Status of the Unitarity Triangle Analysis

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Outline

- CP violation in the SM: the CKM mechanism
- UTfit: method and inputs
- Inputs from Unitarity Triangle Analysis (UTA)
- Actual constraint on the CKM parameters from all measurements
- Compatibility plots – tension in the fit?
- UTfit and lattice QCD
- UTA and NP
- Conclusions
CP violation and CKM matrix

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

weak interaction eigenstates

\[ V_{\text{CKM}} \]

mass eigenstates

**Unitary matrix**

**UNITARITY CONDITION:**
\[
V_{\text{CKM}}^+ V_{\text{CKM}} = V_{\text{CKM}}^* V_{\text{CKM}} = 1
\]

six independent relations, within them we choose:
\[
V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0
\]

**B physics**

In a complex plane \((\bar{\rho}, \bar{\eta})\)

**Cabibbo**

**Kobayashi**

**Maskawa**
Method and Inputs

**Bayes theorem**

\[
f(\tilde{\rho}, \tilde{\eta}, x_1, x_2, \ldots x_N \mid c_1, c_2, \ldots c_M) \propto \prod_{j=1}^{M} f_i(c_j \mid \tilde{\rho}, \tilde{\eta}, x_1, \ldots x_N) \prod_{i=1}^{N} f_i(x_i) f_0(\tilde{\rho}, \tilde{\eta})
\]

**Constraints** \(c_i \sim f_i(c_i \mid \rho, \eta \ldots)\)

- \((b \to u)/(b \to c)\)
- \(\tilde{\rho}^2 + \tilde{\eta}^2\)
- \((\Lambda), \lambda_1, F(1)\)
- \(\epsilon_K\)
- \(\tilde{\eta}[(1-\tilde{\rho}) + P]\)
- \(B_K\)
- \(\Delta m_d, \Delta m_d / \Delta m_s\)
- \((1-\tilde{\rho})^2 + \tilde{\eta}^2\)
- \(f_B^2 B_B, \xi\)
- \(A_{(CP)}(J/\Psi K_S)\)
- \(\sin 2\beta\)

**References**

M.Ciuchini et al. JHEP 0107 (2001) 013. hep-ph/0012308

M.Bona et al. (UTfit collaboration) JHEP 0507 (2005) 028. hep-ph/0501199
Sides + $\varepsilon_K$: inputs and results

**Direct CP violation in the K sector**

68% prob. 95% prob.

$\varepsilon_K$

**LEP-time analysis** (with big recent contribution from Tevatron for $\Delta m_s$ and B-factories for $V_{ub}$ and $V_{cb}$)

**Semileptonic B decays**

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

**Bs and Bd mixing**

$\Delta m_d$

$\Delta m_s/\Delta m_d$

Contours at 68% and 95% probability are shown

Dependence on non-perturbative hadronic parameters

$$\bar{\rho} = 0.177 \pm 0.028$$

$$\bar{\eta} = 0.358 \pm 0.026$$
Angles: inputs and results

$\sin 2 \beta = 0.668 \pm 0.028$

$\alpha = [81^\circ, 102^\circ] \cup [164^\circ, 171^\circ]$ at 95% confidence

$\gamma = (78 \pm 12)^\circ$

$\bar{\rho} = 0.126 \pm 0.028$

$\bar{\eta} = 0.332 \pm 0.018$

$2\beta + \gamma = (\pm 90 \pm 32)^\circ$
Results

\[ \bar{\rho} = 0.177 \pm 0.028 \]
\[ \bar{\eta} = 0.358 \pm 0.026 \]

NP should appear as "corrections" to the CKM pictures

95\% prob. regions shown

\[ \bar{\rho} = 0.126 \pm 0.028 \]
\[ \bar{\eta} = 0.332 \pm 0.018 \]

\[ \bar{\rho} = 0.156 \pm 0.020 \]
\[ \bar{\eta} = 0.342 \pm 0.013 \]
Compatibility plots

A way to “measure” the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavor physics

The cross has the coordinates \((x, y) = (\text{central value, error})\) of the direct measurement.

Color code: agreement between the predicted values and the measurements at better than 1, 2...n \(\sigma\).
Tension in the fit?

Contours (68% and 95%) for the vertex position determined by $\Delta m_s/\Delta m_d$, $|V_{ub}/V_{cb}|$

Relying on semileptonic form factors determined from Lattice QCD and QCD sum rules

$$V^{\text{INDIRECT}}_{ub} = (3.48 \pm 0.16) \times 10^{-3}$$
$$V^{\text{Exclusive}}_{ub} = (3.50 \pm 0.40) \times 10^{-3}$$
$$V^{\text{Inclusive}}_{ub} = (3.99 \pm 0.15 \pm 0.40 [\ flat]) \times 10^{-3}$$

Relying on some HQET parameters extracted from experimental fits with some model dependence
UTfit vs lattice QCD

Fit overconstrained: UT analysis without relying on theoretical calculations of hadronic matrix elements. Using angles measurements, $|V_{ub}/V_{cb}|$ to determine CKM parameters and $\Delta m_d$, $\Delta m_s$, and $\epsilon_K$ to determine the LQCD quantities (assuming the validity of the SM).

Main goal: identify where lattice QCD calculation improvements are necessary

| Parameter          | UTangle     | UTangle + $V_{ub}/V_{cb}$ | lattice QCD results |
|--------------------|-------------|---------------------------|---------------------|
| $B_K$              | 0.78 ± 0.07 | 0.75 ± 0.07               | 0.75 ± 0.07         |
| $f_{B_s}/\sqrt{B_s}$ (MeV) | 265.6 ± 3.6 | 264.7 ± 3.6               | 270 ± 30            |
| $\xi$              | 1.27 ± 0.05 | 1.26 ± 0.05               | 1.21 ± 0.04         |
| $f_{B_d}$ (MeV)    | 191 ± 13    | 191 ± 13                  | 200 ± 20            |

(V.Lubicz, C.Tarantino, arXiv: 0807.4605 [hep-lat])

M.Bona et al. JHEP 0610:081, 2006 (hep-ph/0606167)
UTA beyond the SM

- start from a NP-free CKM determination
- parametrize generic NP in all sectors
- fit simultaneously for CKM and NP parameters

General parametrization for $B_q$-$B_q$ mixing ($q=d,s$)

$$C_{B_q} e^{2i \phi_{B_q}} = \frac{\langle B_q | H_{SM+NP} | \bar{B}_q \rangle}{\langle B_q | H_{SM} | \bar{B}_q \rangle} = 1 + \frac{A_{q}^{NP} e^{2i \phi_{NP}}}{A_{q}^{SM} e^{2i \phi_{SM}}}$$

where:
$$\phi_{d}^{SM} = \beta \quad \phi_{s}^{SM} = -\beta_{s} \quad C_{SM} = 1 \quad \phi_{SM} = 0$$

SM  $\rightarrow$ SM+NP

| SM                  | SM+NP               |
|---------------------|---------------------|
| $\gamma^{SM}$       | $\gamma^{SM}$      |
| $(V_{ub}/V_{cb})^{SM}$ | $(V_{ub}/V_{cb})^{SM}$ |
| $\epsilon_{K}^{SM}$ | $C_{\epsilon_{K}}^{SM}$ |
| $\Delta m_{K}^{SM}$ | $C_{\Delta m_{K}}^{SM}$ |
| $\beta^{SM}$        | $\beta^{SM} + \Phi_{B_{d}}$ |
| $\alpha^{SM}$       | $\alpha^{SM} - \Phi_{B_{d}}$ |
| $\Delta m_{d}^{SM}$ | $C_{B_{d}} \Delta m_{d}^{SM}$ |
| $\Delta m_{s}^{SM}$ | $C_{B_{d}} \Delta m_{s}^{SM}$ |
| $\beta_{s}^{SM}$    | $\beta_{s}^{SM} + \Phi_{B_{s}}$ |
Additional constraints for NP analysis

$\Delta m_s=|A_{full}^s|=C_{B_s} \Delta m_{s}^{SM}$

$2 \phi_s=\text{arg}(A_{full}^s)=2(\beta_s-\phi_{B_s})$

- Semileptonic asymmetry in $B_s$, $A_{SL}^s$ ([D0 Collaboration] Phys.Rev.Lett.98:151801, 2007)

$$A_{SL}^s = \frac{\Gamma(\bar{B}_s \to l^+ X)-\Gamma(\bar{B}_s \to l^- X)}{\Gamma(\bar{B}_s \to l^+ X)-\Gamma(\bar{B}_s \to l^- X)} = \text{Im} \left( \frac{\Gamma_{12}^s}{A_{full}^s} \right)$$

- Dimuon charge asymmetry, $A_{SL}^{\mu\mu}$ ([D0 collaboration] Phys.Rev.D74:092001, 2006 – [CDF collaboration] note 9015)

$$A_{SL}^{\mu\mu} = \frac{\int d\chi d_0 A_{SL}^d + \int s \chi s_0 A_{SL}^s}{\int d\chi d_0 + \int s \chi s_0}$$

- $B_s$ lifetime measurement from flavor specific final states, $\tau_{B_s}^{FS}$ (ALEPH, CDF, DELPHI, D0, OPAL, see ref [19] in arXiv:0803.0659)

$$\tau_{B_s}^{FS} = \frac{1}{\Gamma_s} \left( 1 - \left( \frac{\Delta \Gamma_s}{2 \Gamma_s} \right)^2 \right)$$

- Two-dimensional likelihood scan for $\Delta \Gamma_s$ and $\phi_s$ from the flavor-tagged analysis $B_s \to J/\psi \phi$ ([D0 Collaboration] arXiv:0802.2255)

- Two-dimensional likelihood ratio for $\Delta \Gamma_s$ and $\phi_s$ from the time dependent tagged angular analysis $B_s \to J/\psi \phi$ ([CDF collaboration] arXiv:0712.2397)

see A. Chandra talk on Monday
New physics in K sector

\[ C_{\Delta m_K} = 0.96 \pm 0.34 \]

\[ C_{\epsilon_K} = 0.99 \pm 0.16 \]

NP contributions to the K mixing

\[ C_{\epsilon_K} = \frac{\text{Im} < K^0 | H_{SM+NP} | \bar{K}^0 >}{\text{Im} < K^0 | H_{SM} | \bar{K}^0 >} \]

\[ C_{\Delta m_K} = \frac{\text{Re} < K^0 | H_{SM+NP} | \bar{K}^0 >}{\text{Re} < K^0 | H_{SM} | \bar{K}^0 >} \]
New physics in $B_d$ sector

$C_{B_d} = 0.96 \pm 0.23$

$\phi_{B_d} = (-2.9 \pm 1.9)^\circ$

$\sim 1.5$ sigma effect from sin2b “tension”

NP contributions to the $B_d$ mixing

$C_{Bd} e^{2i \phi_{B_d}} = \frac{\langle B_d | H_{SM+NP} | \bar{B}_d \rangle}{\langle B_d | H_{SM} | \bar{B}_d \rangle}$

$\Delta m_d^{SM}$

up to $\sim 10\%$ effects still allowed
New physics in $B_s$ sector

$C_{B_s} = 0.97 \pm 0.20$

$\phi_{B_s} = (-70 \pm 7)^\circ U (-18 \pm 7)^\circ$

$C_{B_s} e^{2i\phi_{B_s}} = \frac{<B_s|H_{SM+NP}|\bar{B}_s>}{<B_s|H_{SM}|\bar{B}_s>}$

SM contributions

SM at $\sim 2.6\sigma$

68% prob.

95% prob.
Conclusions

- Combination of all the available information
  http://www.utfit.org

- SM description of CP violation through the CKM mechanism is successful: all experimental measurements in agreement, physics beyond the SM should appear as a correction

- Small tension in the fit, due to the Vub measurement

- Extraction of hadronic parameters

- Indication for NP with new sources of flavor violation. Clear pattern arises:
  
  - 1 ↔ 2: strongly suppressed
  - 1 ↔ 3: ≤O(10%)
  - 2 ↔ 3: O(1)
http://www.utfit.org/

Ciuchini et al. "2000 CKM triangle analysis: A Critical review with updated experimental inputs and theoretical parameters." JHEP 0107:013,2001 (hep-ph/0012308)

M. Bona et al. [UTfit Collaboration]
"The Unitarity Triangle Fit in the Standard Model and Hadronic Parameters from Lattice QCD: A Reappraisal after the Measurements of Δms and BR(B → τν)"
JHEP 0610:081,2006 (hep-ph/0606167)

M. Bona et al. [UTfit Collaboration]
"The 2004 UTfit Collaboration Report on the Status of the Unitarity Triangle in the Standard Model",
JHEP 0507 (2005) 028 (hep-ph/0501199)

M. Bona et al. [UTfit Collaboration]
"Model-independent constraints on Delta F=2 operators and the scale of New Physics"
0707.0636 (hep-ph)
Backup
Angles, inputs

\( \sin 2\beta \): from the time dependent asymmetry measurement in \( B^0 \rightarrow J/\Psi K_S \) only, theoretical error taken into account (Ciuchini et al. PRL95:221804, 2005).

Ambiguity removed by measurements from angular analysis of time dependent studies in \( B^0 \rightarrow J/\Psi K_S^* \) and Dalitz analysis of \( B^0 \rightarrow D^0 \pi^0 \).

\[
\sin 2\beta = 0.668 \pm 0.028
\]

68% prob.
95% prob.
B° \rightarrow (\rho\pi)^0 analysis on the Dalitz plot. The penguin contributions delete in:
\[ A = A(B^0 \rightarrow \rho^+\pi^-) + A(B^0 \rightarrow \rho^-\pi^+) + 2A(B^0 \rightarrow \rho^0\pi^0) = (T_{+-} + T_{-+} + 2T_{00}) e^{-i\alpha} \]
and similarly A_{\bar{B}}, for CP conjugated.
We extract \( \alpha \) directly from data measuring
\[ R = \frac{A_{\bar{B}}}{A} = e^{2i\alpha} \]
Penguin contributions cancel out in the sum: non need to fit for them.
As for gamma from Bs (Ciuchini et al. Phys.Lett.B645:201-203,2007)
Angles, inputs

\[ \gamma = \text{arg} \left\{ \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right\} \]

Overall constraint:

\[ B \to D^{(*)0} (D^{(*)0}) K^{(*)} \text{ decays can proceed both through } V_{cb} \text{ and } V_{ub} \text{ amplitudes} \]

- **GLW**
  - \( D^0 (\bar{D}^0) \to K_S \pi^0, K^+ K^-, \pi^+ \pi^- \)

- **ADS**
  - \( D^0 (\bar{D}^0) \to K^- \pi^+, K^- \pi^+ \pi^0 \)

- **DALITZ**
  - \( D^0 (\bar{D}^0) \to K_S \pi \pi, \pi \pi \pi^0 \)

GLW

ADS

DALITZ

\[ \gamma = (78 \pm 12)^\circ \]

68% prob.

95% prob.
Angles, inputs

Sensitivity to $\gamma$ proportional to an important parameter:

**CHARGED B**

$B \rightarrow DK$

$r_B(\text{ch}) = |A_{V_{ub}}(\text{ch})/A_{V_{cb}}(\text{ch})|$

- $r_B(DK)$
  - $0.10 \pm 0.02$

$B \rightarrow DK^*$

$r_B(DK^*) = 0.092 \pm 0.066$

**NEUTRAL B**

$B \rightarrow D^*K$

$r_B(D^*K)$

- $0.091 \pm 0.033$

$B \rightarrow DK^*$

$r_B(DK^*) = 0.092 \pm 0.066$

$B \rightarrow \text{neut}$

$r_B(\text{neut}) = |A_{V_{ub}}(\text{neut})/A_{V_{cb}}(\text{neut})|$

- 68% prob.
- 95% prob.
2$\beta + \gamma$: from the time dependent analysis of $B^0 \to D(\ast) \pi$ and $B^0 \to D \rho$.

The only information we can extract from data is the 2D distributions:

Assuming SU(3) and neglecting annihilations (+-100% error convoluted with the experimental one):

- **Overall constraint:**

  - $2\beta + \gamma = (\pm 90 \pm 32)^\circ$

  - 68% prob.
  - 95% prob.
New physics in $B_d$ sector