Open charm and charmonium production at LHCb

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on behalf of the LHCb collaboration

BEACH2010: IX International Conference on Hyperons, Charm and Beauty Hadrons
21-26 June 2010, Perugia
**Antipasto (spring 2010)**
Charm peaks; first $K_S$ paper

**Primo piatto (summer 2010)**
Charm production studies

**Secondo piatto (winter 2011)**
First searches for NP in flavour physics
(e.g. mixing and CPV in charm; $B_s \to \mu\mu$)

**Dolce (2012?)**
High-luminosity flavour physics
This talk

• Introduction
  • Our detector & acceptance
  • Luminosity measurements

• Charmonia

• Open charm

• Forthcoming attractions

See talk by Sebastian Bachmann for more
LHCb: Acceptance

- Angular acceptance: $15 < \theta < 300$ mrad
- Coverage of very forward region where theoretical uncertainties are larger.

See talk by Sebastian Bachmann for more details.

Detector Acceptance

overlap with ATLAS & CMS
overlap with ALICE
LHCb: Luminosity

• Luminosity comes directly from beam properties:

\[
L = f \sum_i^N \frac{n_{1i} n_{2i}}{4 \pi \sigma_x \sigma_y} \quad + \text{crossing angle correction}
\]

\[
\begin{align*}
\theta_1 & = 0.002167 \pm 0.000015 \\
\delta_1 & = 0.553 \pm 0.009 \\
\theta_2 & = 0.001913 \pm 0.000069 \\
\delta_2 & = 0.489 \pm 0.051
\end{align*}
\]

• Beam positions & crossing angle measured regularly with precision vertex detector using beam-gas interactions:

LHCb preliminary 2009 data, \( \sqrt{s} = 0.9 \, \text{TeV} \)

• Will also determine luminosity from Van der Meer scans
  • First scan already carried out in April; working...

• 2009 uncertainty ~ 15%; expected to be 5-10% by end 2010.
Charmonia

• What we want to accomplish
• Signals in the early data
• Evidence of secondary J/psi
• First look at raw $p_T$ and rapidity spectra
• Towards a measurement
Charmonia: Motivation & plan

• Expect copious production of $J/\psi$ at LHC:
  • Direct production
  • Feed-down from heavier charmonium states
  • Daughters of b-hadrons

• Want to measure cross-section as fn of $y$, $p_T$ for prompt and from-b (secondary) $J/\psi$ separately
  • To better understand production process (colour-singlet vs colour-octet)
  • To improve LHCb simulation for later physics studies

• Full analysis will use $O(10-20 \text{ pb}^{-1})$
  • High statistics needed for $O(5\times12)$ bins of $y$ vs $p_T$...

Plot shows detector acceptance... but polarization-dependent (see later)
Clear charmonium signals

$J/\psi \rightarrow \mu^+\mu^-$

Includes cuts on $p_T$ of $J/\psi$ and of $\mu$ daughters

$J/\psi \rightarrow e^+e^-$

Evidence for $\psi(2S) \rightarrow \mu^+\mu^-$
Prompt & secondary $J/\psi$

$J/\psi \rightarrow \mu^+\mu^-$

Loose selection suitable for cross-section measurements in full range of $\gamma, p_T$

\[ N_{\text{signal}} = 4211.8 \pm 98.2 \]
\[ \text{B/S} = 1.24 \pm 0.03 \]
\[ M = 3088.92 \pm 0.41 \text{ MeV/c}^2 \]
\[ \sigma = 15.8 \pm 0.4 \text{ MeV/c}^2 \]

Pseudo-proper-time of $J/\psi$

Clear evidence of secondary production from long-lived $B$

Note log scale
First look: $J/\psi$ spectra in $p_T$ and $y$

- Just 1D spectra for now! Full 2D distribution needs more statistics.
- Raw yields from bin-by-bin mass fits -- not corrected for efficiency.
- Prompt & secondary $J/\psi$ mingled together

![PT spectrum](image1)

![Y spectrum](image2)
Further steps on the path to a measurement

Polarization of $J/\psi$ is unknown, and strongly affects efficiency. We will measure it later, but for first analysis treat as systematic.

$$I(\cos \theta^*) = \frac{3}{2(\alpha + 3)}(1 + \alpha \cos^2 \theta^*)$$

- $\alpha=+1$: transverse polarization
- $\alpha=0$: unpolarized
- $\alpha=-1$: longitudinal polarization

Trigger requires high-$p_T$ muon, affecting acceptance. Use independent triggers (copious in early data) to verify/correct MC.
Open charm

Similar situation for open charm:

• Signals and Dalitz plots in the early data
• Prompt-secondary discrimination
  • Trickier than J/ψ because of charm lifetime!
  • Using the impact parameter of the D
  • Using semi-leptonic B decays
• Towards production measurements
• Mixing and CPV
Untagged $D^0 \rightarrow h^+ h^-$

- Very clear $D^0 \rightarrow K^-\pi^+$, $K^-K^+$ peaks, benefitting from RICH
- Fewer handles for $D^0 \rightarrow \pi^-\pi^+$
\[ K^- \pi^+ \rightarrow D^{*+} \rightarrow D^0 \pi^+ \, , \, D^0 \rightarrow h^+ h^- \, \]  
\[ K^- K^+ \]  

\[ \Delta M, \text{ taking full range of } m(D^0) \]  

\[ m(D^0), \text{ applying } 2\sigma \text{ cut on } \Delta M \]  

\[ N=1138\pm41 \]  

\[ N=1101\pm37 \]  

\[ N=86\pm13 \]  

\[ N=85\pm11 \]
\[ \text{D}^+/\text{D}_{s}^+ \rightarrow \text{K}^- \pi^+ \pi^+ \text{ and } \text{K}^- \text{K}^+ \pi^+ \]

**K}^-\pi^+\pi^+ \text{ mass spectrum**}

![Graph showing K^-\pi^+\pi^+ mass spectrum with a peak at 2.3 nb^-1 for D^+ and a peak at 2.3 nb^-1 for K^-K^+\pi^+]

**Dalitz plot (non-symmetric)**

![Graph showing Dalitz plot for D^+ \rightarrow K^-\pi^+\pi^+ with a peak at 2.3 nb^-1 for K^*(892)]

**K}^-\text{K}^+\pi^+ \text{ mass spectrum**}

![Graph showing K^-\text{K}^+\pi^+ mass spectrum with a peak at 2.3 nb^-1 for D^+ and a peak at 2.3 nb^-1 for D_s^+ \rightarrow K^-\text{K}^+\pi^+]

**E791 plot for comparison**

![Graph showing E791 plot for K^*_0(1430) and K^*_0(892)]

PRL 89:121801, 2002
Prompt-secondary discrimination

Prompt charm:
D points to primary vertex
Daughters of D don’t in general

Secondary charm:
D doesn’t point to PV in general

Can fit distribution of $D^0$ impact parameter to extract prompt and secondary charm yields separately.
D⁰μ⁻ vs D⁰μ⁺: semi-leptonic B decays

Look for D⁰μ⁻ (right-sign) and D⁰μ⁺ (wrong-sign) vertices:

Right-sign candidates

Wrong-sign candidates

m(K⁻π⁺) for D⁰μ combinations

log(D⁰ IP) for D⁰μ combinations

Teeny D⁰ peak

Pure prompt (plus background)
Towards production measurements

- As with charmonium, plan is to measure cross-section in bins of $y, p_T$.
- Preliminary result on $O(\text{few nb}^{-1})$ planned for summer.
- Paper on larger sample to follow.
Mixing and CP violation searches

- With $O(100 \text{ pb}^{-1})$, we can start probing for NP in open charm
  - Measurement of $y_{\text{CP}}$ with $D^0 \rightarrow K^-K^+, K^-\pi^+$ ... and indirect CPV ($A_{\text{CP}}$)
  - Model-independent search for direct CP violation in $D^+ \rightarrow K^-K^+\pi^+$
  - Search for rare decay $D^0 \rightarrow \mu^+\mu^-$
  - ... and more channels open up with additional data (e.g. $D^0 \rightarrow K_S\pi^+\pi^-$)

- LHCb is a great detector to do this kind of physics
  - High rate (e.g. expect few $10^6$ of $D^+ \rightarrow K^-K^+\pi^+$ in 100 pb-1)
  - Boost & precision vertexing give good lifetime resolution (expect 40ps from MC; alignment not yet optimal in data)
  - RICHes crucial for PID.

- For details of measurements see talk of Jeroen van Tilburg

Current HFAG limits on mixing, indirect CPV
Conclusions

• We see an abundance of charm at LHCb!
• We are working hard on first analyses: production cross-sections
• Mixing and CPV searches to follow once we have $O(100 \text{ pb}^{-1})$ of data
• I hope this has whetted your appetites!
More stuff
Efficiency from data

Reconstruction efficiency

Data driven methods:
- tracking efficiency using \(K_s\) sample
- muon ID using \(J/\psi\)

Good data/simulation agreement

See talks from F. Maciuc (Tracking and alignment in LHCb) and P. Xing (LHCb particle ID)
Motivations (1/2)

\(J/\psi\) production mechanism is not well understood

- colour-singlet model failed to reproduce CDF data (1997)
- colour-octet model introduced to explain the production rate but failed to reproduce the polarization

Measurement of this observable at higher energy will help in understanding the charmonium production mechanism.
Polarization

Polarization effect

\[ \frac{dN}{d\cos \theta} = \frac{1 + \alpha \cos^2 \theta}{2 + 2 \times \alpha / 3}, \quad \alpha = \begin{cases} \ +1: \text{fully transverse} \\ \ -1: \text{fully longitudinal} \\ \ 0: \text{no polarization} \end{cases} \]

LHCb angular acceptance is not trivial
- detector creates artificial polarization

Polarization modifies the acceptance up to 20% in some \((p_T, y)\) bins
- 1\textsuperscript{st} step: measure the cross section for 3 values of \(\alpha\) (to be agreed among LHC experiments)
- 2\textsuperscript{nd} step: measure the polarization
The LHCb unique angular acceptance

Forward spectrometer

- angular acceptance: 
  \[15 < \theta < 300 \text{ mrad}\]
- Special coverage of LHCb experiment, where theoretical predictions are less accurate.

See talks from A. Golutvin (Status of and news from LHCb)
$D^+ \rightarrow K^{-}\pi^+\pi^+$
Dalitz plot (folded)

LHCb Preliminary
$\sqrt{s} = 7$ TeV Data
Magnet Up+Down

$2.6 \text{ nb}^{-1}$
Sensitivity – $D^0$ Mixing Parameters

- Summary from selection
  \[
  \frac{B_{ckgr}/Signal}{\text{Signal}} = 2.56 \\
  N_{\text{Signal}}^{WS} = 46500 \pm 2200 \, fb^{-1} \\
  \epsilon_{\text{Signal}}^{RS/WS} = (1.39 \pm 0.17) \cdot 10^{-3}
  \]

- Extract $y_{\text{CP}}$ and $(x'^2, y')$ from toy MC

- Statistical errors
  \[
  \begin{array}{c|cc}
  & \sigma(x'^2) \cdot 10^{-3} & \sigma(y') \cdot 10^{-3} \\
  \hline
  LHCb[2fb^{-1}] & \pm 0.064 & \pm 0.87 \\
  BABAR & \pm 0.37 & \pm 5.4 \\
  Belle & +0.21 & +4.0 \\
  & -0.23 & -3.9
  \end{array}
  \]

- Sensitivity - combining likelihoods

Jörg Marks  Physics at LHC 2010: Charm Physics Results from LHCb