CKM metrology

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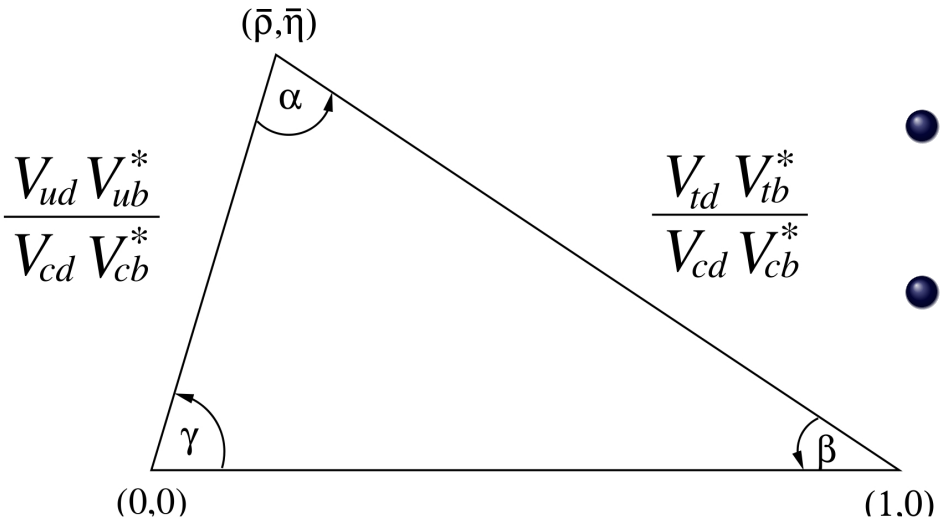
The CKM matrix

In SM, flavour dynamics related to weak charged transitions
which mix quarks of different generations

Encoded in unitary CKM matrix $V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$



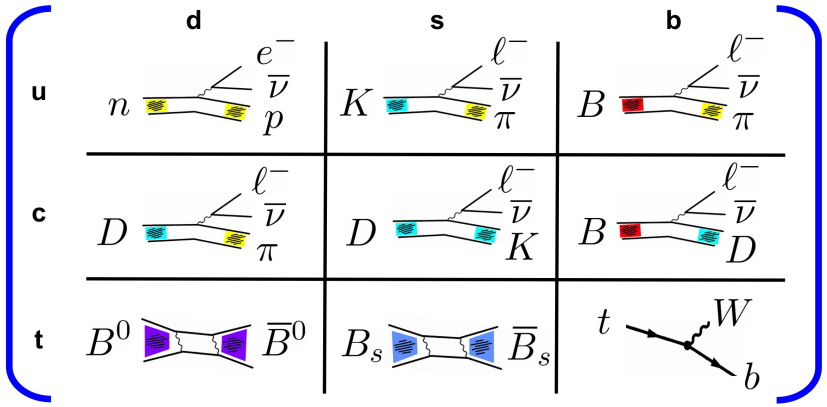
- 3 generations $\Longrightarrow$ 1 phase, only source of *CP*-violation in SM
- Wolfenstein parametrisation, defined to hold to all orders in λ and rephasing invariant

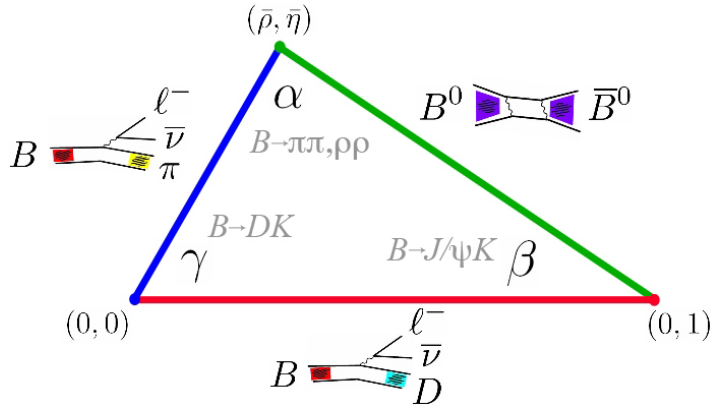
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$\Longrightarrow$ 4 parameters describing the CKM matrix

Extracting the CKM parameters

$V =$





- *CP*-invariance of QCD to build hadronic-indep. *CP*-violating asym. or to determine hadronic inputs from data
- Statistical framework to combine data and assess uncertainties
- Hadronic part treated as nuisance parameters

	Exp. uncert.		Theoretical uncertainties	
Tree	$B \to DK$	γ	$B(b) \to D(c)\ell\nu$	$\lvert V_{cb}\rvert$ vs form factor $F^{B\to D}$ (OPE)
			$B(b) \to \pi(u)\ell\nu$	$\lvert V_{ub}\rvert$ vs form factor $F^{B\to\pi}$ (OPE)
			$M \to \ell\nu, M \to N\ell\nu$	$\lvert V_{UD}\rvert$ vs f_M (decay cst), $F^{M\to N}$
Loop	$B \to J/\Psi K_s$	β	ϵ_K (K mix)	$(\bar{\rho}, \bar{\eta})$ vs B_K (bag parameter)
	$B \to \pi\pi, \rho\rho$	α	$\Delta m_d, \Delta m_s$ (B_d, B_s mix)	$\lvert V_{tb} V_{tq}\rvert$ vs $f_B^2 B_B$ (bag param)

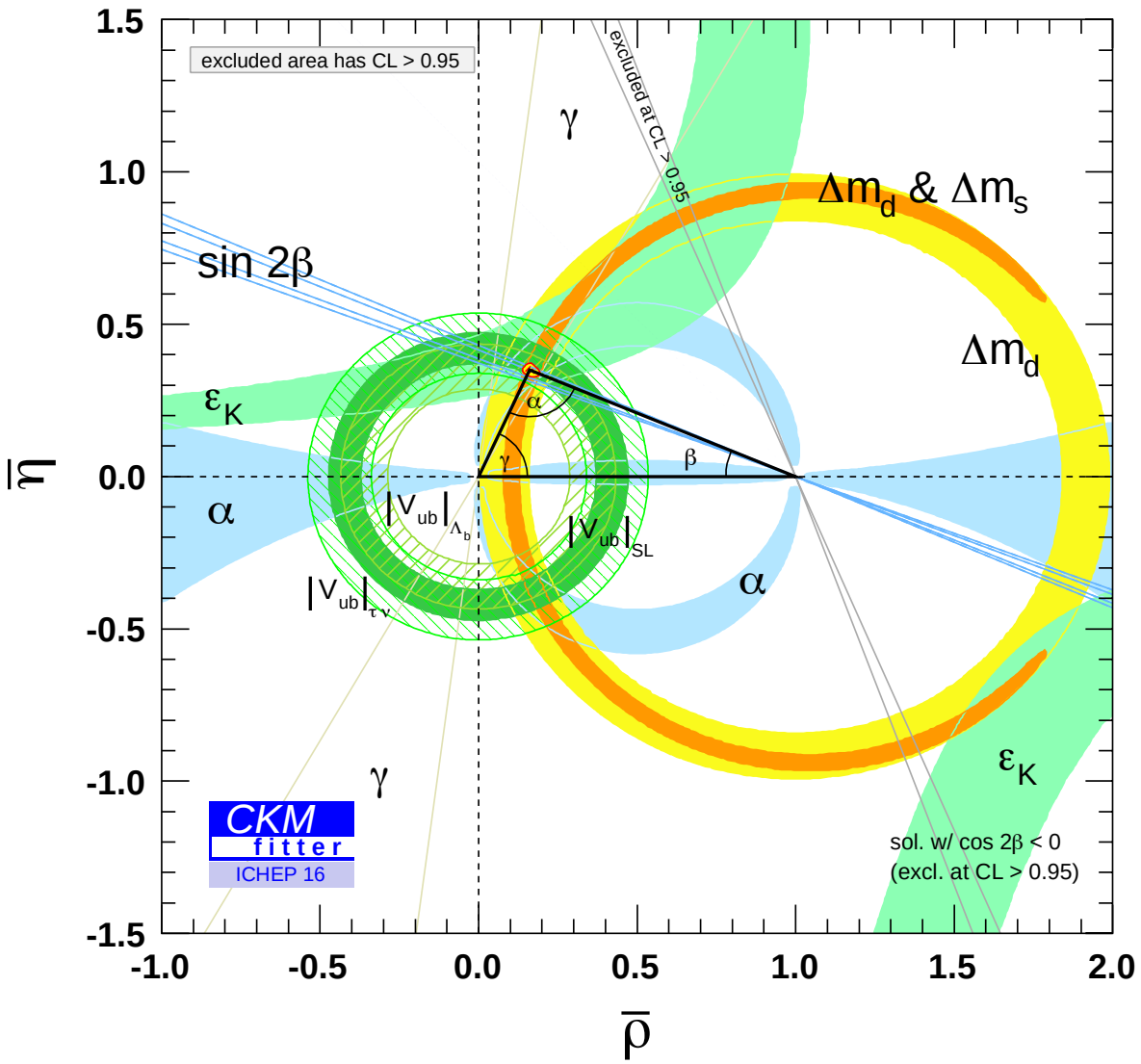
The inputs

CKM fitter frequentist ($\simeq \chi^2$ minim.) + Rfit scheme for theory uncert.

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

$\lvert V_{ud}\rvert$	superallowed β decays	PRC79, 055502 (2009)
$\lvert V_{us}\rvert$	$K_{\ell 3}$	$f_+(0) = 0.9645 \pm 0.0015 \pm 0.0045$
	$K \to \ell\nu, \tau \to K\nu_\tau$	$f_K = 155.2 \pm 0.2 \pm 0.6$ MeV
$\lvert V_{us}/V_{ud}\rvert$	$K \to \ell\nu/\pi \to \ell\nu, \tau \to K\nu_\tau/\tau \to \pi\nu_\tau$	$f_K/f_\pi = 1.1952 \pm 0.0007 \pm 0.0029$
ϵ_K	PDG	$\hat{B}_K = 0.7615 \pm 0.0027 \pm 0.0137$
$\lvert V_{cd}\rvert$	$D \to \mu\nu$, $D \to \pi\ell\nu$	$f_{D_s}/f_D = 1.175 \pm 0.001 \pm 0.004$, $f_+^{D\to\pi}(0)$
$\lvert V_{cs}\rvert$	$D_s \to \mu\nu$, $D_s \to \tau\nu$, $D \to \pi\ell\nu$	$f_{D_s} = 248.2 \pm 0.3 \pm 1.9$ MeV, $f_+^{D\to K}(0)$
$\lvert V_{ub}\rvert$	inclusive and exclusive B semileptonic	$\lvert V_{ub}\rvert \cdot 10^3 = 4.01 \pm 0.08 \pm 0.22$
$\lvert V_{cb}\rvert$	inclusive and exclusive B semileptonic	$\lvert V_{cb}\rvert \cdot 10^3 = 41.00 \pm 0.33 \pm 0.74$
$B \to \tau\nu$	$(1.24 \pm 0.22) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.205 \pm 0.003 \pm 0.006$
		$f_{B_s} = 224.0 \pm 1.0 \pm 2.0$ MeV
$\lvert V_{ub}/V_{cb}\rvert$	Λ_b semileptonic decays	integrals of Λ_b form factors
Δm_d	last WA B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.023 \pm 0.013 \pm 0.014$
Δm_s	last WA B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.320 \pm 0.016 \pm 0.030$
β	last WA $J/\psi K^{(*)}$	no penguin pollution
α	last WA $\pi\pi, \rho\pi, \rho\rho$	isospin
γ	last WA $B \to D^{(*)}K^{(*)}$	GLW/ADS/GGSZ
		as well as inputs on $m_t, m_c, \alpha_s(M_Z)$

Current status



$|V_{ud}|$, $|V_{us}|$

$|V_{cb}|$, $|V_{ub}|_{SL}$

$B \to \tau\nu$

$|V_{ub}/V_{cb}|_{\Lambda_b}$

Δm_d, Δm_s

ϵ_K

$\sin 2\beta$

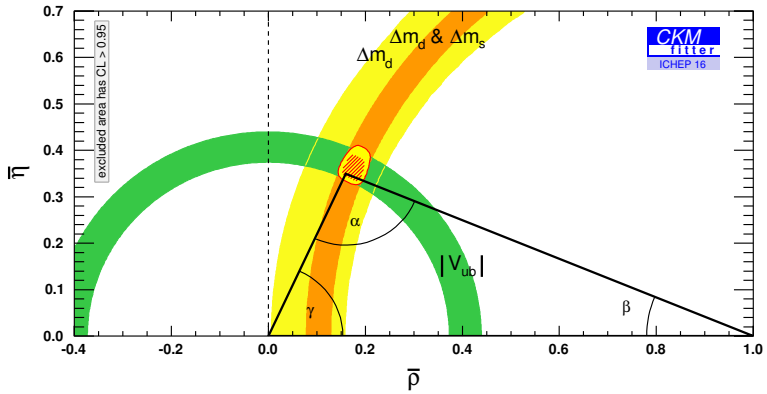
α

γ

$$A = 0.825^{+0.007}_{-0.011}$$
$$\lambda = 0.2251^{+0.0003}_{-0.0003}$$
$$\bar{\rho} = 0.160^{+0.008}_{-0.007}$$
$$\bar{\eta} = 0.350^{+0.006}_{-0.006}$$

(68% CL)

Consistency of the KM mechanism



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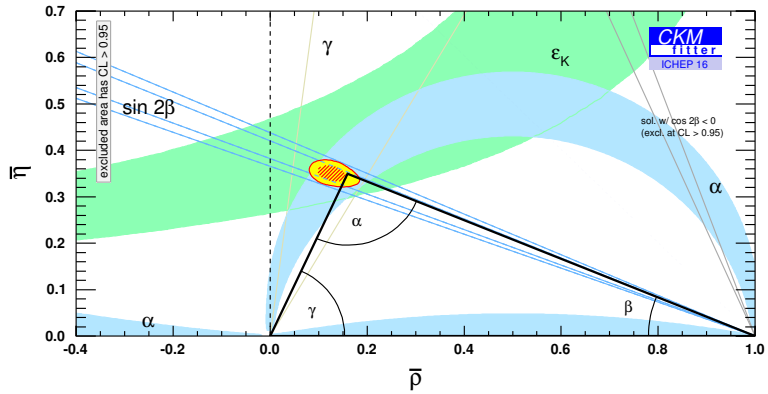
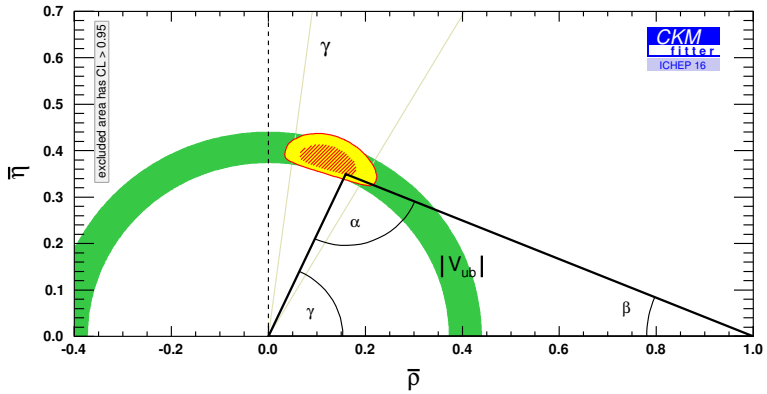
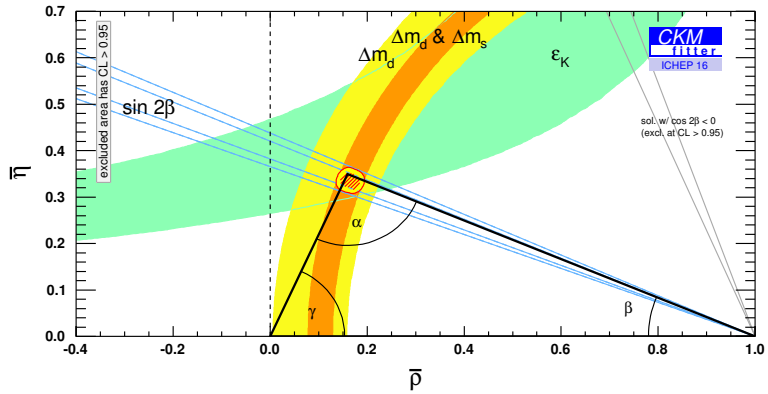


CP-violating only



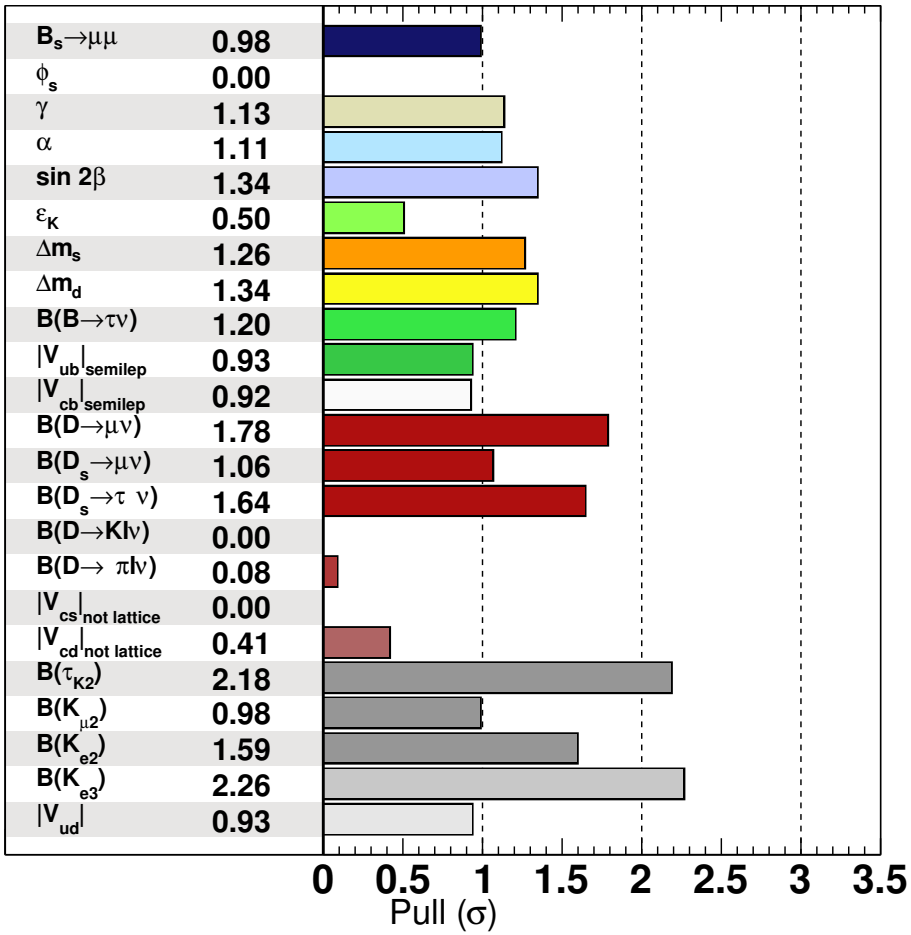
Tree only



Loop only

Validity of Kobayashi-Maskawa picture of *CP* violation

Pulls



- Pulls for various observables (included in the fit or not)
- If Gaussian errors, uncorrelated, random vars of mean 0 and variance 1
- Here correlations, and some pulls $= 0$ due to the Rfit model for syst

No indication of significant deviations from CKM picture
[and no sign here of deviations in relation with *B*-anomalies]

A basis for prospective

Restart from old prospective in *Future sensitivity to new physics in B_d, B_s and K mixings*, hep-ph/1309.2293 [J. Charles et al.]

- Central values chosen to be all consistent within SM
- Gaussian uncertainties based on 2013 extrapolations
  - *Physics at Super B Factory*, arXiv:1002.5012 [hep-ex].
  - *Implications of LHCb measurements and future prospects*, arXiv:1208.3355
  - *Lattice QCD at the Intensity Frontier*, T. Blum et al.
- Stage I of this paper: $\simeq$ 2020, LHCb 7 fb^{-1}, Belle II 5 ab^{-1}
  not completely off the target for theory and LHCb inputs
- Stage II of this paper: $\simeq$ 2025, LHCb 50 fb^{-1}, Belle II 50 ab^{-1}
- Stage II good starting point to include HL-LHC projections

Updating to HL LHC projections

Two HL LHC projections

- Phase 1: $\simeq$ 2025, LHCb 27 fb^{-1}, CMS/ATLAS 300 fb^{-1}
- Phase 2: $\simeq$ Upgrade 2, LHCb 300 fb^{-1}, CMS/ATLAS 3000 fb^{-1}

Start from "old" Stage II exploiting the new HL-LHC projections

- HL-LHC: uncertainties from Phase 1 and Phase 2
- Theory inputs (mainly lattice): uncertainties from Stage II
- Other exp inputs (mainly Belle II): uncertainties from Stage II

Work in progress with certainly wrong numbers !
I am using inputs from other WG and guesstimates...
They will certainly change but are useful to organise the discussions !

HL-LHC inputs

Quantity	Current	Unc. Phase 1	Unc. Phase 2
$\sin 2\beta$	0.017	0.008	0.003
γ	2.3°	1.5°	0.35°
$\lvert V_{ub}/V_{cb}\rvert$	7 %	3 %	1 %
ϕ_s	31 mrad	14 mrad	4 mrad
m_t	0.4 %	0.4 %	0.4 %

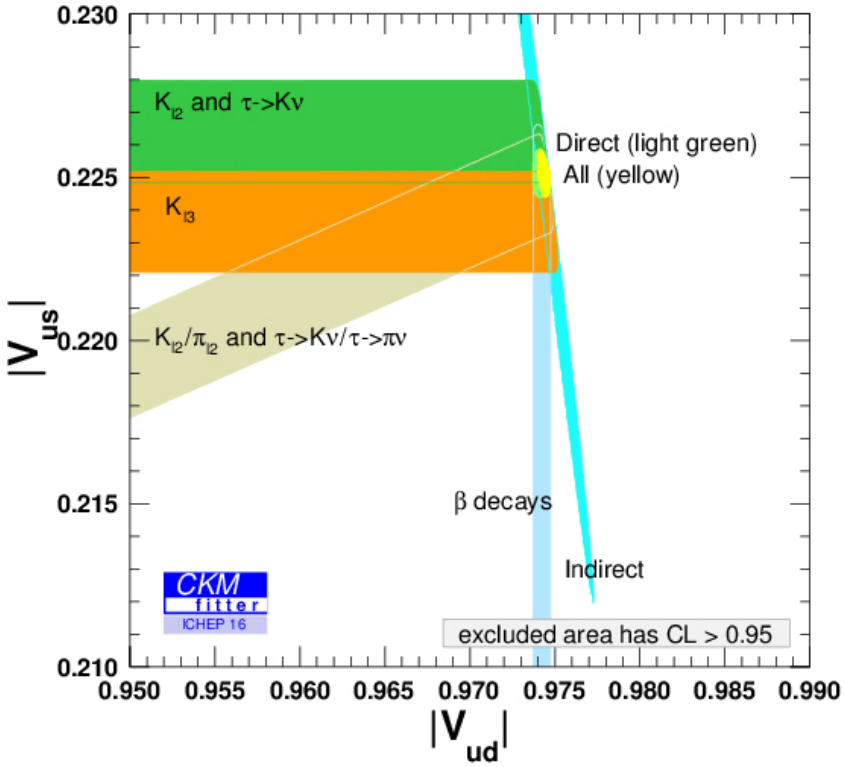
- m_t: Uncertainty related to the definition (MC mass vers $\overline{\rm MS}$ mass)
- $|V_{ub}/V_{cb}|$: Assumptions on lattice determination of Λ_b form factors
- β and ϕ_s: What to do with penguin pollution ?
  - $SU(3)$ flavour: $|\Delta\beta| \leq 0.5°$ [R. Fleischer et al., M. Ciuchini et al.]
  - OPE + factorisation: $|\Delta\beta| \leq 0.3°$, $|\Delta\phi_s| \leq 1°$ [U. Nierste et al.]
  - other approaches ? forget about the problem ?

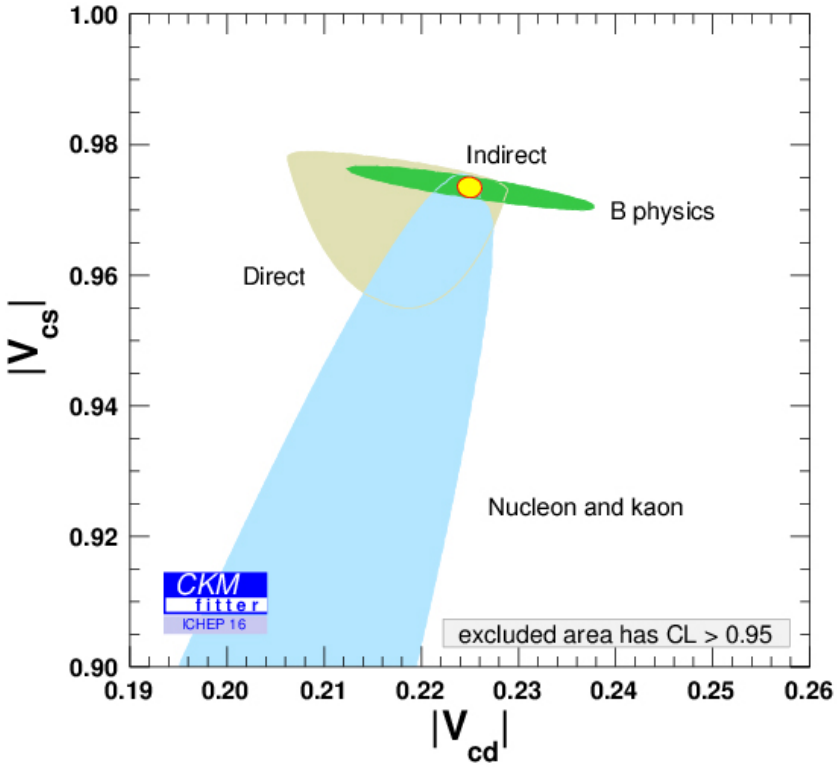
Other experimental inputs (1)

Quantity	Current	Unc. (Phases 1 and 2)
α	2.3°	1°
$\lvert V_{ub}\rvert$	5.8 %	2.2 %
$\lvert V_{cb}\rvert$	2.0 %	0.7 %
Δm_d	0.4 %	0.4 %
Δm_s	1.2 %	1.2 %
$\lvert\epsilon_K\rvert$	0.5 %	0.5 %
$B \to \tau\nu$	24 %	12 %
$B \to \mu\nu$	–	24 %

- α: measurements from Belle II et LHC, but main improvements for α expected from Belle II (main limitation on α from neutral modes) and isospin-breaking systematics [O. Deschamps et al, arXiv:1705.02981]
- $|V_{ub}|$ and $|V_{cb}|$: assumptions about both lattice improvements and convergence of inclusive and exclusive decays
- What about $K \to \pi\nu\nu$ (constraint on $\bar{\eta}$) ? and more generally...

Other experimental inputs (2)





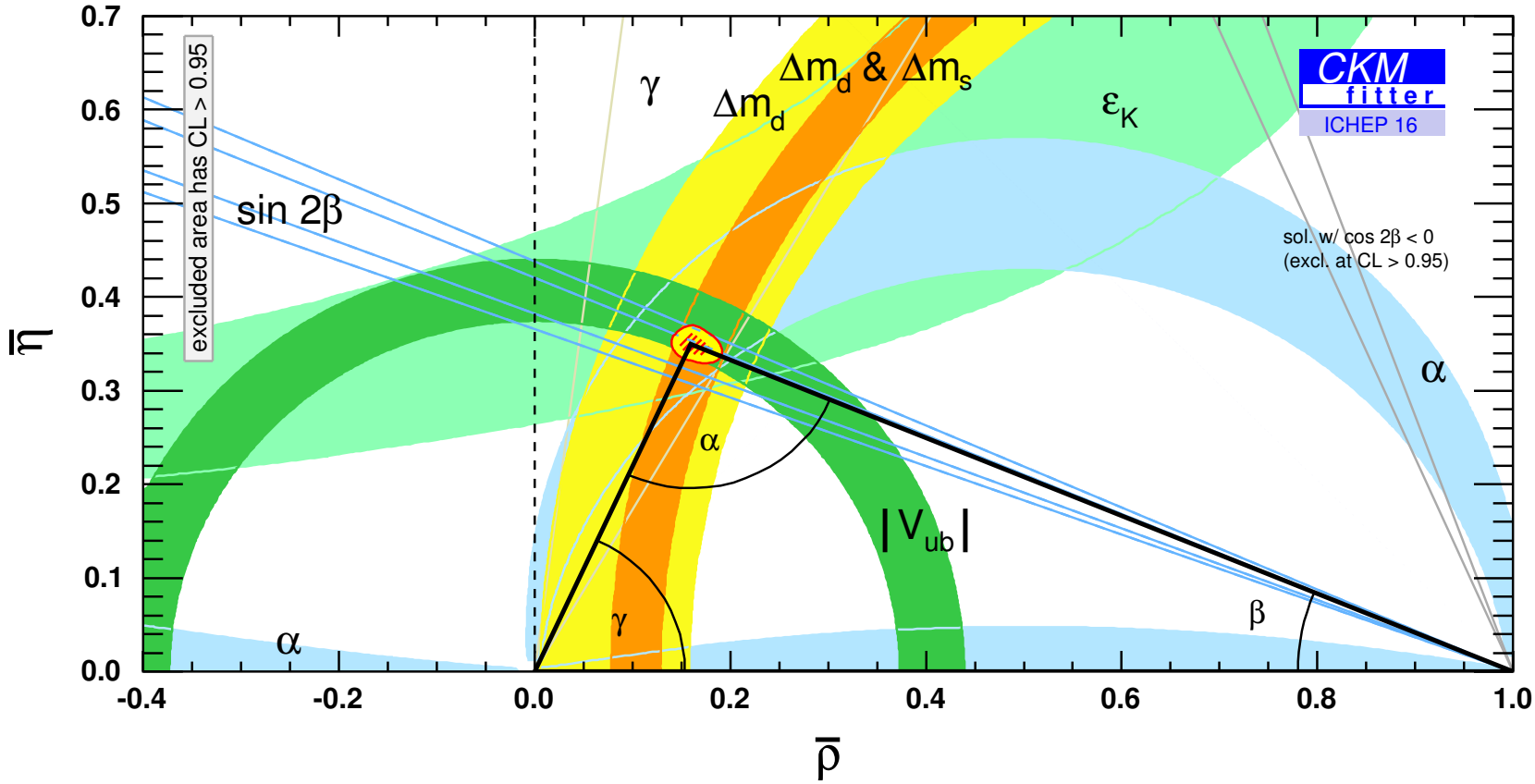
- $|V_{ud}|, |V_{us}|$: no expected change from leptonic and semileptonic decays (apart from lattice)
- $|V_{cd}|, |V_{cs}|$: any exp improvement from the charm sector (leptonic and semileptonic D and D_s decays) ?

Lattice inputs

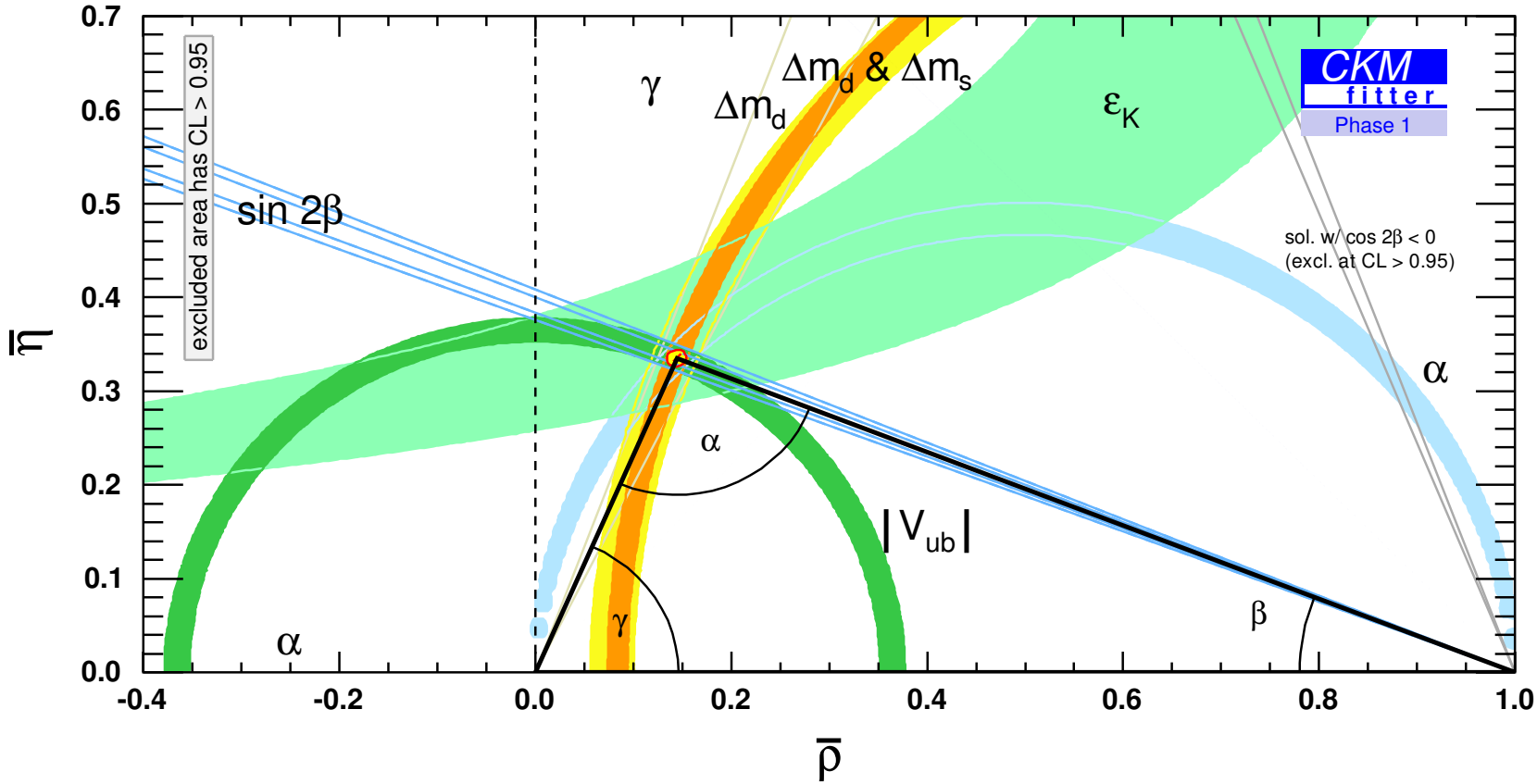
Quantity	Current	Unc. (Phases 1 and 2)
f_K	0.4 %	0.4 %
$f_+^{K\to\pi}(0)$	0.3 %	0.2 %
B_K	1.6 %	0.5 %
f_{B_s}	1 %	0.4 %
B_{B_s}	3 %	0.8 %
f_{B_s}/f_{B_d}	0.6 %	0.4 %
B_{B_s}/B_{B_d}	1.9 %	0.5 %
m_c	1 %	1 %

- Are these guesstimates realistic for lattice extrapolations ?
  hep-ph/1309.2293 Stage I guesstimates $\simeq$ now, as expected
- If leptonic and semileptonic charm decays included, extrapolations for decay constants and form factors needed
- What about isospin and QED corrections for leptonic and semilept decays ? *known and around 1% for K, but for D and B ?*

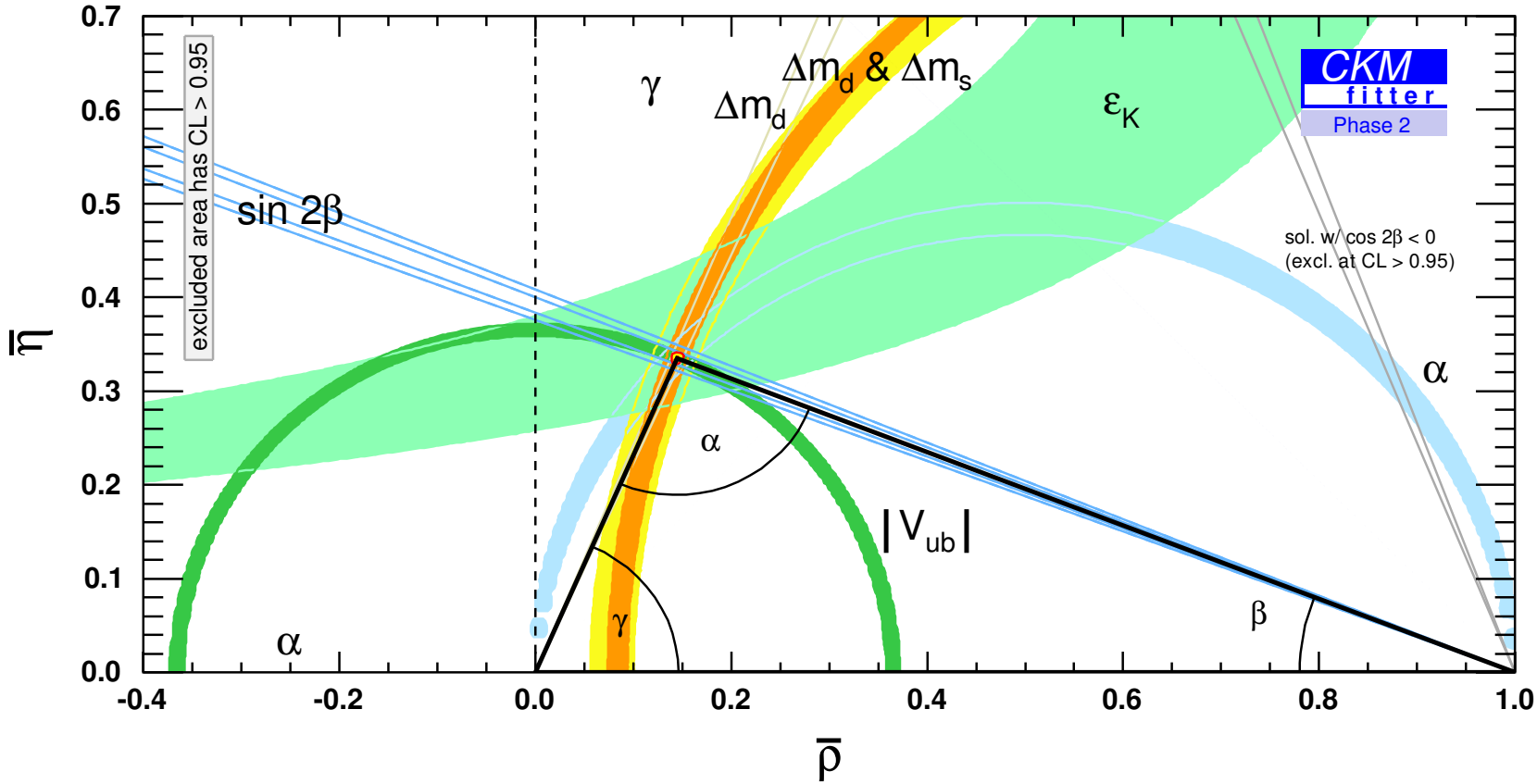
Current status



Phase 1 (Preliminary !)



Phase 2 (Preliminary !)

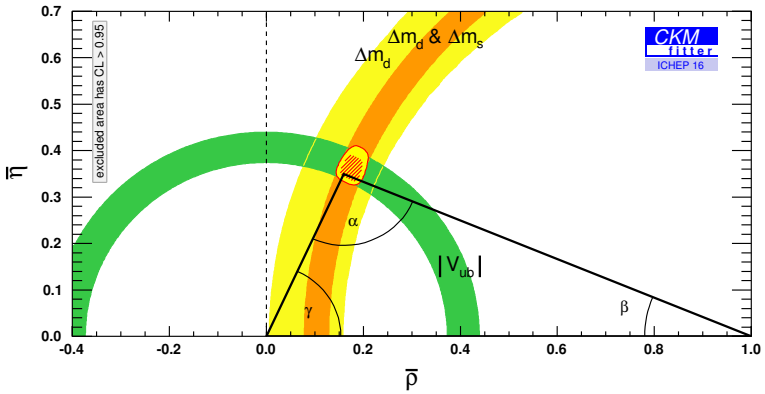


CKM metrology (Preliminary !)

Quantity	Current (No discr)	Unc. Phase 1	Unc. Phase 2
A	1.1% (1.4%)	0.7%	0.7%
λ	1.2% (2.6%)	2.4%	2.3%
$\bar{\rho}$	4.6% (5.9%)	2.6%	1.4%
$\bar{\eta}$	1.7% (2.6%)	1.1%	0.8%

- In brackets, same uncertainties as now, but central values adjusted to have perfect agreement of the constraints
- A and λ driven by $|V_{ud}|, |V_{us}|, |V_{cb}|$ inputs
- possibility to play the game with restricted subsets (tree, loop only)

Playing with subsets : Current



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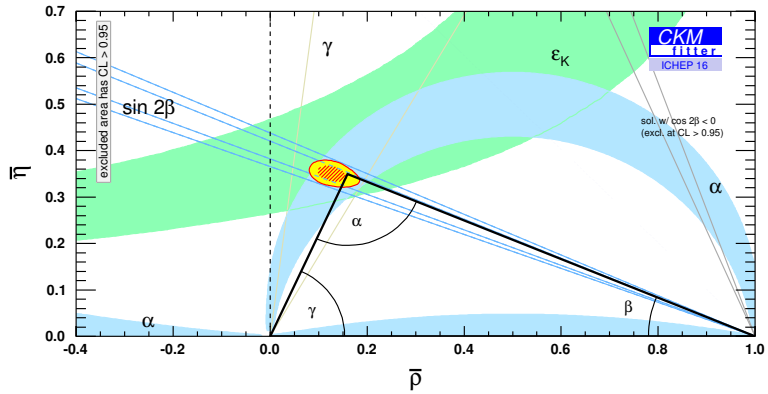

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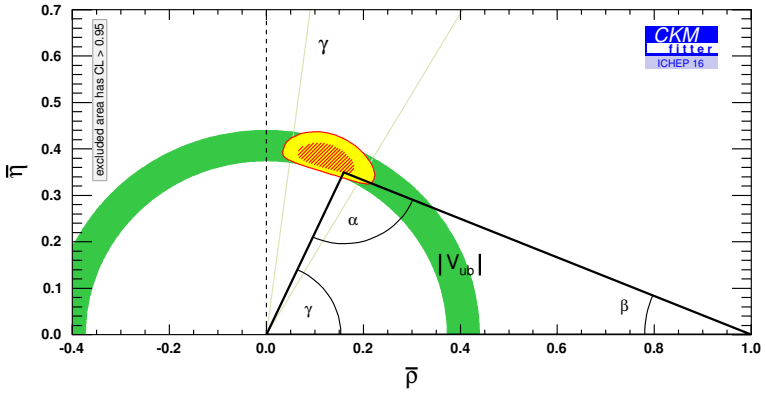
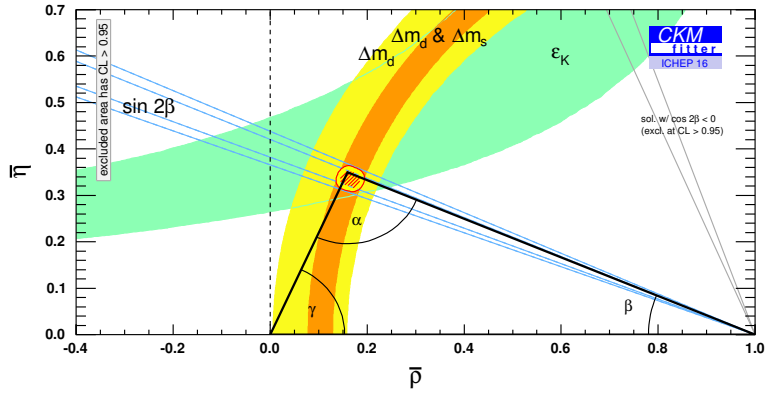
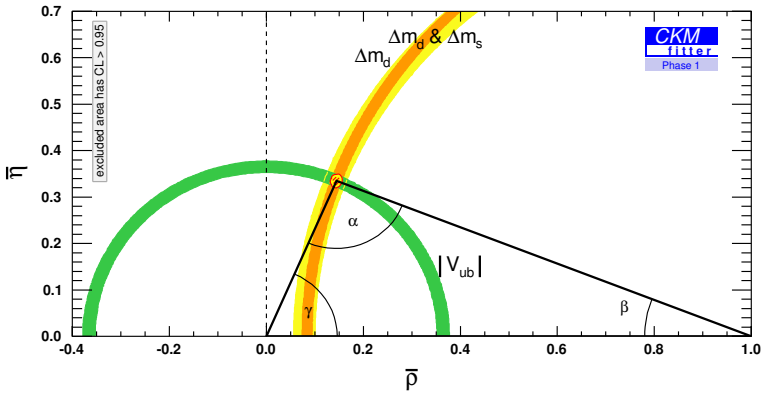


Tree only



Loop only

Playing with subsets : Phase 1 (Preliminary !)



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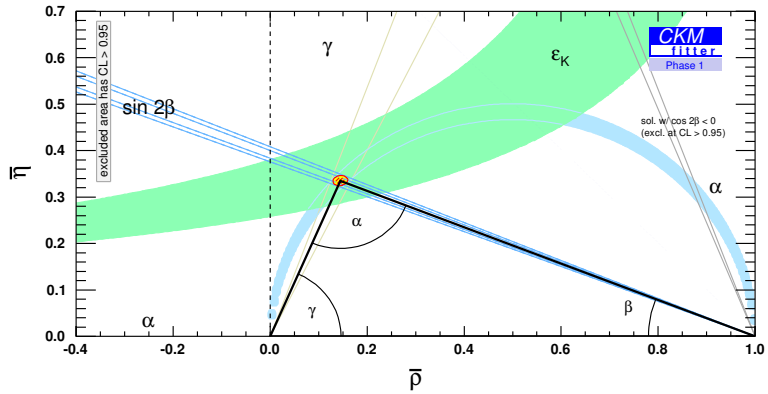

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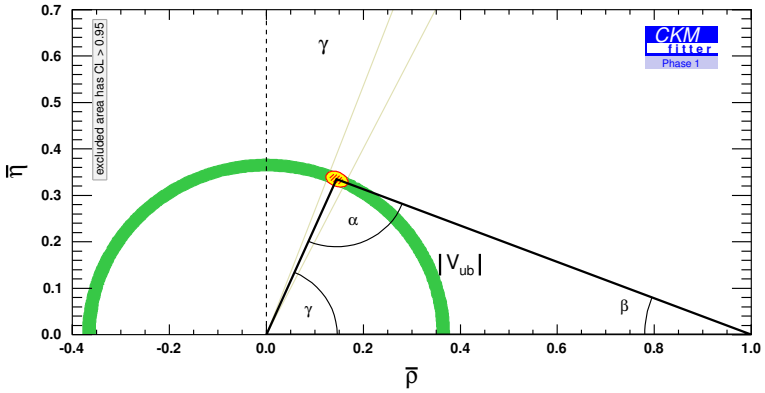
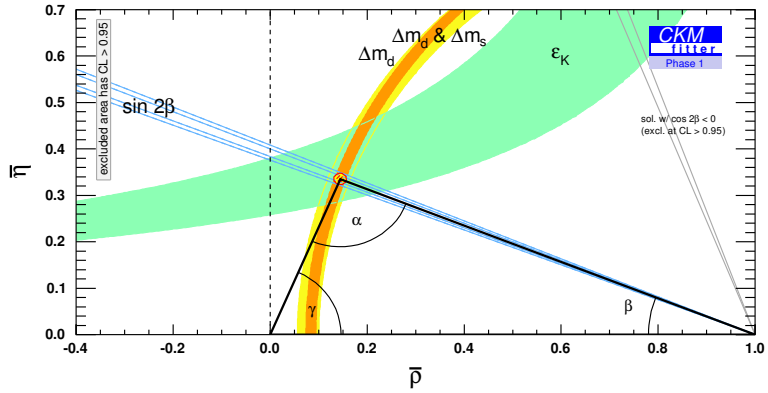
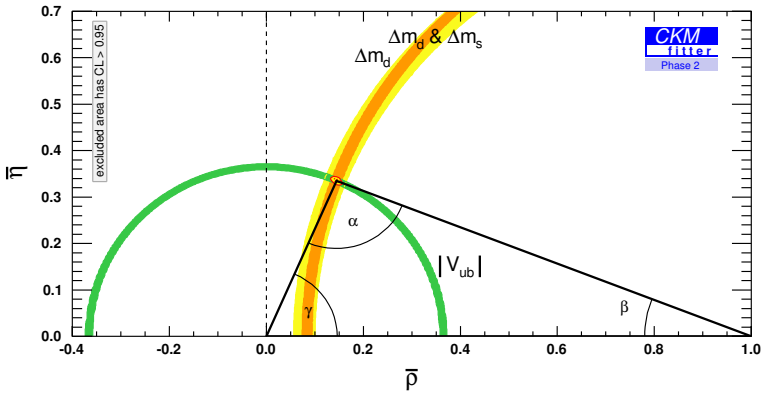


Tree only



Loop only

Playing with subsets : Phase 2 (Preliminary !)



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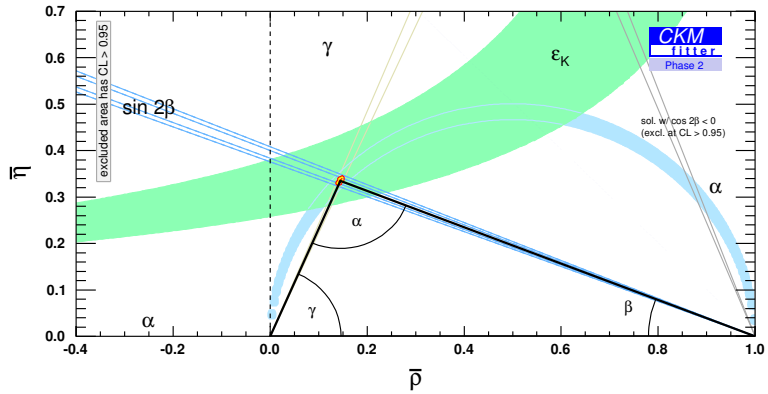

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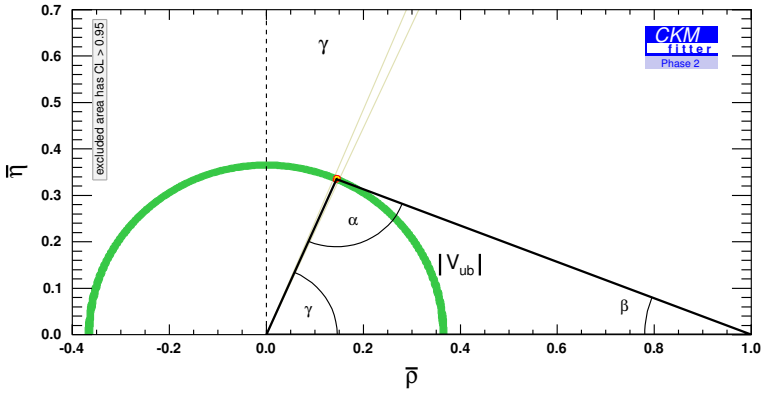
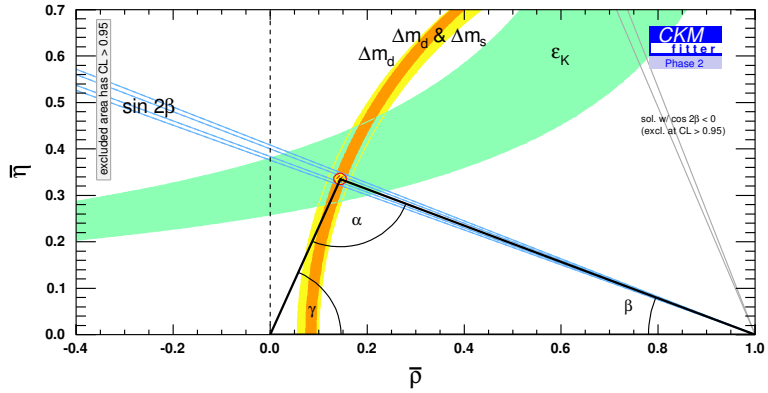


Tree only



Loop only

Uncertainty on a few quantities (Preliminary !)

Assuming the quantities are SM-like (not necessarily the case. . .)

Quantity	Current (No discr)	Unc. Phase 1	Unc. Phase 2
ϕ_s	32 mrad (46 mrad)	20 mrad	14 mrad
$B(B_s \to \mu\mu)$	3.5% (4.3%)	2.8%	2.5%
$B(B_d \to \mu\mu)$	3.6% (4.6%)	2.9%	2.5%
$\frac{B(B_d \to \mu\mu)}{B(B_s \to \mu\mu)}$	1.1% (1.7%)	0.6%	0.6%

- ϕ_s meas. at 14 mrad (Phase 1), 4 mrad (Phase 2)
- $B(B_s \to \mu\mu)$ meas. at 10%-12% (Phase 1), 5%-10% (Phase 2)
- $B(B_d \to \mu\mu)$ meas. at 33%-40% (Phase 1), 10%-20% (Phase 2)
- ratio of Brs meas. at 34%-50% (Phase 1), 10%-20% (Phase 2)

- obs. related to mixing (e.g., a^s_{SL}) accessible, but require further extrapolations (scalar bag parameters) [J. Charles et al., hep-ph/1309.2293]
- obs. related to anomalies either dominated by hadronic unc. (BRs) or no CKM contribution (optimised P_i, LFU ratios R_X)

Discussion

Inputs for discussion

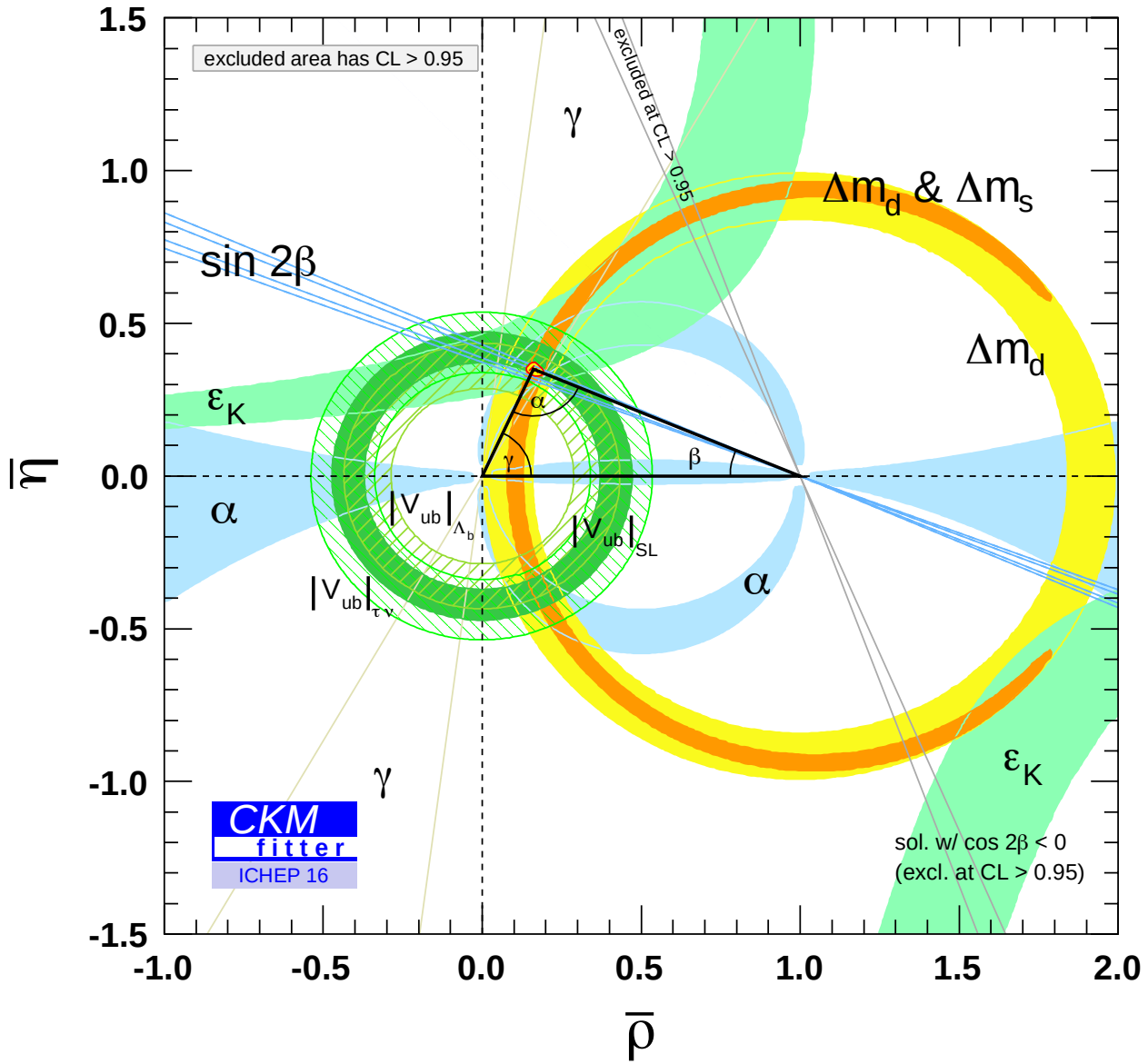
- Lattice extrapolations
- QED corrections for semileptonic and leptonic decays ?
- Penguin pollution for β and ϕ_s ?
- Any charm inputs ? Other inputs to be added ?

CKM metrology

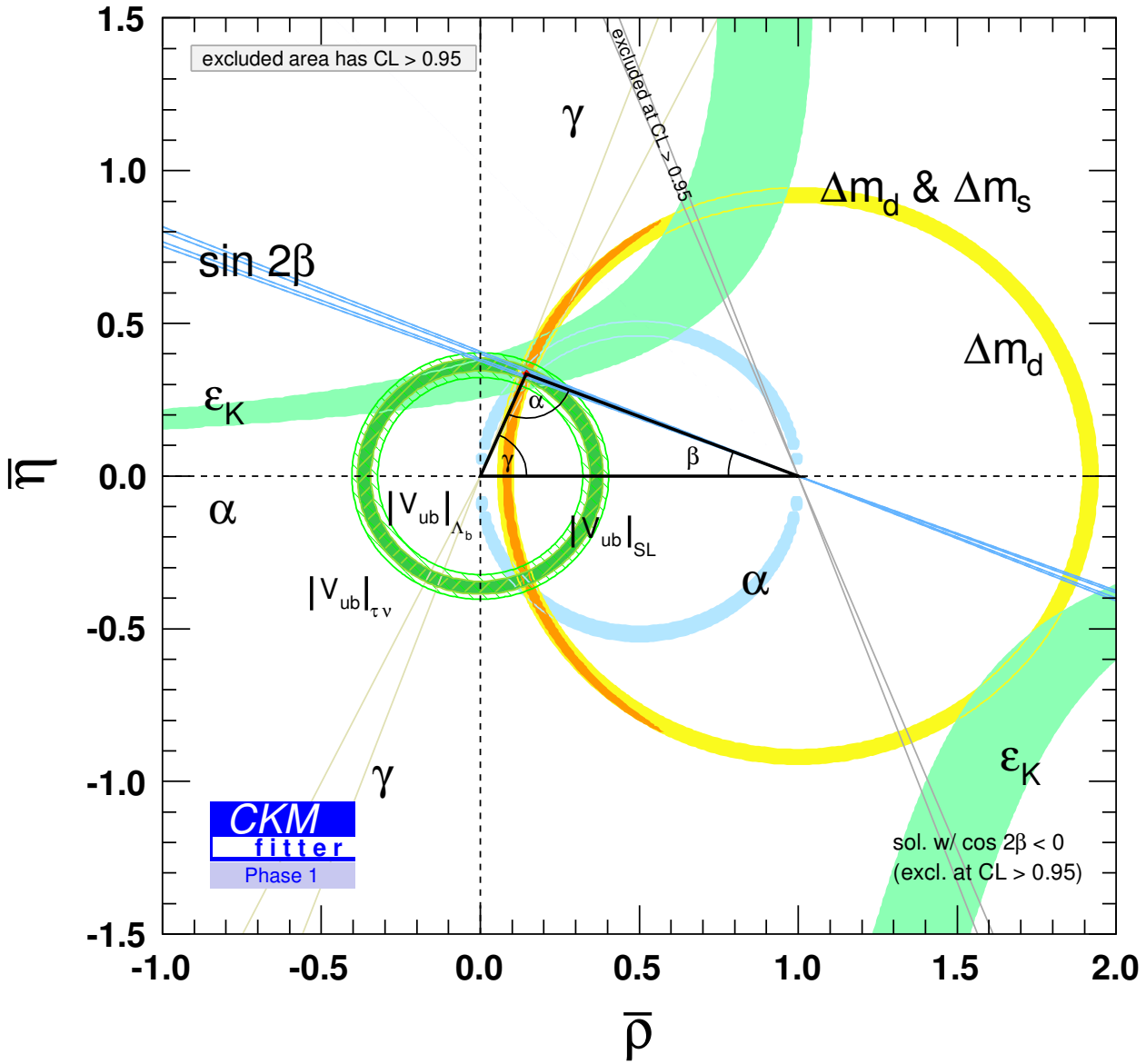
- Improvement in CKM parameters
- Corresponding plots in $\bar{\rho}, \bar{\eta}$ plane
- Other plots of interest (coordinates ? set of constraints ?)
- Other predictions of interest ?

Back-up

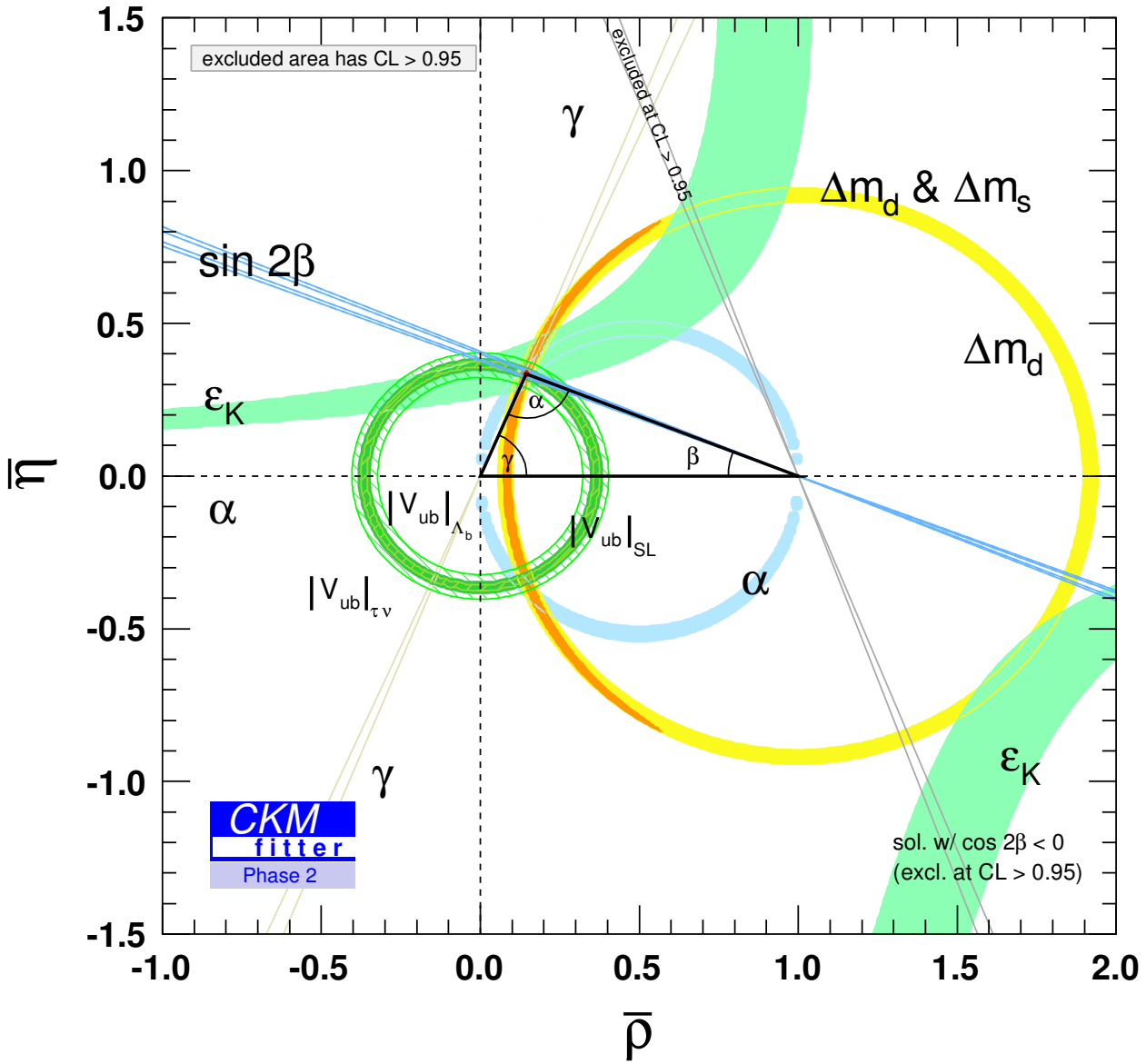
Current status



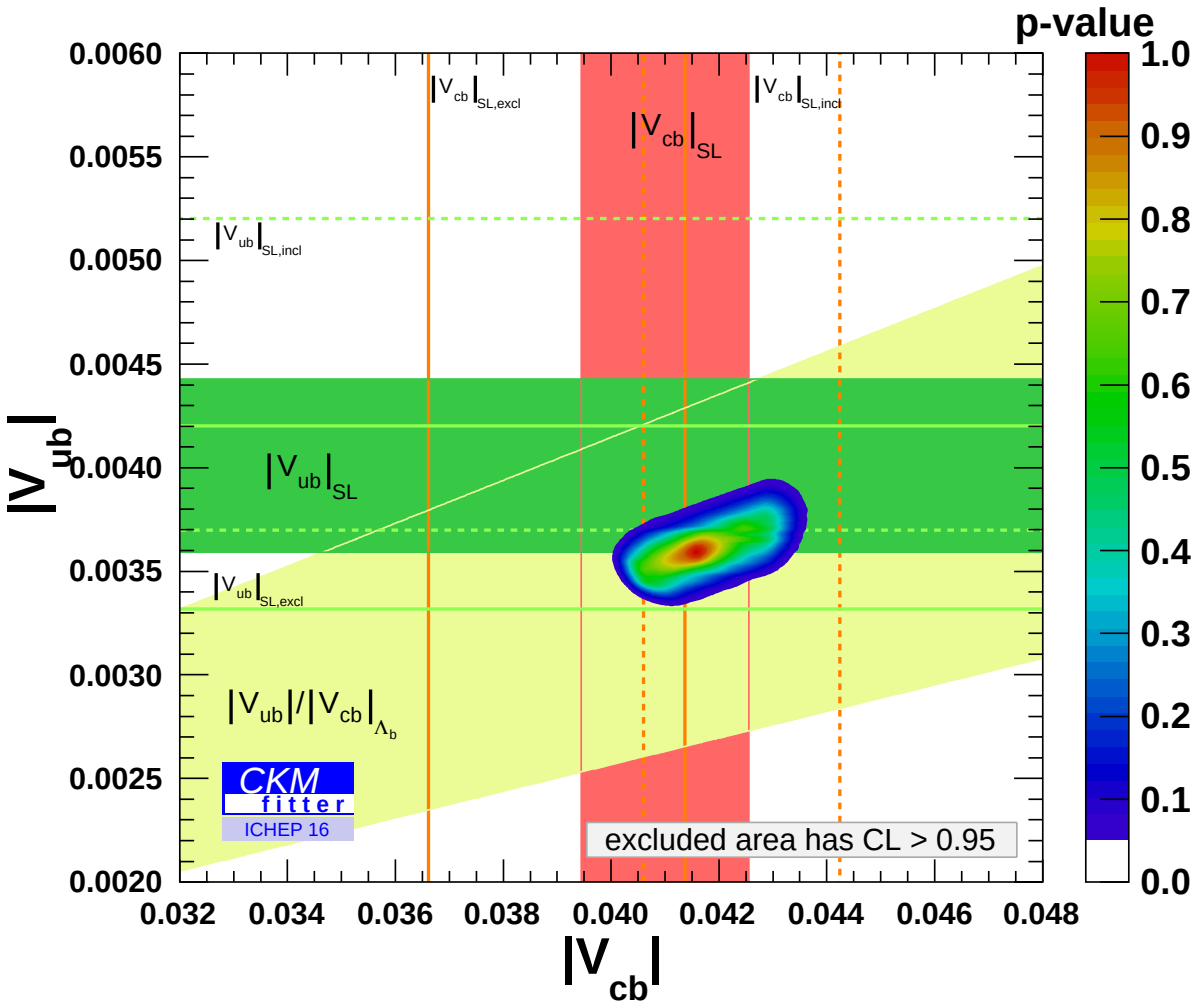
Phase 1


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|_Λb
|V_ub|_SL
|V_ub|_τν
α
γ
ε_K
CKM fitter
Phase 1
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

Phase 2


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|_Λb
|V_ub|_SL
|V_ub|_τν
α
γ
ε_K
CKM fitter
Phase 2
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

Determinations of $|V_{cb}|$ and $|V_{ub}|$



- $|V_{ub}|$ and $|V_{cb}|$ inclusive and exclusive semileptonic
- Global fit of CKM favours excl. $|V_{ub}|_{SL}$ but incl. $|V_{cb}|_{SL}$
- $|V_{ub}|$ from $Br(B \to \tau\nu)$
- $|V_{ub}/V_{cb}|$ from $\Gamma(\Lambda_b \to p\mu\nu)/\Gamma(\Lambda_b \to \Lambda_c\mu\nu)$ (high q^2)
- Averaging procedure between incl and excl

Statistical framework

$q = (A, \lambda, \bar{\rho}, \bar{\eta} \ldots)$ to be determined

- $\mathcal{O}_{\rm meas} \pm \sigma_{\mathcal{O}}$ experimental values of observables
- $\mathcal{O}_{\rm th}(q)$ theoretical description in a given model

In case of statistical uncertainties $\sigma_{\mathcal{O}}$, likelihoods and χ^2

$$\mathcal{L}(q) = \prod_{\mathcal{O}} \mathcal{L}_{\mathcal{O}}(q) \qquad \chi^2(q) = -2 \ln \mathcal{L}(q) = \sum_{\mathcal{O}} \left(\frac{\mathcal{O}_{\rm th}(q) - \mathcal{O}_{\rm meas}}{\sigma_{\mathcal{O}}} \right)^2$$

- Central value: estimator $\hat{q}$ max likelihood: $\chi^2(\hat{q}) = \min_q \chi^2(q)$
- Range: confidence level for each q_0 (p-value for $q = q_0$) by:

$$\Delta\chi^2(q_0) = \chi^2(q_0) - \min_q \chi^2(q)$$

  assumed to obey χ^2 law with $N = dim(q)$ to yield CIs
- Pull: comparison of $\chi^2_{\rm min}$ with and without one measurement

$$p_{\mathcal{O}} = \sqrt{\min_q \chi^2_{\text{with meas}}(q) - \min_q \chi^2_{\text{without meas}}(q)}$$

$\Longrightarrow$Specific scheme to treat theoretical uncertains (currently Rfit)