FPCP 2022 — Oxford, Mississippi, USA — 05/25/22

Update on the Unitarity Triangle global fits by the UTfit Collaboration

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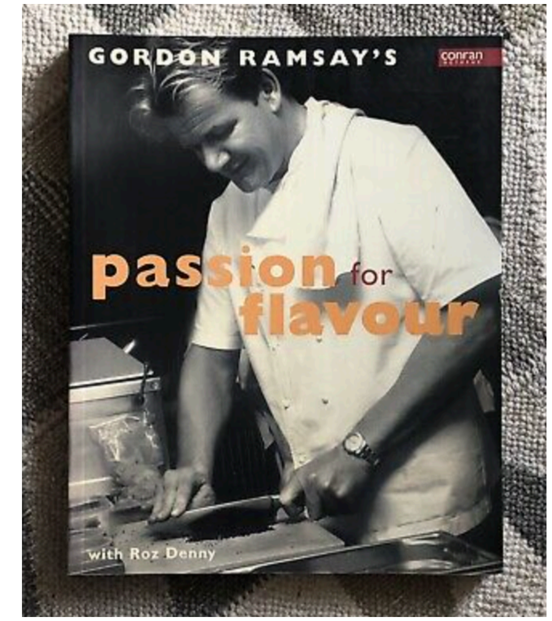
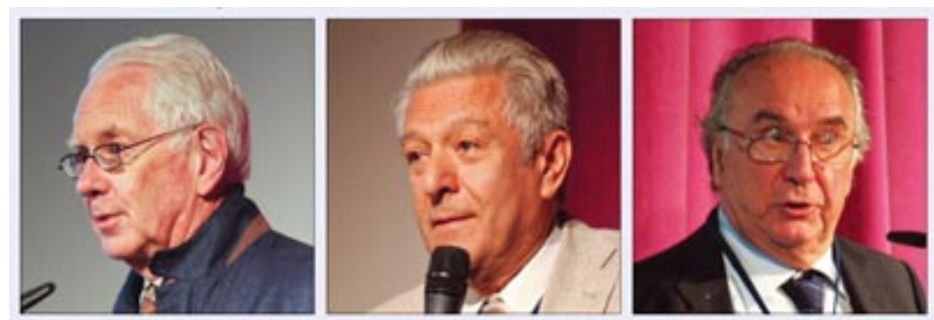
MANY SPECIAL THANKS TO MARCELLA BONA!

Why Flavor matters ?



Historically, it lead to "New Physics" (NP)!

E.g., prediction of charm quark:



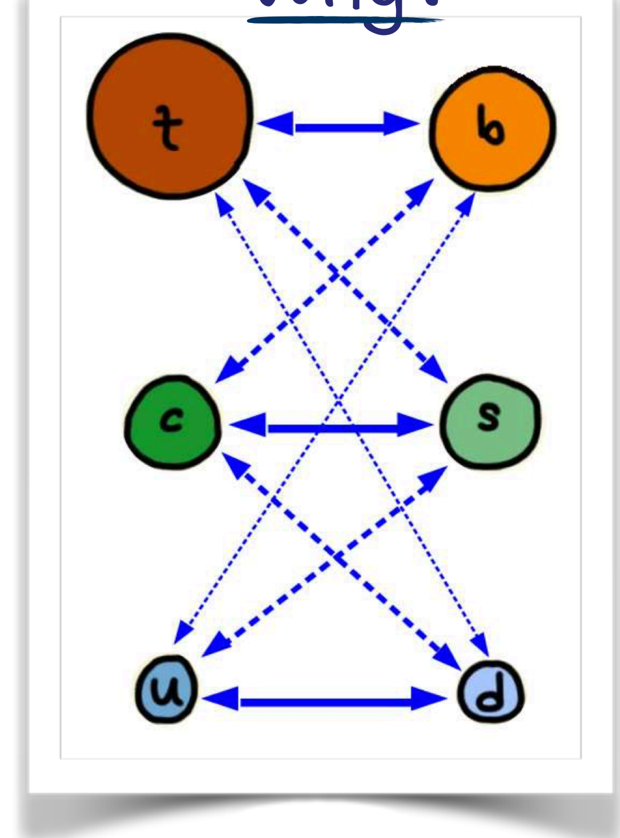
It leads to a Standard Model (SM) puzzle ...

Λ_{NP} @ TeV

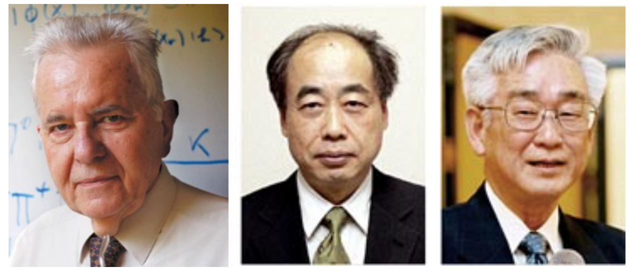
@ https://profmattstrassler.com

$\Lambda_{NP} \gg$ TeV

Why?



... and Beyond!



: Testing the SM

- Flavor violation in the (mass basis of) SM only from charged weak-current couplings <—> matrix V_{CKM}

  —> FCNCs @ one loop (& GIM suppressed)

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

- Top-quark dominates short-distant physics in FCNCs, CPV @ stake only if all 3 generations are involved

  —> CKM 3rd row very relevant for phenomenology

$(\bar\rho, \bar\eta)$ apex of $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

UTfit

www.utfit.org

M.Bona, M. Ciuchini, D. Derkach, F. Ferrari, E. Franco, V. Lubicz, G. Martinelli, M. Pierini, L. Silvestrini, C. Tarantino, V. Vagnoni, M. Valli, and L.Vittorio

— EXP
— TH

UTfit : Bayes aficionados

$$\mathcal{P}\left(\bar\rho,\bar\eta,\vec p \mid \vec{\mathcal{O}}\right) \sim \mathcal{P}\left(\vec{\mathcal{O}} \mid \bar\rho,\bar\eta,\vec p\right) \times \mathcal{P}_0(\bar\rho,\bar\eta,\vec p)$$

$$\text{posterior} \sim \text{likelihood} \times \text{prior}$$

see, e.g., arXiv:hep-ph/0012308

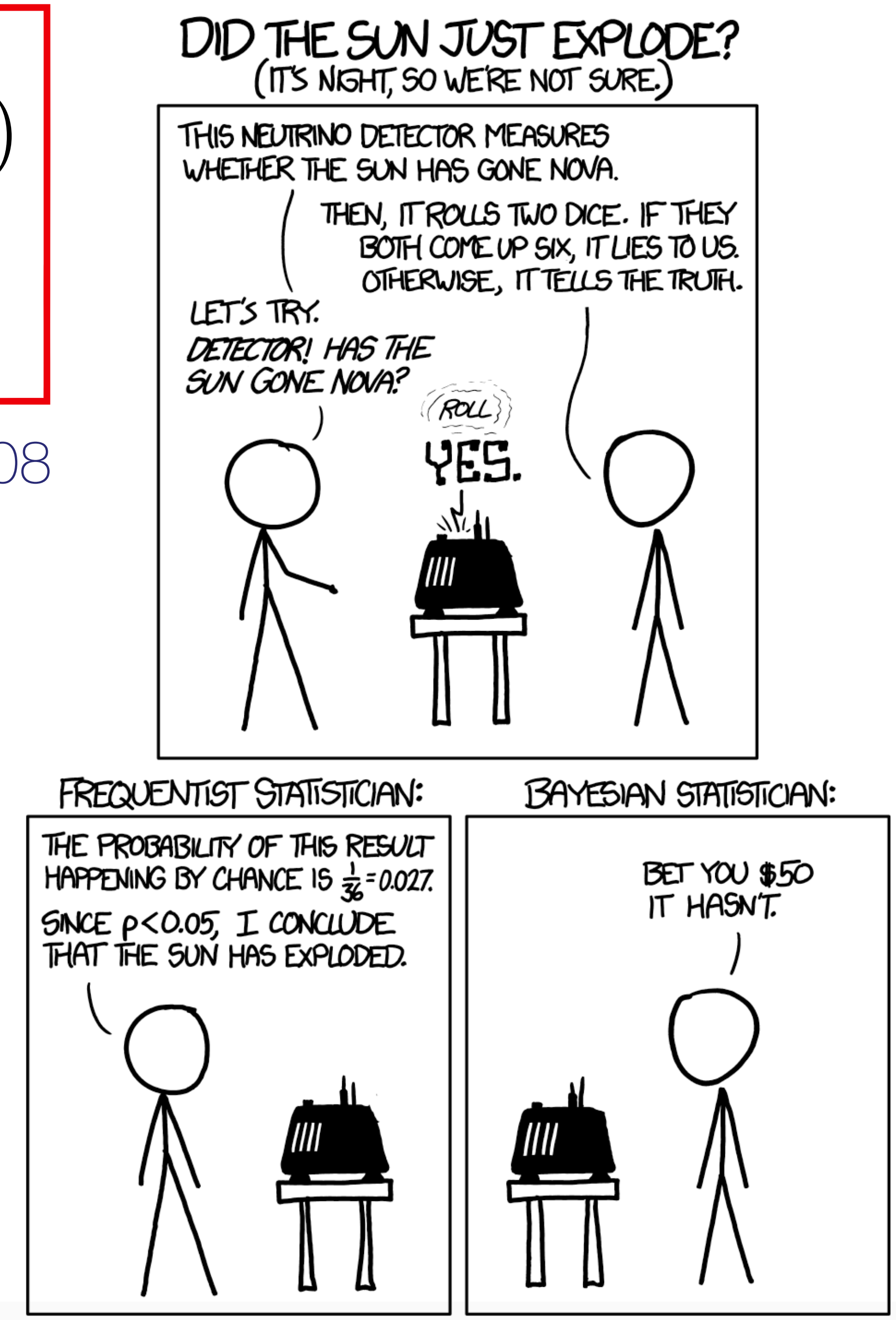
- $\vec{\mathcal{O}} = \{\epsilon_K, \Delta m_{d,s}, \cdots\}$

  Observables <—> constraints in the fit

- $\vec p = \{f_{K,B}, B_{K,B}, \cdots\}$

  Parameters we can marginalize over

- $(\bar\rho, \bar\eta)$ <—> CKM pair we wish to infer

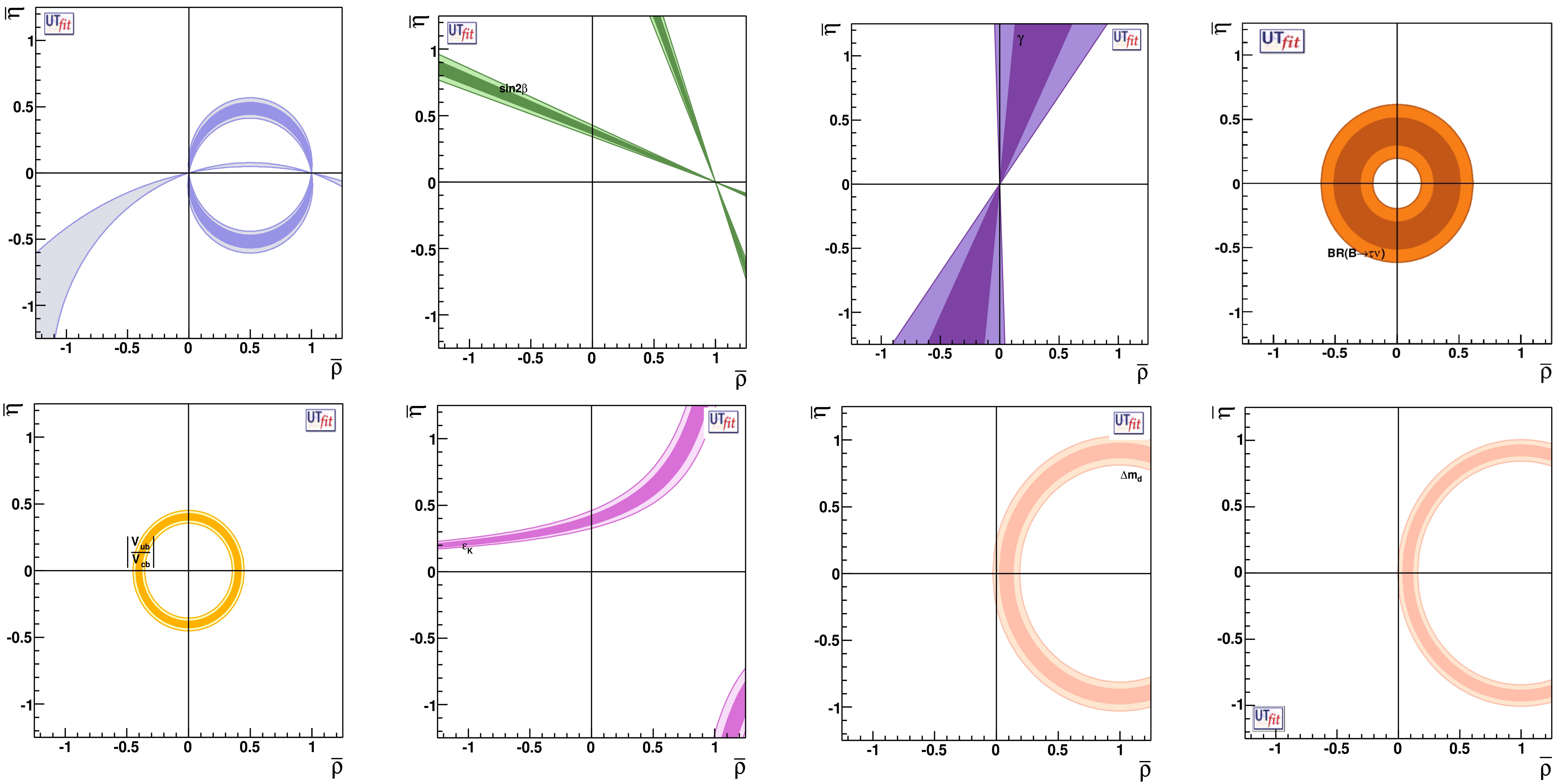


@ https://xkcd.com/1132

UTA : How it really works ...

see, e.g., arXiv:1905.00798

$\alpha\ (B \to \pi\pi, \rho\rho)$ | $\beta\ (B \to J/\psi K^{(*)})$ | $\gamma\ (B \to D^{(*)} K)$ | $\mathrm{BR}(B \to \tau\nu)$



$|V_{ub}/V_{cb}|$ | ϵ_K | Δm_d | $\Delta m_d/\Delta m_s$

(semileptonic decays) | (CPV in $K-\bar{K}$) | $(B_{d,s}-\bar{B}_{d,s})$

Novelties I

*** new UTfit 2D skeptical combination of $|V_{cb}|$ and $|V_{ub}|$ ***

à la D'Agostini, similar to PDG

$|V_{cb}|_{excl} \times 10^3 = 42.16 \pm 0.50$

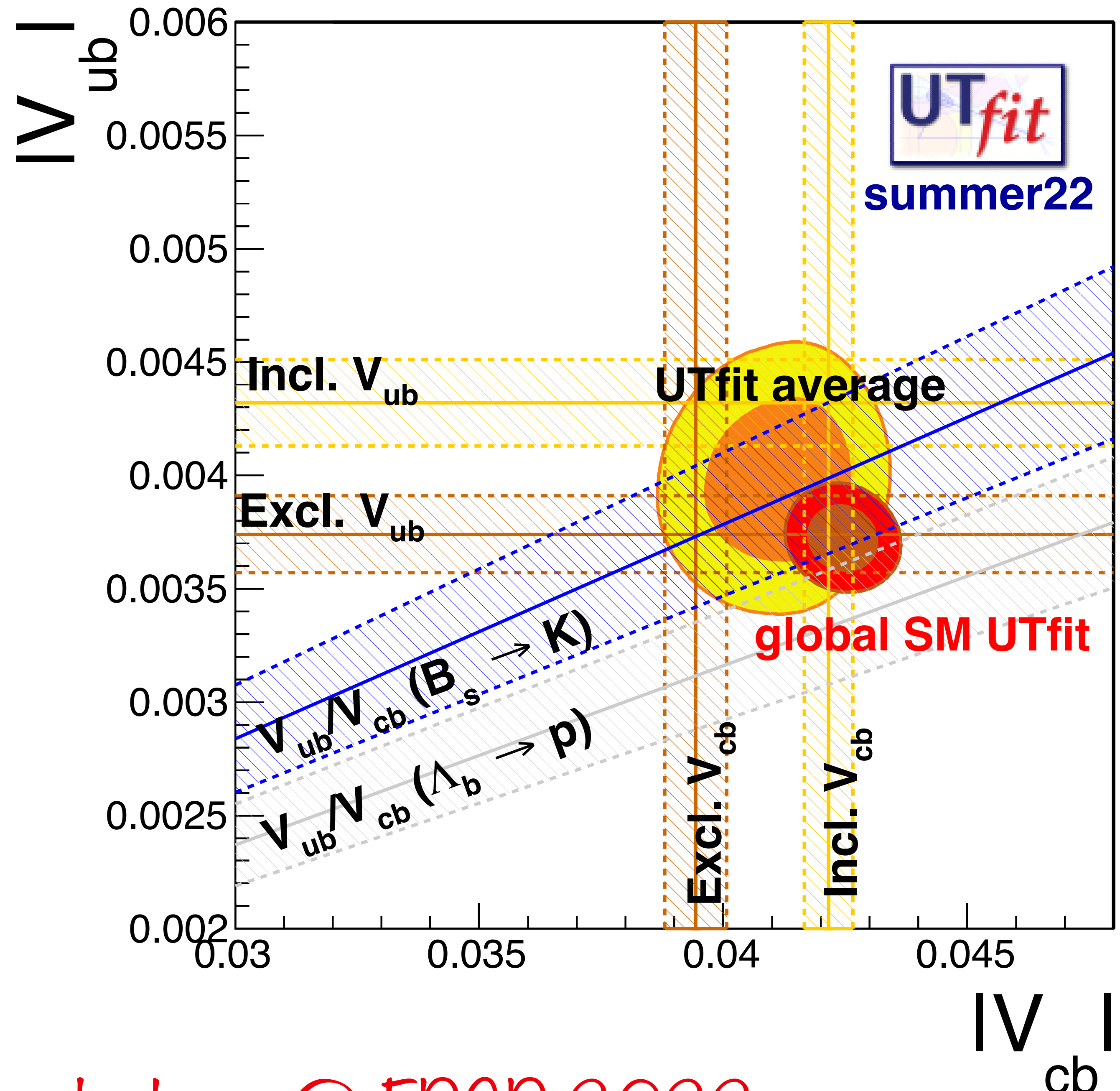
$|V_{cb}|_{incl} \times 10^3 = 39.44 \pm 0.63$

$|V_{cb}|_{ave} \times 10^3 = 41.1 \pm 1.3$

$|V_{ub}|_{excl} \times 10^3 = 3.74 \pm 0.17$

$|V_{ub}|_{incl} \times 10^3 = 4.32 \pm 0.29$

$|V_{ub}|_{ave} \times 10^3 = 3.89 \pm 0.25$



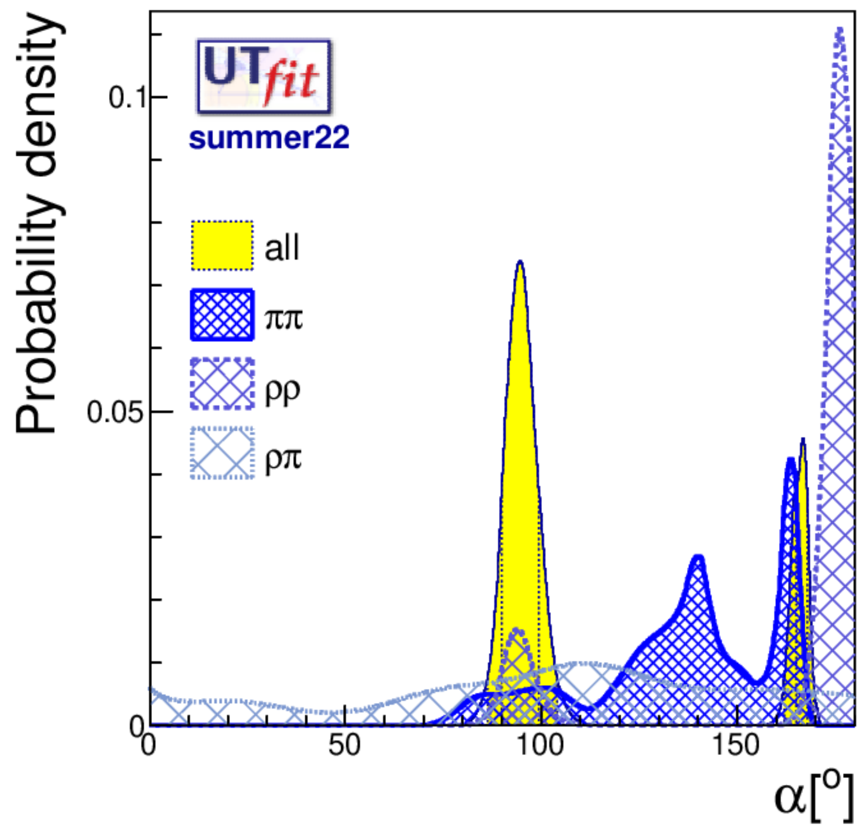
HIGHLY RECOMMENDED

See review from F. Bernlochner @ FPCP 2022

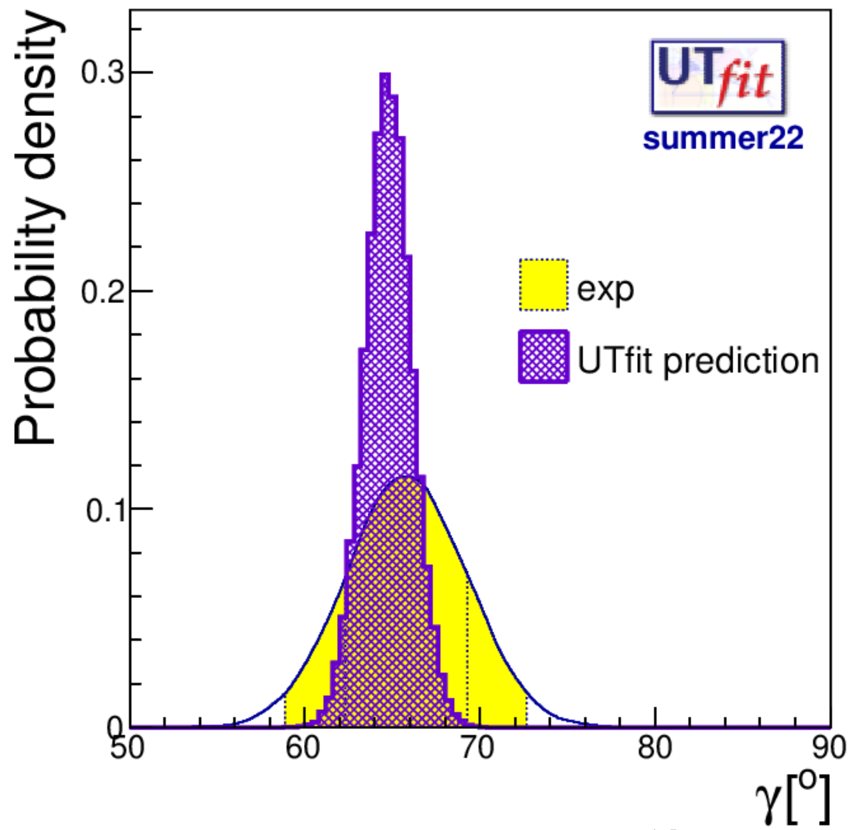
Novelties II

*** new UTfit average of α, latest γ from HFLAV ***

$\alpha = (95 \pm 4.7)^\circ$



$\gamma = (65.8 \pm 3.4)^\circ$

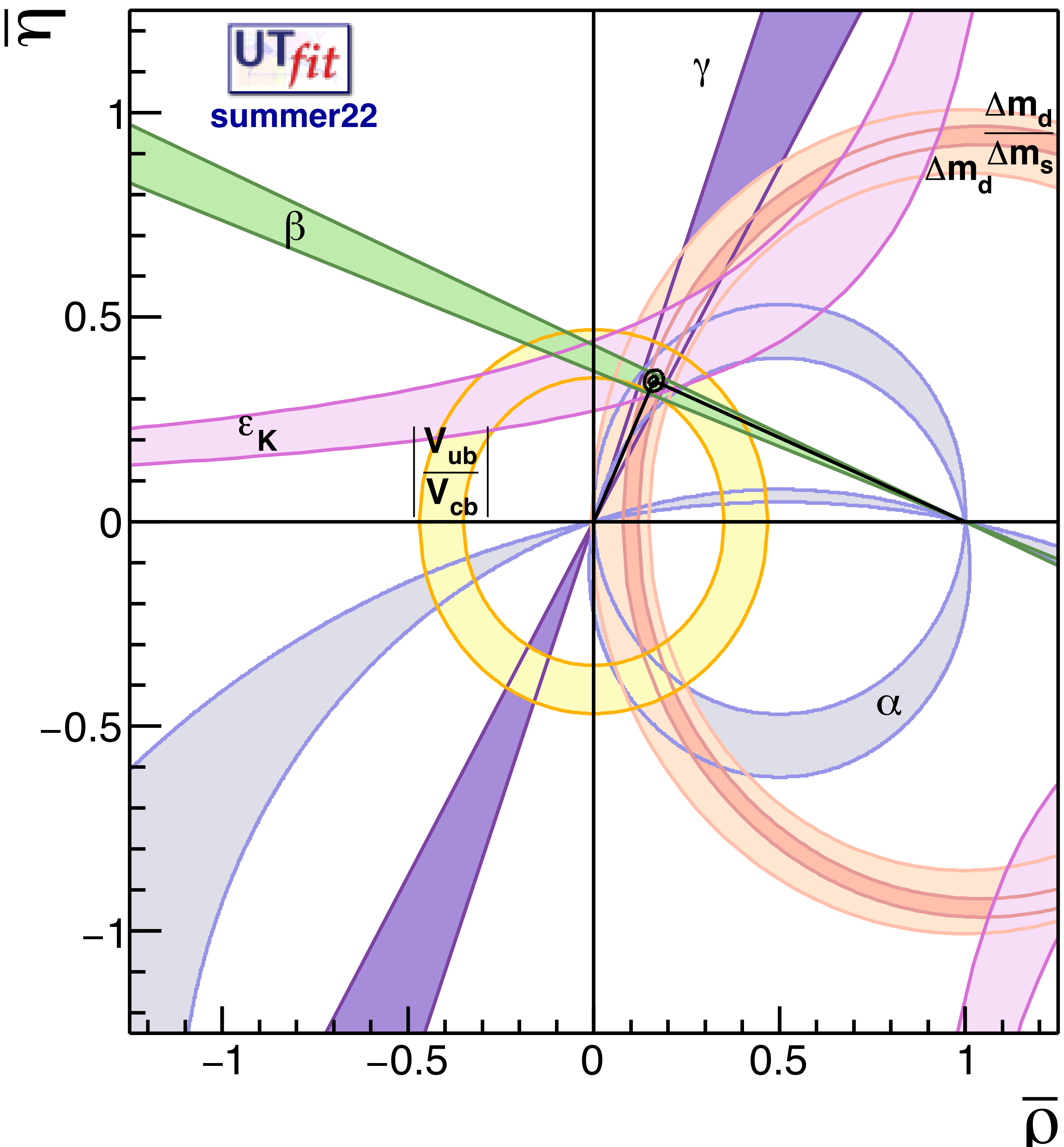


Last, but not least:

- Updated lattice inputs from FLAG $N_f = 2+1, 2+1+1$ (arXiv:2111.09849)
- Skeptical combination for V_{ud}, i.e. $|V_{ud}| = 0.97433 \pm 0.00019$

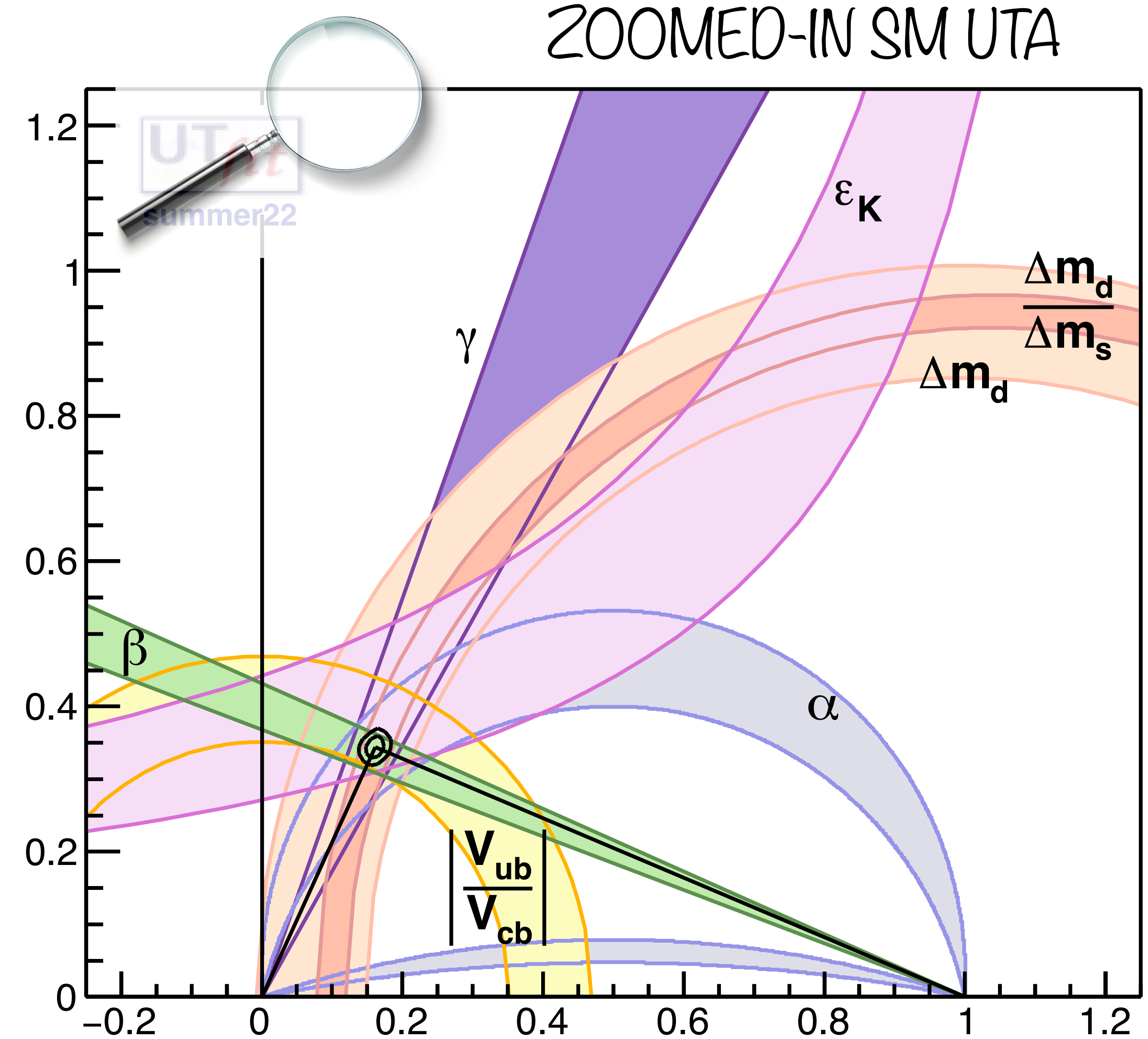
SM UTA as of '22 !

@ 95% prob



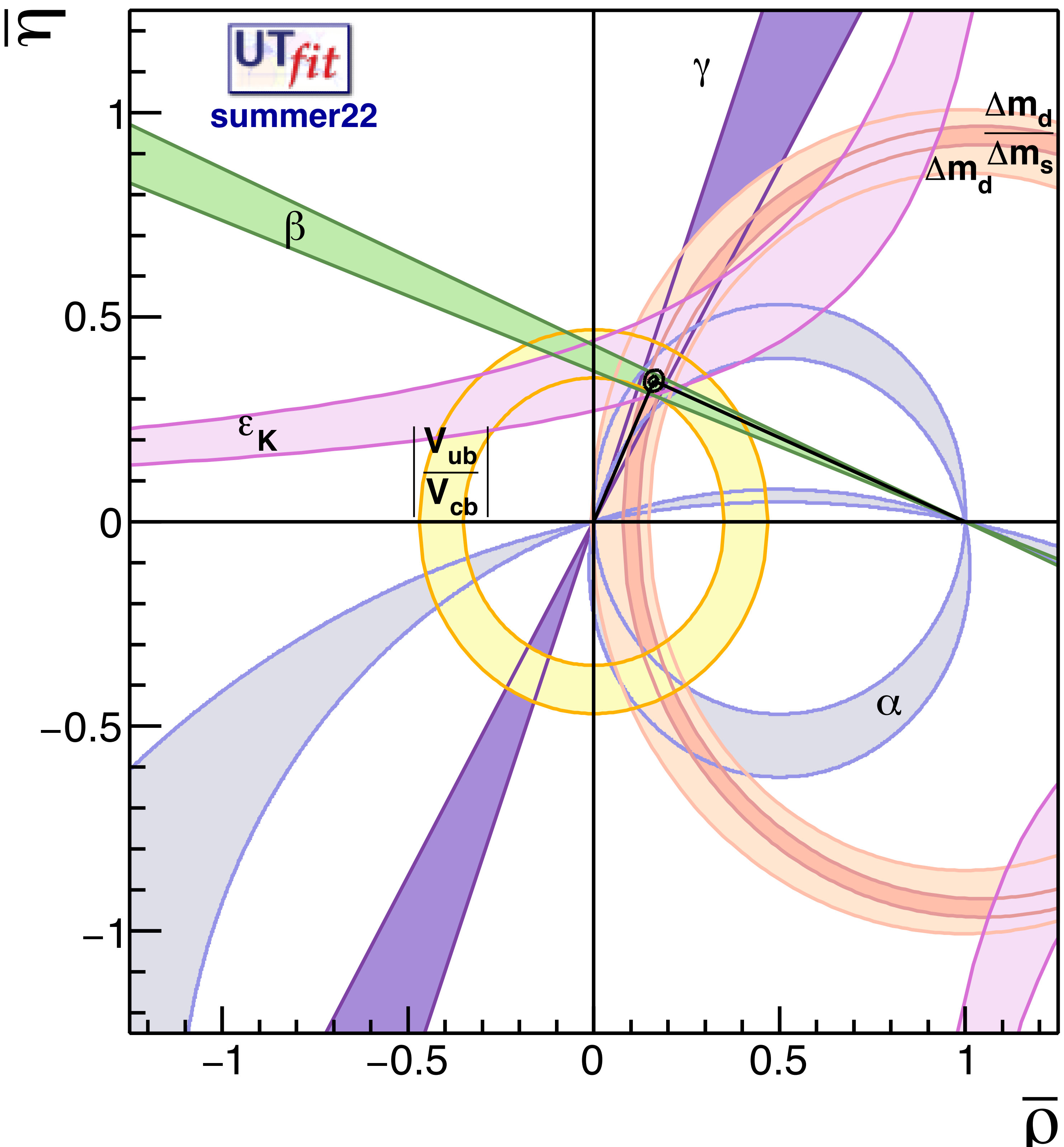
$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

ZOOMED-IN SM UTA

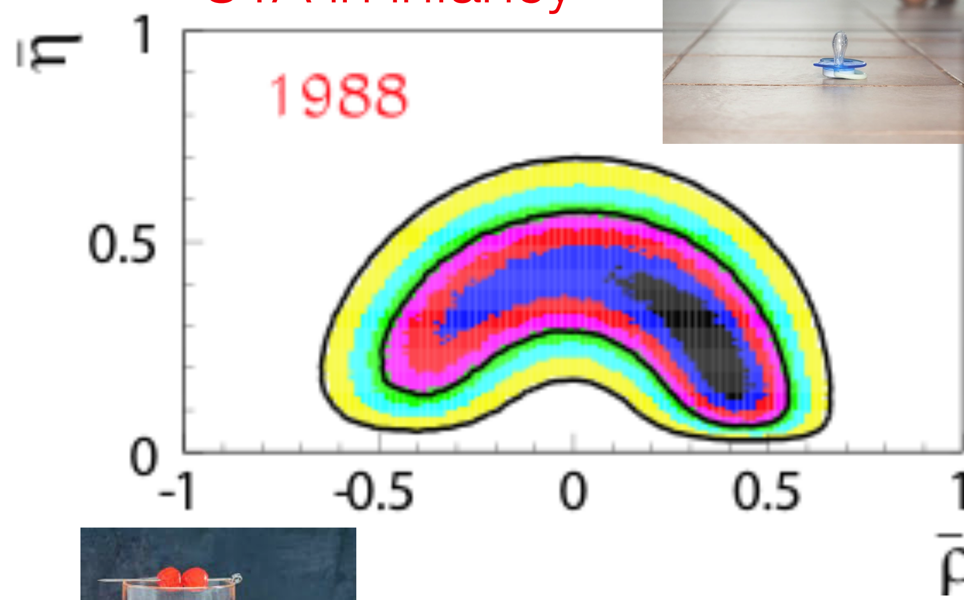


few % determination = decades of tremendous EXP + TH progress!

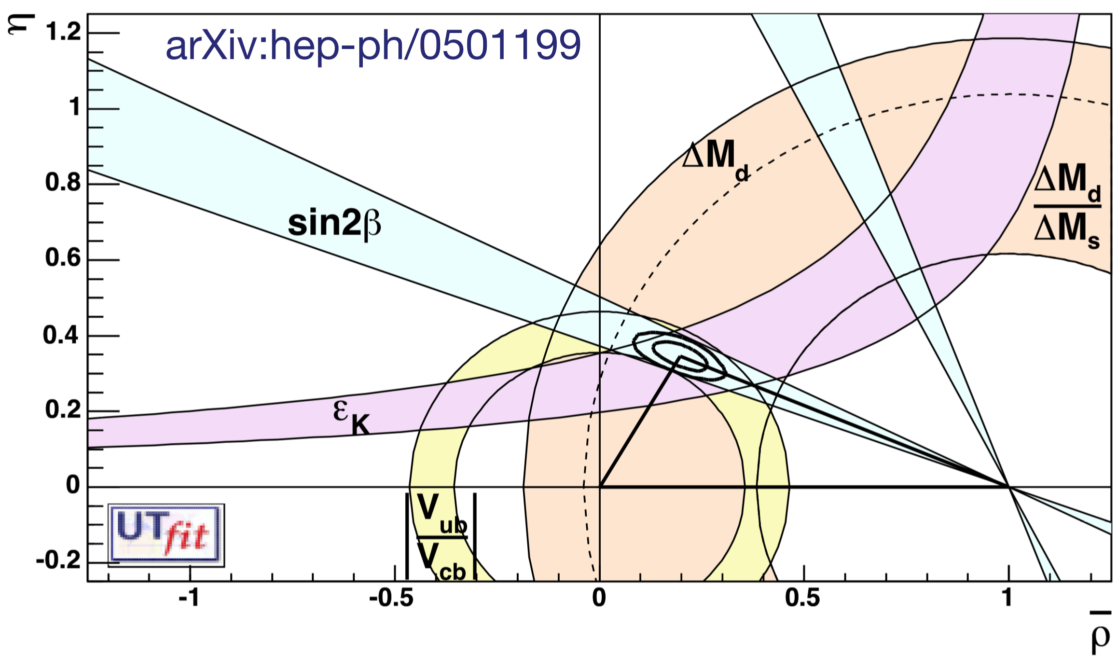
@ 95% prob



UTA in infancy



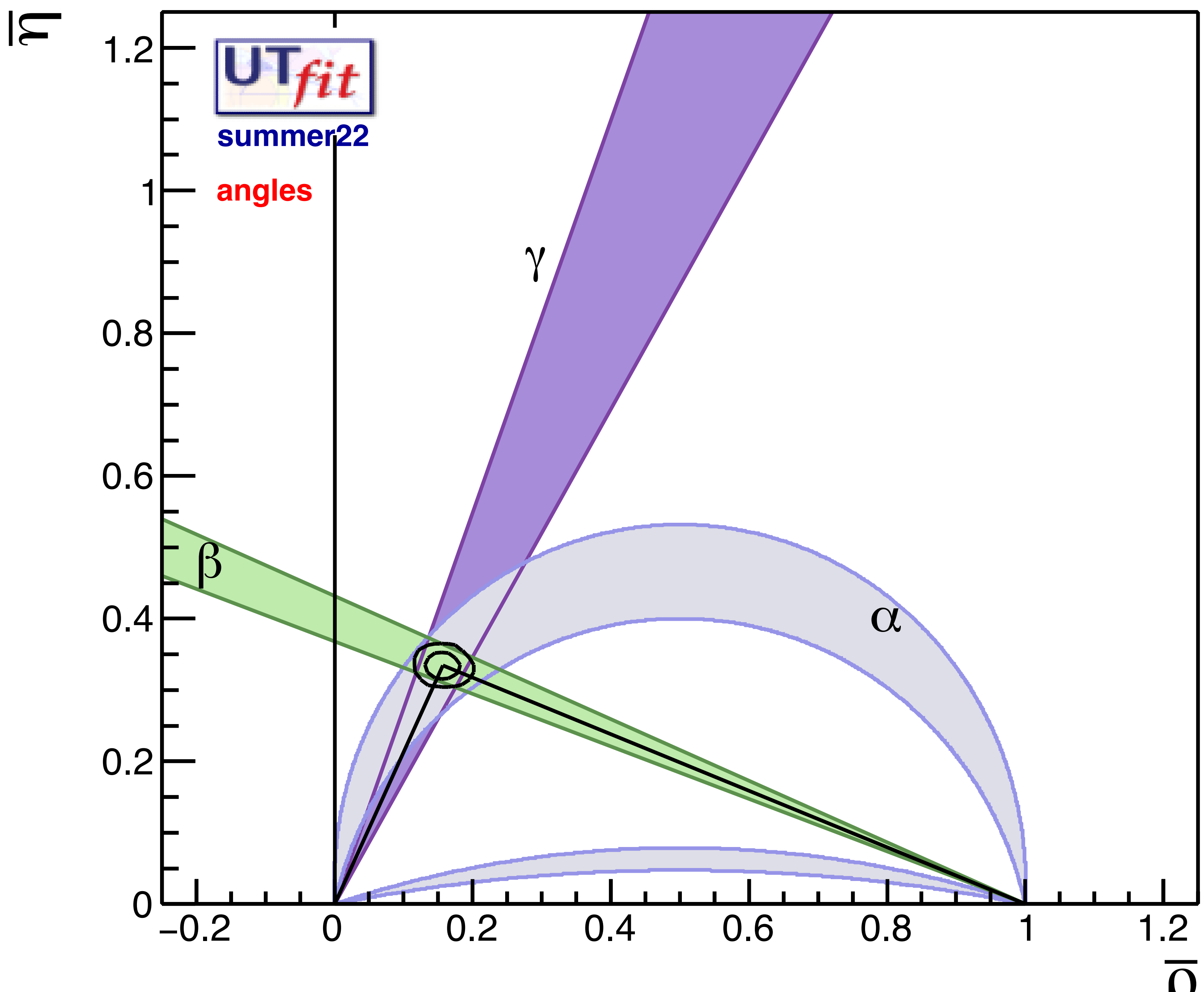
Old-Fashioned SM UTA



$$\bar{\rho} = 0.196 \pm 0.045 \sim 23\%$$
$$\bar{\eta} = 0.347 \pm 0.025 \sim 7\%$$

UTA : angles only

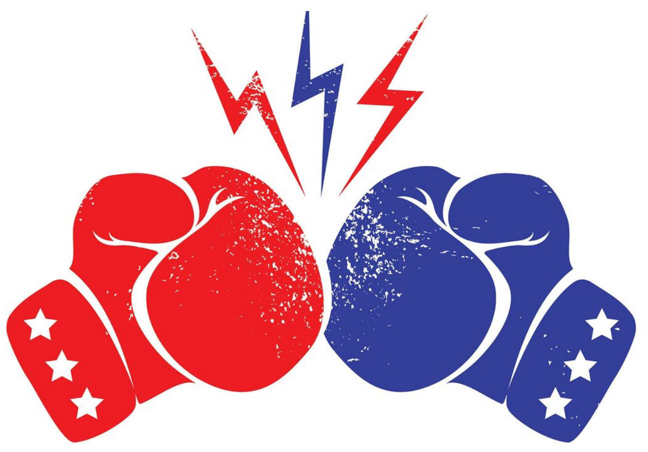
*** i.e., only hadronic B decay modes shaping the UT ***



Angles-only UTA

$\bar{\rho} = 0.157 \pm 0.017 \sim 10\%$

$\bar{\eta} = 0.334 \pm 0.012 \sim 4\%$



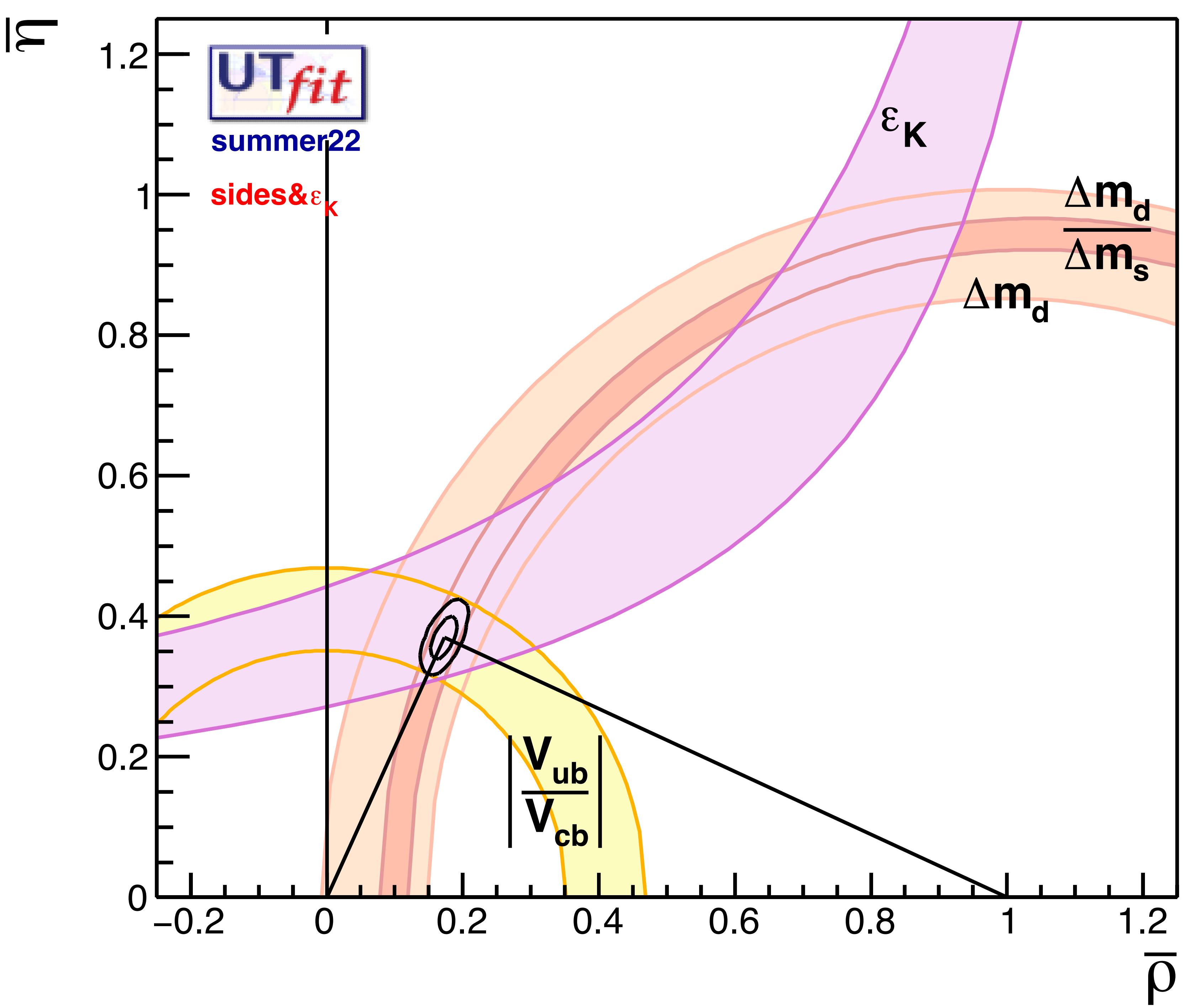
$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$

$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$

SM UTA

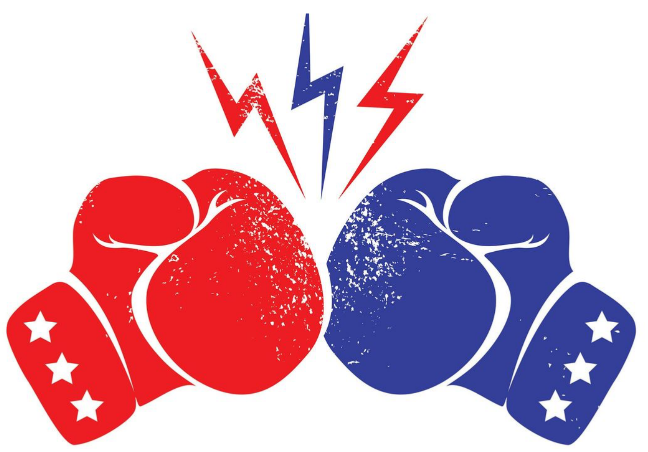
UTA : sides & ε_K

*** i.e., meson anti-meson mixing + tree-level semileptonic ***



Sides & ϵ_K UTA

$$\bar{\rho} = 0.171 \pm 0.014 \sim 8\%$$
$$\bar{\eta} = 0.364 \pm 0.026 \sim 7\%$$



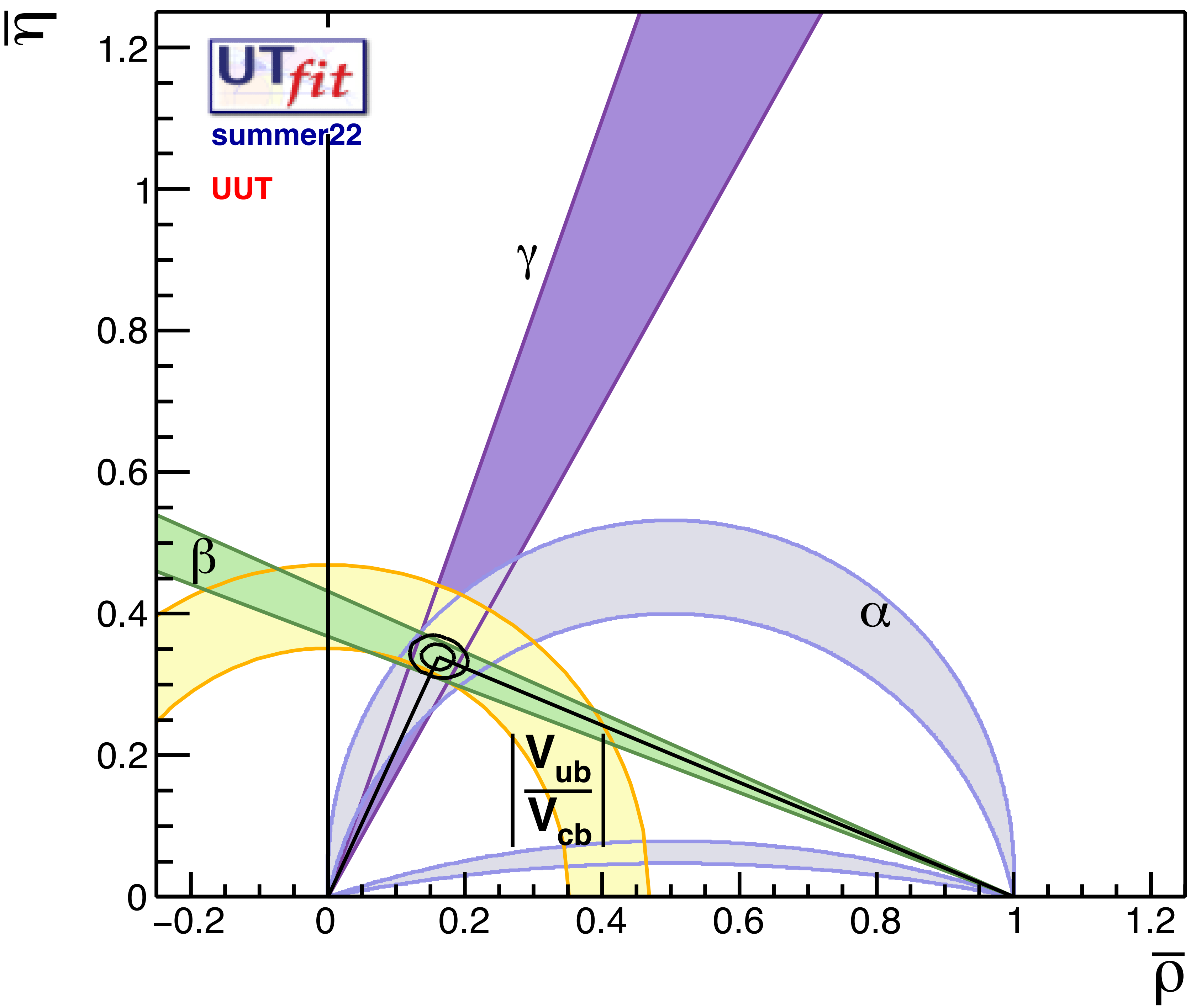
$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

SM UTA

Universal Unitarity Triangle

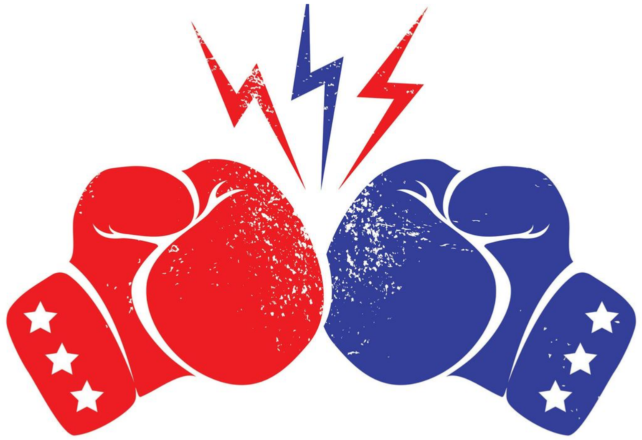
*** i.e., only observables Minimal Flavor Violation (MFV) friendly ***

arXiv:hep-ph/0007085, arXiv:hep-ph/0207036



Universal UTA

$$\bar{\rho} = 0.161 \pm 0.017 \sim 11\%$$
$$\bar{\eta} = 0.339 \pm 0.011 \sim 3\%$$



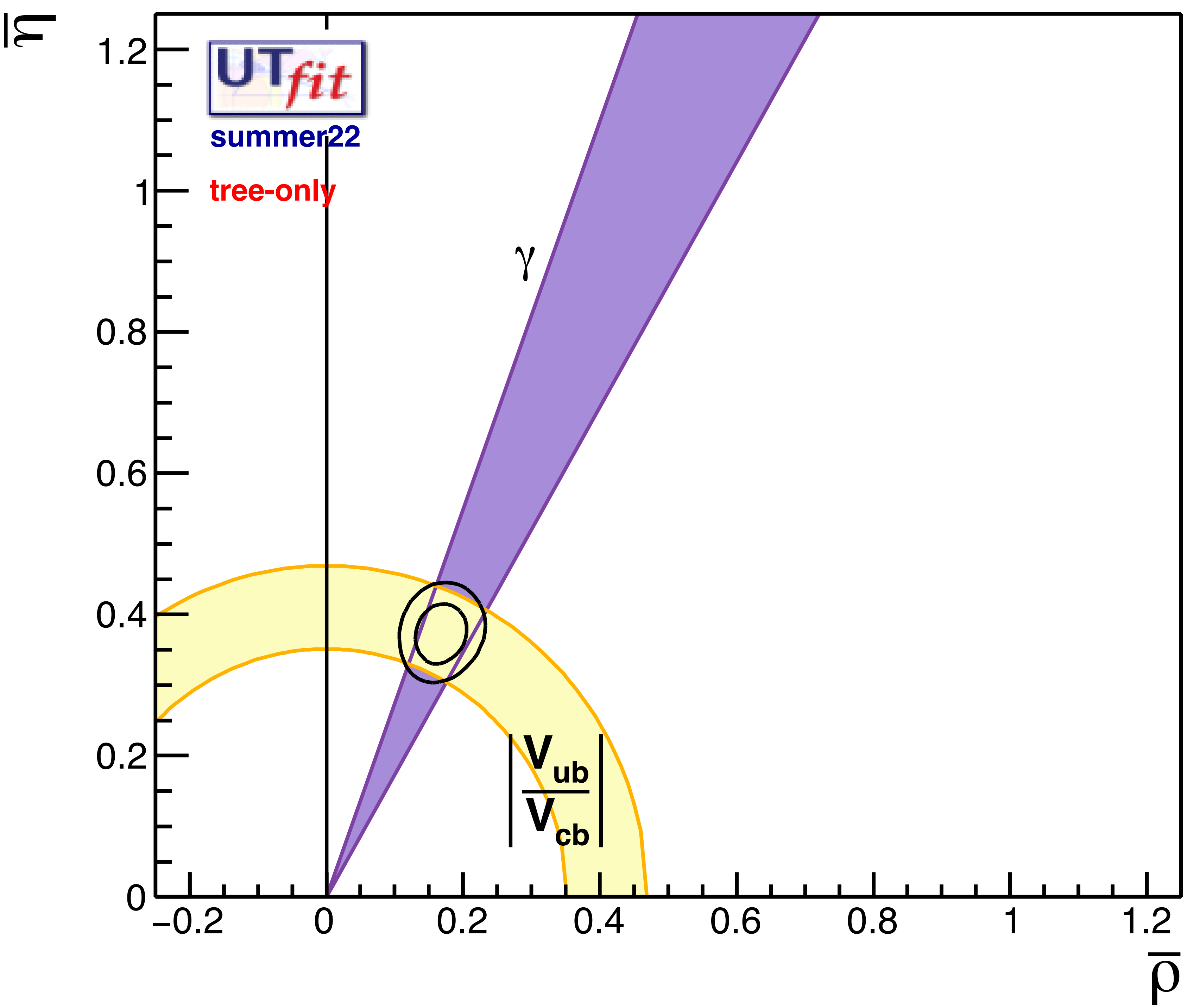
$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

SM UTA

UTA : tree-level only

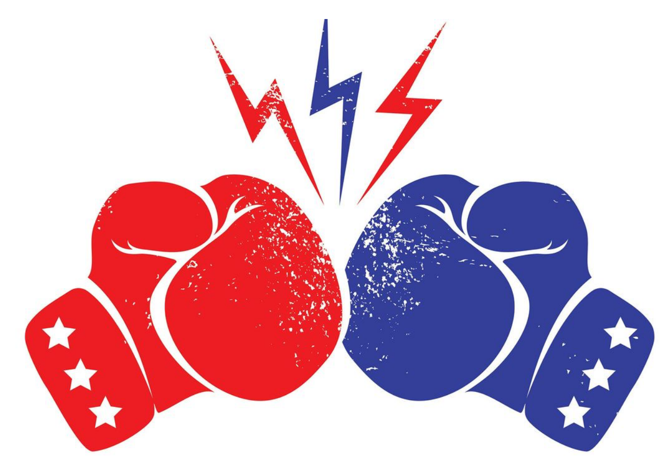
*** i.e., using constraints from tree-level processes only ***

b —> c



tree-only UTA

$$\bar{\rho} = 0.168 \pm 0.025 \sim 15\%$$
$$\bar{\eta} = 0.374 \pm 0.029 \sim 8\%$$



$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

SM UTA

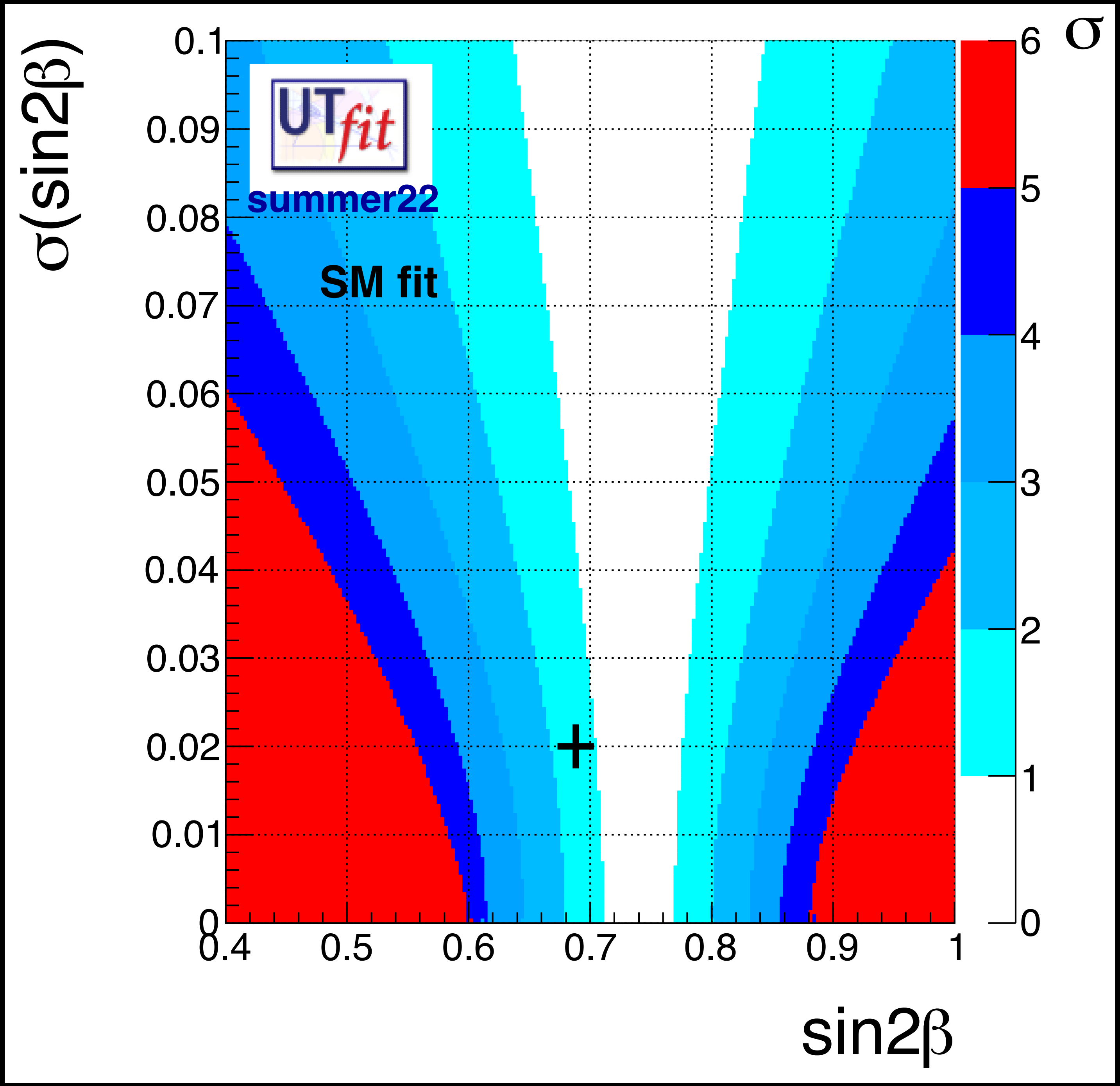
Compatibility plot

graphical pull of obs

Tensions I

+ <—> measurement

$\sin 2\beta = 0.688 \pm 0.020$



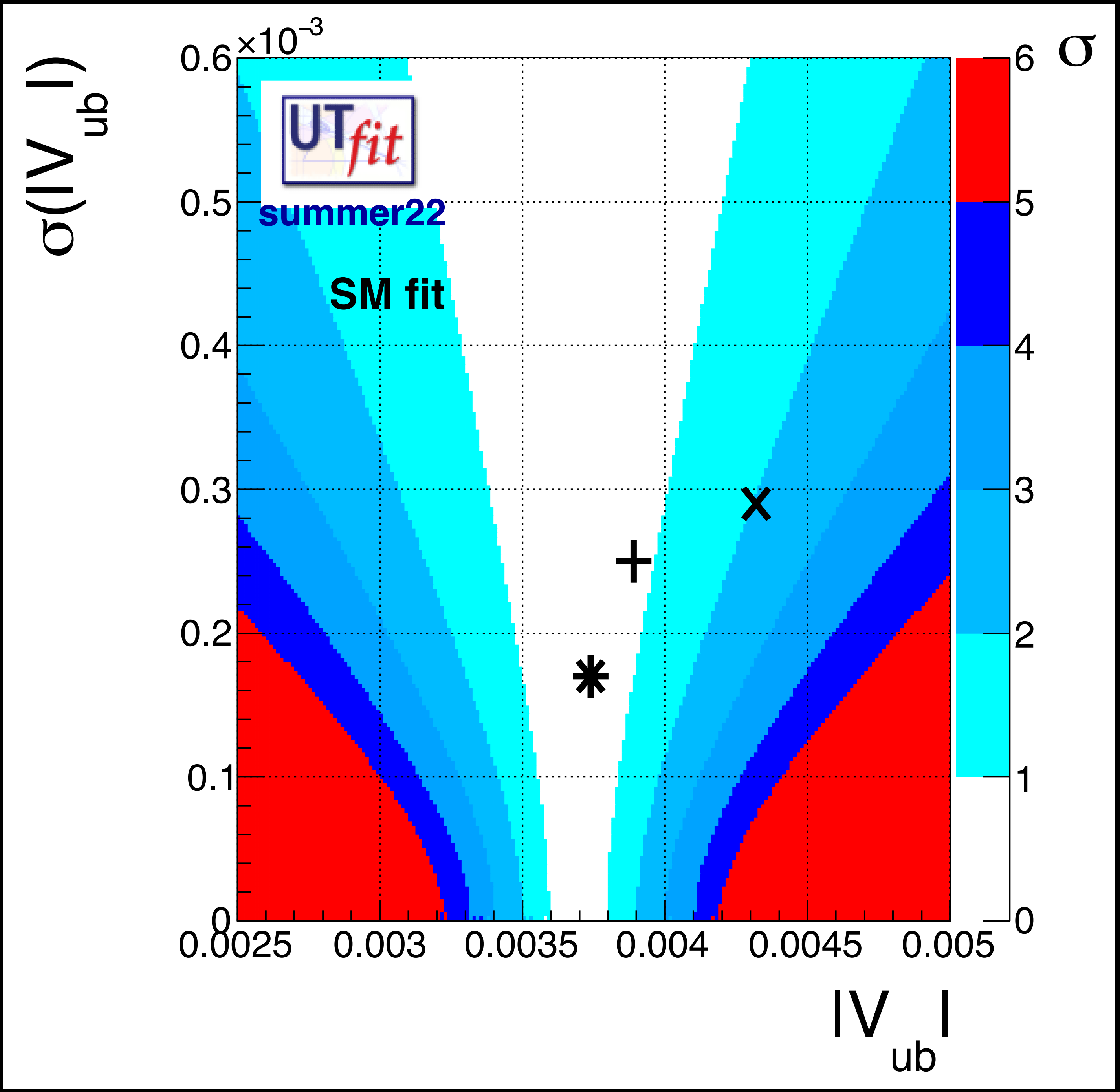
$< 1.5\sigma$ tension in the fit

$\times$ <—> inclusive
$|V_{ub}| \times 10^3 = 4.32 \pm 0.29$

$*$ <—> exclusive
$|V_{ub}| \times 10^3 = 3.74 \pm 0.17$

Tensions II

$+$ <—> measurement
$|V_{ub}| \times 10^3 = 3.89 \pm 0.25$



~ 2σ tension in the fit

x <—> inclusive

$|V_{cb}| \times 10^3 = 42.16 \pm 0.50$

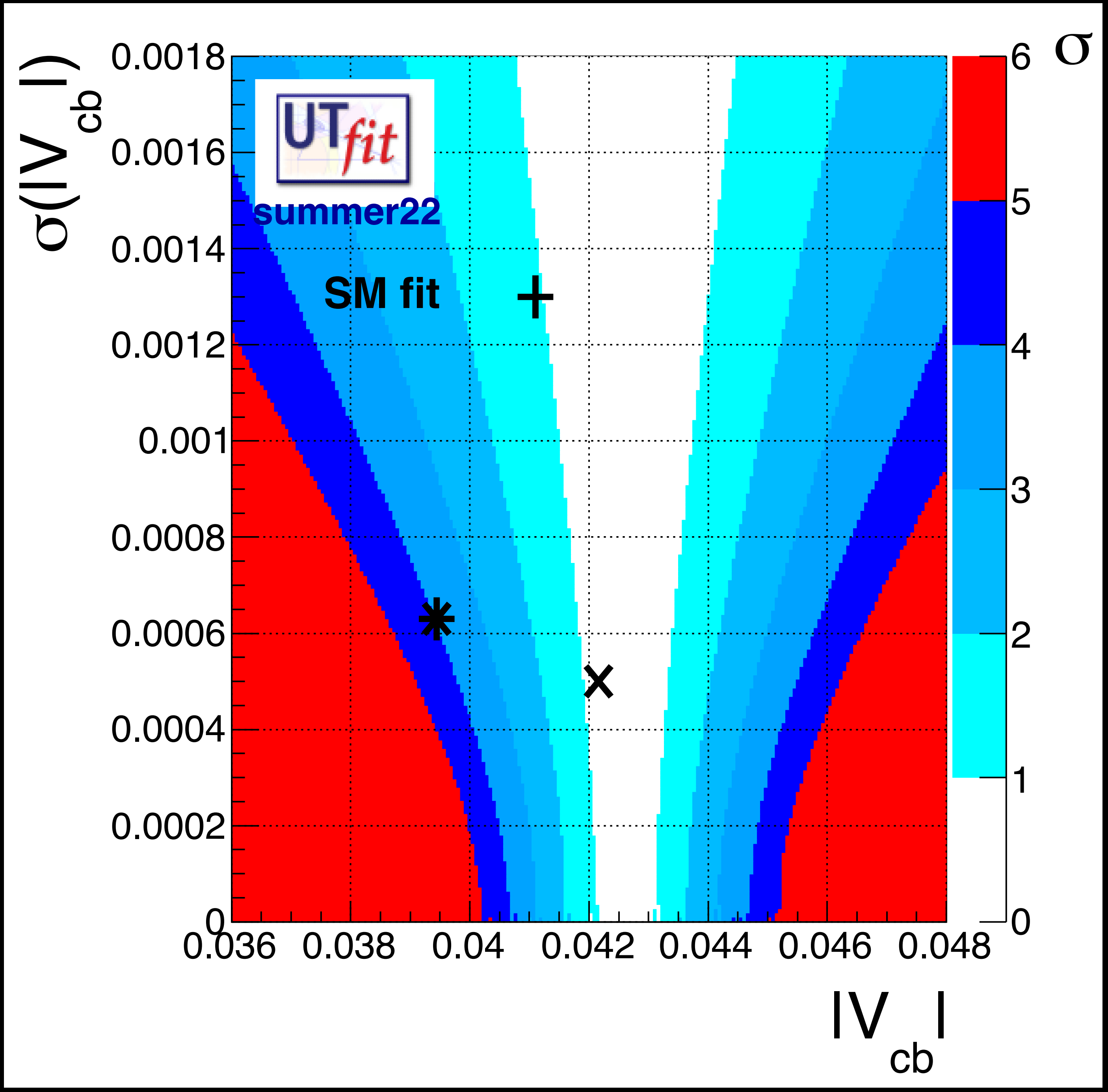
* <—> exclusive

$|V_{cb}| \times 10^3 = 39.44 \pm 0.63$

Tensions III

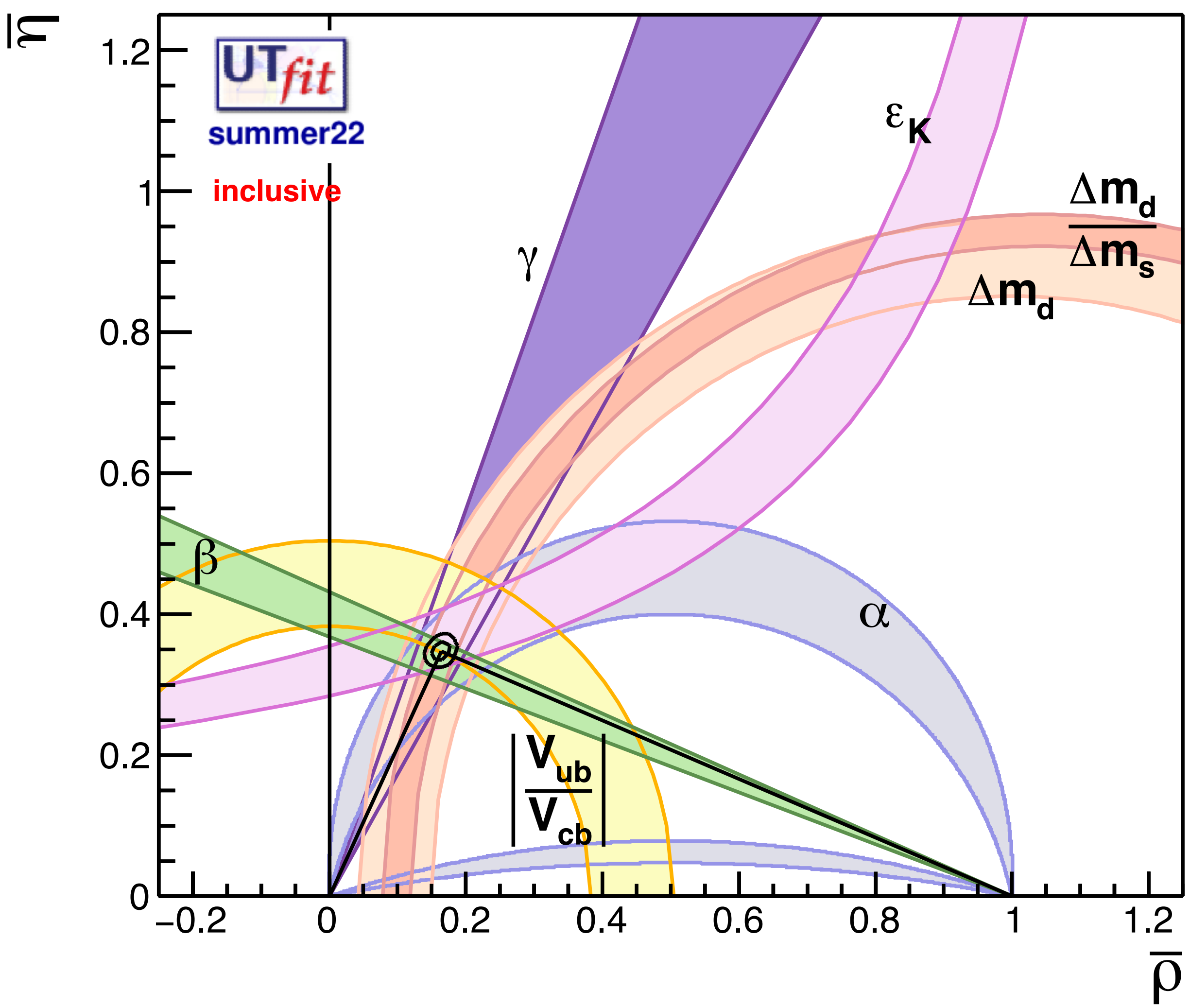
+ <—> measurement

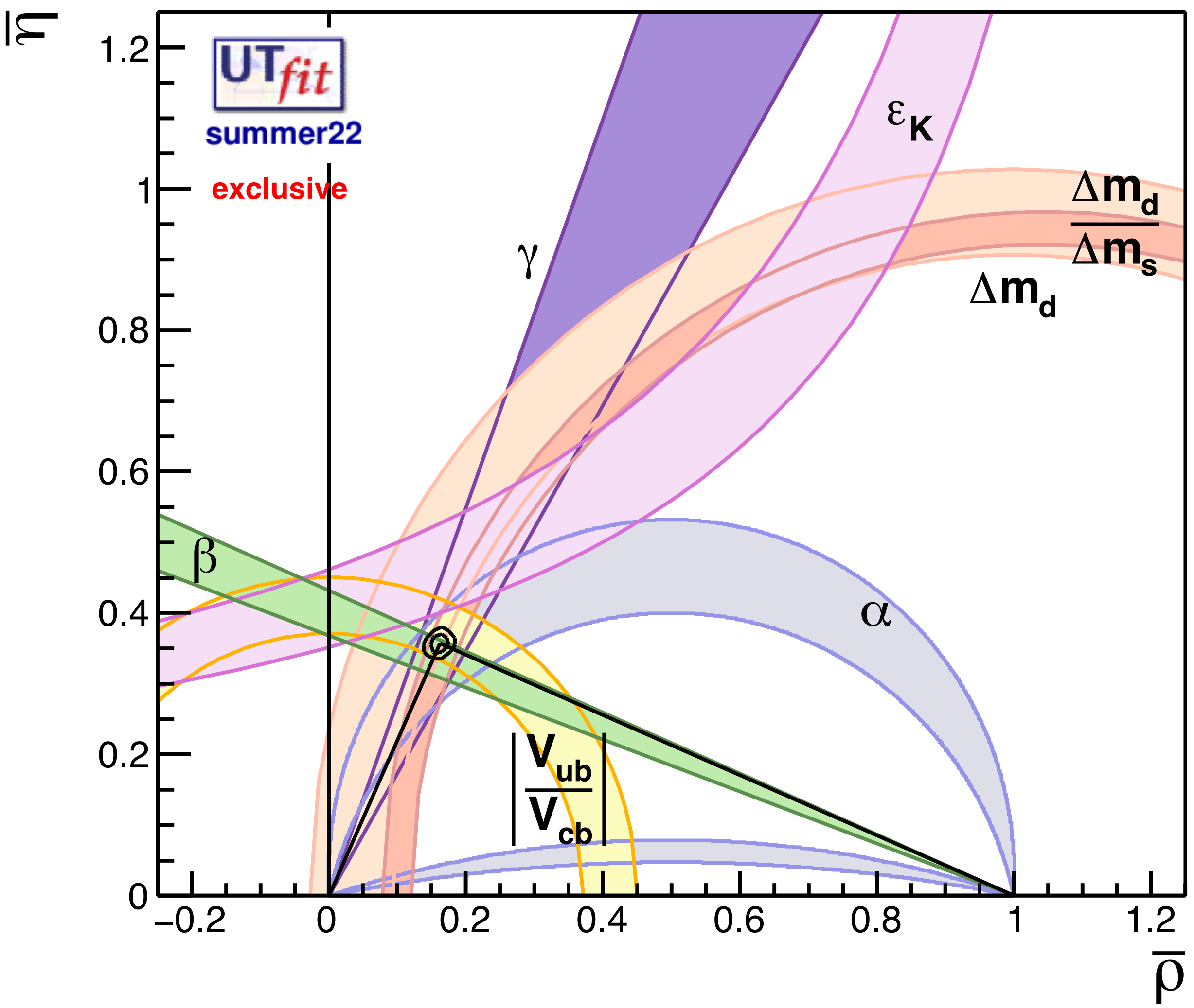
$|V_{cb}| \times 10^3 = 41.1 \pm 1.3$



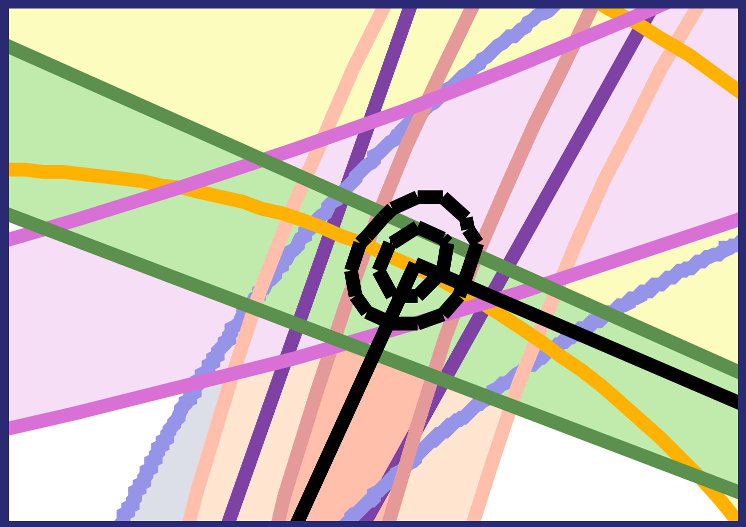
~ 4σ tension in the fit

UTA : Inclusive VS Exclusive

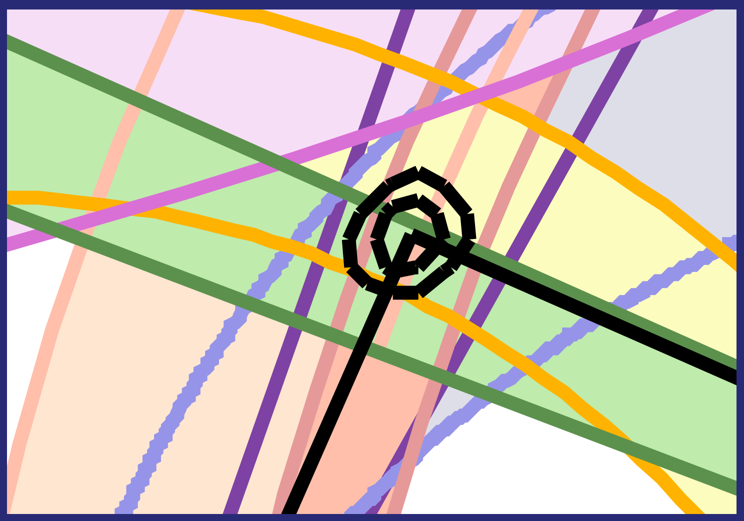




Inclusive



Exclusive



SM UTA as of '22

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.688 ± 0.020	0.740 ± 0.030	~ 1.4
γ	65.8 ± 3.4	64.8 ± 1.4	< 1
α	95.0 ± 4.7	92.5 ± 1.6	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.07 ± 0.15	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	41.1 ± 1.3	42.6 ± 0.5	< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	42.16 0.50		< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	39.44 0.63		~ 3.9
$\lvert V_{ub}\rvert \cdot 10^3$	3.89 ± 0.25	3.70 ± 0.10	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.32 ± 0.29	-	~ 2.0
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.74 ± 0.17	-	< 1
$BR(B \to \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.88 ± 0.05	< 1
$A_{SL}^{d} \cdot 10^3$	-2.1 ± 1.7	-0.33 ± 0.03	< 1
$A_{SL}^{s} \cdot 10^3$	-0.6 ± 2.8	0.014 ± 0.001	< 1

NP Analysis: Wiki How

- Most generic NP effects in $|\Delta F| = 2$ transitions:

$$K - \bar{K}: \quad \mathrm{Re}\, A_K = C_{\Delta m_K} \mathrm{Re}\, A_K^{SM}\ , \quad \mathrm{Im}\, A_K = C_\varepsilon \mathrm{Im}\, A_K^{SM}$$

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

- Include all relevant observables for $|\Delta F| = 2$ NP:

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$
$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

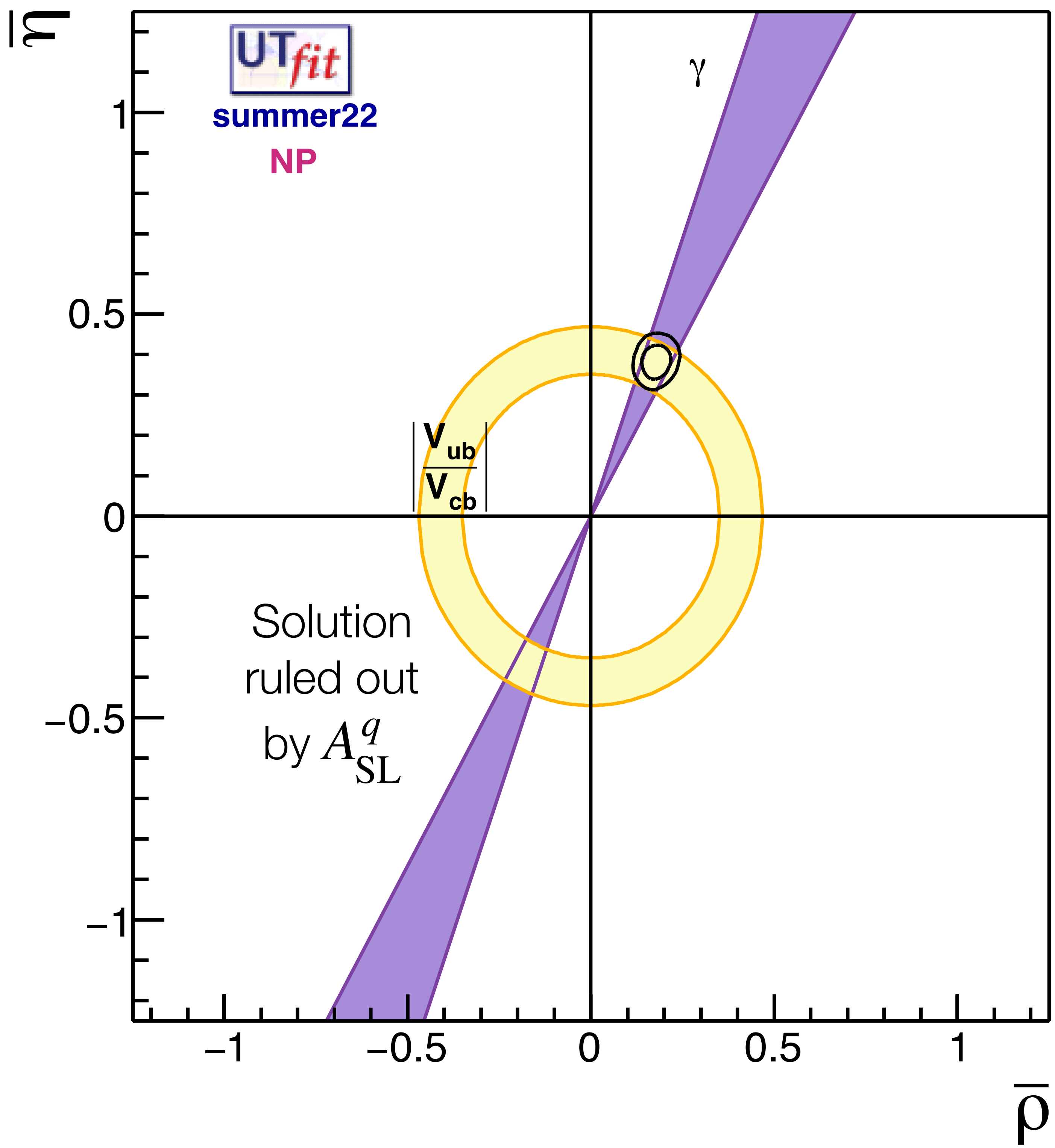
$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$
$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

- Fit simultaneously CKM & NP —> **bound on NP scale**

6 new parameters

UTA x New Physics

*** i.e., assuming only tree-level obs to be SM ***



NP UTA

$$\bar{\rho} = 0.178 \pm 0.027 \sim 15\%$$
$$\bar{\eta} = 0.384 \pm 0.029 \sim 8\%$$

When New Flavors matter ...

$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

SM UTA

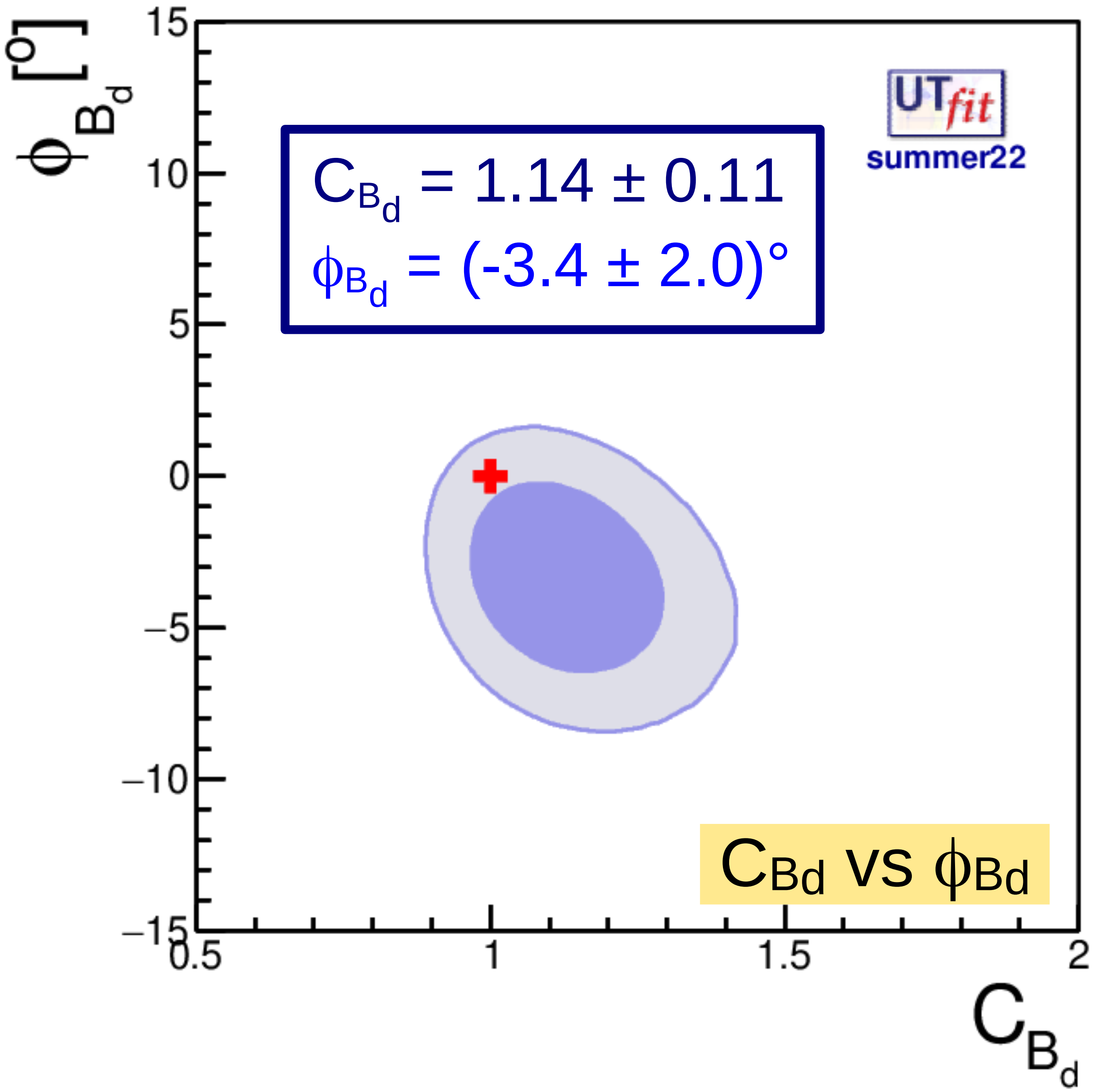
NP Analysis: Results I

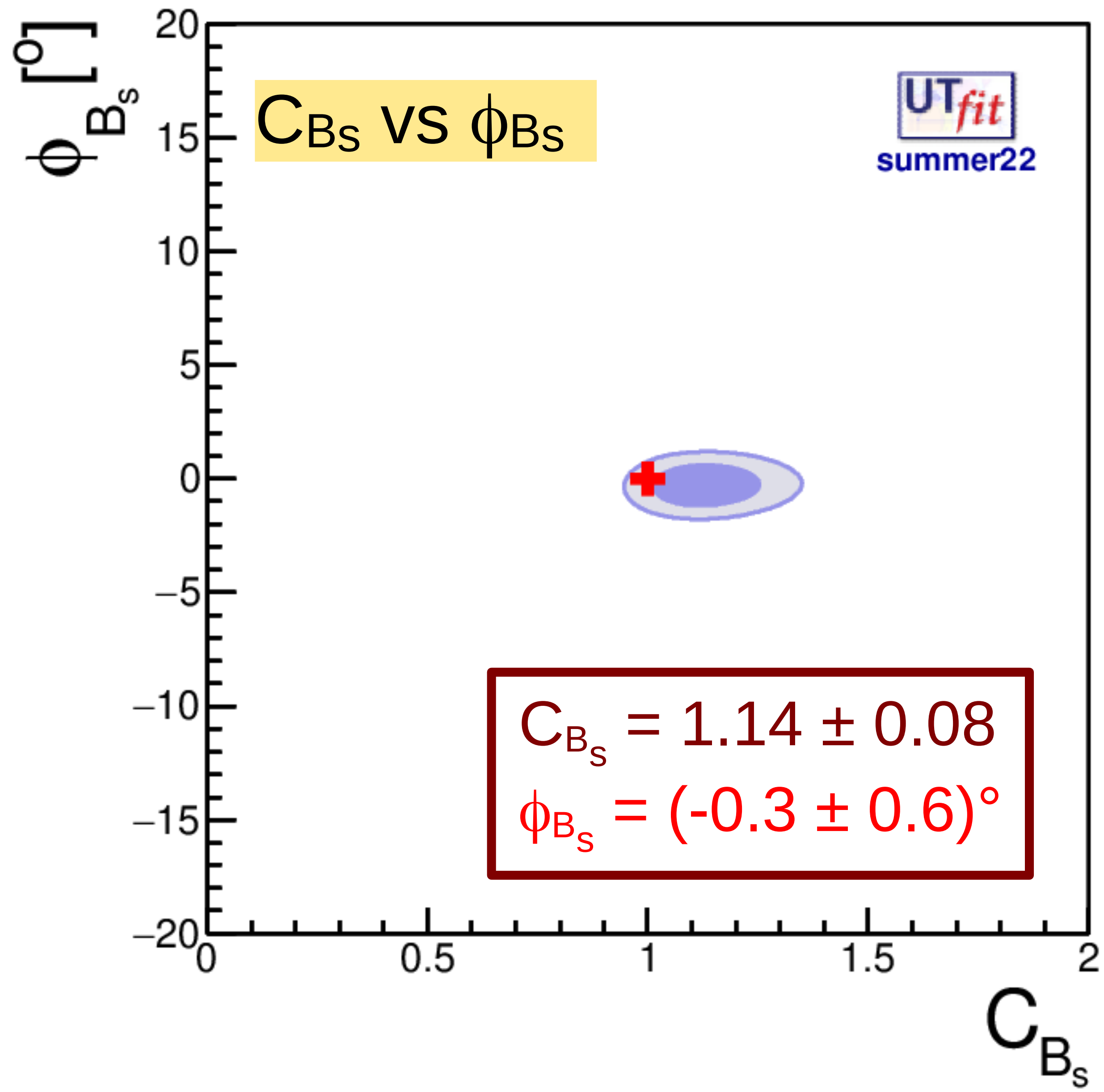
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

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

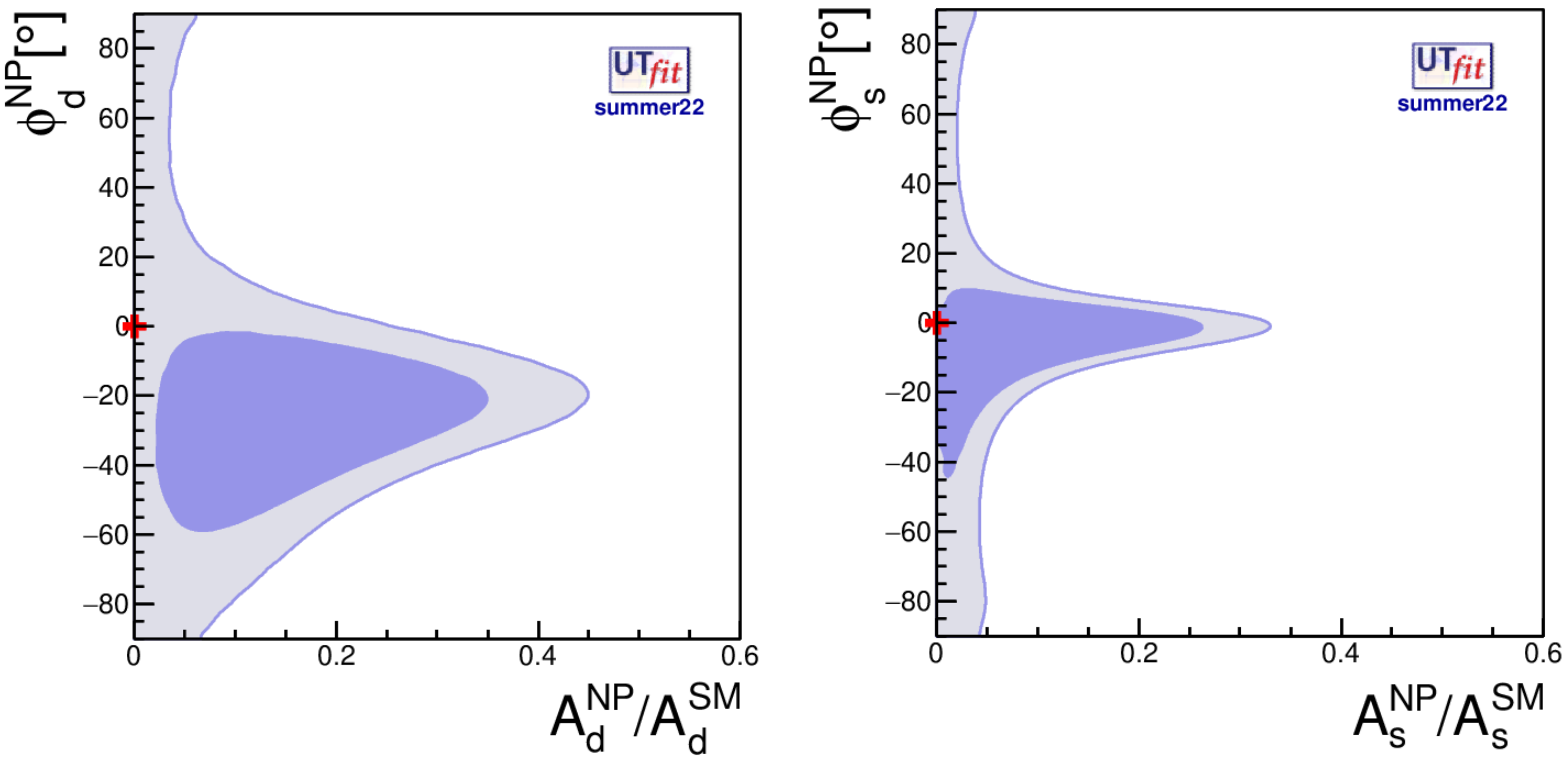
K system

$C_{\epsilon_K} = 1.12 \pm 0.12$





NP Analysis: Results II



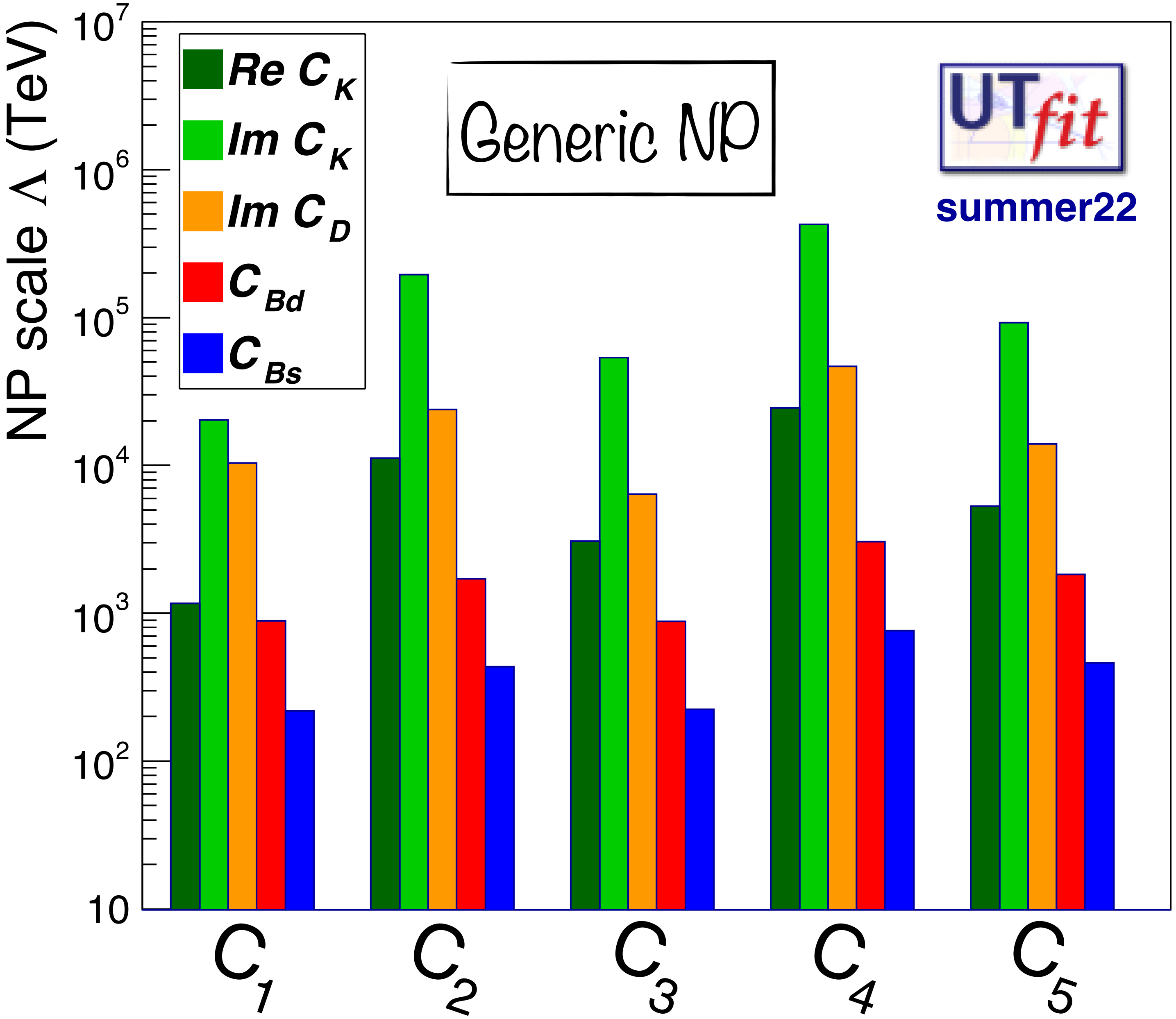
$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

Ratio of NP/SM amplitudes is:

< 35 % @ 68% prob (45% @ 95% prob) [q=d]

< 25 % @ 68% prob (35% @ 95% prob) [q=s]

NP Analysis: Results III



|ΔF| = 2 Weak EFT

SM/MFV

$$O_1^{q_iq_j} = \bar{q}^\alpha_{jL}\gamma_\mu q^\alpha_{iL}\,\bar{q}^\beta_{jL}\gamma^\mu q^\beta_{iL}$$

$$O_2^{q_iq_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL}\,\bar{q}^\beta_{jR} q^\beta_{iL}$$

$$O_3^{q_iq_j} = \bar{q}^\alpha_{jR} q^\beta_{iL}\,\bar{q}^\beta_{jR} q^\alpha_{iL}$$

$$O_4^{q_iq_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL}\,\bar{q}^\beta_{jL} q^\beta_{iR}$$

$$O_5^{q_iq_j} = \bar{q}^\alpha_{jR} q^\beta_{iL}\,\bar{q}^\beta_{jL} q^\alpha_{iR}$$

$$+ \text{ chirally flipped } \widetilde{O}^{q_iq_j}_{1,2,3}$$

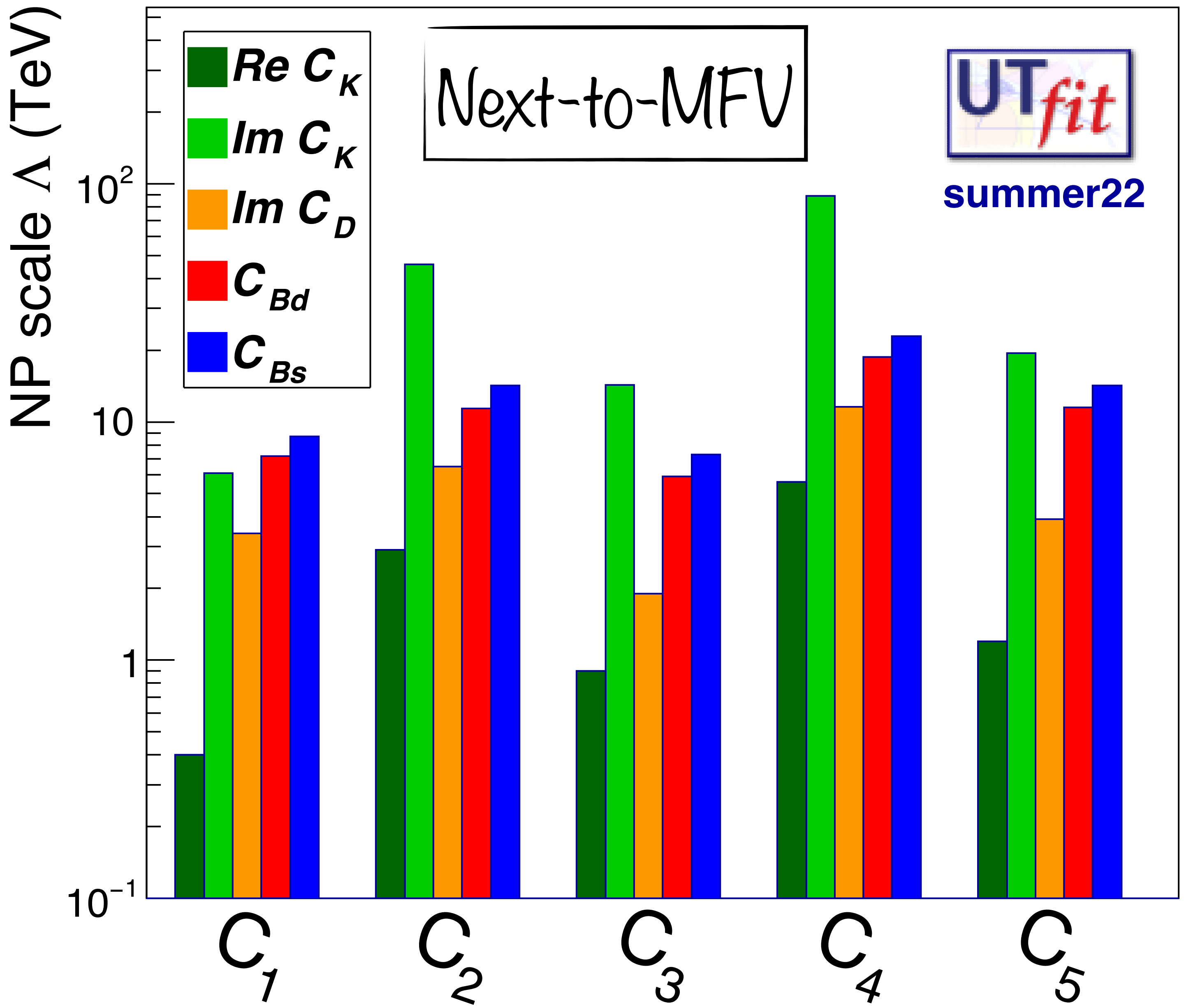
see, e.g. arXiv:/0707.0636

$$C(\Lambda) \lesssim (4.3\times 10^5\ \text{TeV})^{-2}$$

Generic NP = no SM protection,

namely : $C(\Lambda) = C/\Lambda^2$

NP Analysis: Results IV



|ΔF| = 2 Weak EFT

SM/MFV

$$O_1^{q_i q_j} = \bar{q}^\alpha_{jL} \gamma_\mu q^\alpha_{iL} \, \bar{q}^\beta_{jL} \gamma^\mu q^\beta_{iL}$$

$$O_2^{q_i q_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL} \, \bar{q}^\beta_{jR} q^\beta_{iL}$$

$$O_3^{q_i q_j} = \bar{q}^\alpha_{jR} q^\beta_{iL} \, \bar{q}^\beta_{jR} q^\alpha_{iL}$$

$$O_4^{q_i q_j} = \bar{q}^\alpha_{jR} q^\alpha_{iL} \, \bar{q}^\beta_{jL} q^\beta_{iR}$$

$$O_5^{q_i q_j} = \bar{q}^\alpha_{jR} q^\beta_{iL} \, \bar{q}^\beta_{jL} q^\alpha_{iR}$$

$$+ \text{ chirally flipped } \widetilde{O}_{1,2,3}^{q_i q_j}$$

see, e.g. arXiv:/0707.0636

$$C(\Lambda) \lesssim (89\,\mathrm{TeV})^{-2}$$

Next-to-MFV = SM-like protection, but O(1) phases

| ΔF | = 2 Beyond the Weak EFT

SU(2)$_L$ x U(1)$_Y$ gauge invariance

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,d>4} \frac{C_i \mathcal{O}_i^{(d)}}{\Lambda_{\rm NP}^{d-4}}$$

SMEFT RGE

$O_{jk}^{HQ(1[3])}$ $(H^\dagger i \overset{\leftrightarrow}{D}{}_\mu^{[A]} H)\,(\bar{Q}_j \gamma^\mu [\tau^A]\, Q_k)$	O_{jjkl}^{LedQ} $(\bar{L}_j e_j)\,(\bar{d}_k Q_l)$	O_{jjkl}^{LeQu} $(\bar{L}_j e_j) i\tau^2\,(\bar{Q}_k u_l)$	$O^{ud(1[8])}_{jklm}$ $(\bar{u}_j \gamma_\mu [T^a] u_k)\,(\bar{d}_l \gamma^\mu [T^a] d_m)$	$O_{jklm}^{QuQd(1[8])}$ $(\bar{Q}_j \gamma_\mu [T^a] u_k) i\tau^2\,(\bar{Q}_l \gamma^\mu [T^a] d_m)$
$O_{jklm}^{QQ(1[3])}$ $(\bar{Q}_j \gamma_\mu [\tau^A] Q_k)\,(\bar{Q}_l \gamma^\mu [\tau^A] Q_m)$	O_{jklm}^{uu} $(\bar{u}_j \gamma_\mu u_k)\,(\bar{u}_l \gamma^\mu u_m)$	O_{jklm}^{dd} $(\bar{d}_j \gamma_\mu d_k)\,(\bar{d}_l \gamma^\mu d_m)$	$O_{jklm}^{Qd(1[8])}$ $(\bar{Q}_j \gamma_\mu [T^a] Q_k)\,(\bar{d}_l \gamma^\mu [T^a] d_m)$	$O_{jklm}^{Qu(1[8])}$ $(\bar{Q}_j \gamma_\mu [T^a] Q_k)\,(\bar{u}_l \gamma^\mu [T^a] u_m)$

poorly constrained

FLAVOR MISALIGNMENT

For more details:

Model-independent bounds on the standard model effective theory from flavour physics

Luca Silvestrini [a,b], Mauro Valli [c,*] Physics Letters B 799 (2019) 135062

SMEFT atlas of $\Delta F = 2$ transitions

Jason Aebischer, Christoph Bobeth, Andrzej J. Buras & Jacky Kumar

Journal of High Energy Physics **2020**, Article number: 187 (2020)

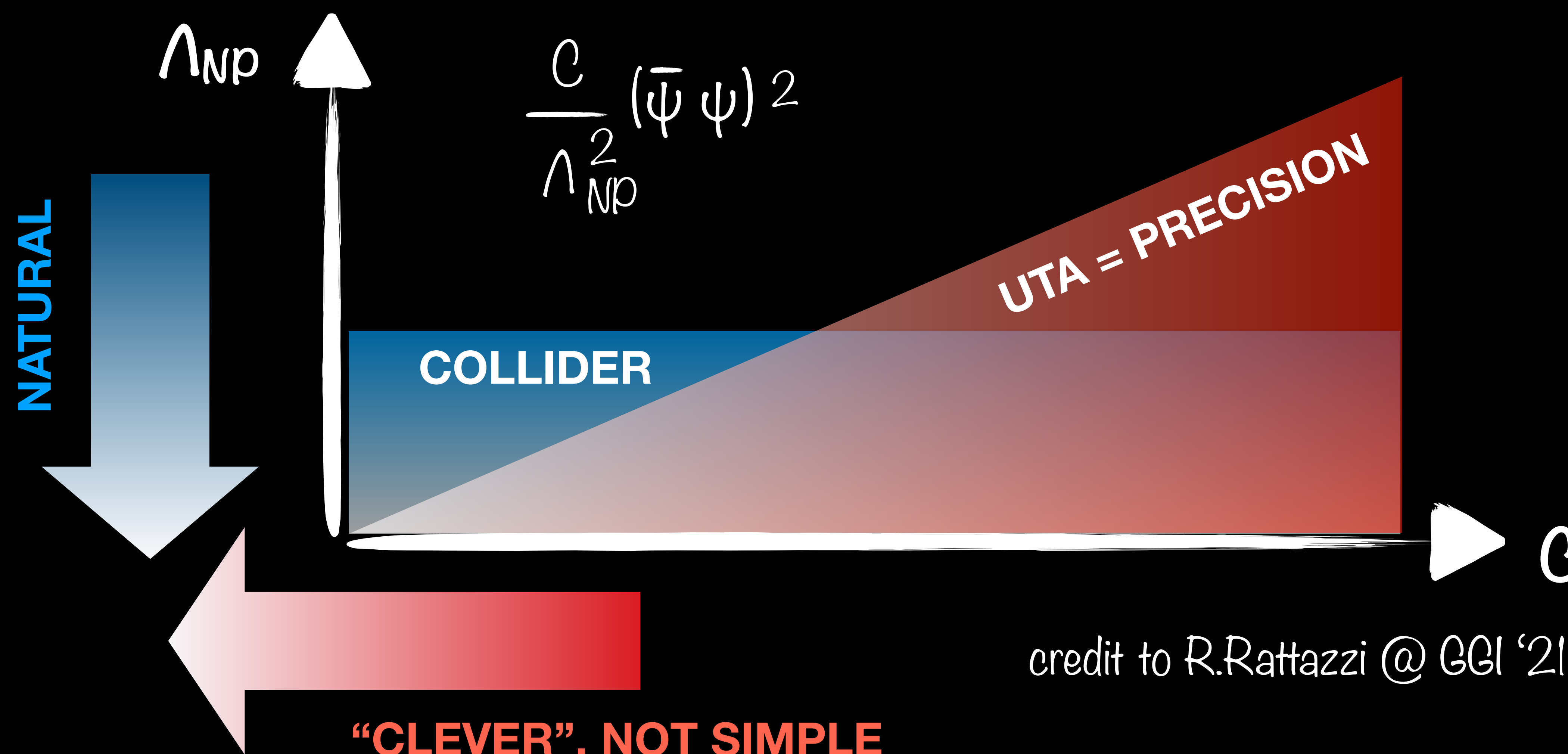
Take Home

- **SM UTA :** Towards % precision: Overall consistency amazing!

  → current pull from | Vcb | @ 4σ ($B_{(s)} \longrightarrow D^{(*)}_{(s)} l \nu$)

  but see recent work by *G.Martinelli, S.Simula, L.Vittorio* 2109.15248, 2204.05925

- **NP UTA :**



BACKUP

V_{cb} and V_{ub}

A-la-D'Agostini two-dimensional average procedure:

$|V_{cb}| = (41.1 \pm 1.3)\ 10^{-3}$

uncertainty ~ 3.2%

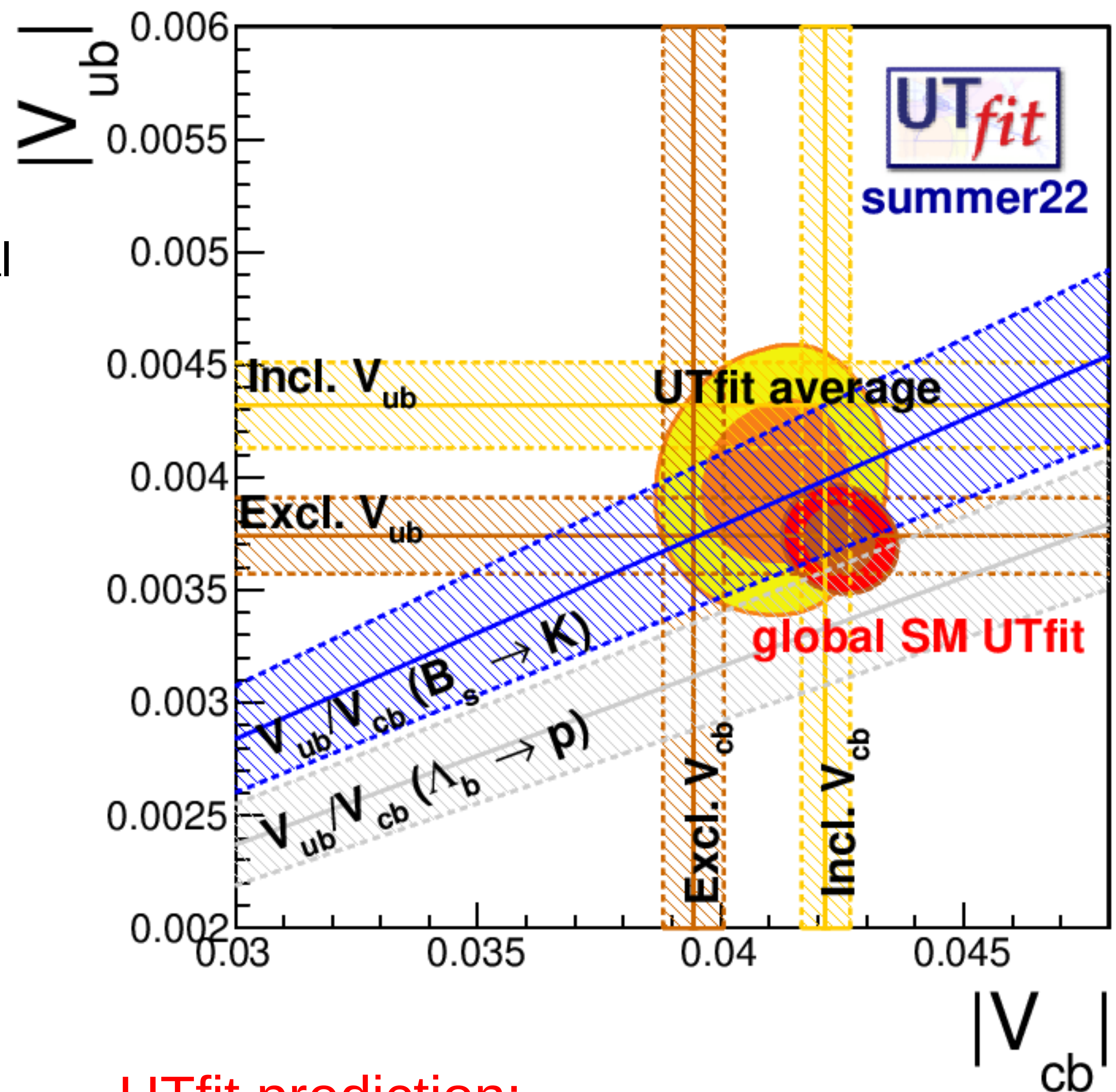
$|V_{ub}| = (3.89 \pm 0.25)\ 10^{-3}$

uncertainty ~ 6.4%

From global SM fit

$|V_{cb}| = (42.4 \pm 0.5)\ 10^{-3}$

$|V_{ub}| = (3.72 \pm 0.10)\ 10^{-3}$



UTfit prediction:

$|V_{cb}| = (42.6 \pm 0.5)\ 10^{-3}$

$|V_{ub}| = (3.70 \pm 0.10)\ 10^{-3}$

new-physics-specific constraints

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

semileptonic asymmetries in B^0 and B_s: sensitive to NP effects in both size and phase. Taken from the latest HFLAV.

Cleo, BaBar, Belle, D0 and LHCb

same-side dilepton charge asymmetry:
admixture of B_s and B_d so sensitive to NP effects in both.

D0 arXiv:1106.6308

$$A^{\mu\mu}_{\rm SL} \times 10^3 = -7.9 \pm 2.0$$

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

lifetime τ^{FS} in flavour-specific final states:
average lifetime is a function to the width and the width difference

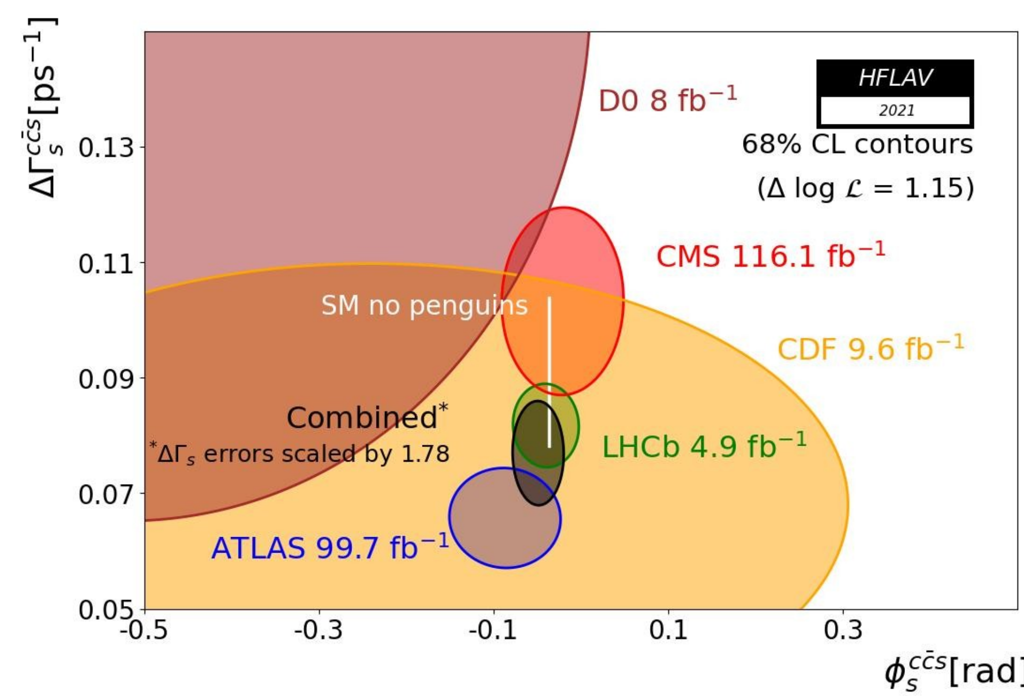
$$\tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps}$$

HFLAV

$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

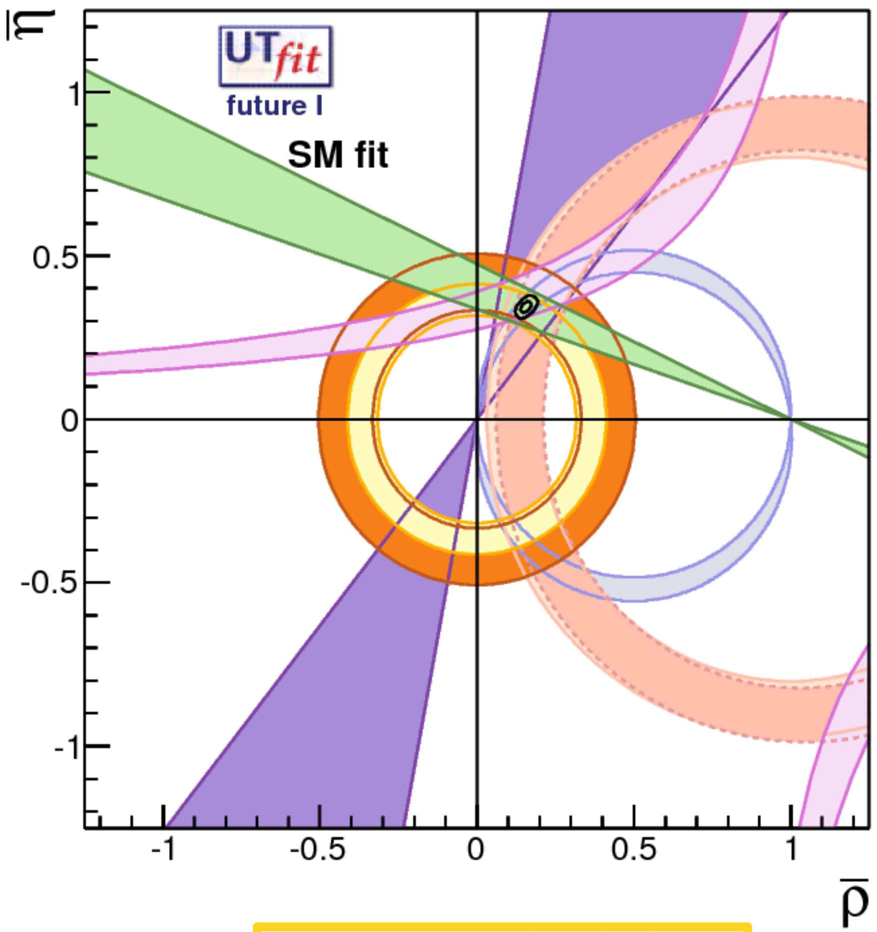
angular analysis as a function of proper time and b-tagging

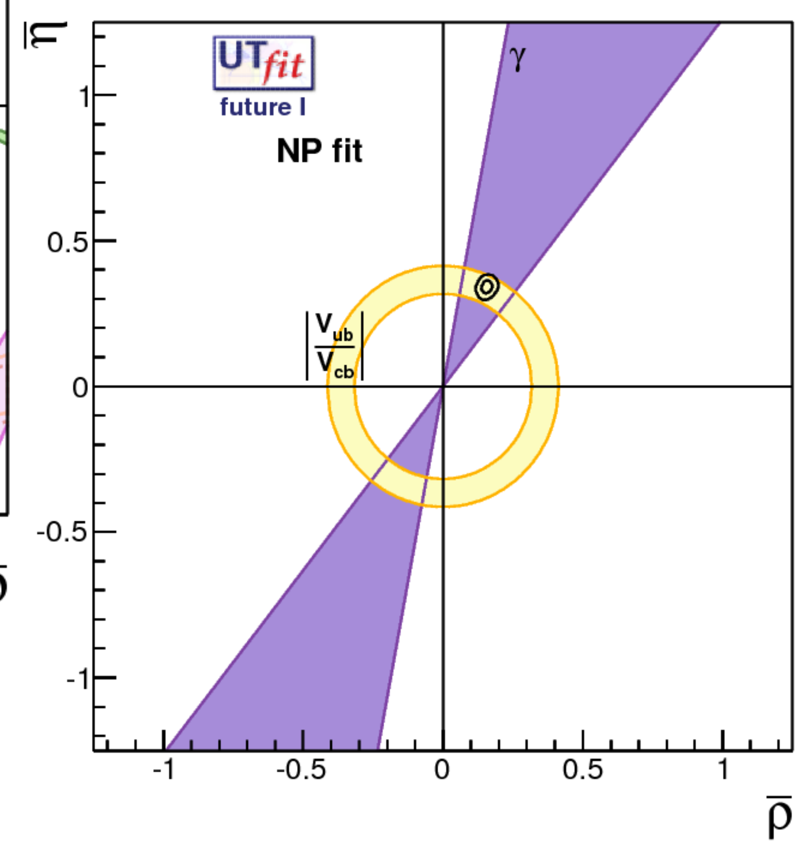
$$\phi_s = -0.049 \pm 0.019 \text{ rad}$$

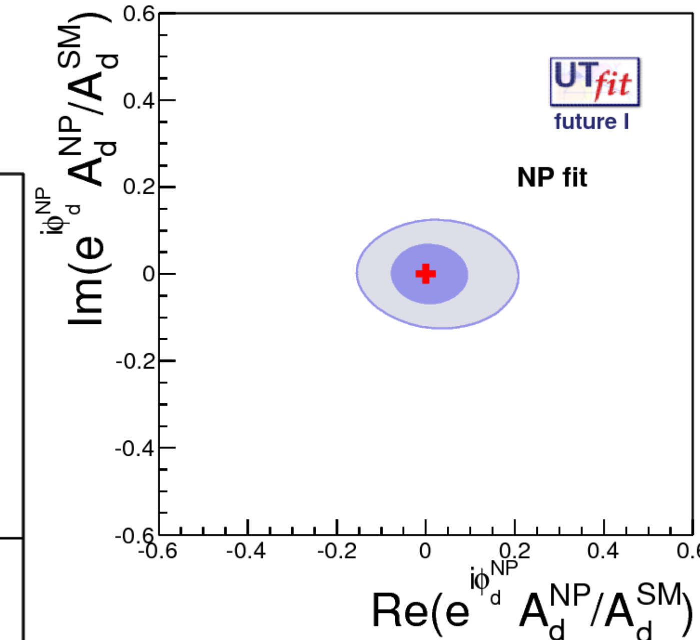


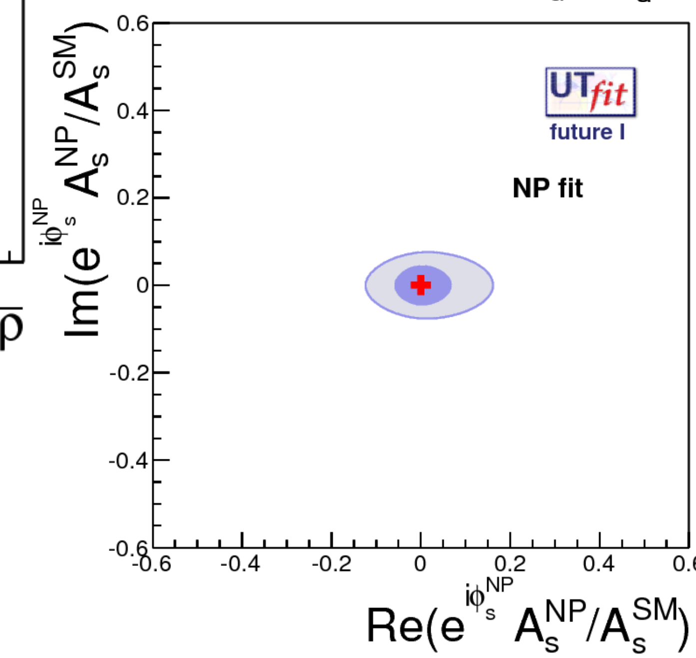
Look at the near future

future I scenario:
errors from
Belle II at 5/ab
+ **LHCb at 10/fb**









$\rho = \pm\, 0.015$
$\eta = \pm\, 0.015$

$\bar{\rho} = 0.154 \pm 0.015$
$\bar{\eta} = 0.344 \pm 0.013$

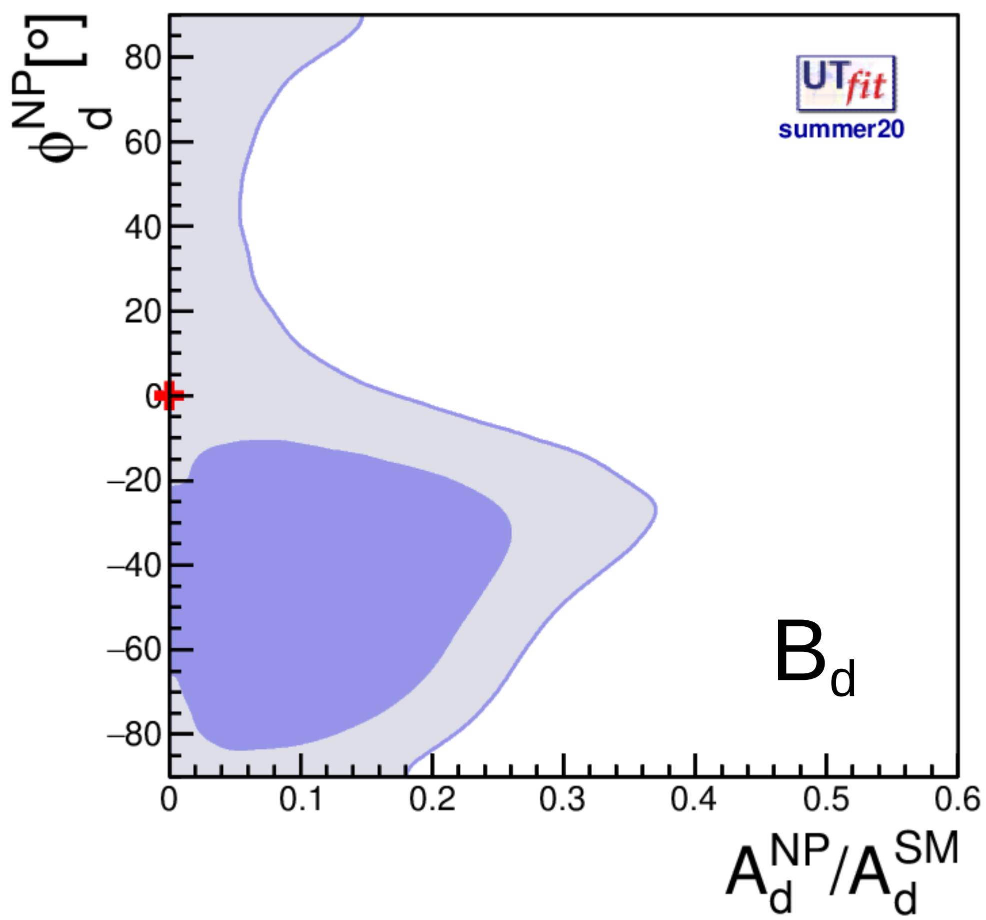
current sensitivity

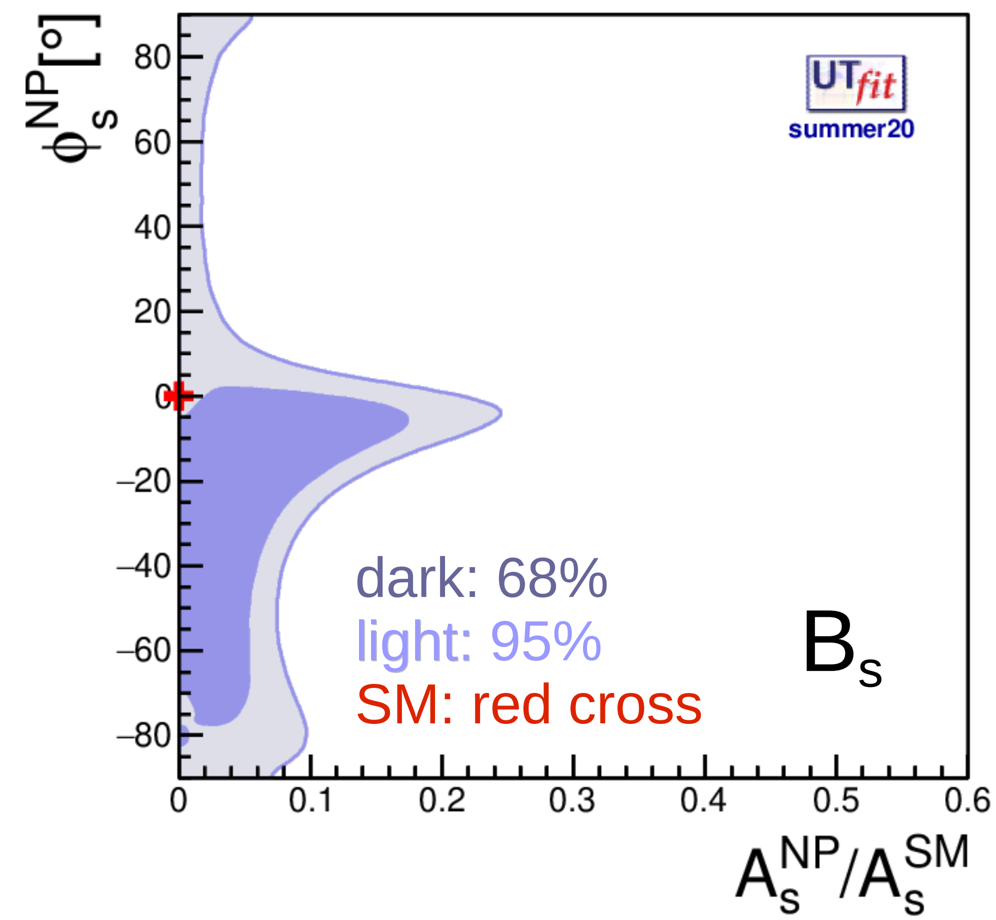
$\bar{\rho} = 0.150 \pm 0.027$
$\bar{\eta} = 0.363 \pm 0.025$

$\rho = \pm\, 0.016$
$\eta = \pm\, 0.019$

NP parameter results

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





The ratio of NP/SM amplitudes is:

< 26% @68% prob. (37% @95%) in B_d mixing

< 18% @68% prob. (25% @95%) in B_s mixing