EXPERIMENTAL QUARKONIUM STUDIES OF $\eta_q$ and $\chi_q$

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Sources of quarkonium:
- prompt hadroproduction
- decays of higher resonances
- production in $b$-hadron decays (for charmonium)

No consensus on the quarkonium production mechanism

Nearly all approaches assume **factorisation** between the $Q\bar{Q}$ formation and its **hadronization** into a meson.

Essential difference in various approaches is in the **description of the hadronization**:

- **Colour evaporation model (CEM)**: application of quark-hadron duality; only the invariant mass matters;
- **Colour-singlet model (CS)**: intermediate $Q\bar{Q}$ state is colourless and has the same $J^{PC}$ as the final-state quarkonium;
- **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and $J^{PC}$ allowed for the intermediate $QQ$ state;

MODELS OF QUARKONIUM PRODUCTION

\[
t_z = \frac{Z_{SV} - Z_{PV}}{p_z} M_{pp}
\]
QUARKONIUM PRODUCTION IN NRQCD

- Two scales of production: hard process of **Q\bar{Q}** formation and **hadronization of Q\bar{Q}** at softer scales

- **Factorization:** 
  \[ d\sigma_{A+B\rightarrow H+X} = \sum_n d\sigma_{A+B\rightarrow Q\bar{Q}(n)+X} \times \langle O^H(n) \rangle \]

  **Short distance:** perturbative cross-sections 
  + pdf for the production of a **Q\bar{Q}** pair

  **Long distance matrix elements (LDMEs),** non-perturbative part

- Both **CS** and **CO states** are allowed with varying probabilities; LDMEs from experimental data

- **Universality:** same LDMEs for different \( \sqrt{s} \), prompt production and production in **b-decays**

- Heavy-Quark **Spin-Symmetry:** links between CS and CO LDMEs of different quarkonium states
• Current status of quarkonium spectrum

- Hadronic final states allow to study different quarkonium states simultaneously
• **ATLAS** and **CMS**: mid-rapidity region, with muons in final state

• **LHCb**: forward-rapidity region, with muons and hadrons in final state

• **ALICE**: both mid- and forward-rapidity regions, with muons and electrons in final state

• Experiments provide complementary measurements
LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:

- $\sigma_{b\bar{b}} \sim 0.5$ mb in LHCb @ $\sqrt{s} = 13$ TeV
- $\sigma_{c\bar{c}} \sim 3.0$ mb

Single-arm forward spectrometer:
- 10-250 mrad (V), 10-300 mrad (H)

Forward region $2.0 < \eta < 5.0$,
- $\sim 4\%$ of solid angle,
  - but $\sim 40\%$ of heavy quarkonium (HQ) production x-section

Forward peaked HQ production at the LHC, second $b$ in acceptance once the first $b$ is in

Key detector systems for production measurement:
- Vertex reconstruction with VELO
- Particle identification with 2 Ring Imaging Cherenkov Detectors (RICH) and Muon detector
- Trigger
Prompt and $b$-decay production distinguished via decay time:

$$t_z = \frac{z_{SV}-z_{PV}}{p_z} M_{pp}$$

First measurements of $\eta_c(1S)$ prompt production at 7 and 8 TeV and $b$-decay production

Challenging background conditions
$\eta_c(1S)$ PRODUCTION AT LHCb AT $\sqrt{s}=7$ AND 8 TeV

- Measurement of $p_T$-differential production cross-sections, experimental precision is worse than theoretical one

- **Strong impact on theory models**: contrary to theory expectations, $\eta_c(1S)$ prompt production entirely described by CS contribution

- $\eta_c(1S)$ production:
  
  \begin{align*}
  6.5 \leq p_T < 14.0 \text{ GeV/c}, \quad 2.0 < y < 4.5 \\
  \sigma_{\eta_c}^{\text{prompt}} &= 0.52 \pm 0.09_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.06_{1/\psi} \mu b \quad \sqrt{s} = 7 \text{ TeV} \\
  \sigma_{\eta_c}^{\text{prompt}} &= 0.59 \pm 0.11_{\text{stat}} \pm 0.09_{\text{syst}} \pm 0.08_{1/\psi} \mu b \quad \sqrt{s} = 8 \text{ TeV} \\
  \mathcal{B}_{b \rightarrow \eta_c X} &= (4.88 \pm 0.64_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.67_{1/\psi}) \times 10^{-3}
  \end{align*}
• $\eta_c(1S)$ LDMEs determined from known HQSS relation for $J/\psi$
  \[
  \langle \mathcal{O}_{1,8}^{\eta_c} (1 S_0) \rangle = \frac{1}{3} \langle \mathcal{O}_{1,8}^{J/\psi} (3 S_1) \rangle \\
  \langle \mathcal{O}_{8}^{\eta_c} (3 S_1) \rangle = \langle \mathcal{O}_{8}^{J/\psi} (1 S_0) \rangle \\
  \langle \mathcal{O}_{8}^{\eta_c} (1 P_1) \rangle = 3 \langle \mathcal{O}_{8}^{J/\psi} (3 P_0) \rangle 
  \]

• Direct projection to LHCb data

• LHCb data saturated by CS contribution

• Tension in simultaneous description of $\eta_c$ production and $J/\psi$ production and polarization?

• Recent progress in theory:
  \[\rightarrow\] JHEP 05(2015) 103
  \[\rightarrow\] Phys.Rev.D 93 (2016) 034041
SIMULTANEOUS STUDY OF $\eta_c$ AND $J/\psi$

- $\eta_c$ production @ $\sqrt{s}=7$ and 8 TeV sets new constraint on $J/\psi$ polarization

**Outcome:**
- Impressive progress
- Tension with CDF data
- Two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?

**Joint study of hadroproduction and production in inclusive b-decays**

- Same links for $\eta_c(2S)$ and $\psi(2S)$ are expected ⇒ powerful test of NRQCD

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PRL 114(2015), 092005
arXiv:1910.08796

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EPJ C 79(2019) 621
PRL 114(2015), 092005
PRD 84, (2011) 051501
Data LHCb 7 TeV

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\[ \frac{\sigma(\eta_c)}{\sigma(J/\psi)} = \frac{N_{\eta_c}^p}{N_{J/\psi}^p} \times \frac{B_{J/\psi \to p\bar{p}}}{B_{\eta_c \to p\bar{p}}} \times \frac{\epsilon_{J/\psi \to p\bar{p}}}{\epsilon_{\eta_c \to p\bar{p}}} \]

- **Prompt** and **b-decay production** distinguished via decay time value:

\[ t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}} \]

- **Cross-feed** between samples are accounted in simultaneous fit

- **Two techniques** are used for cross-section measurement

- Extracted from DATA
- Calculated from PDG:

\[ B_{J/\psi \to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3} \]
\[ B_{\eta_c(1S) \to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3} \]

- From Simulation
**t_\text{Z}-CUT TECHNIQUE**

- **Prompt** and **b-decay production** separated using $t_\text{Z}$-value

  - Relative charmonium yields:
    \[ \frac{N_{\eta_c}^{\text{prompt}}}{N_{J/\psi}^{\text{prompt}}} = 1.18 \pm 0.10 \quad \frac{N_{\eta_c}^{\text{from-b}}}{N_{J/\psi}^{\text{from-b}}} = 0.33 \pm 0.02 \]

  - Cross-feed probabilities:
    \[ \varepsilon^{\text{prompt}\rightarrow\text{prompt}} = 0.965 \pm 0.021 \]
    \[ \varepsilon^{\text{prompt}\rightarrow\text{from-b}} = 0.0002 \pm 0.0001 \]
    \[ \varepsilon^{\text{from-b}\rightarrow\text{prompt}} = 0.066 \pm 0.005 \]
    \[ \varepsilon^{\text{from-b}\rightarrow\text{from-b}} = 0.689 \pm 0.022 \]

- The **most precise** determination of $\eta_c$ **mass** up to date:
  \[ \Delta M_{J/\psi, \eta_c} = 113.0 \pm 0.7_{\text{stat}} \pm 0.1_{\text{syst}} \text{MeV} \]
Simultaneous likelihood fit to $M_{pp}$ in bins of $[p_T, t_z]$ to extract charmonium yields

Simultaneous integral $\chi^2$ fit to $t_z$ in $p_T$-bins to separate prompt and from $b$-decays charmonium

$n_c$ mass correction applied in bins of $t_z$

Results consistent with $t_z$-cut technique

$6.5 < p_T < 14$ GeV, $2.0 < y < 4.5$
RATIO BETWEEN $\eta_c$ AND J/$\psi$ PRODUCTION

- Relative $\eta_c$ to J/$\psi$ $p_T$-differential production cross-sections

- **Relative $\eta_c(1S)$ to J/$\psi$ production** in LHCb at $\sqrt{s}=13$ TeV
  
  $6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

  
  $\frac{\sigma_{\eta_c}^{\text{prompt}}}{\sigma_{J/\psi}^{\text{prompt}}} = 1.69 \pm 0.15_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.18 \mathcal{B}_{c\bar{c} \rightarrow p\bar{p}} \mu b$

  
  $\mathcal{B}_{b \rightarrow \eta_c X}/\mathcal{B}_{b \rightarrow J/\psi X} = 0.48 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.05 \mathcal{B}_{c\bar{c} \rightarrow p\bar{p}}$

- Measurement in extended $p_T$ is required

- Larger slope would indicate possible CO contribution

- Interpretation of $\eta_c(2S)/\psi(2S)$ much more clean than of $\eta_c(1S)/J/\psi$ due to absence of feed-down contributions
INTEGRATED AND DIFFERENTIAL CROSS-SECTIONS

- Measurement of integrated and $p_T$-differential production cross-sections

![Graph](image1.png)

**$\eta_c(1S)$ production** in LHCb at $\sqrt{s}=13$ TeV:

\[
6.5 < p_T < 14.0 \text{ GeV/c}, \ 2.0 < y < 4.5
\]

\[
\sigma_{\eta_c}^{\text{prompt}} = 1.26 \pm 0.11_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.14_{J/\psi} \mu b
\]

\[
\mathcal{B}_{b \to \eta_c X} = (5.51 \pm 0.32_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.77_{J/\psi}) \times 10^{-3}
\]

- $\eta_c(1S)$ production can be described by CS contribution only

![Graph](image2.png)
\( \eta_c(2S) \) PRODUCTION IN \( b \)-DECAYS AT LHCb

- Charmonium reconstructed via \textbf{decays to} \( \phi\phi \); true \( \phi\phi \) combinations extracted using 2D fit technique

- First measurement of \( \eta_c(2S) \) production in \( b \)-decays; first evidence for \( \eta_c(2S) \to \phi\phi \)

- Important to measure \( \eta_c(2S) \) hadroproduction:
  - theory prediction \( \Rightarrow \)
  - dedicated LHCb trigger in 2018

\[
\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004
\]


Charmonium reconstructed via decays to φφ; true φφ combinations extracted using 2D fit technique

First measurement of $\chi_{c0}$ production in $b$-decays:
$$B(b \to \chi_{c0} X) = (3.02 \pm 0.47_{\text{stat}} \pm 0.23_{\text{syst}} \pm 0.94_{\text{B}}) \times 10^{-3}$$

Most precise measurements of $\chi_{c1}$ and $\chi_{c2}$ production in $b$-decays, consistent with B-factories

Promising channel to study $\chi_c$ polarization [Phys.Rev.D 103 (2021) 9, 096006]
\( \chi_{c1,2} \) PRODUCTION USING \( \chi_{c1,2} \rightarrow J/\psi \gamma 

- ATLAS experiment \( \chi_{c1} \) and \( \chi_{c2} \) \( p_T \)-differential production cross-section

- Prompt and b-decays are distinguished using simultaneous fit mass difference and pseudo-proper decay time

- Estimated \( J/\psi \) fraction from \( \chi_c \) decays: result in agreement with LHCb measurement [PLB 714 (2012) 215]

- Results compared with theoretical predictions: good agreement with NRQCD
\( \chi_{c1,2} \) PRODUCTION USING \( \chi_{c1,2} \rightarrow J/\psi \gamma 

- **Relative** \( \chi_{c2} / \chi_{c1} \) prompt \( p_T \)-differential production cross-section:

\[
R_P = \frac{\sigma(pp \rightarrow \chi_{c2}X \times B(\chi_{c2} \rightarrow J/\psi \gamma))}{\sigma(pp \rightarrow \chi_{c1}X \times B(\chi_{c1} \rightarrow J/\psi \gamma))}
\]

- **Relative** \( \chi_{c2} / \chi_{c1} \) and \( \chi_{c0} / \chi_{c2} \) prompt \( p_T \)-differential production cross-section

- **\( \chi_{c0} \) relative production** measured with 4\( \sigma \) significance:

\[
\frac{\sigma_{\chi_{c0}}}{\sigma_{\chi_{c2}}} = 1.19 \pm 0.27_{\text{stat}} \pm 0.29_{\text{syst}} \pm 0.16_{\text{p}_T \text{ model}} \pm 0.09_{B}
\]
$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \rightarrow J/\psi \gamma$

- NRQCD fit for production cross-section
  - absolute =>
  - relative =>

- CO LDME for $\chi_c$ is obtained from fit to data

- More precise when looking for ratio

- Small $p_T$ region has to be explored
First observation of $\chi_{c1,2} \rightarrow J/\psi \mu^+ \mu^-$ decay modes

Extremely clean signals

$\chi_{c1,2}$ resonance parameters measured with world average precision

<table>
<thead>
<tr>
<th>Quantity</th>
<th>LHCb measurement</th>
<th>Best previous measurement</th>
<th>World average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\chi_{c1})$</td>
<td>$3510.71 \pm 0.10$</td>
<td>$3510.72 \pm 0.05$</td>
<td>$3510.66 \pm 0.07$</td>
</tr>
<tr>
<td>$m(\chi_{c2})$</td>
<td>$3556.10 \pm 0.13$</td>
<td>$3556.16 \pm 0.12$</td>
<td>$3556.20 \pm 0.09$</td>
</tr>
<tr>
<td>$\Gamma(\chi_{c2})$</td>
<td>$2.10 \pm 0.20$</td>
<td>$1.92 \pm 0.19$</td>
<td>$1.93 \pm 0.11$</td>
</tr>
</tbody>
</table>

New channel for production measurement

Promising channel for $\chi_c$ hadroproduction at low $p_T$

Similar studies can be done at CMS?
First measurement of $P$-wave quarkonium polarization with $\chi_{c2}/\chi_{c1}$ ratios as a function of $|\cos\theta^{HX}|$ and $\phi^{HX}$

Unpolarized scenario and large part of the physically allowed region (red rectangle) excluded at 99.7 % CL

→ at least one state is strongly polarized

Good agreement with NRQCD prediction
**$\chi_b$ PRODUCTION IN LHCb AT $\sqrt{s}=7$ AND 8 TeV**

- Search for $\chi_b(nP)$ using decay to $Y(nS)\gamma$
  $$\mathcal{R}_{Y(nS)}^{\chi_b(mP)} = \frac{N_{\chi_b(mP)}}{N_{Y(nS)}} \times \frac{\mathcal{E}_{Y(nS)}}{\mathcal{E}_{\chi_b(mP)}}$$

- Invariant mass fit to extract yields

- Fraction $\mathcal{R}_{Y(nS)}^{\chi_b(mP)}$ measured in bins of $p_T$

- $\chi_b(3S) \rightarrow Y(3S)\gamma$ observed for the first time
• First measurement of $\chi_b(1P)/\chi_b(1P)$ production using decay to $\Upsilon(1S)\gamma$
$5 < p_T^\Upsilon < 25$ GeV/c, $2. < y < 4.5$

$$\frac{\sigma_{\chi_b(1P)}}{\sigma_{\chi_b(1P)}} = \frac{N_{\chi_b(1P)}}{N_{\chi_b(1P)}} \times \frac{\epsilon_{\chi_b(1P)}}{\epsilon_{\chi_b(1P)}} \times \frac{B(\chi_b \rightarrow \Upsilon(1S)\gamma)}{B(\chi_b \rightarrow \Upsilon(1S)\gamma)}$$

• Results have reasonable agreement with CMS results and LHCb-based LO NRQCD prediction [JHEP 10 (2013) 115] at high-$p_T$
**χ_b PRODUCTION IN CMS AT √s=8 TeV**

- Precise measurement of χ_b2(1P)/χ_b1(1P) production cross-section in complementary region to LHCb: 5 < p_T^γ < 25 GeV/c, |y| < 1.5

- χ_b relative production in integrated p_T-range:
  \[ \frac{\sigma_{χ_b2}}{\sigma_{χ_b1}} = 0.85 ± 0.07 _{stat+syst} ± 0.08_B \]

- Ratio does not show significant dependence on Y(1S) p_T

- >2σ discrepancy with NRQCD prediction at high-p_T
SUMMARY

• Comprehensive model still missing to describe Heavy Flavor production
• LHC results allow to perform powerful tests of QCD and constrain theory
  • $\eta_c(1S)$ prompt production measurement constrains CO LDMEs
• Current progress:
  • prompt $\chi_c$ observed in decay to $J/\psi\mu\mu$
  • $\chi_c$ production from $b$-decays measured via $\phi\phi$
  • first evidence of $\eta_c(2S)$ production
• $\Upsilon$ and $\chi_b$ hadroproduction has been measured at LHC
• Prospects for future study:
  • $\eta_b(1S)$, $h_{c,b}$ and $\eta_c(2S)$ production
  • simultaneous study of $\psi(2S)$ and $\eta_c(2S)$
  • decays to $\Lambda\Lambda$, $\Lambda^*\Lambda^*$, $\Sigma\Sigma$, $\Xi\Xi$ final states
BACKUP
Vertex reconstruction **VELO**

- **Spatial resolution**, down to 4 μm for single tracks
- **Impact parameter** measurement, \( \sigma_{IP} = 15 + 29/p_T \) [μm]
- **Primary vertex** reconstruction, \( \sigma_x = \sigma_y = 13 \) μm, \( \sigma_z = 71 \) μm for vertex of 25 tracks
Particle identification

- **2 Ring Imaging Cherenkov Detectors (RICH):** 3 Radiators covering $p_T$ range 1.5-100 GeV/c
- **Muon detector** – triggering muons and measuring muon momenta
- Particle ID efficiency:
  - $K^{\pm}$ ID ~ 95 % for ~ 5 % $\pi \rightarrow K$ mis-id probability
  - $\mu^{\pm}$ ID ~ 97 % for 1-3 % $\pi \rightarrow \mu$ mis-id probability

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**KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS**

- **Silica Aerogel:**
  - $n=1.03$
  - 1.5-10 GeV/c

- **$C_4F_{10}$:**
  - $n=1.0014$
  - up to ~70 GeV/c

- **$CF_4$:**
  - $n=1.0005$
  - up to ~100 GeV/c
Trigger

• **Two-level** trigger system
• LHCb detector designed to **trigger on decay products of** $b$ **or** $c$ **hadrons**: moderate $p_T$ physics
• Trigger efficiency:
  • ~ 90% for dimuon channels
  • ~ 30% for multi-body hadronic final states
CHARMONIUM SPECTROSCOPY: LHCb PROGRESS

χ_c prompt production measured via J/ψγ
χ_c and η_c(2S) b-decays production measured via φφ, 7 and 8 TeV: EPJC 77(2017) 609

J/ψ and ψ(2S) prompt, b-decays production
and polarization measured via μμ
7, 8 and 13 TeV: JHEP 10(2015) 172, EPJC 80(2020) 185 ...

η_c(1S) prompt and b-decays production measured via pp
7, 8 and 13 TeV: EPJC 75(2015) 311, EPJC 80(2020) 191

Non-conventional charmonia:
talk by Matthew Needham at QWG2021

Prospects:
• h_c and η_c(2S) prompt production
• All states accessible via hadronic decays
  → study decays to ΛΛ, Λ*Λ*, ΣΣ, ΞΞ final states

Rev.Mod.Phys 90 (2018) 015003
BOTTOMONIUM SPECTROSCOPY: LHCb PROGRESS

$Y(nS)$ production measured via $\mu\mu$
- 7 and 8 TeV: JHEP 11(2015) 103
- 13 TeV: JHEP 07(2018) 134
  talk by C.Patrignani at QWG2019

$Y(nS)$ polarization measured via $\mu\mu$
- 7 and 8 TeV: JHEP 12(2017) 110

$\chi_b(nP)$ production measured via $Y(nS)\gamma$

Prospects:
- $h_b$ and $\eta_b(1S)$ production

Rev.Mod.Phys 90 (2018) 015003
QUARKONIUM DECAYS

- Possible transitions between quarkonium states
• Cross-section determination

in bin\([p_T, y]\) as a function of \(p_T(0<p_T<30\text{GeV/c})\) and \(y(2.0<y<4.5)\)

\[
\frac{d^2\sigma}{dydp_T} = \frac{N(Y\rightarrow\mu^+\mu^-)}{\mathcal{L}\times\epsilon_{\text{tot}}\times\mathcal{B}(Y\rightarrow\mu^+\mu^-)\times\Delta y\times\Delta p_T}
\]

• Unbinned likelihood fit in bins of \([p_T, y]\) to \(M_{\mu\mu}\) to extract \(Y(nS)\) yields
Y(nS) PRODUCTION AT $\sqrt{s}=13$ TeV

- Double differential production cross-section measured in range $0 < p_T < 30$ GeV/c and $2.0 < y < 4.5$
- Good agreement between NRQCD and data at high $p_T$ for all states
• BESIII: $\mathcal{B}(\chi_{c1,2} \to J/\psi \mu \mu)$  
  
  _PRD 99 (2019) 5, 051101_