Production of heavy quarks and quarkonia at LHC(b)

Vanya Belyaev (ITEP/Moscow)
Outline

• Heavy quark and quarkonia production
  • Why?
• LHCb experiment
• Open charm \( D^0 \), \( D^+ \), \( D_s \), \( \Lambda_c \)
• Hidden charm \( J/\psi \), \( \psi' \), \( \chi_c \)
• Associative charm \( 2 \times J/\psi \), \( J/\psi + C \), \( 2 \times C \), \( Z^0 + C \)
• Bottomonia \( \Upsilon \)
• Next steps and conclusion
• HQ is likely the most powerful tool for quantitative study of QCD: $\alpha_s(m_Q)$, $\Lambda_{QCD}/m_Q$, ....

• Why one needs to know QCD?
  • All mass of visible Universe is due to QCD
    - Higgs takes care only on $O(1\%)$ of proton mass
  • All fundamental quantities are affected by QCD corrections.
    The precise extraction is not possible without deep understanding of QCD
    - Dominant source of systematic for Higgs properties
  • strong CP-problem
  • QCD effects could nicely mimic New Physics: DPS
  • ....
• For high energy proton-proton collision (LHC)
  • Mainly gluon-gluon fusion
  • Contribution for other sources is small
  • Simple?

• Long and rich history, experimental and theoretical
  • End of XX-century @ Tevatron:
    • DATA/theory >> 10
  • Some improvements around mid 2000
  • Becomes clear that the pattern is not so simple....
Some old slide: 2005

Beauty production at High Energy

D0 Run I [PRL 84(2000) 5478]

CDF Run I [PRL 85(2002) 5068]

Run II Moriond QCD’04

Too much beauty?

13 March ’2k+5

“Heavy Flavours” Ivan Belyaev

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Another example $J/\psi & \Upsilon$ @Tevatron

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Progress with theory

J.P. Lansberg

\[ d\sigma/dP_T|_{|y|<0.4} \times Br \]

\[ \gamma(1S) \text{ prompt data} \times F_{\text{direct}} \]

LO

NLO

NNLO

+ double $t$-channel gluon exchange at $\alpha_s^5$

Attention: the NNLO* is not a complete NNLO

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And what now?

- Almost 20 years of continuous progress
- Great improvement between experiment and theory for cross-sections.
- Everything understood?

Warning bell!
Polarization fiasco

• Reconsider the role of various mechanisms?
  • $k_T$-factorization?
• Importance of feed-down?
  • Important to compare $J/\psi$ and $\psi'$
  • Important to know production of P-wave states
• More data needed
• Other observables: $2 \times J/\psi$, quarkonia in $pPb$, $J/\psi + C$, $J/\psi + \Upsilon$,..... may shed light on the problem

LHCb is trying to attack all these targets.

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LHCb Experiment

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- 1057 members
- 67 institutes
- 16 counties

2 groups from PRC
- Tsinghua
- CCNU

pp-collisions
\( \sqrt{s} = 0.9, 2.76, 7 \) & 8
(13++ in 2015)
pA and Ap

pp collisions
\( \sqrt{s} = 0.9, 2.76, 7 \) & 8
(13++ in 2015)
Trigger & Selection

• Very flexible trigger, down to low-$p_T$ particles
  • Hardware: energetic (di)muon, hadron, e± or γ
  • Software: full reconstruction & particle ID
  • Typical efficiency for $2\mu$ states >70%, for hadronic states ~30%

• Offline:
  • Refine reconstruction, track quality, particle ID, good common vertices,
  • For open charm and beauty exploit finite lifetime and require vertex separation
Prompt open charm $D^0, D^{*+}, D^+$

- "Early" measurement
- only $15 \text{nb}^{-1}$
- $5 \times 10^{-6}$ from full dataset
- Contribution from $b \to c$ decays

$D^{*+} \to (D^0 \to K^- \pi^+) \pi^+$

$D^0 \to K^- \pi^+

$D^+ \to K^- \pi^+ \pi^+$

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Prompt open charm $D_s, \Lambda_c$

- All efficiencies were validated using data-driven techniques
- Major background has been extracted directly from data

$D_s \rightarrow K^-K^+\pi^+$

$\Lambda_c \rightarrow pK^-\pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

Signal

Combinatorial bkg

$b \rightarrow c$ bkg

NPB 871(2013) 1
Cross-sections vs theory

\[ \sigma(c\bar{c})_{p_T<8 \text{ GeV/c}, \ 2.0<y<4.5} = 1419 \pm 12(\text{stat}) \pm 116(\text{syst}) \pm 65(\text{frag}) \text{ \mu b.} \]

**D^0**

**D^+**

**D^{*+}**

**D_s**

**\Lambda_c**

Good agreement with GMVFNS Kniehl et al. FONLL Cacciari et al.

NPB 871(2013) 1
Hidden charm $J/\psi$

$J/\psi \rightarrow \mu^+\mu^-$ very nice signature, easy to trigger, low background

- Measure double differential cross-section

$$\frac{d^2 \sigma}{dy dp_T} = \frac{N(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \times \Delta y \times \Delta p_T},$$

$2 < y(J/\psi) < 4.5$

$p_T(J/\psi) < 14 \text{ GeV/c}$

Efficiencies are validated on data

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Contribution from $B$-decays

- There is large contribution from decays of long-lived $B$-hadrons, $\beta\gamma e\tau \sim O(1\text{cm})$
- Use “pseudo-lifetime”

\[
    t_z = \frac{(z_J/\psi - z_{PV}) \times M_{J/\psi}}{p_z},
\]

- Simultaneous 2D-fit

$m(\mu^+\mu^-)$

$t_z$

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Differential cross-sections

\[
\frac{d^2\sigma}{dydp_T} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{\text{tot}} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T},
\]

The slopes are different!
Fraction of $J/\psi$ from $B$-decays

Large raise with $p_T$

$\sqrt{s} = 7$ TeV

$Frac_{J/\psi}^{b}$

2.0 < $y$ < 2.5
2.5 < $y$ < 3.0
3.0 < $y$ < 3.5
3.5 < $y$ < 4.0
4.0 < $y$ < 4.5

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Prompt $J/\psi$ DATA vs theory

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EPJ C71 (2011) 1675

Artoisenet LO
Butenshoen & Kniehl NLO
Artoisenet et al, Lansberg, NNLO*
Artoisenet, Lansberg, Maltoni;
Campbell, Maltoni, Tramontano NLO CSM
Ma, Wang, Chao NLO CS+CO
Frawley, Ulrich, Vogt NLO CEM
J/ψ at $\sqrt{s}=2.76$ & 8 TeV

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Interesting case \(2 \times J/\psi\)

- Valuable information for CS vs CO discrimination

- 36 diagrams of two types
  - Type 1
    - 32\(\times\)
  - Type 2
    - 4\(\times\)

- Intrinsically it can't be small!

- Selection rules:
  - (go off at (N)NLO)

- No selection rules
  - Type 1 \((\sim 1/p_T^8)\)
  - Type 2 \((\sim 1/p_T^6)\)
  - Type 3 \((\sim 1/p_T^4)\)

- "Small" \(\sim 10^{-2-3}\) color-octet contribution to wave function of quarkonium

- However could be dominating:
  - For high \(p_T\)-region due to gluon fragmentation graph
  - For final states, suppressed for CS scenario
$2 \times J/\psi$ at $(\pi,p)Pt$ collisions

**NA3, 1982**


J. Badier et al., "$\psi\psi$ production and limits on beauty meson production from 400 GeV/c protons", Phys Lett B 158, 85 (1985)

**$\pi Pt$:** 13 ($= 6 + 7$) $J/\psi J/\psi$

**$p Pt$:** 16 ± 4 $J/\psi J/\psi$

$J/\psi J/\psi /J/\psi = (3 \pm 1) \times 10^{-4}$
2\times J/\psi \text{ at LHCb}

#J/\psi J/\psi = 136.7 \pm 17.5

\[ \sigma_{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9 \text{nb} \]

Theory: CS \sim 4\text{nb}

\bullet\text{ Qiao, Sun, Sun}

\bullet\text{ Berezhnaya et al.}
Double Parton Scattering is Not Rare « Collider Blog

muon.wordpress.com/.../double-parton-scatt... - Перевести эту страницу
29 Dec 2009 – The thrust of the Barger, Jackson and Sheargstessy paper is a study showing that clear evidence for double-parton scattering can be obtained ...

PDF Double Parton Scattering at the LHC –

monond.in2p3.fr/QCD/2011/.../Berger.pdf - Перевести эту страницу
Формат файлов: PDF/Adobe Acrobat - Быстрый просмотр
Double Parton Scattering at the LHC – Dynamic and Kinematic Characteristics. Example: pp → b\bar{b}jet jet X. Edmond L Berger. Argonne National Laboratory ...

Phys. Rev. D 56, 3811 (1997): Double parton scattering in p(over) channel ...

link.aps.org/... Volume 56 > Issue 7 - Перевести эту страницу
The process-independent parameter of double parton scattering, \( a_{ef} \), is obtained without reference to theoretical calculations by comparing observed DP events ...

Fresh look at double parton scattering - APS Link Manager

link.aps.org/... Volume 83 > Issue 11 - Перевести эту страницу
24 Jun 2011 – A revised formula for the inclusive cross section of a double parton scattering process in a hadron collision is suggested basing on the modified ...

Double Parton Scattering

www-cdf.fnal.gov/.../double_parton_summ... - Перевести эту страницу
Double Parton Scattering in pbar-p Collisions at root \( s = 1.8 \) TeV In a paper submitted to Physical Review Letters, the CDF collaboration announced the first ...

Signals for Double Parton Scattering at the Fermilab Tevatron

arxiv.org/.../hep-ph - Перевести эту страницу
29 May 1996 – Abstract: Four double-parton scattering processes are examined at the Fermilab Tevatron energy. With optimized kinematical cuts and realistic ...

Double parton scattering of hadron-hadron interaction and its ...

arxiv.org/.../hep-ph - Перевести эту страницу
25 Apr 1997 – Title: Double parton scattering of hadron-hadron interaction and its gluonic contribution. Authors: Hung Hsiang Liu (Inst. of Phys, Academia ...

PDF Signals for Double Parton

www.phys.psu.edu/~ctag/.../laugher.pdf - Перевести эту страницу
Формат файлов: PDF/Adobe Acrobat - Быстрый просмотр
Double Parton Scattering (DPS). Two parton-parton hard scatters in one pp collision. Extend knowledge of proton structure. Spacial distribution of partons inside ...

High Energy Physics Group - Double Parton Scattering

www.hep.phy.cam.ac.uk/theory/.../dps.html - Перевести эту страницу

Is double parton scattering useful?

www.physicsforums.com/showthread.php?t... - Перевести эту страницу
Заблокировать все результаты с www.physicsforums.com
Сообщений: 2 - Авторов: 2 - 19 июл 2011
Is double parton scattering useful? High Energy, Nuclear, Particle Physics discussion.
Two independent scattering processes

\[ \Gamma_{ij}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) = D_{ij}^{(2)}(x_1, x_2; Q_1^2, Q_2^2) f(b_1) f(b_2). \]

Assume factorization of PDFs

\[ D_{ij}^{(2)}(x_1, x_2; Q_1^2, Q_2^2) = D_i^{(2)}(x_1; Q_1^2) D_j^{(2)}(x_2; Q_2^2). \]

(Can't be true for all \(x, Q^2\))

\[ \sigma_{DPS} = \frac{m_A}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}. \]

Universal (energy and process independent) factor

\[ \frac{1}{\sigma_{eff}} = \int d^2 b F^2(b) \]

CDF, F.Abe et al., PDR 56 3811 (1997)

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How to test DPS?

• For two species A and B one need to measure associative production $\sigma(A+B)$ as well as their inclusive productions $\sigma(A)$, $\sigma(B)$

• DPS contribution follows from identity:

$$\sigma_{DPS}^{AB} = \frac{m}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}.$$ 

• Look for the correlations:
  
  $p_T$ spectra, $\Delta\phi$ & $\Delta\gamma$ correlations, mass spectra, polarization effects, .... ?

• Inclusive production is well measured at LHCb for many species

- J/$\psi$
- Z$^0$
- Open charm: D$^0$, D$^+$, D$_s$, $\Lambda_c$
- Jets
- and many-many others: $\psi'$, Y(nS), W$^\pm$, $\chi_c$, $\chi_b$, B-hadrons, ...

Today 26 pairs:

- $2 \times$ J/$\psi$ (1)
- J/$\psi$+open charm (4)
- $2 \times$ open charm (6+10)
- Z$^0$+jets (1)

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Open charm signals

$N(D^0) \approx 2 \times 10^8/fb^{-1}$

$N(D^+) \approx 1 \times 10^8/fb^{-1}$

$N(D_s) \approx 1 \times 10^7/fb^{-1}$

$N(\Lambda_c) \approx 2 \times 10^6/fb^{-1}$
Event Selection

$J/\psi C$ two charm with common vertex

$\mu^-, K^-, \pi^+, \mu^+$

$2 \times$ Open charm hadrons

$K^-, \pi^+, D^0, D^0$
Signal extraction

- $J/\psi + \text{open charm}$
- Clear signals for all four modes
- Significances $> 7\sigma$
(open charm)²

**D⁰ & open charm**

- **D⁰D⁰**
- **D⁰D⁺**
- **D⁰Dₛ**
- **D⁰Λₑ**

**D⁺ & open charm**

- **D⁺D⁺**
- **D⁺Dₛ**
- **D⁺Λₑ**

For all cases significance > 5σ, 2.5 sigma D⁺Λₑ⁺

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Open charm + open anti-charm

$D^0$ & open anti-charm

$D^0 \bar{D}^0$

$D^0 D^-$

$D^0 D_s^-$

$D^0 \bar{A}_c^-$

$D^+ & open anti-charm$

$D^+ D^-$

$D^+ D_s^-$

$D^+ \bar{A}_c^-$

For all cases significance > $8\sigma$

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Cross-sections

- Use per-event efficiency, mainly from DATA: trigger, particle ID, background etc.

\[ \sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}, \]

- Major systematic: tracking (reducible)

\[ Br(\Lambda_c), Br(D_s), \ldots. \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\sigma) [nb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/\psi D^0</td>
<td>161.0 \pm 3.7 \pm 12.2</td>
</tr>
<tr>
<td>J/\psi D^+</td>
<td>56.6 \pm 1.7 \pm 5.9</td>
</tr>
<tr>
<td>J/\psi D_s^+</td>
<td>30.5 \pm 2.6 \pm 3.4</td>
</tr>
<tr>
<td>J/\psi \Lambda_c^+</td>
<td>43.2 \pm 7.0 \pm 12.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\sigma_{J/\psi C}/\sigma_{J/\psi}) (10^{-3})</th>
<th>(\sigma_{J/\psi C}/\sigma_C) (10^{-4})</th>
<th>(\sigma_{J/\psi} \sigma_C/\sigma_{J/\psi C}) [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/\psi D^0</td>
<td>16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}</td>
<td>6.7 \pm 0.2 \pm 0.5</td>
<td>14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}</td>
</tr>
<tr>
<td>J/\psi D^+</td>
<td>5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}</td>
<td>5.7 \pm 0.2 \pm 0.4</td>
<td>17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}</td>
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<tr>
<td>J/\psi D_s^+</td>
<td>3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}</td>
<td>7.8 \pm 0.8 \pm 0.6</td>
<td>12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}</td>
</tr>
<tr>
<td>J/\psi \Lambda_c^+</td>
<td>4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}</td>
<td>5.5 \pm 1.0 \pm 0.6</td>
<td>18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}</td>
</tr>
</tbody>
</table>
### Cross-sections

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma$ [mb]</th>
<th>$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]</th>
<th>$\sigma_{C_1C_2}/\sigma_{C_1C_2}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0D^0$</td>
<td>$690 \pm 40 \pm 70$</td>
<td>$10.9 \pm 0.8$</td>
<td>$2 \times (42 \pm 3 \pm 4)$</td>
</tr>
<tr>
<td>$\bar{D}^0D^0$</td>
<td>$6230 \pm 120 \pm 630$</td>
<td></td>
<td>$2 \times (4.7 \pm 0.1 \pm 0.4)$</td>
</tr>
<tr>
<td>$D^0D^+$</td>
<td>$520 \pm 80 \pm 70$</td>
<td>$12.8 \pm 2.1$</td>
<td>$47 \pm 7 \pm 4$</td>
</tr>
<tr>
<td>$D^0D^-$</td>
<td>$3990 \pm 90 \pm 500$</td>
<td></td>
<td>$6.0 \pm 0.2 \pm 0.5$</td>
</tr>
<tr>
<td>$D^0D^+_s$</td>
<td>$270 \pm 50 \pm 40$</td>
<td>$15.7 \pm 3.4$</td>
<td>$36 \pm 8 \pm 4$</td>
</tr>
<tr>
<td>$D^0D^-_s$</td>
<td>$1680 \pm 110 \pm 240$</td>
<td></td>
<td>$5.6 \pm 0.5 \pm 0.6$</td>
</tr>
<tr>
<td>$D^0\bar{\Lambda}_c$</td>
<td>$2010 \pm 280 \pm 600$</td>
<td></td>
<td>$9 \pm 2 \pm 1$</td>
</tr>
<tr>
<td>$D^+D^+$</td>
<td>$80 \pm 10 \pm 10$</td>
<td>$9.6 \pm 1.6$</td>
<td>$2 \times (66 \pm 11 \pm 7)$</td>
</tr>
<tr>
<td>$D^+D^-$</td>
<td>$780 \pm 40 \pm 130$</td>
<td></td>
<td>$2 \times (6.4 \pm 0.4 \pm 0.7)$</td>
</tr>
<tr>
<td>$D^+D^+_s$</td>
<td>$70 \pm 15 \pm 10$</td>
<td>$12.1 \pm 3.3$</td>
<td>$59 \pm 15 \pm 6$</td>
</tr>
<tr>
<td>$D^+D^-_s$</td>
<td>$550 \pm 60 \pm 90$</td>
<td></td>
<td>$7 \pm 1 \pm 1$</td>
</tr>
<tr>
<td>$D^+\Lambda^+_c$</td>
<td>$60 \pm 30 \pm 20$</td>
<td></td>
<td>$140 \pm 70 \pm 20$</td>
</tr>
<tr>
<td>$D^+\bar{\Lambda}^-_c$</td>
<td>$530 \pm 130 \pm 170$</td>
<td></td>
<td>$15 \pm 4 \pm 2$</td>
</tr>
</tbody>
</table>
Cross-sections


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Event Properties: $p_T$

$J/\psi$ + open charm:

![Graphs showing the distribution of $p_T$ for $J/\psi$ and open charm particles](image-url)
Slope parameter for $p_T$-spectra

- Fit $p_T$-spectra with exponential function:
  $$\sim \exp (\beta \times p_T)$$

- DPS: expected similarity between inclusive and $c\bar{c}c\bar{c}$

- Expected to be similar between $J/\psi C$ and CC

- No reason to be the same for $J/\psi C$ and inclusive

- Expected to be similar between $c\bar{c}$ and inclusive
Δφ & Δy correlations

No evident correlations

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Clear correlations!
**CDF:** azimuthal correlations for $D^{(0,+)} D^{*-}$

- Large gluon splitting contribution

**Very different kinematical region**

### CDF Run II Preliminary, 1.1 fb$^{-1}$

- $D^0$: $|y| < 1$, $5.5 < p_T < 20$ GeV/c
- $D^{*-}$: $|y| < 1$, $5.5 < p_T < 20$ GeV/c

#### Legend:
- Data
- Pythia, $c\bar{c}$, $\hat{p}_T > 5$ GeV/c
- Flavor Creation
- Flavor Excitation
- Gluon Splitting

---

**http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-double-charm-corr/**
Mass distributions

The same shape for $m > 7$ GeV/c$^2$
We have clear $D$-signals, we have clear $Z^0 \rightarrow \mu^+\mu^-$ signals: try to merge them together.
Z\(^0\) + charm mesons

- 11 signal events: 7 Z\(^0\)&D\(^0\) and 4 Z\(^0\)&D\(^+\)
- Statistical significance >5\(\sigma\)
**Cross-section: sum of SPS and DPS**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$Z + D^0$</td>
<td>$2.50 \pm 1.12 \pm 0.22$</td>
<td>$0.85^{+0.12}<em>{-0.07}^{+0.11}</em>{-0.17} \pm 0.05$</td>
<td>$0.64^{+0.01}<em>{-0.01}^{+0.08}</em>{-0.13} \pm 0.04$</td>
<td>$3.28^{+0.68}_{-0.58}$</td>
</tr>
<tr>
<td>$Z + D^+$</td>
<td>$0.44 \pm 0.23 \pm 0.03$</td>
<td>$0.37^{+0.05}<em>{-0.03}^{+0.05}</em>{-0.07} \pm 0.03$</td>
<td>$0.28^{+0.01}<em>{-0.01}^{+0.04}</em>{-0.06} \pm 0.02$</td>
<td>$1.29^{+0.27}_{-0.23}$</td>
</tr>
</tbody>
</table>

**For $Z^0 + D^0$ case: in agreement, for $Z^0 + D^+$ case too small**

**More data needed to make conclusions**

* Only $\sim 1/3$ of data is used in this analysis
P-wave charmonia: $\chi_c$ states

$\chi_c \rightarrow (J/\psi \rightarrow \mu^+ \mu^-) \gamma$ with $\gamma$-conversions

• Excellent mass resolution: resolve $\chi_{c1}$ and $\chi_{c2}$!

• First evidence of $\chi_{c0}$ at hadron machines!

\[
\frac{\sigma(\chi_{c0})}{\sigma(\chi_{c2})} = 1.19 \pm 0.27\text{(stat)} \pm 0.29\text{(sys)} \pm 0.16(p_T\text{ model}) \pm 0.09(B)
\]
\[
\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.787 \pm 0.014\text{(stat)} \pm 0.034\text{(sys)} \pm 0.051(p_T\text{ model}) \pm 0.047(B)
\]
\( \chi_{c2}/\chi_{c1} \) ratio

- for on-shell gluons \( \sigma(gg \rightarrow \chi_{c1}) = 0 \)
- Important ingredient for S & P-wave CO

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$\gamma \to \mu^+\mu^-$: excellent mass resolution!

**LHCb**

- $\sqrt{s} = 8$ TeV
- $\sqrt{s} = 2.76$ TeV

**Publications**
- JHEP 06 (2013) 064
- EPJ C72 (2012) 2025
- EPJ C74 (2014) 2835

**Conference**
- 30 May 2k+14 Tsinghua

Vanya Belyaev: "Heavy quarks & Quarkonia @LHCb"
$\gamma$ production

JHEP 06 (2013) 064

EPJ C74 (2014) 2835

LHCb

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$\gamma(nS)/\gamma(1S)$ ratios

$\gamma$ of $\gamma_{\text{c}}$, $\gamma_{\text{b}}$

30 May 2k+14 Tsinghua

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Other interesting topics

- Production in pA & Ap collisions
  - JHEP 02 (2014) 074

- B-hadron production
  - JHEP 08 (2013) 117

- B_c production
  - PRL 109 (2012) 231001

- Search for double charmed baryons
  - JHEP 12 (2013) 090

Leading role of Tsinghua group

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Polarisation fiasco (again)

\[ \psi' \] was expected to be easier:

- Free from feeddown


\[ \lambda_0 \]

\[ \begin{align*}
&\text{NRQCD: feed-down from } \chi_c(3P_J^1, 3S_J^0) \text{ and } \psi(2S) \text{ Phys. Rev. Lett. 110 (2013) 042002} \\
&\text{NRQCD: feed-down from } 3P^8 \text{ Phys.Rev. Lett. 108 (2012) 242004}
\end{align*} \]
Summary

- HQ production is interesting & hot topic
  - Many active players, including LHCb
- There is great theory progress
  - .. and nice collaboration
- Some “old” puzzles are still with us
  - Polarization, role of CO
- Interesting data appears from LHC that need to be explained: challenge for theory
  - At high collision energies/large gluon densities new effects appears, e.g. DPS