Conventional and exotic charmonium production at the ATLAS experiment

Bruce Yabsley

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CHARM 2015, 18th May, Wayne State University, Detroit
Outline

1. **Hidden flavour production at ATLAS**
   - physics motivation
   - experimental environment and techniques

2. **ϒ(nS) production cross-sections at 7 TeV**

3. **Search for a \(X_b \rightarrow \pi^+\pi^-\Upsilon\) signal**
   - summary of the analysis
   - results as a function of mass
   - interpretation and plans

4. **\(\psi(2S) \rightarrow \pi^+\pi^- J/\psi\) at 7 TeV**

5. **\(\chi_{c1}\) and \(\chi_{c2}\) production at 7 TeV**

6. **Summary**

- lots in the backup: ask me a question!
Hidden flavour production

from CHARM 2013 / Manchester:

Overview: Three $J/\psi$ Production Works

<table>
<thead>
<tr>
<th>Butenschön, Kniehl:</th>
<th>Gong, Wan, J.-X. Wang, H.-F. Zhang:</th>
<th>Chao, Ma, Shao, K. Wang, Y.-J. Zhang:</th>
</tr>
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M. Butenschön

Theory of Charmonium Production

15/21
Hidden flavour production

from CHARM 2013 / Manchester:

Overview: Three J/ψ Production Works

AGREEMENT:
Can NOT describe e⁺e⁻, γp, pp yield and pp polarization
with same LDMEs.

M. Butenschön

Theory of Charmonium Production

Bruce Yabsley (ATLAS / Sydney)
Charmonium production at ATLAS
Hidden flavour production

from CHARM 2013 / Manchester:

Summary

- 40 years after $J/\psi$ discovery:
  Still no successful description of charmonium production!
- Traditional color singlet model:
  - Can successfully describe only $e^+e^-$ data
  - Theoretically incomplete due to uncancelled IR divergences
- NRQCD factorization based on solid effective field theory approach, but
  - Factorization theorem not yet proven (IR safe to all orders?)
  - Current NLO analyses in combination with recent polarization measurements cast doubt on LDME universality.
- Possible ways out:
  - NRQCD factorization may not hold in all kinematic regions / for all observables
  - Resummation of large logarithms $p_T^2/m_c^2$ (large $p_T$ resummation)
  - Apply $k_T$-dependent PDFs.
high production rates for signal and background, in a detector optimized for high-$p_T$ discovery physics at $\sqrt{s} = 14$ TeV
Hidden flavour at ATLAS: experimental techniques

- rate limited by trigger bandwidth, especially at Level 1 (hardware)
- $B$-physics & onia: high-$p_T$ $\mu$, $M(\mu\mu)$-restricted-dimuon, ... triggers
- increasing $\mathcal{L} \rightarrow$ higher-$p_T$ triggers, prescaling, ...

$\sqrt{s} = 7$ TeV $\int L \, dt \sim 2.3$ fb$^{-1}$

Bruce Yabsley (ATLAS / Sydney)
Hidden flavour at ATLAS: experimental techniques

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![Graph showing distributions of $J/\psi$, $\psi(2S)$, $Y(1S)$, $Y(2S)$, and $Y(3S)$ with trigger efficiencies labeled.](attachment:graph.png)

$\sqrt{s} = 7$ TeV $\int L \, dt \sim 2.3$ fb$^{-1}$

Bruce Yabsley (ATLAS / Sydney)  Charmonium production at ATLAS  CHARM 2015/05/18
dimuon trigger: $p_T^{\mu} > 4 \text{ GeV}$, $|\eta^{\mu}| < 2.3$; largely un-prescaled, $1.8 \text{ fb}^{-1}$

- resolution differs at high $|y|$
$\Upsilon(nS)$ production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

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- resolution differs at high $|y|$ and at central $|y|$.
- weighted event-by-event for $\epsilon$; fits in $p_T$ bins: e.g. [0.5, 1.0]
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- resolution differs at high $|y|$ and at central $|y|$
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- corrected cross-sections: full $\Upsilon$ decay parameter space
\( \Upsilon(nS) \) production cross-sections

ATLAS Collaboration, PRD 87, 052004 (2013)

dimuon trigger: \( p_T^{\mu} > 4 \text{ GeV}, |\eta^{\mu}| < 2.3; \) largely un-prescaled, \( 1.8 \text{ fb}^{-1} \)

- resolution differs at high \( |y| \) and at central \( |y| \)
- weighted event-by-event for \( \epsilon \); fits in \( p_T \) bins: e.g. [40.0, 45.0]
- fiducial cross-sections: no spin-alignment uncertainty
- corrected cross-sections: full \( \Upsilon \) decay parameter space
- data disagrees w predictions; NNLO* CSM: at high \( p_T \); colour evaporation: on shape; note \( p_T \) dependence of the spin-alignment uncertainty
Search for a $X_b \rightarrow \pi^+\pi^-\Upsilon$ signal


- hidden-beauty analogue of $X(3872) \rightarrow \pi^+\pi^- J/\psi$
- $16.2\,\text{fb}^{-1}$ of $\sqrt{s} = 8\,\text{TeV}$ data; $2 \times (p_T > 4\,\text{GeV} \text{ muon})$ trigger
- fit in $2 \times 2 \times 2$ bins of $(|y|, p_T, \cos \theta^*)$ to discriminate vs bkgd

- kinematics: ATLAS/CMS
  $\Upsilon(nS) \frac{d^2\sigma}{dydp_T}$; validated on $34300 \pm 800 \Upsilon(2S)$ signal
- $\Upsilon(3S)$: model for $X_b$ search
- significance $z = 8.7$;
  most sensitive bin $z = 6.5 \rightarrow$
- $\chi^2/n_{dof} = 1.0$ for simultaneous fit

\[
N_{3S}^{\text{fit}} = 11600 \pm 1300
\]
\[
N_{3S}^{\text{pred}} = (\sigma B)_{3S} \cdot L \cdot A \cdot \epsilon
= 11400 \pm 1500
\]
Search for a $X_b \rightarrow \pi^+\pi^-\gamma$ signal


- $p_T > 20\text{ GeV}, \cos \theta^* > 0$ (most sensitive bin):

**BARREL**

- ATLAS
  - $\sqrt{s} = 8\text{ TeV, 16.2 fb}^{-1}$
  - 2012 Data
  - Total Fit
  - Background Component

**ENDCAP**

- ATLAS
  - $\sqrt{s} = 8\text{ TeV, 16.2 fb}^{-1}$
  - 2012 Data
  - Total Fit
  - Background Component

Data - Fitted Background

Total Signal Fit

Gaussian Components

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Charmonium production at ATLAS

CHARM 2015/05/18
Search for a $X_b \rightarrow \pi^+\pi^-\Upsilon$ signal


- $p_T > 20 \text{ GeV}, \cos \theta^* < 0$ (top-left bin):

**BARREL**

<table>
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<th>Candidates / 2 MeV</th>
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<tbody>
<tr>
<td>6500</td>
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<td>1000</td>
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<td>500</td>
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$\Upsilon = 8 \text{ TeV}, 16.2 \text{ fb}^{-1}$

$N_S = 809 \pm 93$

$|y| < 1.2$

$1.2 < |y| < 2.4$

$|p_T| > 20 \text{ GeV}$

$\cos \theta^* < 0$

**ENDCAP**

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$\Upsilon = 8 \text{ TeV}, 16.2 \text{ fb}^{-1}$

$N_S = 471 \pm 54$

$1.2 < |y| < 2.4$

$|p_T| > 20 \text{ GeV}$

$\cos \theta^* < 0$
Search for a $X_b \rightarrow \pi^+\pi^-\Upsilon$ signal


- $p_T < 20$ GeV, $\cos \theta^* > 0$ (bottom-right bin):

**BARREL**

**ENDCAP**

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Charmonium production at ATLAS
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Search for a $X_b \rightarrow \pi^+\pi^-\Upsilon$ signal


- $p_T < 20 \text{ GeV}, \cos \theta^* < 0$ (least sensitive bin):

BARREL

ENDCAP

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$X_b \rightarrow \pi^+\pi^−\Upsilon$: results as a function of mass


- hypothesis test every 10 MeV from 10–11 GeV, excluding $\Upsilon(2S, 3S)$
- fit range $m \pm 8\sigma_{\text{endcap}}$: $\pm 72$ MeV at 10 GeV; $\pm 224$ MeV at 10.9 GeV
- simultaneous fit to the 8 ($|y|$, $p_T$, $\cos \theta^*$) bins, for $R = \sigma B / (\sigma B)_{2S}$
$X_b \rightarrow \pi^+ \pi^- \Upsilon$: results as a function of mass

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**Fig. 7.** The $\pi^+ \pi^- \Upsilon(1S)$ invariant mass distributions for each of the analysis bins.
$X_b \rightarrow \pi^+\pi^- \Upsilon$: results as a function of mass


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- local signif. $z < 3$ by asymptotic formulae
$X_b \rightarrow \pi^+\pi^-\Upsilon$: results as a function of mass


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- $\text{cf. } R = 3\%, 6.56\%$

![Graph showing p-value and significance as functions of parent mass](image)
\( X_b \rightarrow \pi^+\pi^-\Upsilon: \) results as a function of mass


- hypothesis test every 10 MeV from 10–11 GeV, excluding \( \Upsilon(2S, 3S) \)
- fit range \( m \pm 8\sigma_{\text{endcap}}: \pm 72 \text{ MeV} \) at 10 GeV; \( \pm 224 \text{ MeV} \) at 10.9 GeV
- simultaneous fit to the 8 (|y|, \( p_T \), cos \( \theta^* \)) bins, for \( R = \sigma_B / (\sigma_B)_{2S} \)

- local signif. \( z < 3 \) by asymptotic formulae
- \( \text{cf. } R = 3\%, 6.56\% \)
- set ULs using CLs

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
\text{Parent Mass [MeV]} & 10000 & 10200 & 10400 & 10600 & 10800 & 11000 & 11200 \\
\hline
\text{Upper Limit on } R_{95\% CL} & 2^{-10} & 1^{-10} & \text{TRPP} & \text{TRP0} & \text{TRPM} & \text{LONG} \\
\end{array}
\]
$X_b \rightarrow \pi^+\pi^-\Upsilon$: results as a function of mass


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- local signif. $z < 3$ by asymptotic formulae
- cf. $R = 3\%$, 6.56\%
- set ULs using CL$_S$
- syst’s first added:
  - using $G$ constraints
  - increases limits $< 13\%$
  - inflates $\pm 1\sigma$ bands 9.5–25\%

![Graph showing upper limits on $R_s$ at 95% CL](chart.png)

**Observed**: Black line
**Median Expected**: Dotted black line
**±1σ Band**: Green band
**±2σ Band**: Yellow band

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$X_b \rightarrow \pi^+ \pi^- \gamma$: results as a function of mass


- hypothesis test every $10 \text{ MeV}$ from $10–11 \text{ GeV}$, excluding $\Upsilon(2S, 3S)$
- fit range $m \pm 8\sigma_{\text{endcap}}$: $\pm 72 \text{ MeV}$ at $10 \text{ GeV}$; $\pm 224 \text{ MeV}$ at $10.9 \text{ GeV}$
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- local signif. $z < 3$ by asymptotic formulae
- $cf. \ R = 3\%, \ 6.56\%$
- set ULs using $CL_S$
- syst’s first added:
  - using $G$ constraints
  - increases limits $\lesssim 13\%$
  - inflates $\pm 1\sigma$ bands 9.5–25%
- recalculated for the other spin-align$^t$ working pts
$X_b \rightarrow \pi^+ \pi^- \Upsilon$: results as a function of mass


- hypothesis test every 10 MeV from 10–11 GeV, excluding $\Upsilon(2S, 3S)$
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- cf. $R = 3\%$, 6.56\%
- set ULs using $\text{CL}_S$
- syst’s first added:
  - using $G$ constraints
  - increases limits $\lesssim 13\%$
  - inflates $\pm 1\sigma$ bands 9.5–25\%
- recalculated for the other spin-align$^t$ working pts
- reported in detail
$X_b \rightarrow \pi^+ \pi^- \Upsilon$: interpretation and plans

- this is the most sensitive $X_b$ production search for $m > 10.1$ GeV
- excludes $R = \sigma B / (\sigma B)_{\Upsilon(2S)} = 6.56\%$ throughout search range
  - cf. $\pi \pi \psi$ [CMS, JHEP 04 (2013) 154]: $(\sigma B)_{X(3872)} / (\sigma B)_{\psi(2S)} = 6.56\%$
  - if $X_b$ exists, relative production $\sigma / \sigma_{2S}$ or branching $B / B_{2S}$, or both, are weaker than for $X(3872)$

- an $X_b$ is not in general a carbon copy of the $X(3872)$:
  - $X(3872)$ is within sub-MeV resolution of $D^0 \overline{D}^{*0}$ threshold
  - even a molecular $X_b$ is bound by tens of MeV
  - further, large $D \overline{D}^*$ isospin breaking ($m_\pm - m_{00} = +8.08 \pm 0.11$ MeV) is absent for $B \overline{B}^*$ ($m_\pm - m_{00} = -0.64 \pm 0.12$ MeV)$^\dagger$
  - stressed by theorists [Guo/Meißner/Wang, 1204.2158; Karliner ...]

$X(3872)$: $|m_\pm - m_{00}| \gg E_b$; $\approx$ pure $D^0 \overline{D}^{*0}$ state; $B_{\rho \psi} \sim B_{\omega \psi}$

$X_b$: $|m_\pm - m_{00}| \ll E_b$; $\approx$ pure $I = 0$ state; $B_{\rho \Upsilon}$ “strongly” suppressed

- $I$-allowed modes — $\{\gamma, \pi\pi\pi^0\} \Upsilon, \pi\pi\chi_b$ — have severe $\mathcal{A} \cdot \epsilon$ problems; further searches are under investigation
\( \psi(2S) \rightarrow \pi^+\pi^- J/\psi \) at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

little feed-down from higher states: test of direct charmonium production also constrains feed-down to \( J/\psi \) if measured in bins of \( J/\psi \) \((p_T, y)\)

dimuon trigger: \( p_T^\mu > 4 \text{ GeV}, |\eta^\mu| < 2.3 \); un-prescaled, \( 2.1 \text{ fb}^{-1} \)

- full spectrum; note the \( X(3872) \)
\( \psi(2S) \rightarrow \pi^+\pi^- J/\psi \) at 7 TeV

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- full spectrum;
- note the \( X(3872) \)
- \( \pi^+\pi^-\mu^+\mu^- \) fit, constraining \( \mu\mu \rightarrow J/\psi \) mass;
- \(|y| \in [0, 0.75]\)

\[ |y| < 0.75 \]

\[ \sqrt{s} = 7 \text{ TeV}, 2.1 \text{ fb}^{-1} \]

\[ \times 10^3 \]

\[ \text{Entries / 4 MeV} \]

\[ \text{ATLAS} \]

\[ |y| < 0.75 \]

\[ \sqrt{s} = 7 \text{ TeV}, 2.1 \text{ fb}^{-1} \]

\[ \text{Data} \]

\[ \text{Fit} \]

\[ \text{Background} \]

\[ \psi(2S) \text{ Signal} \]

Signal \( \sim 96 \text{ k} \)

Peak \( \sigma \sim 5.6 \text{ MeV} \)

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$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$ at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

little feed-down from higher states: test of direct charmonium production
also constrains feed-down to $J/\psi$ if measured in bins of $J/\psi$ ($p_T, y$)

dimuon trigger: $p_T^{\mu} > 4$ GeV, $|\eta^{\mu}| < 2.3$; un-prescaled, 2.1 fb$^{-1}$

- full spectrum;
  - note the $X(3872)$
- $\pi^+ \pi^- \mu^+ \mu^-$ fit, constraining
  - $\mu\mu \rightarrow J/\psi$ mass;
  - $|y| \in [0, 0.75)$
  - $|y| \in [0.75, 1.5)$

![Graph](image-url)
\( \psi(2S) \rightarrow \pi^+ \pi^- \ J/\psi \) at 7 TeV

ATLAS Collaboration, JHEP 09 (2014) 079

little feed-down from higher states: test of direct charmonium production
also constrains feed-down to \( J/\psi \) if measured in bins of \( J/\psi \) \( (p_T, y) \)

dimuon trigger: \( p_T^\mu > 4 \text{ GeV}, |\eta^\mu| < 2.3; \) un-prescaled, \( 2.1 \text{ fb}^{-1} \)

- full spectrum;
  - note the \( X(3872) \)
- \( \pi^+ \pi^- \mu^+ \mu^- \) fit,
  - constraining
  \( \mu \mu \rightarrow J/\psi \) mass;
  \( |y| \in [0, 0.75) \)
  \( |y| \in [0.75, 1.5) \)
  \( |y| \in [1.5, 2.0) \)
Charmonium production at ATLAS

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\( \psi(2S) \to \pi^+ \pi^- J/\psi \) at 7 TeV: 2D fit to \((m, \tau)\)

ATLAS Collaboration, JHEP 09 (2014) 079

mass:

\[

t \mathcal{G}_1(m) + [1 - t] \mathcal{G}_2(m)
\]

pseudo proper time:

\[
\delta(\tau) \otimes \mathcal{G}_{\text{res}}(\tau)
\]

\[
(E_1(\tau) \equiv \exp(-\tau/\tau_1)\Theta(\tau)) \otimes \mathcal{G}_{\text{res}}(\tau)
\]

\[
\{\delta(\tau), \sum_i k_i E_i(\tau), E_4(1|\tau|)\} \otimes \mathcal{G}_{\text{res}}(\tau)
\]

prompt:

\[
\mathcal{P}_2(m)
\]

non-prompt:

\[
\mathcal{P}_2(m)
\]

bkgds:

in bins of the \( \psi(2S) \) \((p_T, |y|)\);

representative examples at low \( y, p_T \)

likewise for \( J/\psi \) \((p_T, |y|)\)
$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ at 7 TeV: 2D fit to $(m, \tau)$

**ATLAS Collaboration, JHEP 09 (2014) 079**

**mass:**

prompt: $fG_1(m) + [1 - f]G_2(m)$

non-prompt: $fG_1(m) + [1 - f]G_2(m)$

bkgds: $P_2(m)$

**pseudo proper time:**

$\delta(\tau) \otimes G_{\text{res}}(\tau)$

$(E_1(\tau) \equiv \exp(-\tau/\tau_1)\Theta(\tau)) \otimes G_{\text{res}}(\tau)$

$\{\delta(\tau), \sum_i k_i E_i(\tau), E_4(|\tau|)\} \otimes G_{\text{res}}(\tau)$

in bins of the $\psi(2S)$ ($p_T, |y|$);

representative examples at

low $y, p_T$

mid $y, p_T$

likewise for $J/\psi$ ($p_T, |y|$)
\( \psi(2S) \rightarrow \pi^+\pi^- \ J/\psi \ \text{at} \ 7 \ \text{TeV} \): 2D fit to \((m, \tau)\)

**mass:**

- prompt: \( f G_1(m) + [1 - f] G_2(m) \)
- non-prompt: \( f G_1(m) + [1 - f] G_2(m) \)
- bkgds: \( P_2(m) \)

**pseudo proper time:**

\[ \delta(\tau) \otimes G_{\text{res}}(\tau) \]

\[ (E_1(\tau) \equiv \exp(-\tau/\tau_1)\Theta(\tau)) \otimes G_{\text{res}}(\tau) \]

\[ \{ \delta(\tau), \sum_i k_i E_i(\tau), E_4(|\tau|) \} \otimes G_{\text{res}}(\tau) \]

in bins of the \( \psi(2S) \) \((p_T, |y|)\);

representative examples at

- low \( y, p_T \)
- mid \( y, p_T \)
- high \( y, p_T \); likewise for \( J/\psi \) \((p_T, |y|)\)
\[ \psi(2S) \rightarrow \pi^+\pi^- J/\psi \text{ at } 7 \text{ TeV: comparison with theory} \]

**ATLAS Collaboration, JHEP 09 (2014) 079**

**prompt production:**

NNLO* CS undershoots (esp. at high \( p_T \)); NLO NRQCD \( \approx \) matches data; colour evaporation predicts a harder spectrum than seen; \( k_T \) factorization significantly (and as a fn of \( p_T \)) underestimates data

cf. spin-alignment uncertainty: \( (^{+6}_{-3})\% \) at 10 GeV \( \rightarrow (^{+8}_{-12})\% \) at high \( p_T \)

\[ B(\psi(2S) \rightarrow J/\psi \rightarrow \pi^+\pi^-) \approx n_\pi^+n_\pi^- J/\psi \]

\[ \sigma_B(\psi(2S) \rightarrow J/\psi \rightarrow \pi^+\pi^-) \times \frac{1}{100} \]

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\[ \sigma_B(\psi(2S) \rightarrow J/\psi \rightarrow \pi^+\pi^-) \times \frac{1}{100} \]

\[ \sigma_B(\psi(2S) \rightarrow J/\psi \rightarrow \pi^+\pi^-) \times \frac{1}{100} \]
\( \psi(2S) \rightarrow \pi^+\pi^- J/\psi \), at 7 TeV: comparison w theory


**non-prompt production:** reasonable agreement with both
general-mass variable-flavour-number scheme (GM-VFNS) at NLO, and
fixed-order next-to-leading logarithm (FONLL) calculations,
but both predict production that’s harder in \( p_T \);

FONLL reproduces \( B^+ \Rightarrow \exists b \)-hadron composition & decay mismodelling?
[for same trigger & dataset]
**χc1 and χc2 production at 7 TeV**

**ATLAS Collaboration, JHEP 07 (2014) 154**

- example of $P$-wave quarkonium production
- significant source of feed-down to $J/\psi$
- multiple states $\rightarrow \chi_{c2}/\chi_{c1}$ ratios provide precision tests

---

**cf. $\psi(2S)$:** ππ replaced by $\gamma \rightarrow e^+e^-$ in pixels, $p_T^\gamma > 1.5$ GeV, $|\eta^\gamma| < 2.0$

again, 2D fit in mass and pseudo-proper time:

---

*Bruce Yabsley (ATLAS / Sydney)*

Charmonium production at ATLAS

CHARM 2015/05/18 14 / 32
a series of absolute cross-section $\times \mathcal{B}_{\chi_{c1,c2}} \times \mathcal{B}_{J/\psi}$ measurements in

- $\chi_{c1,c2} p_T$ bins, for $\chi_{c1,c2}$ production studies
- $J/\psi p_T$ bins, for constraint of feed-down to $J/\psi$; examples:

- prompt $\chi_{c1}$ and
a series of absolute cross-section $\times B_{\chi_{c1,c2}} \times B_{J/\psi}$ measurements in
- $\chi_{c1,c2} p_T$ bins, for $\chi_{c1,c2}$ production studies
- $J/\psi p_T$ bins, for constraint of feed-down to $J/\psi$; examples:

- prompt $\chi_{c1}$ and
  prompt $\chi_{c2}$:
good agreement w NLO NRQCD, not LO CSM, or $k_T$ (now constrained by $\psi(2S)$ & $\chi_{cJ}$ measurements).
a series of absolute cross-section \( \times B_{\chi_{c1,c2}} \times B_{J/\psi} \) measurements in
- \( \chi_{c1,c2} \) \( p_T \) bins, for \( \chi_{c1,c2} \) production studies
- \( J/\psi \) \( p_T \) bins, for constraint of feed-down to \( J/\psi \); examples:

- prompt \( \chi_{c1} \) and prompt \( \chi_{c2} \):
good agreement w NLO NRQCD, not LO CSM, or \( k_T \) (now constrained by \( \psi(2S) \) & \( \chi_{cJ} \) meas\( ^{\text{ts}} \)).

- non-prompt \( \chi_{c1}, \chi_{c2} \):
FONLL does well; overshoots at high \( p_T \).
\( \chi_{c2}/\chi_{c1} \) ratios of production cross-section \( \times B_{\chi_{c1,c2}} \times B_{J/\psi} \):

**prompt production:**

- LO colour singlet consistently low
- NLO NRQCD matches well
- results, including ?NRQCD high-\( p_T \) over-prediction?, consistent w CMS

\[ B_{2\chi_c} / B_{\chi_c} \times (\sigma \times B_{J/\psi}) \]

<table>
<thead>
<tr>
<th>( p_T^{J/\psi} [\text{GeV}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

Promt \( |y^{J/\psi}| < 0.75 \)

Data

CMS \( |y^{J/\psi}| < 1.0 \)

\( \sqrt{s} = 7 \text{ TeV} \int L \, dt = 4.5 \text{ fb}^{-1} \)

Isotropic Decay

ATLAS

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$\chi_{c1}$ and $\chi_{c2}$ production at 7 TeV
ATLAS Collaboration, JHEP 07 (2014) 154

$\chi_{c2}/\chi_{c1}$ ratios of production cross-section $\times B_{\chi_{c1,c2}} \times B_{J/\psi}$:

**Prompt production:**
- LO colour singlet consistently low
- NLO NRQCD matches well
- Results, including ?NRQCD high-$p_T$ over-prediction?, consistent w CMS

**Non-prompt:**
- Agrees with CDF $\sqrt{s} = 1.96$ TeV $p\bar{p}$ measurement

![Graph showing $B_{\chi_{c2}} \times B_{\chi_{c1}} / B_{\sigma(\chi_{c1})}$ ratios vs. $p_T^{J/\psi}$ for ATLAS and CDF data.](image_url)
Summary

ATLAS has an active programme measuring charmonium production, featuring

- differential cross-section measurements in $|y|$ and $p_T$
- careful treatment and reporting of spin-alignment uncertainties
- both prompt and non-prompt production for hidden charm
- a reasonably comprehensive set of states:
  - $J/\psi$ (older results not shown here)
  - $\chi_{c1}$ and $\chi_{c2}$
  - $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$
  - $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$
  - $\chi_{bJ}(mP)$ measurements (not shown here)

- a sensitive $X_b$ production test has also been performed

Further measurements, on 8 TeV and 13 TeV data, will be released in the next year or so.
for \( (J^{PC} = 1^{--}) \), \( |V\rangle = b_{+1} | + 1 \rangle + b_{-1} | - 1 \rangle + b_0 |0 \rangle \) decaying \( \rightarrow \ell^+ \ell^- \),

- the angular distribution \( W(\cos \vartheta, \varphi) \)

\[
\alpha \frac{\mathcal{N}}{(3 + \lambda_{\vartheta})} \left( 1 + \lambda_{\vartheta} \cos^2 \vartheta \right) \\
+ \lambda_{\varphi} \sin^2 \vartheta \cos 2\varphi \\
+ \lambda_{\vartheta \varphi} \sin 2\vartheta \cos \varphi \\
+ \lambda_{\varphi}^{\perp} \sin^2 \vartheta \sin 2\varphi \\
+ \lambda_{\vartheta \varphi}^{\perp} \sin 2\vartheta \sin \varphi
\]
for \((J^{PC} = 1^{--})\) \(|V⟩ = b_{+1} |+1⟩ + b_{-1} |−1⟩ + b_{0} |0⟩\) decaying \(→ ℓ^+ ℓ^−\),

- the angular distribution \(W(\cos ϑ, ϕ)\)

\[
\propto \frac{N}{(3 + \lambda_ϑ)} \left( 1 + \lambda_ϑ \cos^2 ϑ \right)
\]

\[
+ \lambda_φ \sin^2 ϑ \cos 2φ + \lambda_ϑφ \sin 2ϑ \cos φ
\]

\[
+ \lambda_{⊥φ} \sin^2 ϑ \sin 2φ + \lambda_{⊥ϑφ} \sin 2ϑ \sin φ
\]

- inclusive production: \(p_1, p_2, \text{and } V \text{ only;}\)
  we \(\sim \text{must}\) choose \((x, z) : \text{production plane}\)

Bruce Yabsley (ATLAS / Sydney) Charmonium production at ATLAS CHARM 2015/05/18 19 / 32
for \((J^{PC} = 1^{--})\) \(|V\rangle = b_{+1} |+1\rangle + b_{-1} |-1\rangle + b_0 |0\rangle\) decaying \(\rightarrow \ell^+\ell^-\),

- the angular distribution \(W(\cos \vartheta, \varphi)\)

\[
\propto \frac{N}{(3 + \lambda_\vartheta)} \left( \cos^2 \vartheta + \lambda_\vartheta \cos^2 \vartheta \right)
+ \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi
+ \lambda_{\varphi} \sin^2 \vartheta \sin 2\varphi + \lambda_{\varphi} \sin 2\vartheta \sin \varphi
\]

- inclusive production: \(p_1, p_2,\) and \(V\) only;
  we \((\sim\) must\) choose \((x, z)\): production plane

- reflection-odd terms unobservable (parity)
for \((J^{PC} = 1^{--})\), \(|V⟩ = b_{+1} | +1⟩ + b_{-1} | -1⟩ + b_0 |0⟩\) decaying \(→ \ell^+ \ell^-\),

- the angular distribution \(W(\cos \vartheta, \varphi)\)
  \[
  \alpha \frac{N}{(3 + \lambda_\vartheta)} \left( 1 + \lambda_\vartheta \cos^2 \vartheta \right)
  + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_\vartheta \varphi \sin 2\vartheta \cos \varphi
  + \lambda_\varphi^\perp \sin^2 \vartheta \sin 2\varphi + \lambda_\vartheta \varphi^\perp \sin 2\vartheta \sin \varphi
  \]

- inclusive production: \(p_1, p_2,\) and \(V\) only; we (~ must) choose \((x, z)\) : production plane

- reflection-odd terms unobservable (parity)
for \((J^{PC} = 1^{--})\)
\[
|V⟩ = b_{+1} | + 1⟩ + b_{-1} | - 1⟩ + b_0 |0⟩ \text{ decaying } → ℓ^+ ℓ^-,
\]

- the angular distribution \(W(\cos ϑ, φ)\)

\[
N \left( 1 + \lambda_ϑ \cos^2 ϑ \right)
+ \lambda_φ \sin^2 ϑ \cos 2φ + λ_ϑφ \sin 2ϑ \cos φ
+ \lambda_⊥φ \sin^2 ϑ \sin 2φ + λ_ϑφ \sin 2ϑ \sin φ
\]

- inclusive production: \(p_1, p_2,\) and \(V\) only;
  we (∼ must) choose \((x, z)\) : production plane

- reflection-odd terms unobservable (parity)

- full angular distributions \((λ_ϑ, λ_φ, λ_ϑφ)\) in general needed . . .
L: polarized \{ transversely, longitudinally \}

\begin{align*}
  &a) m = \pm 1 \\
  &b) m = 0 \\
  &c) \quad m = \pm 1 \\
  &d) \quad m = 0
\end{align*}
L: polarized \{ \text{transversely, longitudinally} \}

R: meas\textsuperscript{t} frame rotated by 90°
L: polarized \( \begin{cases} \text{transversely} \\ \text{longitudinally} \end{cases} \)

R: meas\(^t\) frame rotated by 90°

integration over azimuth \( \varphi \)

\[ m = \pm 1 \]

\[ m = 0 \]
L: polarized \( \left\{ \begin{array}{l} \text{transversely} \\ \text{longitudinally} \end{array} \right. \)

R: meas\(^t\) frame rotated by 90\(^\circ\)

integration over azimuth \( \varphi \) → longitudinal dist\(^n\) (d) looks like
L: polarized \{ \text{transversely} \\
\text{longitudinally} \}

R: meas\textsuperscript{t} frame rotated by 90°
integration over azimuth $\varphi$ \rightarrow longitudinal dist\textsuperscript{n} (d) looks like transverse dist\textsuperscript{n} (a)
L: polarized \{ transversely, longitudinally \}

R: meas$^t$ frame rotated by 90°

integration over azimuth $\varphi$ \quad \text{longitudinal dist}^n (d) looks like transverse dist$^n$ (a)

$\lambda_\varphi$-only measurements (à la TeVatron Run I)
can’t be compared without assumptions about pol$^n$ frame
L: polarized \( \begin{cases} \text{transversely} \\ \text{longitudinally} \end{cases} \)

R: meas\(^t\) frame rotated by 90°
integration over azimuth \( \varphi \rightarrow \)
longitudinal dist\(^n\) (d) looks like transverse dist\(^n\) (a)

\( \lambda_\varphi \)-only measurements
(à la TeVatron Run I)
can’t be compared without assumptions about pol\(^n\) frame

**experimental acceptance** is also typically a \( f^n \) of \( (\lambda_\varphi, \lambda_\varphi, \lambda_\varphi) \)
limited range of $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})$ values allowed
limited range of \((\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})\) values allowed

LHC experiments quote results for each of a set of working points
acceptance $\mathcal{A}(p_T^\Upsilon, y^\Upsilon) = P(\text{both muons pass } p_T^\mu > 4\text{ GeV, } |\eta^\mu| < 2.3)$

function of $\Upsilon$ spin alignment: isotropic (default) + 4 working points in

$$\frac{d^2N}{d\cos \theta^* d\phi^*} \propto 1 + \lambda_\theta \cos^2 \theta^* + \lambda_\phi \sin^2 \theta^* \cos 2\phi^* + \lambda_{\theta\phi} \sin 2\theta^* \cos \phi^*$$

Lowest $\mathcal{A}$, and largest variation, for $p_T \simeq \frac{1}{2} m_\Upsilon$ (consider “backward” $\mu$)
fiducial cross-sections (no theoretical predictions to compare to so far!): little \( (p_T, y) \) structure in the weight, \( w_{\text{fid}} = (\epsilon_{\text{reco}} \cdot \epsilon_{\text{trig}})^{-1} \); dominated by trigger efficiency \( \epsilon_{\text{trig}} = \epsilon_{\text{RoI}}(p_T, q \cdot \eta) \mu_1 \cdot \epsilon_{\text{RoI}}(p_T, q \cdot \eta) \mu_2 \cdot c_{\mu \mu}(\Delta R, |y_{\mu \mu}|) \); see paper & http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/BPHY-2011-06/
corrected cross-sections:

weight $w_{\text{tot}} = (A \cdot \epsilon_{\text{reco}} \cdot \epsilon_{\text{trig}})^{-1}$ dominated by acceptance at low $p_T$

$\Rightarrow$ spin-alignment dependence

Bruce Yabsley (ATLAS / Sydney)
systematics dominated by trigger efficiency and fit modelling; — falls below stat\textsuperscript{uncert} for $p_T \gtrsim 30\ (20)\ GeV$ for $\Upsilon(1S)$ ($\Upsilon(2S, 3S)$)

low acceptance correction uncertainties due to spread in interaction point (subleading: statistical noise due to very fine binning)
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— falls below statistical uncertainty for $p_T \gtrsim 30$ (20) GeV for $\Upsilon$(1S) ($\Upsilon$(2S, 3S))

low acceptance correction uncertainties due to spread in interaction point (subleading: statistical noise due to very fine binning)
The $X(3872)$ is the first (2003) & best-studied (> 25 experimental papers) of the new hidden-charm states seen in the last decade.

- $\pi\pi\psi$ [discovery] & other decays
- narrow: $\Gamma < 1.2$ MeV, 90% C.L.
- $J^{PC} = 1^{++}$ ($2^{-+}$ finally excluded)
- direct $p\bar{p}$ & $pp$ production seen
- very poor match to $c\bar{c}$ structure
- very close to $D^*0\bar{D}^0$ threshold:
  - $D^*0\bar{D}^0$ molecule, very weak $E_b \approx \frac{1}{10} E_b(2^H)$?
  - $\exists$ tetraquark, other models
- heavy-flavour symmetry: expect a hidden-beauty analogue
The $\pi^+\pi^-\Upsilon(1S)$ (c.f. $\pi^+\pi^-J/\psi$) channel provides an experimentally feasible search option:

1. **Reconstruct** $X_b \rightarrow \pi^+\pi^-\Upsilon(\mu\mu)$ using large ATLAS $\Upsilon(\mu\mu)$ sample
2. Either **observe** $X_b$ at mass $M$ with significance $z$, or
3. **Set upper limits** for $X_b \rightarrow \pi^+\pi^-\Upsilon(\mu\mu)$ production
4. Also look for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$ decays
I. Find $\Upsilon \rightarrow \mu^+ \mu^-$ candidates:

- $p_T(\mu) > 4 \text{ GeV} \ \text{trigger}$
- two “combined” $\mu$ tracks
- $|\eta(\mu)| < 2.3$
- $|m(\mu\mu) - m_{1S}| < 350 \text{ MeV}$

Bruce Yabsley (ATLAS / Sydney)  Charmonium production at ATLAS  CHARM 2015/05/18  25 / 32
Ⅰ. Find $\Upsilon \rightarrow \mu^+\mu^-$ candidates:

- $p_T(\mu) > 4$ GeV $\Upsilon$ trigger
- two “combined” $\mu$ tracks
- $|\eta(\mu)| < 2.3$
- $|m(\mu\mu) - m_{1S}| < 350$ MeV

Ⅱ. Add two tracks ($\pi\pi$):

- $p_T(\pi) > 400$ MeV
- $|\eta(\pi)| < 2.5$
- 4-track vertex fit
  - $m(\mu\mu) = m_{1S}$ constraint
  - $\chi^2 < 20$
  - masses $< 11.2$ GeV
barrel ($|y| < 1.2$) resolution better than endcap ($1.2 < |y| < 2.4$)

- constraint $\mu^+\mu^- \rightarrow \Upsilon$ mitigates this, but not higher bkgd under peak
- unknown $X_b$ mass: $\pi\pi$ effect on $m(\pi\pi\Upsilon)$ resolution can’t be removed

$\rightarrow$ perform the analysis in bins of rapidity

**BARREL**

**ENDCAP**
BACKUP: $X_b$: discrimination in $(|y|, p_T, \cos \theta^*)$


- barrel ($|y| < 1.2$) resolution better than endcap ($1.2 < |y| < 2.4$)
  - perform the analysis in bins of rapidity
- different signal and background distributions in $(p_T, \cos \theta^*)$:
  - $\cos \theta^*(\pi^+\pi^-)$ flat in parent rest frame for unpolarized signal
  - in background, $\pi^+\pi^-$ unrelated to $\mu^+\mu^-$, and has low $p_{\pi\pi}^T$
  - background is lower in $p_T$, more backward in $\cos \theta^*$

$X_b$, rest frame

$\pi\pi$, $\gamma$

[classic discrimination by decay angle for (quasi-)2-body decays]
**BACKUP: X_b: discrimination in (|y|, p_T, cos θ*)**


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  - trigger threshold effects
    - → distributions change but discrimination remains
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- **barrel (|y| < 1.2) resolution** better than endcap (1.2 < |y| < 2.4)
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- **different signal and background distributions in (p_T, cos θ*)**:
  - cos θ*(π^+π^-) flat in parent rest frame for unpolarized signal
  - in background, π^+π^- unrelated to μ^+μ^-, and has low p_T^ππ
  - background is lower in p_T, more backward in cos θ*
  - trigger threshold effects
  - distributions change but discrimination remains

we chose bin boundaries at (p_T, cos θ*) = (20 GeV, 0)
  - simult. fit to 2 × 2 × 2 bins in (|y|, p_T, cos θ*):

considered ΔR cut [CMS]:
  - less sensitive than binning

**ΔR cut à la CMS**

\[ \frac{S}{\sqrt{B}} \]
background:

- mix of inclusive $\Upsilon(1S)$ and combinatorial $\mu^+\mu^-$
- preliminary studies performed on 2011 (7 TeV) data:
  - lower-sideband $\mu^+\mu^-$ and same-sign $\mu^\pm\mu^\pm$ samples
- $m(\pi^+\pi^-\Upsilon)$ distributions featureless above 9800 MeV
- confirmed in $\Upsilon \rightarrow \mu^+\mu^-$ signal region for various $m(\pi^+\pi^-\Upsilon)$ ranges

$\rightarrow$ **polynomial fit** to $m(\pi^+\pi^-\Upsilon)$ region about each test mass
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  $\rightarrow$ polynomial fit to $m(\pi^+\pi^-\Upsilon)$ region about each test mass

signal:

- narrow state search: fit with $f \cdot G(m, \sigma) + (1 - f) \cdot G(m, r\sigma)$
- $f, r \sim$ indep$^t$ of mass; fixed to average over MC samples
- $\sigma$ then found to be linear in mass
- remaining issues: division among analysis bins, acceptance, efficiency
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signal:

- narrow state search: fit with $f \cdot \mathcal{G}(m, \sigma) + (1 - f) \cdot \mathcal{G}(m, r\sigma)$
- $f, r \sim \text{indep}^t$ of mass; fixed to average over MC samples
- $\sigma$ then found to be linear in mass
- remaining issues: division among analysis bins, acceptance, efficiency
  — all depend on distribution of final-state particles in $(\eta, p_T, \phi)$
spin-alignment uncertainty:
spin-alignment uncertainty:

\[
\psi(2S) \rightarrow \pi^+\pi^- J/\psi \text{ at } 7 \text{ TeV}
\]

ATLAS Collaboration, JHEP 09 (2014) 079
spin-alignment uncertainty:

\[ \psi(2S) \rightarrow \pi^+\pi^- J/\psi \text{ at 7 TeV} \]

ATLAS Collaboration, JHEP 09 (2014) 079
spin-alignment uncertainty:

\[
\psi(2S) \rightarrow \pi^+\pi^- \ J/\psi \text{ at } 7 \text{ TeV}
\]

ATLAS Collaboration, JHEP 09 (2014) 079
prompt production uncertainty budget (excluding spin alignment):

\[
\psi(2S) \rightarrow \pi^+\pi^- J/\psi \text{ at } 7 \text{ TeV}
\]

**ATLAS**

Prompt $|y| < 0.75$

\[\sqrt{s} = 7 \text{ TeV}, \ 2.1 \text{ fb}^{-1}\]

- Total Uncertainty
- Total Systematic Unc.
- Statistical Uncertainty
- Muon Reconstruction
- Pion Reconstruction
- Trigger
- Inner Detector Tracking
- Fit Model
- Selection Criteria
prompt production uncertainty budget (excluding spin alignment):
prompt production uncertainty budget (excluding spin alignment):

**ATLAS**

Prompt

1.5 \leq |y| < 2.0

\sqrt{s}=7\text{TeV}, 2.1\text{fb}^{-1}

-60 -40 -20 0 20 40 60

Fractional Uncertainty [%]

10 20 30 40 50 100

\(\psi(2S) p_T [\text{GeV}]\)

Total Uncertainty

Total Systematic Unc.

Statistical Uncertainty

Muon Reconstruction

Pion Reconstruction

Trigger

Inner Detector Tracking

Fit Model

Selection Criteria
non-prompt uncertainty budget (excluding spin alignment):

\[ \psi(2S) \rightarrow \pi^+\pi^- J/\psi \text{ at } 7 \text{ TeV} \]

ATLAS Collaboration, JHEP 09 (2014) 079
non-prompt uncertainty budget  (excluding spin alignment):

\[ \psi(2S) \rightarrow \pi^+\pi^- \ J/\psi \text{ at } 7 \text{ TeV} \]
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\[ \sqrt{s} = 7 \text{ TeV}, 2.1 \text{ fb}^{-1} \]

- Total Uncertainty
- Total Systematic Unc.
- Statistical Uncertainty
- Muon Reconstruction
- Pion Reconstruction
- Trigger
- Fit Model
- Selection Criteria
acceptance $A(p_{T}^{\chi}, y^{\chi}) = P(\text{both muons pass } p_{T}^{\mu} > 4 \text{ GeV, } |\eta^{\mu}| < 2.3, \text{ and photon passes } p_{T}^{\gamma} > 1.5 \text{ GeV, } |\eta^{\gamma}| < 2.0)$

The $\frac{d^2N}{d \cos \theta^* d \phi^*} \propto 1 + \lambda_{\theta} \cos^2 \theta^* + \lambda_{\phi} \sin^2 \theta^* \cos 2\phi^* + \lambda_{\theta\phi} \sin 2\theta^* \cos \phi^*$

treatment relies on Faccioli/Lourenco/Seixas/Wohri PRD 83, 096001 (2011) results, and neglect of the (suppressed) higher multipole contributions to $\chi_{c2} \rightarrow \gamma J/\psi$

Note the high effective $p_{T}$ threshold on the $\chi$
uncertainty budget for the prompt measurement:

![Graphs showing fractional uncertainty for Prompt $\chi_{c1}$ and $\chi_{c2}$ production at ATLAS](image)
uncertainty budget for the non-prompt measurement: