Experimental aspects of the CP violation.

S. Monteil,
LPC – Université Blaise Pascal – in2p3.
[Aleph and LHCb experiments]

Some authoritative literature about the lecture :

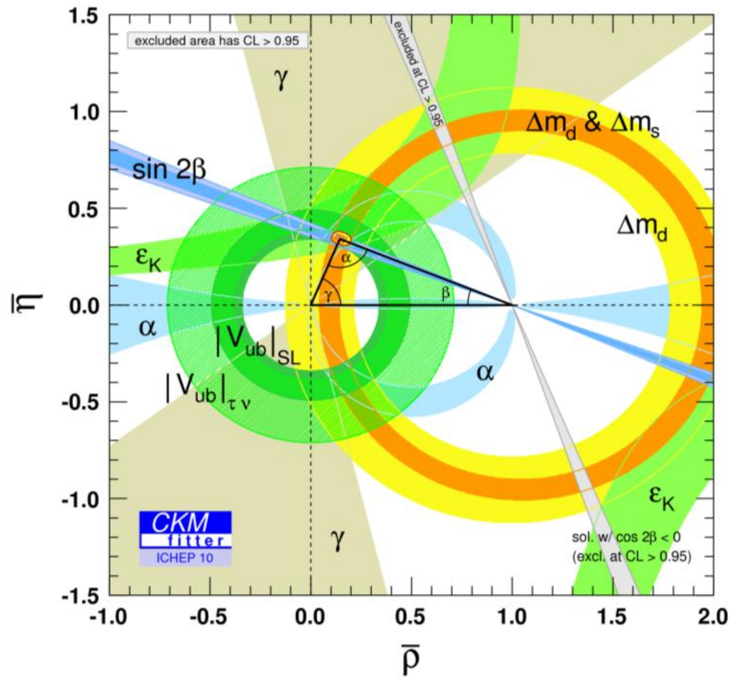
- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- A. Höcker and Z. Ligeti: *CP Violation and the CKM Matrix. hep-ph/0605217*

World Averages and Global Fits:

- Heavy Flavour Averaging Group: http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter: http://ckmfitter.in2p3.fr/
- UTFit: http://www.utfit.org/

Motivation

- In any HEP physics conference summary talk, you will find this plot, stating that heavy flavours and CP violation physics is a pillar of the Standard Model.



- One objective of these serie of lectures is to undress this plot.

A more detailed outline

1. History and recent past of the parity violation experiments. The discovery of the CP violation.

2. Observables and measurements relevant to study CP violation.

3. The global fit of the SM.

4. Outlook. New Physics exploration with current data: two examples.

3. The Standard Model global fit results

1. Some words about the statistical method.
2. The global picture: fit, detailed view of the constraints, metrology of the SM parameters.
3. Historical perspective.
4. The tensions of the global fit.

3.1 Some words about the statistical method.

- I will present in this chapter the big picture of the global fit of the flavour data to establish the Standard Model CKM profile.
- Though several approaches exist, there are two main groups aiming at establishing CKM profile from flavour data: The UTFit collaboration and the CKMfitter group, which results will be shown in this chapter.
- They differ by their statistical approach to make the metrology of the parameters: bayesian for UTFit and frequentist for CKMfitter.
- They differ also in the treatment of the theoretical uncertainties. The CKMfitter group uses the Rfit approach.

3.1 Sketch of the statistical method.

- The frequentist approach:

- Use Frequentist Hypothesis testing to build statistical significance(p-value) functions from which estimates and confidence intervals are obtained.

- The statistical test is a Maximum Likelihood Ratio $=\Delta\chi^2$.

- The situation is further complicated by the presence of theoretical uncertainties for which a dedicated scheme is considered: *R*fit.

- When the theoretical uncertainty is not controled at a satisfactory enough level, the related observable is not considered in the global fit (e.g the ε' measurement – direct CP violation in the kaon system).

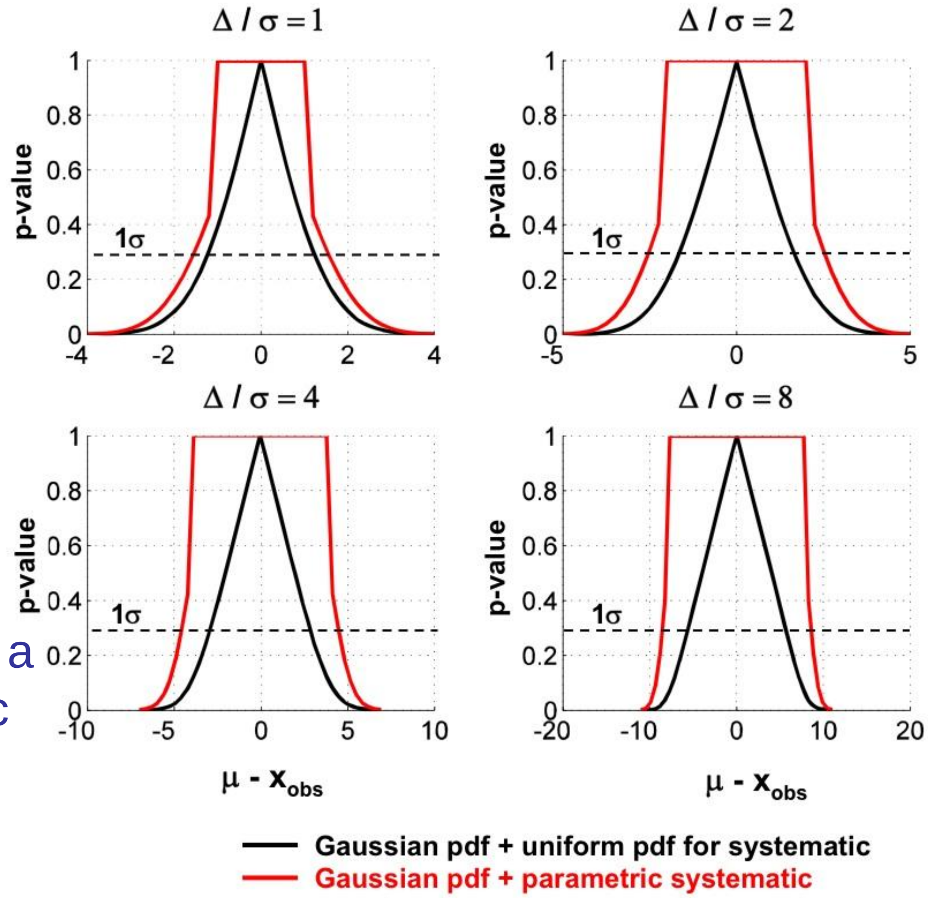
3.1 Sketch of the statistical method.

- The *R*fit treatment of theoretical uncertainties:

- Theoretical systematics are considered as additional nuisance parameters bounded over a confidence interval.

- These errors are not statistically distributed.

- This approach yields very different results from what one would get from a statistical modelling of the systematic (ex ample here : uniform over the range)



3.2 The global picture

- List of the inputs: in the details.
- The ones we discussed in previous chapter, and:
- α, γ
- Lattice parameters. And ratios.
- The tauonic B decay. Deserves a brief description.

Parameter	Value ± Error(s)	Reference	Errors	
			GS	TH
$\|V_{ud}\|$ (nuclei)	0.97425 ± 0.00022	[1]	$\star$	-
$\|V_{us}\|$ ($K_{\ell 3}$)	0.2254 ± 0.0013	[2]	$\star$	-
$\|V_{ub}\|$	$(3.92 \pm 0.09 \pm 0.45) \times 10^{-3}$	[3, 4]	$\star$	$\star$
$\|V_{cb}\|$	$(40.89 \pm 0.38 \pm 0.59) \times 10^{-3}$	[3]	$\star$	$\star$
$\|\varepsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$	[5]	$\star$	-
Δm_d	(0.507 ± 0.005) ps^{-1}	[3]	$\star$	-
Δm_s	(17.77 ± 0.12) ps^{-1}	[6]	$\star$	-
$\sin(2\beta)_{[c\bar{c}]}$	0.673 ± 0.023	[3]	$\star$	-
$S^{+-}_{\pi\pi}$, $C^{+-}_{\pi\pi}$, $C^{00}_{\pi\pi}$	Inputs to isospin analysis	[3]	$\star$	-
$\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis	[3]	$\star$	-
$S^{+-}_{\rho\rho,L}$, $C^{+-}_{\rho\rho,L}$, $S^{00}_{\rho\rho}$, $C^{00}_{\rho\rho}$	Inputs to isospin analysis	[3]	$\star$	-
$\mathcal{B}_{\rho\rho,L}$ all charges	Inputs to isospin analysis	[3]	$\star$	-
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-dependent Dalitz analysis	[7, 8]	$\star$	-
$B^- \to D^{(*)}K^{(*)-}$	Inputs to GLW analysis	[3]	$\star$	-
$B^- \to D^{(*)}K^{(*)-}$	Inputs to ADS analysis	[3]	$\star$	-
$B^- \to D^{(*)}K^{(*)-}$	GGSZ Dalitz analysis	[3]	$\star$	-
$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau)$	$(1.68 \pm 0.31) \times 10^{-4}$	[9]	$\star$	-
$\overline{m}_c(m_c)$	$(1.286 \pm 0.013 \pm 0.040)$ GeV	[12]	$\star$	$\star$
$\overline{m}_t(m_t)$	$(165.02 \pm 1.16 \pm 0.11)$ GeV	[10]	$\star$	$\star$
B_K	$0.723 \pm 0.004 \pm 0.067$	[16]	$\star$	$\star$
$\alpha_s(m_Z^2)$	0.1176 ± 0.0020	[5]	-	$\star$
η_{cc}	Calculated from $\overline{m}_c(m_c)$ and α_s	[17]	-	$\star$
η_{ct}	0.47 ± 0.04	[18]	-	$\star$
η_{tt}	0.5765 ± 0.0065	[17, 18]	-	$\star$
$\eta_B(\overline{\mathrm{MS}})$	0.551 ± 0.007	[19]	-	$\star$
f_{B_s}	$(228 \pm 3 \pm 17)$ MeV	[16]	$\star$	$\star$
$\mathcal{B}_s$	$1.28 \pm 0.02 \pm 0.03$	[16]	$\star$	$\star$
f_{B_s}/f_{B_d}	$1.199 \pm 0.008 \pm 0.023$	[16]	$\star$	$\star$
$\mathcal{B}_s/\mathcal{B}_d$	$1.05 \pm 0.01 \pm 0.03$	[16]	$\star$	$\star$

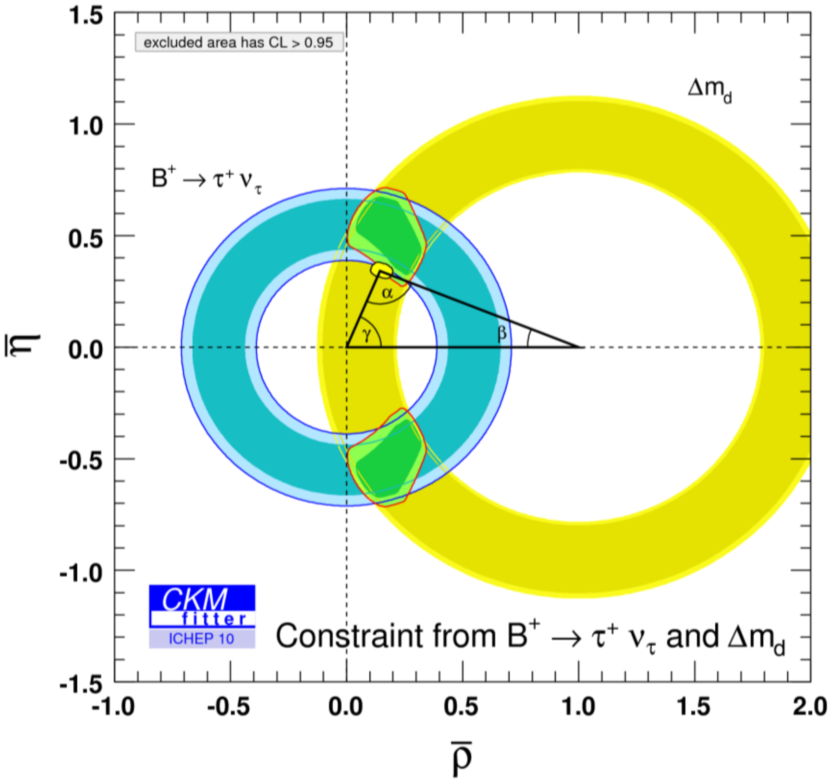
3.2 The global picture. Aparte : Taunic B decay.

$$\mathcal{B}[M \to \ell\nu] = \frac{G_F^2 m_M m_\ell^2}{8\pi\hbar}\left(1 - \frac{m_\ell^2}{m_M^2}\right)^2 |V_{q_u q_d}|^2 f_M^2 \tau_M (1 + \delta_{\rm em}^{Ml2})$$

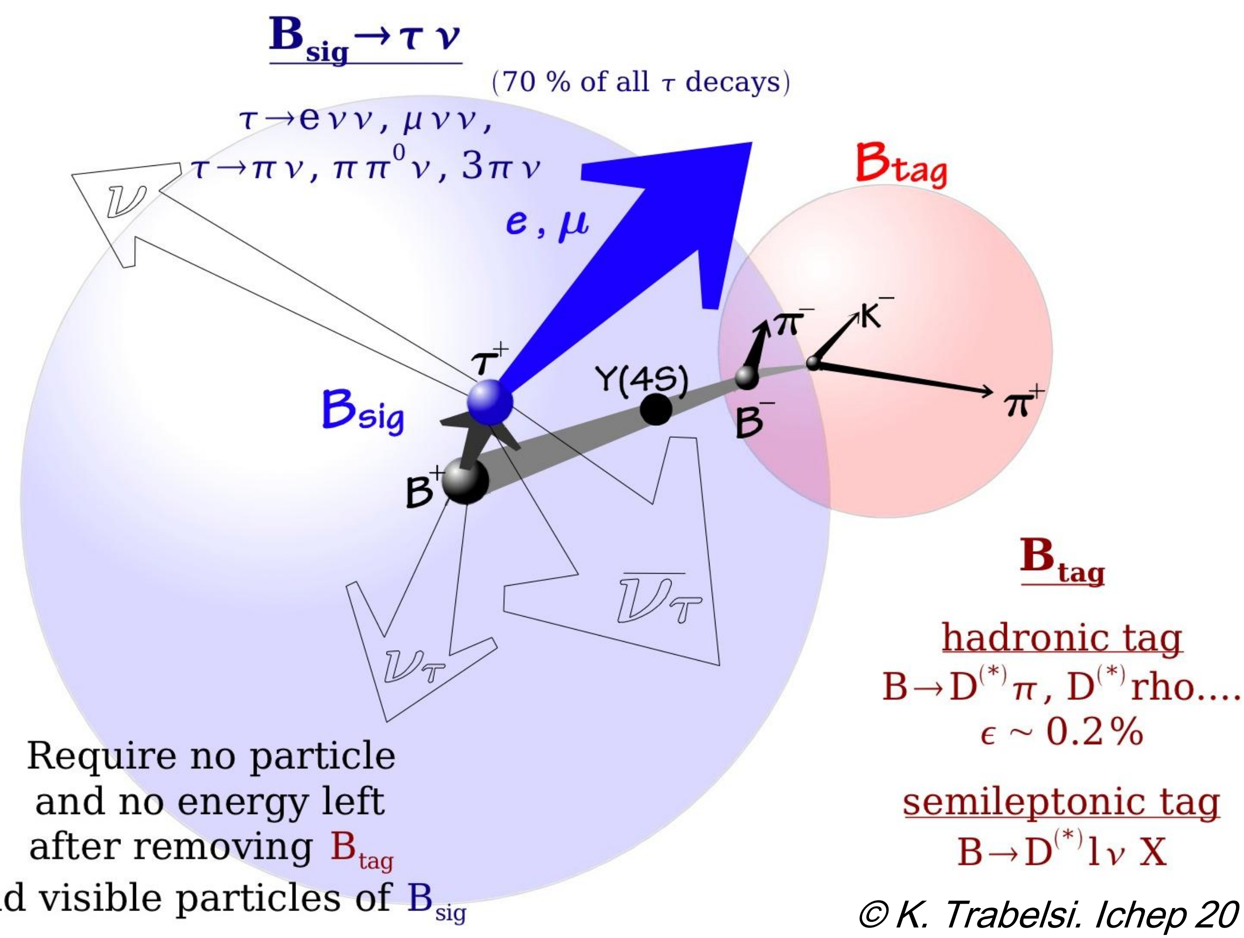
- $B^+ \to \tau^+ \nu$ is another way to access the matrix element $|V_{ub}|$. Remember that we have seen in Chapter II that exclusive and inclusive determinations only marginally agrees.

- Actually it's not only $|V_{ub}|$ but the product $f_B|V_{ub}|$.

- The simultaneous treatment of Δm_d and Br[$B^+ \to \tau^+ \nu$] allows to get rid from the B decay constant.

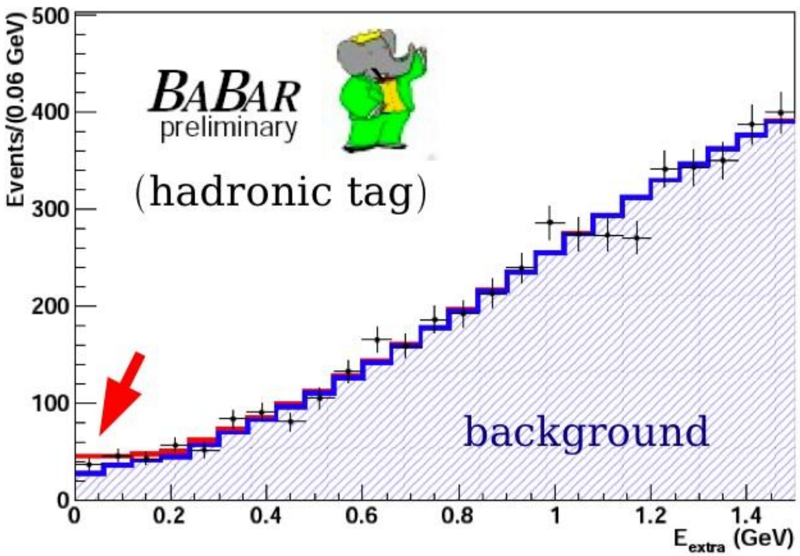


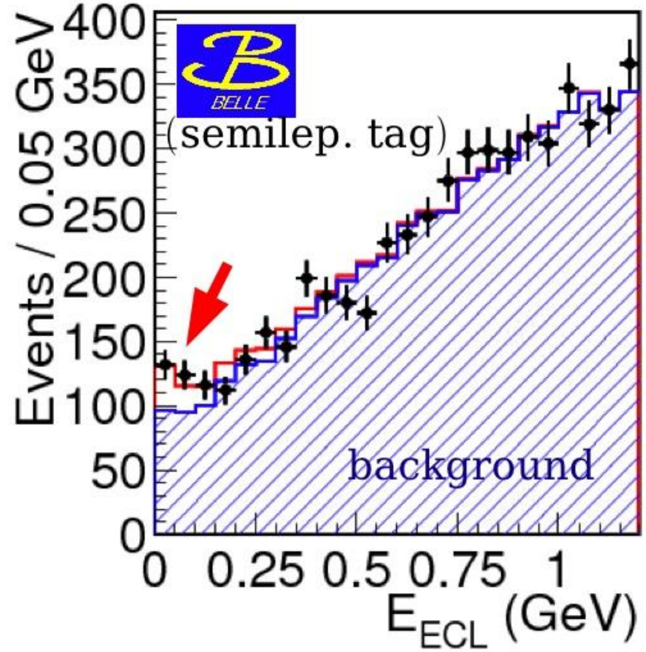
3.2 The global picture. Aparte : Taunic B decay reconstruction.



© K. Trabelsi. Ichep 2010

3.2 The global picture. Aparte : Taunic B decay reconstruction.





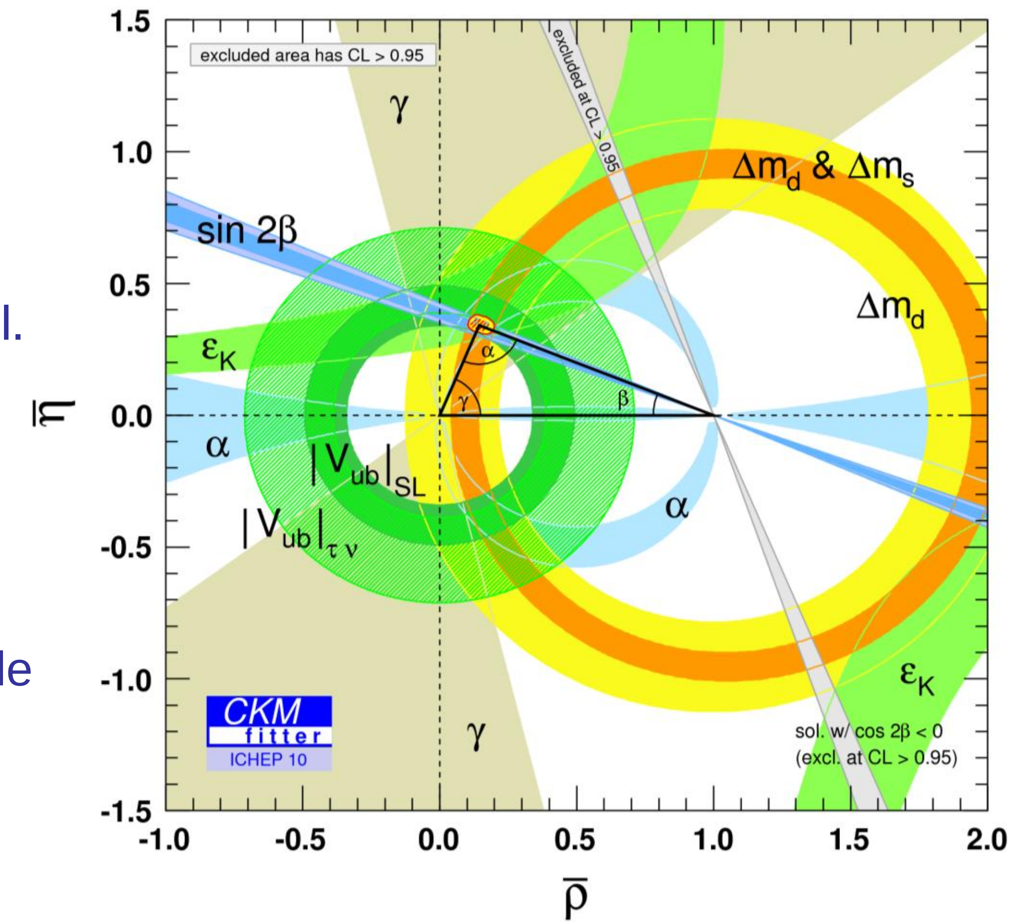
	tag	BF(→τν)[10^{-4}]
BaBar	SL (459M)	1.70±0.82
	Had (467M)	1.80±0.61 *NEW*
	Average	1.76±0.49
Belle	SL (657M)	1.54±0.48 *NEW*
	Had (449M)	1.79±0.71
	Average	1.62±0.40
World Average		1.68±0.31

- ECL/Extra = extra calorimeter energy
- SM prediction(CKMfitter):

$$B(B^+ \to \tau^+ \nu_\tau) = (0.763^{+0.114}_{-0.061}) \cdot 10^{-4}$$

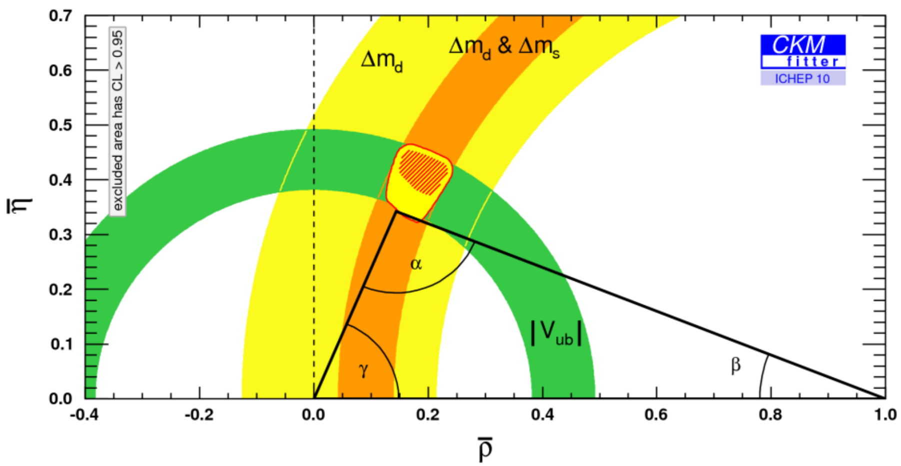
3.2 Standard Model: the CKM profile

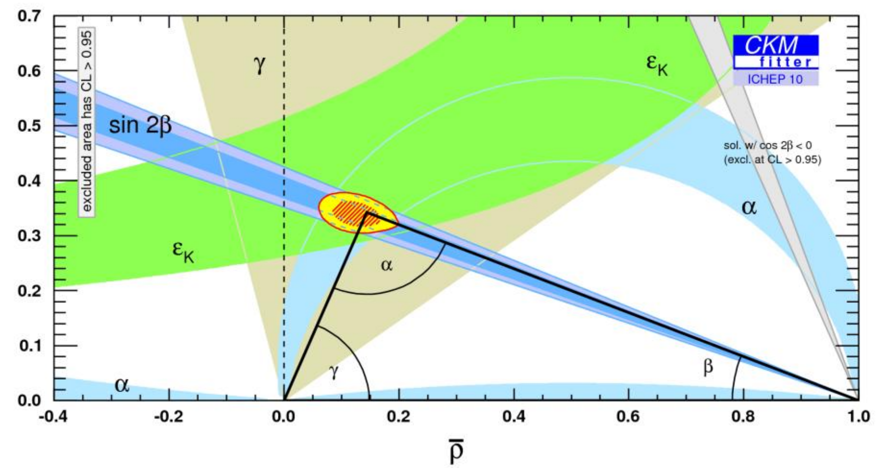
- The global picture:
- Notice to read the picture: regions outside the coloured area are excluded at 95 % Confidence Level.
- There is a region of Wolfenstein parameter space which is common to all the constraints.
- In other terms, there is a remarkable consistency between all of the observables at the 95 % CL.



3.2 Standard Model: the CKM profile

- The global picture: comparison of observables constraints.
- CP-conserving against CP violating.



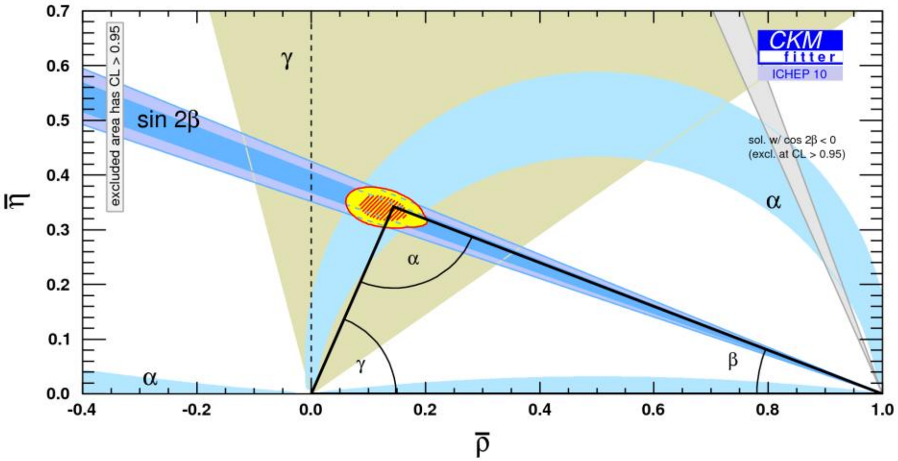


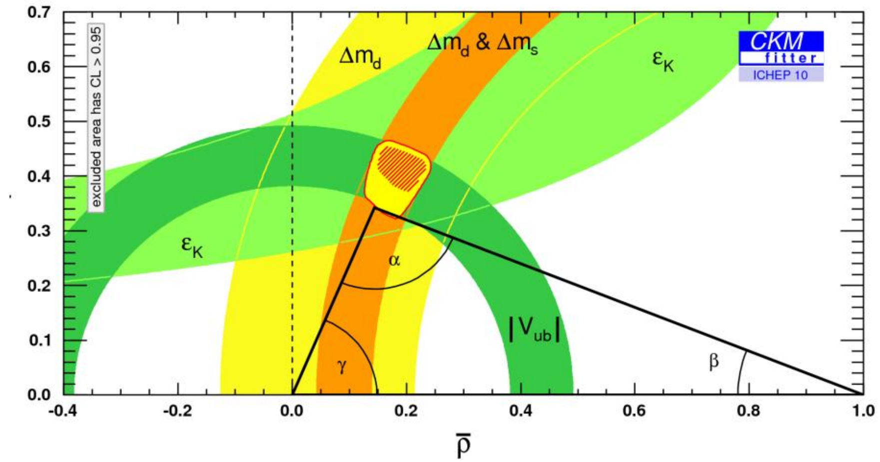
- Correct agreement. CP-conserving observables can quantify CP violation.

3.2 Standard Model: the CKM profile

- The global picture: comparison of observables constraints.

- Angles (No theory) against No angles (Hadronic uncert.)

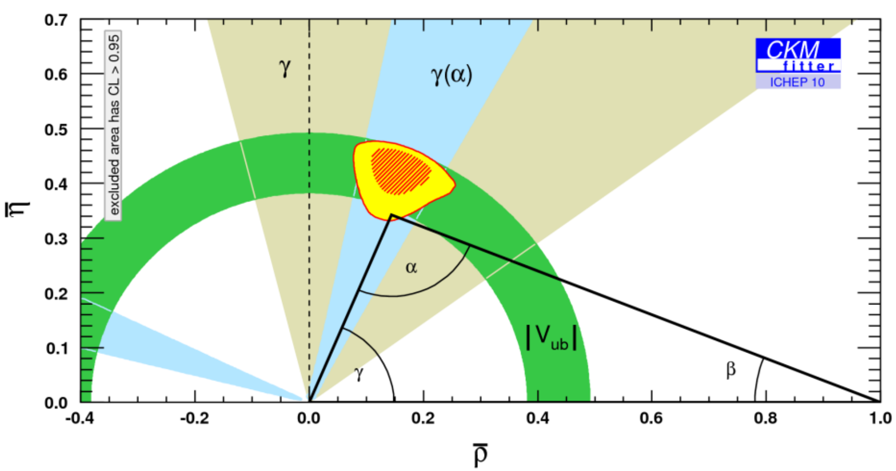


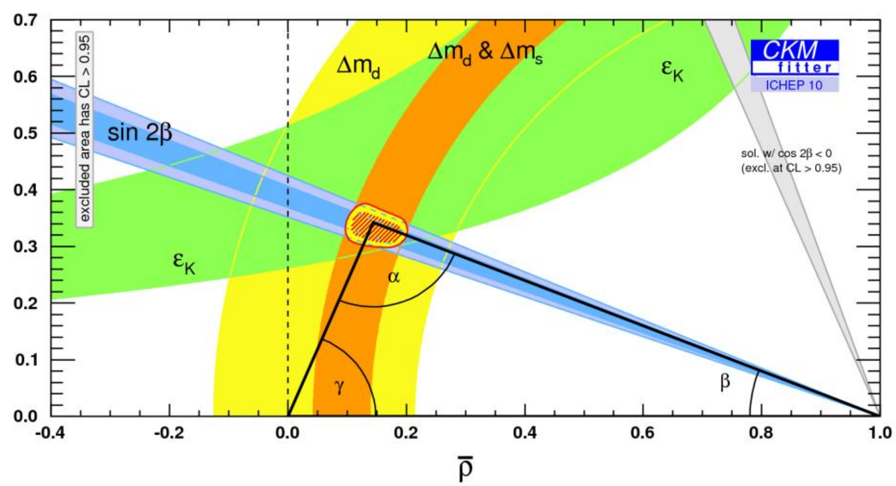


- Correct agreement. Remember that only observables with a good theoretical control are considered in the global fit.

3.2 Standard Model: the CKM profile

- The global picture: comparison of observables constraints.
- Trees against Loops.





- Trees are thought to be pure SM. Loops could exhibit New Physics. Fair agreement.

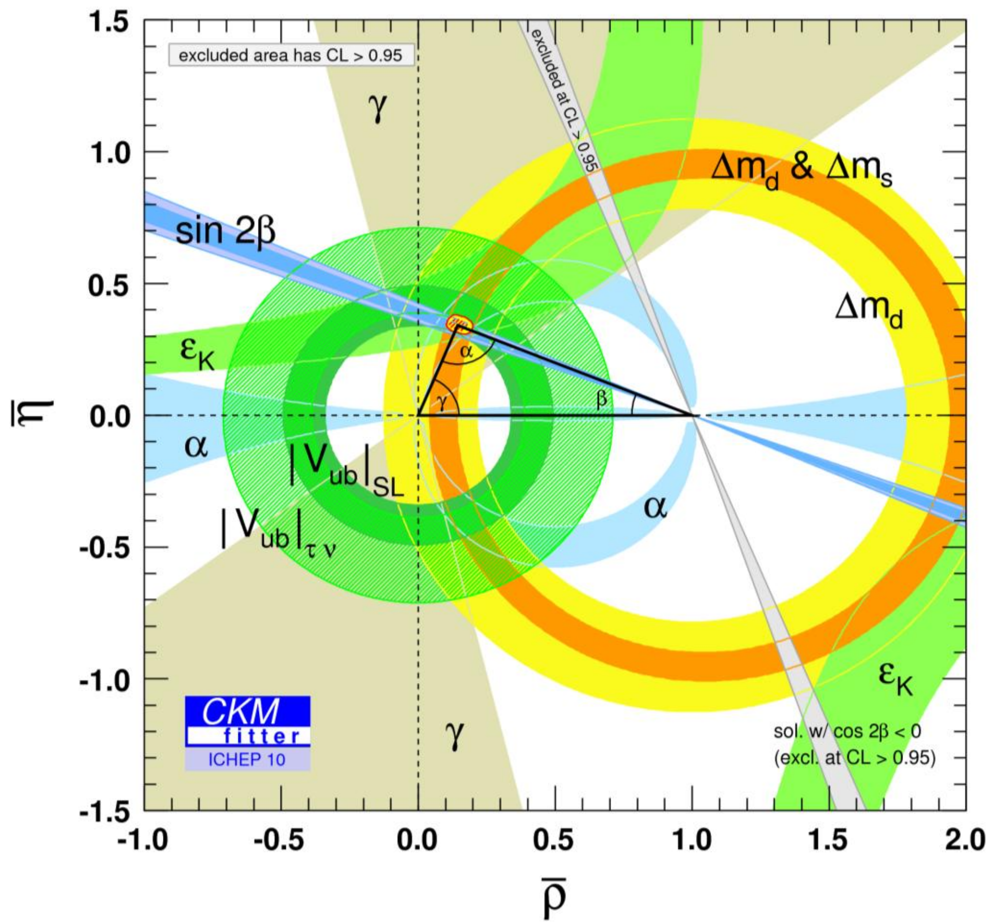
3.2 Standard Model: the CKM profile.

- The global picture:

- This is a tremendous success of the Standard Model and especially the Kobayashi-Maskawa mechanism. This is simultaneously an outstanding experimental achievement by the B factories.

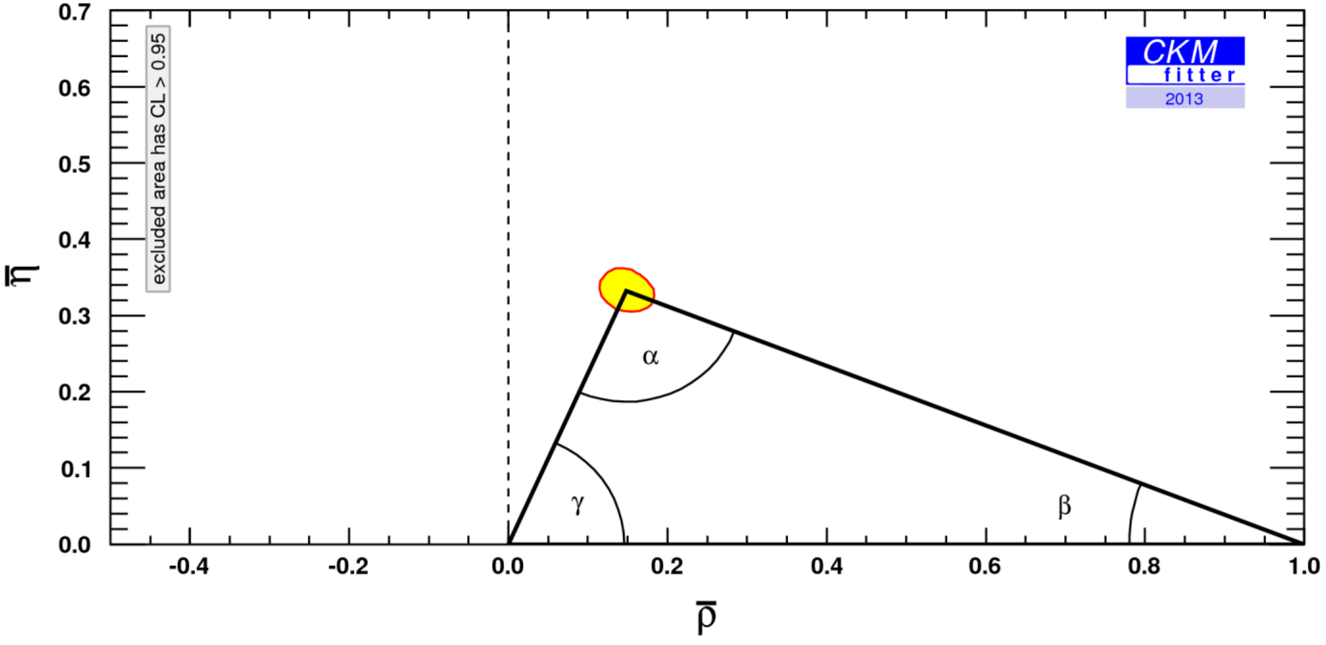
- CKM is at work in weak charged current.

- The KM phase IS the dominant source of CP violation in K and B system.

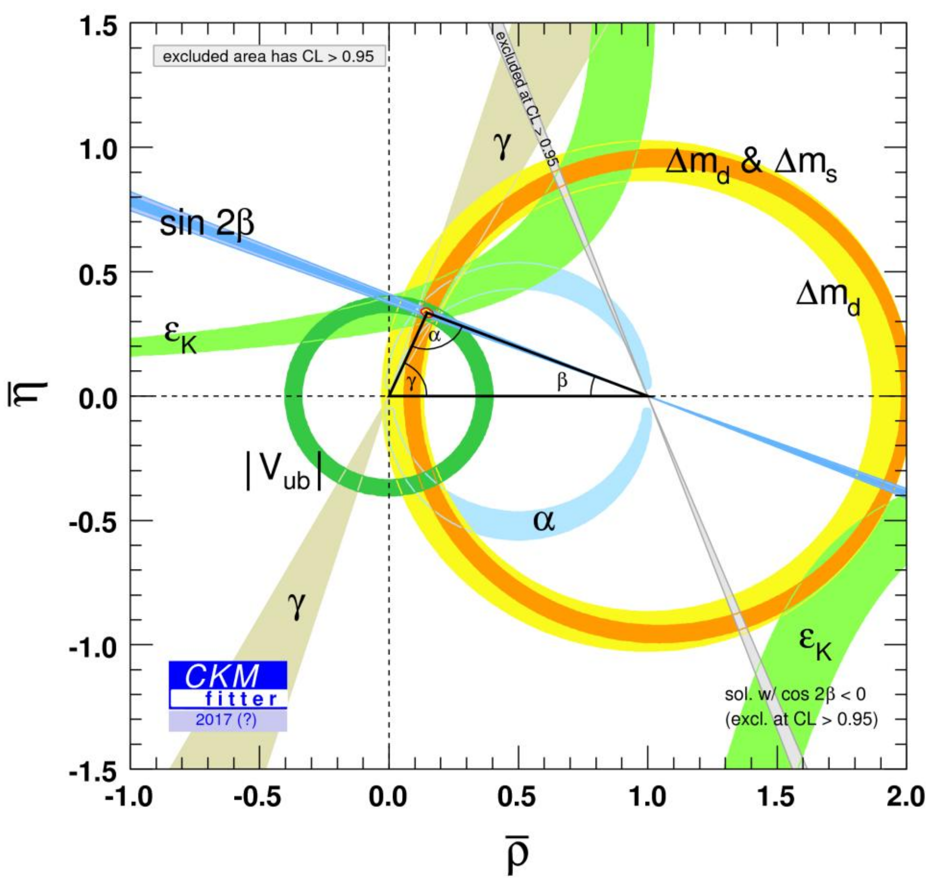


3.3 Back to the future .

- Recreational Homework. Find the break through measurements along ages.



3.3 Back to the future .



3.3 Back to the future .

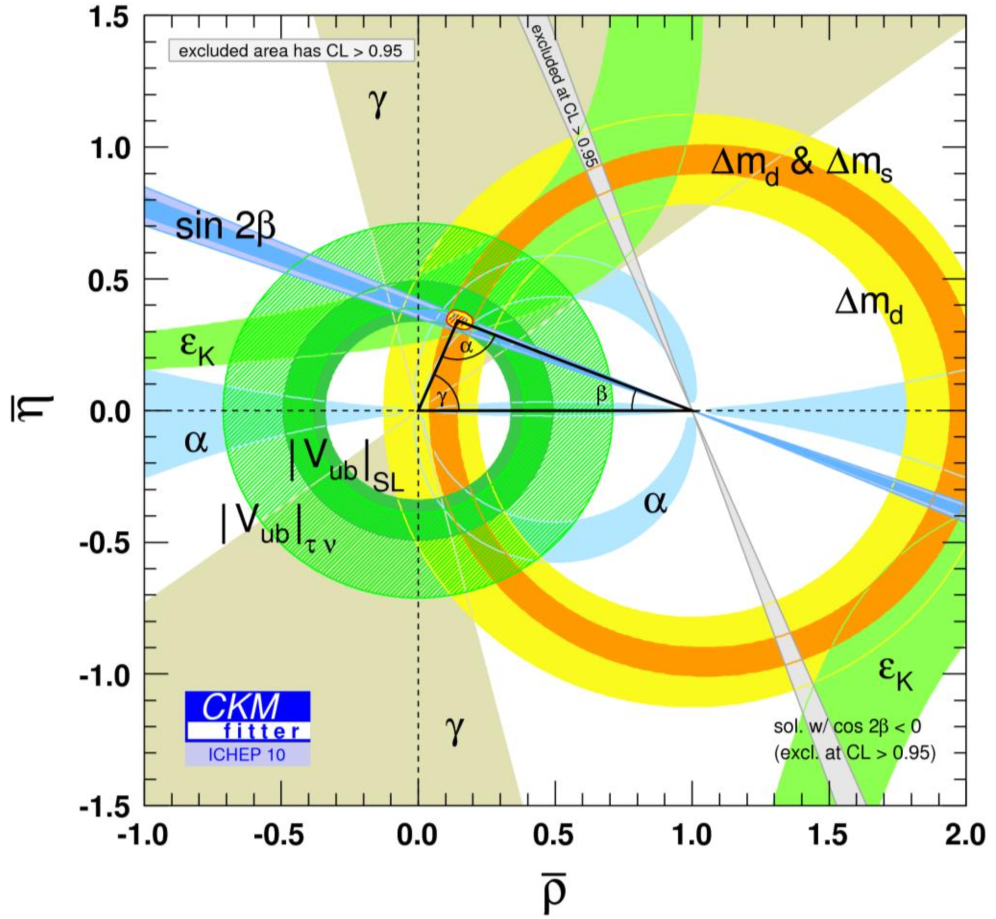
- 1995: starting point given by the top quark mass measurement. K and B mixings can be predicted.
- 2001: pre-Bfactories era. LEP/CLEO based UT. Comparison with kaon mixing gives a consistency check.
- 2002: CP violation in the interference between decay and mixing is observed. This is the first true consistency test of the Standard Model.
- 2004: precise β measurement. First alpha measurement.
- 2006-2009: Δm_s First gamma measurement. Δm_s is measured.
- 2013: LHCb with precise gamma measurement.
- 2017: Super Flavour Factories (including LQCD improvements.)

3.3 Standard Model Predictions from the global fit.

- Now that the Standard Model hypothesis is validated [Validated does not mean that the SM is THE theory: it means that it passed the statistical test !!!] it's relevant to make the metrology of the CKM parameters.

- Additonally, perform consistency checks. Exclude the meas. of the observable you want to predict from the global fit and … compare !

- Please pick your favourite around here: http://ckmfitter.in2p3.fr.



3.3 Standard Model Predictions from the global fit.

- CKM parameters:

$$
\begin{aligned}
A &= 0.812^{+0.013}_{-0.027} \\
\lambda &= 0.22543 \pm 0.00077 \\
\bar{\rho} &= 0.144 \pm 0.025 \\
\bar{\eta} &= 0.342^{+0.016}_{-0.015} \\
J &= (2.96^{+0.18}_{-0.17})10^{-5}
\end{aligned}
$$

- Rare decays:

$$
\begin{aligned}
\mathcal{B}(B^+ \to \tau^+\nu_\tau) &= (0.763^{+0.114}_{-0.061})10^{-4} \\
\mathcal{B}(B^+ \to \mu^+\nu_\mu) &= (0.387^{+0.045}_{-0.043})10^{-6} \\
\mathcal{B}(B_s \to \mu^+\mu^-) &= (3.073^{+0.070}_{-0.190})10^{-9} \\
\mathcal{B}(B_s \to \mu^+\mu^-) &= (9.87^{+0.25}_{-0.67})10^{-11}
\end{aligned}
$$

- Matrix element / angles (including Bs system)

$$
\begin{aligned}
|V_{ub}| &= 0.00354^{+0.00016}_{-0.00020} \\
\sin 2\beta &= 0.830^{+0.013}_{-0.034} \\
\sin 2\beta_s &= 0.0363 \pm 0.0017
\end{aligned}
$$

- Lattice parameters (!)

$$
\begin{aligned}
B_K &= 0.83^{+0.26}_{-0.15} \\
\xi &= 1.195^{+0.053}_{-0.044} \\
f_{B_s} &= 235.8 \pm 8.9 \text{ MeV}
\end{aligned}
$$

3.4 Les tensions de l'ajustement global

- Among the consistency checks, we find some discrepancies (would it be better to say marginal agreement?).
- We will review what could be possible hints of New Physics as indicated by the big picture.
- The only significant one is the marginal agreement of tauonic B decay branching ratio and sin 2β.
- The outlook will de dedicated to specific New Physics analysis which can accomodate the observed discrepancy.

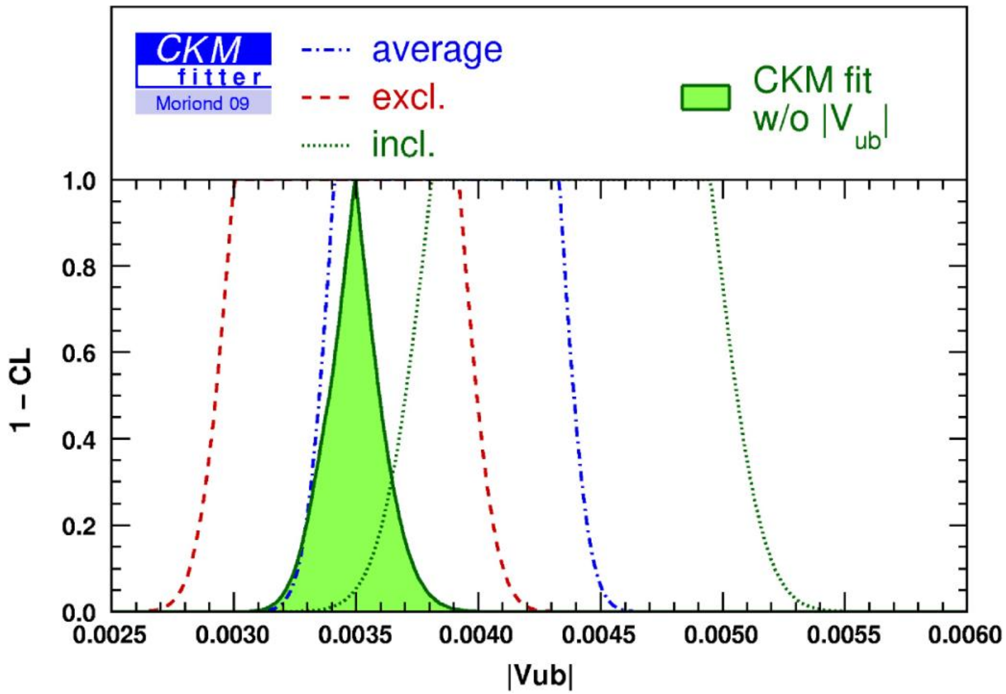
3.4 The tensions in the global fit.

3.4.1 $|V_{ub}|$ vs $\sin 2\beta$?

- It is actually more a $|V_{ub}|$ vs $|V_{ub}|$ tension.

- We are living with a significant difference between exclusive and inclusive measurements: a longstanding issue. (See all theo. lectures in this school …)

- The $\sin 2\beta$ measurement prefers the exclusive value under SM hypothesis.

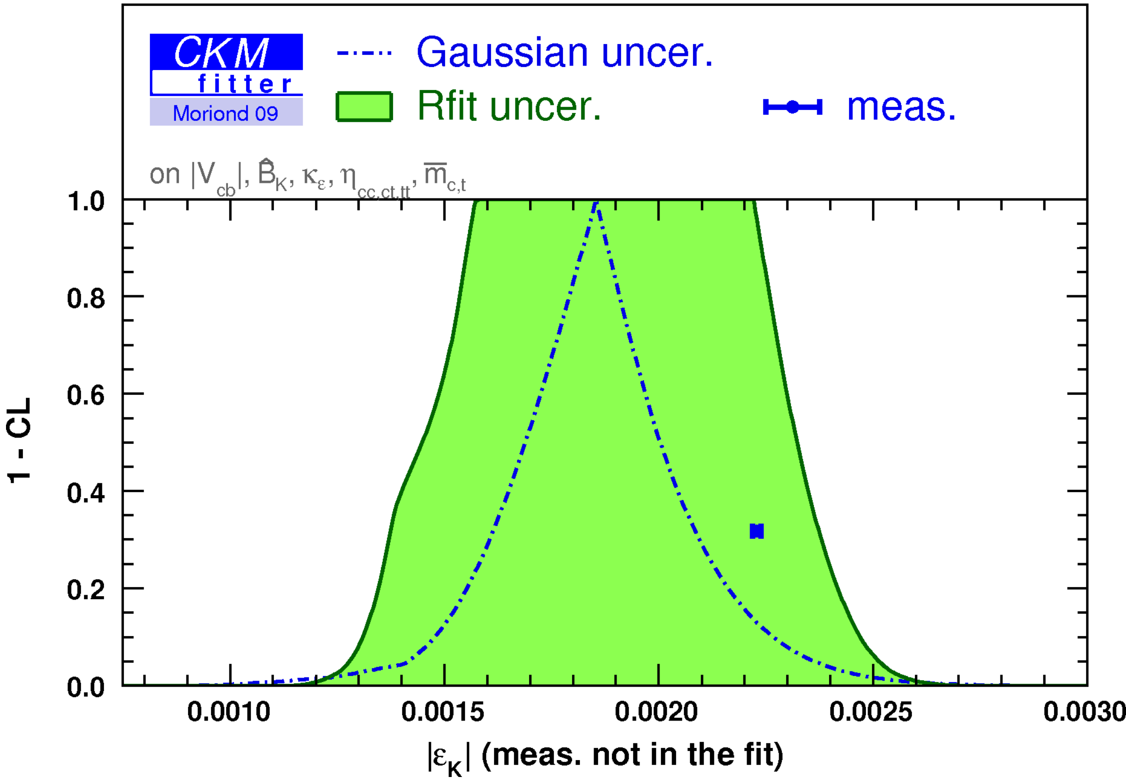


3.4 The tensions in the global fit.

3.4.2 $|\varepsilon_K|$ vs $\sin 2\beta$?

Buras & Guadagnoli recently advocated necessity of an additional parameter in the SM lowering the prediction.

A possible tension $|\varepsilon_K|$ vs $\sin 2\beta$ was mentioned and received appealing explanations (Soni & Lunghi).

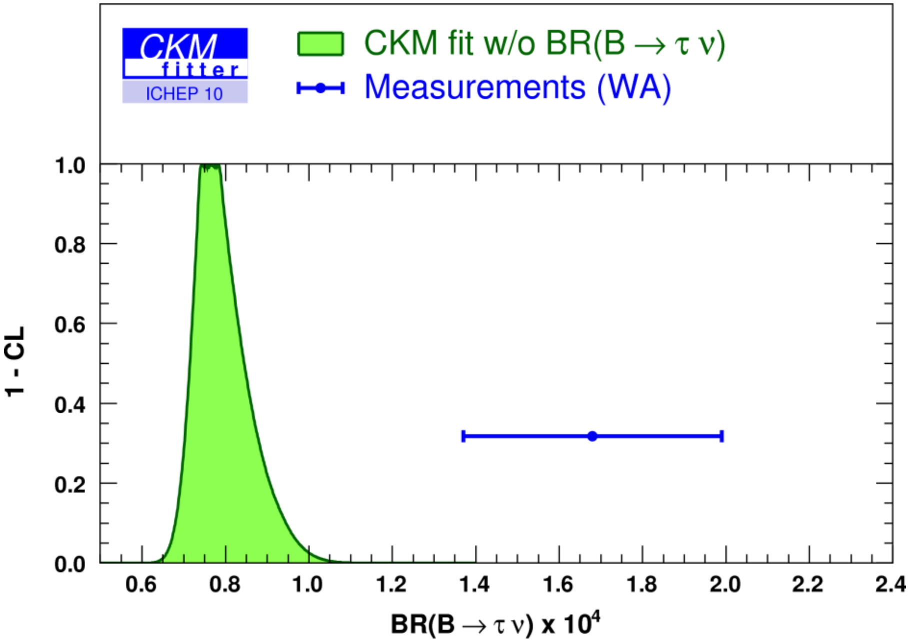


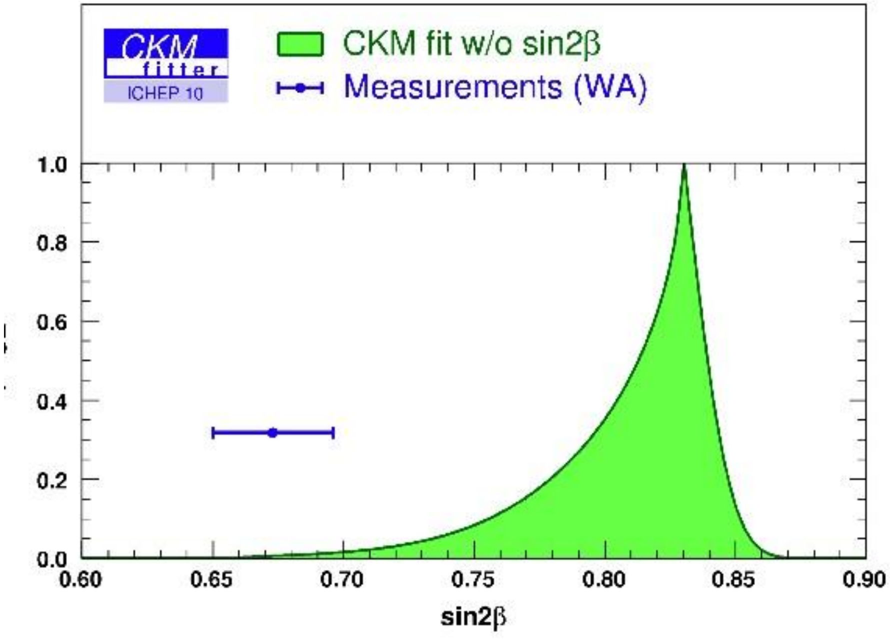
A tension arises in CKMfitter only if all the uncertainties on QCD parameters are Gaussian.

3.4 The tensions in the global fit.

3.4.3 $B^+ \to \tau^+ \nu$ vs sin2β ?

Actually, all measurements are consistent with their predictions within one standard deviation apart Br($B^+ \to \tau^+ \nu$) [2.8 σ] and sin2β [2.6 σ]

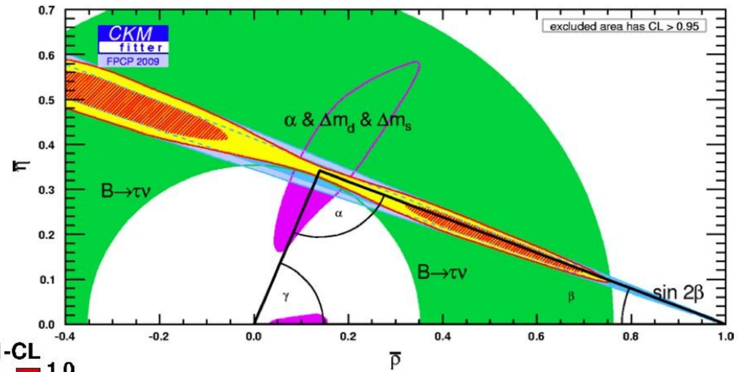


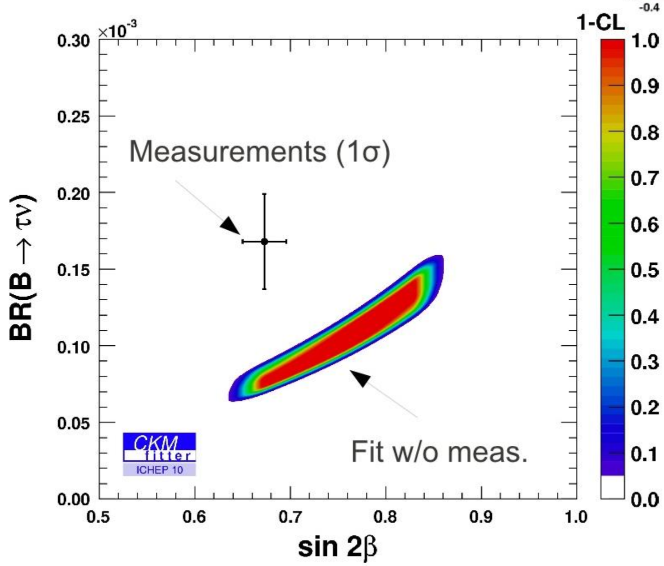


3.4 The tensions in the global fit.

3.4.3 $B^+ \to \tau^+ \nu$ vs $\sin 2\beta$?

• The combination sin2β and B →τν favors 2 solutions in contradictions with other inputs.
• One cannot accommodate both inputs simultaneously in the global fit.





Non-trivial correlation of indirect constraints on sin2β and B →τν.

The low value of the prediction of B →τν is mainly driven by the measured value of sin2β

Sources of discrepancies:
1) Measurements (stat. fluctuations)?
2) Lattice estimate of f_B?
3) New Physics in B→τν and/or sin2β?

9

© S.T'Jampens. Ichep 2010

4. Outlook and conclusions.

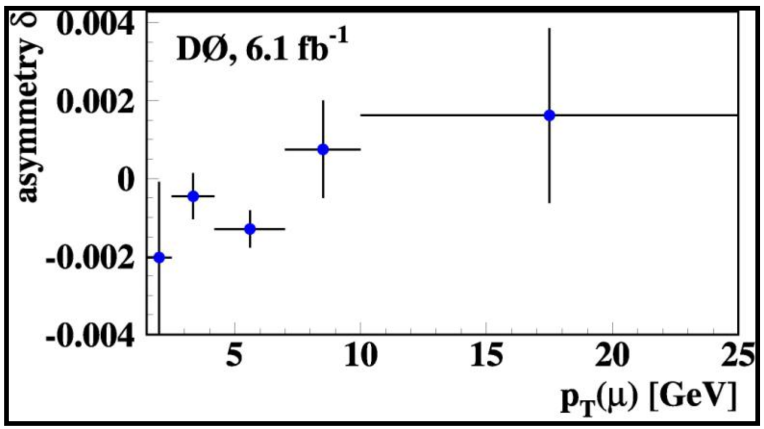
1. Additional mesaurements from Tevatron: the angle β_s, the semileptonic asymmetries a_{SL},

1. Model independent analysis of mixing processes. Which room left for new physics.

1. Concluding remarks.

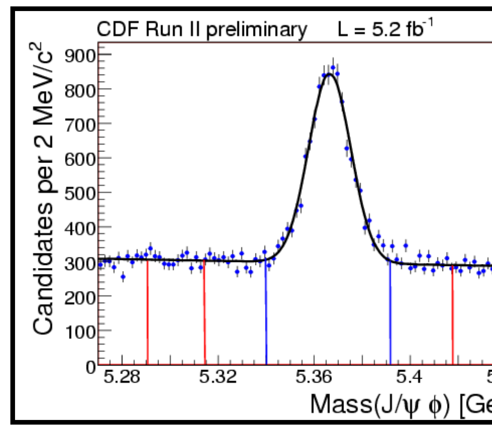
4.1 Tevatron measurements.

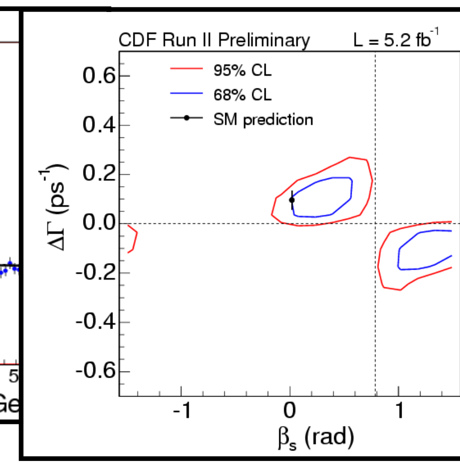
- See Zoltan's lecture for the SM parameters dependencies of these observables.
- A_{SL} measures the CP violation in the mixing of the B mesons.
- β_s is the measure of the weak phase of B_s mixing, analogously to β for B^0 mixing.



$$A_{sl}^b = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

- D0 meas. 3.2 σ from SM.
- Excellent muon coverage.
- Flip the magnetic field..





- Very complicated (VV, angular) analysis.
- Some discrepancy w.r.t /SM.
- World Averaging not
- Young experts in the room.

4.2 NP in ΔF=2 processes

Aim at investigating in a model-independent manner the space left to NP contributions by the current data. Only two additional parameters added. Several equivalent parametrisations exist:

$$\langle B_q \,|\, \mathcal{H}^{\mathrm{SM+NP}}_{\Delta B=2} \,|\, \bar{B}_q \rangle \equiv \langle B_q \,|\, \mathcal{H}^{\mathrm{SM}}_{\Delta B=2} \,|\, \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q)$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)
Goto et al., PRD 53, 6662 (1996)

Hypotheses:

•only the short distance part of the mixing processes might receive NP contributions.

•Unitary 3X3 CKM matrix.

• tree-level processes are not affected by NP (so-called SM4FC: $b \to q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario *are:*

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

4.2 NP in $\Delta F=2$ processes

Following the cartesian coordinates parametrisation proposed by Lenz and Nierste (JHEP0706:072,2007)

$$\Delta_q = |\Delta_q| e^{i2\Phi_q^{\mathrm{NP}}}$$

The predictions of the observables sensitive to NP contributions are modified as:

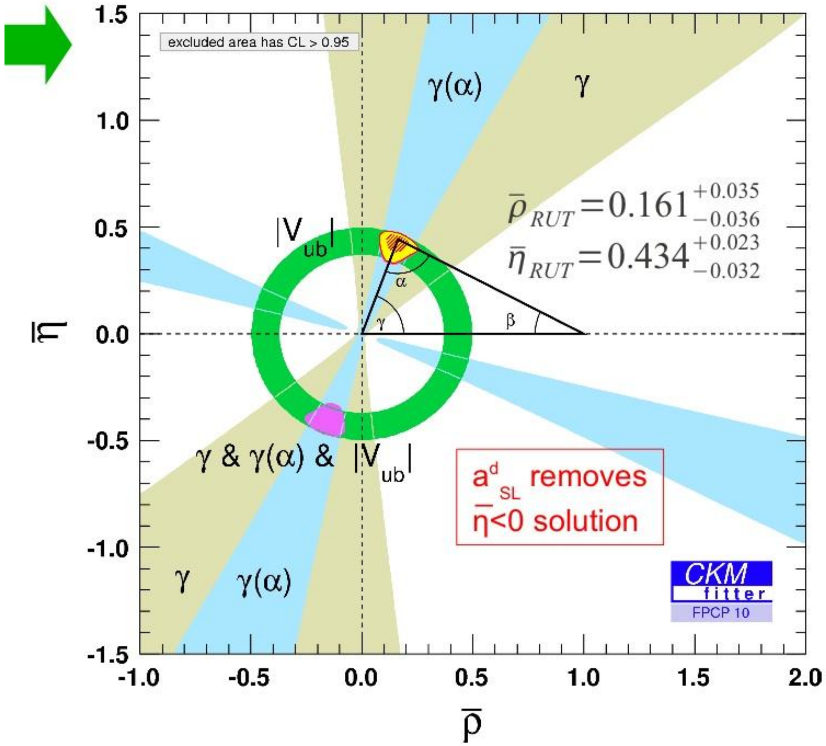
parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\mathrm{NP}}\rvert \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}}+\Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

4.2 NP in $\Delta F=2$ processes

Hypotheses:

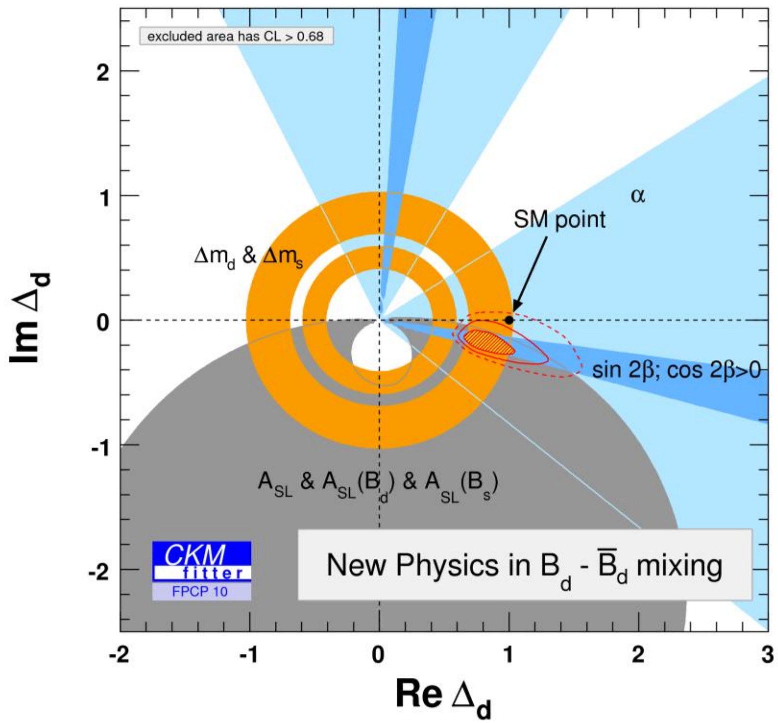
• tree-level processes are not affected by NP (so-called SM4FC: $b \to q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario *are:*

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$



- They fix the apex of the UT.
- α and β receives the same additionnal phase with opposite sign and hence can be interpreted as γ tree.
- The second (symmetric) solution is disfavored by the semileptonic charge asymmetry.

4.2 NP in ΔF=2 processes

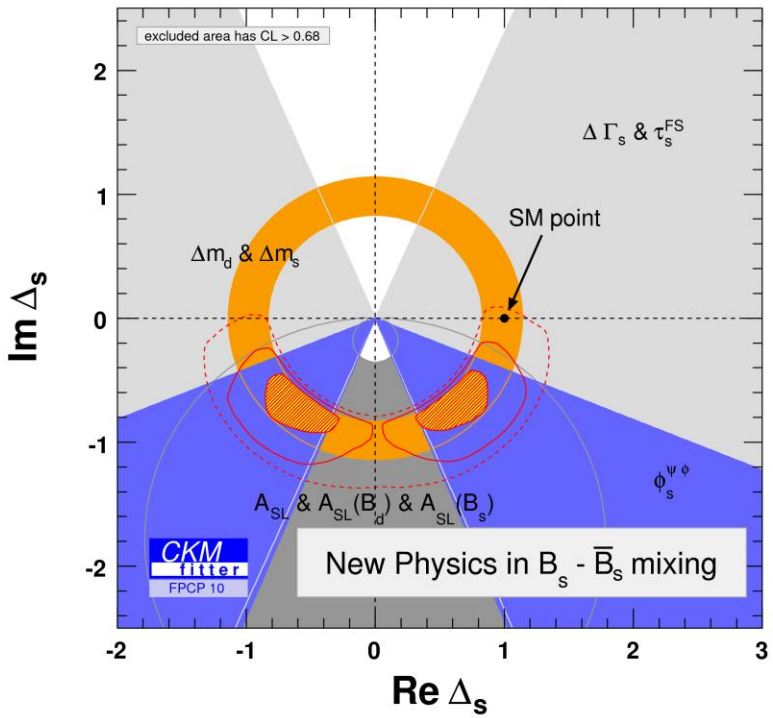


- β and A_{SL} are both favouring the negative imaginary part.
- SM hypothesis (2D): 2.5σ

1. Sizeable NP contributions allowed in the Bd mixing.

2. A new phase in the Bd mixing accomodates the $B^+ \to \tau^+ \nu$ vs sin2β discrepancy of the SM global fit

4.2 NP in $\Delta F=2$ processes



- β_s and A_{SL} are both favouring the negative imaginary part.
- SM hypothesis (2D): 2.7σ

1. Sizeable NP contributions allowed in the Bs mixing.
2. Recent CDF measurement (more SM like) not taken into account. LHCb contribution will be decisive in the near future.

Experimental aspects of the CP violation. Chapter IV

- CKM mechanism is at work for describing quark flavor transitions.
- KM phase likely to be dominant in B's.

- Triumph of the SM and the B factories.

- Still, sizeable NP contributions still allowed in both Bd and Bs systems.

- We are not yet at the level of precision achieved for Z pole EW fits. For instance, the CKM unitarity triangle is not much constrained: *Winter09*

$$\alpha + \beta + \gamma = (180 \pm 31)\,\mathrm{deg}\,.$$

- Hunt for rare decays where significant BSM contributions might occur.

- Improve the UT consistency test: measure the gamma angle.

- *This is the physics case of the LHCb experiment ! Exciting times.*