QCD measurements in the forward region at LHCb

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QCD and High Energy Interactions

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1. LHCb experiment

2. Selected QCD results
   - $\sigma(\chi_c \rightarrow J/\psi \gamma)/\sigma(J/\psi)$
   - $\psi(2S)$ production cross section
   - Double charm production
   - Charged track multiplicity
   - $\bar{p}/p$ ratio
- Designed for CP violation and rare decays of heavy mesons
- Single arm forward spectrometer, $b\bar{b}$ pair production correlated, 40% in the acceptance.
- Unique kinematic region (among the LHC experiments): high rapidity ($2 < \eta < 5$) and able to access low $p_T$
- Huge amount of $b\bar{b}$ produced ($\sigma \sim 300 \mu b$)
- Excellent momentum resolution and PID
New result - Never shown before.

\[ \sigma(\chi_c \rightarrow J/\psi \gamma) / \sigma(J/\psi) \]

LHCb-PAPER-2011-030
\[ \sigma(\chi_c \rightarrow J/\psi \gamma) / \sigma(J/\psi) \]

- \( \chi_c \) provide important test of NRQCD and color-singlet / color-octet production mechanisms
- Prompt \( \chi_c \) give substantial feed-down to \( J/\psi \) production: crucial for polarization studies

**First measurement**

- Ratio of P-wave charmonia \( \chi_{cJ}(1P) \) with \( J=0,1,2 \) production cross-section to the production of \( J/\psi \) in promptly produced charmonium \( \sigma(\chi_c \rightarrow J/\psi \gamma) / \sigma(J/\psi) \) as a function of \( p_T^{J/\psi} \).

- Complementary to the measurement of \( J/\psi \) production [EPJ C71 (2011) 1645] and to the cross-section ratio \( \sigma(\chi_{c1}) / \sigma(\chi_{c2}) \) for prompt production [LHCb-PAPER-2011-0119].
- Extend the \( p_T^{J/\psi} \) coverage with respect from HERA-B and CDF measurements [PRD 79 (2009) 012001, PRL 98 (2007) 232001].

\[ \chi_c \rightarrow J/\psi \gamma \]
\[ J/\psi \rightarrow \mu^- \mu^+ \]
\[ 2 < y_{J/\psi} < 4.5 \]
\[ 2 < p_{J/\psi}^T < 15 \text{ GeV} / c \]
\[ \int \mathcal{L} = 36 \text{ pb}^{-1} \]
\[ \gamma \text{ reconstruction using calorimeter clusters only} \]

prompt separation: \( d_Z(M(J/\psi)/p_Z) < 0.1 \text{ ps} \)

QCD measurements in the forward region at LHCb
Results

**photon efficiency**

- Measurement relies on knowing the photon efficiency $\epsilon^{\chi_c J}_\gamma$.
- $\epsilon^{\chi_c J}_\gamma$ using MC is validated on data $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{\pm} \rightarrow \chi_c K^{\pm}$.

**J/ψ and χc polarization’s**

- $J/\psi$ and $\chi_c$ polarized states modify $\epsilon^{\text{part}}_x$ from MC (unpolarized).
- A polarisation weights in $p^T_{J/\psi}$ bins all combinations ($J/\psi$, $\chi_c1$, $\chi_c2$) with $\lambda_{J/\psi} = +1, -1, 0$: ie. fully transverse, fully longitudinal, unpolarised.
- The polarisation error is given separately.
$\frac{\sigma(\chi_c \to J/\psi \gamma)}{\sigma(J/\psi)}$

Results

ratio $\frac{\sigma(\chi_c \to J/\psi \gamma)}{\sigma(J/\psi)}$ in bins of $p_T^{J/\psi}$

- Lines surrounding the data: the maximum effect of the unknown $J/\psi$ and $\chi_c$ polarizations.
- Results in agreement with NLO NRQCD (Ma, Wang and Chao [PR D83 (2001) 111503])
- *ChiGen* Monte Carlo generator (LO+CSM) does not well reproduce the total $J/\psi$ cross-section (prompt + feeddown) at low $p_T$ [hepforge.org/superchic/chigen.html]
ψ(2S)
ψ(2S) production cross section

- Ideal laboratory for QCD studies: since prompt ψ(2S) = direct ψ(2S) the cross-section is easy to interpret (no feed-down mechanism).
- Several theoretical predictions (NRQCD CSM and COM) have been carried out over the last years.

ψ(2S) cross-section through two decay channels:
ψ(2S) → µ⁻µ⁺ and ψ(2S) → J/ψ(µ⁻µ⁺)π⁺π⁻

Separation between prompt and coming from B hadron with the decay time variables ($t = dZ(M/pZ)$)

$2 < y_{ψ(2S)} < 4.5$
$p_{T,ψ(2S)} < 16 \text{ GeV}/c$
$\int L = 36 \text{ pb}^{-1}$

QCD measurements in the forward region at LHCb
\( \psi(2S) \) production cross sections

\[
\sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01(\text{stat}) \pm 0.12(\text{sys})^{+0.20}_{-0.40}(\text{pol}) \mu b^{-1}
\]
\[
\sigma_b(\psi(2S)) = 0.25 \pm 0.01(\text{stat}) \pm 0.02(\text{sys}) \mu b^{-1}
\]

MWC: Ma, Wang and Chao [1012:1030]
KB: Kniehl and Butenschön [PRL 106 (2006) 022003]
FONLL: [JHEP 0407 (2004) 033]
ψ(2S) production cross section

Results

\[ \sigma_{\text{prompt}}(\psi(2S)) \]

\[ \sigma_{\text{prompt}}(J/\psi) \]

\[ \sigma_b(\psi(2S)) \]

\[ \sigma_b(J/\psi) \]

\[ \mathcal{B}(b \to \psi(2S)X) = \zeta \frac{\sigma_b(\psi(2S))}{\sigma_b(J/\psi)} \mathcal{B}(b \to J/\psi X), \]

\( \zeta \): extrapolation factor to the full phase space of both decays.

\[ \mathcal{B}(b \to \psi(2S)X) = (2.73 \pm 0.06\text{(stat)} \pm 0.16\text{(stat)} \pm 0.24\text{(BR)}) \times 10^{-3} \]

agreement with CMS [CMS-BPH-10-014]: \[ \mathcal{B}(b \to \psi(2S)X) = (3.08 \pm 0.18\text{(stat + sys)} \pm 0.42\text{(BR)}) \times 10^{-3} \]

inclusive \( b \to J/\psi \) and \( b \to \psi(2S) \) can be used to extract \( \mathcal{B}(b \to \psi(2S)X) \) know at 50\% level: \( (4.8 \pm 2.4) \times 10^{-3} \) [PDG]
Double Charm Production

LHCb-PAPER-2012-003
Double Charm production

Double $J/\psi$, $J/\psi$ with open charm ($J/\psi C$) and double open charm ($CC$)

Double Charm production models:

- Perturbative QCD (pQCD) matrix elements, agrees well with $J/\psi J/\psi$
  $gg \to J/\psi J/\psi$ is measured by NA3 in 1982 [PLB 114 457, PLB 158, 85] and LHCb in 2011 [PLB 707 52]
  LHCb measurement is in excellent agreement with pQCD calculations for
  $\sigma_{LHCb} = 5.1 \pm 1.0 \pm 1.1\text{nb}$ vs $\sigma_{pQCD} = 4.1 \pm 1.2\text{nb}$
  Calculation in LHCb acceptance region: $\sigma(J/\psi C) \sim 18\text{nb}$ and : $\sigma(CC) \sim 100\text{nb}$

- Intrinsic Charm Model (IC): testing/constraining (badly known) charm PDFs

- Double Parton Scattering (DPS), neglecting partonic correlation in the proton:
  $\sigma_{AB}^{DPS} = \frac{1}{2} \frac{\sigma_{A}^{SPS} \sigma_{B}^{SPS}}{\sigma_{DPS}^{eff}}, m = 1 (2)$ for $A = B (\neq)$,
  CDF measured in multi-jet events: $\sigma_{DPS}^{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}\text{mb}$ [PDR 56 3811 (1997)]

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma_{gg}$</th>
<th>$\sigma_{DPS}$</th>
<th>$\sigma_{IC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi D^0$</td>
<td>10 $\pm$ 6</td>
<td>7.4 $\pm$ 3.7</td>
<td>146 $\pm$ 39</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>5 $\pm$ 3</td>
<td>2.6 $\pm$ 1.3</td>
<td>60 $\pm$ 17</td>
</tr>
<tr>
<td>$J/\psi D_s^+$</td>
<td>1.0 $\pm$ 0.8</td>
<td>1.5 $\pm$ 0.7</td>
<td>24 $\pm$ 7</td>
</tr>
<tr>
<td>$J/\psi \Lambda_c^+$</td>
<td>0.8 $\pm$ 0.5</td>
<td>0.9 $\pm$ 0.5</td>
<td>56 $\pm$ 22</td>
</tr>
</tbody>
</table>

QCD measurements in the forward region at LHCb
Double Charm @ LHCb

- We want to measure $c\bar{c}c\bar{c}$: $J/\psi C$ and $CC$
  (bonus: $C\bar{C}$, dominated by the regular $gg \rightarrow c\bar{c}$)

- In total 25 possible modes:
  $c\bar{c}c\bar{c}: J/\psi J/\psi + 4J/\psi C + 10CC$
  $gg \rightarrow c\bar{c}: 10C\bar{C}$

- Charm hadron selection:
  - Cuts on tracks $\chi^2$ and particle PID
  - Vertex quality cuts: PV and decay consistency
  - Cut on $c_\tau$ for open charm hadrons
  - Require both hadrons consistent with the same PV

\[
\begin{align*}
C &= D^0, D^+, D^+_s, \Lambda_c^+ \\
2 < y_{J/\psi,C} < 4 \\
3 < p^T_C < 12 \text{ GeV/c} \\
p^T_{J/\psi} < 12 \text{ GeV/c} \\
\int \mathcal{L} &= 355 \text{ pb}^{-1} \\
J/\psi &\rightarrow \mu^+\mu^- \\
P^0 &\rightarrow K^-\pi^+, \\
P^+ &\rightarrow K^-\pi^+\pi^+, \\
P^+_{s} &\rightarrow (K^+K^-)_{\phi}\pi^+, \\
\Lambda_c^+ &\rightarrow pK^-\pi^+.
\end{align*}
\]

QCD measurements in the forward region at LHCb
Double charm production

- $J/\psi C$ production has been measured ($> 7\sigma$) for the first time in a hadron machine. CC production has been observed for the first time for six modes with $> 5\sigma$ significance.
- the $J/\psi C$ measured coress-section significantly exceed the expectation from gluon-gluon fusion, but agree qualitatively with the DPS.
- For $c\bar{c}c\bar{c}$ and $c\bar{c}$ theoretical uncertainties cancel in the ratio. In DPS the ratio is the effective cross-section. Effective Cross-section for $J/\psi C$ agrees with Tevatron value, for $c\bar{c}c\bar{c} \sim 3$ higher.

QCD measurements in the forward region at LHCb
Double charm production

Results - properties

Extensive study of spectra in transverse momenta and global invariant mass. Harder $p_T$ for $J/\psi$ from $J/\psi C$ compared to prompt one (a), no difference for $C'$.

Azimuthal (a) and rapidity (b) correlations for three $J/\psi C$ decays. No correlation in the angle (expected in gluon fusion), but mostly uncorrelated.
Charged Track Multiplicity

LHCb-PAPER-2011-011
Charged Track Multiplicity

- Important for good simulation of environment aside from hard scatter
- Particles counted by reconstructing tracks in the VELO outside magnetic field, no momentum measurement
- Correction for non-prompt contamination (5-10%) and for efficiency drop at low $p_T$ (residual field)
- All models fail to describe the mean charged particle multiplicity per unit of pseudorapidity, (mainly at high $\eta$).
- The Perugia (NOCR) tune [PR D82 (2010) 074018] gives the best description of the data in the backward direction but fails to reproduce the size of the asymmetry.

QCD measurements in the forward region at LHCb
$\overline{p}/p$ ratio

LHCb-CONF-2010-009 Updated
$p/p$ ratios at $\sqrt{s} = 900\,\text{GeV}$ and $\sqrt{s} = 7\,\text{TeV}$

- $\bar{p}/p = \frac{\sigma_{pp\rightarrow \bar{p}X}}{\sigma_{pp\rightarrow pX}}$ probes the baryon number transport.
- Several models exist to describe this transport, but it is not clear which mechanisms are most important in driving the phenomenon.
- Prompt protons with $p > 5\,\text{GeV}/c$ are selected with PID requirements ($\sim 95\%$ purity on MC, with efficiency $\sim 85\%$).
- Efficiency and purity of the PID evaluated on data using tag and probe method on calibration samples: $\phi \rightarrow K^+K^-$, $K_S^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow \pi p$.

Measurements are done in 3 bins of $p_T$ (0; 0.8; 1.2 GeV/c) and 5 bins of rapidity $2.0 < y < 4.5$
- Measurements performed at $\sqrt{s} = 900\,\text{GeV}$ ($0.3\,\text{nb}^{-1}$) and $\sqrt{s} = 7\,\text{TeV}$ ($1.8\,\text{nb}^{-1}$).
$p/p$ at $\sqrt{s} = 900\,\text{GeV}$

$\bar{p}/p$ at $\sqrt{s} = 7\,\text{TeV}$

analysis extended to $K^-/K^+$, $\pi^-/\pi^+$, $(\bar{p} + p)/(K^- + K^+)$, $(\bar{p} + p)/(\pi^- + \pi^+)$ and $(K^- + K^+)/($$\pi^- + \pi^+$)
No evidence of significant $p_T$ dependency.
Consistent with previous experiments but significantly more precise.
Conclusions

- LHCb probes high rapidity region at LHC.
- Important results for improving models, charged track multiplicity above any generator prediction.
- A lot of measurements in the quarkonia sector as input for theories: production cross-sections, ratios.
- This was only a non-exhaustive list of LHCb soft QCD measurements, more are available and/or in preparation.
- Looking forward to run at 8 TeV.