

Charm physics

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On behalf of the LHCb collaboration Including recent results from LHC and Tevatron

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Charm physics

Why heavy flavour?

- Search for effects from new, heavy particles in loop diagrams.
 - CP violation and rare decays allow to make precision tests.
- Complementary to direct searches at GPD's.

Why charm physics?

- Huge amounts of charm decays available at hadron colliders.
- Ultra-high precision tests possible.
- Sensitive to other flavour couplings compared to B decays.

Status of charm physics

- Broad field, dominated for long time by electron collider experiments
 - Hadron collider experiments come more into play.
- Many on-going activities. This talk focuses on:
 - Open charm production and production asymmetries
 - D mass measurements
 - D⁰ mixing
 - CP violation in the charm system •
 - Rare charm decays (including new result)



1.27 GeV/c²

charm

^{2/3} **C**

1/2

Open charm cross section

Open charm cross section

Motivation

- Understanding of QCD in hadronic collisions at new energy scale.
- Background estimate for SM processes, such as Higgs production.
- Powerful test of QCD@NLO calculations.
 - FONLL: Fixed-Order Next-to-Leading Logarithm JHEP 1210 (2012) 137 (M. Cacciari et al.)
 - GM-VFNS: Generalized Mass Variable Flavour Number Scheme EPJ C72 (2012) 2082 (B. Kniehl et al.)

Measurements at LHC

- LHCb:
 - Exclusive final states at 7 TeV <u>Nucl.Phys.B871 (2013) 1-20</u> and <u>LHCb-CONF-2010-013</u>.
 - Inclusive final states in high- p_T region <u>LHCb-CONF-2013-002</u>.
- ALICE:
 - Exclusive final states at 2.76 and 7 TeV JHEP 07 (2012) 191.
 - Inclusive (electron) states at 7 TeV PLB 721(2013)13.
- ATLAS:
 - Exclusive final states at 7 TeV <u>ATLAS-CONF-2011-017</u>.
 - D* production in jets at 7 TeV PRD85 (2012) 052005.

Measured cross sections above FONLL and below GM-VFNS prediction, but in general in good agreement.

Charm production versus energy

Comparison plot from ALICE paper

JHEP 07 (2012) 191



- pA and dA collisions scaled down to # binary collisions from Glauber model.
- Compared to NLO (MNR) calculations. Nucl. Phys. B 373 295 (1992).

Large charm cross section

Factor 20 more than beauty cross section.

More details in QCD2 session.

Charm production asymmetry

$D_{d,s}$ production asymmetry

Motivation

- Need good understanding of production asymmetry for precise measurements of CP violation.
 - Subtract from observed charge asymmetry.
- More relevant at pp collider compared to $p\overline{p}$ collider.

Mechanism

• Production mechanism is charge symmetric:



Define: $A_{p} = \frac{\sigma(D_{d,s}^{+}) - \sigma(D_{d,s}^{-})}{\sigma(D_{d,s}^{+}) + \sigma(D_{d,s}^{-})}$

- But, hadronisation can cause asymmetry:
 - Beam drag (colour connection between the *c* and the beam remnants)
 - \overline{c} prefers to form a meson, c a baryon $\Rightarrow \sigma(D^-) > \sigma(D^+) \Rightarrow A_P < 0$.
 - Other hadronisation effects (which could depend on p_{T} or rapidity)

D[±] production asymmetry

LHCb (1.0 fb⁻¹), PLB 718 (2013) 902

Method

- D^+ reconstructed as $D^+ \rightarrow K_S^0(\pi^+\pi^-)\pi^+$
- Cabibbo favoured mode: expect negligible CP violation.
 - Correct for small effect from neutral kaon asymmetry (0.03%).
- Correct for pion detection asymmetry.
 - Use D_s⁺ production asymmetry measurement: <u>PLB 713 (2012) 186</u>
- Measurement: $A_P = (-0.96 \pm 0.26 \pm 0.18)\%$
 - For 2 < y < 4.75 and $2 < p_T < 18$ GeV.
 - Sub-percent precision.
 - Systematics (PID, π^{\pm} asymmetry) can be reduced with more data.



D mass measurements

D mass measurements

Motivation

- In contrast to *B* mesons, relatively few precision measurement exist.
- Knowledge on D^+ and D_s^+ mass relatively limited.
- Limits precision on B_c mass in $B_c^+ \rightarrow J/\psi D_s^+$ channel
- D^0 mass also needed for understanding nature of X(3872)
 - X(3872) could be a D^0D^{*0} molecule

New measurement (LHCb)

- Use low Q-value modes: $D^0 \rightarrow K^- K^+ K^- \pi^+$, $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ and $D_{(s)} \rightarrow K^+ K^- \pi^+$
- Main systematics from momentum scale and energy loss correction
 - Calibrate momentum scale using $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow J/\psi K^+ \pi^- \pi^+$

LHCb 1.0 fb⁻¹, arXiv:1304.6865

Quantity	LHCb	Best previous	PDG fit
	measurement	measurement	
$M(D^0)$	1864.75 ± 0.19	1864.85 ± 0.18 [5]	1864.86 ± 0.13
$M(D^+) - M(D^0)$	4.76 ± 0.14	4.7 ± 0.3 [7]	4.76 ± 0.10
$M(D_s^+) - M(D^+)$	98.68 ± 0.05	98.4 ± 0.3 [10]	98.88 ± 0.25
	·		

[5] CLEO, PRL 98:092002 (2007)

[7] Mark II, PRD 24, 78–97 (1981)

[10] BaBar, PRD 65:091104 (2002)

D⁰ mass measurement

LHCb 1.0 fb⁻¹, <u>arXiv:1304.6865</u>



New average formed using PDG prescription

\rightarrow Same precision as previous best measurement from CLEO (2007).

Also preliminary results available from BaBar and Tomaradze et.al.

$D^+ - D^0$ mass measurement

LHCb 1.0 fb⁻¹, <u>arXiv:1304.6865</u>



New average formed using PDG prescription

→ First reported result in more than 30 years, factor 3 better than PDG average.

$D_s^+ - D^0$ mass measurement

LHCb 1.0 fb⁻¹, <u>arXiv:1304.6865</u>



New average formed using PDG prescription

- → Factor 5 improvement on PDG average (midway between BaBar and CDF)
- \rightarrow Will reduce uncertainty on Bc mass.



D⁰ mixing

Motivation

- Mixing occurs in neutral mesons: K⁰, B⁰, B_s, D⁰.
- $D^0 \overline{D}{}^0$ mixing expected to be very small.
 - Dominated by long range contributions (y); hard to predict.

Measurement

• Measure time-dependent ratio of wrong sign to right sign *D*⁰ decays



• In the limit of small mixing $|x|, |y| \ll 1$, and no CP violation:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2 \quad \begin{array}{c} x' = x\cos\delta + y\sin\delta\\ y' = y\cos\delta - x\sin\delta\\ \end{array}$$
Ratio of DCS to
CF decay rates Interference of DCS and mixed decays parameters DCS and CF amplitudes

D⁰ mixing at LHCb



D⁰ mixing at CDF

New result, <u>CDF Public Note 10990</u>







More details in HF2 session: P. Maestro

CP violation in charm

CP violation in charm

Current status

- CP violation well established in the kaon and B decays
- No CP violation yet observed in charm system

Why look for CP violation in the charm sector

- Charm system special: FCNC processes with up-type quarks
- Complementary to those with down quarks (*B* or *K* mesons).
- Direct CP violation possible in singly-Cabibbo suppressed decays
 - Interference between tree and penguin. Naïve expectation $\leq 0.1\%$
- Indirect CP violation prediction much smaller

Direct CP violation in D⁰ decays



All of order 1% or smaller

Analysis strategy

$$\Delta A_{CP} = A_{raw}(K^{-}K^{+}) - A_{raw}(\pi^{-}\pi^{+})$$
$$= A_{CP}(K^{-}K^{+}) - A_{CP}(\pi^{-}\pi^{+})$$

Detection and production asymmetry cancel at first order.

- ΔA_{CP} mainly measurement of direct CP violation
- In SM, assuming SU(3)_F symmetry: $a_{CP}^{dir}(K^-K^+) = -a_{CP}^{dir}(\pi^-\pi^+)$

The ΔA_{CP} surprise



LHCP2013, Barcelona, 13-18 May 2013

Recent update of ΔA_{CP}

- LHCb performed two independent analyses on full 2011 data set
- Preliminary update of pion-tagged analysis

LHCb-CONF-2013-003

- $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$
- New measurement of muon-tagged analysis <u>arXiv:1303.2614</u>
 - $\Delta A_{CP} = (+0.49 \pm 0.30 \pm 0.14)\%$



Direct CP violation in $D_{(s)}^{+}$

LHCb, 1.0 fb⁻¹, arXiv:1303.4906

CP violation in $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow K_s^0 \pi^+$ decays

- Use Cabibbo favoured modes to subtract production and detection asymmetry Control channels $D^+ \rightarrow K_S^0 \pi^+$ and $D_S^+ \rightarrow \phi \pi^+$ decays
- Also CP violation across ϕ mass in $D^+ \rightarrow K^+ K^- \pi^+$ Dalitz plane is measured: $A_{CP|S}$

 $A_{CP}(D^+ \to \phi \pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%$ $A_{CP}|_{S}(D^{+} \to \phi \pi^{+}) = (-0.18 \pm 0.17 \pm 0.18)\%$ $A_{CP}(D_s^+ \to K_s^0 \pi^+) = (+0.61 \pm 0.83 \pm 0.13)\%$

 \rightarrow No evidence for CP violation observed



Rare charm decays

Rare charm decays

LHCb 0.9 fb⁻¹, LHCb-PAPER-2013-013 Final result shown in public for 1st time

Search for $D^0 \rightarrow \mu^+ \mu^-$

- Similar analysis as $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$ in previous talk .
- Current limits: $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 1.4 \times 10^{-7}$ (90% CL). Belle <u>PRD 81 (2010) 091102</u>.
 - Preliminary LHCb result was best previous limit.
- SM prediction: $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 6 \times 10^{-11}$
 - Dominated by long distance contributions (2γ intermediate state).

Method

- Search for D^* -tagged $D^0 \rightarrow \mu^+\mu^-$ decays.
- Use $J/\psi \rightarrow \mu^+\mu^-$, $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ as normalization channels.

Result

- $\mathcal{B}(D^0 \to \mu^+ \mu^-) < 7.6 \times 10^{-9}$ (95% CL)
- More than factor 20 improvement with respect to previous best measurement.





Rare charm decays

Search for $D_{(s)}^+ \rightarrow \pi \mu \mu$

• Three decays with similar topologies. Previous best limits at 10⁻⁵–10⁻⁶ levels.









More details in HF2 session: H. Cliff

Summary

- Many more interesting results (soon) available:
 - Charmonium and double charm production
 - Recent results in $D_{(s)J}$ spectroscopy.
 - More CP violation analyses ongoing
 - A_{Γ} , y_{CP} WS mixing asymmetry, $D^0 \rightarrow K_S^0 h^+ h^-$
- Large statistics is the strength at hadron colliders
 - High sensitivity to small CP violation effects
 - Access to very rare decays
 - Systematics is challenging
- Charm physics at hadron colliders is delivering many results
 - Shown LHCb results are on 2011 data only → 3 x more data on tape
- Interesting times ahead of us!

Backup slides

Charm production measurements

LHCb

Exclusive final states at 7 TeV:

 $\sigma_{c\bar{c}}(p_{\rm T} < 8 {\rm GeV \& 2.0 < y < 4.5}) = (1419 \pm 12_{\rm stat} \pm 116_{\rm syst} \pm 65_{\rm frag}) \ \mu b \quad \text{Nucl.Phys.B871 (2013) 1-20}$

 $\sigma_{c\bar{c}}^{\text{tot}} = (6.1 \pm 0.9) \text{ mb}$ Preliminary, extrapolated using tuned-Pythia,

• Inclusive final states in high- p_{T} region:

 $\sigma_{c\bar{c}}(p_{\rm T} > 5 \text{GeV \& } 2.5 < y < 4.0) = (104.6 \pm 2.7_{\rm stat} \pm 11.4_{\rm syst}) \ \mu \text{b} \qquad \text{LHCb-CONF-2013-002}$

ALICE

• Exclusive final states at 2.76 and 7 TeV: (extrapolated using FONLL) <u>JHEP 07 (2012) 191</u> $\sigma_{c\bar{c}}^{tot}(2.76 \text{ TeV}) = (4.8 \pm 0.8(\text{stat})_{-1.3}^{+1.0}(\text{syst}) \pm 0.06(\text{BR}) \pm 0.1(\text{frag}) \pm 0.1(\text{lum})_{-0.4}^{+2.6}(\text{extr})) \text{ mb}$

 $\sigma_{c\bar{c}}^{\text{tot}}(7 \text{ TeV}) = (8.5 \pm 0.5(\text{stat})_{-2.4}^{+1.0}(\text{syst}) \pm 0.1(\text{BR}) \pm 0.2(\text{frag}) \pm 0.3(\text{lum})_{-0.4}^{+5.0}(\text{extr})) \text{ mb}$

• Inclusive (electrons) at 7 TeV: $\sigma_{c\bar{c}}^{tot}(7 \text{ TeV}) = (10.0 \pm 1.7(\text{stat})_{-5.5}^{+5.4}(\text{syst}) \pm 0.4(\text{BR})_{-0.5}^{+3.5}(\text{extr})) \text{ mb}$ PLB 721(2013)13

ATLAS

• Exclusive final states at 7 TeV: (extrapolated using Powheg-Pythia) $\sigma_{c\bar{c}}^{\text{tot}} = (7.13 \pm 0.28(\text{stat})_{-0.66}^{+0.90}(\text{syst}) \pm 0.78(\text{lum})_{-1.90}^{+3.82}(\text{extr})) \text{ mb}$ ATLAS-CONF-2011-017

LHCb-CONF-2010-013

D_s^{\pm} production asymmetry

LHCb (1.0 fb⁻¹), PLB 713 (2012) 186

Method

- D_s^+ reconstructed as $D_s^+ \rightarrow \phi(K^+K^-)\pi^+$
- Cabibbo favoured mode: expect negligible CP violation.
- Need to measure detection and reconstruction asymmetry from pion:
 - Use reconstructed D^* -tagged $D^0 \rightarrow K^- \pi^+ \pi^- \pi^-$ where one pion is missing.
 - Measure efficiency ratio for π^+ and π^-
 - No large asymmetry measured; ratio compatible with 1.
- Measurement: $A_P = (-0.33 \pm 0.22 \pm 0.10)\%$
 - For 2 < y < 4.5 and $p_{T} > 2$ GeV.
 - Sub-percent precision.



HFAG average of D⁰ mixing

