CP violation

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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/

Disclaimers

• This is an experimentalist point of view on a subject which is all about intrications between experiment and theory.

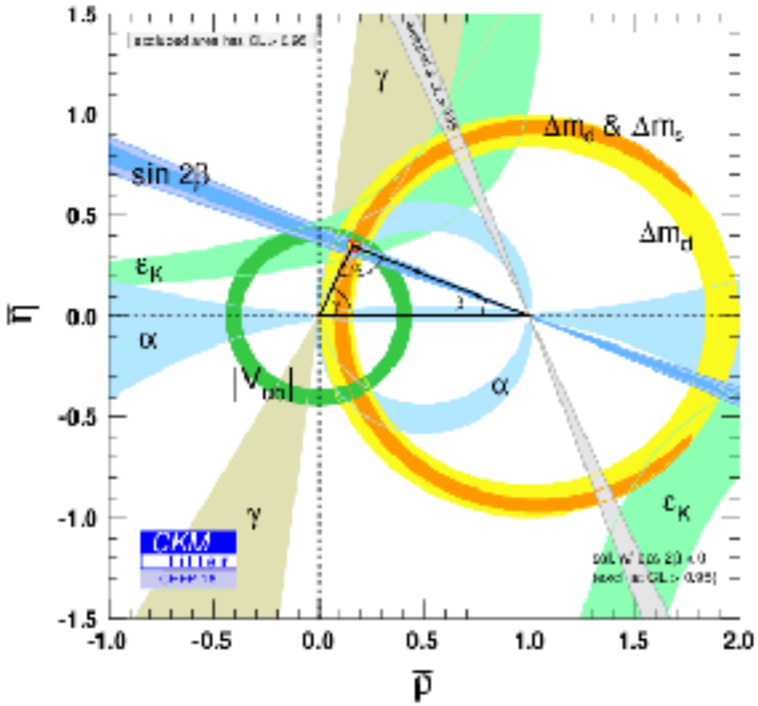
• I won't discuss (at all) CP violation in the lepton sector.

• The main machines in question here are the TeVatron (Fermilab, US), PEPII (SLAC, US), KEKB (KEK, Japan) and LHC (CERN, EU). Former experiments played a pioneering role: LEP (CERN, EU) and CLEO (CESR, US).

• Most of the material concerning global tests of the SM and above is taken from the CKMfitter group results (assumed bias) and Heavy Flavour Averaging Group (and hence the experiments themselves). I borrowed materials in presentations from colleagues which I tried to cite correctly.

A 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 series of lectures is to undress this plot.

A more detailed outline

1. Introduction: setting the scene. History and recent past of the parity violation experiments. The discovery of the *CP* violation.

2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.

3. The global fit of the SM: CKM profile.

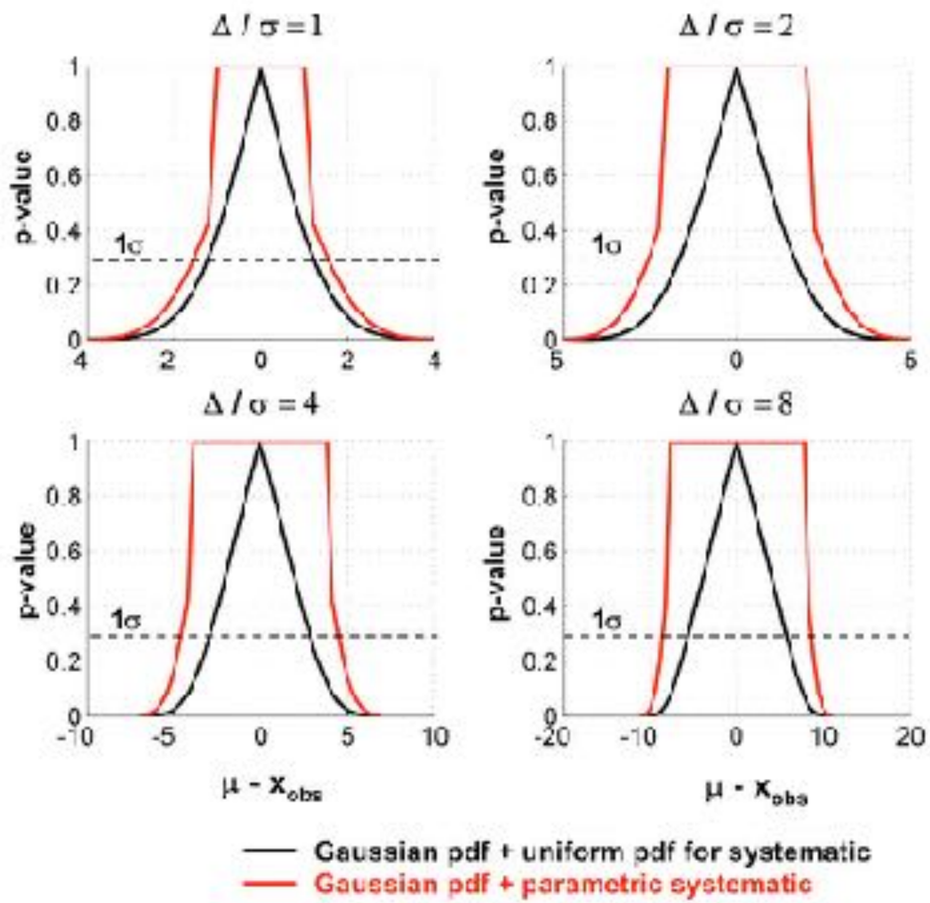
4. New Physics exploration with current data: two examples.

3.1 Sketch of the statistical method.

- The frequentist approach:
- Use Frequentist Hypothesis testing to build statistical significance (*p*-value) functions from which estimates of 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 controlled 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 can be discussed).
- This approach yields very different results from what one would get from a statistical modelling of the systematic (example here : uniform over the range)



3.2 The global picture

Parameter	Value ± Error(s)	Reference	Errors GS	Errors RFit
$\|V_{ud}\|$ (nuclei)	0.97425 ± 0.00022	[1]	★	-
$\|V_{us}\|$ ($K_{\ell 3}$)	0.2254 ± 0.0013	[2]	★	-
$\|V_{ub}\|$	$(3.92 \pm 0.09 \pm 0.45) \times 10^{-3}$	[3, 4]	★	★
$\|V_{cb}\|$	$(40.89 \pm 0.38 \pm 0.59) \times 10^{-3}$	[3]	★	★
$\|\epsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$	[5]	★	-
Δm_d	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$	[3]	★	-
Δm_s	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$	[6]	★	-
$\sin(2\beta)_{[c\bar{c}]}$	0.673 ± 0.023	[3]	★	-
$S_{\pi\pi}^{+-}, C_{\pi\pi}^{+-}, C_{\pi\pi}^{00}$	Inputs to isospin analysis	[3]	★	-
$\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis	[3]	★	-
$S_{\rho\rho,L}^{+-}, C_{\rho\rho,L}^{+-}, S_{\rho\rho}^{00}, C_{\rho\rho}^{00}$	Inputs to isospin analysis	[3]	★	-
$\mathcal{B}_{\rho\rho,L}$ all charges	Inputs to isospin analysis	[3]	★	-
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-dependent Dalitz analysis	[7, 8]	★	-
$B^- \to D^{(*)} K^{(*)-}$	Inputs to GLW analysis	[3]	★	-
$B^- \to D^{(*)} K^{(*)-}$	Inputs to ADS analysis	[3]	★	-
$B^- \to D^{(*)} K^{(*)-}$	GGSZ Dalitz analysis	[3]	★	-
$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$	$(1.68 \pm 0.31) \times 10^{-4}$	[3]	★	-
$\bar{m}_c(m_c)$	$(1.286 \pm 0.013 \pm 0.040)\ \mathrm{GeV}$	[12]	★	★
$\bar{m}_t(m_t)$	$(165.02 \pm 1.16 \pm 0.11)\ \mathrm{GeV}$	[10]	★	★
B_K	$0.723 \pm 0.004 \pm 0.067$	[16]	★	★
$\alpha_s(m_Z^2)$	0.1176 ± 0.0020	[5]	-	★
η_{cc}	Calculated from $\bar{m}_c(m_c)$ and α_s	[17]	-	★
η_{tt}	0.47 ± 0.04	[18]	-	★
η_{ct}	0.5765 ± 0.0065	[17, 18]	-	★
$\eta_B(\overline{MS})$	0.551 ± 0.007	[19]	-	★
f_{B_s}	$(231 \pm 3 \pm 15)\ \mathrm{MeV}$	[16]	★	★
B_s	$1.28 \pm 0.02 \pm 0.03$	[16]	★	★
f_{B_s}/f_{B_d}	$1.199 \pm 0.008 \pm 0.023$	[16]	★	★
B_s/B_d	$1.05 \pm 0.01 \pm 0.03$	[16]	★	★

- 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.

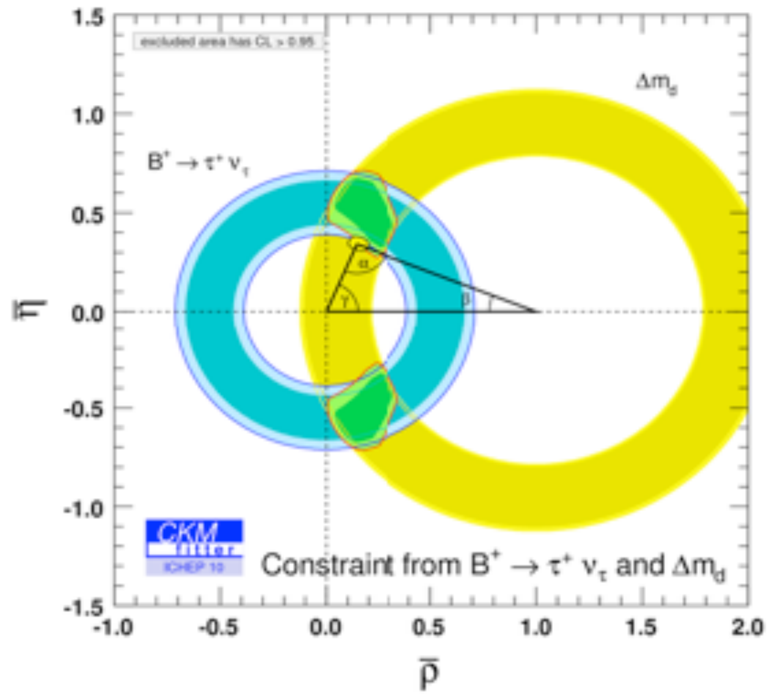
3.2 The global picture. Aparté : Tauonic *B* decay.

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

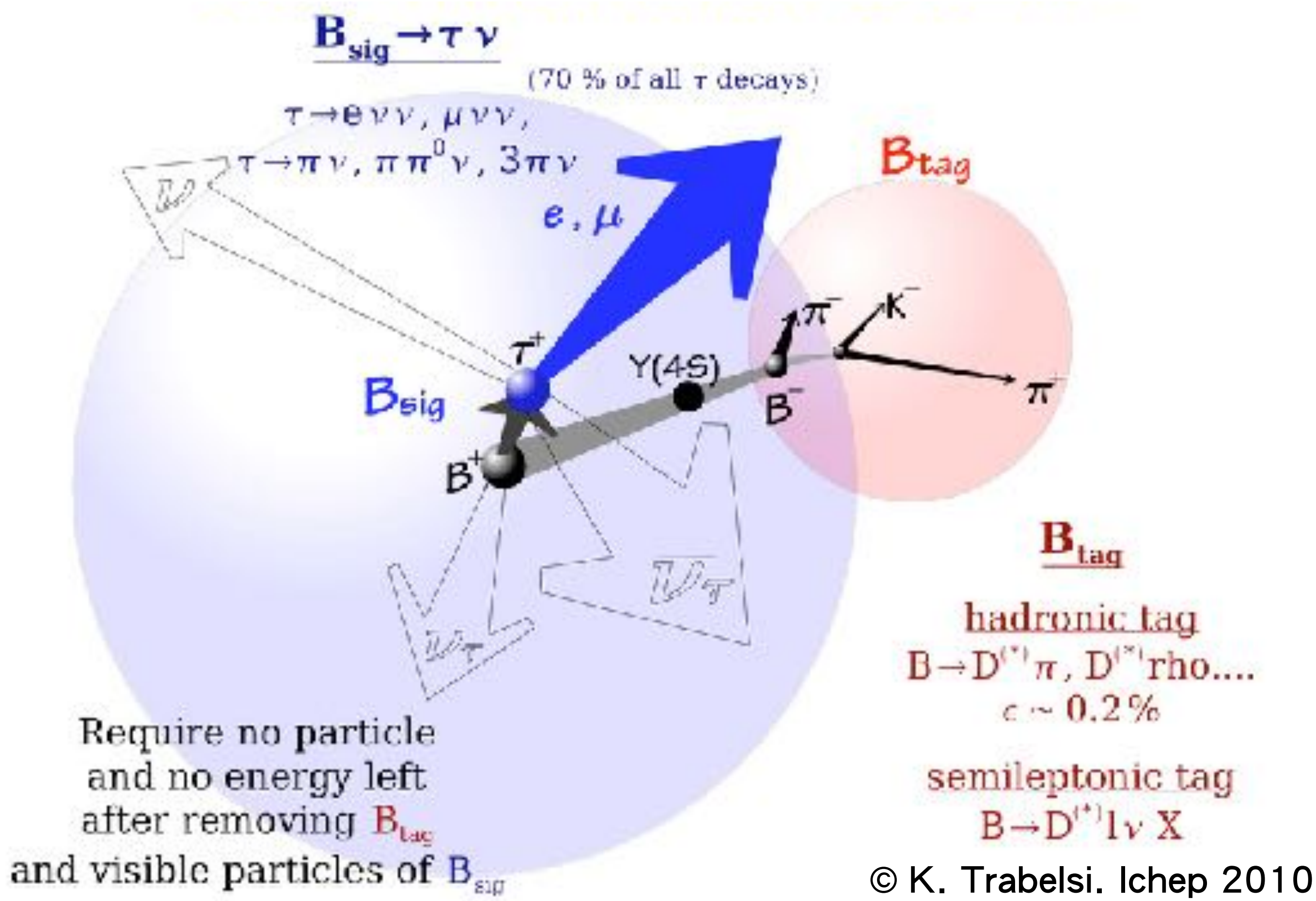
- $B^+ \to \tau^+\nu$ is another way to access the matrix element $|V_{ub}|$. Remember that we have seen in Chapter II that exclusive and inclusive determinations only marginally agrees.

- 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 of the *B* decay constant.



3.2 The global picture. Aparté : Tauonic *B* decay reconstruction.



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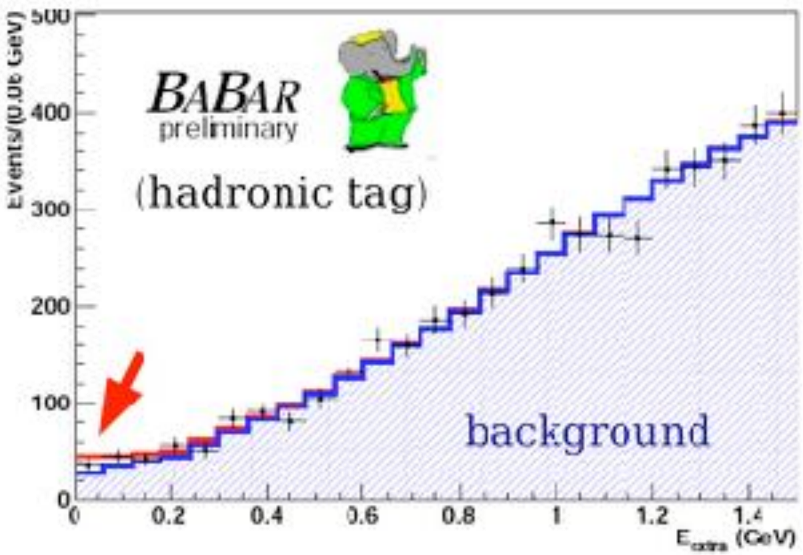
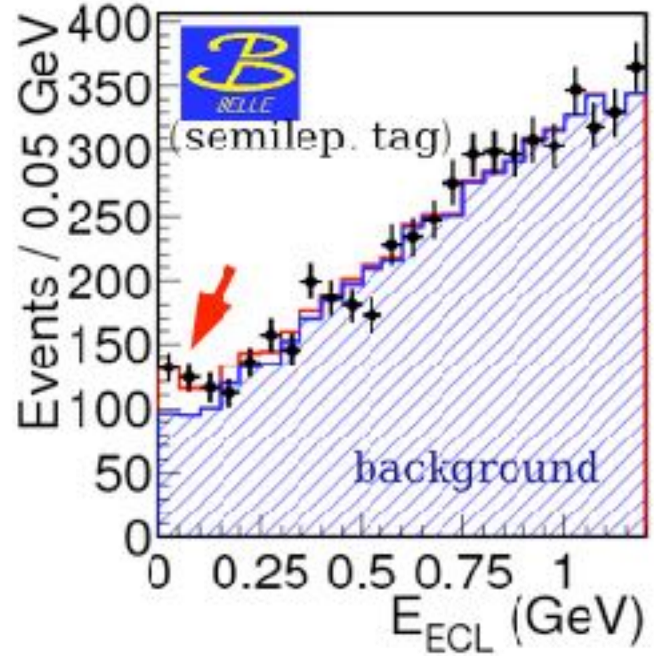


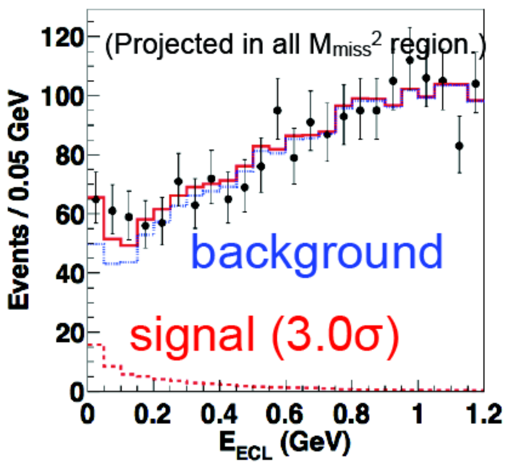


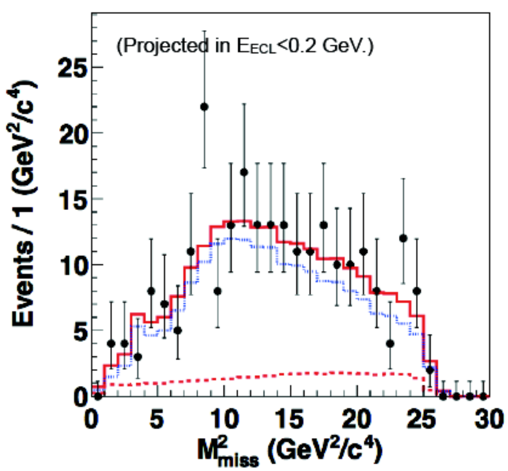
	tag	BF($\to\tau\nu$)[10^{-4}]	
BaBar	SL (459M)	1.70±0.82	
	Had (467M)	1.80±0.61	NEW
	Average	1.76±0.49	
Belle	SL (657M)	1.54±0.48	NEW
	Had (449M)	1.79±0.71	
	Average	1.62±0.40	
World Average		1.68±0.31	

- ECL/Extra = extra calorimeter energy
- SM prediction:

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

3.2 The global picture. Aparté : tauonic *B* decay reconstruction.





- New measurement (well, more an evidence of) from Belle experiment with hadronic tag.

Belle

- based on 772 M $B\bar{B}$ (full data sample),
- four τ decay channels: $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$;
- improved tracking,
- improved tagging (NeuroBayes),
- K_L veto added,
- better understanding of the peaking background,
- signal extracted from 2D fit in $(E_{\mathrm{ECL}}, M^2_{\mathrm{miss}})$,
- $\mathcal{B} = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$.

- Much more consistent w/ SM expectation. Strong implications, see later.

3.2 Standard Model: the CKM profile

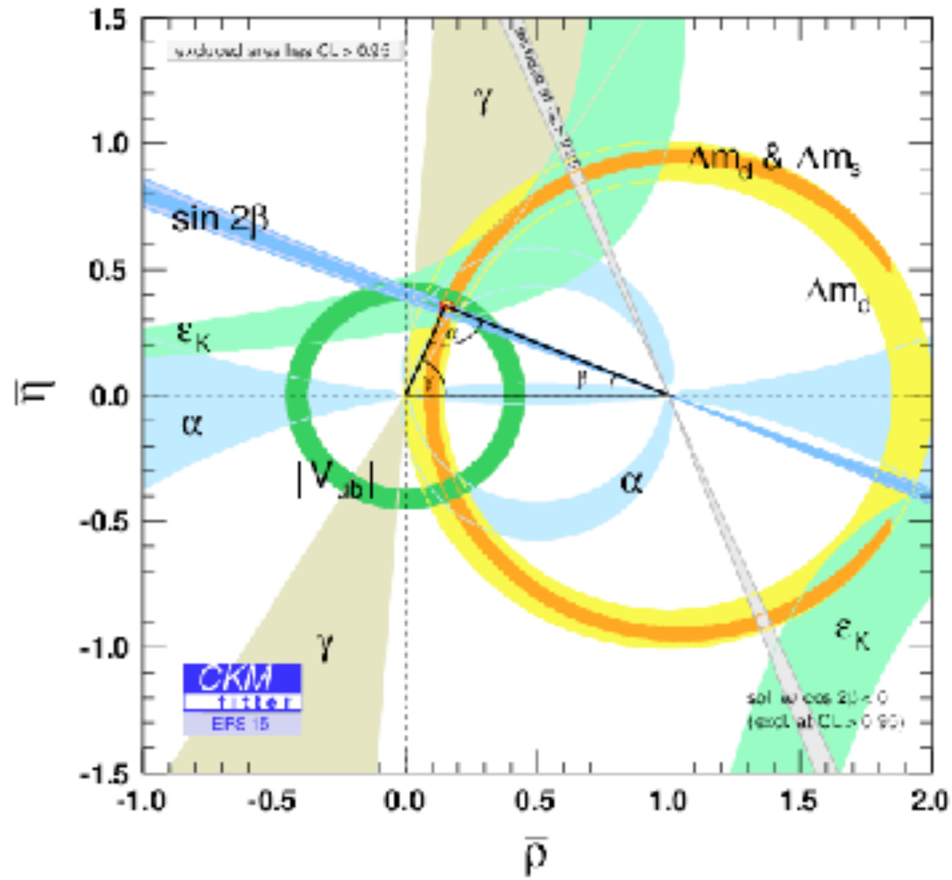
- The global picture:

- Notice to read the picture: regions outside the coloured area are excluded at 95 % Confidence Level.

- There is one and only one region of Wolfenstein parameter space which is common to all the constraints.

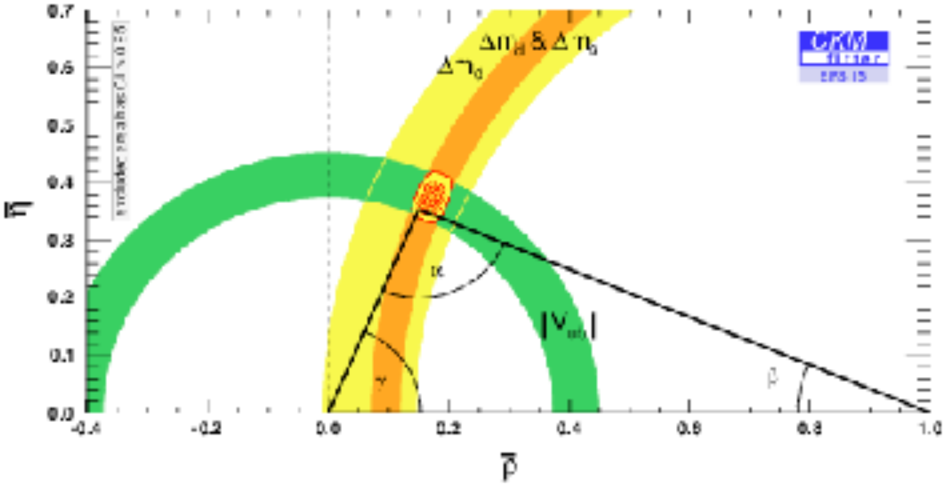
- In other terms, there is a remarkable consistency between all of the observables at the 95 % CL.

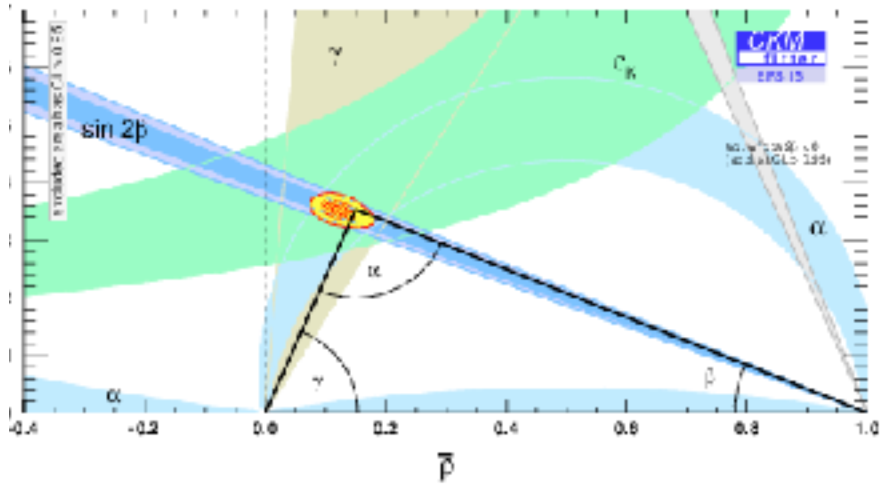
- The superimposed triangle is the best fit result.



3.2 Standard Model: the CKM profile

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

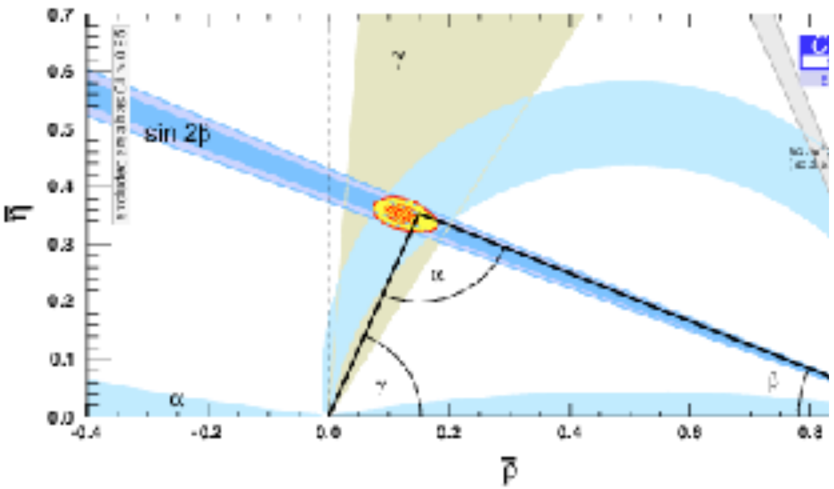


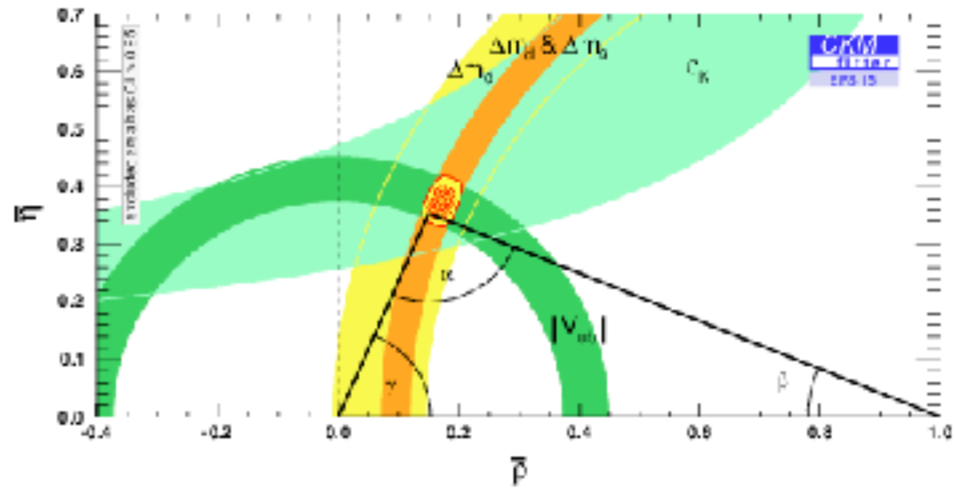


- Correct agreement. *CP*-conserving observables can quantify *CP* violation.

3.2 Standard Model: the CKM profile

- The global picture: comparison of observables constraints.
- Angles (No theory) against No angles (Hadronic uncert.).

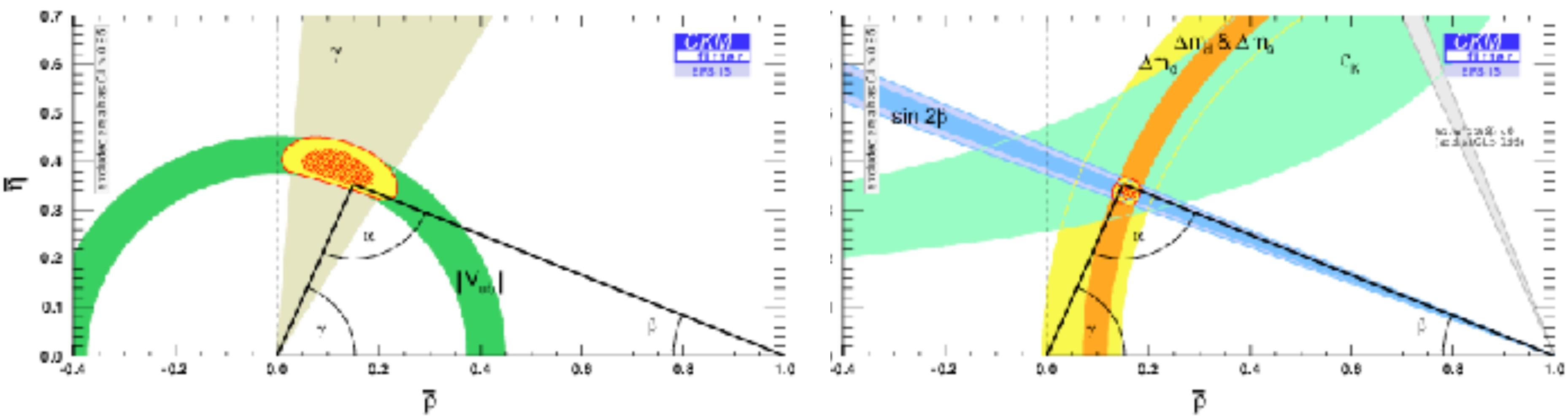




- Correct agreement. Remember that only observables with a good theoretical control are considered in the global fit.

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.

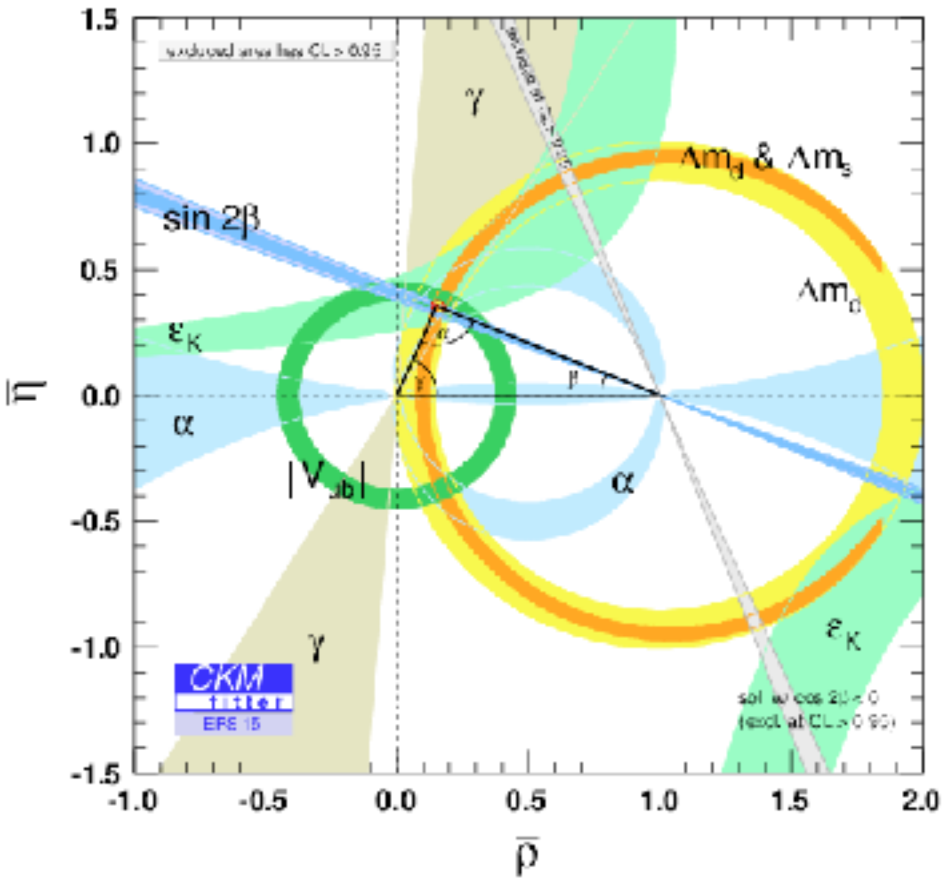
3.2 Standard Model: the CKM profile.

- 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 the past two decades.

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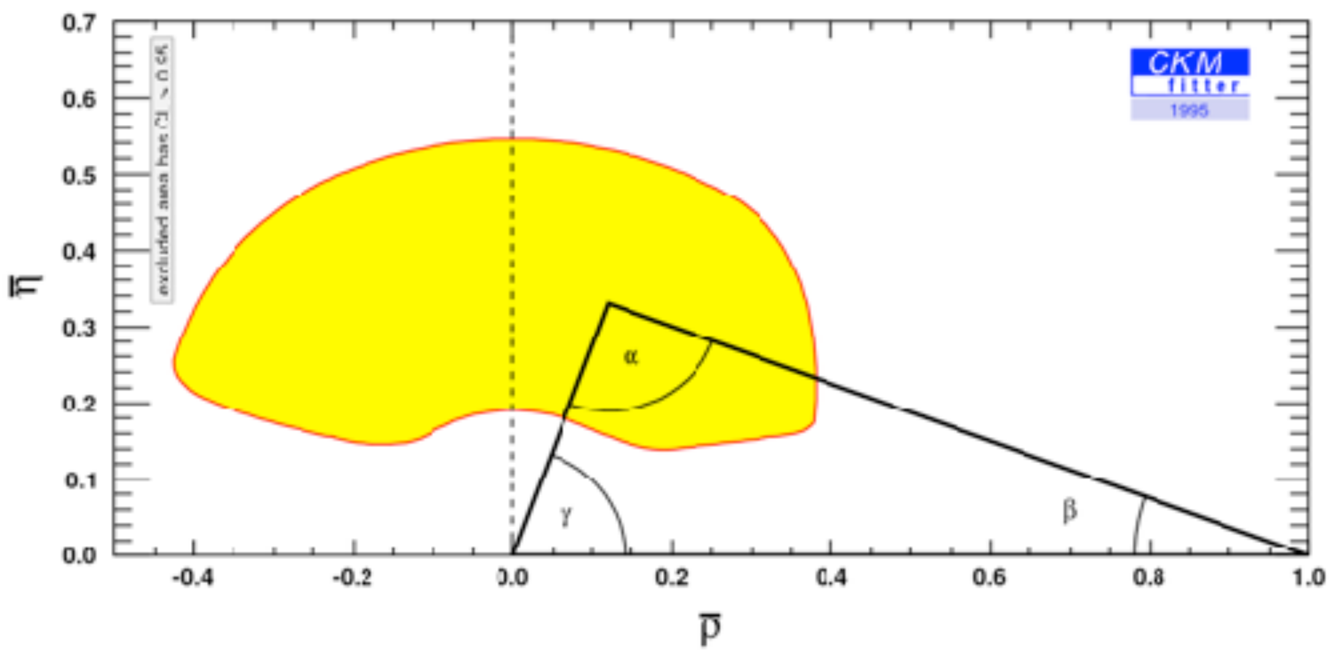

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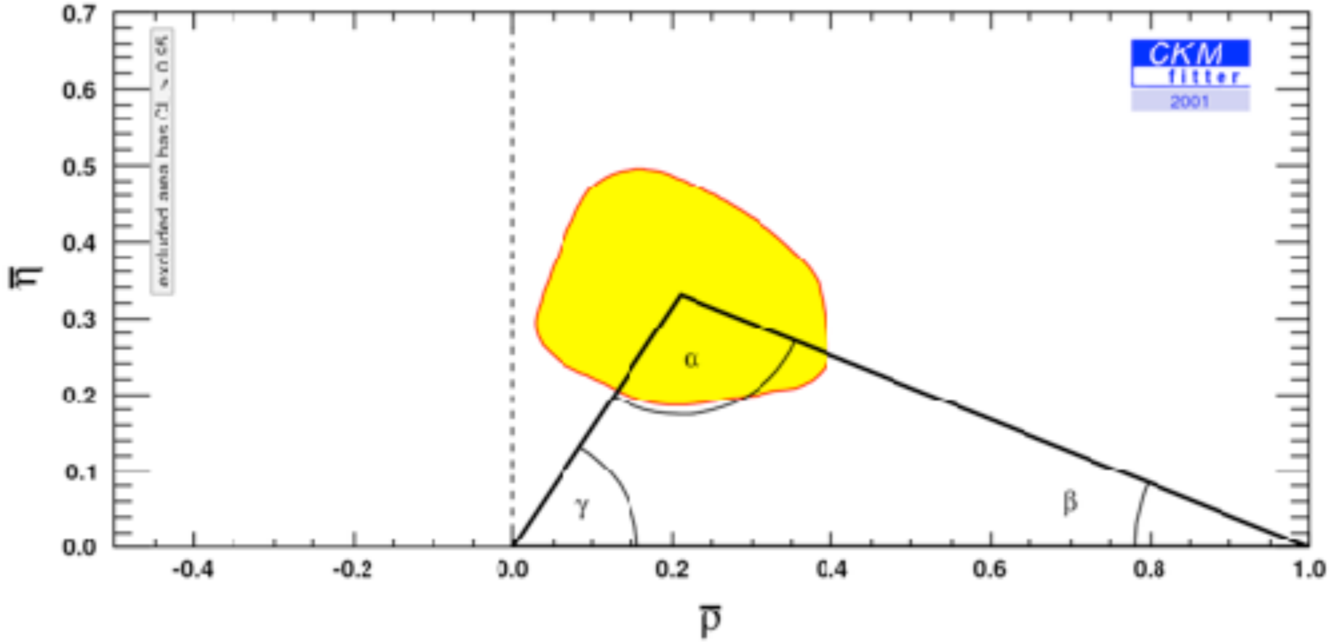

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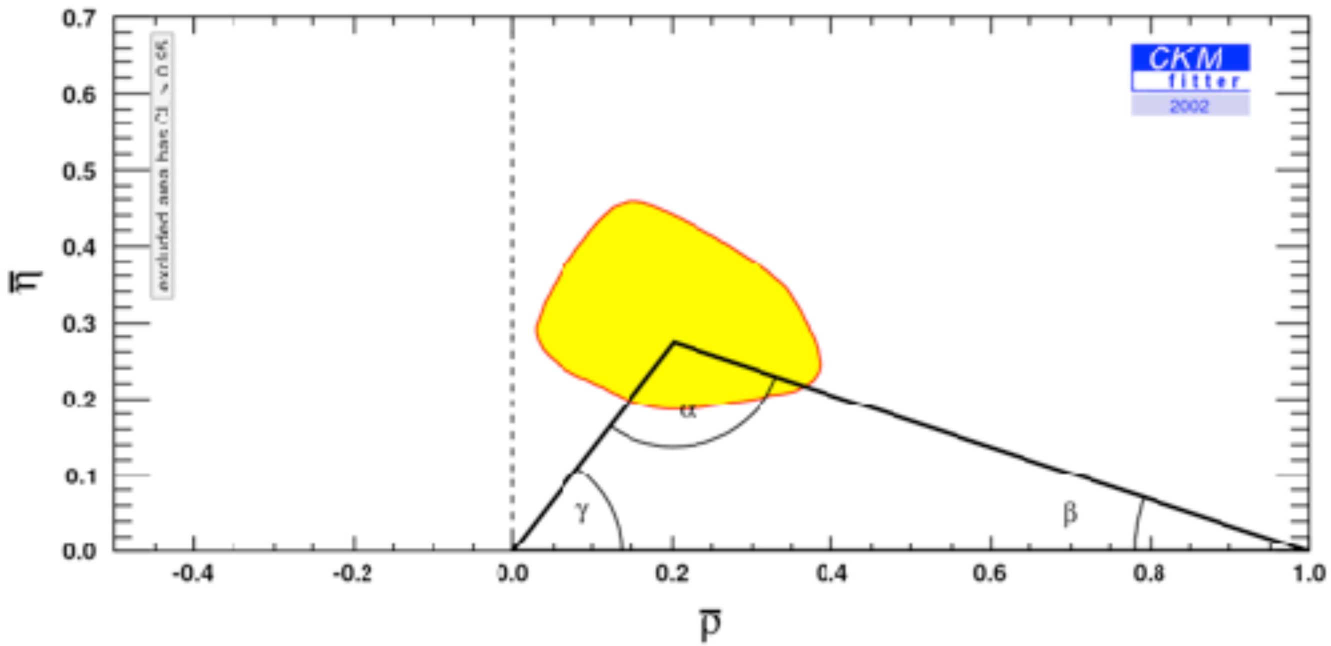

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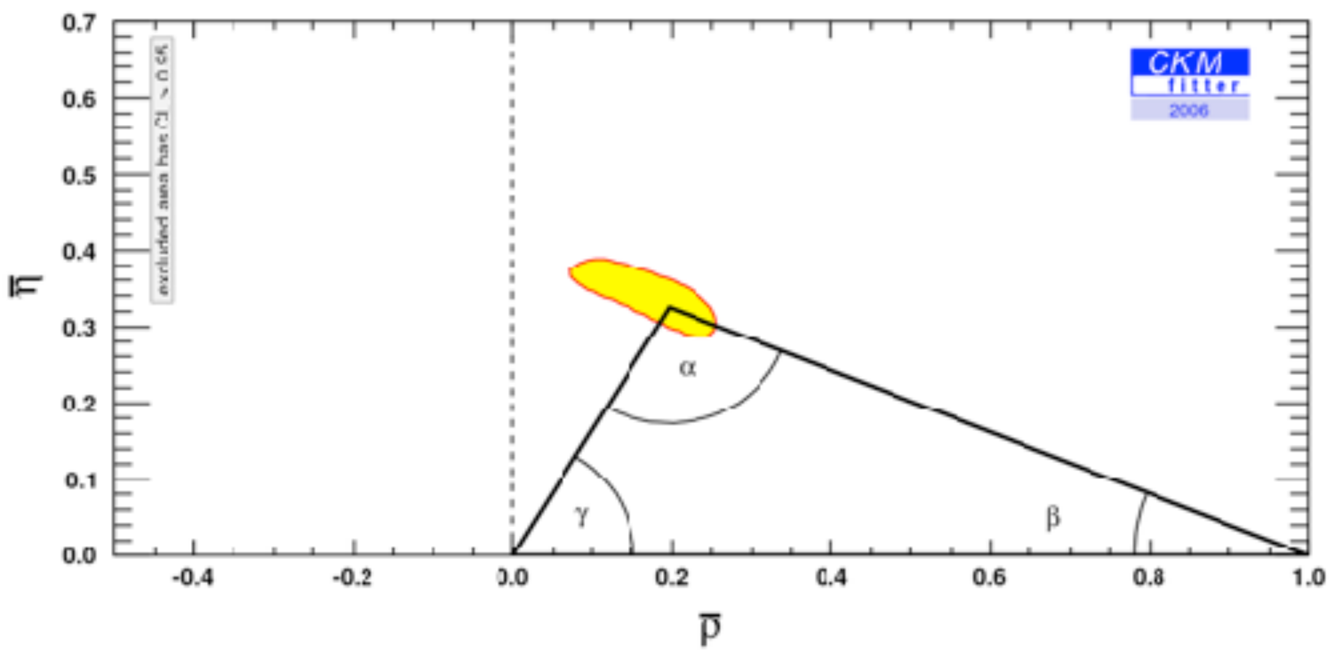

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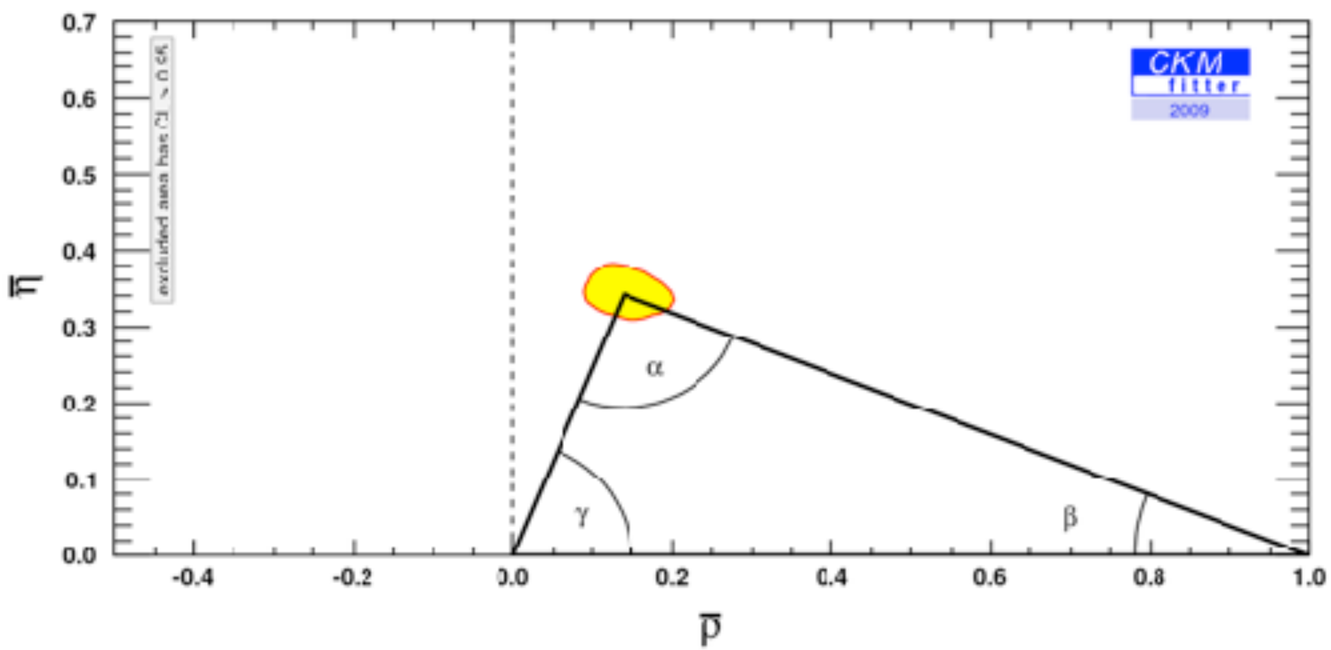

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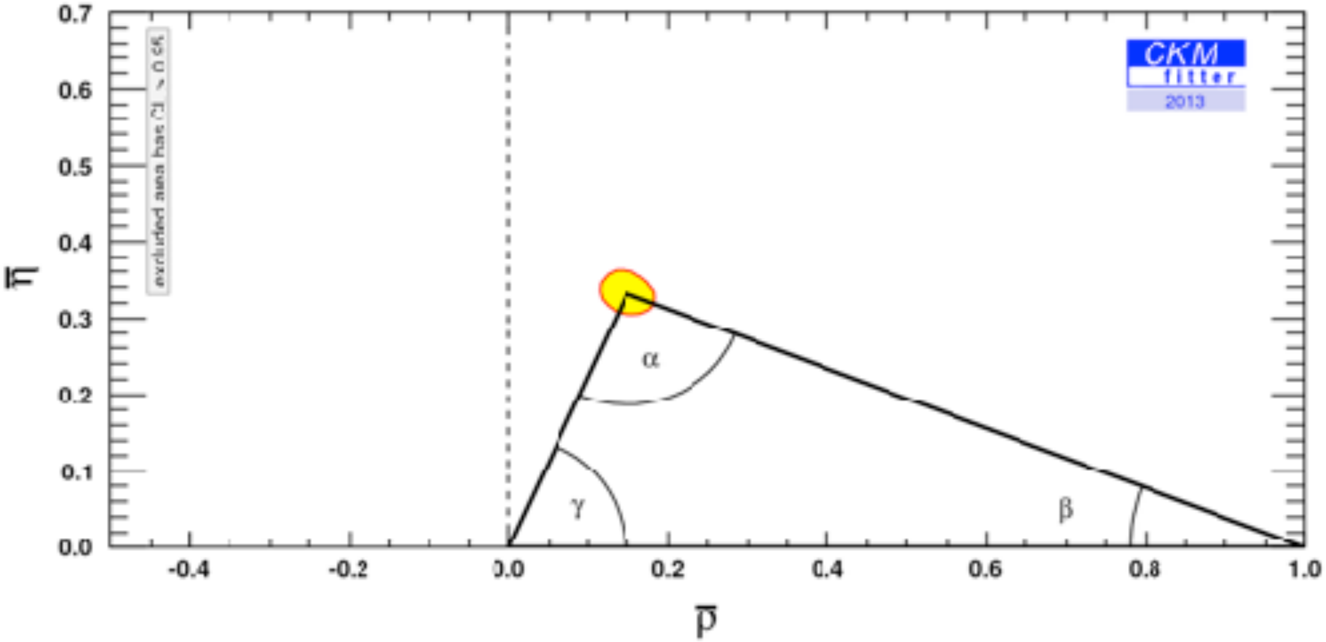

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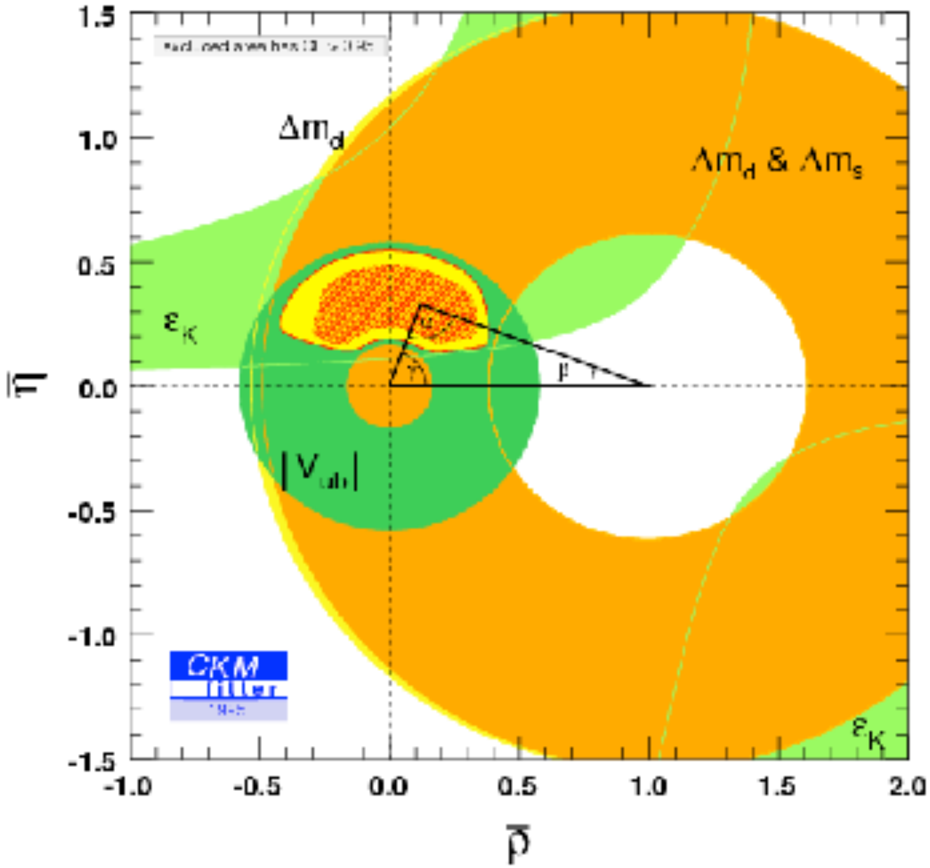

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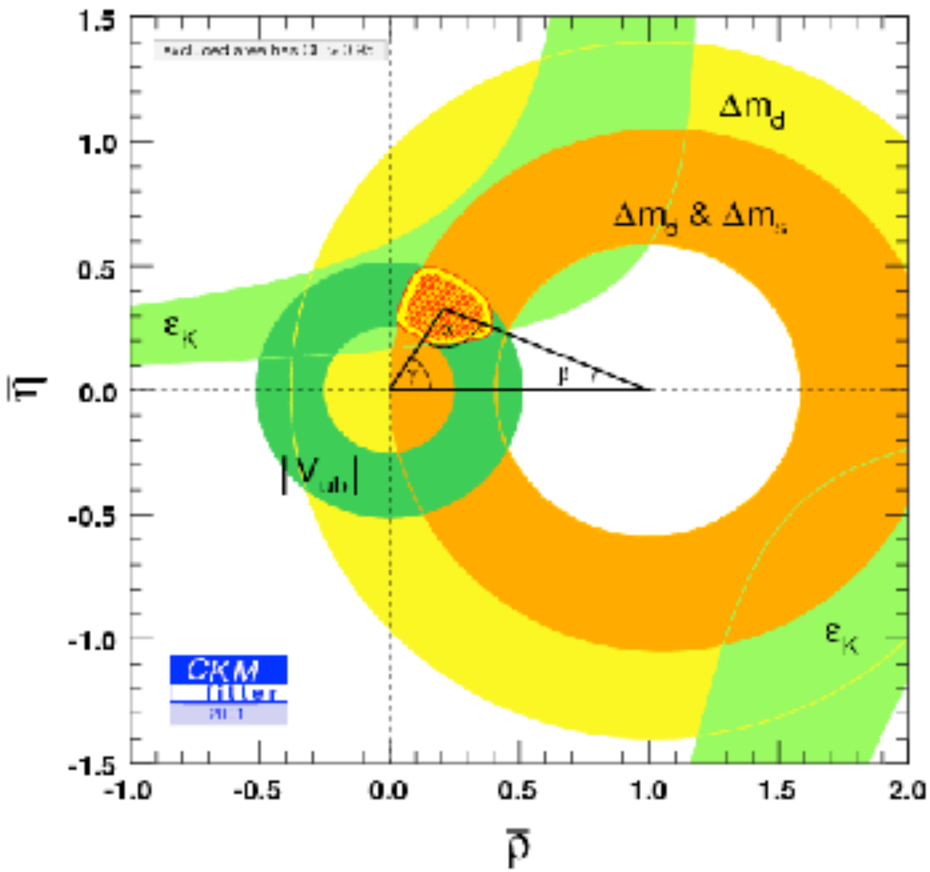

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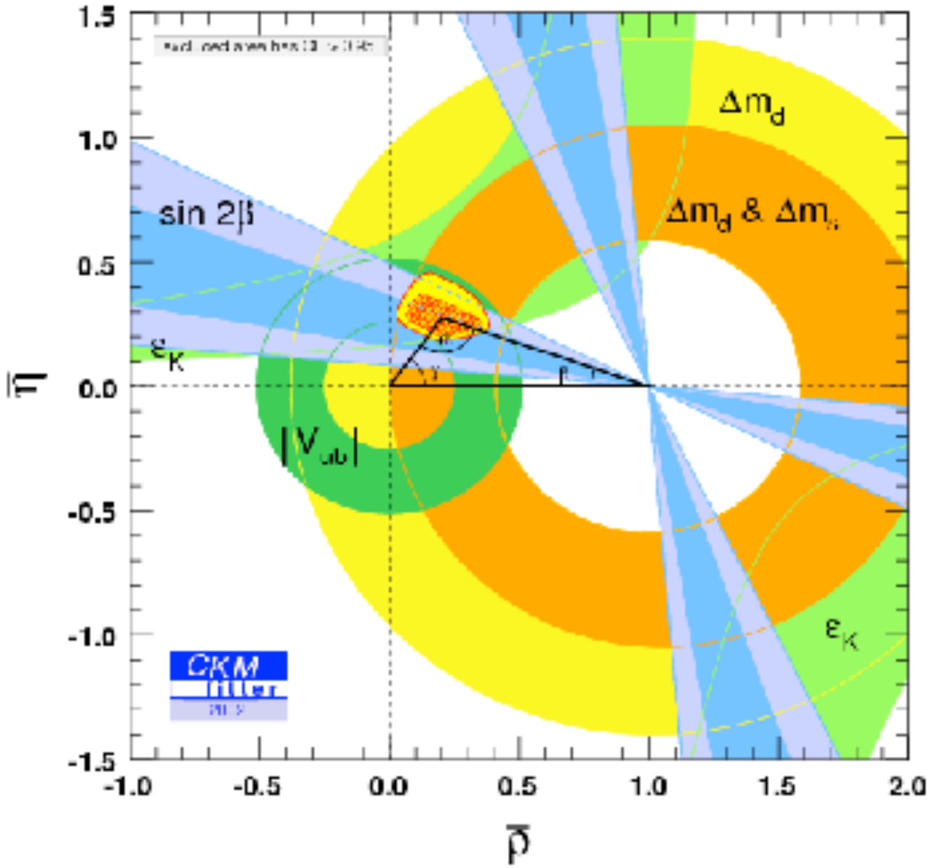

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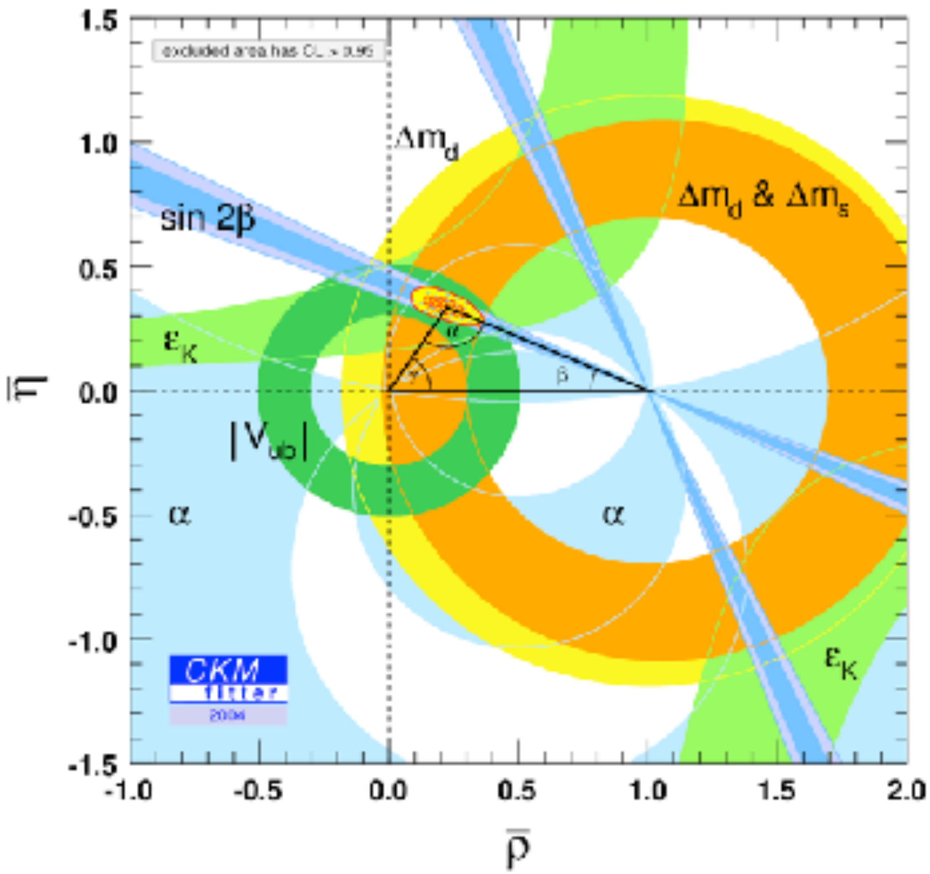

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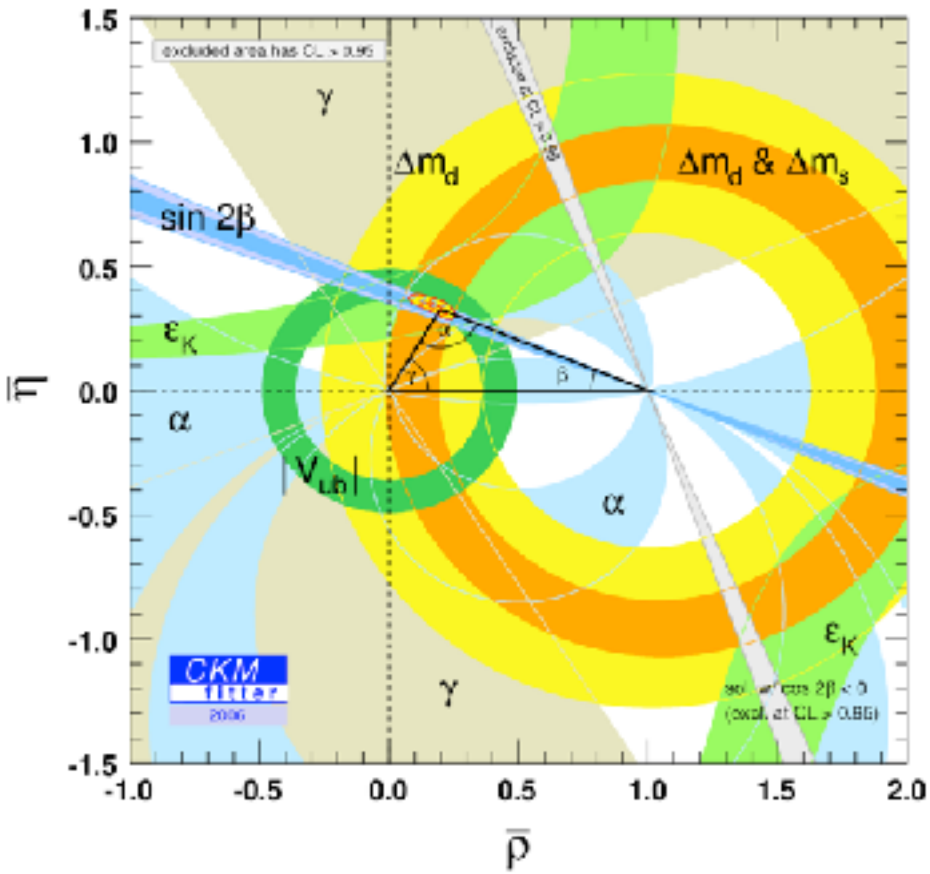

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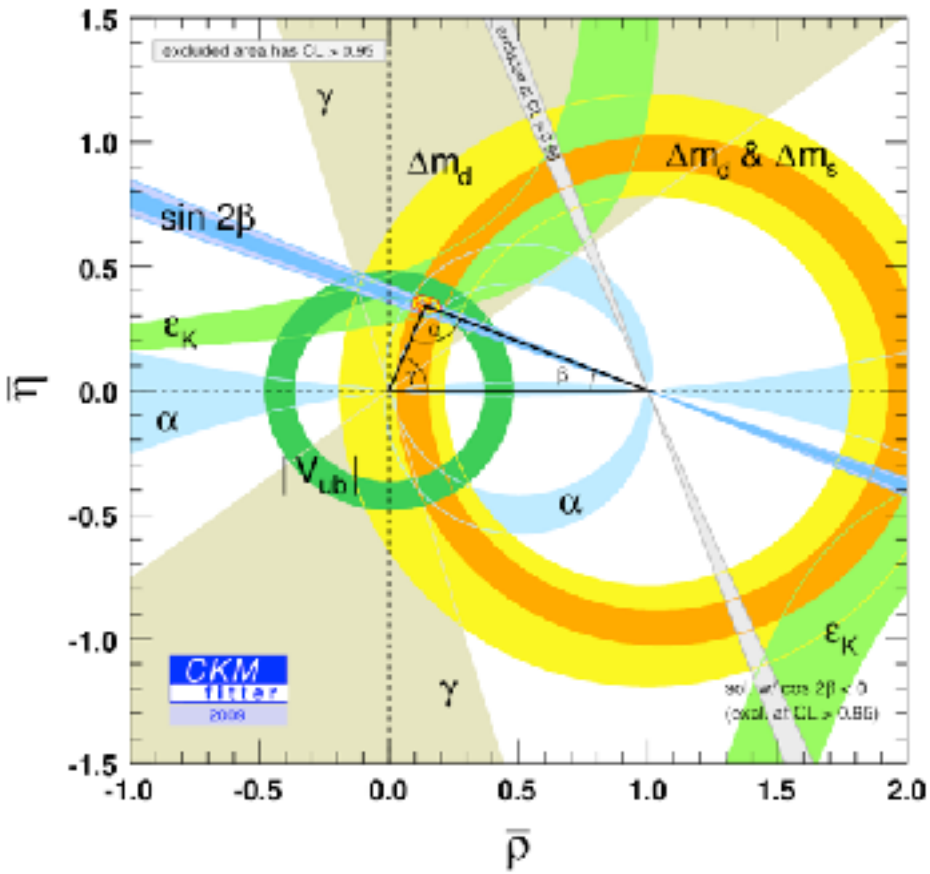

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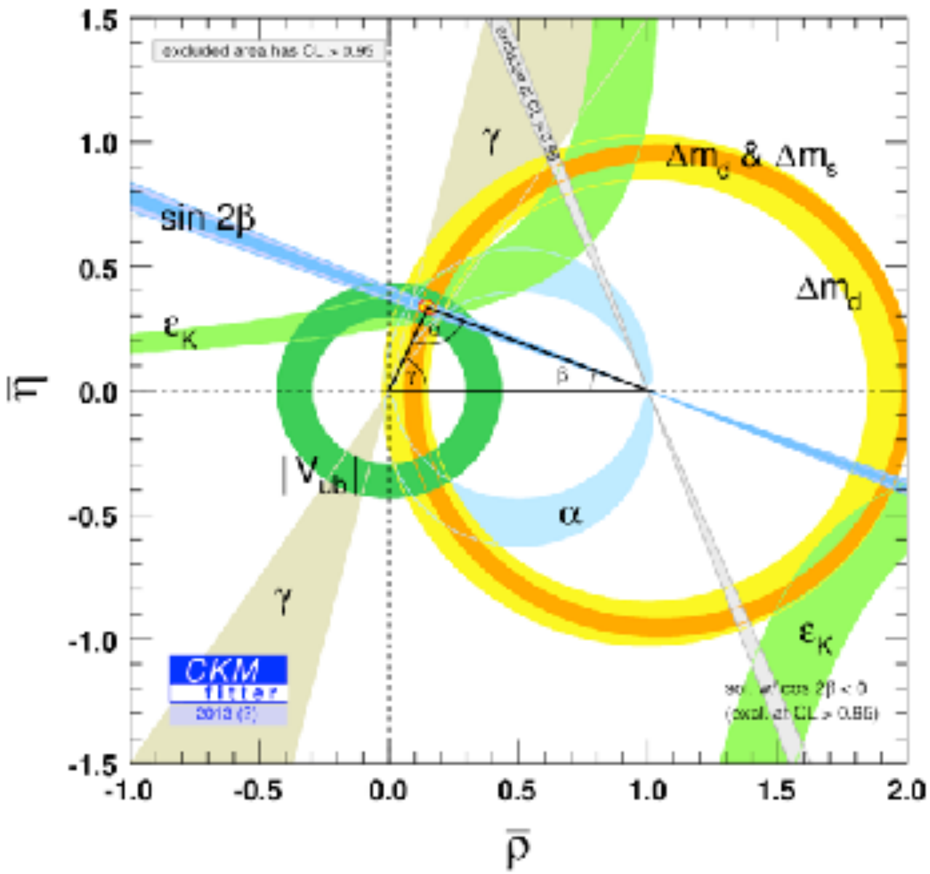

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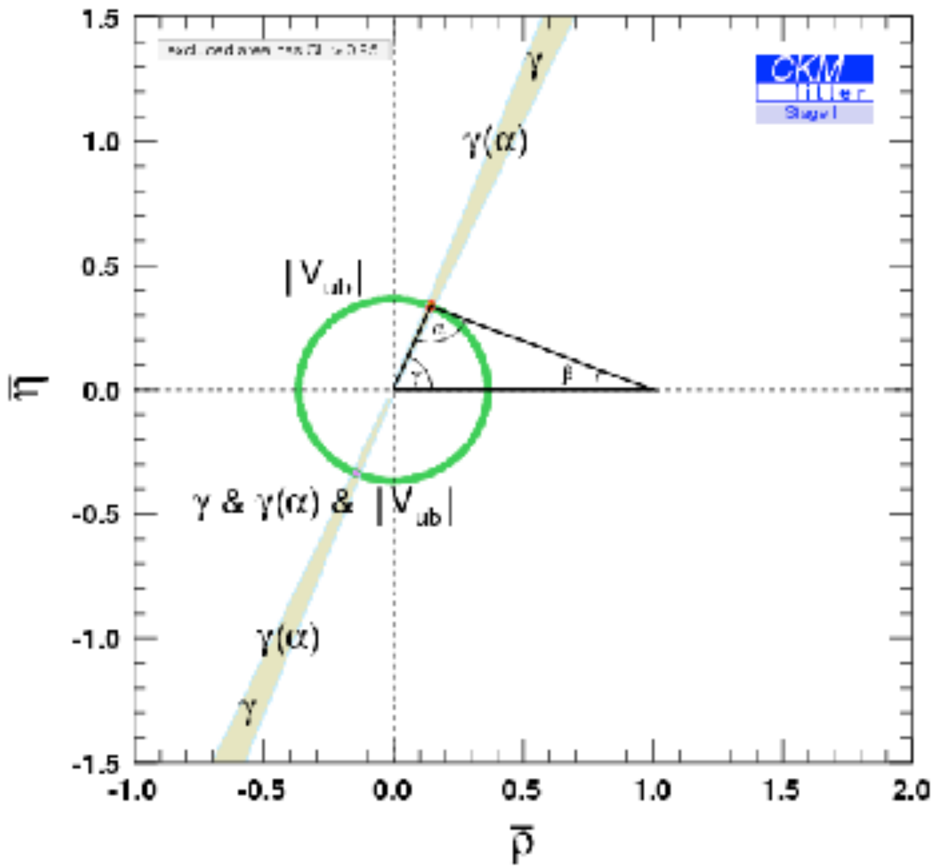


CP violation

3.3 Back to the future .

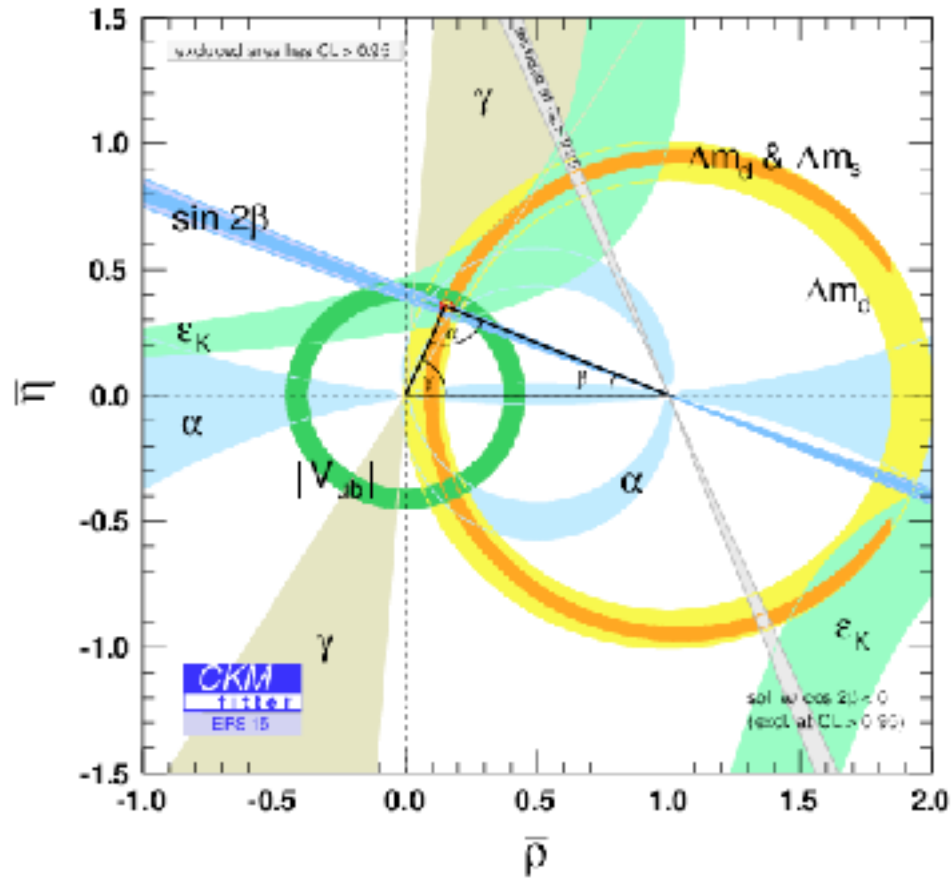
- 1995: starting point given by the top quark mass measurement. *K* and *B* mixings can be predicted.
- 2001: pre-*B*-factories era. LEP/CLEO based UT. Comparison with kaon mixing gives a consistency check.
- 2002: *CP* violation in the interference between decay and mixing is observed. This is the first true consistency test of the Standard Model.
- 2004: alpha angle is constrained.
- 2006: Δm_s (and first gamma angle constraint).
- 2013: LHCb dominating the gamma measurement.
- 2025: Super Flavour Factory (SuperKEKB) and LHCb (upgrade): additionally LQCD improvement. A New Physics perspective.

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.

- Additionally, 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. An example out of the global fit as it used to be in 2010.

- 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 (!)

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

3.3 The consistency check in details. Is it that good ?

- Yes it is !

- Predictions can be made on single observables not present in the global fit but depending on the CKM parameters.

- Here is an example of such predictions Phys.Rev. D84 (2011) 033005

- LHCb and Belle II can measure some of these observables: null test of the SM hypothesis.

Charged Leptonic Decays				
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	$(16.8 \pm 3.1) \cdot 10^{-5}$	[4]	$(7.57\ ^{+0.98}_{-0.61}) \cdot 10^{-5}$	2.8
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	$< 10^{-6}$	[10]	$(3.74\ ^{+0.44}_{-0.38}) \cdot 10^{-7}$	-
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$(5.29 \pm 0.28) \cdot 10^{-2}$	[10]	$(5.44\ ^{+0.05}_{-0.17}) \cdot 10^{-2}$	0.5
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	$(5.90 \pm 0.33) \cdot 10^{-3}$	[10]	$(5.39\ ^{+0.21}_{-0.22}) \cdot 10^{-3}$	1.3
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	$(3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$	[9]	$(4.18\ ^{+0.13}_{-0.20}) \cdot 10^{-4}$	0.6
Neutral Leptonic B decays				
$\mathcal{B}(B_s^0 \to \tau^+\tau^-)$	-		$(7.73\ ^{+0.37}_{[illegible]}) \cdot 10^{-7}$	-
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$< 32 \cdot 10^{-9}$	[10]	$(3.64\ ^{+0.17}_{-0.31}) \cdot 10^{-9}$	-
$\mathcal{B}(B_s^0 \to e^+e^-)$	$< 2.8 \cdot 10^{[illegible]}$	[10]	$(8.54\ ^{+0.40}_{-0.72}) \cdot 10^{-14}$	-
$\mathcal{B}(B_d^0 \to \tau^+\tau^-)$	$< 4.1 \cdot 10^{-3}$	[10]	$(2.36\ ^{+0.12}_{-0.21}) \cdot 10^{-8}$	-
$\mathcal{B}(B_d^0 \to \mu^+\mu^-)$	$< 6 \cdot 10^{-9}$	[10]	$(1.13\ ^{+0.06}_{-0.11}) \cdot 10^{-10}$	-
$\mathcal{B}(B_d^0 \to e^+e^-)$	$< 8.3 \cdot 10^{-9}$	[10]	$(2.64\ ^{+0.13}_{-0.24}) \cdot 10^{-15}$	-
$B_q - \bar{B}_q$ mixing observables				
$\Delta\Gamma_s/\Gamma_s$	$0.092^{+0.051}_{-0.054}$	[10]	$0.179\ ^{+0.067}_{-0.071}$	0.[illegible]
a_{SL}^d	$(-47 \pm 46) \cdot 10^{-4}$	[10]	$(-6.5\ ^{+1.9}_{-1.7}) \cdot 10^{-4}$	0.8
a_{SL}^s	$(-17 \pm 91^{+12}_{-23}) \cdot 10^{-4}$	[26]	$(0.29\ ^{+0.09}_{-0.08}) \cdot 10^{-4}$	0.2
$a_{SL}^s - a_{SL}^d$	-		$(6.8\ ^{+1.9}_{-1.7}) \cdot 10^{-4}$	-
$\sin(2\beta)$	0.678 ± 0.020	[10]	$0.832\ ^{[illegible]}_{-0.033}$	2.7
$2\beta_s$	$[0.04; 1.04] \cup [2.16; 3.10]$	[27]	$0.0363\ ^{+0.0016}_{-0.0015}$	-
	$0.76\ ^{+0.36}_{-0.38} \pm 0.02$	[28]		
Radiative B decays				
$\mathcal{B}(B_d \to K^*(892)\gamma)$	$(43.3 \pm 1.8) \cdot 10^{-6}$	[10]	$(64\ ^{+22}_{-21}) \cdot 10^{-6}$	1.2
$\mathcal{B}(B^- \to K^{*-}(892)\gamma)$	$(42.1 \pm 1.5) \cdot 10^{-6}$	[10]	$(66\ ^{+21}_{-20}) \cdot 10^{-6}$	1.1
$\mathcal{B}(B_s \to \phi\gamma)$	$(57^{+21}_{-18}) \cdot 10^{-6}$	[10]	$(65\ ^{+31}_{-24}) \cdot 10^{-6}$	0.1
$\mathcal{B}(B \to X_s\gamma)/\ \mathcal{B}(B \to X_c\ell\nu)$	$(3.346 \pm 0.247) \cdot 10^{-3}$	[10]	$(3.03\ ^{+0.34}_{-0.32}) \cdot 10^{-3}$	0.2
Rare K decays				
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.75^{+1.15}_{-1.05}) \cdot 10^{-10}$	[29]	$(0.854\ ^{+0.116}_{-0.098}) \cdot 10^{-10}$	0.8

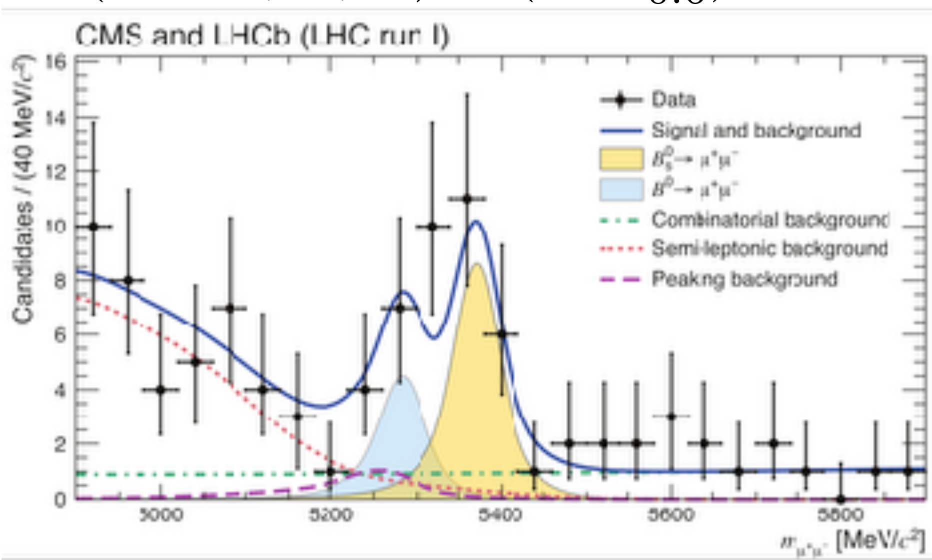
3.3 The consistency check in details. Is it that good ?

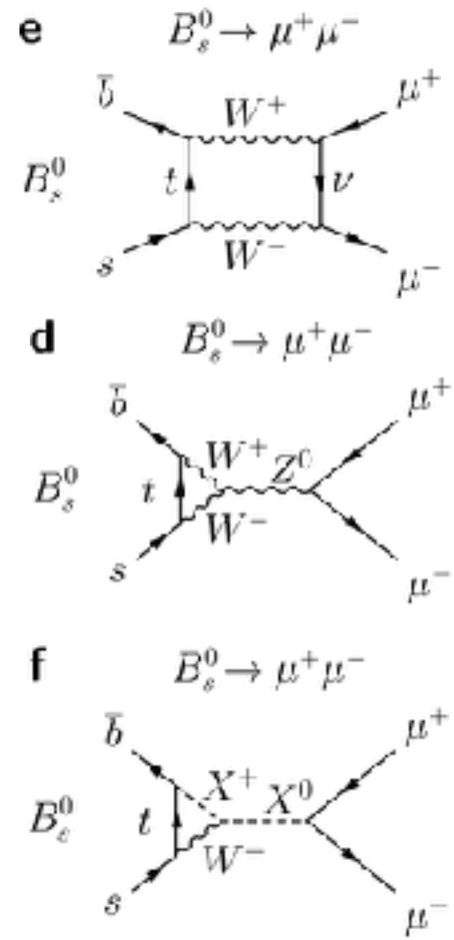
- The very rare decay *Bs* → *μμ* is predicted to be:

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.21^{+0.22}_{-0.14}) \times 10^{-9}$$

- Both LHCb and CMS experiments have seen a signal of it in the ballpark of the SM.

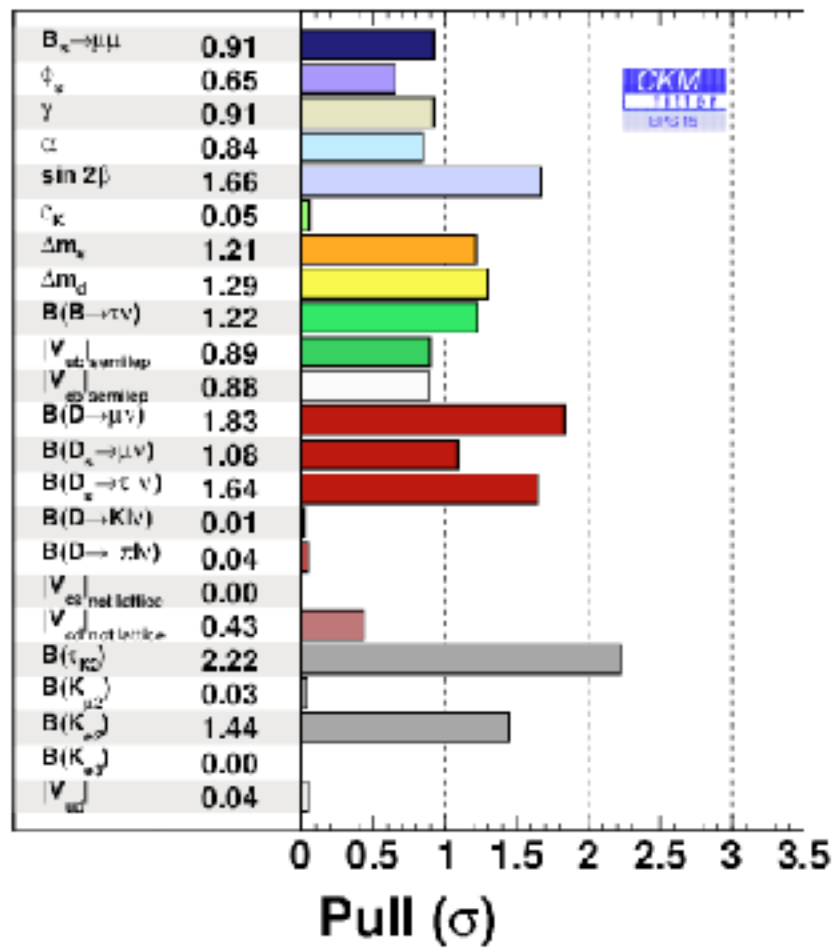
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$





3.3 The consistency check in details. Is it that good ?

- Pick an observable
- Remove it from the fit
- Compute the *p*-value
- Think of the expected number of departures
- Think of the values close to 0
- CKM-wise, the SM is so far in good shape.



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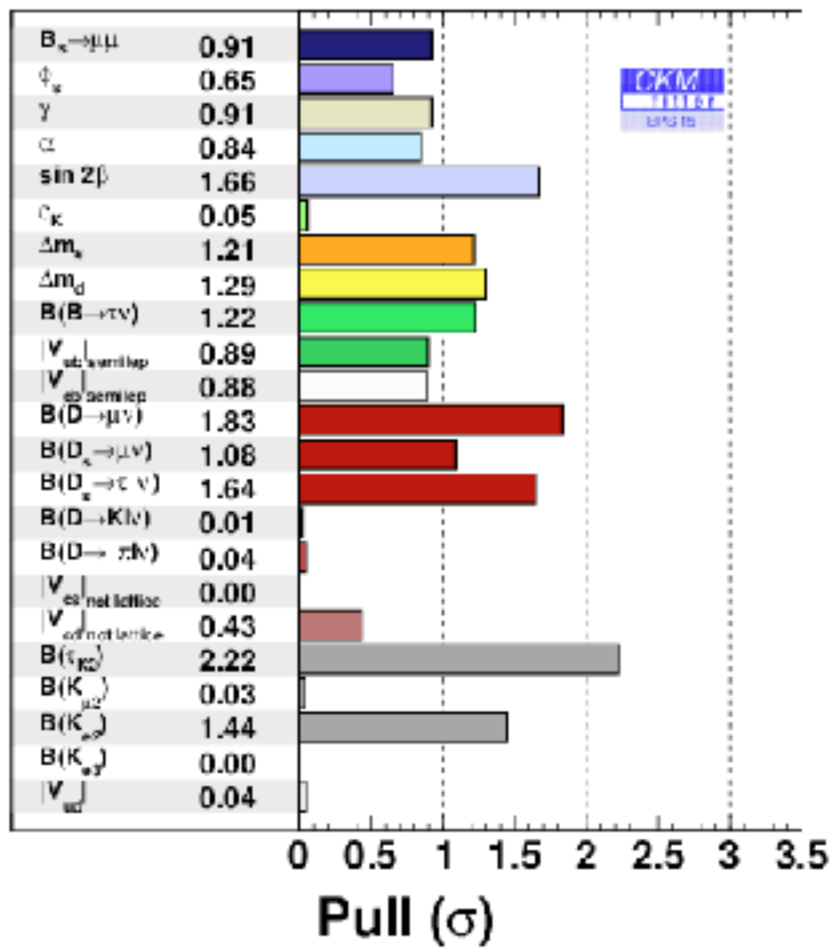


CP violation and antimatter disappearance

3.4 What is our Universe telling us ?

- Well, close by, we (are trying to) articulate a matter-made speech about *where is the antimatter gone in the Universe?*

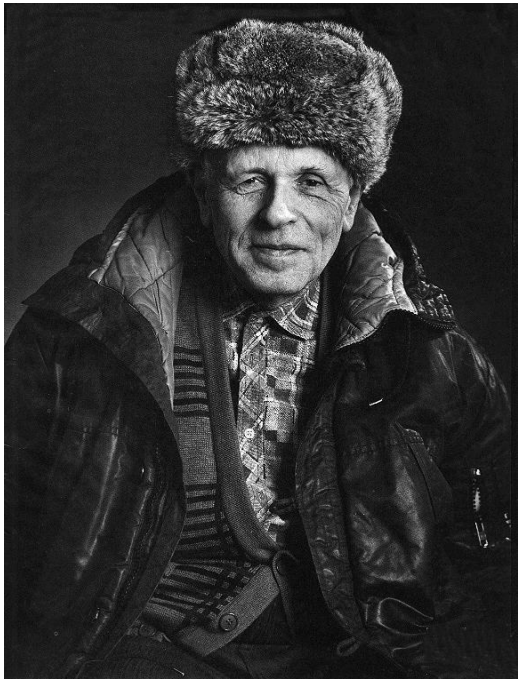
- Let's hear from the great minds. Dirac's NP lecture:

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

3.4 Sakharov and the absence of antimatter

A slight asymmetry matter / antimatter is enough to explain the matter dominance of our Universe

10,000,000,000 antiprotons or antineutrons… for
10,000,000,001 protons or neutrons.



Sakharov (1967) is teaching us:

- The proton must decay / baryonic number not conserved (not seen to date …)
- The symmetries *C* et *CP* must be broken (that is realised).
- One needs to be out of equilibrium.

3.4 What is our Universe telling us ?

- Pierre gave us a key parameter to measure how badly / happily asymmetric is the situation. The ratio of baryons to photons. It is observed to be an apparently small number:

$$n = \frac{N_b}{n_\gamma} \sim 10^{-10}$$

- I choose here heuristic arguments to predict the baryon abundance from the magnitude of CP violation (remember *J*) [A convincing derivation can be found here]

$$n \sim \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_t^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{T_{\mathrm{EW}}^{12}} .J$$

$$n \sim 10^{-21}$$

- The SM is short by several orders of magnitude to explain what we observe. There must be additional *CP*-violating phases / phenomena.

A more detailed outline

1. Introduction: setting the scene. History and recent past of the parity violation experiments. The discovery of the *CP* violation.

2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.

3. The global fit of the SM: CKM profile.

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

4. Outlook and conclusions.

1. Analysis of mixing processes. Which room left for new physics. A bottom-up approach (model-independent).

2. A top-down appproach (dedicated model testing): the Two Higgs Doublet (Type II).

3. Concluding remarks.

Note: the two analyses reported in the following are on purpose not the state of the art. They are illustrations of BSM Physics searches. The focus nowadays moved towards lepton universality tests in flavour observables.

4.1 Bottom-Up: 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:

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

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

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: $b \rightarrow q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario **are:**

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

4.1 NP in ΔF=2 processes

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

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

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

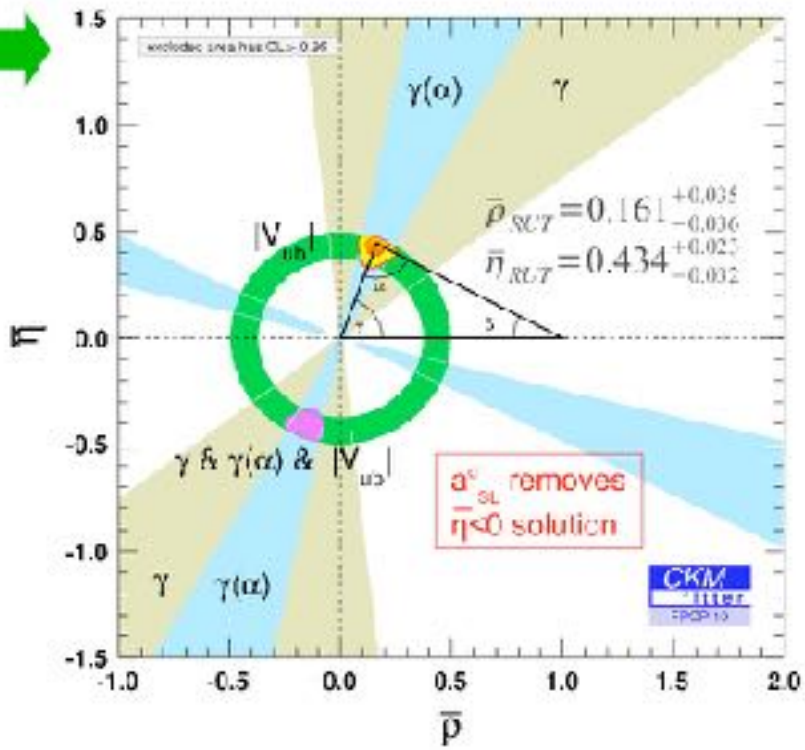
parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{NP}\rvert \times \Delta m_q^{SM}$
2β	$2\beta^{SM} + \Phi_d^{NP}$
$2\beta_s$	$2\beta_s^{SM} - \Phi_s^{NP}$
2α	$2(\pi - \beta^{SM} - \gamma) - \Phi_d^{NP}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{SM} +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

4.1 NP in ΔF=2 processes as of 2010

Hypotheses:

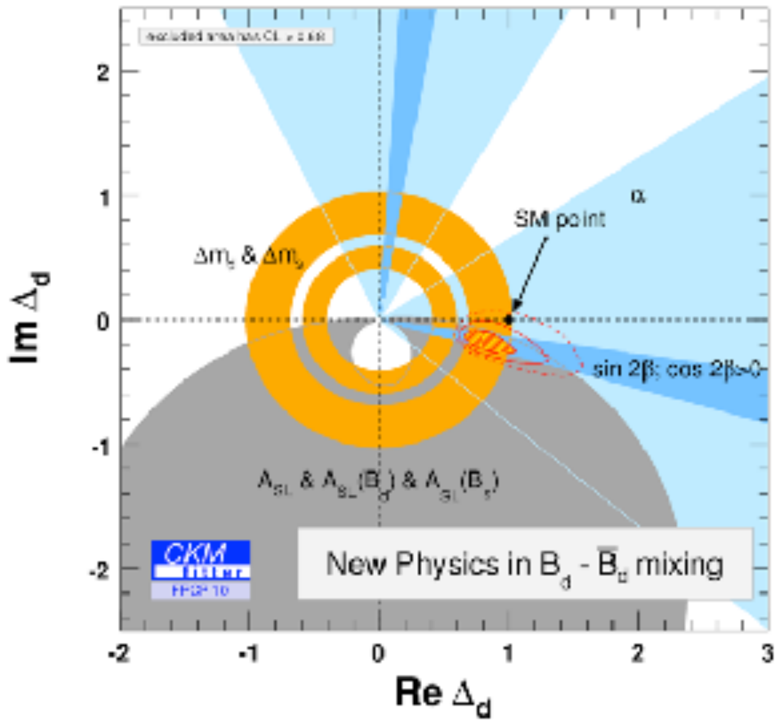
• tree-level processes are not affected by NP (so-called SM4FC: $b \rightarrow q_i q_j q_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario **are:**

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



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

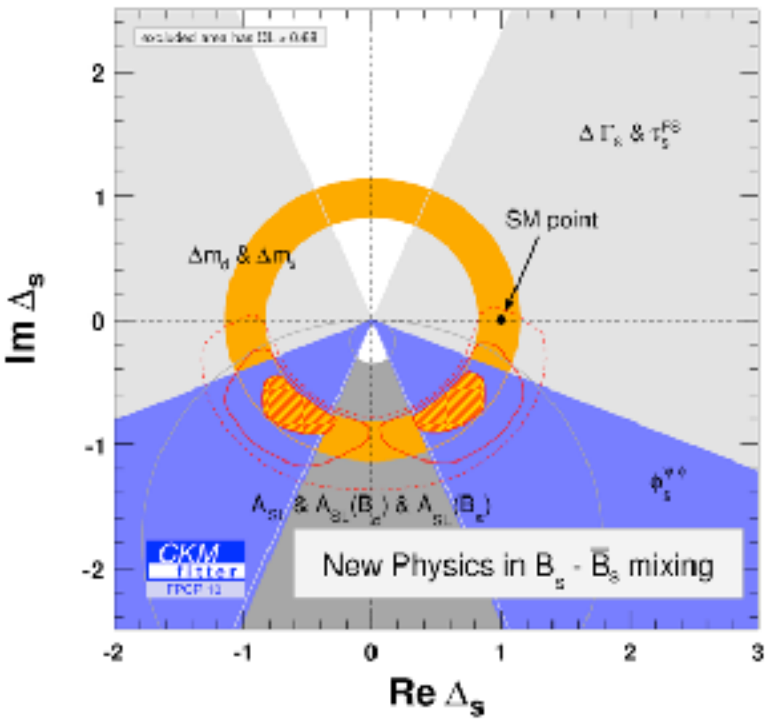
4.1 NP in $\Delta F=2$ processes as of 2010



- 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 $\sin 2\beta$ discrepancy of the SM global fit

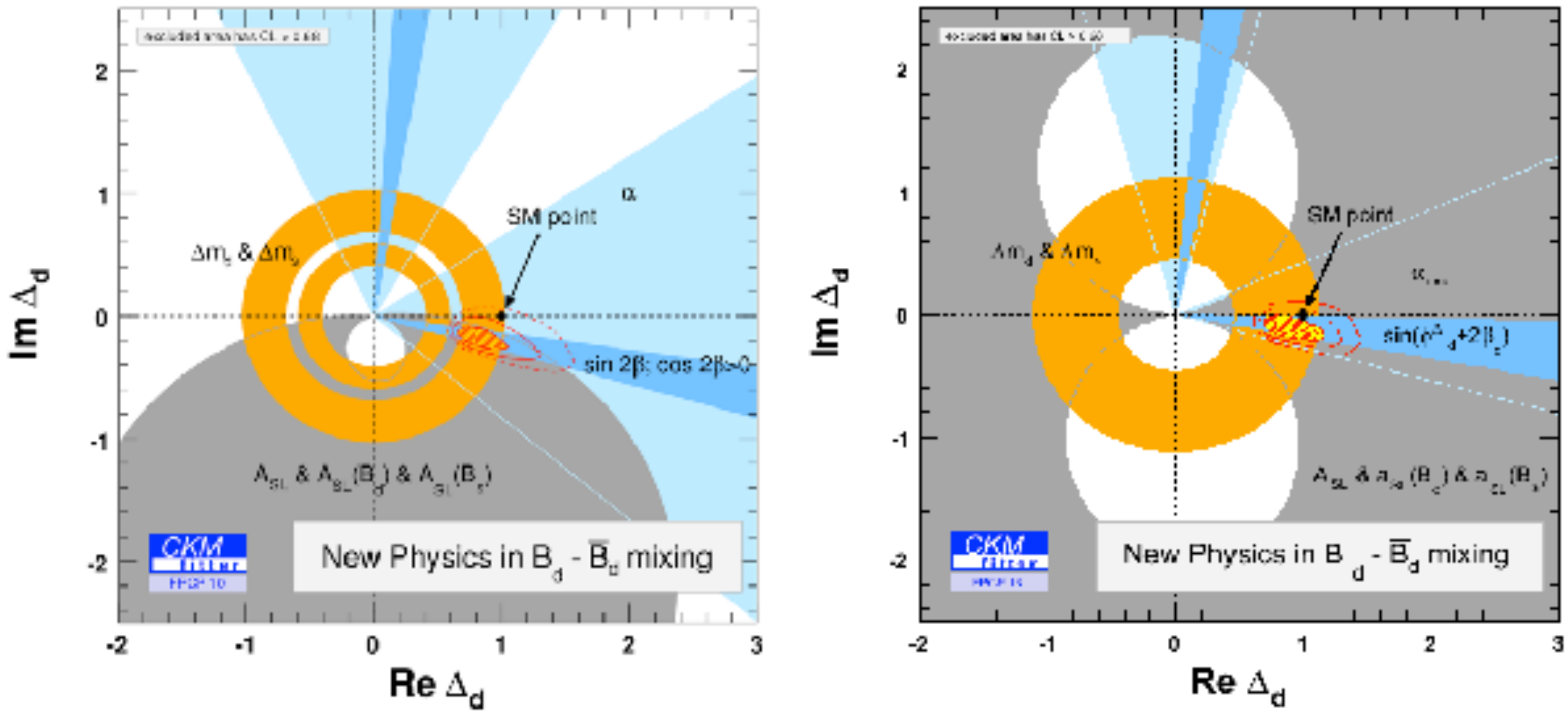
4.1 NP in ΔF=2 processes as of 2010



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

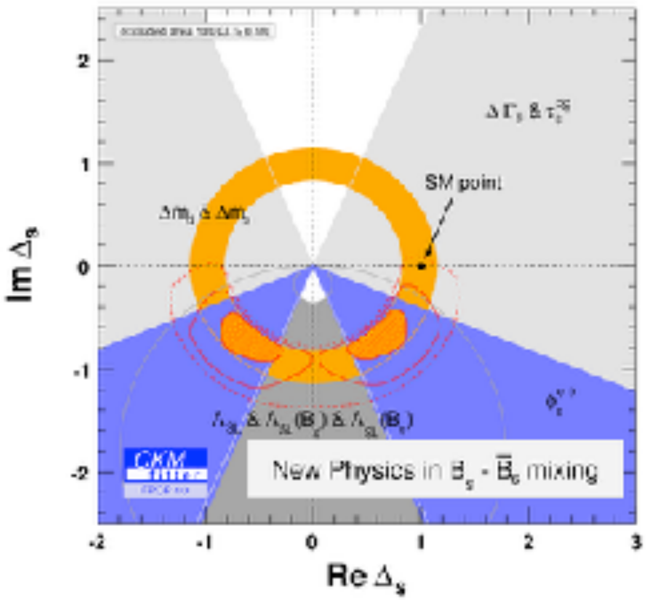
1. Sizeable NP contributions allowed in the *Bs* mixing.
2. LHCb contribution should be decisive.

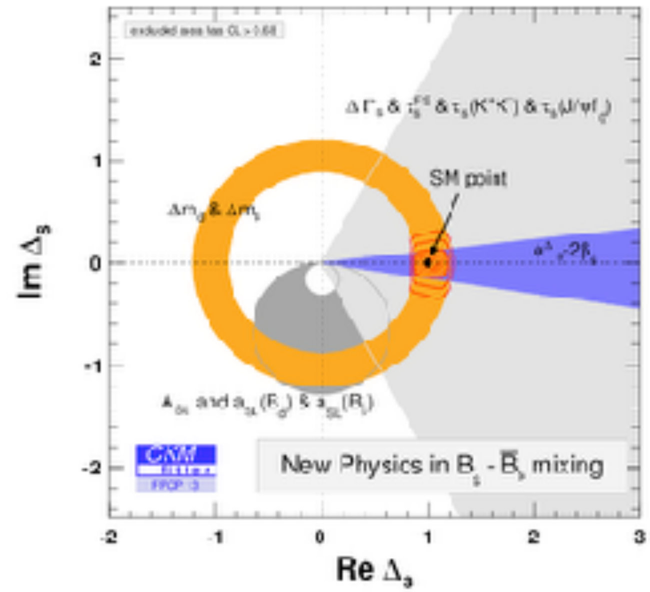
4.1 NP in ΔF=2 processes. After the Belle results.



- Damned! SM strikes back.

4.1 NP in ΔF=2 processes. After LHCb 1/fb.





- The 2D SM hypothesis is: 0.2 σ (used to be ~ 3 σ)

- But don't infer a wrong statement: sizeable NP is still allowed by the LHCb constraint in both *Bd* and *Bs* mixing.

4.1 NP in $\Delta F=2$ processes. Conclusion.

Take away message:

A single evidence almost smashed the SM. If NP is there and close, I believe it would come as naturally as in the example I chose.

4.2 Two Higgs Doublets Model (Top-Down)

• Charged Higgs transition is something we immediately imagine for BF($B^+ \rightarrow \tau^+ \nu$). What the flavour data say on a 2HDM model?

• Motivations: it is a simple and predictive extension of the Standard Model. Same structure for the quark sector but new flavour changing charged interactions mediated by a charged Higgs.

• Track charged Higgs contributions into tree or loop decays. Redefinition of the SM expression through corrections implying only 2 additional parameters:

$$M_{H^+}, \tan\beta = \frac{v_2}{v_1}$$

• 2HDM is embedded into supersymmetric models (MSSM).

• Note: There are of course neutral higgses in 2HDM, which do not enter (or mildly) the processes under consideration in this study.

4.2 Two Higgs Doublets Model (Top-Down)

- All inputs are potentially subjected to receive charged Higgs contributions.

- Yet, we neglected charged Higgs contribution for the following inputs, hence used to determine the apex of the unitarity triangle. Driven by (m_light/m_heavy)^2 couplings $\rightarrow$ $|V_{ud}|$, $|V_{ub}|$, $|V_{cb}|$ and $\gamma(\alpha+\beta)$.

- We consider several observables subjected to receive Higgs contributions:

  - Leptonic decays $\rightarrow$ { $\Gamma[K \to \mu\nu]/\Gamma[\pi \to \mu\nu]$, $\mathcal{B}[D \to \mu\nu]$, $\mathcal{B}[D_s \to \mu\nu]$, $\mathcal{B}[D_s \to \tau\nu]$ and $\mathcal{B}[B \to \tau\nu]$

  - Semileptonic decays $\rightarrow$ $\mathcal{B}(B \to D\tau\nu)$ and $\mathcal{B}(K \to \pi\ell\nu)$

  - The partial width of Z to bb (used to be a hint of NP!) [consider B mixing also]

  - $b \rightarrow s\gamma$

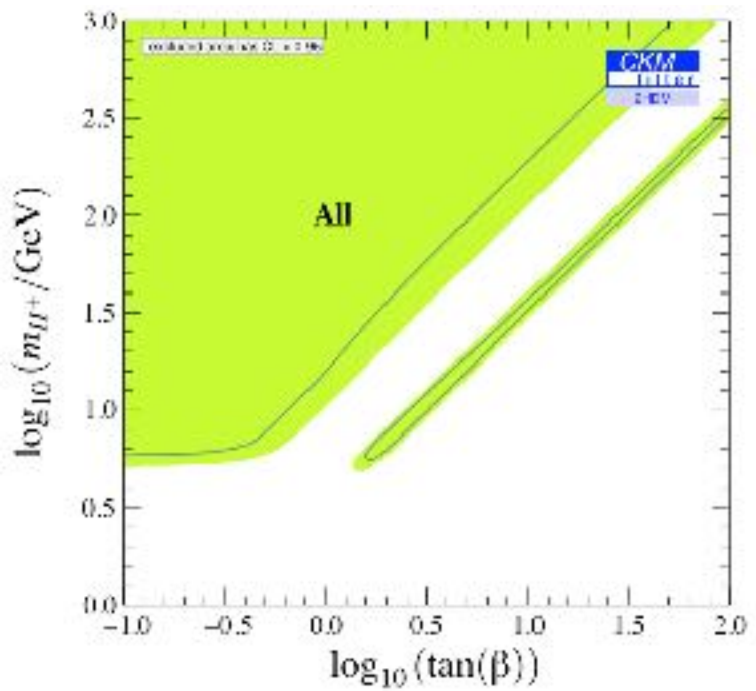
4.2 Two Higgs Doublets Model (Top-Down)

- Leptonic constraints:

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

$$\mathcal{B}[M \to l\nu] = \mathcal{B}[M \to l\nu]_{SM}(1 + r_H^{Ml2}) \text{ where}$$

$$r_H^{Ml2} = \left(\frac{m_{q_u} - m_{q_d}\tan^2\beta}{m_{q_u} + m_{q_d}}\right)\left(\frac{m_M}{m_{H^+}}\right)^2$$



- Most of the individual fined-tuned solutions are removed at 95% CL

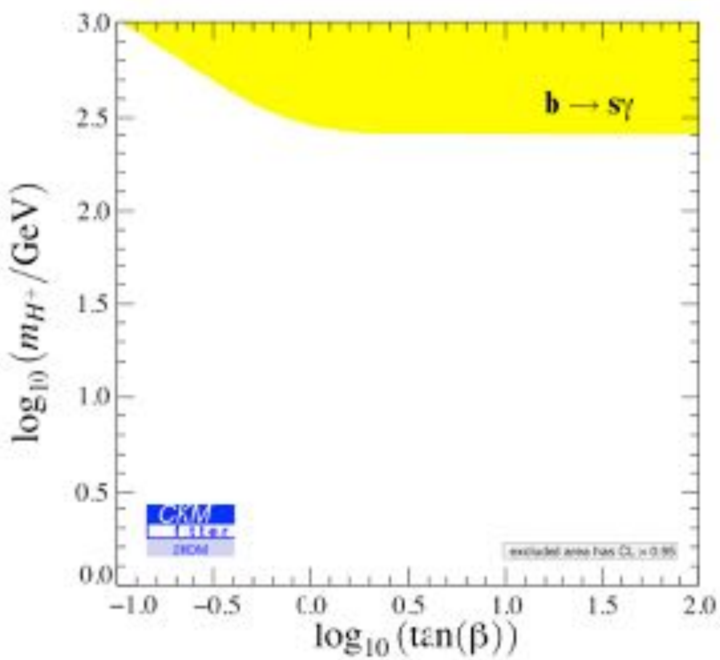
- Large tan β are excluded at small Higgs masses.

4.2 Two Higgs Doublets Model (Top-Down)

- Radiative decay

$$\mathcal{R}_{b\to s\gamma} = \frac{\mathcal{B}[\bar{B}\to X_s\gamma]}{\mathcal{B}[\bar{B}\to X_c l\bar{\nu}]} = \left|\frac{V_{ts}^{\star}V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha_{em}}{\pi C}(P+N)$$

$$P+N = (C_{7,SM}^{\mathrm{eff},(0)} + B\Delta C_{7,H^+}^{\mathrm{eff},(0)})^2 + A$$

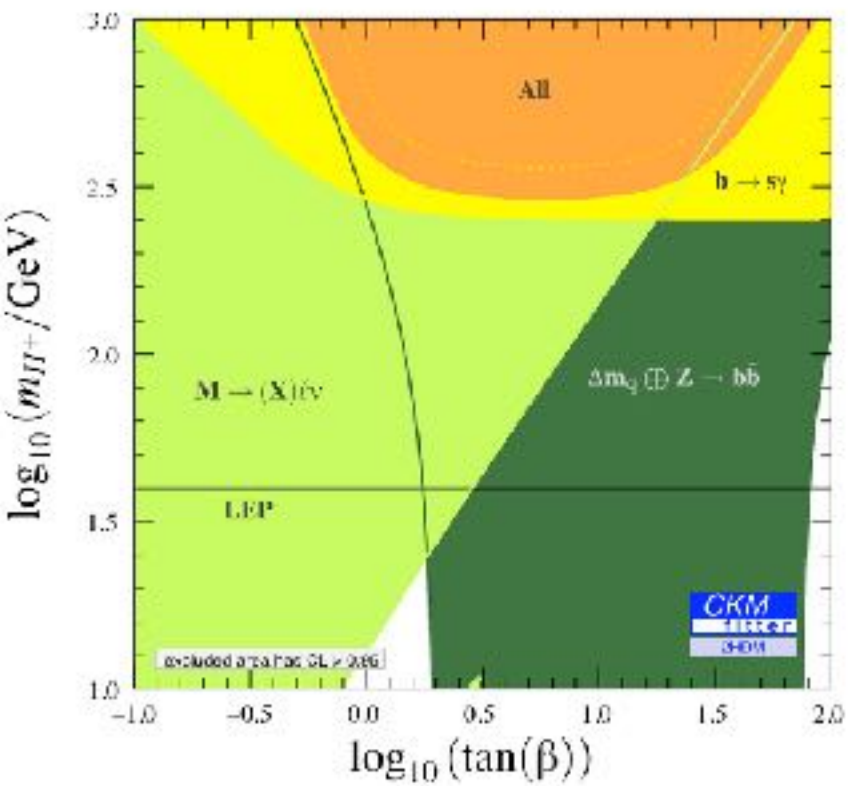


Widely investigated in the literature.
- A.J. Buras, M.Misiak, M.Munz, S. Pokorski, Nucl Phys. B424
- K. Chetyrkin, M. Misiak, M. Munz, Phys. Lett. B400.
- P. Gambino, M.Misiak Nucl., Phys. B611.
- M.Misiak, M. Steinhauser Nucl. Phys. B764.
- C. Degrassi, P. Gambino, P. Slavich, CERN/2007-265
- T. Besmer, C. Greub, T. Hurth, Nucl. Phys. B 609.

- Almost unidimensional constraint on the charged Higgs mass. Weak tanβ dependance at large values, where leptonic decays ARE constraining.

4.2 Two Higgs Doublets Model (Top-Down)

- Combined constraints:

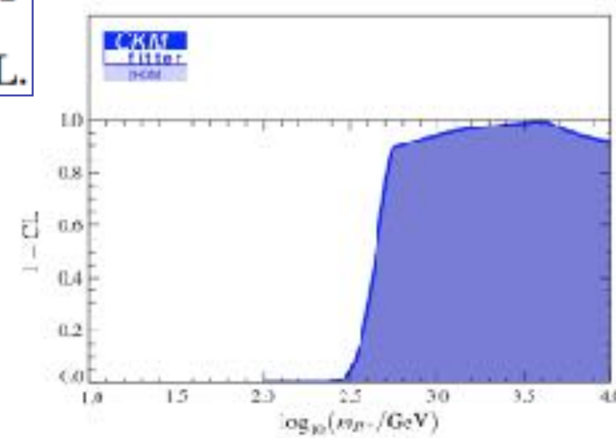


- Leptonic decays (mainly BR($B^+ \to \tau^+\nu$)) constrain the parameter space at large tanβ.

- unidimensional constraint (orange) on M_{H+} mostly by $b \to s\gamma$.

- 2HDM(II) does not perform better than the SM.

$$\boxed{M_{H+} > 310\ \text{GeV}/c^2 \text{ at } 95\%\ \text{CL.}}$$



CP violation

- CKM mechanism is at work for describing quark flavor transitions.
- KM phase likely to be dominant in *K* and *B* mesons.

- 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:

$$\alpha + \beta + \gamma = (182.7 \pm 7.1)^\circ$$

- Hunt for rare decays (and less rare) where BSM contributions might occur.

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

- This is the physics case of the LHCb experiment and super KEKB programs ! Exciting times ahead.

Concluding remarks

- Symmetries in Physics are beautiful and powerful.
- Symmetry violations and breaking are not less beautiful.
- The SM has been raised legitimately to a theory of Nature.
- But it's still an effective model. Strong experimental evidences (mostly cosmological) that we need beyond SM *CP*-violating phases and dark matter. On top of that, neutrino sector is still to be understood. Particle Physicists's job to reach BSM.
- Particle Physics is orphan now of the LHC no-loose theorem.
- We need to find the way (the energy scale of BSM Physics) but we have the tools to write the maps:
  - Precision measurements (flavour physics (CP and rare decays) for near future).
  - Direct searches (LHC Run II for near future).