QCD Results from LHCb

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On behalf of the LHCb collaboration

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Lund University
Introduction: LHCb

Originally designed to study CPV and new physics in rare b and c decays, nowadays a GPD in forward region

- Excellent momentum resolution \( \delta p/p \sim 0.5 - 1.0\% \) (5 – 100 GeV/c)
- Tracking efficiency > 96%
- IP resolution \( \sim 20 \mu m \) for high \( p_T \) tracks
- Excellent PID capability

Well suited for QCD studies especially in the forward region, complementary to other LHC experiments

- fully instrumented for \( 2 < \eta < 4.5 \) ⇒ allows exploring high and low Bjorken-\( x \) regions
- VELO provides backward coverage: \(-3.5 < \eta < -1.5\)
- low \( p_T \), low mass triggers
- low pile-up environment ⇒ suitable for CEP studies
Introduction - a new tool: HeRSCheL

HeRSCheL: High Rapidity Shower Counters for LHCb

- Forward scintillators for selecting rapidity gaps
- Up to ±114 m from IP: full gap size $2 < \eta < 8$
- Fully operative since 2015!
Introduction: QCD at LHCb

- Rich physics program in QCD:
  - Central Exclusive Production (*this talk*)
  - Multi- Parton Interactions (*this talk*)
  - Study of PDFs (*talk by Katharina Mueller*)
  - Vector boson production (*talk by Murilo Santana Rangel*)
  - Vector boson production in association with (heavy) jets (*talk by Murilo Santana Rangel*)
  - Heavy ion and fixed target physics program (*talk by Laure Massacrier*)
  - Top production
  - Soft QCD
  - Hadron production
  - ... many others with Run 1 data...
  - ...and many others to come with Run 2 data!
Central Exclusive Production of heavy quarkonia

- **Diffractive process**
- At LO proceeds via the exchange of a photon and a pomeron
- @LHCb sensitive to $g(x)$ for small $x$ [O(10^{-5})], where knowledge of $g(x)$ is limited; *(see talk by K. Mueller)*
- **Signature**: decay products of resonances and no other activity in the detector (rapidity gap)
- **Background**: inelastic processes where most of the tracks go undetected in the beam pipe

Backward VELO tracks help to reject inelastic processes
Central Exclusive Production of heavy quarkonia

- $J/\psi$, $\psi(2S)$, $\Upsilon(nS) \rightarrow \mu^+\mu^-$; rapidity range $2 < \eta(\mu^\pm) < 4.5$
- low $p_T^2$ to enhance the diffractive component: $p_T^2 < 0.8 \text{ GeV}^2/c^2$ (2.0 $\text{ GeV}^2/c^2$) for $J/\psi$ ($\Upsilon$)
- Mass peaks fit with double-sided crystal ball function; non resonant background with exponential
- Mass peaks include contributions from feed-down (from $\chi_{c,b}$) and inelastic background
- Datasets: $\sqrt{s} = 7 \text{ TeV}: 37 + 930 \text{ pb}^{-1}$ (945 $\text{ pb}^{-1}$) for $J/\psi$ ($\Upsilon$) analysis; $\sqrt{s} = 8 \text{ TeV}: 1985 \text{ pb}^{-1}$ for $\Upsilon$ analysis
CEP: results for J/ψ and Ψ(2S)

- Exclusive signal extracted from non-resonant-background-subtracted $p_T^2$ distributions
- Feed-down estimated from simulation normalised to data $[\chi_{c(b)} \rightarrow J/\psi \gamma \ (\Upsilon \gamma)]$
- Signal, as well as inelastic background assumed to be exponential according to HERA measurements:
  $d\sigma/dt \sim e^{-b(W)t}$ ($W = p\gamma$ c.o.m energy)
- $b(W)$ obtained from HERA and extrapolated to LHCb energies according to Regge theory

![Graphs showing J/ψ and Ψ(2S) distributions](JPG 41 (2014) 055002)

LHCb expect:
- $b_{\text{signal}} \sim 6$ GeV$^{-2}$
- $b_{\text{inel}} \sim 1$ GeV$^{-2}$
- LHCb fit:
- $b_{\text{signal}} = 5.70 \pm 0.11$ GeV$^{-2}$
- $b_{\text{inel}} = 0.97 \pm 0.04$ GeV$^{-2}$

LHCb Expect:
- $b_{\text{signal}} \sim 5.5$ GeV$^{-2}$
- $b_{\text{inel}} \sim 0.6$ GeV$^{-2}$
- LHCb Fit:
- $b_{\text{signal}} = 5.1 \pm 0.7$ GeV$^{-2}$
- $b_{\text{inel}} = 0.8 \pm 0.2$ GeV$^{-2}$

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CEP: results for $J/\psi$ and $\psi(2S)$

- Differential cross sections in 10 bins of meson rapidity $y$
- Good agreement with NLO order calculations
- Integrated cross-sections*BR for both muons in pseudorapidity range $2<\eta<4.5$ are also in good agreement with theoretical calculations

CEP: results for $\Upsilon(nS)$

- Data samples at $\sqrt{s} = 7$ and 8 TeV combined
- Exclusive signal extracted from non-resonant-background-subtracted $p_T^2$ distributions
- Feed-down estimated from simulation normalised to data $[\chi_{c(b)} \rightarrow J/\psi \gamma (\Upsilon\gamma)]$
- Signal, as well as inelastic background assumed to be exponential

$$d\sigma/dt \sim e^{-b(W)t} \quad (W = p_\gamma \text{ c.o.m energy})$$

- $b(W)$ obtained according to Regge theory from MC generator (SUPERCHIC) tuned on $J/\psi$ results;
- Fit PDF obtained from simulated events with a kernel estimation
CEP: results for $\Upsilon(nS)$

- Differential cross sections in 3 bins of meson rapidity $y$;
- Good agreement with NLO order calculations
- Integrated cross-sections*BR for both muons in pseudorapidity range $2<\eta<4.5$ are also in good agreement with theoretical calculations

Photoproduction of heavy quarkonia

- From previous measurements extract photoproduction cross section:

\[ \frac{d\sigma}{dy_{pp\rightarrow p(J/\psi,\gamma)}} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p\rightarrow (J/\psi,\gamma)p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p\rightarrow (J/\psi,\gamma)p}(W_-) \]

- For J/ψ obtain both W_+ and W_- contribution using power law result from HERA; result in agreement with past measurements

- For ϒ, extract only the W_+ term (W_- term neglected); very good agreement with NLO calculation
Double charm production

- At LHC: large open charm and charmonium production cross sections $\rightarrow$ multiple production relevant;
- Sheds light on charmonium production mechanisms;
- Double parton scattering represents an important background to physics processes (Higgs, BSM searches,...)
- At LHCb: study J/$\psi$ + open charm (J/$\psi$C) or double open charm (CC) production
- Receives contributions from: pQCD, double parton scattering (DPS), intrinsic proton charm content; DPS expected dominant
- DPS can be estimated, neglecting partonic correlations in the proton, as:
  \[ \sigma_{C_1C_2}^{DPS} = \alpha \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{eff}^{DPS}} \]
  \[ \alpha = \text{constant depending on the } C_1C_2 \text{ combination} \]
  \[ \sigma_{eff}^{DPS} \text{ is related to the transverse overlap function between the partons in the proton} \]
Double charm production: results

- **Dataset:** √s = 7 TeV, 355 pb⁻¹
- 17 combinations J/ψC, CC and C̅C channels measured with > 5σ significance
- J/ψ → μ⁺μ⁻
- C = D⁰(K⁻π⁺); D⁺(K⁻π⁺π⁺); D⁺₅ (K⁻K⁺π⁺); Λ⁺ᶜ(pK⁻π⁺)

The ratio:

\[ \mathcal{R}_{C_1C_2} \equiv \alpha' \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{C_1C_2}} \]

where \( \alpha' \) depends on the \( C_1C_2 \) combination is in reasonable agreement with \( \sigma_{\text{DPS}}^{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \) mb measured at Tevatron for J/ψC and CC modes (for \( C\overline{C} \) it has a less direct interpretation)

- DPS is the dominant production process for the above modes
Double charm production: results

- Dominance of DPS supported also by kinematic distributions.
- $\Delta\phi$ and $\Delta y$ between the two charmed mesons show absence of correlation.

![Graphs showing $d\ln\sigma^*/d(\Delta\phi/\pi)$ and $d\ln\sigma^*/d\Delta y$ distributions for $J/\psi D^0$, $J/\psi D^+$, and $J/\psi D_s^+$, with data points and error bars.](image)
Associated production of $\Upsilon$ and open charm

- Dataset: $\sqrt{s} = 7$ TeV and 8 TeV, 3 fb$^{-1}$

- $\{\Upsilon(1S), \Upsilon(2S)\}D^0, \{\Upsilon(1S), \Upsilon(2S)\}D^+$, $\{\Upsilon(1S), \Upsilon(2S)\}D^+_s$ pairs observed with $>$5σ significance

- Measured production cross section of $\Upsilon(1S)D^0$ and $\Upsilon(1S)D^+$ at $\sqrt{s} = 7$ TeV and 8 TeV

- DPS found to be the dominant process.

- $\sigma_{\text{eff}}^{\text{DPS}}|_{\Upsilon(1S)D^0,+} = 18.3 \pm 1.3 \pm 1.2$

  in good agreement with previous measurements from LHCb and TeVatron

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Outlook: exclusive J/ψ production at 13 TeV

- Same analysis as at √s = 7 TeV but now with HeRSChel extending the veto down to η~8
- Approximately half background from inelastic processes for p_T^2 < 0.8 GeV^2
Conclusions

• Wide program on QCD physics at LHCb

• It exploits LHCb unique geometry to complement other experiments

• Presented results from Run 1 data, related to
  ★ Central Exclusive Production
  ★ Double charm and bottom-charm associated production

• Many other results not covered in this talk/conference:

• Many results expected soon with 2015 data!
LHCb QCD publications

- 34 papers published; full list at:
- [http://lhcbproject.web.cern.ch/lhcbsubject/Publications/LHCbProjectPublic/Summary_QEE.html](http://lhcbproject.web.cern.ch/lhcbsubject/Publications/LHCbProjectPublic/Summary_QEE.html)
CEP results: integrated cross sections

- Integrated cross-sections*BR for both muons in pseudorapidity range $2<\eta<4.5$

<table>
<thead>
<tr>
<th>Predictions</th>
<th>$\sigma_{pp\rightarrow J/\psi (\rightarrow \mu^+\mu^-)}$</th>
<th>$\sigma_{pp\rightarrow \psi(2S) (\rightarrow \mu^+\mu^-)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonçalves and Machado</td>
<td>275</td>
<td>6.1</td>
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<td>STARLIGHT</td>
<td>292</td>
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<td>Motyka and Watt</td>
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<td>SUPERChic$^a$</td>
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<td>Schäfer and Szczurek</td>
<td>710</td>
<td>17</td>
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<tr>
<td><strong>LHCb measured value</strong></td>
<td><strong>307 \pm 21 \pm 36</strong></td>
<td><strong>7.8 \pm 1.3 \pm 1.0</strong></td>
</tr>
</tbody>
</table>

\[
\sigma(pp \rightarrow p \Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb},
\]
\[
\sigma(pp \rightarrow p \Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb}, \quad \text{and}
\]
\[
\sigma(pp \rightarrow p \Upsilon(3S)p) < 3.4 \text{ pb at the 95\% confidence level}.
\]
Double charm production: results

- Kinematic distributions for $\bar{c}c$ combinations
- Contributions from SPS are evident
Associated production of $\gamma$ and open charm

arXiv:1510.05949v1 [hep-ex], supplementary material