WIFAI 2023

Workshop Italiano sulla Fisica ad Alta Intensità

— Rome —

8 November 2023

UTfit Thanks!

Overview and theoretical prospects for CKM matrix & CP violation

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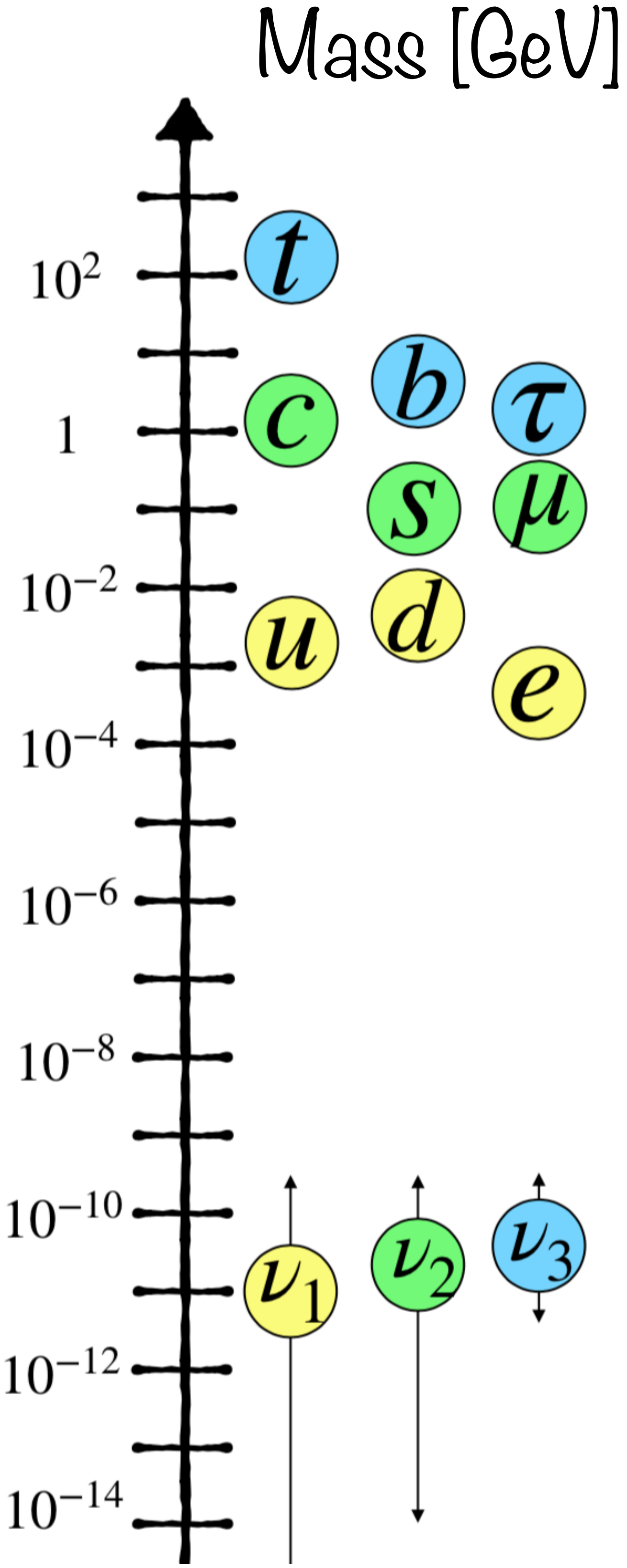
INFN Rome

INFN

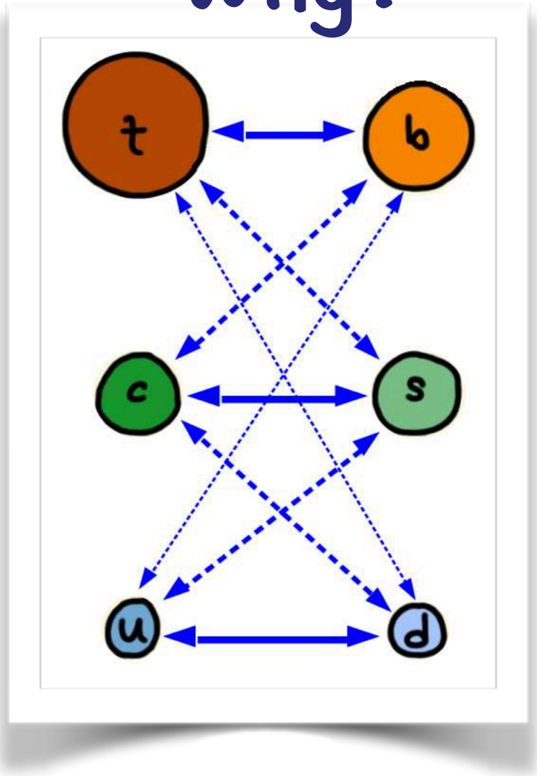
The Standard Model

THE SM
FLAVOR
PUZZLE

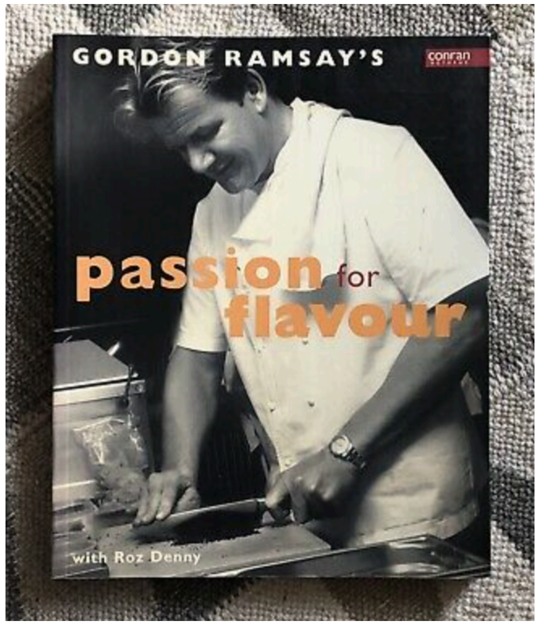


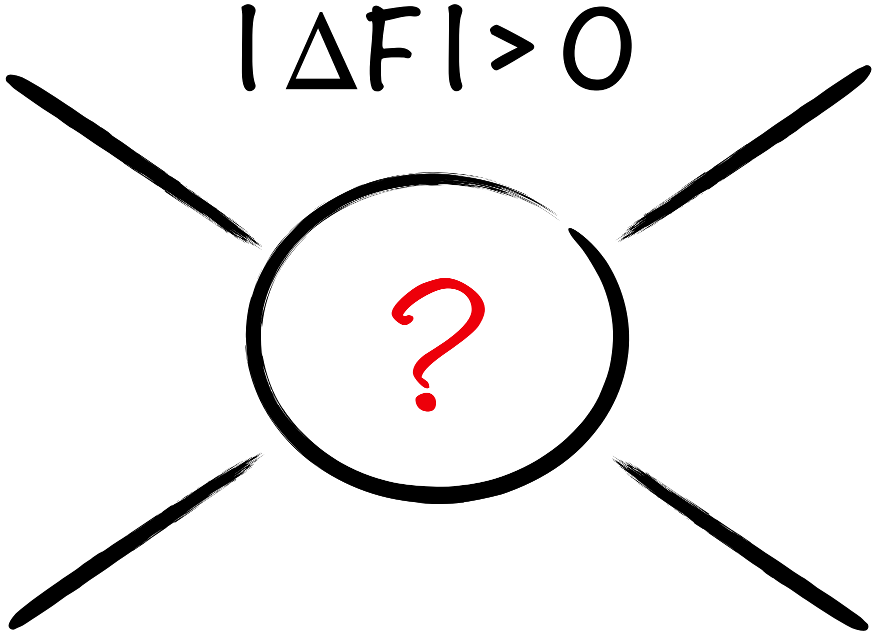
$$V_{\text{CKM}} = \begin{array}{cc} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \begin{array}{c} u \\ c \\ t \end{array} \\ \begin{array}{ccc} d & s & b \end{array} & \end{array}$$

Why?



Precision Tests: Flavor

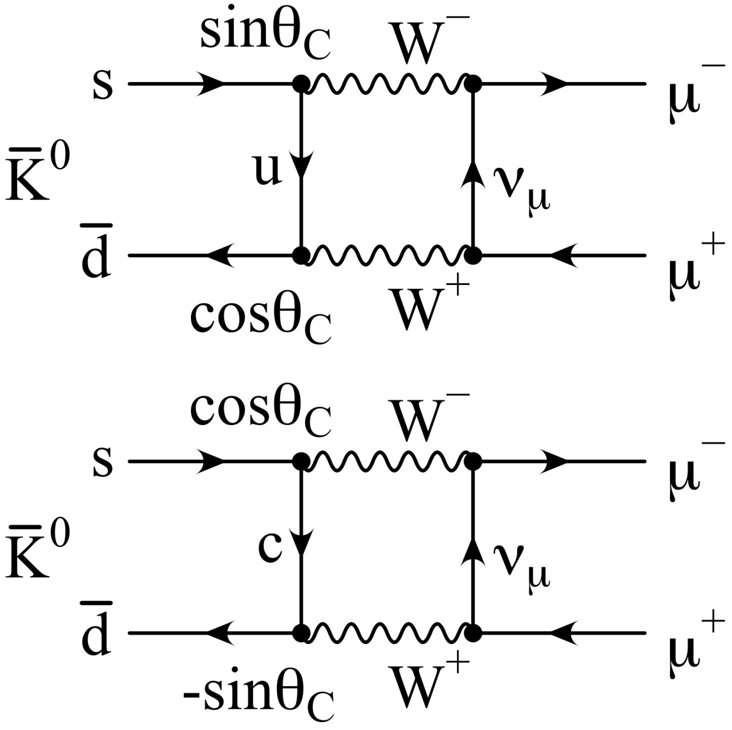




Look @ processes w/ ΔF units of flavor violation

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

E.g., prediction of charm quark:



Flavor Metrology:

- Flavor violation in SM in charged weak-current <—> V_{CKM}

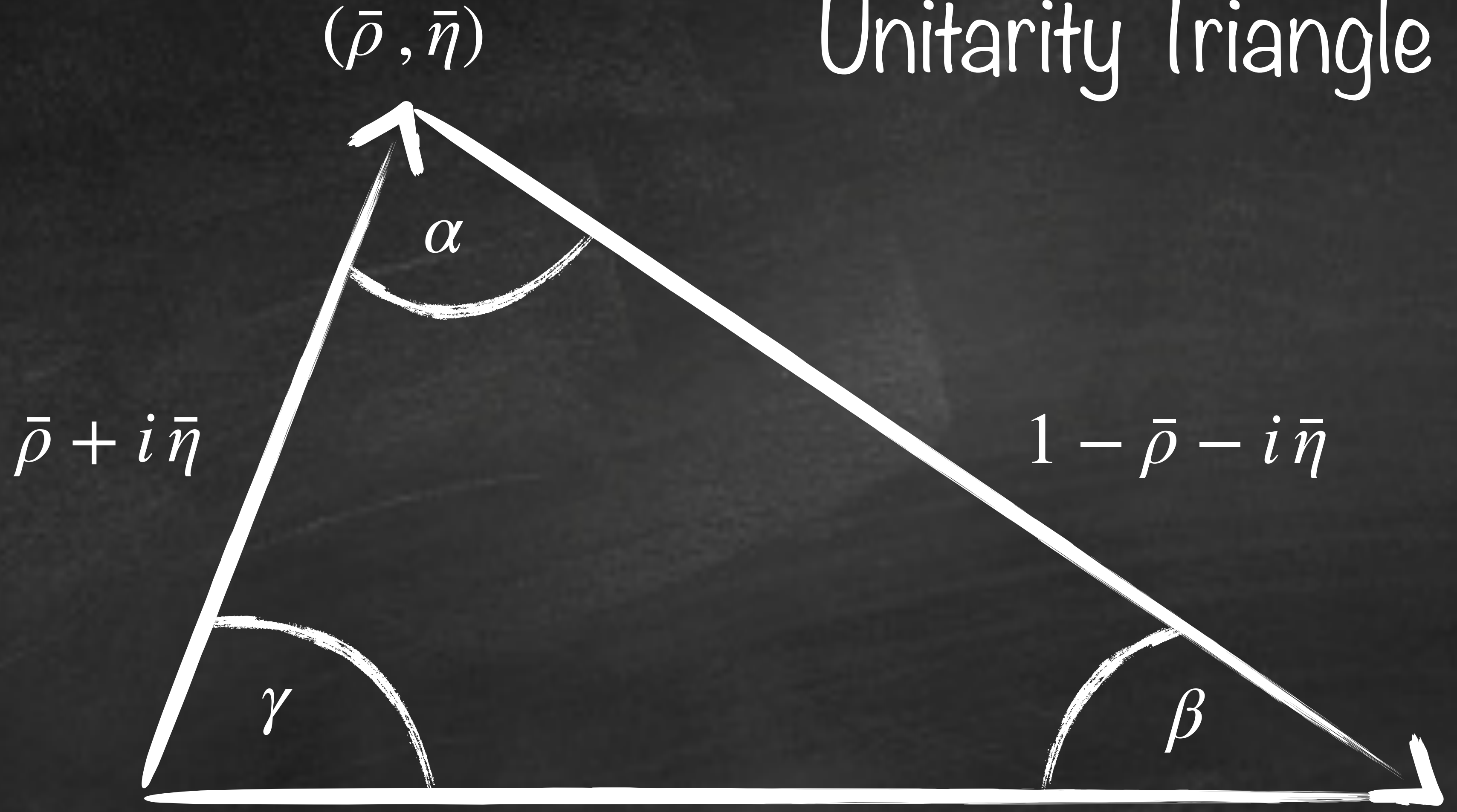
—> Flavor Changing Neutral Currents (FCNCs) **ONLY** @ one loop

- CKM matrix described by 4 params (3 angles and a C~~P~~ phase)

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

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

Unitarity Triangle (UT)



$$-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}-\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=R_b\,e^{i\gamma}+R_t\,e^{-i\beta}=1\simeq(\bar{\rho}+i\bar{\eta})+(1-\bar{\rho}-i\bar{\eta})$$

UT*fit*

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

LINCEI CELEBRATIVE ESSAYS

New UT*fit* analysis of the unitarity triangle in the Cabibbo–Kobayashi–Maskawa scheme

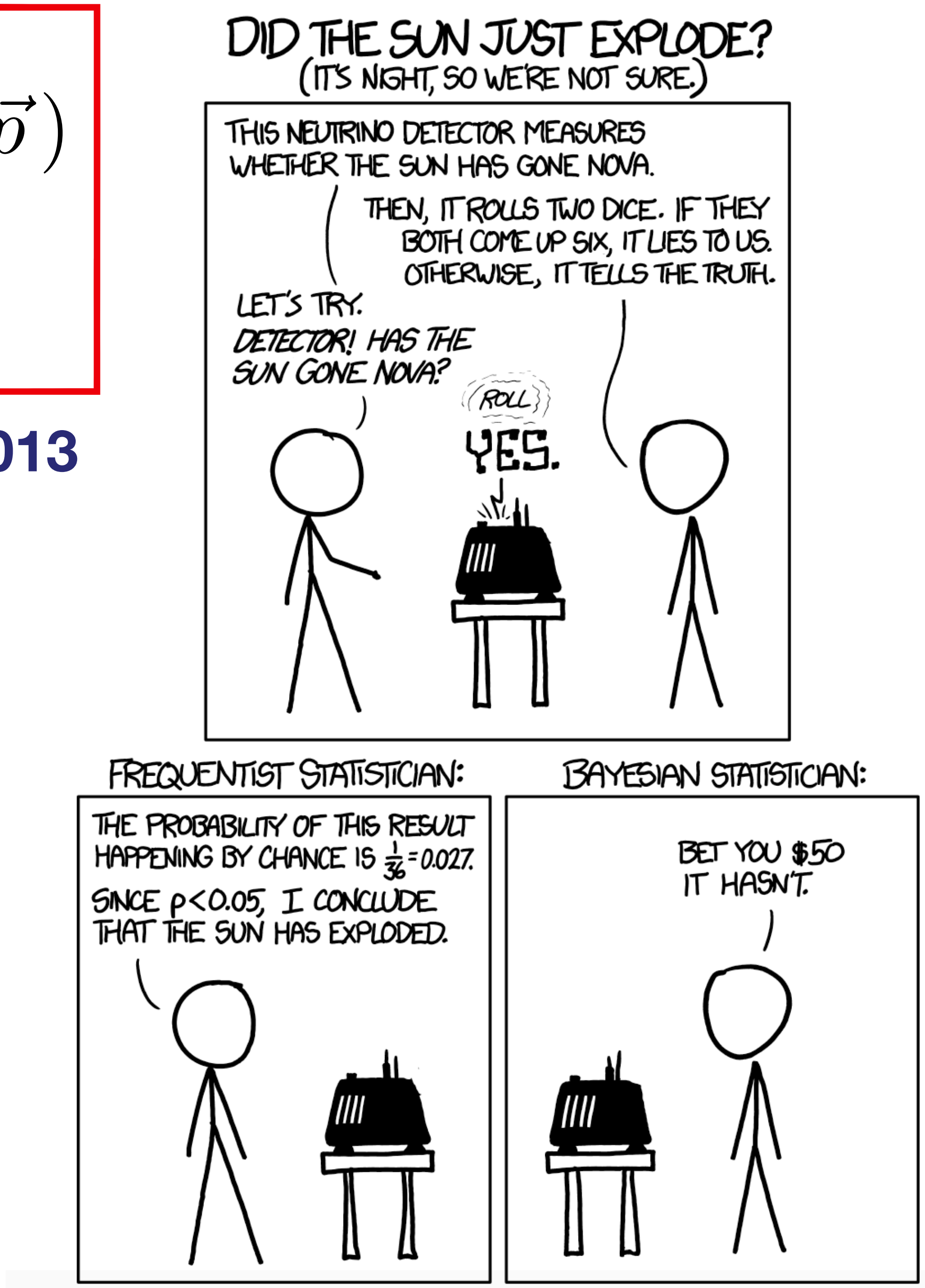
arXiv: **2212.03894**

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., ***JHEP* 07 (2001) 013**



@ https://xkcd.com/1132

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

  Observables <—> constraints in the fit

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

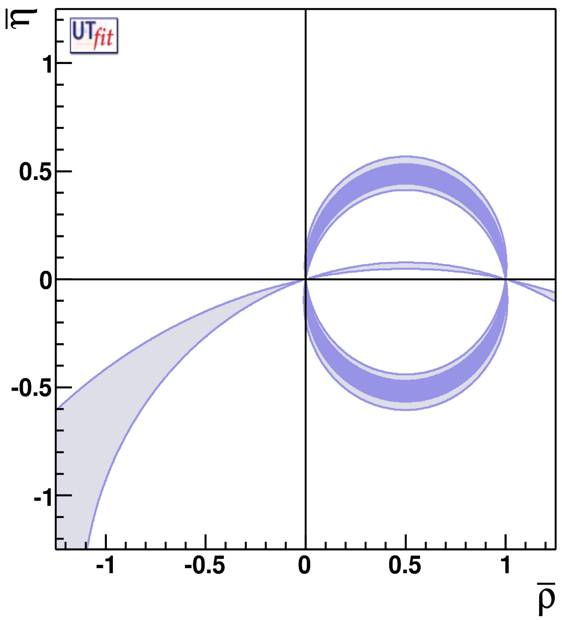
  Parameters we can marginalize over

- $(\bar\rho, \bar\eta)$ <—> CKM pair to be inferred

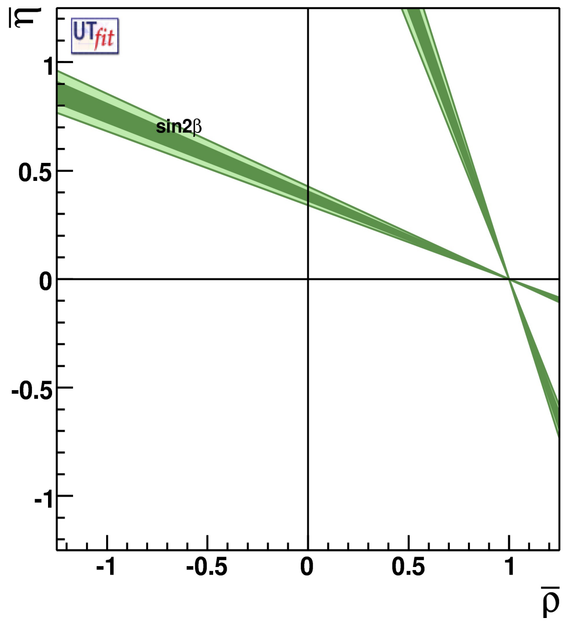
UT: The Power of Redundancy

see, e.g., ***Les Houches Lect.Notes 108 (2020)* - L.Silvestrini**

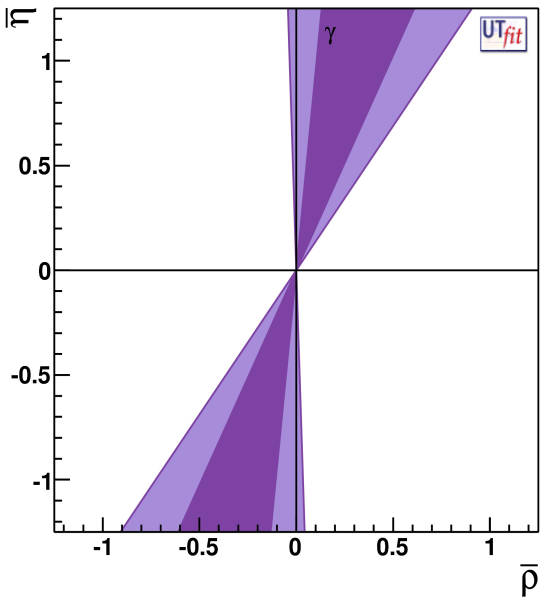
$\alpha\ (B \to \pi\pi, \rho\rho)$



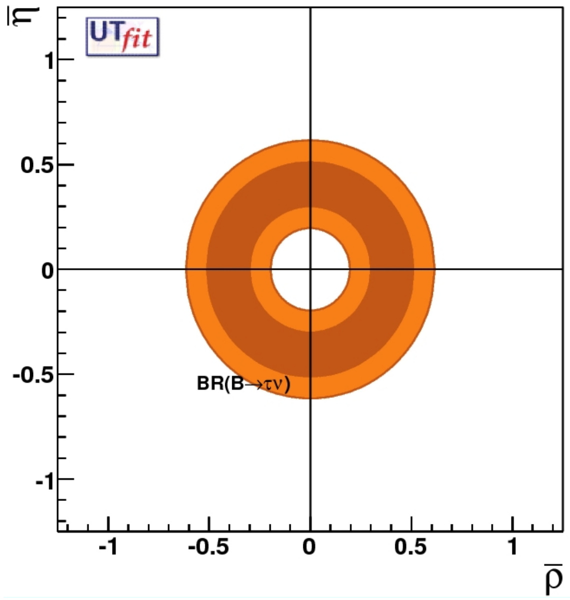
$\beta\ (B \to J/\psi K^{(*)})$

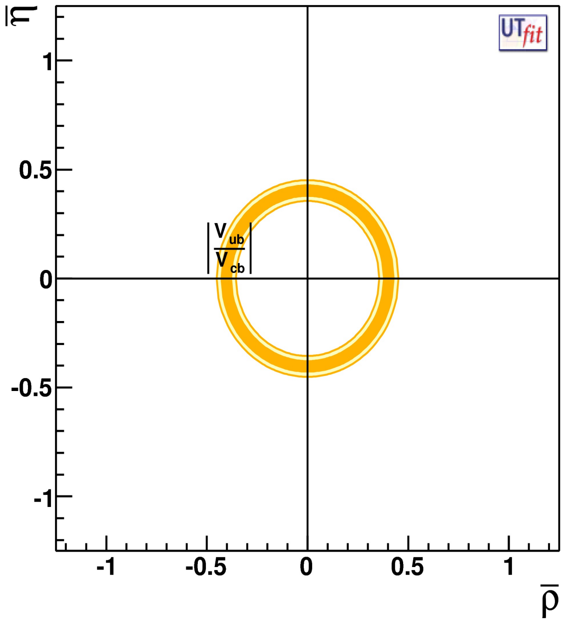


$\gamma\ (B \to D^{(*)} K)$



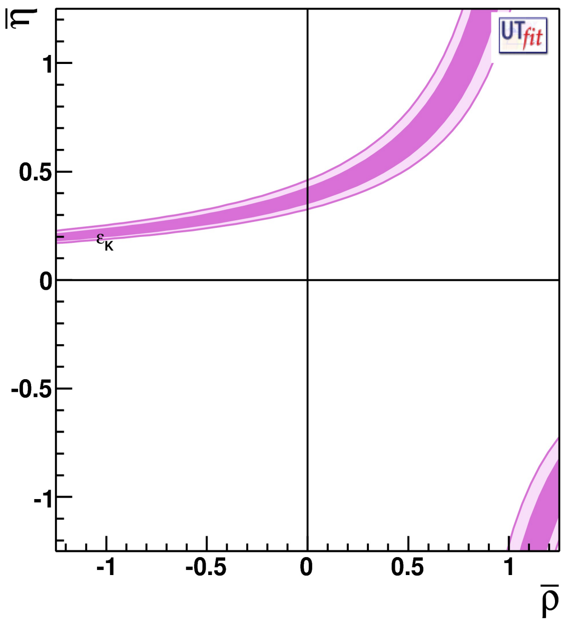
$\mathrm{BR}(B \to \tau\nu)$





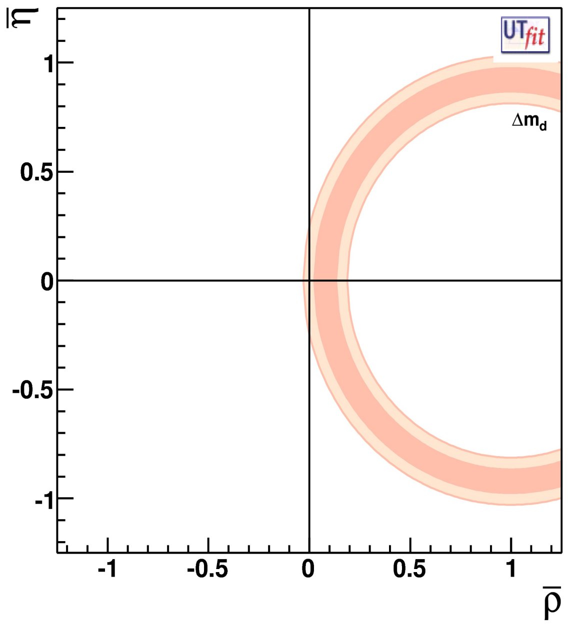
$|V_{ub}/V_{cb}|$

(semileptonic decays)

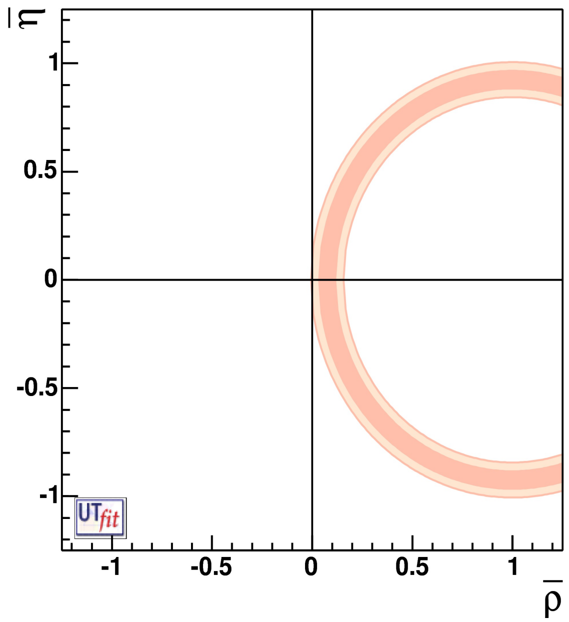


ϵ_K

(CPV in $K - \bar{K}$)



Δm_d



$\Delta m_d / \Delta m_s$

$(B_{d,s} - \bar{B}_{d,s})$

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What's New

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

à la D'Agostini, n-dim generalization of PDG scale factor

$|V_{cb}|_{excl} \times 10^3 = 40.55 \pm 0.46$

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

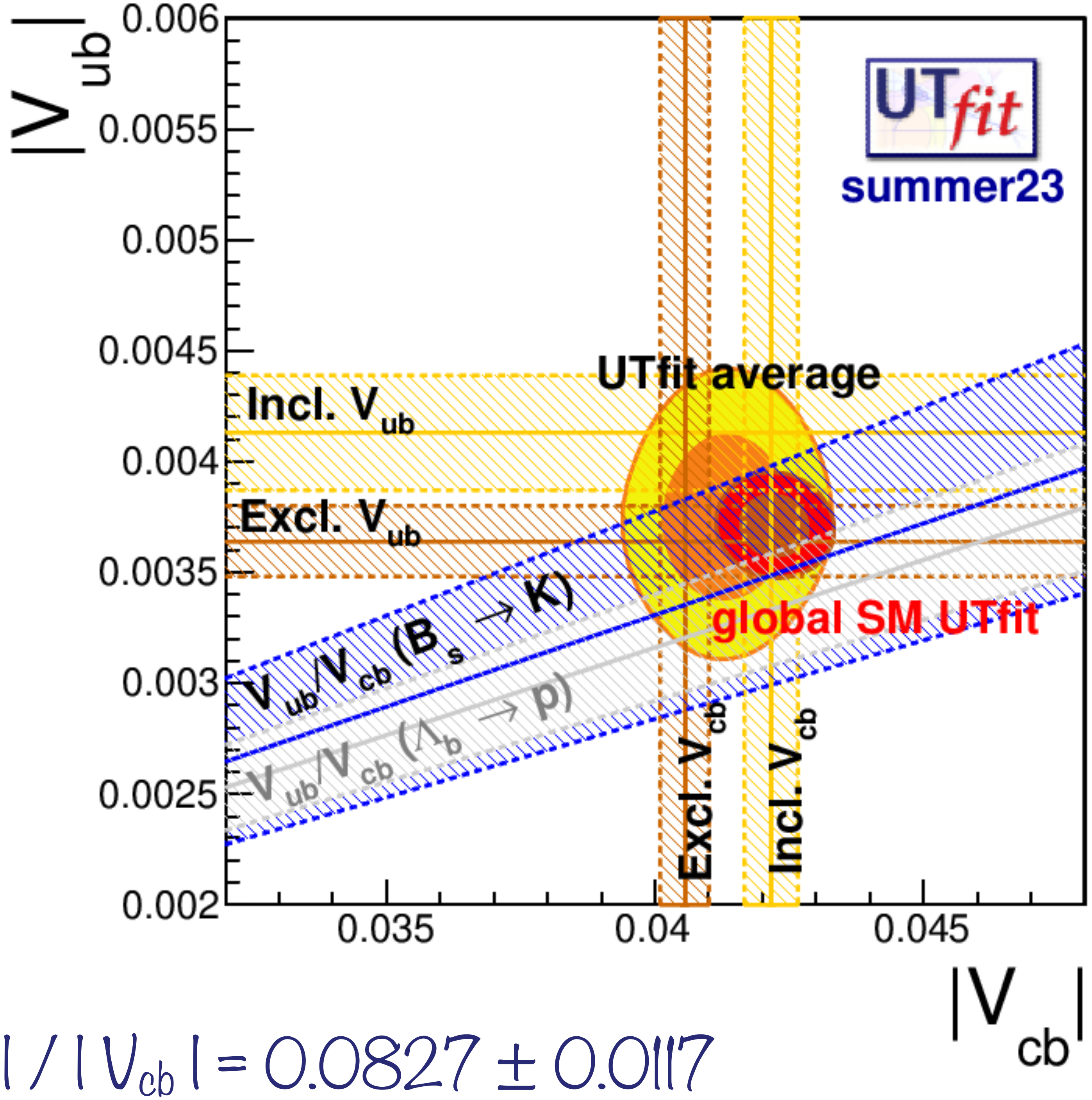
$|V_{cb}|_{ave} \times 10^3 = 41.1 \pm 1.3$

$|V_{ub}|_{excl} \times 10^3 = 3.64 \pm 0.16$

$|V_{ub}|_{incl} \times 10^3 = 4.13 \pm 0.26$

$|V_{ub}|_{ave} \times 10^3 = 3.75 \pm 0.26$

Exclusive determinations updated w/ FLAG '23



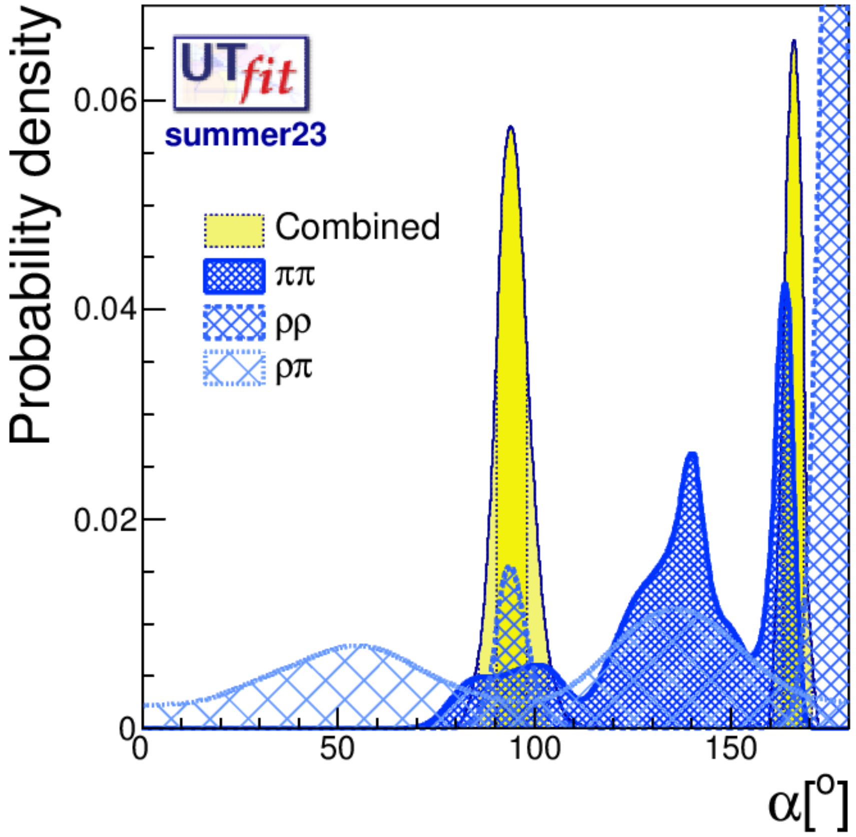
— This also implies an updated $|V_{ub}| / |V_{cb}| = 0.0827 \pm 0.0117$

SUMMER 2023

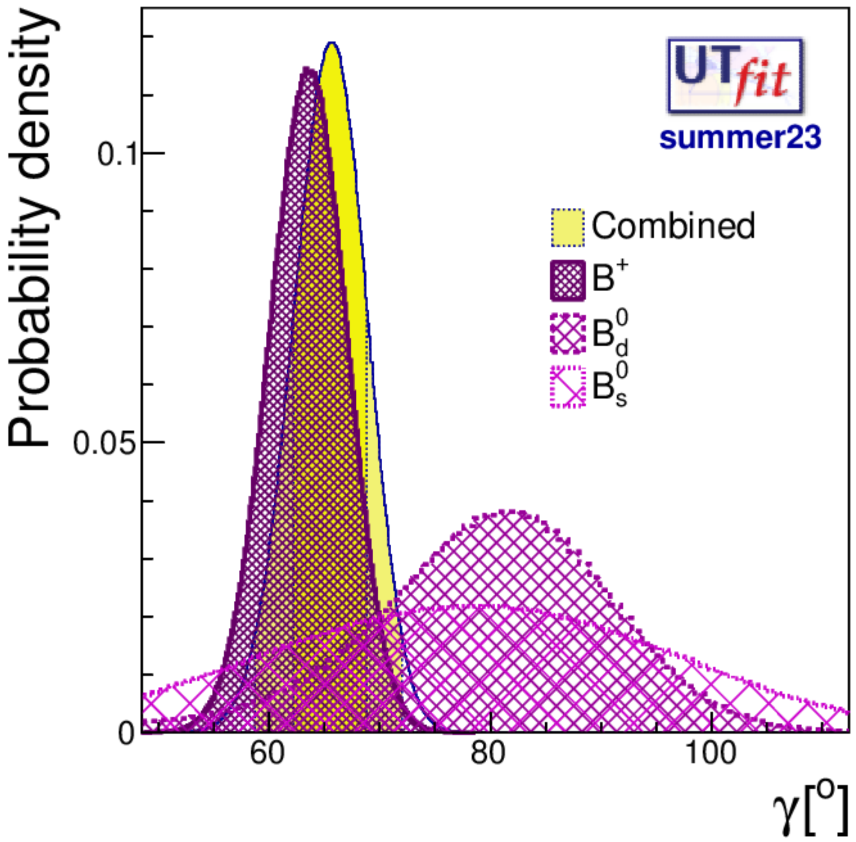
What's New

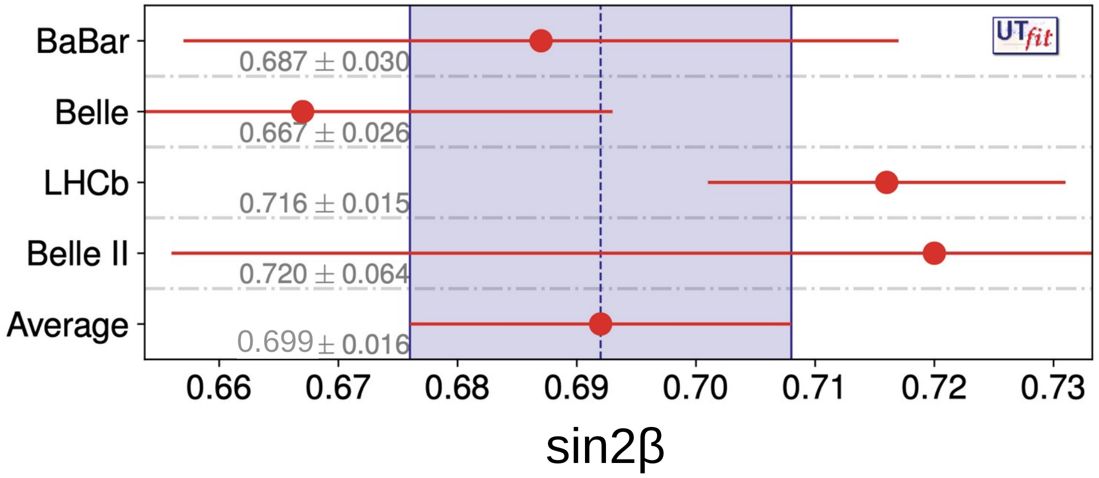
*** new sin2β from LHCb, new in-house averages for α and γ ***

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



$\gamma = (65.4 \pm 3.3)^\circ$



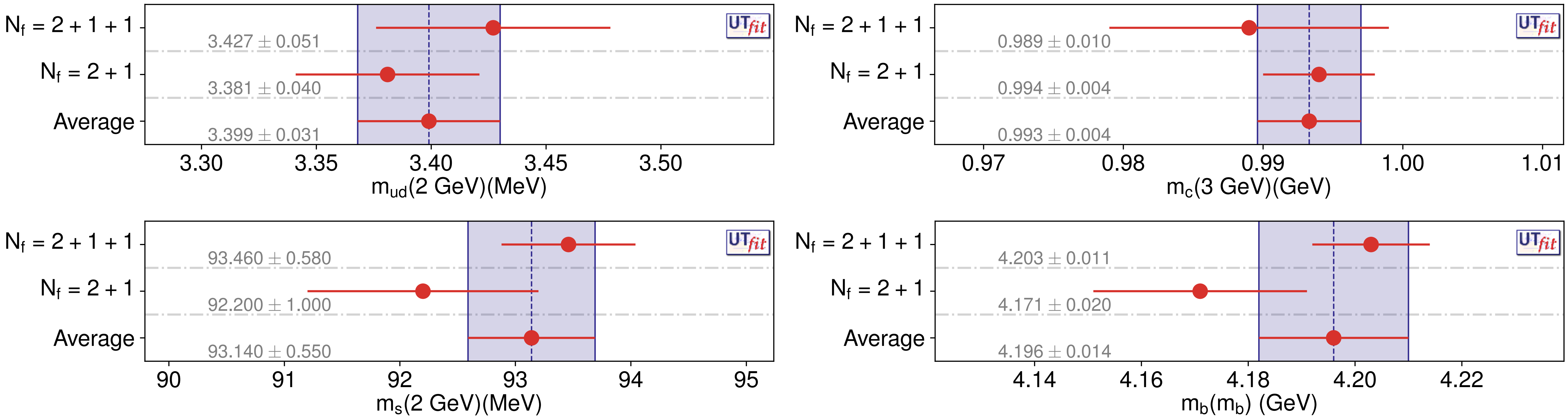


HFLAV: 0.698 ± 0.017
adding Belle II: 0.720 ± 0.064
getting average: 0.699 +/- 0.016
Corrected with -0.01 +- 0.01 [PRL 95 (2005) 221804]
final number is **0.689 +/- 0.019**

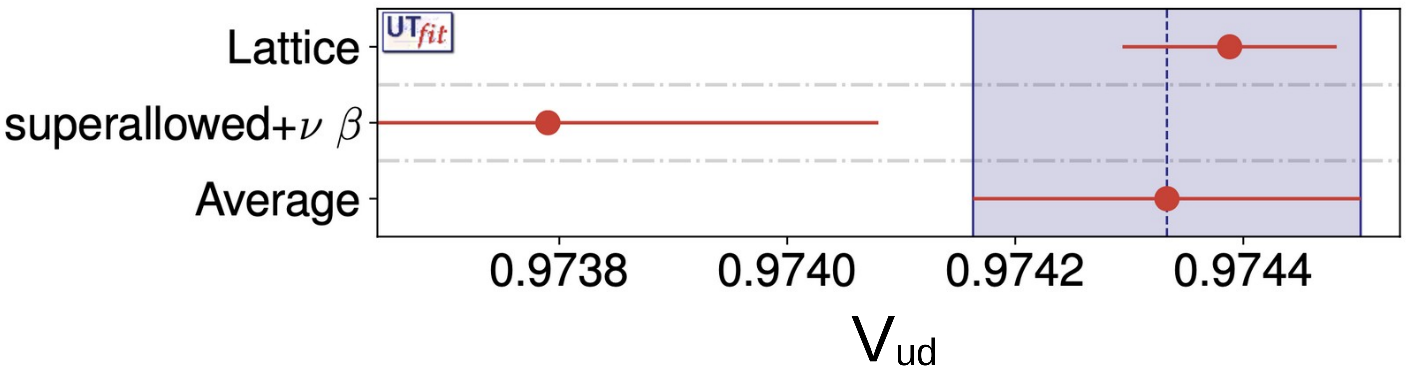
What's New

*** Updated quark masses & V_{ud} from neutron decay ***

Quark masses computed in $\overline{\text{MS}}$ and averaged with PDG scale factors.



V_{us} is not an input of the fit (CKM unitarity allows V_{us} <—> V_{ud}).

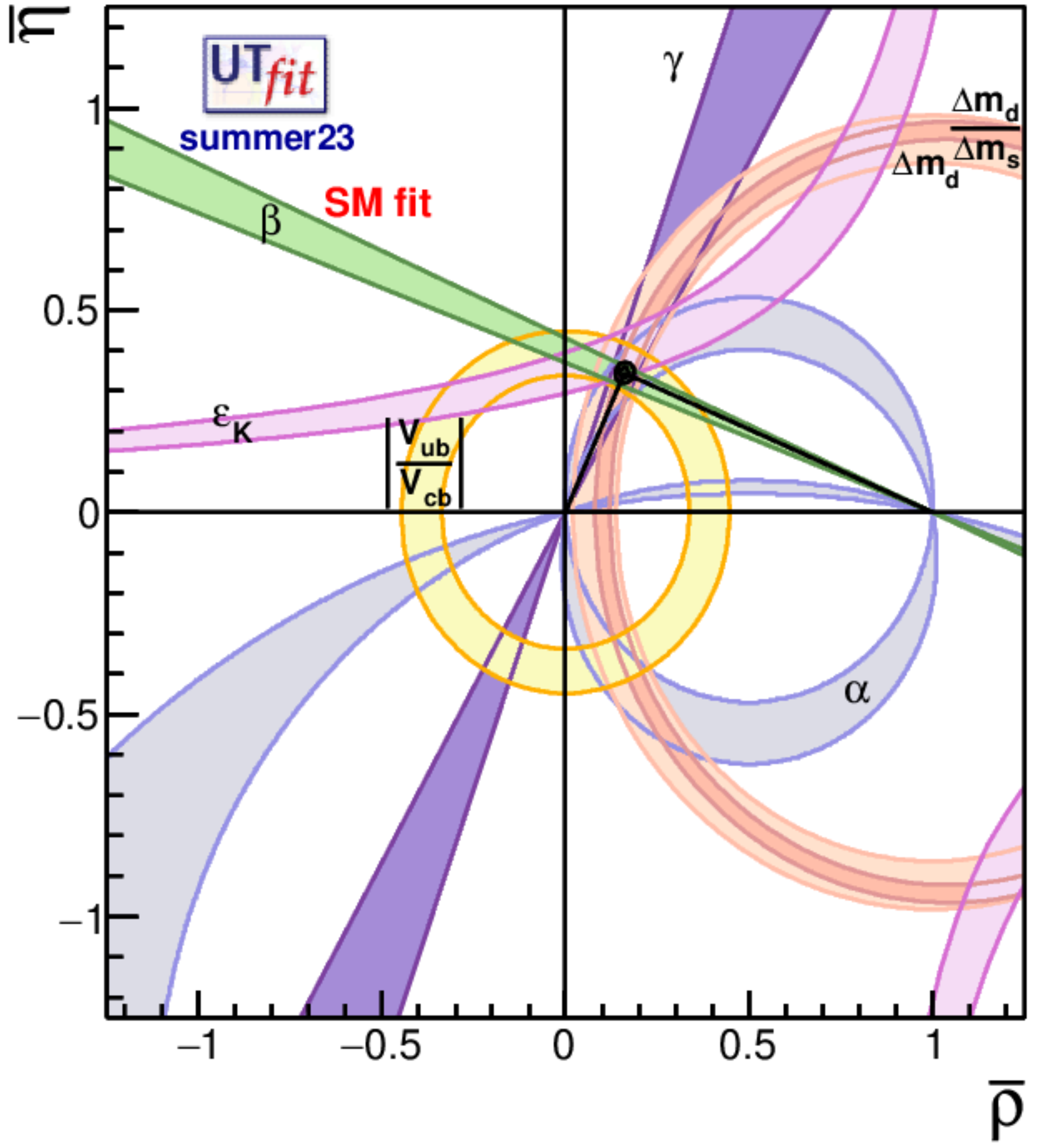


Cirigliano et al., ***Phys.Rev.D 108 (2023) 5, 053003***

$$\boxed{V_{ud}^{\text{n, PDG}} = 0.97430(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}}$$

SM UT Analysis — 2023

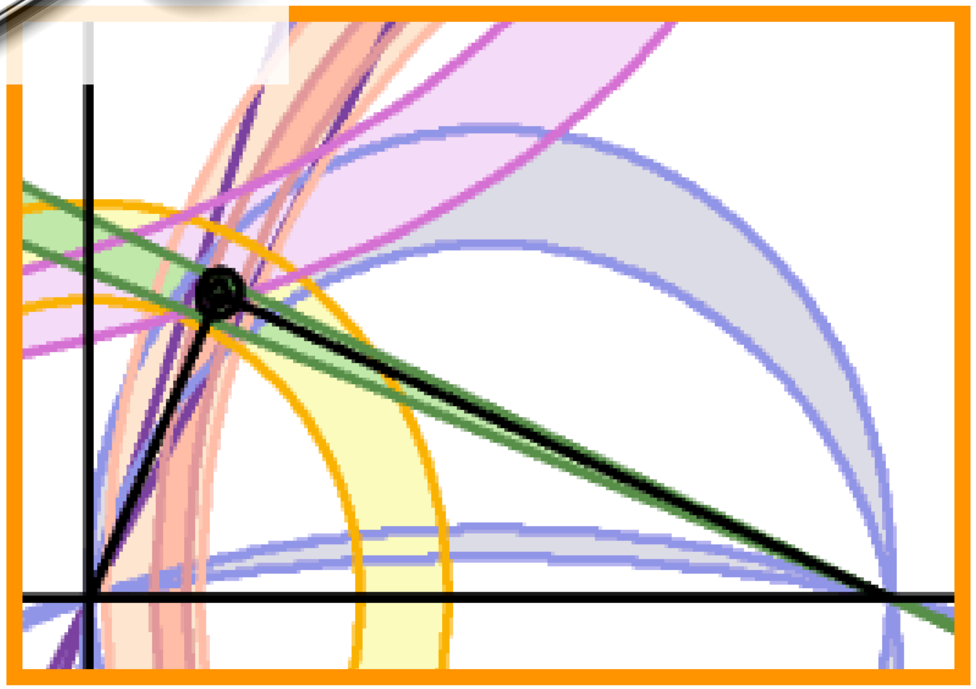
@ 95% prob

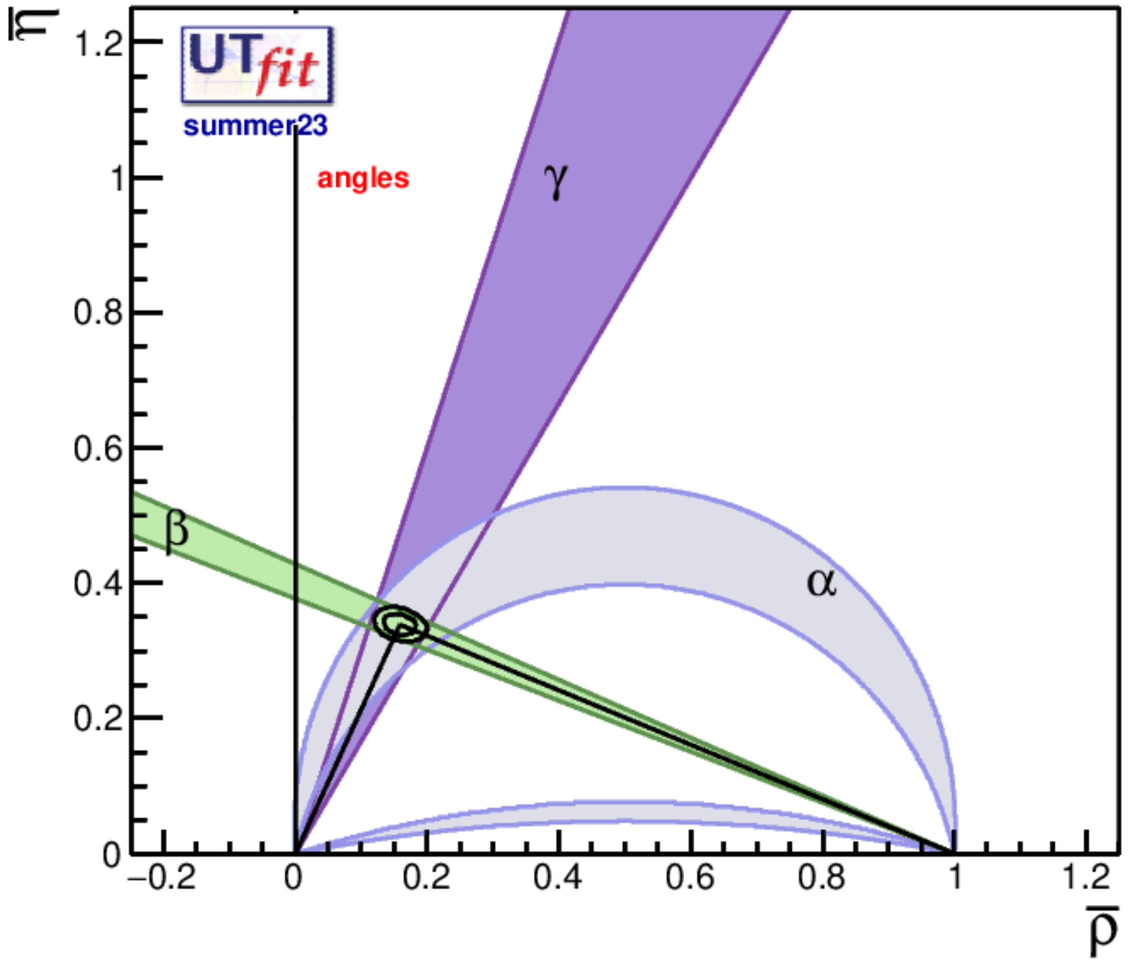


$$\boxed{\begin{aligned}\bar{\rho} &= 0.160 \pm 0.009 \sim 6\% \\ \bar{\eta} &= 0.346 \pm 0.009 \sim 3\%\end{aligned}}$$

$$\lambda = 0.2251 \pm 0.0008$$
$$A = 0.827 \pm 0.010$$

Zoomed-in SM UT Analysis





$$\bar{\rho} = 0.159 \pm 0.016 \sim 10\%$$
$$\bar{\eta} = 0.339 \pm 0.010 \sim 3\%$$

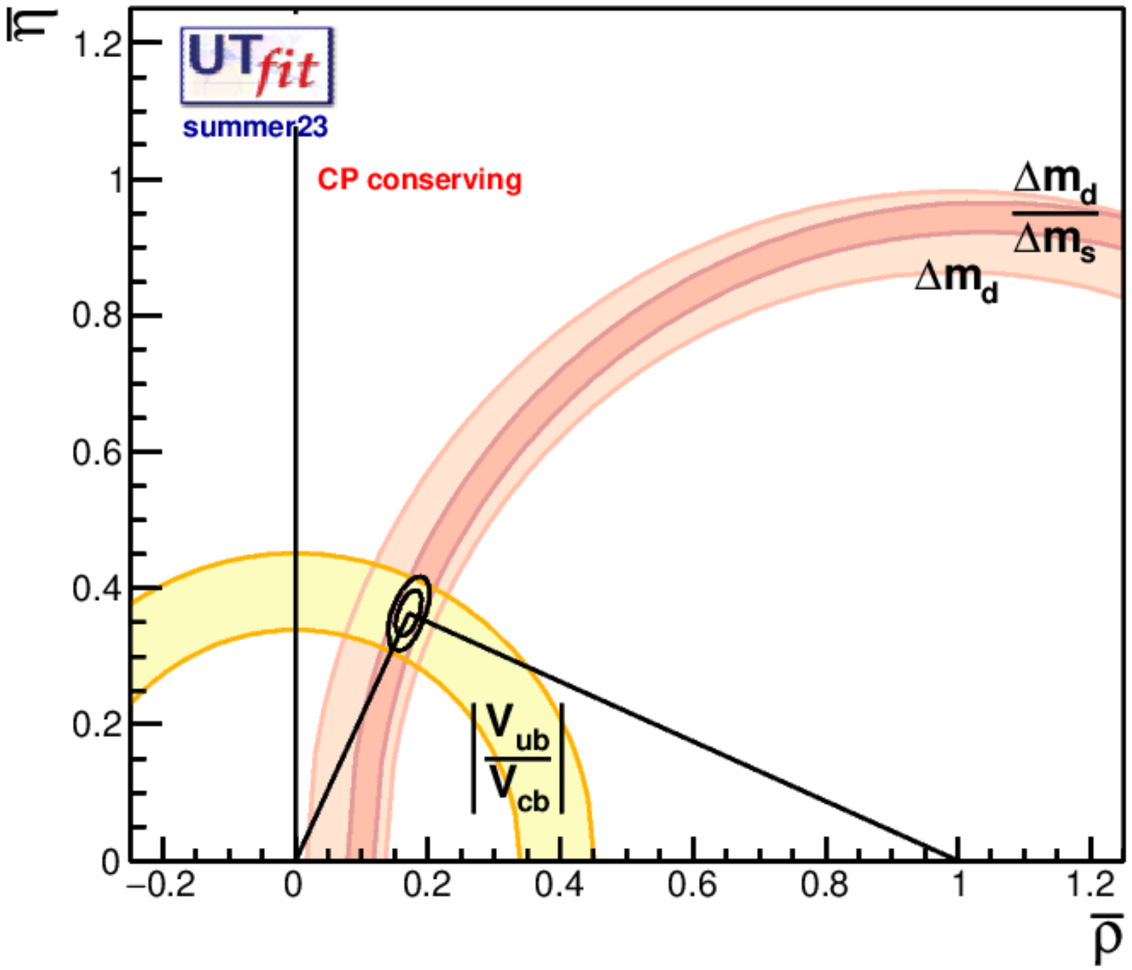
angles

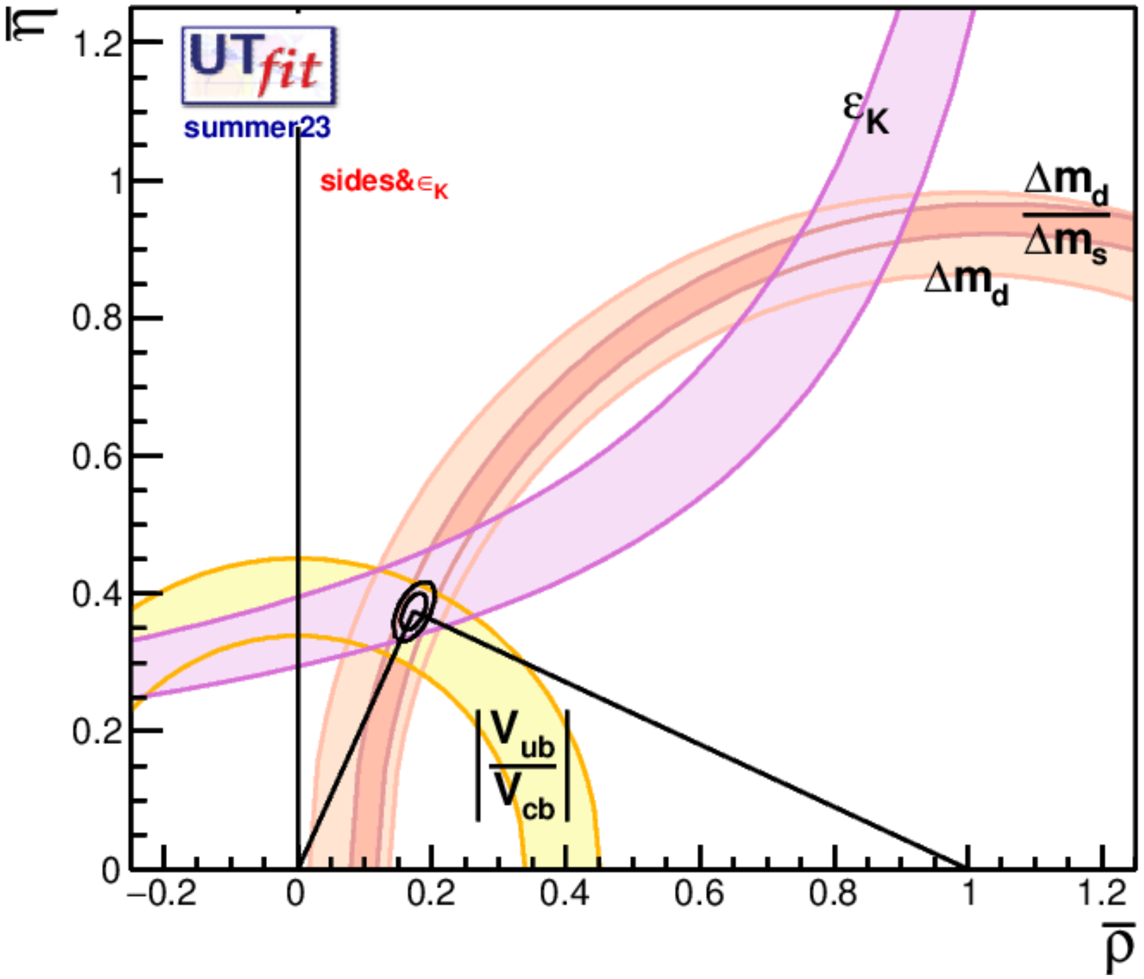
$$\bar{\rho} = 0.171 \pm 0.013 \sim 8\%$$
$$\bar{\eta} = 0.363 \pm 0.022 \sim 6\%$$

CP conserving

$$\bar{\rho} = 0.173 \pm 0.012 \sim 7\%$$
$$\bar{\eta} = 0.374 \pm 0.018 \sim 5\%$$

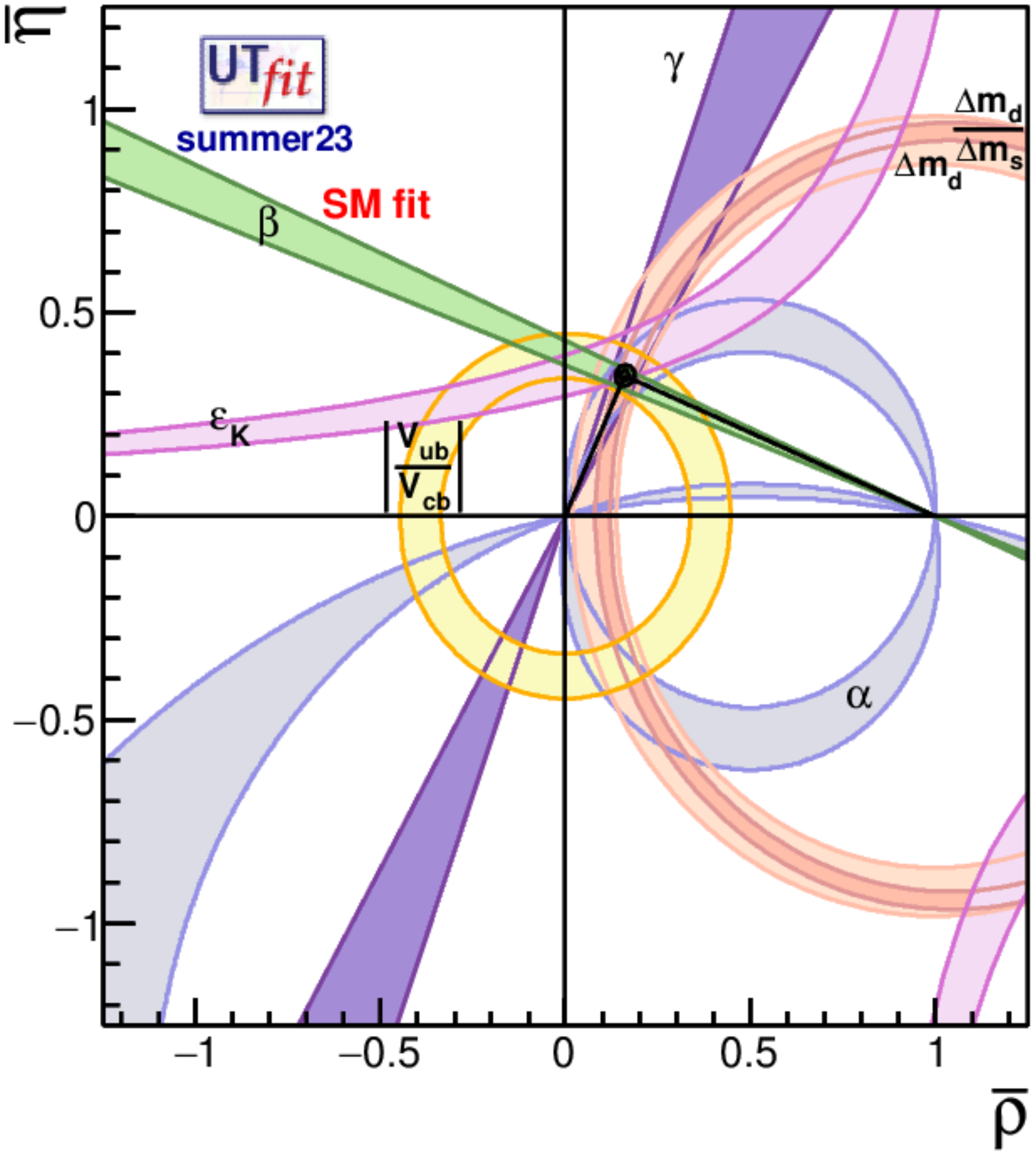
sides & ε_K



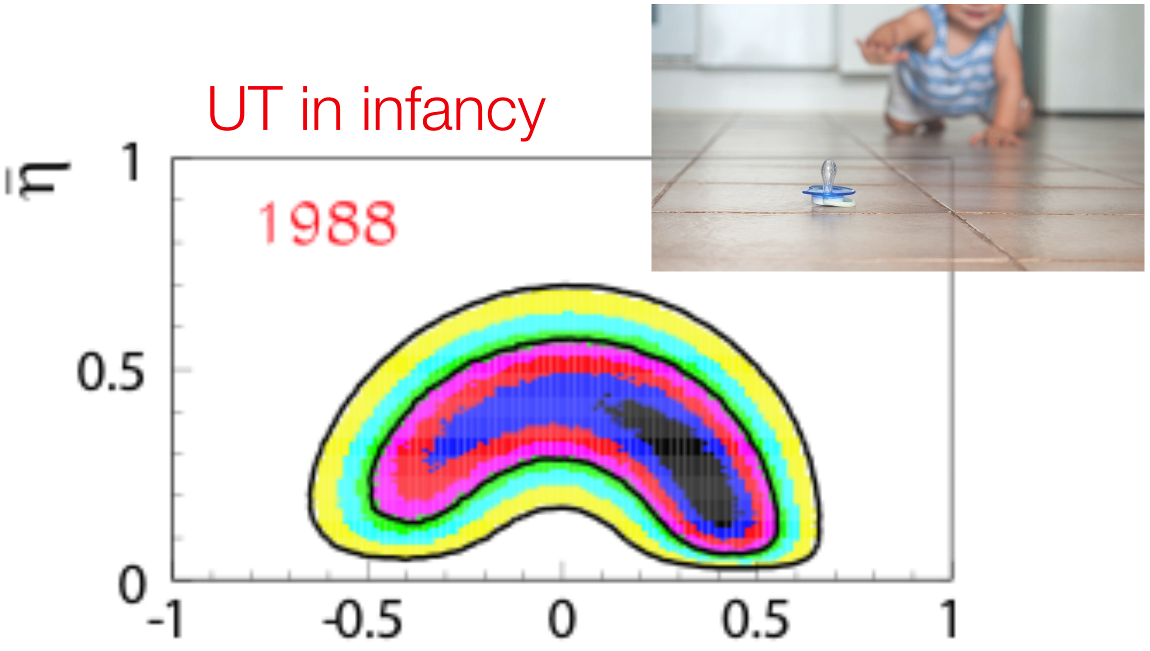


UT @ few % = decades of tremendous EXP + TH progress!

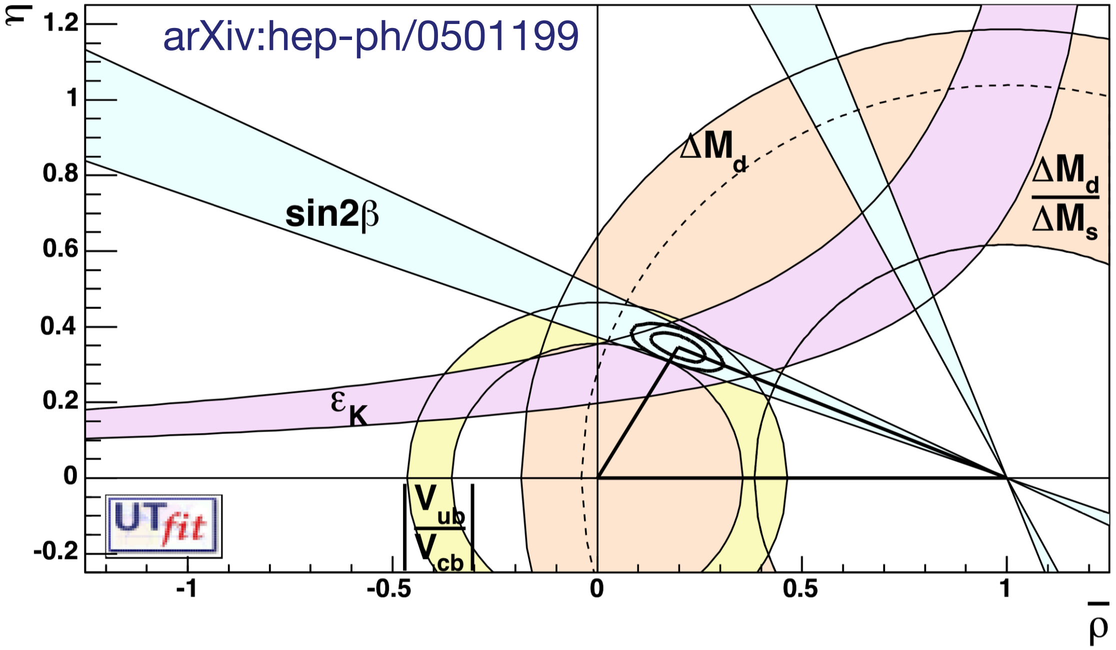
@ 95% prob



UT in infancy



Old-Fashioned SM UT



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

Compatibility plots

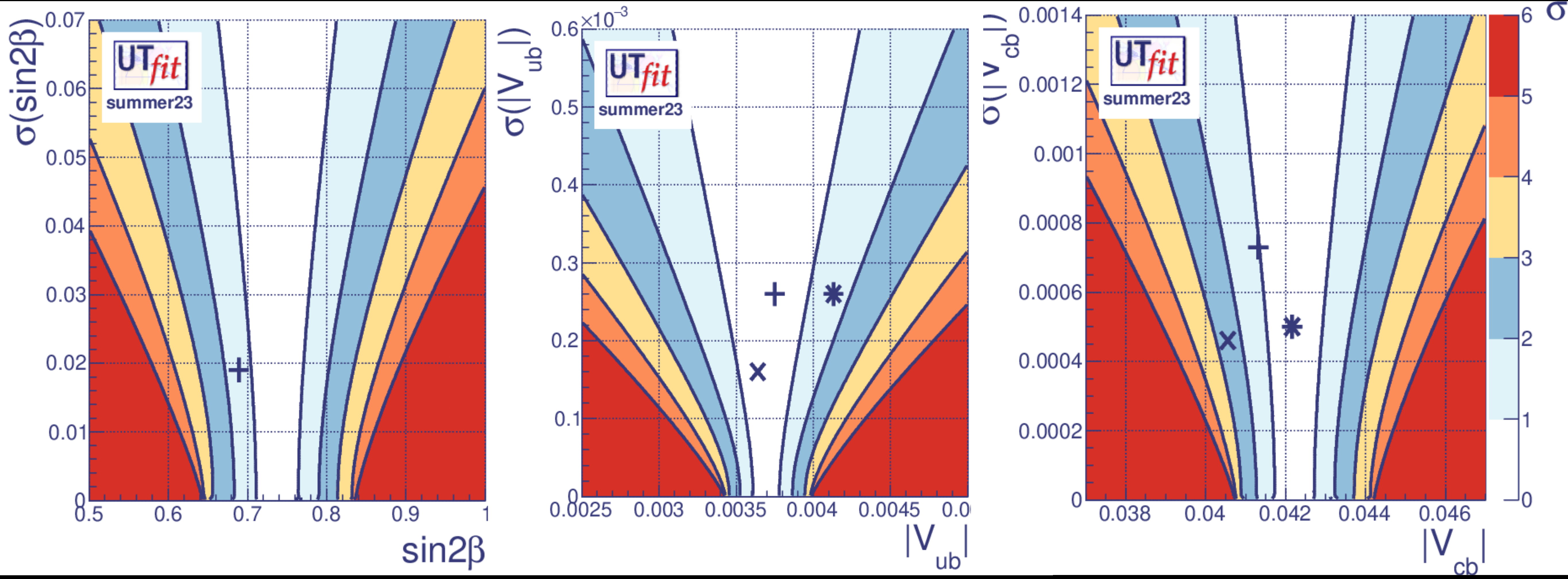
graphical pull of observables

Tensions in the fit

+ <—> measurement

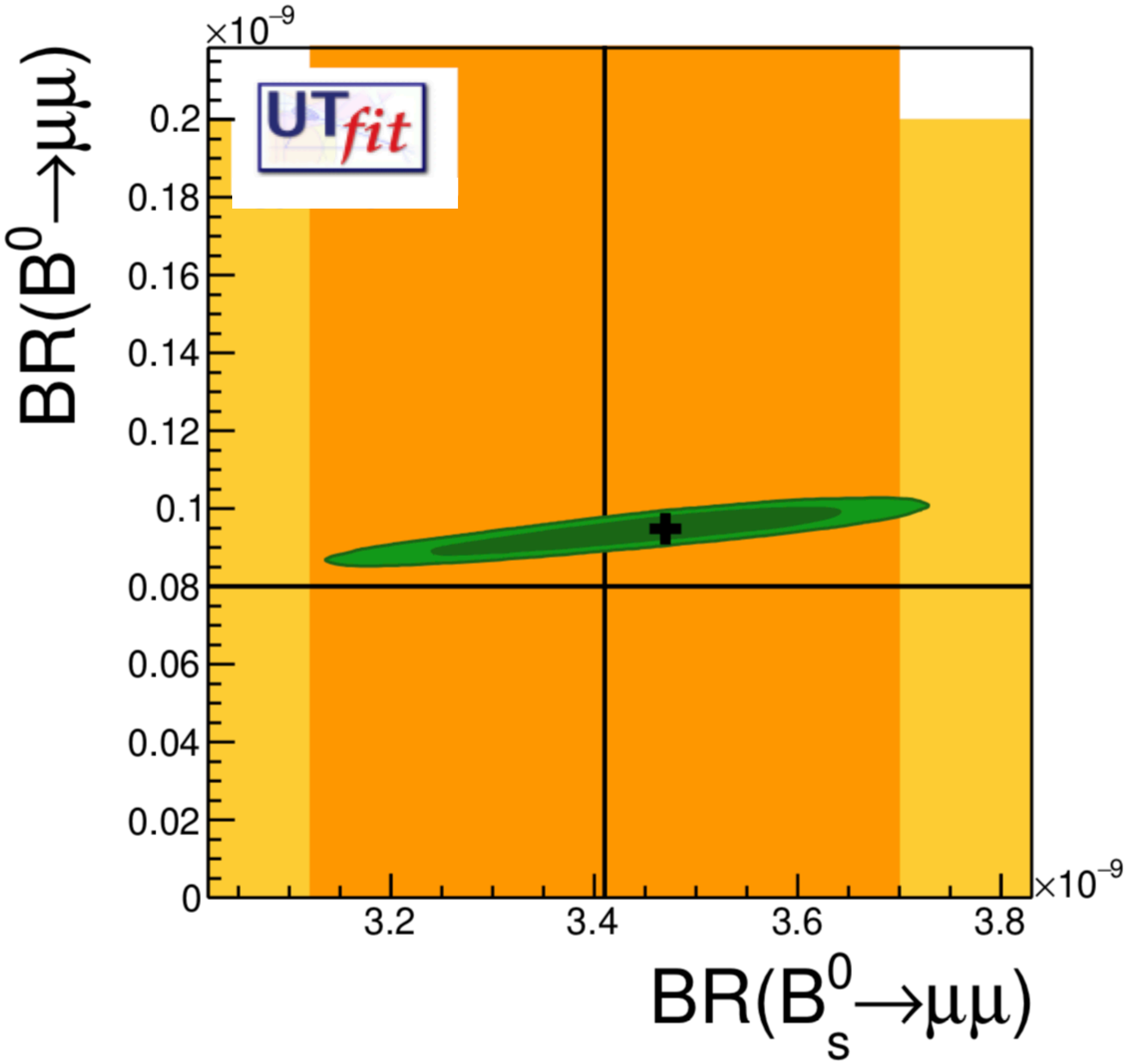
x <—> exclusive

∗ <—> inclusive



Greatest tension from exclusive determination of V_{cb} ($< 3\sigma$)

UT Highlights — | ΔF | = 1



BR(s) in agreement w/ EXP data

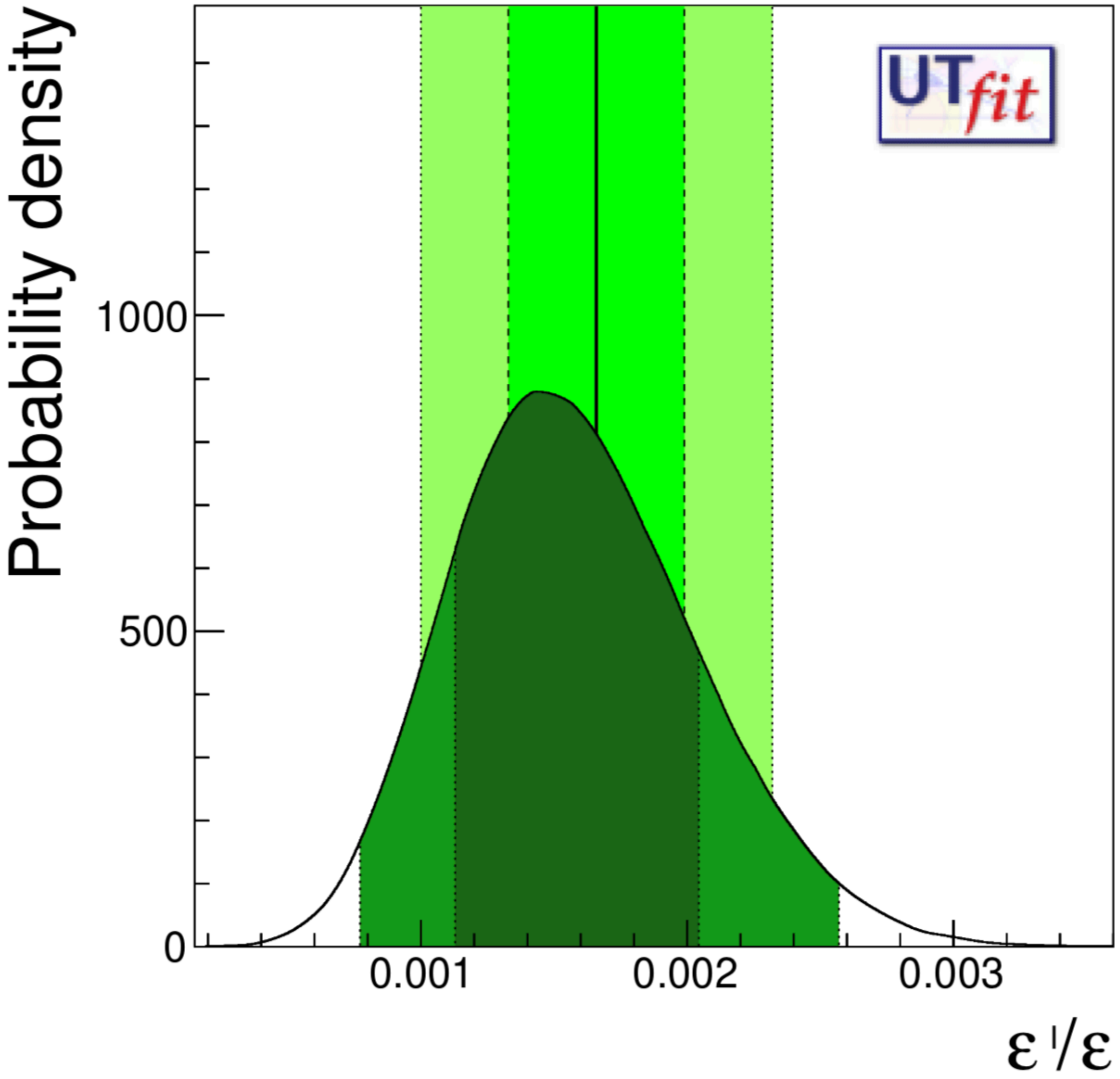
—> disfavoring NP for "*B anomalies*"

— see **Marco Fedele's talk** tomorrow —

UT now includes both indirect and direct CP from $K \to \pi\pi$

to RBC/UKQCD Coll.

PRD 102 (2020) 5, 054509



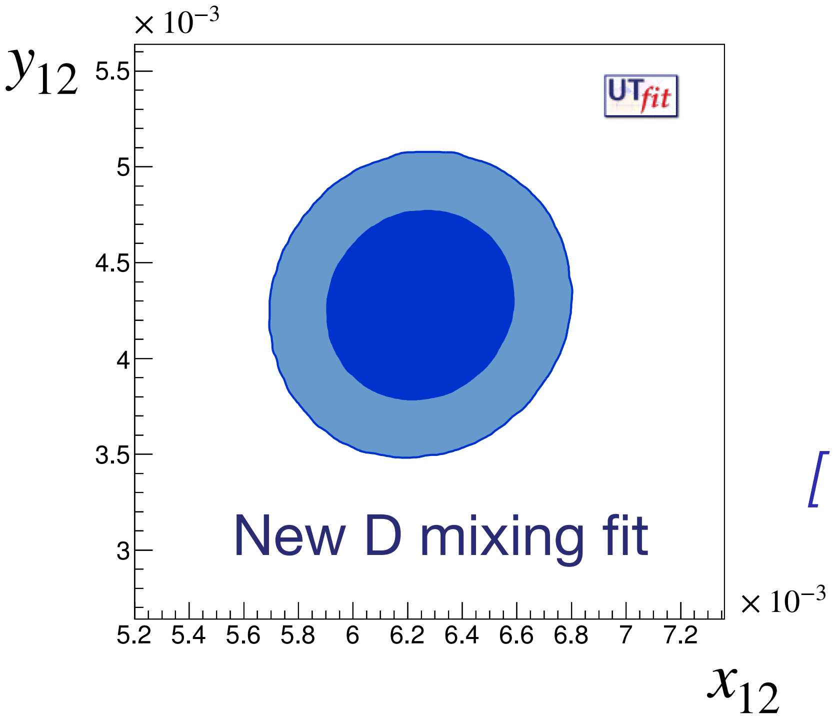
NP Analysis — Wiki How

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

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

- Include an extended list of observables to study also NP:

- **same-side dilepton charge asymmetry**
- **semileptonic asymmetries in B^0 and B_s**
- **lifetime τ^{FS} in flavour-specific final states**
- **$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$**



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R. Di Palma* & *L. Silvestrini

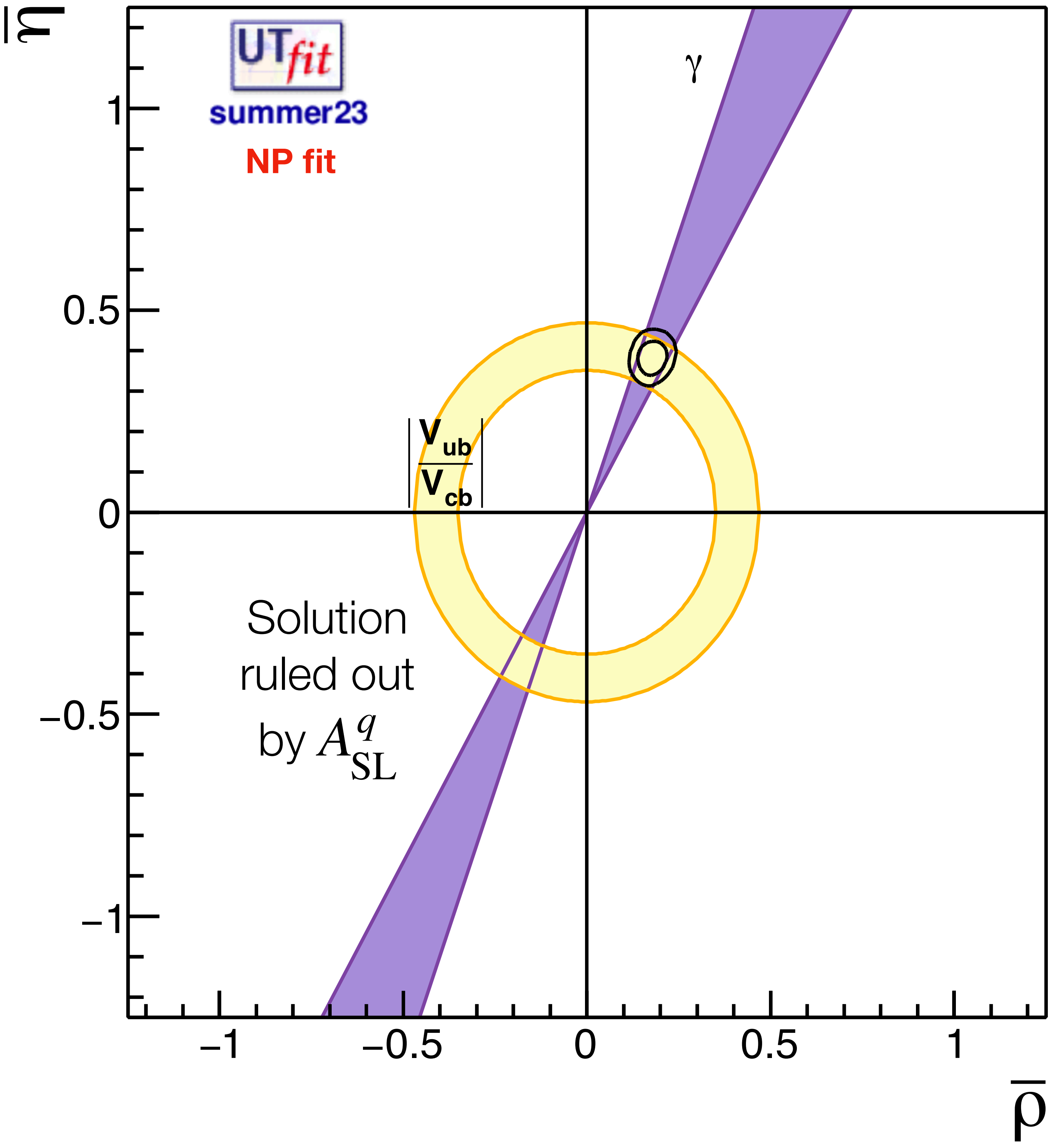
[to appear soon]

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

O(10) new parameters

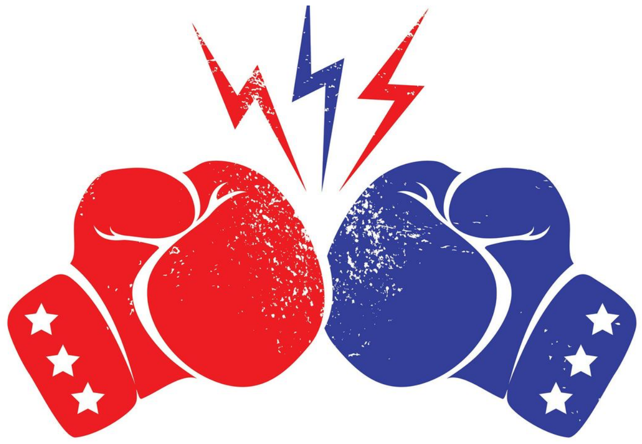
NP UT Analysis — 2023

*** **Assumption:** only FCNC amplitudes affected by NP ***



NP UT Analysis

$$\bar\rho = 0.167 \pm 0.025 \sim 15\%$$
$$\bar\eta = 0.361 \pm 0.027 \sim 7.5\%$$



$$\bar\rho = 0.160 \pm 0.009 \sim 6\%$$
$$\bar\eta = 0.346 \pm 0.009 \sim 3\%$$

SM UT Analysis

UT Bounds on NP

|ΔF| = 2 Weak EFT

SM/MFV

$$O_1^{q_iq_j} = \bar{q}^{\alpha}_{jL}\gamma_\mu q^{\alpha}_{iL}\, \bar{q}^{\beta}_{jL}\gamma^\mu q^{\beta}_{iL}$$

$$O_2^{q_iq_j} = \bar{q}^{\alpha}_{jR} q^{\alpha}_{iL}\, \bar{q}^{\beta}_{jR} q^{\beta}_{iL}$$

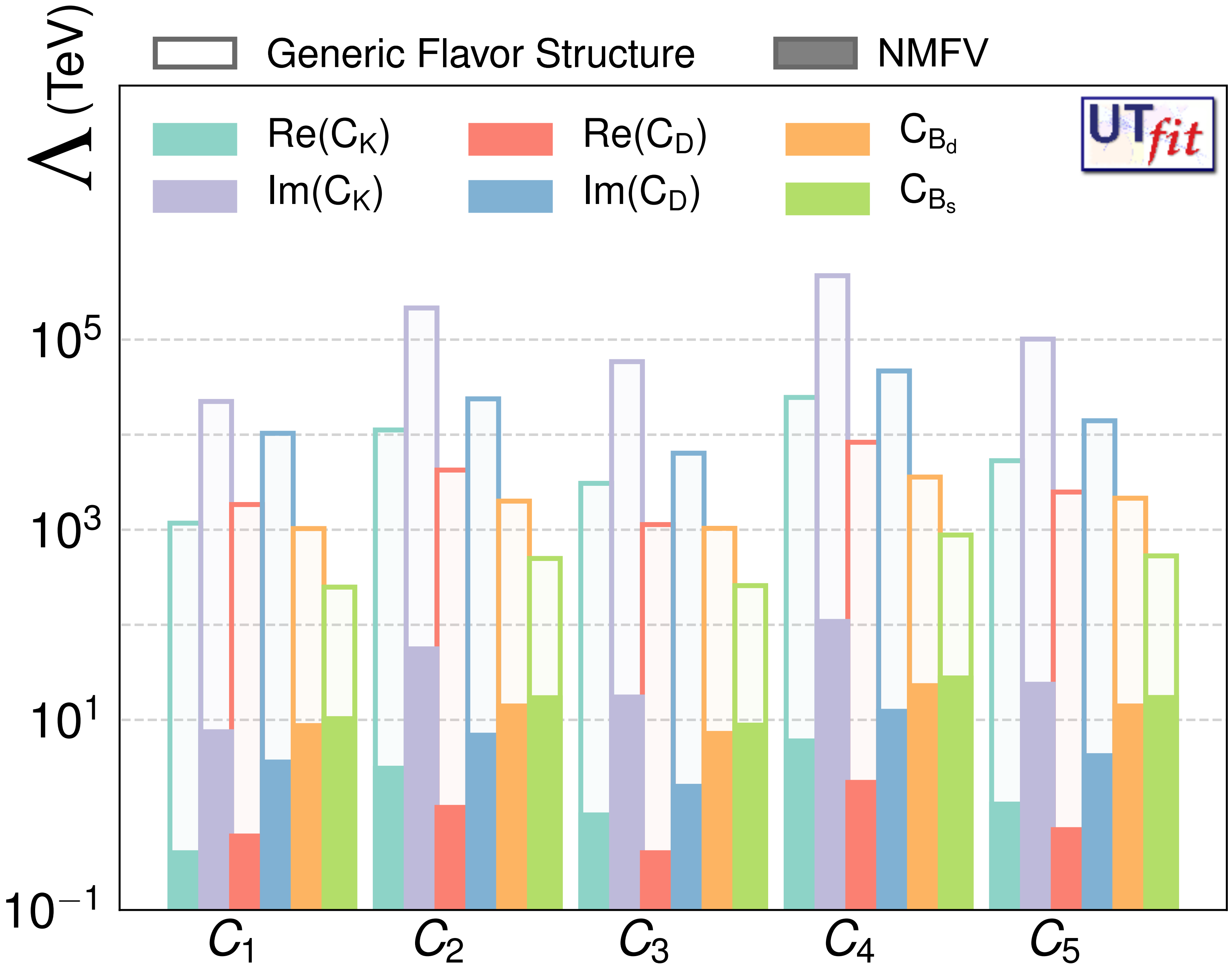
$$O_3^{q_iq_j} = \bar{q}^{\alpha}_{jR} q^{\beta}_{iL}\, \bar{q}^{\beta}_{jR} q^{\alpha}_{iL}$$

$$O_4^{q_iq_j} = \bar{q}^{\alpha}_{jR} q^{\alpha}_{iL}\, \bar{q}^{\beta}_{jL} q^{\beta}_{iR}$$

$$O_5^{q_iq_j} = \bar{q}^{\alpha}_{jR} q^{\beta}_{iL}\, \bar{q}^{\beta}_{jL} q^{\alpha}_{iR}$$

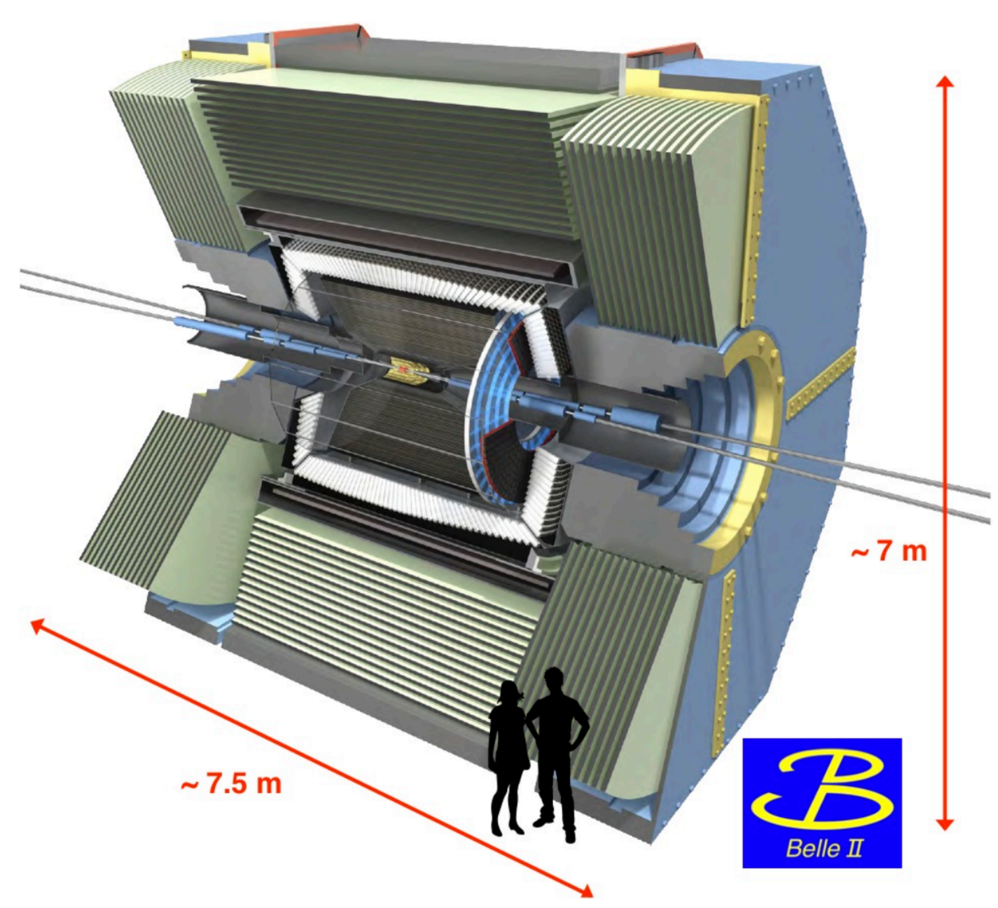
$+$ chirally flipped $\widetilde{O}^{q_iq_j}_{1,2,3}$

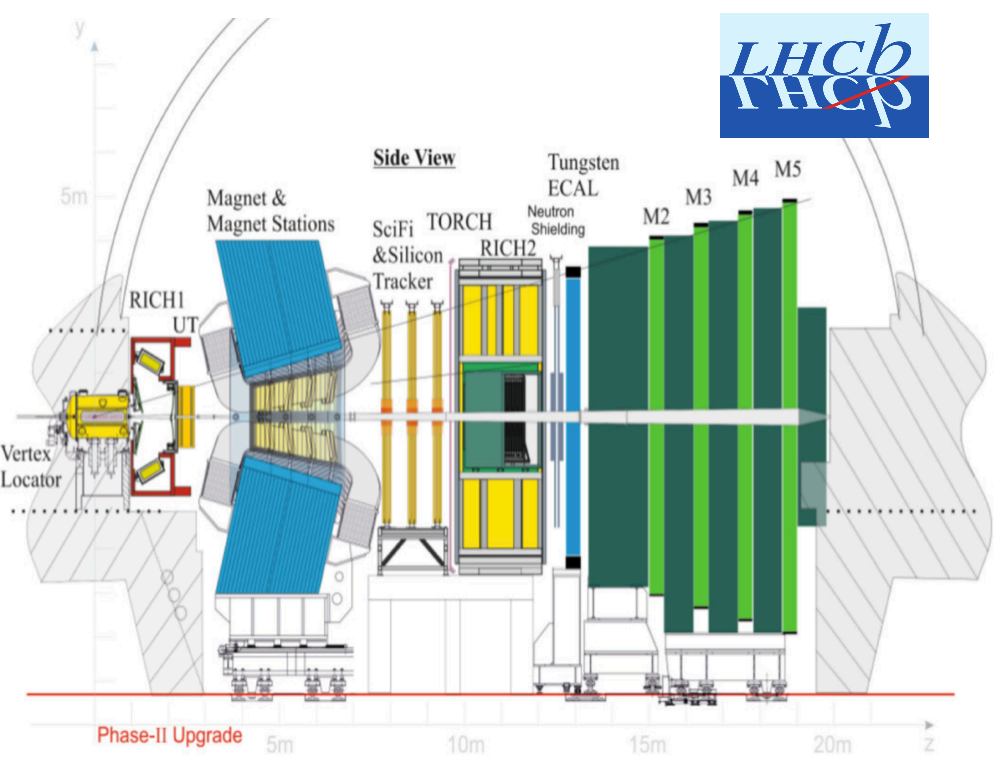
see, e.g. arXiv:/0707.0636



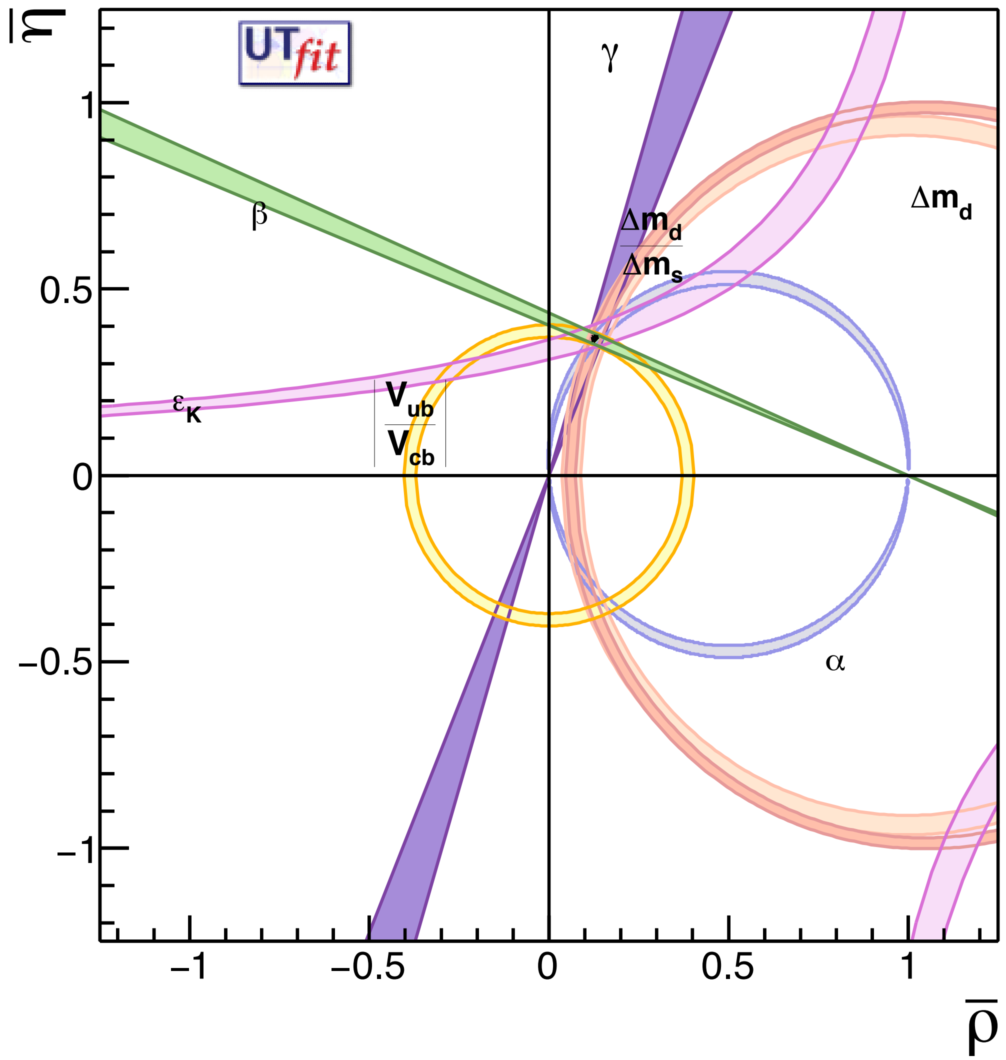
- ○ **Generic NP** = no SM protection, i.e.: $C(\Lambda) \sim 1/\Lambda^2$ ⇨ $\Lambda > 4.7 \times 10^5$ TeV
- ● **Next-to-MFV** = SM-like protection + O(1) phases ➡ $\Lambda > 108$ TeV

A LOOK @ [BACK TO] THE FUTURE …





UT: (G)old Future Projections



— 5/ab @ Belle II + 10/fb @ LHCb

SM fit $\bar{\rho} \sim 4\%$ $\bar{\eta} \sim 2\%$

NP fit $\bar{\rho} \sim 5\%$ $\bar{\eta} \sim 3\%$

— 50/ab @ Belle II (?)

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

NP fit $\bar{\rho} \sim 3.5\%$ $\bar{\eta} \sim 2\%$

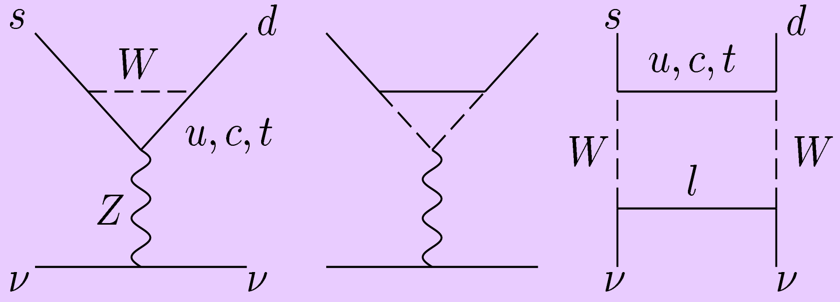
For more details, arXiv:1808.10567

TH inputs improvement

Parameter	Error (5ab^{-1})	Error (50ab^{-1})
$\alpha_s(M_Z)$	±0.0012	±0.0004
m_t (GeV)	±0.73	±0.6
$\lvert V_{us}\rvert$	±0.0011	±0.0002
B_K	±0.029	±0.002
f_{B_s} (GeV)	±0.05	±0.001
f_{B_s}/f_{B_d}	±0.013	±0.006
B_{B_s}/B_{B_d}	±0.036	±0.007
B_{B_s}	±0.053	±0.007

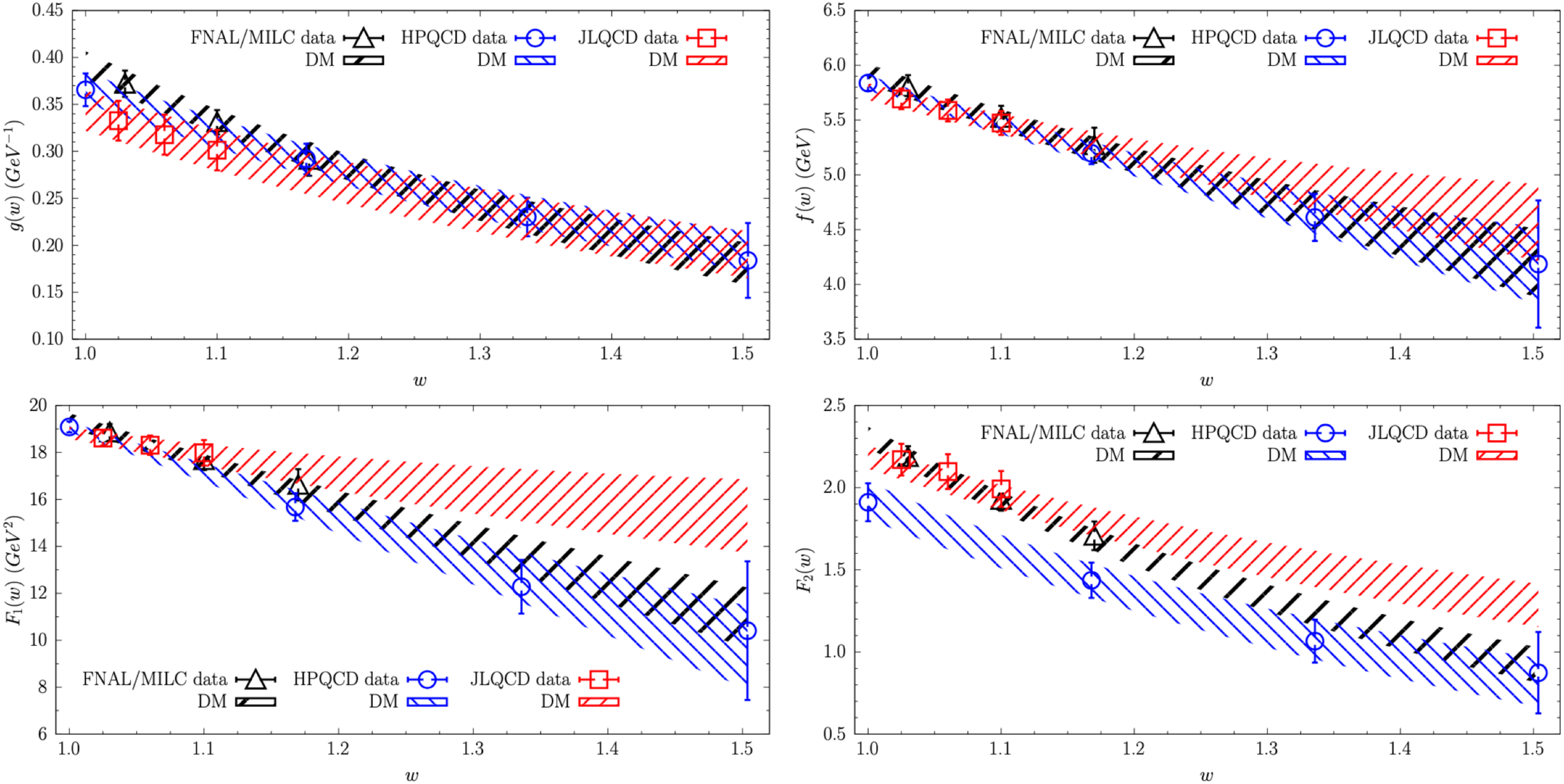
New observables in UT

E.g.: $BR(K \to \pi\nu\bar{\nu})$



A look @ V_{cb}

Ludovico Vittorio @ CKM 23



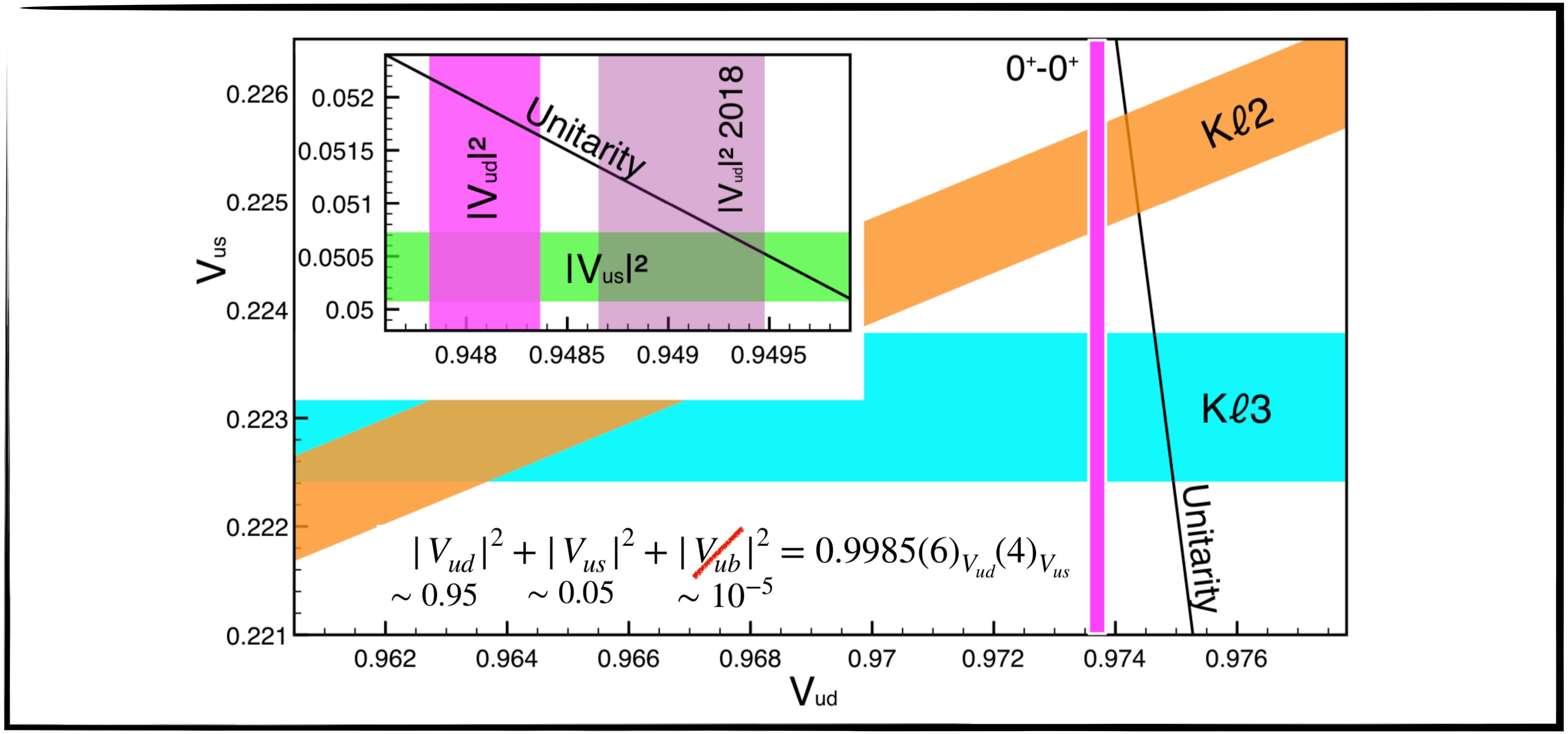
JLQCD:
arXiv:2306.05657

FNAL/MILC:
EPJC '22
(arXiv:2105.14019)

HPQCD:
arXiv:2304.03137

A look @ the 1st row

Misha Gorshteyn @ CKM 23



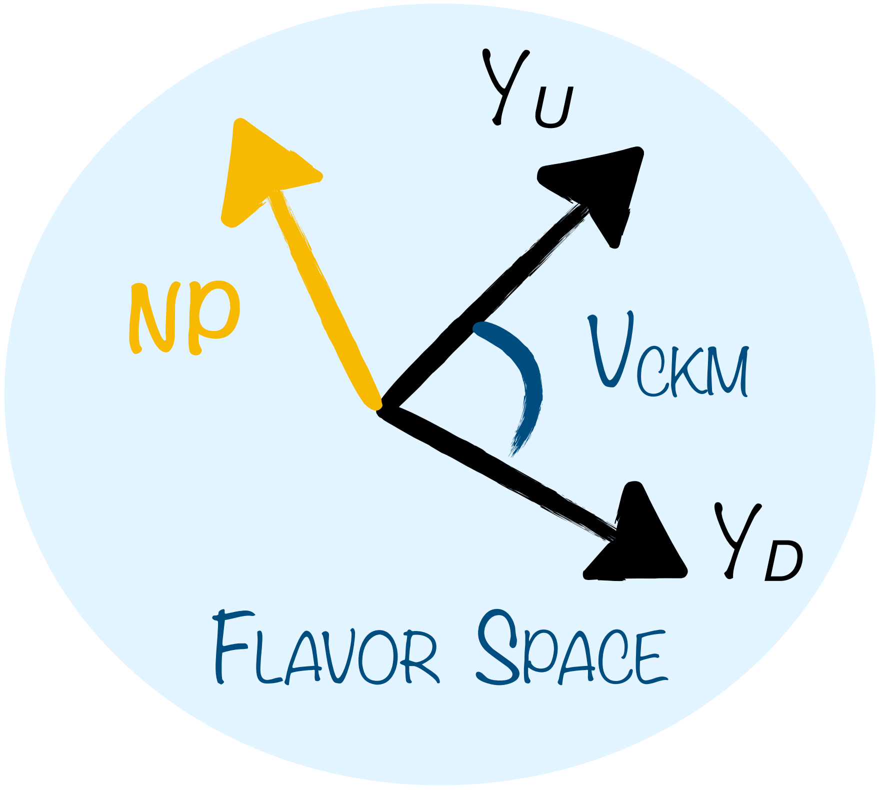
- LQCD on (semi)leptonic decays : Beyond % precision —> **control of ΔI & QED**

See , e.g., *Phys.Rev.D 105 (2022) 11, 114507*

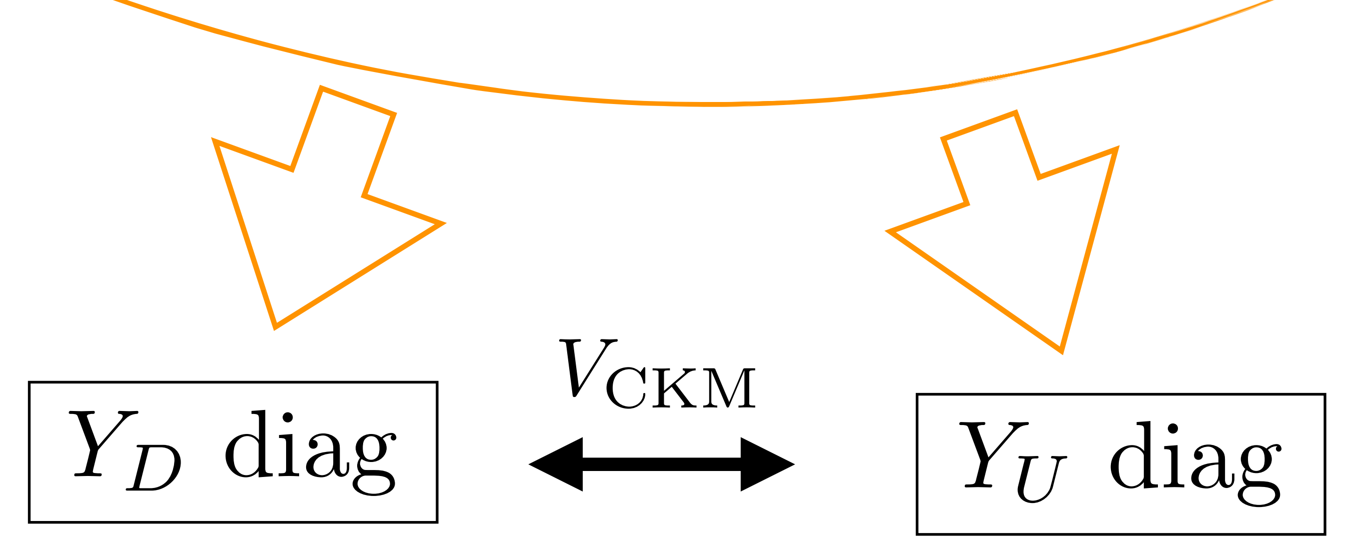
- 0^+ —> 0^+ transitions “better” than neutron decay, **but $\pi^+ \to \pi^0 e^+ \nu$ cleanest though**

Interesting proposal: PIONEER — *arXiv:2203.01981*

NP: Going Beyond the Weak EFT



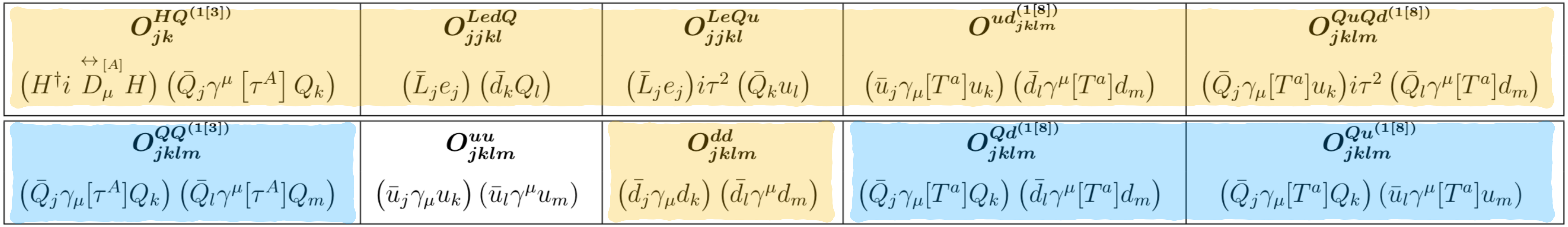
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i,d>4} \frac{C_i \mathcal{O}_i^{(d)}}{\Lambda_{\text{NP}}^{d-4}}$$



$\boxed{Y_D \text{ diag}}$ $\xleftrightarrow{V_{\text{CKM}}}$ $\boxed{Y_U \text{ diag}}$

$|\Delta F| = 2$ bounds in the SMEFT — ***Phys. Lett. B 799 (2019) 135062***

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

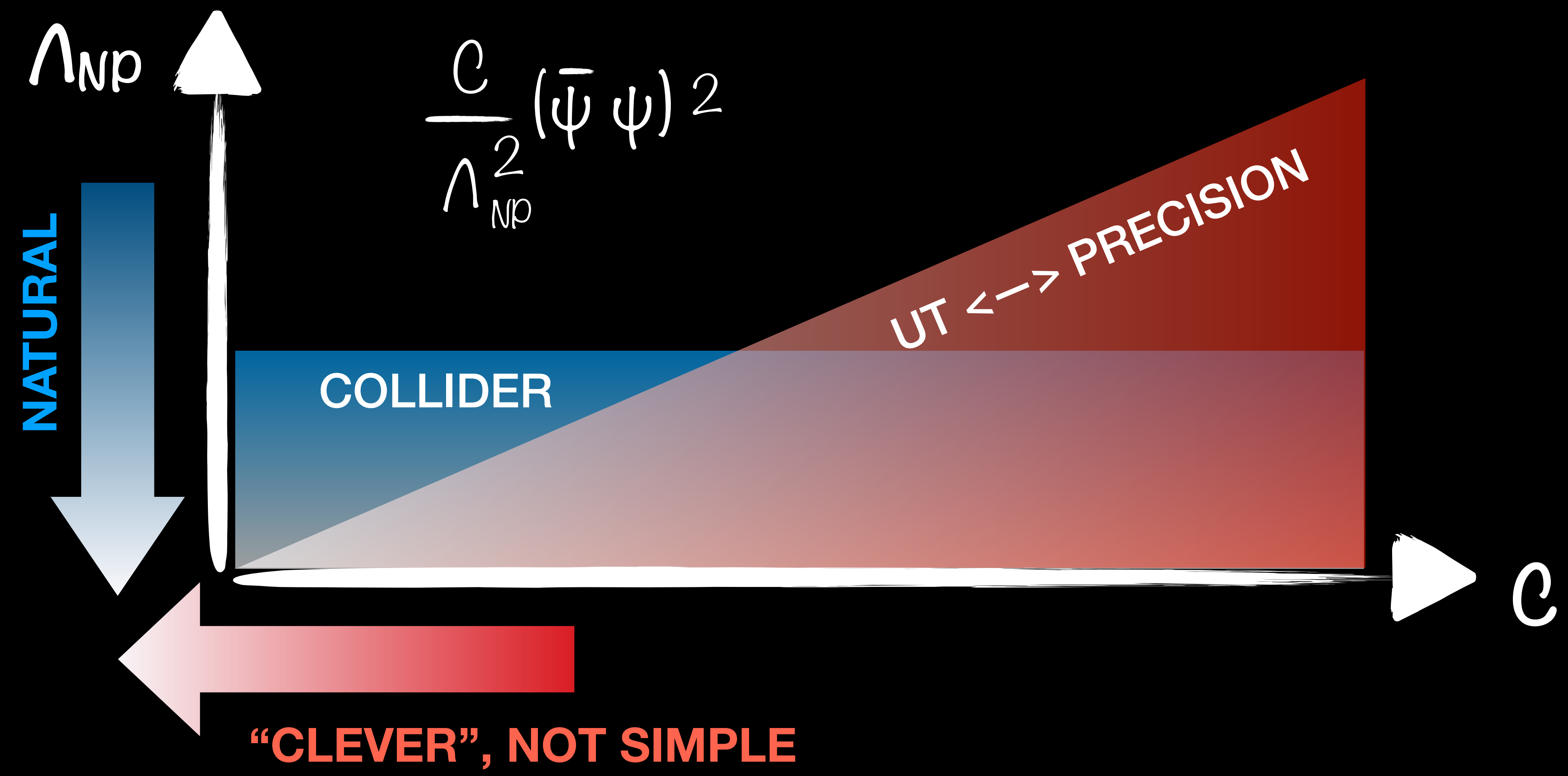
poorly constrained

FLAVOR MISALIGNMENT

... UT IN THE SMEFT: A LOT OF WORK STILL TO BE DONE !

Take Home

- SM UT : Towards % precision … Overall remarkable consistency.
- NP UT :



- NEXT-GEN UT : Reaching % precision = EXP efforts + TH leap!

BACKUP

Result summary

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.689 ± 0.019	0.739 ± 0.027	~ 1.5
γ	65.4 ± 3.3	65.2 ± 1.5	< 1
α	93.8 ± 4.5	92.3 ± 1.5	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.01 ± 0.14	~ 1.6
$\lvert V_{cb} \rvert \cdot 10^3$	41.32 ± 0.73	42.21 ± 0.51	~ 1
$\lvert V_{cb} \rvert \cdot 10^3$ (excl)	40.55 ± 0.46		~ 2.5
$\lvert V_{cb} \rvert \cdot 10^3$ (incl)	42.16 ± 0.50		< 1
$\lvert V_{ub} \rvert \cdot 10^3$	3.75 ± 0.26	3.70 ± 0.09	< 1
$\lvert V_{ub} \rvert \cdot 10^3$ (excl)	3.64 ± 0.16	-	< 1
$\lvert V_{ub} \rvert \cdot 10^3$ (incl)	4.13 ± 0.26	-	~ 1.5
$BR(B \to \tau\nu)[10^4]$	1.06 ± 0.19	0.865 ± 0.041	~ 1
$BR(B \to \mu\mu)[10^9]$	3.41 ± 0.29	3.45 ± 0.13	< 1
$\lvert V_{ud} \rvert$	0.97433 ± 0.00017	0.9737 ± 0.0011	< 1

Lattice inputs summary

Observables	**Measurement**
B_K	**0.756 ± 0.016**
f_{Bs}	**0.2301 ± 0.0012**
f_{Bs}/f_{Bd}	**1.208 ± 0.005**
B_{Bs}/B_{Bd}	**1.015 ± 0.021**
B_{Bs}	**1.284 ± 0.059**

We quote the weighted average of the N_f=2+1+1 and N_f=2+1 results with the error rescaled when chi2/dof > 1, as done by FLAG for the N_f=2+1+1 and N_f=2+1 averages separately

Observables	**Measurement**
V_{ud}	**0.97432 ± 0.00013**
V_{us}	**0.2249 (± 0.0004)**

V_{ud} is taken from the PDG average of V_{ud} FLAG numbers (for 2+1+1 and 2+1) and superallowed beta decays value.

V_{us} is not used in the fit

Lattice result summary

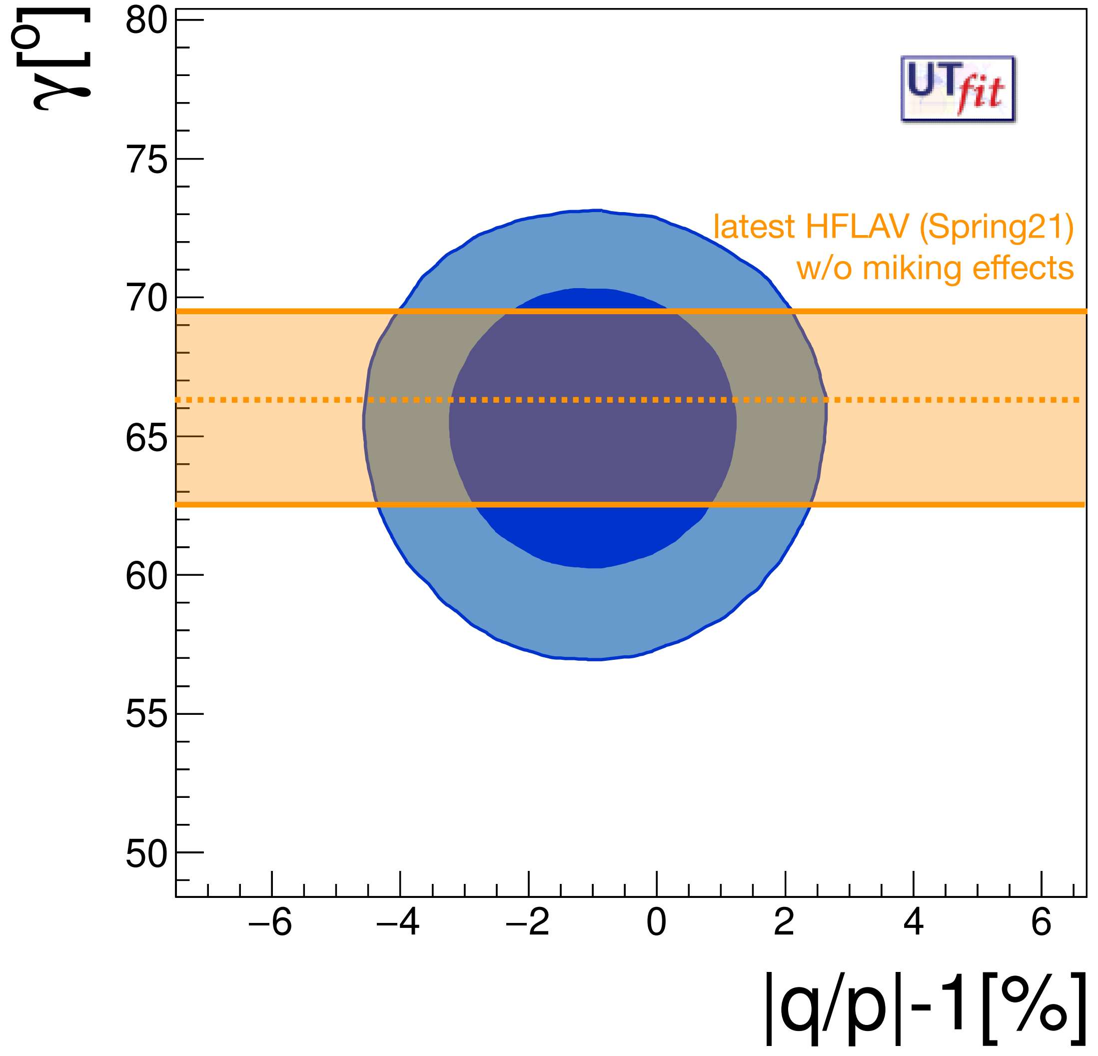
We obtain the predictions for the lattice parameters in different configurations in the fit:

- 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 B_K parameter

Observables	Measurement	Prediction
B_K	**0.756 ± 0.016**	**0.840 ± 0.053**
Ratios only		
f_{Bs}	**0.2301 ± 0.0012**	**0.234 ± 0.010**
B_{Bs}	**1.284 ± 0.059**	**1.27 ± 0.10**
B pars only		
f_{Bs}/f_{Bd}	**1.208 ± 0.005**	**1.201 ± 0.027**
f_{Bs}	**0.2301 ± 0.0012**	**0.229 ± 0.006**
B_K only		
f_{Bs}	**0.2301 ± 0.0012**	**0.226 ± 0.011**
f_{Bs}/f_{Bd}	**1.208 ± 0.005**	**1.07 ± 0.12**
B_{Bs}	**1.284 ± 0.059**	**1.32 ± 0.12**
B_{Bs}/B_{Bd}	**1.015 ± 0.021**	**1.29 ± 0.29**

What’s new for EPS23

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



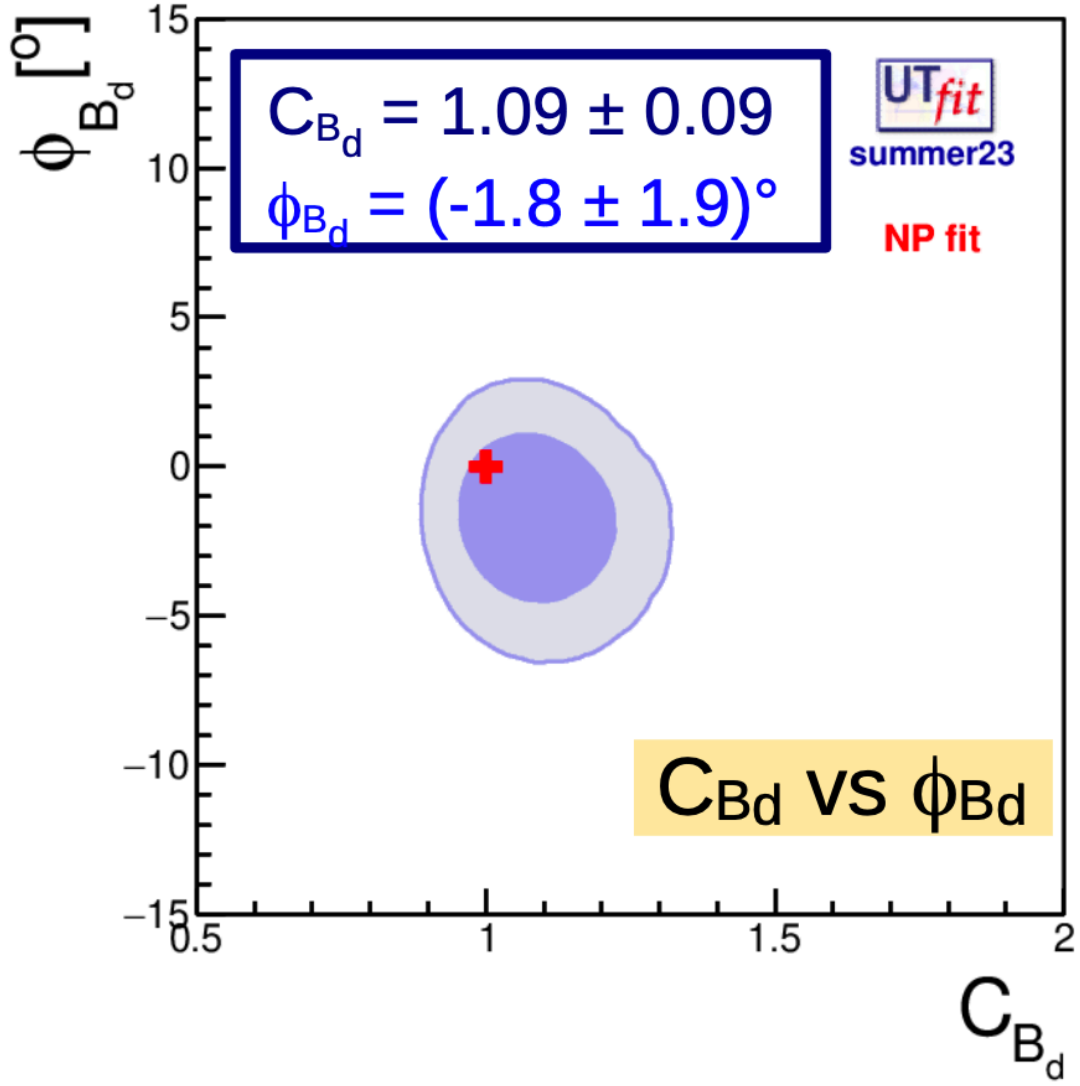
Results of BSM analysis: New Physics parameters

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

K system

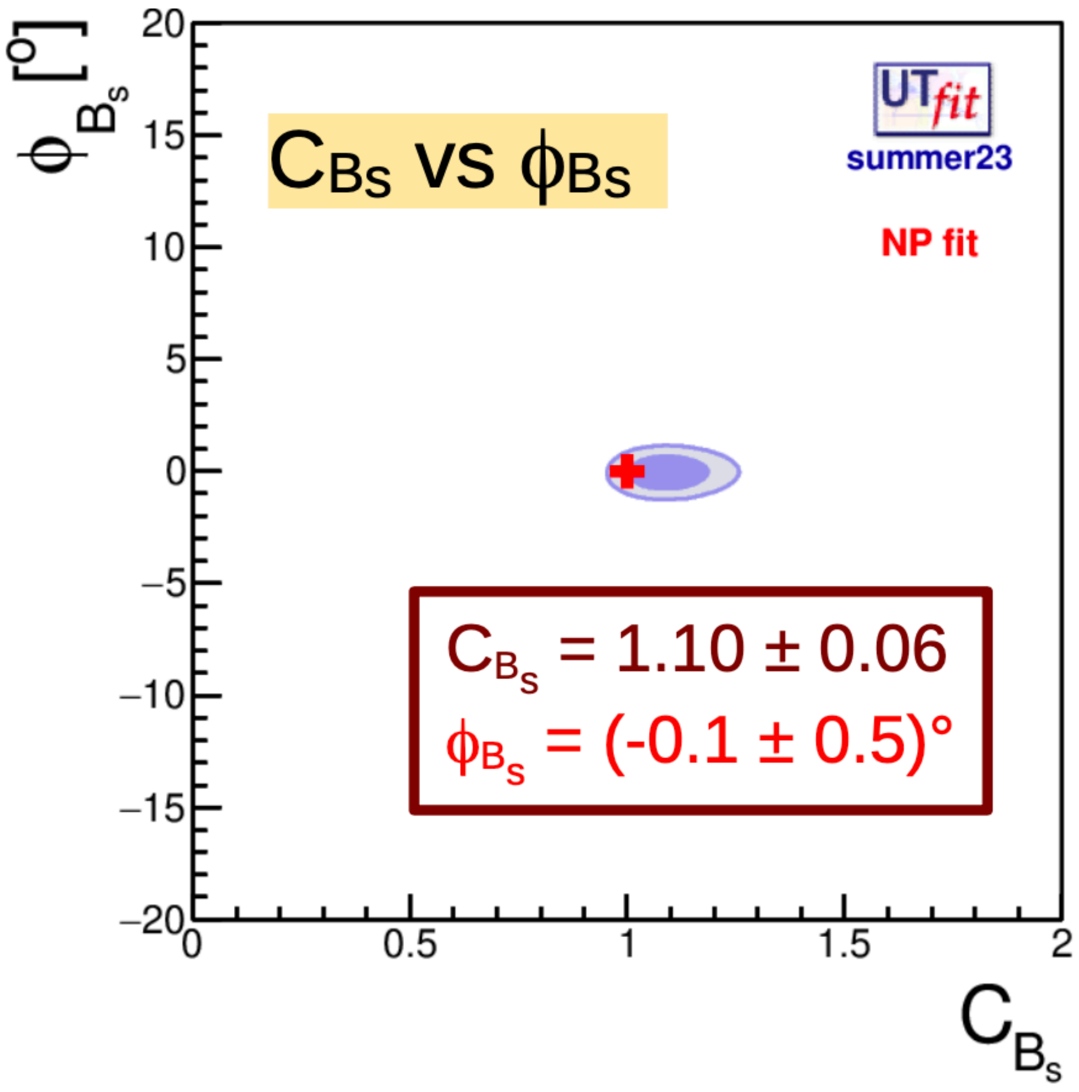
$C_{\epsilon_K} = 1.09 \pm 0.10$

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_d} vs ϕ_{B_d}



C_{B_s} vs ϕ_{B_s}

$C_{B_s} = 1.10 \pm 0.06$
$\phi_{B_s} = (-0.1 \pm 0.5)°$

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