XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

Sep. 16 to 21, 2013 Natal, Brazil

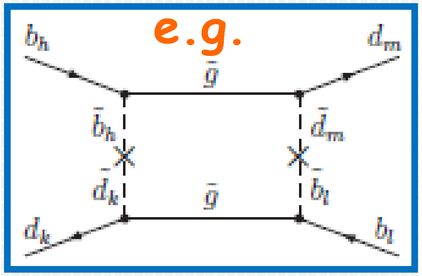
Theory Summary of WG 3
-Weak decays, CKM and CP-violation-

Theory talks:

The Unitarity Triangle Analysis (Denis Derkach)
Lattice QCD and Flavor (Benoit Blossier)
K- and D-meson Physics (Joachim Brod)
B-Physics (Diego Guadagnoli)
Lepton Flavor Violation (Oscar Vives)

Cecilia Tarantino
Università Roma Tre

Flavor Physics is complementary,
in NP searches,
to the direct production
of NP particles



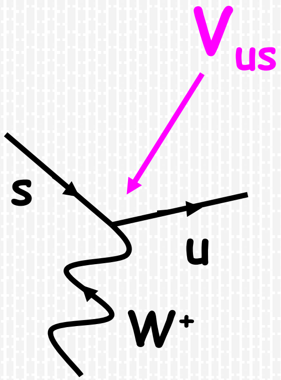
In SM suppressed
Flavor processes
NP effects
may be visible

It is crucial to have accurate theoretical predictions
in order to reveal possible NP effects

A prerequisite is the accurate determination of the parameters of the Cabibbo-Kobayashi-Maskawa mixing matrix

Weak eigenstates → Mass eigenstates

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



The Wolfenstein parameterization
$(A,\ \lambda,\ \rho,\ \eta)$

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

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

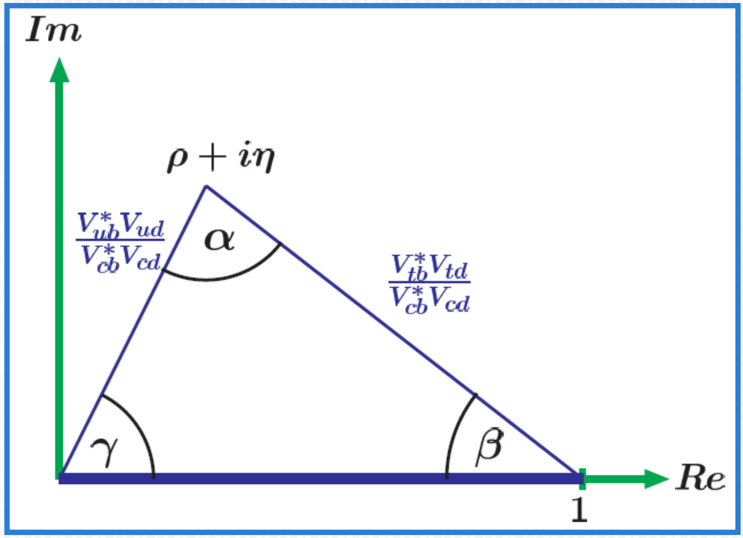
($O(\lambda^5)$) corrections are required by the present accuracy)

The Unitarity Triangle Analysis (UTA)

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

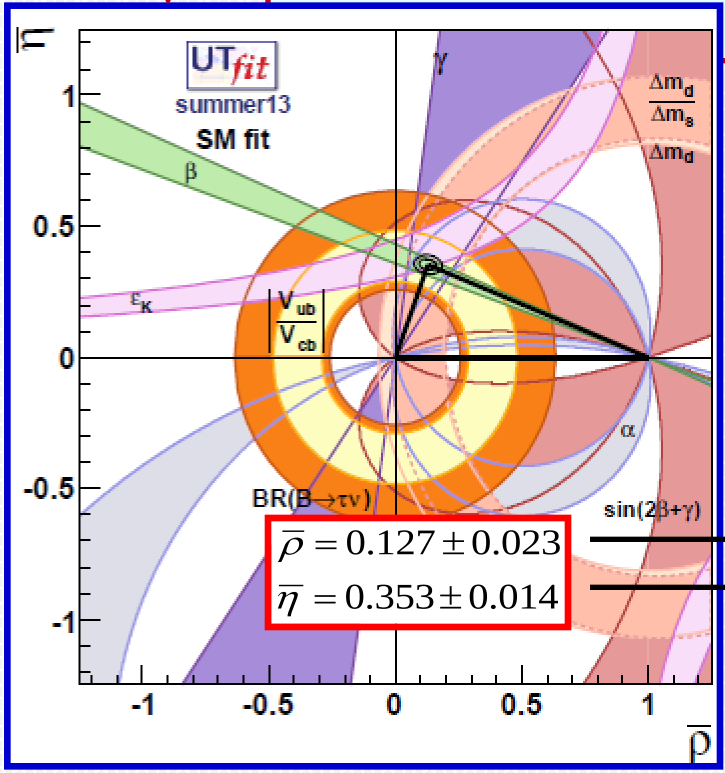
$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$

is of great phenomenological interest



The UTA (summer 2013, post-EPS) by UTfit [Denis Derkach]

SM analysis



$\bar\rho = 0.127 \pm 0.023$ → ~18%

$\bar\eta = 0.353 \pm 0.014$ → ~ 4%

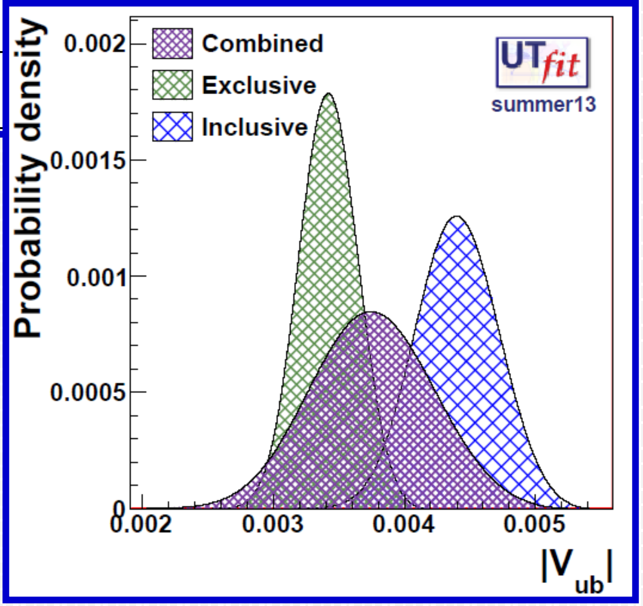
The experimental constraints overconstrain the CKM parameters consistently

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

From a closer look

	Measurement	Prediction	Pull
α, °	(90.7 ± 7.4)	(87.7 ± 3.3)	<1
$\sin(2\beta)$	(0.680 ± 0.023)	(0.754 ± 0.042)	-1.5
γ, °	(70.1 ± 7.1)	(69.8 ± 3.9)	~0
V_{ub}, 10^{-3}	(3.75 ± 0.46)	(3.62 ± 0.13)	+0.3
V_{cb}, 10^{-3}	(40.9 ± 1.0)	(42.1 ± 0.7)	-1.0
ε_K, 10^{-3}	(2.228 ± 0.011)	(2.04 ± 0.19)	+1.0
Δm_s, ps^{-1}	(17.768 ± 0.024)	(17.4 ± 1.1)	-0.3
$B(B_u\to\tau\nu)$, 10^{-4}	(1.14 ± 0.22)	(0.806 ± 0.07)	-1.4
$B(B_s\to\mu\mu)$, 10^{-9}	(2.9 ± 0.7)	(3.91 ± 0.16)	1.3
$B(B_d\to\mu\mu)$, 10^{-9}	(0.37 ± 0.15)	(0.115 ± 0.007)	-1.7

+ the still present V_{ub} inclusive-exclusive tension



$|V_{ub}|_{excl} = (34.2 \pm 2.2)\cdot 10^{-4}$

2.9 σ

$|V_{ub}|_{incl} = (44.0 \pm 2.5)\cdot 10^{-4}$

Generic NP parameterization

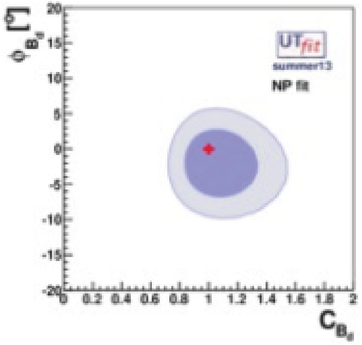
Since the fit is over constrained, we can introduce new parameters added in order to parameterize generic NP ΔF=2 processes in all sectors

B_d and B_s mixing amplitudes (2+2 real parameters):

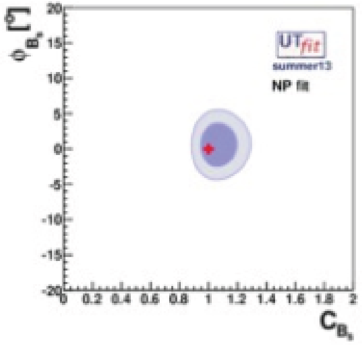
$$A_q e^{2i\phi_q} = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1+\frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP}-\phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

Generic NP Fit results

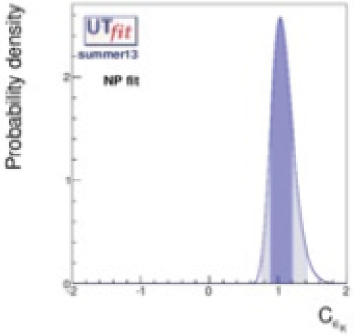
We thus obtain the following results.



C_{Bd} = 1.10 ± 0.17
φ_{Bd} = (-2.1 ± 3.2)°



C_{Bs} = 1.08 ± 0.09
φ_{Bs} = (0.6 ± 2.0)°



$C_{\epsilon K}$ = 1.08 ± 0.16

SM:

$$\bar{\rho} = 0.127 \pm 0.023$$
$$\bar{\eta} = 0.353 \pm 0.014$$

NP:

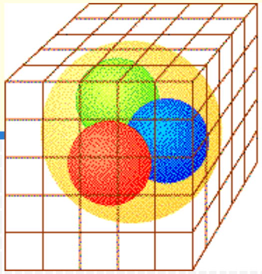
$$\bar{\rho} = 0.147 \pm 0.045$$
$$\bar{\eta} = 0.368 \pm 0.048$$

In the UTA and more in general in Flavor analyses
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**



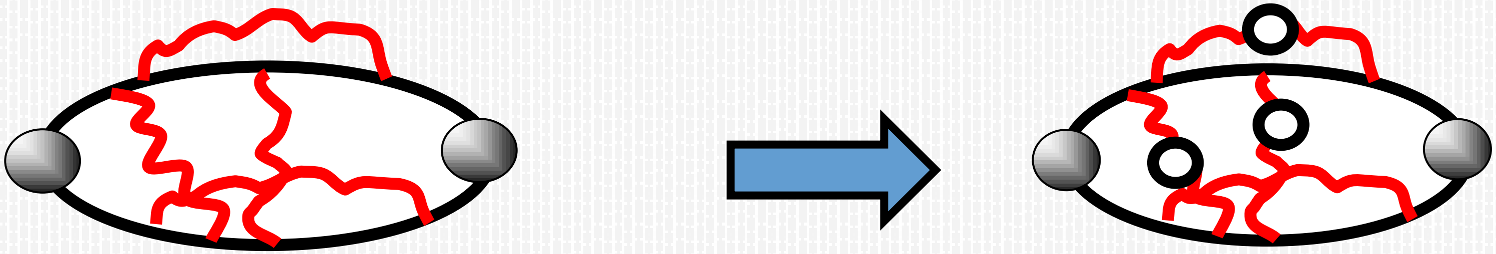
We are in the era of

"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)

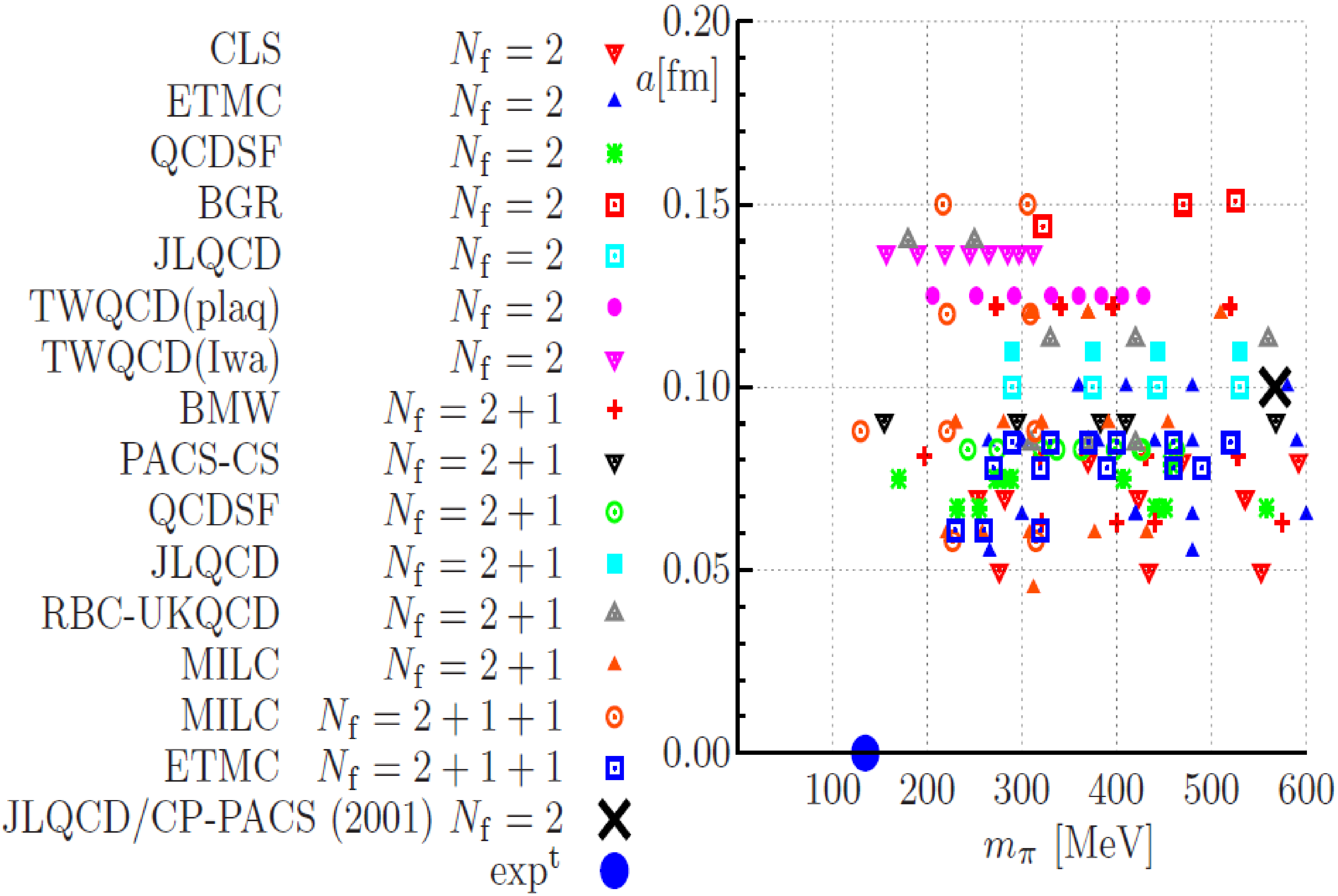
2) Algorithmic improvements:

→ Light quark masses in the ChPT regime

State of the art of Flavor Lattice QCD
[Benoit Blossier]

Simulations set up

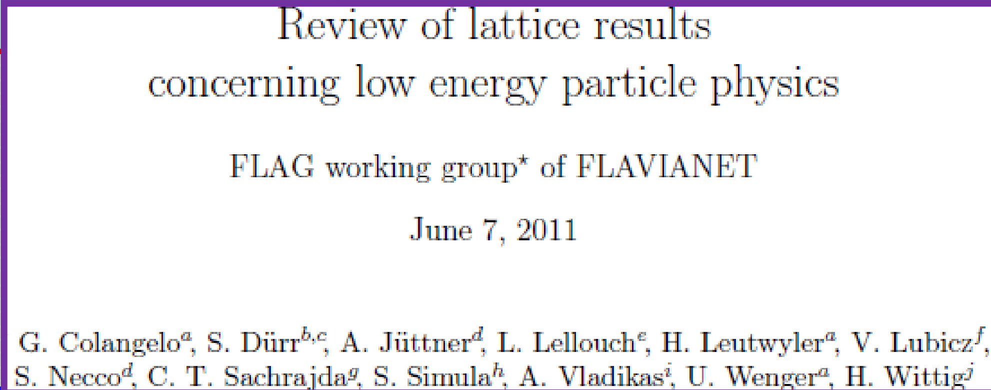
Nowadays, simulations are quite close to the physical point.



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)



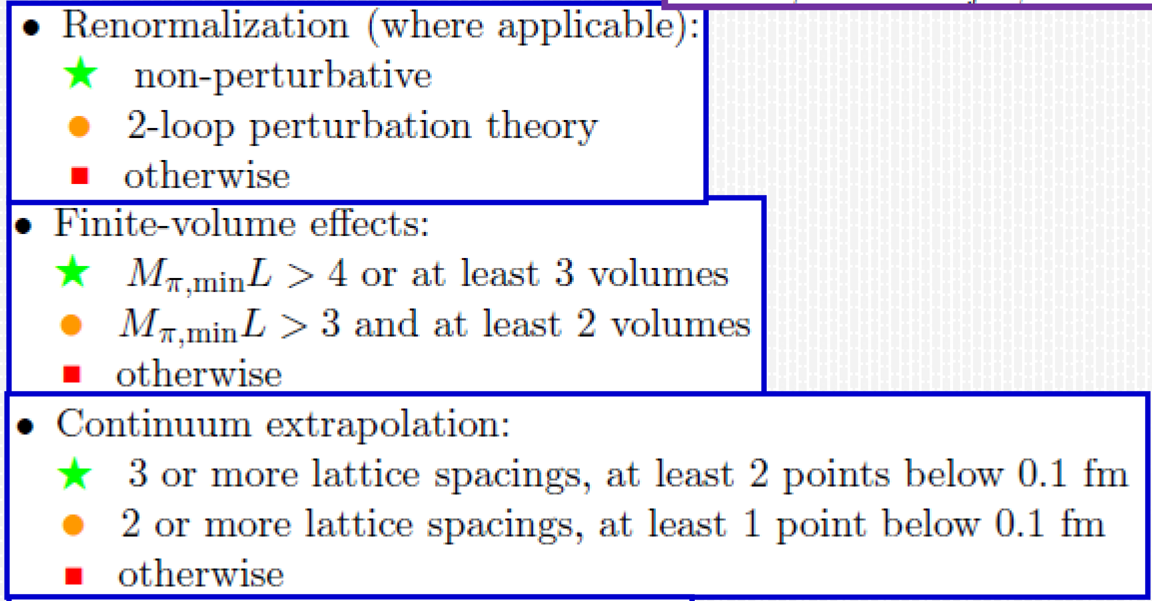
Review of lattice results
concerning low energy particle physics

FLAG working group* of FLAVIANET

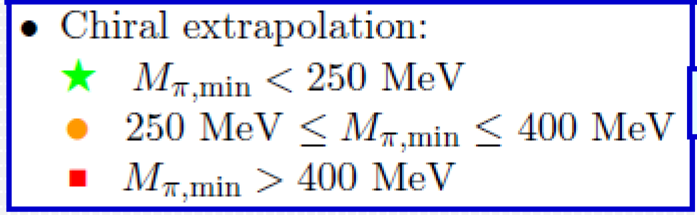
June 7, 2011

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. Vladikas[i], U. Wenger[a], H. Wittig[j]

Several recent lattice results have green stars



- 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
- 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

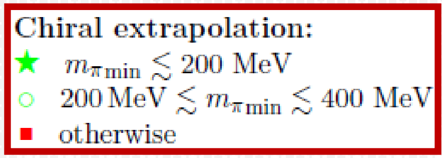


- Chiral extrapolation:
  - ★ $M_{\pi,\min} < 250$ MeV
  - ● $250\ \text{MeV} \le M_{\pi,\min} \le 400$ MeV
  - ■ $M_{\pi,\min} > 400$ MeV

2013: FLAG2
updates +
heavy-flavor Physics

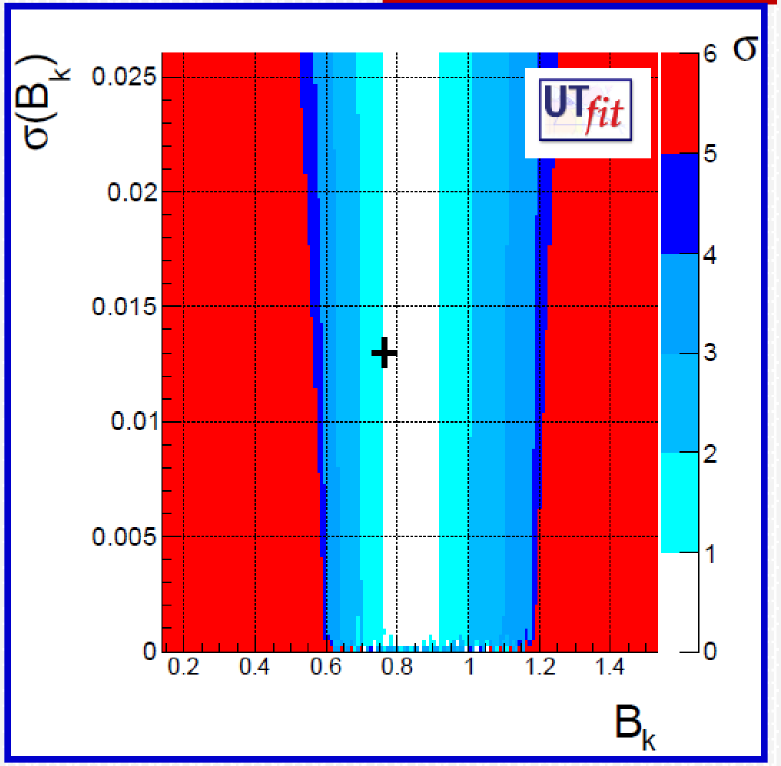
http://itpwiki.unibe.ch/flag/
(preliminary)

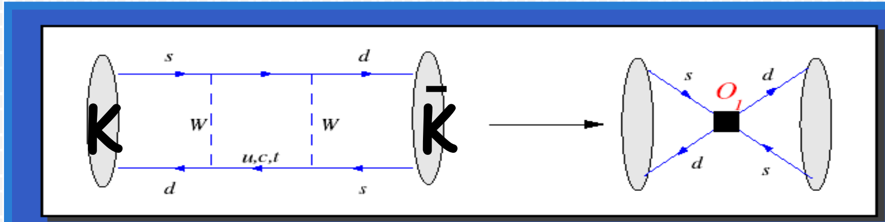
First N_f=2+1+1 results appear



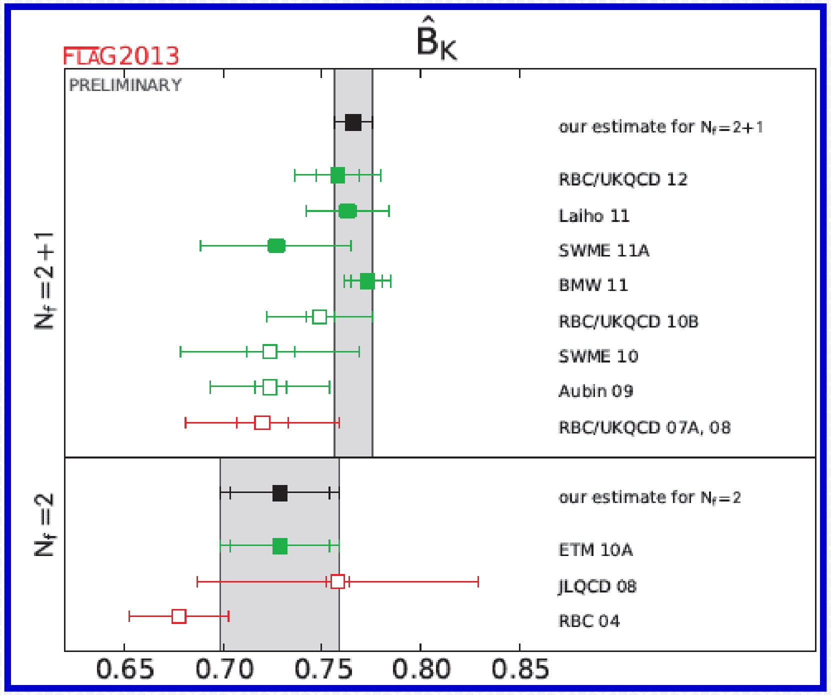
Chiral extrapolation:
★ $m_{\pi\min} \lesssim 200$ MeV
○ $200\ \text{MeV} \lesssim m_{\pi\min} \lesssim 400$ MeV
■ otherwise

ε_K (⟺ B_K)





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



$(\hat{B}_K)_{N_f=2+1} = 0.766(10)$

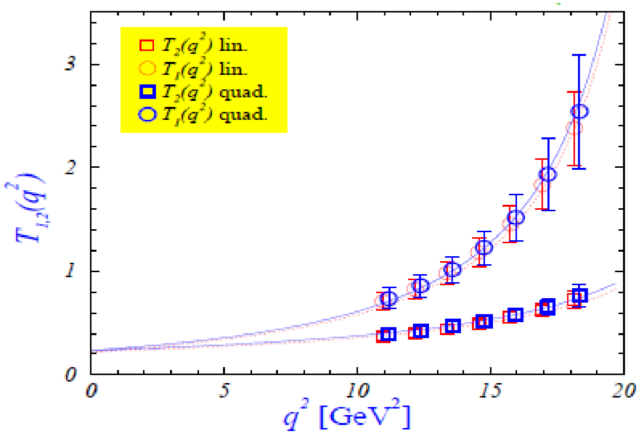
- BMW and RBC/UKQCD results are obtained with pion masses close to the physical point
- First N_f=2+1+1 computation is in progress (ETMC)

Recent unquenched Lattice calculations of the form factors entering rare B-decays

$B \to K^*\gamma$: extrapolation of the lattice results to $q^2 = 0$ (emission of a real photon)

$$T_1(q^2) = \frac{T(0)}{\left(1 - q^2/m^2_{B_s^*}\right)\left(1 - \alpha q^2/m^2_{B_s^*}\right)} \quad T_2(q^2) = \frac{T(0)}{\left[1 - q^2/\left(\beta m^2_{B_s^*}\right)\right]}$$ [D. Becirevic, A. Kaidalov, '98]

[D. Becirevic *et al*, '06]

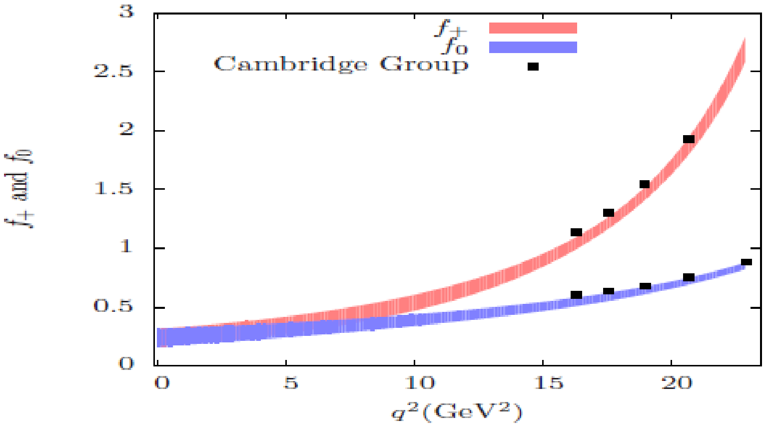


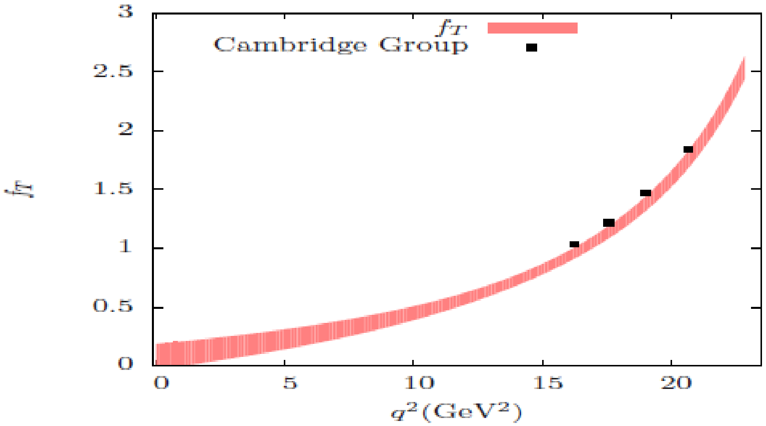
$N_f = 0$: $T(0) = 0.23(3)$ [D. Becirevic *et al*, '06]

$N_f = 2+1$: $T(0) = 0.17(3)$ [Z. Liu *et al*, '11]

$B \to K\ell^+\ell^-$: the lattice sets a normalization point at $q^2_{\max}$, the z expansion (for instance) can be used at other q^2

[Z. Liu *et al*, '11; R. Zhou *et al*, '12]





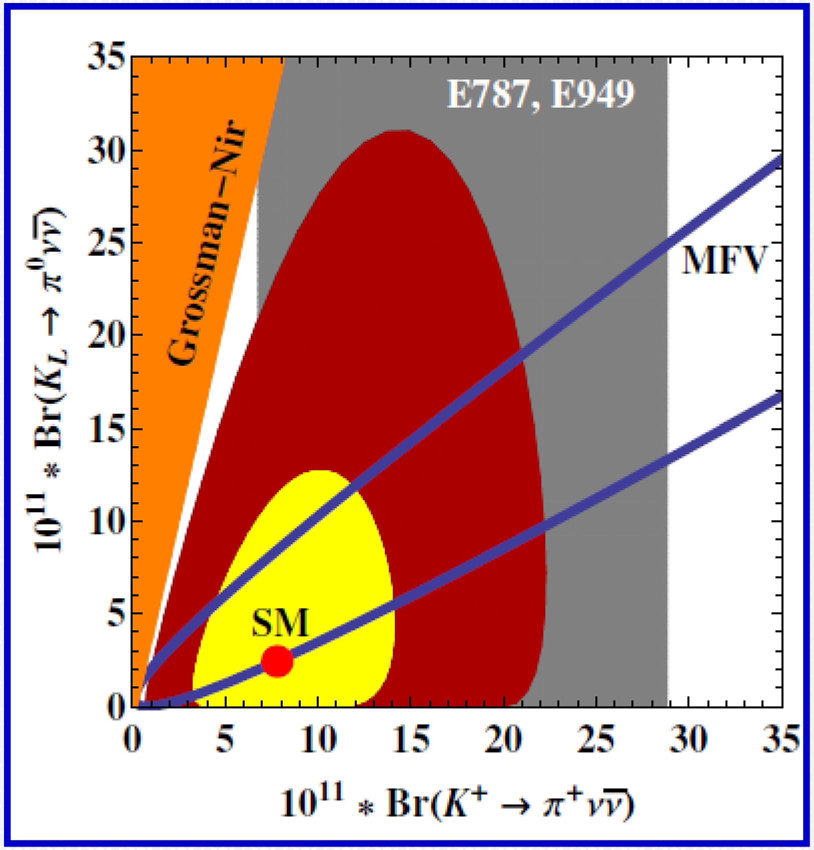
Besides Lattice accurate results
it is important to have accurate perturbative results
for the Wilson coefficients

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) Q_i$$

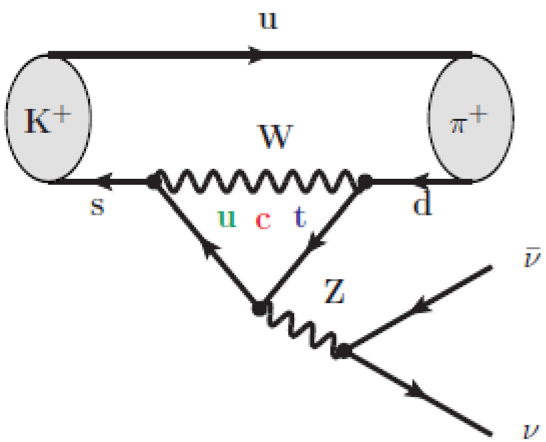
State of the art of the theoretical predictions
in the K- and D-meson sectors
[Joachim Brod]

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

Very precise theoretical predictions possible



Importance of correlations between observables to constrain/dscriminate NP models



$X_t(m_t^2)$ NLO QCD [Misiak et al., '99]
NLO EW [Brod et al., '11]

$P_c(m_c^2)$ NNLO QCD [Buras et al., '06]
NLO EW [Brod et al., '08]

$\delta P_{c,u}$ $+6\%$ [Isidori et al., '05]

Matrix elements

$K \to \pi\nu\nu$		$K \to \pi\ell\nu$
$\langle\pi^+\vert(\bar{s}d)_{V-A}\vert K^+\rangle$	$=$	$\sqrt{2} \times \langle\pi^0\vert(\bar{s}u)_{V-A}\vert K^+\rangle$
Unknown		Well measured

Isospin-breaking (plus QED radiative) corrections have been computed to (N)NLO in chiral perturbation theory
[Mescia, Smith 0705.2025]

$K \to \pi\nu\bar{\nu}$: Branching Ratios

[Brod, Gorbahn, Stamou 1009.0947]

$$B^{\text{theo}}(K^+ \to \pi^+\nu\bar{\nu}) = 7.81(75)(29) \times 10^{-11}$$

$$B^{\text{theo}}(K_L \to \pi^0\nu\bar{\nu}) = 2.43(39)(6) \times 10^{-11}$$

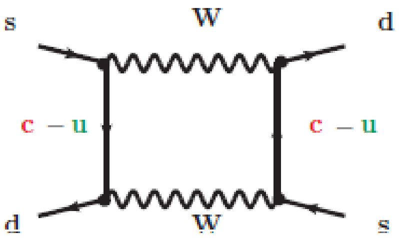
$$B^{\text{exp}}(K^+ \to \pi^+\nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right)\times 10^{-11}$$ E787, E949 '08

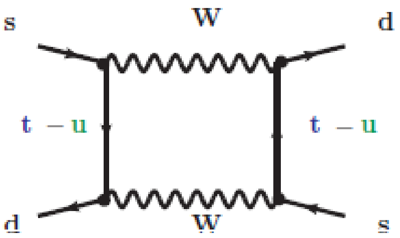
$$B^{\text{exp}}(K_L \to \pi^0\nu\bar{\nu}) < 2.6\times 10^{-8}$$ E391a '08

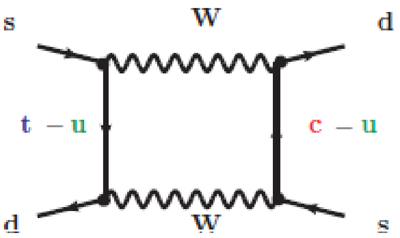
Uncertainty largely dominated by parametric input (mainly V_{cb})

ϵ_K: Effective Hamiltonian

$$H^{|\Delta S|=2} \propto \left[\lambda_c^2 \eta_{cc}\, S(x_c) + \lambda_t^2 \eta_{tt}\, S(x_t) + \lambda_c \lambda_t \eta_{ct}\, S(x_c, x_t)\right] Q^{|\Delta S|=2}$$







$\eta_{cc} = 1.87(76)$
@ NNLO

[Brod, Gorbahn '11]

$\eta_{tt} = 0.5765(65)$
@ NLO

[Buras et al. '90]

$\eta_{ct} = 0.496(47)$
@ NNLO

[Brod, Gorbahn '10]

$$\epsilon_K \overset{\text{theo}}{=} 1.81(28) \times 10^{-3}$$

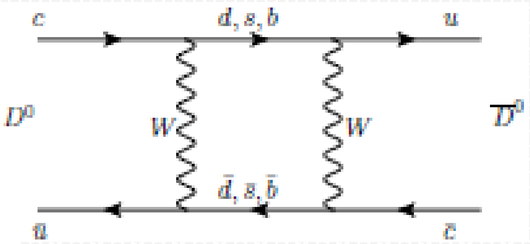
[Brod, Gorbahn '11]

$$\epsilon_K \overset{\text{exp}}{=} 2.228(11) \times 10^{-3}$$

[PDG '10]

Why charm physics?

- Search for new physics in the up-quark sector!



- Large long-distance contributions make theory predictions difficult.

HOT TOPIC

$\Delta\mathcal{A}_{CP}$: SM

$$\Delta\mathcal{A}_{CP} := a_{K^+K^-} - a_{\pi^+\pi^-}$$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

World average [HFAG March 2013].

$$\Delta\mathcal{A}_{CP} = (-0.329 \pm 0.121)\%$$

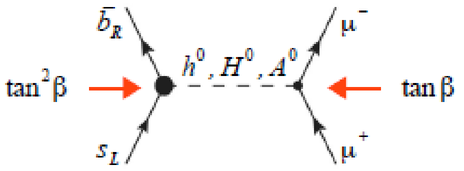
- Estimation of hadronic matrix elements in $m_c \to \infty$ limit ("leading power") yields $\Delta\mathcal{A}_{CP}$ factor 3 below measurement.
- From $SU(3)$ fits [Cheng et al. 1001.0987, 1201.0785; Bhattacharya et al. 1201.2351; Pirtskhalava et al. 1112.5451] we know that power corrections are large. → Signals breakdown of $1/m_c$ expansion
- Penguin contraction matrix elements can be large [Savage PLB 257 (1991) 414]
- Penguin contractions can account for $\Delta\mathcal{A}_{CP}$ and decay rate difference, with nominal U-spin breaking [Brod et al. PRD 86 (2012) 014023]

**SM or NP?
Not known yet**

State of the art of B-physics [Diego Guadagnoli]

$B_s \longrightarrow \mu\mu$

One famous example:
the MSSM with large tanß



Effectively tree-level diagrams:
Enhancement going as:

$$BR[B_s \to \mu^+\mu^-] \propto A_t^2 \frac{\tan^6\beta}{M_A^4}$$

BR[$B_s \to \mu\mu$] error: parametric

☑ The main sources of error within the BR formula are:

$$BR[B_s \to \mu^+\mu^-] \simeq \boxed{\frac{1}{\Gamma_s}} \times \left(\frac{G_F^2 \alpha_{\mathrm{e.m.}}^2}{16\pi^3 s_W^4}\right) \cdot \boxed{\left|V_{tb}^* V_{ts}\right|^2} \cdot \boxed{f_{B_s}^2} m_{B_s} \cdot m_\mu^2 \cdot Y^2\left(\boxed{m_t^2} / M_W^2\right)$$

☞ Thus, one can write the following phenomenological expression for the BR

top "pole" mass here

$$BR[B_s \to \mu^+\mu^-] = 3.23 \cdot 10^{-9} \cdot \left(\frac{\tau_{B_s}}{1.466\,\mathrm{ps}}\right) \cdot \left(\frac{\mathrm{Re}\left(V_{tb}^* V_{ts}\right)}{4.05 \cdot 10^{-2}}\right)^2 \cdot \left(\frac{f_{B_s}}{227\,\mathrm{MeV}}\right)^2 \cdot \left(\frac{\boxed{M_t}}{173.2\,\mathrm{GeV}}\right)^{3.07}$$

☑ Using this expression, one can easily work out the main error components as follows

	pdgLive	CKMfitter or UTfit	LQCD average (central value from C. Davies)	Tevatron average on 5.8/fb: 1107.5255
Input	$\tau_{B_s} =$ $1.466(31)\,\mathrm{ps}$	$\mathrm{Re}\left(V_{tb}^* V_{ts}\right) =$ $4.05(8) \cdot 10^{-2}$	$f_{B_s} =$ $227(8)\,\mathrm{MeV}$	$M_t =$ $173.2(0.9)\,\mathrm{GeV}$
Contribution to BR relative error	$2\,\%$	$4\,\%$	$7\,\%$	$1.6\,\%$

BR[$B_s \to \mu\mu$] error: systematics

☑ **Various effects**

- **Effect of $B_s - \overline{B}_s$ oscillations:**

  De Bruyn *et al.*, PRL 12 & PRD 12

$$BR_{\rm exp} = BR_{\rm th} \frac{1}{1-\Delta\Gamma_s/2\Gamma_s} = BR_{\rm th} \times 1.09$$

- **Effect of soft undetected photons in the final state:**

  Buras, Girrbach, DG, Isidori, EPJC 13

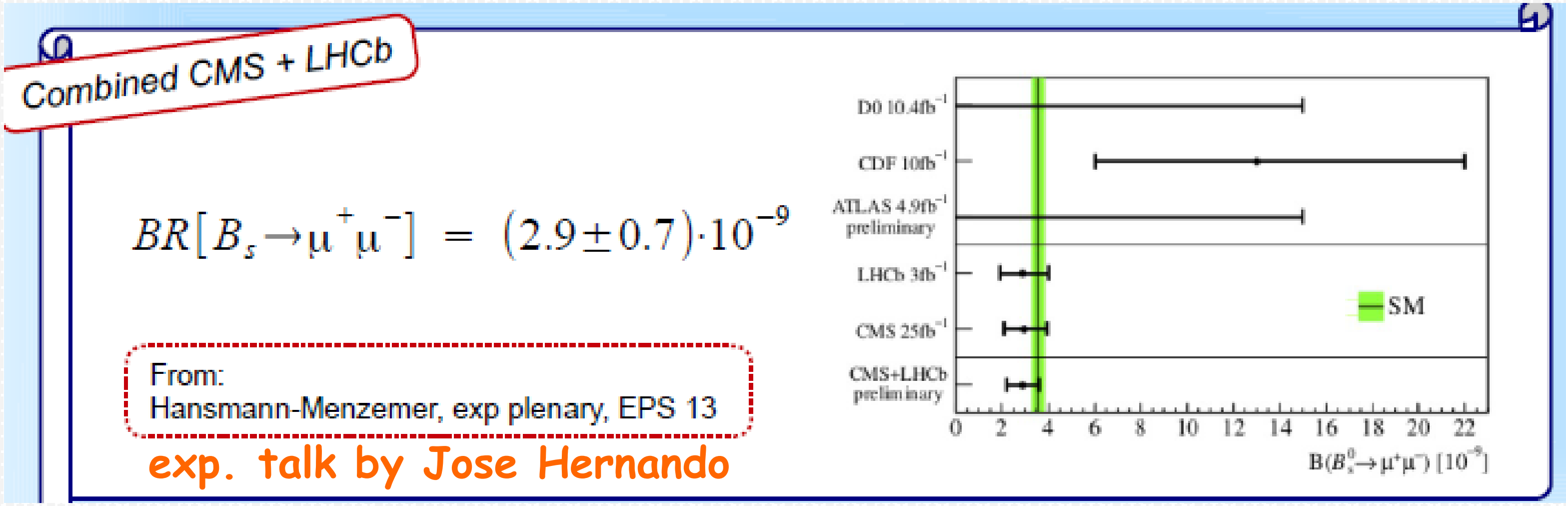
$$BR_{\rm exp} = BR_{\rm th} \times 0.89$$

Taken into account by exp

- **Incomplete knowledge of NLO EW corrections:**

- *Implied syst. error comparable to f_{Bs} error*
- *Impact on above central value arguably small (~ O(1%)) in appropriate scheme [see Buras, Girrbach, DG, Isidori, EPJC 13]*
- *Final answer only from full calculation (Gorbahn et al., in progress)*

All in all, theory (SM) ready to match expected experimental accuracy



Combined CMS + LHCb

$$BR[B_s\to\mu^+\mu^-] = (2.9\pm0.7)\cdot10^{-9}$$

From:
Hansmann-Menzemer, exp plenary, EPS 13

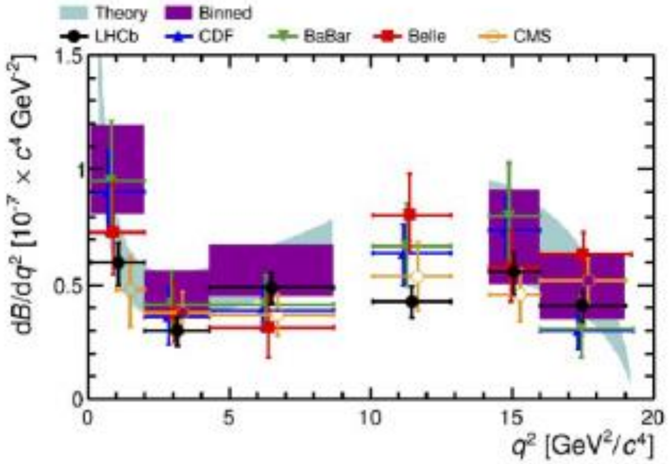
exp. talk by Jose Hernando

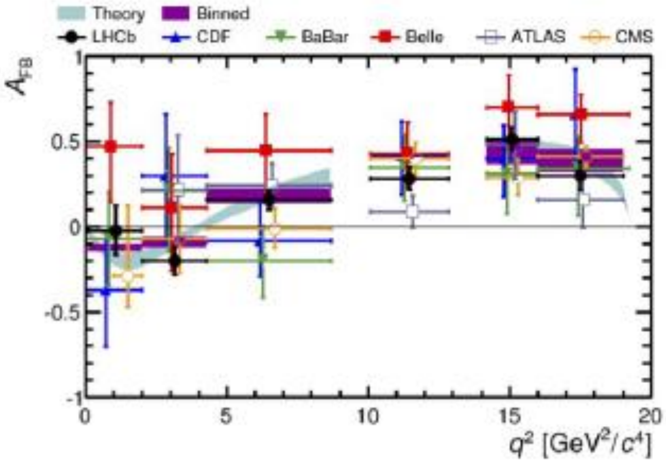
$$BR[B_d\to\mu^+\mu^-]_{\text{SM pred.}} = (1.07\pm0.10)\cdot10^{-10} \quad\Longleftrightarrow\quad BR[B_d\to\mu^+\mu^-]_{\text{LHCb+CMS}} = (3.6^{+1.6}_{-1.4})\cdot10^{-10}$$

$B \to K^* \mu\mu$ HOT TOPIC

Data !

☑ Agreement between SM and exp is generally good. Recent exp combinations look like:



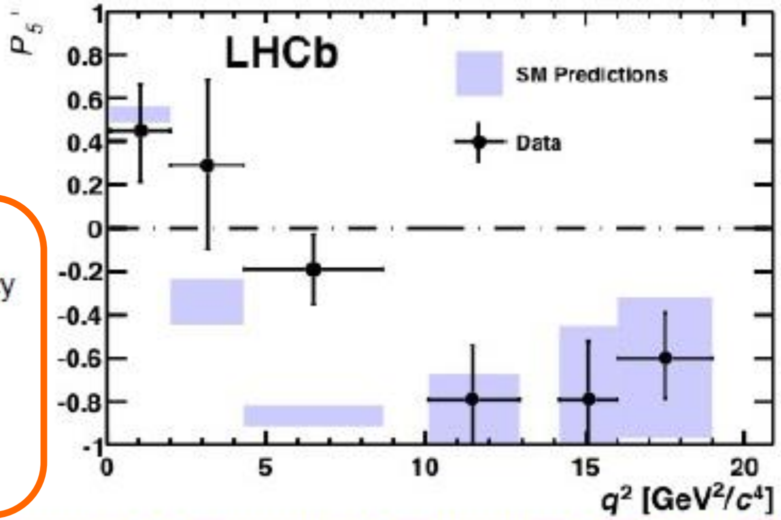


LHCb updates 1304.6325 & 1308.1707

- **Interesting:**

  A discrepancy of 3.7σ (LHCb fit) is observed in one P'_5 bin ($q^2 \in [4.3, 8.68]$ GeV²)

- **Beware:**
  - Taking the (more robust) $q^2 \in [1, 6]$ GeV² bin, the discrepancy goes down to 2.5σ
  - Analysis based on 2011 (1/fb) data. 2012 (2/fb) data are yet to be included



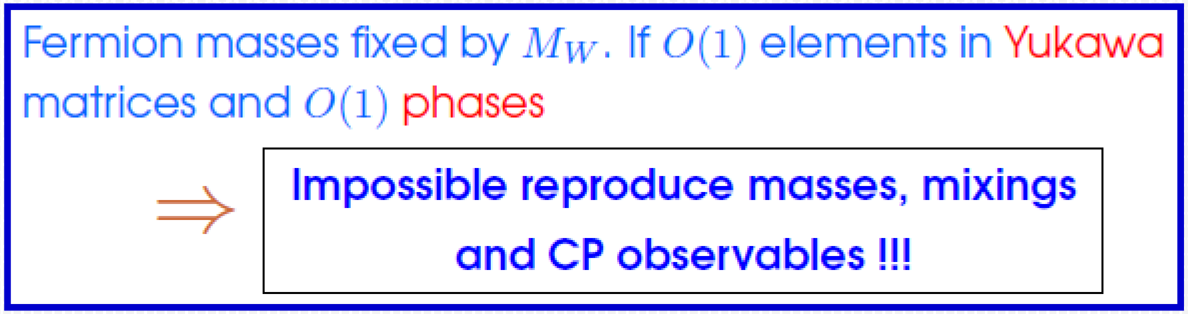
In short, we can say:

Measurements in Flavor are well compatible to the SM predictions

Few tensions are still to be understood
(if we had to bet we would bet on the SM-explanation)

BUT

Our understanding of flavour is UNSATISFACTORY



Fermion masses fixed by M_W. If $O(1)$ elements in Yukawa matrices and $O(1)$ phases

$\Rightarrow$ Impossible reproduce masses, mixings and CP observables !!!

Lepton Flavor Violation
[Oscar Vives]

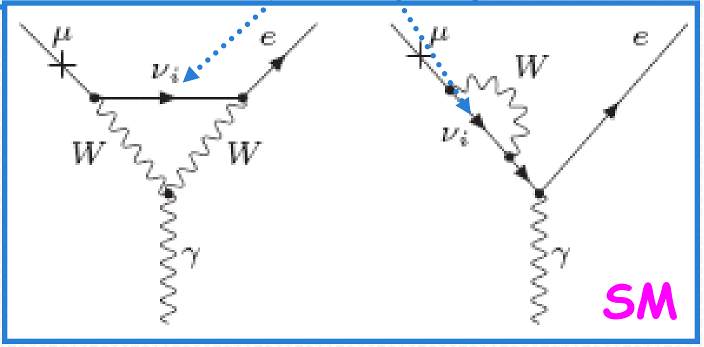
Models to explain mass hierarchies and mixing patterns
have been formulated
(based on flavor symmetries and Froggatt-Nielsen mechanism)

LFV has a crucial role in testing flavor models
(and the SM predictions)

LFV decays are strongly suppressed in the SM,
due to tiny neutrino masses

e.g.

$$Br(\mu \to e\gamma)_{SM} \approx 10^{-50}$$



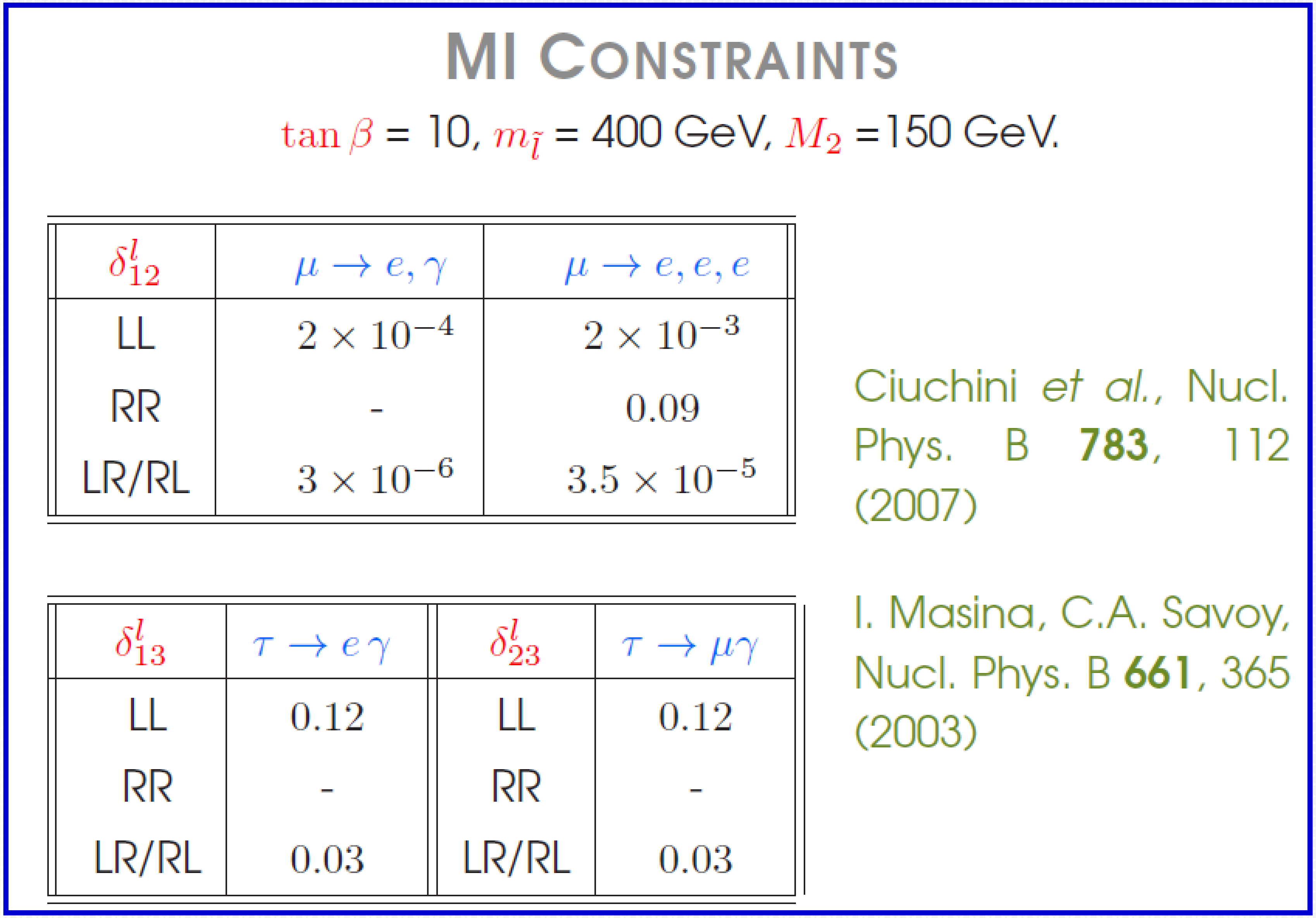
EXPERIMENTAL RESULTS

mode	BR. upper limit (90%)	Experiment	Year
$\mu^+ \to e\gamma$	5.7×10^{-13}	MEG	2013
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	SINDRUM I	1988
$\mu^-\,\mathrm{Ti} \to e^-\,\mathrm{Ti}$	5.7×10^{-13}	SINDRUM II	1998
$\mu^-\,\mathrm{Au} \to e^-\,\mathrm{Au}$	7×10^{-13}	SINDRUM II	2006
$\tau \to \mu\,\gamma$	4.4×10^{-8}	BaBar	2011
$\tau \to e\,\gamma$	3.3×10^{-8}	BaBar	2011
$\tau \to \mu\,\mu\,\mu$	4.0×10^{-8}	Belle	2011
$\tau \to \mu\,\rho$	1.2×10^{-8}	Belle	2012

Future prospects:

MEG $\Rightarrow \mathrm{B}(\mu \to e\gamma) < 5 \times\ 10^{-14}$, Mu3e $\Rightarrow \mathrm{B}(\mu \to eee) < O(10^{-16})$,
mu2e $\Rightarrow \mu \to e$ conv. $< O(10^{-16})$, LHCb $\Rightarrow \mathrm{B}(\tau \to \mu \ldots) < O(10^{-9})$

Constraints on NP models (e.g. MSSM)



MI CONSTRAINTS

$\tan\beta$ = 10, $m_{\tilde{l}}$ = 400 GeV, M_2 =150 GeV.

δ^l_{12}	$\mu \to e, \gamma$	$\mu \to e, e, e$
LL	2×10^{-4}	2×10^{-3}
RR	-	0.09
LR/RL	3×10^{-6}	3.5×10^{-5}

Ciuchini *et al.*, Nucl. Phys. B **783**, 112 (2007)

δ^l_{13}	$\tau \to e\gamma$	δ^l_{23}	$\tau \to \mu\gamma$
LL	0.12	LL	0.12
RR	-	RR	-
LR/RL	0.03	LR/RL	0.03

I. Masina, C.A. Savoy, Nucl. Phys. B **661**, 365 (2003)

Tests of Flavor models

LEPTON FLAVOUR VIOLATION

Off-diagonal entries in slepton masses generate *LFV* processes:

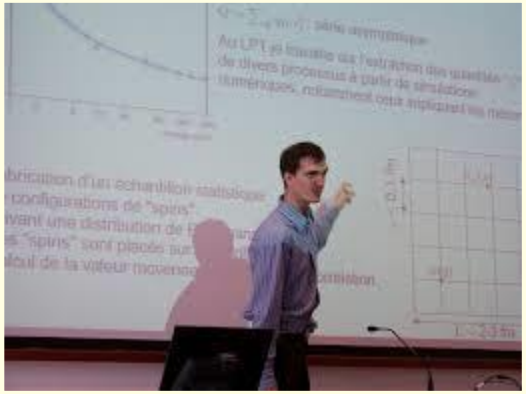
$$\mathrm{BR}(l_i \to l_j \gamma) \;\simeq\; \frac{3\pi\alpha_2^3}{G_F^2}\left|\frac{(\delta^e_{\mathrm{L}})_{ij}}{m^2_{\tilde{l}}}\;\frac{\mu M_2 \tan\beta}{(M_2^2-\mu^2)}\;F_{2L}(a_2,b)\right|^2$$

$SU(3)$ Flavour model

$$M^2_{\tilde{E}_L} \;\simeq\; 0.5\, M^2_{1/2}\,\mathbb{1} + \begin{pmatrix} 1+\varepsilon^3 & \frac{\varepsilon^2\bar{\varepsilon}}{3} & \varepsilon^2\bar{\varepsilon} + c_{\mathrm{run}}\,\bar{\varepsilon}^3 \\ \frac{\varepsilon^2\bar{\varepsilon}}{3} & 1+\varepsilon^2 & \varepsilon^2 + 3\,c_{\mathrm{run}}\,\bar{\varepsilon}^2 \\ \varepsilon^2\bar{\varepsilon} + c_{\mathrm{run}}\,\bar{\varepsilon}^3 & \varepsilon^2 + 3\,c_{\mathrm{run}}\,\bar{\varepsilon}^2 & 1+\varepsilon \end{pmatrix} m_0^2$$

$$\Rightarrow \quad (\delta^e_{\mathrm{L}})_{12} = \tfrac{1}{3}\varepsilon^2\bar{\varepsilon} \simeq 10^{-4}.$$

$$\Rightarrow \quad (\delta^e_{\mathrm{L}})_{23} = 3y_t\bar{\varepsilon}^2 \simeq 10^{-2}.$$



OBRIGADA!

OBRIGADA!