Charmonium, open charm and beauty production at HERA-B

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HERA-B detector and physics topics
results and comparison with previous experiments

**outline**

- **J/ψ production**
  - $p_T$ and $x_F$ distributions, $A$-dependence
  - **new: decay angular distributions**

- **heavier states and feeddown to J/ψ**
  - $ψ'/ψ$ and kinematics
  - fraction of $J/ψ$’s from $χ_c$
  - fraction of $J/ψ$’s from $b$ decays

- **charm**
  - inclusive $D^0, D^+, D^{*+}$ and ratios
  - $A$-dependence

**first data at negative $x_F$**

**highest energy among fixed-target experiments**

**often unclear experimental picture, especially for p-A collisions**

**observation of low-$p_T/|x_F|$ effects**

**largest $χ_c$ statistics analyzed in hadron collisions**

**test production models (pQCD + initial/final state interactions in nuclei)**
**the HERA-B detector**

**large acceptance**
(15-220 mrad)

**high resolution**

**good PID**
($e^\pm, \mu^\pm, \pi, K, p$) + photon reconstruction

**fixed nuclear target**

\[ \sqrt{s} = 41.6 \text{ GeV} \]
\[ A = 12 \div 184 \]

**Tracking**

**Vertex Detector**

**MUON**

**RICH**

**ECAL**

**920 GeV/c protons**

**electrons**

**target wires**
(C, Ti, W)

(top view)
**physics at HERA-B**

**dilepton trigger: \( \sim 150 \cdot 10^6 \) events**

- \( J/\psi, \chi_c, \psi' \), with \( A \)-dependence
- \( D^o \rightarrow \mu^+\mu^- \) (FCNC)
- **inclusive b production**
- \( \Upsilon, \phi, \rho/\omega \)

\[ \begin{array}{c}
\text{entries (a.u.)} \\
\hline
0.4 & 0.8 & 1.2 & m_{\mu\mu} \text{ [GeV/c}^2]\hline
\text{entries (a.u.)} \\
2.5 & 3.0 & 3.5 & 4.0 & 4.5 & m_{ee} \text{ [GeV/c}^2]\hline
\text{entries (a.u.)} \\
6 & 7 & 8 & 9 & 10 & 11 & 12 & m_{\mu\mu} \text{ [GeV/c}^2]\hline
\end{array} \]

\[ \begin{array}{c}
\rho/\omega & \phi & J/\psi & \gamma(1S) & \gamma(2-3S) \\
\mu^+\mu^- & e^+e^- & \psi' & \mu^+\mu^- & \\
\end{array} \]

**\( \sim 210 \cdot 10^6 \) minimum bias events**

- \( K_s, K^*, \Lambda, \phi, \Xi^{++} \)
- pentaquarks
- \( D^o, D^+, D^{*+}, D_s \)
- \( J/\psi \)

**‘hard photon’ trigger: \( \sim 35 \cdot 10^6 \) events**

- direct \( \gamma, \pi^0, \eta \)
- production with four different nuclei

\[ \begin{array}{c}
\text{MinBias data, run 20478} \\
\text{HP trigger, run 20595} \\
\end{array} \]

\[ \begin{array}{c}
pC \rightarrow \gamma X \\
E_T \text{ [GeV]} \\
\end{array} \]
**J/ψ and ψ’ signals**

**full dilepton data sample (3 target materials)**

\[ \text{e}^+\text{e}^- \]

\[ \text{μ}^+\text{μ}^- \]

\[ \sim 120\,000 \text{ J/ψ} \]
\[ \sim 2\,200 \text{ ψ’} \]
\[ \sigma_{J/ψ} \sim 64 \text{ MeV} \]

\[ \sim 170\,000 \text{ J/ψ} \]
\[ \sim 3\,000 \text{ ψ’} \]
\[ \sigma_{J/ψ} \sim 44 \text{ MeV} \]
**J/ψ production kinematics: \( p_T \) distribution**

**Preliminary data** (di-electron channel). Compatible results from the di-muon data, not shown here.

[Graph showing \( \frac{d\sigma}{dp_T^2} \) as a function of \( p_T \) with data points for different nuclei.]  

Comparison with \( p-A \) results at similar energy (\( \sqrt{s} = 38.8 \) GeV)

Increase of \( \langle p_T \rangle \) with \( A \)
**$x_F$ distribution**

**Preliminary data** ($e^+e^-$), compared with $p$-$A$ results at 38.8 GeV

First data centred at negative $x_F$
 Models (with variants):

**HERA-B preliminary**
(di-muon channel, carbon+tungsten double-wire runs)
errors statistical only

**Vogt: final state absorption**

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**Models (with variants):**

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(di-muon channel, carbon+tungsten double-wire runs)
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**Vogt: final state absorption**
decay angular distribution: polarization frames

direction of $e^+(\mu^+)$ as seen in the $J/\psi$ rest frame

\[ \theta \]

- **target direction** in the $J/\psi$ rest frame = $(-)J/\psi$ direction in the lab frame
- **beam direction** in the $J/\psi$ rest frame
- **$J/\psi$ direction** in the hadron (p-n) CM frame

**1) Collins-Soper ("CS")**
- bisector between beam and $(-)$target directions in the $J/\psi$ rest frame
- reformulated as helicity "HCM"

**2) "BEAM"**
- E615, E672-706, E771, E537, etc.

**3) helicity "HCM"**
- E866, NA3, etc.

Il Nuovo Cimento Vol. XXXIII, N. 2 (1964)
- Gottfried-Jackson ("GJ")

- E771, E537, etc.
- CDF, NA60, etc.

reformulated as
\[
\frac{dN}{d\varphi} \propto 1 + \frac{2\lambda_\varphi}{3 + \lambda_\theta} \cos 2\varphi
\]

example: \(\lambda_\varphi > 0\)

\[
\frac{dN}{d(\cos \theta)} \propto 1 + \lambda_\theta \cos^2 \theta
\]

example: \(\lambda_\theta < 0\)

\[
\frac{dN}{d(\cos \theta) d\varphi} \propto 1 + \boxed{\lambda_\theta \cos^2 \theta} + \boxed{\lambda_\theta \varphi \sin 2\theta \sin \varphi} + \boxed{\lambda_\varphi \sin^2 \theta \cos 2\varphi}
\]

(x axis \(\perp\) reaction plane)
$\lambda_{\varphi}$ vs. $\langle p_T \rangle$ (GeV/c) for different experiments:

- **HB**: 41.6 GeV, $p$-C/Ti/W
- **NA3**: 22.9 GeV, $p$-Pt/$p$-$H_2$
- **E615**: 21.8 GeV, $\pi^{\pm}$-$W$
- **E537**: 15.4 GeV, $p$-$Be/\pi$-$Be$, $p$-$Cu/\pi$-$Cu$

The graph shows the distribution of $\lambda_{\varphi}$ for different values of $\langle p_T \rangle$ and $\langle x_F \rangle$. The data points are color-coded for different experiments and inclusive reactions.
The "natural" polarization frame has $\lambda_{\theta\phi}$ equal to zero: in such frame the decay distribution is symmetric and is described by only two parameters.

$\lambda_{\theta\phi} \neq 0$ means that the axes of the current frame are not principal axes of symmetry for the angular distribution.

But it is always possible to define a reference frame with this property: the angular distribution can always be diagonalized to a form with $\lambda_{\theta\phi} = 0$. 
\( \lambda_{\theta \phi} \) in the three frames

preliminary, \( \mu^+ \mu^- + e^+ e^- \)

- The three frames actually see the decay kinematics from different perspectives
- \(|\lambda_{\theta \phi}| \lesssim \left| \lambda_{\theta \phi} \right|, \lambda_{\theta \phi} \mid \Rightarrow \text{CS the best frame?} \)
$\lambda_\theta$ and the hierarchy of frames

$$\frac{dN}{d(cos\theta)} \propto 1 + \lambda_\theta \cos^2\theta$$

preliminary

HCM (arb. norm.)

BEAM (arb. norm.)

CS

$\lambda_\theta$

preliminary

HCM BEAM CS

$|\lambda_\theta|$ > $|\lambda_\theta|$ > $|\lambda_\theta|$
The data are consistent (for example) with a polarization generated in the CS frame, and translated into the HCM frame. The CS frame is the best approximation of the “natural” polarization frame.

\[ \lambda_\theta = -1 \cdot \exp\left[-p_{J/\psi}^{CM}/(2\text{GeV}/c)\right] \]

No hypothesis of generation in the HCM frame can reproduce the data in the CS frame.
**experimental situation: CS frame**

$J/\psi$ significantly polarized at low momentum (low $p_T$ and $|x_F|$)
\[ \lambda_\theta \]

\[ \langle x_F \rangle \]

\[ \langle p_T \rangle \text{ (GeV/c)} \]

**BEAM frame**

- WA11 16.8 GeV π⁻-Be
- E672 31.1 GeV π⁻-Be
- /706 31.6 GeV p-Be
- E537 15.4 GeV p⁻-W/π⁻-W
- E771 38.8 GeV p⁻-Be
- E615 21.8 GeV π⁺⁻-W
- HB 41.6 GeV p⁻-C/Ti/W
polarization almost completely smeared out, except for $p_T$ very close to zero
$\psi'$-to-$J/\psi$ production ratio

Analysis finished. Combined results ($e^+e^- + \mu^+\mu^-$):

$$\rho_{\psi'}^{e^+e^-} = \frac{B_{\psi' \rightarrow \ell^+ \ell^-} \sigma_{\psi'}}{B_{J/\psi \rightarrow \ell^+ \ell^-} \sigma_{J/\psi}} = \begin{cases} 1.63 \pm 0.08 \% \text{(C)} \\ 1.99 \pm 0.26 \% \text{(Ti)} \\ 1.62 \pm 0.11 \% \text{(W)} \end{cases}$$

$$R_{\psi'} = \rho_{\psi'} \times \frac{B_{J/\psi \rightarrow \ell^+ \ell^-}}{B_{\psi' \rightarrow \ell^+ \ell^-}} \cdot B_{\psi' \rightarrow J/\psi^{\pi^+ \pi^-}} \cdot B_{J/\psi^{\pi^0 \pi^0}}$$

= $(7.0 \pm 0.2 \pm 0.4_{BRs})\%$

$p$-$A$ results consistent within a 4% variation:

- no apparent dependence on production energy and kinematics (different $x_F/y$, $\cos \theta$ windows)
- slight dependence on the target nucleus: NA38/50/51 (+ E866)
$\psi'$ kinematics

measured relative to the $J/\psi$ distributions: $B'\sigma(\psi')/B\sigma(J/\psi)$ as a function of $x_F$, $p_T$, $\cos\theta$

HERA-B (full stat, $e^+e^-/\mu^+\mu^-$ avg.)
E789 (38.8 GeV)
E771 (38.8 GeV)
NA50 (29.1 GeV)

$\lambda_\theta(\psi') - \lambda_\theta(J/\psi) = 0.23 \pm 0.17$
\( \chi_c \) production

selection:

\[
\chi_c \rightarrow J/\psi \gamma \left\{ e^+ e^- \right. \left. \mu^+ \mu^- \right\}
\]

measurement:

- fraction of \( J/\psi \)'s from \( \chi_c \):
  \[
  R_{\chi c} = \frac{\sum \sigma(\chi_{c(i)} \rightarrow J/\psi \gamma)}{\sigma_{\text{INCL}}(J/\psi)}
  \]
- kinematical distributions
- \( A \)-dependence

from the 2000 data, with

\[
370 \pm 74 \ \chi_c \text{'s} (\mu^+ \mu^- + e^+ e^-):
R(\chi_c) = 0.32 \pm 0.06 \pm 0.04
\]


**new data:** 40× bigger \( \chi_c \) statistics

(the largest analyzed in a hadronic experiment)
preliminary evaluation
(2002/2003 data):

(21 ± 5)% of the produced
J/ψ’s come from χc decays
based on 1300 χc’s
reconstructed in the di-muon channel
(less than 10% of the total statistics)
$pA \rightarrow b\bar{b} \ X$

$b \rightarrow J/\psi \ Y \rightarrow e^+e^-/\mu^+\mu^- \ Y$

$$R_b = \frac{N(J/\psi \leftarrow b)}{N_{\text{TOT}}(J/\psi)} = (0.065 \pm 0.011)\%$$

- extrapolation to full $x_F$ range
- normalization by total $J/\psi$ cross sect.
- correction by BR of $b \rightarrow J/\psi$

$\sigma(b\bar{b}) = 14.9 \pm 2.2_{\text{stat}} \pm 2.4_{\text{syst}} \ \text{nb/nucleon}$

[Phys. Rev. D 73, 052005]

**HERA-B**

N. Kidonakis *et al.*

**E789**

**E771**

R. Bonciani *et al.*
indirect and direct $J/\psi$ production

Using partial/preliminary HERA-B results:

$(21 \pm 5)\%$

$(7.0 \pm 0.4)\%$

$(0.065 \pm 0.011)\%$

\[
\sigma_{\text{DIR}}^{J/\psi} = \sigma_{\text{INCL}}^{J/\psi} \left[ 1 - R \left( \chi_c \rightarrow J/\psi \right) - R \left( \psi' \rightarrow J/\psi \right) - R \left( b \rightarrow J/\psi \right) - \ldots \right]
\]

\[
\sigma_{pN}^{J/\psi}[41.6 \text{ GeV}] = (663 \pm 74_{\text{stat}} \pm 46_{\text{syst}}) \text{nb/nucl}
\]

extracted from MB data

$(72 \pm 5)\%$ of the $J/\psi$'s are produced directly

curve: NLO NRQCD fit of all data

(Maltoni et al., hep-ph/0601203)
**open charm: reconstructed signals**

- **$D^0 + \overline{D}^0$**
  - Preliminary
  - $194 \pm 20$

- **$D^\pm$**
  - Preliminary
  - $92 \pm 11$

- **$D^{*\pm}$**
  - Preliminary
  - $49 \pm 10$

- **$m(K\pi) - m(D^0) < 50\text{ MeV}$**
- **$m(K\pi) - m(D^0) > 50\text{ MeV}$**
**D cross sections**

**comparison with p-p/p-A results**

- **D±**
  - HERA-B prel.
  - E653
  - E743
  - E769
  - NA16
  - NA27
  \[ \chi^2/5 = 0.03 \]

- **D*±**
  - HERA-B prel.
  - E769
  - NA27
  \[ \chi^2/2 = 0.51 \]

- **D0 + D0**
  - HERA-B prel.
  - E653
  - E743
  - E789
  - NA16
  - NA27
  - without E789: \[ \chi^2/5 = 0.8 \]
  - with E789: \[ \chi^2/6 = 4.1 \]

- **D0**: unclear situation at high \( \sqrt{s} \)
  - E789 result clearly disfavoured

- **energy dependence** well described in each case by the function
  \[
  \sigma_D \propto \left[ 1 - 1.2 / (\sqrt{s})^{0.35} \right]^{12}
  \]
reflecting the behaviour of proton PDFs (Lourenço & Wöhri)
cross section ratios: experiments vs. isospin symmetry

isospin symmetry

\[ \sigma_{\text{DIR}}(D^0) = \sigma_{\text{DIR}}(D^+) = \frac{1}{3} \sigma(D^*) \]

3 polar. states

PDG averages for \( D^{*0}, D^{*\pm} \to D^0, D^\pm \) feeddown BRs

\[ \frac{\sigma_{\text{INCL}}(D^{\pm})}{\sigma_{\text{INCL}}(D^0)} = 0.326 \pm 0.003 \]

violated by a factor of \( 1.87 \pm 0.25 \)

\[ \frac{\sigma_{\text{INCL}}(D^{*\pm})}{\sigma_{\text{INCL}}(D^0)} = 0.497 \pm 0.001 \]

experiments

\[ \text{avg. } D^{\pm}/D^0 = 0.61 \pm 0.08 \]

\[ \text{avg. } D^{*\pm}/D^0 = 0.43 \pm 0.09 \]

\[ \chi^2/5 = 0.30 \]

\[ \chi^2/2 = 0.49 \]
**A-dependence**

mass spectra by target material (e.g. for $D^0$):

- $\alpha(D^0) = 0.92 \pm 0.08$
- $\alpha(D^\pm) = 1.02 \pm 0.09$
- $\alpha(D^{*\pm}) = 1.05 \pm 0.14$

**Experimental situation ($p-A$):**

- $\alpha_{AVG}(x_F \sim 0) = 1.01 \pm 0.03$

consistent with no suppression

curves: $\sigma_{pA} = \sigma_{pN} \cdot A^\alpha$
J/ψ production in p-A collisions at $\sqrt{s} = 41.6$ GeV ...

- high statistics, clean signals, two decay channels
- wide kinematical coverage
  - $p_T$ up to 5.5 GeV/c
  - negative $x_F$
- A-dependence:
  - flat suppression
    down to $x_F \sim -0.35$

J/ψ decay angular distributions

- longitudinal polarization rapidly increasing in magnitude with decreasing $p_T$ and $|x_F|$
- strong hierarchy of frames: the direction of the original interaction (CS frame) is better than the J/ψ “flight” direction (HCM) as a reference for the observation of the “true” decay distribution

open charm

- $D^0$, $D^\pm$, $D^{*\pm}$ inclusive production cross sections and ratios
- A-dependence consistent with $\alpha = 1$