Physique des Saveurs et Matrice CKM : un état des lieux

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pour le groupe CKMfitter.

OUTLINE

- ✓Introduction to unitarity triangle
- ✓SM metrology : the global CKM fit
  - ✓Angles
  - ✓Sides
  - ✓Summary and CKM mechanism tests
- ✓Where to search for NP ?
- ✓Conclusions

1. Introduction to unitarity triangle in the Standard Model

The transition between quark flavours by charged current are described in the Standard Model by a unitary complex (nXn) matrix, n being the number of quarks weak isospin doublets.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

With n=3, the CKM matrix can be written from 3 real parameters and one phase δ_{CKM} . CP violation means δ_{CKM} non zero.

Most popular parametrisation is due to Wolfenstein.

unitarity-exact and convention-independent version of the Wolfenstein parametrization

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

1. Introduction to unitarity triangle in the Standard Model

FOUR UNKNOWNS

✓λ from |*Vud*| (nuclear transitions) and |*Vus*| (semileptonic *K* decays) (0.5% precision)
✓*A* from |*Vcb*| (incl. and excl. semileptonic *B* decays) (2% precision)
✓The 2 other parameters are the subject of the following.

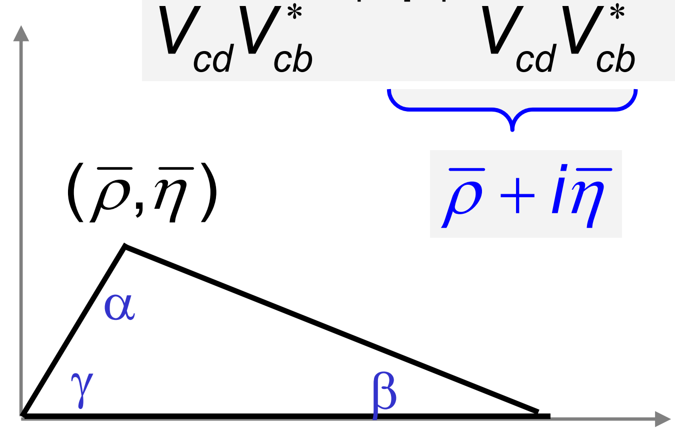
The unitarity relations can be elegantly displayed by triangles in the complex plane. One is not flat:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

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

$$\left(\propto A\lambda^3 \propto -A\lambda^3 \propto A\lambda^3\right)$$

$$\bar{\rho} + i\bar{\eta}$$

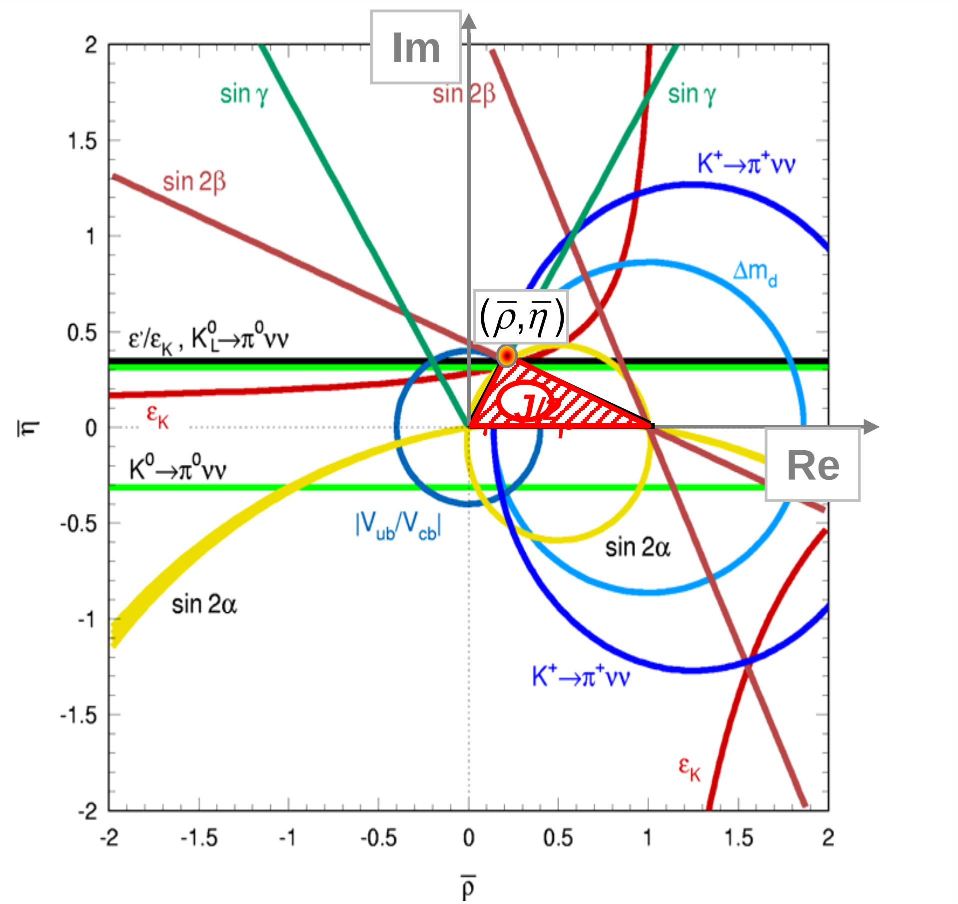


1. Introduction to unitarity triangle in the Standard Model

The game consists in over-constraining the SM apex of the triangle w/ as much as possible observables for which a good theory control exists.

If overall agreement (and it is !), then can do the metrology of the Standard Model parameters.

Not a word on kaons in this presentation (covered later).



2. The global CKM fit

The list of inputs used in the global CKM fit:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

CP CONSERVING

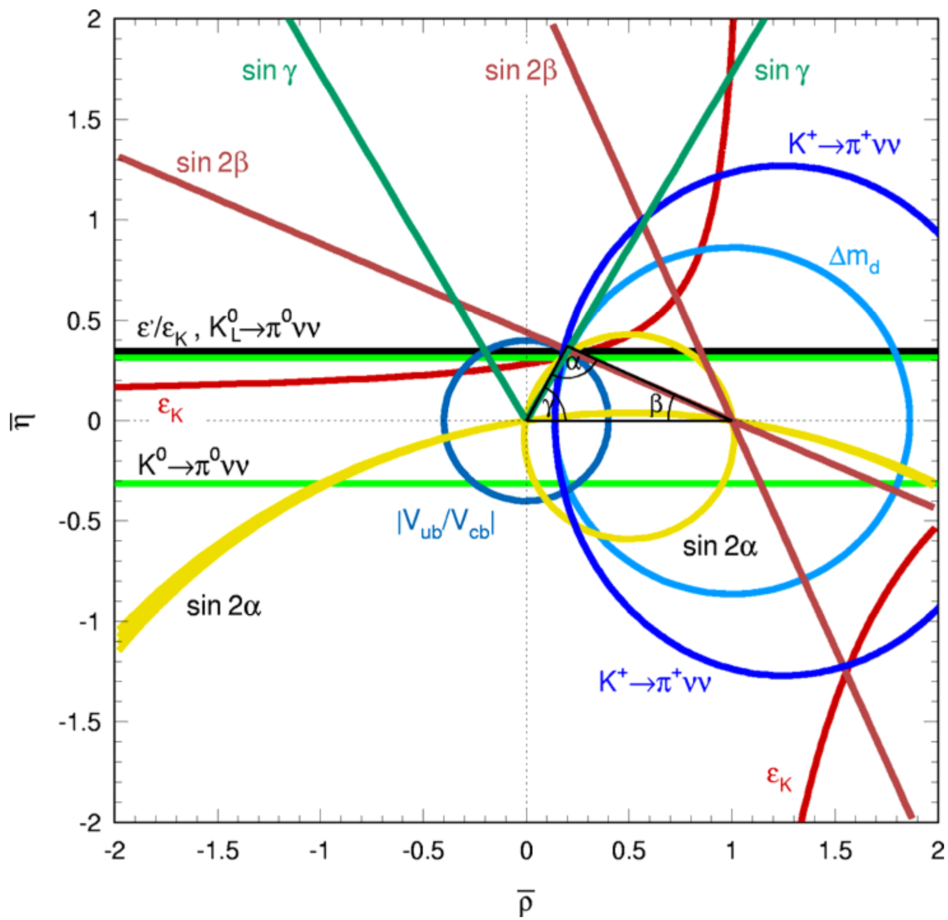
$|\varepsilon_K|$

$\sin 2\beta$

α

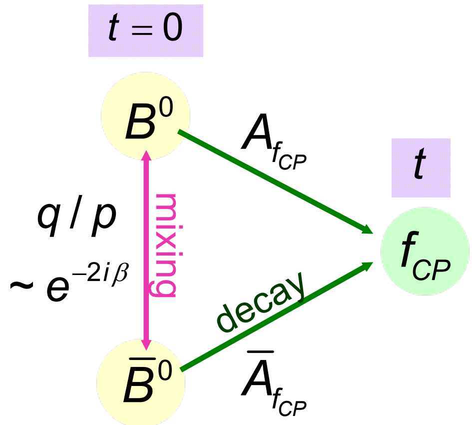
γ

CP VIOLATING

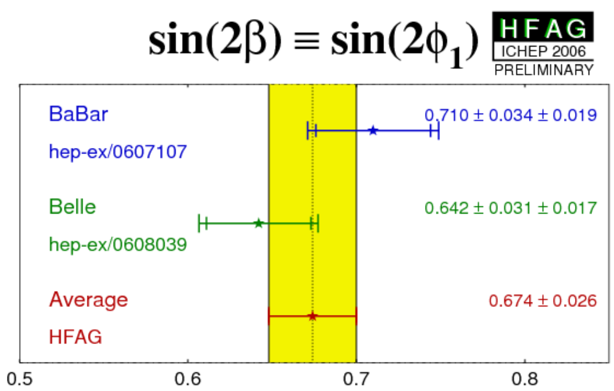


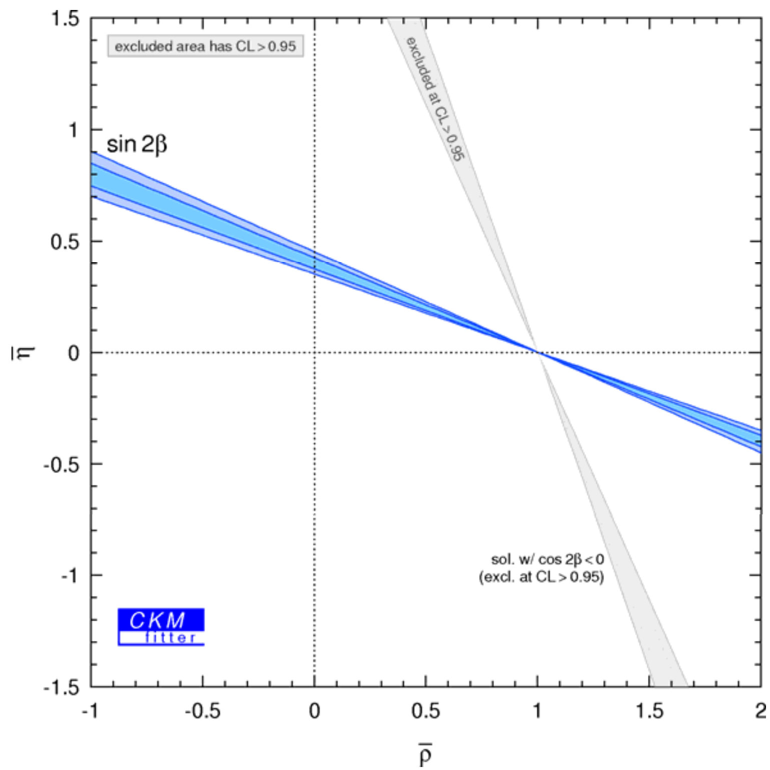
2. The global CKM fit : some details on the inputs

The inputs : sin 2β



$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$
$$= S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t)$$



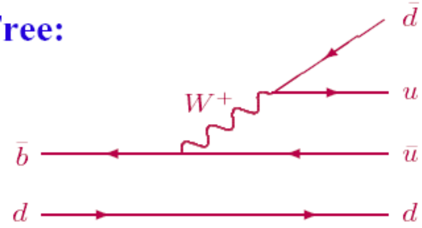


2. The global CKM fit : some details on the inputs

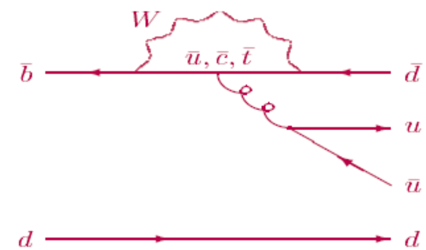
The inputs : α w/ $\pi\pi$ and $\rho\rho$

Actually $\alpha = \pi-(\beta+\gamma)$
Interference between mixing and decay but significant penguin contributions.

Tree:

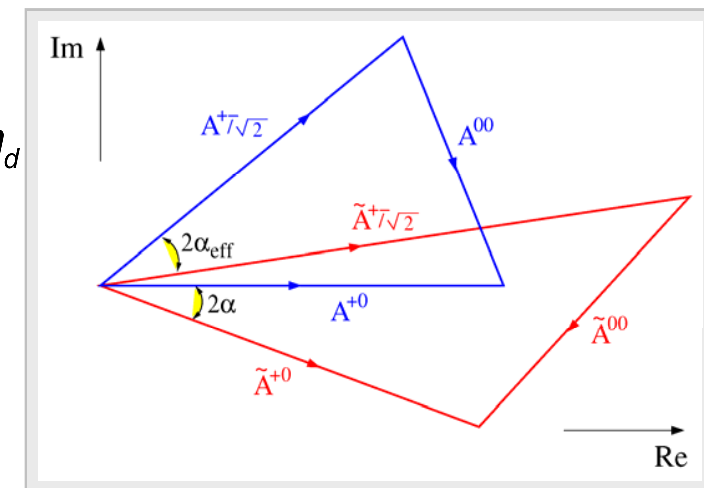


Penguin:



Time-dependent *CP* analysis of $B^0 \to \pi^+\pi^-$ determines a biased α_{eff} . We want α.

$$A_{h^+h^-}(t) = S_{h^+h^-}\sin(\Delta m_d t) - C_{h^+h^-}\cos(\Delta m_d t)$$
$$= \sqrt{1-C^2_{h^+h^-}}\sin(2\alpha_{eff})\cdot\sin(\Delta m_d t) - C_{h^+h^-}\cos(\Delta m_d$$

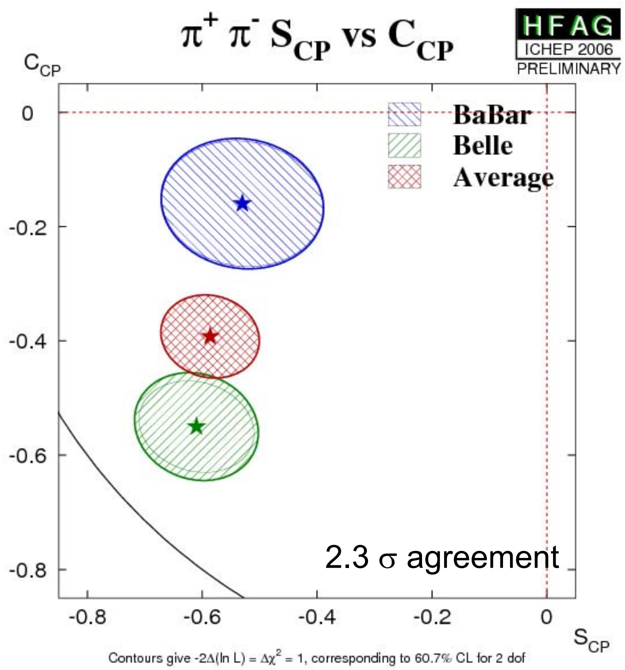


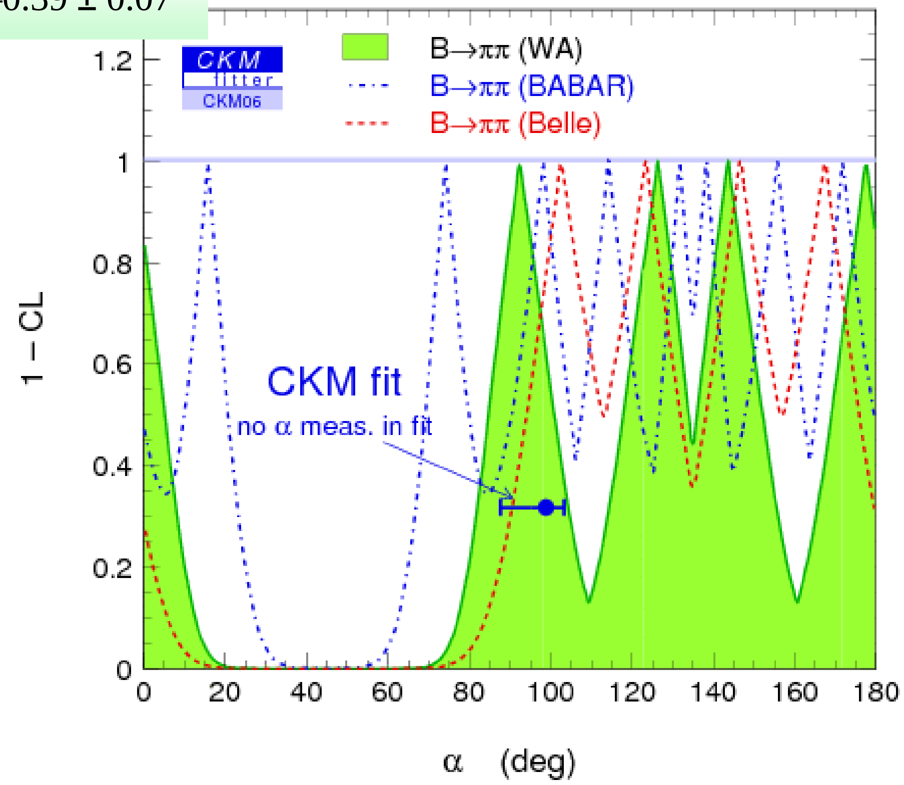
Thanks to SU(2) symmetry, use all $\pi\pi$ to resolve α up to an 8-fold ambiguity within [0,π]. True also for $\rho\rho$ provided that mostly longitudinally polarised (true).

2. The global CKM fit : some details on the inputs

The inputs : α the $(\pi\pi)$ system

	BABAR (347m)	Belle (532m)	Average
$S_{\pi\pi}$	–0.53 ± 0.14 ± 0.02	–0.61 ± 0.10 ± 0.04	–0.58 ± 0.09
$C_{\pi\pi}$	–0.16 ± 0.11 ± 0.03	–0.55 ± 0.08 ± 0.05	–0.39 ± 0.07

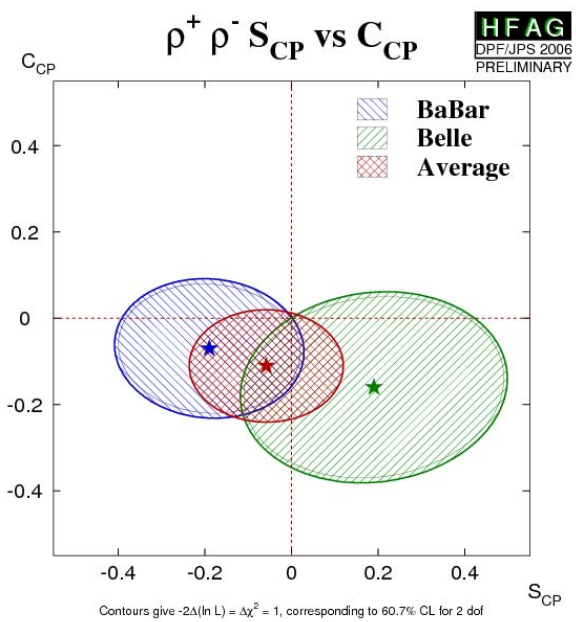


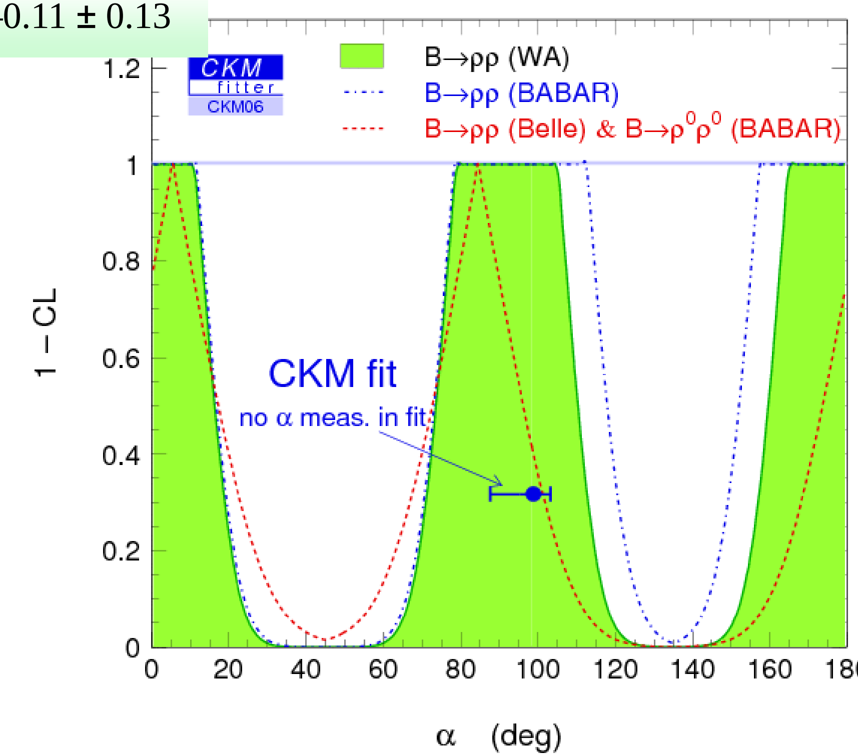


2. The global CKM fit : some details on the inputs

The inputs : α the (ρρ) system

	BABAR (347m)	Belle (535m)	Average
$S_{\rho\rho}$	–0.19 ± 0.21	0.19 ± 0.30 ± 0.07	–0.06 ± 0.18
$C_{\rho\rho}$	–0.07 ± 0.15 ± 0.06	-0.16 ± 0.21 ± 0.07	–0.11 ± 0.13





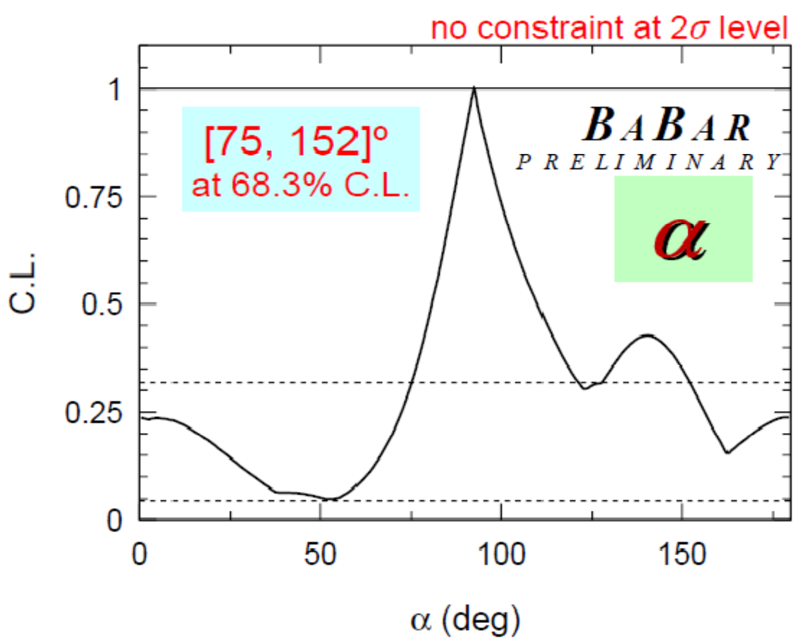
2. The global CKM fit : some details on the inputs

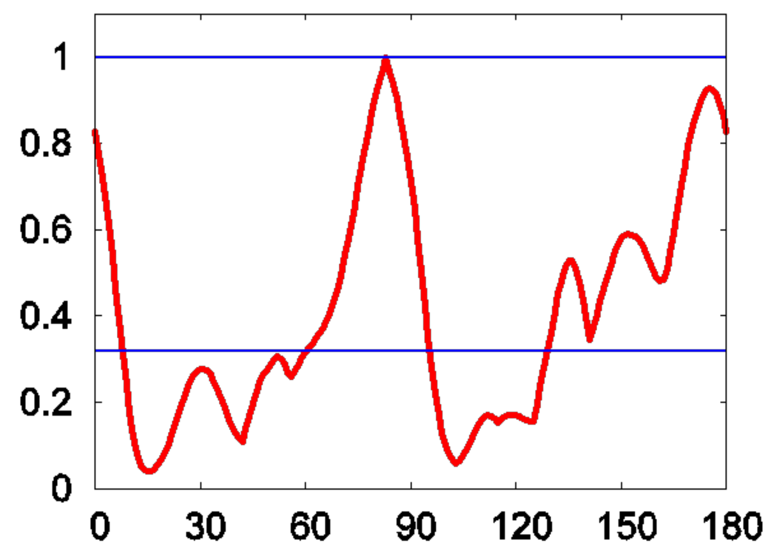
The inputs : α the ($\rho\pi$) system

Dominant mode $\rho^{+}\pi^{-}$ is not a *CP* eigenstate

Amplitude interference in Dalitz plot

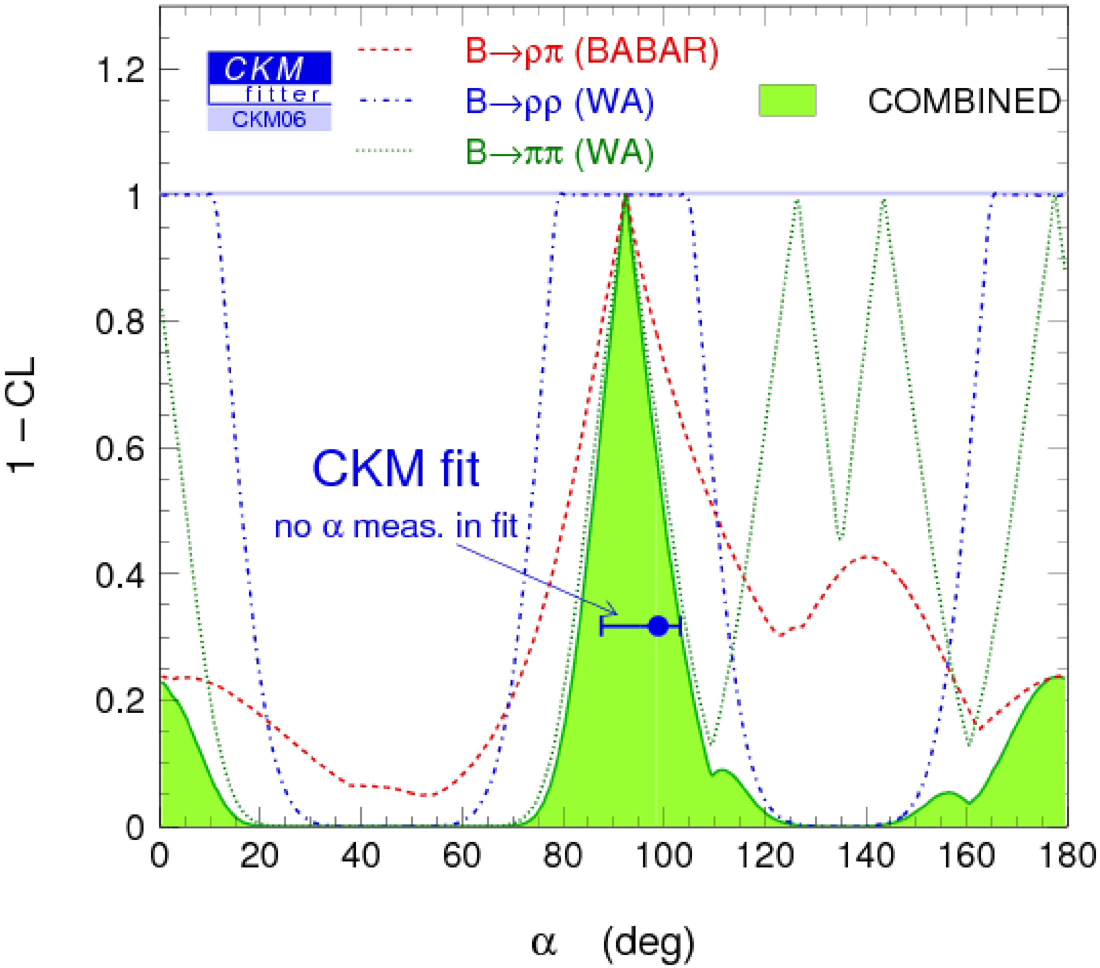
- ✓ simultaneous fit of α and strong phases
- ✓ Measure 26 (27) bilinear Form Factor coefficients
- ✓ correlated χ^2 fit to determine physics quantities





2. The global CKM fit : some details on the inputs

The inputs : α all together



$$\alpha_{\pi\pi} = (92^{+12}_{-10})^{o}$$

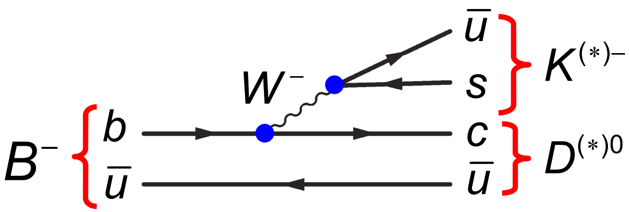
$$\alpha_{\rho\rho} = (92 \pm 21)^{o}$$

COMBINED

$$\boxed{\alpha = (93^{+11}_{-9})^{o}}$$

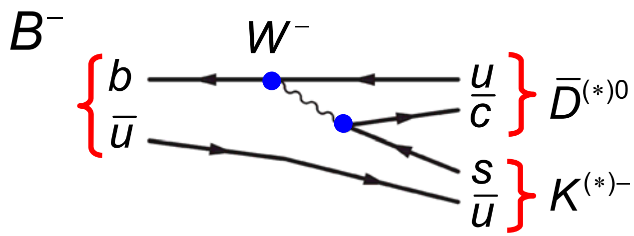
2. The global CKM fit : some details on the inputs

The inputs : γ



$\propto V_{cb}V_{us}^{*}$

$\propto \lambda^{3}$



$\propto V_{ub}V_{cs}^{*}$

$\propto \lambda^{3}\sqrt{\rho^{2}+\eta^{2}}$

$$r_B = \frac{|A(b\to u)|}{|A(b\to c)|}$$

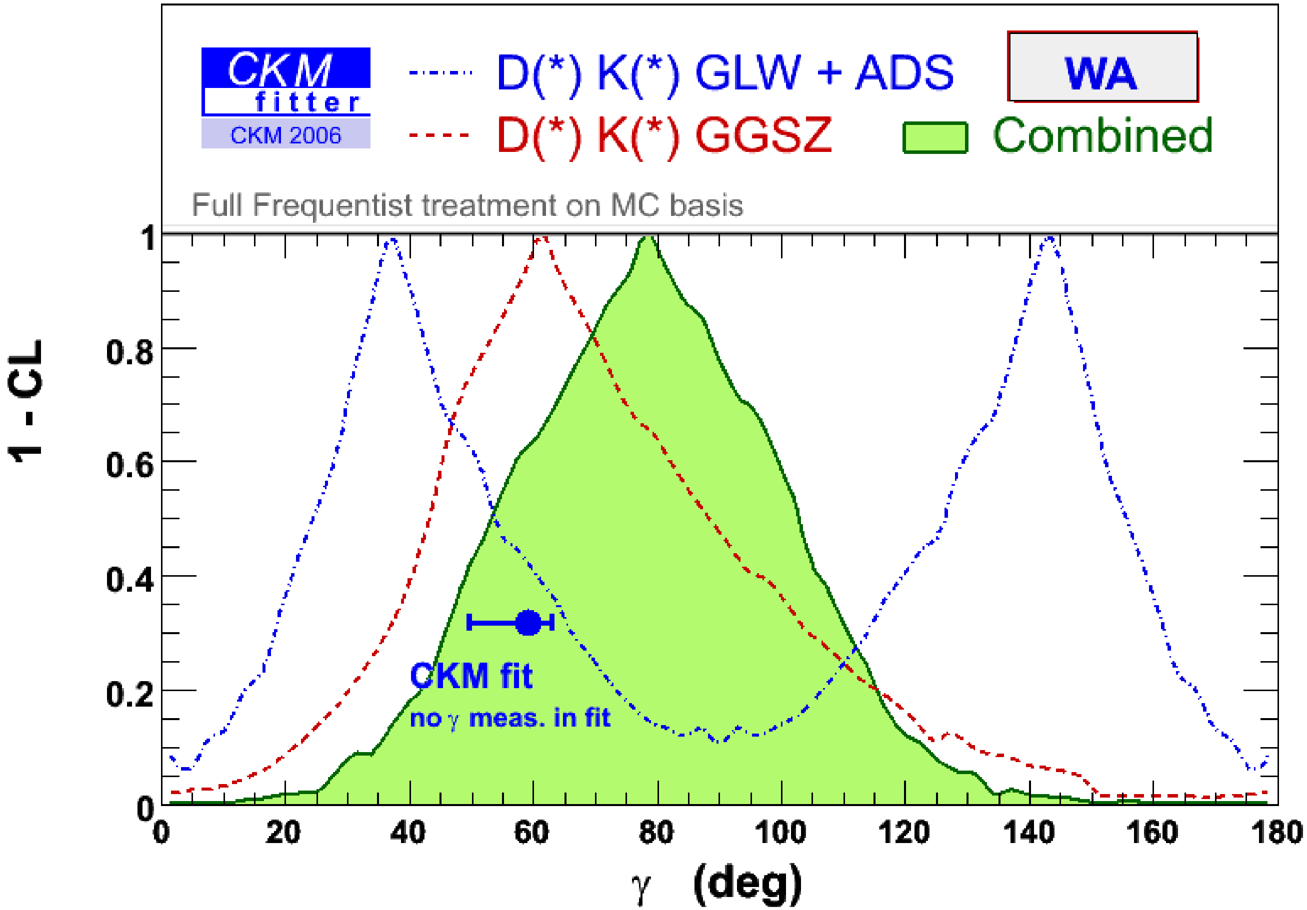
Here lies γ

- ✓ GLW : D^0 decays into *CP* eigenstate
- ✓ ADS : D^0 decays to $K^-\pi^+$ (favored) and $K^+\pi^-$ (suppressed)
- ✓ GGSZ : D^0 decays to $K_S\pi^+\pi^-$ (interference in Dalitz plot)
  - ✓ All methods fit simultaneously: γ, r_B and *strong phase (a priori different).*

σ_γ depends significantly on the value of r_B.

2. The global CKM fit : some details on the inputs

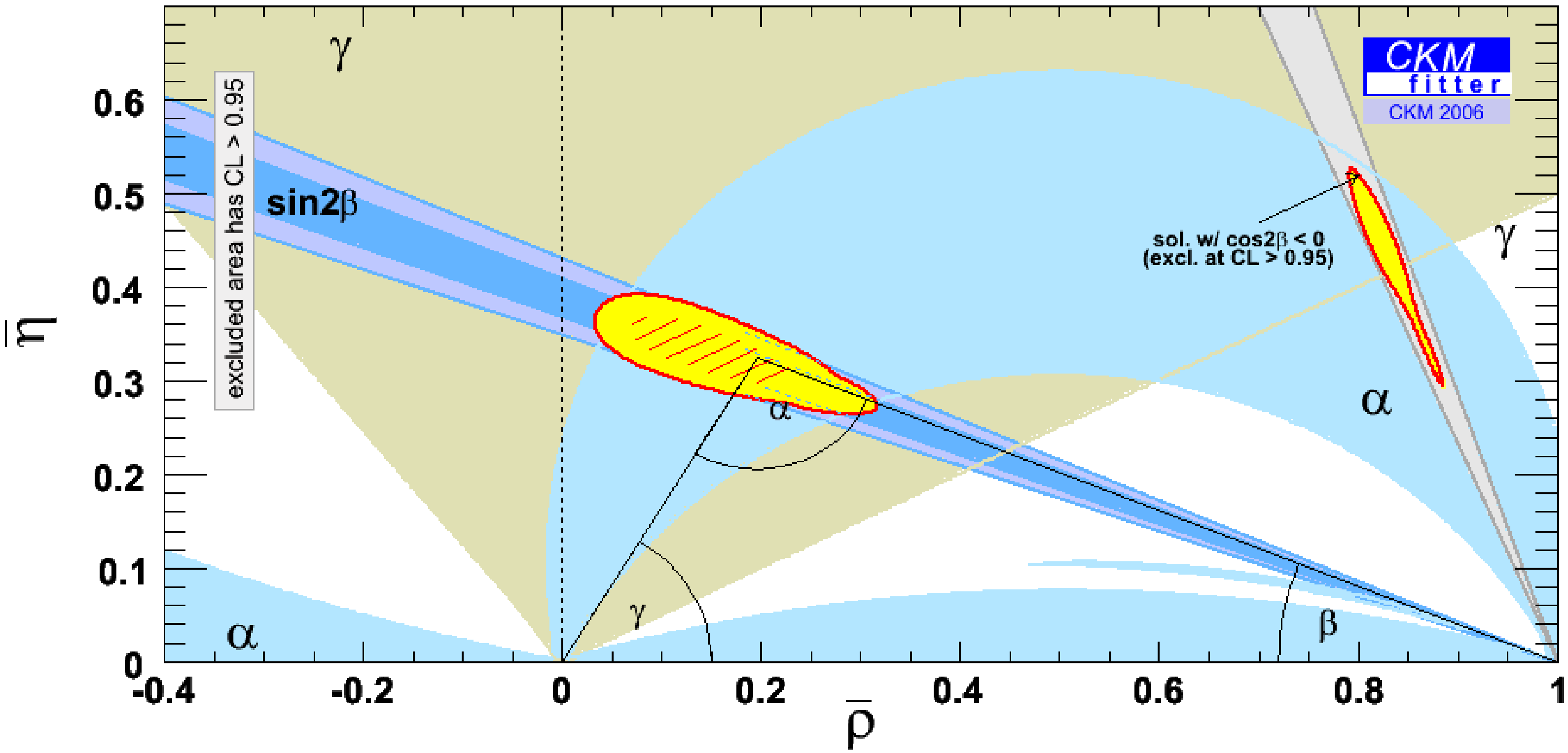
The inputs : γ



$$\gamma = (77 \pm 31)^{o}$$

2. The global CKM fit

The apex from the angles – remarkable achievement from B-factories



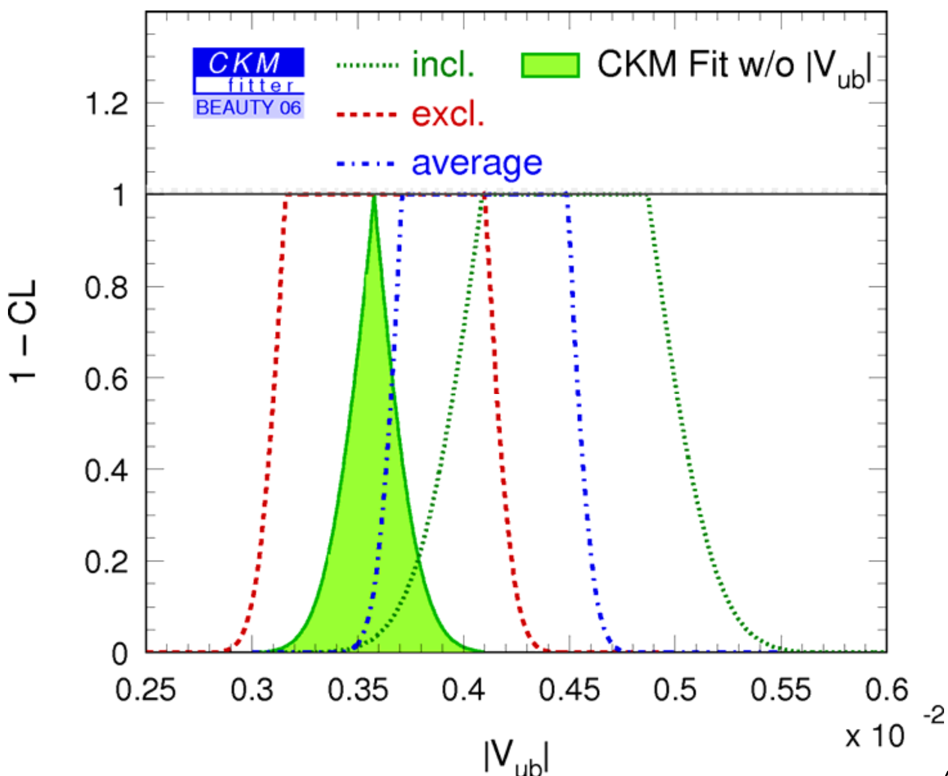
2. The global CKM fit : Sides

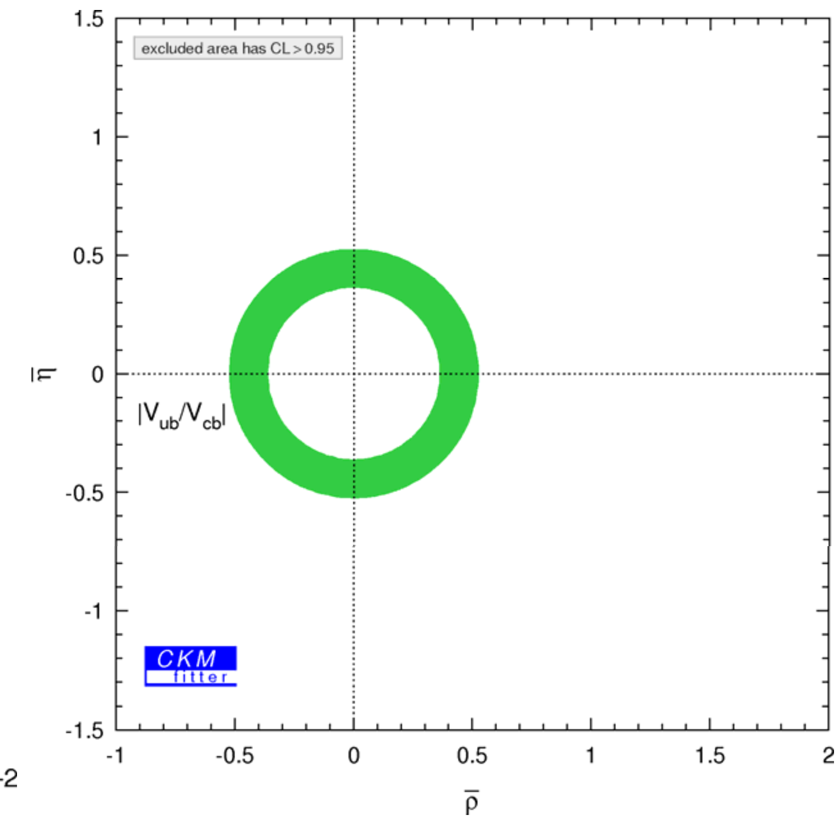
The inputs : |Vub| and |Vcb|

$|V_{cb}|_{incl.}[10^{-3}] = 41.70 \pm 0.70$

$|V_{ub}|\ [10^{-3}] = 4.10 \pm 0.09_{exp} \pm 0.39_{theo}$

Average of inclusive and exclusive measurement from semileptonic decays. Vub is very difficult to extract both from experimental and theoretical sides.





2. The global CKM fit : Sides

The inputs : Δm_d and Δm_s

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \eta_B S_0(x_t) f_{B_d}^2 B_d \left|V_{td} V_{tb}^*\right|^2 \propto A^2 \lambda^6 \left[(1-\bar{\rho})^2 + \bar{\eta}^2\right]$$

$$\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_s} m_W^2 \eta_B S_0(x_t) f_{B_s}^2 B_s \left|V_{ts} V_{tb}^*\right|^2$$

✓Large hadronic uncertainties, but

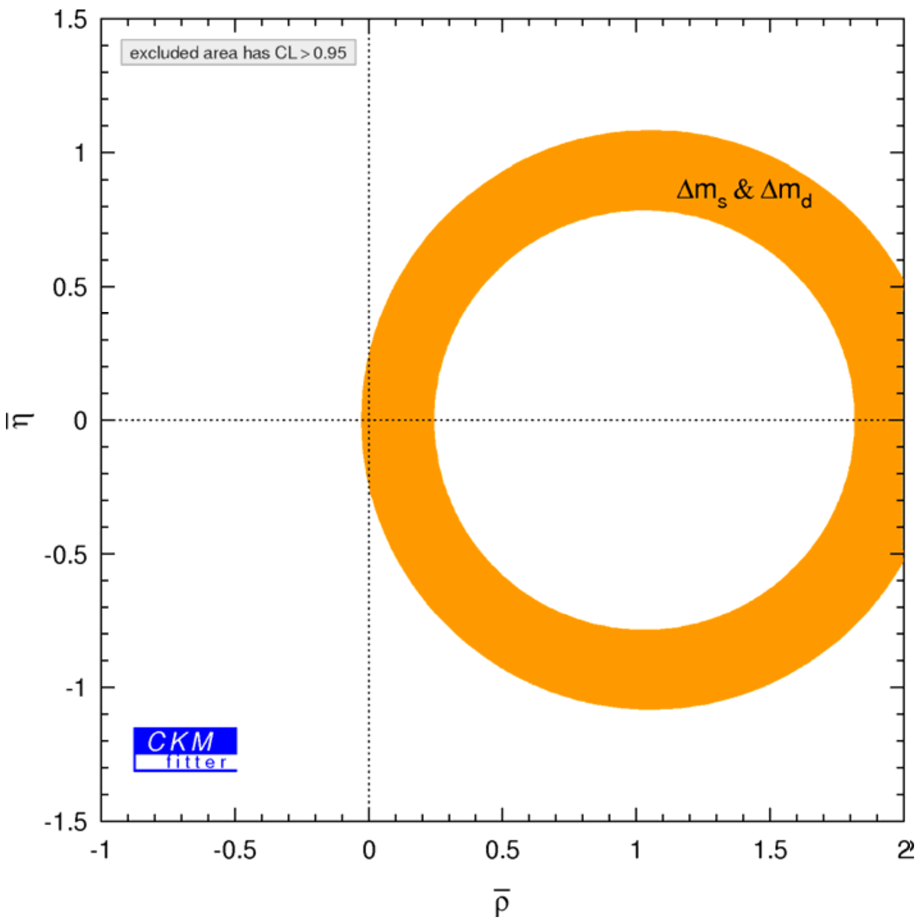
✓the ratio $f^2_{B_s} B_s / f^2_{B_d} B_d$ is much better known than $f^2_{B_d} B_d$ from Lattice QCD

$$\sigma_{rel}(f_{B_d}{}^2 B_d) \approx 35\% \text{ and } \sigma_{rel}\left(\frac{f_{B_d}{}^2 B_d}{f_{Bs}{}^2 B_s}\right) \approx 10\%$$

✓Though Δm_s has very weak dependence on ρ and η, it's very powerful to improve the Δm_d constraint.

2. The global CKM fit : Sides

The inputs : Δm_d and Δm_s



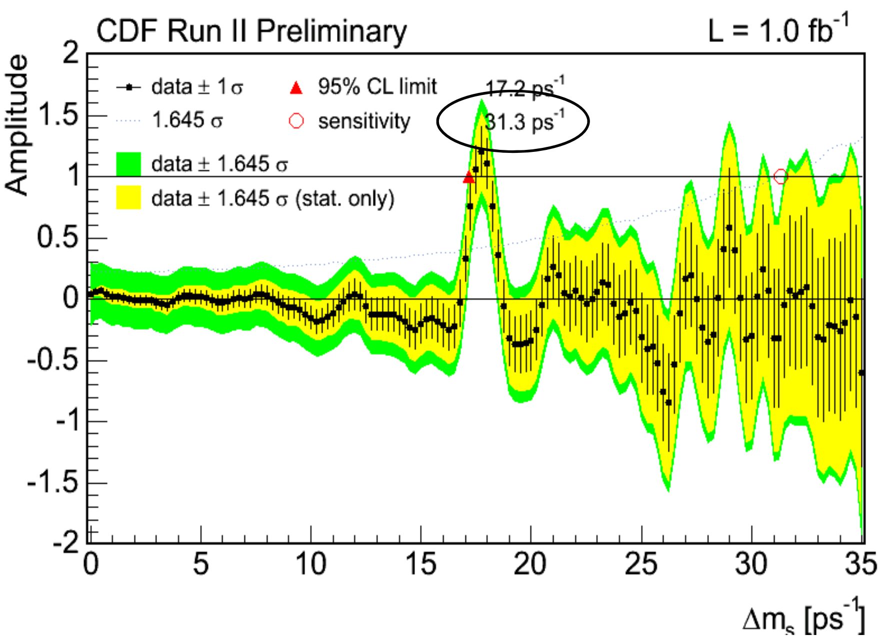
2. The global CKM fit : Sides

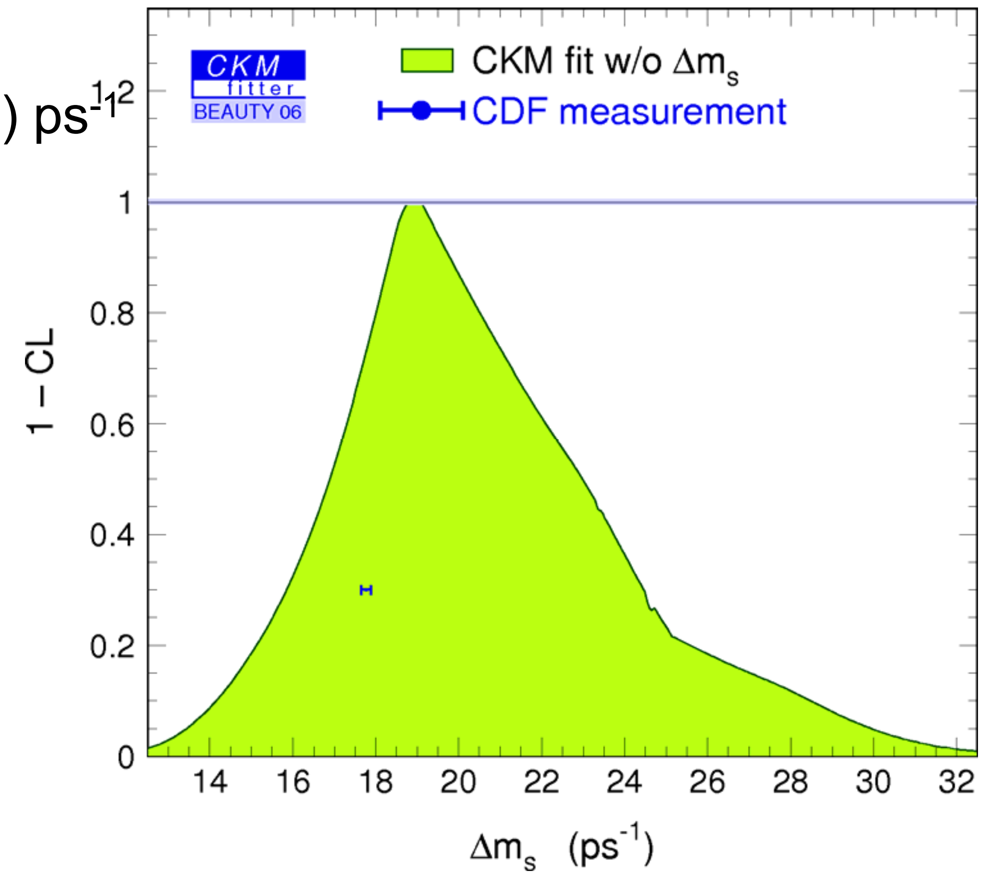
The inputs : Δm_d and Δm_s

Bs oscillations eventually resolved at CDF – at the value suggested by LEP

CDF MEASUREMENT (2006)

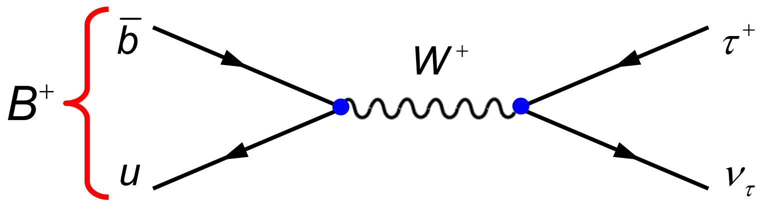
Δm_s : 17.77±0.10(stat.) ± 0.07 (syst.) ps^{-1}





2. The global CKM fit : Sides

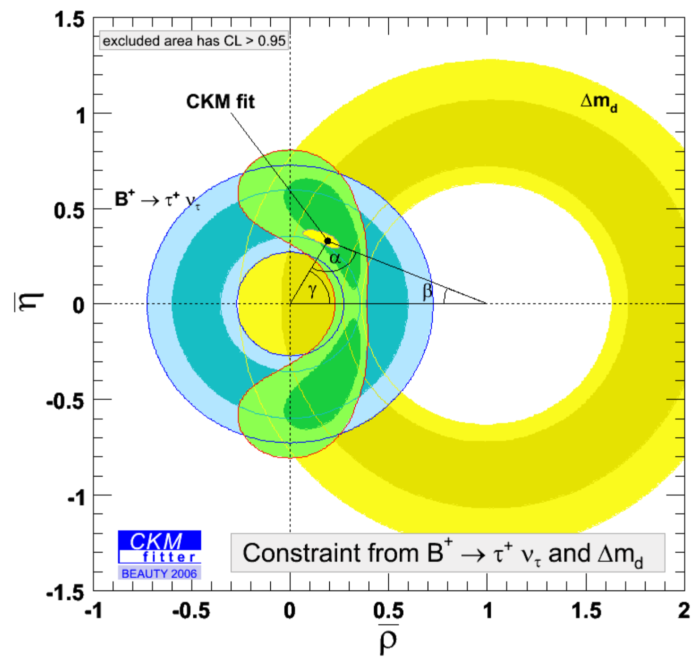
The inputs : $B^+ \to \tau^+ \nu_\tau$



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

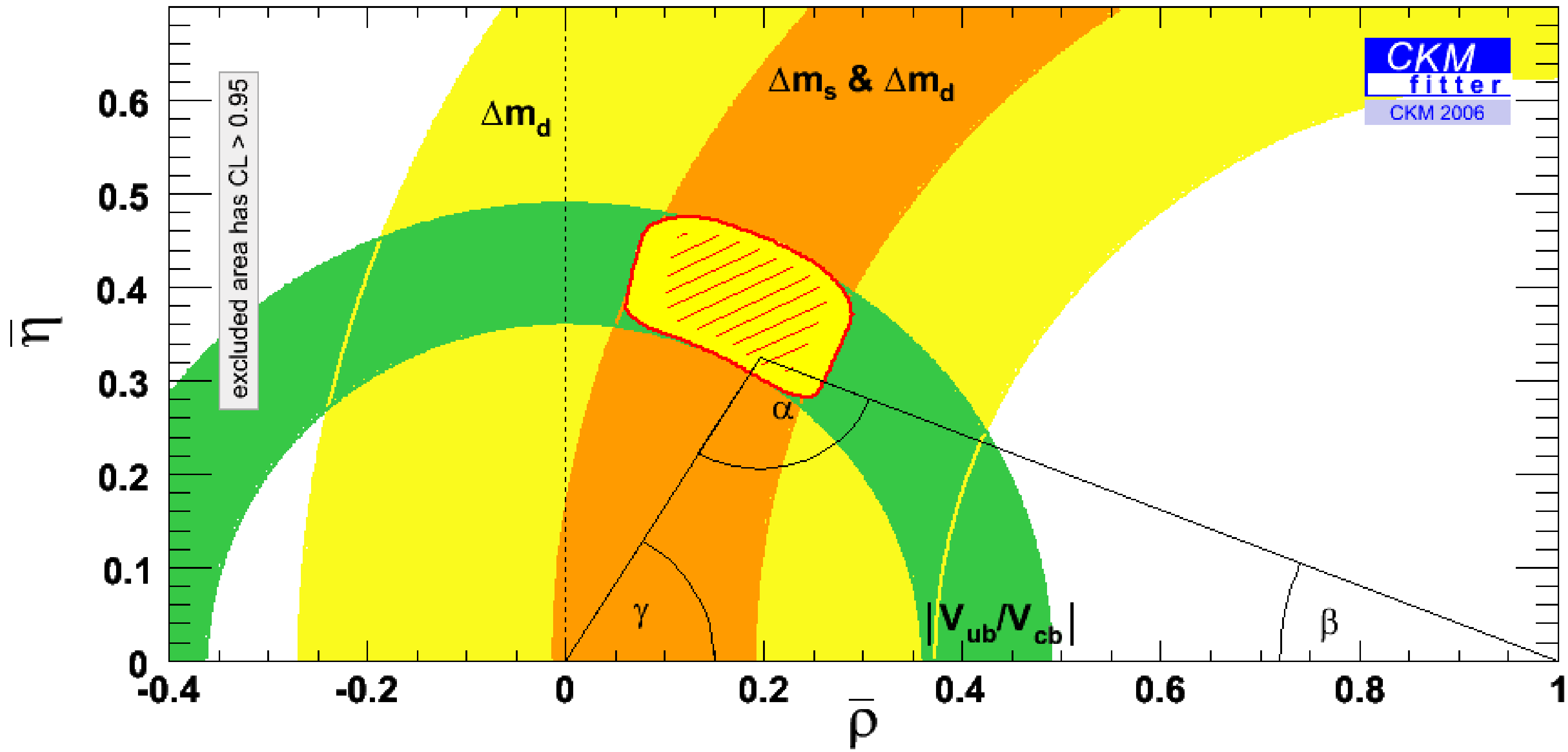
- ✓ Powerful <u>together</u> with Δm_d to remove hadronic uncertainty on f_B
- ✓ Remarkable agreement between measurements and prediction.

	$\mathrm{BF}(B^+ \to \tau^+ \nu_\tau)/10^{-4}$
BaBaR	$1.06^{+0.34}_{-0.28}\,(stat)^{+0.18}_{-0.16}\,(syst)$
Belle	$1.79^{+0.56}_{-0.49}\,(stat)^{+0.39}_{-0.46}\,(syst)$
CKM Fit	$0.92^{+0.20}_{-0.19}$



2. The global CKM fit : Sides only

CP CONSERVING OBSERVABLES



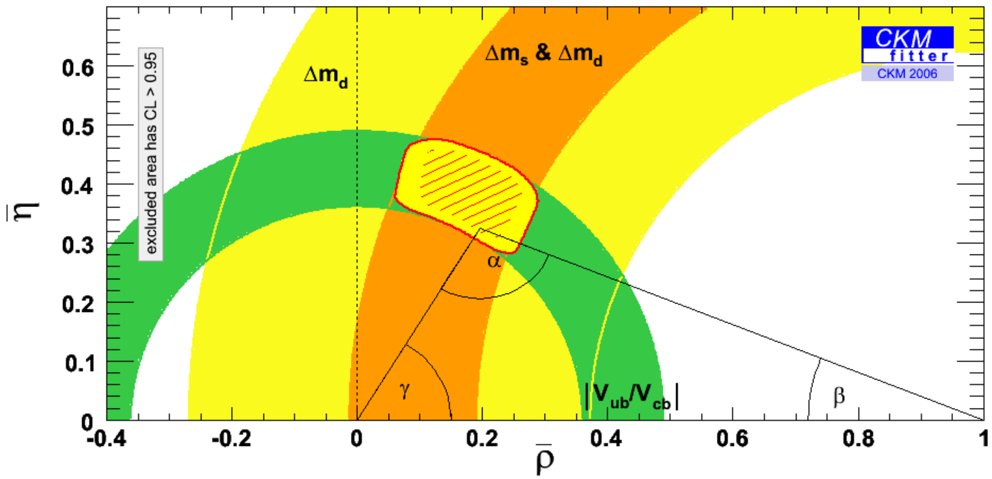
$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$

2. The global CKM fit : consistency



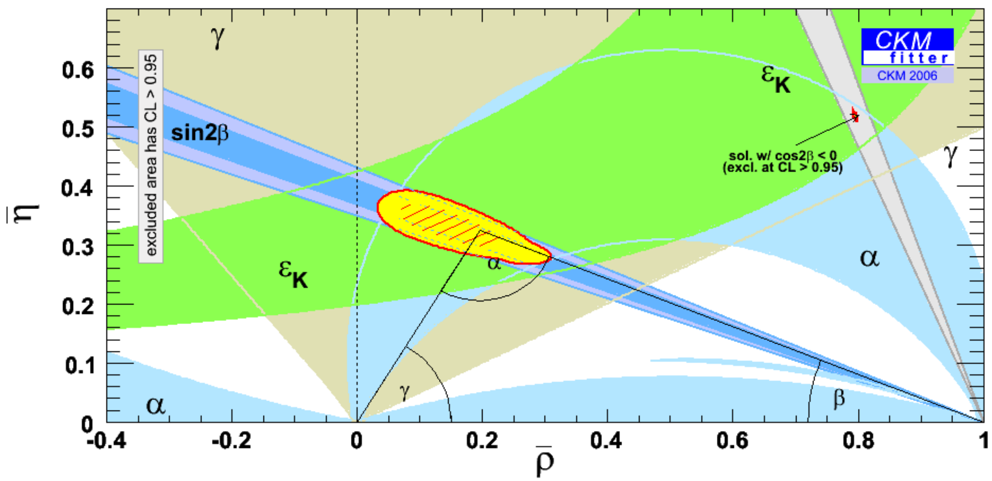
CP CONSERVING

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s

$B \to \tau\nu$



CP VIOLATING

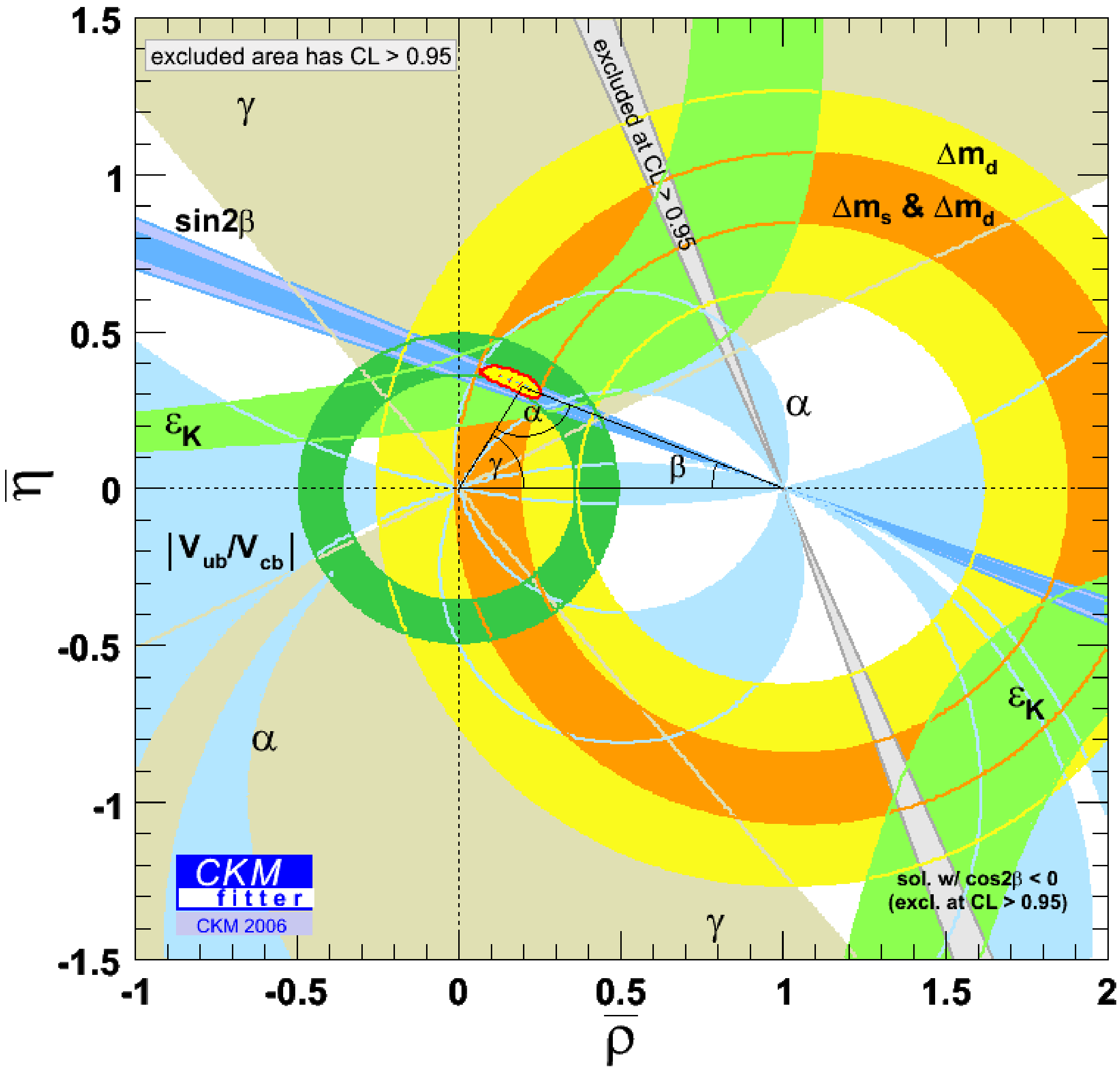
$|\varepsilon_K|$

$\sin 2\beta$

α

γ

2. The CKM global fit : a conclusion



2. The CKM global fit : SM metrology

Wolfenstein parameters:

$$A = 0.806 \pm 0.014$$

$$\lambda = 02272 \pm 0.0010$$

$$\bar{\rho} = 0.195^{+0.024}_{-0.067}$$

$$\bar{\eta} = 0.326^{+0.032}_{-0.015}$$

Jarlskog invariant:

$$J = (2.90^{+0.29}_{-0.15}) \times 10^{-5}$$

The UT angles:

$$\alpha = (98.9^{+4.4}_{-11.3})^{\circ},$$

$$\beta = (22.00^{+0.69}_{-0.63})^{\circ},$$

$$\gamma = (59.1^{+11.1}_{-4.1})^{\circ}.$$

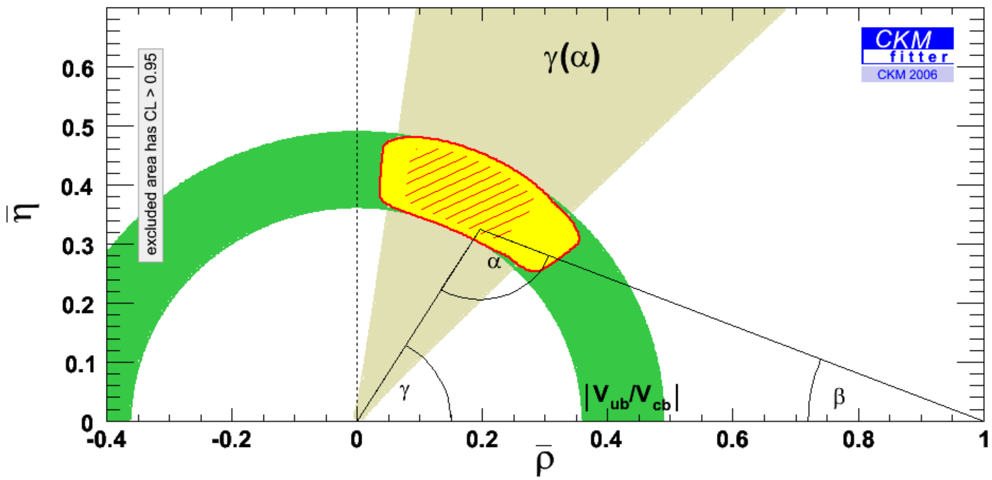
$$\alpha + \beta + \gamma = (191^{+33}_{-32})^{\circ}$$

2. The CKM global fit : a selection of SM predictions

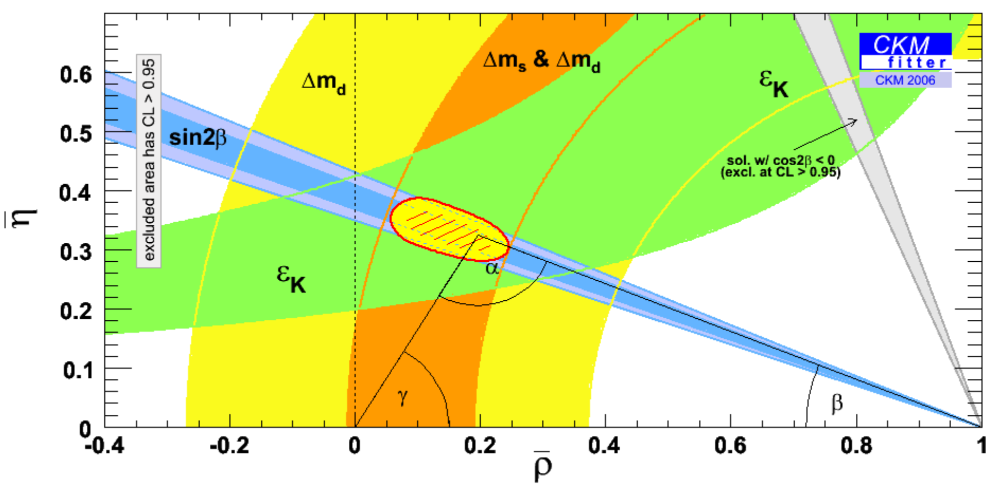
OBSERVABLE	CKM FIT	MEASUREMENT
$\Delta m_s \quad (ps^{-1})$	$19.2^{+5.1}_{-3.4}$	$17.77 \pm 0.10 \pm 0.07$
$BF(B^+ \to \tau^+ \nu_\tau)/10^{-4}$	$0.92^{+0.20}_{-0.19}$	$1.45^{+0.46}_{-0.43}$
$BF(B^+ \to \mu^+ \nu_\mu)/10^{-7}$	$4.15^{+0.56}_{-0.64}$	
$\chi \equiv \beta_s \quad (\mathrm{deg})$	$1.005^{+0.089}_{-0.045}$	

2. The CKM global fit

TREE



LOOP



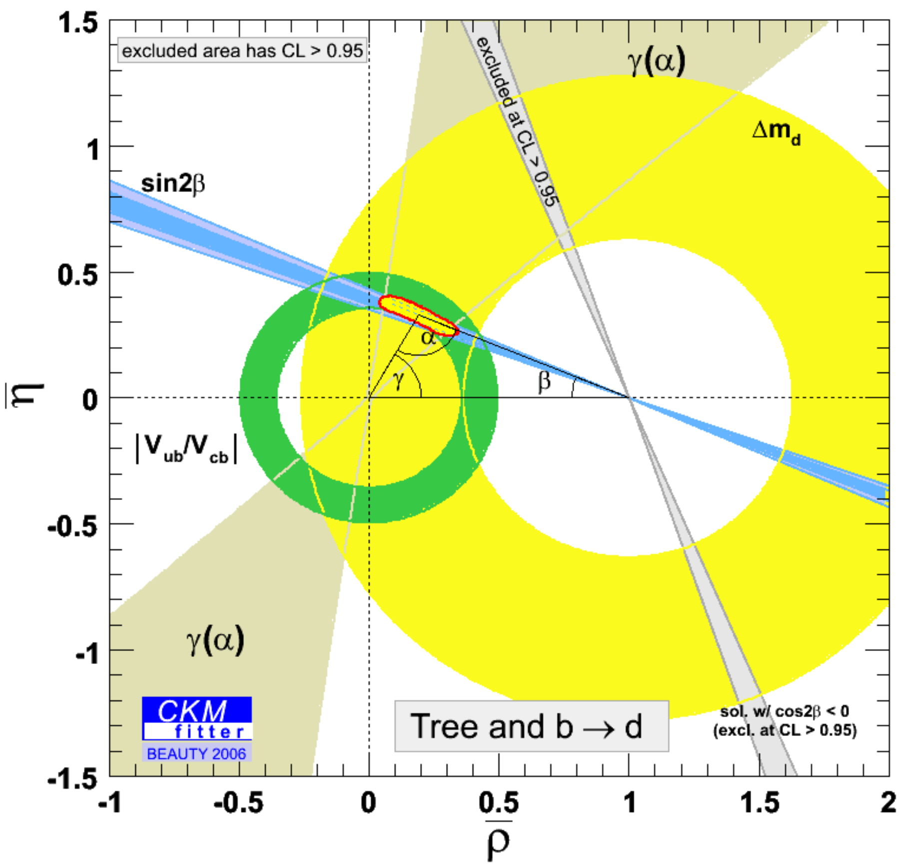
δ_{CKM} is the dominant source of CP violation

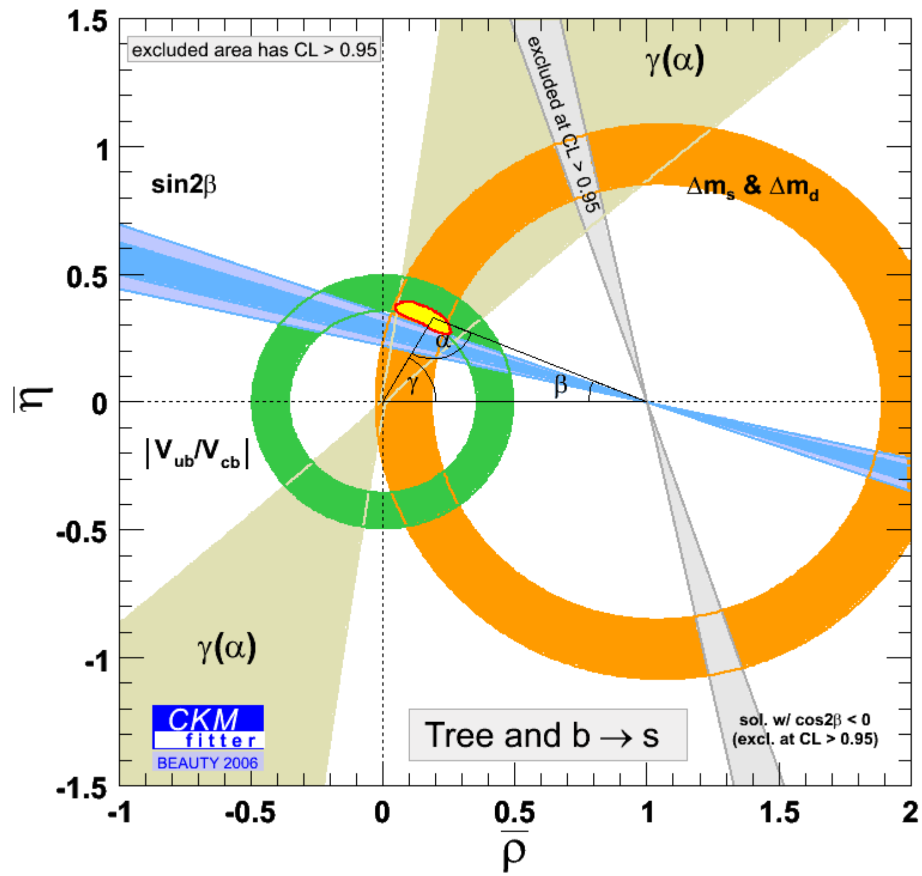
3. NP : where to look for ?

- ✓Comparison of sin 2β from ΨK and s-penguins diagrams
- ✓ $(b \to s\ell^+\ell^-)$
- ✓ Rare decays $(B_s \to \mu^+\mu^-)$
- ✓ Annihilation diagram $(B^+ \to \tau^+\nu_\tau)$
- ✓ NP in ΔF = 2 transitions

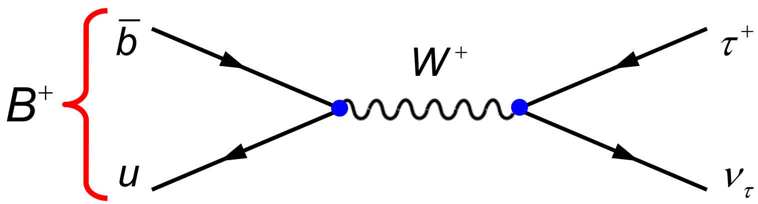
Focus on the last two points

3. NP : where to look for ?





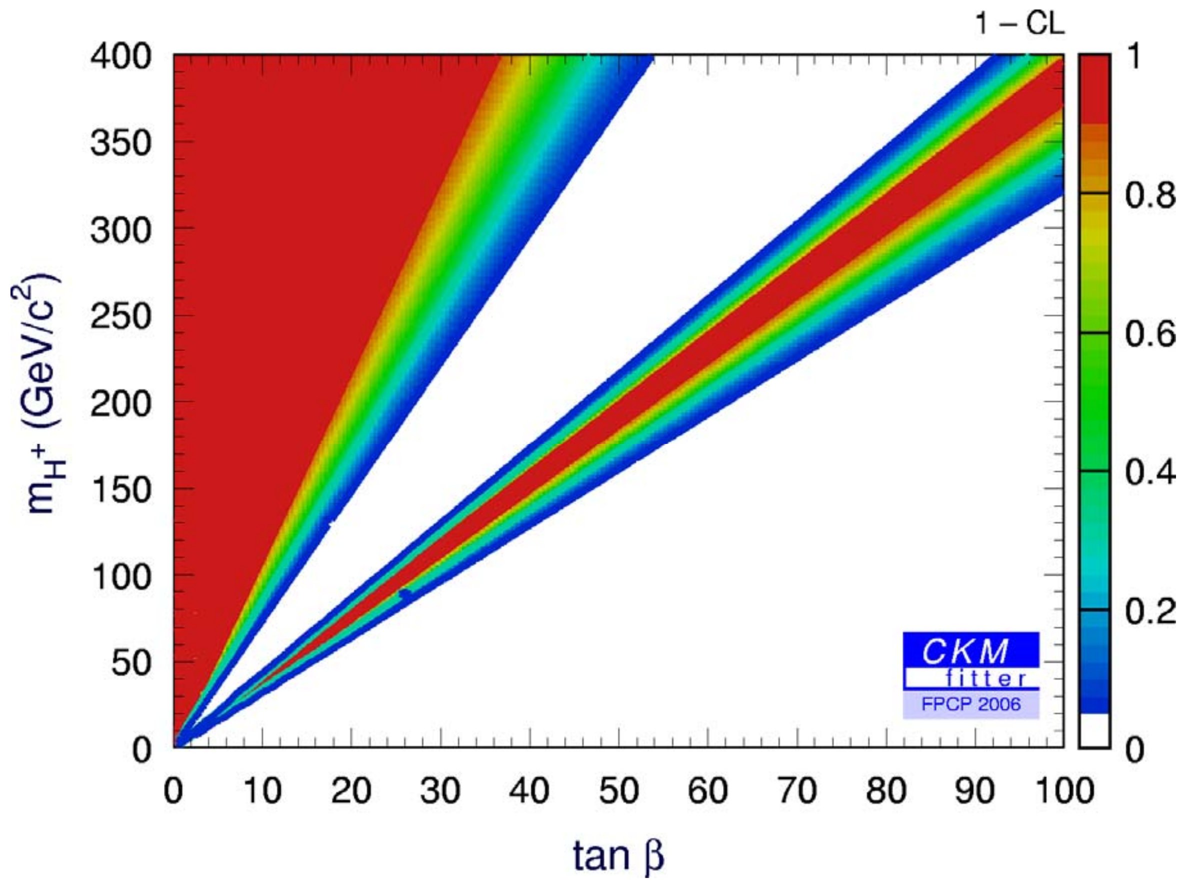
3. NP : $B^+ \to \tau^+ \nu_\tau$



In addition, decay mediated by a charged Higgs.

$$BF(B^+ \to \tau^+ \nu_\tau) =$$
$$BF(B^+ \to \tau^+ \nu_\tau)_{SM} \times c_H$$

$$c_H = (1 - \frac{m_B^2}{m_H^2}) \tan^2 \beta$$



3. NP : ΔF = 2 TRANSITIONS

Asumption : Vub/Vcb and γ are the basic inputs of the analysis since it is tree-mediated.

Introduce NP in ΔF = 2 model-independantly by means of two additional parameters:

$$r_d^2 \exp(2 i \theta_d) = \frac{\langle B^0 | H_{eff}^{full} | \bar{B}^0 \rangle}{\langle B^0 | H_{eff}^{SM} | \bar{B}^0 \rangle}$$

3. NP : $\Delta F = 2$ TRANSITIONS B_d-B_d system

$$r_d^2 \exp(2 i \theta_d) = \frac{\langle B^0 | H_{eff}^{full} | \bar{B}^0 \rangle}{\langle B^0 | H_{eff}^{SM} | \bar{B}^0 \rangle}$$

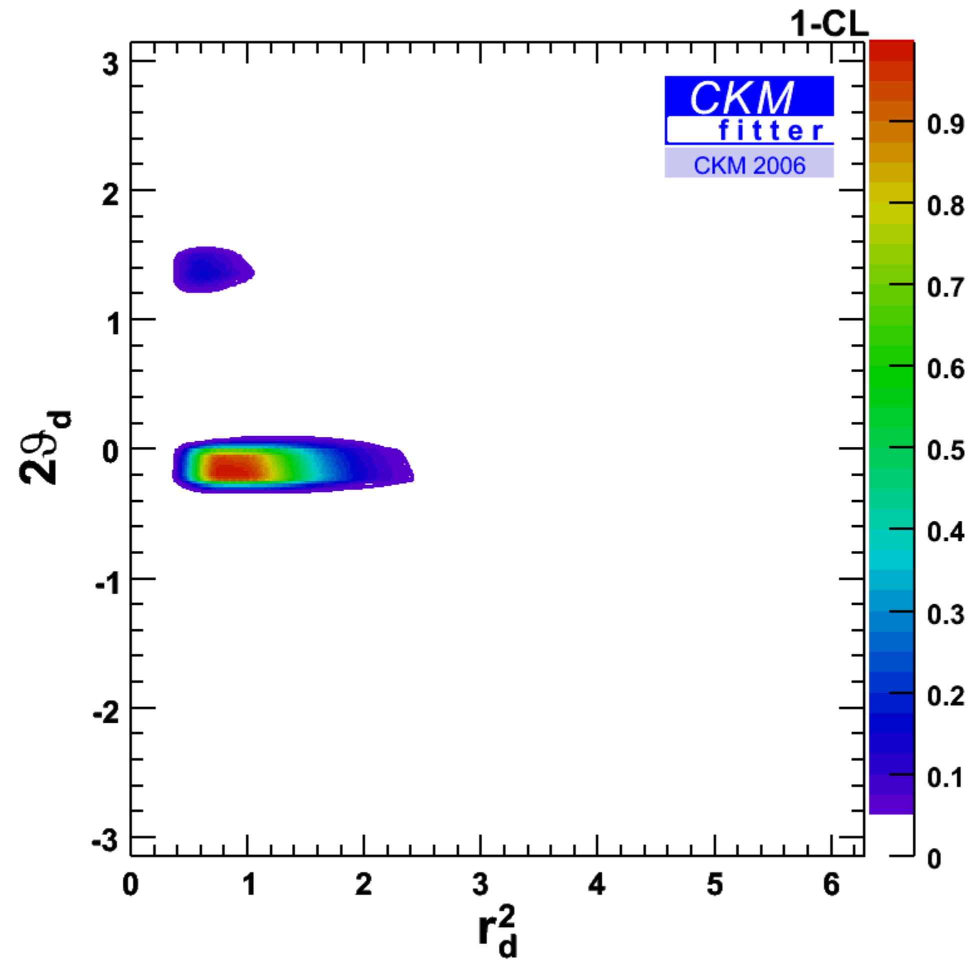
The parameters are modified as :

$\Delta m_d = (\Delta m_d)^{SM}\, r_d^2$

$\sin(2\beta) = \sin(2\beta - 2\theta_d)$

CP-violating charge asymmetry in semileptonic B decay is a crucial measurement to remove NP solutions:

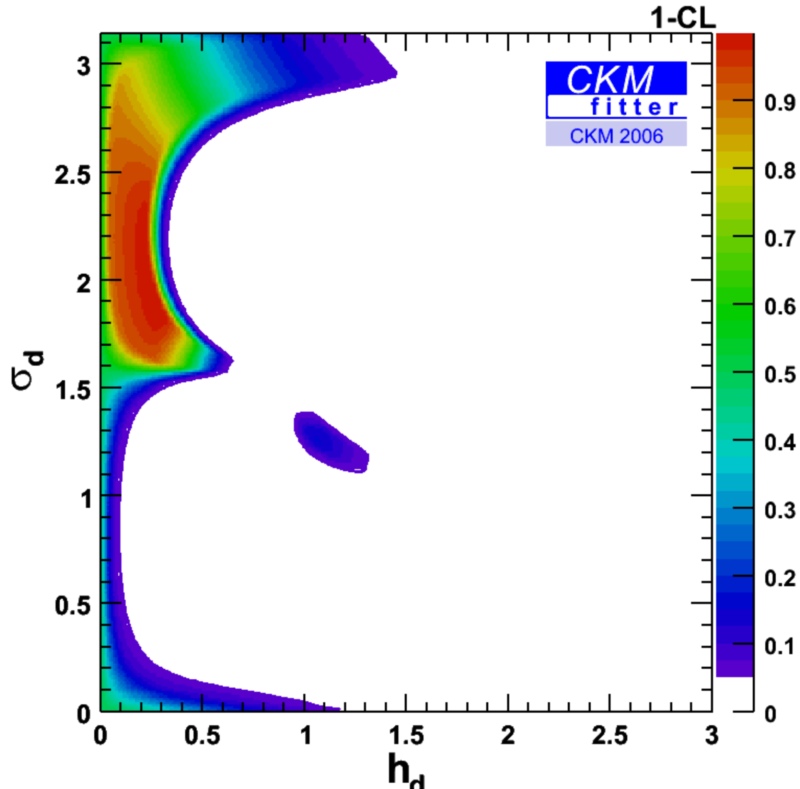
$A^d_{SL} = -\mathrm{Re}(\Gamma_{12}/M_{12})^{SM} \sin(2\theta_d)/r_d^2$
$\quad + \mathrm{Im}(\Gamma_{12}/M_{12})^{SM} \cos(2\theta_d)/r_d^2$

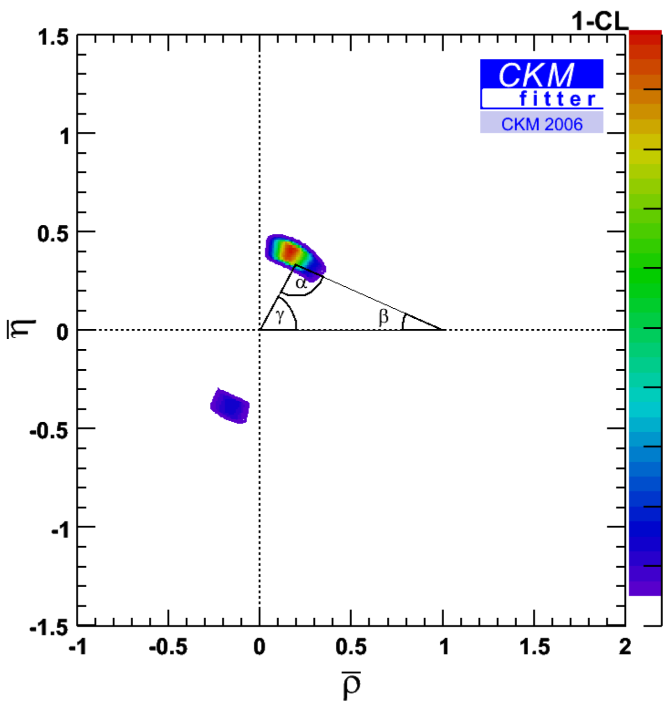


3. NP : $\Delta F = 2$ TRANSITIONS B_d-B_d system

Another equivalent parametrisation can be used, displaying explicitely the NP amplitude

$$\frac{\langle B_d^0 | H_{eff}^{SM+NP} | \overline{B_d}^0 \rangle}{\langle B_d^0 | H_{eff}^{SM} | \overline{B_d}^0 \rangle} = r_d^2 e^{i2\theta_d} = 1 + h_d e^{i2\sigma_d}$$



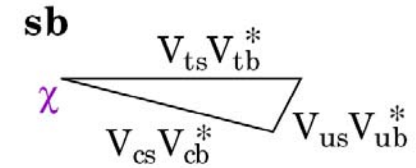


Not much room left for NP in the Bd system

3. NP : $\Delta F = 2$ TRANSITIONS - B_s-B_s system

$$\frac{\langle B_s^0 | H_{eff}^{\mathrm{SM+NP}} | \overline{B}_s^0 \rangle}{\langle B_s^0 | H_{eff}^{\mathrm{SM}} | \overline{B}_s^0 \rangle} = r_s^2 e^{i2\theta_s} = 1 + h_s e^{i2\sigma_s}$$

The recent results from Tevatron (CDF and D0) allow to constrain for the first time the NP contribution ($\Delta m_{s,}$ $\Delta\Gamma_{s,}$ A_{SL})

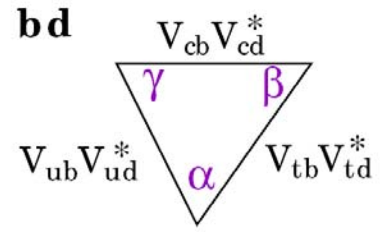


Mass difference: $\Delta m_s = (\Delta m_s)^{SM} r_s^2$

Width difference: $\Delta\Gamma_s = (\Delta\Gamma_s)^{SM} \cos^2(2\chi - 2\theta_s)$

Semileptonic asymmetry:
$A^s_{SL} = -\mathrm{Re}(\Gamma_{12}/M_{12})^{SM} \sin(2\theta_s)/r_s^2$

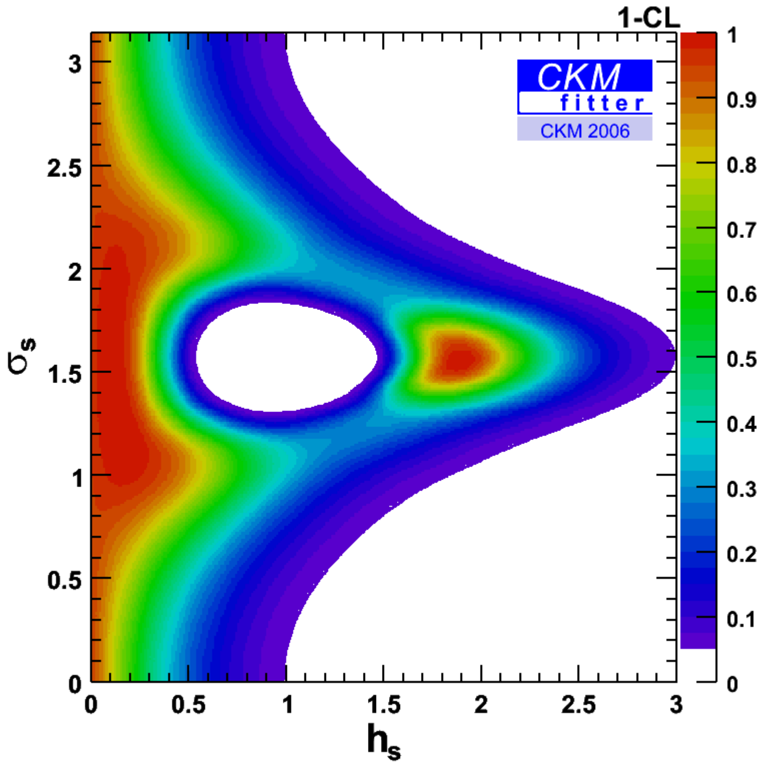
$\sin(2\chi) = \sin(2\chi - 2\theta_s)$



B_s mixing phase very small in SM (1°) and very well predicted (O(5%))
Bs mixing: very sensitive probe to NP

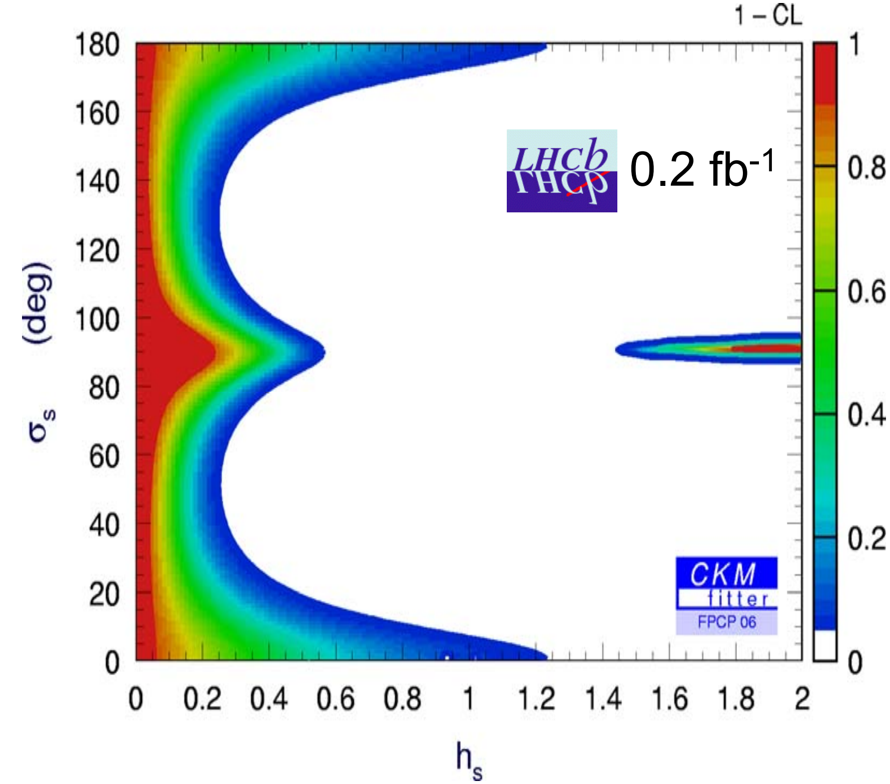
3. NP : $\Delta F = 2$ TRANSITIONS - B_s-B_s system

Δm_s, $\Delta\Gamma_s$ and A^s_{SL}



h_s ~<= 3 (h_d ~<=0.3, h_K ~<= 0.6) Tevatron measurement. Still plenty of room for NP.

$\sigma(\Delta m_s)$= 0.035, $\sigma(\sin(2\chi)$=0.1



LHCb shall rapidly say something.

4. Conclusions

✓B-factories provided a fantastic success for the SM

✓CKM mechanism is at work to describe CP violation

✓The CKM phase is the dominant source of CP violation in B processes.

✓No evidence so far for corrections to CKM mechanism. Yet, we are just entering a precision era in flavour physics.

✓Major results went last year from the Tevatron, especially in fully hadronic modes. Encouraging for the LHC experiments, singularly for LHCb. The Bs system must be explored. Has to make gamma a precision measurements.