Global fits of the Unitarity Triangle: updates from the UTfit collaboration

Ludovico Vittorio (University of Rome Sapienza and INFN, Rome)

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SAPIENZA UNIVERSITÀ DI ROMA

INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma

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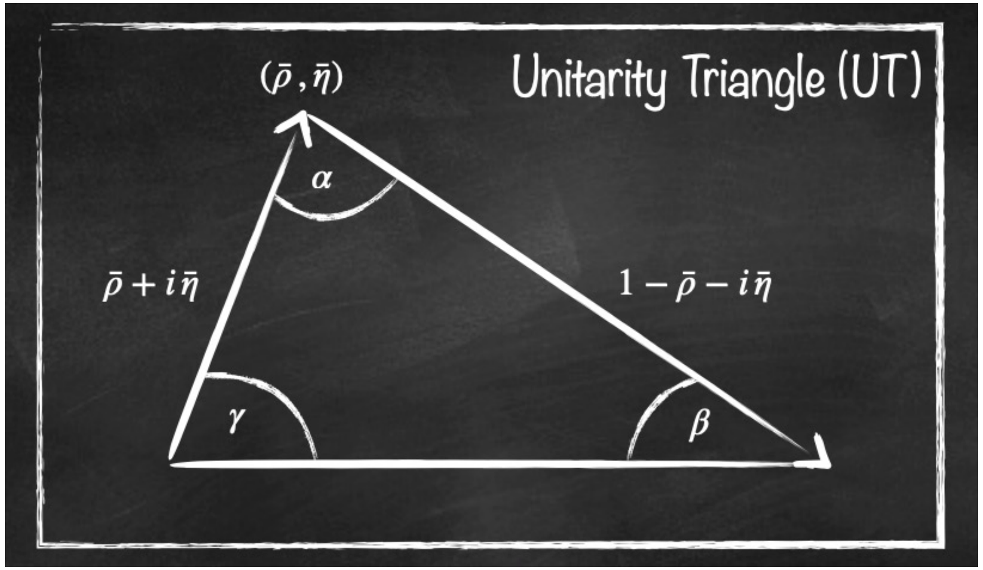

Many thanks to M. Bona, G. Martinelli, M. Pierini, L. Silvestrini, S. Simula, M. Valli

The UTfit Collaboration

Marcella Bona[1] Marco Ciuchini[2] Denis Derkach[3] Fabio Ferrari[4,5] Vittorio Lubicz[2,7] Guido Martinelli[6,8] Davide Morgante[9,10] Maurizio Pierini[11] Luca Silvestrini[6] Silvano Simula[2] Achille Stocchi[12] Cecilia Tarantino[2,7] Vincenzo Vagnoni[4] Mauro Valli[6] and Ludovico Vittorio[6,8]

(1) Queen Mary University of London (2) INFN Roma Tre,
(3) HSE University, (4) INFN Bologna, (5) Università di Bologna (6) INFN Roma, (7) Università Roma Tre
(8) Università di Roma La Sapienza, (9) INFN Milano (10) Università degli Studi di Milano, (11) CERN (12) Université Paris-Saclay and IJCLab

In this talk: plots and numbers updated for Summer 2025!

Latest paper: **Rendiconti Lincei. Scienze Fisiche e Naturali (2023) 34:37–57 (arXiv:2212.03894)**

Basics of the Unitarity Triangle analysis

The Cabibbo-Kobayashi-Maskawa (CKM) matrix described the mixing amon quarks (with different electric charges): it is a unitary 3x3 matrix

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

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Wolfenstein parametrization (L. Wolfenstein, PRL 51 (1983) 1945-1947):

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

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By exploiting the property of unitarity:

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

Triangle in the complex $(\bar{\rho}, \bar{\eta})$ plane

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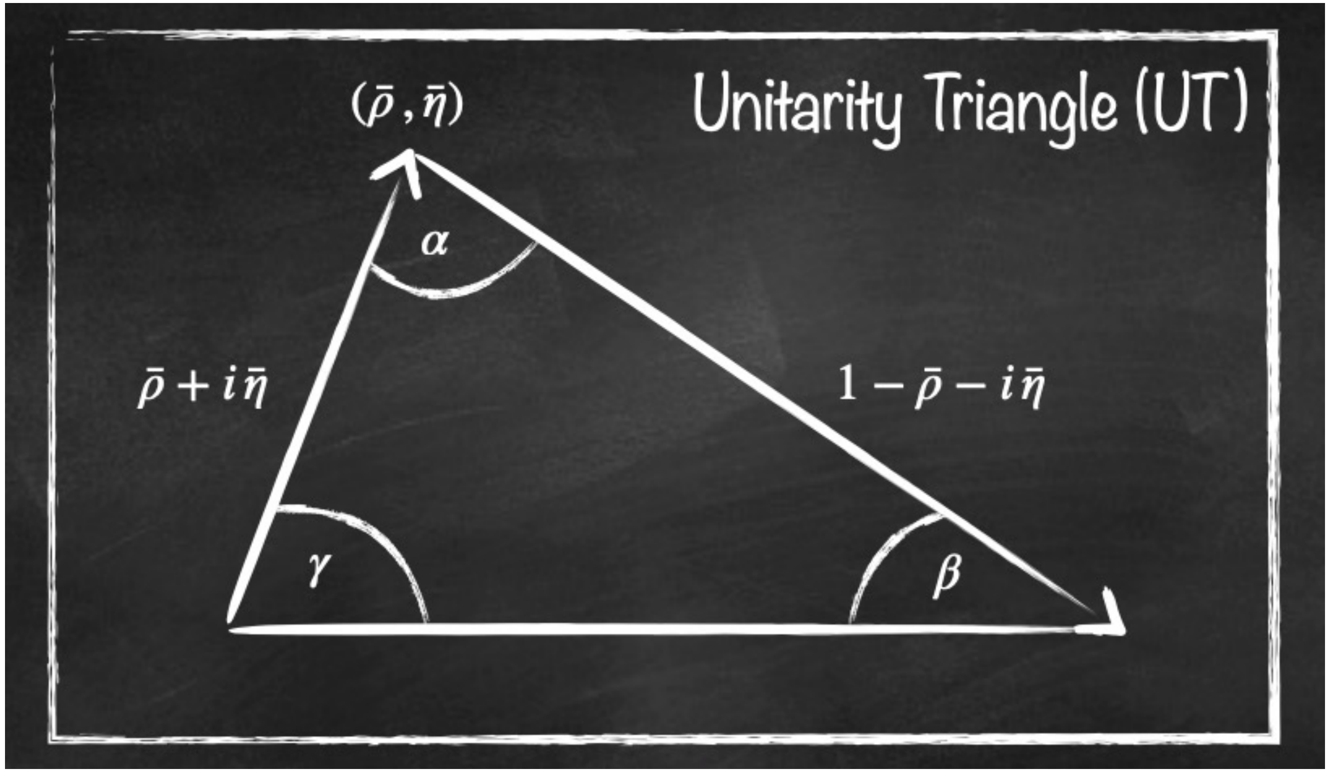

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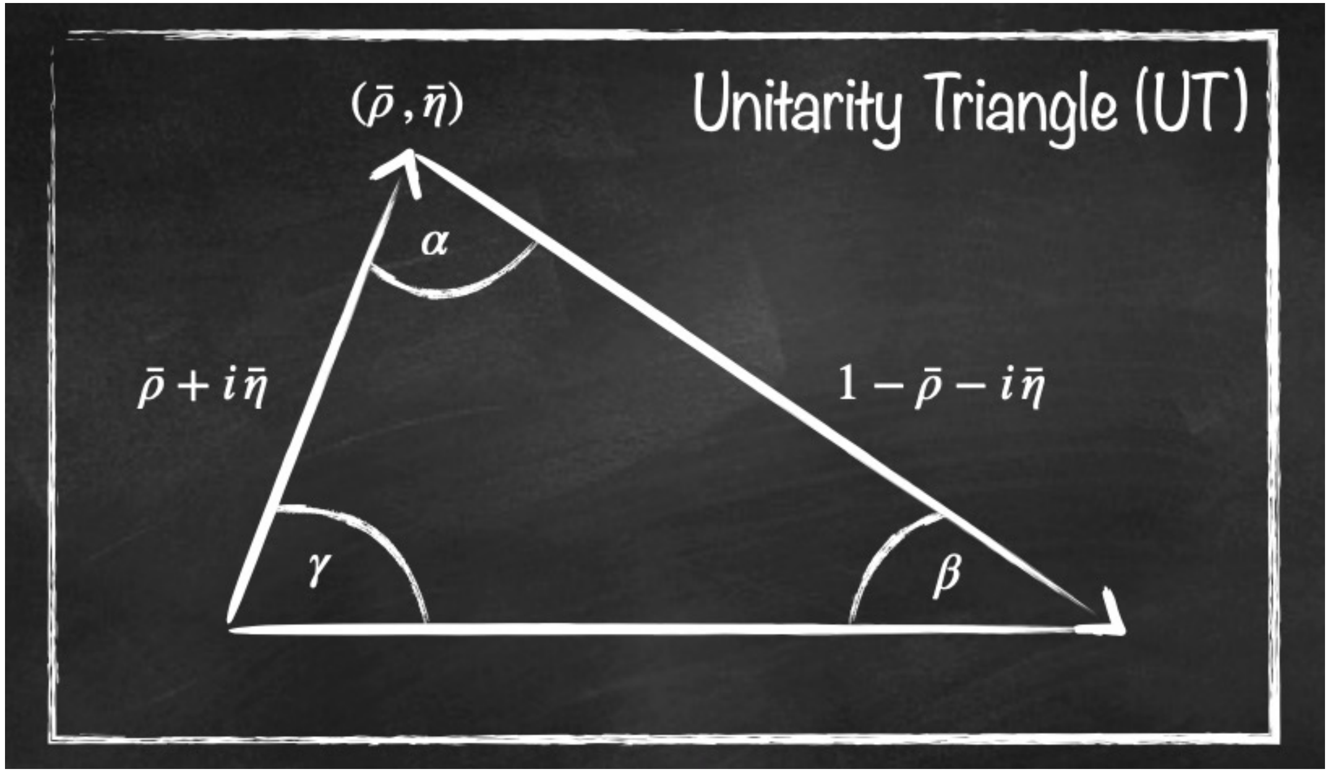

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→ ***Triangle in the complex $(\bar{\rho}, \bar{\eta})$ plane***

KEY INFORMATION: the sides, the angles and the area are physical quantities!

Why doing the Unitarity Triangle Analysis (UTA) ?

Several advantages within the Standard Model (SM) …

1. **it provides the best determination of CKM parameters within a global fit analysis**
2. **it allows to test the consistency of the SM (*i.e. the compatibility of the experimental results with the theoretical calculations*)**
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… and also beyond the Standard Model (BSM) !

1. **it is a model-independent study that provides limits on the *allowed* deviations from the SM**
2. **it allows to obtain bounds on the New Physics (NP) scale**
3. **it is complementary to the search of new particles at multi-TeV colliders**

New inputs for the Summer 2025 UTA

- **HFLAV updated numbers for lifetimes and mass differences**

- **Updated kaon bag parameter $\hat{B}_K$ = 0.7627(60) (new averages of lattice results is arXiv:2411.19861)**

- **Updated V_{ud} = 0.97433(21) due to:**
  - new values of the averages performed by FLAG Collaboration (arXiv:2411.04268)
  - updated exptraction of V_{ud} from from nuclear beta transitions (arXiv:2311.00044v3)

- **Updated values of quark masses (from FLAG Collaboration or from PDG 2025)**

- **Updated V_{ub} and V_{cb} (see next slides)**

- **Updated unitarity triangle angles (see next slides)**

Zoom on V_{cb} and V_{ub}

Latest inputs for V_{cb}:

- **Exclusive value:** V_{cb} = 40.12 (55) x 10^{-3}
  (average of arXiv:2105.08674, 2204.05925, 2310.03680)
- **Inclusive value:** V_{cb} = 41.97 (48) x 10^{-3}
  (arXiv:2310.20324)

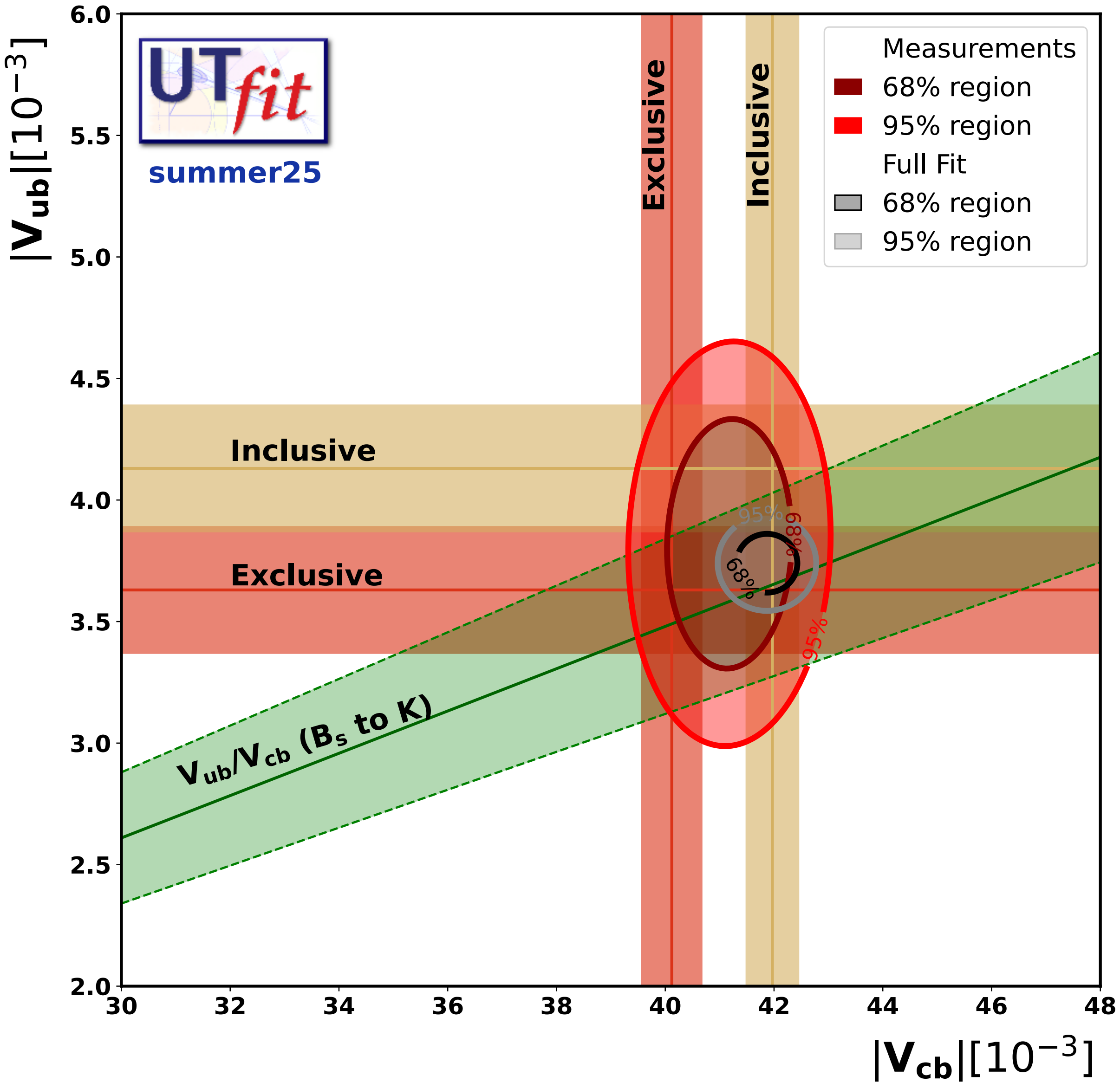
Latest inputs for V_{ub}:

- **Exclusive value:** V_{ub} = 3.63 (26) x 10^{-3}
  (update of arXiv:2202.10285)
- **Inclusive value:** V_{ub} = 4.13 (26) x 10^{-3}
  (PDG 2025)

Latest inputs for V_{ub} / V_{cb} :

V_{ub} / V_{cb} = 0.087 (9) *(arXiv:2310.03680)*

(Λ_b decays excluded, following FLAG guidelines)



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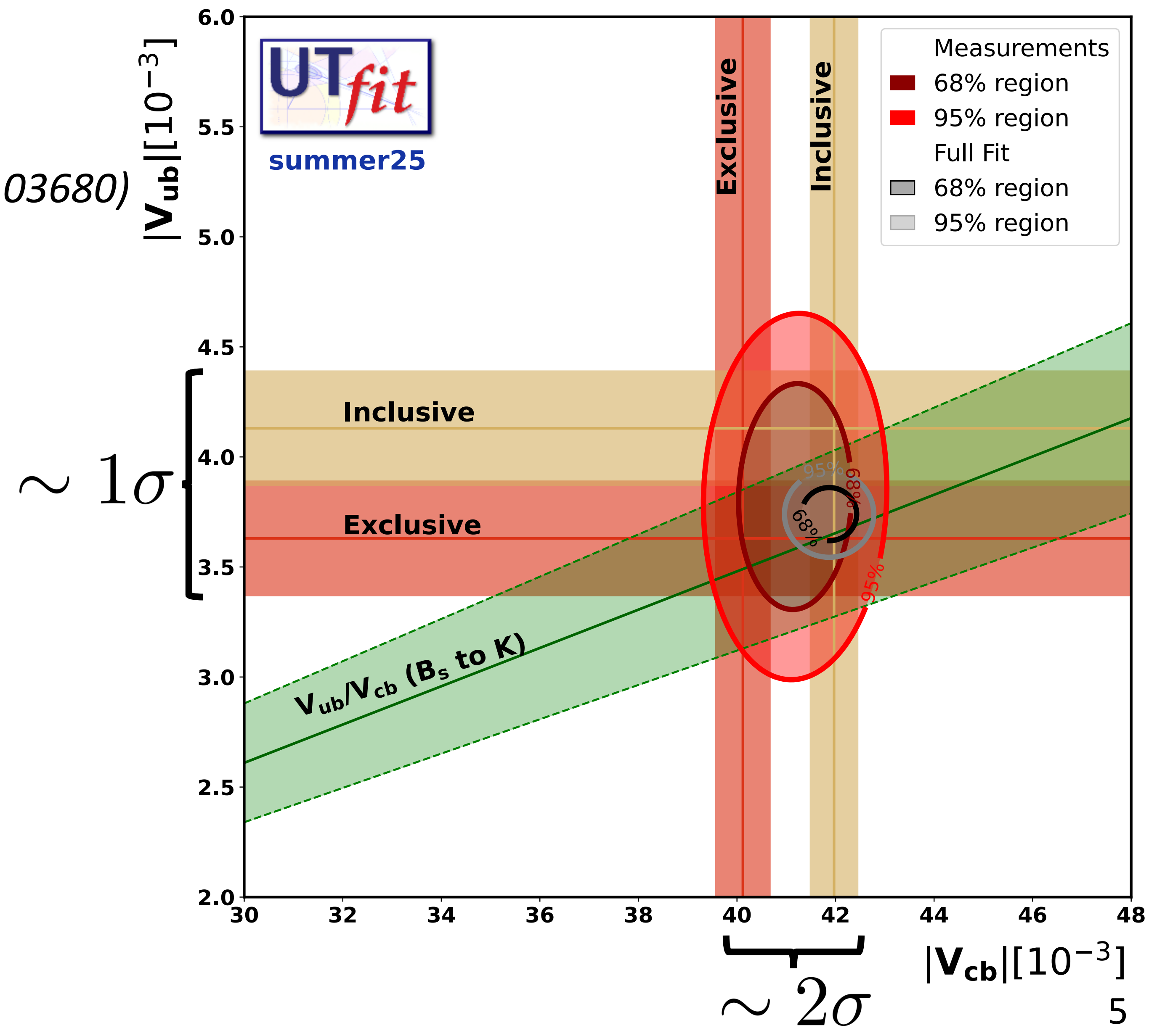


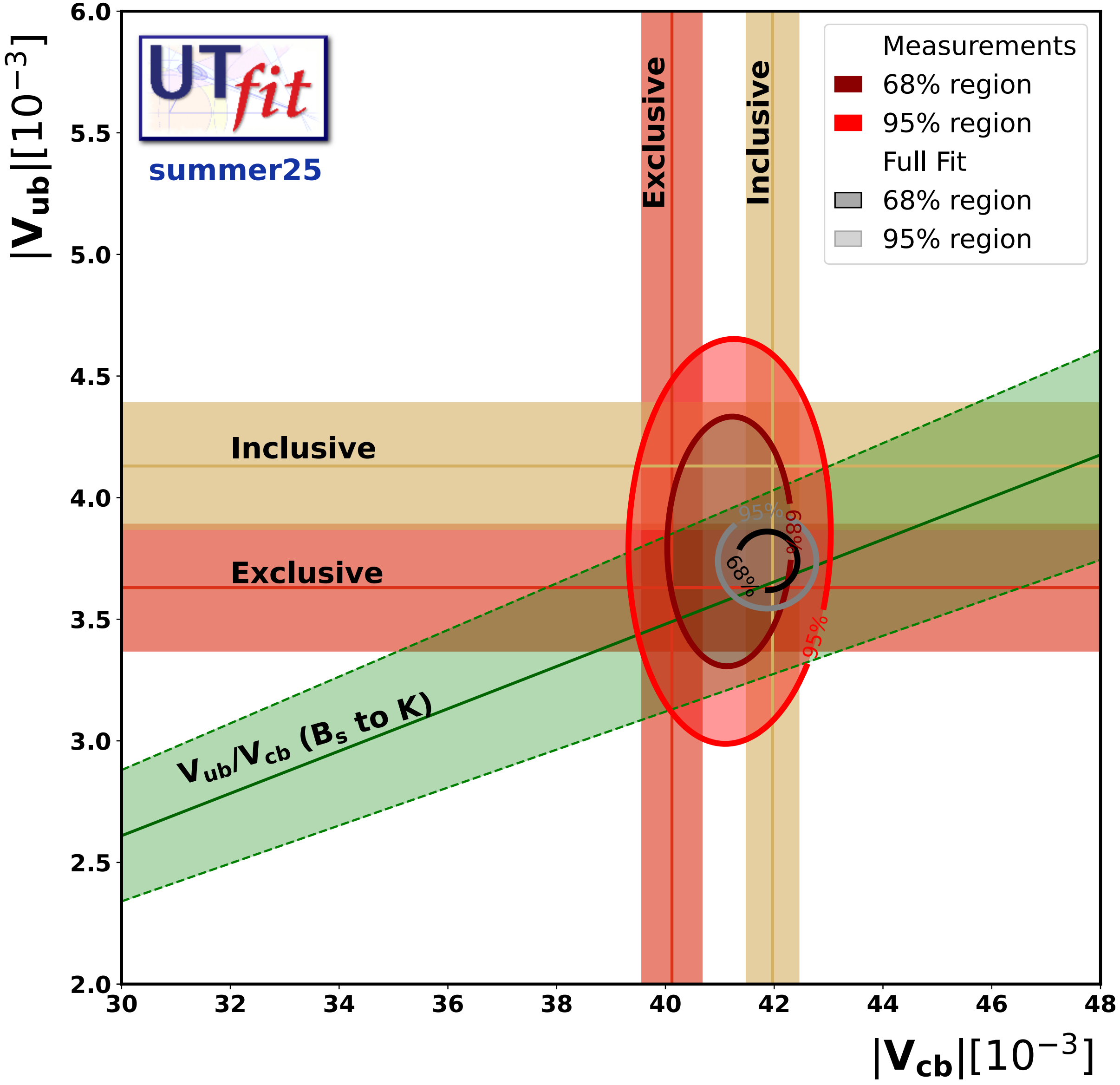
Zoom on V_{cb} and V_{ub}

Inputs to the global fit from averages à la D'Agostini:

- $V_{cb,\ UTfit} = 41.18\ (76) \times 10^{-3}$
- $V_{ub,\ UTfit} = 3.82\ (34) \times 10^{-3}$

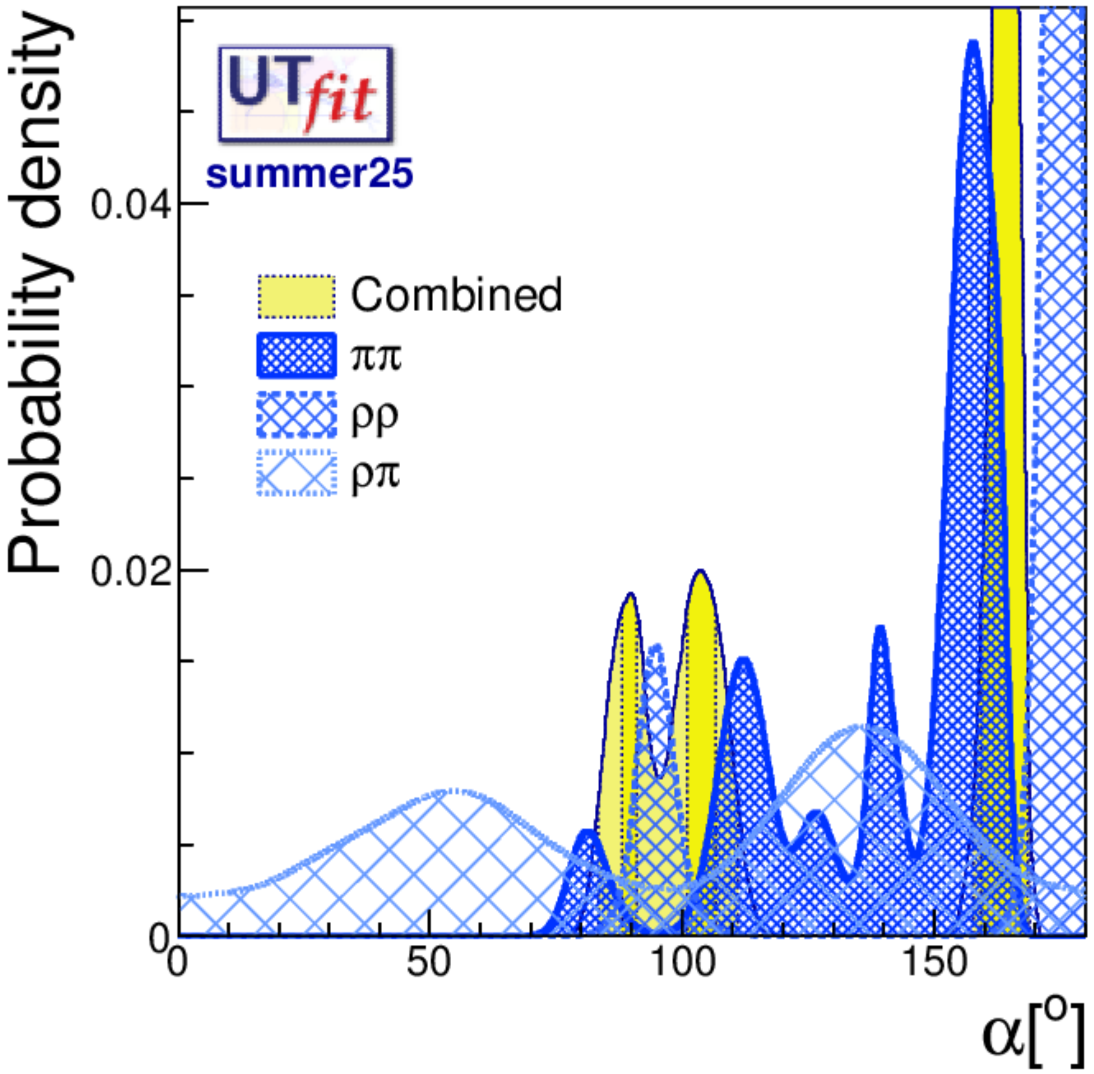
UTfit full fit:

- $V_{cb,\ UTfit} = 41.87\ (37) \times 10^{-3}$
- $V_{ub,\ UTfit} = 3.74\ (8) \times 10^{-3}$



Zoom on ϕ_2/α angle

- **Updated BRs for $\pi^+\pi^-$ or $\pi^+\pi^0$**
- **Updated BRs (and CPV) for $\pi^0\pi^0$**
- **Updated BRs (and CPV) for $\rho^+\rho^-$**



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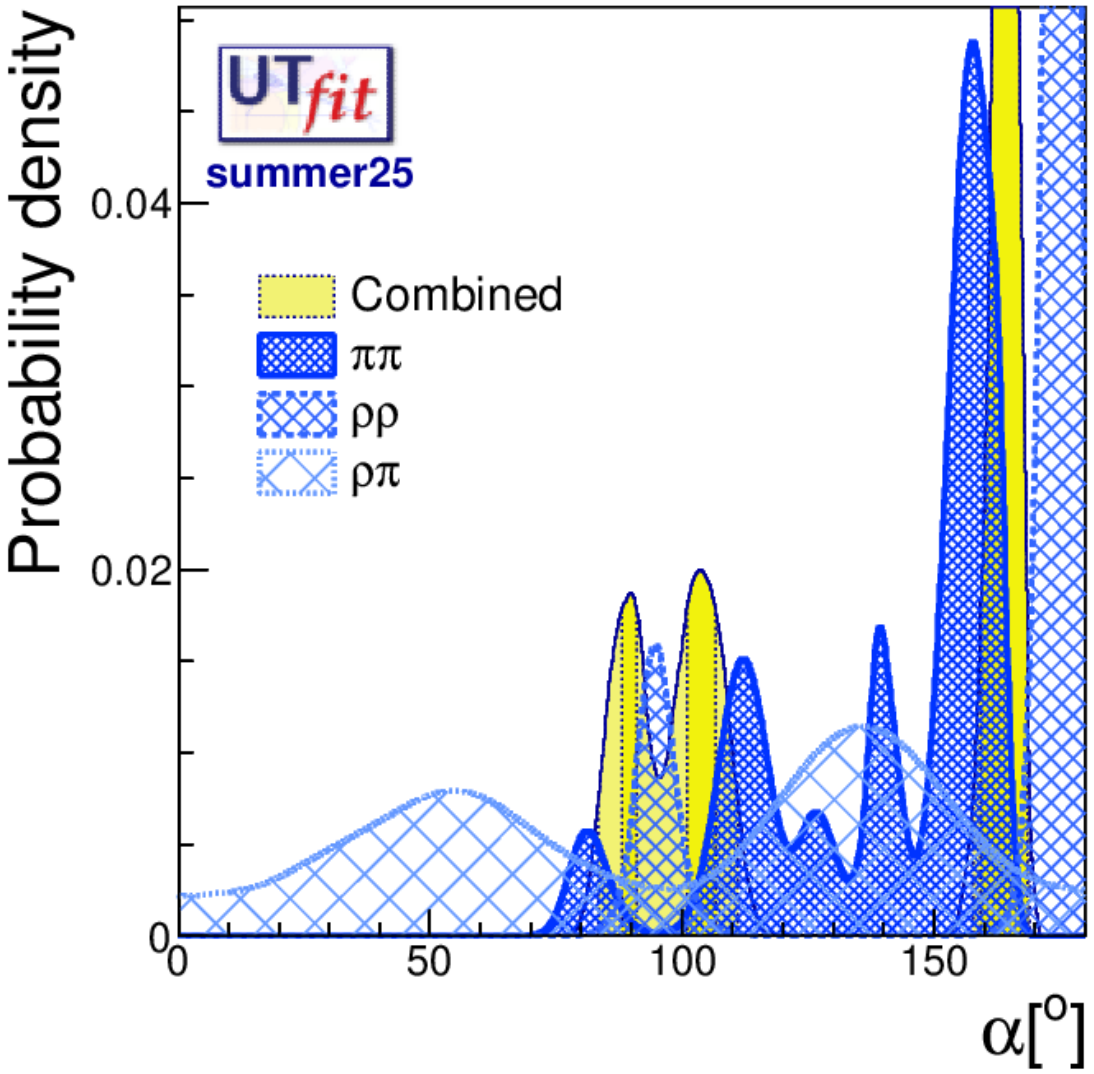
The **bi-modal solution** is explained by the fact that **the value of α preferred by the ππ channels is statistically incompatible with the one preferred by ρρ channels …**

Important issue to be investigated!



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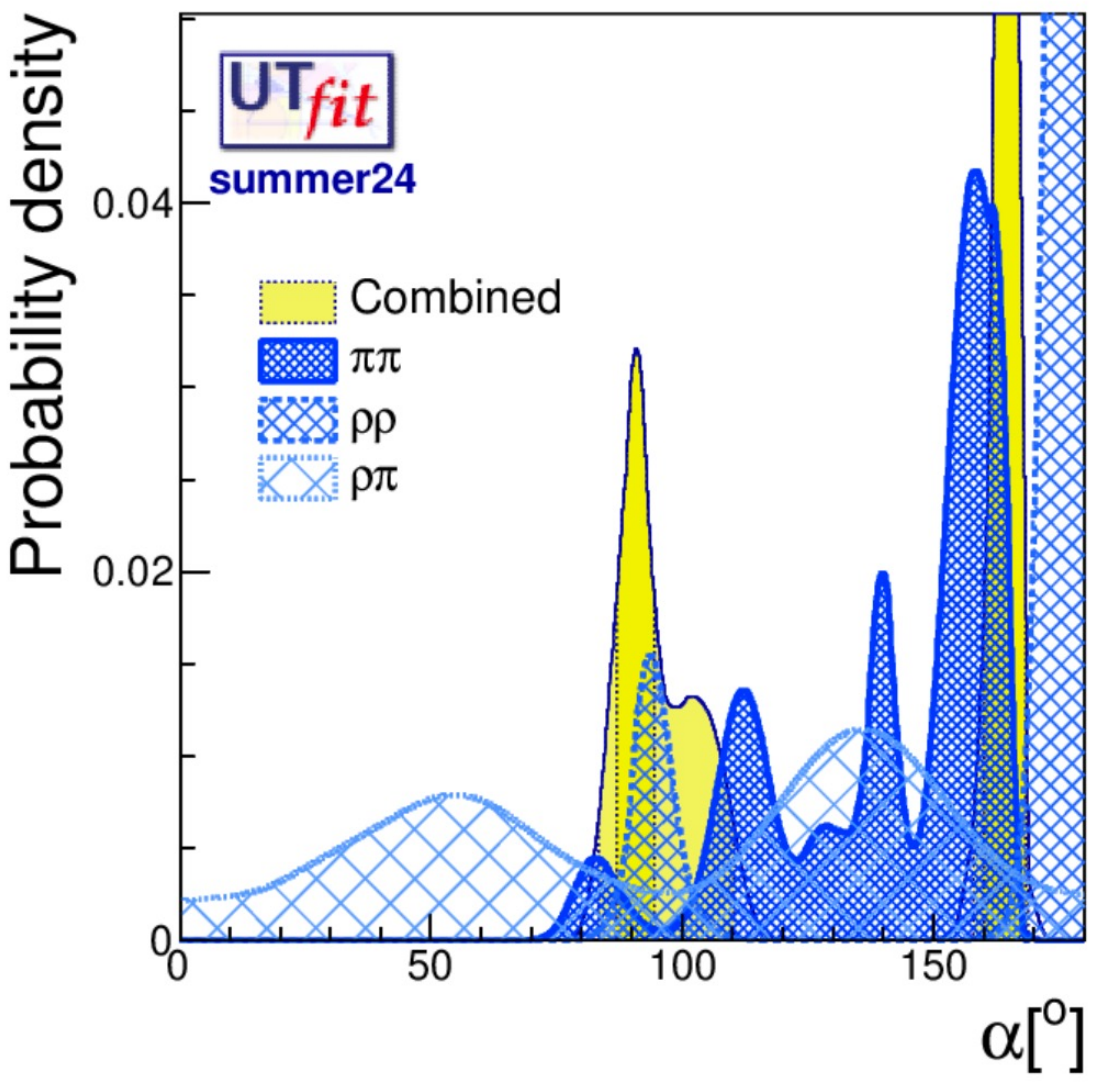
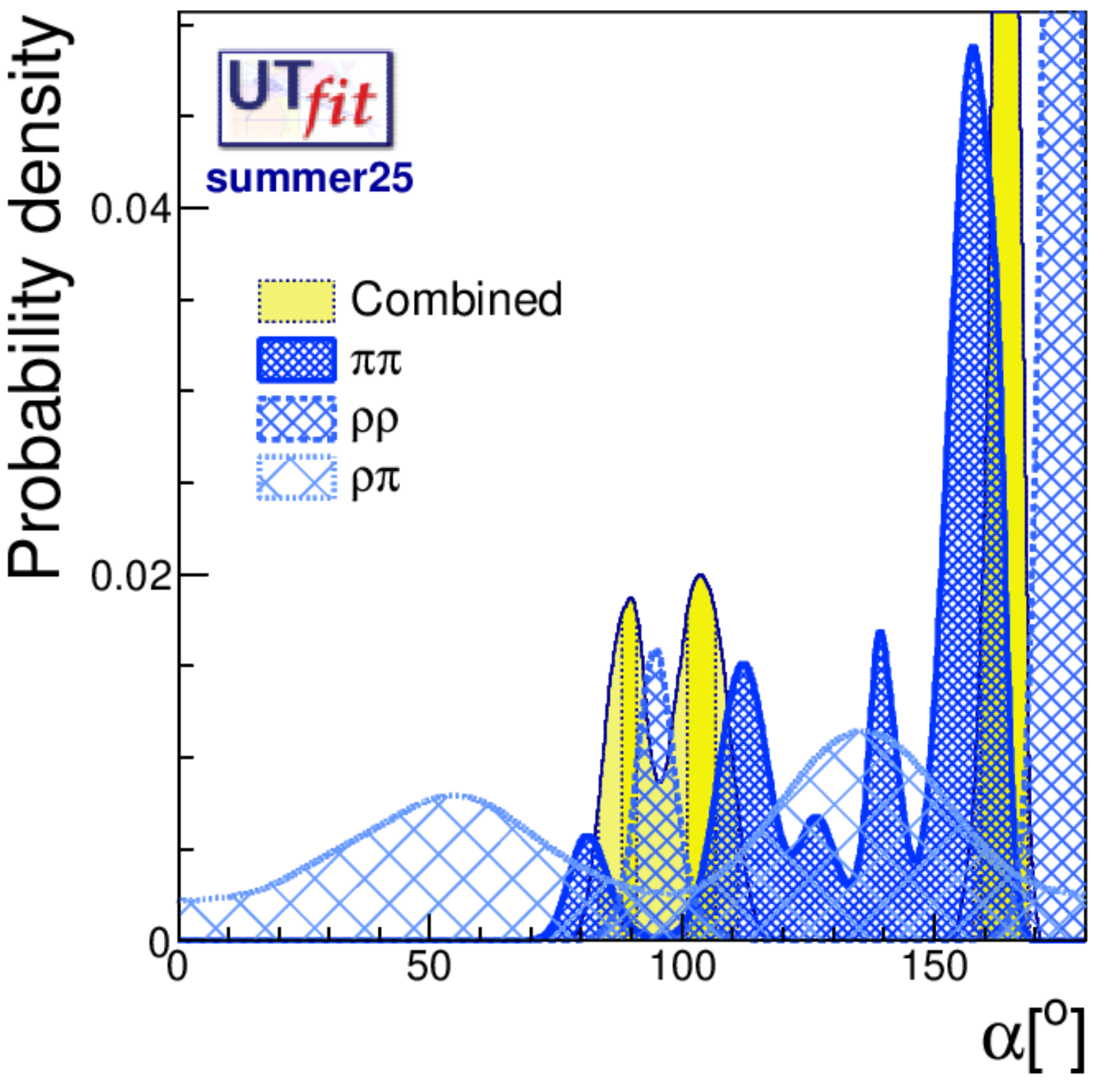


vs.



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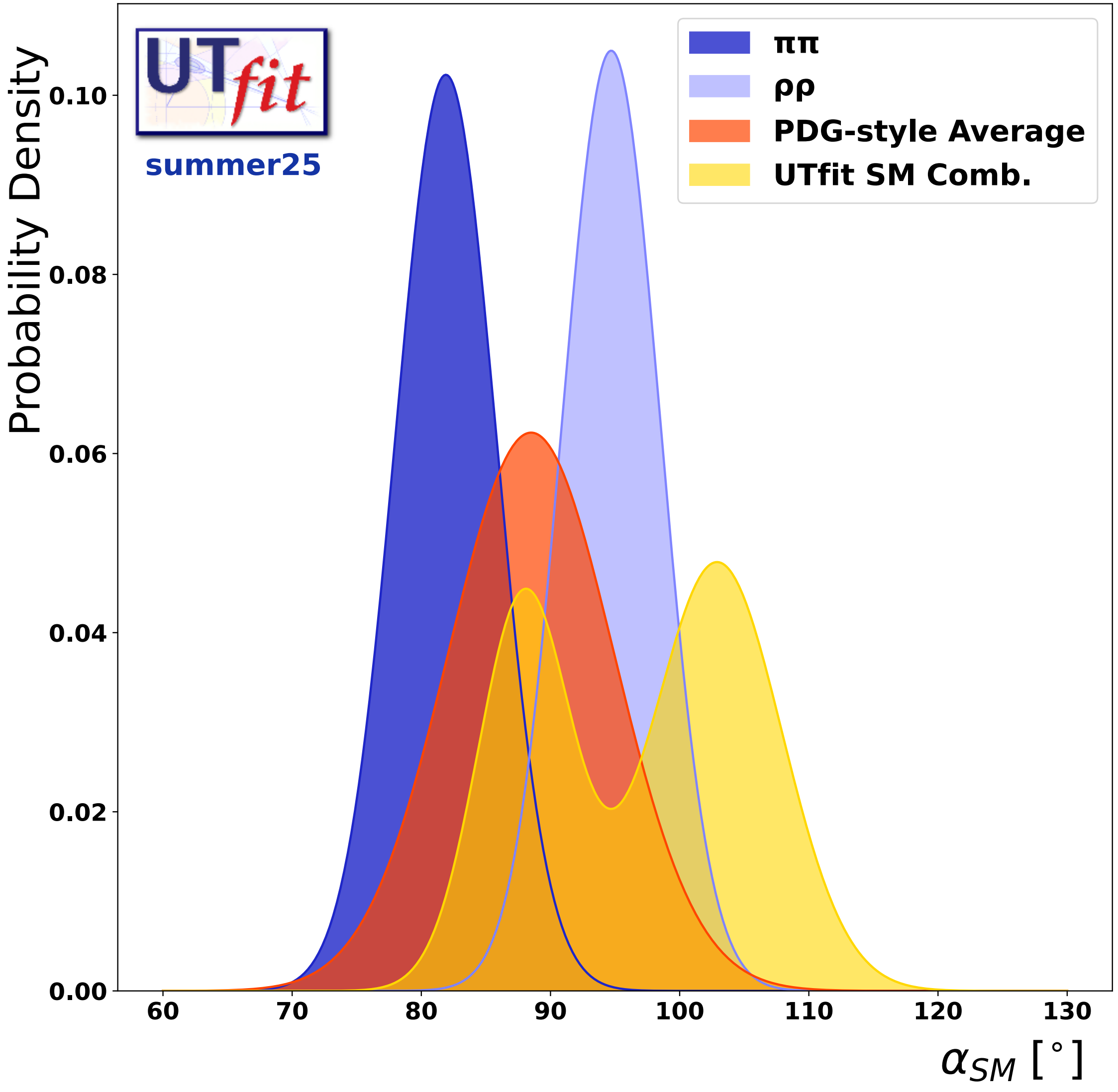
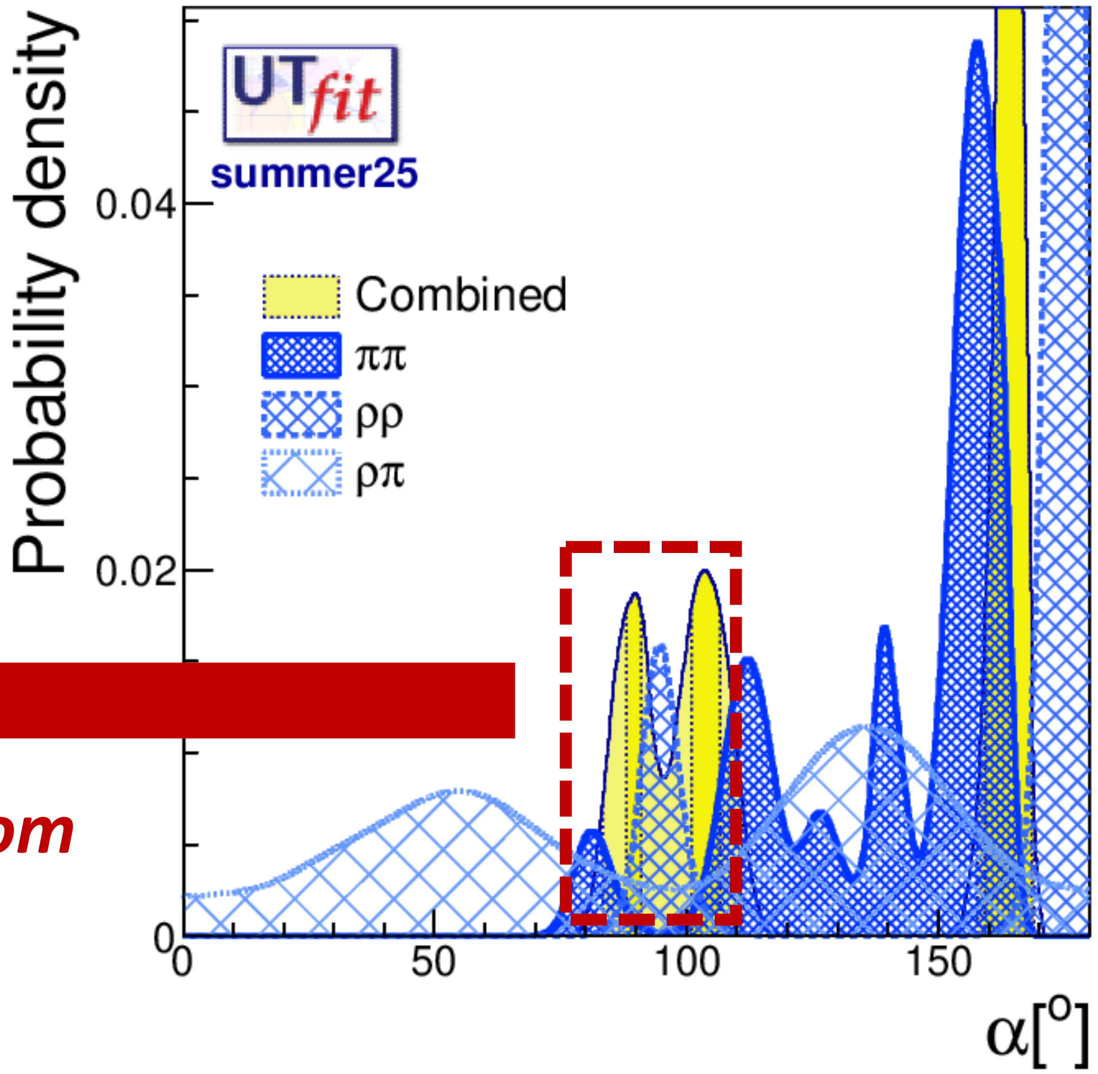


Zoom



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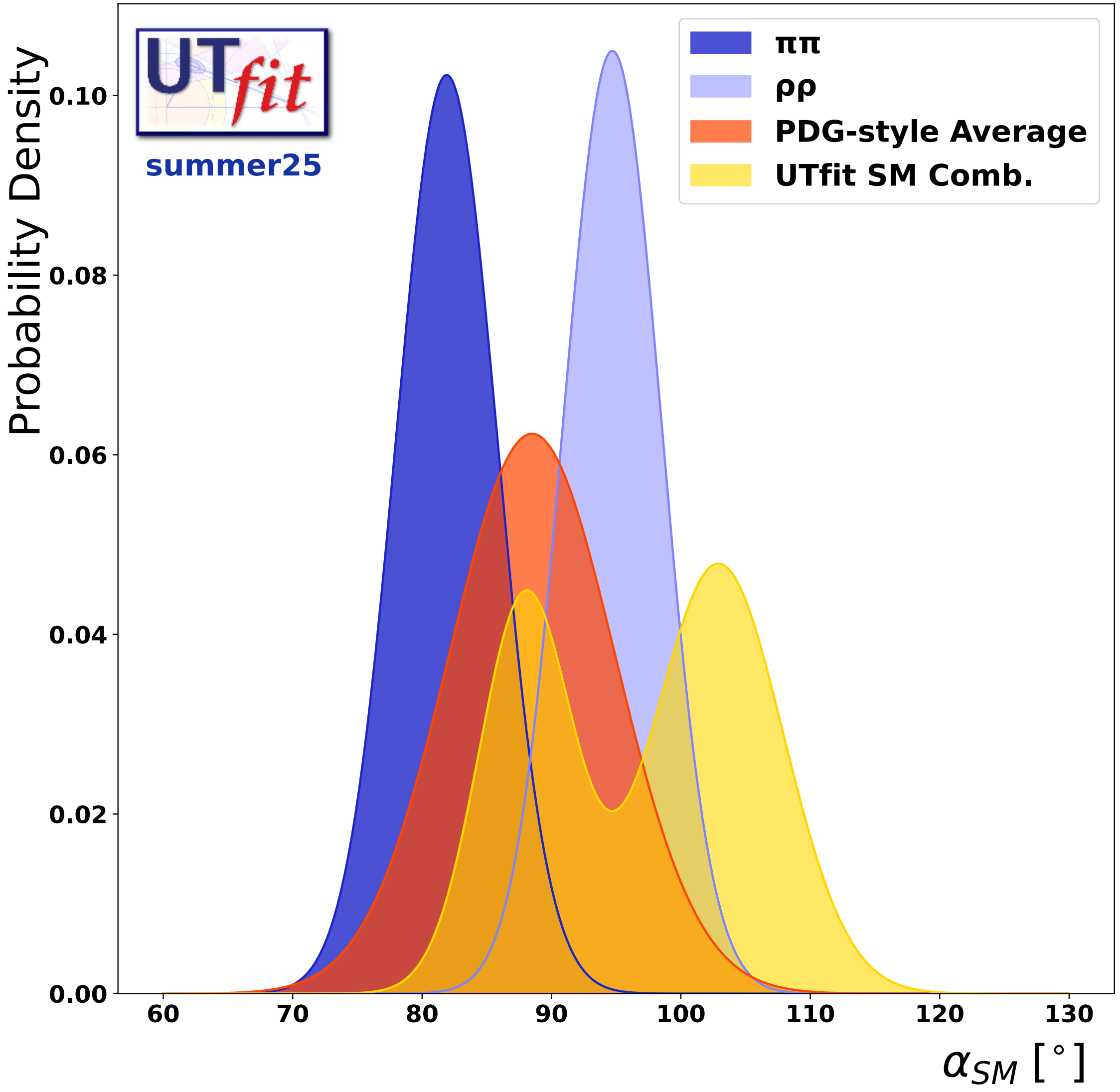


α values from single channels separately:

- $\alpha_{\pi\pi} = (81.9 \pm 3.9)°$
- $\alpha_{\rho\rho} = (94.7 \pm 3.8)°$

α value after combination:

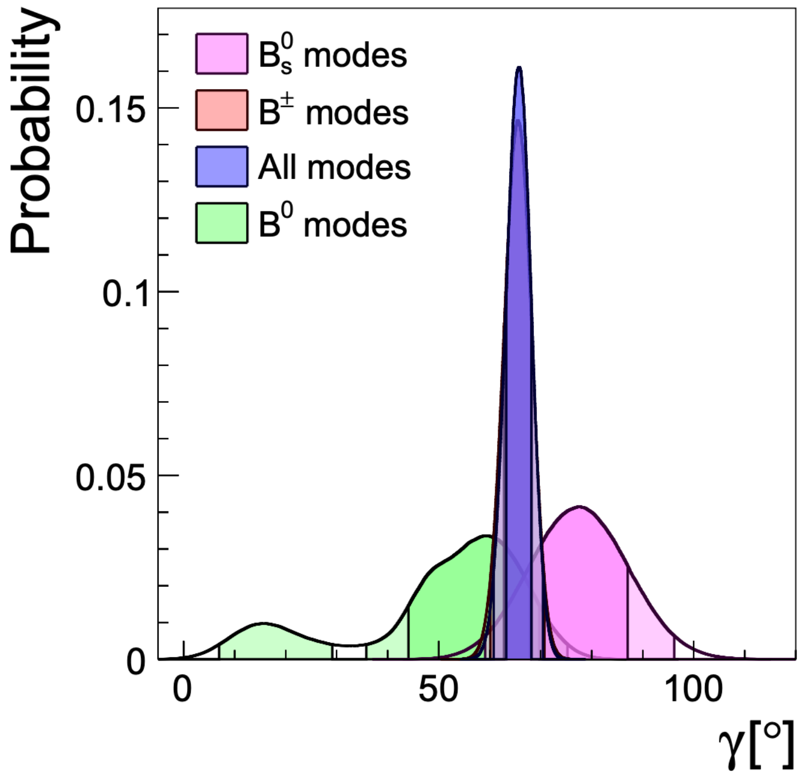
- $\alpha_{comb,peak\ \#1} = (88.0 \pm 3.6)°$
- $\alpha_{comb,peak\ \#2} = (102.9 \pm 5.0)°$

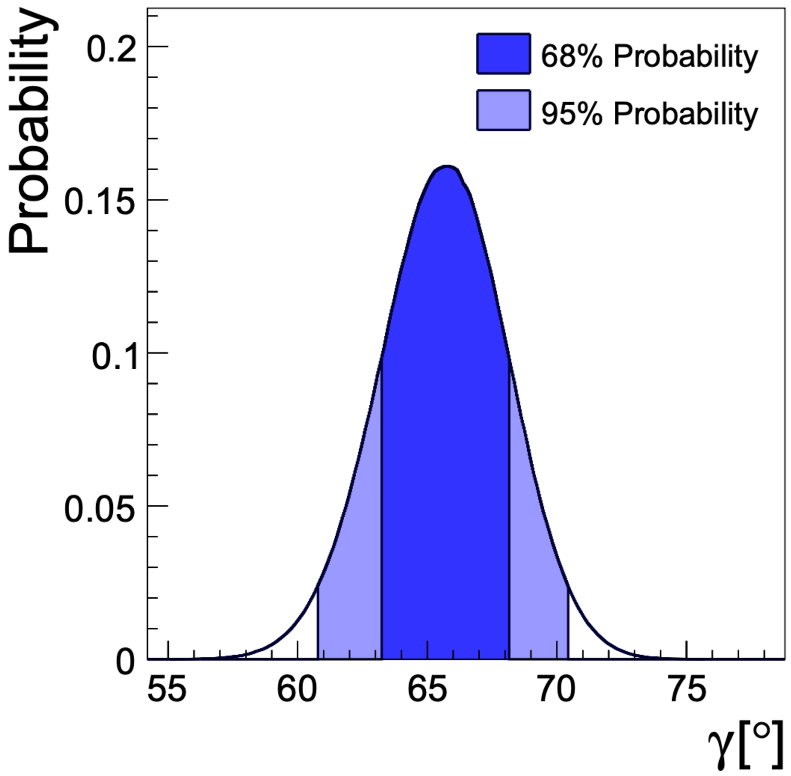
α value after average à la PDG:

- $\alpha_{aver} = (88.5 \pm 6.4)°$

Zoom on ϕ_3/γ angle

Novel analysis in arXiv:2409.06449, which develops a Bayesian analysis of charm and beauty observables, together with neutral D mixing and CP-violating parameters

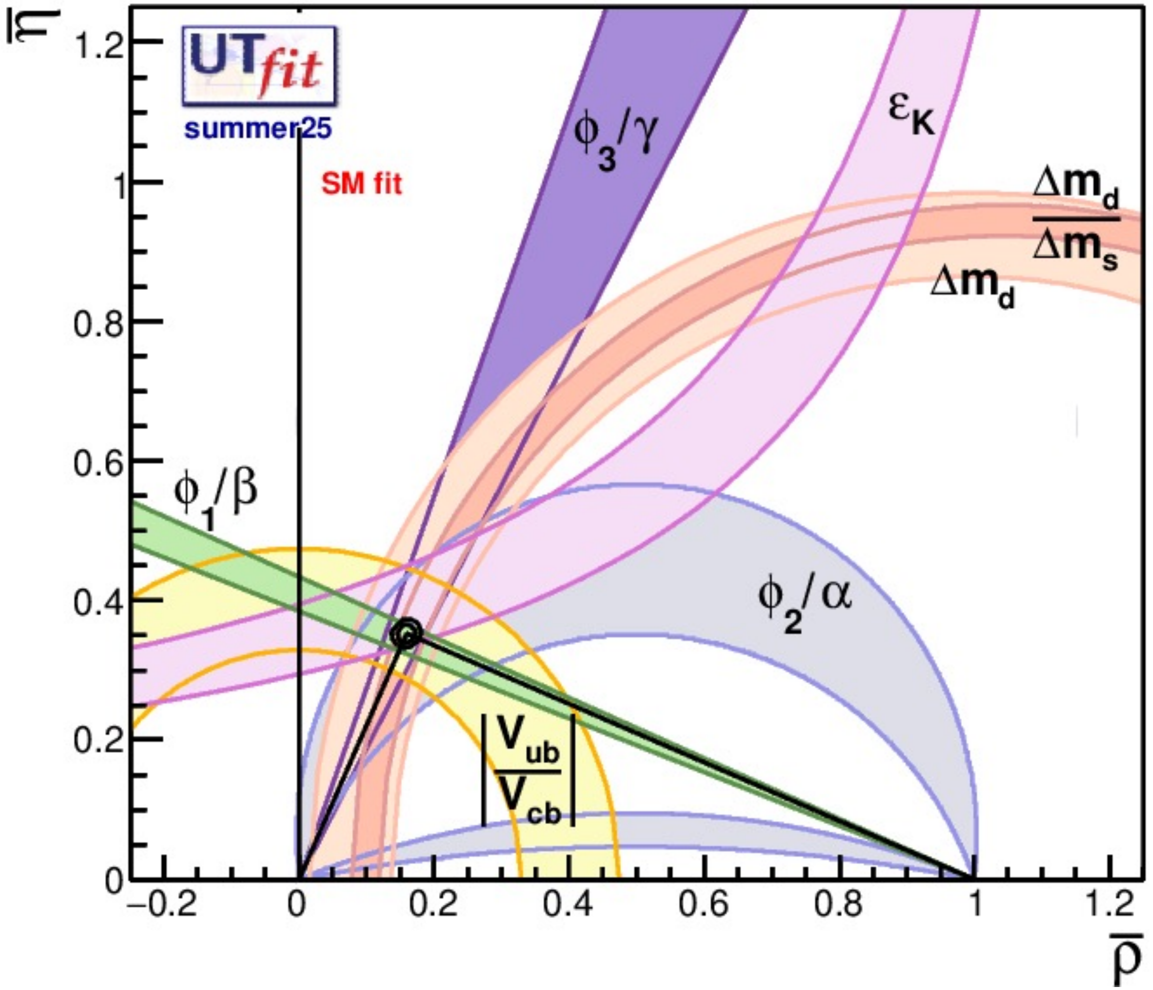




$$\gamma = (65.7 \pm 2.5)^\circ$$

See Roberto di Palma's slides for all the details of this study!

UTA within the SM: results



Example of relations to understand the coloured bands:

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

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

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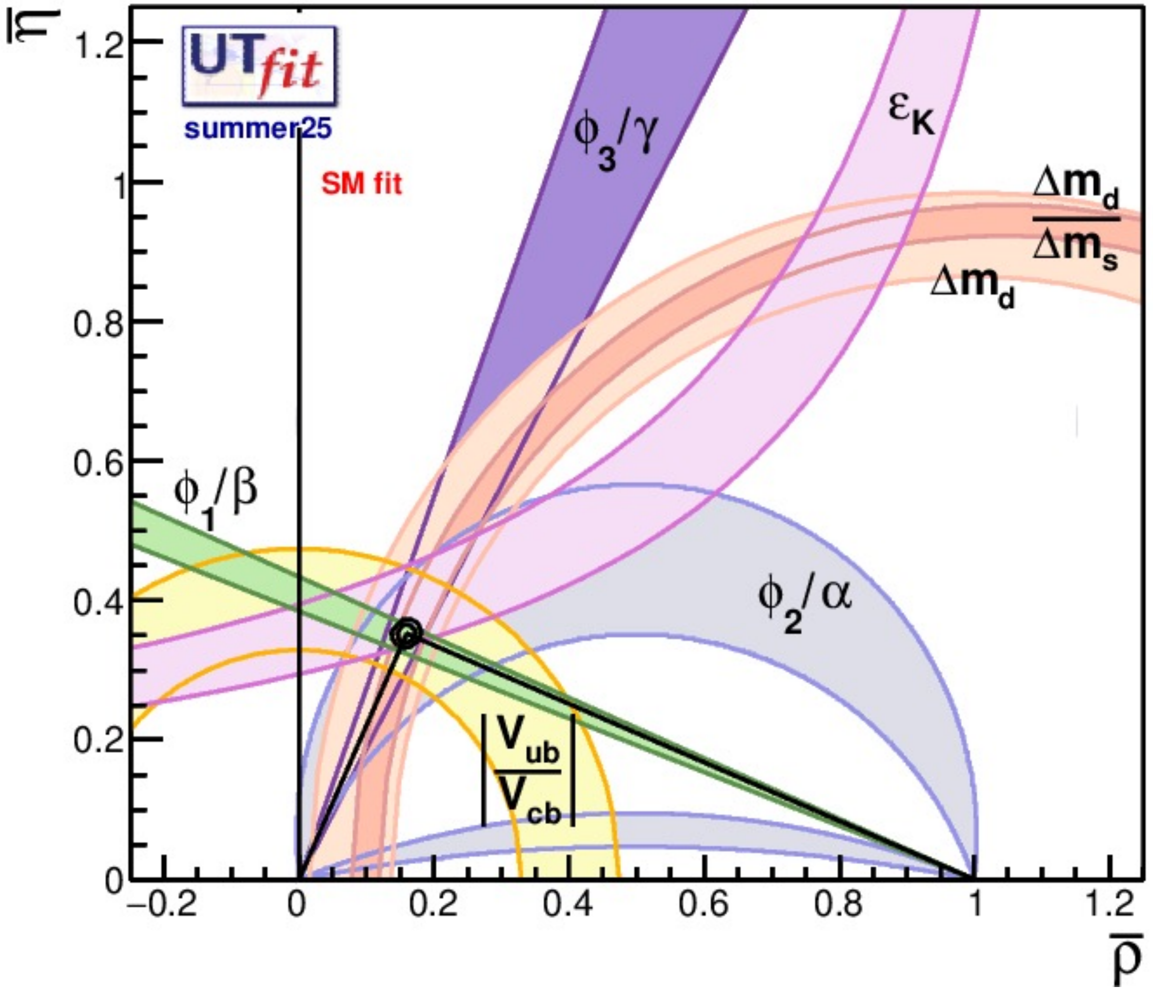

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Fit results:

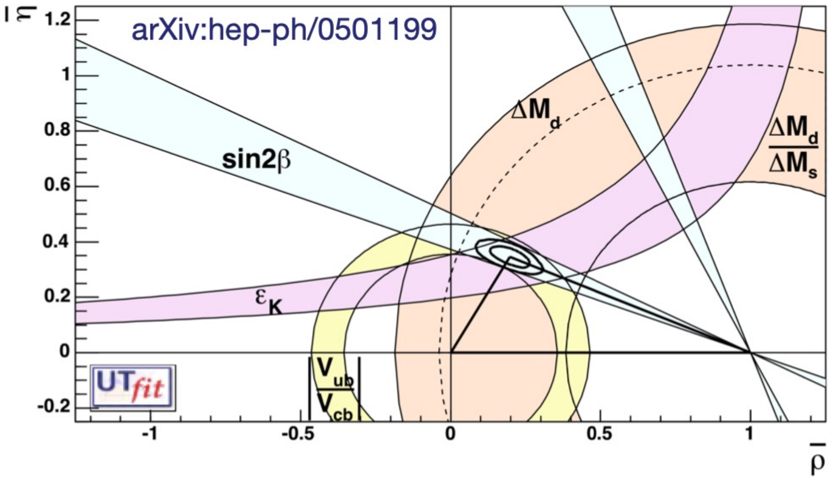
$\bar{\rho}$ = **0.159 ± 0.009**

$\bar{\eta}$ = **0.353 ± 0.008**

λ = **0.2250 ± 0.0006**

A = **0.827 ± 0.008**

Past, present and future of the Unitarity Triangle



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

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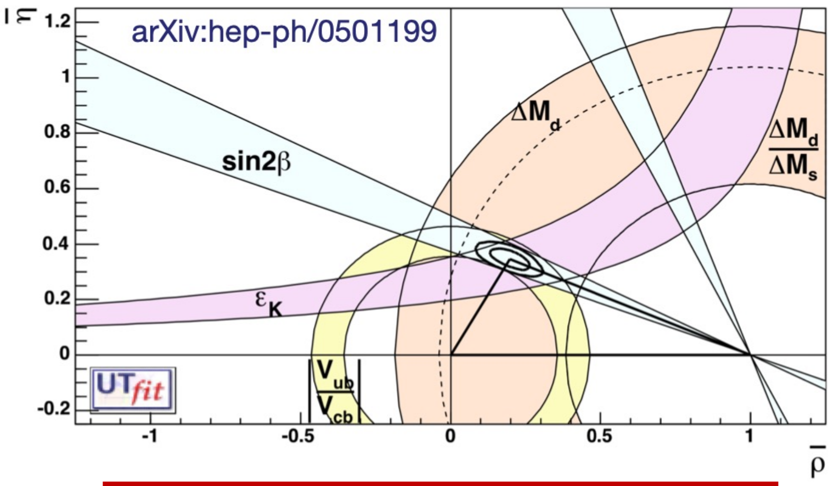

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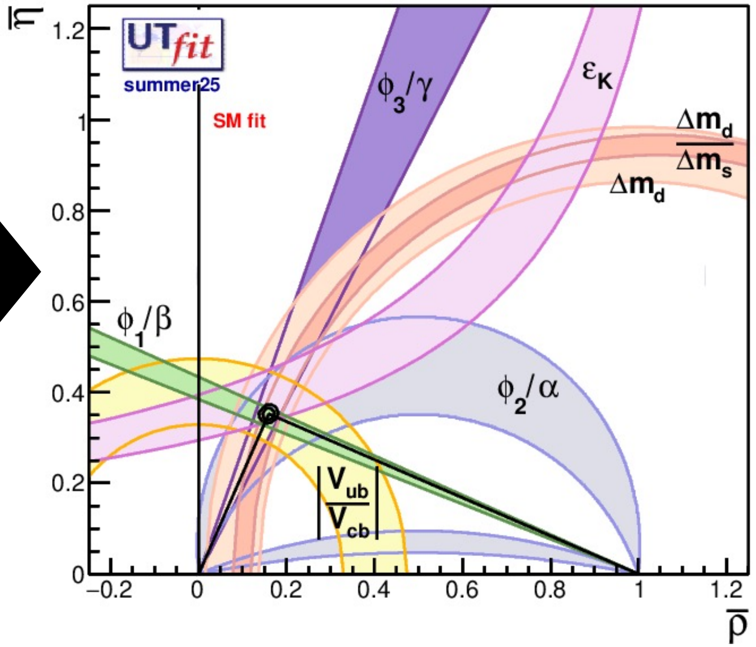

$$\bar{\rho} = 0.159 \pm 0.009 \sim 5.6\%$$
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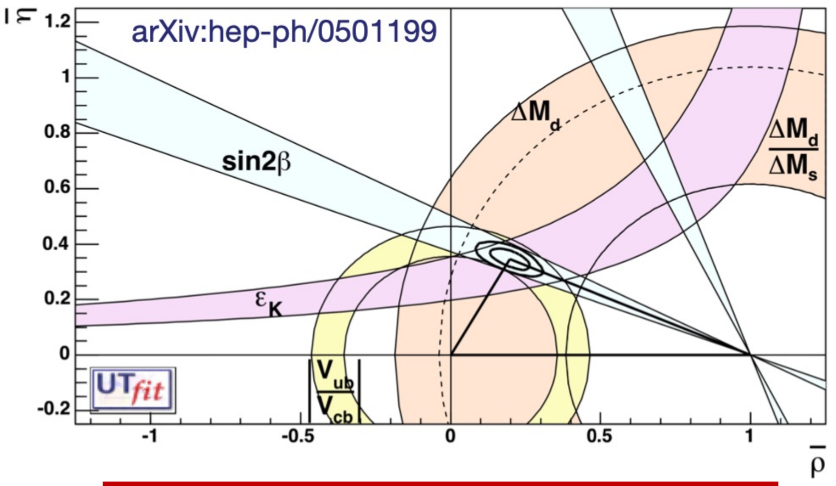

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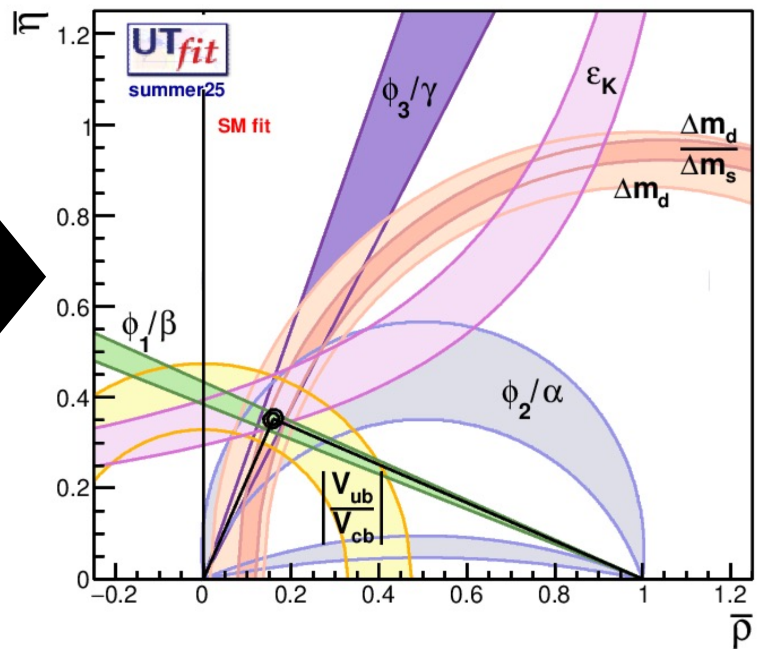

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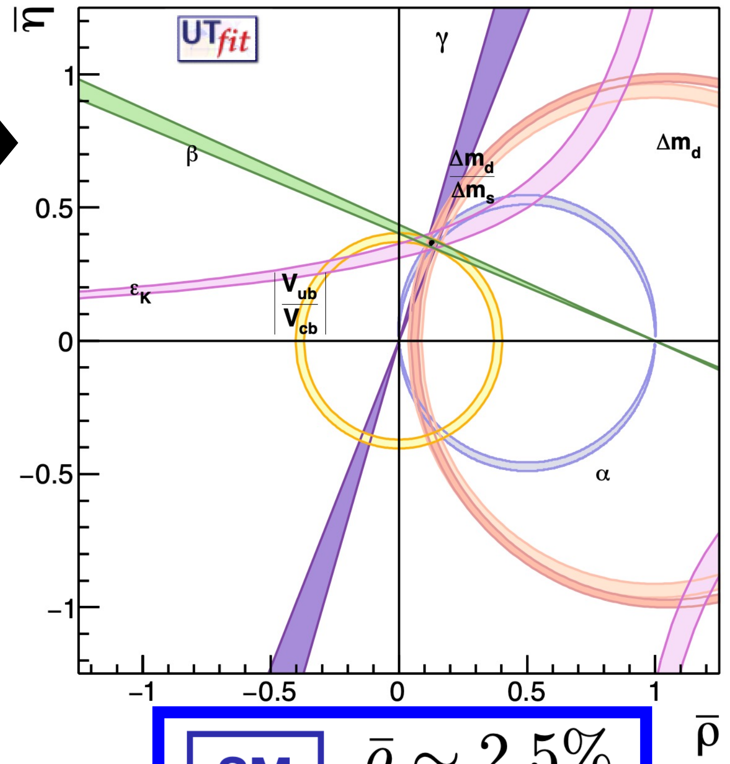
Assumption: 50 ab^{-1} lum. @ Belle II (arXiv:1808.10567)



SM fit

$$\bar{\rho} \sim 2.5\%$$
$$\bar{\eta} \sim 1\%$$

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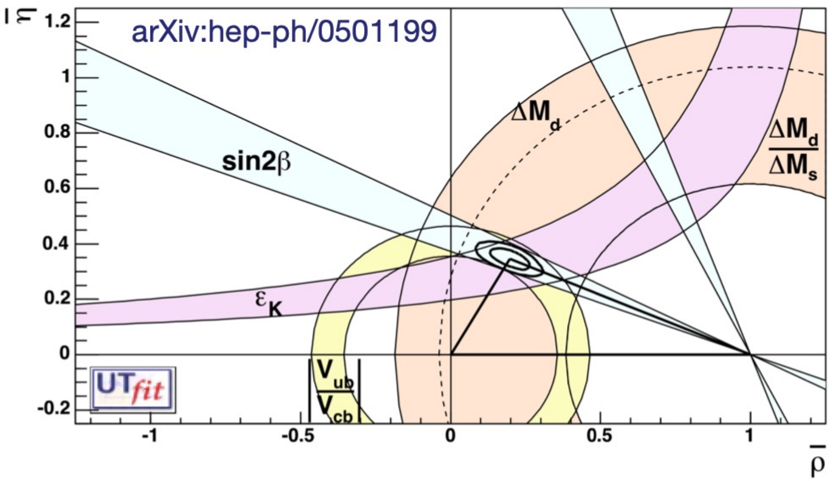

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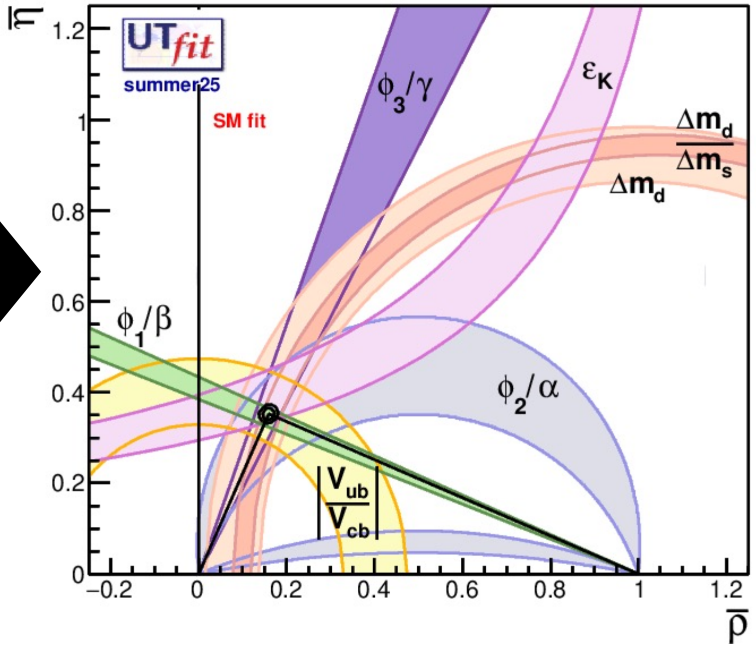

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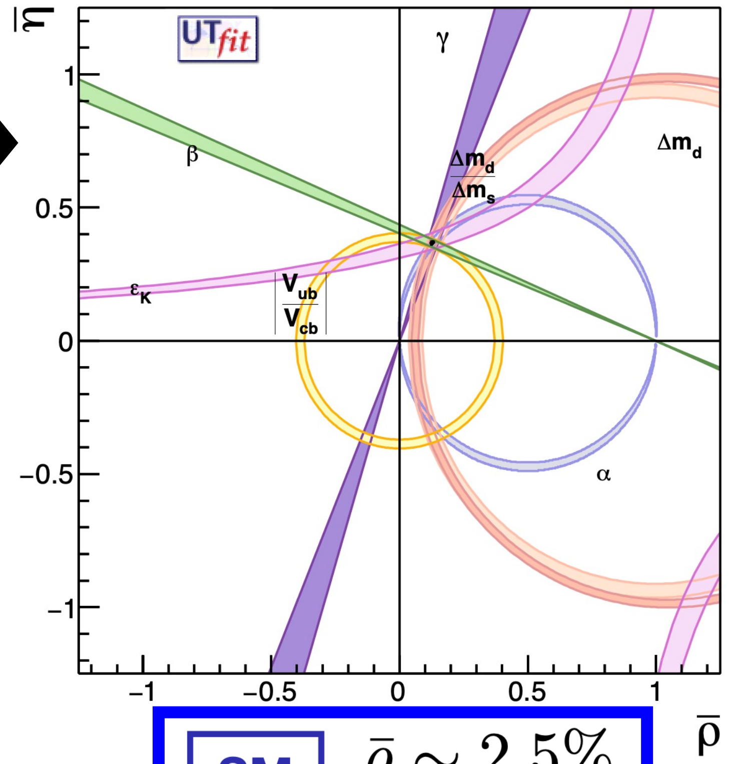

SM fit

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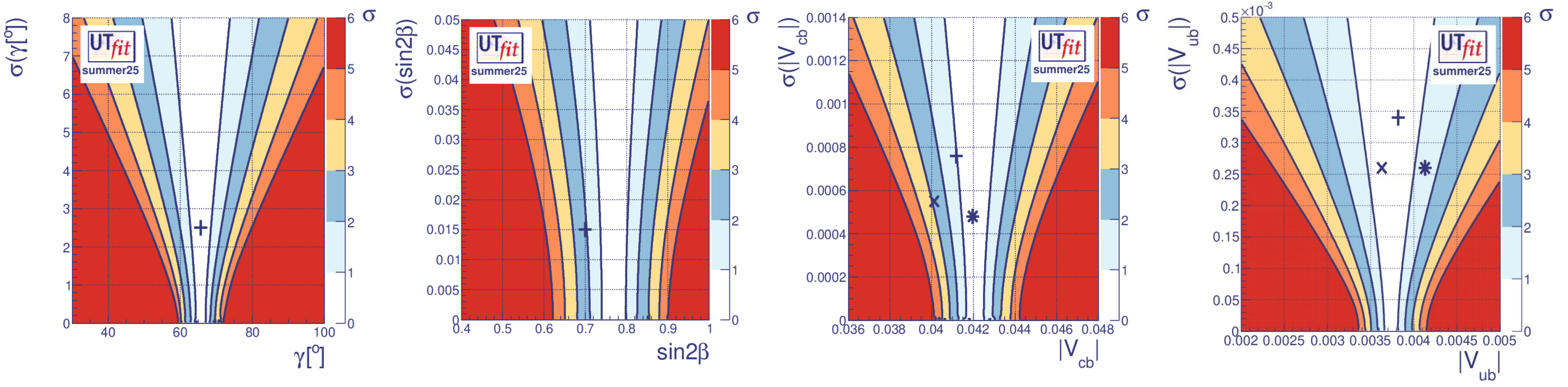
To this end: increasing the precision on both the theoretical and experimental sides is fundamental !

Summary of results for some observables

Observables	Measurement	Prediction	Pull (#σ)
sin2β	0.700 ± 0.015	0.768 ± 0.029	2.08
γ [°]	65.7 ± 2.5	65.7 ± 1.3	~ 0
α [°]	88.5 ± 3.1	91.7 ± 1.4	0.94
$\|V_{cb}\| \times 10^3$	41.18 ± 0.76	42.07 ± 0.42	1.02
$\|V_{cb}\| \times 10^3$ (excl.)	40.12 ± 0.55		2.81
$\|V_{cb}\| \times 10^3$ (incl.)	41.97 ± 0.48		0.15
$\|V_{ub}\| \times 10^3$	3.82 ± 0.34	3.74 ± 0.08	0.22
$\|V_{ub}\| \times 10^3$ (excl.)	3.63 ± 0.26		0.40
$\|V_{ub}\| \times 10^3$ (incl.)	4.13 ± 0.26		1.43
B_K	0.537 ± 0.004	0.595 ± 0.036	1.60

Compatibility plots to verify consistency

A way to "measure" the agreement of a single measurement with the indirect determination from the fit (using the other inputs):



- **Colour code:** agreement between the predicted values and the measurements at better than 1, 2, ...nσ
- The crosses have the **coordinates (x,y)=(central value, error) of the direct measurements**

x = exclusive
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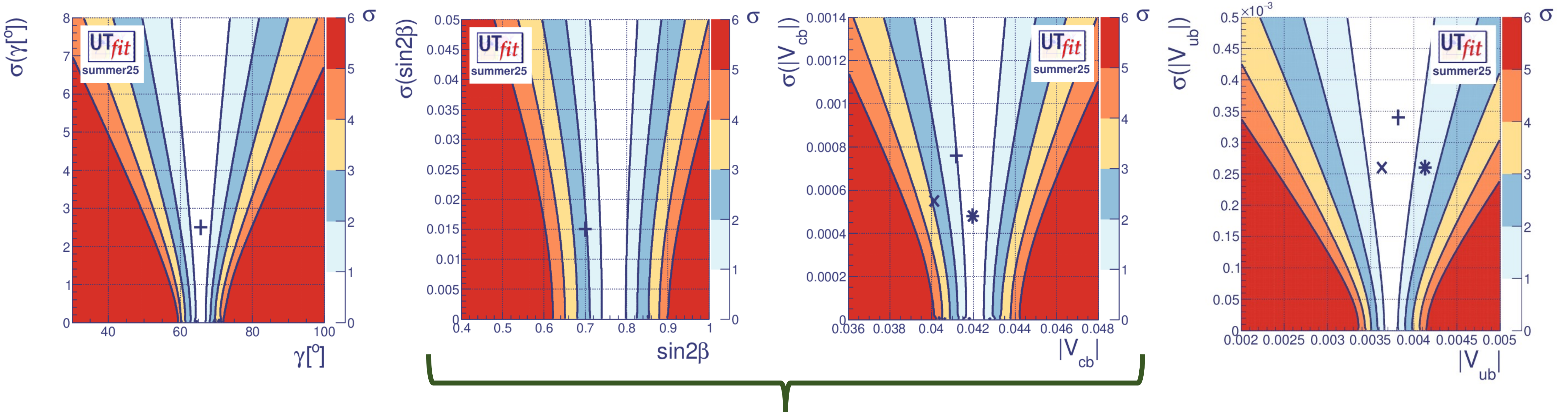

Still some tensions in these two cases

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Unitarity triangle beyond the SM

"Model-independent constraints on ΔF= 2 operators and the scale of New Physics", JHEP '08 [0707.0636]

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

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ΔF=2

$$\begin{aligned}
Q_1 &= (\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Li}\gamma^\mu q_{Lj}), & \tilde{Q}_1 &= (\bar{q}_{Ri}\gamma^\mu q_{Rj})(\bar{q}_{Ri}\gamma^\mu q_{Rj}) \\
Q_2 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Ri} q_{Lj}), & \tilde{Q}_2 &= (\bar{q}_{Li} q_{Rj})(\bar{q}_{Li} q_{Rj}) \\
Q_3 &= (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Ri} q^\alpha_{Lj}), & \tilde{Q}_3 &= (\bar{q}^\alpha_{Li} q^\beta_{Rj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}) \\
Q_4 &= (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Li} q_{Rj}), \\
Q_5 &= (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}).
\end{aligned}$$

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$$Q_4 = (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Li} q_{Rj}),$$

$$Q_5 = (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}).$$

Within the SM, only the operator Q_1 is present

Unitarity triangle beyond the SM

"Model-independent constraints on ΔF= 2 operators and the scale of New Physics", JHEP '08 [0707.0636]

$$\mathcal{H}_{\text{eff}}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq} \qquad C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2}$$

NP couplings
Loop factors
NP scale

ΔF=2

$$Q_1 = (\bar{q}_{Li}\gamma^\mu q_{Lj})(\bar{q}_{Li}\gamma^\mu q_{Lj}), \qquad Q_1' = (\bar{q}_{Ri}\gamma^\mu q_{Rj})(\bar{q}_{Ri}\gamma^\mu q_{Rj})$$
$$Q_2 = (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Ri} q_{Lj}), \qquad Q_2' = (\bar{q}_{Li} q_{Rj})(\bar{q}_{Li} q_{Rj})$$
$$Q_3 = (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Ri} q^\alpha_{Lj}), \qquad Q_3' = (\bar{q}^\alpha_{Li} q^\beta_{Rj})(\bar{q}^\beta_{Li} q^\alpha_{Rj})$$
$$Q_4 = (\bar{q}_{Ri} q_{Lj})(\bar{q}_{Li} q_{Rj}),$$
$$Q_5 = (\bar{q}^\alpha_{Ri} q^\beta_{Lj})(\bar{q}^\beta_{Li} q^\alpha_{Rj}).$$

Within the SM, only the operator Q_1 is present

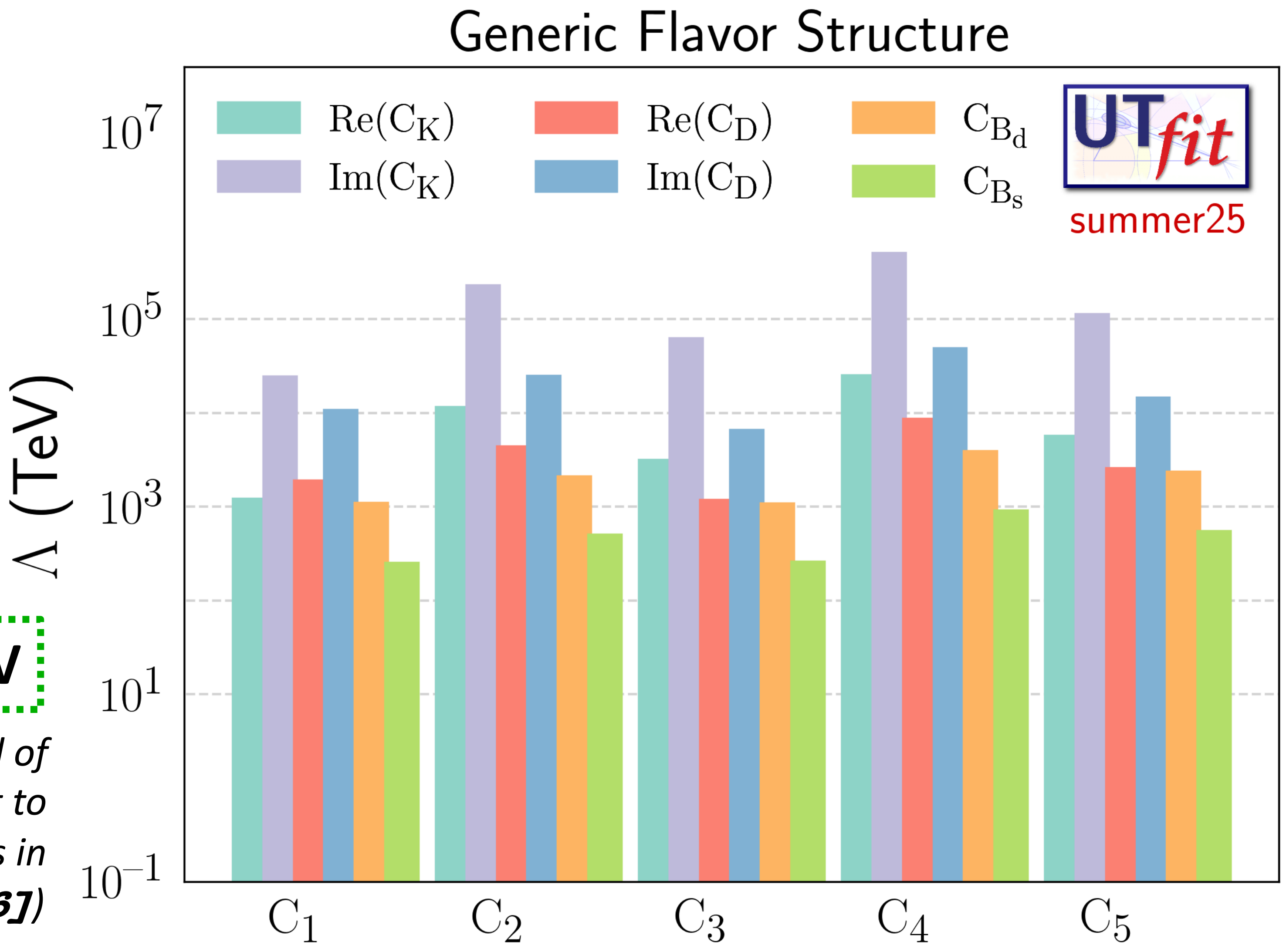
Unitarity triangle beyond the SM

Generic:
$C(\Lambda) = \alpha/\Lambda^2$,
$F_i \sim 1$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP

$\Lambda > 4.9 \times 10^5$ TeV

*(the bound has increased of a factor of 2 with respect to the first UTfit NP analysis in **JHEP ' 08 [0707.0636]**)*



for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

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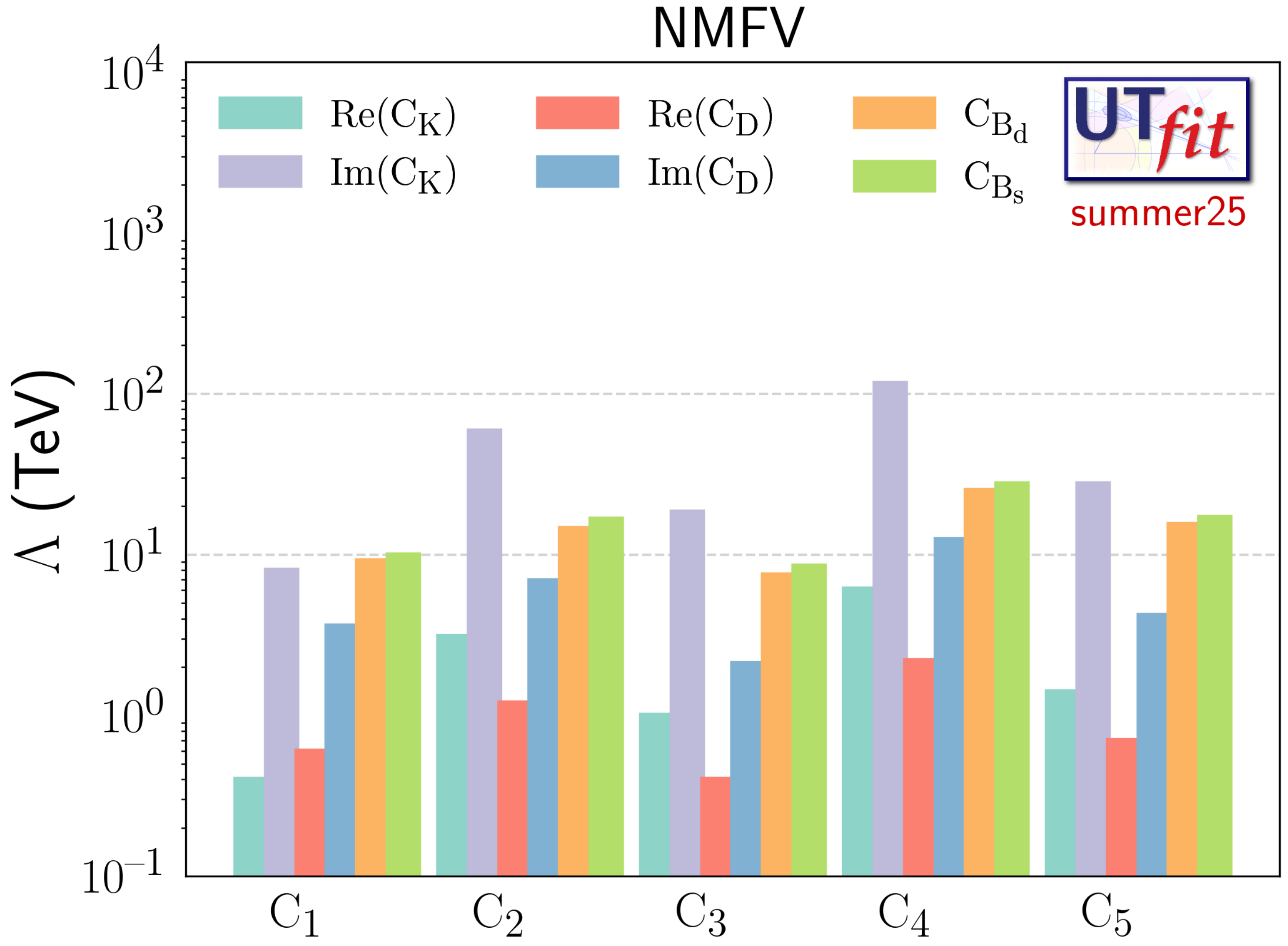

NMFV:
$C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, $F_i \sim |F_{SM}|$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP

$\Lambda > 1.5 \times 10^2$ TeV

*(the bound has increased of a factor of 2.5 with respect to the first UTfit NP analysis in **JHEP '08 [0707.0636]**)*

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

Conclusions

The Summer 2025 update of the Unitarity Triangle within the SM shows that:

- **there is an overall consistency of the SM fit**
- **a precision of 5.6% (2.2%) has been reached on** $\bar{\rho}$ **(** $\bar{\eta}$ **)**

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Some incompatibilities within the SM have to be better understood…

→ B → $\pi\pi$ vs. B → ρρ for the determination of α

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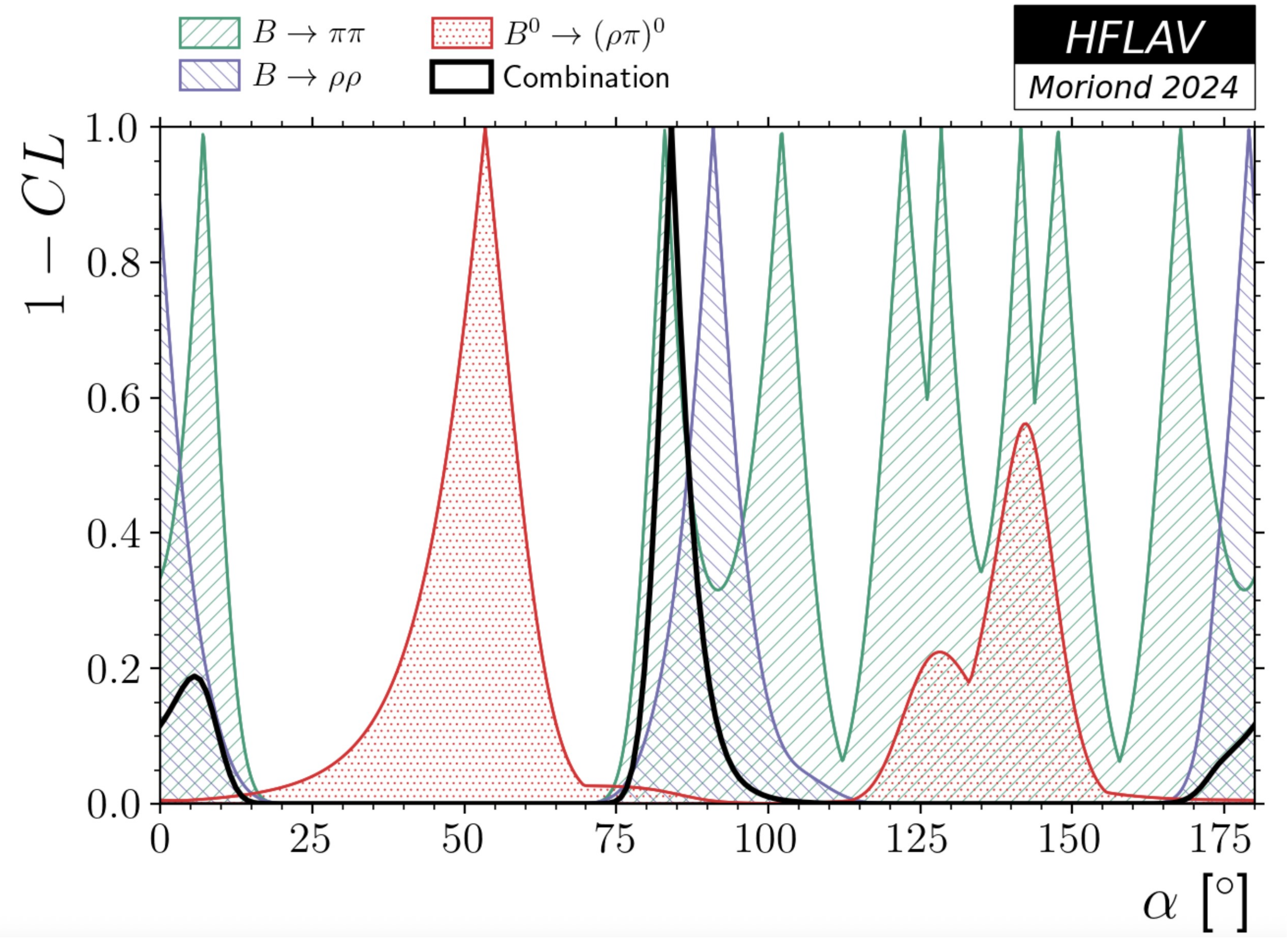
Beyond the SM, the Unitarity Triangle is complementary to the search of new particles at colliders working at multi-TeV energies! By providing a generic parameterization of New Physics contributions in ΔF=2 processes, we find the following lower limits on the scale of New Physics:

- **$\Lambda > 4.9 \times 10^5$ TeV for New Physics with a generic flavour structure**
- **$\Lambda > 1.5 \times 10^2$ TeV for a Next-to-Minimal-Flavour violation scenario**

THANKS FOR YOUR ATTENTION !

More on ϕ_2/α angle



https://hflav-eos.web.cern.ch/hflav-eos/triangle/latest/plots/alpha/alpha_wa_hflav_pub.png

More on ϕ_2/α angle

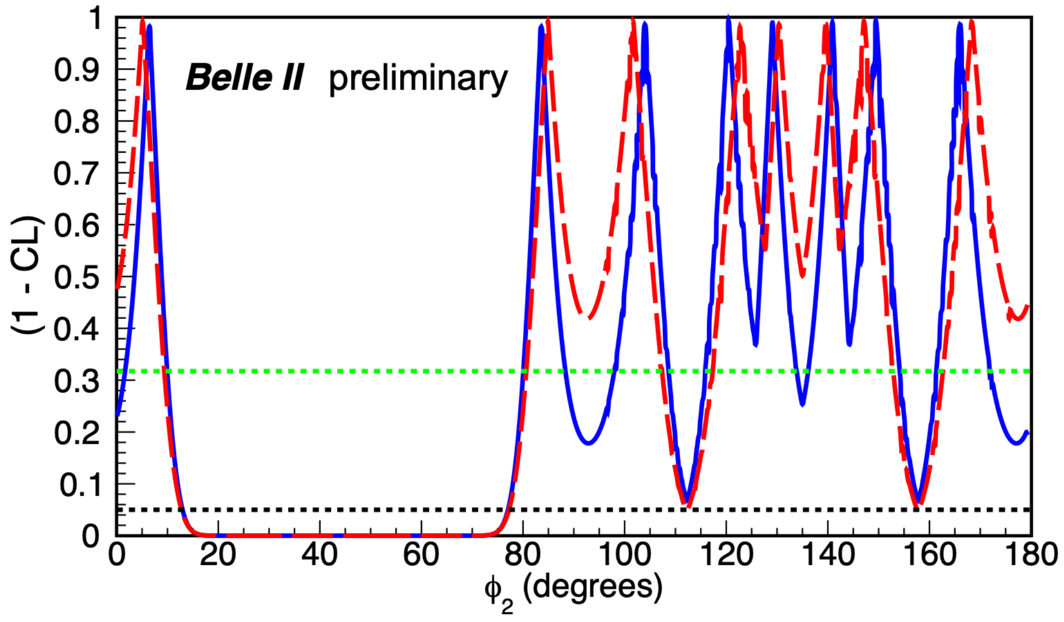


FIG. 3. P-value as a function of the CKM angle ϕ_2 from an isospin-based combination of all $B \to \pi\pi$ results (red dashed) without and (blue solid) with the inclusion of the results of this work.

Belle II Coll., arXiv:2412.14260

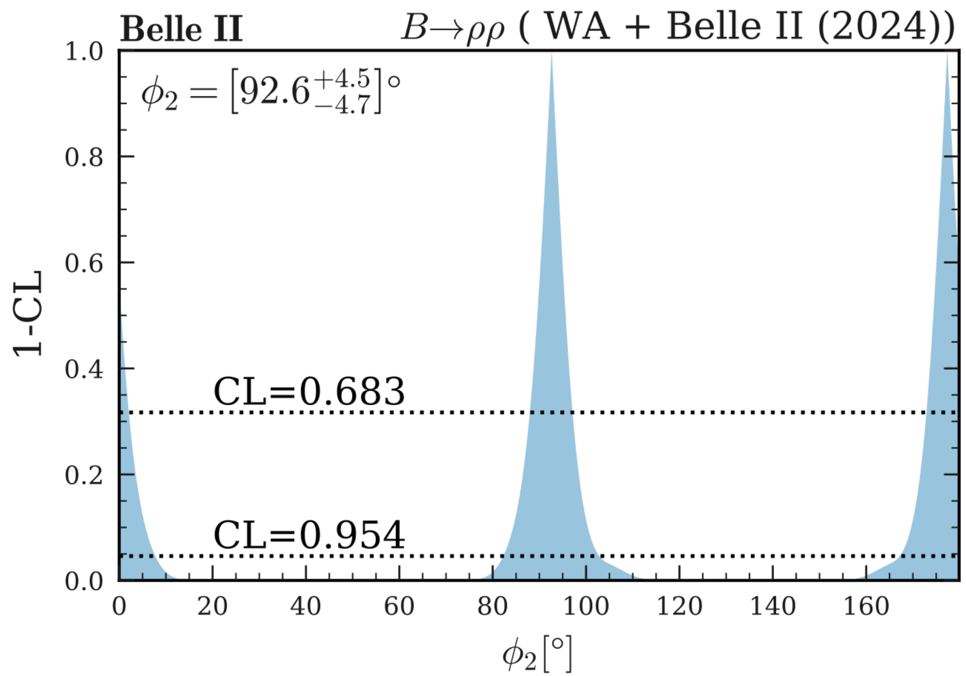


Fig. 4. Probability (1−Confidence-Level) for the CKM angle ϕ_2 based on combined inputs from the world averages [12] and our results of $B \to \rho\rho$ decays. The black dotted lines correspond to the 0.683 and 0.954 confidence levels.

Belle II Coll., arXiv:2412.19624

Lattice result summary (summer22)

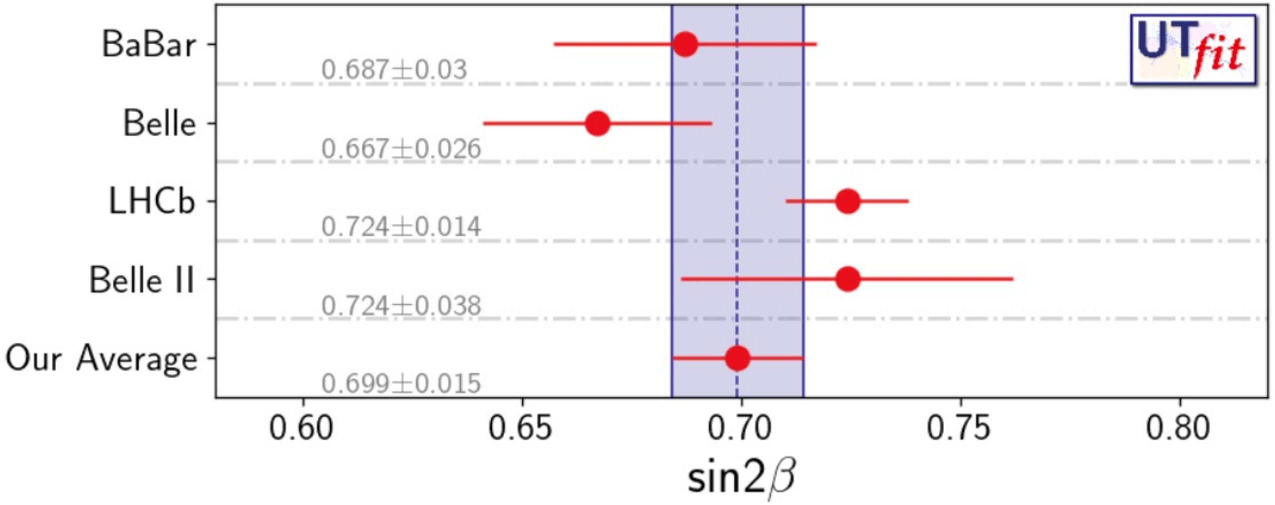
We obtain the predictions for the lattice parameters in different configurations in the fit:

- only lattice parameters ratios
  - (F_{Bs}/F_B, B_{Bs}/B_{Bd} used)
- only B parameters
  - (B_{Bs}[1], B_{Bs}/B_{Bd} used)
- only decay constants f
  - (f_{Bs}, f_{Bs}/f_B included)

Observables	Measurement	Prediction
B_K	**0.756 ± 0.016**	**0.840 ± 0.053**
No B lattice		
$f_B\sqrt{B_{Bd}}$	**(0.2142 ± 0.0056)**	**0.212 ± 0.010**
$f_{Bs}\sqrt{B_{Bs}}$	**(0.2607 ± 0.0061)**	**0.259 ± 0.010**
ξ	**(1.217 ± 0.014)**	**1.225 ± 0.033**
Ratios only		
f_{Bs}	**0.2301 ± 0.0012**	**0.227 ± 0.009**
B_{Bs}	**1.284 ± 0.059**	**1.30 ± 0.10**
B pars only		
f_{Bs}/f_{Bd}	**1.208 ± 0.005**	**1.215 ± 0.028**
f_{Bs}	**0.2301 ± 0.0012**	**0.228 ± 0.008**
f pars only		
B_{Bs}/B_{Bd}	**1.015 ± 0.021**	**1.017 ± 0.028**
B_{Bs}	**1.284 ± 0.059**	**1.290 ± 0.065**

Another update on the ϕ_1/β angle

- In July 2024, HFLAV had a Winter2024 value update including latest LHCb (arXiv:2309.09728)
- So our average now will go to here:



From all charmonium
HFLAV Winter2024: 0.708 ± 0.011
adding Belle II: 0.724 ± 0.038
getting average: 0.709 +/- 0.011
Corrected with -0.01 +- 0.01
final number is **0.699 +/- 0.015**

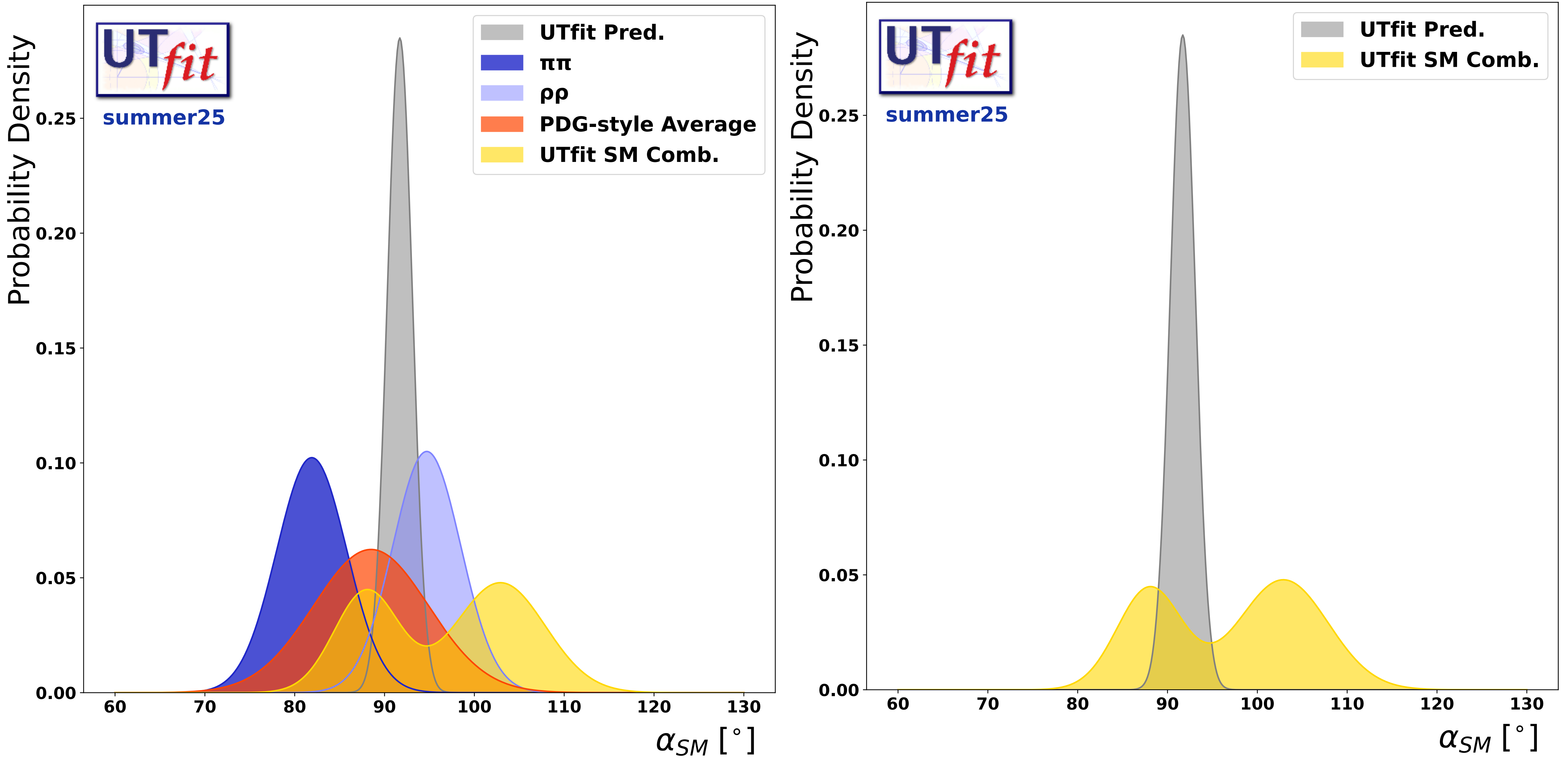
UT generalization Beyond the Standard Model

- Thanks to experimental redundancy, one can fit additional degrees of freedom
  - Use all available experimental information (including Bs-, D-(*) and K- related observables not used in SM UT analysis)
  - Parameterize BSM effects in $\Delta F = 2$ Hamiltonian in model-independent
  - Simultaneously determine the CKM and the NP parameters (generalized UT analysis)
- find out NP contributions to ΔF=2 transitions

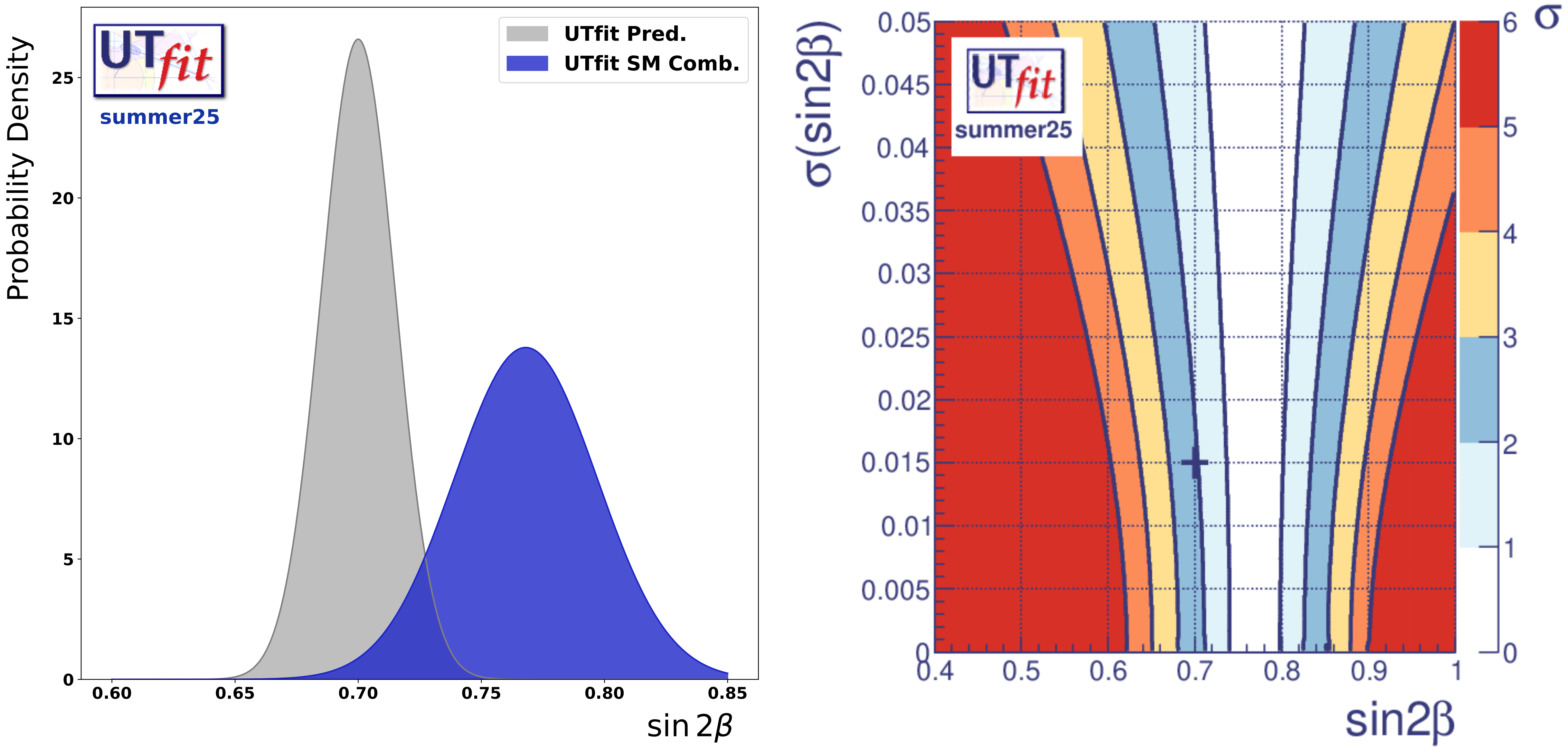
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP}-\phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$
$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^q = \mathrm{Im}(\Gamma_{12}^q / A_q)$$
$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$
$$A_{CP}^{B_s \to J/\psi\phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}(\Gamma_{12}^q / A_q)$$

(*) I don't discuss the results in the D sector in this talk, for lack of time



summer25
UTfit Pred.
ππ
ρρ
PDG-style Average
UTfit SM Comb.
Probability Density
α_{SM} [°]
0.00
0.05
0.10
0.15
0.20
0.25
60
70
80
90
100
110
120
130
summer25
UTfit Pred.
UTfit SM Comb.
Probability Density
α_{SM} [°]


UTfit
summer25
UTfit Pred.
UTfit SM Comb.
Probability Density
sin 2β
0.60
0.65
0.70
0.75
0.80
0.85
0
5
10
15
20
25
σ(sin2β)
sin2β
σ
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.4
0.5
0.6
0.7
0.8
0.9
1
6
5
4
3
2
1
0