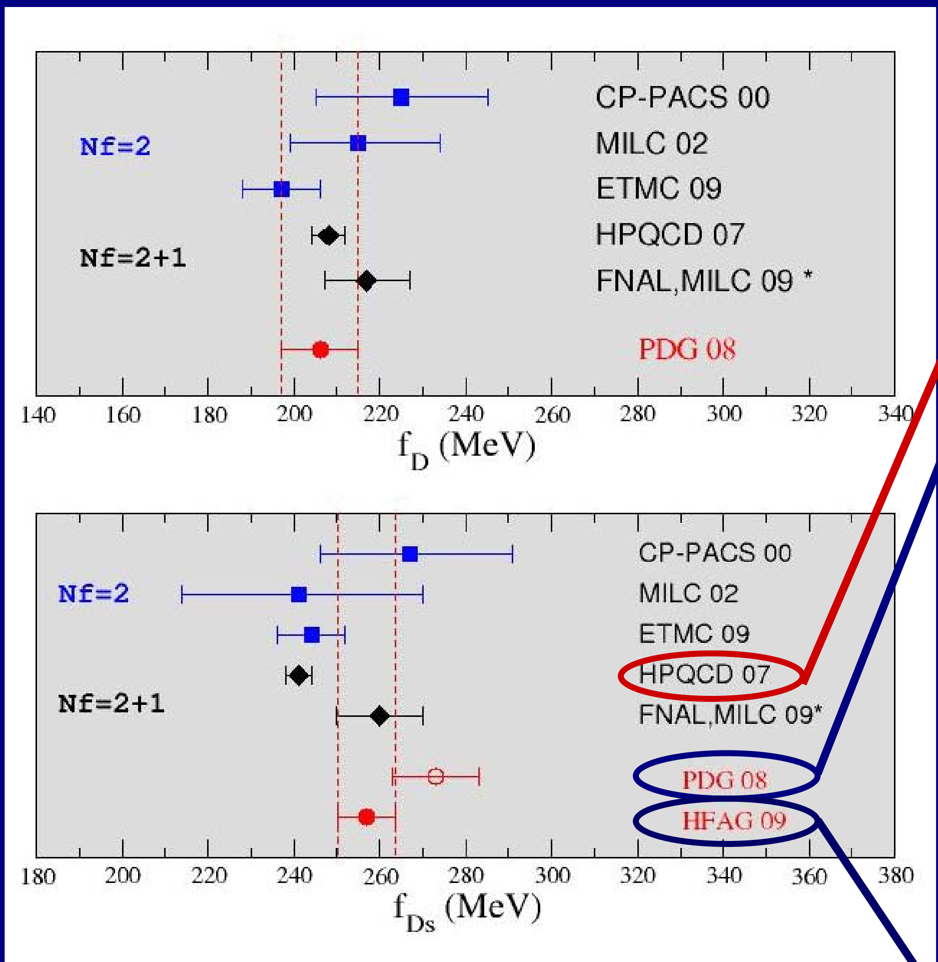
f_{Bs}/f_B = 1.231 ± 0.027

2%

Error in 2006: 14%

Error in 2006: 5%

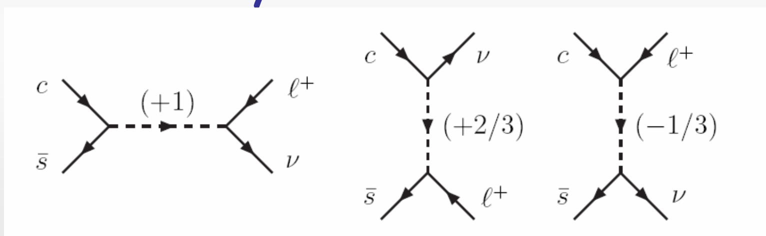
Is there an “f_{Ds} puzzle” ?



A lattice result by HPQCD, which claims a 1.2% precision on fDs, shows a discrepancy of about 3σ with the PDG’08 average:

- f_{Ds}= 241 ± 3 MeV **HPQCD 07**
- f_{Ds}= 273 ± 10 MeV **PDG 08**

B.Dobrescu, A.Kronfeld, 0803.0512
“Evidence for nonstandard leptonic decays of Ds mesons”

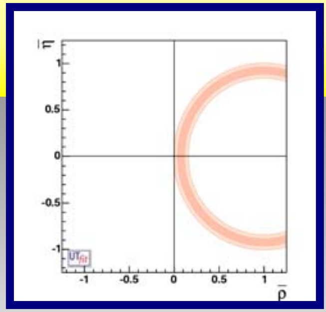


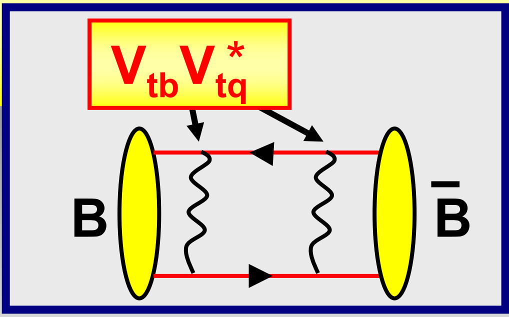
This year, after a new CLEO-c result, the tension is reduced at the 2σ level:

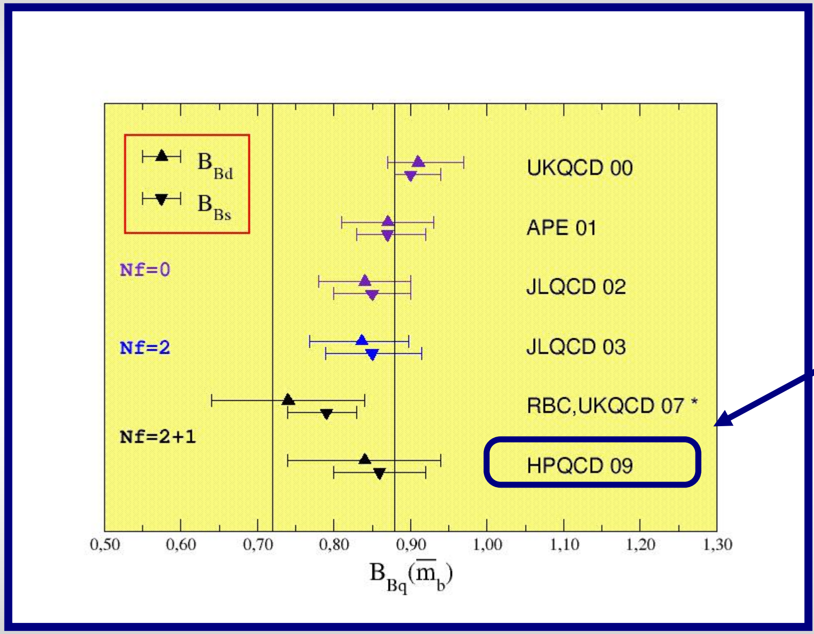
- f_{Ds}= 256.9 ± 6.8 MeV **HFAG 09**

B-$\bar{B}$ mixing: $B_{Bd/s}$

$$\langle \bar{B} | Q(\mu) | B \rangle = \frac{8}{3} m_B^2 f_B^2 B_B(\mu)$$







Only one modern calculation
HPQCD [0902.1815]

$\hat{B}_{Bd} = 1.26 \pm 0.11$

$\hat{B}_{Bs} = 1.33 \pm 0.06$

Combining with fB and fBs:

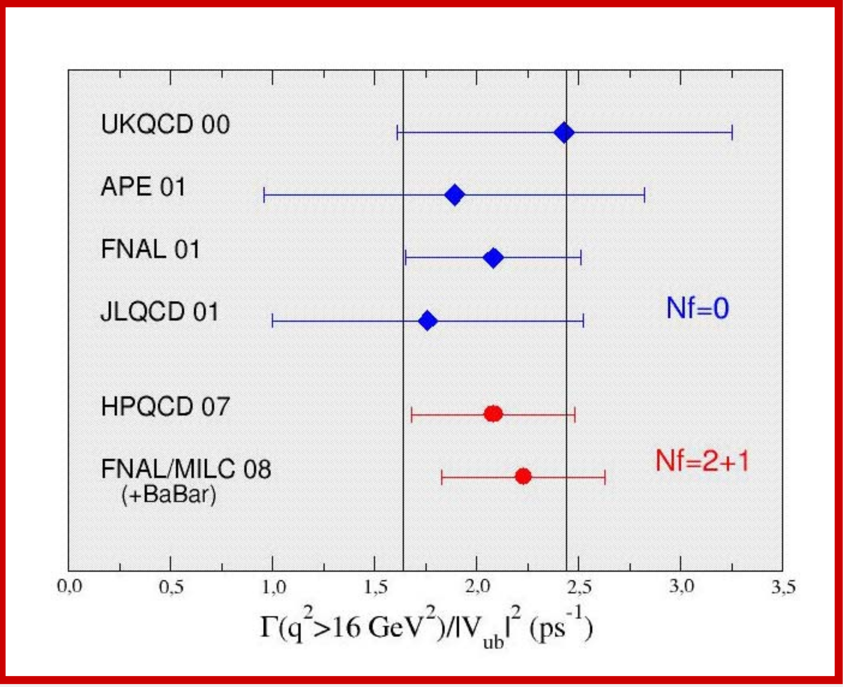
$f_{Bs}\sqrt{\hat{B}_{Bs}} = 275 \pm 13$ MeV — 5%

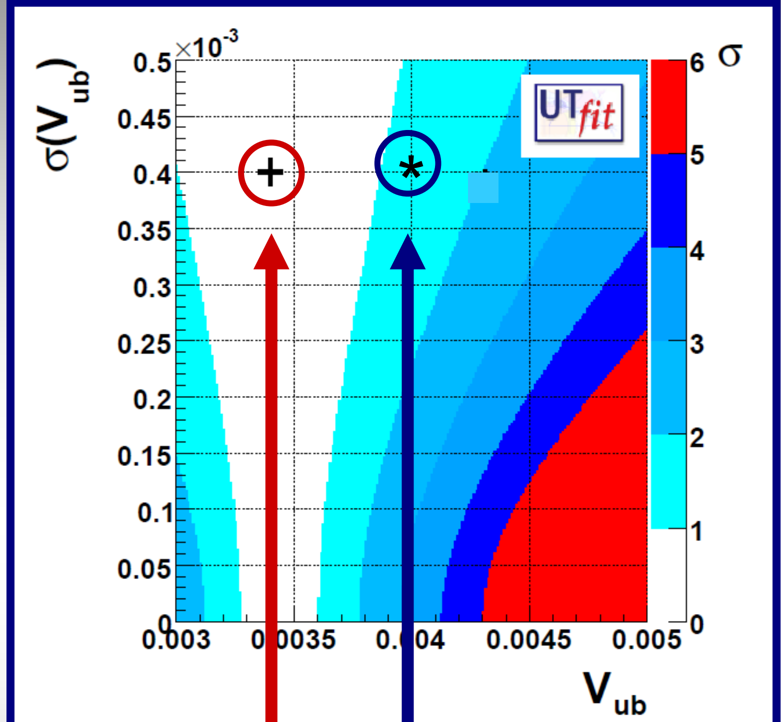
$\xi = 1.243 \pm 0.028$ — 2%

Error in 2006: 13%

Error in 2006: 5%

Exclusive Vub - B→πlν





$|V_{ub}|_{excl.} = (35.0 \pm 4.0)\ 10^{-4}$

11%

Error in 2006: 11%

MORE LATTICE CALCULATIONS REQUIRED

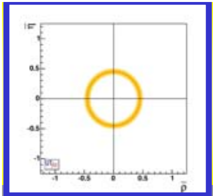
$V_{ub}^{excl.} = (3.5 \pm 0.4)\ 10^{-3}$

From LQCD and QCDSR

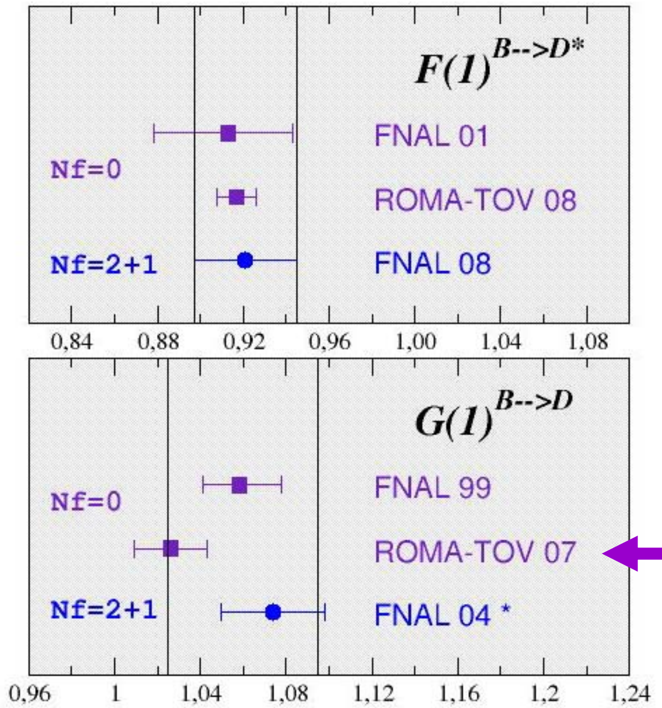
$V_{ub}^{incl.} = (4.0 \pm 0.4)\ 10^{-3}$

Model dependent

BLNP, DGE, GGOU, ADFR, BLL



Exclusive Vcb - B→D/D*lν



Averages from
VL, C.Tarantino 0807.4605

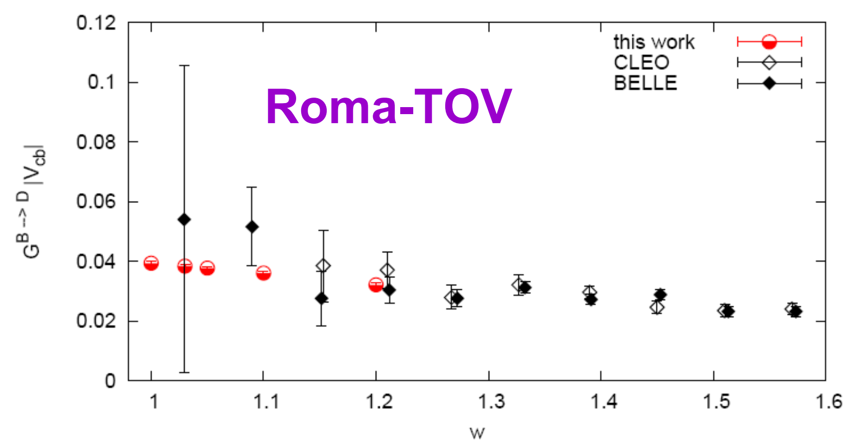
F(1) = 0.924 ± 0.022 **2%**

G(1) = 1.060 ± 0.035 **3%**

TWO DIFFERENT APPROACHES:

- "double ratios" (FNAL)
- "step scaling" (TOV)

Remarkable agreement



Error in 2006: 4%

THE UNITARITY TRIANGLE ANALYSIS

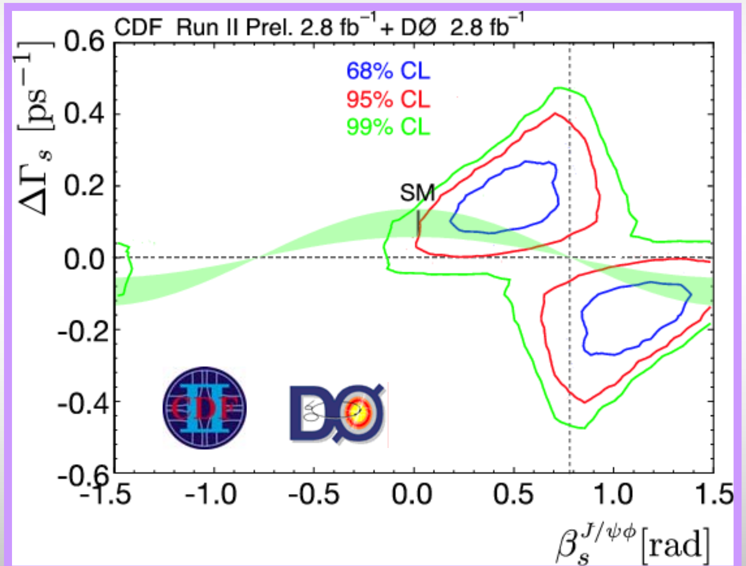
2. Deviations from the Standard Model

Overall, flavour data are in excellent agreement with the SM expectation at the present level of accuracy.
Yet there are few processes showing 2-3σ deviations…

1) THE PHASE OF Bs MIXING

update from UTfit Coll., PMC Physics A 2009, 3:6 [arXiv:0803.0659]

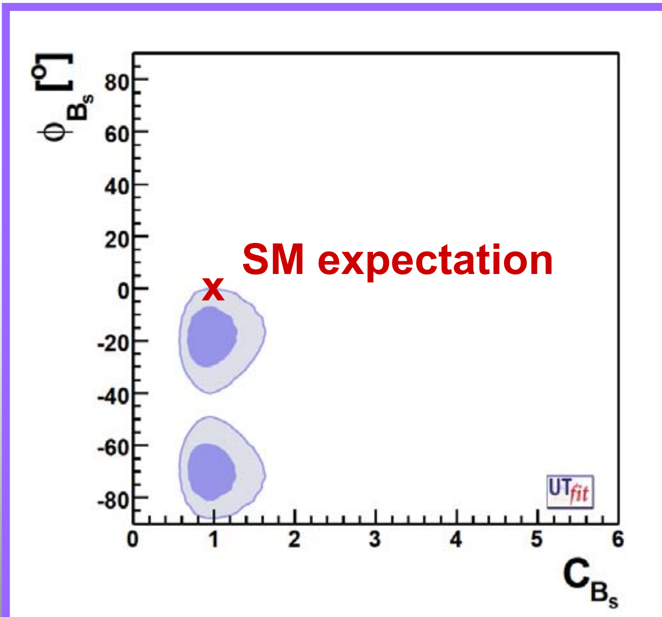
The time-dependent CP asymmetry in $B_s \to J/\Psi\varphi$ has been measured at Tevatron



2.12σ from the SM

From a global fit

$$C_{B_s} e^{2i\varphi_{B_s}} = \frac{\langle B_s^0 | H_{\rm eff}^{\rm full} | \bar{B}_s^0 \rangle}{\langle B_s^0 | H_{\rm eff}^{\rm SM} | \bar{B}_s^0 \rangle}$$



2.5σ from the SM

NB: A 5σ measurement could be possible at the Tevatron

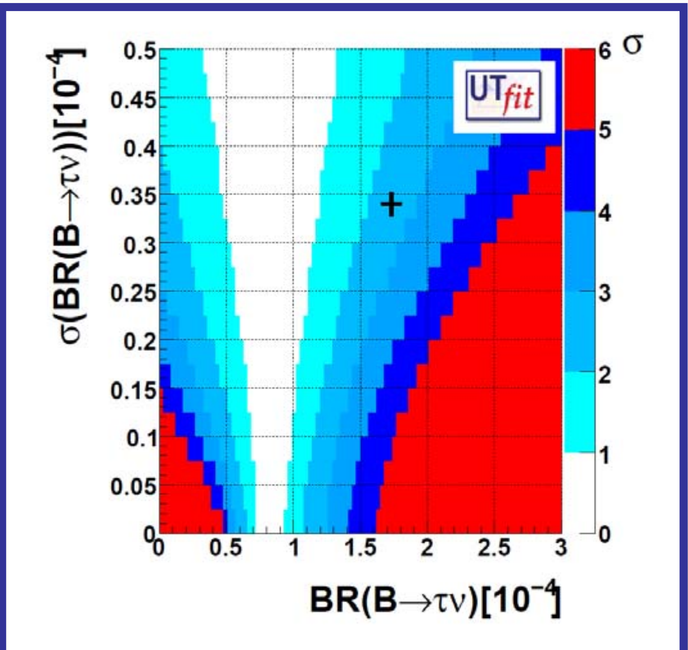
2) Br(B→τν)   UTfit Coll., arXiv:0908.3470

$$BR(B\to\tau\nu_\tau)_{exp} = (1.73\pm0.34)\times10^{-4}$$

$$BR(B\to\tau\nu_\tau)_{no-fit} = (0.98\pm0.24)\times10^{-4}$$ 1.8 σ

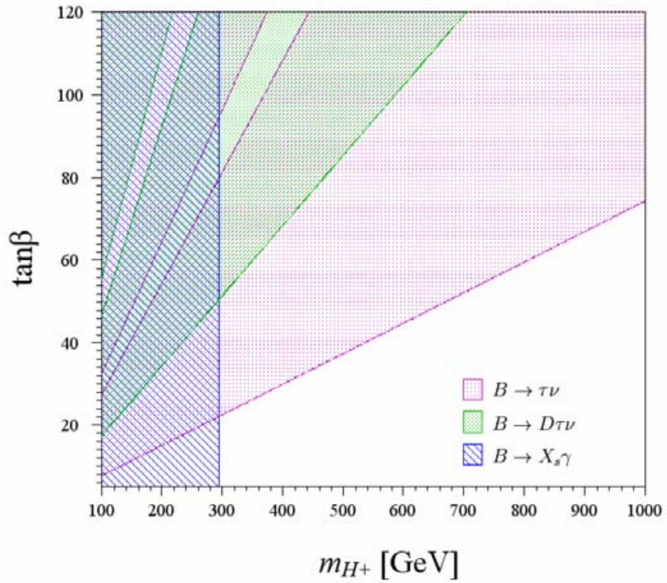
$$BR(B\to\tau\nu_\tau)_{UT} = (0.84\pm0.11)\times10^{-4}$$ 2.5 σ

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



2.5 σ from the SM

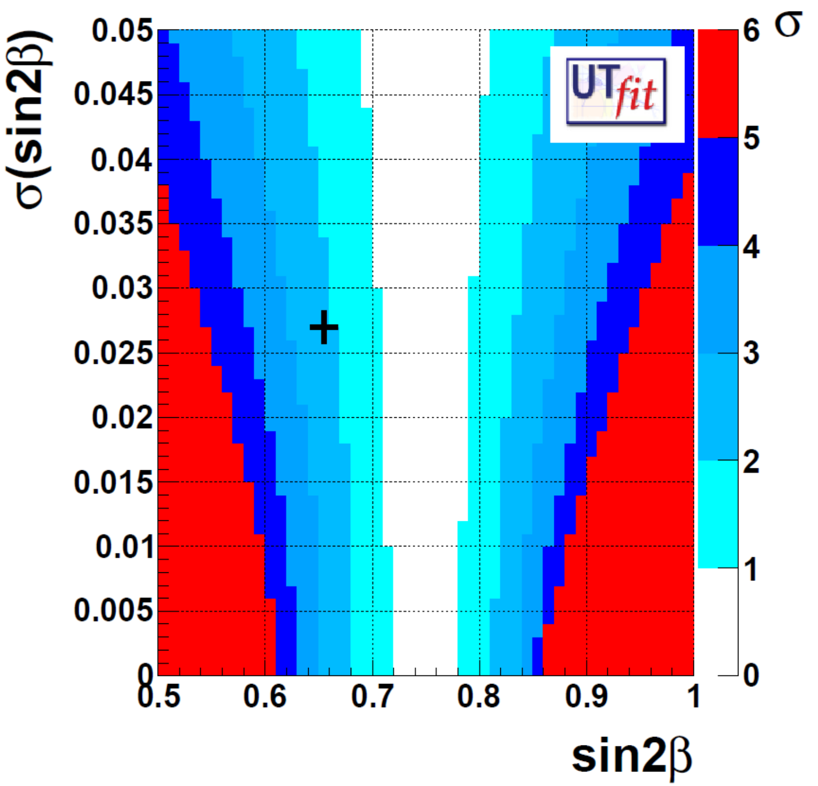
2HDM-II

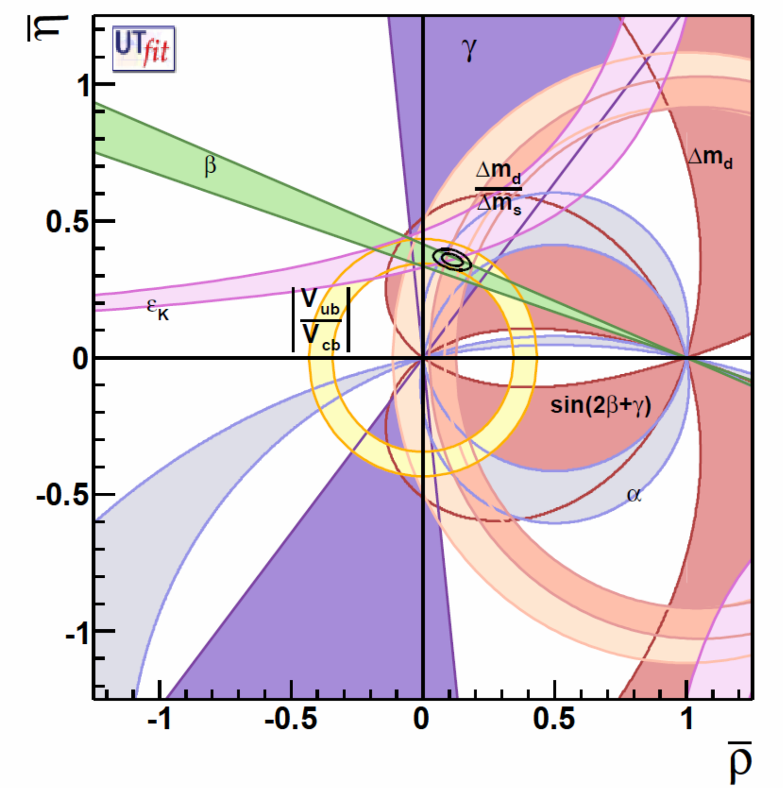


$$BR(B\to\tau\nu) = BR(B\to\tau\nu)_{SM}\left(1-\tan^2\beta\,\frac{m_B^2}{m_{H^+}^2}\right)^2$$

$$\tan\beta < 7.4\,\frac{m_{H^+}}{100\,\mathrm{GeV}}$$ @ 95%

3) TENSION IN THE SM FIT





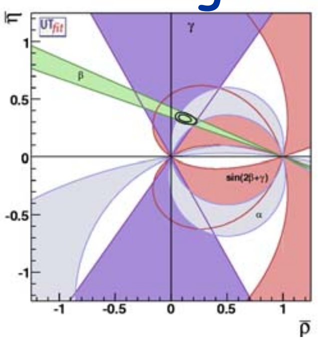
$\mathbf{Sin2\beta_{J/\psi\ K0} = 0.655 \pm 0.027}$

$\mathbf{Sin2\beta_{UTA} = 0.751 \pm 0.035}$

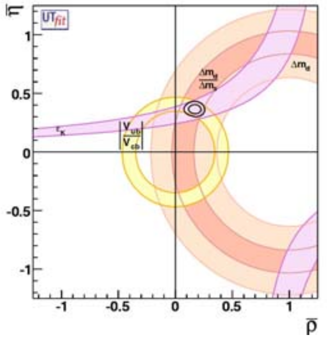
~2.2σ from the SM

UTfit OF LATTICE PARAMETERS

UT-angles



UT-lattice



Assuming the validity of the **Standard Model** one can perform a fit of the hadronic parameters:

Tension in the fit

2%! from Δms

	B_K	$f_{Bs}\sqrt{B_{Bs}}$ (MeV)	ξ
UTA	0.87 ± 0.08	265 ± 4	1.25 ± 0.06
Lattice	0.73 ± 0.04	275 ± 13	1.24 ± 0.03

Lattice inputs are less relevant today for the SM analysis.
But they are crucial when looking for new physics effects

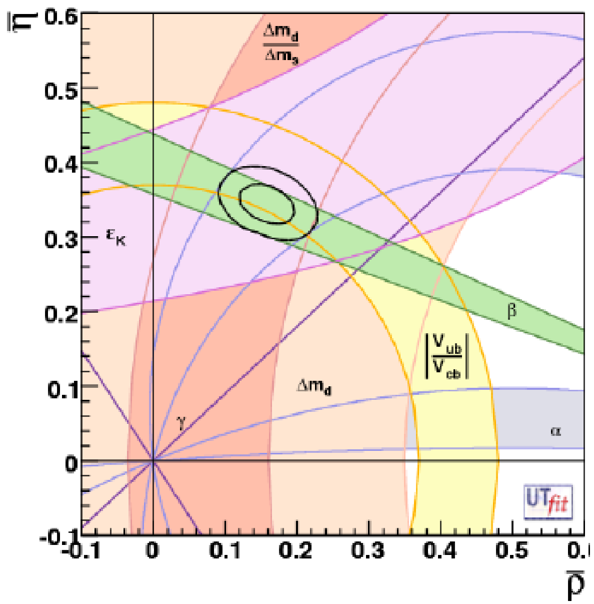
Accuracy of Lattice QCD

3. The future

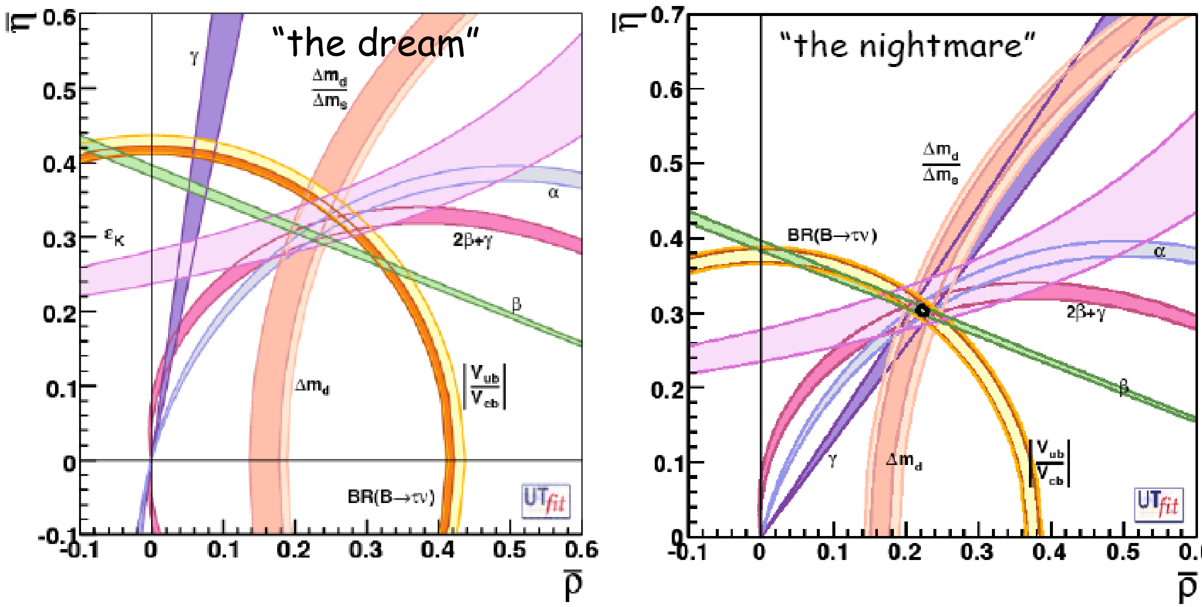
The goal of the SuperB factory is precision flavour physics for indirect New Physics searches

For example: testing the CKM paradigm at the 1% level

Today



With a SuperB in 2015



The theoretical accuracy must compete with the experimental one.

Can we reach the 1% accuracy in Lattice QCD ??

Cost of the “SuperB” lattice simulation

Simulation parameters

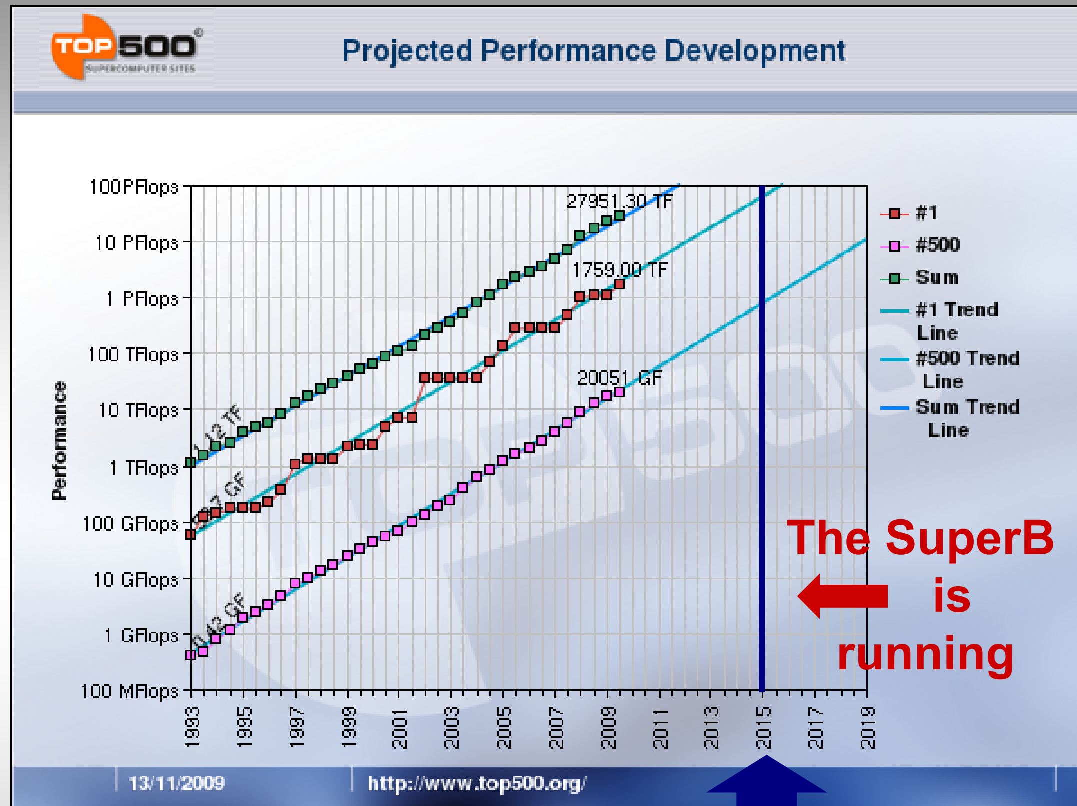
Nconf = 120

a = 0.033 fm
[$1/a$ = 6.0 GeV]

$\hat{m}/m_s$ = 1/12
[M_π = 200 MeV]

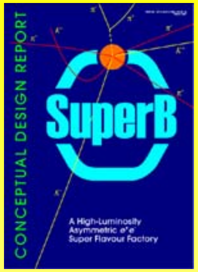
L_s = 4.5 fm
[$V = 136^3 \times 270$]

~ 3 PFlop-years



Affordable with 1-10 PFlops available for Lattice QCD in 2015 !

VL @ 

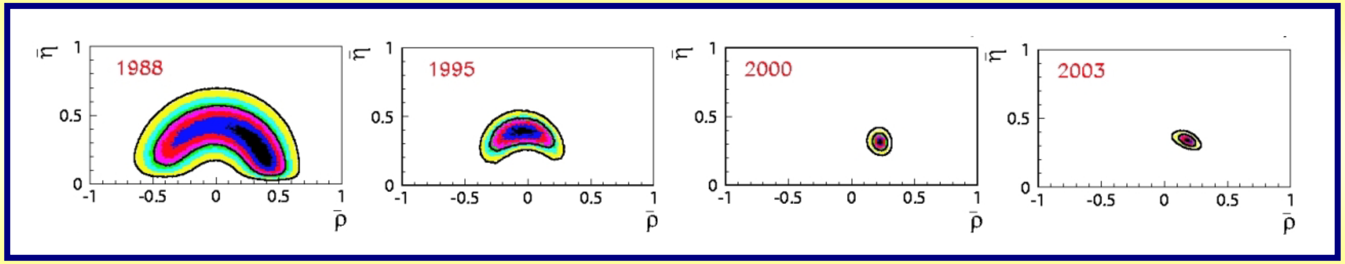


V.Lubicz @

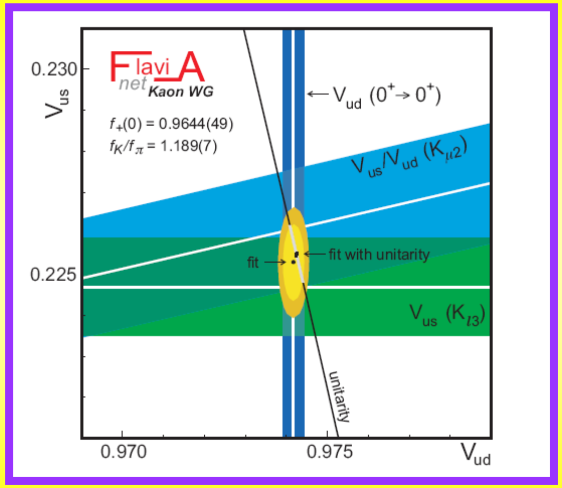
Villa Mondragone
Monte Porzio Catone - Italy
13 - 15 November 2006

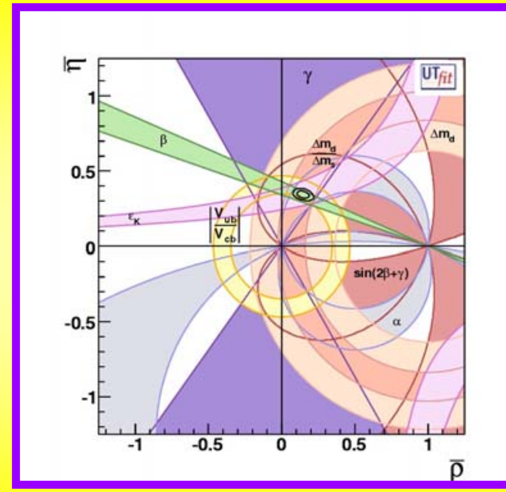
Hadronic matrix element	Lattice error in 2006	Lattice error in 2009	6 TFlop Year [2009]	60 TFlop Year [2011 LHCb]	1-10 PFlop Year [2015 SuperB]
$f_+^{K\pi}(0)$	0.9%	**0.5%**	0.7%	0.4%	**< 0.1%**
$\hat{B}_K$	11%	**5%**	5%	3%	**1%**
f_B	14%	**5%**	3.5 - 4.5%	2.5 - 4.0%	**1 – 1.5%**
$f_{Bs}B_{Bs}^{1/2}$	13%	**5%**	4 - 5%	3 - 4%	**1 – 1.5%**
ξ	5%	**2%**	3%	1.5 - 2 %	**0.5 – 0.8 %**
$\mathcal{F}_{B \to D/D^* l\nu}$	4%	**2%**	2%	1.2%	**0.5%**
$f_+^{B\pi}, \ldots$	11%	**11%**	5.5 - 6.5%	4 - 5%	**2 – 3%**
$T_1^{B \to K^*/\rho}$	13%	**13%**	----	----	**3 – 4%**

The past



the present





and the future