Status of quark flavor mixing and CP violation

GDR "Physique subatomique et calculs sur réseau", June 26th

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http://ckmfitter.in2p3.fr

The CKMfitter project

Don't be deceived, common sense is much too common to really be sense, it's just a chapter from a statistics book, the one everyone always trots out [José Saramago]

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 rigorous frequentist statistical framework taking into account the different error types and possible biases due to low statistics, non linearities, nuisance parameters . . .
- test the Standard Model and different New Physics scenarios

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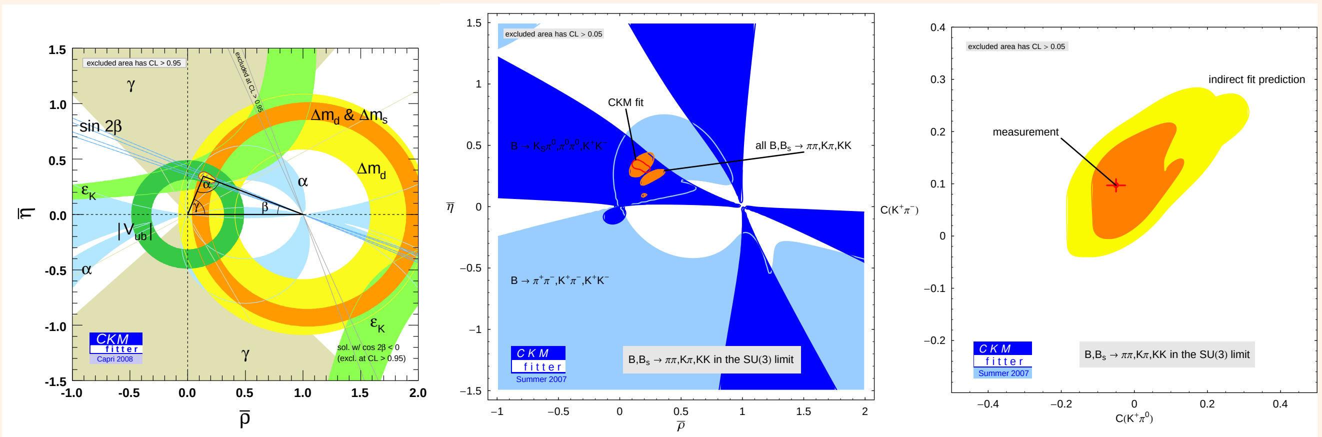
- test the Standard Model and different New Physics scenarios
- make nice complicated plots



Outline

brief update of the CKM matrix with emphasis on the rôle of lattice calculations

New Physics in $B - \overline{B}$ mixing in view of the recent Tevatron data

Quark mixing

mixing of the quark flavors because of the weak interaction

$\longrightarrow$ bi-diagonalization *vía* the Cabibbo-Kobayashi-Maskawa (CKM) matrix

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

this unitary matrix is complex as soon as there are more than three quark generations: this produces CP violation

CKM with three generations is predictive, in the sense one can prove the existence of CP-violation from CP-conserving measurements only

Hierarchy and Unitarity Triangle(s)

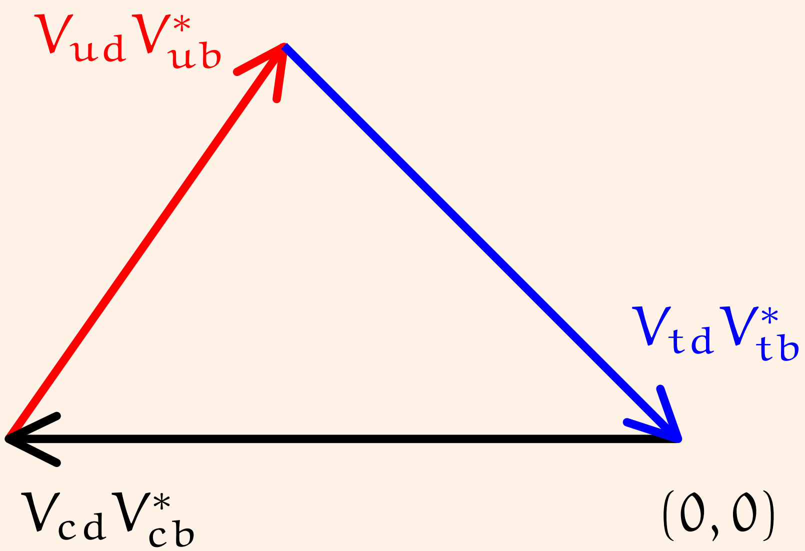
strong hierarchy of the CKM matrix:

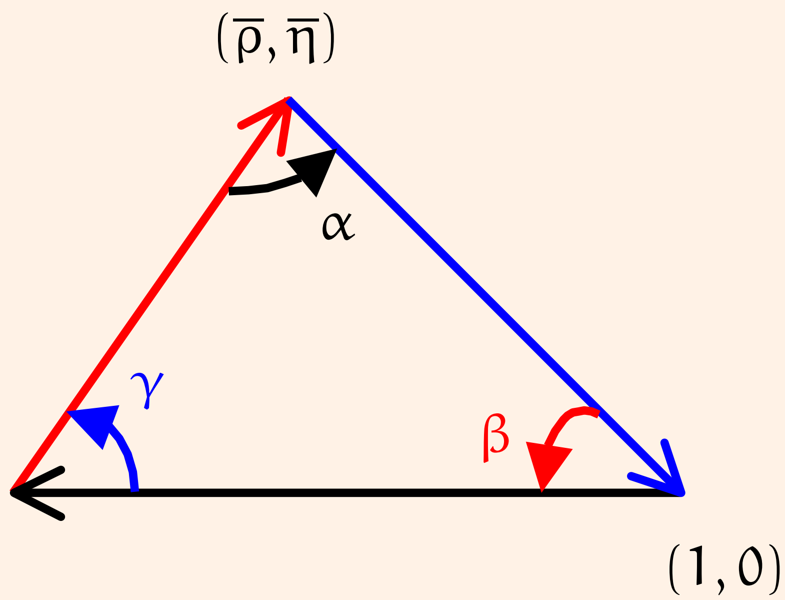
diagonal couplings $\propto 1$

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

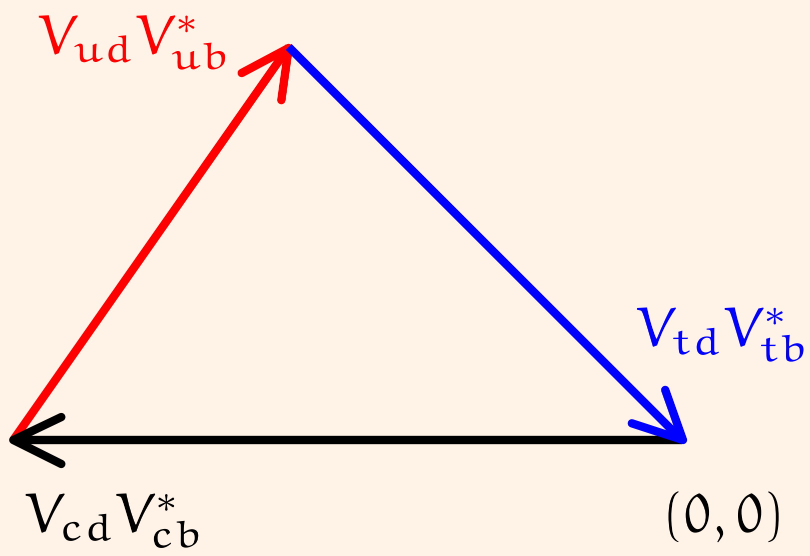


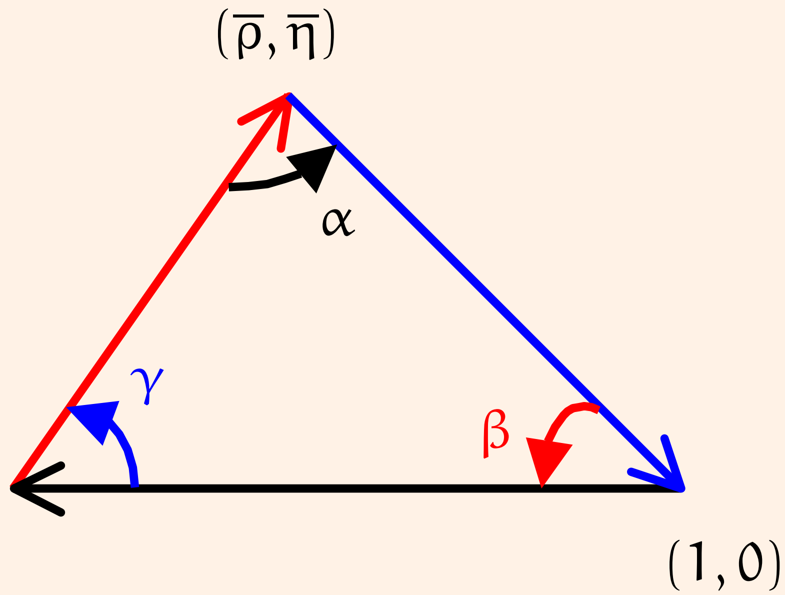


unitary-exact and convention-independent version of the Wolfenstein parametrization

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

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





The global CKM fit

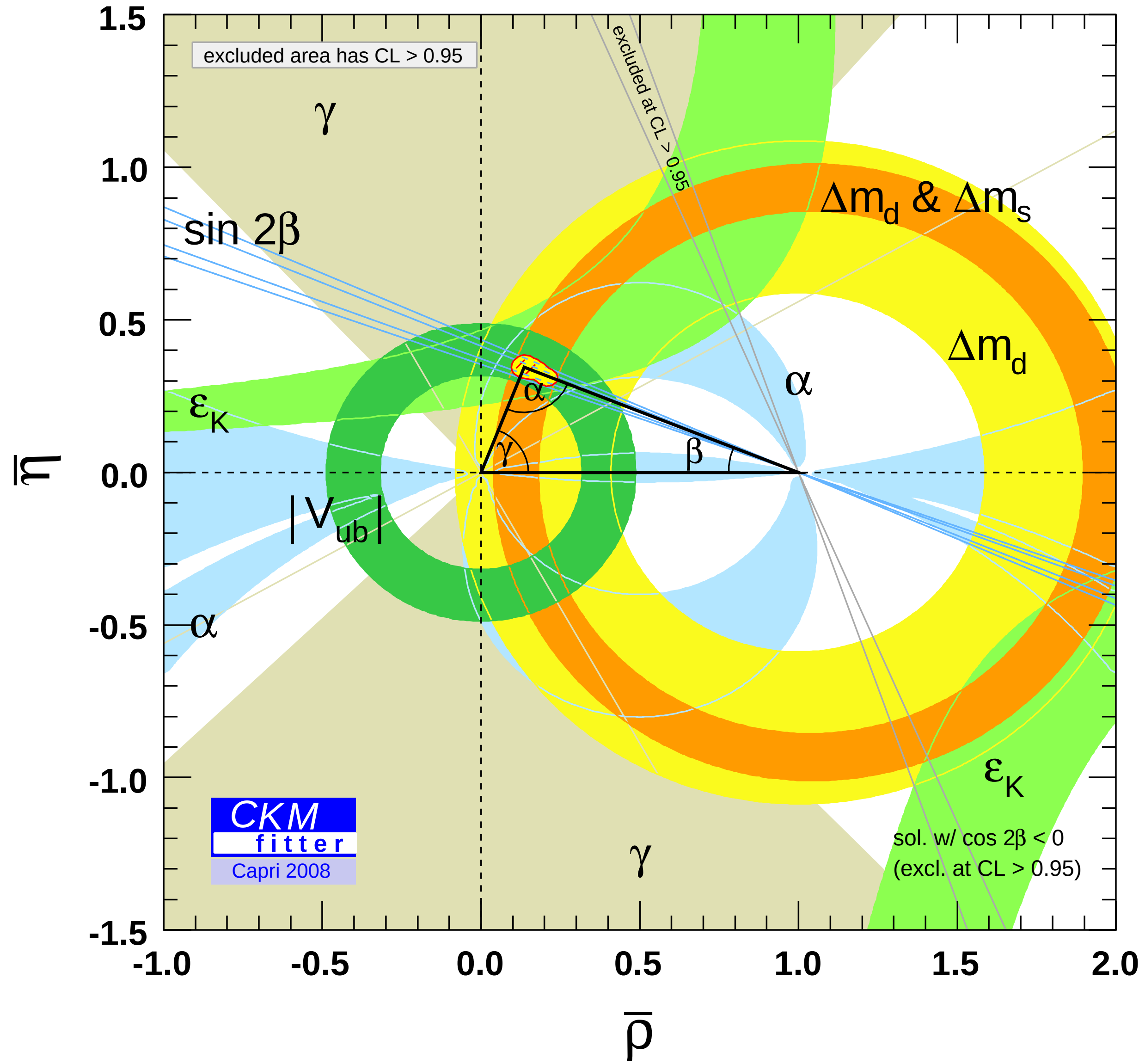
the constraints on the CKM matrix come from the decays of the neutron, the kaon, the B meson and to a lesser extent the D meson

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

$\|V_{ud}\|$, $\|V_{us}\|$, $\|V_{cb}\|$	PDG, HFAG and Flavianet WG
ε_K	exp: KTeV/KLOE, theo: CKM06
$\|V_{ub}\|$	our average
Δm_d	exp: last WA, theo: CKM06
Δm_s	dominated by CDF, theo: CKM06
β	last WA
α	exp: last $\pi\pi$, $\rho\pi$, $\rho\rho$ WA, theo: SU(2)
γ	exp: last $B \to DK$ WA, theo: GLW/ADS/GGSZ
$B \to \tau\nu$	exp: last WA, theo: CKM06

(more details can be found on http://ckmfitter.in2p3.fr)

The global CKM fit: result



Winter 2008

once A and λ have been mainly determined from $|V_{ud}|$, $|V_{us}|$ and $|V_{cb}|$, $(\bar{\rho}, \bar{\eta})$ are constrained by combination of the observables

$$A = 0.795^{+0.025}_{-0.015}$$

$$\lambda = 0.2252 \pm 0.0008$$

$$\bar{\rho} = 0.135^{+0.033}_{-0.016}$$

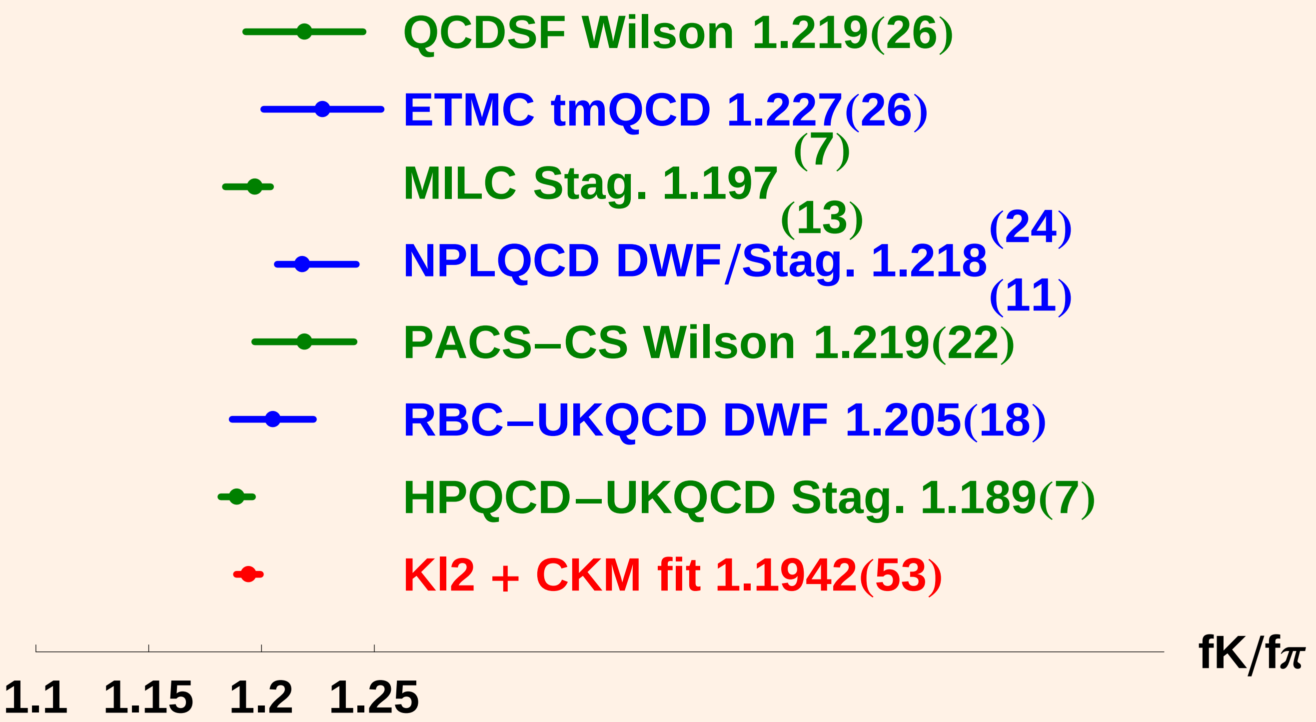
$$\bar{\eta} = 0.345^{+0.015}_{-0.018}$$

Lattice QCD inputs for CKM analyses

a few examples

f_K/f_π

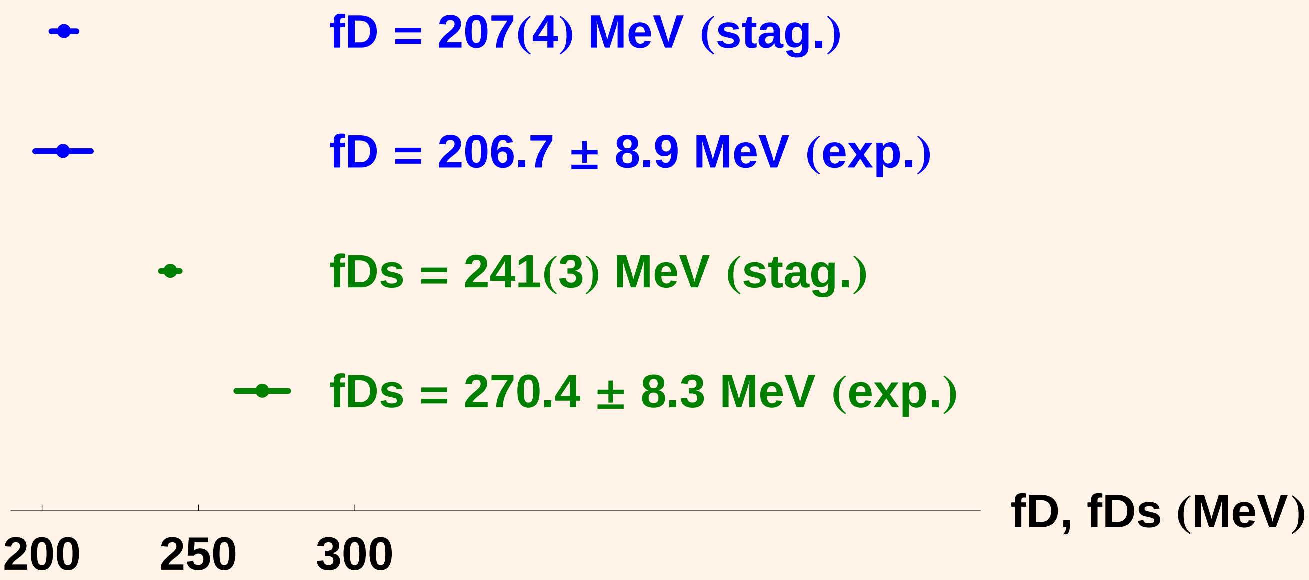
in CKMfitter we use $|V_{us}|$ from semileptonic K decays (Kl3); from leptonic decay (Kl2) data and CKMfit we can extract f_K/f_π and compare with most recent lattice calculations



lattice error is still larger than the one from Kl2 and CKM fit, but the agreement is good; possible improvement if closer to the physical limit

The f_D puzzle

recent staggered QCD calculations of the decay constants agree well with the most precise data for f_π, f_K and f_D, but show a clear discrepancy for f_{D_s}



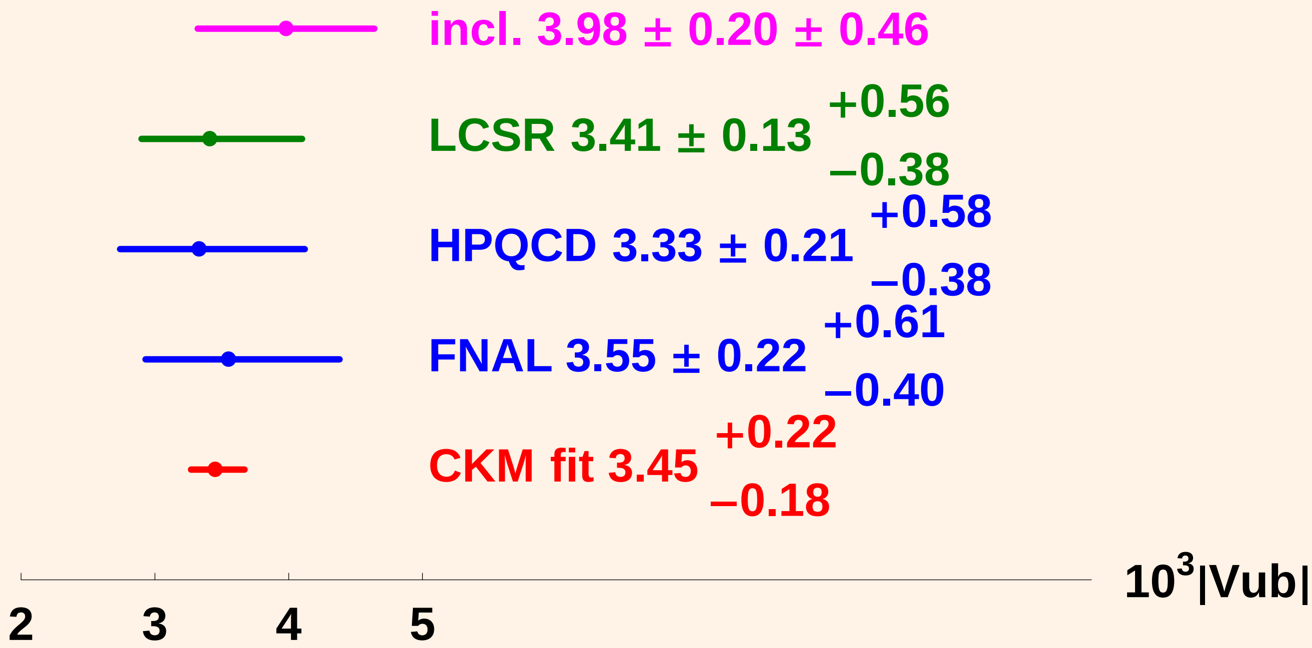
no single explanation is satisfying; even New Physics is a bit weird (why in cs but not in cd ?)

$|V_{ub}|$

several determinations: inclusive $b \to u$ (magenta), exclusive $B \to \pi$ with form factor from light-cone sum rules (green) or lattice staggered QCD (blue)

good agreement between inclusive and exclusive if we don't use $b \to s\gamma$ fitted moments as an input to $b \to u$

LCSR error more or less irreducible; there is room for improvement for lattice (smaller q^2, better parametrization, non staggered quarks)

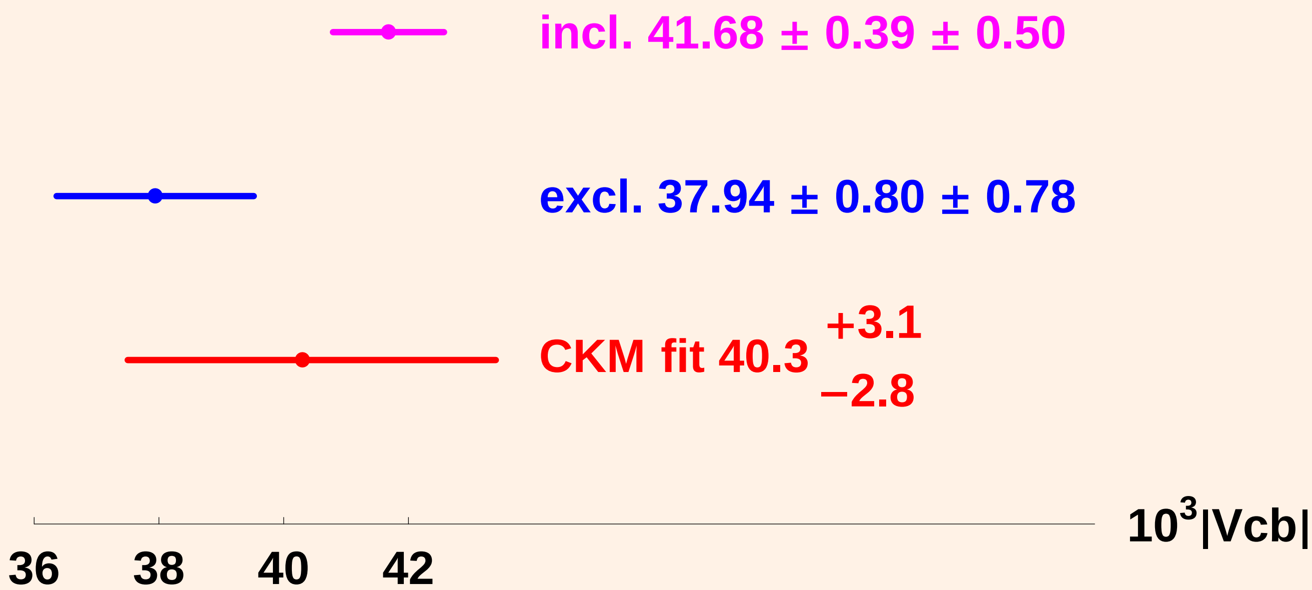


$|V_{cb}|$

for the exclusive modes the corrections to the heavy quark limit are computed with lattice QCD

a discrepancy is appearing between the inclusive and exclusive determinations

$|V_{cb}|$ is a crucial input for the global CKM fit ! still it will be very difficult to reduce the error that is already very small

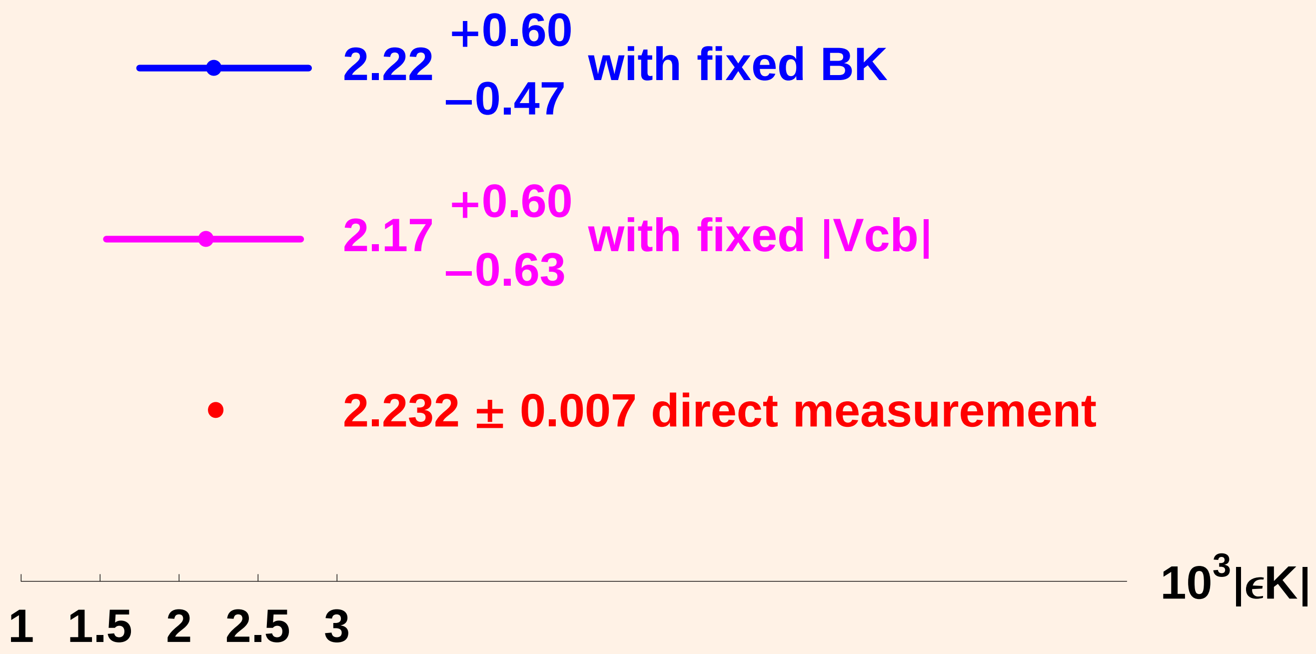


$|\varepsilon_K|$ from the global CKM fit

B_K is a kind of benchmark for lattice QCD; average is dominated by quenched determinations

the error coming from $|V_{cb}|$ actually slightly dominates over the one coming from $B_K = 0.78 \pm 0.02 \pm 0.09$ because of the A^4 dependence

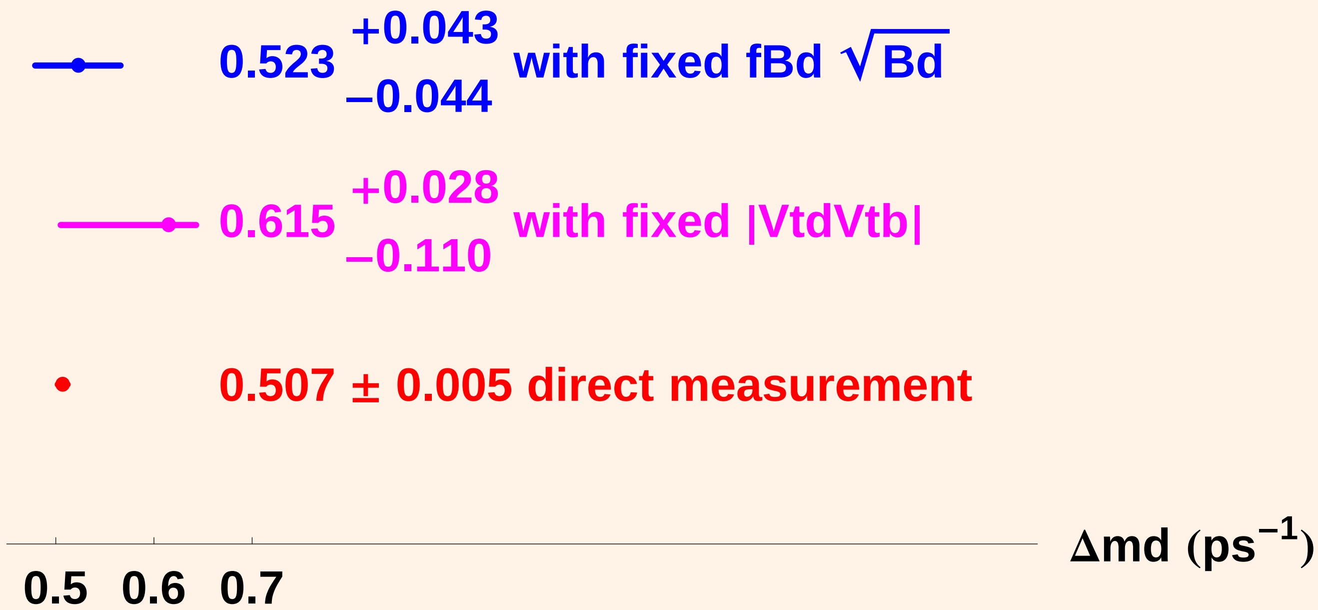
also for $K \to \pi\nu\bar{\nu}$ the error from $|V_{cb}|$ has a crucial impact



Δm_d from the global CKM fit

the error coming from the mixing matrix element dominates

crucial for New Physics scenarios (see below)



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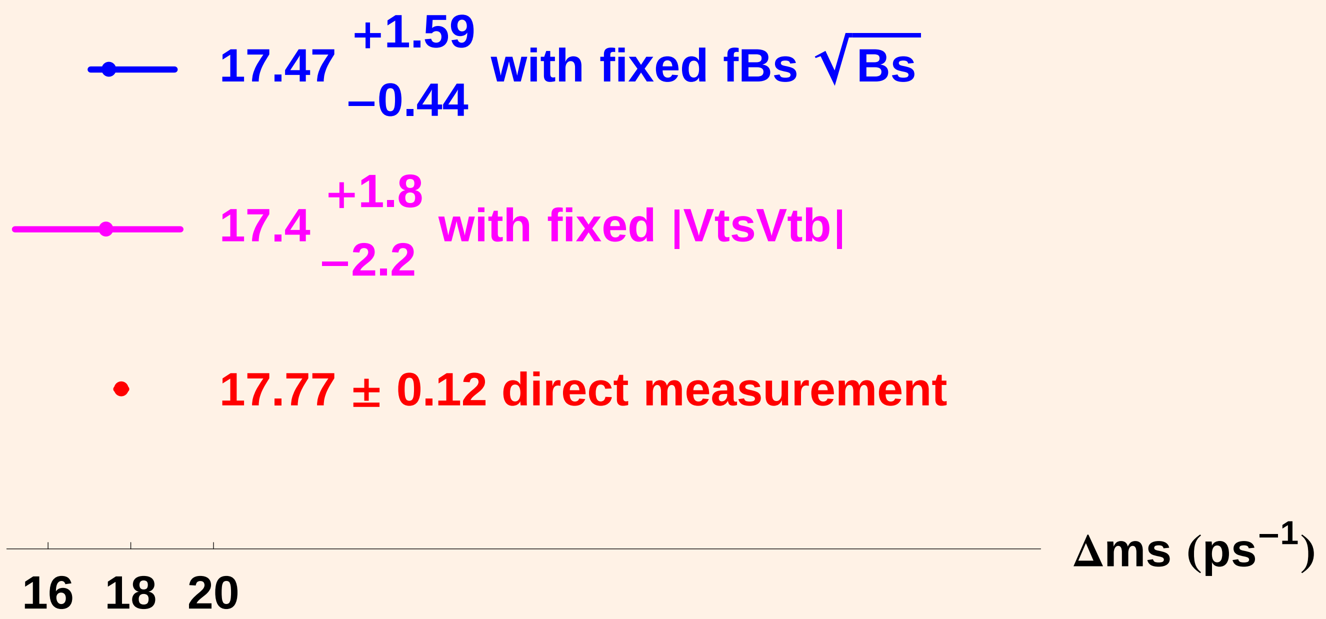

Helicity suppressed decays

from the global analysis,

$$BR(B \to \tau\nu_\tau) = \left(9.1^{+1.1}_{-1.5}\right) \times 10^{-5}$$

$$BR(B_s \to \mu^+\mu^-) = \left(3.10^{+0.15}_{-0.33}\right) \times 10^{-9}$$

here, experimental error will dominate for a while ...

Summary

there is room for improvement for the lattice QCD calculations of the matrix elements that enter CKM analyses

f_K/f_π: try to get closer to the physical point, and maybe beyond (chiral limit)

$f_{D_{d,s}}$: independent calculation needed !

$|V_{ub}|$ in $B \to \pi$: compute at smaller q^2, use better q^2 parametrizations, be careful about the correlations between different q^2

$|V_{cb}|$ in $B \to D$: ?

B_K: again, try to understand better the chiral behavior, and do unquenched calculations

$f_{B_{d,s}}$ and $B_{B_{d,s}}$: intrinsic error due to staggering presumably already reached; try different unquenched calculations

New Physics in $B\overline{B}$ mixing

abstract from more complete work in collaboration with A. Lenz and U. Nierste

Model-independent parametrization

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

SM is thus located at $\Delta_d = \Delta_s = 1$; additional notation $2\theta_q \equiv \arg(\Delta_q)$

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

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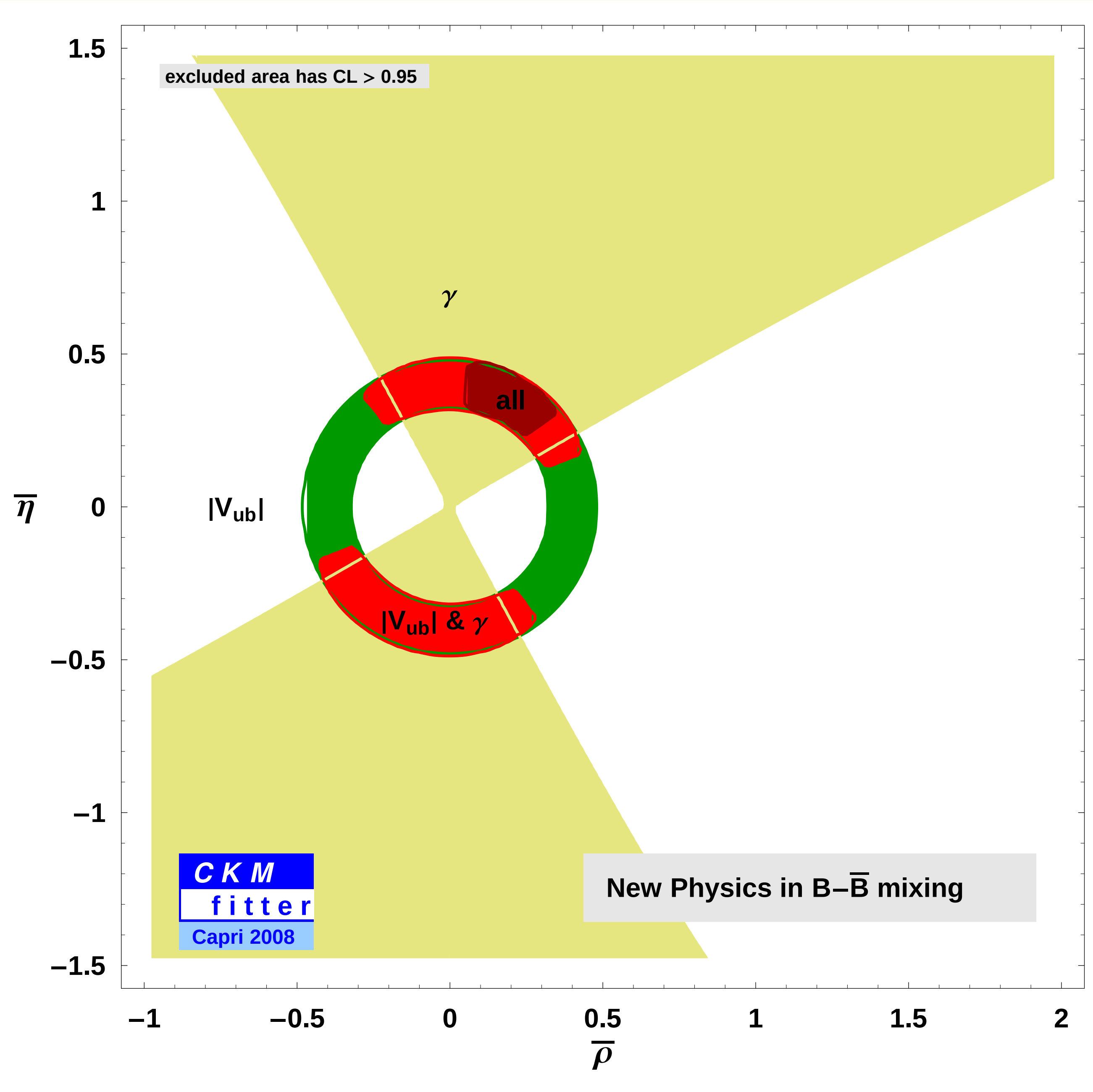
Strategy and inputs

- assume that tree-level transitions are 100% SM
- fix SM parameters with $|V_{ud}|$,$|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ and $\alpha = \pi - \gamma - \beta_{\mathrm{eff}}((c\bar{c})K)$
- $(\mathrm{Re}(\Delta_d), \mathrm{Im}(\Delta_d))$ are then constrained by Δm_d (circle), by $\phi_d = 2\beta_{\mathrm{eff}} = 2\beta + 2\theta_d$ (straight line) and by $\alpha = \pi - \gamma - \beta_{\mathrm{eff}}((c\bar{c})K)$
- $(\mathrm{Re}(\Delta_s), \mathrm{Im}(\Delta_s))$ 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 $\Delta\Gamma_q = \cos\phi_s \,\Delta\Gamma_q^{\mathrm{SM}}$ (straight line)

Result in the $(\bar\rho, \bar\eta)$ plane

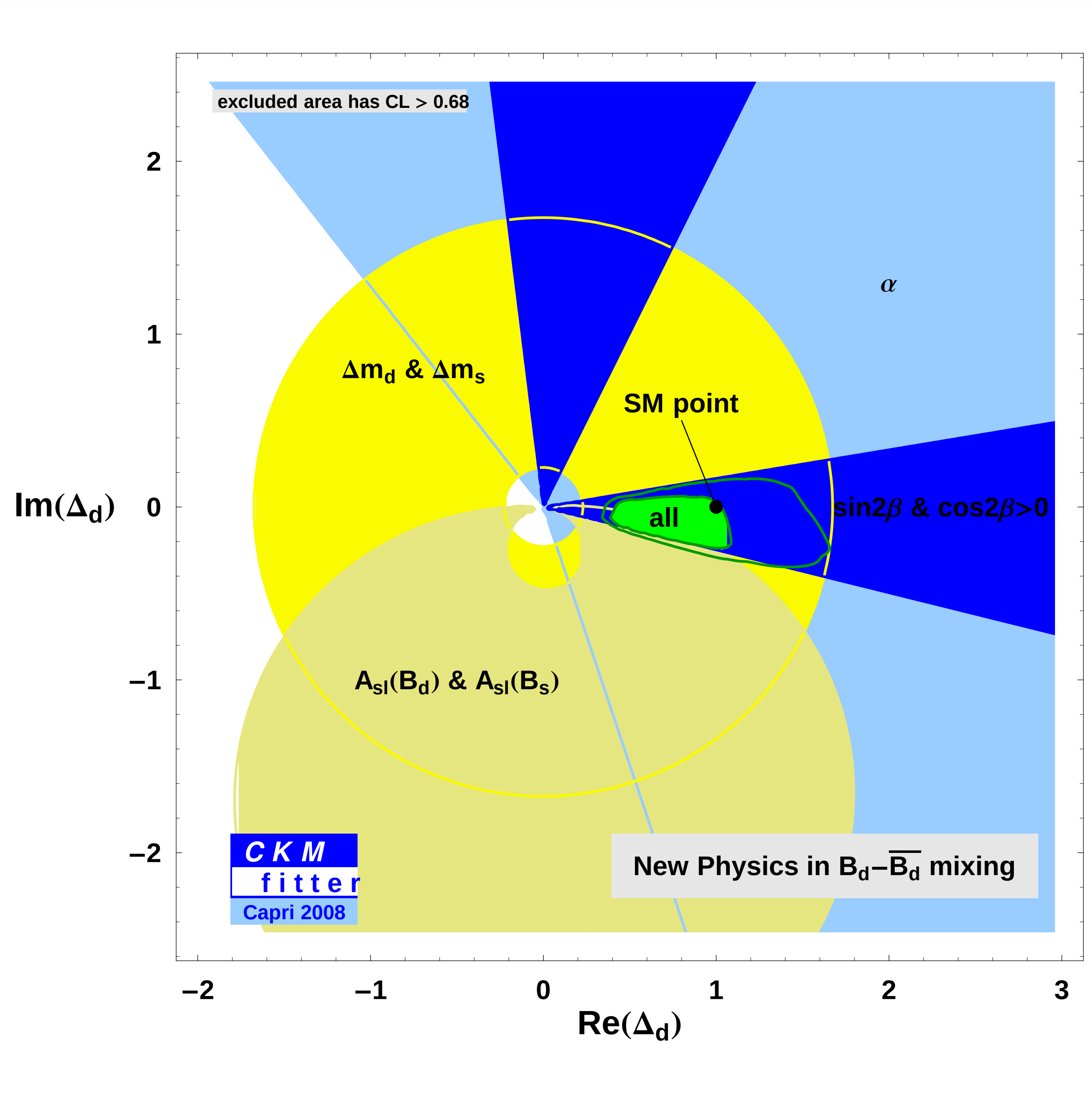


inputs: $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ, α and oscillation observables

NP-dependent inputs are crucial to improve the determination of $(\bar\rho, \bar\eta)$ from tree-level decays

compatible with full SM fit

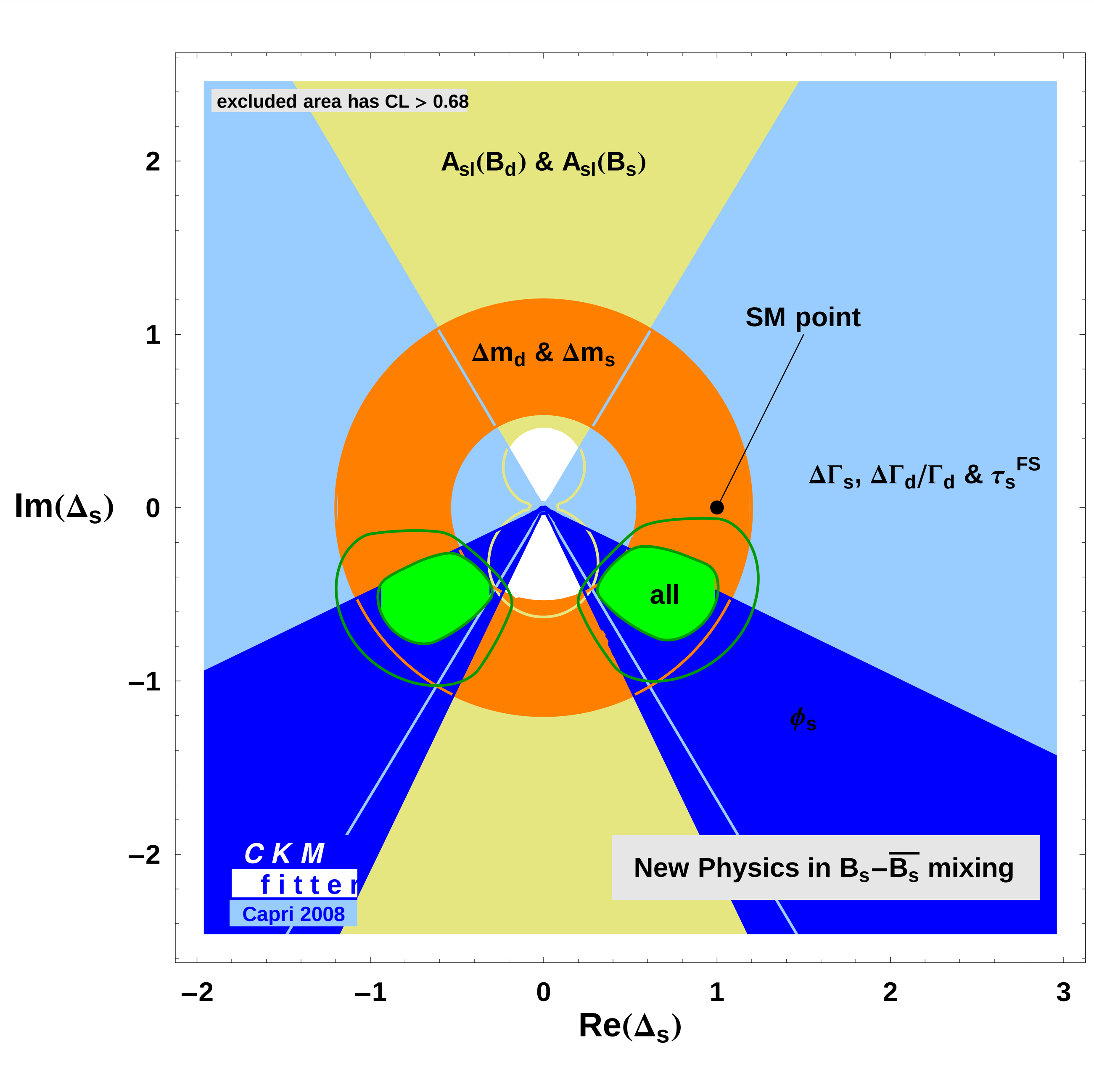
Result in the $\mathrm{Re}(\Delta_d), \mathrm{Im}(\Delta_d)$ plane



warning: only 68% CL regions are shown because of large errors

no evidence for New Physics, but sizable contributions are allowed

Result in the $Re(\Delta_s), Im(\Delta_s)$ plane



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one sees that the dominant constraints are Δm_s (in agreement with SM) and ϕ_s (slight discrepancy)

other inputs have minor impact, see below

Testing the Standard Model

assume that the scenario with NP in mixing only is the correct one

hypothesis	p-Value	standard deviations
$\Delta_d = \Delta_s = 1$	0.071	1.8
$\mathrm{Re}(\Delta_d) - 1 = \mathrm{Im}(\Delta_d) = 0$	0.35	0.93
$\mathrm{Re}(\Delta_s) - 1 = \mathrm{Im}(\Delta_s) = 0$	0.029	2.2
$\phi_d = 2\beta$	0.68	0.41
$\phi_s = -2\beta_s$	0.013	2.5

no strong evidence for New Physics

warning: p-Values from error function assuming χ^2 distribution for the log-likelihood, see below

Focusing on the relevant inputs

Δm_s agrees well with SM prediction: $\Delta m_s = 17.77 \pm 0.12$ vs. $\Delta m_s|_{\text{SM}} = 17.3^{+1.9}_{-2.3}$

A^s_{SL} is plagued by too large error : from $A^{d,s}_{\text{SL}}$ and the mixture A^{ds}_{SL} one gets
$A^s_{\text{SL}} = 0.0015 \pm 0.0088$, to be compared with the SM prediction $A^s_{\text{SL}} \sim 10^{-5}$

only the 2D $(\phi_s, \Delta\Gamma_s)$ plane really matters !

The impact of the recent Tevatron $B_s \to J/\psi\phi$ tagged analyses

both CDF and D0 perform a time-dependent angular analysis of the $B_s \to J/\psi\phi$ decay and obtain a correlated measurement of $(\phi_s, \Delta\Gamma_s)$ PRL 100, 161802 (2008); arXiv:0802.225

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a CDF/D0/HFAG working group has been settled to provide with a complete data combination independent of the SU(3) assumption

http://www-cdf.fnal.gov/physics/new/bottom/071214.blessed-tagged_BsJPsiPhi/

http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B08A/likelihoods/

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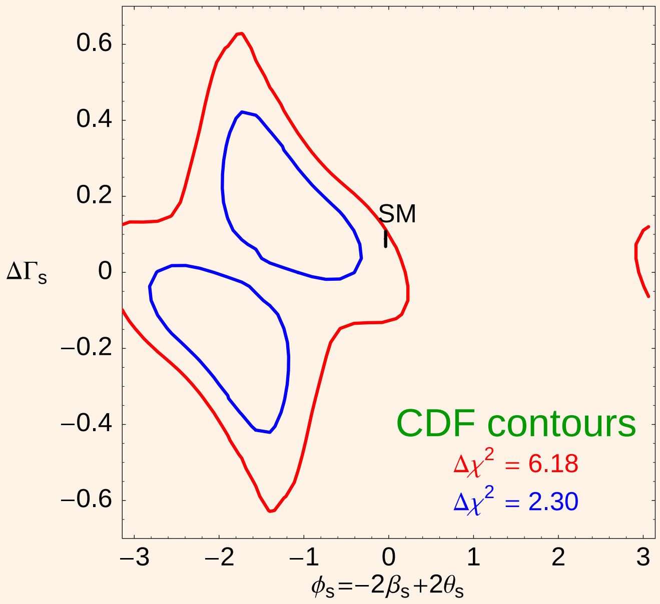
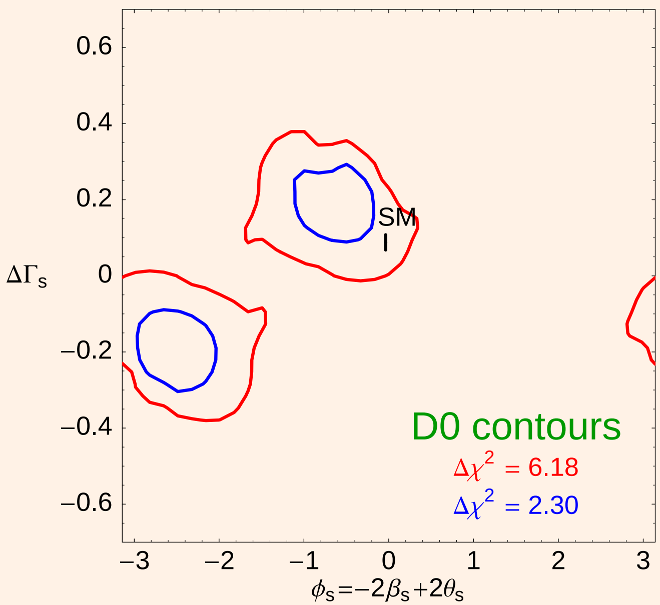
http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B08A/likelihoods/

in arXiv:0803.0659 using CDF/D0 data and Bayesian statistics the UTfit collaboration claims:

- a 3.7 sigmas evidence for NP contribution to $B_s - \overline{B}_s$ mixing phase
- stability of the result wrt to different treatments of the D0 data
- this result is the outcome of the full SM+NP fit, but is robust wrt theoretical uncertainties

A closer look at the Tevatron data and their interpretation





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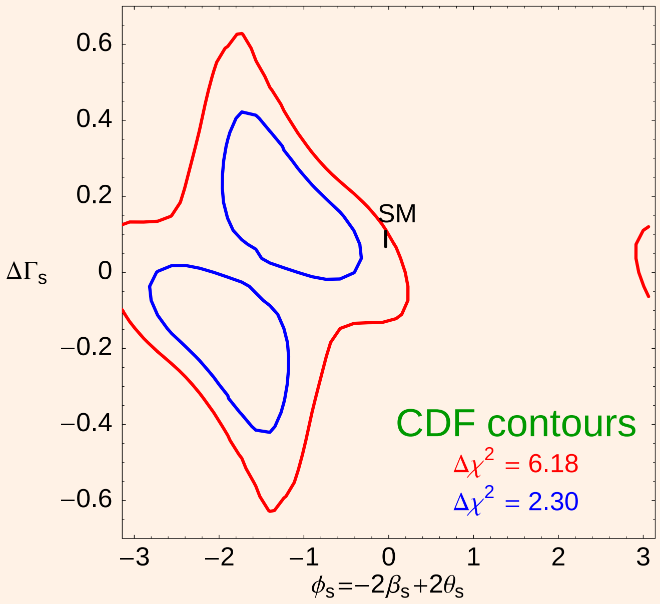

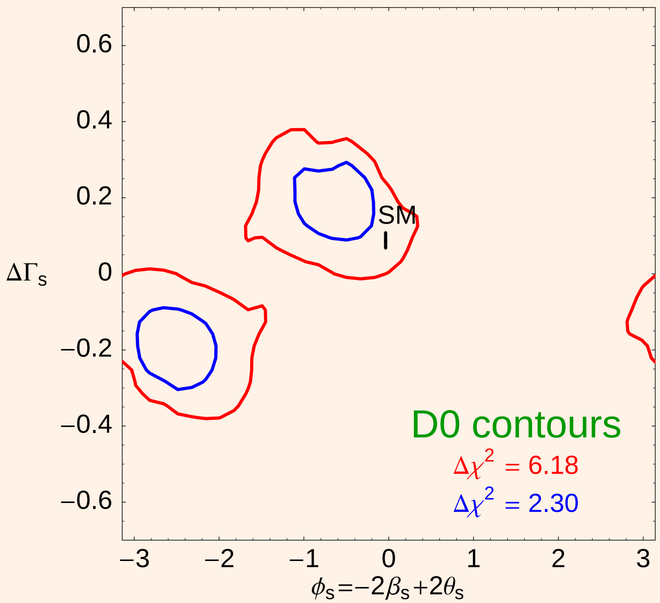

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blue and red contours would correspond to 68.3% and 95.5% CL in the asymptotic Gaussian regim

however CDF finds a significant bias towards smaller error values (possible explanation: the untagged analysis is insensitive to ϕ_s when $\Delta\Gamma_s = 0$); CDF corrects for this bias by a full Feldman-Cousins frequentist analysis

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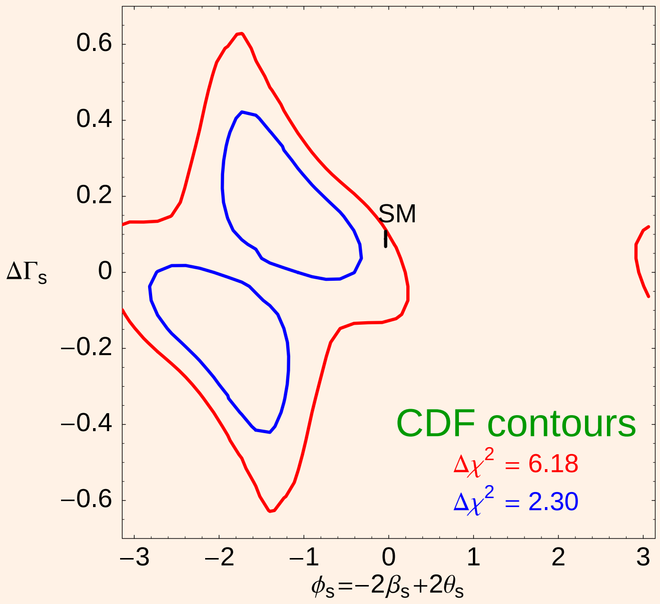

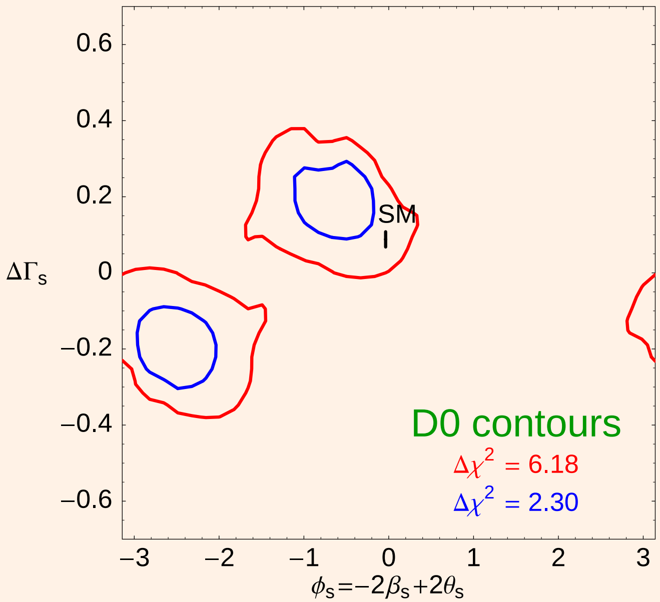

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in principle one should do the same for D0 data and for the combination; this requires the knowledge of the experimental PDF's

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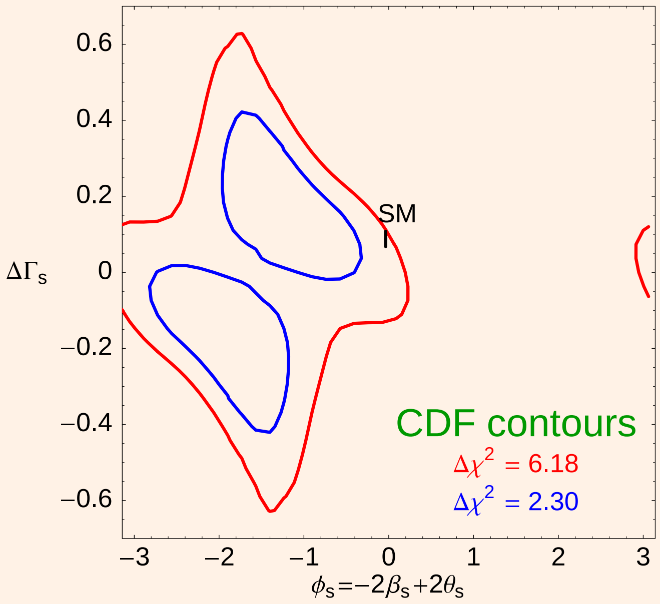

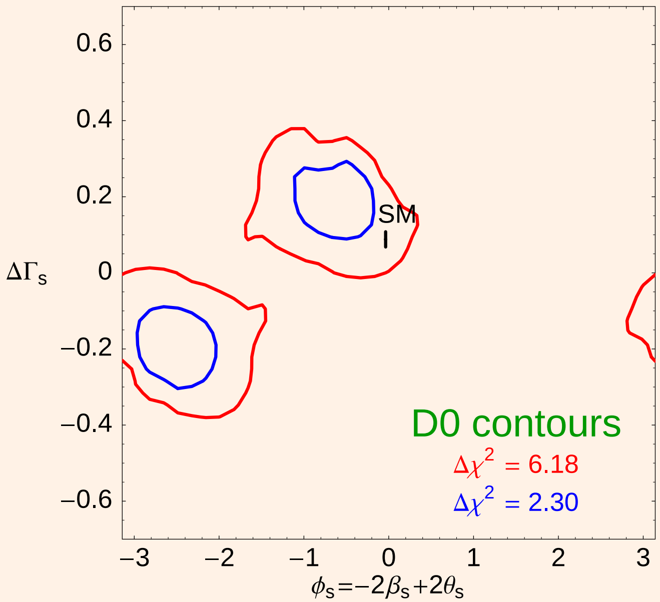

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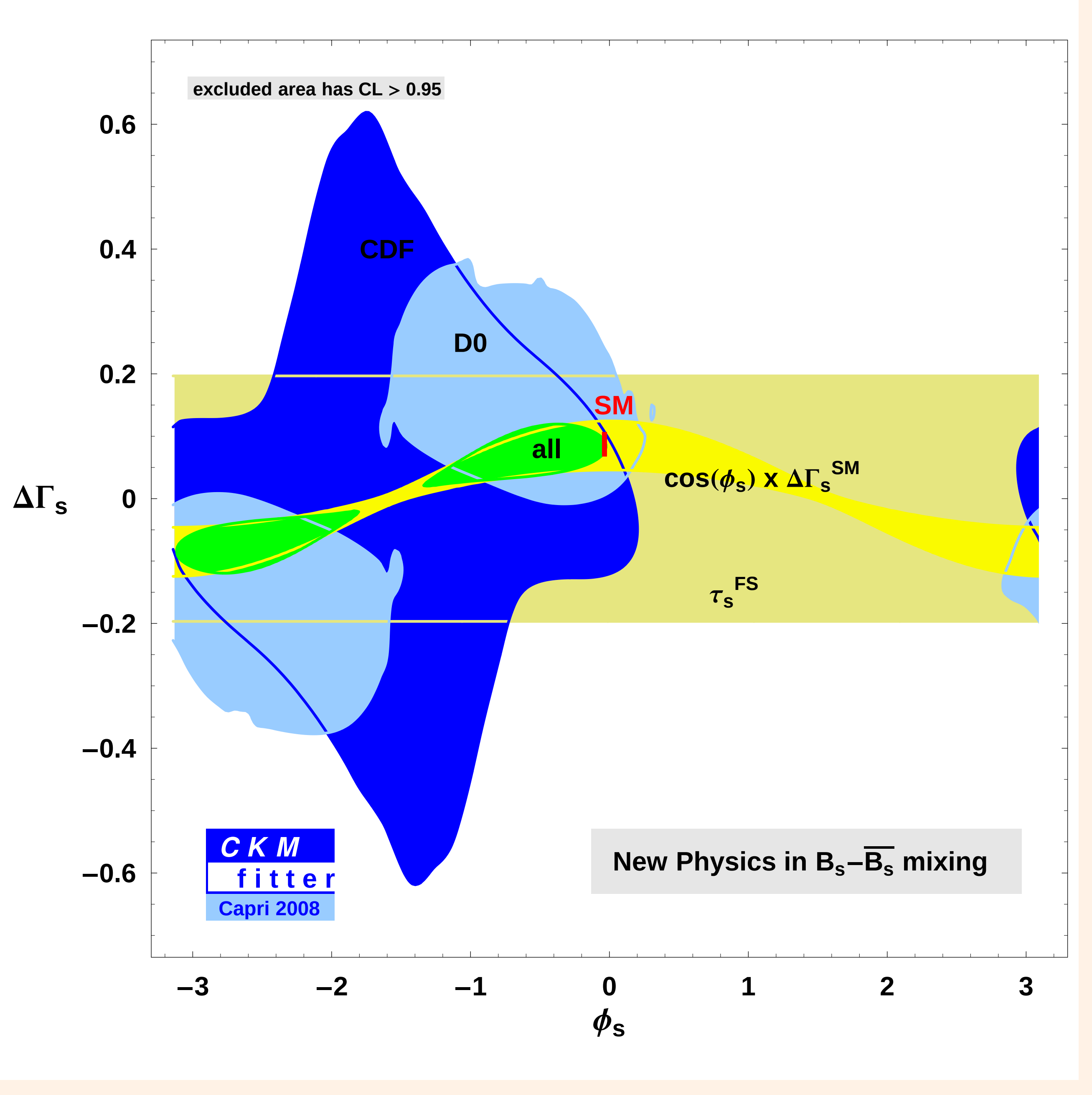
it is known that this simplification is *not conservative*: it tends to underestimate the errors

Back to the $(\phi_s, \Delta\Gamma_s)$ plane



here $\tau_s^{FS} = \frac{1+(\tau_s \Delta\Gamma_s)^2}{1-(\tau_s \Delta\Gamma_s)^2}$ can be viewed as an independent measurement of $\Delta\Gamma_s$

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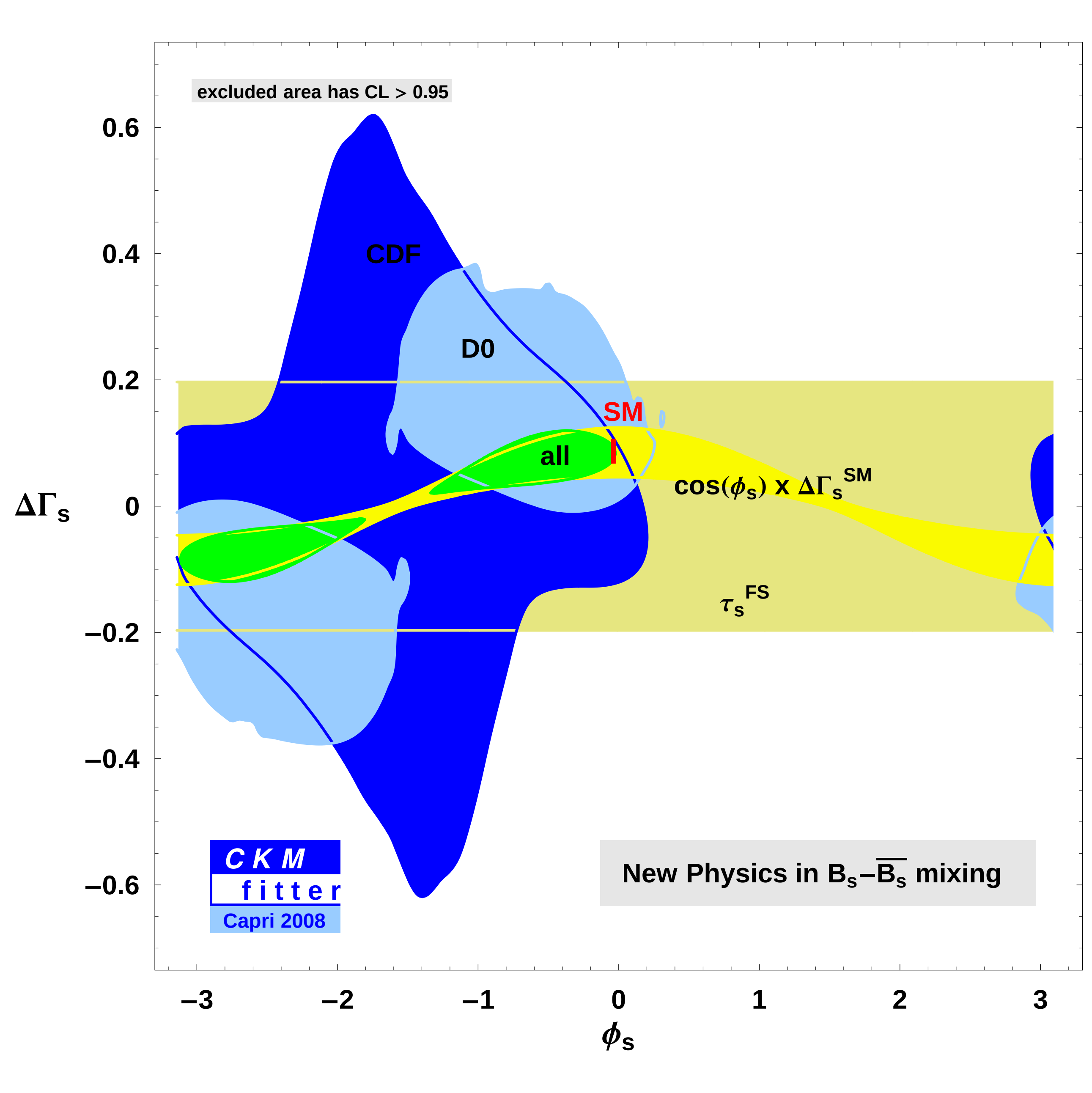

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$\phi_s = -2\beta_s$ is excluded at 2.4σ

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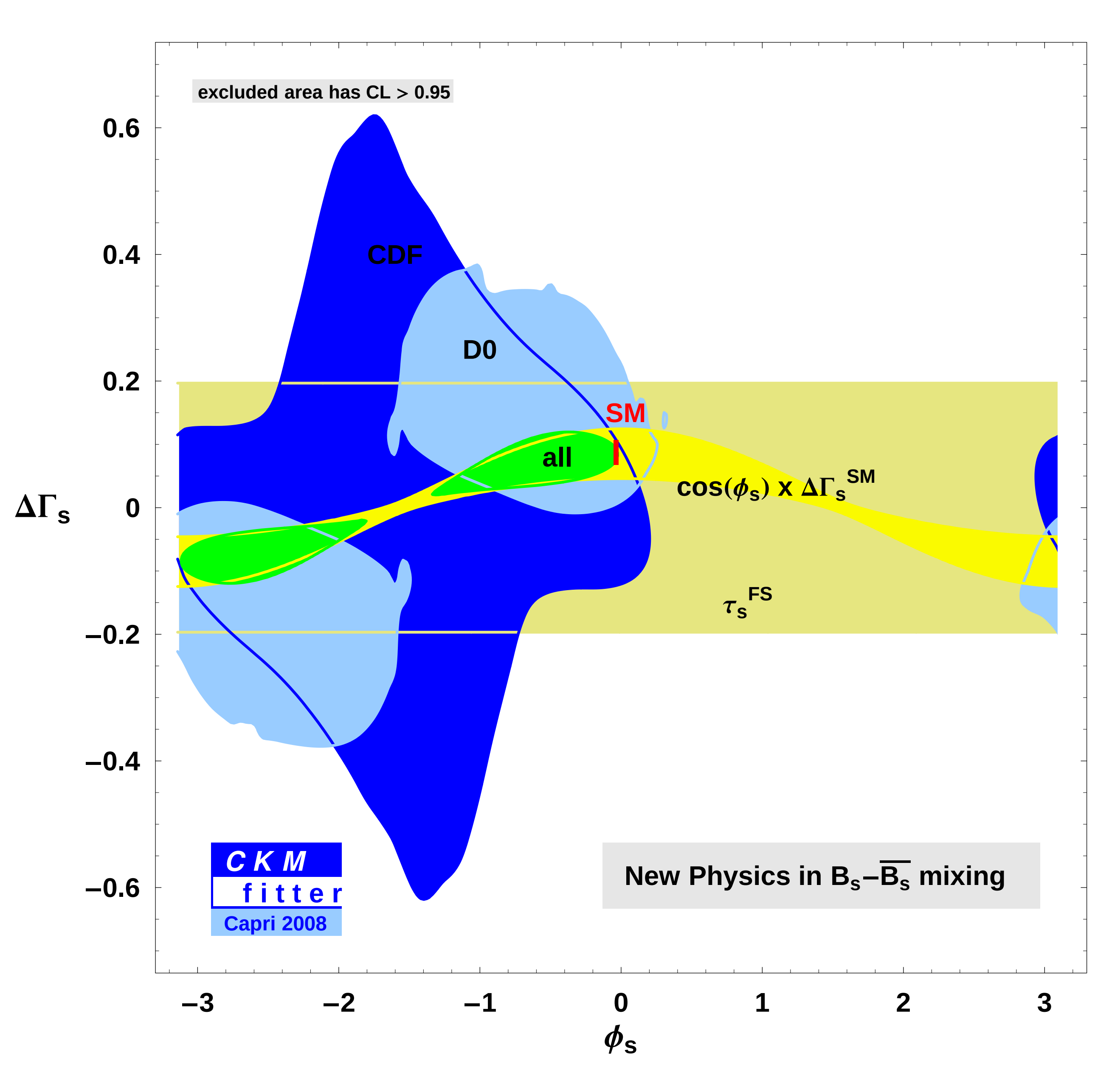

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the combined region is tangent to the SM one, simply because the phase is vanishingly small there and thus $\cos 2\phi_s \sim 1 + \mathcal{O}(\phi_s^2)$

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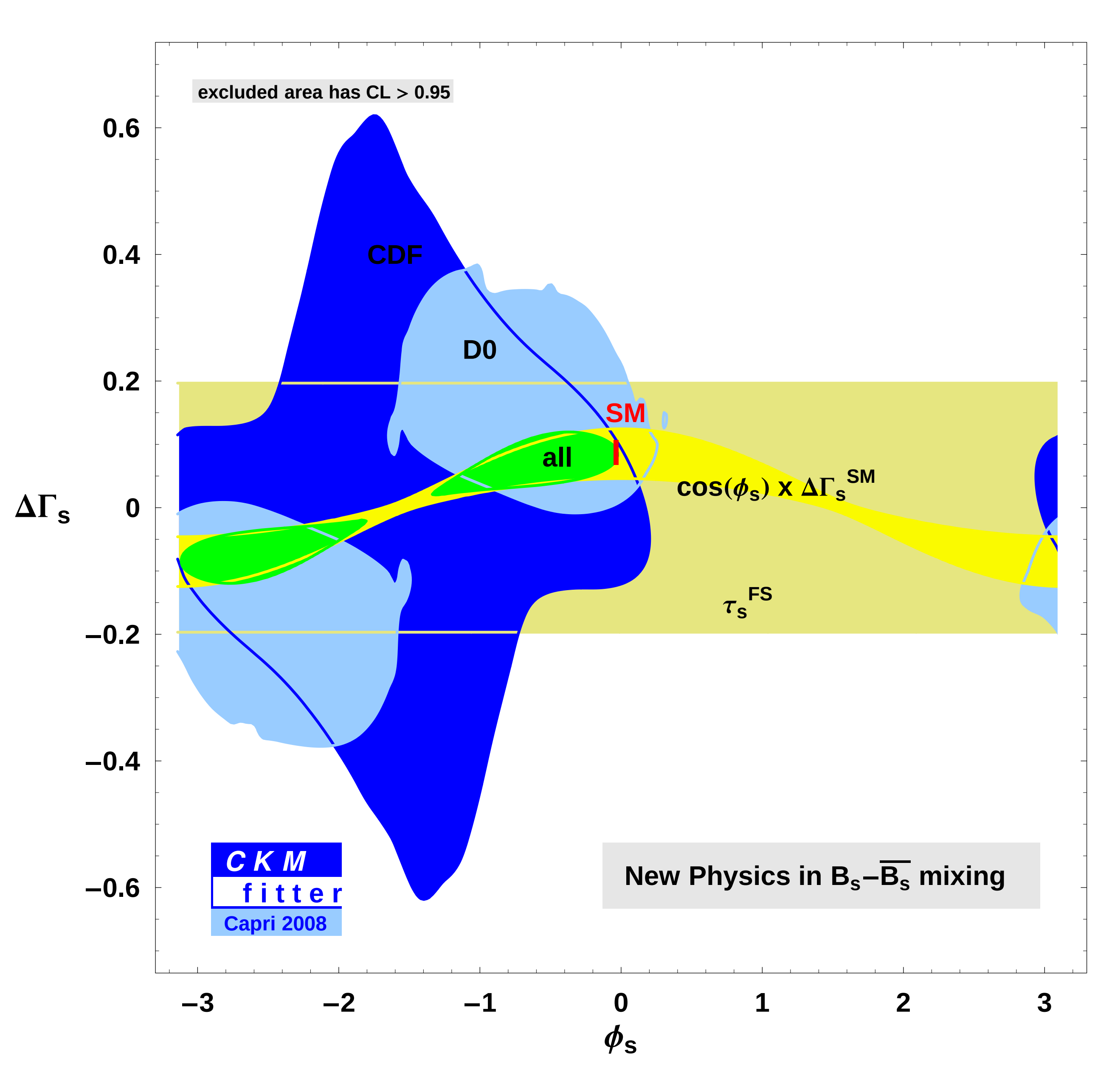

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very transparent analysis: all theoretical uncertainties are contained in the SM prediction

$\Delta\Gamma_s^{SM} = 0.090^{+0.017}_{-0.022}$ ps (red line)

Conclusion

we do not see New Physics in $B_d - \overline{B}_d$ mixing beyond the $0.93\ \sigma$ level, and in $B_s - \overline{B}_s$ mixing beyond the $2.2\ \sigma$ level

the discrepancy of ϕ_s wrt the SM value does not exceed $\sim 2.5\ \sigma$

CDF only	2.1
D0 only	1.9
CDF & D0	2.7
CDF & D0 & $\cos\phi_s\ \Delta\Gamma_s^{SM}$	2.4
CDF & D0 & τ_s^{FS} & $\cos\phi_s\ \Delta\Gamma_s^{SM}$	2.4
full SM+NP fit	2.5

as for the $B_s - \overline{B}_s$ mixing the correct frequentist treatment would need a sufficient knowledge of the experimental PDF's, and would presumably enlarge the errors (by comparison with the published CDF analysis) and improve the compatibility with the Standard Model

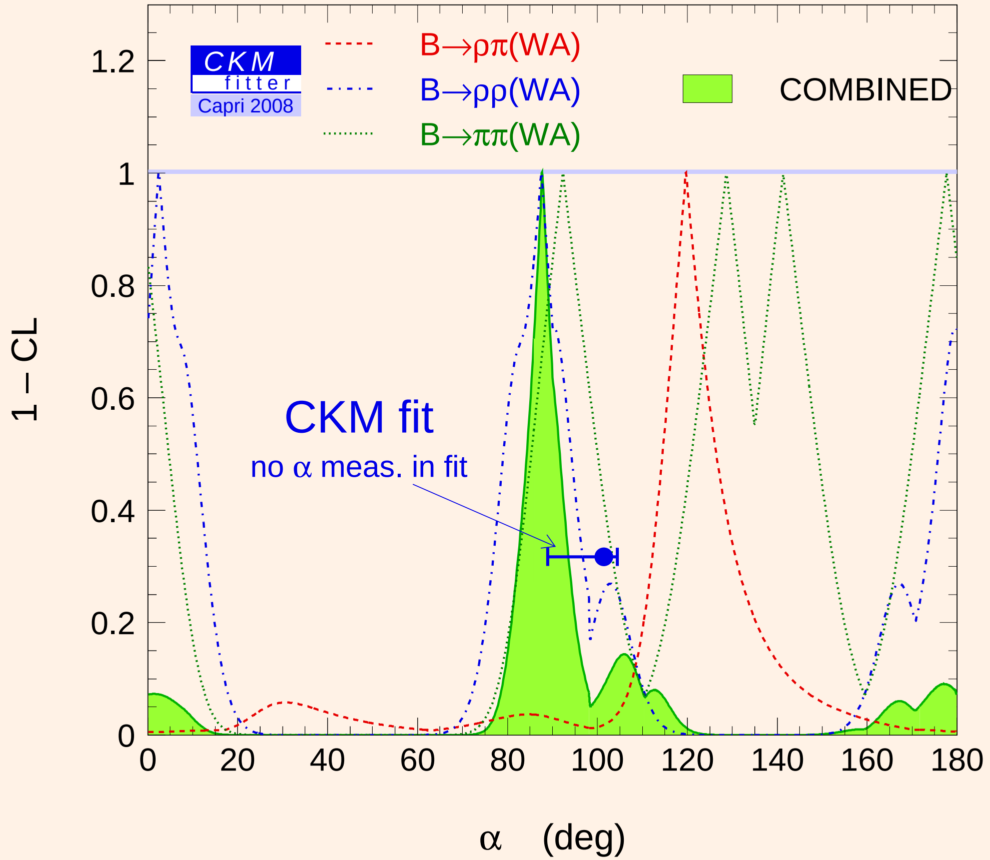
we are waiting for new data...

Backup

More on selected inputs…

the angle α

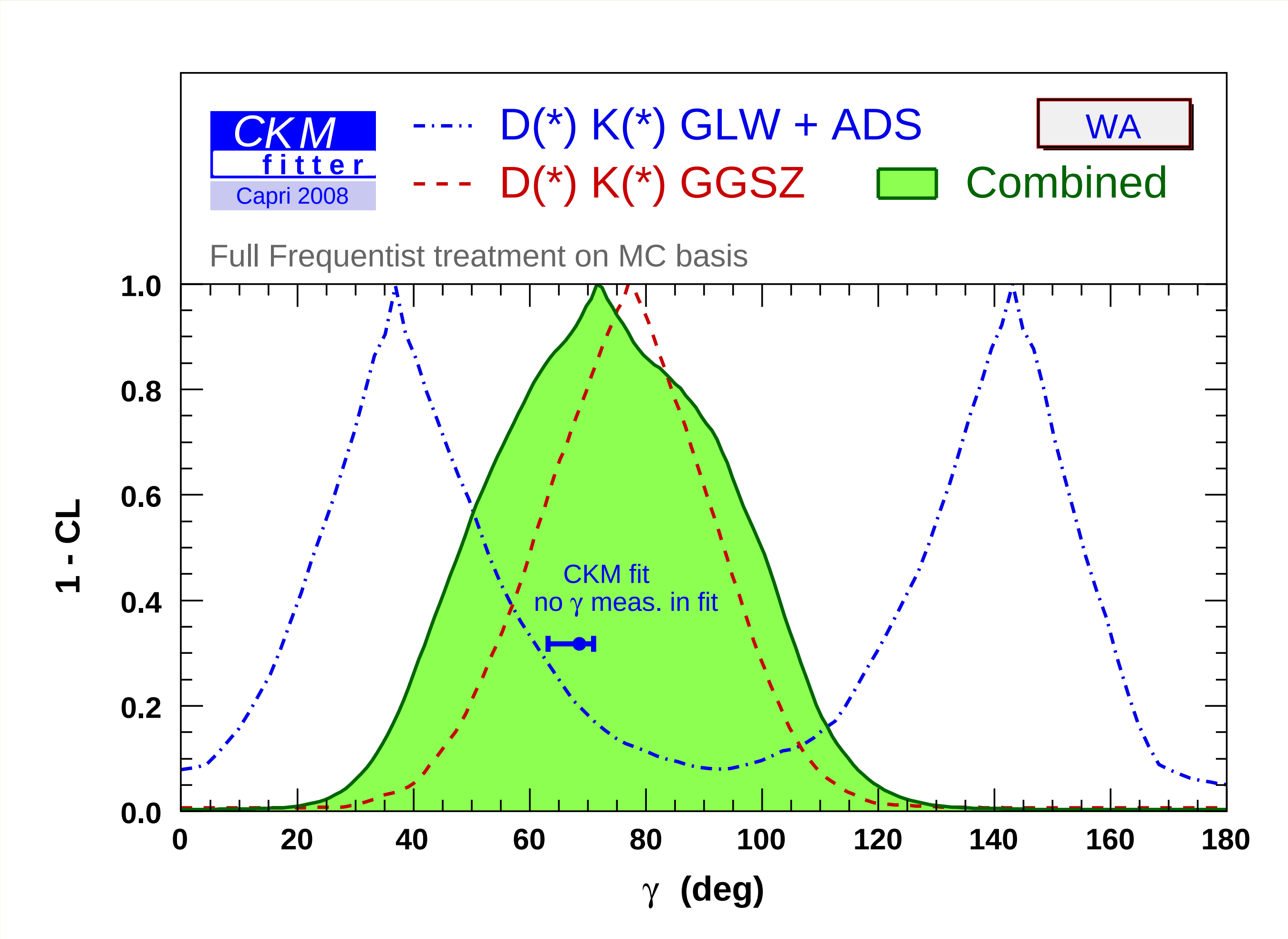
the best constraint comes from the $\rho\pi$ and $\rho\rho$ modes, which show a tendency to different central values



new average $\alpha = (87.8^{+5.8}_{-5.4})^\circ$

...more on selected inputs

the angle γ (preliminary)



the analysis is non trivial: naive interpretation of χ^2 in terms of the error function underestimates the error on γ because of the bias on r_B due to r_B compatible with 0; both Babar and Belle use their own frequentist approach, while we use a different one

meanwhile the central value of r_B has decreased

we find a somewhat loose constraint, with $\gamma = (72^{+34}_{-30})^\circ$

Bayesian vs. frequentist statistics

conceptual difference: Bayesian inference states whether theory is likely given the data, while frequentist inference states whether data are likely if the theory is true

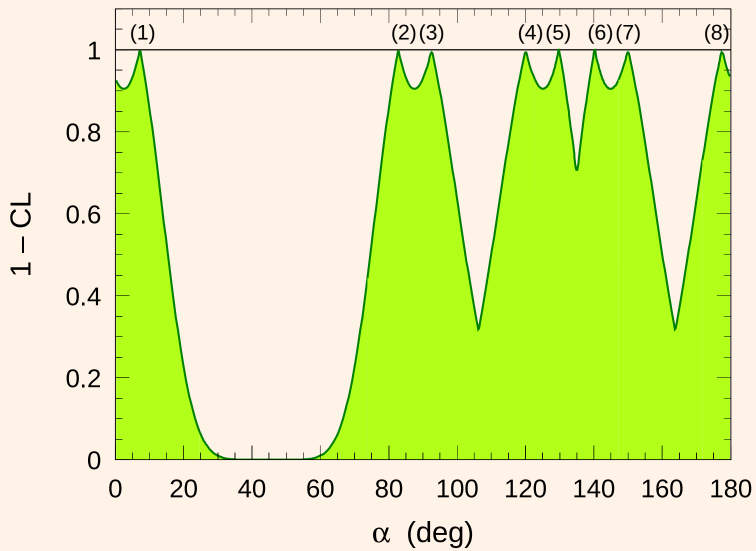
common prejudices:

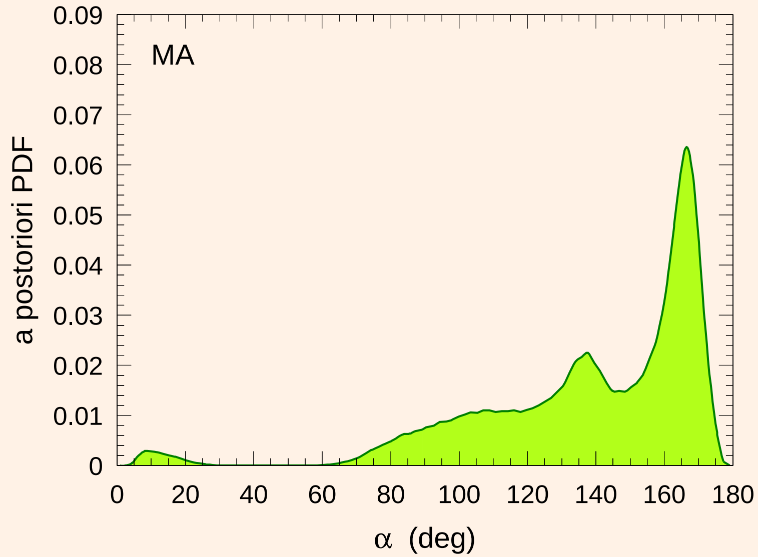
- the two treatments differ only in presence of theoretical, i.e. ill-defined, uncertainties
- the two treatments give similar numerical answer in pure Gaussian regime

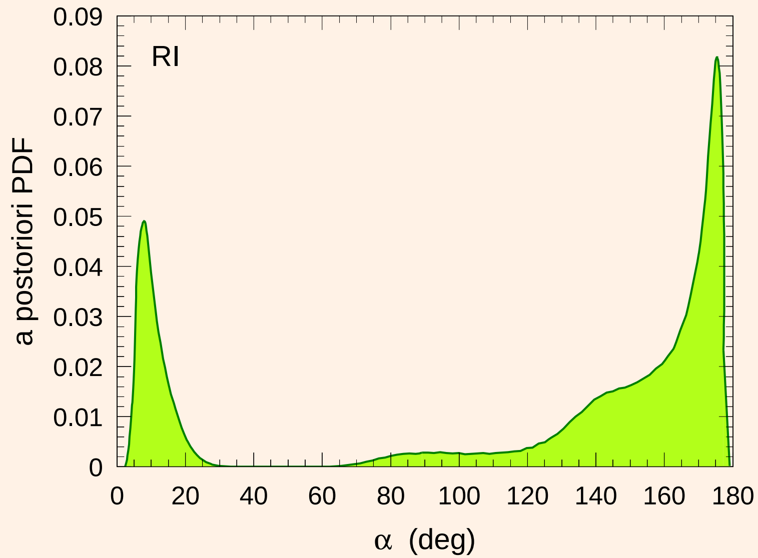
these prejudices are simply wrong

The $B \to \pi\pi$ isospin analysis as a benchmark

in hep-ph/0607243 it was shown that while the frequentist treatment is parametrization-independent and exactly symetric, the Bayesian procedure heavily depends on the parametrization; furthermore, whatever the choice of priors it breaks the SU(2) symmetry because of integration over mirror solutions; and finally the Bayesian procedure diverges in the Re,Im parametrization of the amplitudes





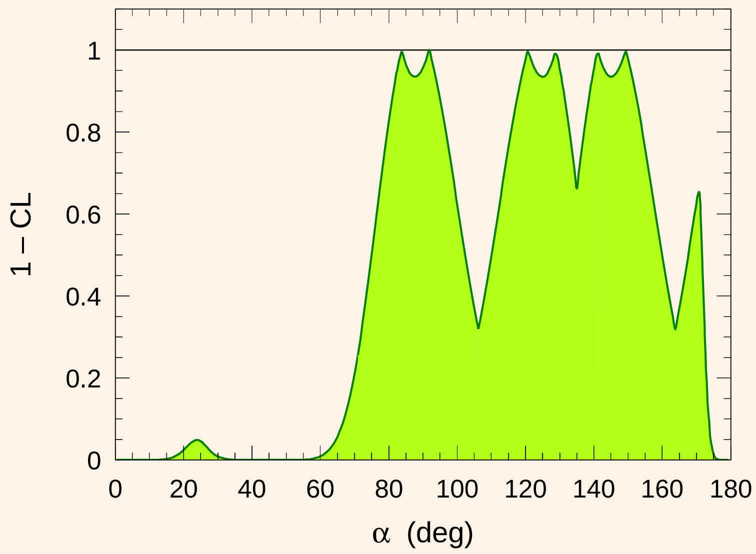


UTfit answer (hep-ph/0701204): the pure isospin analysis is not phenomenologically relevant anyway; one knows from theory that the non-leptonic amplitudes cannot be arbitrary large; one should perform the analysis with bounded (e.g. from SU(3) arguments) parameters

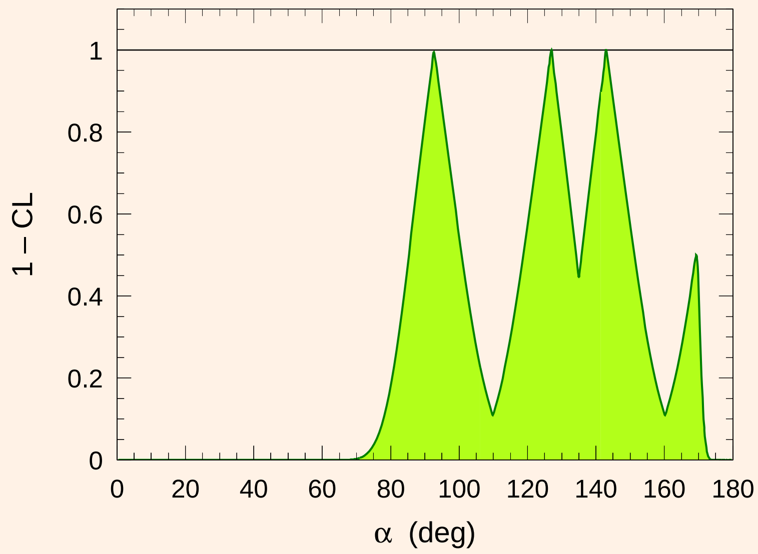
our answer: why not, but it does not solve the problem (hep-ph/0703073)

here is the constrained frequentist fit

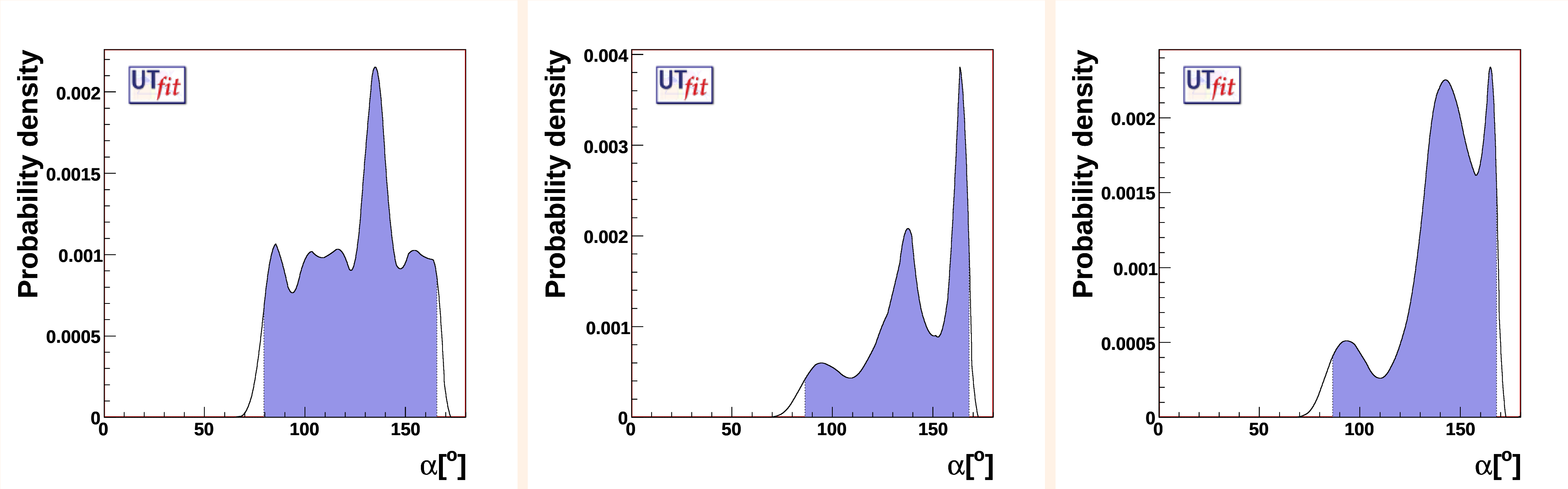
for marginally SU(2) compatible data



for fully SU(2) compatible data



to be compared with the Bayesian analysis



in the frequentist approach parameter values that correspond to the exactly degenerate frequentist CL peaks lead to exactly degenerate values for the experimental observables: no way to choose between them

the isospin analysis is a real physical problem where one encouters major differences between the two statistical approaches