Charmonium production using decays to hadronic final states at LHCb 
vs Non-Relativistic QCD (NRQCD)

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Charmonium

- Bound state of \textit{ccbar} under strong interaction \\
  \textit{e.g.} \( \eta_c(1S), \chi_c, J/\psi, \eta_c(2S), \psi(2S) \)

- “Hydrogen atom in QCD”

- Non-relativistic QCD object:
  - Charmonium: \( v^2 \approx 0.3 \)
  - Bottomonium: \( v^2 \approx 0.1 \)

- Charmonium states below DDbar threshold are well identified by spectroscopy (potential models, lattice)

- Production: multiple well-separated scales (both perturb. and non-perturbative aspects) \\
  \( \rightarrow \) charmonium ideal to understand hadronization, to study QGP
Charmonia production in the NRQCD

NRQCD assumptions:

➔ **Factorization**

\[ \mathcal{L}_{NRQCD} = \sum_{n} \frac{c_n(\alpha_s(m), \mu)}{m^n} \times O_n(\mu, mv, mv^2, \ldots) \]

- ccbar pair production - **short-distance elements**, calculated perturbatively
- hadronisation - **long-distance matrix elements** (LDMEs), non-perturbative
  
  (expansion on quark velocity \( v \))
  
  (can be extracted from fits to data as free parameters)

➔ **Universality**

LDMEs does not depend from ccbar pair creation process

Alternative theoretical approaches:
- Color evaporation model (CEM)
- \( kt \) – factorization
- ...

NRQCD is the most powerful tool to predict charmonia production
Charmonia production in the NRQCD

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

Production mechanisms:

- **Color Singlet (CS):**
  quantum numbers ccbar pair and charmonium match

- **Color Octet (CO):**
  quantum numbers ccbar pair in CO state are different from charmonium

Spin-symmetry for LDMEs:
Links between the CS and CO matrix elements of different charmonia states

**Simultaneous studying of J/ψ and η_c**
Available data from $4\pi$ experiments at ISR, RHIC, Tevatron and LHC

Four groups of theorists are in the game
NRQCD description of J/ψ production and polarization at LHCb

Production:

- Measurements of LHC and Tevatron are in agreement
- CS NLO and NNLO* could not describe prompt production
- NRQCD description dominates by CO contribution

Polarization:

- CO predicts strong polarization
- Large CS contribution is required
Charmonium production via decays to hadronic final states at LHCb
Charmonia decay channels for production measurements at LHCb

<table>
<thead>
<tr>
<th></th>
<th>μμ (LL)</th>
<th>J/ψ γ</th>
<th>ppbar</th>
<th>φφ</th>
<th>baryons</th>
</tr>
</thead>
<tbody>
<tr>
<td>ηc(1S)</td>
<td>forbidden</td>
<td>-</td>
<td>~ 0.15%</td>
<td>~ 0.2%</td>
<td>~ 0.1%</td>
</tr>
<tr>
<td>J/ψ(1S)</td>
<td>~ 6%</td>
<td>-</td>
<td>~ 0.2%</td>
<td>forbidden</td>
<td>~ 0.1%</td>
</tr>
<tr>
<td>χc0(1P)</td>
<td>forbidden</td>
<td>~ 1.3%</td>
<td>~ 0.02%</td>
<td>~ 0.08%</td>
<td>~ 0.04%</td>
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<tr>
<td>h_c(1P)</td>
<td>forbidden</td>
<td>forbidden</td>
<td>?</td>
<td>forbidden</td>
<td>~ 0.01%</td>
</tr>
<tr>
<td>χc1(1P)</td>
<td>forbidden</td>
<td>34%</td>
<td>~ 0.01%</td>
<td>~ 0.04%</td>
<td>~ 0.01%</td>
</tr>
<tr>
<td>χc2(1P)</td>
<td>forbidden</td>
<td>19%</td>
<td>~ 0.1%</td>
<td>~ 0.01%</td>
<td>~ 0.01%</td>
</tr>
<tr>
<td>ηc(2S)</td>
<td>forbidden</td>
<td>-</td>
<td>~ 0.01%</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>ψ(2S)</td>
<td>~ 1%</td>
<td>-</td>
<td>~ 0.03%</td>
<td>forbidden</td>
<td>~ 0.02%</td>
</tr>
</tbody>
</table>

seen in prompt production  
seen in b-decays, promising channels

- Decays to hadrons (can) give access to ηc(1S), χc0(1P), ηc(2S) and h_c(1P) (?), whose production can’t be measured using μμ or J/ψγ
• Precise vertex reconstruction with VELO
• Powerful charge particle ID by RICH detectors
• Robust trigger
LHCb detector

IJMPA30 (2015), 1530022
JINST 3 (2008) S08005

• Precise vertex reconstruction with VELO
• Powerful charge particle ID by RICH detectors
• Robust trigger

• Coverage complementary to ATLAS and CMS in $p_T$ and $\eta$
**Challenging background conditions**

- prompt hadroproduction
- b-decays production, inclusive

- $t_z > 80$ ps and $\chi^2 > 16$
- $t_z < 80$ ps

- Knowing yields in two samples from fit, efficiencies and cross-talk from MC, differential production was measured:

- **First $\eta_c$ prompt and from inclusive b-decays production measurement**
$\eta_c(1S)$ production at the LHC challenges NRQCD factorization

$\eta_c$ LDMEs determination:
- determined from known HQSS relation for $J/\psi$
- direct projection to LHCb data

Results:
- LHCb data saturated by CS contribution

PRL 114(2015), 092004
PRL 108(2012), 242004
PRD 84(2011), 051501 (R)
PRL 110(2013), 042002
PRL 113(2014), 022001

\[
\begin{align*}
\langle O_1^{\eta_c(1S_0)} \rangle &= \frac{1}{3} \langle O_1^{J/\psi(3S_1)} \rangle, \\
\langle O_8^{\eta_c(1S_0)} \rangle &= \frac{1}{3} \langle O_8^{J/\psi(3S_1)} \rangle, \\
\langle O_8^{\eta_c(3S_1)} \rangle &= \langle O_8^{J/\psi(1S_0)} \rangle, \\
\langle O_8^{\eta_c(1P_1)} \rangle &= 3 \langle O_8^{J/\psi(3P_0)} \rangle.
\end{align*}
\]
using constraints from fits to $J/\psi$ production measurements and fit to $\eta_c$ production measurement, upper limit on CO LMDE extracted

The only reasonable description of data points
**Upper limit on O^{(3S_1)}_c \Rightarrow new constraint on J/\psi polarization**

**Outcome:**
- reasonable (****) description of data achieved
- tension with CDF data
- two large CO contributions cancel each other \( \Rightarrow \) hierarchy problem \( \Rightarrow \) Soft Gluon Fragmentation, etc.?
- joint study of hadroproduction and production in inclusive \( b \)-decays?

**Prospects:**
- Measure \( \eta_c(1S) \) more precisely using Run II data (ongoing)
- Same links for \( \eta_c(2S) \) and \( \psi(2S) \) are expected \( \Rightarrow \) powerful test of NRQCD
- measure prompt \( \eta_c(2S) \rightarrow \bar{p}p \) or \( \eta_c(2S) \rightarrow \phi\phi \)
$\chi_c$ and $\eta_c(2S)$ production in inclusive $b$-decays using $\varphi\varphi$ as $\sqrt{s} = 7,8$ TeV

EPJC 77 (2017), 609

- Powerful test of NRQCD factorization, universality of LDME and heavy quark spin symmetry assumptions
- Aiming at constraining LDMEs simultaneously by prompt and $b$-decays measurements

- $\chi_c$ and $\eta_c(2S)$ production rates measured using measurement of $BR(b \rightarrow \eta_c(1S)X)$
EPJC 75, 311
$\chi_c$ and $\eta_c(2S)$ production in inclusive $b$-decays using $\phi\phi$ as $\sqrt{s} = 7,8$ TeV

- First measurement of $\text{BR}(b \rightarrow \chi_{c0}X)$ production in inclusive $b$-decays $\text{BR}(b \rightarrow \chi_{c0}X)$
- The most precise measurements of $\text{BR}(b \rightarrow \chi_{c1}X)$ and $\text{BR}(b \rightarrow \chi_{c2}X)$
- $\text{BR}(b \rightarrow \chi_{c1}X)$ and $\text{BR}(b \rightarrow \chi_{c2}X)$ are in agreement with measurements at B-factories

- First measurement of $\eta_c(2S)$ production in inclusive $b$-decays; first evidence of $\eta_c(2S) \rightarrow \phi\phi$ ($3.7\sigma$ significance)

$\eta_c(2S)$ production as a function of assumed $\Gamma(\eta_c(2S))$ [MeV]

$\rightarrow$ first step to measure $\eta_c(2S)$ prompt production, waiting for 2018 data!
\( \chi_c \) and \( \eta_c(2S) \) production in inclusive b-decays: test of NRQCD

Barsuk, Kou, Usachov LAL-17-051

1. Fit two LDMEs to three measurements:

2. Discrepancy when fitting two LDMEs to two relative production measurements:

- From EPJC 77 (2017), 609 and PDG:

- Relation between LDME from HQSS:

- Short-distance coefficients calculated within NRQCD NLO
  Beneke, Maltoni, Rothstein, PRD 59, 054003
Conclusions

• Description of charmonium production at LHC is a challenge for QCD

• Decays to hadrons give access to $\eta_c(1S)$, $\chi_{c0}(1P)$, $\eta_c(2S)$ and $h_c(1P)$ states

• LHCb is well suited to measure charmonia decays to hadrons

• First measurement of $\eta_c(1S)$ prompt production using its decay to ppbar at LHCb is saturated by CS contribution

• The only reasonable theoretical description of $\eta_c(1S)$ prompt production in the market, hierarchy problem in CO contributions

• First measurement of $\chi_c$ production in inclusive b-decays using $\phi\phi$

• $\chi_c$ production in inclusive b-decays is in disagreement with theory

Prospects

• new more precise measurement of $\eta_c(1S)$ production using Run II data on the way

• strong request for prompt $\eta_c(2S)$ production measurement: hunting for prompt $\eta_c(2S)$ using ppbar and/or $\phi\phi$ using 2018 data
Results:

- The total CEM-like contribution overshoots the data, by a factor >100.

Possible solutions:

- Large NNLO corrections are expected (?)
- Resume initial state radiation (?)
Available data from $4\pi$ experiments at ISR, RHIC, Tevatron and LHC

- Driven by medium- and large-$p_T$ data:
  
  $7 \text{ GeV} < p_T < 20 \text{ GeV} \Rightarrow pp$

- Good description of large-$p_T$ data
- Contradiction with low-$p_T$ data
Driven by low- and medium-$p_T$ data:
3 GeV < $p_T$ < 20 GeV ⇒ $pp$
1 GeV < $p_T$ < 10 GeV ⇒ $\gamma\gamma$, $ep$
• Agreement with $e^+e^-$ and $p_T$-integrated
• Contradiction with polarization data
• Tension with $\gamma\gamma$ data
Available data from 4π experiments at RHIC, Tevatron and LHC

- Driven by medium- and large-p$_T$ data:
  - $7 \text{ GeV} < p_T < 20 \text{ GeV} \Rightarrow pp$ collisions
- Good description of large-p$_T$ data
- Worse p$_T$-integrated description
Simultaneous fit to $M(pp)$

Example: first bin of PT ($6.5 < p_T < 8$ GeV/c):

<table>
<thead>
<tr>
<th></th>
<th>Fit result, [MeV/c^2]</th>
<th>PDG, [MeV/c^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\eta c}$</td>
<td>$8.24 \pm 0.14$</td>
<td>-</td>
</tr>
<tr>
<td>$m_{J/\psi}$</td>
<td>$3097.1 \pm 0.1$</td>
<td>$3096.900 \pm 0.006$</td>
</tr>
<tr>
<td>$m_{J/\psi} - m_{\eta c}$</td>
<td>$111.6 \pm 1.1$</td>
<td>$113.5 \pm 0.5$</td>
</tr>
</tbody>
</table>

Mass values are consistent with PDG
$F(t_z) = (N_p \delta(t_z)) + \frac{N_b}{\tau_b} \exp\left(-\frac{t_z}{\tau_b}\right) \ast DG(\mu, S_{J/\psi}, S_n/S_w, \beta) + N_t f_{tail}(t_z)$

- **prompt ccbar**
- **ccbar from b-decays**
- **tz - resolution**
- **events with mismatched PV**
Simultaneous $\chi^2$ fit to $N_{\eta_c}$ and $N_{J/\psi}$ points from mass fit

$$F_{\eta_c}(t_z) = (N_p \delta(t_z)) + \left( \frac{N_b}{\tau_b} \exp\left(-\frac{t_z}{\tau_b}\right) \right) \ast DG(\mu, S_{J/\psi}, S_n/S_w, \beta) + N_t f_{tail}(t_z)$$

**prompt $N^p_{\eta_c}/N^p_{J/\psi}$ and from $b$-decays $N^b_{\eta_c}/N^b_{J/\psi}$ extracted in PT bins**

**tz bin**

$$\mu = (-0.5 \pm 1.8) \times 10^{-3} \text{ ps}$$

$$S_{\eta_c,J/\psi} = (4.10 \pm 0.26) \times 10^{-2} \text{ ps}$$

$$\tau_b = 1.269 \pm 0.040 \text{ ps}$$

$$\frac{N_{\eta_c}^{\text{tail}}}{N_{\eta_c}^{\text{prompt}} + N_{\eta_c}^{\text{from-b}}} < 2\%$$
and production in inclusive b-decays

- From EPJC 75 (2015) 311 and PDG:

\[
\frac{\mathcal{B}(b \to \eta_c(1S)^{\text{direct}} X) \mathcal{B}(b \to J/\psi^{\text{direct}} X)}{\mathcal{B}(b \to J/\psi^{\text{direct}} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103.
\]

- Relation between LDME from HQSS:

\[
\begin{align*}
\langle O_{10}^{\eta_c(1S_0)} \rangle &= \frac{1}{3} \langle O_{10}^{J/\psi(3S_1)} \rangle, \\
\langle O_{8}^{\eta_c(1S_0)} \rangle &= \frac{1}{3} \langle O_{8}^{J/\psi(3S_1)} \rangle, \\
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\langle O_{8}^{\eta_c(1P_1)} \rangle &= 3 \langle O_{8}^{J/\psi(3P_0)} \rangle.
\end{align*}
\]


- Fit two LDMEs to measurements

- Consecutively fix two remaining LDME from Chao et al., PRL 108 (2012) 242004

- Constrain theory using simultaneously results on charmonia hadroproduction and on charmonia from b-inclusive decays
Spectroscopy with $\eta_c(1S)$ decays to hadrons at LHCb

- General agreement with world average
- Similar to PDG precision expected for $\eta_c$ mass with Run II data