Implications of recent data on CKM analyses

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Jérôme Charles (CPT - Marseille)

the CKMfitter group

JC, theory, Marseille

Olivier Deschamps, LHCb, Clermont-Ferrand

Sébastien Descotes-Genon, theory, Orsay

Ryosuke Itoh, Belle, Tsukuba

Andreas Jantsch, ATLAS, Munich

Heiko Lacker, ATLAS, Berlin

Andreas Menzel, Atlas, Berlin

Stéphane Monteil, LHCb, Clermont-Ferrand

Valentin Niess, LHCb, Clermont-Ferrand

Jose Ocariz, BaBar, Paris

Jean Orloff, theory, Clermont-Ferrand

Stéphane T'Jampens, LHCb, Annecy-le-Vieux

Vincent Tisserand, BaBar, Annecy-le-Vieux

Karim Trabelsi, Belle, Tsukuba

http://ckmfitter.in2p3.fr

The CKMfitter project

Our goal

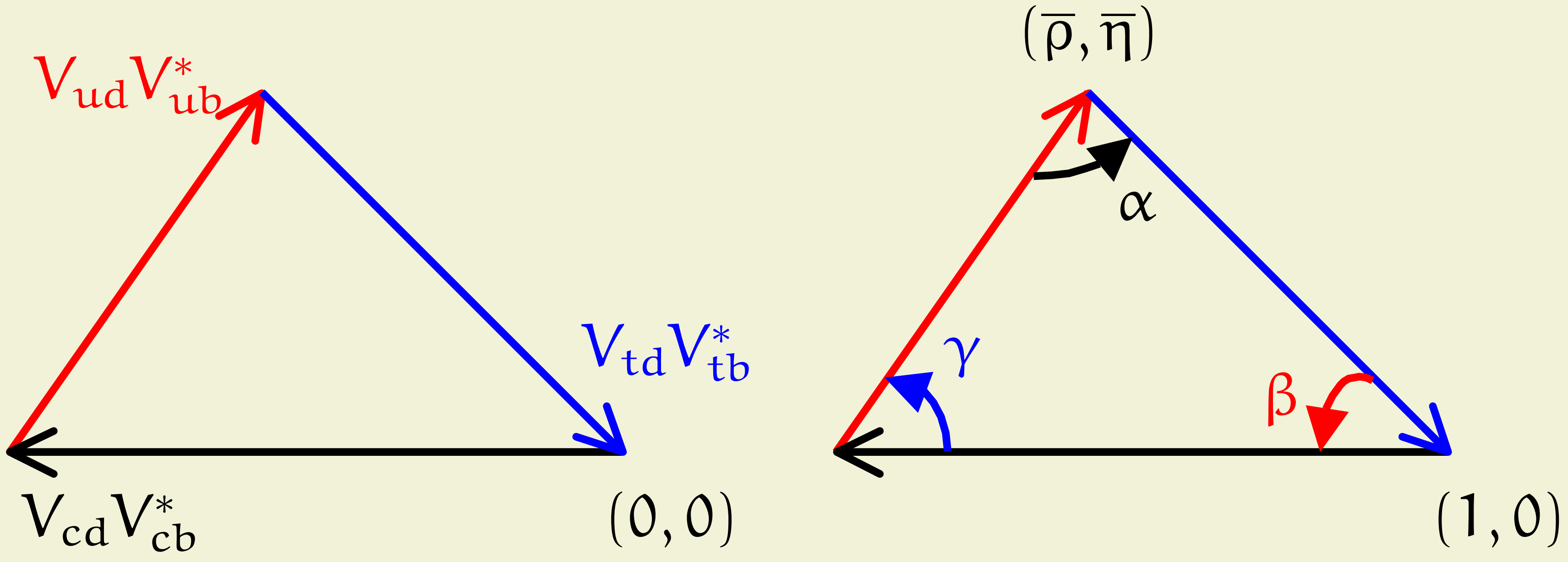
- combine as many as possible experimental measurements related to quark flavor mixing
- define and understand the theoretical uncertainties, and propose ways to control them
- work within a frequentist statistical framework taking into account the different error types and possible biases due to theory, low statistics, non linearities, nuisance parameters …
- test the Standard Model and different New Physics scenarios

Hierarchy and the Unitarity Triangle(s) of the CKM matrix

strong hierarchy of the CKM matrix:

- diagonal couplings $\propto 1$
- 1st $\leftrightarrow$ (resp. 2nd $\leftrightarrow$ 3rd) generation
  $\propto \lambda \sim 0.22$ (resp. $\propto \lambda^2$)
- 1st $\leftrightarrow$ 3rd generation $\propto \lambda^3$

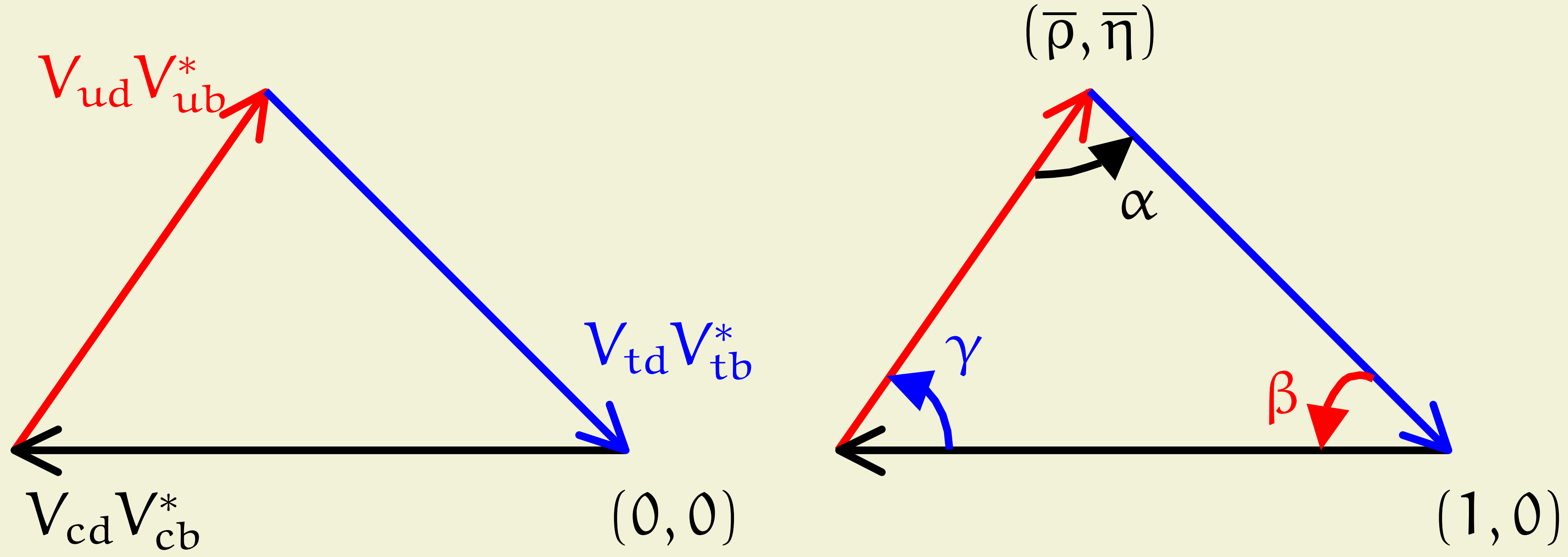
CKM unitarity $\Rightarrow$ six triangles in the complex plane, of which four are quasi flat, two are non flat and quasi degenerate



unitary-exact and phase-convention-independent version of the Wolfenstein parametrization

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\bar\rho + i\bar\eta \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



The statistical framework

we use a standard frequentist approach: likelihood maximization (χ^2 minimization)

where necessary, we treat non gaussian behavior by Monte-Carlo simulation of virtual experiments

theoretical errors
no model-independent treatment available, due to lack of precise definition; we use the Rfit model: a theoretical parameter that has been computed (e.g. B_K) is assumed to lie within a definite range, without any preference inside this range
the best fit will thus be searched by moving uniformly in the theoretical parameter space

The global CKM fit

the constraints on the CKM matrix come from the decays of the neutron, the kaon, the B meson and to a lesser extent the D meson

"standard fit": uses all constraints on which we think we have a good theoretical control

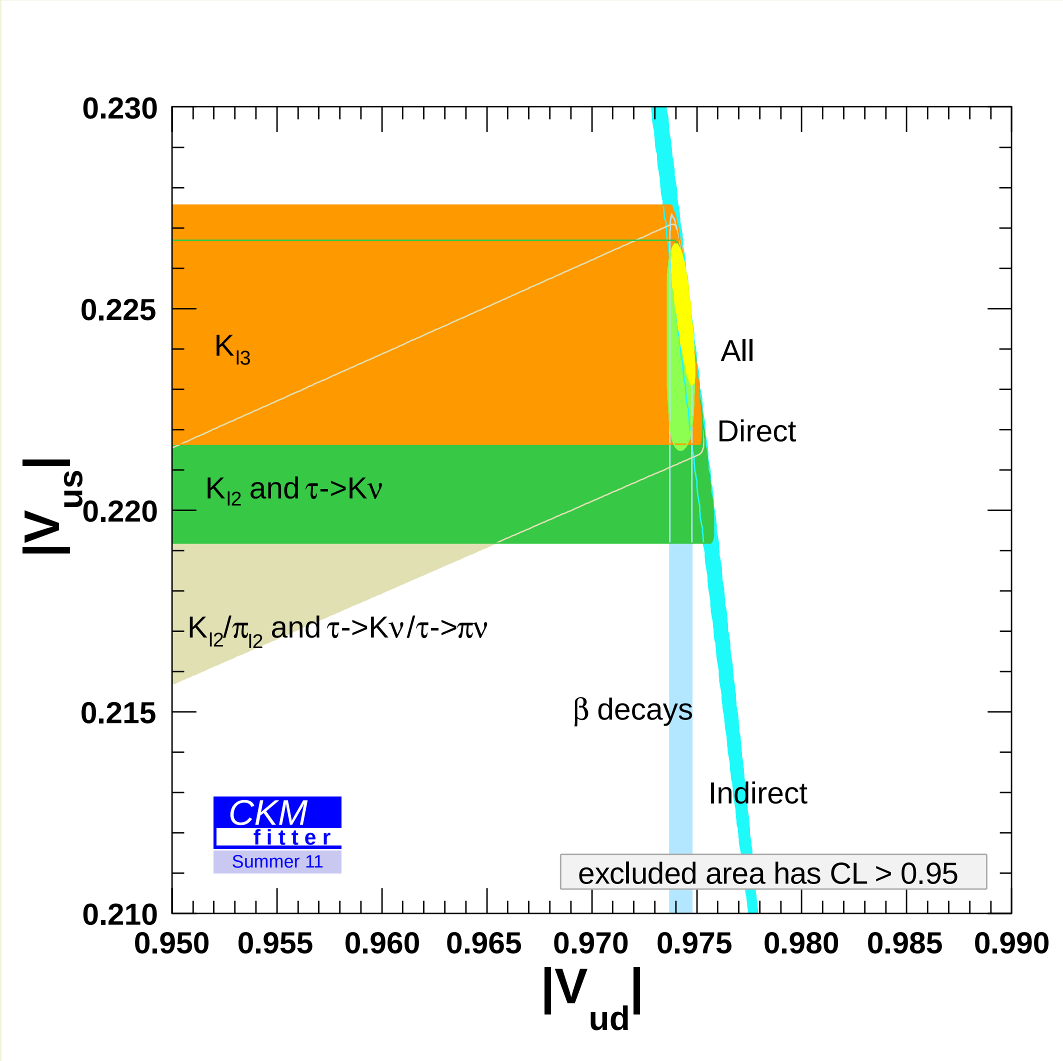
CKM	Process	Observables	Theoretical inputs
$\lvert V_{ud}\rvert$	$0^+ \to 0^+$ transitions	$\lvert V_{ud}\rvert_{\rm nucl} = 0.97425 \pm 0.00022$	Nuclear matrix elements
$\lvert V_{us}\rvert$	$K \to \pi \ell \nu$ $K \to e\nu_e$ $K \to \mu\nu_\mu$ $\tau \to K\nu_\tau$	$\lvert V_{us}\rvert_{\rm semi} f_+(0) = 0.2163 \pm 0.0005$ $\mathcal{B}(K \to e\nu_e) = (1.584 \pm 0.0020) \cdot 10^{-5}$ $\mathcal{B}(K \to \mu\nu_\mu) = 0.6347 \pm 0.0018$ $\mathcal{B}(\tau \to K\nu_\tau) = 0.00696 \pm 0.00023$	$f_+(0) = 0.9632 \pm 0.0028 \pm 0.0051$ $f_K = 156.3 \pm 0.3 \pm 1.9$ MeV
$\lvert V_{us}\rvert / \lvert V_{ud}\rvert$	$K \to \mu\nu / \pi \to \mu\nu$ $\tau \to K\nu / \tau \to \pi\nu$	$\frac{\mathcal{B}(K \to \mu\nu_\mu)}{\mathcal{B}(\pi \to \mu\nu_\mu)} = (1.3344 \pm 0.0041) \cdot 10^{-2}$ $\frac{\mathcal{B}(\tau \to K\nu_\tau)}{\mathcal{B}(\tau \to \pi\nu_\tau)} = (6.33 \pm 0.092) \cdot 10^{-2}$	$f_K/f_\pi = 1.205 \pm 0.001 \pm 0.010$
$\lvert V_{cd}\rvert$	$D \to \mu\nu$	$\mathcal{B}(D \to \mu\nu) = (3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$	$f_{D_s}/f_D = 1.186 \pm 0.005 \pm 0.010$
$\lvert V_{cs}\rvert$	$D_s \to \tau\nu$ $D_s \to \mu\nu$	$\mathcal{B}(D_s \to \tau\nu) = (5.29 \pm 0.28) \cdot 10^{-2}$ $\mathcal{B}(D_s \to \mu\nu_\mu) = (5.90 \pm 0.33) \cdot 10^{-3}$	$f_{D_s} = 251.3 \pm 1.2 \pm 4.5$ MeV
$\lvert V_{ub}\rvert$	semileptonic decays $B \to \tau\nu$	$\lvert V_{ub}\rvert_{\rm semi} = (3.92 \pm 0.09 \pm 0.45) \cdot 10^{-3}$ $\mathcal{B}(B \to \tau\nu) = (1.68 \pm 0.31) \cdot 10^{-4}$	form factors, shape functions $f_{B_s} = 231 \pm 3 \pm 15$ MeV $f_{B_s}/f_B = 1.209 \pm 0.007 \pm 0.023$
$\lvert V_{cb}\rvert$	semileptonic decays	$\lvert V_{cb}\rvert_{\rm semi} = (40.89 \pm 0.38 \pm 0.59) \cdot 10^{-3}$	form factors, OPE matrix elts
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries	isospin symmetry
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]} = 0.678 \pm 0.020$	
γ	$B \to D^{(*)}K^{(*)}$	inputs for the 3 methods	GGSZ, GLW, ADS methods
$V_{tq}^* V_{tq'}$	Δm_d Δm_s	$\Delta m_d = 0.507 \pm 0.005$ ps^{-1} $\Delta m_s = 17.77 \pm 0.12$ ps^{-1}	$\hat{B}_{B_s}/\hat{B}_{B_d} = 1.01 \pm 0.01 \pm 0.03$ $\hat{B}_{B_s} = 1.28 \pm 0.02 \pm 0.03$
$V_{tq}^* V_{tq'}, V_{cq}^* V_{cq'}$	ϵ_K	$\lvert \epsilon_K \rvert = (2.229 \pm 0.010) \cdot 10^{-3}$	$\hat{B}_K = 0.730 \pm 0.004 \pm 0.036$ $\kappa_\epsilon = 0.940 \pm 0.013 \pm 0.023$

2011 novelties

improved treatment of γ

τ decays and leptonic kaon decays: significative improvement of $|V_{us}|$

good agreement between all constraints in the $(|V_{ud}|, |V_{us}|)$ plane



The global CKM fit: result

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$(\bar\rho, \bar\eta)$ are dominated by the constraints from α, β and $\Delta m_d/\Delta m_s$, all in excellent agreement

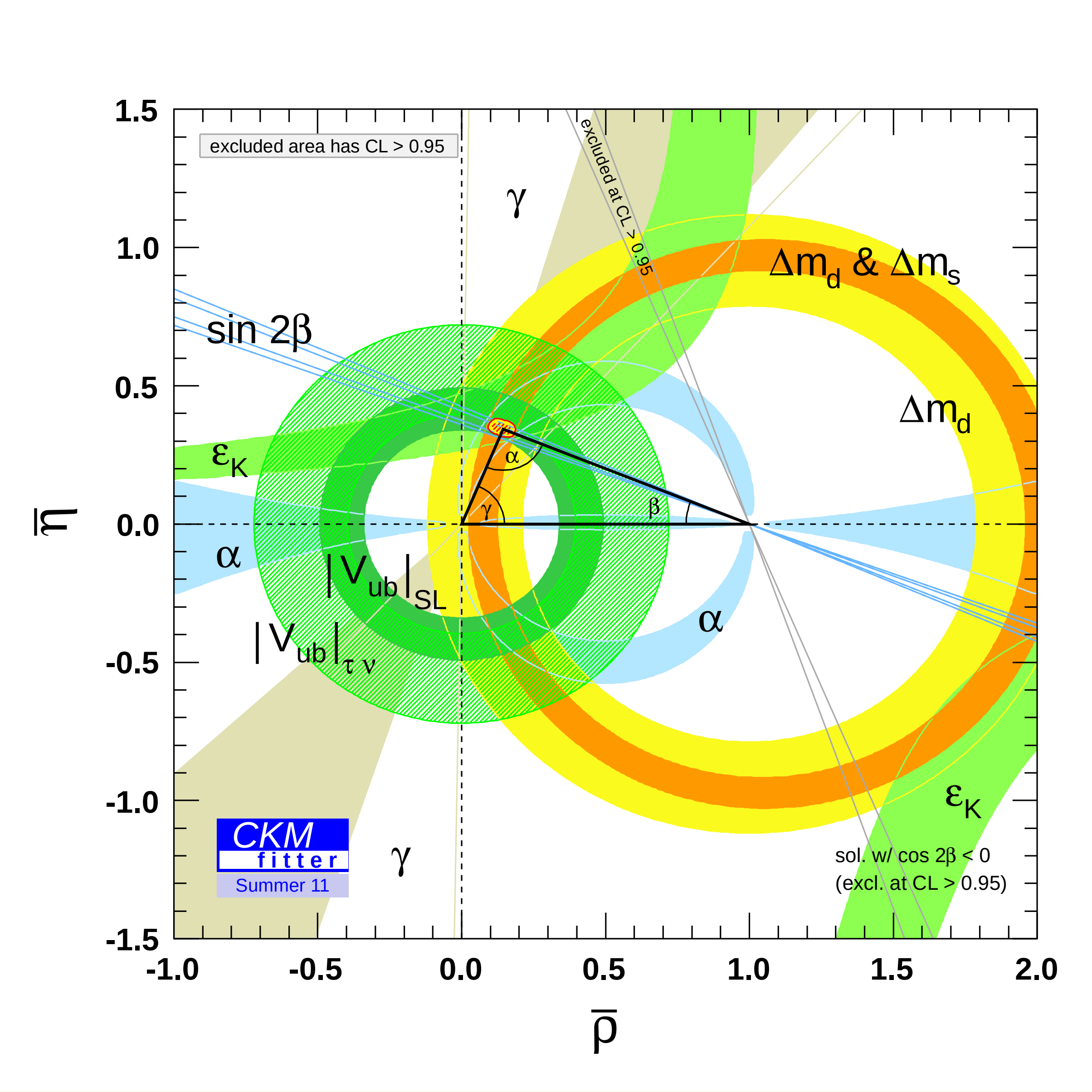
overall consistent picture: the KM mechanism is the dominant source of CP violation

$$A = 0.801^{+0.026}_{-0.014}$$

$$\lambda = 0.22539^{+0.00062}_{-0.00095}$$

$$\bar\rho = 0.144^{+0.023}_{-0.026}$$

$$\bar\eta = 0.343^{+0.015}_{-0.014}$$



The D meson UT: $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$

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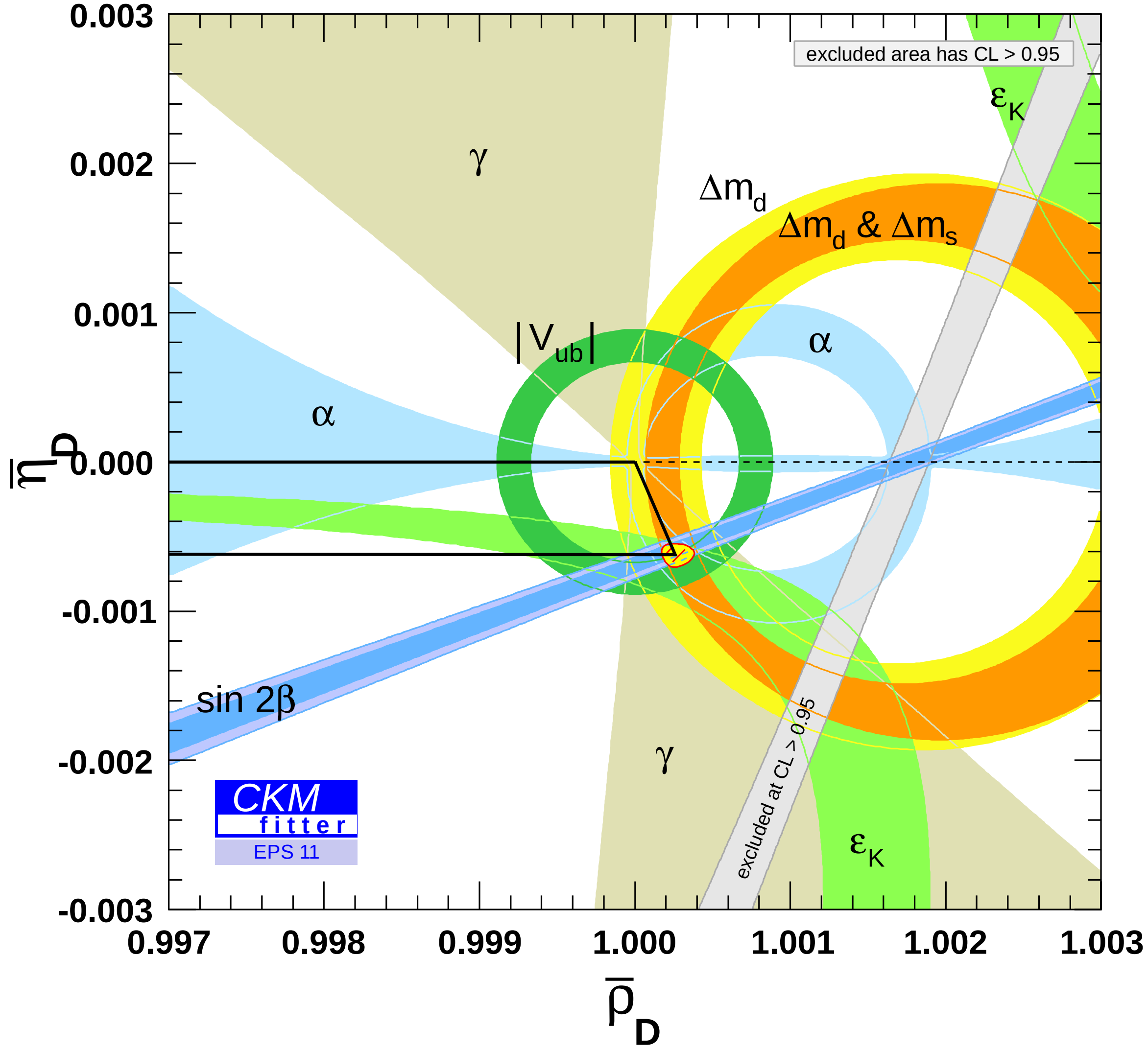
all order definition

$$\bar{\rho}_D + i\,\bar{\eta}_D \equiv -\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}$$

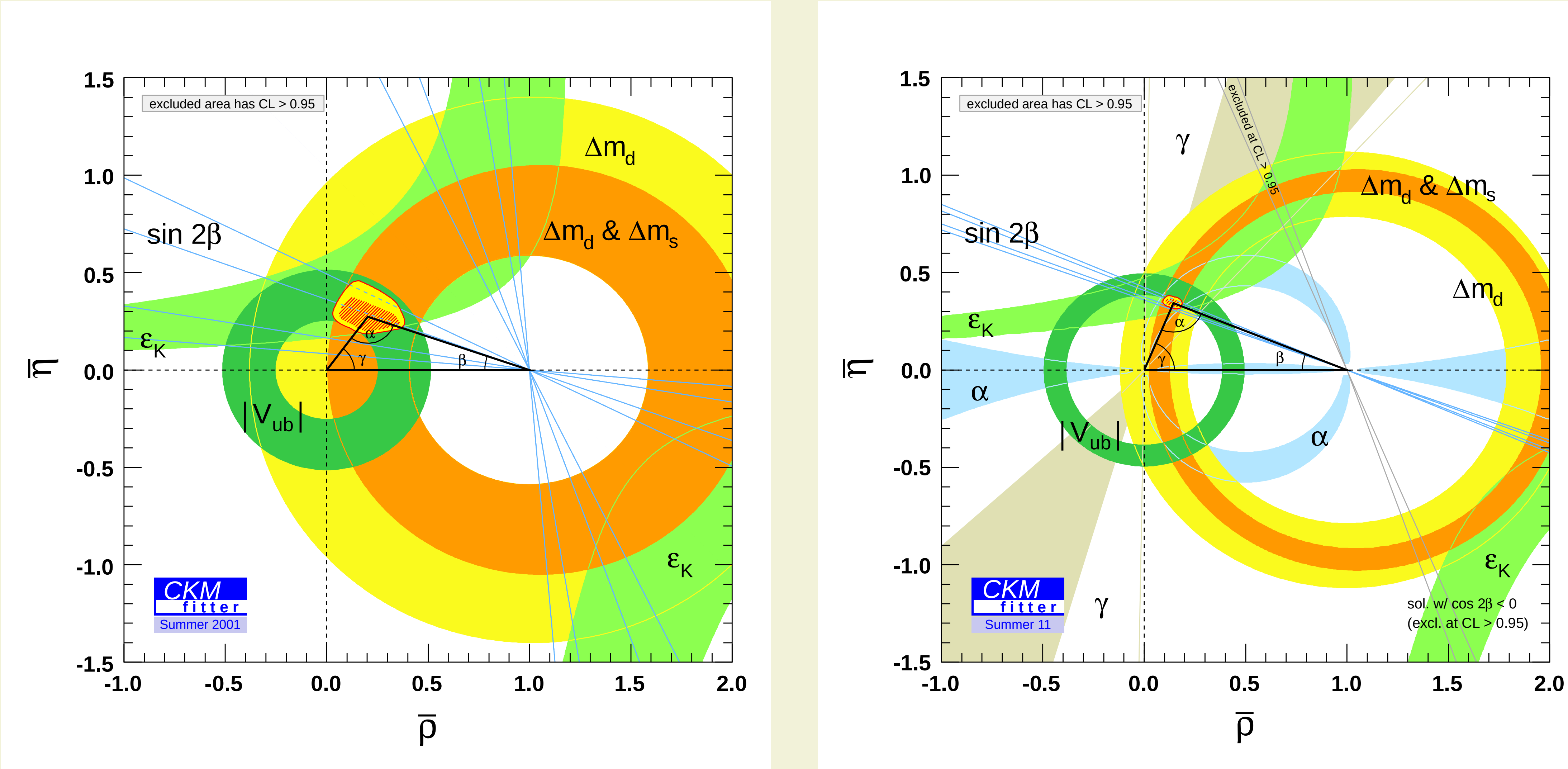
$$\alpha_D \equiv \mathrm{Arg}\left(-\frac{V_{ub}V_{cb}^*}{V_{ud}V_{cd}^*}\right) = -\gamma$$

$$\beta_D \equiv \mathrm{Arg}\left(-\frac{V_{ud}V_{cd}^*}{V_{us}V_{cs}^*}\right) = \mathcal{O}(\lambda^4)$$

$$\gamma_D \equiv \mathrm{Arg}\left(-\frac{V_{us}V_{cs}^*}{V_{ub}V_{cb}^*}\right) = \pi - \alpha_D - \beta$$



Ten years of B-factories



more history plots at ckmfitter.in2p3.fr other flavor observables, among which some radiative and rare decays, are predicted from the CKM global analysis and the appropriate theoretical formulae in JC et al., Phys. Rev. D84, 033005 (2011)

the only discrepancies in the SM are the $BR(B \to \tau\nu)$ vs. $\sin 2\beta$ correlation, and the semileptonic asymmetry A_{SL} (other hints in $B_s \to \mu^+\mu^-$ and $\phi_s(\psi\phi)$ are now disfavored by LHC measurements)

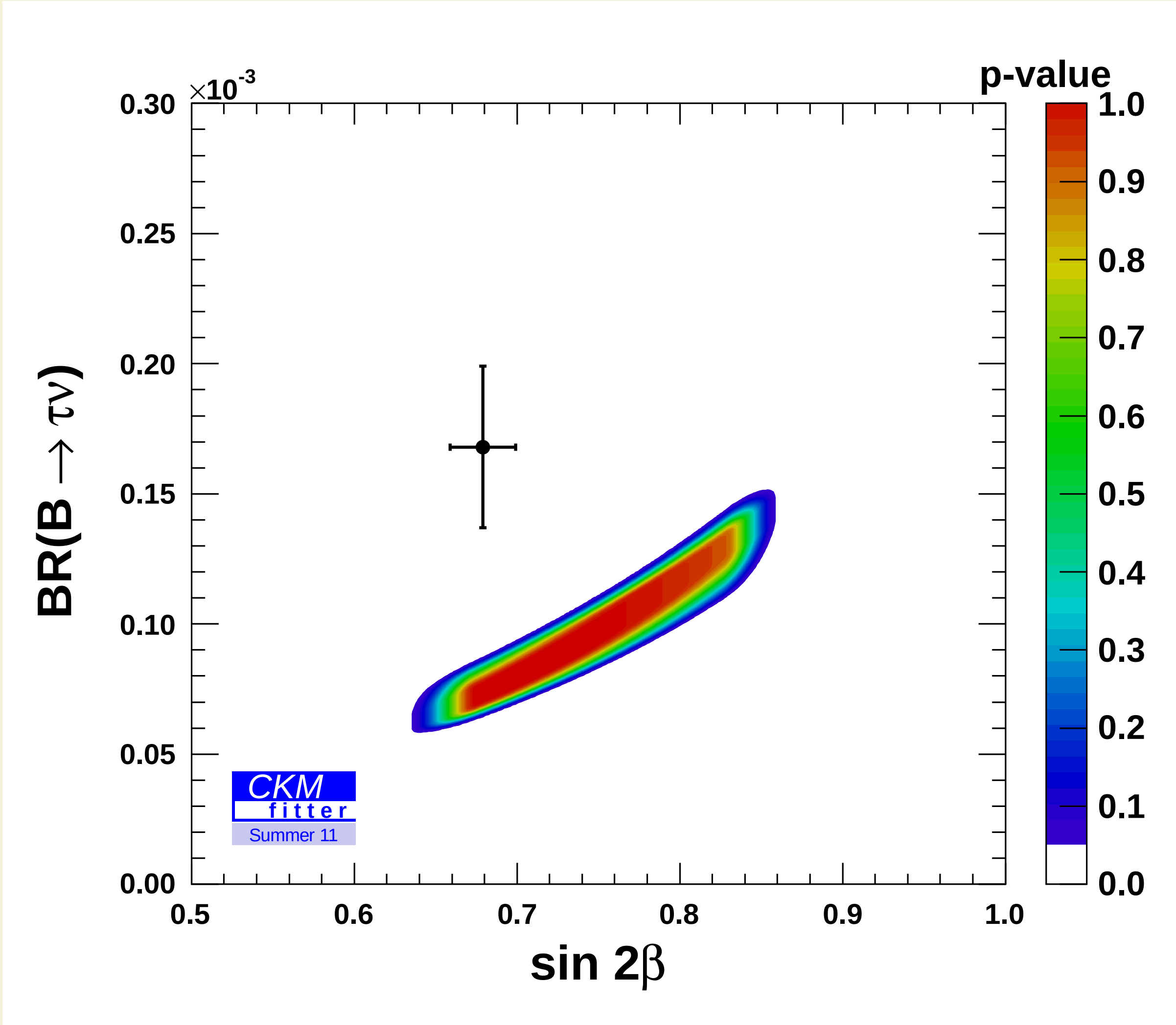
$B \to \tau\nu$: a closer look

$B \to \tau\nu$ vs. $\sin 2\beta$

cross is direct measurement ; color levels are indirect fit prediction

either $B \to \tau\nu$ is too large or $\sin 2\beta$ is too small by 2.8 standard deviations

experimental data are consistent among experiments and different tagging channels; on the theory side, solving for the discrepancy would need a larger (smaller) f_{B_d} (B_{B_d}) keeping the product $f_{B_d}\sqrt{B_{B_d}}$ consistent with Δm_d



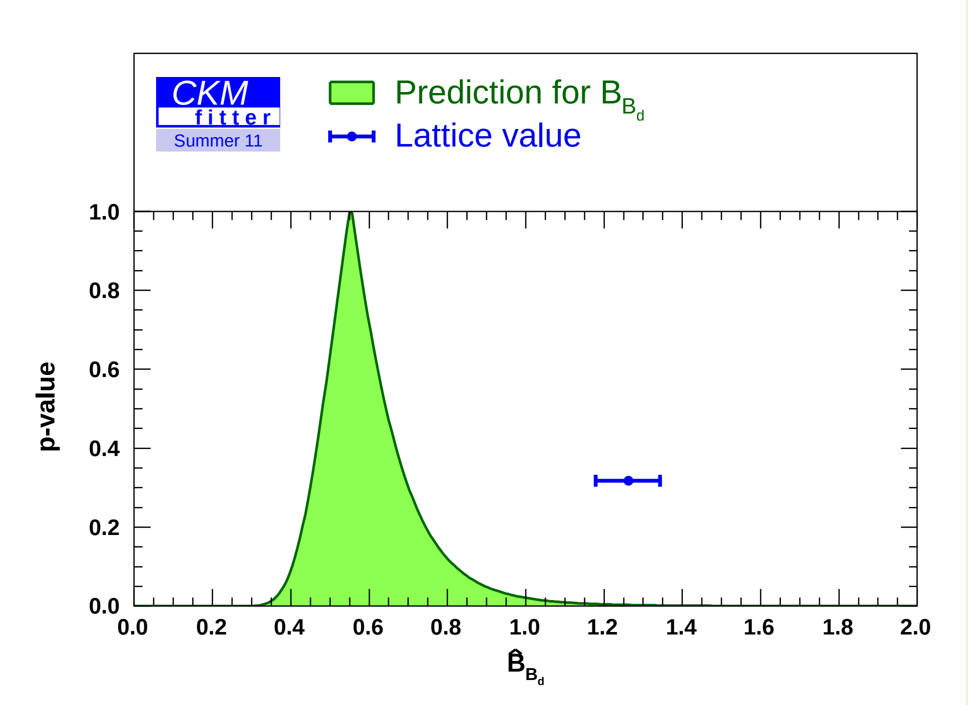
we have found that the shape of the correlation is given by the ratio $\mathrm{BR}(B \to \tau\nu)/\Delta m_d$:

$$\frac{\mathrm{BR}(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4}\frac{m_\tau^2}{m_W^2 S(x_t)}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+}\frac{1}{B_{B_d}}\frac{1}{|V_{ud}|^2}\left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

where $B_{B_d} = 1.1262 \pm 0.083 \pm 0.081$ is the only source of theoretical uncertainty

alternatively one can take the above formula as a pure experimental prediction for the bag parameter B_{B_d}

here the discrepancy is 2.8σ (taking only Δm_d, α, β, γ as inputs), where the contribution from the theory uncertainty is subdominant



Semileptonic asymmetries

they are related to the parameter q/p in the mixing (as ε_K)

$$a_{SL} = \frac{\Gamma(\bar{B}^0(t) \to \ell^+ X) - \Gamma(B^0(t) \to \ell^- X)}{\Gamma(\bar{B}^0(t) \to \ell^+ X) + \Gamma(B^0(t) \to \ell^- X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

very small for the B mesons in the Standard Model

separate measurements for B_d and B_s have sizable errors that prevent deriving strong constraints from them

however in 2010 the D0 experiment reported a measurement A_{SL} of a specific linear combination of a_{SL}^d and a_{SL}^s, that deviates by 3.2 standard deviations from the SM prediction: first single evidence against the SM in the flavor sector !

in 2011 D0 updated the analysis, leading to $A_{SL} = -0.0074 \pm 0.0019$, 3.9σ from the SM

New Physics in mixing

the flavor problem states that New Physics at the TeV scale should already have shown up in flavor observables

independently of the flavor problem, the natural “to start with” choice is to assume that New Physics only contribute to FCNC

then only a few new parameters are needed to describe neutral meson mixing, and other FCNC observables can be discarded from the inputs

in other words New Physics only enters M_{12} which is the real part of the mixing Hamiltonian

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

SM is thus located at $\Delta_d = \Delta_s = 1$; additional notation $2\theta_q \equiv \arg(\Delta_q)$ (this holds for B_d and B_s; for K one introduces three parameters corresponding to the tt, ct and cc contributions to M_{12})

Δ_q are complex parameters, and the SM is located at $\Delta_d = \Delta_s = 1$

the parameters of the CKM matrix can be fixed from charged current transitions, but since their determination is correlated with the one of Δ_q, one has to do a complete global analysis

this cartesian parametrization allows for a simple geometrical interpretation of each individual constraint (Lenz & Nierste 2006)

Strategy and inputs

- assume that tree-level transitions are 100% SM
- fix SM parameters with $|V_{ud}|$,$|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ and $\alpha = \pi - \gamma - \beta_{\rm eff}((c\bar{c})K)$
- $(\mathrm{Re}(\Delta_d), \mathrm{Im}(\Delta_d))$ are then constrained by Δm_d (circle), by $\phi_d = 2\beta_{\rm eff} = 2\beta + 2\theta_d$ (straight line) and by $\alpha = \pi - \gamma - \beta_{\rm eff}((c\bar{c})K)$
- $(\mathrm{Re}(\Delta_s), \mathrm{Im}(\Delta_s))$ are constrained by Δm_s (circle) and by $\phi_s = -2\beta_s + 2\theta_s$
- additional information is brought by the measurement of the semileptonic asymmetries A_{SL}^d, A_{SL}^s (circle) and the width difference $\Delta\Gamma_q = \cos\phi_s\,\Delta\Gamma_q^{SM}$ (straight line)

NP in mixing modified predictions

observable	NP prediction
Δm_q	$\Delta m_{q,SM} \times \lvert\Delta_q\rvert$
$2\beta_{c\bar{c}K}$	$2\beta + \mathrm{Arg}(\Delta_d)$
$\phi_{s,\psi\phi}$	$-2\beta_s + \mathrm{Arg}(\Delta_s)$
$2\alpha_{\pi\pi,\rho\pi,\rho\rho}$	$2\alpha - \mathrm{Arg}(\Delta_d)$
$A_{sl,q}$	$\frac{\Gamma 12_{q,SM}}{M12_{q,SM}} \times \frac{\sin(\phi 12_{q,SM} + \mathrm{Arg}(\Delta_q))}{\lvert\Delta_q\rvert}$
$\Delta\Gamma_q$	$2\Gamma 12_{q,SM} \times \cos(\phi 12_{q,SM} + \mathrm{Arg}(\Delta_q))$

NB: $\Gamma 12$ (in A_{sl} and $\Delta\Gamma$) has a very complicated theoretical expression, taken from Lenz-Nierste 2006; in this quantity theoretical uncertainties play a major rôle and are not completely under control the analysis was done in 2010 (JC et al. Phys. Rev. D83, 036004) with the nice result that both the $B \to \tau\nu$ and A_{SL} anomalies could be described by non standard CP phases in B_d and B_s mixing (more than 3σ away from zero); furthermore it was going into the same direction as the hints for non standard CP in $B_s \to J/\psi\phi$ (CDF & D0)

this Summer the situation has changed because the more precise LHCb measurement of $\phi_s(\psi\phi)$ is compatible with the SM at 1σ

furthermore it was pointed out by (Khodjamirian et al., Phys. Rev. D83, 094031) that the $B \to \tau\nu$ anomaly survives when constructing the ratio $B \to \tau\nu / B \to \pi\ell\nu$ which is independent of the mixing

The Δ_d plane

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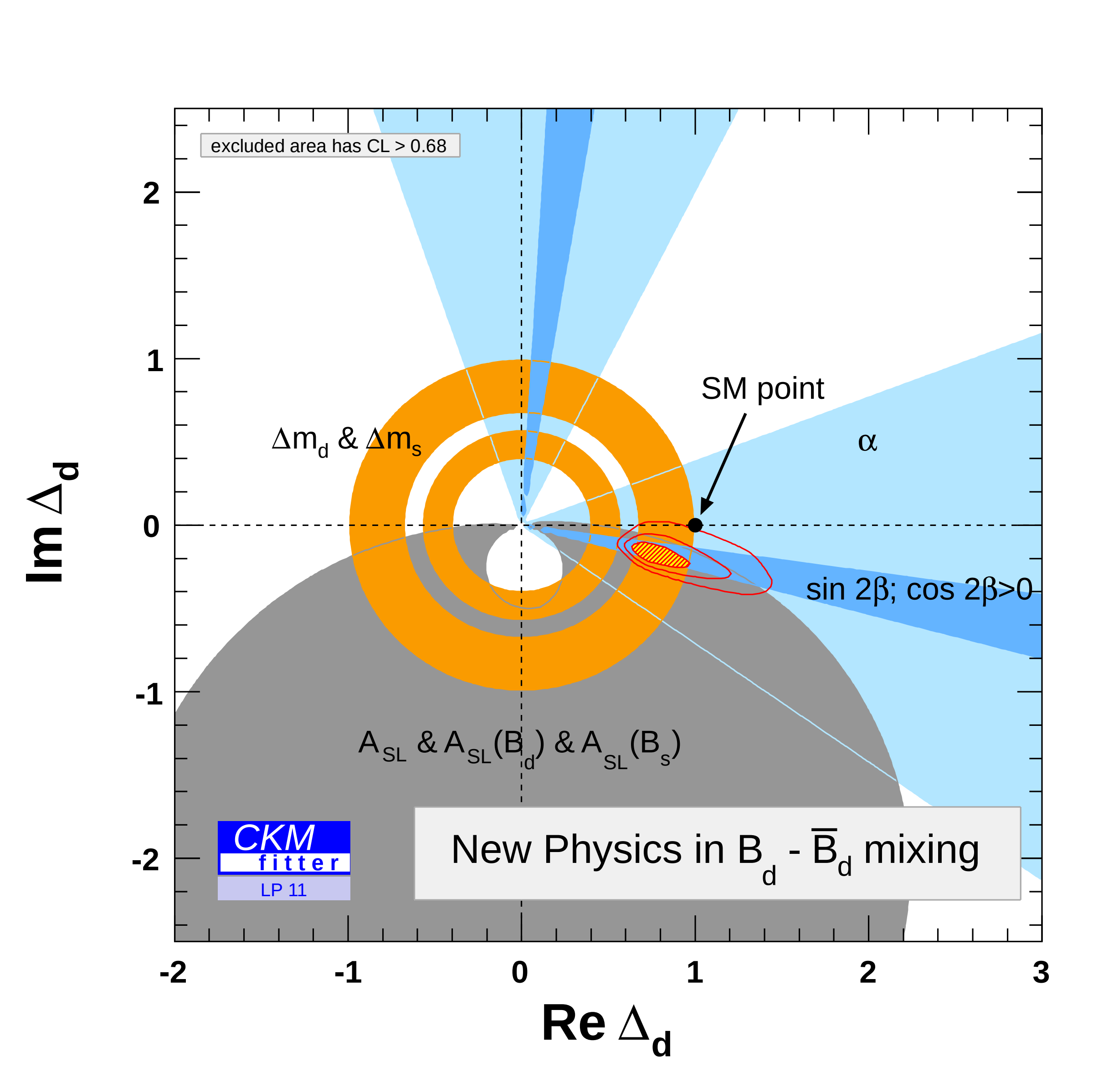
$\mathrm{Im}\Delta_d$ is driven away from zero by both $\sin 2\beta$ and A_{SL}

the p-value for $\Delta_d = 1$ is 3.2σ



The Δ_s plane

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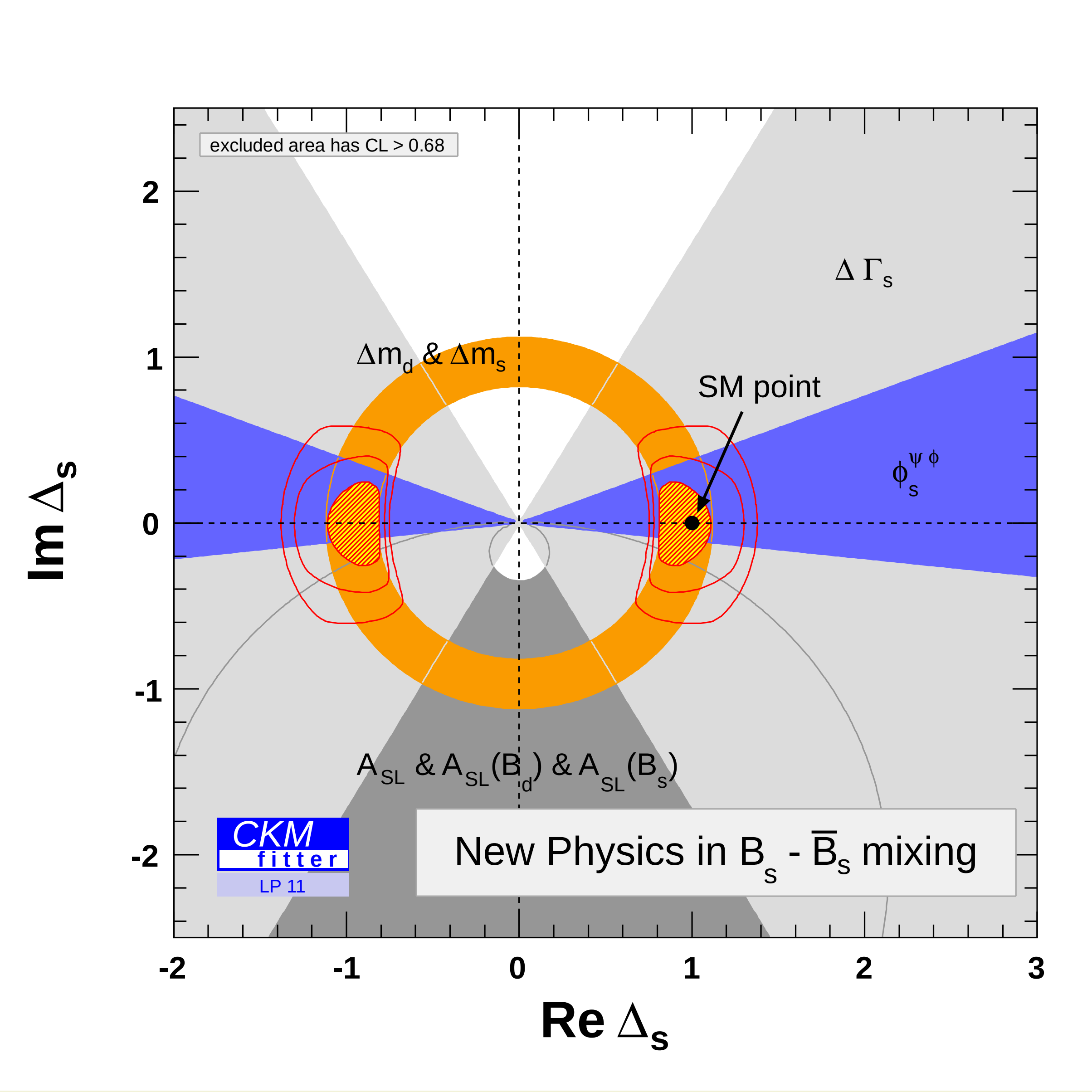
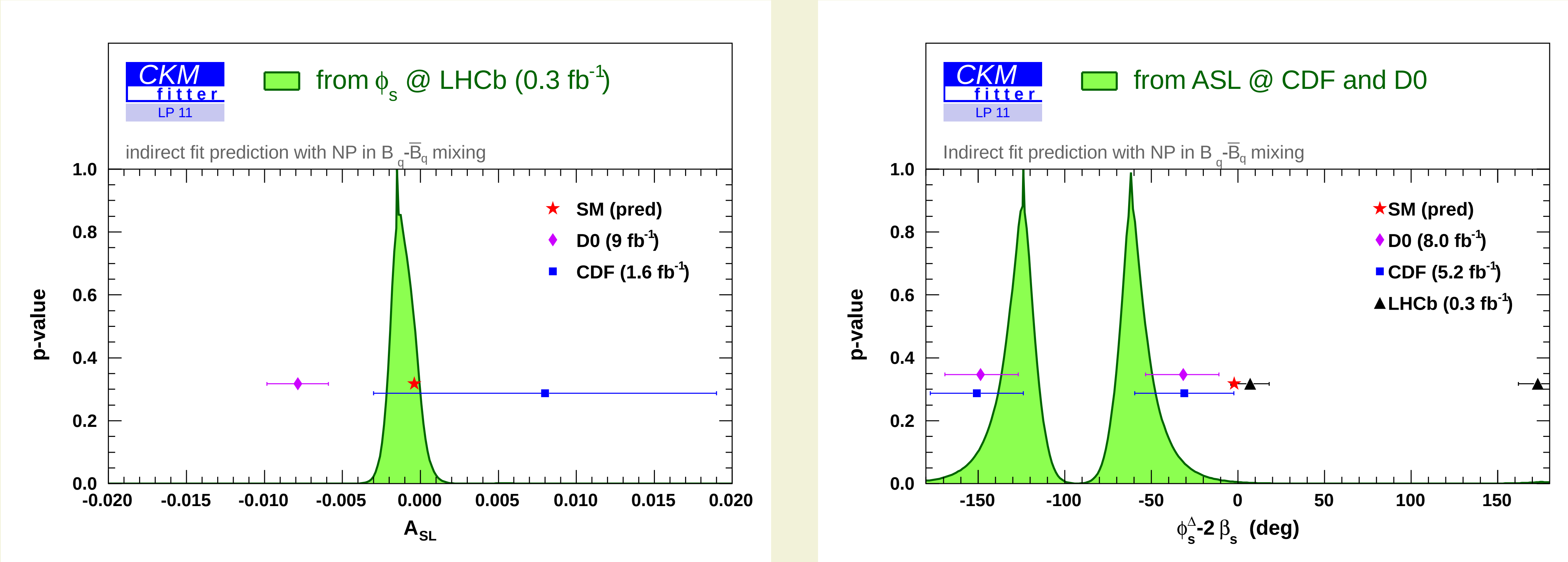
$\mathrm{Im}\Delta_s$ is forced close to zero by $\phi_s(\psi\phi)$, in contradiction with A_{SL}

the p-value for $\Delta_s = 1$ is 1.1σ



Indirect fit prediction for A_{SL} vs. $\phi_s(\psi\phi)$



there is a $\sim 3\sigma$ discrepancy between A_{SL} and the hypothesis that there is New Physics only in mixing

could be good news: New Physics in Γ_{12} ? and/or in the observables that were assumed to be dominated by SM contributions ?

could be bad news: New Physics beyond reach of analysis ?

Conclusion

the goal of CKM analyses has changed: it is not only to determine SM parameters, but to perform precision tests of the SM against possible New Physics scenarios

in the last three years, a few hints of deviations wrt SM have appeared: $B \to \tau\nu$ vs. $\sin 2\beta$, $\phi_s(\psi\phi)$, A_{SL}, $B_s \to \mu^+\mu^-\dots$

however very recent measurements of B_s decays at LHCb have somewhat washed out the related anomalies; still the overall image remains puzzling, since neither SM nor NP in mixing can describe very well $B \to \tau\nu$ nor A_{SL}

improved measurements at Belle using the full data set, as well as new LHCb analyses will shed some light on these issues in a close future

we may have to wait for SuperB factories to get a definite answer