CP violation in the quark sector

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GDR-InF workshop: The future of the intensity frontier ?

Why CP violation

Measurements of CP asymmetries and searches for new sources of CP violation are a particular case of indirect tests of the Standard Model (as opposed to direct searches of new particles).

Yet CP violation plays a special rôle:

- C, P and T are (the only ?) fundamental discrete symmetries
- C, P and CP violation are necessary ingredients for baryogenesis, which cannot be described by known physics
- Through CPT conservation theorem, CP violation is related to T violation and, maybe, to the 'arrow of time'
- Despite its deep consequences, CP violation is 'easy' to get in particle physics models, as it is related to the presence of non trivial complex couplings
- Standard Model is, at least in principle, very predictive in the CP violating sector: one free parameter for all

The Jarlskog invariant

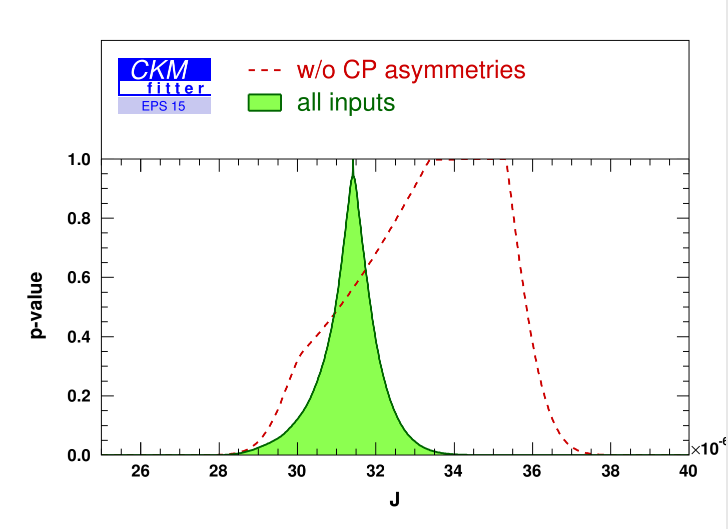
In the SM, CP violation is driven by the Jarlskog invariant

Jarlskog '85

$$\begin{aligned} \mathrm{Im}\left(V_{ij}V_{kl}V_{il}^*V_{kj}^*\right) &= J\sum_{m,n=1}^{3}\varepsilon_{ikm}\varepsilon_{jln} \\ J &= c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta \end{aligned}$$

where we see that three generation mixing ((12), (23), (13)) and CP-violating phase (δ) are necessary ingredients for CP violation.

The Jarlskog invariant is precisely known from global analyses:



The possibility to predict J from CP conserving observables only is a peculiar feature of the SM, related to the three generation KM mechanism.

Testing models through CP violation

The accuracy of predictions of CP asymmetries in the quark sector depend on the possibility to get rid of hadronic effects, or to compute them.

CP violation generically needs both CP even and CP odd phases. In the simplest cases (B-$\bar{B}$ oscillations), the CP even phase cancels.

Theoretical cleanliness

***	γ	exact at LO of weak int.
***	$A_{\mathrm{SL,(d,s)}}$ [if null test]	SM pred. vanishingly small
**	α, β, β_s	penguins may show up
*	ε_K, $A_{\mathrm{SL,(d,s)}}$ [if finite value]	non trivial had. input
*/?	ε'/ε, rare B, D system, direct CP …	requires further progress

The extraction of γ

Construct interferences between CP conjugate decay modes that differ by phase γ.
The necessary hadronic information (ratio of matrix elements) is directly taken from data (of B and/or D decays):

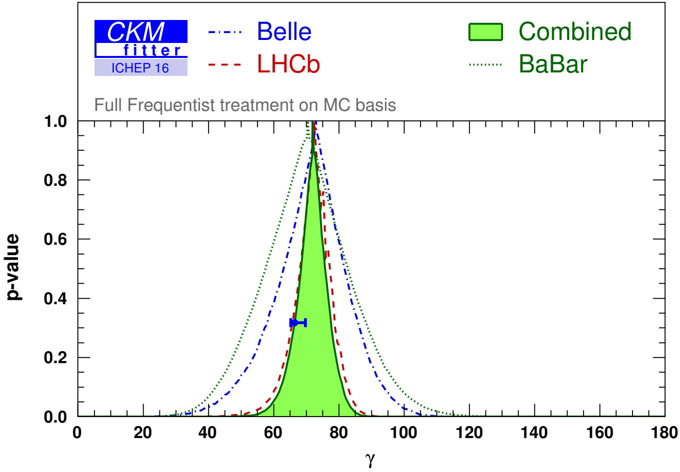
GLW: use $B^\pm \to D_{\rm CP} K^\pm$ to let $b \to c\bar{u}s$ interfere with $b \to u\bar{c}s$
Gronau, London, Wyler '91

ADS: use $B^\pm \to (D^0, \overline{D}^0) K^\pm \to (K^+\pi^-) K^\pm$ that is
$(b \to c\bar{u}s) \times (c \to d\bar{u}s)$ vs. $(b \to u\bar{c}s) \times (\bar{c} \to \bar{s}u\bar{d})$
Atwood, Dunietz, Soni '96

GGSZ: use instead three body decay of D, that is either described by a resonance (isobar) model, or by a binned Dalitz plot analysis
Giri, Grossman, Soffer, Zupan '03; Bondar, Poluetkov '05

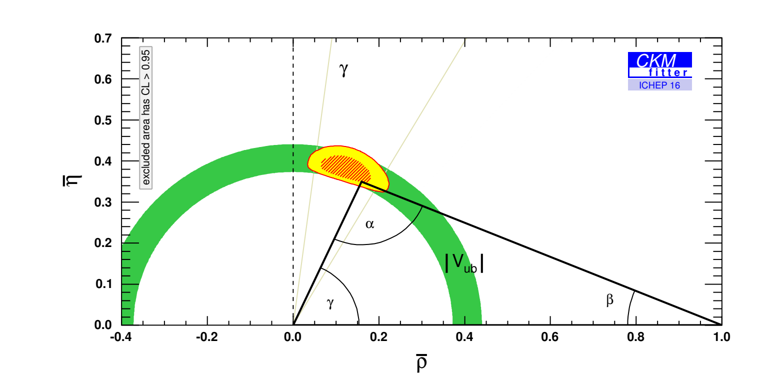
Many variants (D^*, K^*, more particles in the final state. . .).

γ Grand combination



$$\gamma\ (\text{direct}) = (72.1^{+5.4}_{-5.8})^\circ \text{ vs. } \gamma\ (\text{indirect}) = (65.33^{+0.96}_{-2.54})^\circ$$

Since these methods use tree level decays without penguin contributions, they provide a 'universal' determination of γ that is valid in any New Physics model where non standard effects occur in loop diagrams:



In the future it is crucial to measure γ as best as possible, since it's basically the only CP parameter than can be extracted without theoretical uncertainties

The extraction of β and β_s

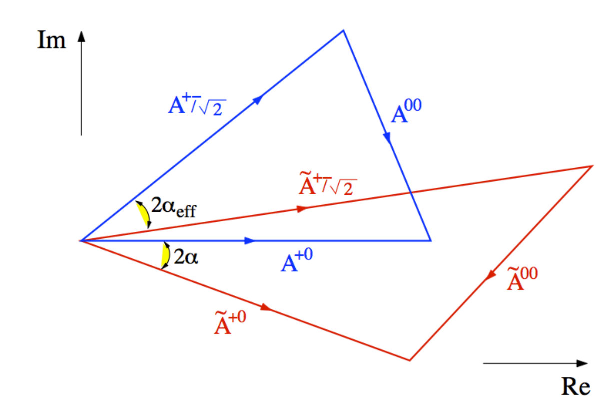
To a very good approximation the mixing induced CP asymmetry in $B \to J/\psi K_S$ and $B_s \to J/\psi \phi$ is independent of any non trivial hadronic quantity.

However when statistical uncertainty decreases corrections from penguin contributions may have to be taken into account. A difficult challenge in non leptonic decays !

The extraction of α

To extract the angle α one uses $b \to u\bar{u}d$ transitions in the strict isospin limit, where penguin contractions transform differently ($\Delta I = 1/2$) wrt tree contributions (both $\Delta I = 3/2, 1/2$).

In $B \to \pi\pi$ and $B \to \rho\rho$, a triangle construction allows a clean extraction of α, up to an 8-fold discrete ambiguity (Gronau, London '90)

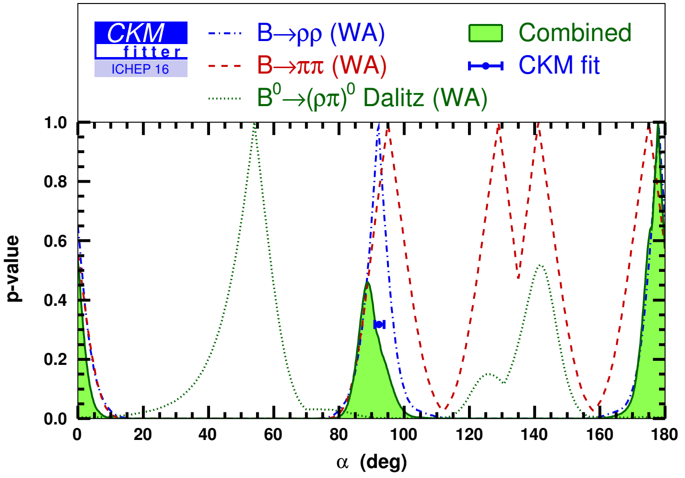


In $B \to \rho\pi \to \pi\pi\pi$ one has to model the shape of resonances to perform a Dalitz plot analysis, allowing the determination of α from resonance terms

Snyder, Quinn '93

Due to complicated fit and low statistics, non trivial statistical issues appear.

α Grand combination



Interpretation and further studies

The best constraint on α actually comes from $B \to \rho\rho$, thanks to the accidental/lucky shape of the isospin triangles

Simplest isospin breaking correction come from dominant (Q_9, Q_{10}) electroweak penguin operators and are calculable without introducing new parameters: this typically leads to a shift $\Delta\alpha \sim 1-2^\circ$ [JC *et* al. '17]

Other corrections involve subleading EWP, strong isospin violating effects (*e.g.* π^0, η, η' mixing), resonance shape of the ρ (in $B \to \rho\pi$ and $B \to \rho\rho$)... and may be numerically similar or smaller.

Significant theoretical progress will presumably be necessary to match the accuracy of future experiments related to α

Theory of charmless non leptonic decays

In principle dynamical calculations of hadronic matrix elements would allow to extract fundamental couplings (both in SM and in BSM) and test CP violation in a sector where asymmetries can be large.

One of the most cited work in flavor physics is the series of BBNS papers on QCD factorization: establishes factorization of non leptonic matrix elements into simpler quantities (SL form factors, decay constants, distribution amplitudes) at leading order of the heavy mass expansion. QCDF was the long awaited (diagrammatic) proof of Bjorken's color transparency argument, and can be seen as a development of the (also very famous) Brodsky-Lepage approach to hard scattering.

Beneke *et al.*, '99-'01

QCDF successfully predicts observables in $B \to D\pi$-like modes and, generally speaking, correct pattern of decay rates, non trivial CP asymmetries etc.

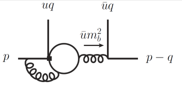
However in charmless decays the predictivity of QCDF is spoiled by chirally enhanced power corrections $\sim 2m_\pi^2/((m_u+m_d)m_b) \sim 1$ that are only partly factorizable/computable: it is still not known how to treat these terms. SCET is an operator-based version of QCDF and suffers from the same problem. pQCD pushes perturbative calculation further, at the price of introducing more complicated objects (wave functions in the transverse momenta).

Bauer *et al.* '00-'02; Li *et al.*, '97

Recent progress

NNLO corrections to QCDF amplitudes have been completed for tree topologies; a few ingredients also for penguins, but many are missing due to the complexity of calculations.

G. Bell, M. Beneke (workshop in Bad Honnef, Feb. 2016)



Individual NNLO terms appear to be sizable, but significant cancellations among them $\Rightarrow$ moderate effect on physical amplitudes ?

$$\begin{aligned} T \equiv a_1(\pi\pi) &= 1.009 + [0.023 + 0.010i]_{\rm NLO} + [0.026 + 0.028i]_{\rm NNLO} \\ &\quad - \left[\frac{r_{\rm sp}}{0.485}\right] \left\{ [0.015]_{\rm LOsp} + [0.037 + 0.029i]_{\rm NLOsp} + [0.009]_{\rm tw3} \right\} \\ &= 1.00 + 0.01i \quad \rightarrow \quad 0.93 - 0.02i \quad (\text{if } 2 \times r_{\rm sp}) \end{aligned}$$

$$r_{\rm sp} = \frac{9 f_{M_1} \hat{f}_B}{m_b f_+^{B\pi}(0) \lambda_B}$$

$$\begin{aligned} C \equiv a_2(\pi\pi) &= 0.220 - [0.179 + 0.077i]_{\rm NLO} - [0.031 + 0.050i]_{\rm NNLO} \\ &\quad + \left[\frac{r_{\rm sp}}{0.485}\right] \left\{ [0.123]_{\rm LOsp} + [0.053 + 0.054i]_{\rm NLOsp} + [0.072]_{\rm tw3} \right\} \\ &= 0.26 - 0.07i \quad \rightarrow \quad 0.51 - 0.02i \quad (\text{if } 2 \times r_{\rm sp}) \end{aligned}$$

Impressive achievement from the point of view of perturbative calculations; yet the problem of large power corrections remains open.

An example where QCDF is really predictive: the extraction of $\sin 2\beta$ from penguin channels

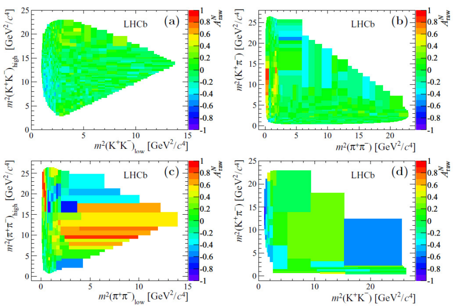
Mode	ΔS_f (Theory)	ΔS_f [Range*]
ϕK_S	$0.02^{+0.01}_{-0.01}$	$[+0.01, 0.05]$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[+0.00, 0.03]$
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[+0.03, 0.13]$
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.01]$
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-0.76, 0.27]$
ωK_S	$0.13^{+0.08}_{-0.08}$	$[+0.02, 0.21]$

[MB; Cheng, Chua, Soni; Buchalla, Hiller, Nir, Raz; 2005]

Large CP violation in multibody B decays

Multihadronic decays are even more complicated. Simplest approach is QCDF for quasi two-body decay followed by the Breit-Wigner parametrization of resonance amplitude. That may be not sufficient for exotic resonances or non resonant contributions.

Recent interest due to large 'local' CP asymmetries in Dalitz distribution of $B^{\pm} \to (\pi\pi\pi)^{\pm}, (K\pi\pi)^{\pm}, (KK\pi)^{\pm}$ channels at LHCb:



LHCb '14

With QCDF it is in principle to go beyond the naive quasi two body + resonance decay approximation. However new non perturbative objects, such as generalized form factors and distribution amplitudes for two hadrons, appear and need to be calculated or at least modelled.

Semileptonic asymmetries

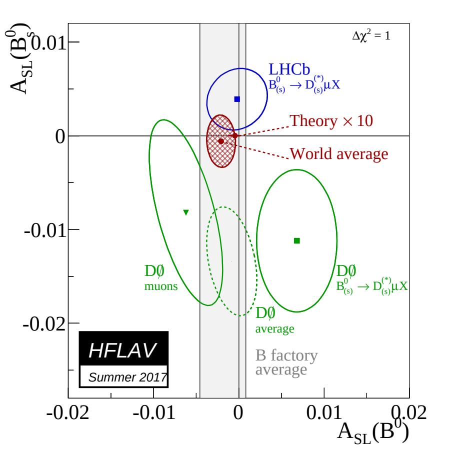
In the kaon sector, the (53 year old !) ε_K CP asymmetry determines a well-known constraint on the CKM matrix, the accuracy of which is however limited by the knowledge of $|V_{cb}|$ and the perturbative charm contribution.
Semileptonic asymmetries are defined from the mixing Hamiltonian $H_{12} = M_{12} + i\Gamma_{12}$ with

$$a^q_{SL} = \mathrm{Im} \frac{\Gamma^q_{12}}{M^q_{12}}$$

In the B_d, B_s systems the SM predicts they are small. Can be calculated in a systematic heavy mass expansion, in terms of $\Delta B = 2$ matrix elements which in turn can be evaluated in Lattice QCD [Lenz, Nierste '06].

D0 measures a linear combination of these two observables that deviates by almost 4σ from the SM. However it is a semi-inclusive measurement for which it is still debated whether it is fed only by the semileptonic asymmetries.

Semileptonic asymmetries



In any case, NP in $B\bar{B}$ mixing remains allowed at $30 - 40\%$ at 3σ: effort needs to be pursued !

Other CP violating observables in B decays

CP violation in rare radiative/semileptonic decays: allows to define additional observables with different/reduced hadronic uncertainties

Bobeth *et al.* '08, '11.

These observables will presumably be extremely useful to further explore and interpret the current 'anomalies' seen in exclusive $b \longrightarrow s$ transitions.

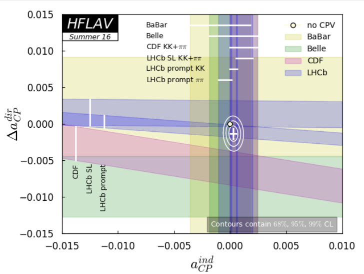
However FCNC semileptonic decays are not free from four quark operators contributions, and thus face the same theoretical challenges as the non leptonic decays.

Charm observables

The c quark and D meson scales are typically of the order of $\Lambda_{\rm QCD}$, so that the matrix elements cannot be well approximated by a low or large mass/energy expansion, in contrast to K and B physics.

There is a large amount of data in the D system that is extremely difficult to interpret in terms of short-distance couplings and hence, to discriminate New Physics

Still, many of the D observables are approximate Null tests of the SM, and could hint to NP if BSM couplings are large.



Lattice QCD

In the nineties it was thought impossible to extract final state interactions (and thus CP even phases) from LQCD simulations: Maiani-Testa no go theorem states that only euclidean objects can be extracted.
Since then it was shown that LQCD in a finite volume allows to extract matrix elements with hadronic interactions, and that their relation to infinite volume matrix elements can be analytically computed up to exponentially suppressed effects [Lellouch and Lüscher '90].
Nowadays Lattice groups are close to a determination of ε'/ε that could compete with the experimental measurement:

$$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{th}} = (15 \pm 7) \times 10^{-4}$$

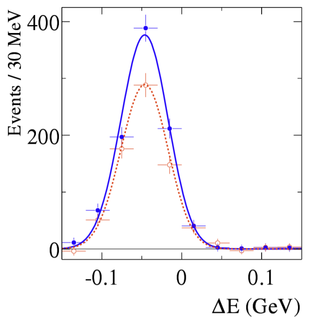
$$\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$

[Gisbert and Pich '17, PDG '17]

Lattice QCD

Same techniques could be used for the D system in the future. B physics is *really* more difficult: both large and small masses and momenta need to be simulated on the Lattice.

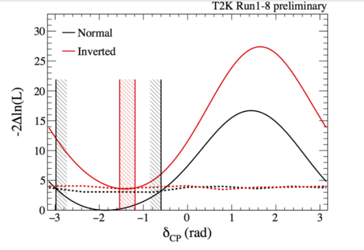
First direct CP asymmetry in B decays ($B \to K\pi$) was established in 2004 [BaBar, Belle]



We are still far from a prediction from first principles !

LFV/LUV and CP violation

CP violation in the neutrino sector might be close to be measured [T2K '17]



a 2σ effect !

If B observables confirm BSM couplings between quarks and leptons, then it might be well possible that also CP violation plays a rôle in these interactions

Conclusion

Among indirect tests of the Standard Model and searches for New Physics, CP violation plays a special rôle, since it is presumably a very fundamental property of Nature.

As the Standard Model is predictive in the CP violating sector, it can be tested in many different ways.

From the QCD/hadronic point of view, CP violating observables in the quark sector may either be amazingly simple, or awfully complicated.

CP violating non leptonic decays remain a theoretical challenge. Accurate results may come from the Lattice, at least for kaon decays and maybe D decays. Without a theoretical breakthrough, the interpretation of non leptonic B decays need a lot of data to measure what cannot be computed.