Global fits of the Unitarity Triangle within the Standard Model. Updates from the UTfit collaboration.

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The Unitarity Triangle Analysis

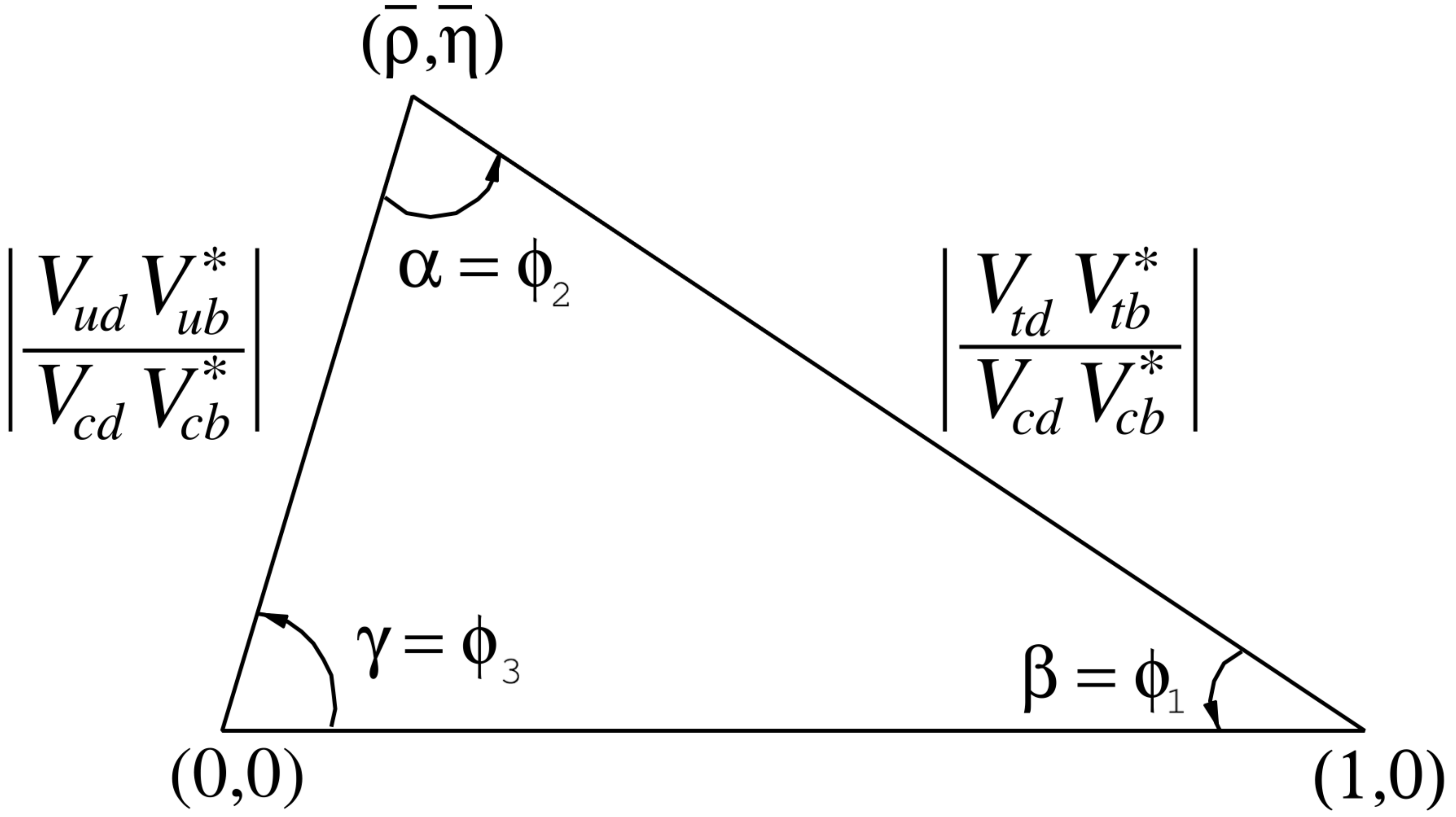
- Flavor-changing processes and CP violation in the SM ruled by 4 parameters in the 3x3 CKM (unitary) matrix

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

  - $A, \lambda, \bar{\rho}$ and $\bar{\eta}$

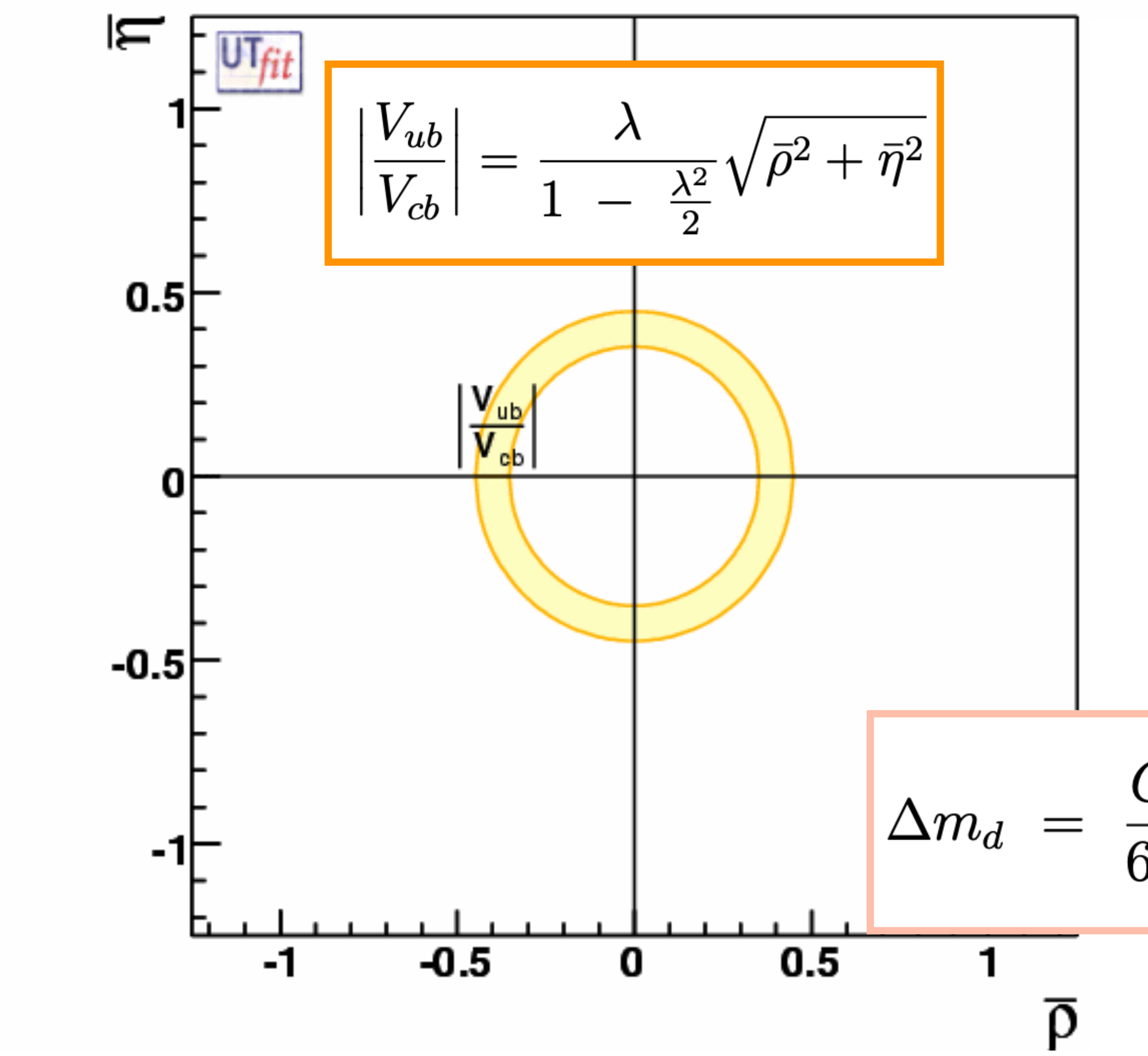
$$\boxed{\bar{\rho} = \rho(1-\lambda^2/2+\ldots) \quad \bar{\eta} = \eta(1-\lambda^2/2+\ldots)}$$

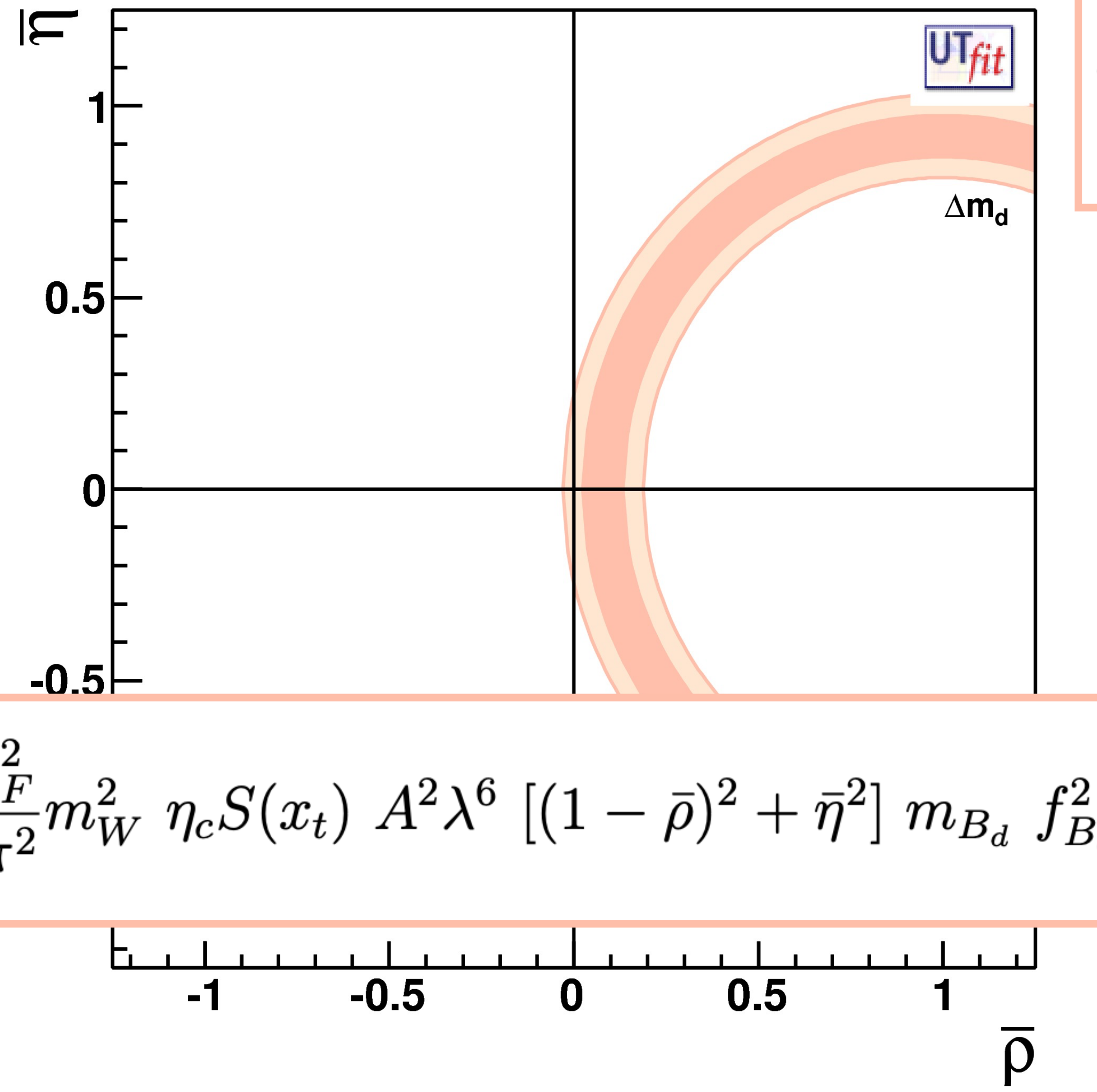
- Small value sin of Cabibbo angle (λ) makes the CKM matrix close to diagonal
- Unitarity implies relations between elements, that can be represented as a triangle in a plane
- By determining the apex, one determines the CKM matrix



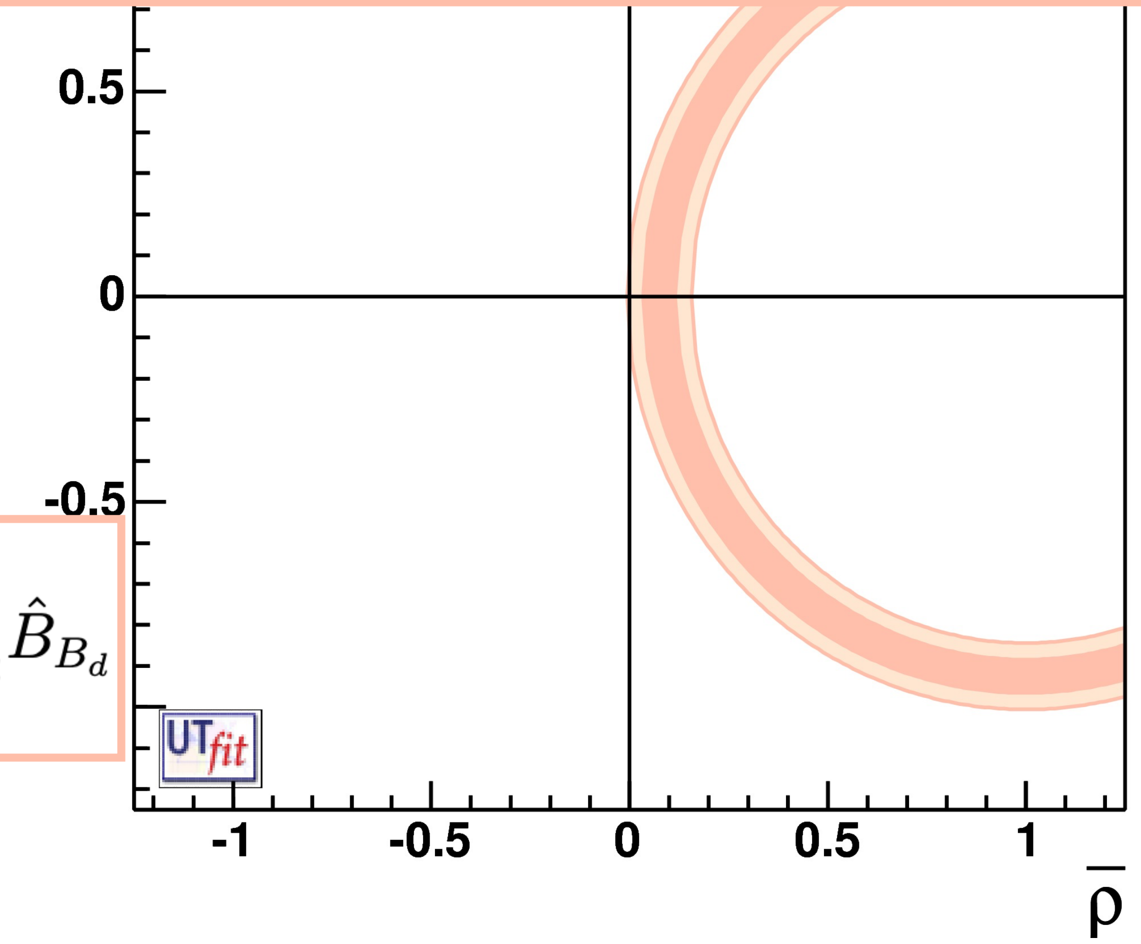
UT constraints

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar\rho^2+\bar\eta^2}$$

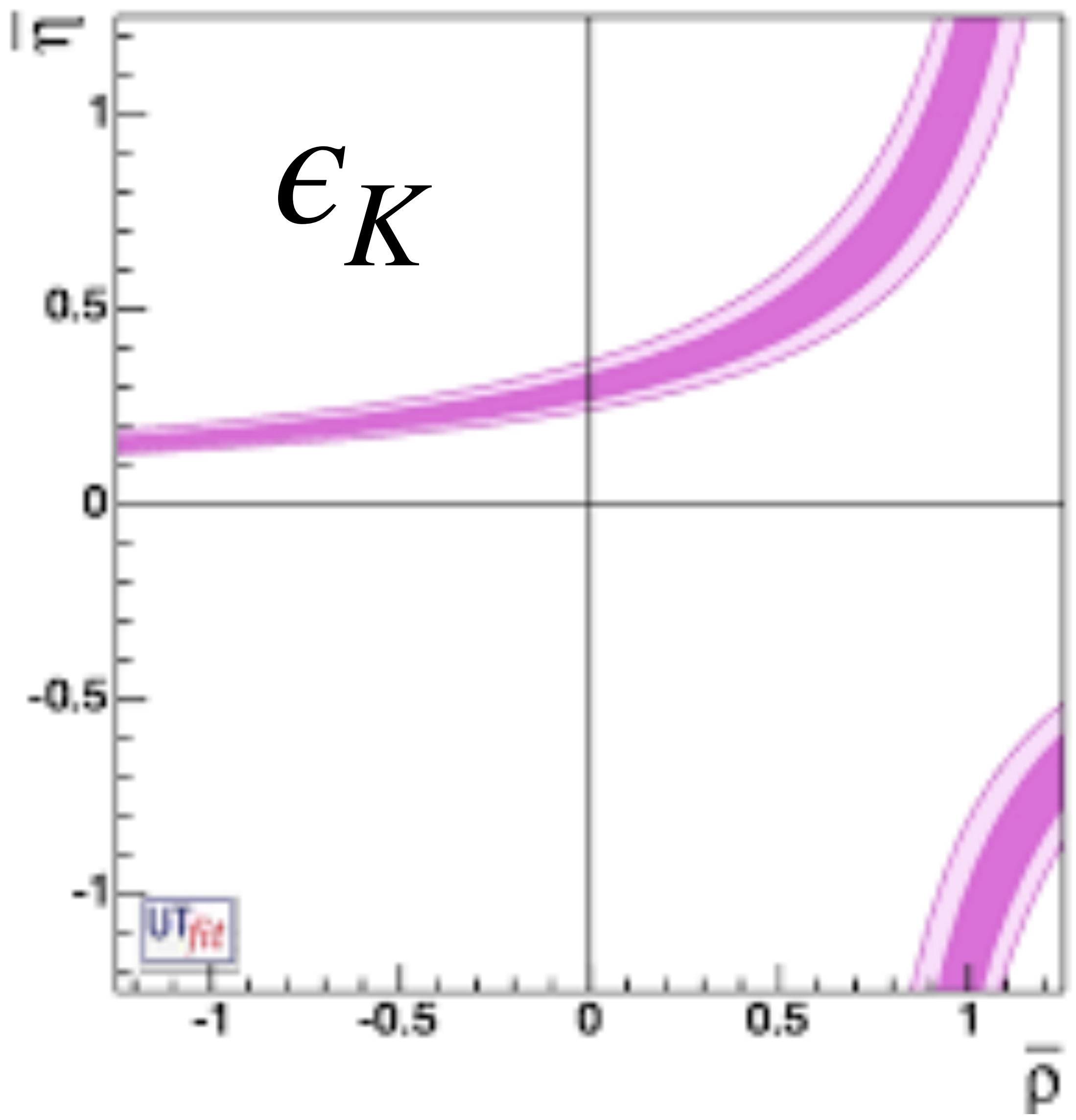


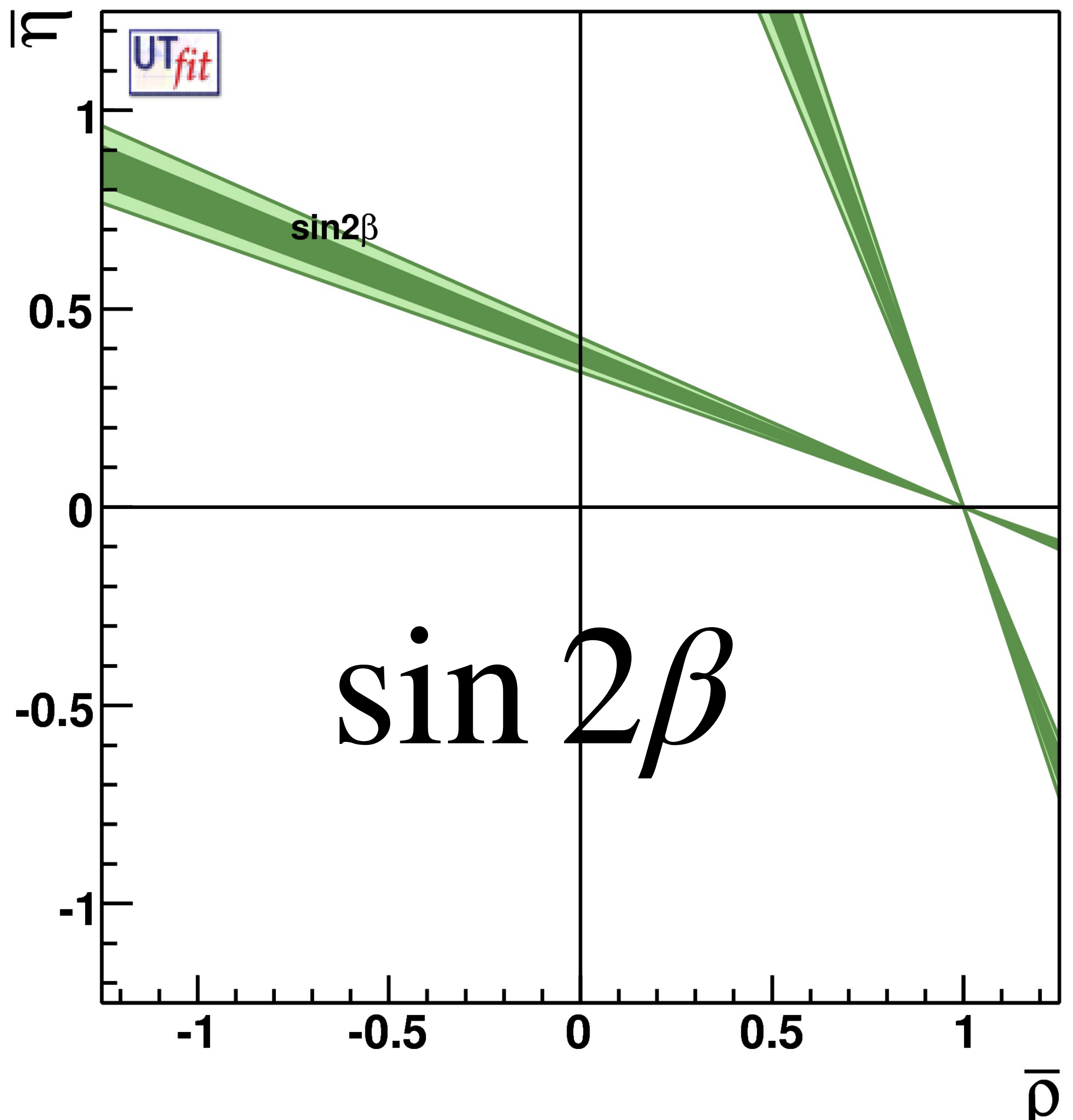


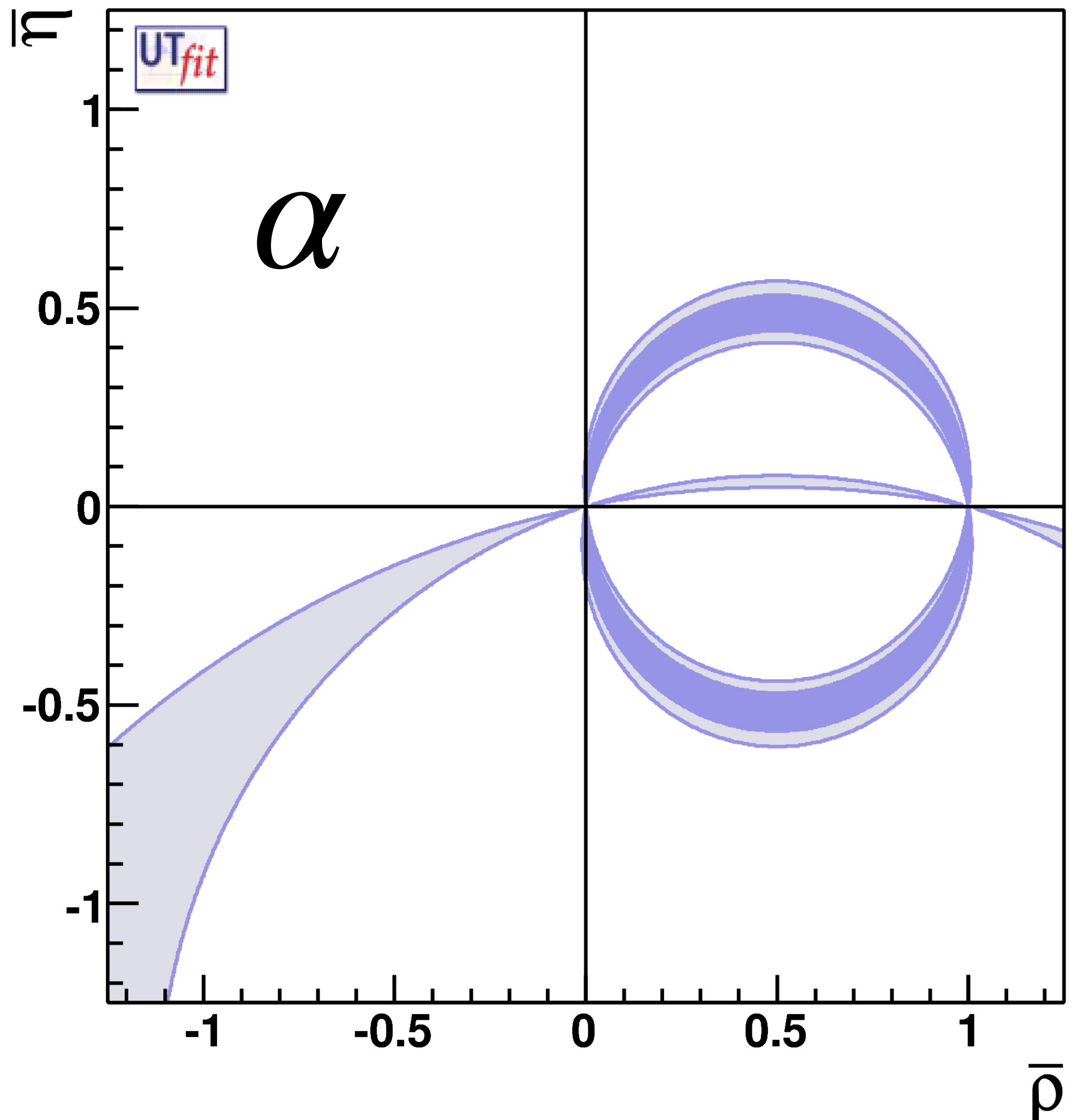
$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat B_{B_d}}{m_{B_s} f_{B_s}^2 \hat B_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar\rho)^2+\bar\eta^2]$$

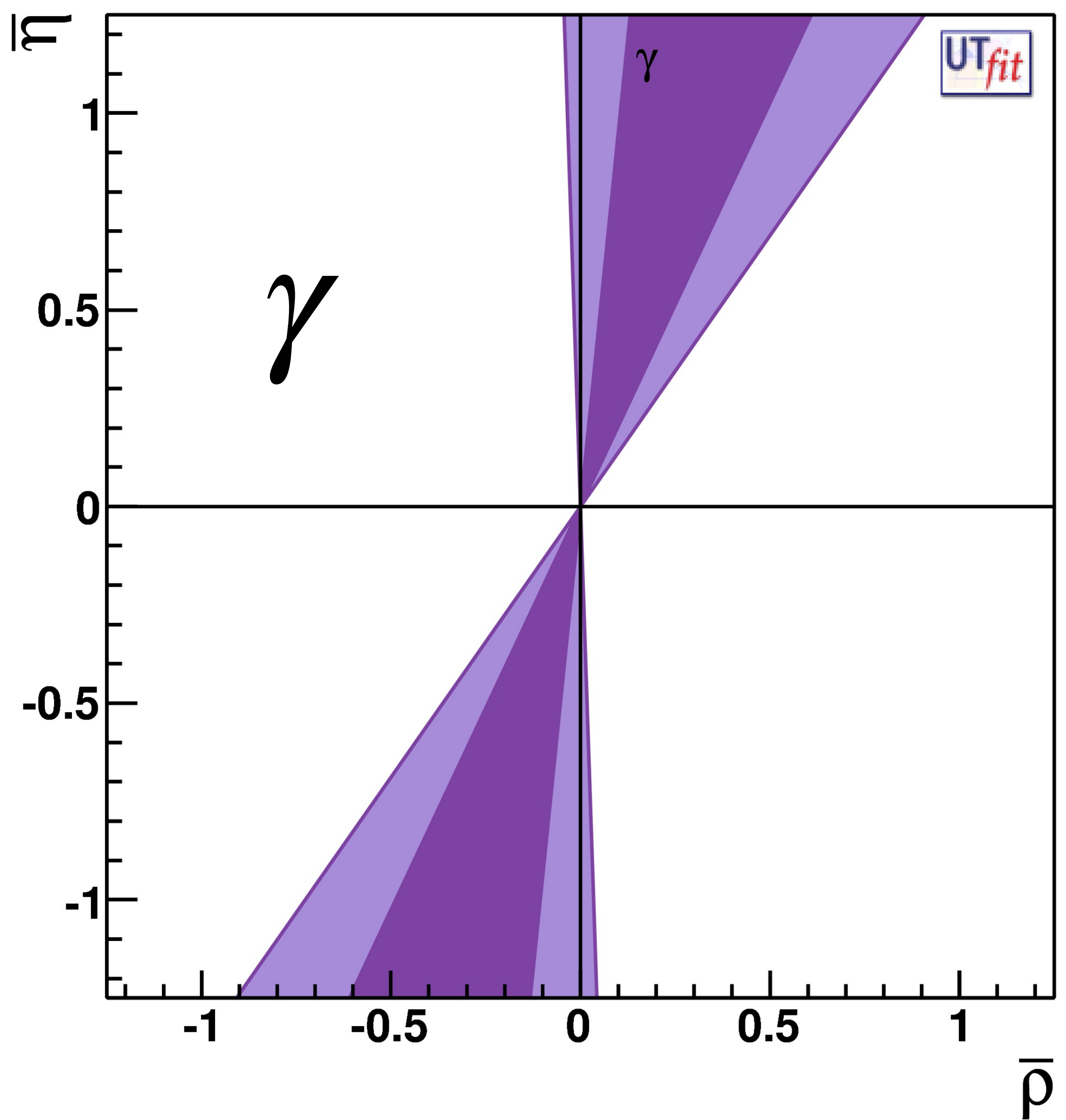


$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar\rho)^2+\bar\eta^2]\ m_{B_d}\ f_{B_d}^2 \hat B_{B_d}$$

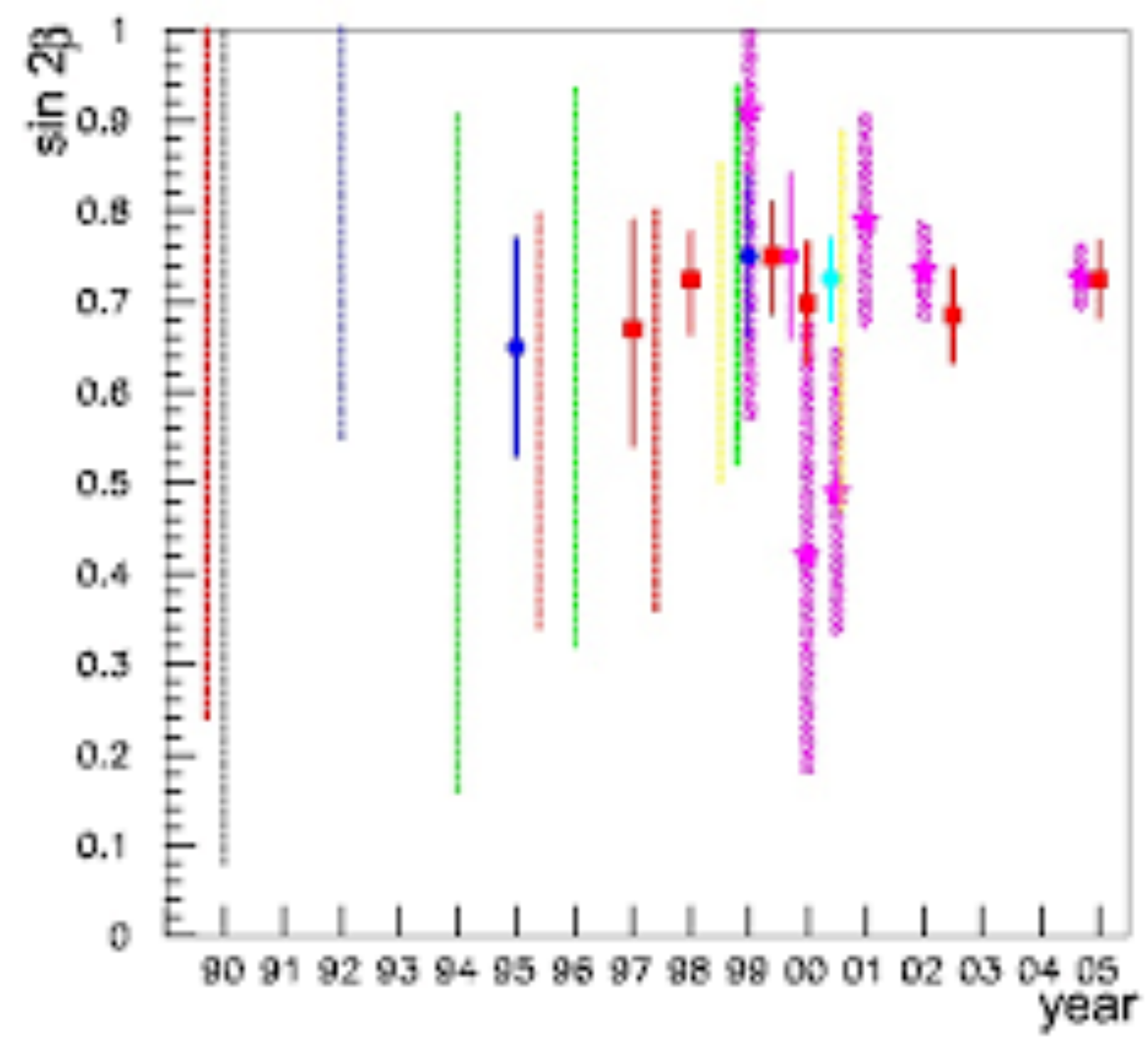




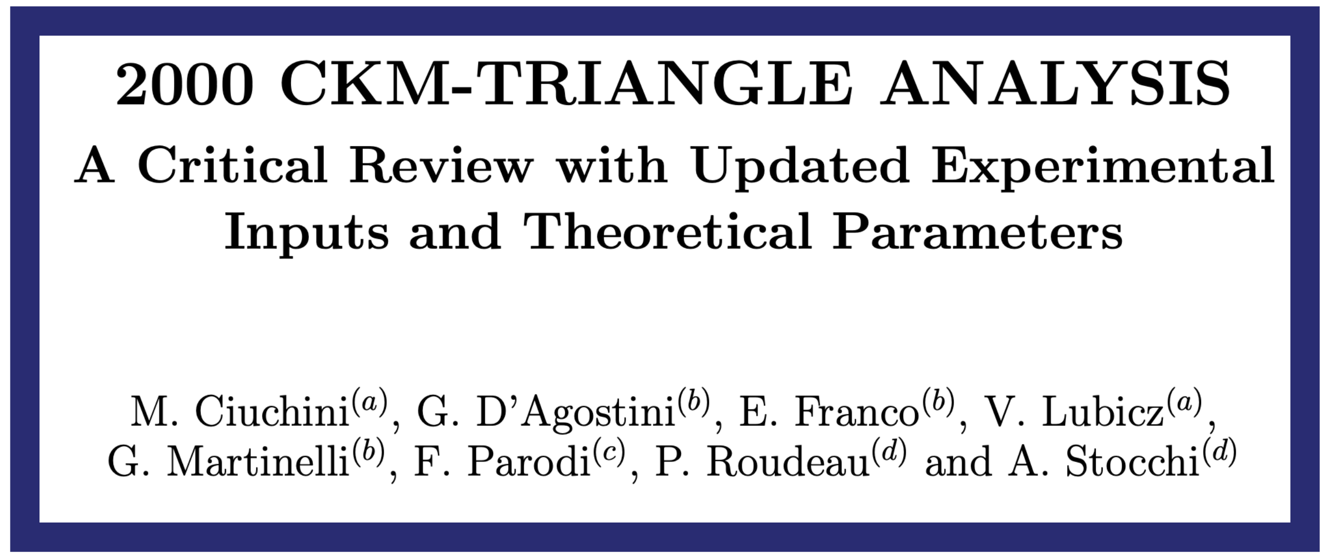




30 years of UT fit



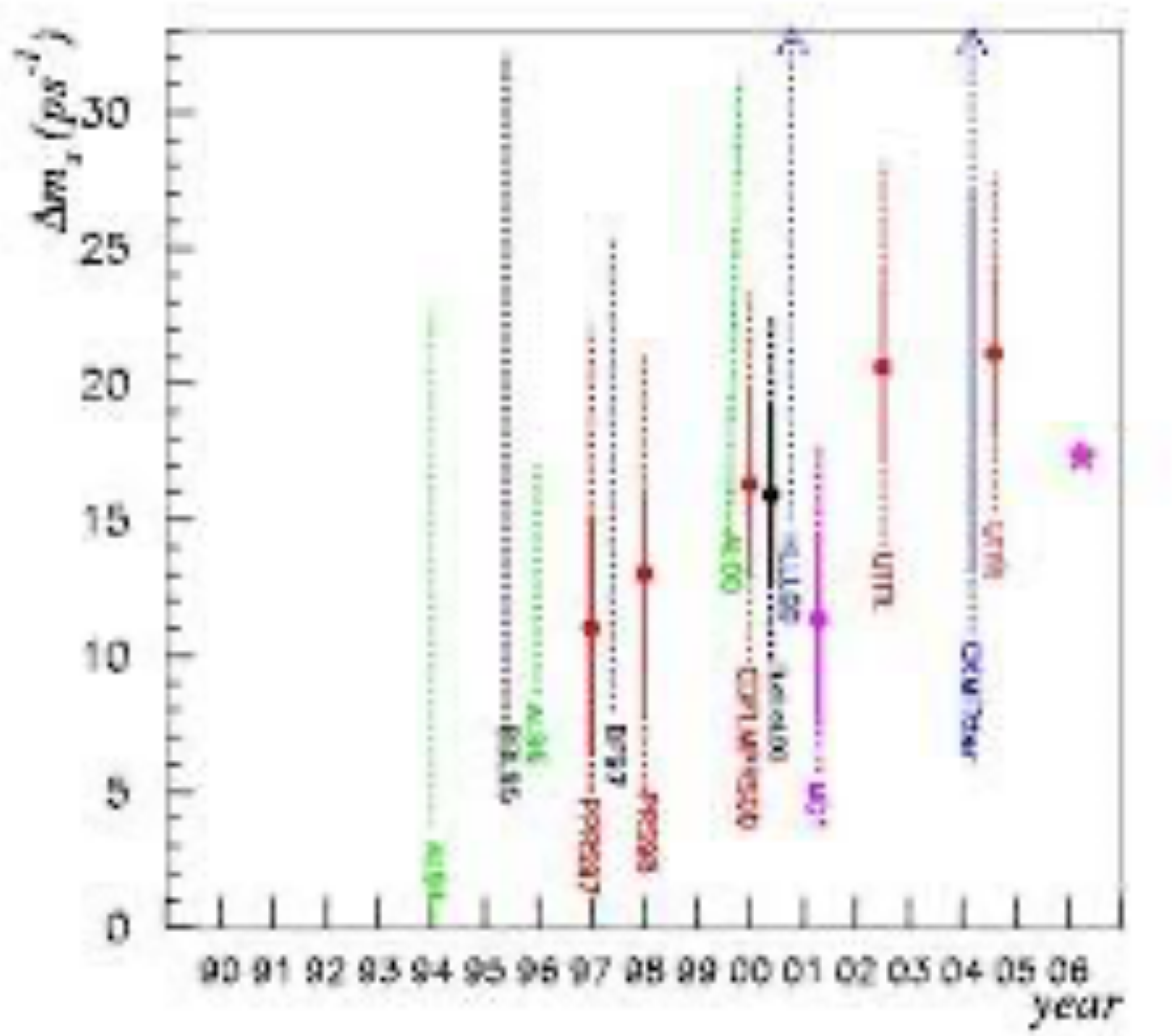
- Since early ‘90s, the UT framework has been established to probe CP violation in the flavor sector
  - sin2b (CPV in $B_d\bar{B}_d$ mixing) the reference quantity
  - very loose predictions once its value
  - jump in accuracy ~ ’95, when the <u>first full statistical analysis was attempted</u>, strongly benefiting of the first determination of the top mass. The UT analysis was born, predicting a few still unknown quantities
    - $\sin 2\beta = 0.65 \pm 0.12$
  - In 2000, Rome and Orsay/Genova groups (running similar fits) joined forces. This was the beginning of the UTfit collaboration



2000 CKM-TRIANGLE ANALYSIS

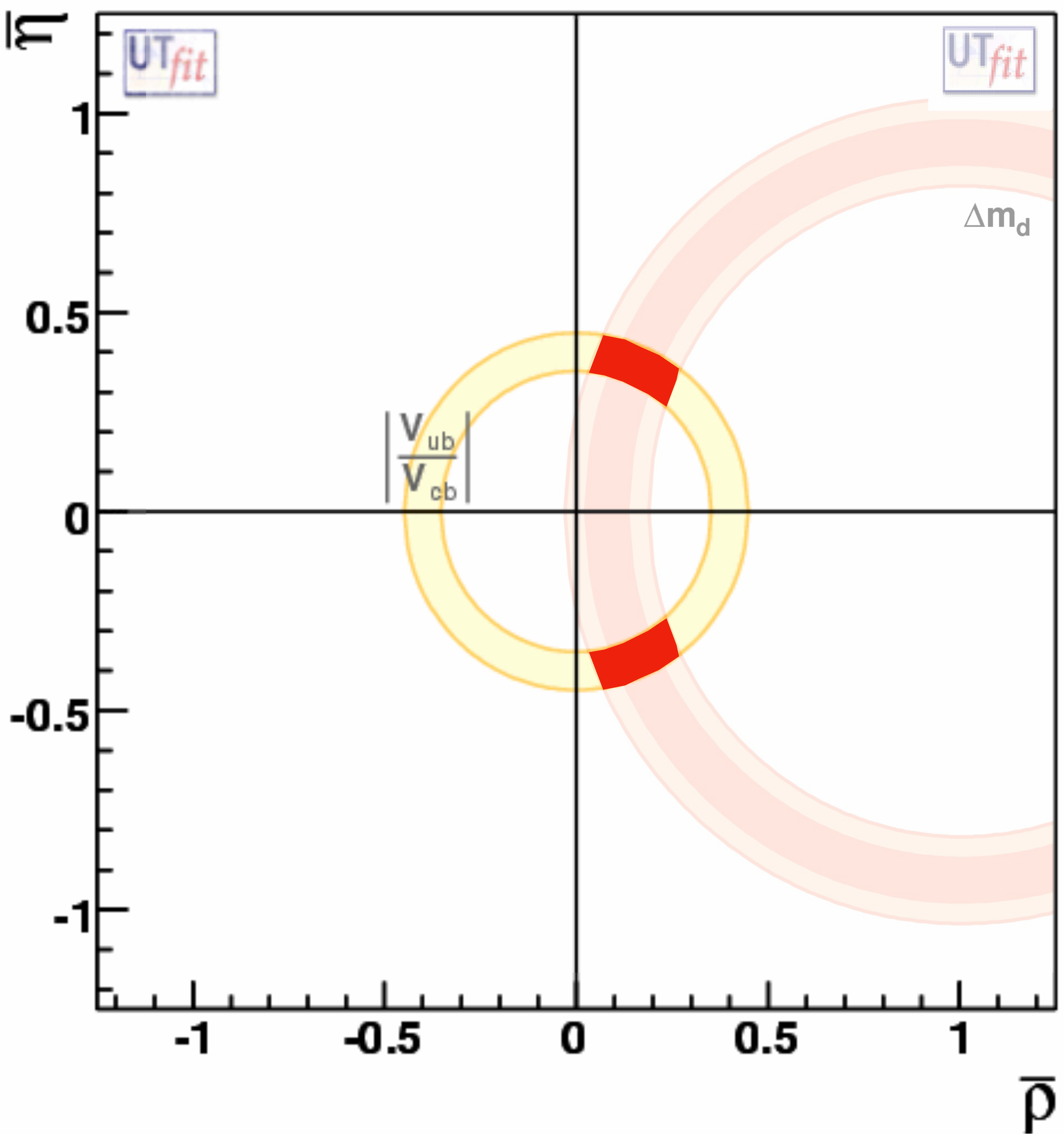
A Critical Review with Updated Experimental Inputs and Theoretical Parameters

M. Ciuchini[(a)], G. D’Agostini[(b)], E. Franco[(b)], V. Lubicz[(a)],
G. Martinelli[(b)], F. Parodi[(c)], P. Roudeau[(d)] and A. Stocchi[(d)]



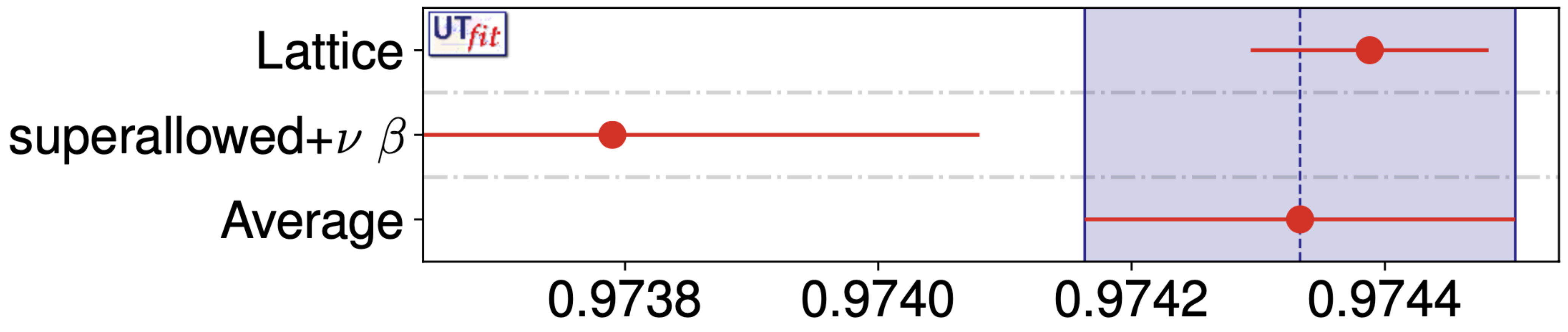
The value of redundancy

- Redundancy is the biggest strength of the UT analysis
  - Many observables, depending on a few parameters
  - one can remove a subset of the inputs and still be able to determine the CKM parameters
- In particular, one can fit for the CKM parameters using only CP conserving quantities
  - Can exclude $\bar{\eta} = 0$, establishing CP violation without directly observing it



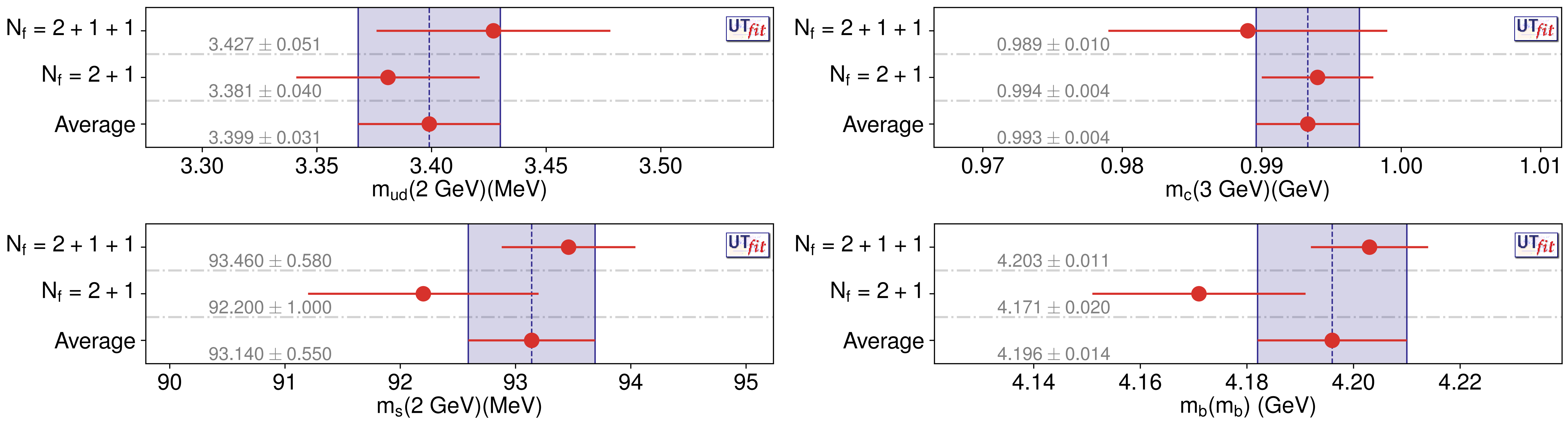
What's new for EPS23

- Theory updates:
  - New V_{ud} extraction from neutron decays, following V. Cirigliano et al. arXiv:2306.03138
  - New lattice values for masses
  - New lattice form factors for exclusive $b \to q\ell\nu$



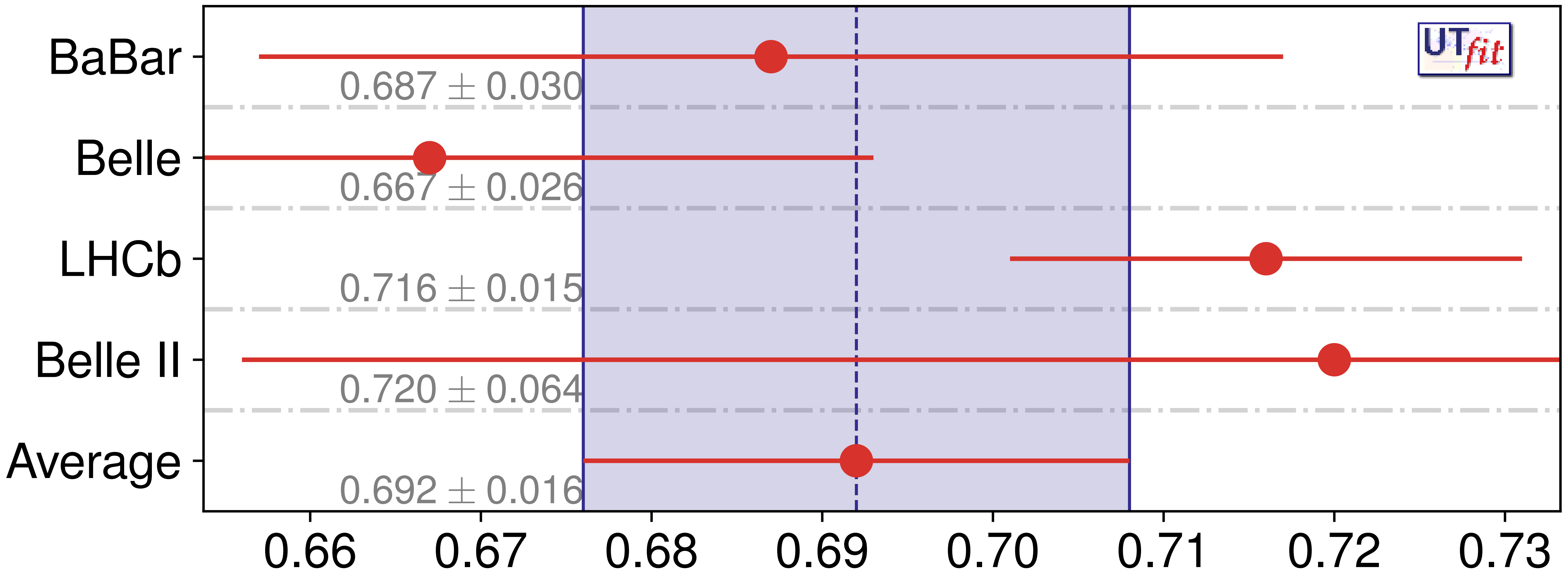
- Experiment updates:
  - New sin2β by LHCb
  - New γ by LHCb
  - New α
  - …

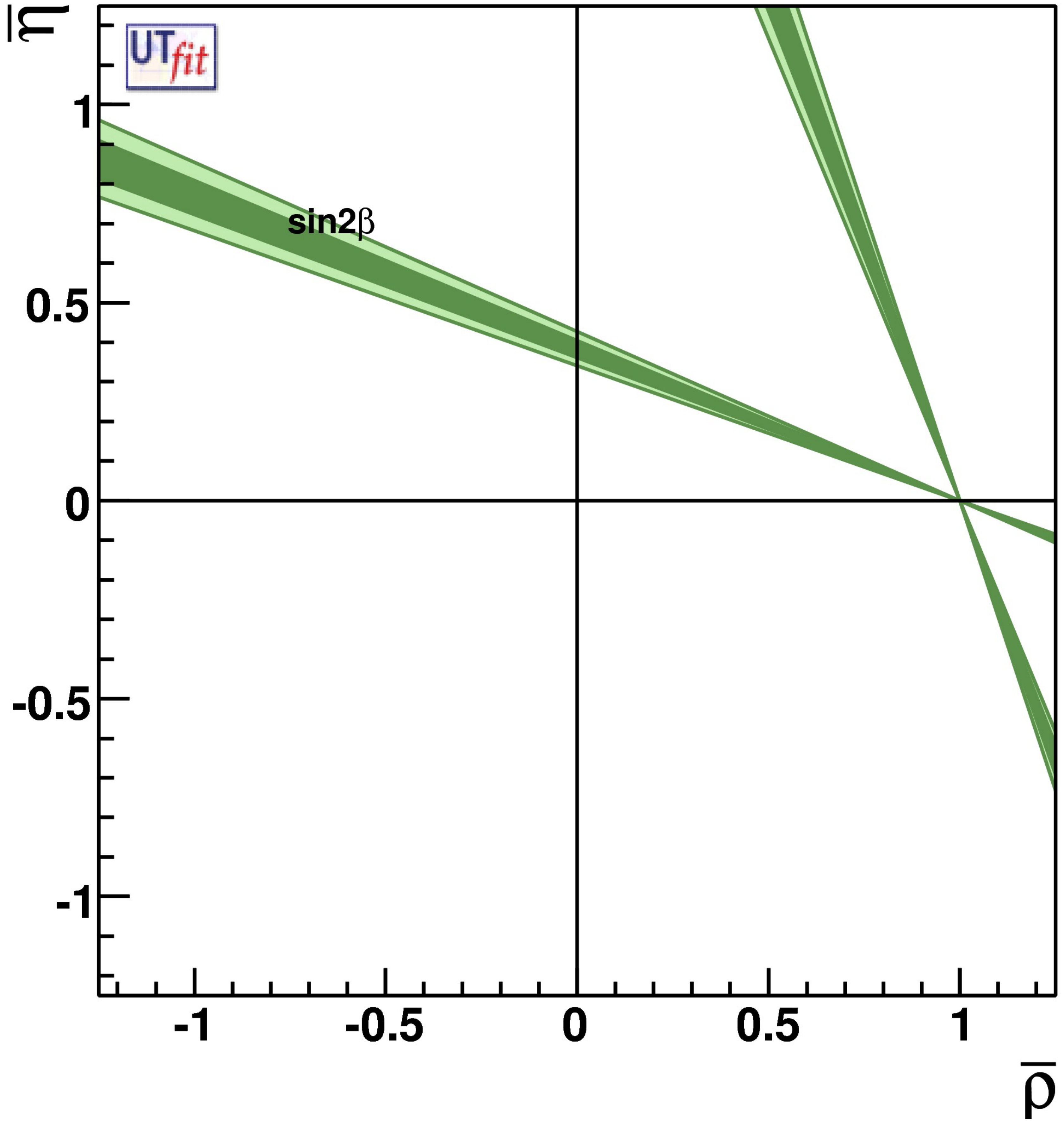
All masses computed in $\overline{\rm MS}$ and averaged with PDG scale factors



What’s new for EPS23: $sin(2\beta)$

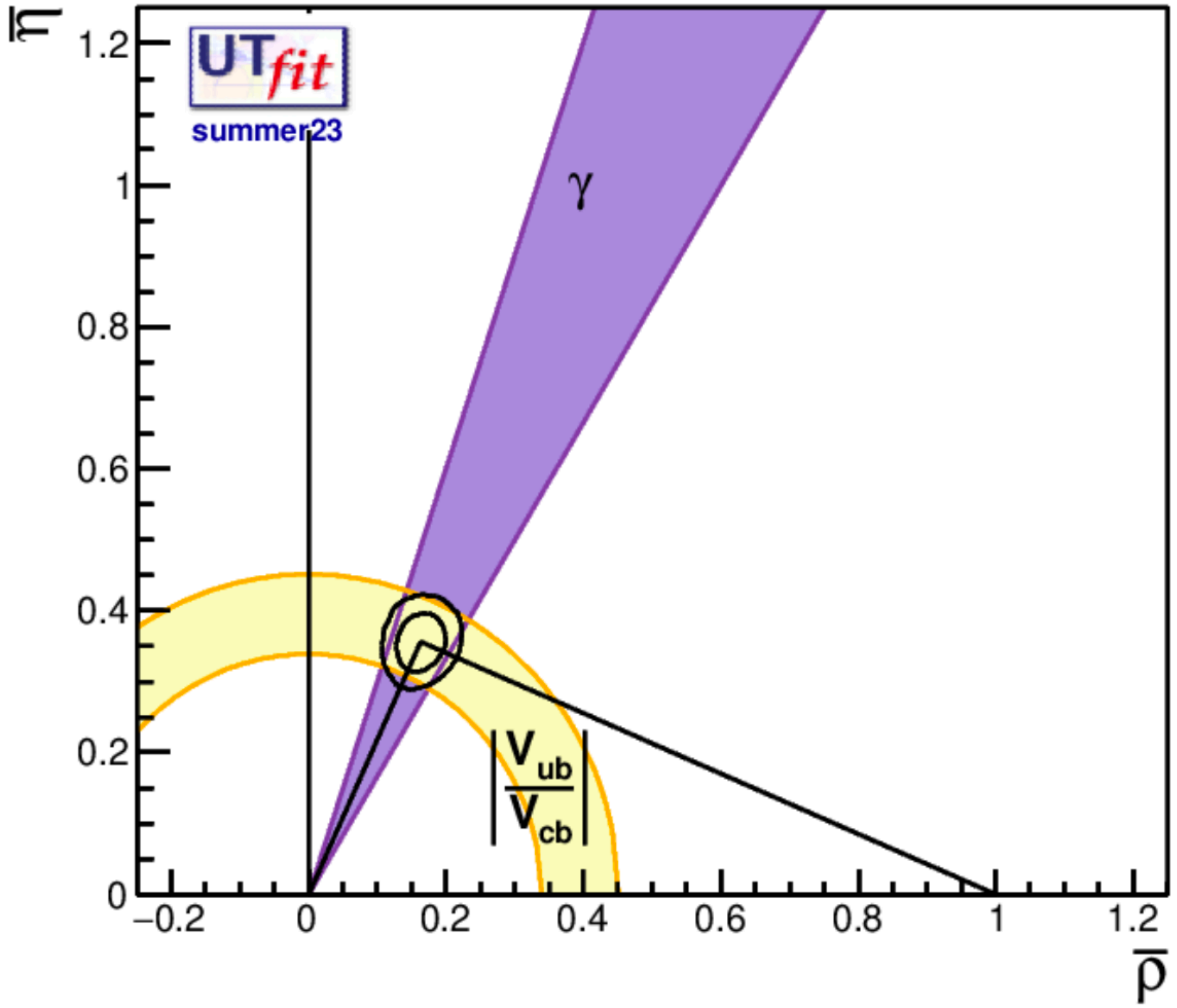
- Averaged charmonium values
- New sin2β from LHCb
- Average including correction due to Cabibbo-suppressed penguin contribution:
  - Most recent estimate $\Delta(\sin 2\beta) = -0.1 \pm 0.1$
  - Theoretical uncertainty comparable to experimental error





What’s new for EPS23

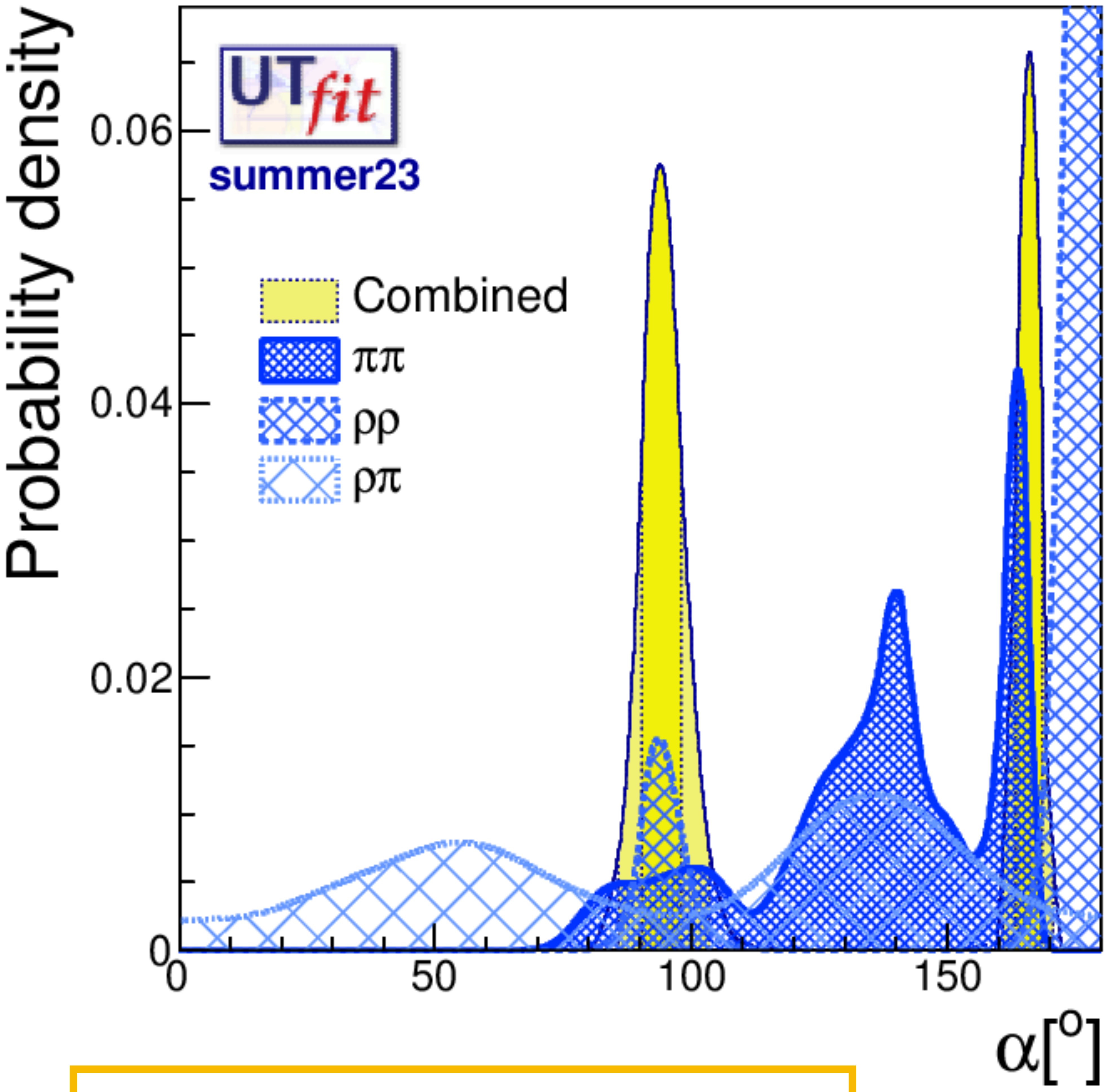
- Determination combining all D$^{(*)}$K$^{(*)}$ modes
  - Simultaneous extraction of γ and $D\bar{D}$ mixing parameters (which enter the BSM analysis)
  - Details are given in dedicated talk by R. Di Palma on Friday
- Tree-level determination
  - Baseline determination of CP violation in the SM, assuming BSM effects enter only at loop
  - With |V$_{ub}$/V$_{cb}$|, allows for a robust fit of the CKM parameters in the SM, even in presence of new physics



$$\bar{\rho} = \pm 0.163 \pm 0.024$$
$$\bar{\eta} = \pm 0.356 \pm 0.027$$

What's new for EPS23

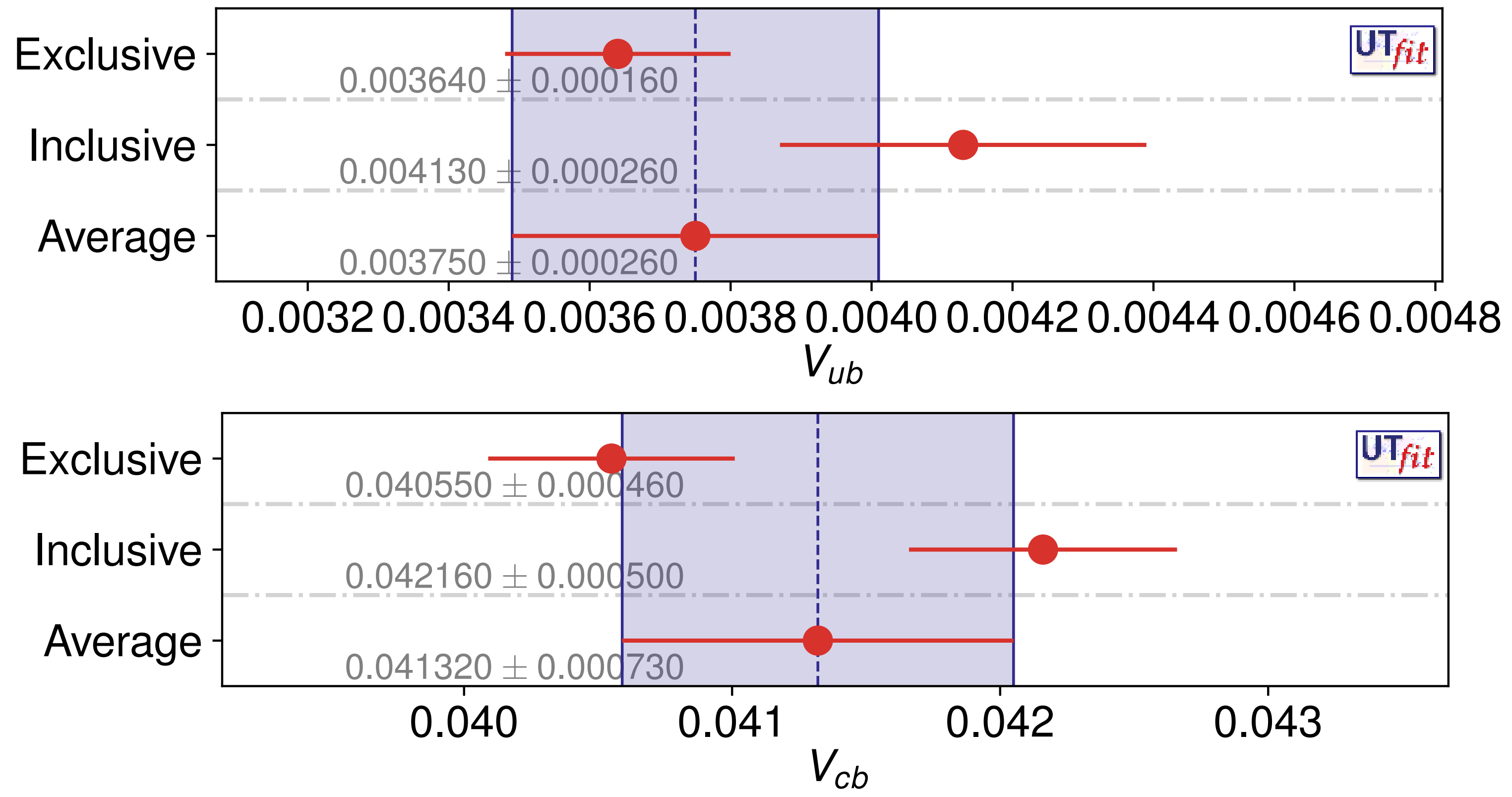
- Updated the bound on α with
  - Bounds from ππ and ρρ derived from PDG averages (including PDG rescaling of the error)
  - Bound from ρπ derived from same inputs used by HFLAV
- As usual, main difference wrt other combinations is in the treatment of the multiple solutions
  - Profiling vs marginalization: in our case, multiple overlapping solutions counts more than a single solution when integrating out the other quantities (T, P, and strong phases)

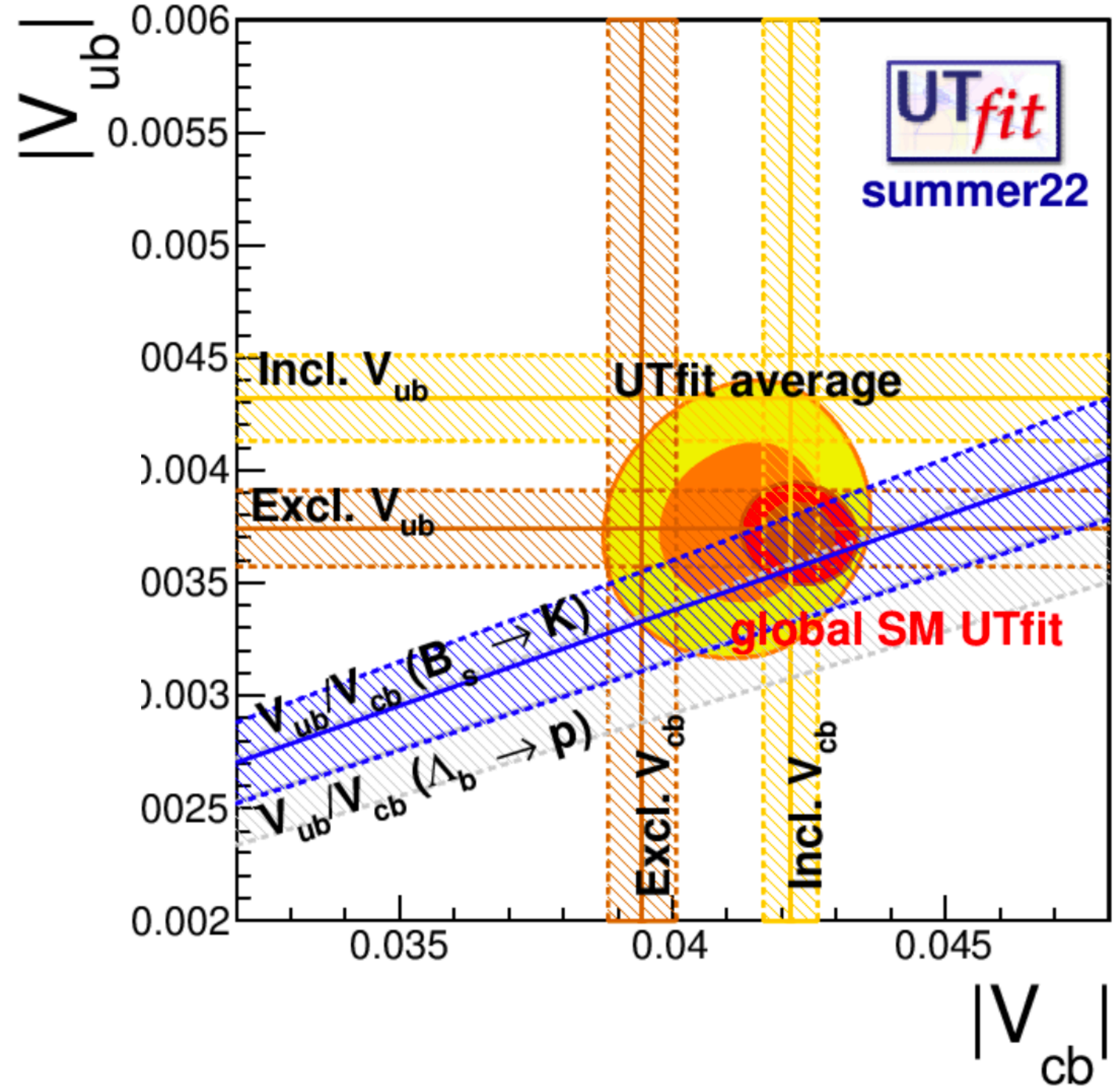


$$\alpha = (93.8 \pm 4.5)^o$$

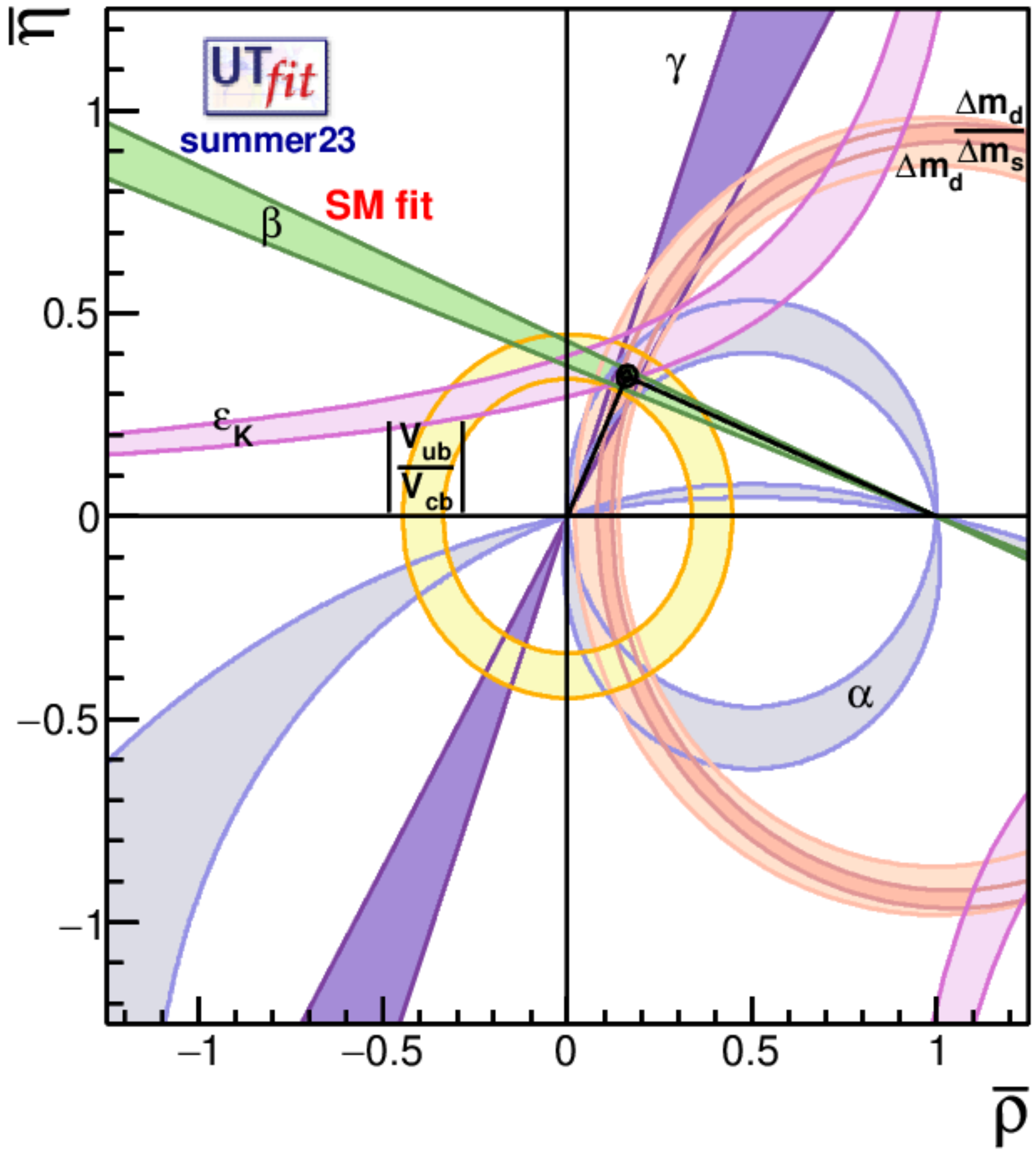
What’s new for EPS23

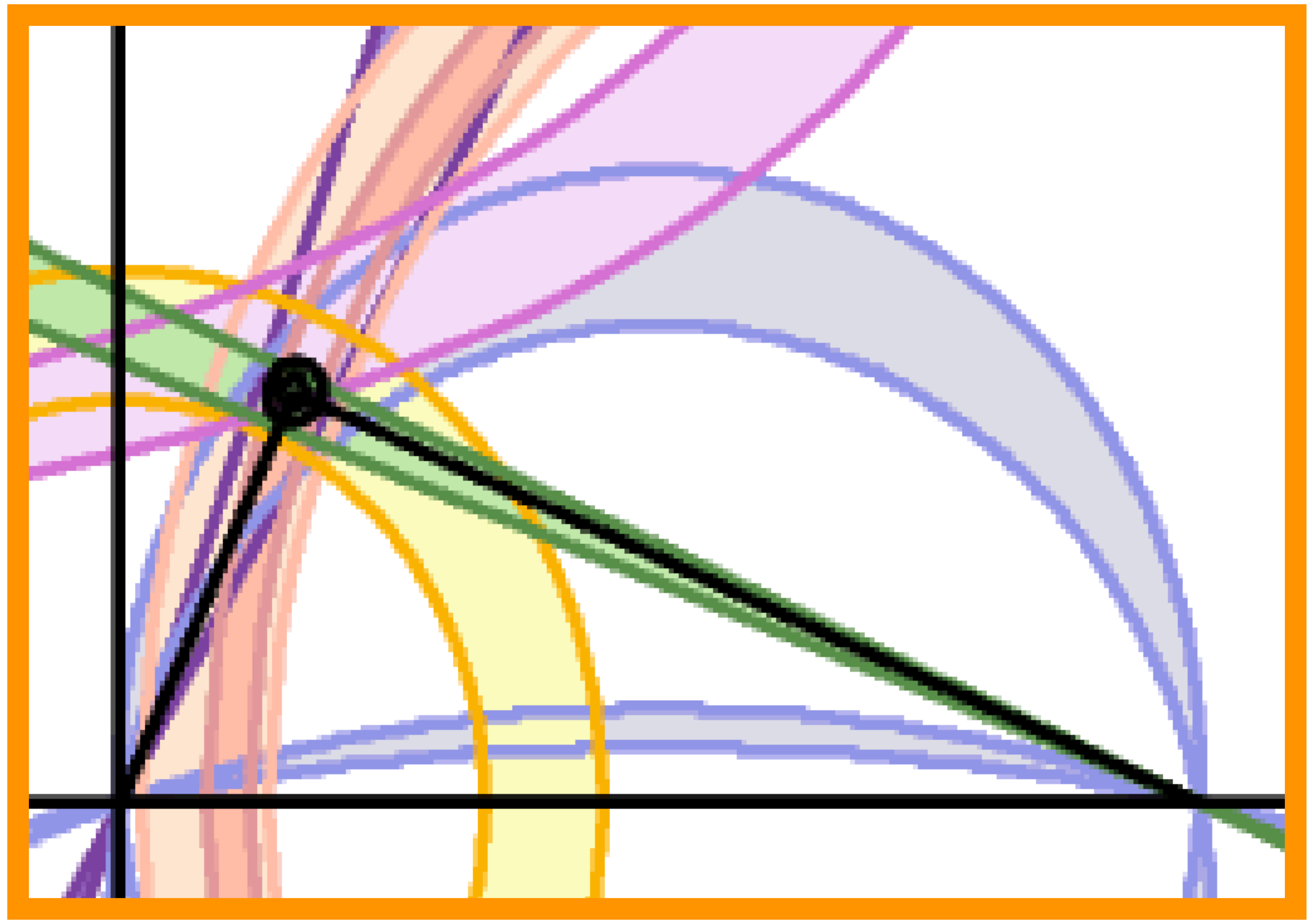
- This is the most delicate set of inputs, due to the long standing tension between different determinations
- For Summer23:
  - inclusive determinations are the same
  - new lattice inputs are used to determine the inclusive values
  - updated input on $|V_{ub}/V_{cb}| = 0.0827 \pm 0.0117$ (FLAV) with improved treatment of correlations for lattice inputs
    - The larger error reduces the correlation between the two quantities to 0.028 when running the 2D Skeptic Bayesian combination (n-dim generalization of PDG scale factor)





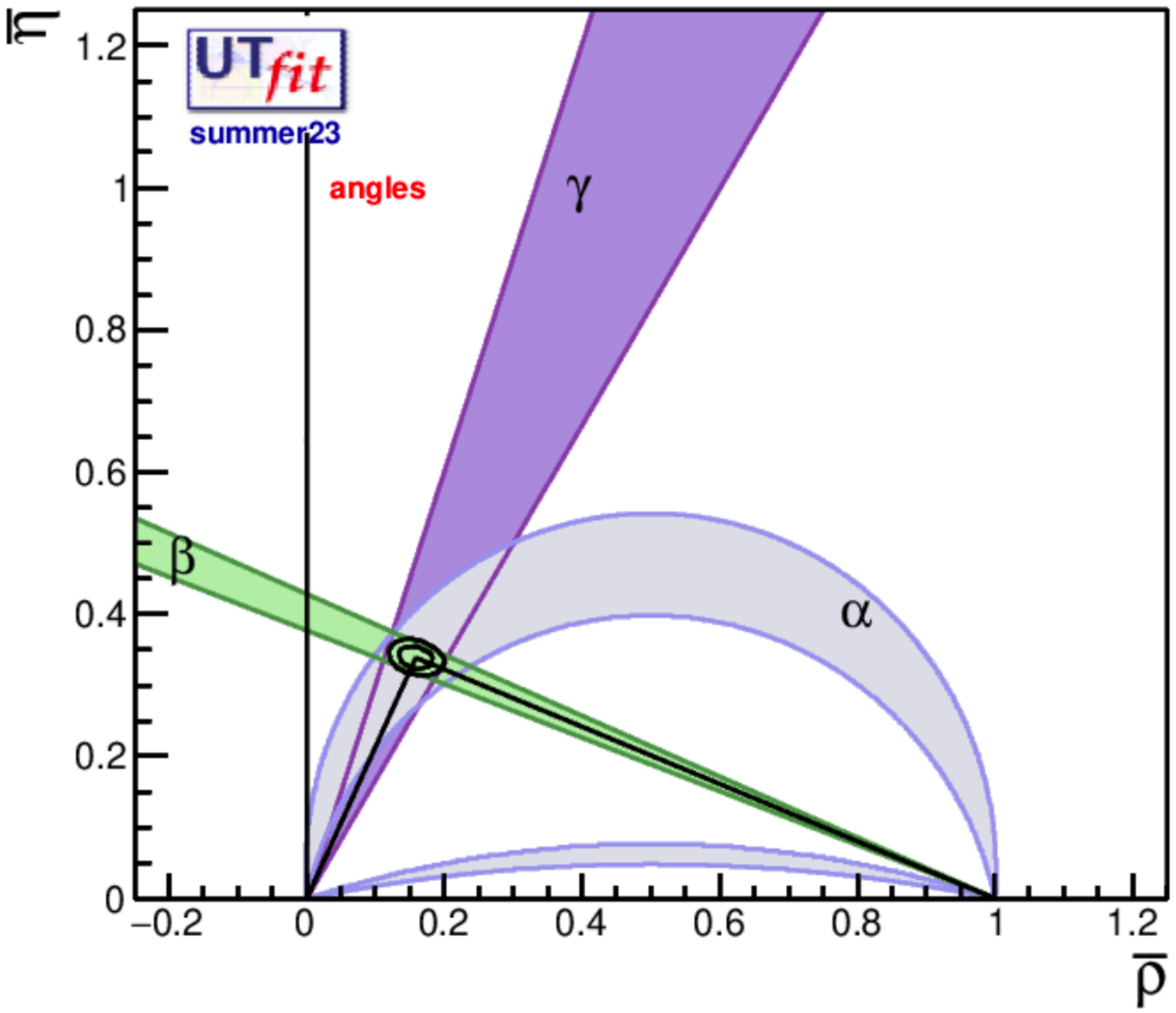
Standard Model Fit result



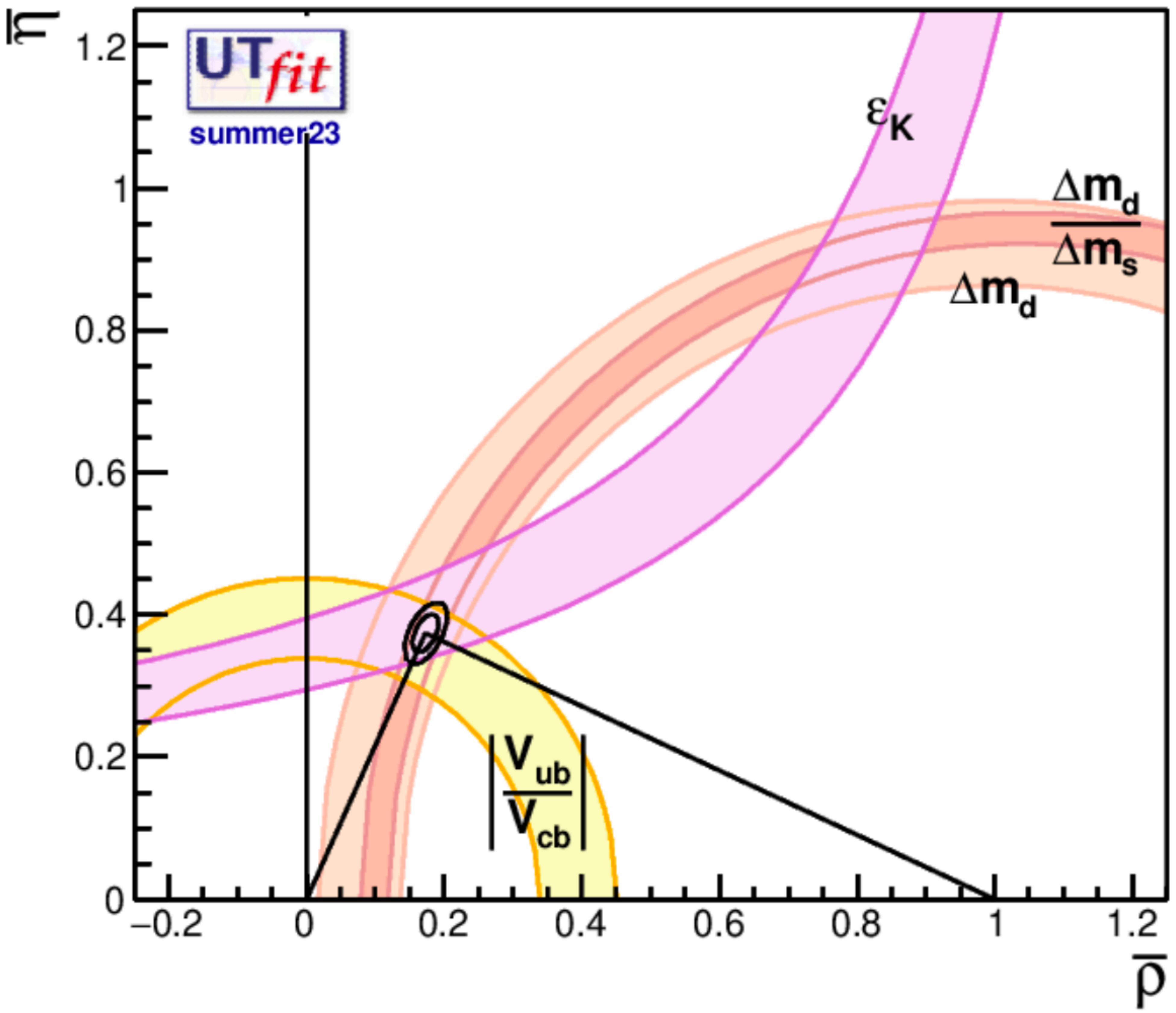


$$\bar{\rho} = 0.160 \pm 0.009$$
$$\bar{\eta} = 0.345 \pm 0.011$$

Standard Model Fit result

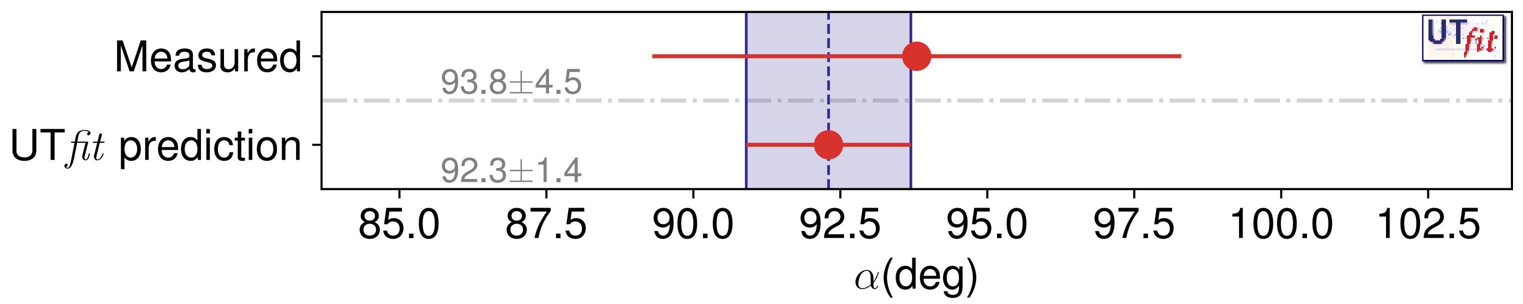


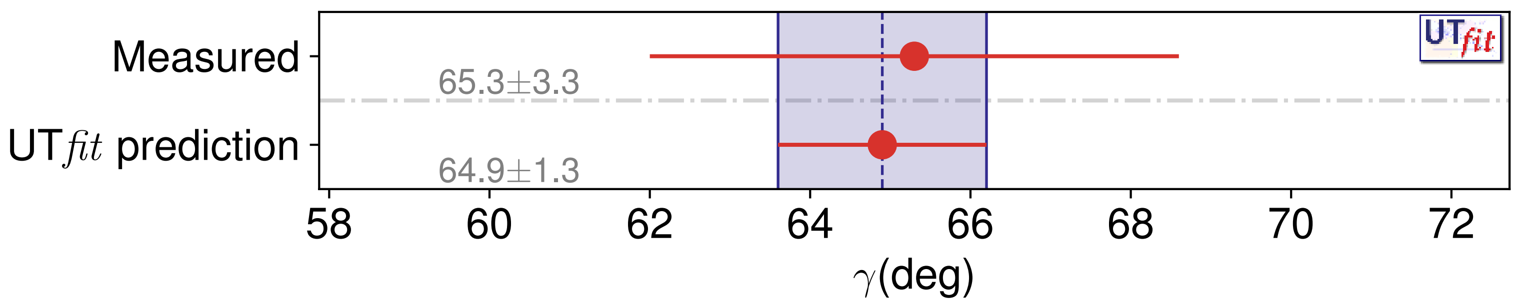
$$\bar{\rho} = 0.159 \pm 0.016$$
$$\bar{\eta} = 0.339 \pm 0.010$$

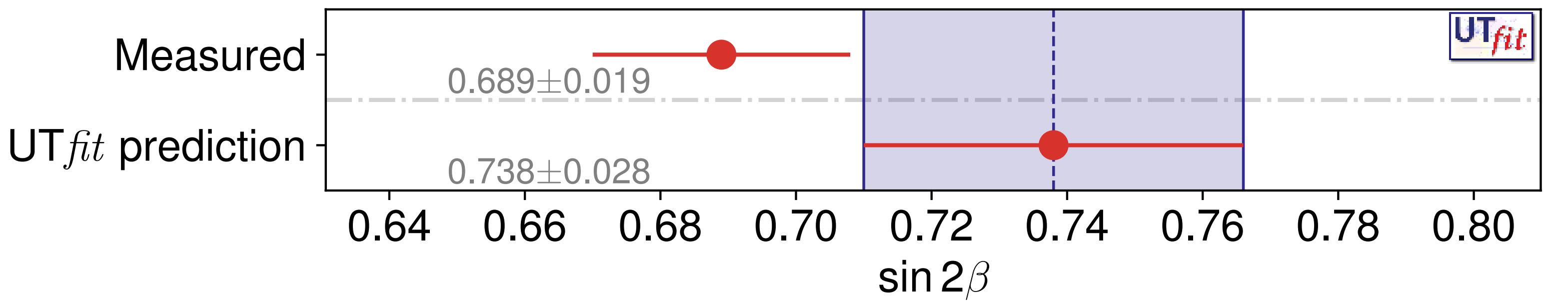


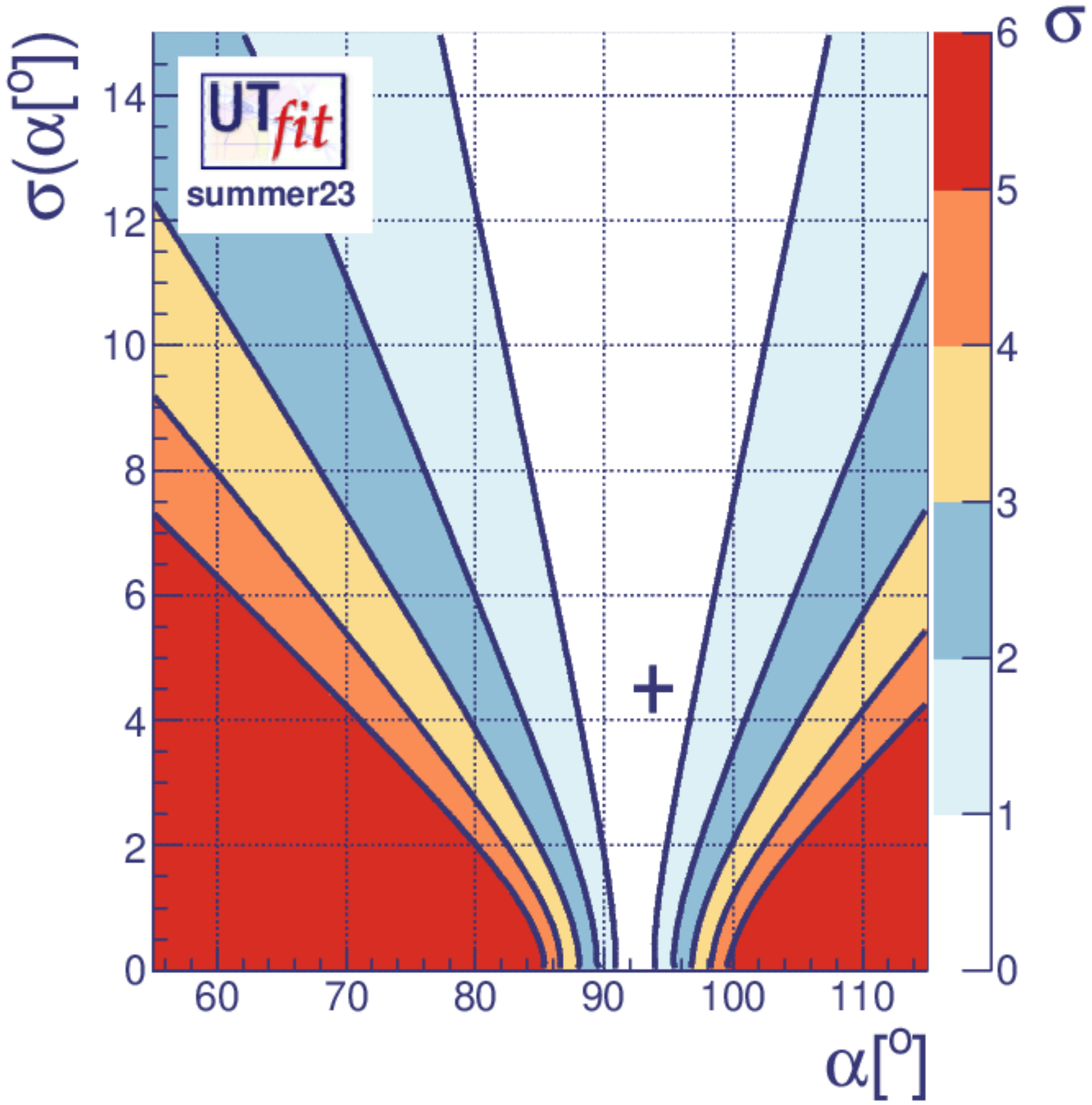
$$\bar{\rho} = 0.173 \pm 0.012$$
$$\bar{\eta} = 0.374 \pm 0.019$$

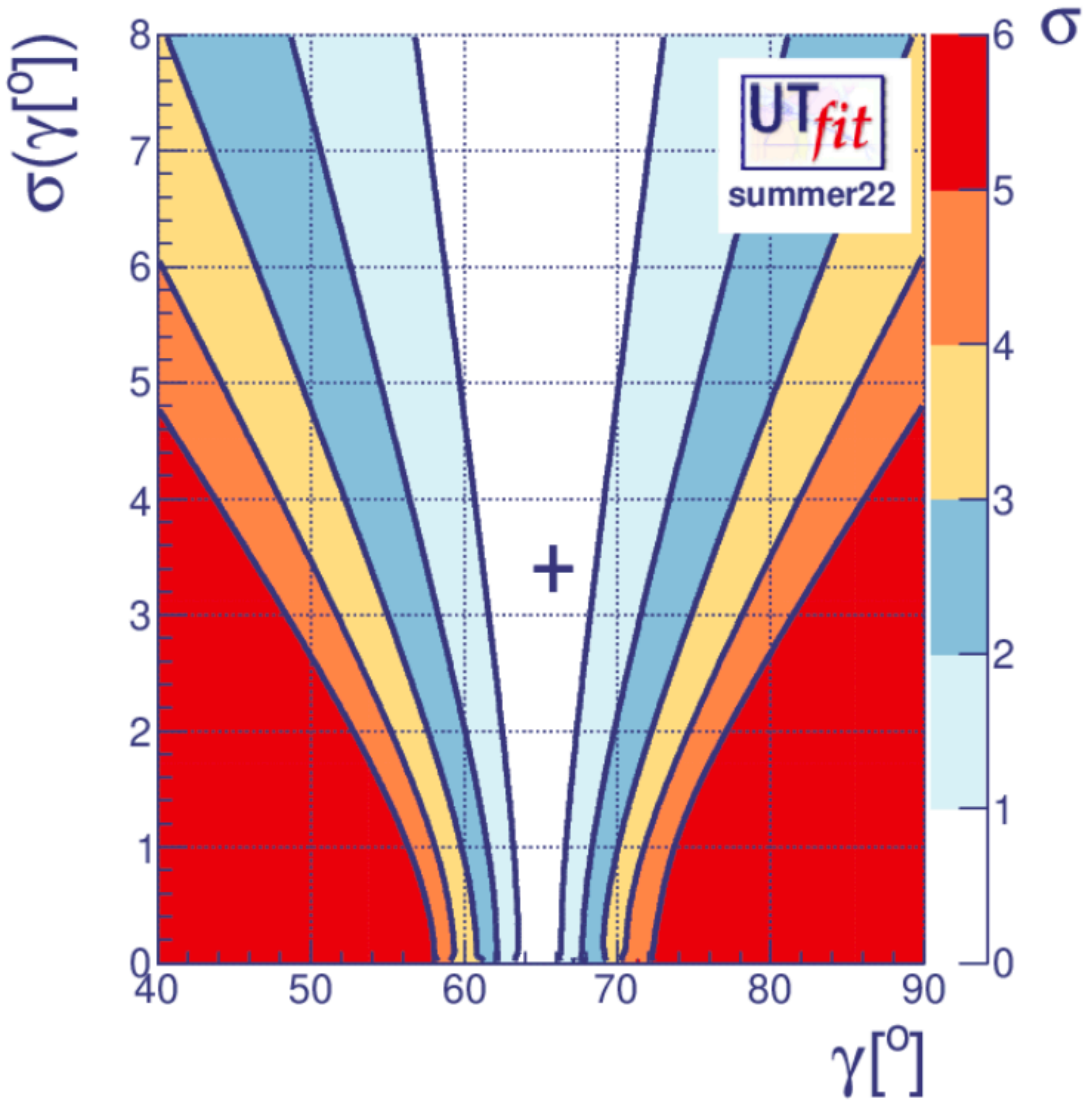
Standard Model Fit compatibility

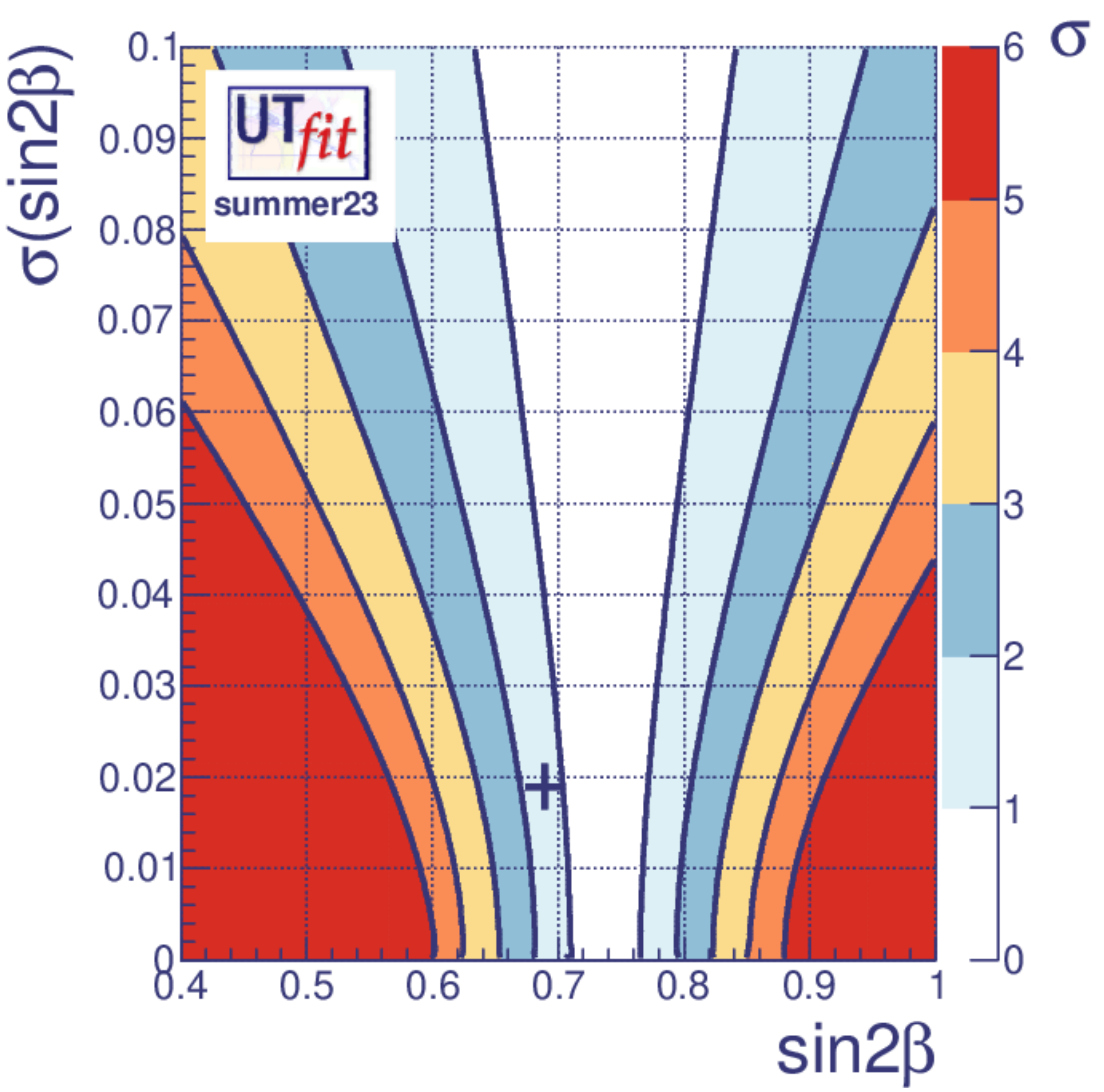












UT generalization Beyond the Standard Model

- fit simultaneously for the CKM and the NP parameters (generalized UT analysis)
  - parameterize BSM effects in $\Delta F = 2$ Hamiltonian in model-independent
  - use all available experimental information
- find out NP contributions to $\Delta F=2$ transitions

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$

$$A_{SL}^{q} = \mathrm{Im}\left(\Gamma_{12}^{q} / A_q\right)$$

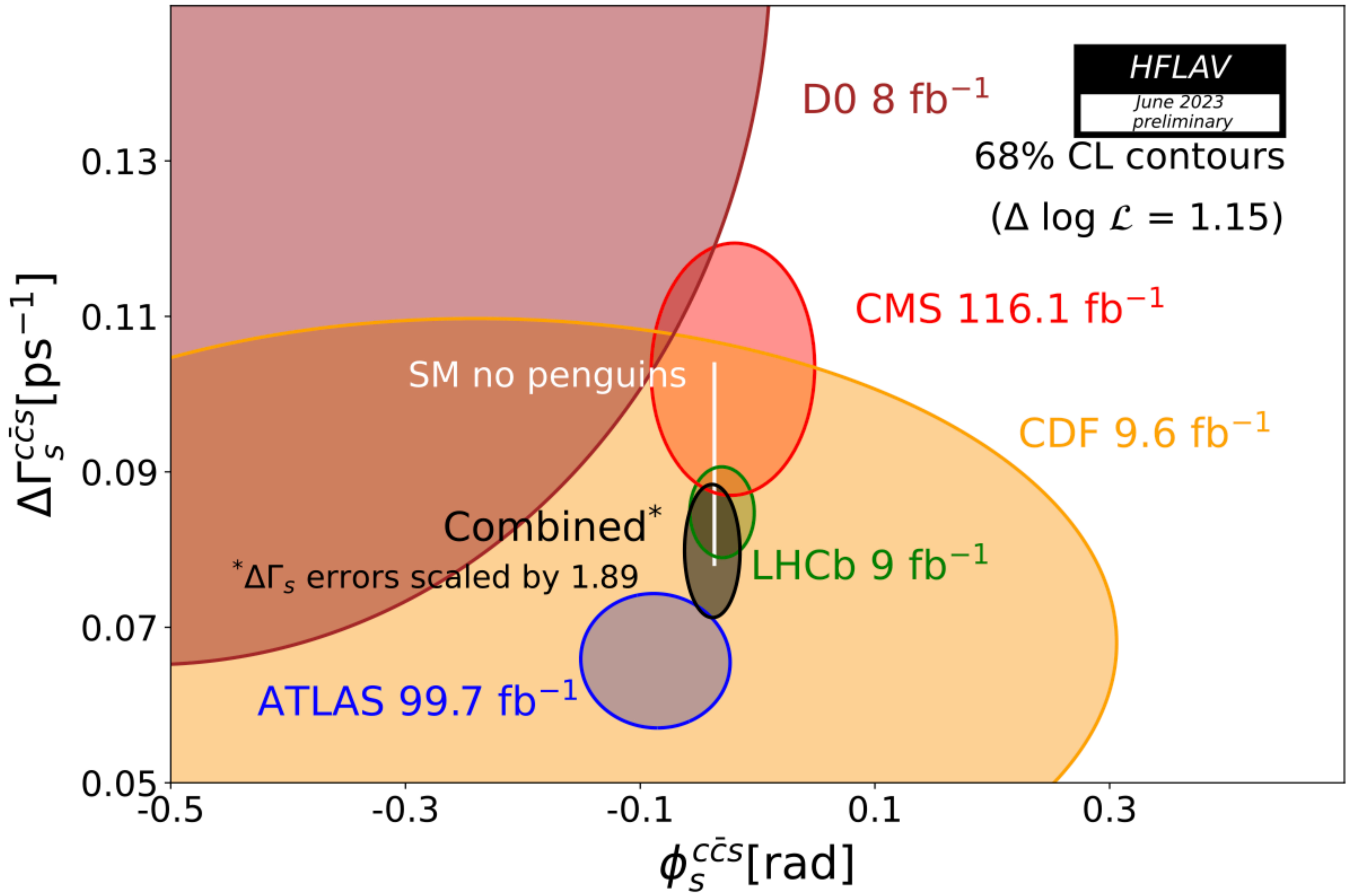
$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^{q} / A_q\right)$$

Extended list of experimental inputs

- All inputs to the SM UT analysis
- $B_s\bar{B}_s$ mixing
- $D\bar{D}$ mixing
- Additional B_s mixing parameters (HFLAV averages)
  - $\Delta\Gamma_s$, effective lifetime, etc.
- Charge asymmetry in semileptonic B_d and B_s decays
- Same-sign dilepton asymmetry in semileptonic B decays by D0

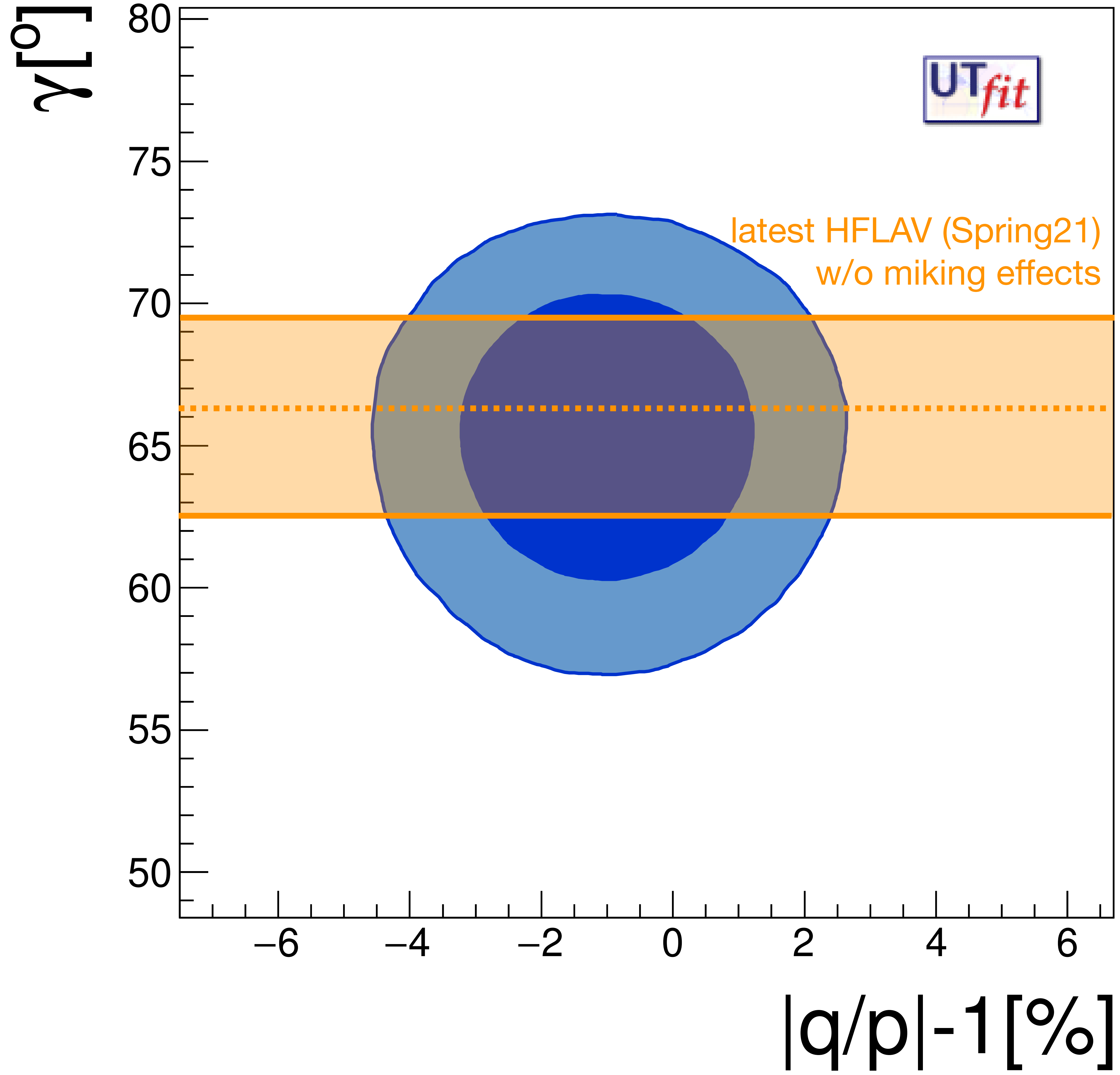


$$A^s_{\rm SL} \equiv \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) + \Gamma(B_s \to \ell^- X)} = {\rm Im}\left(\frac{\Gamma^s_{12}}{A^{\rm full}_s}\right)$$

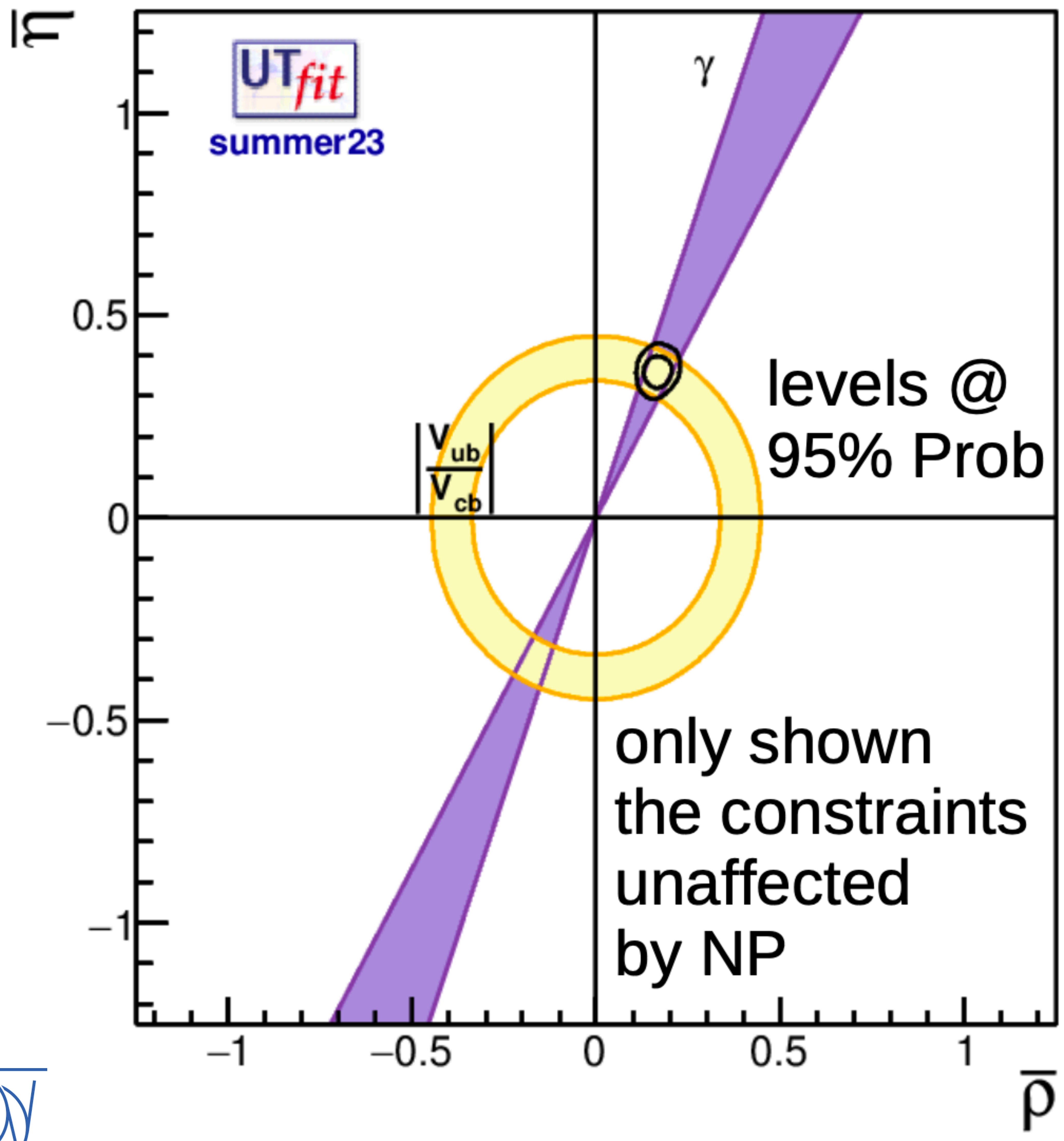
$$A^{\mu\mu}_{\rm SL} = \frac{f_d \chi_{d0} A^d_{\rm SL} + f_s \chi_{s0} A^s_{\rm SL}}{f_d \chi_{d0} + f_s \chi_{s0}}$$

What’s new for EPS23

- Experiment updates:
  - New D mixing fit (see talk by R. Di Palma on Friday)
  - New ϕ_s by LHCb:
    $$\phi_s = -0.039 \pm 0.016 \text{ rad}$$
- Theory updates:
  - New lattice values for BSM matrix elements



Results of BSM analysis: CKM parameters



levels @ 95% Prob

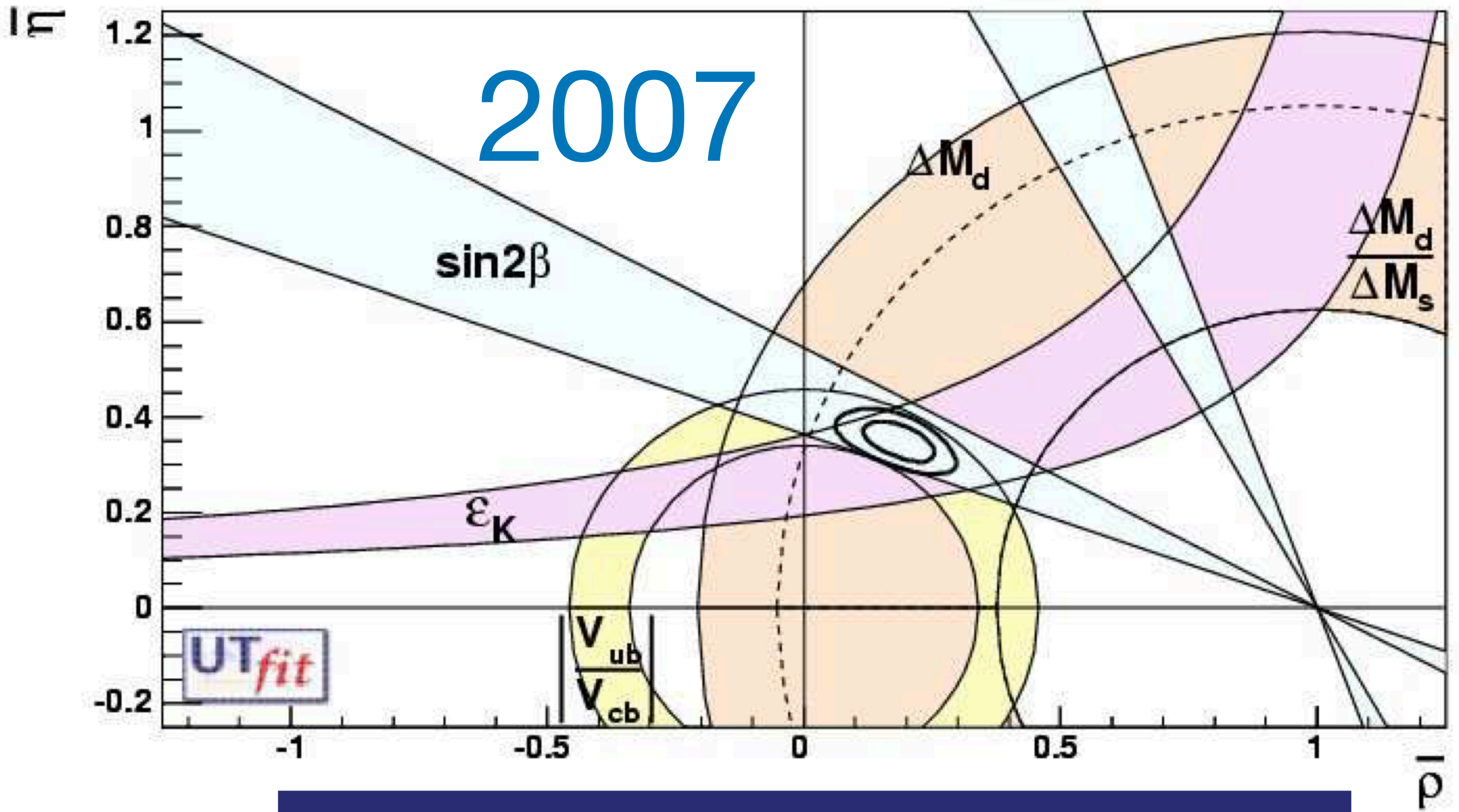
only shown the constraints unaffected by NP

CKM parameters from BSM analysis

$$\bar{\rho} = 0.167 \pm 0.025$$
$$\bar{\eta} = 0.361 \pm 0.027$$

CKM parameters known (even in presence of NP effects) with similar precision of pre-LHC SM analysis

2004



$$\bar{\rho} = 0.164 \pm 0.028$$
$$\bar{\eta} = 0.340 \pm 0.016$$

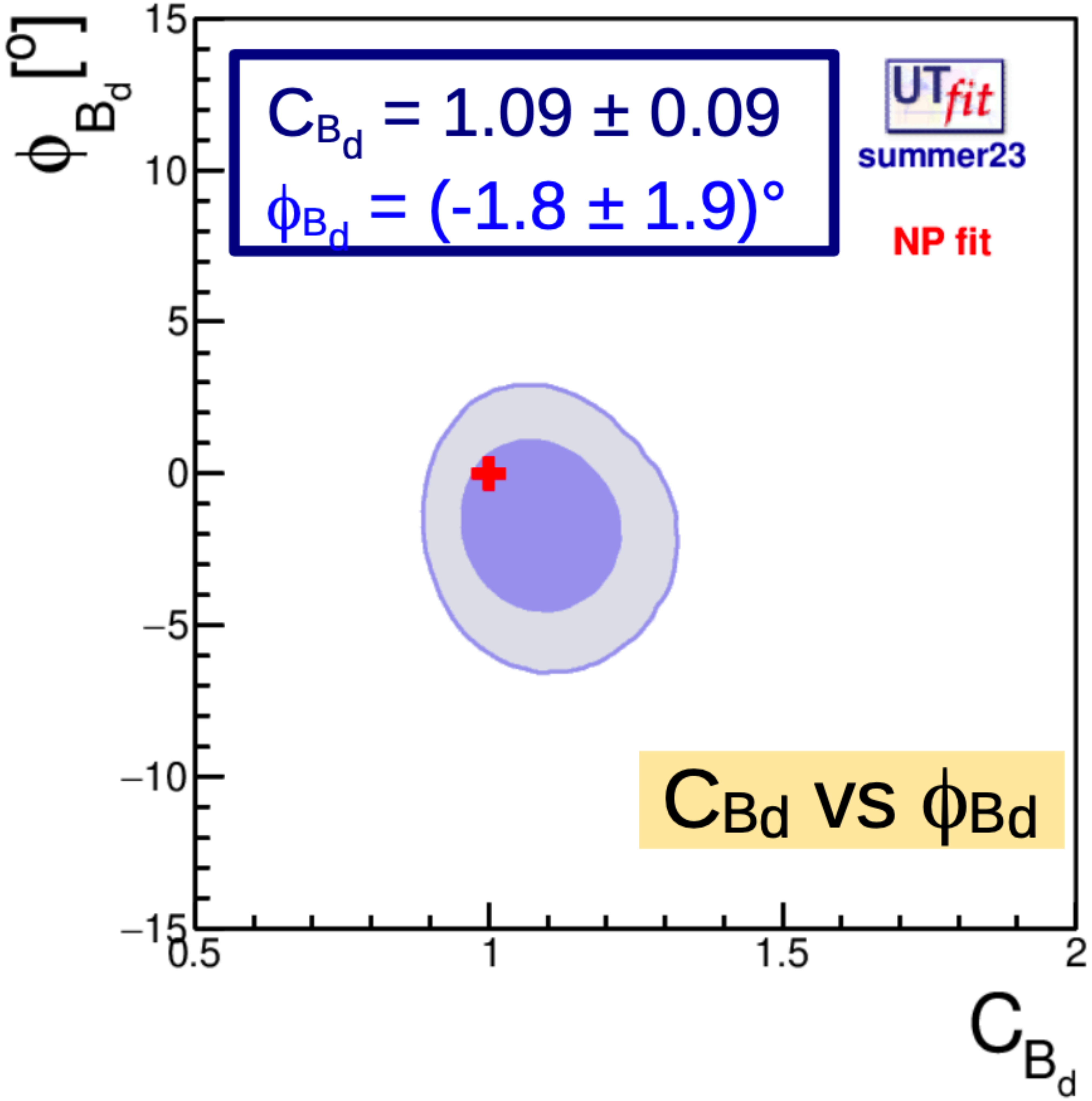
Results of BSM analysis: New Physics parameters

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

K system

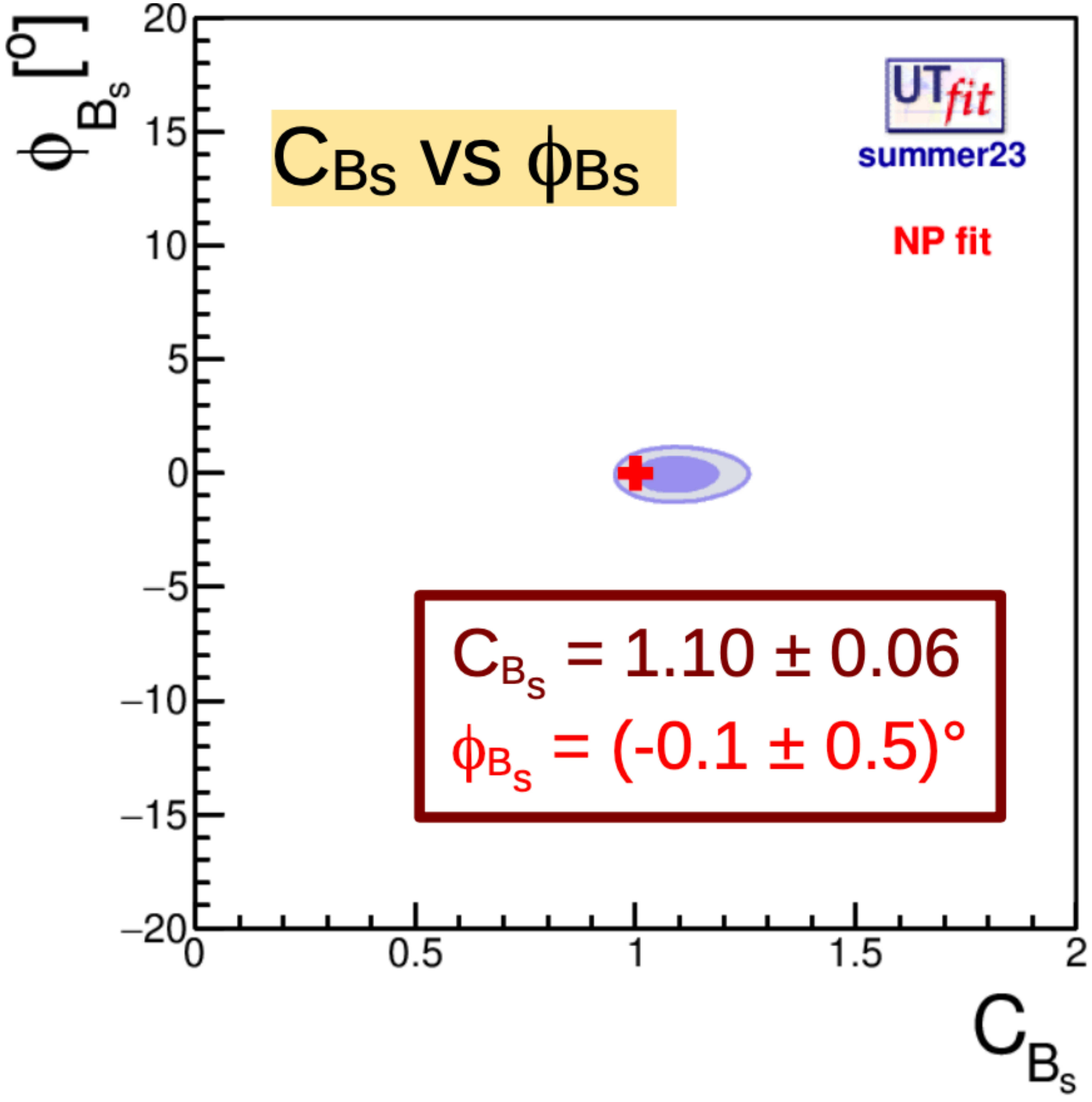
$C_{\epsilon_K} = 1.09 \pm 0.10$

dark: 68%
light: 95%
SM: red cross



$C_{B_d} = 1.09 \pm 0.09$

$\phi_{B_d} = (-1.8 \pm 1.9)°$



$C_{B_s} = 1.10 \pm 0.06$

$\phi_{B_s} = (-0.1 \pm 0.5)°$

Results of BSM analysis: New Physics parameters

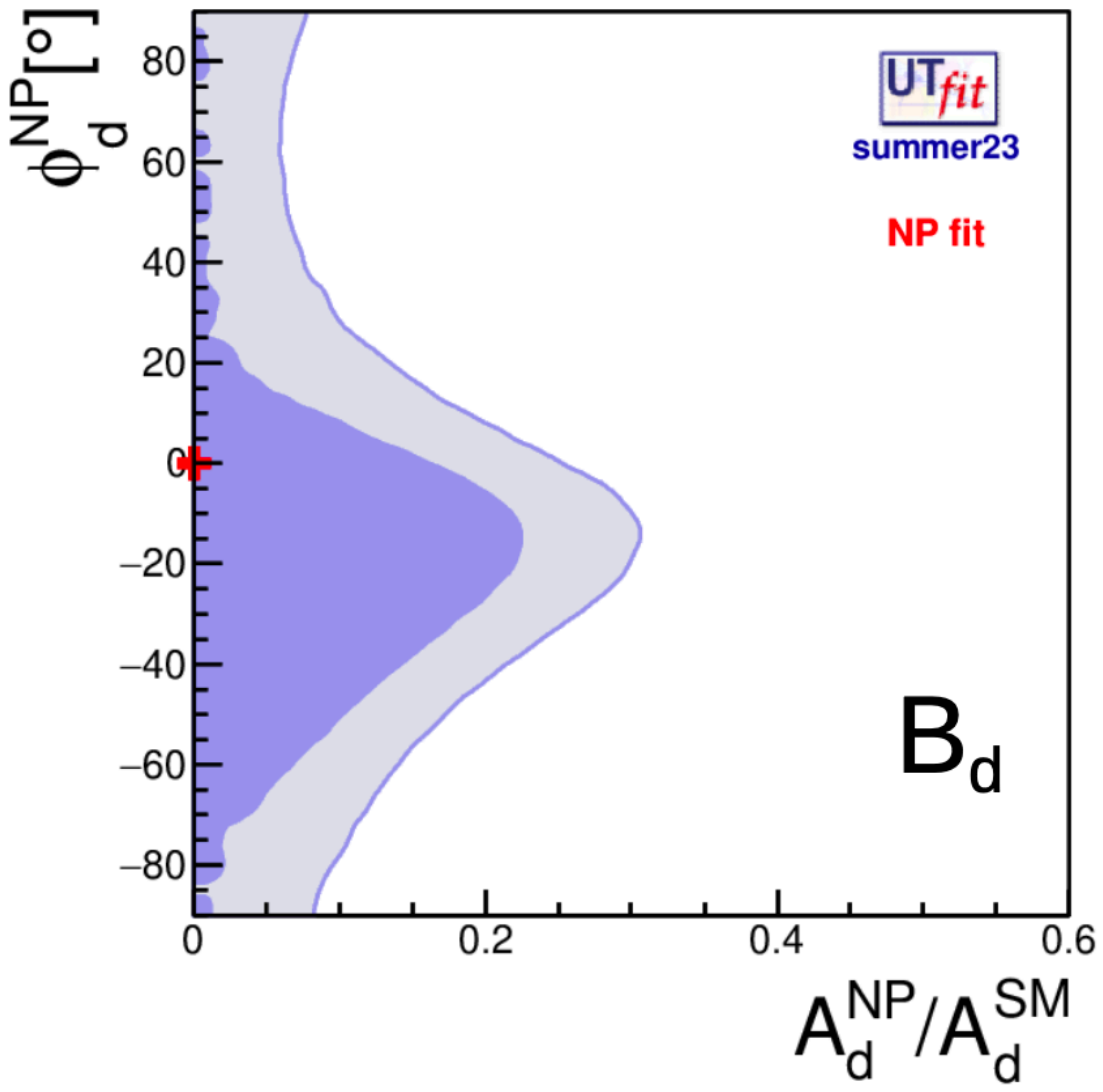
$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

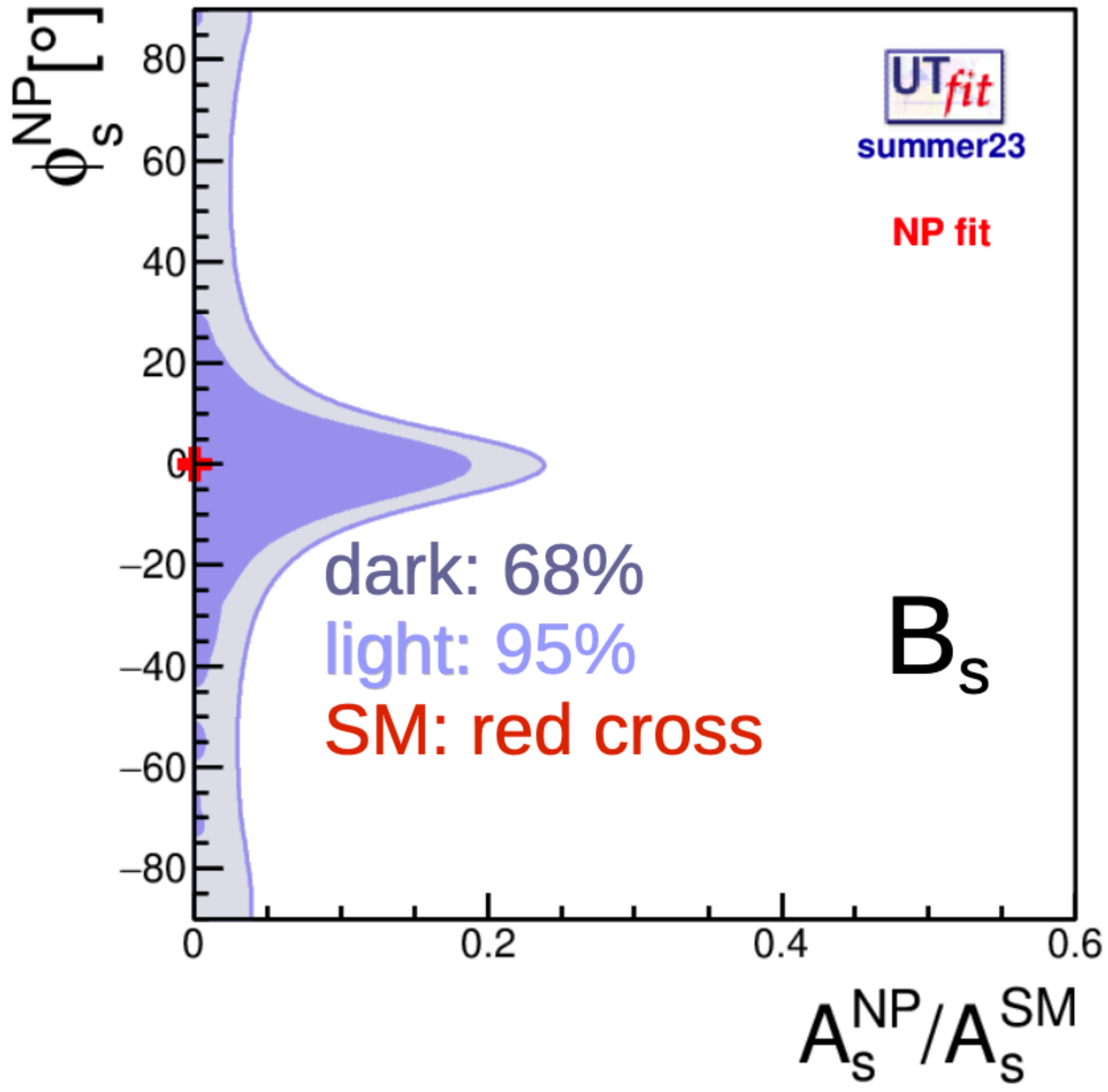
The ratio of NP/SM amplitudes is:

< 25% @68% prob. (35% @95%) in B_d mixing

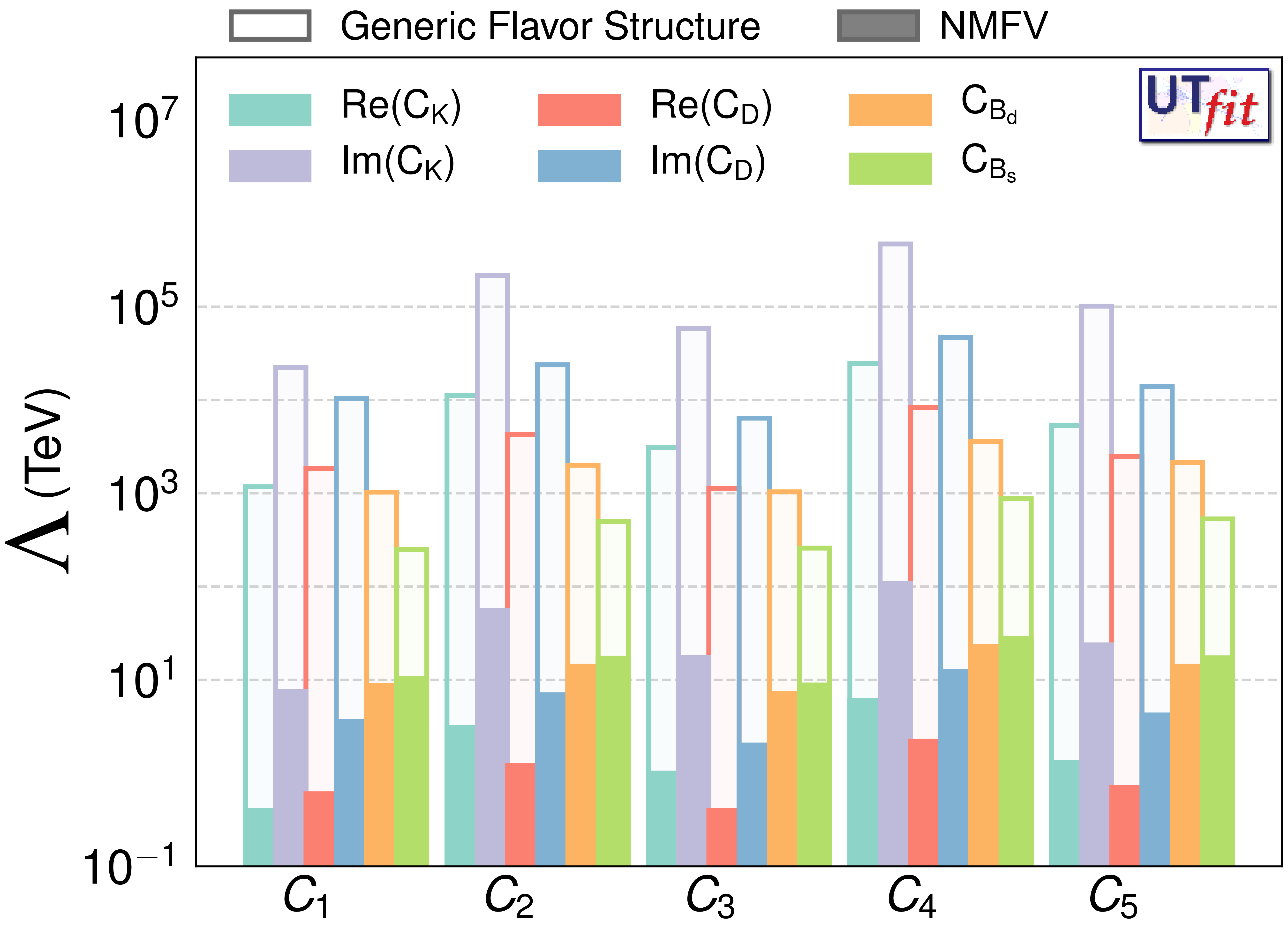
< 25% @68% prob. (30% @95%) in B_s mixing

dark: 68%
light: 95%
SM: red cross





Results of BSM analysis: probing New Physics Scale



$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

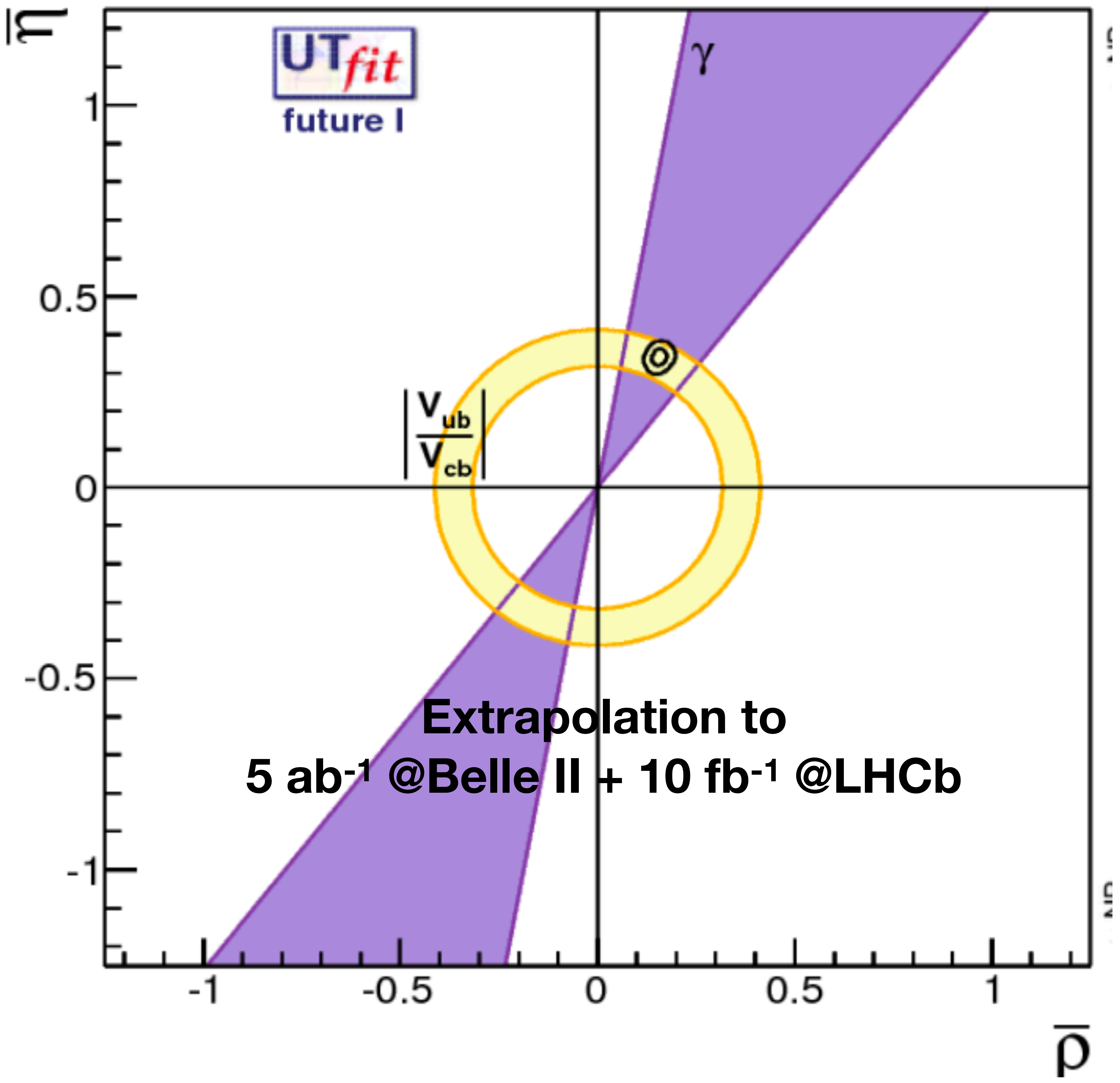
$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha}\gamma_\mu q_{iL}^{\alpha}\bar{q}_{jL}^{\beta}\gamma^\mu q_{iL}^{\beta}\ ,\\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jR}^{\beta} q_{iL}^{\beta}\ ,\\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jR}^{\beta} q_{iL}^{\alpha}\ ,\\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha}\bar{q}_{jL}^{\beta} q_{iR}^{\beta}\ ,\\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta}\bar{q}_{jL}^{\beta} q_{iR}^{\alpha}\ .
\end{aligned}$$

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

- ◉ Generic: $C(\Lambda) = \alpha/\Lambda^2$ $F_i \sim 1$, arbitrary phase
- ◉ NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_i \sim |F_{SM}|$, arbitrary phase

Conclusions

- We updated the UT analysis to Summer 23 inputs
  - New experimental determinations of the UT angles
  - New theory inputs (lattice, V_{ud})
- Overall consistency of the fit
- Reached precision of ~5% (~3%) on $\bar{\rho}$ ($\bar{\eta}$)
- Extended the analysis to include new physics in DF=2 Hamiltonians
  - new inputs for $D-\bar{D}$ mixing
  - new results
  - probed new physics effects up to
    - $\mathcal{O}$(1000) PeV for new physics with generic flavor structure
    - $\mathcal{O}$(100-1000) GeV in MFV scenarios



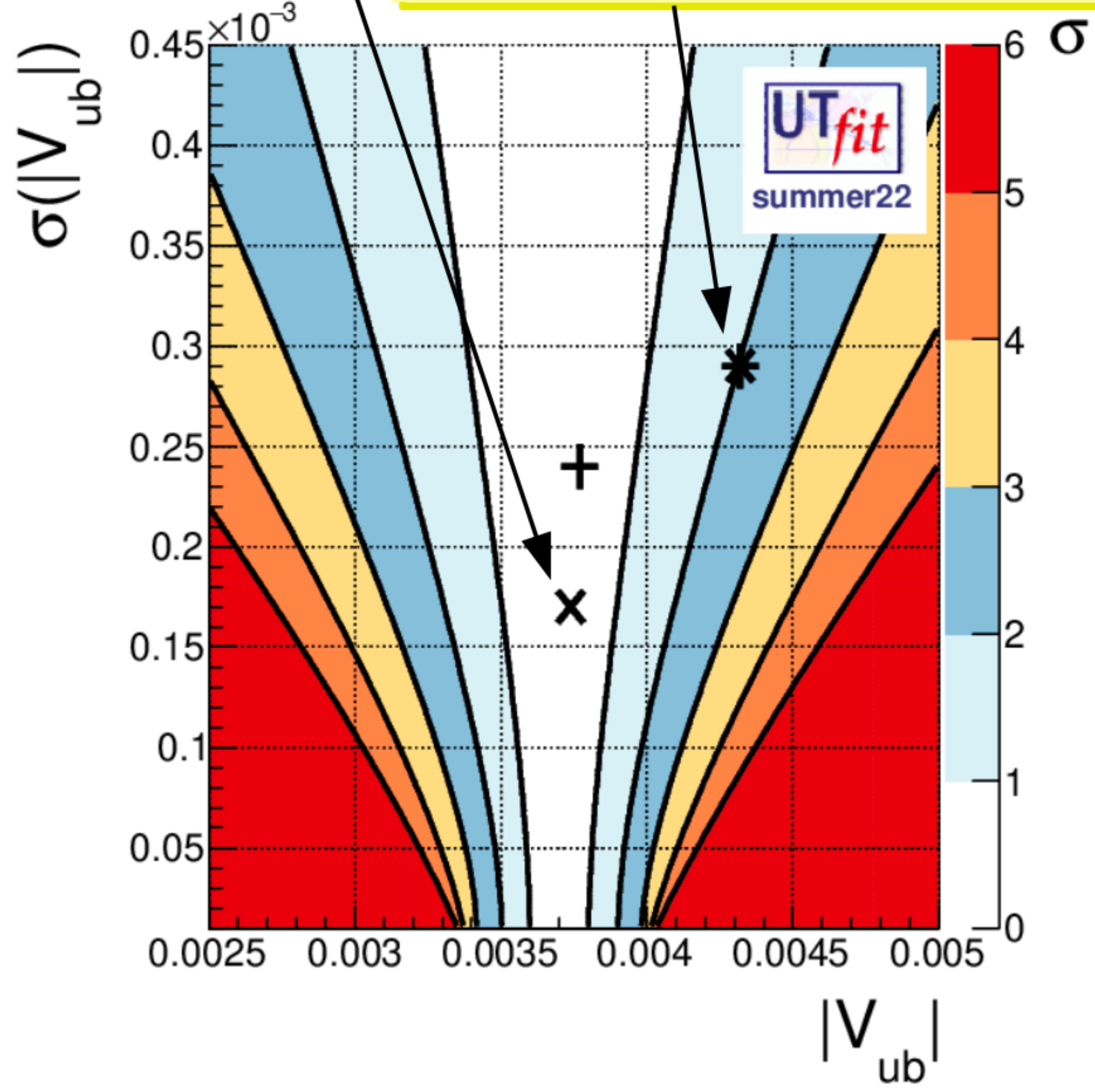
Extrapolation to
5 ab^{-1} @Belle II + 10 fb^{-1} @LHCb

Backup

Standard Model Fit compatibility

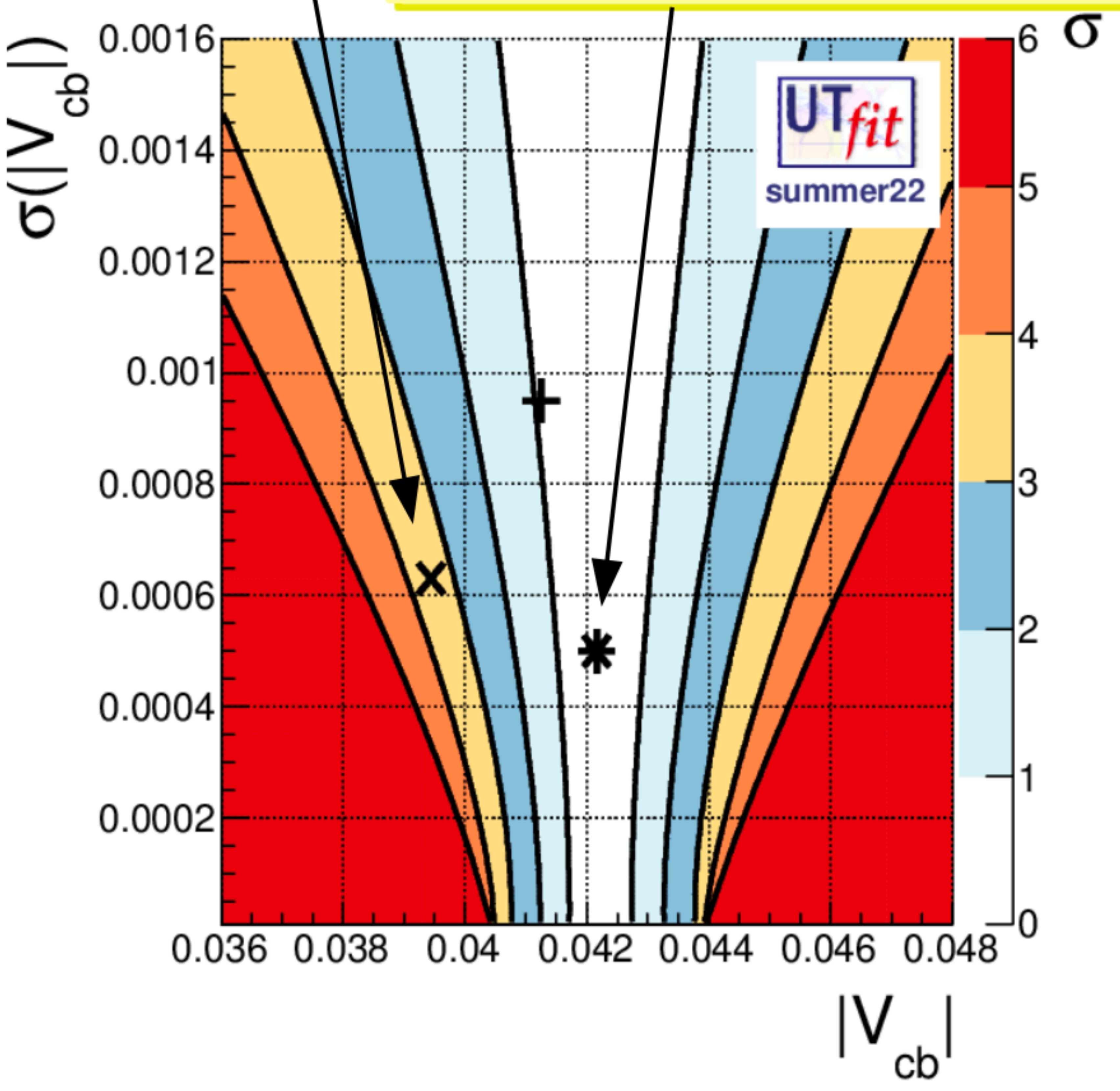
$|V_{ub}|$ *(excl)* = $(3.74 \pm 0.17)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.32 \pm 0.29)\ 10^{-3}$



$|V_{cb}|$ *(excl)* = $(39.44 \pm 0.63)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.16 \pm 0.50)\ 10^{-3}$



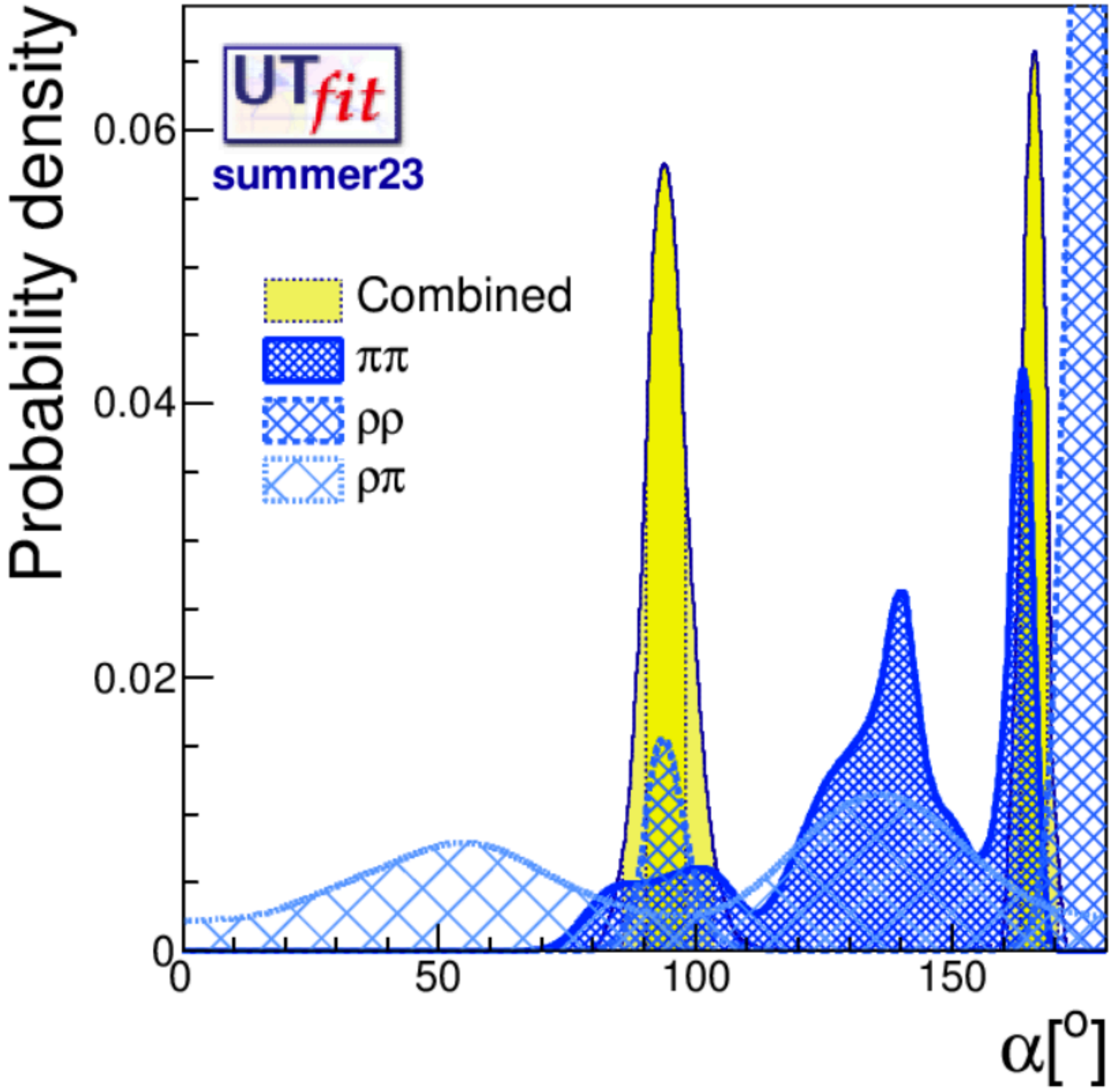
$Vub_{exp} = (3.77 \pm 0.24) \cdot 10^{-3}$

$Vub_{UTfit} = (3.70 \pm 0.10) \cdot 10^{-3}$

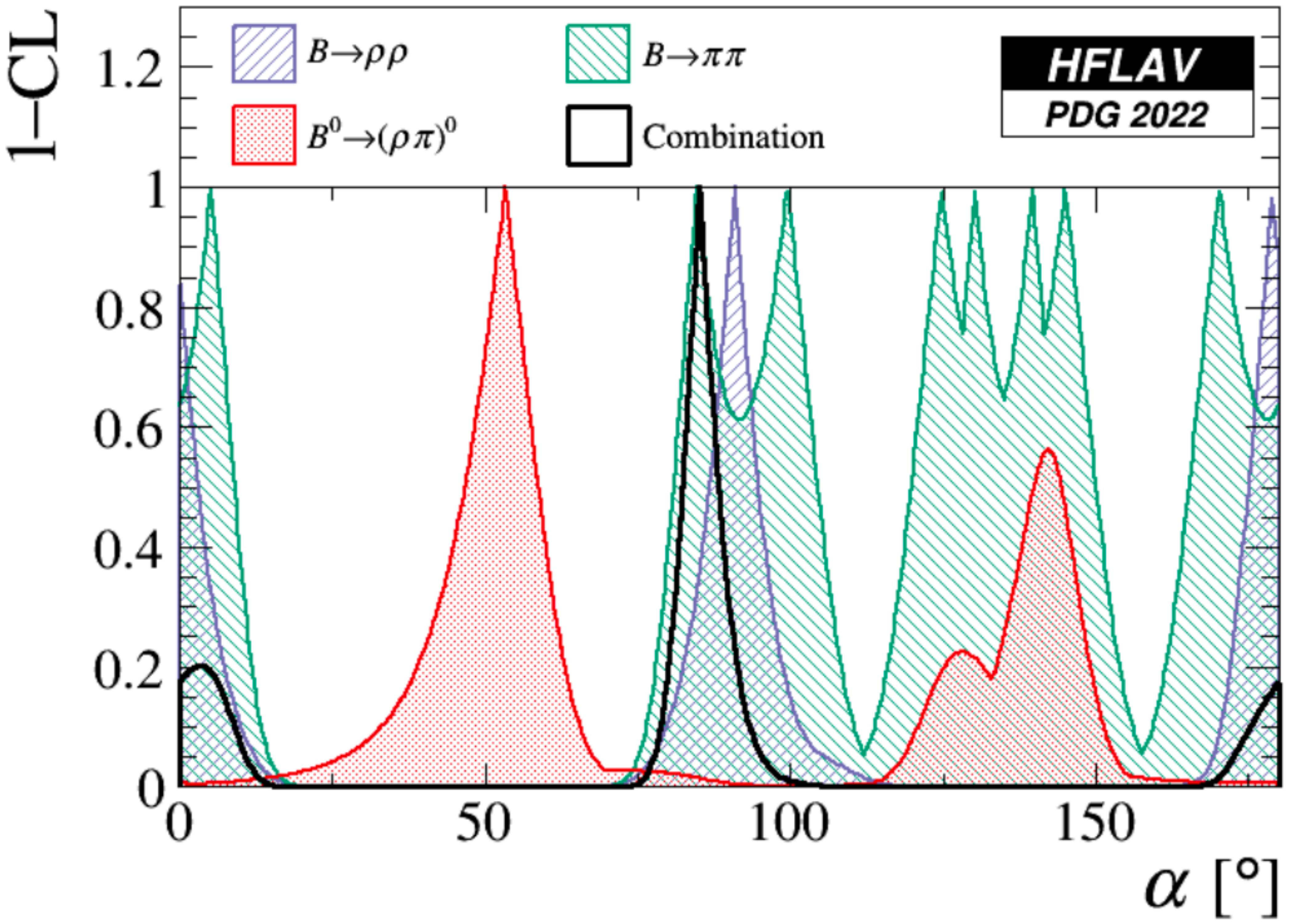
$Vcb_{exp} = (41.25 \pm 0.95) \cdot 10^{-3}$

$Vcb_{UTfit} = (42.6 \pm 0.5) \cdot 10^{-3}$

More on α



α^{exp} = 93.8° ± 4.5°



α_{HFLAV} = 85.5 ± 4.6

testing the TeV scale

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

The dependence of C on Λ changes depending on the flavour structure.
We can consider different flavour scenarios:

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ $F_i \sim 1$, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_i \sim |F_{SM}|$, arbitrary phase
- MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_1 \sim |F_{SM}|$, $F_{i\neq 1} \sim 0$, SM phase

α (L_i) is the coupling among NP and SM
- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

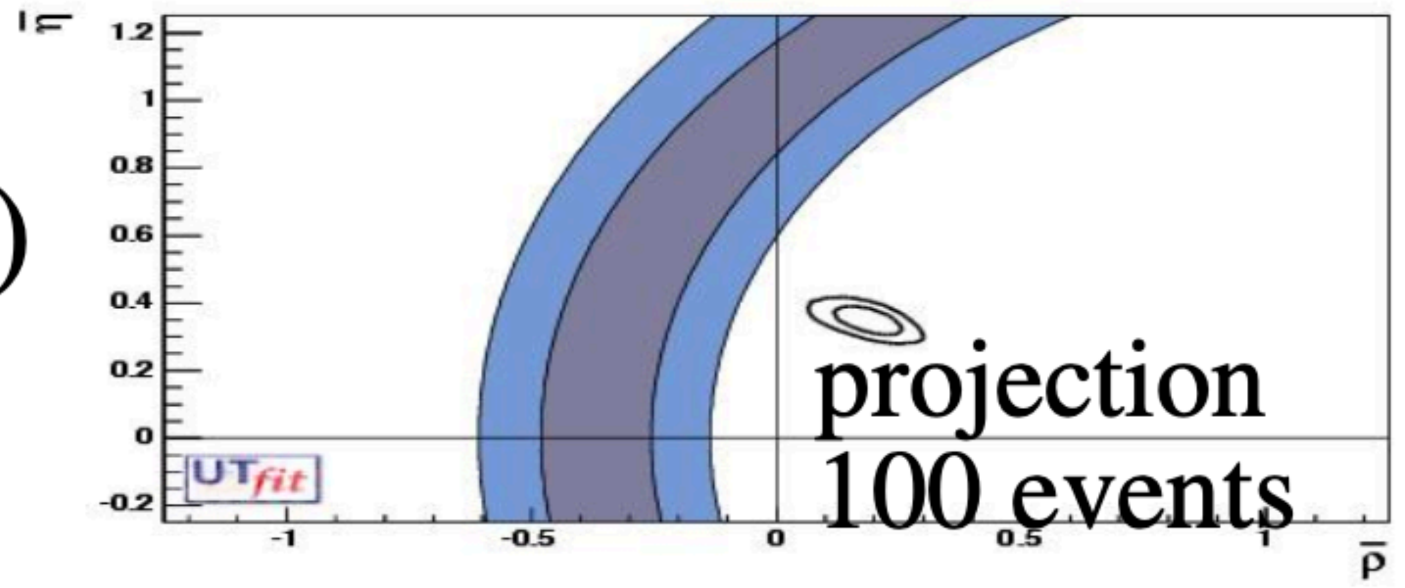
If no NP effect is seen lower bound on NP scale Λ

some old plots coming back to fashion:

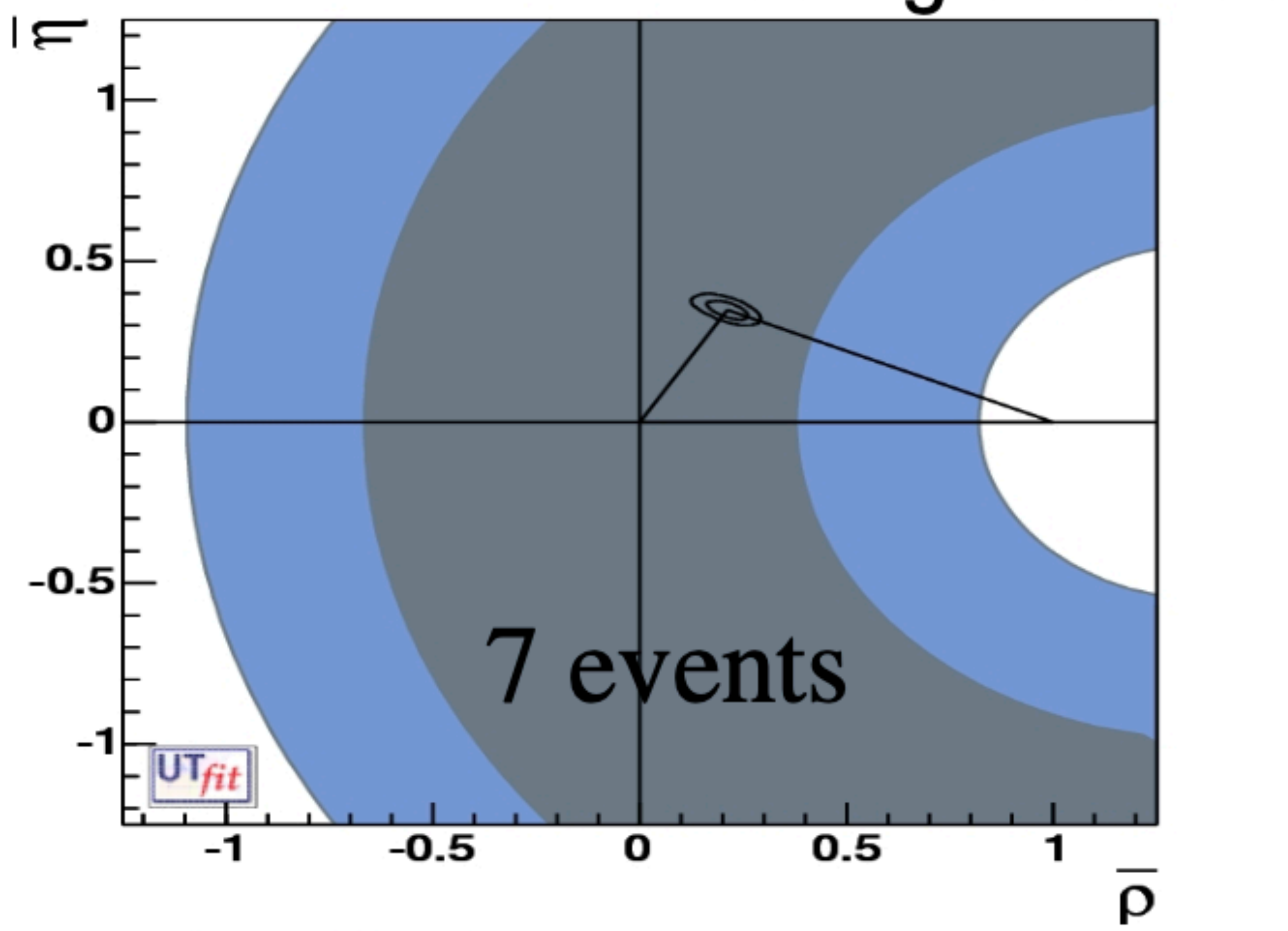
As NA62 and KOTO are analysing data:

$BR(K^+ \to \pi^+ \nu\bar{\nu})$

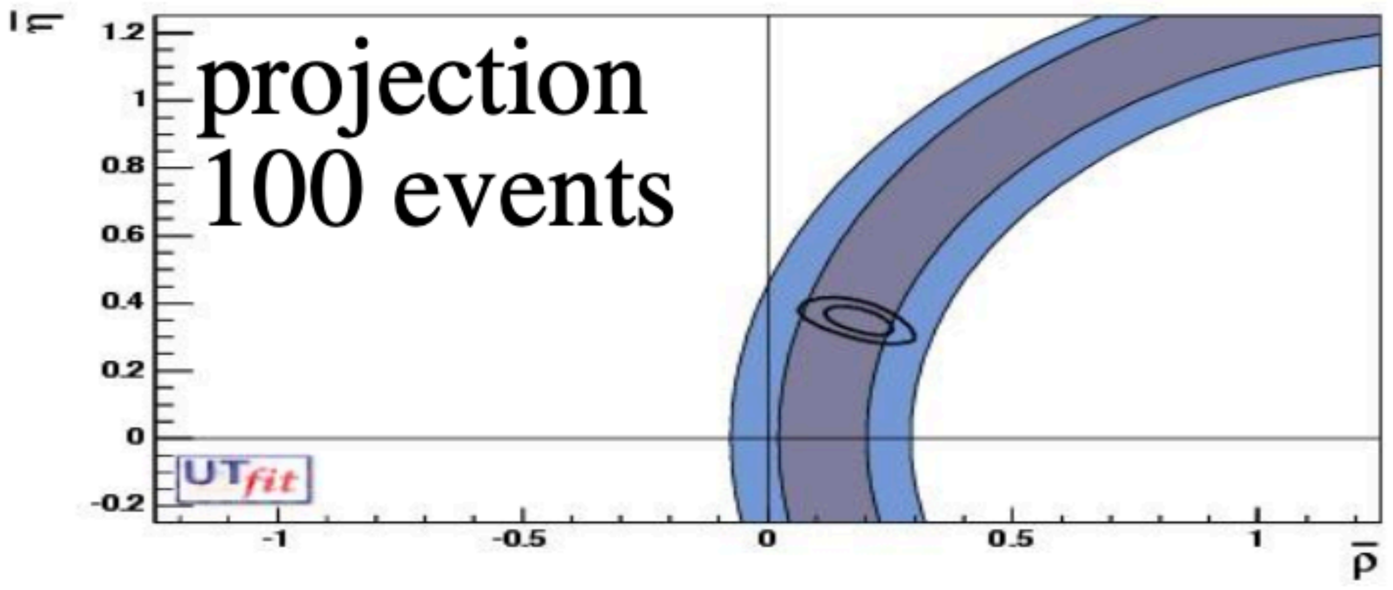
E949 central value

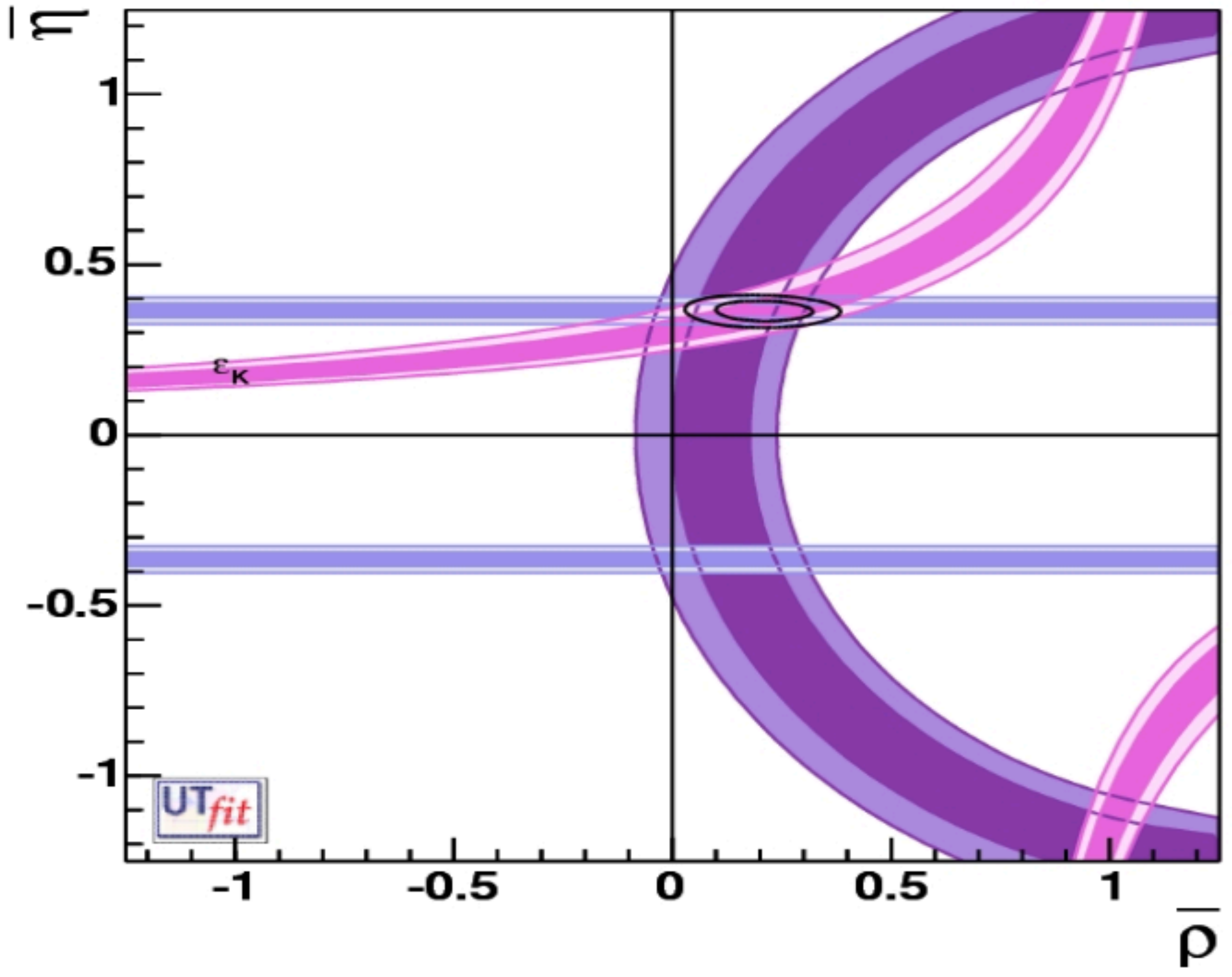


2007 global fit a



SM central value





including
$BR(K^0 \to \pi^0 \nu\bar{\nu}$
SM central va