CP violation in quark flavor physics

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Testing CP-violation for baryogenesis
University of Massachusetts, Amherst,
March 29, 2018
Outline and aim of the talk

Outline
1. Phases of the CKM unitary triangle
2. Meson mixing
3. Kaon rare decays

Aims
* Overview
* Latest updates on the experimental measurements
* Implications on NP theories

CP violation in:
- B mesons \(b \rightarrow s, b \rightarrow d\)
- D mesons \(c \rightarrow u\)
- Kaons \(s \rightarrow d\)

During the rest of the workshop, we will learn its connection to baryogenesis
Standard Model flavor & CP

Flavor and CP-violation arising from the CKM matrix ($V_{\text{CKM}}$)

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

Free parameters:
3 real rotation angles and one (CP-violating) phase

Goal:
over-constrain sides and angles by many measurements sensitive to different short distance physics
Remarkable success of the CKM picture!

\[ \Delta m_d & \Delta m_s \]

\[ A = 0.8250^{+0.0071}_{-0.0111} \]
\[ \lambda = 0.22509^{+0.00029}_{-0.00028} \]
\[ \bar{\rho} = 0.1598^{+0.0076}_{-0.0072} \]
\[ \bar{\eta} = 0.3499^{+0.0063}_{-0.0061} \]

(68% CL)

See also

http://www.utfit.org/UTfit/

Remarkable success of the CKM picture!
Measurement of the $\gamma$ angle

$\gamma = \text{arg} \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \sim \text{arg}(-V_{ub})$

The CKM angle $\gamma$ is the least known constraint:

- **Direct $\gamma$ measurement**: $(73.5^{+4.3}_{-5.0})^\circ$
- **Indirect $\gamma$ extrapolation**: $(65.3^{+1.0}_{-2.5})^\circ$

LHCb expected precision by 2029 (end of Run 4) $< 0.4^\circ$
Measurement of the $\gamma$ angle

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$\gamma$ can be measured using tree level B decays

(only CKM angle accessible at tree level)

Require interference between $b \to cW$ and $b \to uW$ to access it:

LHCb-CONF-2017-004

Most precise measurement from 1 experiment only

S.Gori

M. Kenzie
Theory for the $\gamma$ angle

- $\gamma$ is known very well in the SM
  \[ |\delta \gamma| \lesssim \mathcal{O}(10^{-7}) \]
  second-order electroweak corrections
  (other theory errors can be eliminated using data)
  Brod, Zupan, 1308.5663

- $\gamma$ is a good probe of new physics
  \[ Q_1^{u_1 u_2 d_1} = (\bar{u}_1^\alpha b^\beta)_{V-A} (\bar{d}_1^\beta u_2^\alpha)_{V-A}, \quad Q_2^{u_1 u_2 d_1} = (\bar{u}_1^\alpha b^\alpha)_{V-A} (\bar{d}_1^\beta u_2^\beta)_{V-A} \]
  For example, for $\Delta C_1$

$\text{Im}(\Delta C_1)$ and $\text{Im}(\Delta C_2)$ can be of order $\pm 10\%$ without violating any constraints from data
(constraints from $B \to D\pi$ and $B \to D^{(*)0}h^0$ decays,
$b \to d\gamma$, $B \to \pi\pi, \rho\pi, \rho\rho$-decays).

New physics in $C_{1,2}$ can cause sizeable shifts in $\gamma$ ($|\delta \gamma| \approx 4^\circ$)

Brod et al., 1412.1446
2. The physics of meson mixing
CP violation in the meson system

Let us consider a meson ($M$) decay.

We define the decay amplitudes to the final state $f$

$$A_f = \langle f | \mathcal{H} | M \rangle, \quad \bar{A}_f = \langle f | \mathcal{H} | \bar{M} \rangle$$

The mass eigenstates are

$$|M_{H,L}\rangle = p|M\rangle \mp q|\bar{M}\rangle$$

In general, there are 3 types of CP violation:

- **CP violation in mixing**, when the two neutral mass eigenstate admixtures cannot be chosen to be CP-eigenstates
  
  $$|q/p| \neq 1$$

- **CP violation in decay**, when the amplitude for a decay and its CP-conjugate process have different magnitudes
  
  $$|A_f/\bar{A}_f| \neq 1$$

- **CP violation in the interference** of decays with and without mixing, which occurs in decays into final states that are common to $M$ and $\bar{M}$
  
  $$\text{Im}\left(\frac{q}{p} \frac{\bar{A}_f}{A_f}\right) \neq 0$$
Example for the $B_s$ meson system

Flavor eigenstates

$$
CP(B) = \bar{B}
$$

$$
CP(\bar{B}) = B
$$

Mass eigenstates

$$
|B_{H,L}\rangle = p|B\rangle \mp q|\bar{B}\rangle
$$

$B$ mesons $b \to s, b \to d$

$\phi_{SM} = 2 \arg(V_{ts}V_{tb}^*)$

$\phi_D = \arg(V_{cs}V_{cb}^*)$

$\phi_s = \phi_{SM} - 2\phi_D = -2 \arg \left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) \equiv -2\beta_s$

Small number in the SM

Interference between mixing and decay
Latest measurements, B mesons

\[ \phi_s = \phi_{SM}^M - 2 \phi_D = -2 \arg \left( \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) \equiv -2 \beta_s \]

\[ \arg \left( \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right) \equiv \beta \]

B mesons \( b \rightarrow s, b \rightarrow d \)

LHCb dominates this world average

LHCb is comparable to Belle & Babar

(latest LHCb (2017): 0.760 ± 0.034)
Latest measurements, D mesons

In the SM,

* CP violating effects in the $D - \bar{D}$ system are expected to be small, $O(10^{-3})$
* sizeable uncertainties on hadronic form factors

cc production $\sim 20$ bb production at LHCb!

Latest determination: LHCb, 5.0 fb$^{-1}$ recorded in 2011-2016

* through the decays $D, \bar{D} \rightarrow K^+ \pi^-$ (Cabibbo-suppressed, Cabibbo-favored from the oscillation ("wrong sign" (WS) decay))

$D \rightarrow K^- \pi^+$ (Cabibbo-favored ("right sign" (RS) decay))

* (also past determination through the decays to Kaons and pions)
Latest measurements, D mesons

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* through the decays $D$, $D \rightarrow K^+\pi^-$  
  Cabibbo-suppressed  
  that follows from the oscillation  
  ("wrong sign" (WS) decay)  

* (also past determination through the decays to Kaons and pions)

$R_D^+ \equiv \frac{N(D \rightarrow K^+\pi^-)}{N(D \rightarrow K^-\pi^+)}$,  
$R_D^- \equiv \frac{N(\bar{D} \rightarrow K^-\pi^+)}{N(\bar{D} \rightarrow K^+\pi^-)}$

non-vanishing difference between $R_D^+$ and $R_D^-$ would imply CP violation

No evidence for CP violation in charm mixing is yet observed

\[
1.00 < \frac{|q/p|}{1.35} < 1.35 \\
A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1) \times 10^{-3} (68.3\% \text{ CL.})
\]
Probing high New Physics scales

In the framework of effective field theories...

\[ \mathcal{L}_{BSM} \rightarrow \mathcal{L}_{\nu SM} + \sum_{d>4} \frac{Q_i^{(d)}}{\Lambda^{d-4}} \]

CP violation in D mixing gives the best bound after \( \varepsilon_K \) (Kaon mixing)

S.Gori
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CP violation in D mixing gives the best bound after \( \varepsilon_K \) (Kaon mixing)
New CPV Higgs bosons (MFV 2HDM)

Beyond EFTs, one can set constraints on the (flavor and) CP structure of NP models containing new (~ light) degrees of freedom.

Example: a 2HDM with Minimal Flavor Violation (MFV)

\[
\mathcal{H}^\text{gen}_Y = \bar{Q}_L X_1 D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}
\]

\[
\begin{cases}
X_{d1} = Y_d \ (\text{definition}) \\
X_{u1} = a_u Y_u + \epsilon' Y_u Y_u Y_u + \epsilon'' Y_d Y_d Y_u + \cdots \\
X_{d2} = a_d Y_d + \epsilon'_d Y_d Y_d Y_d + \epsilon'' Y_u Y_u Y_d + \cdots \\
X_{u2} = Y_u \ (\text{definition})
\end{cases}
\]
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$$\mathcal{H}_{Y}^{\text{gen}} = \bar{Q}_{L}X_{d1}D_{R}H_{1} + \bar{Q}_{L}X_{u1}U_{R}H_{1}^{c} + \bar{Q}_{L}X_{d2}D_{R}H_{2}^{c} + \bar{Q}_{L}X_{u2}U_{R}H_{2} + \text{h.c.}$$

\[
\begin{align*}
X_{d1} &= Y_{d} \quad \text{(definition)} \\
X_{u1} &= a_{u}Y_{u} + \epsilon_{1}Y_{d}^{\dagger}Y_{u}Y_{u} + \epsilon_{2}Y_{d}^{\dagger}Y_{d}Y_{u} + \cdots \\
X_{d2} &= a_{d}Y_{d} + \epsilon_{1}Y_{d}^{\dagger}Y_{d}Y_{d} + \epsilon_{2}Y_{u}^{\dagger}Y_{u}Y_{d} + \cdots \\
X_{u2} &= Y_{u} \quad \text{(definition)}
\end{align*}
\]

Generically, O(1) complex coefficients

Matrix element for meson mixing:

$$M_{12}^{B_{d}} \propto \frac{F(\epsilon_{i})}{m_{H}^{2}} y_{b}y_{q} \left[ y_{t}^{2}V_{tb}V_{tq}^{*} \right]^{2}$$

~2σ bound

Buras, Carlucci, SG, Isidori, 1005.5310
New CPV Higgs bosons (flavorful 2HDM)

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MFV is not the full story for 2HDMs

A “flavorful” 2HDM

\[ \mathcal{L} = \overline{t} Y t H + \overline{t} Y' t H' \]

125 Higgs (h) Additional Higgses (H, A, H^+)

\[ \mathcal{M} = \nu Y + \nu' Y' \]

\[ (\mathcal{M}_0 + \Delta \mathcal{M}) \]

(\[ \mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix} \]

\[ \Delta \mathcal{M} = \begin{pmatrix} m_u & \mathcal{O}(m_u) & \mathcal{O}(m_u) \\ \mathcal{O}(m_u) & m_c & \mathcal{O}(m_c) \\ \mathcal{O}(m_u) & \mathcal{O}(m_c) & \mathcal{O}(m_c) \end{pmatrix} \]

(analogous structure in the down-quark sector)

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927
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O(1) complex coefficients

(analogous structure in the down-quark sector)

Approximate U(2) symmetry in each sector

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Approximate U(2) symmetry in each sector

2 of the phases
Complementarity with LHC searches

Broad program for searches for new Higgs bosons
Most searches (and interpretation of searches) are performed in the context of “type-II-like” 2Higgs doublet models.

The typical golden channel is $H \rightarrow \tau \tau$. This is not necessarily true in these new models.
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The LHC tests the absolute value of the free parameters of the theory
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New CPV Higgs bosons (SUSY)

SUSY Higgs sectors do not bring new sources of flavor violation at the tree level. Nevertheless, many new (Higgs) sources of flavor and CP violation (soft masses, trilinear terms)

For example in the squark down sector:

\[
\begin{align*}
\mathcal{M}^2_D &= \text{diag}(\tilde{m}^2) + \tilde{m}^2 \delta_d \\
\delta_d &= \begin{pmatrix}
\delta_{dL}^{LL} & \delta_{dL}^{LR} \\
\delta_{dR}^{RL} & \delta_{dR}^{RR}
\end{pmatrix}
\end{align*}
\]

6X6 matrix

off-diagonal soft masses & trilinear terms
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\]

off-diagonal soft masses & trilinear terms

6X6 matrix

Example diagram:
3. Kaon rare decays

\[ K^+ \to \pi^+ \nu \bar{\nu}, \quad K_L \to \pi^0 \nu \bar{\nu} \]
Kaon rare decays in the SM

Very clean decays (mainly short distance contribution)

Dominant uncertainties originate from the CKM parameters $|V_{cb}|$, $|V_{ub}|$ and $\gamma$.

$$\mathcal{H}_{SM} = g_{SM}^2 \sum_{\ell=e,\mu,\tau} [V^*_{cs} V_{cd} X(x_c) + V^*_{ts} V_{td} X(x_t)] (\bar{s}_L \gamma_\mu d_L) (\bar{\nu}_\ell \gamma^\mu \nu_\ell)$$

Only operator in the SM

Buras, Buttazz, Girbach-Noe, Knegjens, 1503.02693

+ box diagrams
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Only operator in the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \simeq \kappa_+ \left| \frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \frac{V_{cs}^* V_{cd}}{\lambda} \left( \frac{X(x_c)}{\lambda^4} + \delta P \right) \right|^2$$

CP-conserving

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \simeq \kappa_L \Im \left( \frac{V_{ts}^* V_{td}}{\lambda^5} X(x_t) \right)^2$$

CP-violating

$$\begin{cases} \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \\ \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11} \end{cases}$$

Very rare!

Access to NP

Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

Brod, Gorbahn, Stamou 1009.0947; Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

NA62 and KOTO are beginning their experimental program...
News from NA62 (K+)

Predecessor:

\[ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \]

BNL measurement, 2009
(4 event @ BNL-949; 3 events @ BNL-787)

* NA62 has started data taking in Sept. 2016
* Exploratory analysis with 5% of 2016 data set
  0 signal event found

CERN-SPSC-2017-013
Talk by Marchevski

 Kaons s→d

400 GeV SPS protons

Target KTAG GTK

LAV

Kaon

Vacuum

RICH

neutrinos
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* Analysis of the full 2016 data announced at Moriond

Optimized to suppress backgrounds from leading Kaon decay modes

\[
15 < P_{\pi^+} < 35 \text{ GeV}/c \\
m_{miss}^2 = (P_K - P_{\pi^+})^2.
\]

1 event seen! (0.3 expected)

Aim:
Measurement of the SM BR at the \( \sim 10\% \) level

Data taking until the end of 2018
Running after 2018 is approved
News from KOTO (K_L)

Predecessor:
\[ \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \]
KEK E391a bound, 2010
(0 events seen)

Indirect bound:
(using Grossmann-Nir)
\[ \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{GN} < 1.46 \times 10^{-9} \]

Grossman-Nir bound (model independent):
\[ \frac{\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})}{\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})} < 4.4 \]

Experimental challenges associated to the signature (2 photons+nothing)
News from KOTO (K_L)

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Experimental challenges associated to the signature (2 photons+nothing)

\*- initial physics data taken in 2013 (1609.03637)
  \( \text{1 event observed} \) (0.34 expected)

\( \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{ \text{KOTO} } < 5.1 \times 10^{-8} \)

\*- 2015 run: \( \sim 20 \) times more data
Preliminary analysis discussed at Moriond
(still to be optimized)

expectation:
improvement on the bound by a factor of \( \sim 10 \)

Final Aim:
10% measurement of the BR
Putting together future NA62 and KOTO analyses, one can reconstruct the unitary triangle (just using Kaon physics) with 10% measurement.
Implications on New Physics theories

Many NP models induce sizable NP effects in the BRs:

- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, SG, 0812.3803]
- Simplified Z, Z' models [Buras, Buttazzo, Knegjens, 1507.08672]
- Lepton flavor universality violation models [Bordone, et al., 1705.10729]

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...

* At the operator level:

\[ \mathcal{H}_{\text{eff}} = \frac{c_1}{\Lambda^2} (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\ell \gamma^\mu \nu_\ell) \]

\[ + \frac{c_2}{\Lambda^2} (\bar{s}_R \gamma_\mu d_R)(\bar{\nu}_\ell \gamma^\mu \nu_\ell) \]

Region for Minimal Flavor Violating models

Kaons s→d
Conclusions & Outlook

Interesting times for flavor / CPV physics

**Plethora of new data** in the last few years and even more data to come (LHCb, **BelleII**, NA62, KOTO, …)

Complementarity between different systems

\[ b \rightarrow s, \ b \rightarrow d, \ c \rightarrow u, \ s \rightarrow d \]

to test the flavor and CP structure of nature