From the KM ansatz to the search of New Physics in ΔF=2 FCNC

Stéphane T'JAMPENS
on behalf of the CKMfitter group

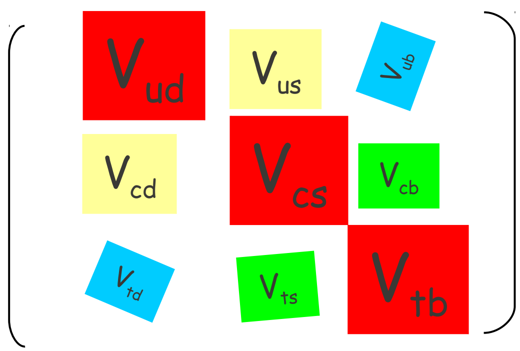
LAPP (CNRS/IN2P3 et Université de Savoie)

CKM Matrix

In SM, weak-charged transitions mix quarks of different generations
↳ CKM matrix: free parameters determined experimentally

- Once we assume unitarity, the CKM matrix can be completely determined using only tree-level CC amplitudes: $\Gamma \propto |V_{ij}|^2$
- The only CKM elements we cannot access via tree-level processes are V_{ts} and V_{td}.

V_{CKM} =



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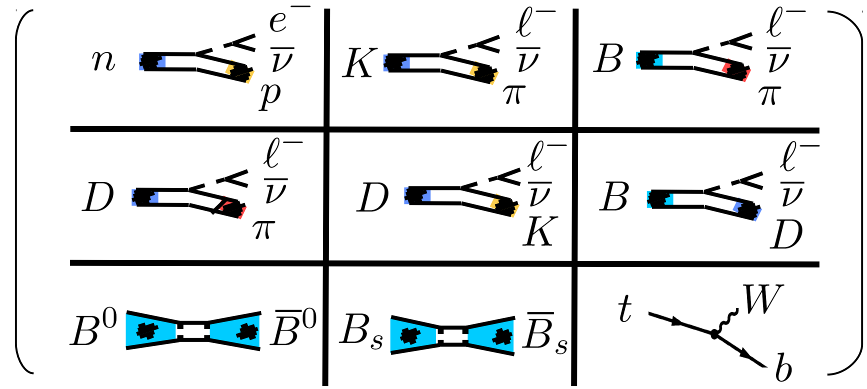


Four unknowns using a <u>unitary</u> Wolfenstein parametrization
➔ Unitarity-exact to all order in λ and phase-convention independent :

Charles *et al.*
EPJC **41**, 1 (2005)

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

KM ansatz (1973): one irreducible phase with 3 families
↳ only source of CP violation in the SM

Kobayashi & Maskawa,
Prog.Theor.Phys.49 (1973) 652

Cited 6032 times (SPIRES)

Inputs

Use Frequentist significance testing to build statistical significance (p-value) functions from which estimates and confidence intervals are obtained; test statistic=likelihood-ratio test. Dedicated Rfit scheme for the treatment of theoretical systematics.

data = weak $\otimes$ QCD $\Longrightarrow$ Need for hadronic inputs (often lattice)

$\lvert V_{ud}\rvert$	superallowed β decays	PRC79, 055502 (2009)
$\lvert V_{us}\rvert$	$K_{\ell 3}$ (Flavianet)	$f_+(0) = 0.963 \pm 0.003 \pm 0.005$
ϵ_K	PDG 08	$\hat{B}_K = 0.723 \pm 0.004 \pm 0.067$
$\lvert V_{ub}\rvert$	inclusive and exclusive	$\lvert V_{ub}\rvert \cdot 10^3 = 3.92 \pm 0.09 \pm 0.45$
$\lvert V_{cb}\rvert$	inclusive and exclusive	$\lvert V_{cb}\rvert \cdot 10^3 = 40.89 \pm 0.38 \pm 0.59$
Δm_d	last WA B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.05 \pm 0.01 \pm 0.03$
Δm_s	last WA B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.28 \pm 0.02 \pm 0.03$
β	last WA $J/\psi K^{(*)}$	
α	last WA $\pi\pi, \rho\pi, \rho\rho$	isospin
NEW γ	last WA $B \to D^{(*)} K^{(*)}$	GLW/ADS/GGSZ
$B \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.199 \pm 0.008 \pm 0.023$
		$f_{B_s} = 228 \pm 3 \pm 17$ MeV

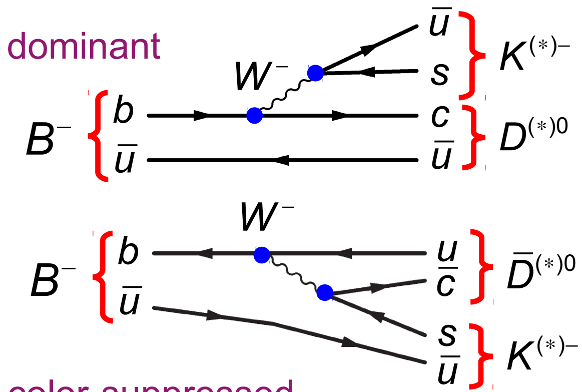
Inputs: γ

- GLW : D^0 decays into *CP* eigenstate
- ADS : D^0 decays to $K^-\pi^+$ (fav.) and $K^+\pi^-$ (sup.)
- GGSZ : D^0 decays to $K_S\pi^+\pi^-$ (interference in Dalitz plot)

All methods fit simultaneously:

γ, r_B and δ *(different r_B and δ)*

Tree: dominant



Tree: color-suppressed

GLW: Gronau-London, PL B253, 483 (1991); Gronau-Wyler, PL B265, 172 (1991)
ADS: Atwood-Dunietz-Soni, PRL 78, 3257 (1997)
GGSZ: Giri *et al*, PRD 68, 054018 (2003)

σ_γ depends significantly on the value of r_B

Coverage-adjusted 1D p-value function for γ:

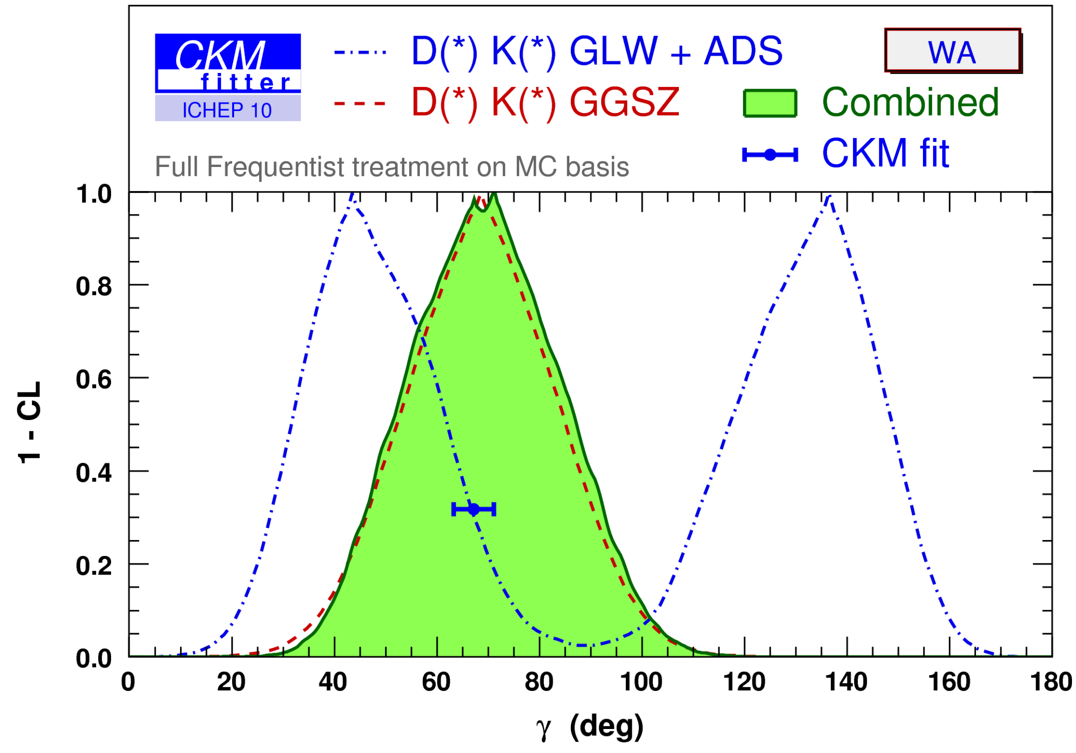
$$71^{+21}_{-25} \quad \text{(deg)}$$

Without coverage adjustment: 71^{+11}_{-17} (deg)

GGSZ: arXiv:1005.1096
ADS: arXiv:1006.4241
GLW: arXiv:1007.0504

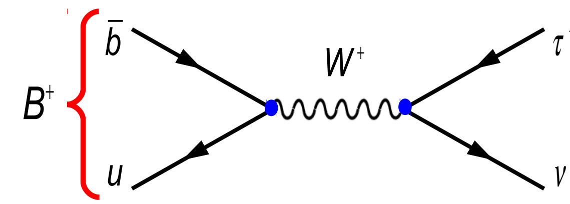
GGSZ: arXiv:1003.3360

NEW



Inputs: B→τν

- helicity-suppressed annihilation decay sensitive to $f_B \times |V_{ub}|$
- Sensitive to charged Higgs replacing the *W* propagator

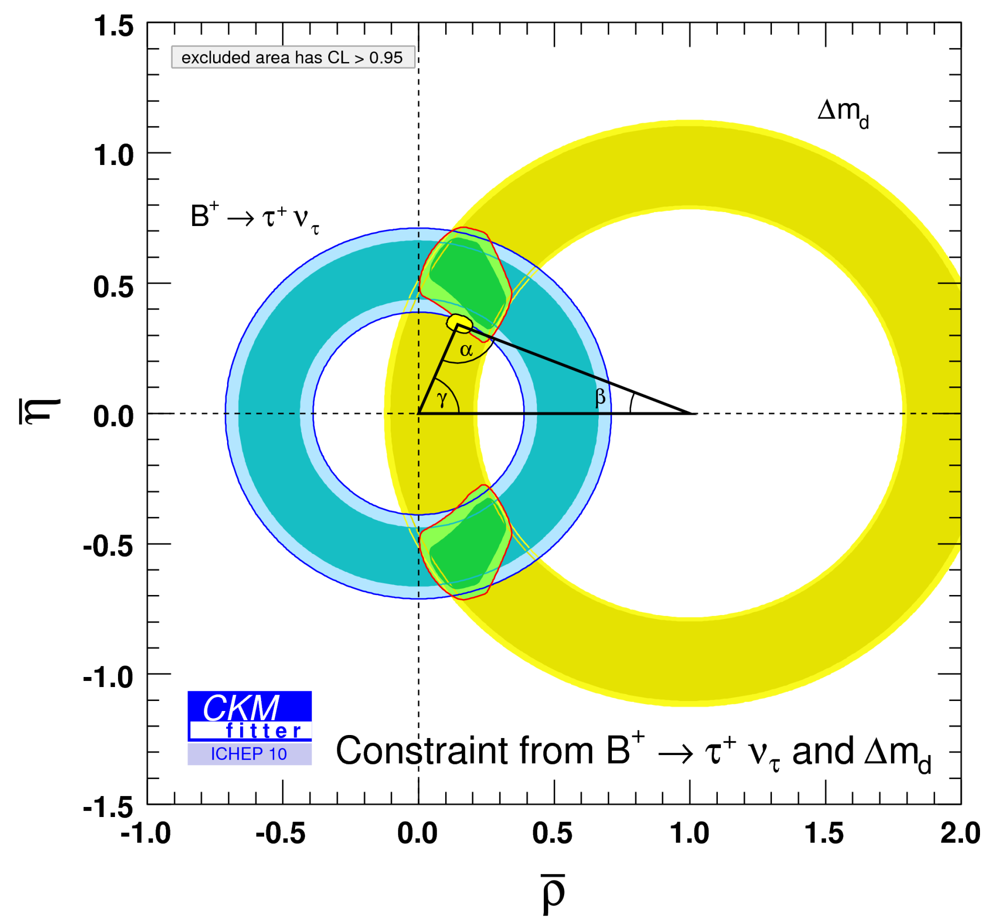


$$BR(B^+ \to \tau^+ \nu) = \frac{G_F^2 m_B \tau_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 \, |V_{ub}|^2$$

	tag	BF(→τν)[10^{-4}]
	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

Prediction from global CKM fit:

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



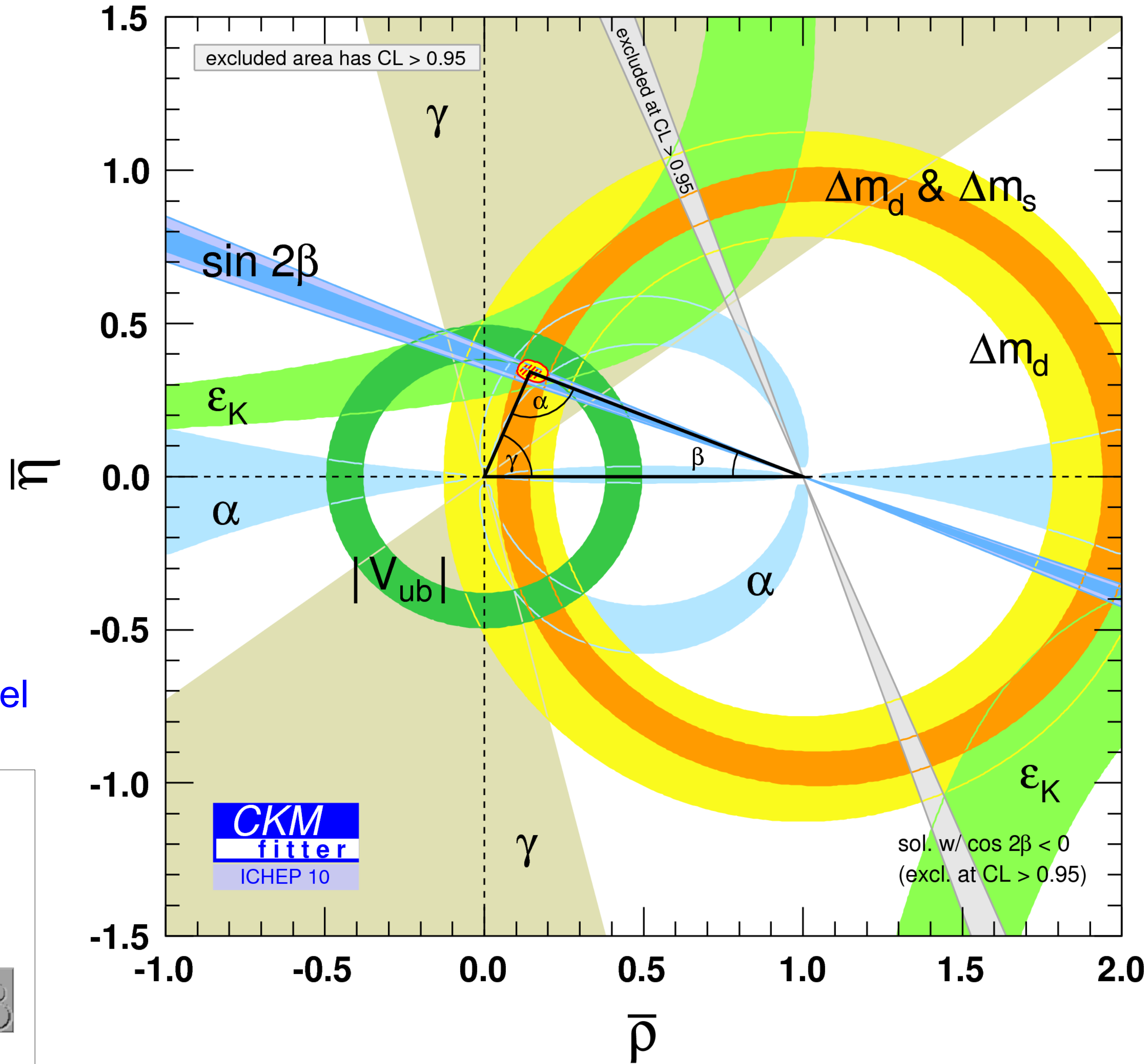
KM ansatz: tested to be dominant source of CPV at the EW scale

Inputs (theor. uncer. under control (LQCD)):

A, λ: $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$

$(\bar{\rho}, \bar{\eta})$:

- $|V_{ub}|$
- B→τν
- γ
- Δm_d
- Δm_d & Δm_s
- $|\varepsilon_K|$
- sin2β
- α



Overall consistency at 2σ level

BaBar May '99-Apr '08

Belle May '99-Jun '10

KTEV Kaons at the Tevatron

HFAG

LQCD

…

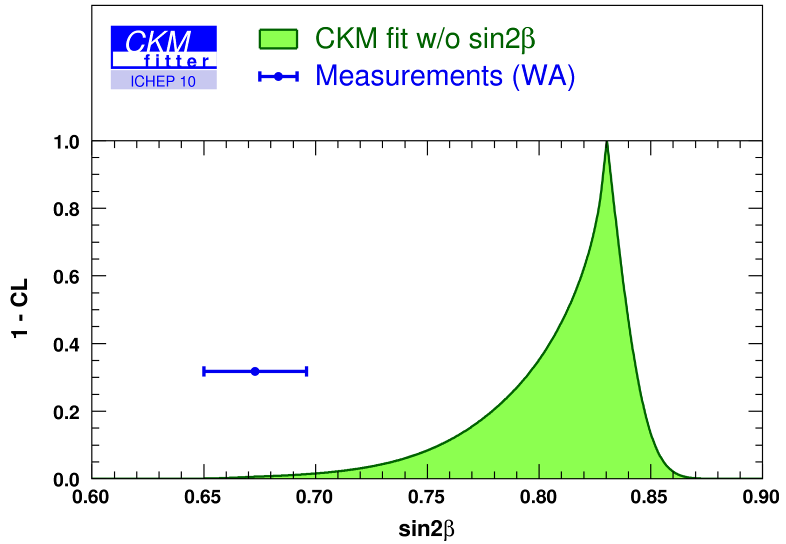
Global Fit results

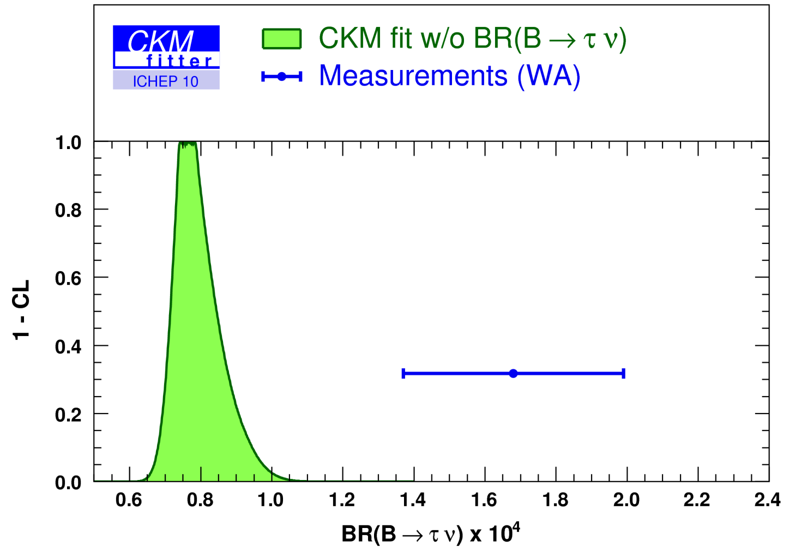
Wolfenstein parameters: (relative precision: 2.5%, 0.4%, 17% and 5%)			
$A = 0.812^{+0.013}_{-0.027}$	$\lambda = 0.22543 \pm 0.00077$	$\bar{\rho} = 0.144 \pm 0.025$	$\bar{\eta} = 0.342^{+0.016}_{-0.015}$

Sides and angles:				
$R_u = 0.371^{+0.015}_{-0.013}$	$R_t = 0.922^{+0.025}_{-0.026}$	$\alpha = (91.0 \pm 3.9)°$	$\beta = (21.76^{+0.92}_{-0.82})°$	$\gamma = (67.2 \pm 3.9)°$

B_s system	
$\beta_s = (1.041^{+0.050}_{-0.048})°$	$BF(B_s \to \mu\mu)[10^{-9}] = 3.073^{+0.070}_{-0.190}$

All measurements consistent with their predictions within ±1σ except sin2β: 2.6σ and B→τν: 2.8σ

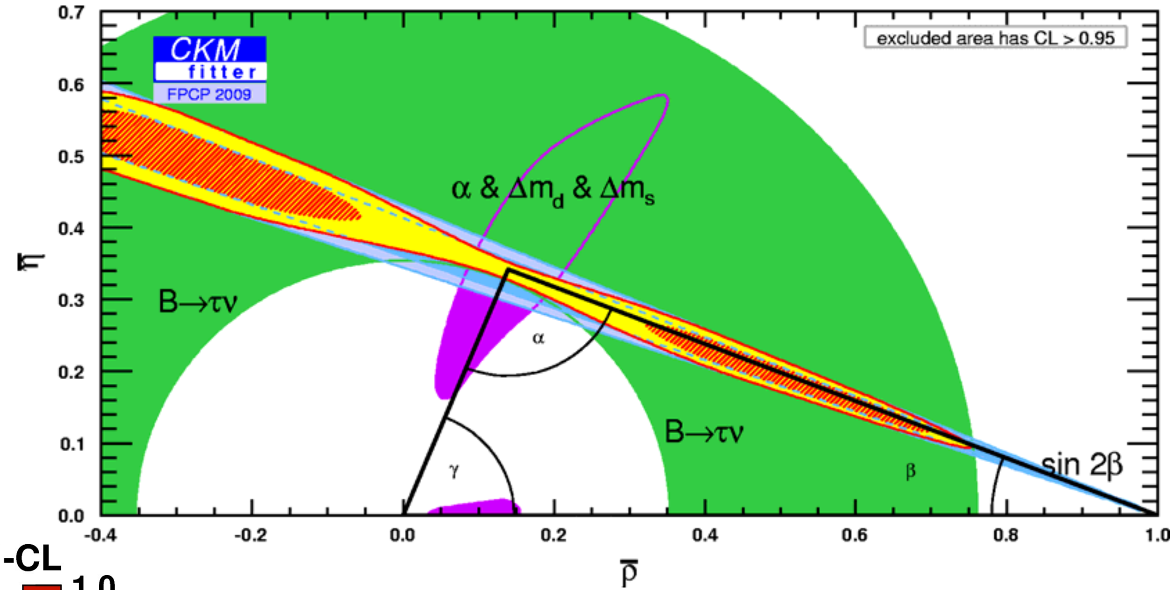


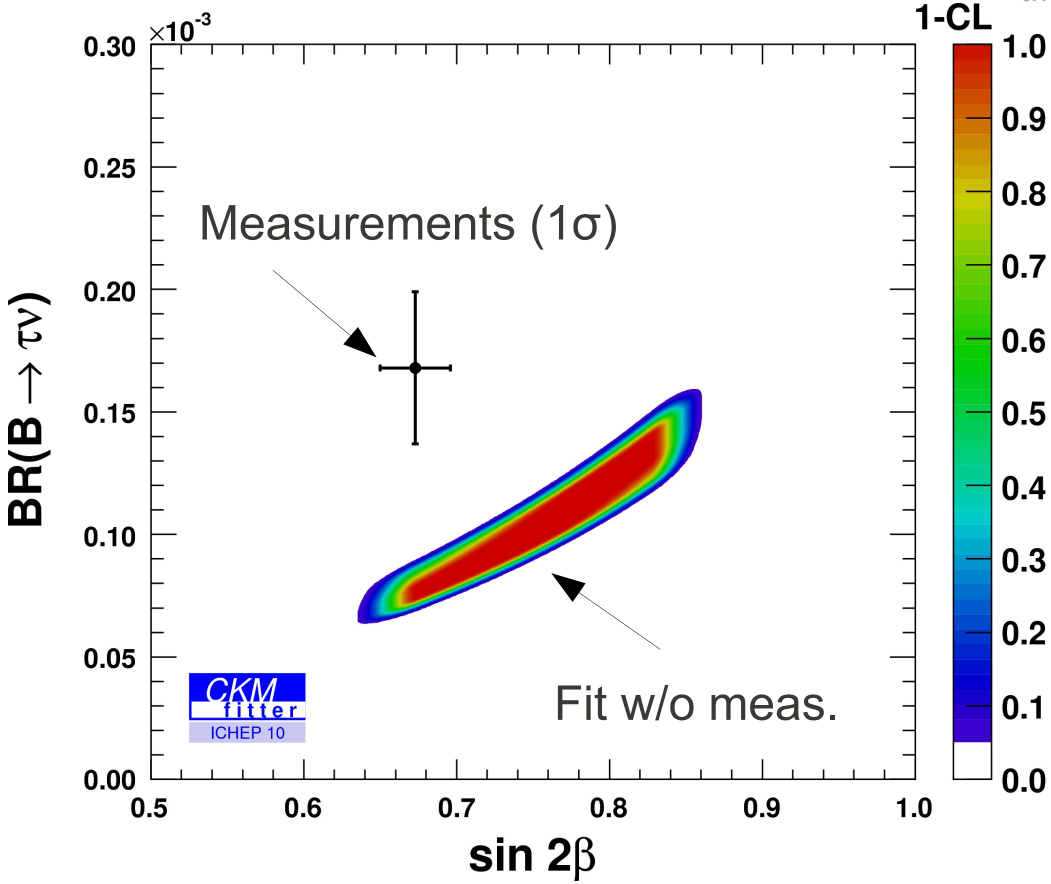


A closer look at the discrepancies

Sin2β and B→τν discrepancies

- 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.

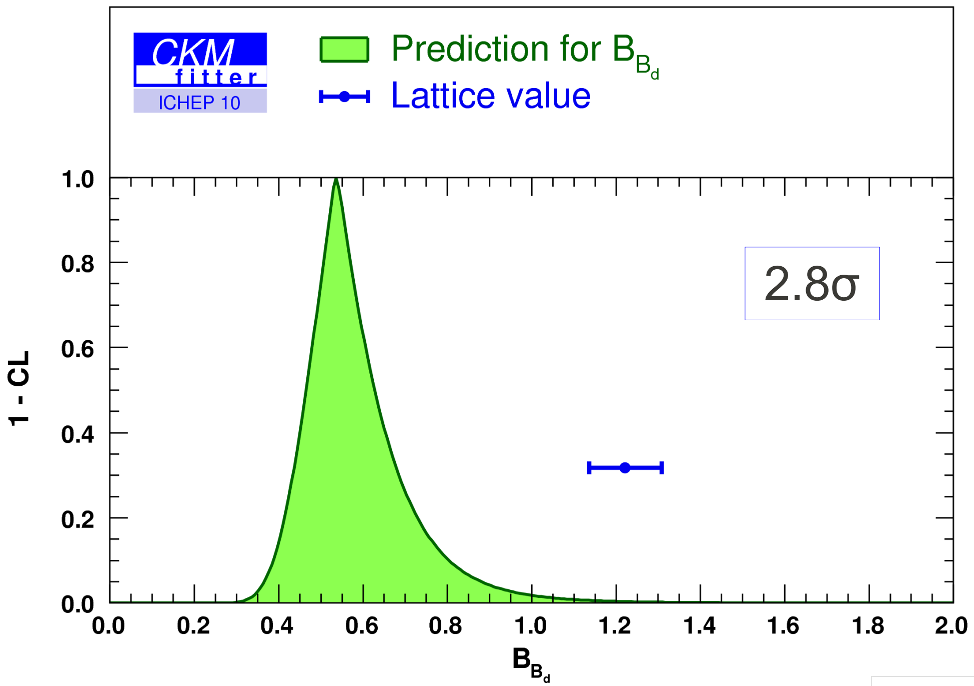
The low value of the prediction of B →τν is mainly driven by the measured value of sin2β

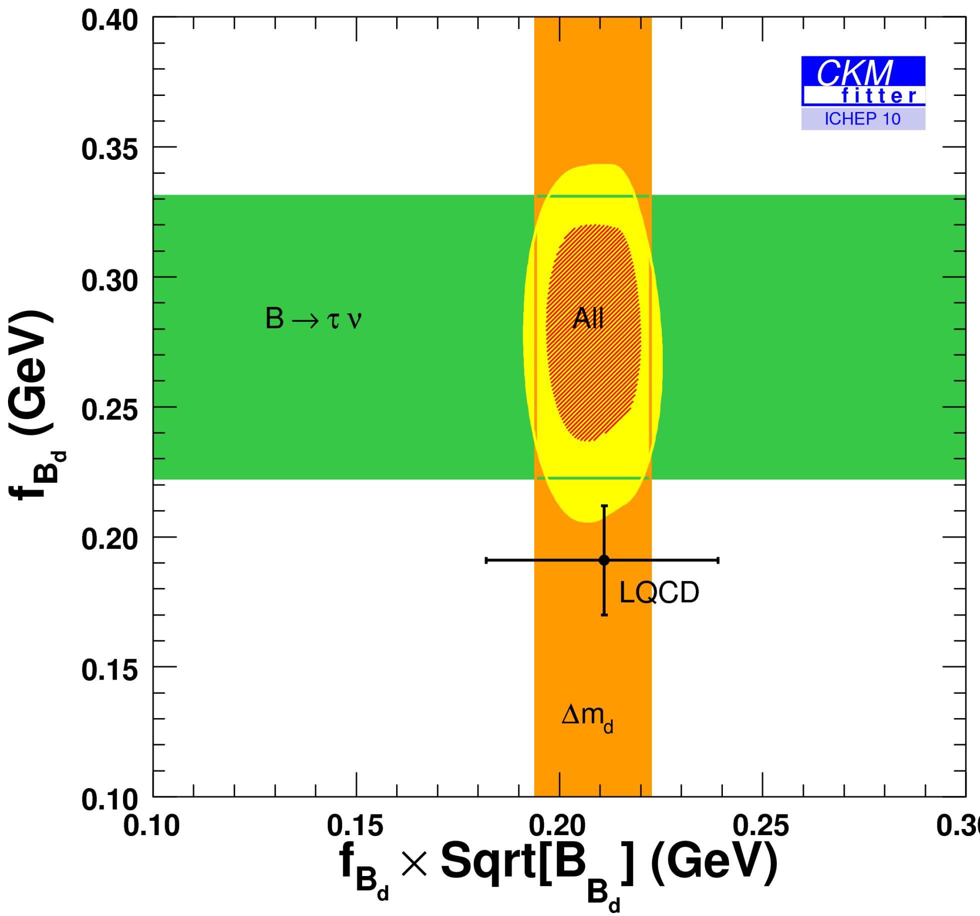
Sources of discrepancies:
1) Measurements (stat. fluctuations)?
2) Lattice estimate of f_B?
3) New Physics in B→τν and/or sin2β?

Lattice QCD

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

"Theory-free" estimation of B_{Bd}:

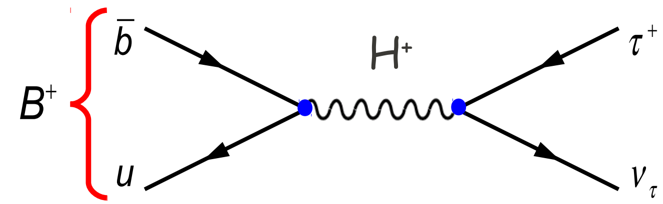




The global fit is accommodated keeping $f_{Bd}^2\times B_{Bd}\approx$ constant to fit Δm_d while increasing f_{Bd} to fit $B\rightarrow\tau\nu$

2HDM

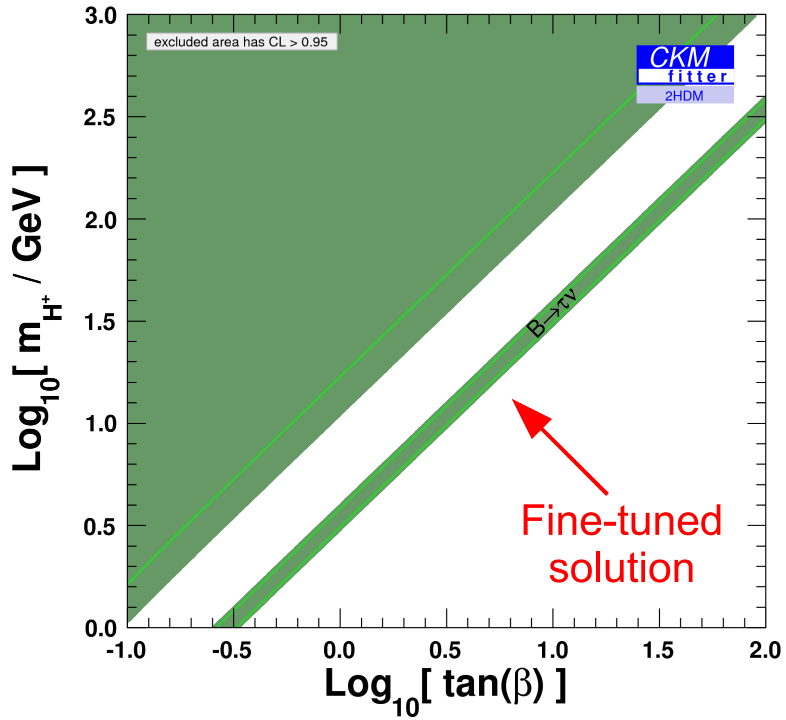
$$\frac{\mathcal{B}[M \to l\nu]}{\mathcal{B}[M \to l\nu]_{\rm SM}} = (1 + r_H)^2 \qquad r_H = \left(\frac{m_{q_u} - m_{q_d} \tan^2\beta}{m_{q_u} + m_{q_d}}\right)\left(\frac{m_M}{m_{H^+}}\right)^2$$



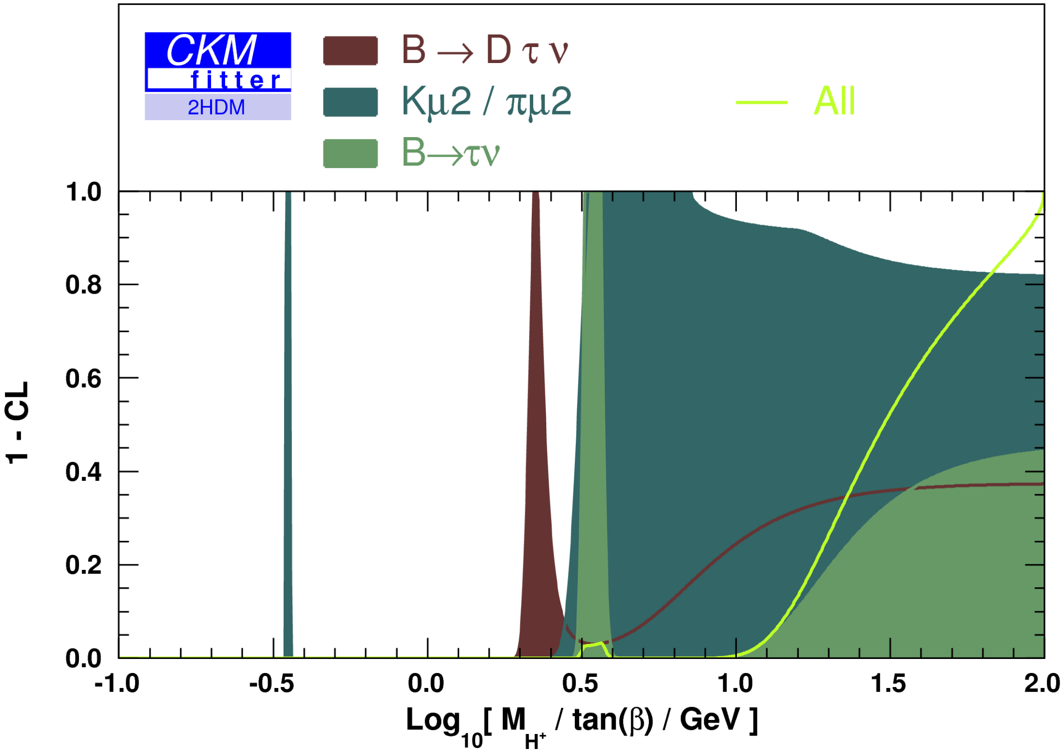
If perfect agreement SM-data, two distinct solutions in 2HDM(II)

- decoupling : $r_H = 0$ ($m_{H^+} \to \infty$, $\tan\beta$ small)
- fine-tuned : $r_H = -2$ (linear correlation between m_{H^+} and large $\tan\beta$, depends on meson mass)

Deschamps *et al.*
ArXiv:0907.5135 [hep-ph]



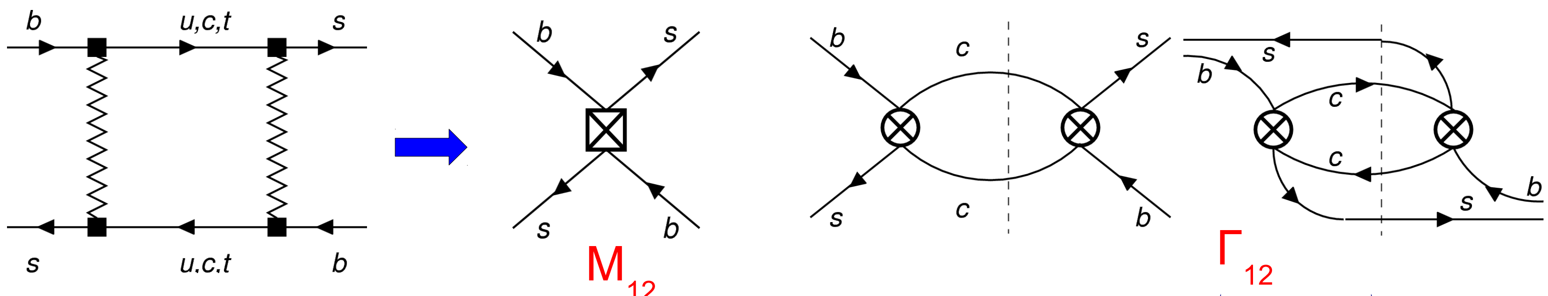
BF(B→τν) meas. favors fine-tuned solution



Fine-tuned solution ruled out at 95% CL by other leptonic+semileptonic observables

Bounds on NP in $\Delta F=2$ FCNC

Neutral-B Mixing and New Physics



Nierste&Lenz, JHEP 706 (2007) 72

3 physical quantities in B-B mixing: $|M_{12}^q|, \ |\Gamma_{12}^q|, \ \phi_q = arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$

Observables to determine them:

- Mass and width difference: $\Delta m_q = M_H^q - M_L^q \simeq 2|M_{12}^q|, \ \Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q \simeq 2|\Gamma_{12}^q|\cos(\phi_q)$
- CP Asymmetry in flavor-specific B decays: $A_{SL}^q = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|\sin(\phi_q) = \frac{\Delta\Gamma_q}{\Delta m_q}\tan(\phi_q)$

Standard Model:

- M_{12} from dispersive part of the box, only internal t relevant
- Γ_{12} from absorptive part of the box, only c,u contribute (u's are negligible). Γ_{12} is a CKM-favored tree-level effect associated with final states containing a $(c\bar{c})$ pair.

New physics:

- Γ_{12} can barely be affected, stems from tree-level decays
- M_{12} is very sensitive to virtual effects of new heavy particles

Generic New Physics in B_q Mixing: Assumptions

Nierste&Lenz, JHEP 706 (2007) 72

Assume that NP only affects short distance physics in ΔB = 2: M_{12}

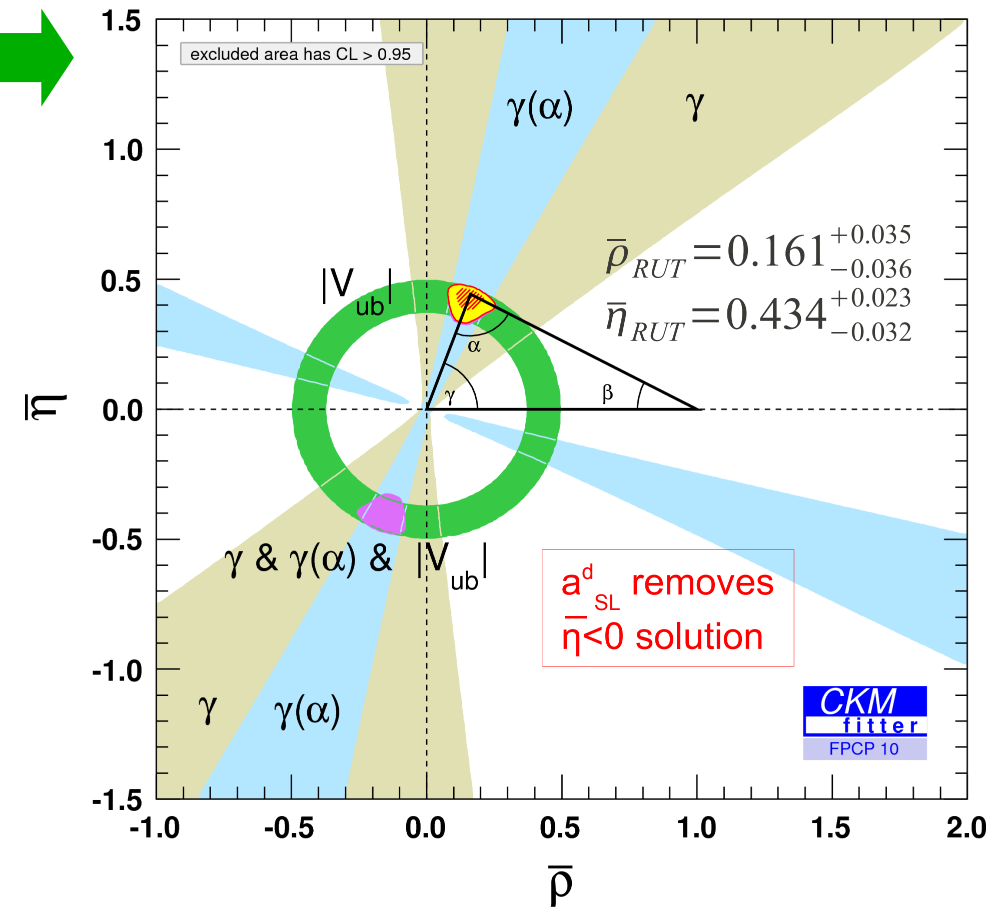
Model-independent param. with a complex parameter Δ_q through:

$$M_{12}^{q} = M_{12}^{SM,q} \cdot \Delta_q$$

In the SM, $\Delta_q = 1$.

➔ To identify or constrain new physics: measure both the magnitude and phase of M_{12}

Reference UT (fix SM param.): $|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|, B\to\tau\nu, \gamma, \gamma(\alpha)=\pi-\beta_{cc}-\alpha$



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

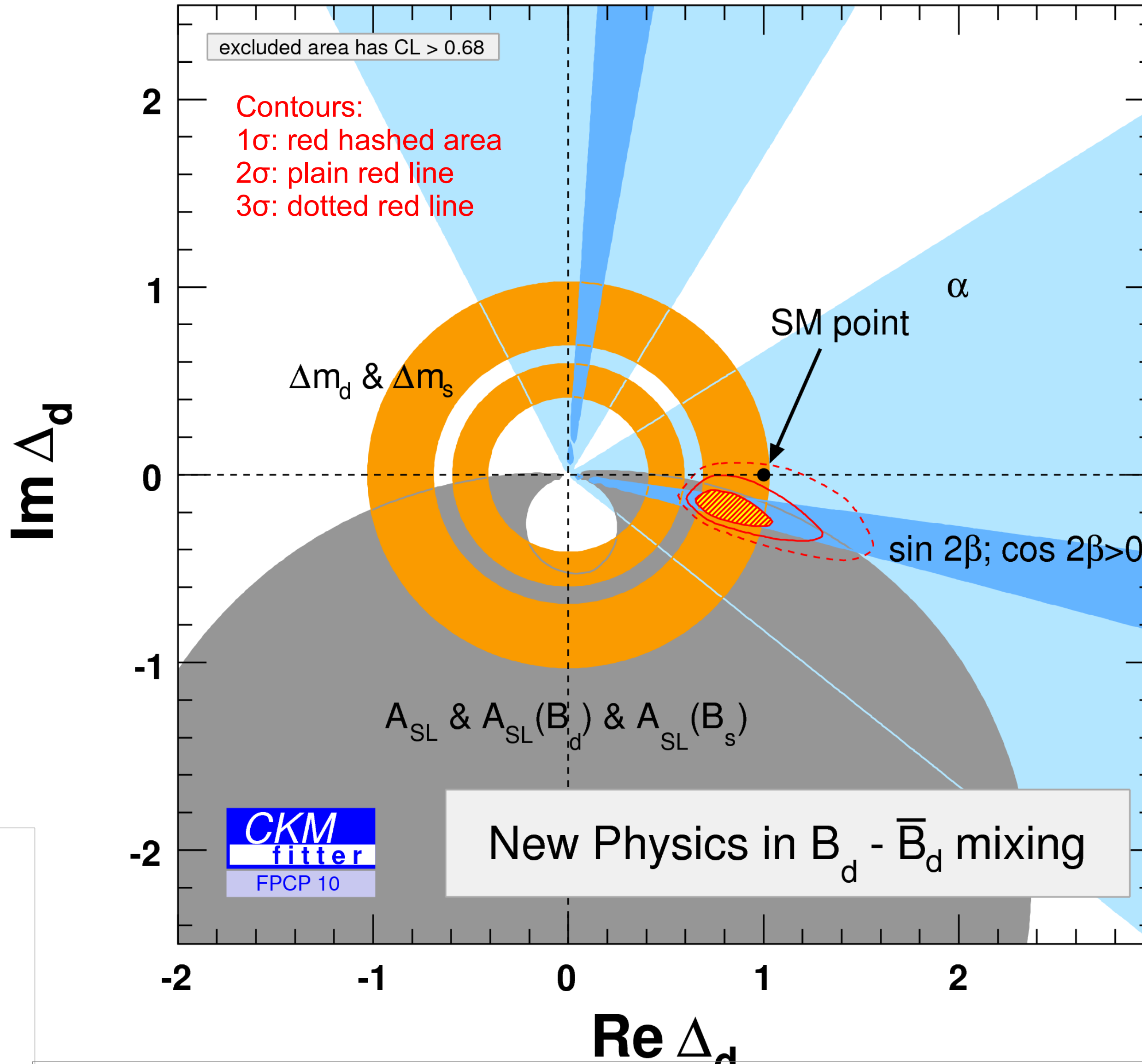
Bounds from the B_d sector

Constraining Δ_d:

- Δm_d
- Δm_d & Δm_s
- sin2β
- α
- A^d_{SL} & A^s_{SL} & A_{SL}
- +Reference UT

$$\mathrm{Re}\Delta_d = +0.732^{+0.216}_{-0.056}$$

$$\mathrm{Im}\Delta_d = -0.156^{+0.039}_{-0.087}$$



- Dominant constraints from sin2β and Δm_d (2 rings from 2 sol. for apex of Reference UT)

- $B\to\tau\nu$ part of Reference UT
  ➔ $\sin 2\beta_{SM} = 0.825^{+0.014}_{-0.051}$
  > $\sin 2\beta_{meas} = \sin(2\beta_{SM} + \Phi_d^{NP})$
  ➔ $\Phi_d^{NP}<0$ preferred

- Disagreement with SM driven in same direction by sin2β and A_{SL}
- 2D SM hypothesis (Δ_d=1): 2.5σ (w/o $B\to\tau\nu$: 1.1σ).
- Still sizable NP contribution possible: ~40%

Bounds from the B_s sector

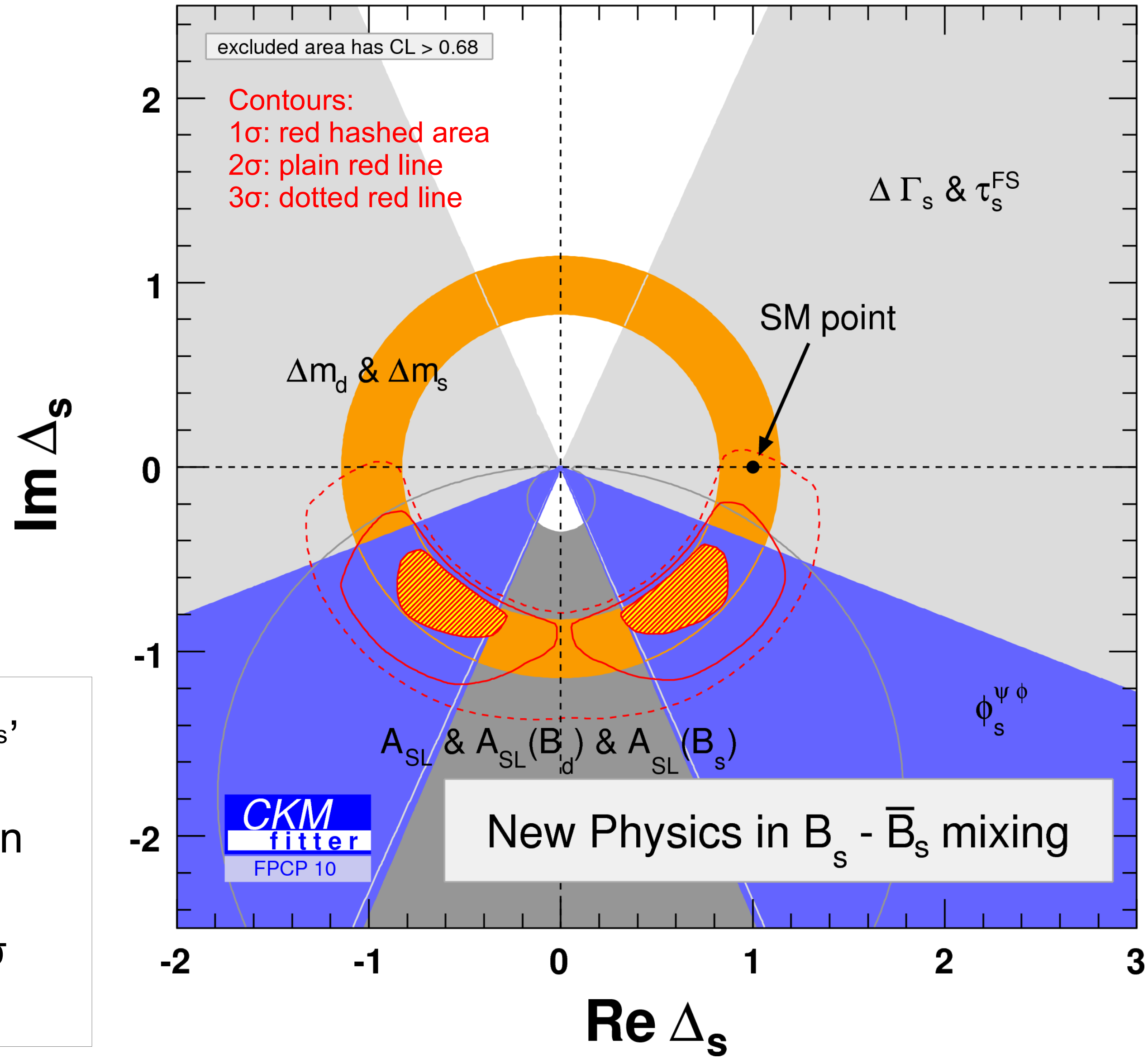
New CDF (5.2 fb^{-1}) meas. of ($\Delta\Gamma_s$,Φ_s) not used yet. Waiting for the official Tevatron average

Constraining Δ_s:

Δm_d & Δm_s
$a_{CP}(\psi\Phi)$
A^d_{SL} & A^s_{SL} & A_{SL}
$\Delta\Gamma_s$ & τ_s^{FS}
+Reference UT

$\mathrm{Re}\Delta_s = +0.55^{+0.21}_{-0.14}$

$\mathrm{Im}\Delta_s = -0.68^{+0.15}_{-0.14}$



- Dominant constraints from Δm_s, $\Phi_s^{\psi\Phi}$ and A_{SL}
- Disagreement with SM driven in same direction by $\Phi_s^{\psi\Phi}$ and A_{SL}
- 2D SM hypothesis (Δ_s=1): 2.7σ (w/o B→$\tau\nu$: 2.7σ).

Still 1.3σ discrepancy between the NP in M_{12} fit prediction: A_{SL}(NP)(meas. not in fit) = -0.0041±0.0019 and the measurement A_{SL}(WA w/ new DØ)=-0.0085±0.0028.

Conclusion

KM mechanism at work at the EW scale.

Unitarity Triangle:

- Overall consistency at 2σ level
- Ongoing discrepancy between $\sin 2\beta$ and $B \to \tau\nu$ ➔ Super Flavor Factory

New Physics in $\Delta F=2$ mixing:

- The discrepancy $B \to \tau\nu$ vs $\sin 2\beta$ can be accommodated by a new CPV phase in the B_d mixing, in agreement with the latest A_{SL}(DØ) measurement.
- Still a lot of room for NP in the B_s, even with the latest CDF measurement of Φ_s

Precision flavor physics: unraveling the flavor structure of New Physics

- Will require a second "quantum jump": going from O(1) to O(0.1) precision is not the same as going from O(0.1) to O(0.01). Many assumptions will need to be revisited.
- An average representing a consensus of the lattice community will be mandatory ("HFAG lattice?").

Let's check that any (so long awaited) deviation from the SM is a true one and let's hope that the next decade will be even more successful than the B-factory decade.

BACKUP SLIDES

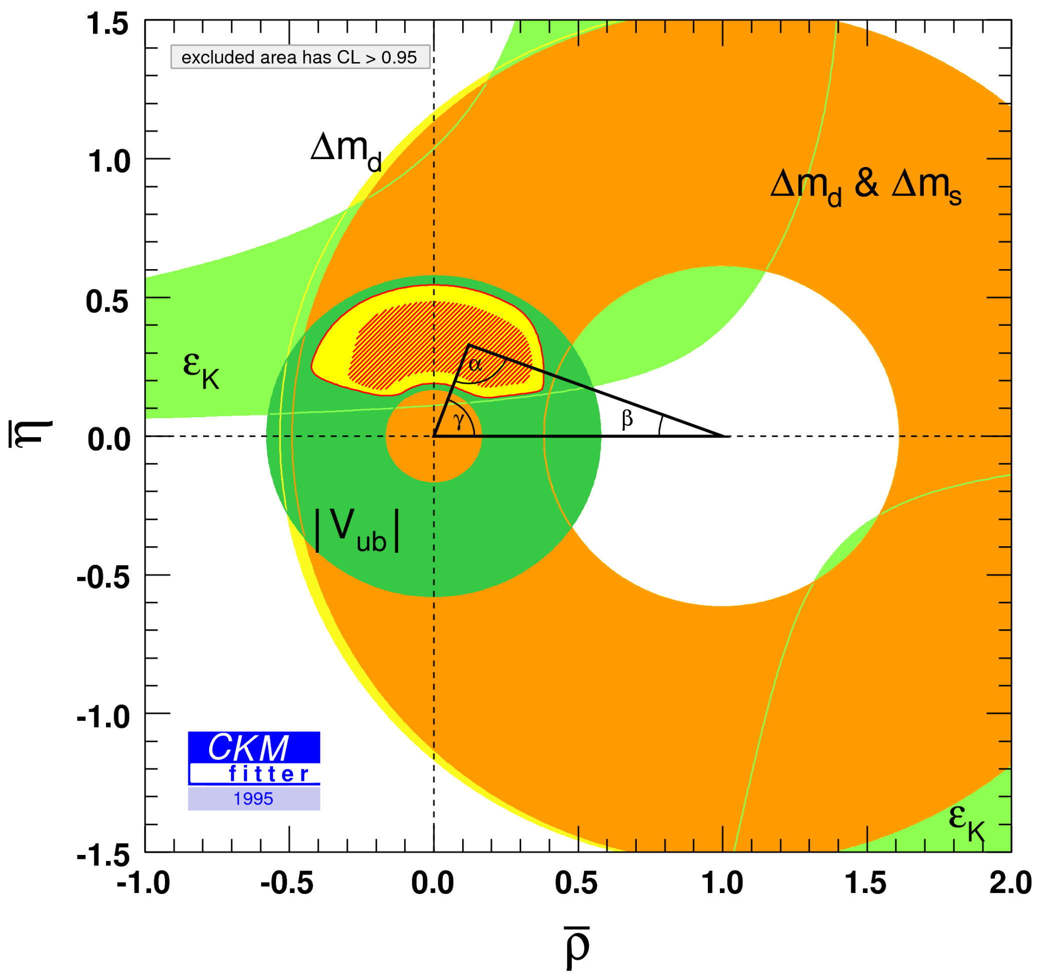
Digression: a bit of history

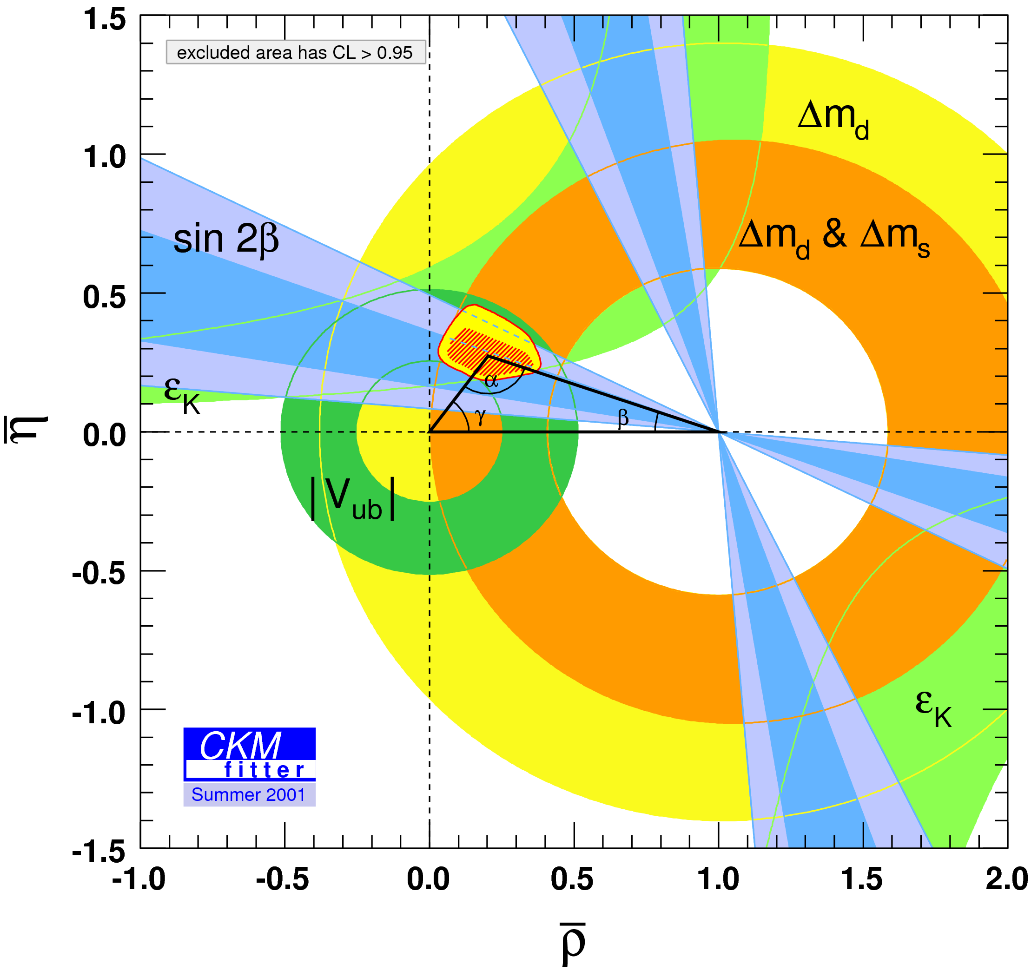
~1995

LEP, TeVatron (top), NA48, KTeV,…

S2001

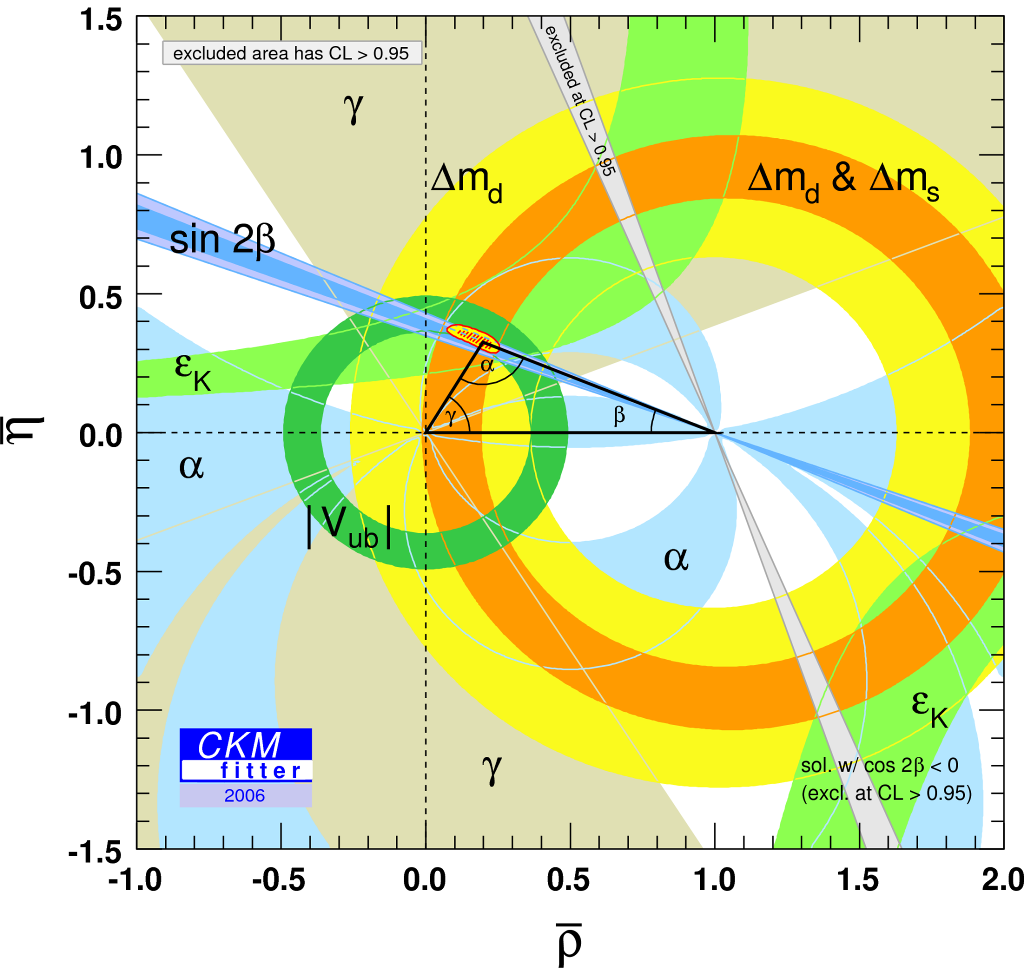
BaBar (SLAC), Belle (KEK), …



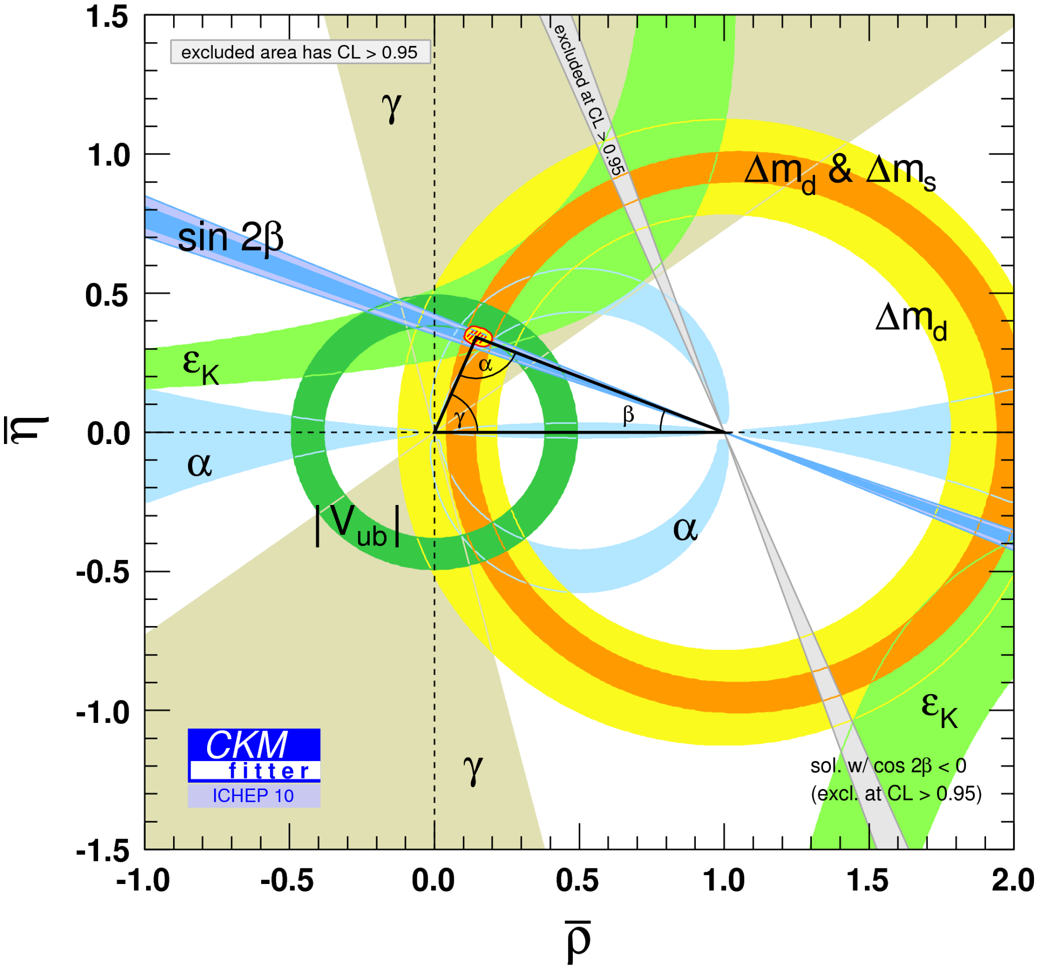


Digression: a bit of history

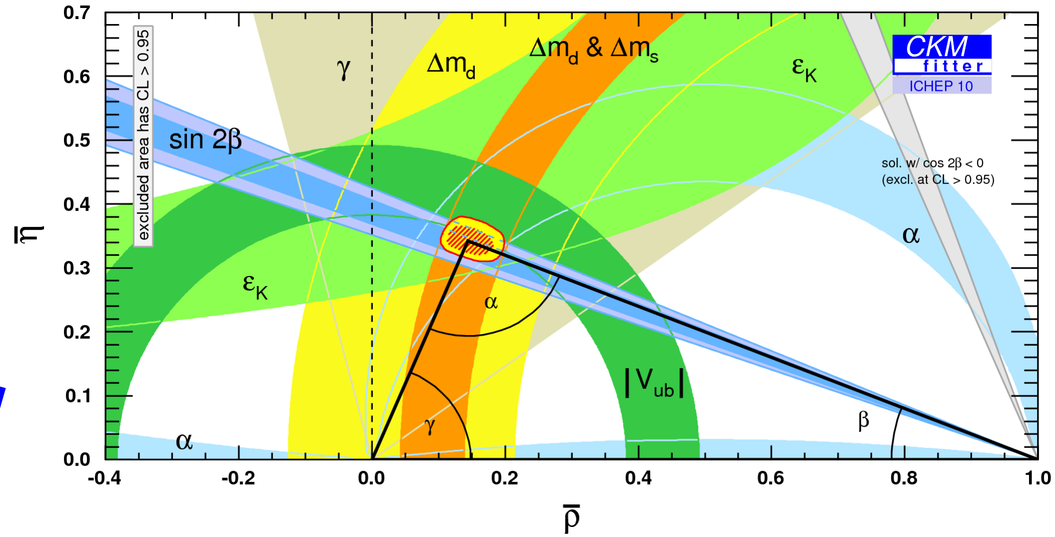
2006 — BaBar, Belle and CDF/DØ (TeVatron Bs), …



2010 — BaBar, Belle and LQCD, …



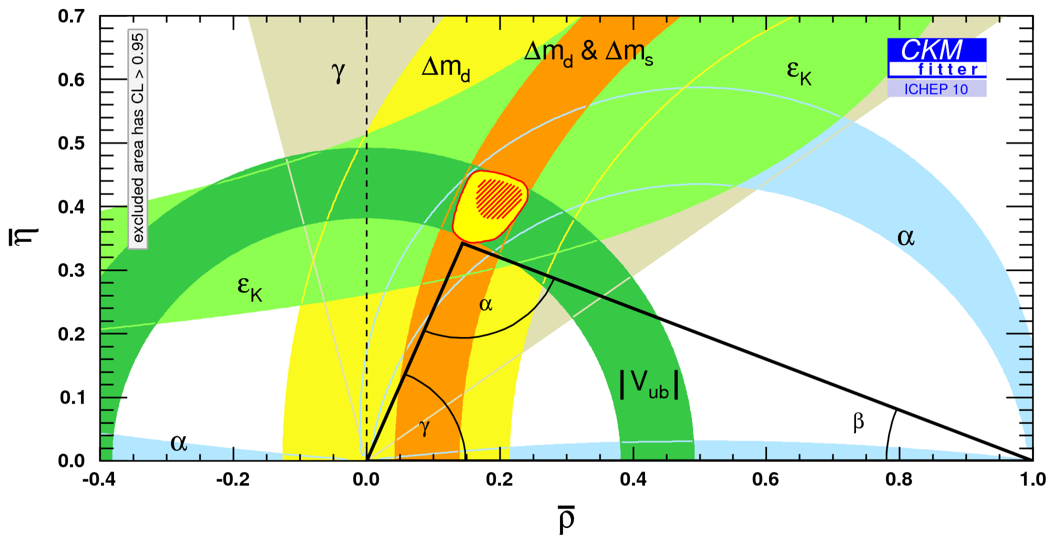
Sin2β and B→τν discrepancies



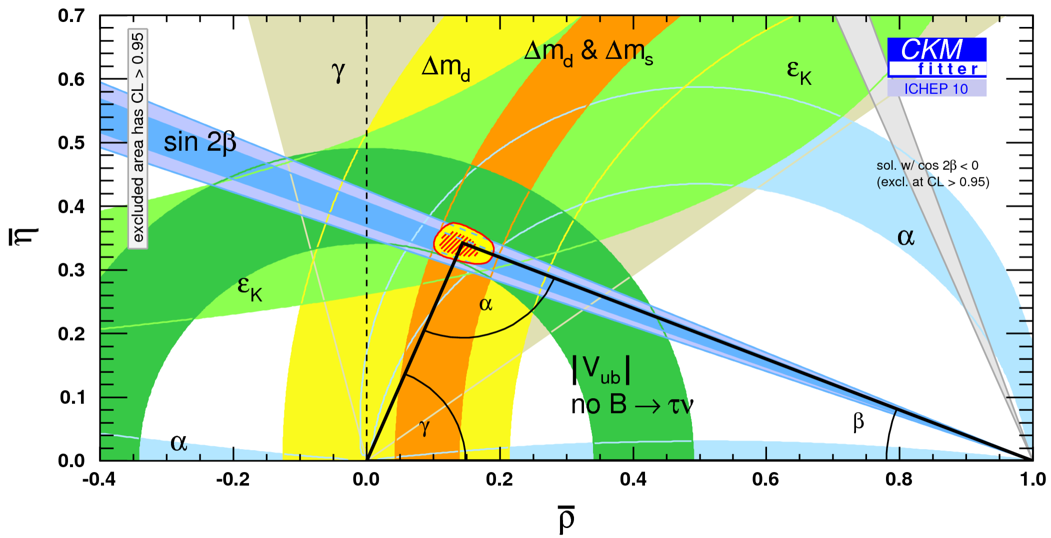
removing sin2β

removing B →τν

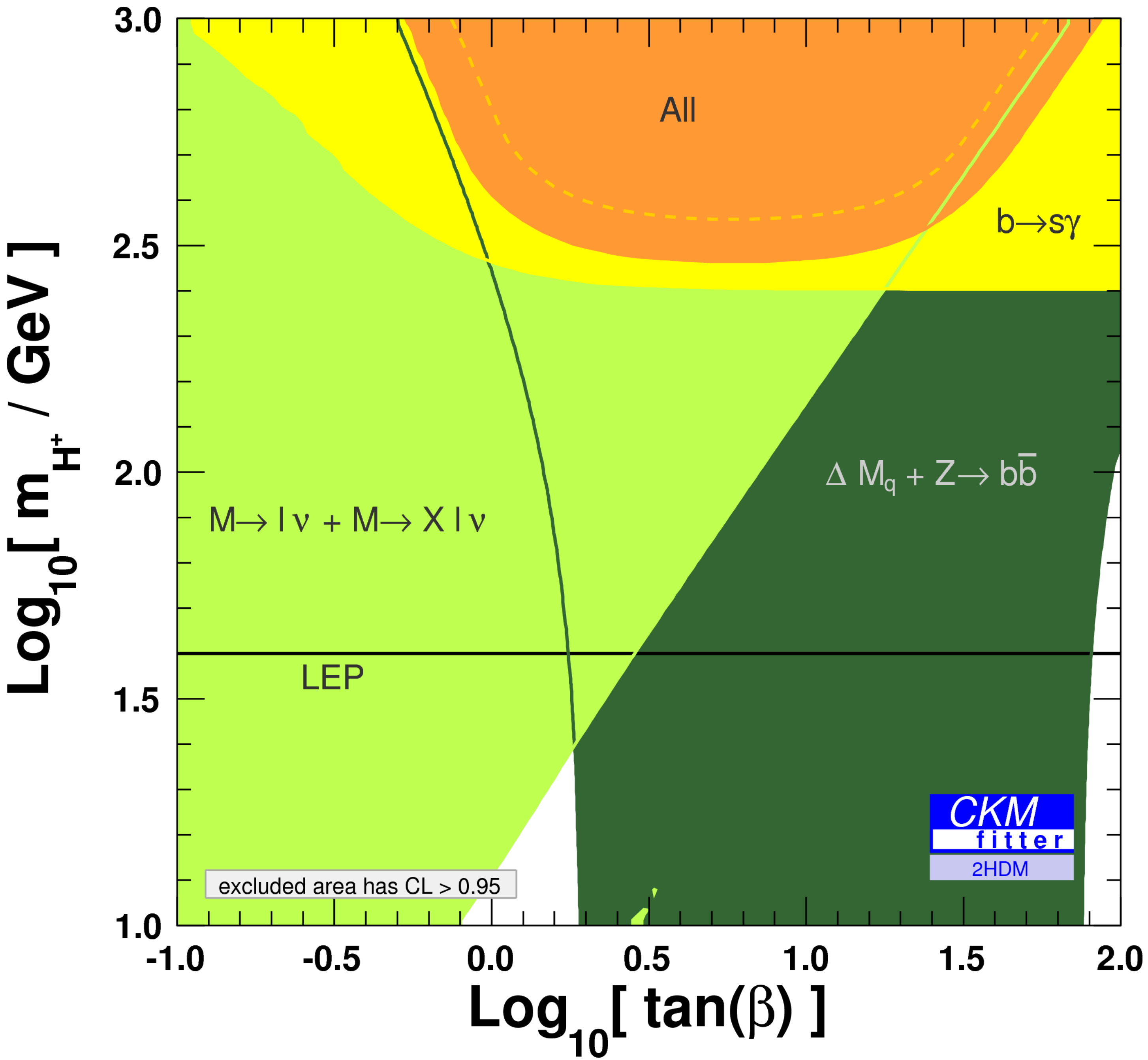
$\Delta\chi^2_{min} = 6.94$



$\Delta\chi^2_{min} = 7.68$

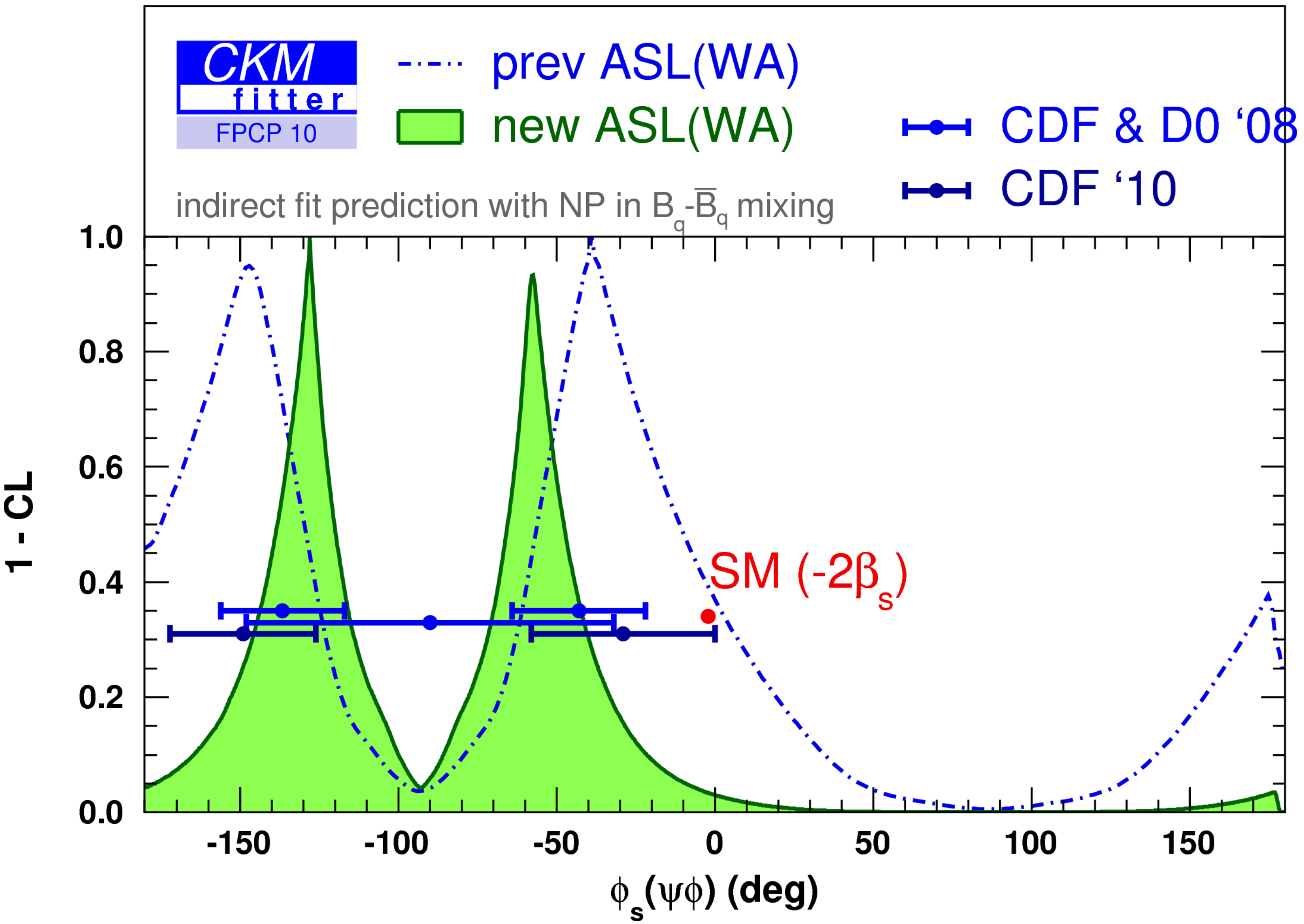


2HDM



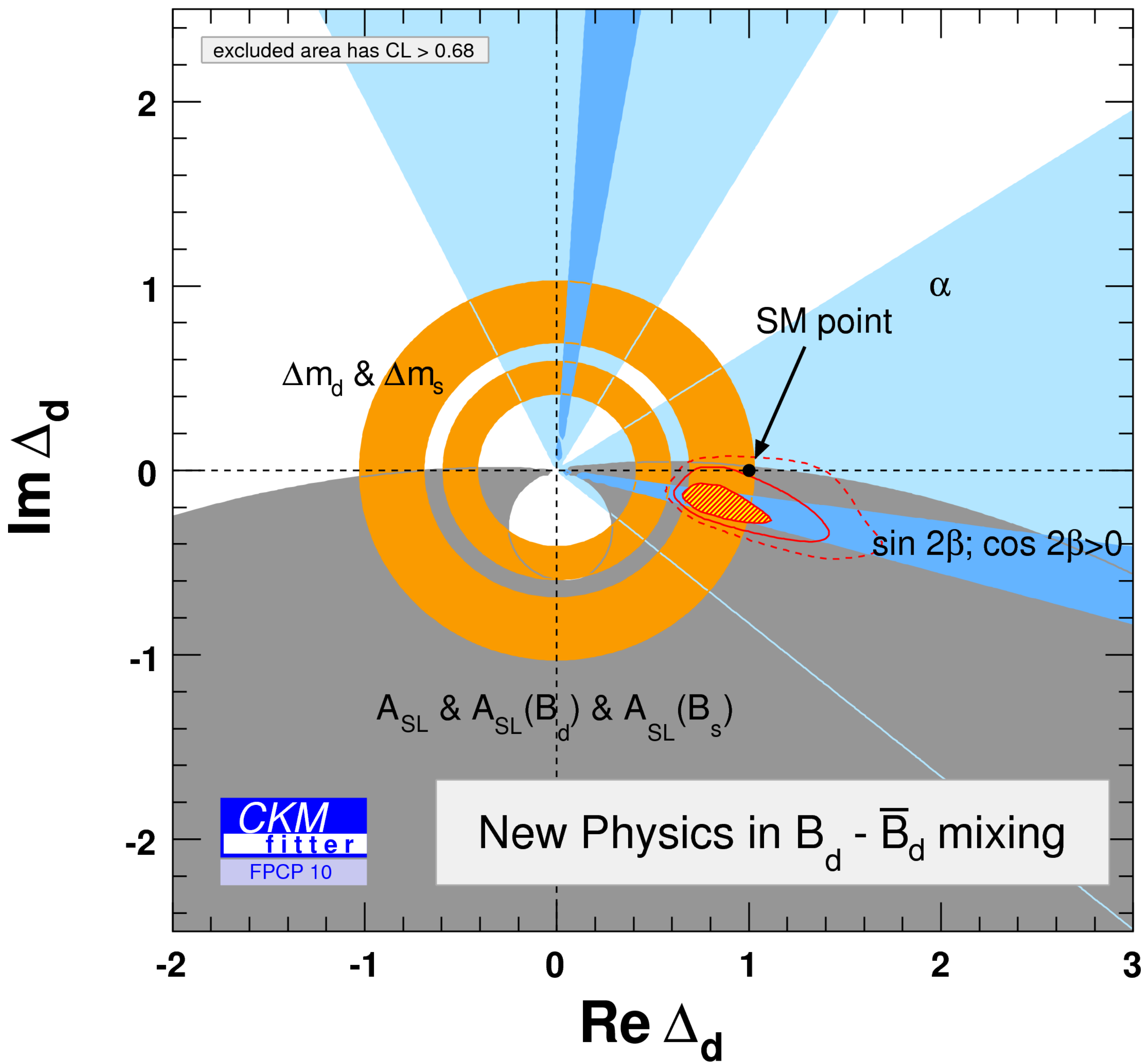
3.0
2.5
2.0
1.5
1.0
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
Log10[m_H+ / GeV]
Log10[tan(β)]
All
b→sγ
Δ Mq + Z→ bb̄
M→ l ν + M→ X l ν
LEP
excluded area has CL > 0.95
CKM
fitter
2HDM

Prediction of Φ_s from the fit



Bounds from the B_d sector

(without new A_{SL}(DØ))



Bounds from the B_s sector

(without new A_{SL}(DØ))