Charm

- a new chapter of CP violation

Marco Gersabeck (CERN)

Teilchenphysikkolloquium
Universität Heidelberg, 17 July 2012

→ MG, Brief review of charm physics, arXiv:1207.2195
THE VERY BEGINNING

- Cosmic showers
- Observed in emulsion chambers
- 500 hours aboard a cargo plane
THE NOBEL BEGINNING
Die Gegenwelt

CP VIOLATION

• CP symmetry: Particle ↔ Anti-particle exchange

• CP violation can occur in decay amplitudes, meson mixing, or their interference

• CP violation in strange mesons: discovered 1964

• CP violation in beauty mesons: discovered 2002
November Revolutions, Zoltan Ligeti, Charm 2012

(November 9, 2011, Pizzeria de la Place, Meyrin)
LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

15 November 2011

REALLY? AND NOW?

• Outline:
  • Short overview of the hardware
  • Zoology and theory
  • Status quo of the measurements
  • Quo vadis charm CP violation?

ΔA_{CP} = [-0.82 \pm 0.21\text{(stat.)} \pm 0.11\text{(syst.)}] \%
THE HARDWARE
look forward!
LUMINOSITY

• Moderate luminosity ($\sim 2\text{-}4\times10^{32}\ \text{cm}^{-2}\text{s}^{-1}$): on average 1-2 hard collisions per bunch crossing

• Constant luminosity through continuous tuning of beam overlap

• $\sim 10\%$ of visible proton-proton collisions contain a $c\bar{c}$-pair

$$\sigma(pp\rightarrow c\bar{c}) \sim 500\ 000\ 000 \times \sigma(pp\rightarrow H+X)_{\text{SM}}$$
• Lifetime of D mesons shorter than that of B mesons
• Flight distance similar: ~O(1)cm
• Detector resolution: ~0.1 \( \tau \)
• Ideal environment for time-dependent measurements
THE THEORY
THE POWER OF LOOPS

• Study (mostly) known processes
• Make precision measurements to examine loop-level contributions
• Probe unknown contributions to quantum-loops
• Examples:
  • mixing
  • penguins
• CP violation: matter-antimatter asymmetry
  → in mixing process (indirect),
  → in decay amplitudes (direct),
  → or in their interference
**D^0 MIXING**

- Mixing box contains down-type quarks
- No dominance of top mass as in B sector
- CKM-suppression balances GIM cancellation
- Huge cancellations: long-distance effects become important

\[
\begin{align*}
\Gamma_{12}(B^0_d) &\approx -\lambda^6 \\
\Gamma_{12}(B^0_s) &\approx -\lambda^4 \\
\Gamma_{12}(D^0) &\approx -\lambda^2
\end{align*}
\]

\[
\begin{align*}
&\times m_c^4/m_b^4 + \lambda^6 \\
&\times m_c^4/m_b^4 + \lambda^4 \\
&\times m_s^4/m_c^4 + \lambda^6
\end{align*}
\]

\[
\begin{align*}
&\times m_c^2/m_b^2 - \lambda^6 \\
&\times m_s^2/m_c^2 - \lambda^4 \\
&\times 1 - \lambda^{10} \\
&\times 1
\end{align*}
\]

\[
\lambda = \sin \theta_C \approx 0.2255
\]
INDIRECT CP VIOLATION

- CPV in mixing in SM experimentally constrained to $O(10^{-4})$
- Enhancement up to $\sim 10^{-3}$ conceivable
- Example: 4$^{th}$ generation $\rightarrow$ changes CKM structure
- Current world average precision $\sim 2 \times 10^{-3}$
- Expected LHCb precision with 2011 data $< 1 \times 10^{-3}$

→ e.g. Kagan, Sokoloff 2009; Bigi, Paul, Recksiegel, 2011
SCS AND PENGUINS

• Singly Cabibbo-suppressed (SCS)
  \[ c \rightarrow d \bar{d} u \quad (D^0 \rightarrow \pi^- \pi^+) \]
  \[ c \rightarrow s s u \quad (D^0 \rightarrow K^- K^+) \]

• Only SCS decays have gluonic penguin contributions (need $q \bar{q}$)

• Penguins carry weak phase w.r.t. trees
DO FISH EAT PENGUINS?

• $qq$ pairs can rescatter
• $c \to u\bar{d}d$ contributes to $c \to u\bar{s}s$
• Dangerous animals in the charm sector
SCS AND CP VIOLATION

• Singly Cabibbo-suppressed (SCS)
  \[ A(D \to f) = C(1+r e^{i(\delta+\phi)}) \]
  \[ A(\bar{D} \to f) = C(1+r e^{i(\delta-\phi)}) \]

• \( r \) is the ratio of sub-leading over leading amplitude

• Size of CP violation:
  \[ a_{CP} \equiv \frac{[\Gamma(D \to f)-\Gamma(\bar{D} \to f)]}{[\Gamma(D \to f)+\Gamma(\bar{D} \to f)]} \]
  \[ = 2 r \sin(\delta) \sin(\phi), \]
  with \( \Gamma(D \to f) = \int_0^\infty \Gamma(D(t) \to f) \, dt \propto |A|^2 \)

• With \( \sin(\phi) \sim \sin(\gamma) \), require \( r \sin(\delta) \sim 2 \times 10^{-3} \)
  \[ \text{→ requires matrix elements enhanced by a factor of } \sim 30 \]
  \[ \text{→ conceivable when comparing with strange and beauty sector} \]
Zoltan: “While the central value of $\Delta a_{CP}$ is much larger than what was expected in the SM, we cannot yet exclude that it may be due to a huge hadronic enhancement in the SM”

Yuval: “While the central value of $\Delta a_{CP}$ fits nicely in the SM, we cannot yet exclude that it may be due to NP”

Topologically the above two statements are equivalent

Just like a bagel and a mug are

Yet, to emphasize, whether Zoltan, me, or anyone else is the bagel is not the issue

The issue is how can we keep on checking
STATUS QUO
MIXING AND INDIRECT CPV
MIXING IN A NUTSHELL

\[ |M_{1,2} \rangle = p |M^0 \rangle \pm q |\overline{M}^0 \rangle \]

\[ \Delta m \equiv m_2 - m_1 \quad \Delta \Gamma \equiv \Gamma_2 - \Gamma_1 \]

\[ x \equiv \Delta m / \Gamma \quad y \equiv \Delta \Gamma / (2 \Gamma) \]

\[ P(M^0 \rightarrow M^0, t) = \frac{1}{2} e^{-\Gamma t} (\cosh(y \Gamma t) + \cos(x \Gamma t)) \]

\[ P(M^0 \rightarrow \overline{M}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} (\cosh(y \Gamma t) - \cos(x \Gamma t)) \]
STATE OF THE ART

• $D^0$ meson mixing known since 2007
• So far no single $5\sigma$ observation
• No-mixing hypothesis excluded at $10\sigma$
• Standard model expectation for CP violation is small
• Significant enhancement through physics beyond the standard model possible
• $y_{CP}$ is measured as the lifetime ratio of two decay modes
• Without CP violation in mixing: ($A_m=0$, $\phi=0$): $y_{CP} = y$
• Interpretation as mixing measurement
• Difference of $y_{CP}$ and $y$ is sign for CP violation
• Independent of CP violation expect $y_{CP} \leq y$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$y_{CP}(10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLE [8]</td>
<td>$13.1 \pm 3.2 \pm 2.5$</td>
</tr>
<tr>
<td>BABAR (tagged) [9]</td>
<td>$10.8 \pm 3.3 \pm 1.9$</td>
</tr>
<tr>
<td>BABAR (untagged) [10]</td>
<td>$11.2 \pm 2.6 \pm 2.2$</td>
</tr>
</tbody>
</table>
TIME-DEPENDENT CPV

• Measure lifetime asymmetries in $D \to hh'$ decays
• Decays to CP eigenstates: $f = K^-K^+, \pi^-\pi^+$

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)}$$

$$\approx \frac{1}{2}(A_m + A_d)y \cos \phi - x \sin \phi$$

• Not a pure measurement of indirect CPV


• Expect $A_\Gamma < 10^{-4}$ in SM and $A_\Gamma < 10^{-3}$ BSM
FLAVOUR TAGGING

• Measurements of raw asymmetries performed with flavour tagging using $D^{*+} \rightarrow D^0\pi^+$

• Strong decay with little $q^2$
  → exploit narrow peak in difference of invariant masses
  → $\Delta m = m(D^*) - m(D^0)$

• Soft (slow) pion charge tags $D^0$ flavour
RESULTS

• Result based on 0.03 fb⁻¹ from 2010

\[ y_{CP} = (5.5 \pm 6.3_{\text{stat}} \pm 4.1_{\text{syst}}) \times 10^{-3} \]

\[ A_{\Gamma} = (-5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-3} \]

• Precision already in the ballpark of existing measurements

• Have nearly 2 fb⁻¹ on tape from 2011 and 2012

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**LHCb collaboration, JHEP04(2012)129**

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NEWS FROM CHARM 2012

• Both BaBar and Belle have released new results on time-dependent two-body analyses ($\gamma_{CP}$ & $A_\Gamma$)
• Both using full dataset for $D^*$-tagged events ($KK + \pi\pi$)
• BaBar also use full dataset of untagged events for $\gamma_{CP}$ ($KK$ only) → four times larger than tagged sample
  → purity decreases from 99% to 74% ($KK$)
  → reduced statistical uncertainty
  → larger systematic uncertainty compared to Belle
• Belle are working on untagged addition but expect similar effect on systematic uncertainty
COMMENTS ON BABAR

• Old BaBar $\gamma_{CP} = (1.03 \pm 0.33 \pm 0.19)\%$
• New BaBar $\gamma_{CP} = (0.72 \pm 0.18 \pm 0.12)\%$
• Significant shift to lower central value
• Argued to be due to statistical fluctuation in non-overlapping part of dataset (384 fb$^{-1}$ → 468 fb$^{-1}$) plus effects of improved reconstruction
• Change caused by increase in CP-eigenstate lifetime as well as reduction in $K\pi$ lifetime
• Credible in terms of physics: $\gamma_{CP} \leq \gamma$
• No trivial explanation for $\gamma_{CP} > \gamma$
\[ M(m_-, m_+, t) = \left| A_1 \right|^2 e^{-yt} + \left| A_2 \right|^2 e^{yt} + 2Re[A_1A_2^*] \cos(xt) + 2Im[A_1A_2^*] \sin(xt) \right] e^{-t} \]

- Presented at ICHEP
- Extract \( x, y \) from decay-time dependent Dalitz fit
- Use CP-conservation assumption \( A_1 = A_2 \)

\[ x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%, \quad y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\% \]
COMMENTS ON BELLE

• New Belle $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$
• New Belle $y = (0.30 \pm 0.15 \ ^{+0.04/-0.05} \ ^{+0.03/-0.06})\%$
• $2.8\sigma$ tension between both results
• Belle $y_{CP}$ result now pulling $y_{CP}$ world average towards 1%
• No trivial explanation for $y_{CP} > y$
NEW B-FACTORY RESULTS

Including new BaBar and Belle results: significant improvement in the uncertainty and lower value for $y_{CP}$.
STATUS QUO
DIRECT CPV
TIME-INTEGRATED CPV

• Measure time-integrated CP asymmetries in $D \rightarrow hh'$ decays

\[
A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})}
\]

• Decays to CP eigenstates: $f = K^-K^+, \pi^-\pi^+$

• $A_{CP}$ is a sum of direct and indirect CP violation, leading to

\[
\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)
\approx \Delta a_{CP}^{dir} \left(1 + y_{CP} \frac{\langle t \rangle}{\tau}\right) + a_{CP}^{ind} \Delta \frac{\langle t \rangle}{\tau}
\]

• Need to measure asymmetries and time distributions

• Expect $a_{CP}^{dir} < 10^{-3}$ in SM and $a_{CP}^{dir} < 10^{-2}$ with NP*

*uncontroversial statement made at Beauty in April
Construct observable without external input:

\[ A_{CP}(KK) - A_{CP}(\pi\pi) = A_{RAW}^{CP}(KK)^* - A_{RAW}^{CP}(\pi\pi)^* \]

Expect indirect CP violation to cancel in difference as caused by common mixing process

Direct CP violation expected to differ for different final states

Expect non-zero result in presence of direct CP violation

Complementary New Physics search to \( A_{\Gamma} \) measurement
RESULTS

Systematics:
- Fiducial requirement: 0.01%
- Peaking background asymmetry: 0.04%
- Fit procedure: 0.08%
- Multiple candidates: 0.06%
- Kinematic binning: 0.02%

\[ \Delta A_{CP} = \left[ -0.82 \pm 0.21 \text{(stat.)} \pm 0.11 \text{(syst.)} \right] \% \]

Based on 0.62 fb\(^{-1}\): only just over half of the 2011 dataset

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( A_{CP}(KK) - A_{CP}(\pi\pi) ) in %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>-0.86(\pm 0.60_{\text{stat}} \pm 0.07_{\text{syst}})</td>
<td>Phys.Lett.B670 (2008) 190</td>
</tr>
<tr>
<td>BaBar*</td>
<td>+0.24(\pm 0.62_{\text{stat}})</td>
<td>Phys.Rev.Lett.100 (2008) 061803</td>
</tr>
<tr>
<td>CDF Preliminary</td>
<td>-0.62(\pm 0.21_{\text{stat}} \pm 0.10_{\text{syst}})</td>
<td>CDF note 10784</td>
</tr>
</tbody>
</table>

*naive difference from individual measurements of \( A_{CP}(KK) \) and \( A_{CP}(\pi\pi) \) ignoring systematics; all input measurements are dominated by statistical uncertainty
\[ \Delta A_{CP} \text{ FROM BELLE} \]

- Presented at ICHEP
- Most precise $A_{CP}(KK)$ to date
- Very small changes in central values with new data
- $2.1 \sigma$ excess from 0

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K K$</td>
<td>282k</td>
<td>97%</td>
</tr>
<tr>
<td>$\pi \pi$</td>
<td>123k</td>
<td>88%</td>
</tr>
<tr>
<td>$K \pi$</td>
<td>3.1M</td>
<td>99%</td>
</tr>
<tr>
<td>$K \pi$ untag.</td>
<td>14.7M</td>
<td>82%</td>
</tr>
</tbody>
</table>

Belle preliminary
\[ \Delta a_{\text{CP}} \approx \Delta a_{\text{CP,dir}} (1 + y_{\text{CP}} \langle \tau \rangle / \tau) + a_{\text{CP,ind}} \Delta \langle \tau \rangle / \tau \]

\[ \Delta A_{\text{CP}} \]

LHCb 2011 sensitivity estimate

no CPV

\[ \Delta A_{\text{CP}} \text{ BaBar} \]

\[ \Delta A_{\text{CP}} \text{ Belle Prelim.} \]

\[ \Delta A_{\text{CP}} \text{ LHCb} \]

\[ \Delta A_{\text{CP}} \text{ CDF Prelim.} \]

\[ A_\tau \text{ LHCb} \]

\[ A_\tau \text{ BaBar Prelim.} \]

\[ A_\tau \text{ Belle Prelim.} \]
THE ROAD AHEAD
• Mixing established
  → but no precise determination of individual parameters

• Evidence of direct CP violation
  → but source not identified

• No indication for direct CP violation in other charm decays
  → see later

• Indirect CP violation still out of reach
  → although maybe only just
• Additional measurement possibilities available for mixing and indirect CPV
• Interplay with direct CPV
• $K_{shh}$ proven very powerful by B-factories
• All these measurements are ongoing or in preparation at LHCb
THE ROAD AHEAD

• More precise measurements of $\Delta A_{\text{CP}}$ are underway → establish charm CPV at more than $5\sigma$ significance
• Measurements of individual asymmetries are more tricky → need to control production and detection asymmetries
• Measurements in other channels aim at observing/excluding related effects:
  → $D \to \text{VP/VV}$ decays with $3/4$-body final states
• Precise Measurements of mixing and indirect CPV parameters
$D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$ FROM LHCb

- Presented at ICHEP
- 4-body decays: 5D “Dalitz” space instead of 2D plane
- Access to several resonances, e.g. $\rho^0\rho^0$, $a_1\pi$
METHOD

• Bin phase space
• Measure per-bin asymmetry significance
• Evaluate distribution of significances
  → no CPV: expect normal distribution
  → non-zero CPV: reduces agreement with normal distribution
• Biggest challenge: choice of binning
  → too few or wrongly placed bins: average out local asymmetries
  → too many bins: local sensitivity too bad, no longer expect normal distribution
• Model-inspired binning can reduce risk of averaging out local asymmetries

• Choice here: adaptive binning
• Split phase space in each of 5 dimensions
• Merge bins with low occupancy
• Continue splitting for others
• Stop when all bins in a range of target occupancies
4πI FROM LHCb

Phase-space projections

<table>
<thead>
<tr>
<th>Bins</th>
<th>p-values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>97.1</td>
</tr>
<tr>
<td>29</td>
<td>95.6</td>
</tr>
<tr>
<td>66</td>
<td>99.8</td>
</tr>
</tbody>
</table>
THE LHC SCHEDULE

- LHC startup, $\sqrt{s} = 900$ GeV

- $\sqrt{s} = 7\sim 8$ TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
  $L = 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

- Go to design energy, nominal luminosity

- $\sqrt{s} = 13\sim 14$ TeV, $L = 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
  $L = 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

- Injector and LHC Phase-1 upgrade to full design luminosity

- $\sqrt{s} = 14$ TeV, $L = 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
  $L \approx 1\sim 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

- HL-LHC Phase-2 upgrade, IR, crab cavities?

- $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity levelling
  $L \approx 1\sim 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

adapted from M. Nessi, Chamonix 2012
TRIGGER UPGRADE

2012

40 MHz
- read out Pileup, Calorimeter, Muon

Level 0
\( p_T \) of \( h, \mu, e, \gamma \)

1 MHz
- Full detector readout

High Level Trigger
- Full event reconstruction:
  - tracking and vertexing
  - \( p_T \) and impact parameter cuts
  - inclusive/exclusive selections

4.5 kHz
- to storage

Upgrade

40 MHz
- read out Pileup, Calorimeter, Muon

Low level trigger
\( p_T \) of \( h, \mu, e, \gamma \)

up to 40 MHz
- Full detector readout

High Level Trigger
- Full event reconstruction:
  - tracking and vertexing
  - \( p_T \) and impact parameter cuts
  - inclusive/exclusive selections

20 kHz
- to storage
FULL 40 MHz FE READOUT

**Tracking**
- New silicon trackers
- Reduce straw coverage +
  - a) fiber tracker
  - b) larger silicon tracker

**Vertex Locator**
- a) New pixel detector
- b) Improved strip detector

**RICH**
- New photon detectors

**Calorimeter+Muon**
- Remove M1, SPD, PS
- New calorimeter FE electronics
CHARM AND THE FUTURE

• c c-cross-section increases by 1.8 from \( \sqrt{s} = 7 \text{ TeV} \) to 14 TeV

• Expect roughly a factor of 2 in charm trigger efficiency for LHCb
  → multibody decays may benefit even more

• Charm signal yield per fb\(^{-1}\) to increase by a factor 3.6

• Luminosity per year to increase by about a factor 3-5

→ Charm yield per year up by about an order of magnitude

• Example reach:
  → With 50 fb\(^{-1}\) expect \(\sim 4 \times 10^{10}\) offline selected \(D^0 \rightarrow K\pi\) decays

(use 50 fb\(^{-1}\) as luminosity beyond 2018, i.e. with upgrade detector)
TIMELINE

• Letter of Intent submitted March 2011
  → Physics case fully endorsed by LHCC
  → Encouraged to proceed to detector TDRs with 40 MHz front-end electronics

• Framework TDR submitted in June 2012
  → Defining cost, milestones and institutes’ interests

• TDRs in 2013
  → Decide on technical choices

• Production and QA in 2014-2017

• Installation and commissioning in 2018
  → Use LHC LS2
FUTURE INTERPLAY

\[ \Delta a_{\text{CP}} \approx -A_{\Gamma} \]

\[ a_{\text{ind}}^\text{CP} \approx -A_{\Gamma} \]
CONCLUSION

• Observed first evidence for CP violation in charm
• Further indication by CDF and Belle
• Need precise SM prediction to distinguish NP from SM in precision measurements
• Many other modes also on the agenda with at least competitive datasets on tape by now → constrain theoretical uncertainties

• 2012 data will allow discovery of large new effects
• To probe down to expected SM CPV with high precision need data beyond 2012 and indeed beyond LHCb → LHCb upgrade!

• Transition from exploratory phase to precision measurements → not only discover CPV but also understand its origin! (I. Bigi)
CHARM 2013
@ Manchester
31/8-4/9 2013