Test of the Standard Model and the Search for New Physics Using Unitarity Triangle Fits

Ayan Paul

ERC Ideas: NPFlavour

INFN, Sezione di Roma. Roma, Italy.

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the plan

- ✓ the look of the Unitarity Triangle till now
- ✓ high-precision Standard Model fits and reaches for new Physics
- ✓ making the analysis more accessible to everyone: migration to a public code: `HEPfit`

the brush strokes that have appeared

$$B_s \to \mu^+\mu^- \; : \; \downarrow \text{SM}$$

$$B_d \to \mu^+\mu^- \; : \; \uparrow \text{SM}$$

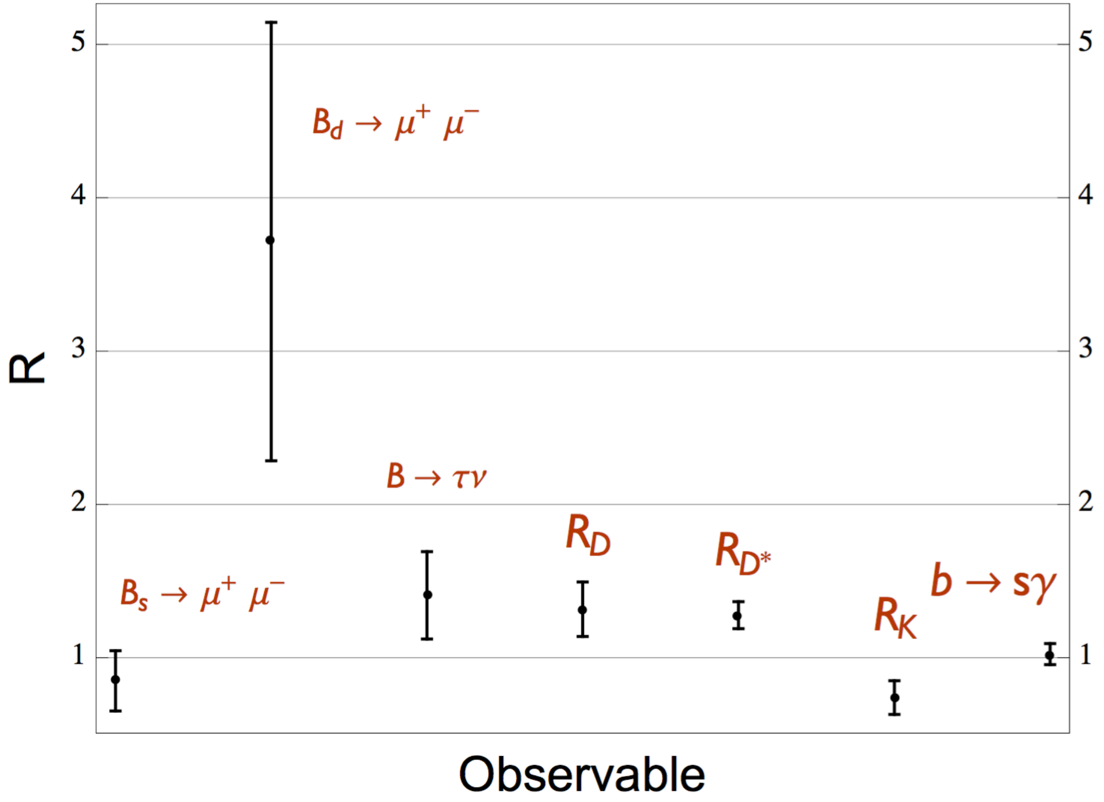
$$B \to \tau\nu \; : \; \uparrow \text{SM}$$

$$R_D \; : \; \uparrow \text{SM}$$

$$R_{D^*} \; : \; \uparrow \text{SM}$$

$$R_K \; : \; \downarrow \text{SM}$$

$$b \to s\gamma \; : \; \to \text{SM} \leftarrow$$



parameterization of quark mixing

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

the definition in terms of 3 angles and a phase

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij} \qquad s_{ij}, c_{ij} \geq 0$$

The angles in terms of the elements

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda\left|\frac{V_{cb}}{V_{us}}\right|$$

$$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar{\rho} + i\bar{\eta})\sqrt{1 - A^2\lambda^4}}{\sqrt{1-\lambda^2}[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})]}$$

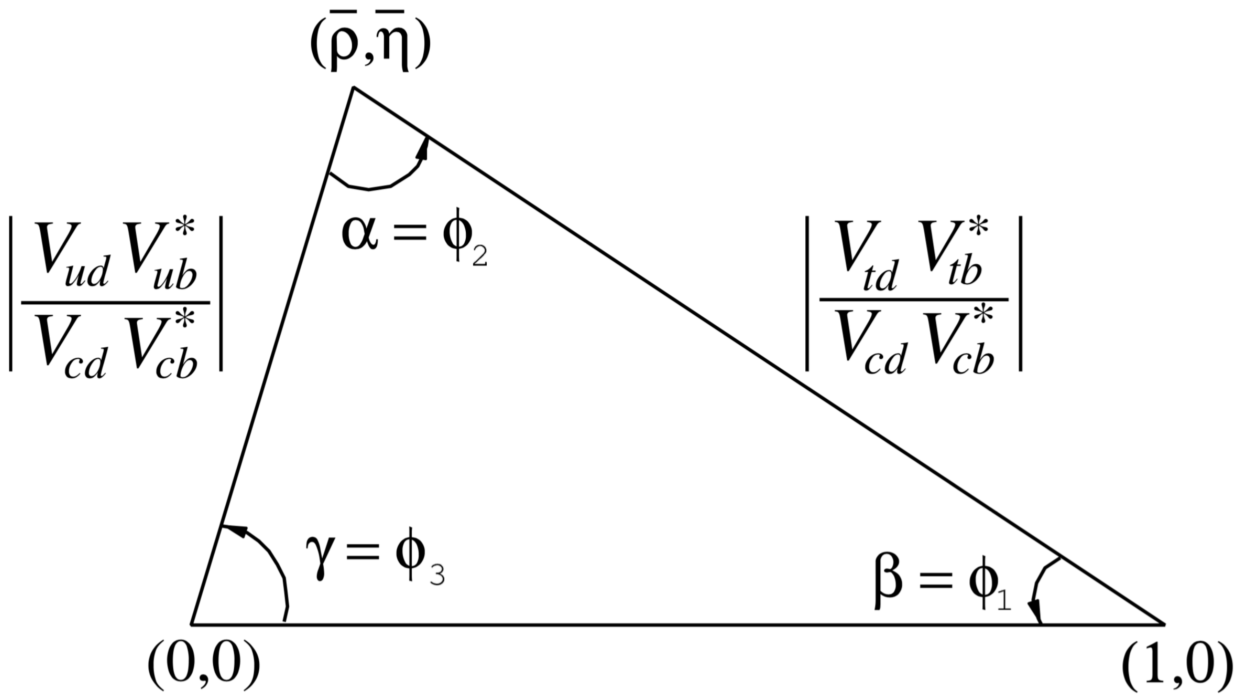
$$\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$$

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

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

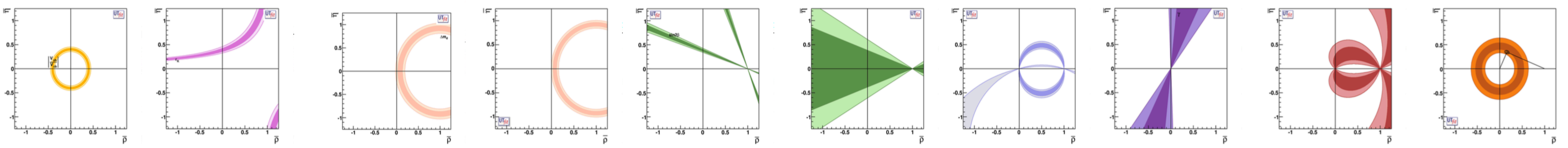
the Wolfenstein parameterization

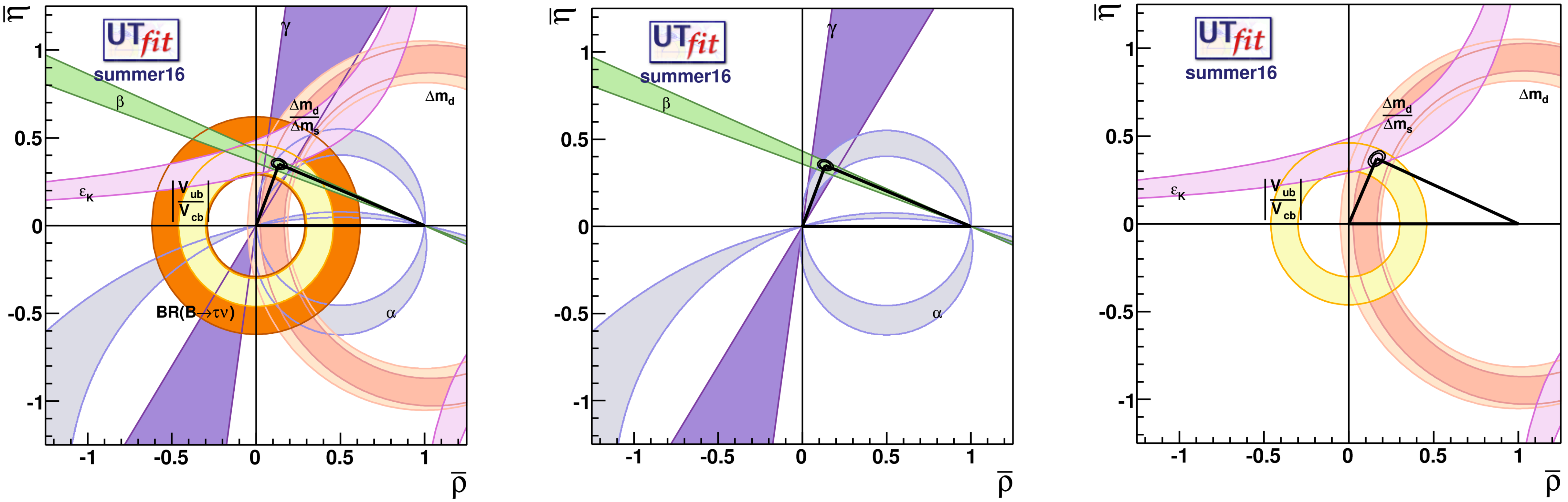
the Unitarity Triangle



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

the Unitarity Triangle

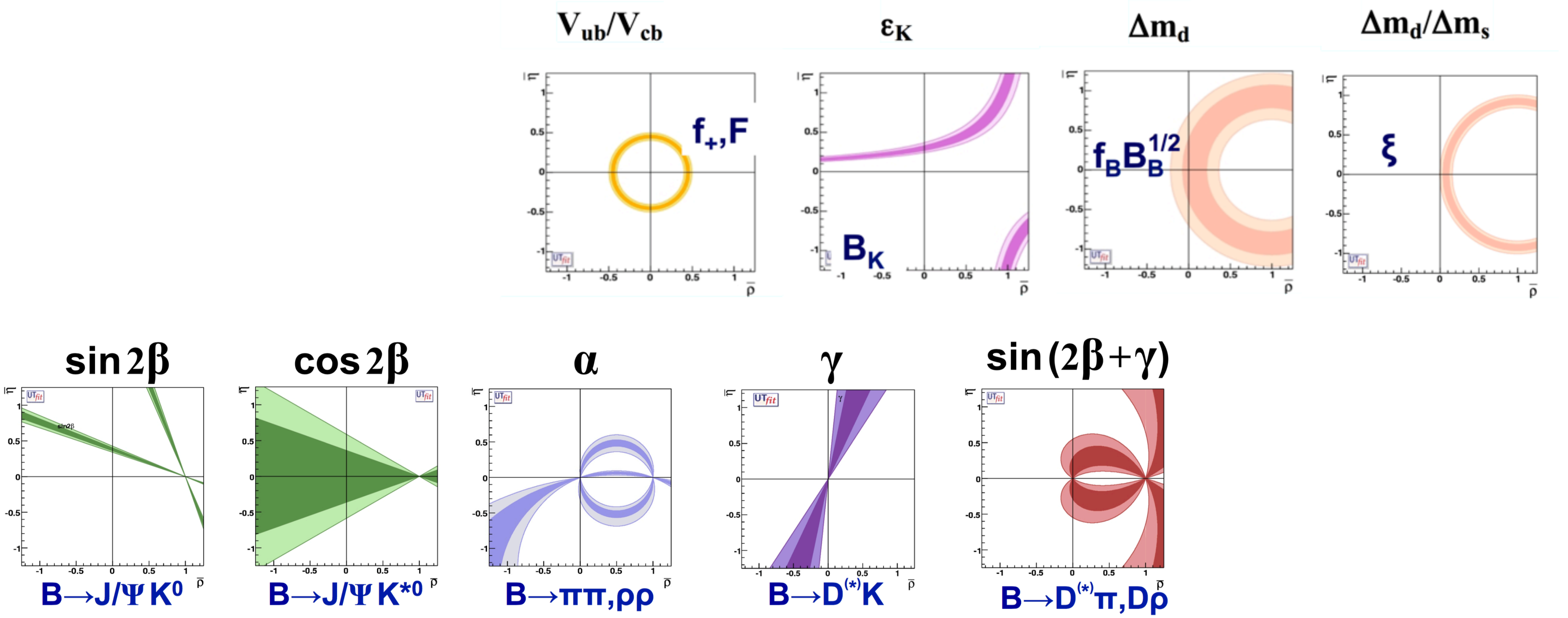




"the big picture"

so how does it help?

- ✓ in the Standard Model flavour violation has withstood the rigors of precision measurement
- ✓ while we wait for some real resonances to show up at the few TeV scale, one can start probing the several TeV scale with flavour dynamics
- ✓ quantum effects at the loop level leave small signatures but also allow for access to much higher scales



the Standard Model fit

Parameter	Input value	Full fit	SM Prediction	Pull
$\bar{\rho}$	–	–	0.144 ± 0.018	–
$\bar{\eta}$	–	–	0.346 ± 0.012	–
ρ	–	–	0.148 ± 0.019	–
η	–	–	0.355 ± 0.013	–
A	–	–	0.831 ± 0.012	–
λ	0.22534 ± 0.00089	–	0.22505 ± 0.00064	-0.2
$\sin\theta_{12}$	–	–	0.22505 ± 0.00064	–
$\sin\theta_{23}$	–	–	0.04219 ± 0.00056	–
$\sin\theta_{13}$	–	–	0.00366 ± 0.00011	–
$\delta[^\circ]$	–	–	67.4 ± 2.8	–
$\alpha[^\circ]$	92.5 ± 5.5 and 166.1 ± 0.6	90.6 ± 2.7	88.9 ± 3.5	-0.6
$\beta[^\circ]$	–	22.07 ± 0.83	23.9 ± 1.6	–
$\gamma[^\circ]$	-109.8 ± 7.7 and 70.9 ± 3.2	67.1 ± 2.8	66.3 ± 3.0	-0.5

Inclusive vs. exclusive tension remains…

Parameter	Input value	Full fit	SM Prediction	Pull
$\|V_{ub}\|$	0.00380 ± 0.00040	0.00366 ± 0.00011	0.00366 ± 0.00011	-0.4
$\|V_{ub}\|$ (excl.)	0.00369 ± 0.00014	–	–	-0.2
$\|V_{ub}\|$ (incl.)	0.00440 ± 0.00022	–	–	-3.0
$\|V_{cb}\|$	0.0408 ± 0.0011	0.04218 ± 0.00057	0.04215 ± 0.00055	$+1.0$
$\|V_{cb}\|$ (excl.)	0.03919 ± 0.00070	–	–	$+3.2$
$\|V_{cb}\|$ (incl.)	0.04220 ± 0.00070	–	–	-0.1

testing for New Physics

Δ B = 2

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\rm eff}^{\rm full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\rm eff}^{\rm SM} | \bar{B}_q^0 \rangle}\,, \qquad (q = d, s)$$

SM limit

$$\boxed{C_{B_q} = 1 \quad \phi_{B_q} = 0}$$

$$\Delta m_d^{\rm exp} = C_{B_d} \Delta m_d^{\rm SM}$$

$$\Delta m_s^{\rm exp} = C_{B_s} \Delta m_s^{\rm SM}$$

$$\sin 2\beta^{\rm exp} = \sin(2\beta^{\rm SM} + 2\phi_{B_d})$$

$$\phi_s^{\rm exp} = (\beta_s^{\rm SM} - \phi_{B_s})$$

$$\alpha^{\rm exp} = \alpha^{\rm SM} - \phi_{B_d}$$

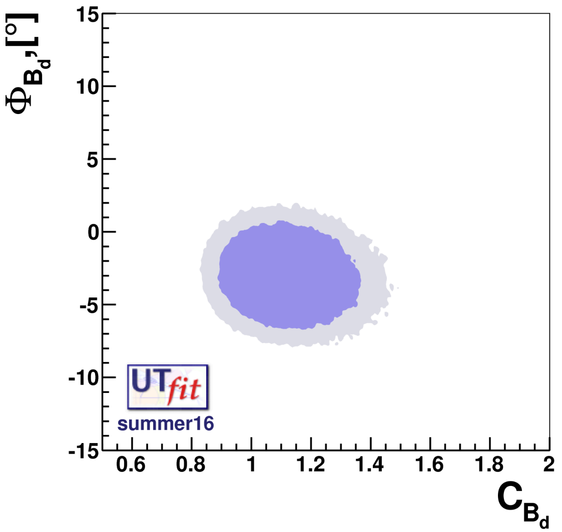
Δ S = 2

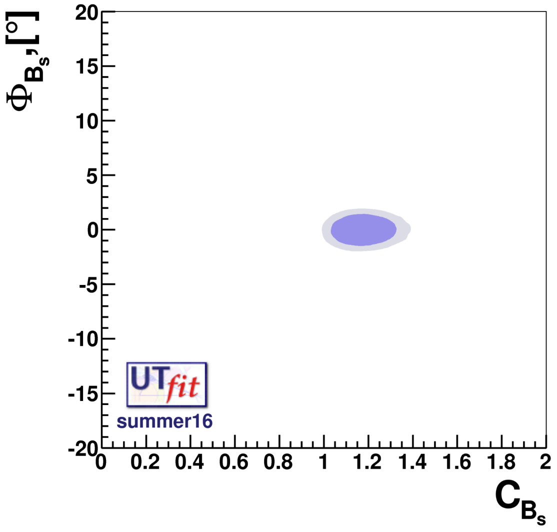
$$\Delta m_K^{\rm exp} = C_{\Delta m_K} \Delta m_K^{\rm SM}$$

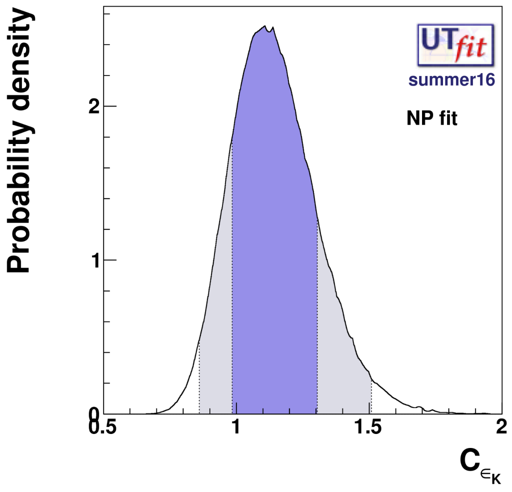
$$\epsilon_K^{\rm exp} = C_{\epsilon_K} \epsilon_K^{\rm SM}$$

the New Physics fit

Parameter	Input value	Prediction
$\bar{\rho}$	–	0.151 ± 0.040
$\bar{\eta}$	–	0.384 ± 0.037
ρ	–	0.155 ± 0.041
η	–	0.394 ± 0.038
A	–	0.777 ± 0.025
λ	0.22534 ± 0.00089	0.22490 ± 0.00064
$\lvert V_{ub}\rvert$	–	–
$\lvert V_{cb}\rvert$	–	–
$\alpha[^\circ]$	–	88.0 ± 5.9
$\beta[^\circ]$	–	23.7 ± 2.2
$\gamma[^\circ]$	–	–
C_{B_d}	–	1.13 ± 0.16
$\phi_{B_d}[^\circ]$	–	-3.0 ± 2.4
C_{B_s}	–	1.18 ± 0.10
$\phi_{B_s}[^\circ]$	–	-0.016 ± 0.955
$C_{\epsilon K}$	–	1.14 ± 0.16
A_{SL_d}	-0.0015 ± 0.0017	-0.0027 ± 0.0014
A_{SL_s}	-0.0075 ± 0.0041	-0.00030 ± 0.00051







bringing UTfit to HEPfit

HEPfit

Rome I&III
- Jorge de Blas
- Debtosh Chowdhury
- Marco Ciuchini
- Otto Eberhardt
- Marco Fedele
- Enrico Franco
- Ayan Paul
- Luca Silvestrini

SISSA Trieste
- Giovanni Grilli di Cortona
- Mauro Valli

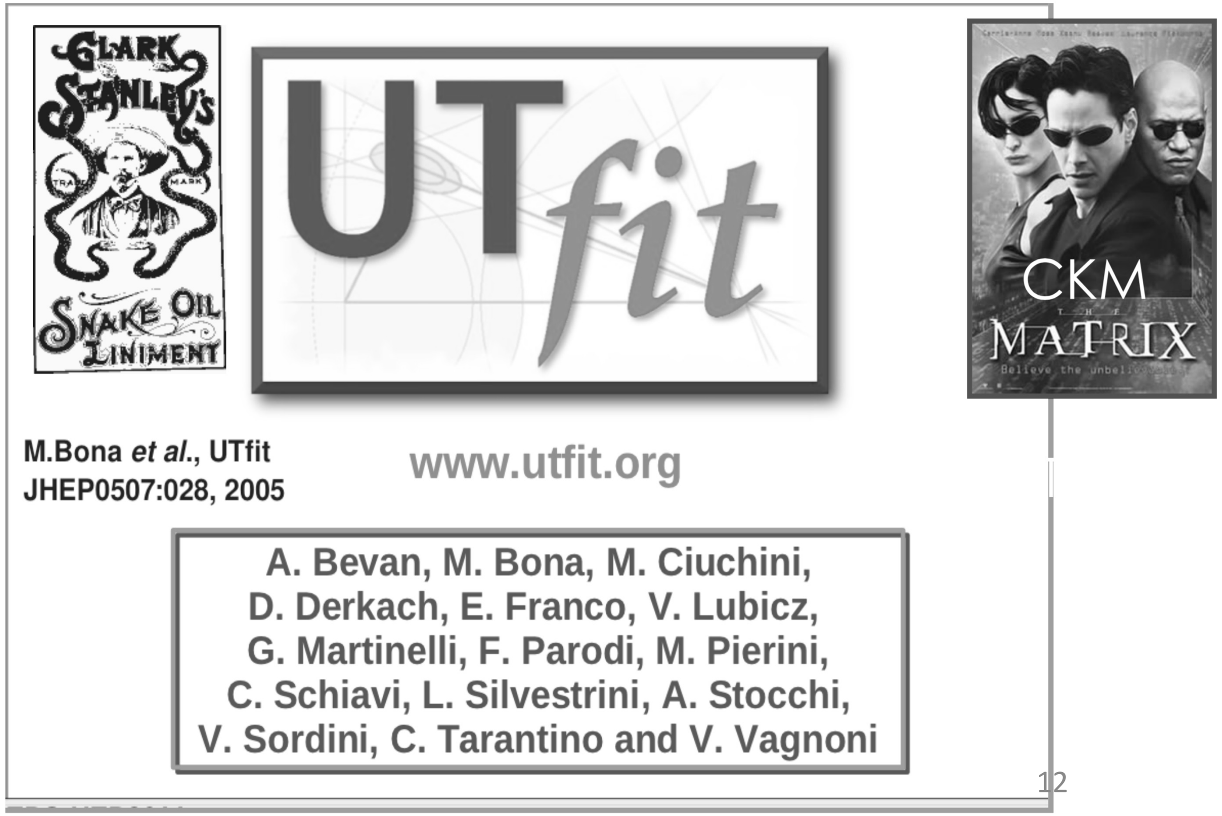
KEK
- Satoshi Mishima

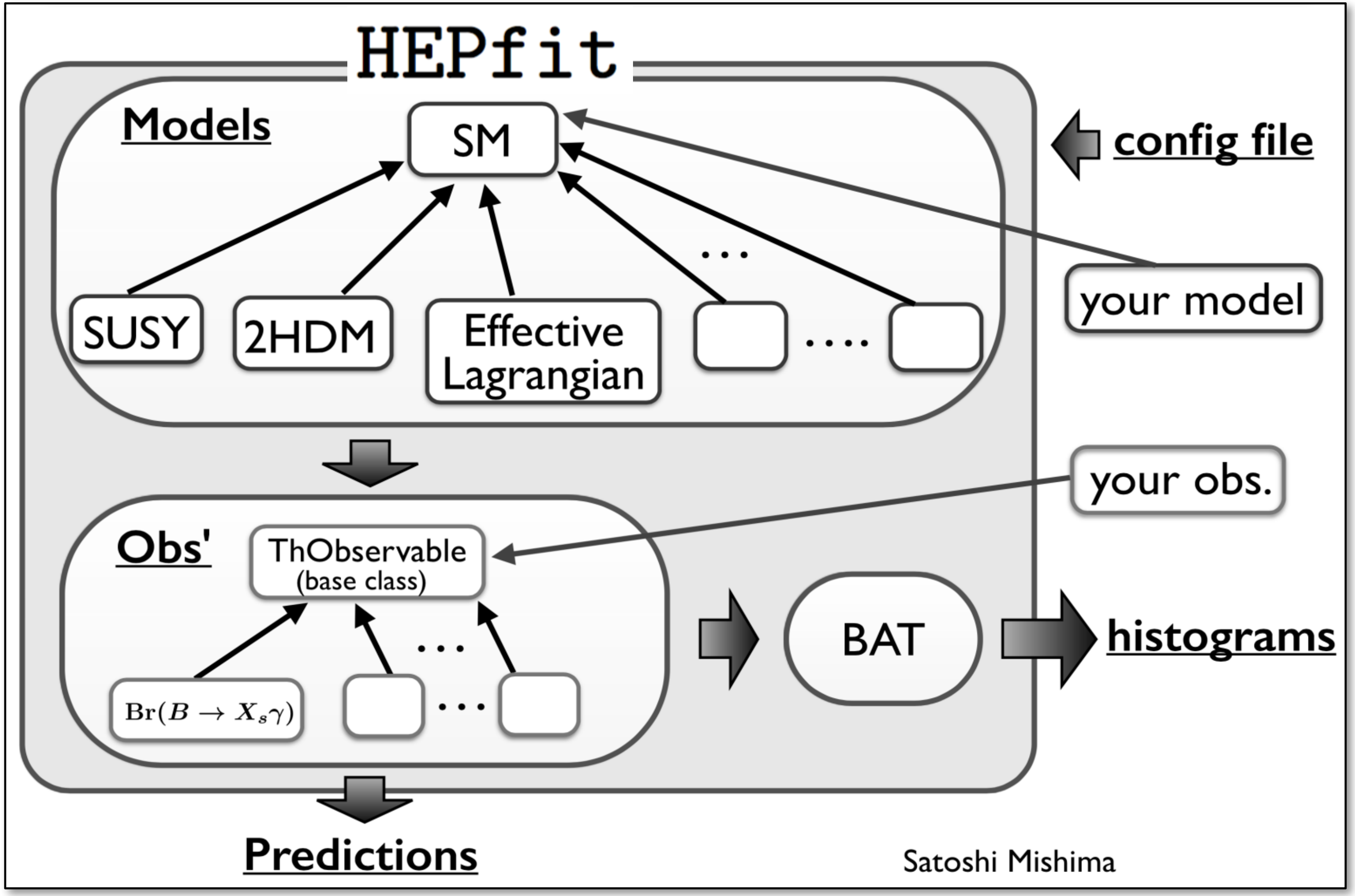
CERN
- Maurizio Pierini

Florida State University
- Laura Reina

Tohoku University
- Norimi Yokozaki

Lanzhou University
- Fu-Sheng Yu



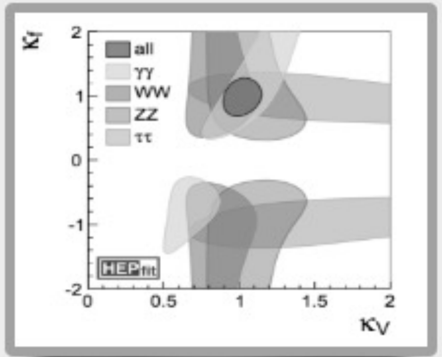


an analysis toolkit for **electroweak**, **flavour** and **Higgs** observables based on BAT (https://www.mppmu.mpg.de/bat/)

HEPfit

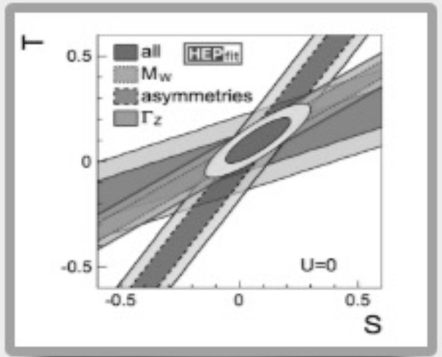
home developers samples documentation

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.



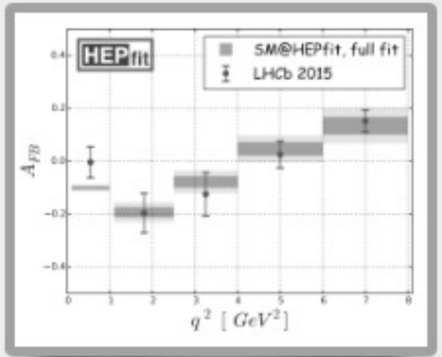
Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



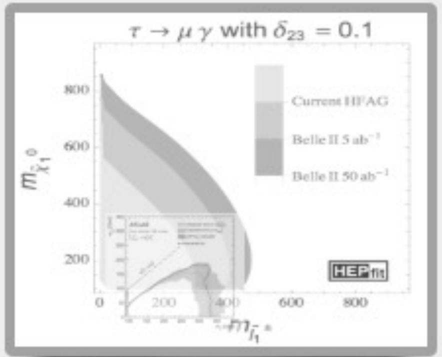
Precision Electroweak

Electroweak precision observables are included in HEPfit



Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.



BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

the HEPfit fit

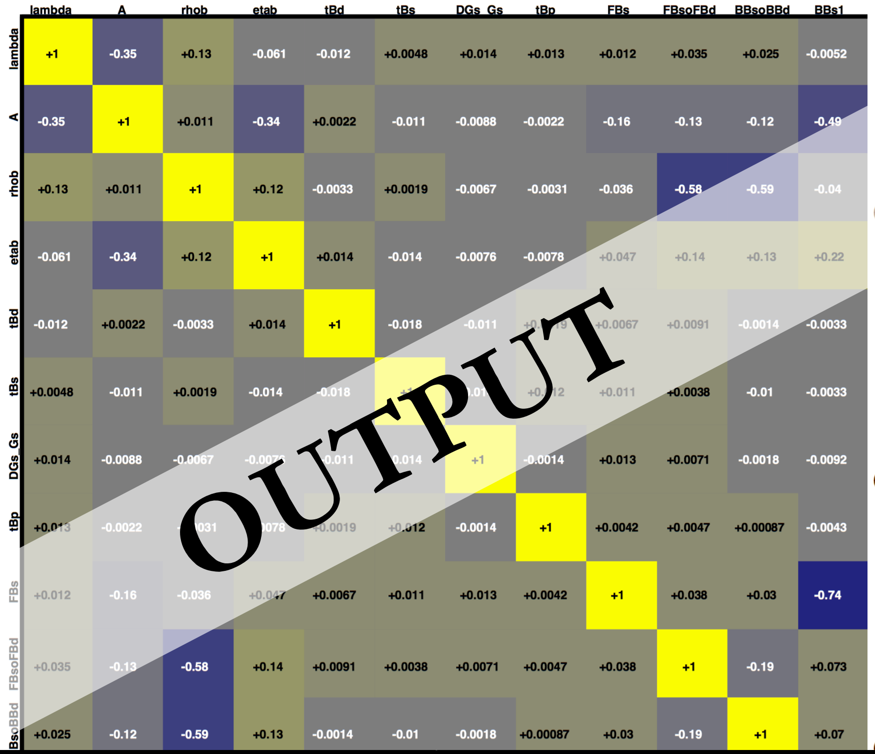
INPUT CONFIGURATION

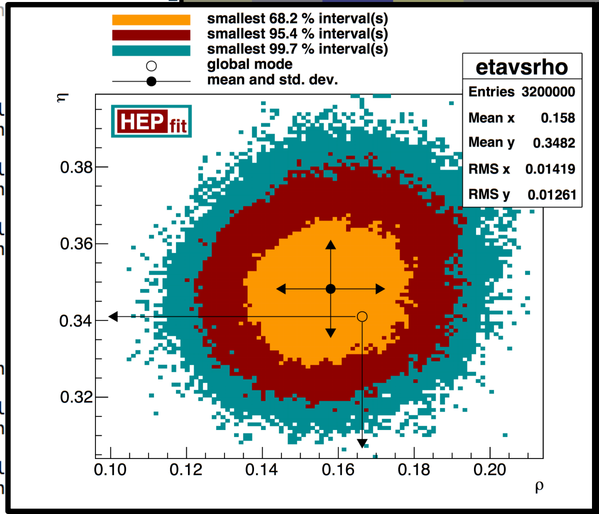
```
ModelFlag FlagCsi false
###########################################################################
# Model Parameters
#               name        ave         errg        errf
#--------------------------------------------------------------------------
### Parameters for Flavour (Mandatory for all models)
#   scheme for bag parameters [NDR=0, HV=1, LRI=2]
ModelParameter  lambda      0.2         0.          0.1
ModelParameter  A           0.8         0.          0.3
ModelParameter  rhob        0.1         0.          0.3
ModelParameter  etab        0.4         0.          0.4
ModelParameter  MBd         5.2796      0.          0.
ModelParameter  tBd         1.520       0.004       0.
ModelParameter  MBs         5.3668      0.          0.
ModelParameter  tBs         1.505       0.004       0.
# exp number in the meanwhile
ModelParameter  DGs_Gs      0.119       0.010       0.
ModelParameter  MBp         5.2793      0.          0.
ModelParameter  tBp         1.638       0.004       0.
ModelParameter  MK0         0.49761     0.          0.
ModelParameter  MKp         0.49368     0.          0.
ModelParameter  MKstar      0.89166     0.          0.
ModelParameter  tKstar      1.          0.          0.
ModelParameter  Mphi        1.019461    0.          0.
ModelParameter  tphi        1.          0.          0.
ModelParameter  FK          0.1561      0.          0.
ModelParameter  FBs         0.226       0.005       0.
ModelParameter  FKstar      0.225       0.          0.
ModelParameter  FKstarp     0.185       0.          0.
ModelParameter  Fphi        0.2         0.          0.
ModelParameter  Fphip       0.215       0.          0.
ModelParameter  alpha2phi   [illegible] 0.          0.
ModelParameter  FBsoFBd     1.204       0.016       0.
# Lubicz + Tarantino email on 15/3/16
ModelParameter  BBsoBBd     1.012       0.027       0.
# BBshat 1.38(11) and conversion factor to MSbar NDR 1.521
ModelParameter  BBs1        0.91        0.07        0.
ModelParameter  BBs2        0.77        0.06        0.
ModelParameter  BBs3        1.          0.18        0.
ModelParameter  BBs4        1.03        0.12        0.
ModelParameter  BBs5        1.7         0.18        0.
ModelParameter  BBd2        0.74        0.06        0.
ModelParameter  BBd3        0.98        0.2         0.
ModelParameter  BBd4        1.05        0.13        0.
ModelParameter  BBd5        1.67        0.25        0.
ModelParameter  BBsscale    4.29        0.          0.
ModelParameter  BBdscale    4.29        0.          0.
```

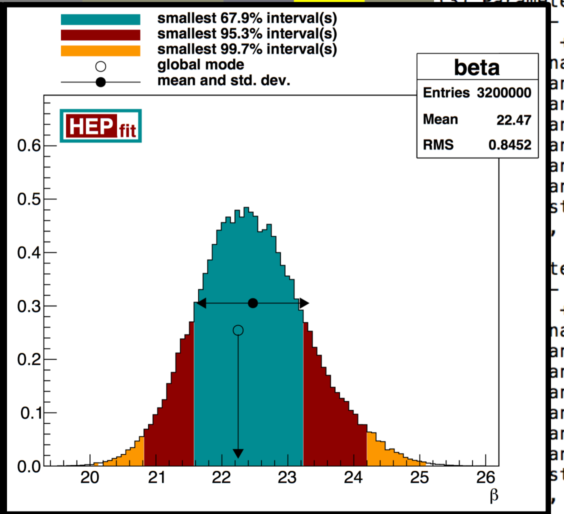
```
###########################################################################
Observable  Dmd       DmBd      #Deltam_{d}  1. -1.  MCMC weight 0.5055    0.002     0.
Observable  Dms       DmBs      #Deltam_{s}  1. -1.  MCMC weight 17.757    0.021     0.
Observable  EpsilonK EpsilonK #epsilon_{K} 1. -1.  MCMC weight 0.00228   0.00011   0.
#
### Flavianet 1005.2323
Observable  Vus       Vus       V_{us}       1. -1.  MCMC weight 0.2249    0.0009    0.
Observable  Vud       Vud       V_{ud}       1. -1.  MCMC weight 0.97428   0.00021   0.
#
### Vcb from exclusive, inclusive and UTfit combination
Observable  Vcb       Vcb       V_{cb}       1. -1.  MCMC weight 0.0409    0.0011    0.
Observable  Vub       Vub       V_{ub}       1. -1.  MCMC weight 0.00381   0.00040   0.
#
### alpha from UTfit combinations: pipi, rhopi, and rhorho
Observable  alpha_pipi   alpha_2a #alpha   1. -1.  MCMC file input/pipi_sum15 Input/pipi_input_alpha
Observable  alpha_rhopi  alpha_2a #alpha   1. -1.  MCMC file input/rhopi_win10 Input/alpharhopi
Observable  alpha_rhorho alpha_2a #alpha   1. -1.  MCMC file input/rhorho_sum15 Input/rhorho_input_alpha
#
### gamma from UTfit combination
Observable  gamma     gamma     #gamma       1. -1.  MCMC file input/gamma_sum16 Input/gamma_all
#
### S coefficient of JPsiK time-dependent CPA
Observable  SJPsiK    SJPsiK    S_{J/#PsiK}  1. -1.  MCMC file input/su3rhoetaflat sin2b_tot
#
### posterior histograms
Observable  BK1           BK1           B_{K}                   1. -1. noMCMC noweight
Observable  FBsoFBd       FBsoFBd       F_{B_{s}}/F_{B_{d}}     1. -1. noMCMC noweight
Observable  FBs           FBs           F_{B_{s}}               1. -1. noMCMC noweight
Observable  BBsoBBd       BBsoBBd       B_{B_{s}}/B_{B_{d}}     1. -1. noMCMC noweight
Observable  BBs1          BBs1          B_{B_{s}}               1. -1. noMCMC noweight
Observable  alpha         alpha         #alpha                  1. -1. noMCMC noweight
Observable  Betas_JPsiPhi Betas_JPsiPhi #beta_{s}               1. -1. noMCMC noweight
Observable  btaunu        btaunu        BR(B#to#tau#nu)         1. -1. noMCMC noweight
Observable  etab          etab          #overline{#eta}         1. -1. noMCMC noweight
Observable  rhob          rhob          #overline{#rho}         1. -1. noMCMC noweight
Observable  gammaAR       gamma         #gamma                  1. -1. noMCMC noweight
Observable  lambda        lambda        #lambda                 1. -1. noMCMC noweight
Observable  A             A             A                       1. -1. noMCMC noweight
Observable  beta          beta          #beta                   1. -1. noMCMC noweight
Observable  2betapgamma   2betapgamma   2#beta+#gamma           1. -1. noMCMC noweight
Observable  s2beta        s2beta        sin(2#beta)             1. -1. noMCMC noweight
Observable  c2beta        c2beta        cos(2#beta)             1. -1. noMCMC noweight
Observable  sintheta12    sintheta12    sin(#theta_{12})        1. -1. noMCMC noweight
Observable  sintheta13    sintheta13    sin(#theta_{13})        1. -1. noMCMC noweight
Observable  sintheta23    sintheta23    sin(#theta_{23})        1. -1. noMCMC noweight
Observable  ckmdelta      ckmdelta      #delta                  1. -1. noMCMC noweight
```

```
(1) Observable "Dmd":
    Mean +- sqrt(V):                0.5056 +- 0.002
    (Marginalized) mode:            0.5053
    Smallest interval(s) containing at least 66.34% and local mode(s):
     (0.5037, 0.5075) (local mode at 0.5053 with rel. height 1; rel. area 1)

    Smallest interval(s) containing at least 95.09% and local mode(s):
     (0.5018, 0.5096) (local mode at 0.5053 with rel. height 1; rel. area 1)

    Smallest interval(s) containing at least 99.71% and local mode(s):
     (0.4997, 0.5115) (local mode at 0.5053 with rel. height 1; rel. area 1)

(2) Observable "Dms":
    Mean +- sqrt(V):                17.757 +- 0.021
    (Marginalized) mode:            17.759
    Smallest interval(s) containing at least 68.215% and local mode(s):
     (17.736, 17.778) (local mode at 17.759 with rel. height 1; rel. area 1)

    Smallest interval(s) containing at least 94.9% and local mode(s):
     (17.716, 17.798) (local mode at 17.759 with rel. height 1; rel. area 1)

    Smallest interval(s) containing at least 99.7% and local mode(s):
     (17.694, 17.818) (local mode at 17.759 with rel. height 1; rel. area 1)

(3) Observable "EpsilonK":
    Mean +- sqrt(V):                0.002198 +- 9.9e-05
    (Marginalized) mode:            0.002197
    Smallest interval(s) containing at least 67.88% and local mode(s):
     (0.002098, 0.002296) (local mode at 0.002197 with rel. height 1; rel. a

    Smallest interval(s) containing at least 95.3617% and local mode(s):
     (0.002004, 0.002399) (local mode at 0.002197 with rel. height 1; rel. a

    Smallest interval(s) containing at least 99.7205% and local mode(s):
     (0.001909, 0.002502) (local mode at 0.002197 with rel. height 1; rel. a

(4) Observable "Vus":
    Mean +- sqrt(V):                0.22508 +- 0.00063
    (Marginalized) mode:            0.22513
    Smallest interval(s) containing at least 67.519% and local mode(s):
     (0.22445, 0.2257) (local mode at 0.22513 with rel. height 1; rel. area

    Smallest interval(s) containing at least 95.247% and local mode(s):
     (0.22385, 0.22635) (local mode at 0.22513 with rel. height 1; rel. area

    Smallest interval(s) containing at least 99.699% and local mode(s):
     (0.22325, 0.22695) (local mode at 0.22513 with rel. heigh

(5) Observable "Vud":
    Mean +- sqrt(V):                0.97433 +- 0.00015
    (Marginalized) mode:            0.97433
    Smallest interval(s) containing at least 67.702% and local
     (0.97418, 0.97447) (local mode at 0.97433 with rel. heigh

    Smallest interval(s) containing at least 95.338% and local
     (0.97404, 0.97462) (local mode at 0.97433 with rel. heigh

    Smallest interval(s) containing at least 99.713% and local
     (0.97391, 0.97476) (local mode at 0.97433 with rel. heigh

(6) Observable "Vcb":
    Mean +- sqrt(V):                0.042 +- 0.00067
    (Marginalized) mode:            0.04193
    Smallest interval(s) containing at least 67.86% and local
     (0.04134, 0.04267) (local mode at 0.04193 with rel. heigh

    Smallest interval(s) containing at least 95.366% and local
     (0.04068, 0.04333) (local mode at 0.04193 with rel. heigh

    Smallest interval(s) containing at least 99.717% and local
     (0.04001, 0.04394) (local mode at 0.04193 with rel. heigh
```

the HEPfit fit








```
Marginalization algorithm used: Metropolis

Results of the marginalization
==============================
List of variables and properties of the marginalized distributions:

  (0) Parameter "lambda" :
      Mean +- sqrt(Variance):          0.22509 +- 0.00063256
      Median +- central 68% interval:  0.22504 +  0.00077137 - -0.00077137
      (Marginalized) mode:             0.225
       5% quantile:                    0.22402
      10% quantile:                    0.22413
      16% quantile:                    0.22427
      84% quantile:                    0.22581
      90% quantile:                    0.22594
      95% quantile:                    0.22667
      Smallest interval containing 0.0% and local mode:

  (1) Parameter "A" :
      Mean +- sqrt(Variance):          0.82902 +- 0.014124
      Median +- central 68% interval:  0.82895 +  0.014374 - -0.014364
      (Marginalized) mode:             0.827
       5% quantile:                    0.80601
      10% quantile:                    0.81064
      16% quantile:                    0.81458
      84% quantile:                    0.84332
      90% quantile:                    0.8474
      95% quantile:                    0.85283
      Smallest interval containing 60.1% and local mode:
      (0.818, 0.842) (local mode at 0.827 with rel. height 1; rel. area 1)

  (2) Parameter "rhob" :
      Mean +- sqrt(Variance):          0.1584 +- 0.01409
      Median +- central 68% interval:  0.1584 +  0.01394 - -0.01428
      (Marginalized) mode:             0.157
       5% quantile:                    0.1349
      10% quantile:                    0.14
      16% quantile:                    0.1441
      84% quantile:                    0.1723
      90% quantile:                    0.1766
      95% quantile:                    0.1821
      Smallest interval containing 60.5% and local mode:
      (0.148, 0.172) (local mode at 0.157 with rel. height 1; rel. area 1)

  (3) Parameter "etab" :
       sqrt(Variance):                 0.3486 +- 0.01281
       +- central 68% interval:        0.3481 +  0.01357 - -0.0121
      nalized) mode:                   0.348
      antile:                          0.3283
      antile:                          0.3318
      antile:                          0.336
      antile:                          0.3617
      antile:                          0.3661
      antile:                          0.3717
      st interval containing 65.7% and local mode:
      , 0.36) (local mode at 0.348 with rel. height 1; rel. area 1)

      ter "tBd" :
       sqrt(Variance):                 1.51999 +- 0.00399224
       +- central 68% interval:        1.51997 +  0.00400822 - -0.00394301
      nalized) mode:                   1.5198
      antile:                          1.51348
      antile:                          1.51491
      antile:                          1.51602
      antile:                          1.52397
      antile:                          1.52513
      antile:                          1.5266
      st interval containing 65.8% and local mode:
      , 1.5236) (local mode at 1.5198 with rel. height 1; rel. area 1)
```

summary

- ✓ the Unitarity Triangle allows for high-precision test of the SM and NP reaches complimentary to and competitive with direct searches
- ✓ SM still seems to provide the dominant source of CP violation as measured experimentally
- ✓ the question of inclusive vs. exclusive still needs to be addressed
- ✓ Keep a watchout for **`HEPfit`**

Thank you…!!

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

"To know what no one else does, what a pleasure it can be!"

– adopted from the words of

Eugene Wigner.