CP violation at Colliders: an introduction

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Introductory Remarks

- We don't know the next energy scale; probably a first since Fermi Theory (in particular, we're orphan of a no-lose theorem).

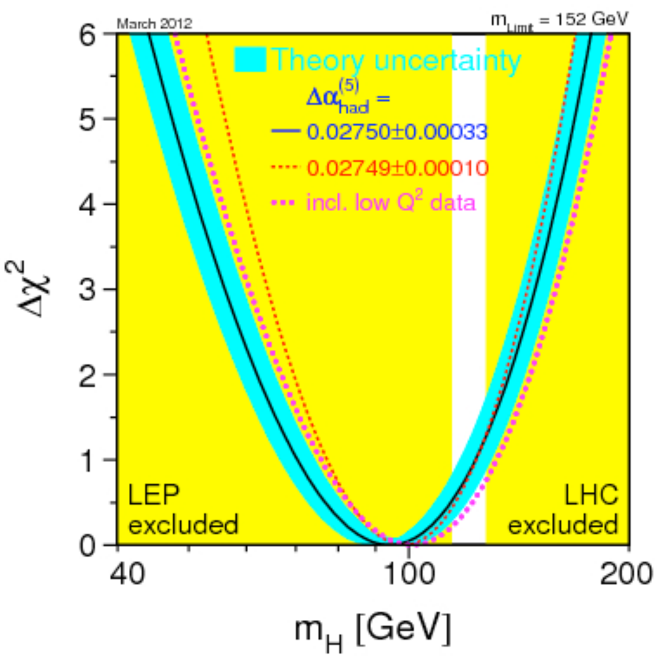
- There are compelling theoretical arguments to go beyond Standard Model (SM). Overlooked here.

- Instead, a number of unnatural features of *Nature* as we grasped it so far, whose study shall guide the quest:
    - Absence of strong *CP* violation
    - Fine-tuned hierarchy of masses (quarks and leptons)
    - Fine-tuned fermion mass mixing matrices
    - *CP* and fine-tuned number of generations

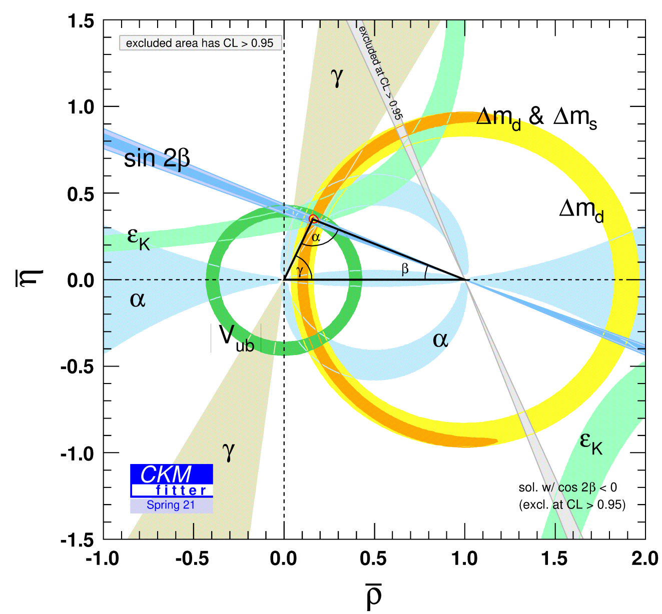
Introductory Remarks

- We don't know the next energy scale; Build on what we know, the two pillars of the SM:

Mass matrix



Mass mixing (quark) matrix



- and gather more precision, at colliders and in focussed experiments.

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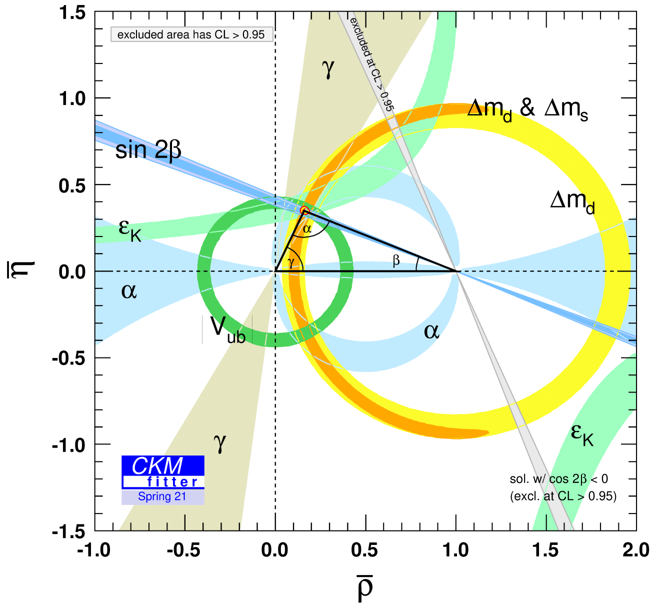

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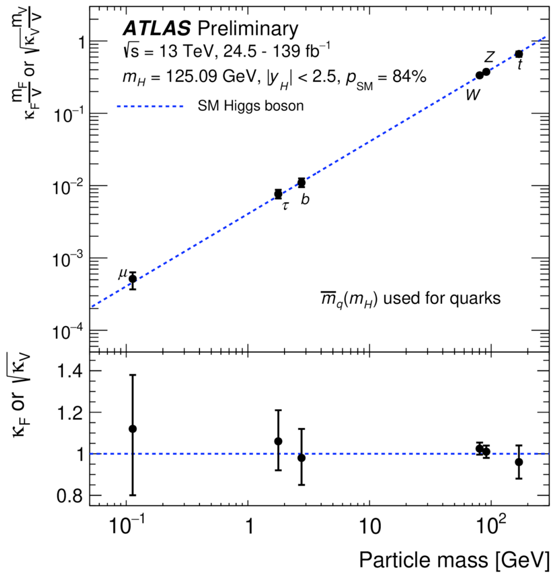

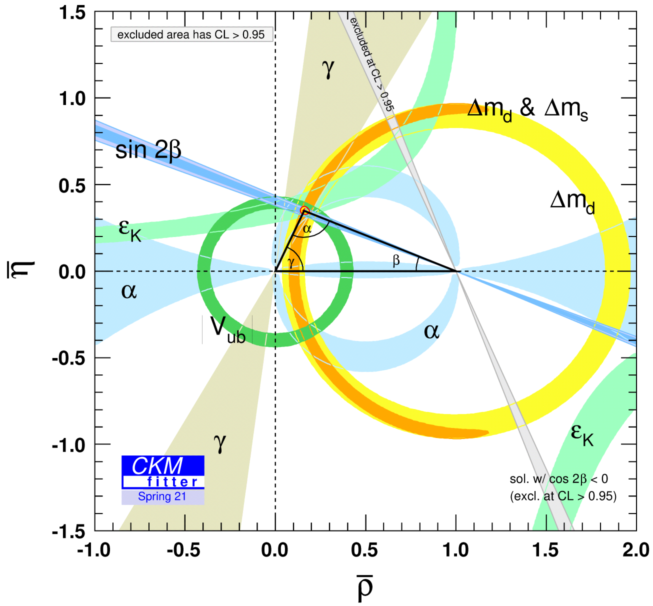

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Outline

- Past and present experimental landscape for Flavours Physics at colliders.

- *CP*V: a state of the art and some lessons for the current programs.

- The projections towards future programmes: HL-LHC and Electroweak—Higgs—Top factories

- Conclusions.

1) The pioneering experiments at colliders.

Several machines, lots of experiments (a selection here)

- e+e- at the Upsilon: symmetrical machines with a wealth of results: DORIS, CESR. B^0 mixing discovery at ARGUS, first hint of non-vanishing $|V_{ub}|$ at CLEO etc…

- e+e- at the Z, LEP era: few millions of bbar pairs produced. B^0 mixing probability accurately measured, first measurements of non-vanishing $|V_{ub}|$, lifetime measurements, B_s mixing cornered etc…

- e+e- at the Upsilon, asymmetric machines PEPII and KEKB: the establishment of the second pillar of the SM.

- Tevatron: a wealth of results mostly with the Bs meson. B_s mixing measured, Bs2mumu cornered, CPV in mixing etc…

1) The present experimental landscape at colliders.

Two machines, four experiments

- LHC: hadron collider, three experiments addressing Flavour Physics. One dedicated, LHCb.

- SuperKEKB: asymmetric e+e- operated at the Upsilon(4S) threshold. One experiment, Belle II.

- Obvious complementarity: distinctive features, different experimental environments.

- Similar timelines from now on. LHCb and Belle II will take concurrently data for the next decade. LHCb Upgrade at HL-LHC EoI→TDR. Belle Coll. envisions as well an upgrade (5x50/ab).

- Let's note that a kaon Physics program is running as well in parallel - another view of the Unitarity from rare kaons $K\to\pi\nu\nu$.

CKM: the unitarity triangle.

- The fundamental scalar field v.e.v. gives mass to bosons (EWSB) but also fermions (quarks and leptons), through the Yukawa couplings but this is not the end of the story:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5)V_{ij}d_j] + \text{h.c}$$

- After spontaneous symmetry breaking, and once the mass matrices are diagonalised, it determines also how the mass and weak eigenstates are related. This is the CKM matrix. As for the (fermion) masses, nothing is predicted except the mass matrix must be unitary and complex.

$$\begin{pmatrix} u \\ s \\ b \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ b \end{pmatrix}_{MASS}$$

CKM: the unitarity triangle.

- Weak eigenstates are therefore a mixture of mass eigenstates, controlled by the Cabibbo-Kobayashi-Maskawa elements V_{ij}: flavour changing charged currents between quark generations.

- This matrix is a 3X3, unitary, complex, and hence described by means of four parameters: 3 rotation angles and a phase. The latter makes possible the *CP* symmetry violation in the Standard Model (3 gen. at least required).

- These four parameters are free parameters of the SM. As for electroweak gauge precision tests, they must be measured with some redundancy and the SM hypothesis is to be falsified by a consistency test. We will review in this talk this global test. But let's define first the parameters.

CKM: parameterisation.

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

Consider the Wolfenstein parametrization as in EPJ C41:1-131,2005 : unitary-exact at each order and phase- convention independent:

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

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively.

- A is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays.

- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

CKM: representation.

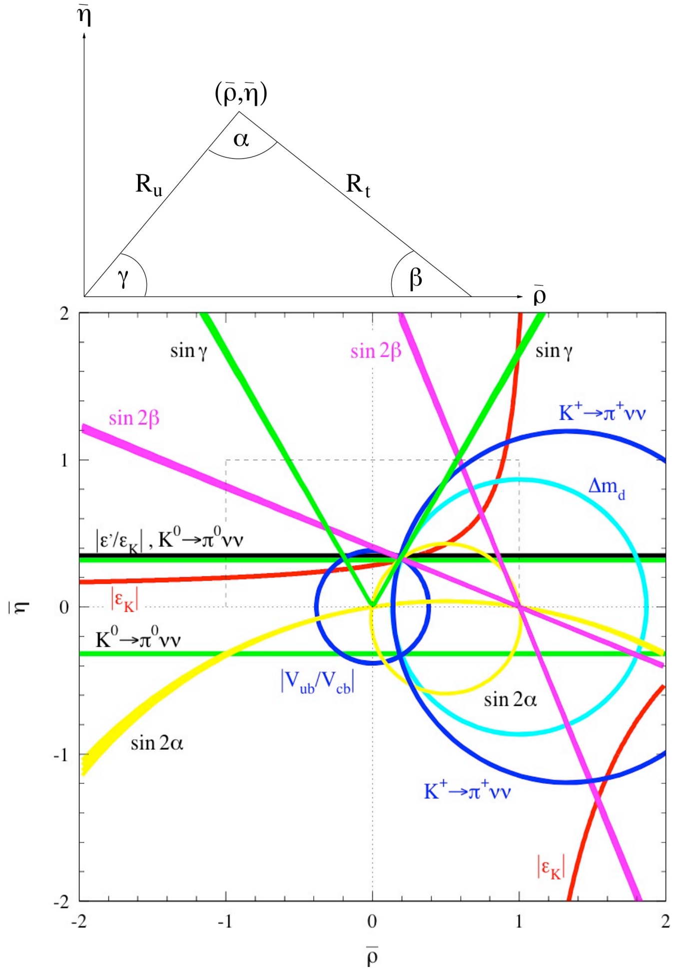
- An elegant way to represent the unitarity relations is to display them in the complex plane.

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

- The area of the triangle is half the Jarlskog invariant and measures the magnitude of the *CP* violation:

$$J \sum_{\sigma\gamma=1}^{3} \epsilon_{\mu\nu\sigma}\epsilon_{\alpha\beta\gamma} = \mathrm{Im}(V_{\mu\alpha}V_{\nu\beta}V_{\mu\beta}^*V_{\nu\alpha}^*)\ ,$$

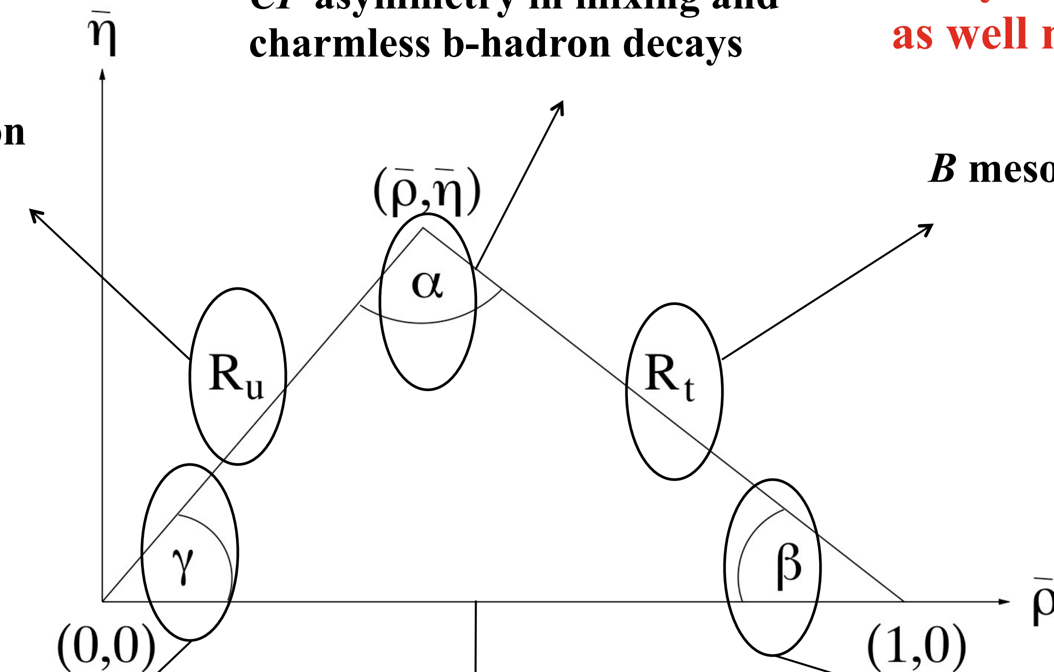
$$J = A^2\lambda^6\eta(1-\lambda^2/2) \simeq 10^{-5}$$



CKM: executive summary

- Summary:

B-factories measure everything but λ. LHCb as well nowadays !



2) CPV, a state of the art at colliders.

The observables relevant to the CKM profile (hence allowing predictions to be made):

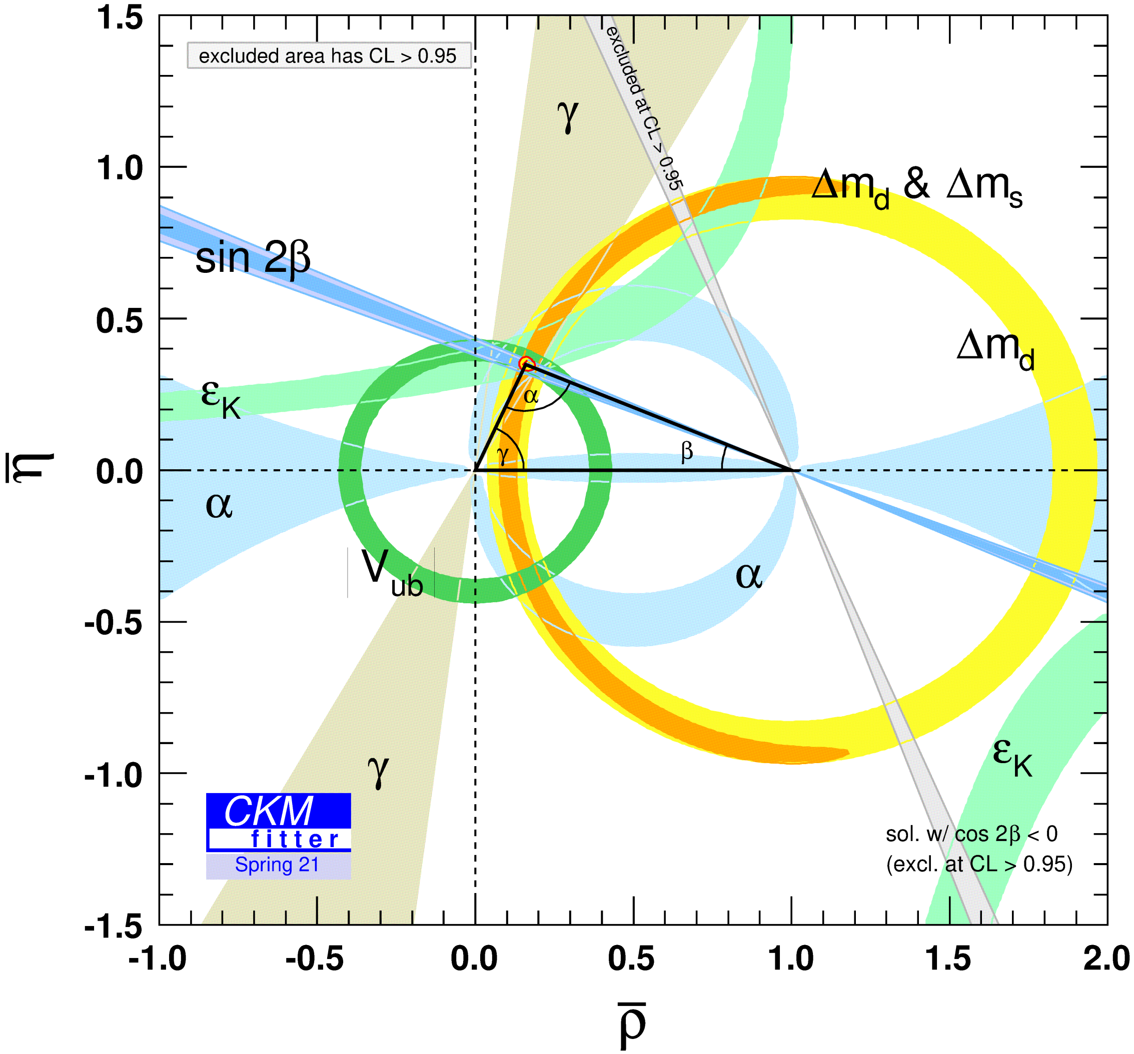
- Chosen to be experimentally precise and theoretically clean (enough).
- The *CP*-conserving observables: neutral *B* meson oscillation frequencies (fully dominated by hadronic parameters - decay constants and bag factors), V_{ub} and V_{cb} matrix elements from semileptonic decays of *b*-hadrons.
- The clean *CP*-violating observables: CKM angles. Almost theory-free presently.
- The (less-clean) *CP*-violating asymmetry in the mixing of kaons.

2) CPV, a state of the art at colliders.

A selection of *CP*-violating observables relevant to the null-tests of the SM:

- Weak mixing phase of the Bs
- *CP*-violating (semileptonic) asymmetries in the *B* mixing.
- Mixing-induced *CP* violation in $\Delta B = 1$ transitions.
- *CP* asymmetries in charm mixing and decays.
- etc…
- … + many others about *CP*-conserving obs. , *e.g.* rare decays

2) CPV, a state of the art at colliders, the broad picture



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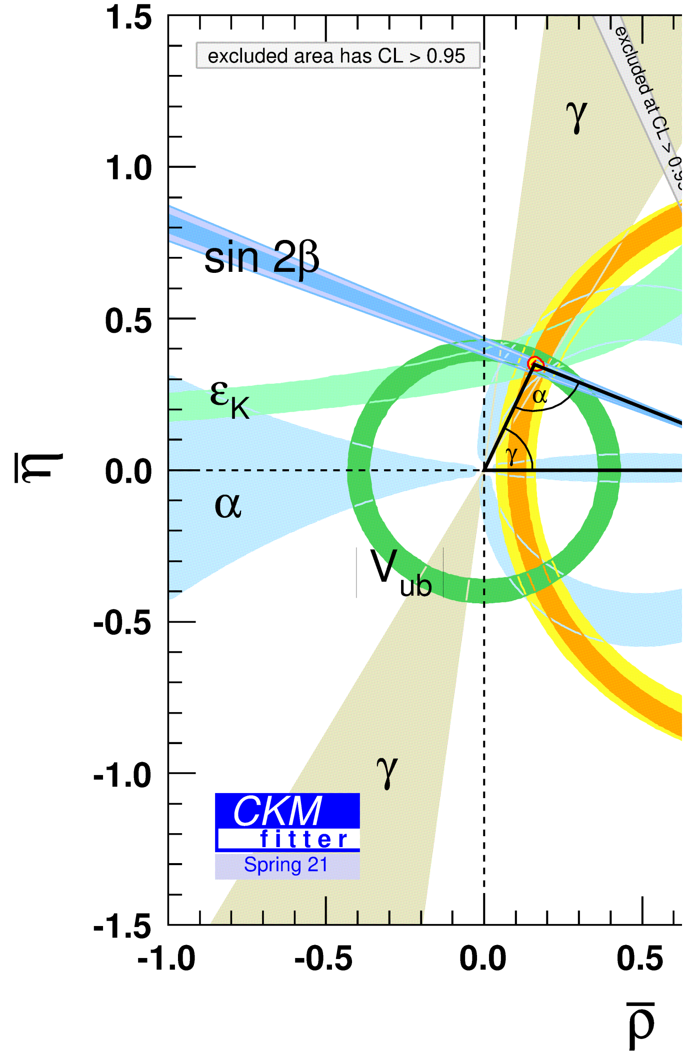
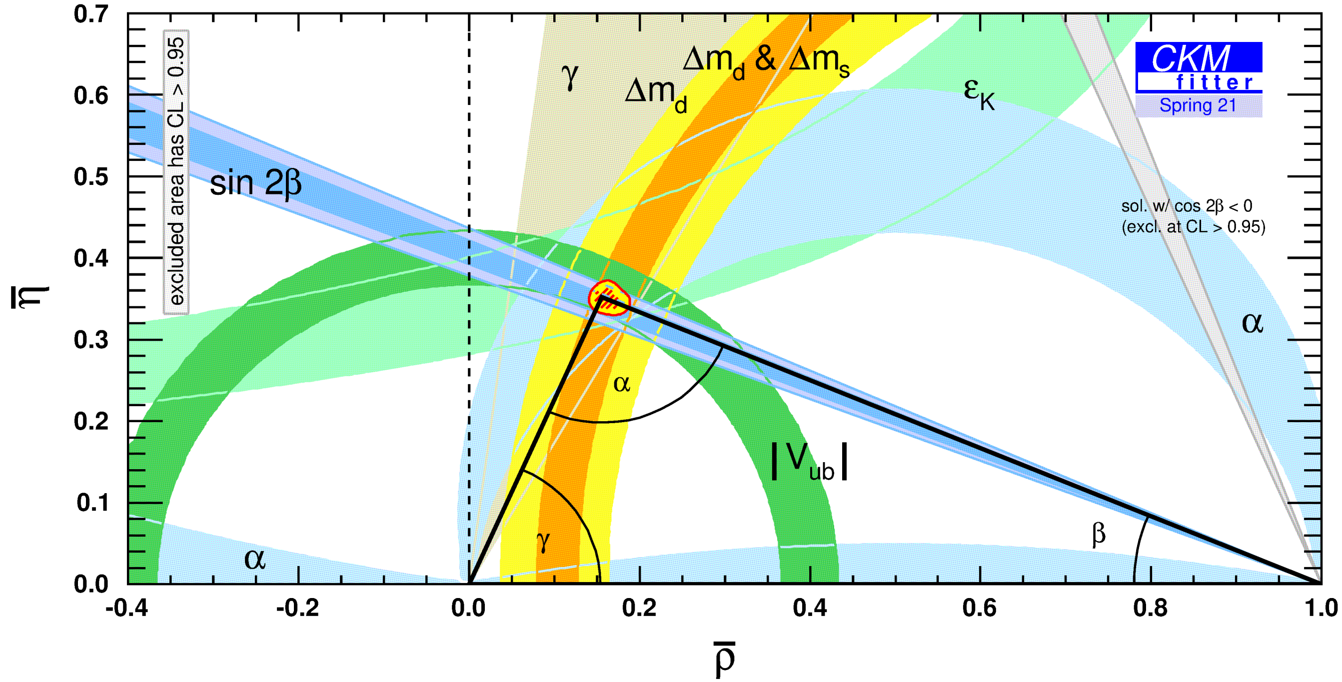


The second pillar of the SM :

- Remarkable consistency of all observables within the SM. The SM passes the test and one can do the metrology of its parameters.
- CKM is at work in charged EW currents.
- KM paradigm IS the dominant source of *CP* symmetry breaking.

2) CPV, a state of the art at colliders.

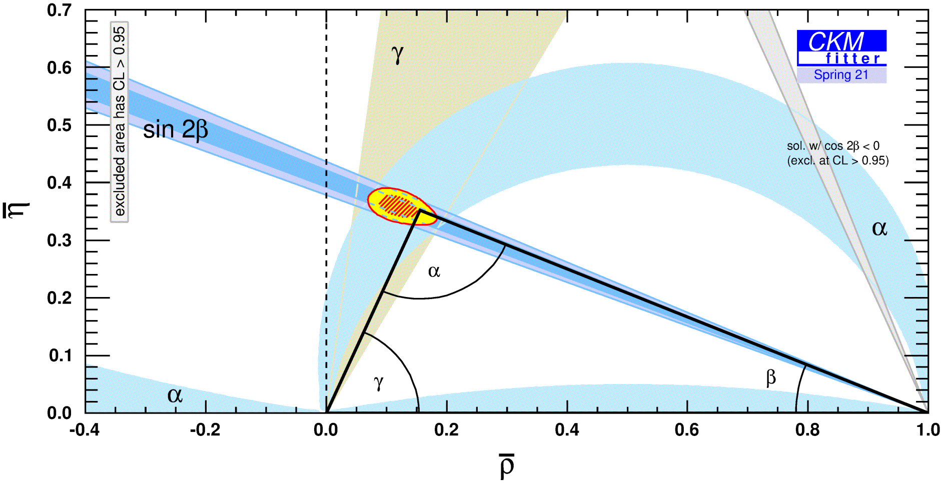
A closer look: the players

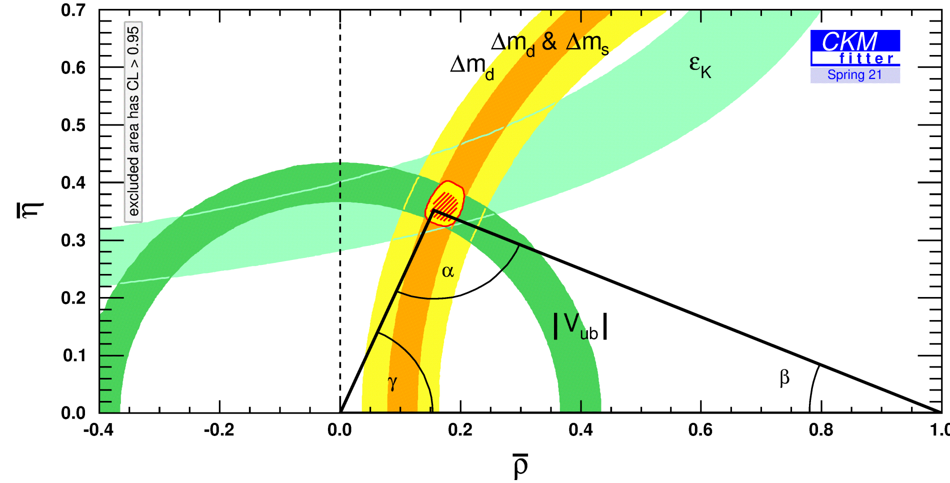


- The *B*-factories established most of this legacy.
- Yet, LHCb drives the gamma angle precision, and stepped in significantly in $|V_{ub}|$ and $|V_{cb}|$ matrix elements determination.

2) CPV, a state of the art.

A closer look: theory-free vs hadronic parameters.

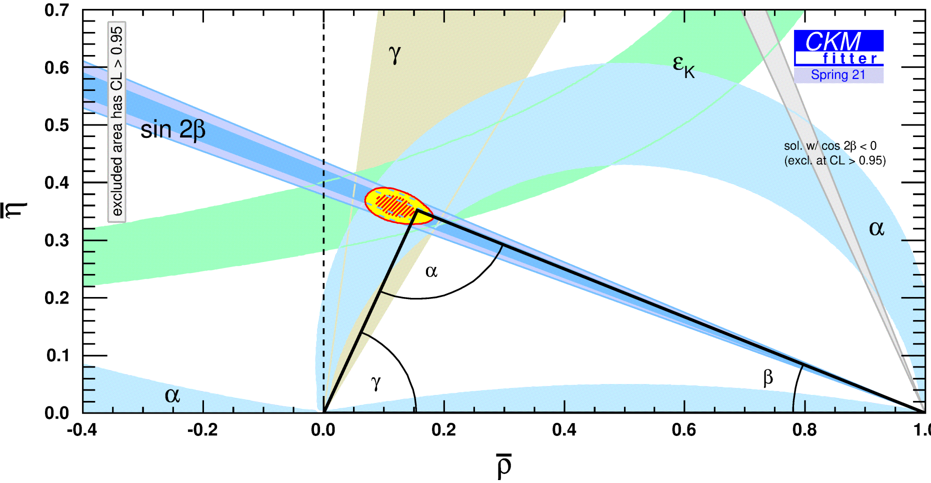


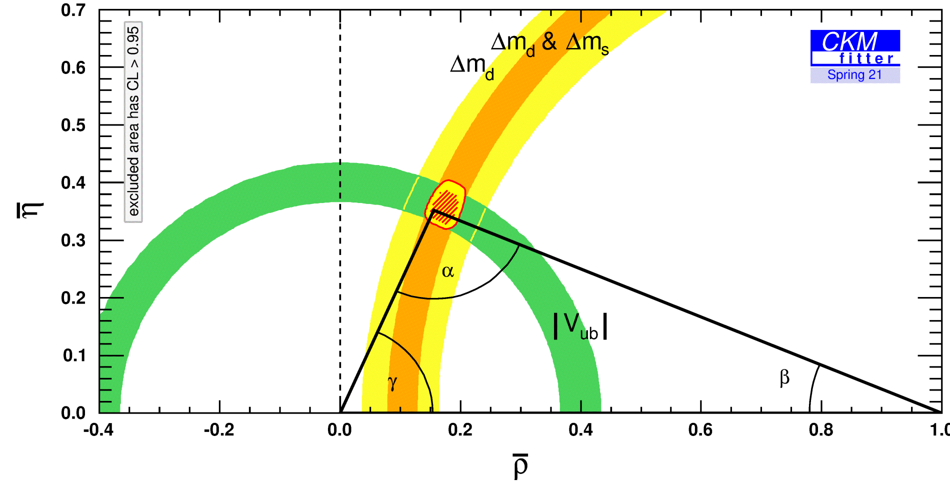


- Remarkable agreement.
- Acknowledgement of the progresses and successes of lattice QCD in particular to predict the hadronic parameters and the form factors.

2) CPV, a state of the art.

A closer look: *CP*-conserving vs *CP*-violating.

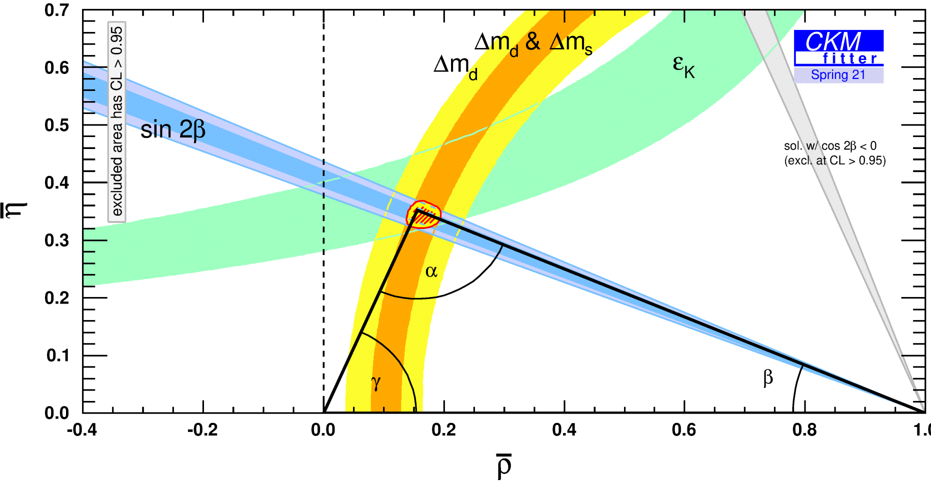


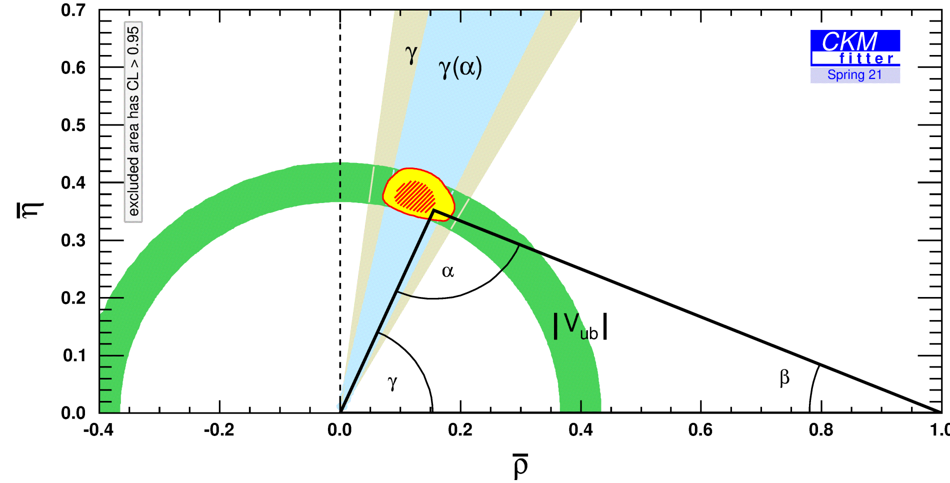


- Again remarkable agreement.
- Acknowledgement of the progresses made in LQCD (here semileptonic form factors, decay constants and bag factors).

2) CPV, a state of the art.

A closer look: loops vs trees.





- Again remarkable agreement.
- Obvious display of the importance / necessity of a more precise gamma. LHCb on its way. LHCb upgrade I/II in perspective.
- Same comment in order for the matrix element $|V_{ub}|$. Belle II soon.

2) CPV, a state of the art, beyond the CKM profile

Quasi-model-independent constraints on BSM in in the mixings

- Fix the apex by considering (model-dependence lies in particular in here) that four-fermions couplings are SM and 3x3 unitarity holds : main players are gamma and V_{ub} (V_{cb}).

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

- Model the BSM contributions in mixing as a complex number multiplying the SM mixing hamiltonian matrix elements

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

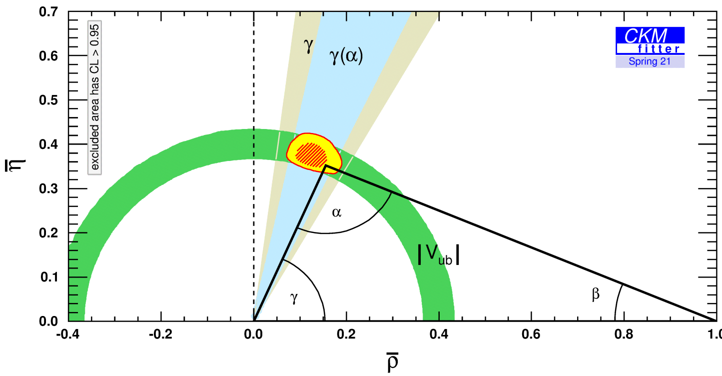
$$\langle B_q | \mathcal{H}^{\rm SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\rm SM}_{\Delta B=2} | \bar{B}_q \rangle \times \left(\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q)\right)$$

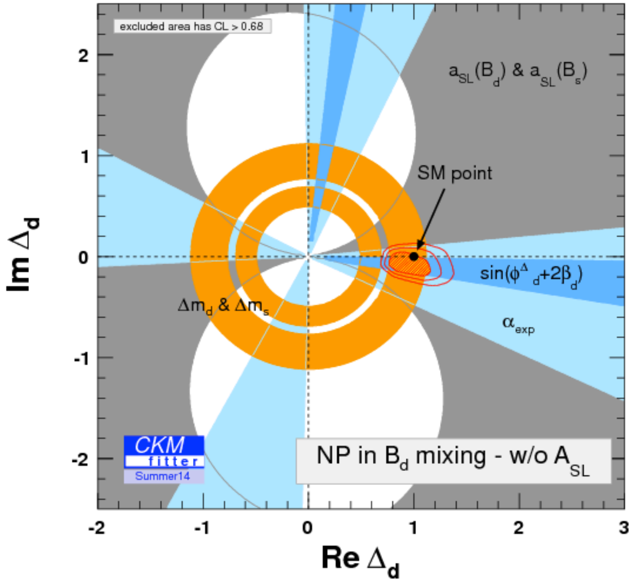
parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\rm NP}\rvert \times \Delta m_q^{\rm SM}$
2β	$2\beta^{\rm SM} + \Phi_d^{\rm NP}$
$2\beta_s$	$2\beta_s^{\rm SM} - \Phi_s^{\rm NP}$
2α	$2(\pi - \beta^{\rm SM} - \gamma) - \Phi_d^{\rm NP}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$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

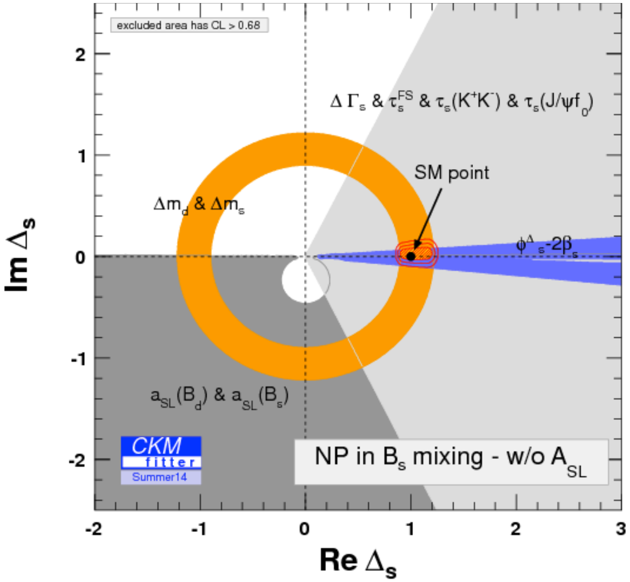
2) CPV, a state of the art, beyond the CKM profile

Model-independent constraints on BSM in in the mixings

- Fix the apex by considering that four fermions couplings are SM : main players are gamma and V_{ub} (V_{cb}).





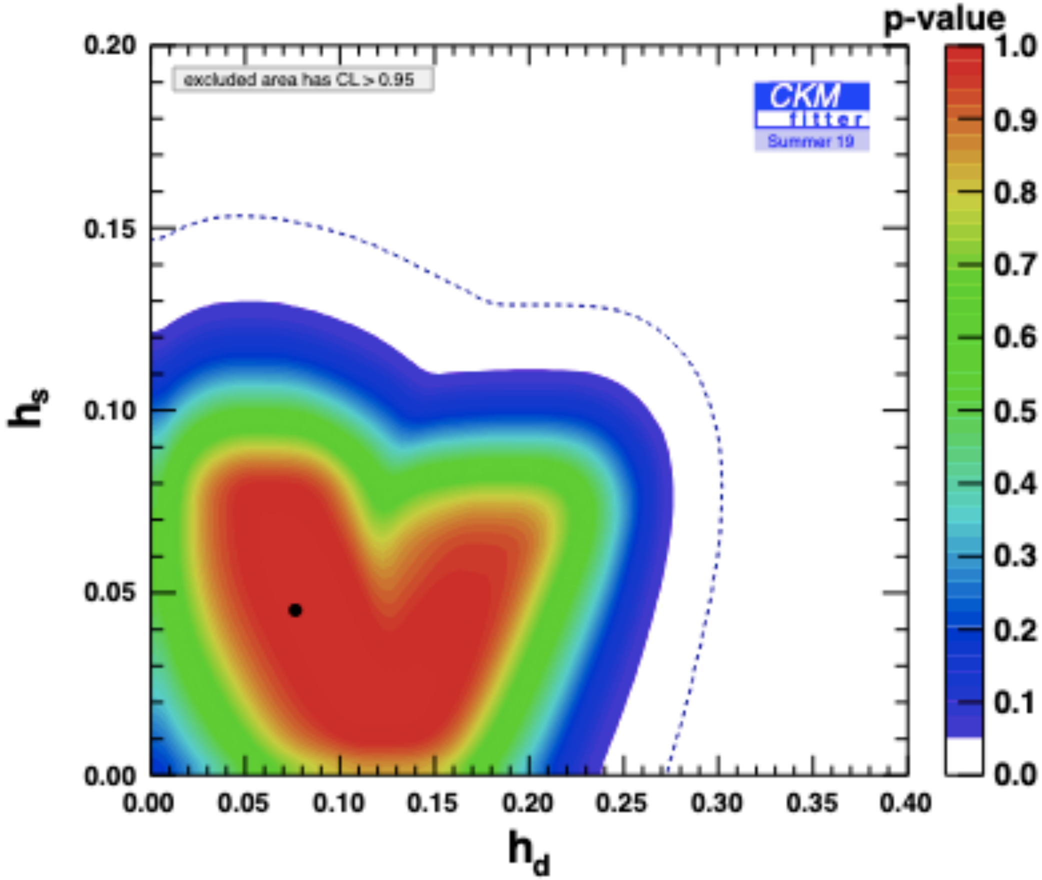


Sizeable NP is still allowed by the LHCb constraint in both B_d and B_s mixing.

Model-independent constraints on BSM in in the mixings

- Another view can be obtained from a parameterisation of New Physics with modulus and phase, instead of cartesian model.

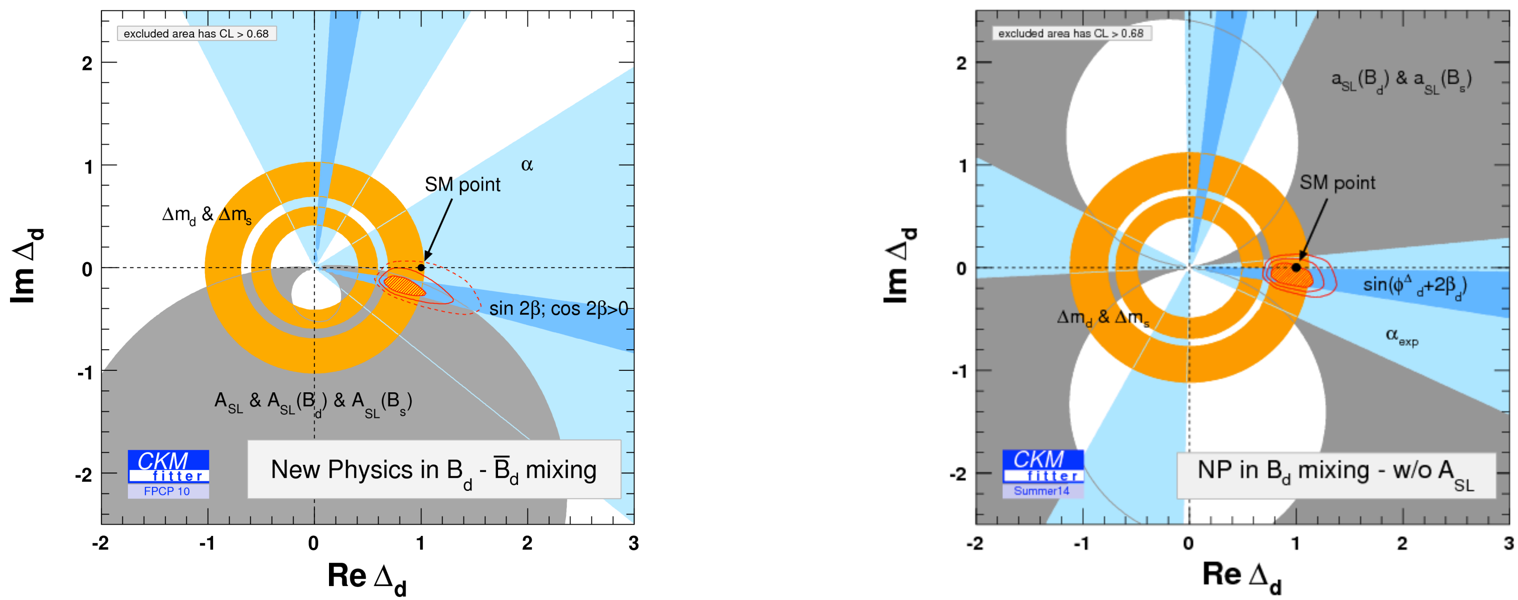
$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$



2) CPV, a state of the art, aparté

Model-independent constraints on BSM in in the mixings

- Back at the beginning of the previous decade, Belle observed for the first time the decay $B^+ \to \tau^+ \nu$ (sensitive to V_{ub}) with a quite high branching fraction.
- This favoured high values of $\sin 2\beta$ in the SM. A new phase in the *Bd* mixing accommodated the SM $B^+ \to \tau^+ \nu$ vs $\sin 2\beta$ discrepancy.



2) CPV, a state of the art, intermediate conclusions.

Take away messages:

#1 Tremendous success of the SM.

#2 Yet a single observation almost smashed the SM. If BSM is there and close, it could come as naturally as in the example I chose. Precision in order ! Remember the Russian experiment which stopped just at the edge of the observation of $K_L \to \pi\pi$.

#3 Normalisation matters: at the anticipated precisions of the relevant experiments to come (Belle II full steam and LHCb upgrade I / II), these explorations will be limited by the knowledge of $|V_{cb}|$ and the LQCD uncertainties.

3) The future prospects

- Based on the documents:
  - LHCb upgrade II — https://arxiv.org/abs/1808.08865
  - HL-LHC — http://arxiv.org/abs/1812.07638
  - Belle II/III — https://arxiv.org/abs/1808.10567
  - FCC-ee — http://cds.cern.ch/record/2651294/

- Machine / Experiments distinctive characteristics:

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

3) The future prospects in the next two decades — Belle II in one slide.

- Belle II is approved, up and running.
- Belle II case for *CP* violation is obvious: *e.g.*

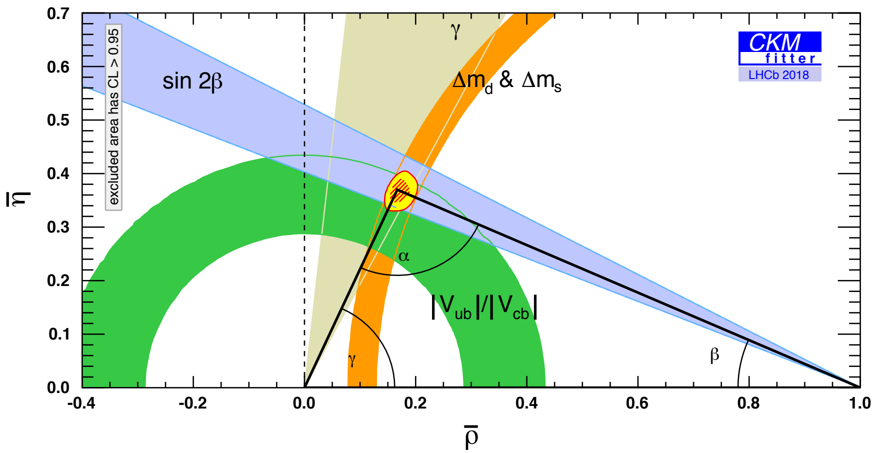
Table 8: Belle II Golden/Silver observables on the measurement of time dependent CP violation in B decays and the measurement of the UT angles ϕ_1 and ϕ_2. See the caption in Table 4 for more details.

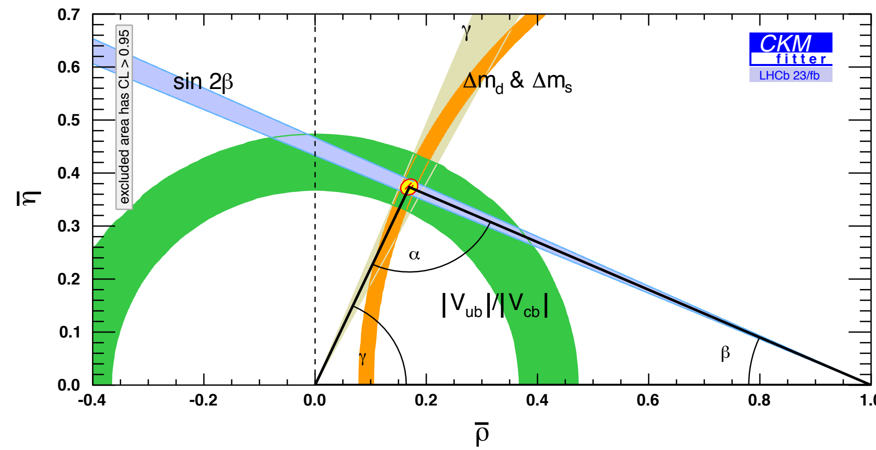
Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to J/\psi K_S^0$	ϕ_1	★★★	5-10	★★	★★	★	★
$B \to \phi K_S^0$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \eta' K_S^0$	ϕ_1	★★	>50	★★	★★★	★	★★★
$B \to \rho^\pm \rho^0$	ϕ_2	★★★	>50	★	★★★	★	★
$B \to J/\psi \pi^0$	ϕ_1	★★★	>50	★	★★★	-	-
$B \to \pi^0 \pi^0$	ϕ_2	★★	>50	★★★	★★★	★★	★★
$B \to \pi^0 K_S^0$	S_{CP}	★★	>50	★★★	★★★	★★	★★

- Relevant at many other places of the case.

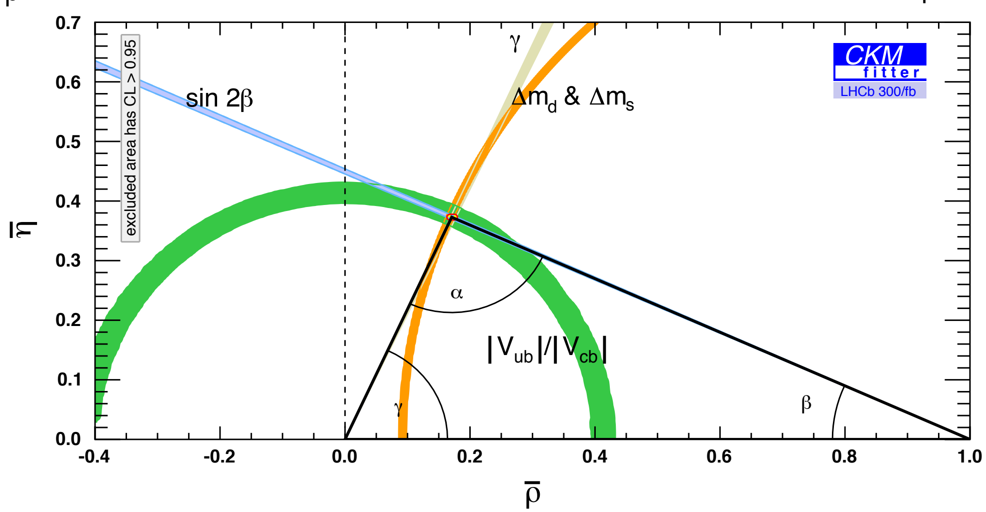
3) The future prospects in the next two decades—LHCbUII in one slide.

- A Framework Technical Design Report is issued by the LHCb collaboration for an upgrade of the experiment in the times of the HL-LHC, **here**, in phase with the full exploitation of HL-LHC.





w/ LQCD extrapolations

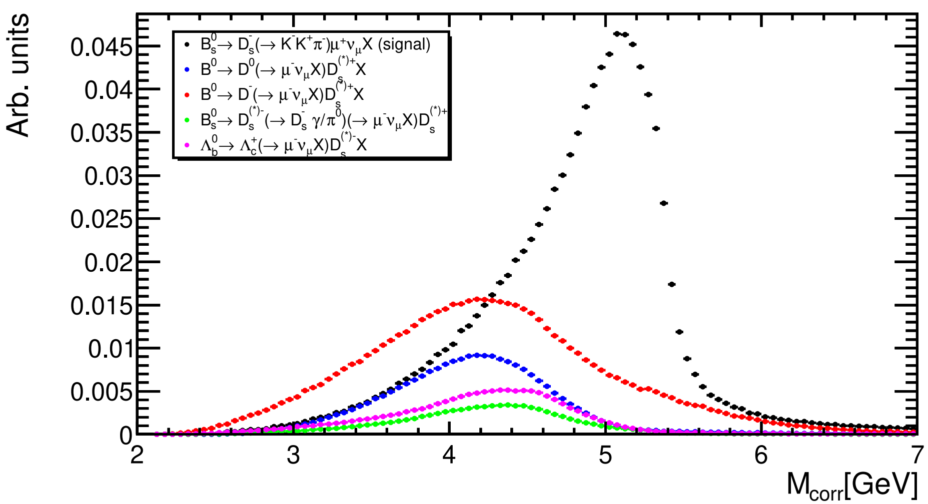


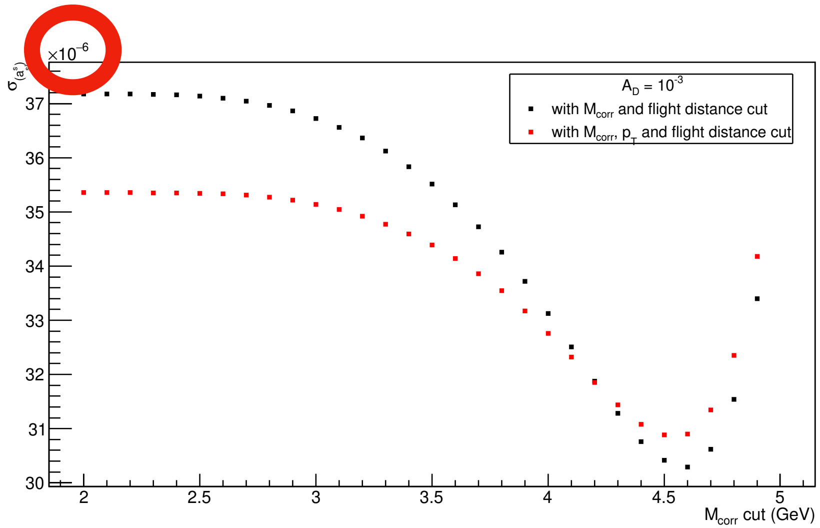
LHCb only

3) The future prospects in two decades— FCC-*ee* in 3 slides

- FCC-*ee* competes favourably with both Belle II and LHCb upgrade precisions, as far as *CP* observables are concerned and can serve as a desirable continuation of the Flavour program (among others).

- One quantitative study (work in progress), to give the flavour of the possible precision. SM value of B_s semileptonic asymmetry is at reach !





- Systematic exploration is yet to perform.

3) The future prospects — FCC-*ee* in three slides

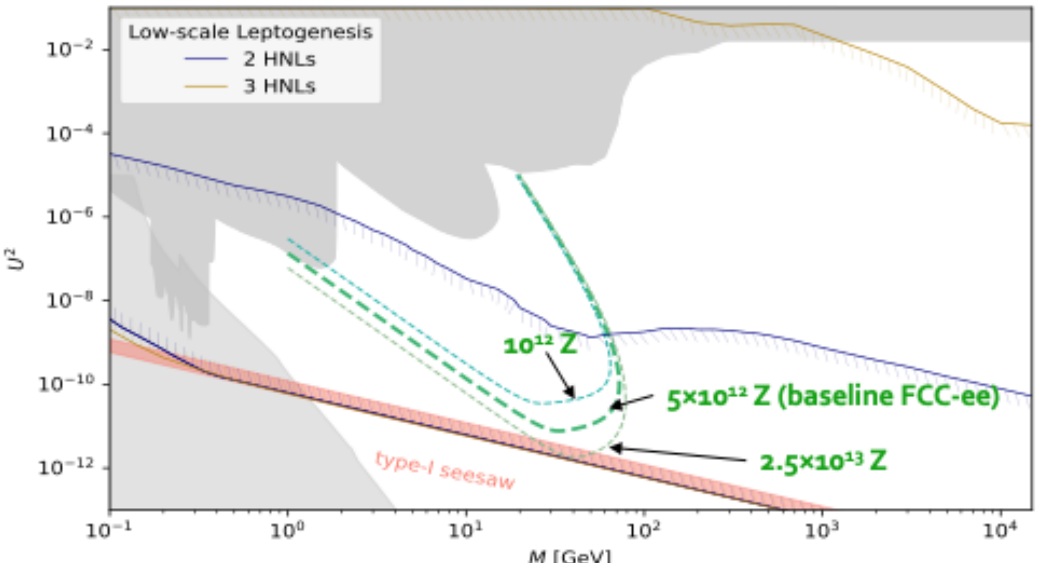
- FCC-*ee* competes favourably with both Belle II and LHCb upgrade, as far as *CP* observables are concerned.

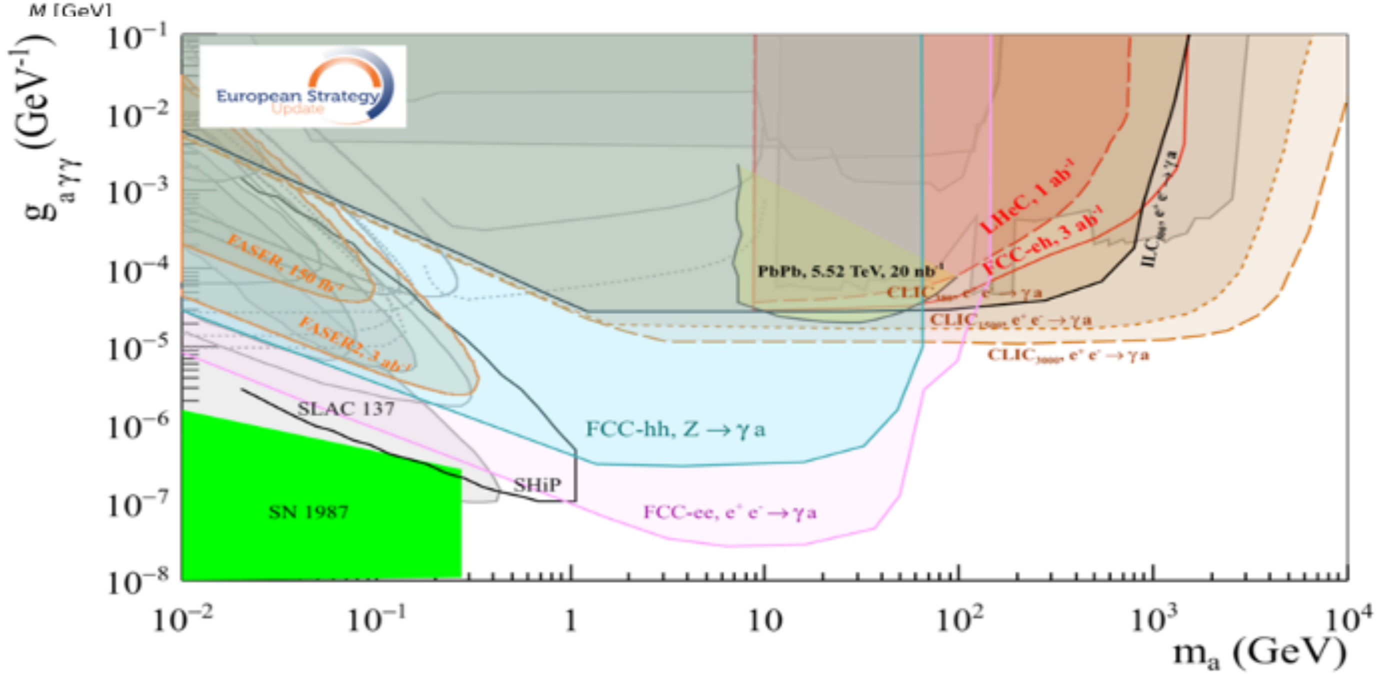
- One of the main limitation of the analysis of BSM contributions in mixings is the normalisation of the CKM profile through V_{cb}.. The possibility of determining it at the *WW* threshold is a game changer.

- Flavour Physics and Electroweak precision tests (the two pillars of the SM) are intertwined.

- Many other areas with discovery potential. For the scope of interest of this Workshop, search for axion-like particles and heavy neutral leptons cover an uncharted territory.

3) The future prospects — FCC-*ee* in three slides





S. Monteil

Concluding remarks.

- Remarkable consistency conveyed by all observables (*CP*-conserving and *CP*-violating) in *b*-, *c*-, *s*-flavoured particle systems. This significantly constrains BSM scenarii. It defines to some extent the Flavour problem.

- The study of *CP* violation in *b*-flavoured hadrons is entering an actual precision era with the LHCb upgrades and Belle II programs which are presently building on. Authentic complementarity, in *CP* studies, as for the rare-and less-rare decays. LHCb Upgrade II under consideration for the full exploitation of the HL-LHC program.

- FCC program has unique capabilities [EWPO (Z and W), Flavours, dark sectors, Higgs factory and top] and is a natural continuation of the Flavour program in the decade 2040s for precision and discovery.

the CKM profile: Back to the future

- As far as *CP* violation is concerned (and by contrast with previous decade)

Vibrant prospectives ahead !

the CKM profile: Back to the future

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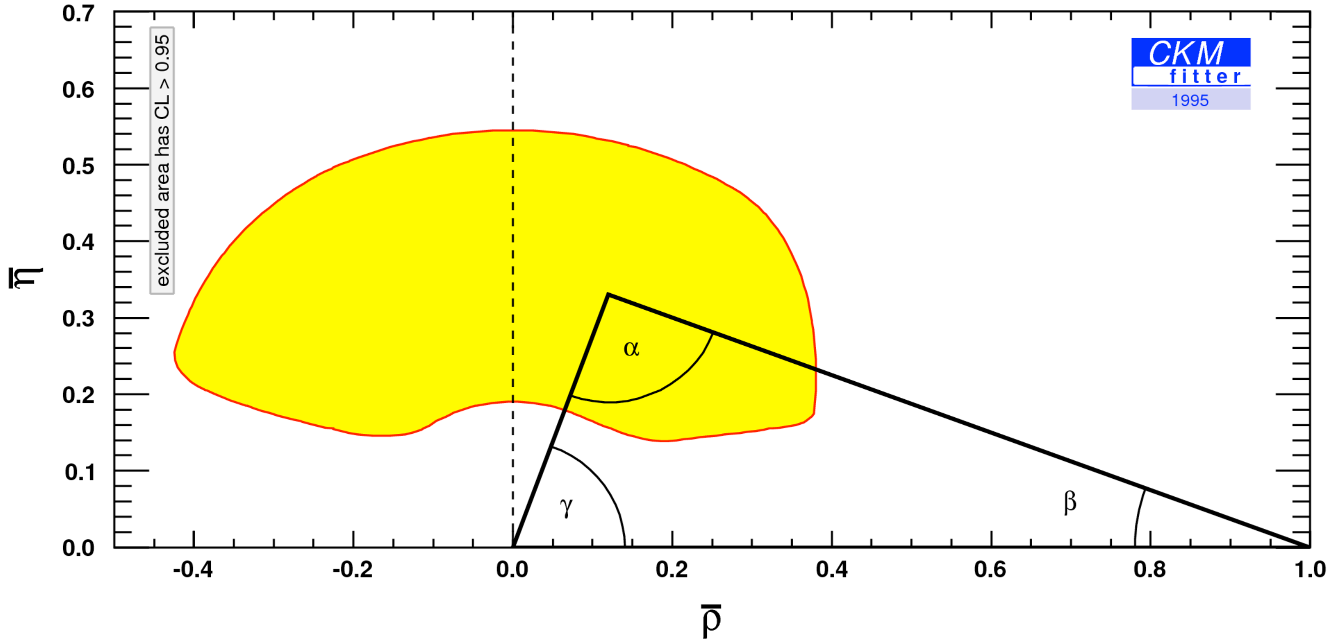

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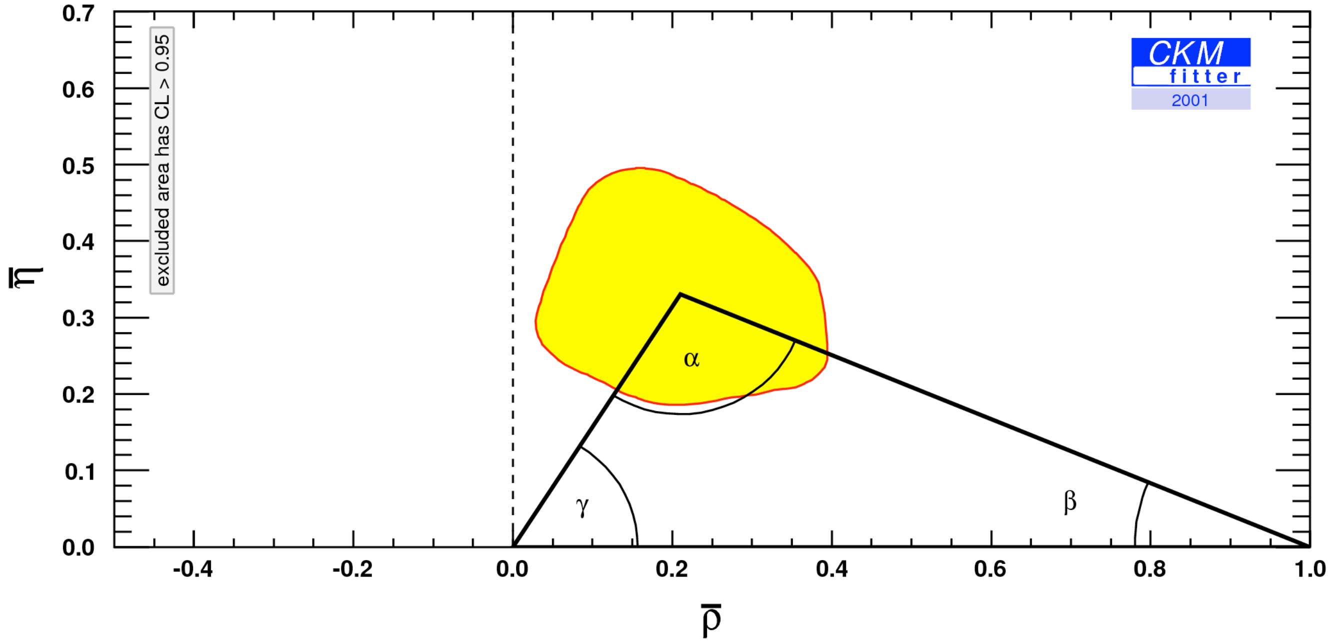

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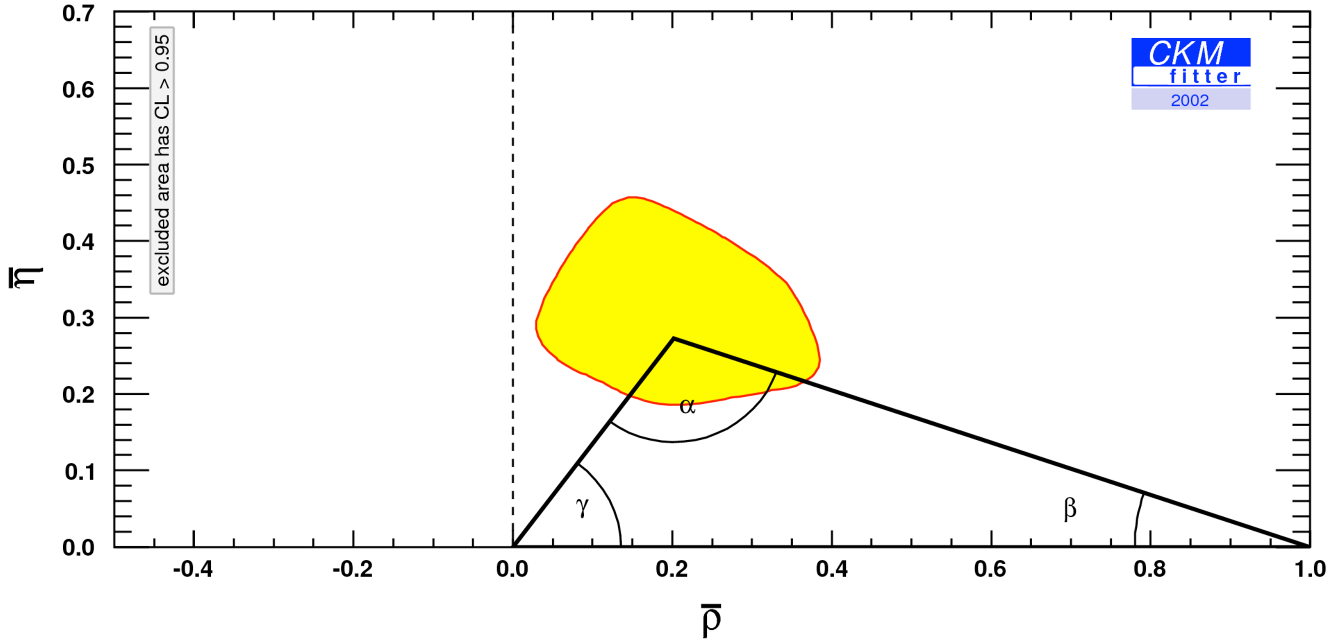

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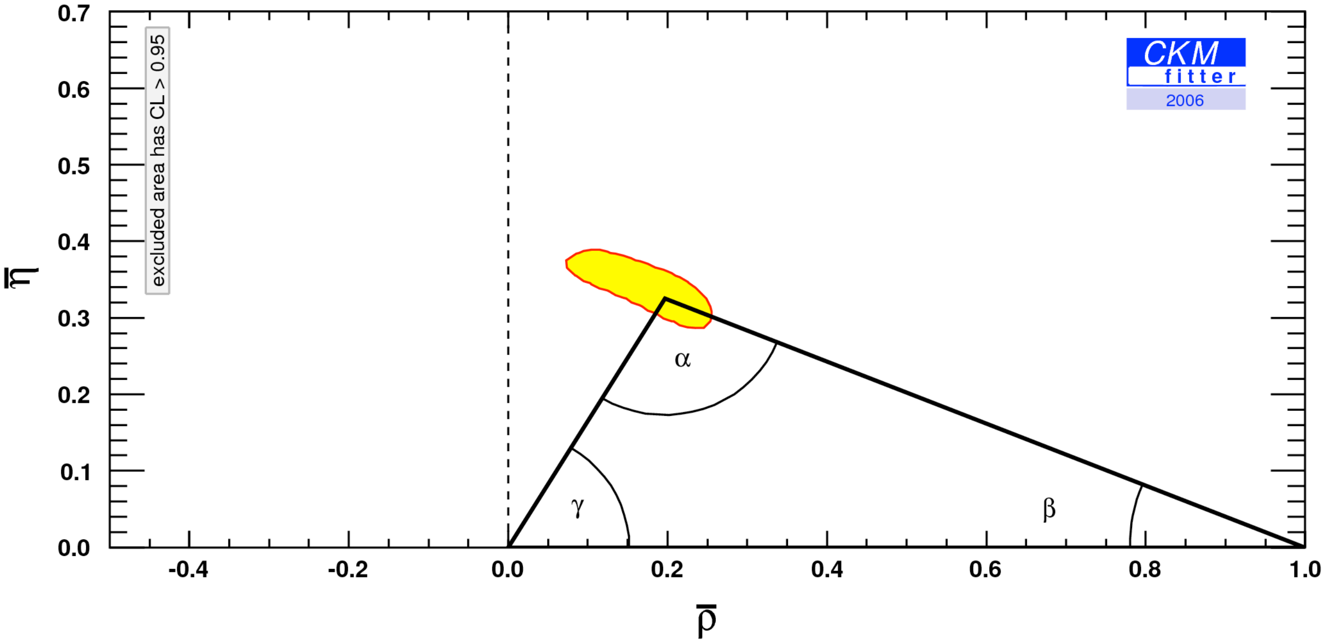
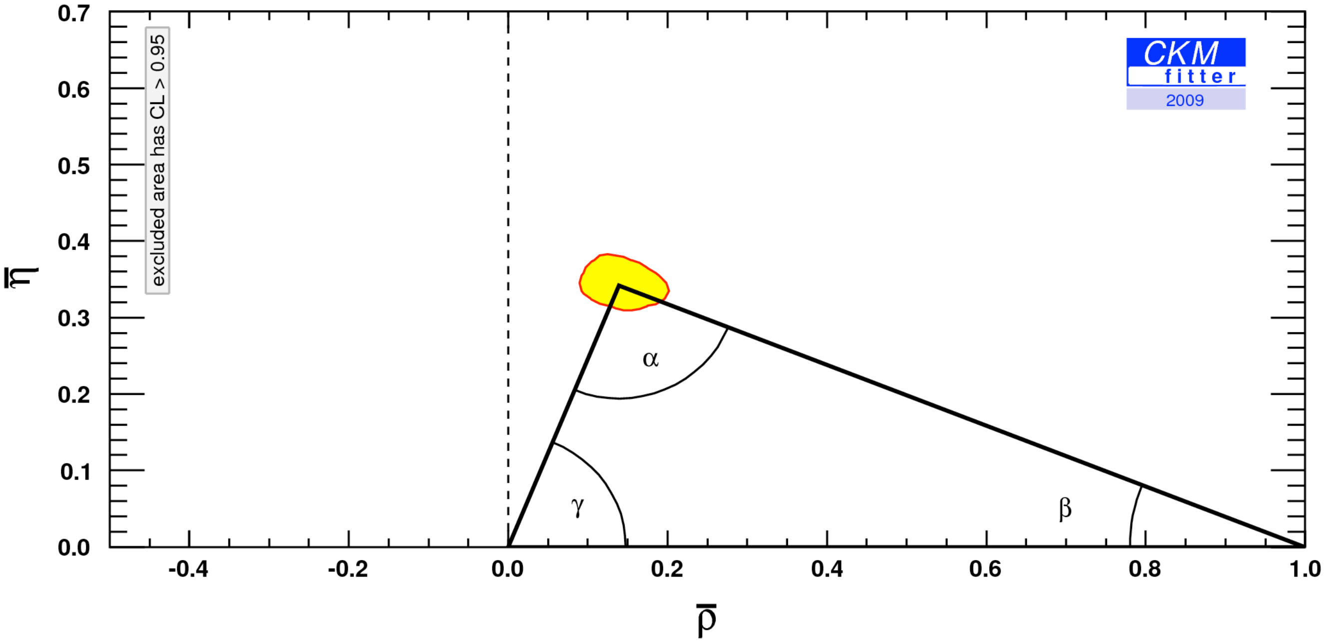


Vibrant prospectives ahead !

the CKM profile: Back to the future

- As far as *CP* violation is concerned (and by contrast with previous decade)



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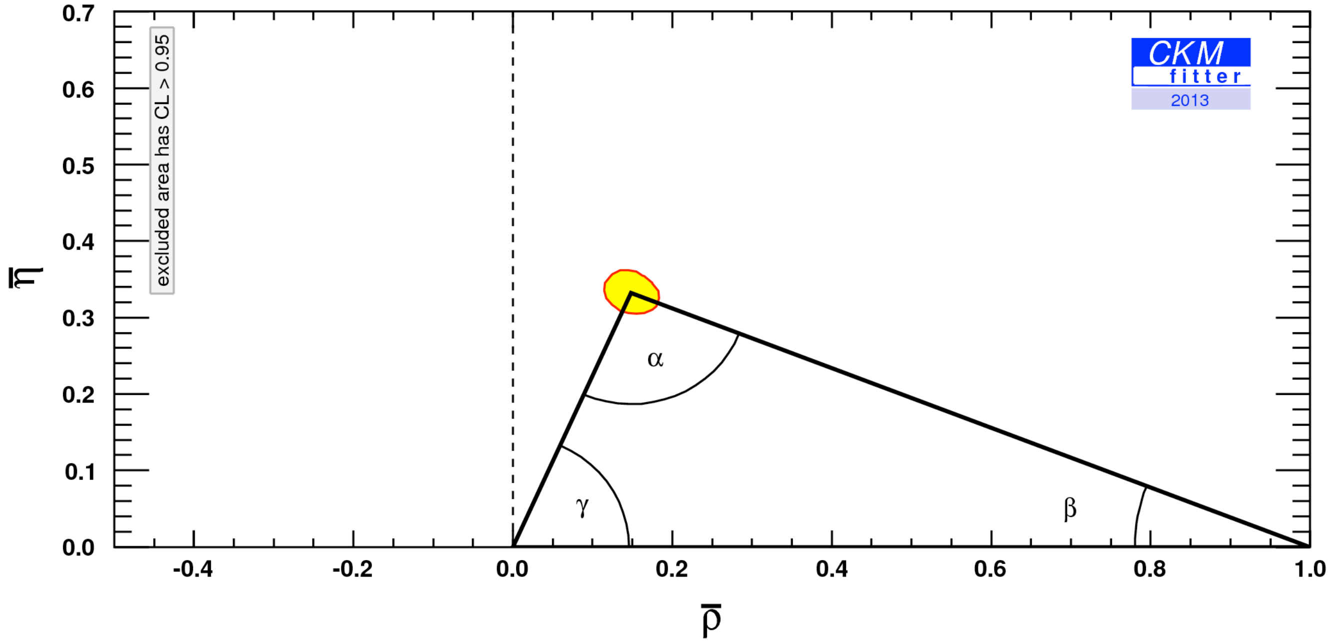

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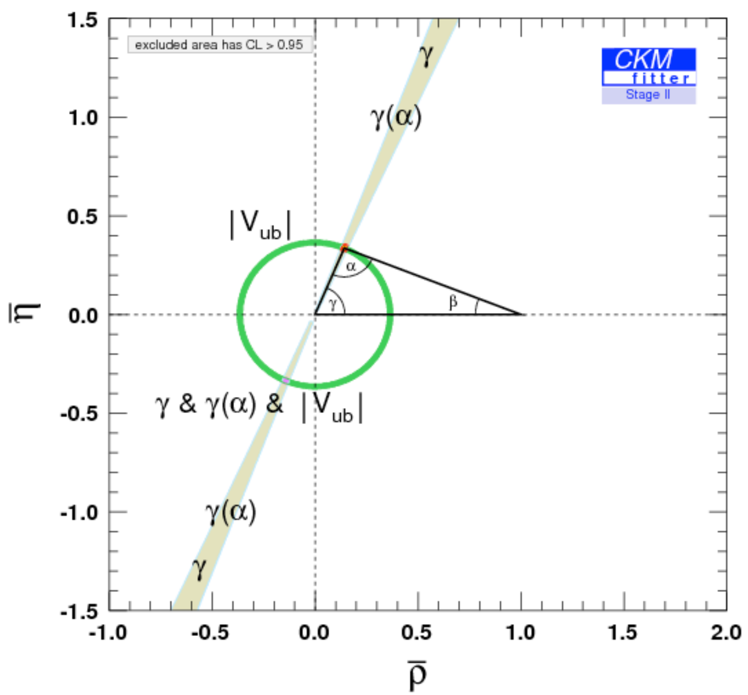


Vibrant prospectives ahead !

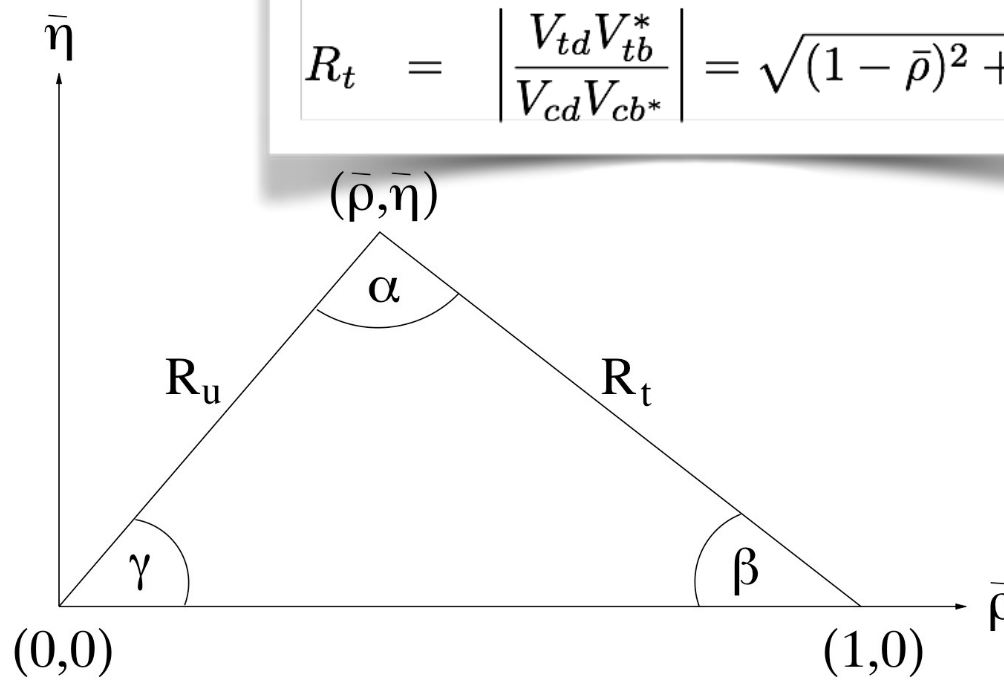
4) Back-up

CKM: the unitarity triangle. Definitions.

- Sides and angles of the unitarity triangle.
- Normalization given by the matrix element $V_{cd}.V_{cb}{}^{*}$.

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar\rho^2+\bar\eta^2}\ ,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}\ .$$



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

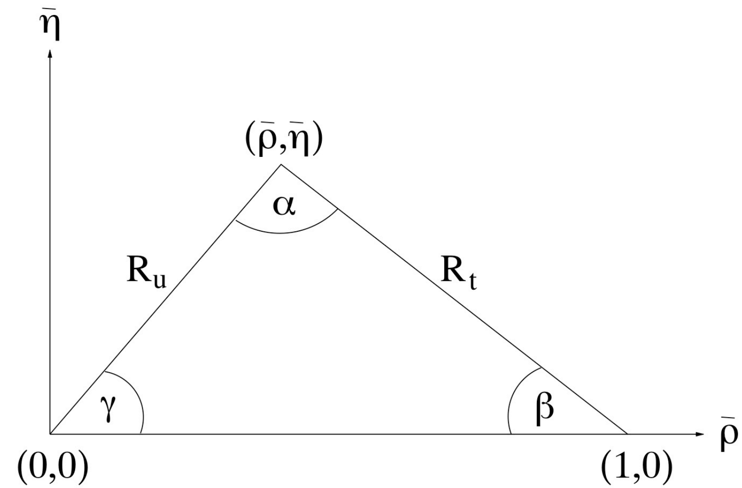
$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

CKM: the unitarity triangle. Definitions.

- Sides of the unitarity triangle. Towards the experimental constraints:

$$
\begin{aligned}
R_u &= \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar{\rho}^2+\bar{\eta}^2}\,, \\
R_t &= \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}\,.
\end{aligned}
$$



- R_u is measured by the matrix elements V_{ub} and V_{cb} determined from the semileptonic decays of *b*-hadrons.

- R_t implies the matrix element V_{td} and hence can be measured from the mixing of B^0 mesons.

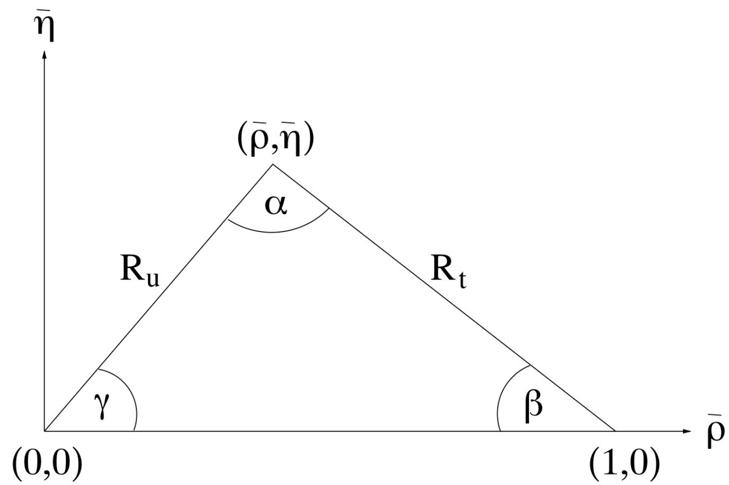
CKM: the unitarity triangle. Definitions.

- Angles of the unitarity triangle. Towards the experimental constraints:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$



- The angle β is directly the weak mixing phase of the of B^0 mixing.
- The angle γ is the weak phase at work in the charmless *b*-hadrons decays.
- The angle α is nothing else than $(\pi-\beta-\gamma)$ and can be exhibited in processes where both charmless decays and mixing are present.

Note: a phase is not an observable. Only phase differences can be measured.

CKM: executive summary

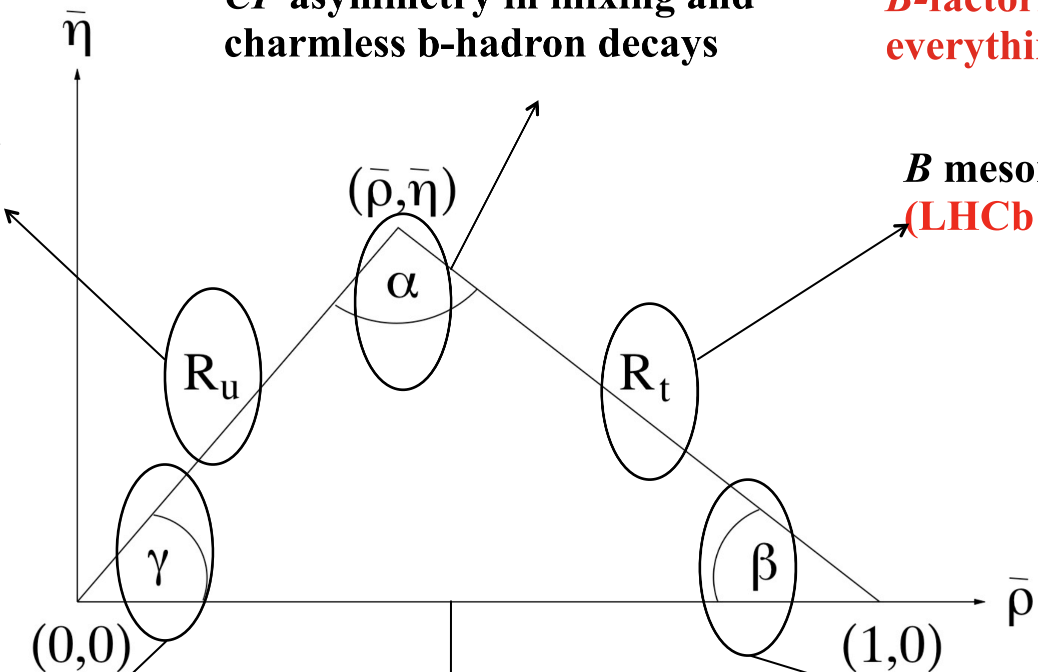
- Summary:

CP asymmetry in mixing and charmless b-hadron decays

B-factories measure everything

Semileptonic b-hadron decays (LHCb in)

B meson mixing (LHCb in)



Overall normalisation given by $|V_{cd}V^*_{cb}|$, hence semileptonic *b* decays

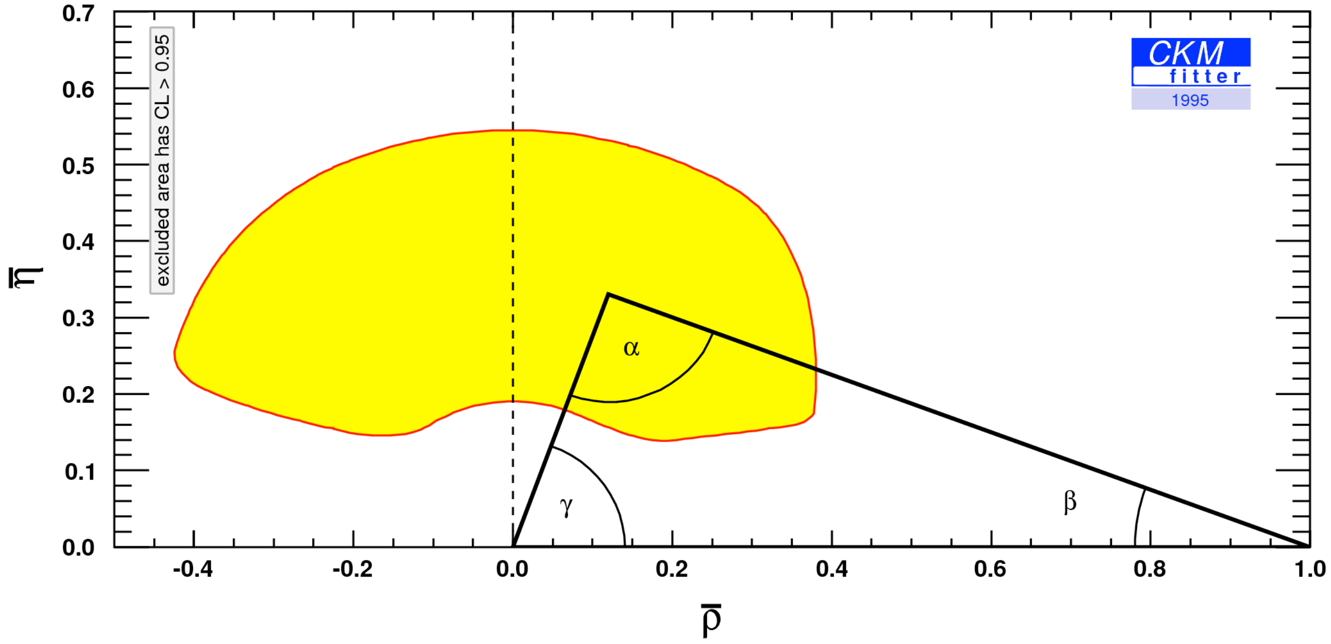
CP asymmetry in $b \to u$ *b*-hadron decays (LHCb in)

CP asymmetry in mixing processes (LHCb in)

the CKM profile: Back to the future

Vibrant prospectives ahead !

the CKM profile: Back to the future



Vibrant prospectives ahead !

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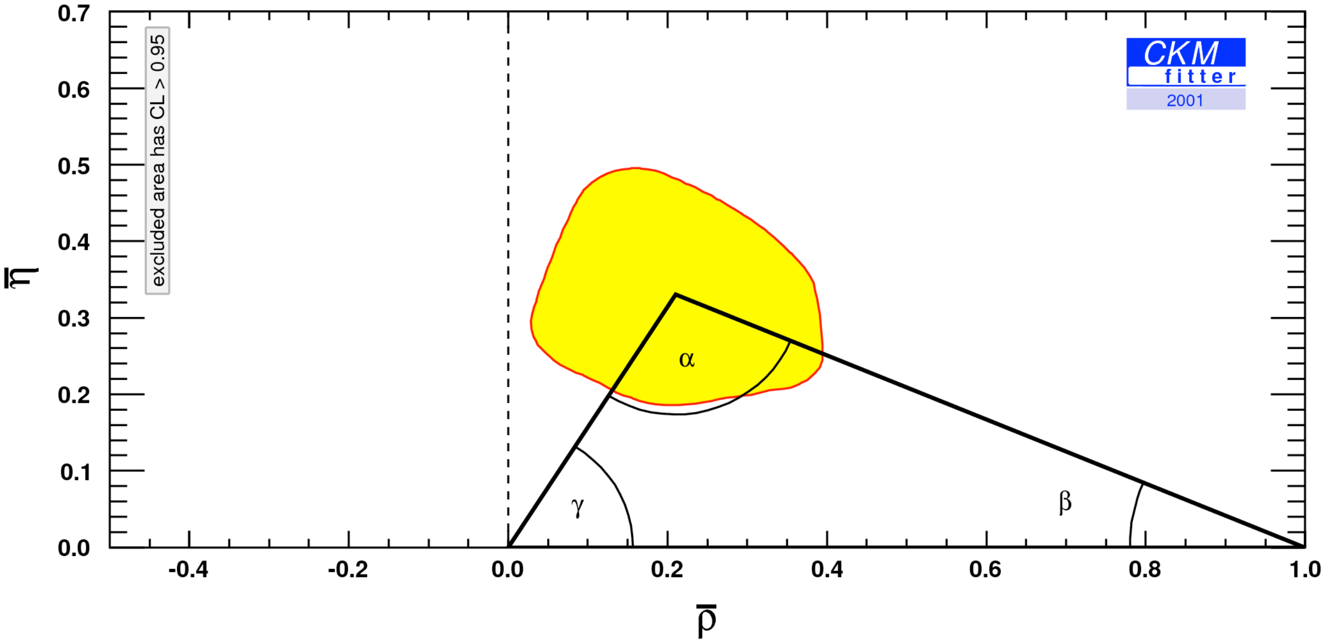

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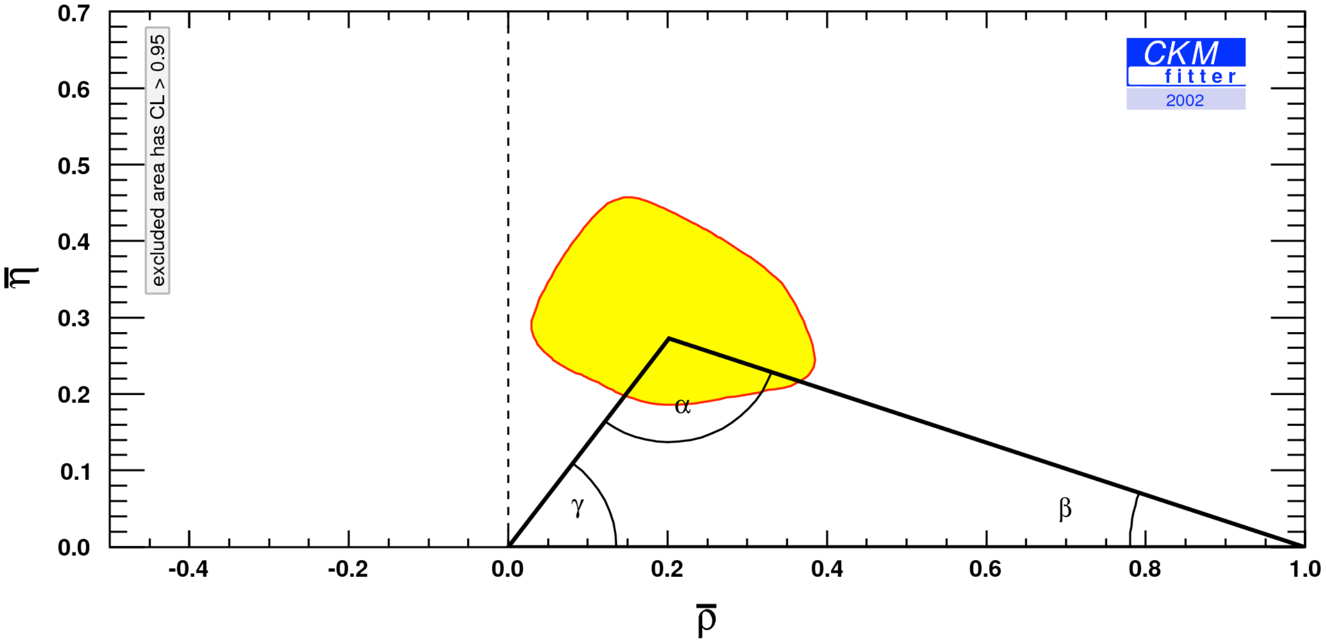

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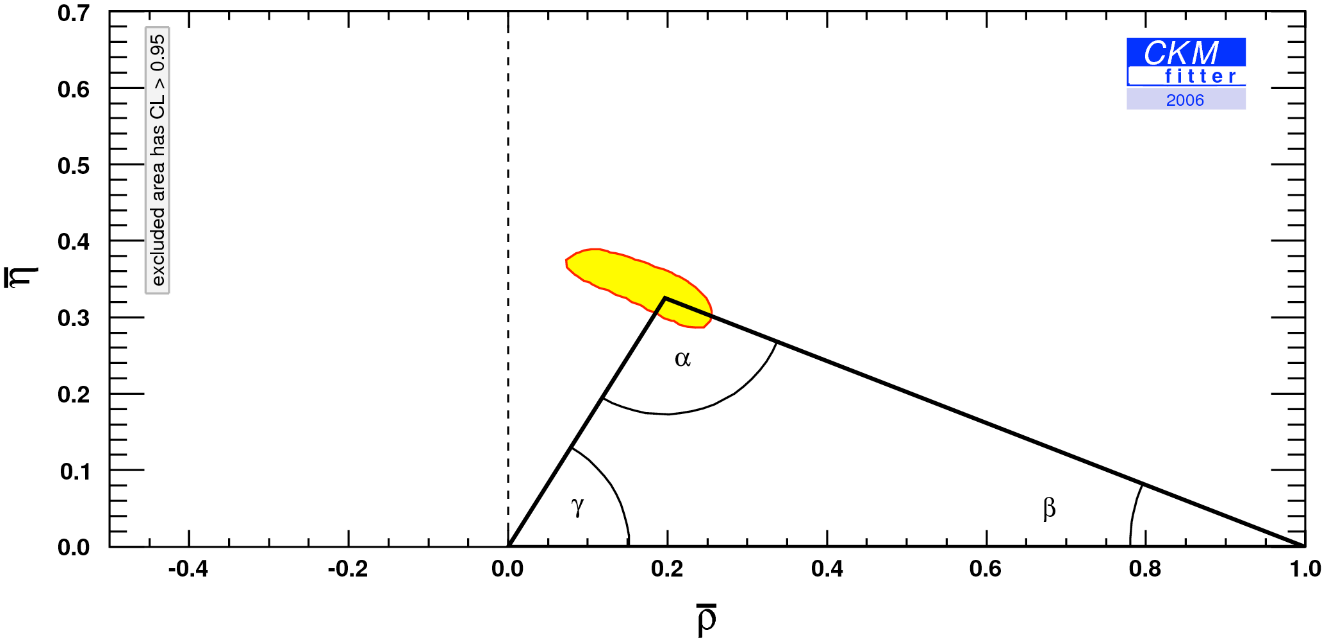

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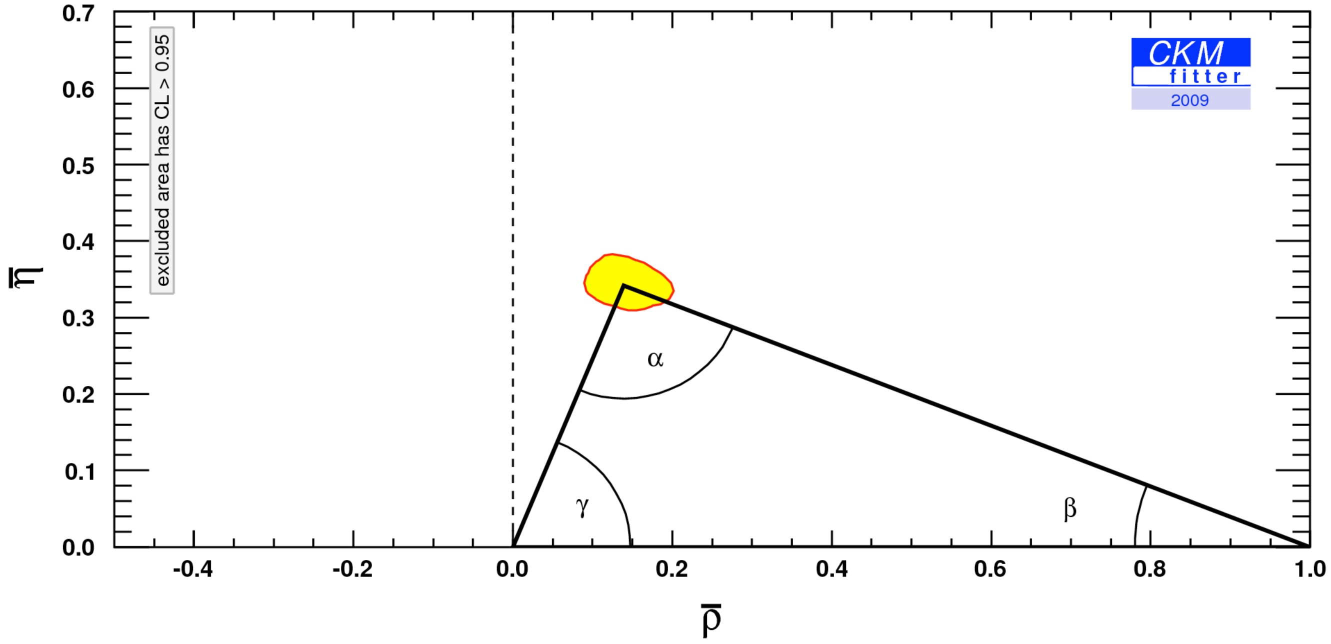

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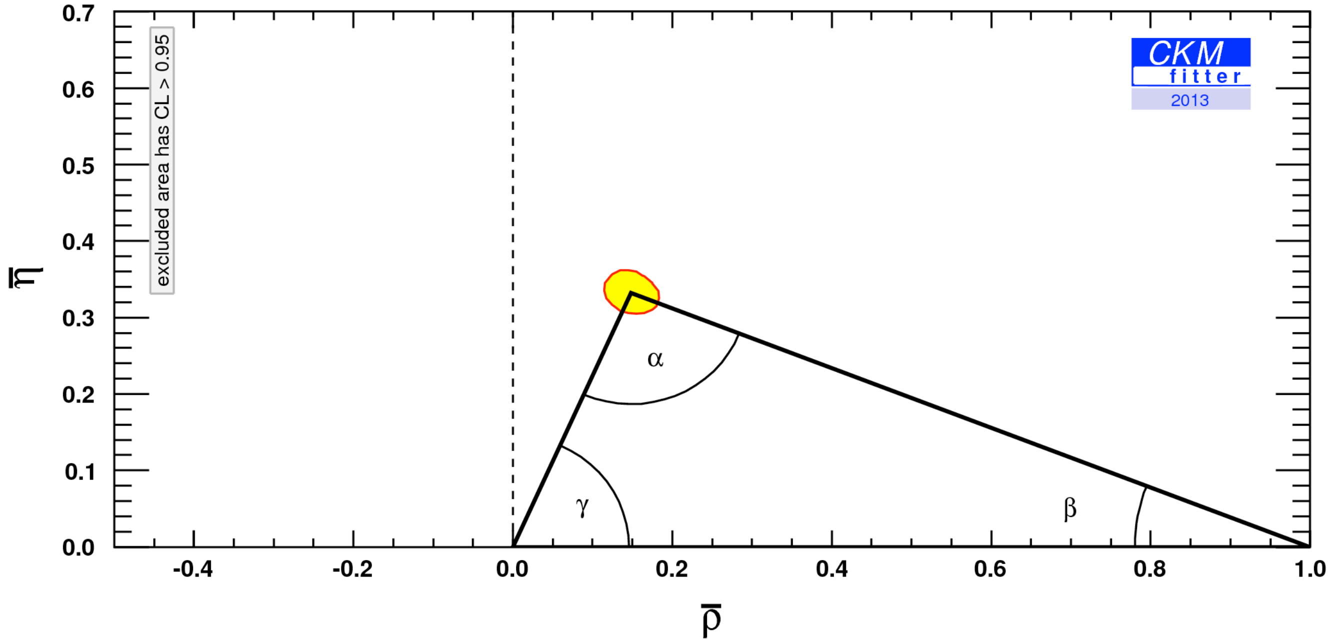

Vibrant prospectives ahead !

the CKM profile: Back to the future

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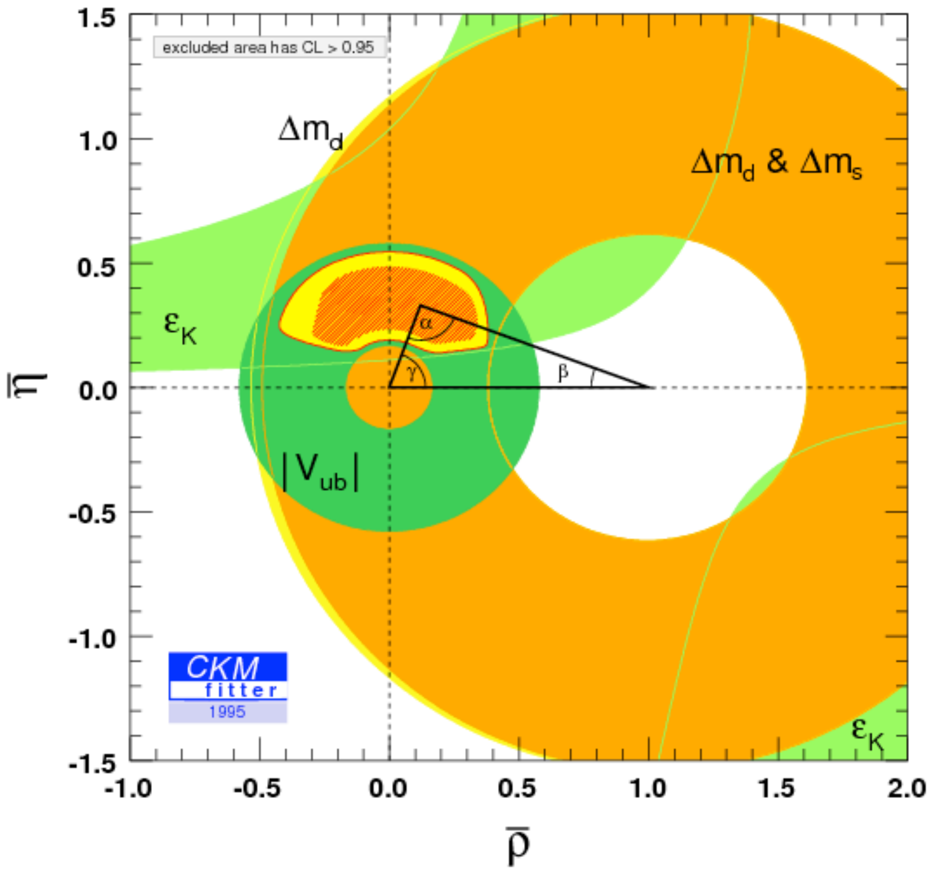

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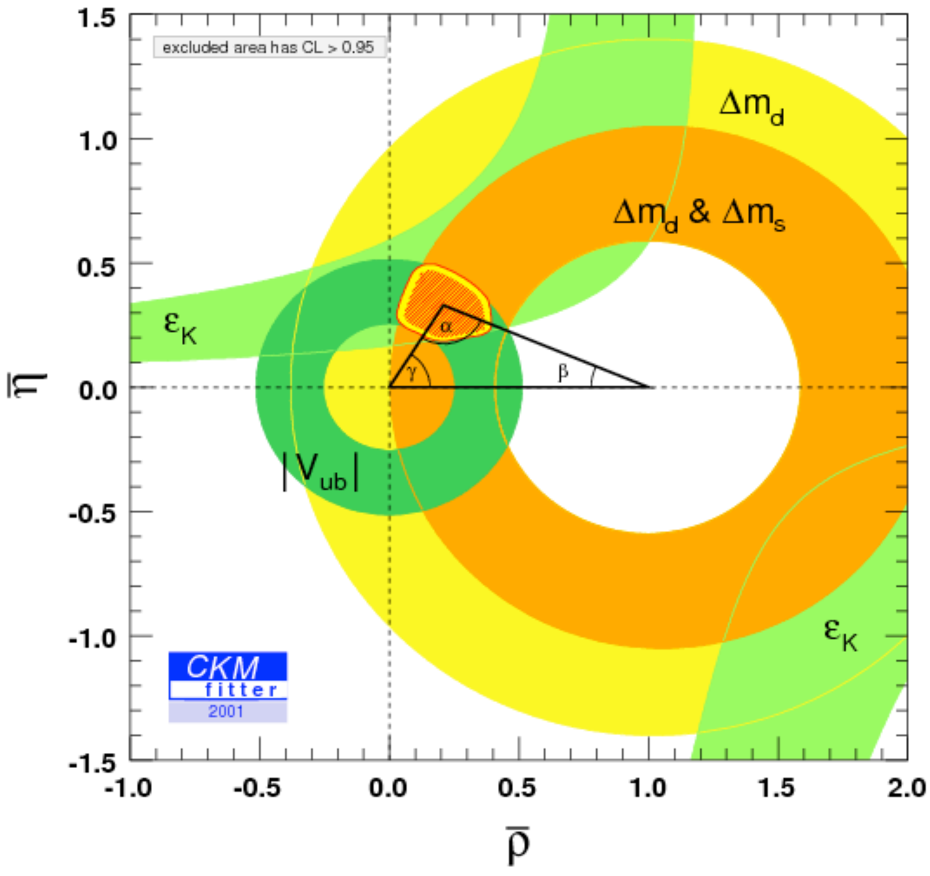

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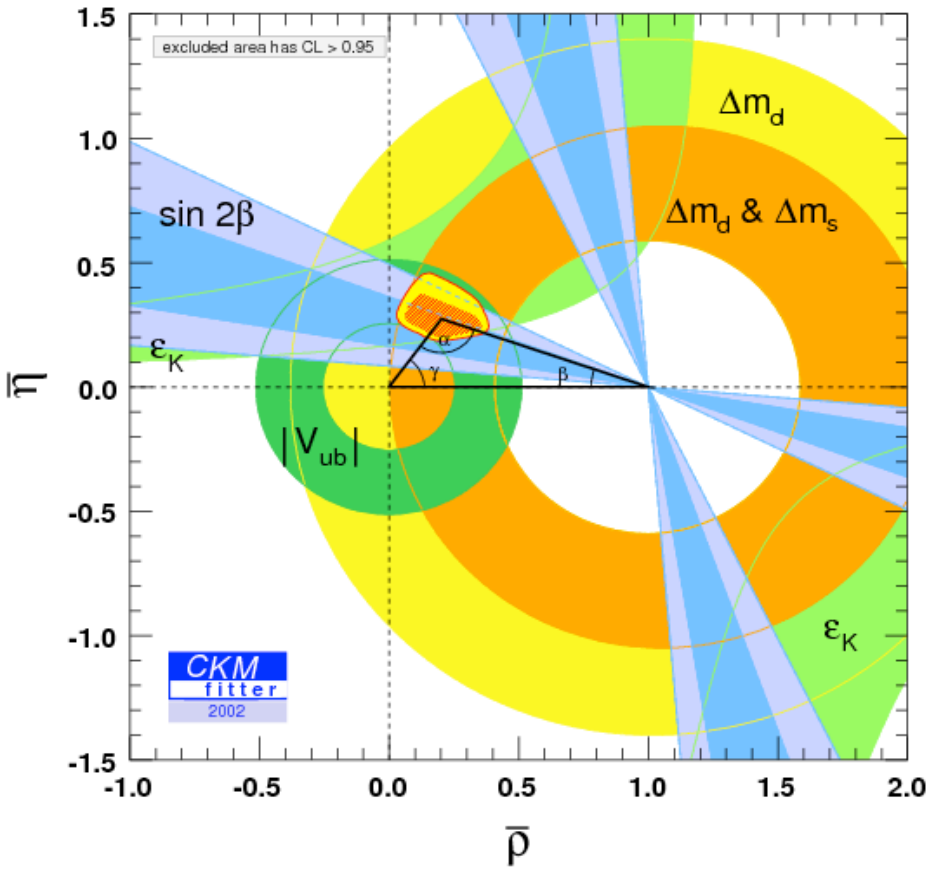

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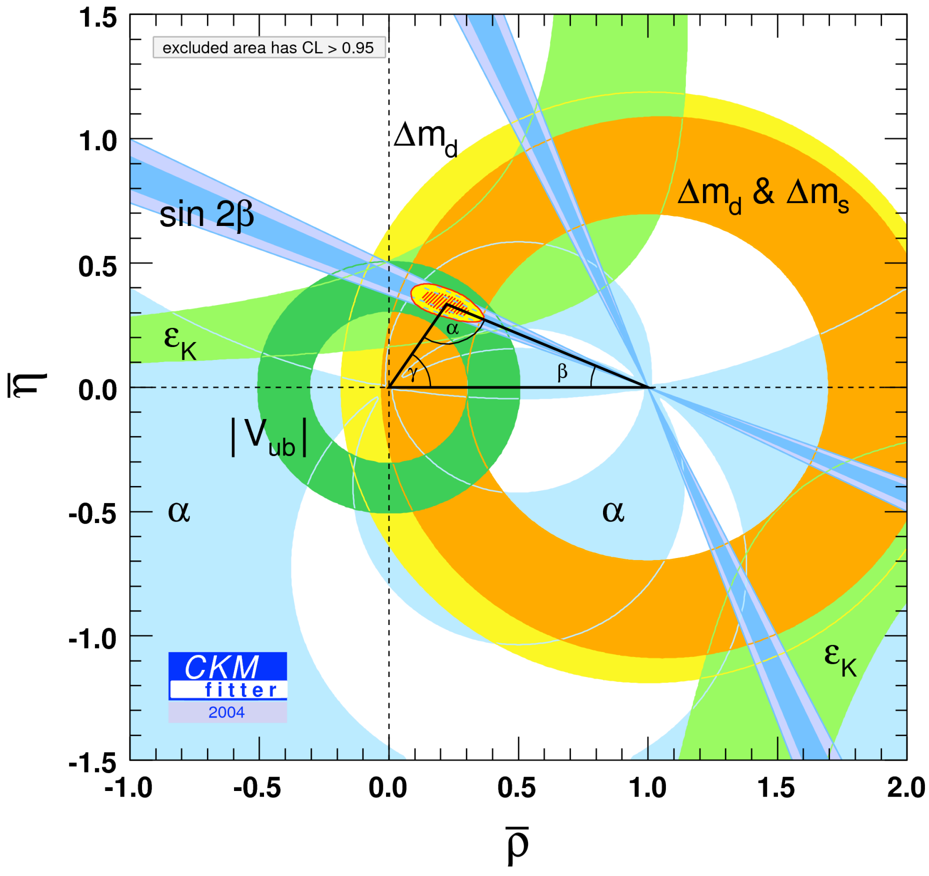

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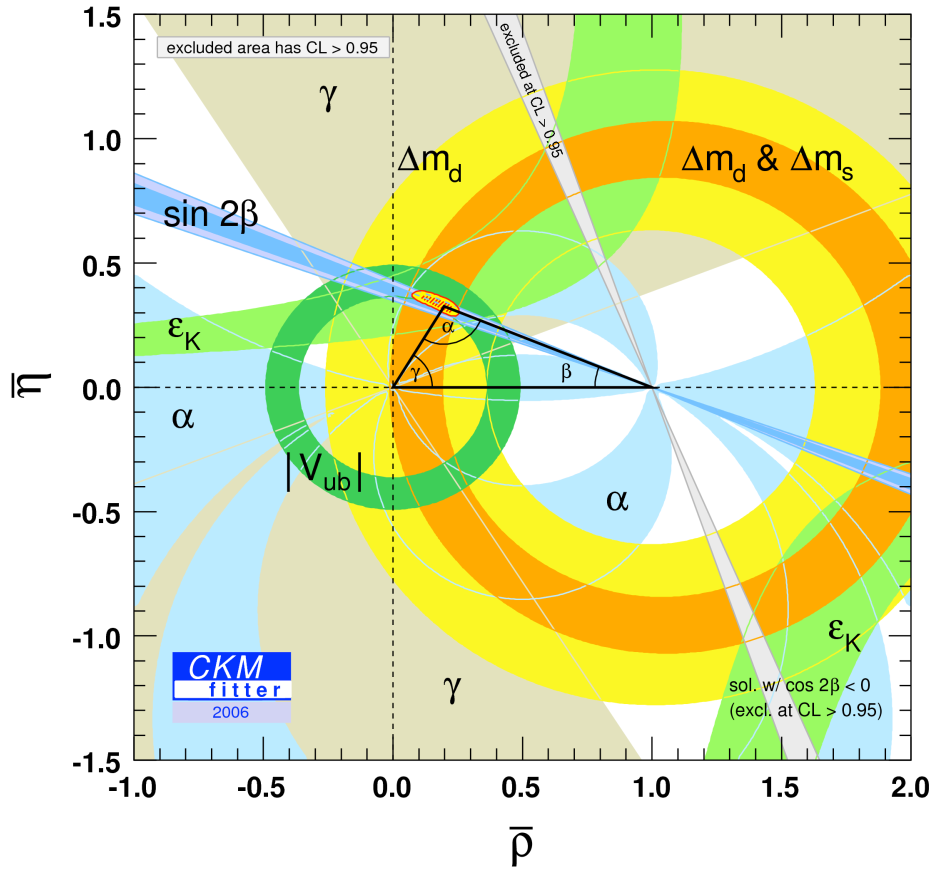

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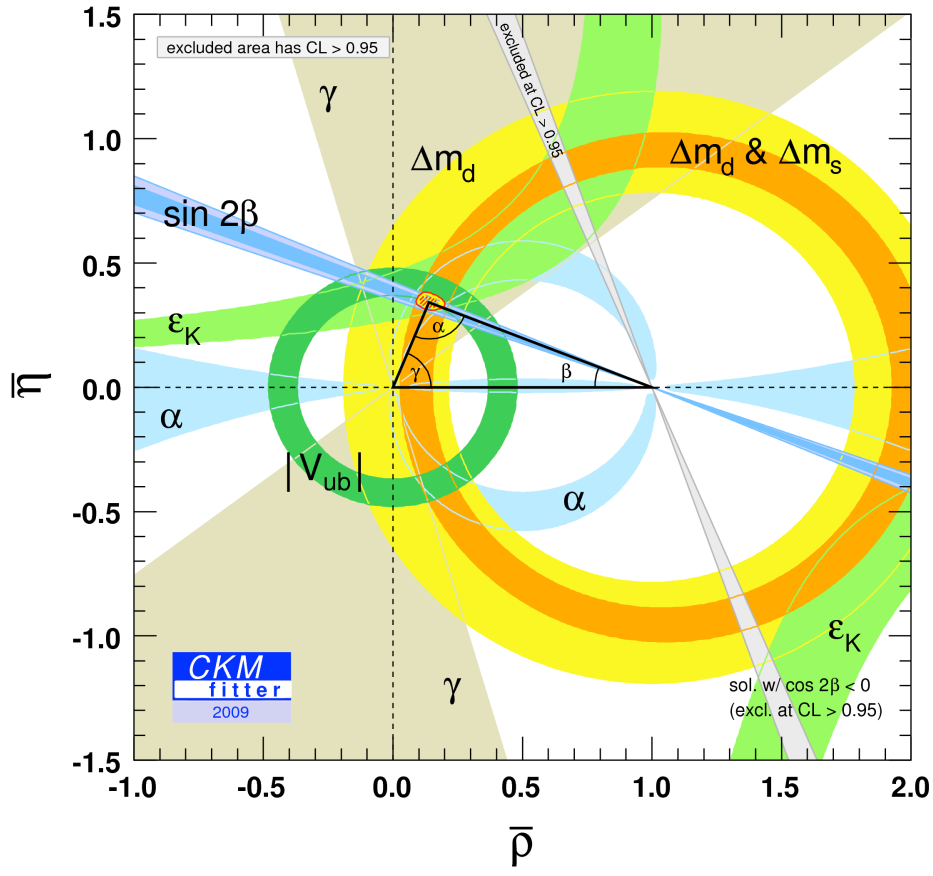

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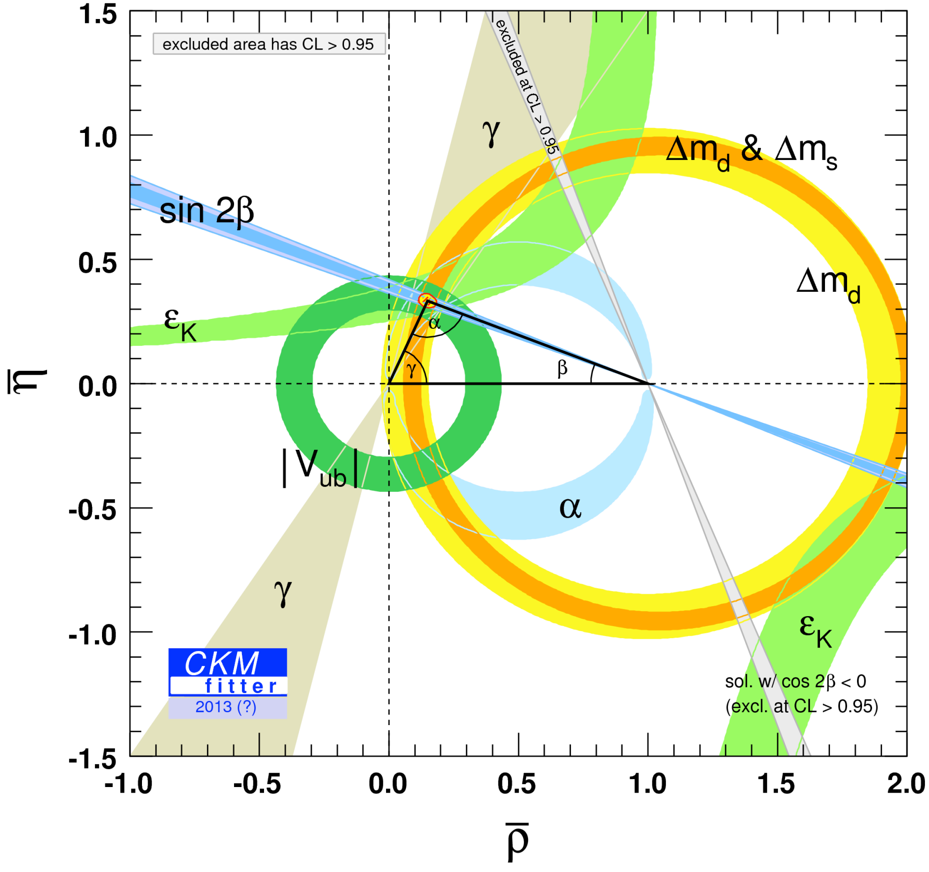

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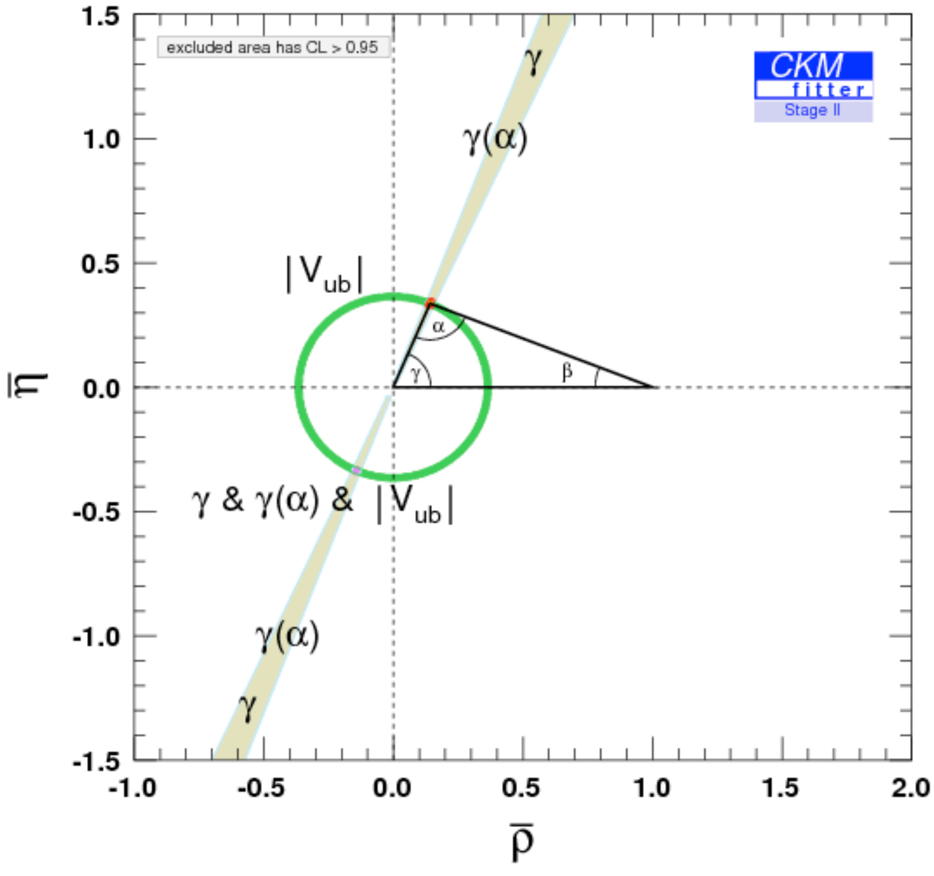
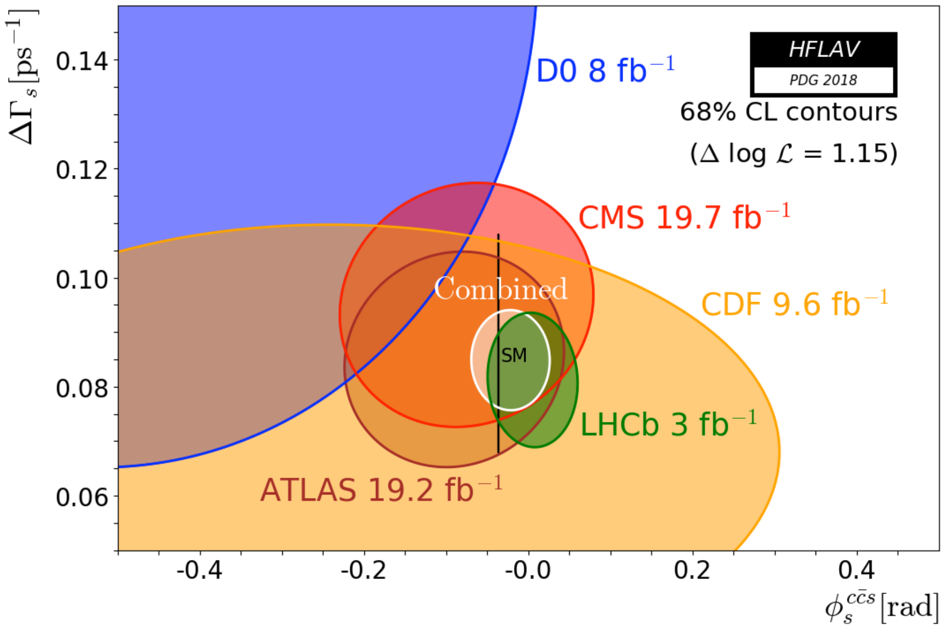


the CKM profile: Back to the future

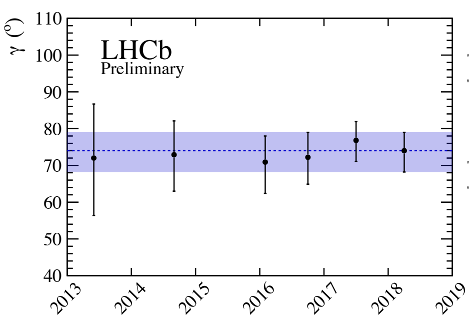
- 1995: starting point given by the top quark mass measurement. *K* and *B* mixings can be predicted.
- 2001: pre-*B*-factories era. LEP/CLEO based UT. Comparison with kaon mixing gives a consistency check.
- 2002: *CP* violation in the interference between decay and mixing is observed. This is the first 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.
- 2028: Super Flavour Factory (SuperKEKB) and LHCb (upgrade): additionally LQCD improvement. A New Physics perspective.

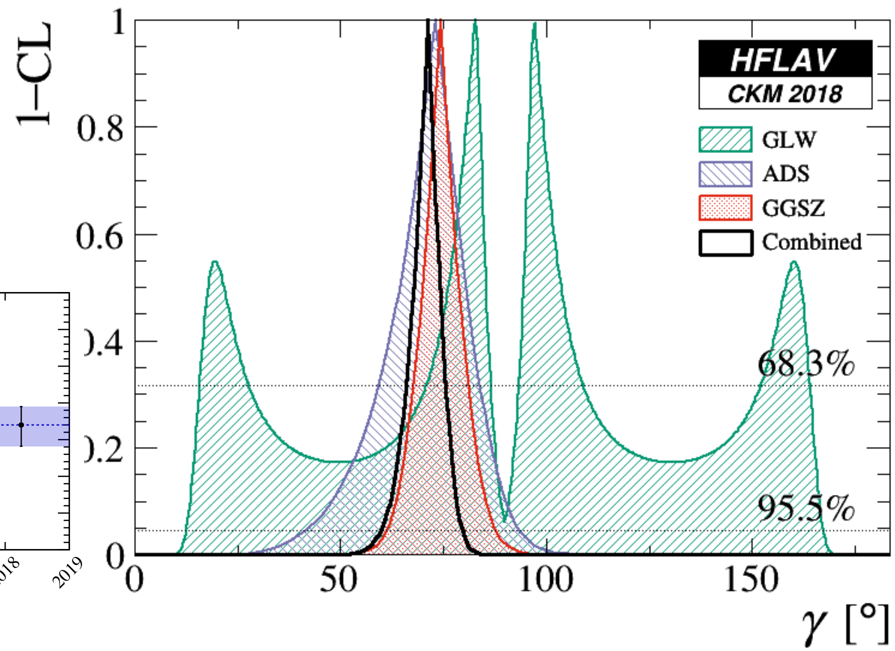
2) CPV, a state of the art

A selection of major recent achievements: weak *Bs* mixing phase, gamma combination



⇒ Powerful null-test of the SM

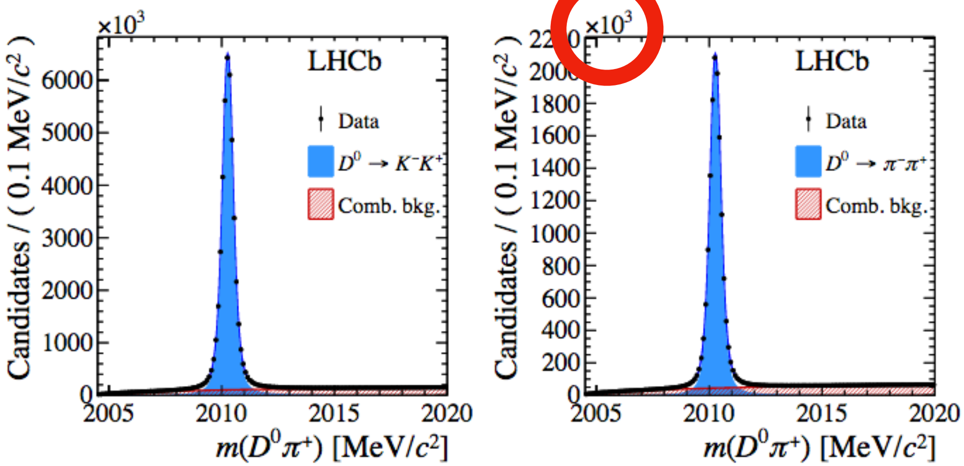




Precision era of the CKM profile ⇐

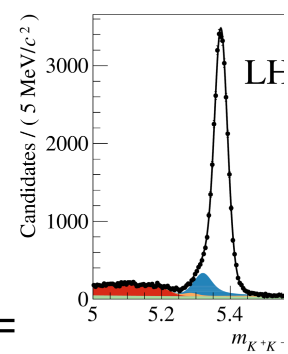
2) CPV, a state of the art

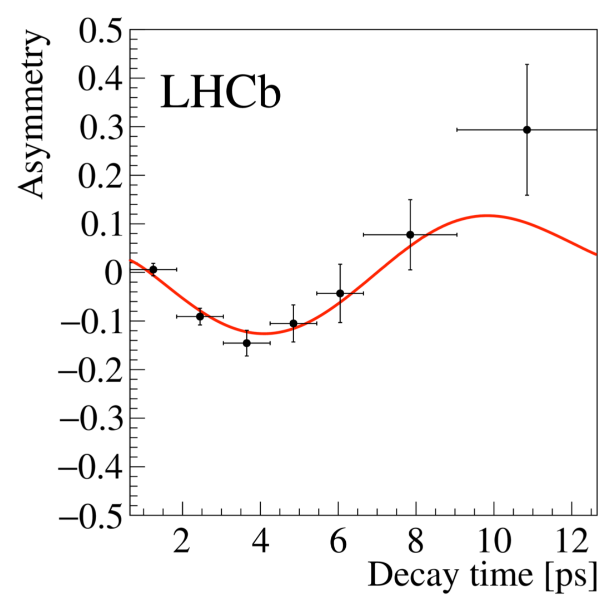
A selection of major recent achievements: *CP* violation in charm, time-dependent CPV in B_s systems,



⇒ Powerful null-test of the SM, New territory

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}.$$





Precision era of the CKM profile ⇐