J/ψ Production at the LHC
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Outline

Motivation

Cern and the LHC

The experiments

J/$\psi$ production and results

Conclusions and outlook
CERN and the LHC

**pp collider: NOW:**
- $\sqrt{s} = 7$ TeV
- $L \approx 1-2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

**NOMINAL (2011):**
- $\sqrt{s} = 14$ TeV
- $L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ (LHCb specific)
Rapidity Range

LHCb

ATLAS

CMS

ALICE

tracking, ECAL, HCAL, counters lumi, muon, hadron PID
LHC running well, all experiments have an efficiency $\approx 90\%$

Already more than 3 pb$^{-1}$ on tape

These analyses:
$L \approx 9\text{–}100 \text{ nb}^{-1}$

Goals:
- 1 pb$^{-1}$ (August 2010)
- 100 pb$^{-1}$ (end of 2010)
- 1 fb$^{-1}$ (end of 2011)
The production mechanism in pp collisions still unclear

Several models around:

- Color singlet and color octet mechanisms (NRQCD) describe the $p_T$ spectrum and cross section of the $J/\psi$ as measured by Tevatron, but not the polarization (and has other failures)
- Other models such as color evaporation model, $k_t$ factorization, soft color interaction model cannot describe the data either

New data from LHC experiments will help to resolve this issue

$J/\psi$ cross section crucial milestone in understanding detector and first step to B cross section measurement
**J/ψ Production**

In this experiment, we observed the production of J/ψ mesons using a setup with approximately 10^6 points. The acceptance was ±1°, ±2°, enabling us to select events from 1 to 5 GeV in the mass region.

FIG. 2. Mass spectrum showing the existence of J.
Production

\( J/\psi \) Production

PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

242 Events

SPECTROMETER

\( \Delta \theta = \pm 1^\circ \), \( \Delta \varphi = \pm 2^\circ \)

0.01 0.02 0.03 0.04 0.05

 EVENTS / 25 MeV

\( m_{e^+e^-} \) [GeV]

FIG. 2. Mass spectrum showing the existence of \( J \).
## J/ψ Production at pp

<table>
<thead>
<tr>
<th>1st step</th>
<th>2nd step</th>
<th>3rd step</th>
<th>Production type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to c\bar{c}, b\bar{b} + X$</td>
<td>$c\bar{c} \to J/\psi + X$</td>
<td>$\chi_c \to J/\psi + \gamma$</td>
<td>Prompt,direct</td>
</tr>
<tr>
<td></td>
<td>$c\bar{c} \to \chi_{c1}, \chi_{c2} + X$</td>
<td>$B \to J/\psi + X$</td>
<td>Prompt,indirect</td>
</tr>
<tr>
<td></td>
<td>$b\bar{b} \to B + X$</td>
<td></td>
<td>Delayed,indirect</td>
</tr>
</tbody>
</table>

### Production at pp

**Prompt J/ψ at LHC**

LO color singlet+color octet

$\sqrt{s}=10$ TeV

**LHCb MC samples (unpolarised J/ψ)**

Pythia 6.4

$\sqrt{s}=7$ TeV

$10^\circ<\theta<400$ mrad

**BR(\(J/\psi \to \mu\mu\)) \approx 6\%**

4.10.2010

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**J/ψ Acceptance**

- **Total Acceptance**: $\approx 13\%$ for LHCb
  - LHCb Acceptance: 85%
- **Total Acceptance**: $\approx 20\%$ for CMS
- **Total Acceptance**: $\approx 2\%-8\%$ for ATLAS
  - ATLAS Acceptance: 80%
  - ATLAS Acceptance: 85%

(Absolute) $J/\psi$ rapidity

$y_{J/\psi}$

$P_T^{J/\psi}$ (GeV/c)

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$J/\psi \rightarrow \mu\mu$ mass distribution

**ALICE**

- Target: $\sigma = 70$ MeV/c$^2$
  - (half in ee channel)
- With high purity muons: $\sigma = 29$ MeV/c$^2$

**LHCb**

- Most recent plots $\sigma \approx 13$ MeV/c$^2$

**CMS**

- CMS Preliminary, $\sqrt{s} = 7$ TeV
  - $L_{\text{int}} = 100$ nb$^{-1}$
- $|y| < 1.4$
- $\sigma = 30$ MeV/c$^2$
- $\sigma = 70$ MeV/c$^2$

**Event Rates**

- $J/\psi$ rate $\approx 300$/nb$^{-1}$
- $\sigma = 70$ MeV/c$^2$

**Data Observed**

- $\sigma_{ee} = 91 \pm 9$ MeV
- $|y| < 1.4$
target: $\sigma = 70$ MeV/c$^2$

**Other Experiments**

- CMS
- ATLAS
- ALICE

**References**

- 4.10.2010
- Giulia Manca
Inclusive cross section measurements

**ALICE**

$pp \rightarrow J/\psi + X$, $\sqrt{s}=7$ TeV

$2.7<y<3.8$

**CMS**

$\sqrt{s}=7$ TeV

$L=100$ nb$^{-1}$

**LHCb**

$\sqrt{s}=7$ TeV

$L=14.2$ nb$^{-1}$

$2.5<y<4$

**ATLAS**

$L_{u/d}=9.5$ nb$^{-1}$

$1.50<|y|<2.25$

$0.75<|y|<1.50$

$0.00<|y|<0.75$
Cross section measurements

Inclusive J/ψ

LHC $\sqrt{s} = 7$ TeV
Preliminary

CMS 100 nb$^{-1}$ $1.4 < |y| < 2.4$
ATLAS 17.5 nb$^{-1}$ $1.5 < |y| < 2.25$
LHCb 14.2 nb$^{-1}$ $2.5 < y < 4.0$
ALICE scaled $2.7 < y < 3.8$

BR(J/ψ → µ+µ−)$ \times \frac{dσ}{dy dp_T}$ [nb/(GeV/c)$^2$]
**J/ψ proper time/decay length**

\[ t_z = \Delta z / p_z \times M_{J/\psi} \]

→ \( t_z \) used to separate \( J/\psi \) prompt from \( J/\psi \) from \( B \)

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**LHCb**

- **Preliminary**
- \( \sqrt{s} = 7 \text{ TeV Data} \)
- \( L = 14.2 \text{ nb}^{-1} \)

**ATLAS**

- **Preliminary**
- \( L_{\text{int}} = 17.5 \text{ nb}^{-1} \)

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**CMS**

- \( \ell = 7 \text{ TeV Data} \)

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Non prompt $J/\psi$

LHC $\sqrt{s} = 7$ TeV
Preliminary

- CMS $100$ nb\textsuperscript{-1} $1.4 < |y| < 2.4$
- CMS $100$ nb\textsuperscript{-1} $|y| < 1.4$
- LHCb $14.2$ nb\textsuperscript{-1} $2.5 < y < 4.0$
- ATLAS $17.5$ nb\textsuperscript{-1} $|y| < 2.25$

- CDF $\sqrt{s} = 1.96$ TeV $|y| < 0.6$

PRD 71 (2005) 032001
Influence of J/ψ Polarisation

- Detector acceptance as a function of helicity angle $\cos \theta$

Example: helicity frame

$\mu^-$

J/ψ rest frame

$\mu^+$

J/ψ - lab virtual flight direction

MC with no polarisation: LHCb

Acceptance generates an artificial polarisation

$\Rightarrow$ large influence of polarisation on measurement

$\Rightarrow$ First step: Treat polarisation as systematic error; present results in three different polarisation scenarios
Different polarisation scenarios

LHCb

CMS

ATLAS

LHCb Preliminary
$s = 7$ TeV
$L = 14.2 \text{ nb}^{-1}$

Up to 20%

CMS $\sqrt{s} = 7$ TeV
Preliminary, $L = 100 \text{ nb}^{-1}$

$|y| < 1.4$

$11\%$ global uncertainty

Preliminary, $L = 100 \text{ nb}^{-1}$

$1.4 < |y| < 2.4$

$11\%$ global uncertainty

ATLAS Preliminary
$L = 9.5 \text{ nb}^{-1}$

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## Integrated cross section measurements

| Experiment Range Luminosity | LHCb (in µb) pT<10 GeV, 2.5<y<4 14.2 nb\(^{-1}\) | CMS (in nb) 4<pT<30 GeV, |y|<2.4 100 nb\(^{-1}\) | ATLAS (in nb) <y>~1.85 100 nb\(^{-1}\) |
|-----------------------------|--------------------------------------------------|--------------------------|--------------------------|--------------------------|
| Inclusive J/ψ              | 7.65 ± 0.19 ± 1.10\(^{+0.87}_{-1.27}\)           | 289.1 ± 16.7 ± 60.1      | 250\(^{+130}_{-80}\)     |
| J/ψ from B                 | 0.81 ± 0.06 ± 0.13                               | 56.1 ± 5.5 ± 7.2         |
| Total bb*                  | 319 ± 24 ± 59                                   |                          |

* Extrapolating to the LHCb acceptance using Pythia 6.4
LHC is in great shape and all experiments are taking data with high efficiency.

All the analysis tools are in place and start to deliver physics results.

J/ψ events clearly reconstructed:

- Crucial standard candle for detector understanding as well as cross check of luminosity.
- Cross section measurements probe of non-relativistic QCD theories.
- Results in four experiments compatible. Publications expected by the end of the year (with 2-5 pb⁻¹).

Polarisation measurement next.
Back-up
Inclusive cross section measurements

- Extrapolations with PYTHIA 6.4 (LEP hadronization fractions assumed)
  1. $\frac{1}{2}$ production cross section for $b$ or $b$ in LHCb acceptance

$$\frac{\sigma(pp \to H_bX, 2 < \eta(H_b) < 6)}{2} = 84.5 \pm 6.3 \pm 15.6 \mu b$$

- Total $bb$ production cross section

$$\sigma(pp \to b\bar{b}X) = 319 \pm 24 \pm 59 \mu b$$

An independent $\sigma( bb)$ measurement by LHCb with results in excellent agreement. Averaging:

$$\frac{\sigma(pp \to H_bX, 2 < \eta(H_b) < 6)}{2} = 77.4 \pm 4.0 \pm 11.4 \mu b$$

$$\sigma(pp \to b\bar{b}X) = 292 \pm 15 \pm 43 \mu b.$$

$$\frac{\sigma(pp \to H_bX, 2 < \eta(H_b) < 6)}{2} = 88.3\pm4.5\pm13.0 \mu b$$

$$\sigma(pp \to b\bar{b}X) = 333\pm17\pm49 \mu b.$$

LEP b hadronization fractions

TeVatron b hadronization fractions
$J/\psi \rightarrow ee$ mass distribution

\begin{align*}
\Delta m_{\text{mass}} &= 109.0 \pm 9.6 \text{ MeV/c}^2 \\
M_{J/\psi} &= 3070.4 \pm 9.1 \text{ MeV/c}^2 \\
N_{\text{sig}} &= 931 \pm 77
\end{align*}

LHCb Preliminary
$\sqrt{s} = 7 \text{ TeV Data}$

$\text{ALICE}$
ALICE Performance
June 1st, 2010

$N_{\text{signal}} = 59 \pm 9$
Significance $= 6.72 \pm 1.14$
$S/B = 3.22 \pm 1.62$
Mass $= 3.076 \pm 0.009 \text{ GeV/c}^2$
width $= 51 \pm 10 \text{ MeV/c}^2$
**J/ψ proper time/decay length**

Data Observed

$t_z$ used to separate J/ψ prompt from J/ψ from B

![Graph showing the distribution of events vs. $t_z$](image1)

-LHCb Preliminary
\(\sqrt{s} = 7 \text{ TeV Data} \)
L = 260 nb \(^{-1}\)

![Graph showing the distribution of events vs. $t_\psi$](image2)

-CMS Preliminary \(\sqrt{s} = 7 \text{ TeV} \)
\(L_{\text{int}} = 100 \text{ nb}^{-1}\)
-7 TeV data
-Combined fit
-Signal component
-Background component

-ATLAS Preliminary
\(L_{\text{int}} = 17.5 \text{ nb}^{-1}\)

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Performance numbers relevant to quarkonium analyses:
- Charged tracks $\Delta p/p = 0.35\% - 0.55\%$, $\sigma(m)=10-25$ MeV/c$^2$
- ECAL $\sigma(E)/E= 10\% (E/\text{GeV})^{-1/2} \pm 1\%$
- Muon ID: $\varepsilon(\mu \rightarrow \mu) = 97\%$, mis-ID rate ($\pi \rightarrow \mu$) = 1-3 \%
- Vertexing: proper time resolution 30-50 fs
- Trigger: dominantly software

possibility to reverse field polarity to check for detector asymmetries
Measure muon trigger efficiencies using trigger lines not involving muons

LO x HLT1 Efficiency $J/\psi \rightarrow \mu\mu$
Muon Reconstruction Efficiency

Muon

Reconstruction Efficiency

\[ \epsilon (\mu) = 97.3 \pm 1.2 \% \]

J/ψ → µµ

μ tag

μ probe

J/ψ used to measure the Muon reconstruction efficiency

LHCb
Preliminary
\( \sqrt{s} = 7 \text{ TeV Data} \)

\[ \sigma = 15.25 \pm 0.45 \text{ MeV}/c^2 \]
\[ N_{\text{bkg}} = 1840 \pm 19 \]
\[ N_{\psi} = 2648 \pm 68 \]
\[ m_\psi = 3089.40 \pm 0.45 \text{ MeV}/c^2 \]
\[ t_{11} = -0.0011656 \pm 0.000079 \]
Muon mis-identification

This plots shows the probability to misidentify a pion from Ks and a proton from Lambda as a muon as a function of momentum.