Study of $p\bar{p} \rightarrow \chi_{c1,2} \rightarrow J/\psi\gamma$

Elisa Fioravanti

INFN Ferrara

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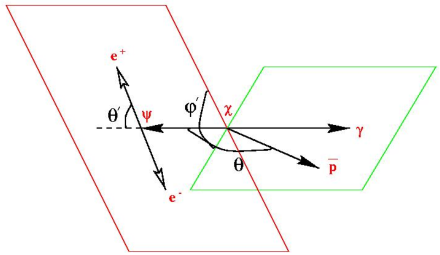
χ_{c1} and χ_{c2} angular distributions



- θ is the polar angle of the J/ψ with respect to the antiproton in the $\overline{p}p$ center of mass system
- θ' is the polar angle of the positron in the J/ψ rest frame with respect to the J/ψ direction in the χ rest of mass system
- ϕ' is the azimuthal angle between the J/ψ decay plane and the χ_c plane

$\overline{p}p \longrightarrow \chi_1 \longrightarrow J/\psi\gamma$

- Production amplitudes: $B_0 = 0$
- Decay Amplitudes: a_2
  $a_2 = 0.002 \pm 0.032 \pm 0.004$

$\overline{p}p \longrightarrow \chi_2 \longrightarrow J/\psi\gamma$

- Production amplitudes: B_0^2
  $B_0^2 = 0.16^{+0.09}_{-0.10} \pm 0.01$
- Decay Amplitudes: a_2, a_3
  $a_2 = -0.076^{+0.054}_{-0.050} \pm 0.009$
  $a_3 = 0.020^{+0.055}_{-0.044} \pm 0.009$

* E835 Collaboration, Nucl. Phys. B 717, 34 (2005)

$\bar{p}p \to \chi_{1,2} \to J/\psi\gamma \to \ell^+\ell^-\gamma$

Cross section

$$\sigma(\chi_{c1} \to J/\psi\gamma) \sim 1.7 \text{ nbarn}$$
$$\sigma(\chi_{c2} \to J/\psi\gamma) \sim 2 \text{ nbarn}$$

E835 Collaboration, Nucl. Phys. B 717, 34 (2005)

Background: $\bar{p}p \to \pi^+\pi^-\pi^0$: $\sigma(\chi_{c2})$=0.12 mb

CERN-HERA 70-03 (1970)

- Fast Simulation
- $J/\psi \to e^+e^-$; $J/\psi \to \mu^+\mu^-$
- PID for Electrons: 1 Electron Loose; 1 Electron Tight (as in the Physics Book)
- PID for Muons: 1 Muon Loose; 1 Muon Tight (as in the Physics Book)
- PID for Photons: Neutral
- Bremsstrahlung effect for the electrons
- MC Truth Match
- 10.000 events generated
- Decay model: $\chi_{c1,2} \to J/\psi\gamma$: Chic1toJpsiGam
- Decay model: $J/\psi \to \ell^+\ell^-$: VLL

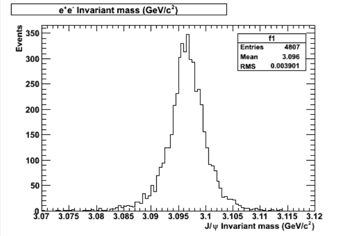
4C fit is performed and best χ_{c1} candidate in each event is selected by minimal χ^2

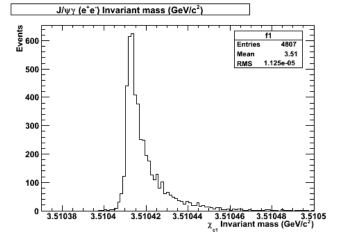
$\overline{p}p \to \chi_{c1} \to J/\psi\gamma \to \ell^+\ell^-\gamma$

$$\overline{p}p \to \chi_{c1} \to J/\psi\gamma \to \ell^+\ell^-\gamma$$

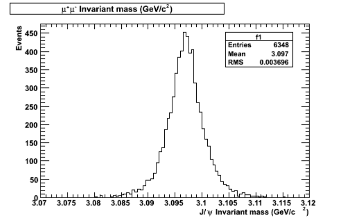
Invariant mass distributions

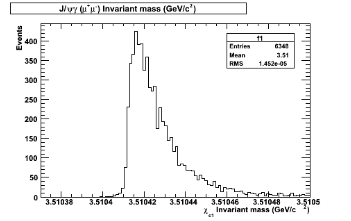
$J/\psi \rightarrow e^+e^-$





$J/\psi \rightarrow \mu^+\mu^-$



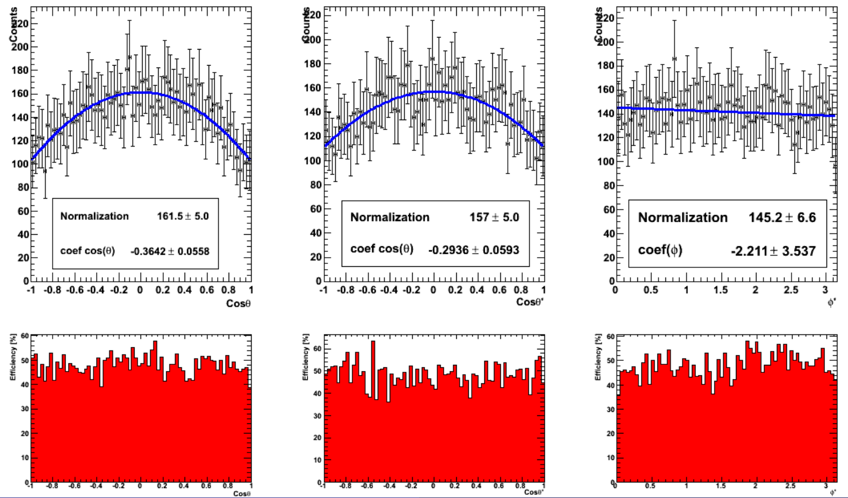


Efficiency ($J/\psi \rightarrow e^+e^-$): 48.1%; Efficiency ($J/\psi \rightarrow \mu^+\mu^-$): 63.5%

Angular distributions for $J/\psi \to e^+e^-$

The angles distributions corrected with the efficiency, which is presented in the lower part. The angular distributions for the three angles can be approximately written as:

$$W(cos\theta) = 1 - \frac{1}{3}cos^2\theta; \quad W(cos\theta') = 1 - \frac{1}{3}cos^2\theta'; \quad W(\phi) = \text{flat}$$



Angular distributions for $J/\psi \to \mu^+\mu^-$

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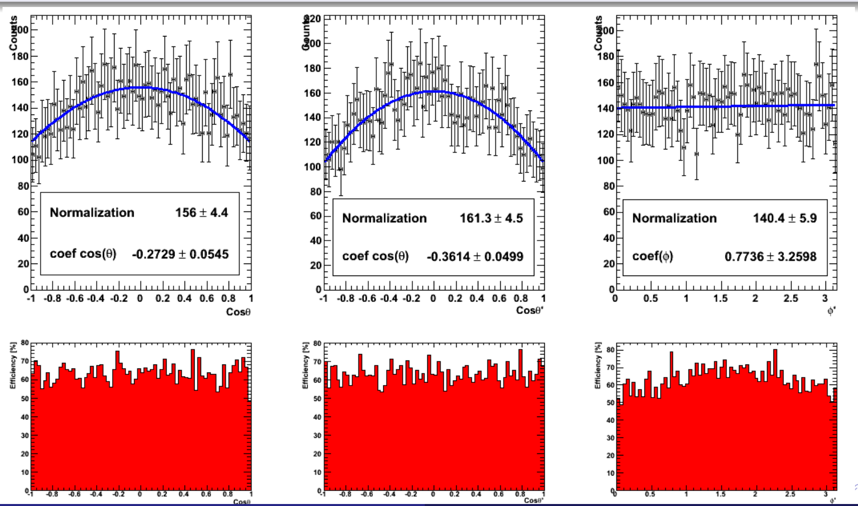

$\overline{p}p \rightarrow \chi_{c2} \rightarrow J/\psi\gamma \rightarrow \ell^+\ell^-\gamma$

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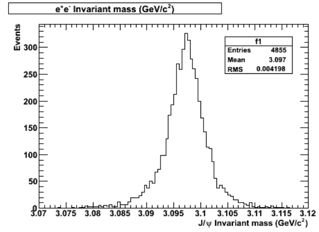
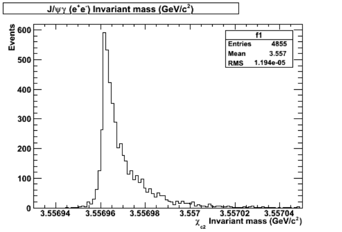
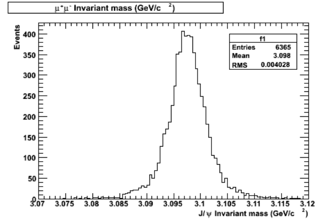
Invariant mass distributions

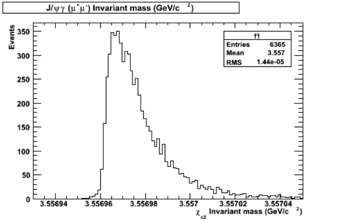
$J/\psi \to e^+e^-$





$J/\psi \to \mu^+\mu^-$





Efficiency ($J/\psi \to e^+e^-$): 48.6%; Efficiency ($J/\psi \to \mu^+\mu^-$): 63.7%

Angular distributions for $J/\psi \to e^+e^-$

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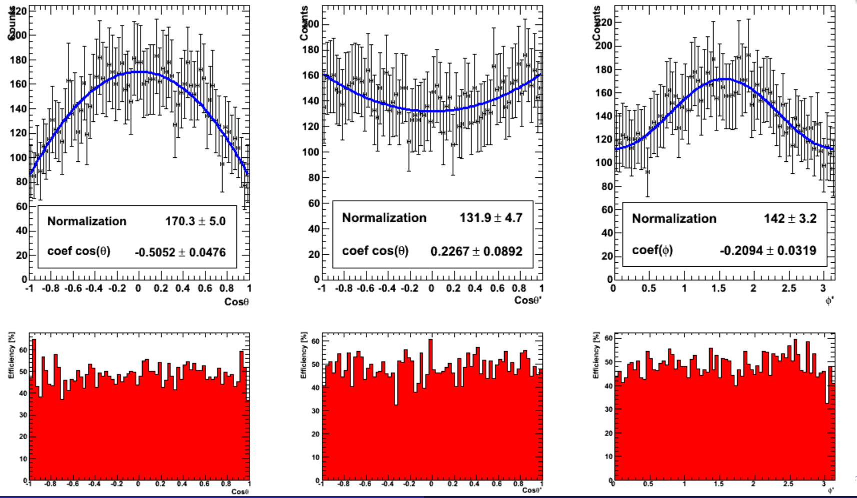
$$W(cos\theta) = 1 - \frac{1}{3}cos^2\theta; \quad W(cos\theta') = 1 - \frac{1}{3}cos^2\theta'; \quad W(\phi') = 1 - \frac{8}{71}cos(2\phi')$$



Angular distributions for $J/\psi \to \mu^+\mu^-$

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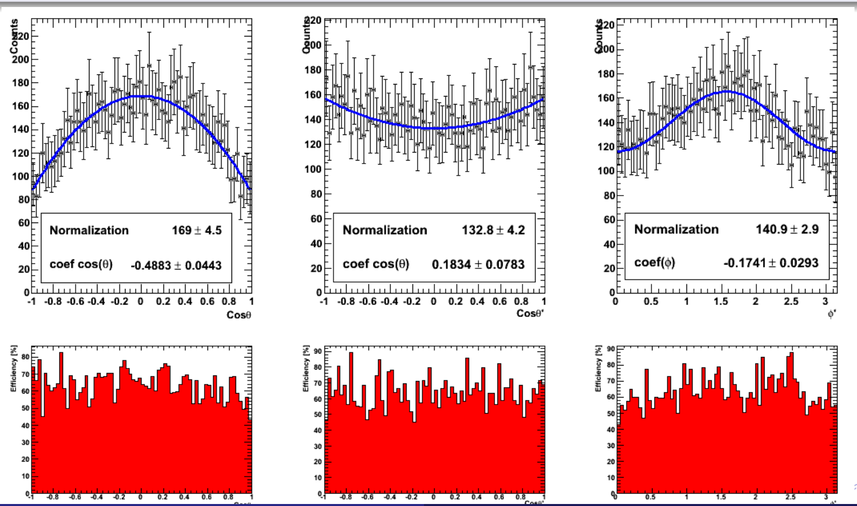


Summary

$\chi_{cj} \to J/\psi\gamma$

- The angular distributions have been implemented in EvtGen
- The selection is in good shape.
- The reconstruction efficiency is:
  - $\sim$48% for $J/\psi \to e^+e^-$ (45% in the physics book)
  - $\sim$63% for $J/\psi \to \mu^+\mu^-$
- Next step: background studies

$X8372) \to J/\psi\pi\pi$

- I'm starting, I hope to show you the results the next week.

BACK-UP SLIDES

Radiative transitions of the χ_{cJ} charmonium states

The measurement of the angular distributions in the radiative decays of the χ_c states provides the multipole structure of the radiative decay and the properties of the $\overline{c}c$ bound state.

$$\overline{p}p \to \chi_c \to J/\psi\gamma \to e^+e^-\gamma$$

dominated by the dipole term E1.
M2 and E3 terms arise in the relativistic treatment of the interaction between the electromagnetic field and the quarkonium system. They contribute to the radiative width at the few percent level.
The angular distribution of the χ_1 and χ_2 are described by 4 indipendent parameters:

$$a_2(\chi_{c1}), a_2(\chi_{c2}), B_0^2(\chi_{c2}), a_3(\chi_{c2})$$

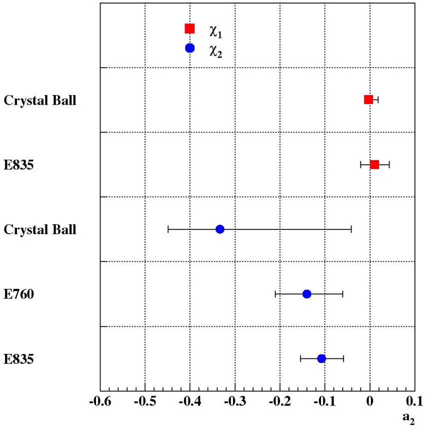
Angular distribution of the χ_{cJ} states

- The coupling between the set of χ states and $\bar{p}p$ is described by four indipendent helicity amplitudes:
  - χ_0 is formed only through the helicity 0 channel
  - χ_1 is formed only through the helicity 1 channel
  - χ_2 can couple to both
- The fractional electric octupole amplitude, $a_3 \approx E3/E1$, can contribute only to the χ_2 decays, and is predicted to vanish in the single quark radiation model if the J/ψ is pure S wave.
- For the fractional M2 amplitude a relativistic calculation yields:

$$a_2(\chi_{c1}) = -\frac{E_\gamma}{4m_c}(1+\kappa_c) = -0.065(1+\kappa_c)$$
$$a_2(\chi_{c2}) = -\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}(1+\kappa_c) = -0.096(1+\kappa_c)$$

where κ_c is the anomalous magnetic moment of the c-quark

χ_{c1} and χ_{c2} angular distributions



$$\left(\frac{a_2(\chi_1)}{a_2(\chi_2)}\right)_{Th} = \frac{\sqrt{5}}{3}\frac{E_\gamma(\chi_1 \to J/\psi\gamma)}{E_\gamma(\chi_2 \to J/\psi\gamma)} = 0.676$$

McClary and Byers (1983) predict that ratio is indipendent of c-quark mass and anomalouse magnetic moment

E835 have been measured for the first time this ratio:

$$\left(\frac{a_2(\chi_1)}{a_2(\chi_2)}\right)_{E835} = -0.02 \pm 0.34$$

Experimental result is $\sim 2\sigma$ away from prediction.

High statistics measurements of these angular distributions are needed to solve this question

E835 Reference "Ambrogiani et al. Physical Review D, Vol. 65, 05002"

χ_{c1} and χ_{c2} angular distributions

For the χ_{c1}:

$$W(cos\theta, cos\theta', \phi') = \frac{1}{2}(1 - cos^2\theta cos2\theta' - sin\theta cos\theta sin\theta' cos\theta' cos\phi)$$

For the χ_{c2}:

$$W(cos\theta, cos\theta', \phi') = \frac{1}{10}[1 + cos^2\theta + cos^4\theta + 2cos^2\theta cos^2\theta' - 3cos^4\theta cos^2\theta' - cos^2\theta sin^2\theta sin^2\theta' cos2\phi' + (\frac{1}{4}sin2\theta - sin2\theta cos^2\theta)sin2\theta' cos\phi']$$

χ_{c1} and χ_{c2} angular distributions

The angular distribution for the reactions (1) can be written as

$$W(\theta,\theta',\phi')=\sum_{i=1}^{N} K_i(B_{|\lambda(\bar{p})-\lambda(p)|},A_{|\lambda(\psi)-\lambda(\gamma)|})T_i(\theta,\theta',\phi') \qquad \text{(A1)}$$

with $N=5$ at the χ_{c1}, and $N=11$ at the χ_{c2}. Tables IV (for the χ_{c1}) and V (for the χ_{c2}) give the full expressions (from Ref. [10]) for the coefficients K_i and the functions T_i that appear in Eq. (A1). The parameter R is defined as

TABLE IV. Coefficients K_i and functions T_i at the χ_{c1}.

i	$T_i(\theta,\theta',\phi')$	$K_i(A_0,A_1)$
1	1	$\frac{1}{2}$
2	$\cos^2\theta$	$\frac{1}{2}(A_1^2-A_0^2)$
3	$\cos^2\theta'$	$\frac{1}{2}(A_0^2-A_1^2)$
4	$\cos^2\theta'\cos^2\theta$	$-\frac{1}{2}$
5	$\sin 2\theta\sin 2\theta'\cos\phi'$	$-\frac{1}{4}A_0A_1$

$$\begin{pmatrix} A_0=\frac{1}{\sqrt{2}}a_1-\frac{1}{\sqrt{2}}a_2 \\ A_1=\frac{1}{\sqrt{2}}a_1+\frac{1}{\sqrt{2}}a_2 \end{pmatrix}_{J=1}$$

TABLE V. Coefficients K_i and functions T_i at the χ_{c2}.

i	$T_i(\theta,\theta',\phi')$	$K_i(R,A_0,A_1,A_2)$
1	1	$\frac{1}{8}(2A_0^2+3A_2^2-R(2A_0^2-4A_1^2+A_2^2))$
2	$\cos^2\theta$	$\frac{3}{4}(-2A_0^2+4A_1^2-A_2^2+R(4A_0^2-6A_1^2+A_2^2))$
3	$\cos^4\theta$	$\frac{1}{8}(6A_0^2-8A_1^2+A_2^2)(3-5R)$
4	$\cos^2\theta'$	$\frac{1}{8}(2A_0^2+3A_2^2-R(2A_0^2+4A_1^2+A_2^2))$
5	$\cos^2\theta'\cos^2\theta$	$\frac{3}{4}(-2A_0^2-4A_1^2-A_2^2+R(4A_0^2+6A_1^2+A_2^2))$
6	$\cos^2\theta'\cos^4\theta$	$\frac{1}{8}(6A_0^2+8A_1^2+A_2^2)(3-5R)$
7	$\sin^2\theta'\cos 2\phi'$	$\sqrt{\frac{6}{4}}(R-1)A_0A_2$
8	$\cos^2\theta\sin^2\theta'\cos 2\phi'$	$\sqrt{\frac{6}{4}}(4-6R)A_0A_2$
9	$\cos^4\theta\sin^2\theta'\cos 2\phi'$	$\sqrt{\frac{6}{4}}(5R-3)A_0A_2$
10	$\sin 2\theta\sin 2\theta'\cos\phi'$	$-\sqrt{\frac{3}{4}}\left(A_0A_1+\sqrt{\frac{3}{2}}A_1A_2-R\left(2A_0A_1+\sqrt{\frac{3}{2}}A_1A_2\right)\right)$
11	$\cos^2\theta\sin 2\theta\sin 2\theta'\cos\phi'$	$-\frac{1}{4\sqrt{3}}(5R-3)\left(3A_0A_1+\sqrt{\frac{3}{2}}A_1A_2\right)$

$$\begin{pmatrix} A_0=\sqrt{\frac{1}{10}}a_1+\sqrt{\frac{1}{2}}a_2+\sqrt{\frac{6}{15}}a_3 \\ A_1=\sqrt{\frac{3}{10}}a_1+\sqrt{\frac{1}{6}}a_2-\sqrt{\frac{8}{15}}a_3 \\ A_2=\sqrt{\frac{6}{10}}a_1-\sqrt{\frac{1}{3}}a_2+\sqrt{\frac{1}{15}}a_3 \end{pmatrix}_{J=2}.$$