# “Photoproduction of $J/\psi$ in the FOCUS Experiment”

(⋆ Preliminary Study ⋆)

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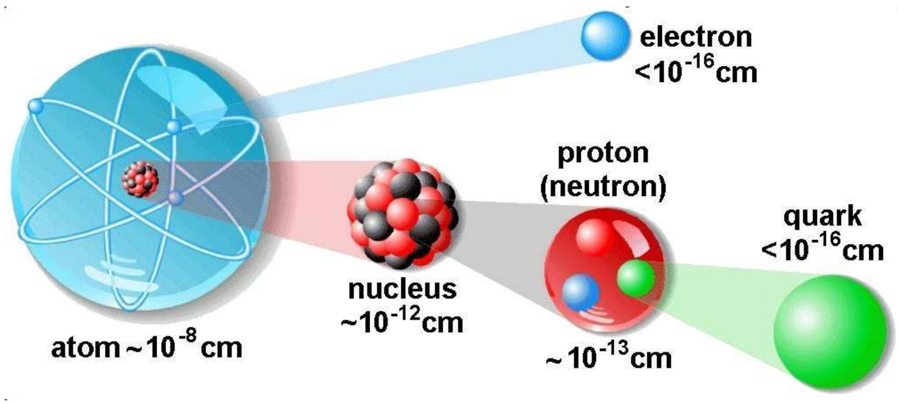


# ABSTRACT

Charmonium states are composed of charm-anticharm $(c\bar{c})$ quarks in bound state and are grouped in the *Charmonium Spectrum*. In this work we present a *preliminary study on direct Photoproduction of $J/\psi$* , the charmonium ground state. The $J/\psi$ is identified by their decays into lepton pairs $\mu^+\mu^-$ and $e^+e^-$ (In progress).

The reconstruction efficiency is determined by a inelastic $J/\psi$ simulation, where the color is conserved explicitly.

Our studies was done using a dileptonic sample collected by the fixed target photoproduction experiment FOCUS at Fermilab.

# OUTLINE

1) Charmonium Photoproduction

♡ Direct Production:

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

♡ Indirect Production:

$\star\ \psi(2S) \to J/\psi\pi^+\pi^-$

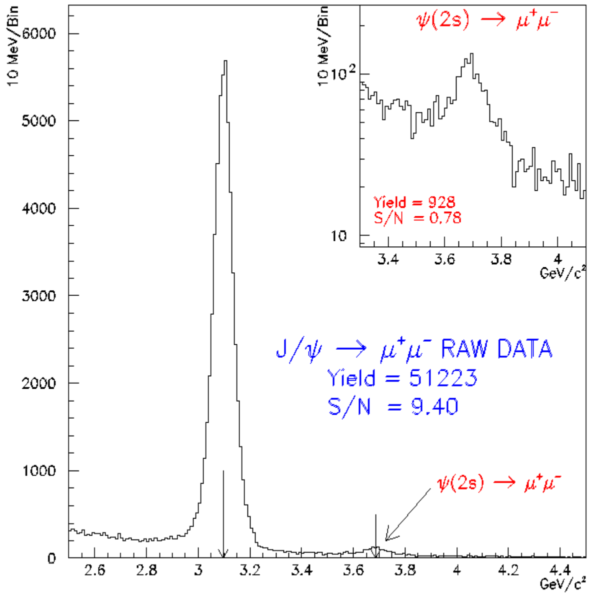
$\star\ \psi(2S) \to J/\psi\pi^0\pi^0$

$\star\ \chi_{cj} \to J/\psi\gamma\ \ (j = 0, 1, 2)$

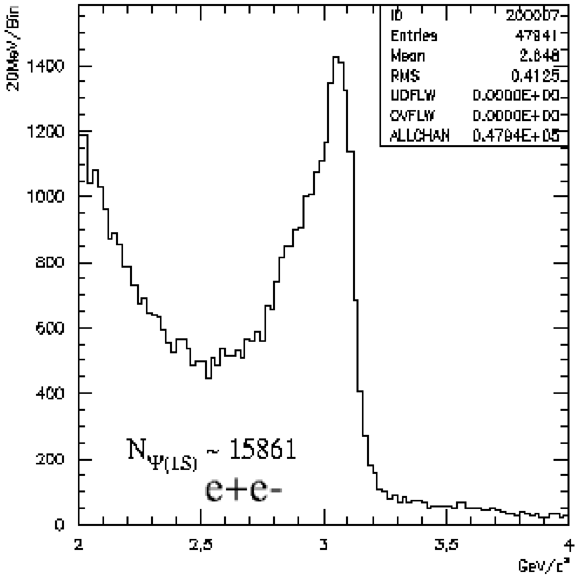
$\star\ \psi(2S) \to \chi_{cj}\gamma\ \ (j = 0, 1, 2).$

2) Conclusions

(a) $J/\psi \rightarrow \mu^+\mu^-$ Sample




(b) $J/\psi \rightarrow e^+e^-$ Sample

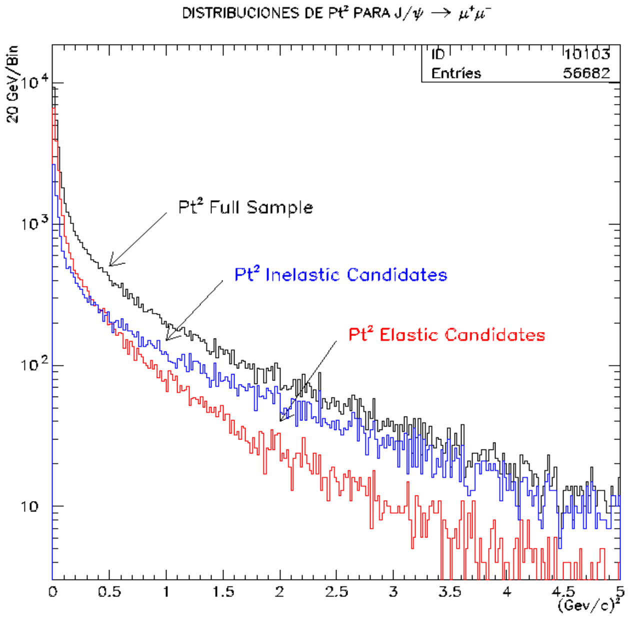



| Decay Channel | Mass $[\mathrm{GeV}/c^2]$ | Width [MeV] | $\frac{S}{N}$ | Events Found |
|---|---|---|---|---|
| $J/\psi \rightarrow \mu^+\mu^-$ | 3.097 | 40.04 | 9.35 | $51223 \pm 236$ |
| $*J/\psi \rightarrow e^+e^-$ | * | * | * | $\sim 15861$ |
| $\psi(2S) \rightarrow \mu^+\mu^-$ | 3.626 | 50.82 | 0.78 | $928 \pm 53$ |

* In progress...

# FOCUS Experiment: $P^2_{T\,J/\psi}$ Distribution FULL SAMPLE

- $2.95 < M_{\mu^+\mu^-} < 3.25\ \mathrm{GeV}/c^2$




⋆ Elastic $J/\psi$ candidates:

- Two opposited charge tracks coming from a single vertex
- $0 < P_{\mu^+\mu^-} < 250\ \mathrm{GeV}/c$

⋆ Inelastic $J/\psi$ candidates:

- $N_{Track} \geq 3$

## ⋆ RAW Data Results:

| $J/\psi \to \mu^+\mu^-$ | Mass [GeV/$c^2$] | $\sigma$ [$MeV$] | S/N | Events Found |
|---|---|---|---|---|
| Elastic | $3.097 \pm 0.19 \times 10^{-3}$ | 38.5 | 6.77 | $26540 \pm 193.8$* |
| Inelastic | $3.097 \pm 0.27 \times 10^{-3}$ | 38.4 | 7.39 | $23150 \pm 175.4$* |

## ⋆ MC Simulation Results:

⋆ Elastic Generation: 2999850 Events

⋆ Inelastic Generation: 1500000 Events

| $J/\psi \to \mu^+\mu^-$ | Mass [GeV/$c^2$] | $\sigma$ [$MeV$] | Events Found | $\epsilon_{ff}^{Rec}$ |
|---|---|---|---|---|
| Elastic | $3.097 \pm 0.23 \times 10^{-4}$ | 41.5 | $1012000 \pm 1004$ | 33.7% |
| Inelastic | $3.096 \pm 0.37 \times 10^{-4}$ | 38.9 | $487100 \pm 708.6$ | 32.4% |

* There exist mutual contamination between elastic and inelastic events.
* No dimuon trigger is simulated yet in MC.
* Actuallly working in $P_T^2$ and energy beam analysis.

♡ $J/\psi$ can be produced directly or through other Charmonium States:

| Channel Decay | Branching Ratio |
|---|---|
| $J/\psi \rightarrow \mu^+\mu^-$ | $5.93 \pm 0.10\%$ |
| $J/\psi \rightarrow e^+e^-$ | $5.88 \pm 0.10\%$ |
| * $\chi_{c0} \rightarrow J/\psi\gamma$ | $1.02 \pm 0.17\%$ |
| $\chi_{c1} \rightarrow J/\psi\gamma$ | $31.6 \pm 3.20\%$ |
| $\chi_{c2} \rightarrow J/\psi\gamma$ | $18.7 \pm 2.20\%$ |
| $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ | $30.5 \pm 1.60\%$ |
| $\psi(2S) \rightarrow J/\psi\pi^0\pi^0$ | $18.2 \pm 1.20\%$ |
| $\psi(2S) \rightarrow \chi_{c0}\gamma$ | $8.70 \pm 0.80\%$ |
| $\psi(2S) \rightarrow \chi_{c1}\gamma$ | $8.40 \pm 0.70\%$ |
| $\psi(2S) \rightarrow \chi_{c2}\gamma$ | $6.80 \pm 0.60\%$ |
| * $B \rightarrow J/\psi + X$ | $< 10^{-3}\%$ |

* Very small production at FOCUS's energy

## The $J/\psi$ Direct Photoproduction

- The total number of observed $J/\psi$:

$$N_{J/\psi}^{Total} = N_{J/\psi}^{Elastic} + N_{J/\psi}^{Inelastic}$$

- INELASTIC Cross Section is very much UNKNOWN.

$$N_{J/\psi}^{Inelastic} = N_{J/\psi}^{Direct} + N_{J/\psi}^{Indirect}$$

$$\boxed{N_{J/\psi}^{Direct} = N_{J/\psi}^{Total} - N_{J/\psi}^{Elastic} - N_{J/\psi}^{Indirect}}$$

- We take into account for the INDIRECT $J/\psi$ production:

$$N_{J/\psi}^{Indirect} = N_{J/\psi\leftarrow\psi(2S)} + N_{J/\psi\leftarrow\chi_{cj}} + N_{J/\psi\leftarrow B}$$

$J/\psi \leftarrow B$ is a very small contribution at our energy (FOCUS's energy).

♣ $J/\psi \leftarrow \psi(2S)$ are $J/\psi$ coming from the processes:

$$\psi(2S) \to J/\psi\pi^+\pi^-, \quad \psi(2S) \to J/\psi\pi^0\pi^0, \quad \psi(2S) \to \chi_{cj}\gamma$$

Where the $\chi_{cj} \to J/\psi\gamma$ and $j = 1, 2.$

♠ $J/\psi \leftarrow \chi_{cj}$ are $J/\psi$ coming <u>only</u> from the processes:

$$\chi_{c1} \to J/\psi\gamma \quad \text{and} \quad \chi_{c2} \to J/\psi\gamma.$$

As we can see, Photons are very important in our work!!!

- The total number of produced $J/\psi$: $N^{Prod} = \frac{N^{MCobs}}{\epsilon_{ff}^{Rec}}$

  where $\epsilon_{ff}^{Rec}$ comes from the Monte Carlo (MC) Simulation.

- The *Cross Section* for the ELASTIC MC generator is parametrized by:

  $\frac{d\sigma}{dt} = Ae^{-bP_T^2}$ with the slope $b = 45$

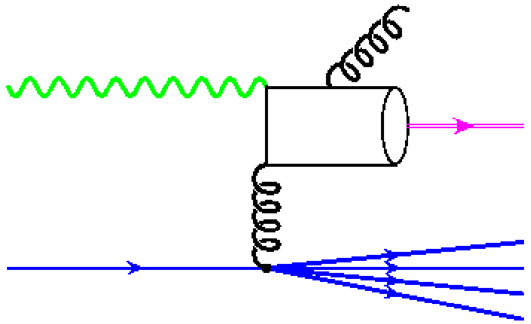
  ♡ Elastic Case $\Longrightarrow$ Color is Implicity Conserved

- MC INELASTIC simulation is generated using the variable *Inelasticity*:

  $Z = \frac{E_{c\bar{c}}}{E_\gamma} < 0.9$

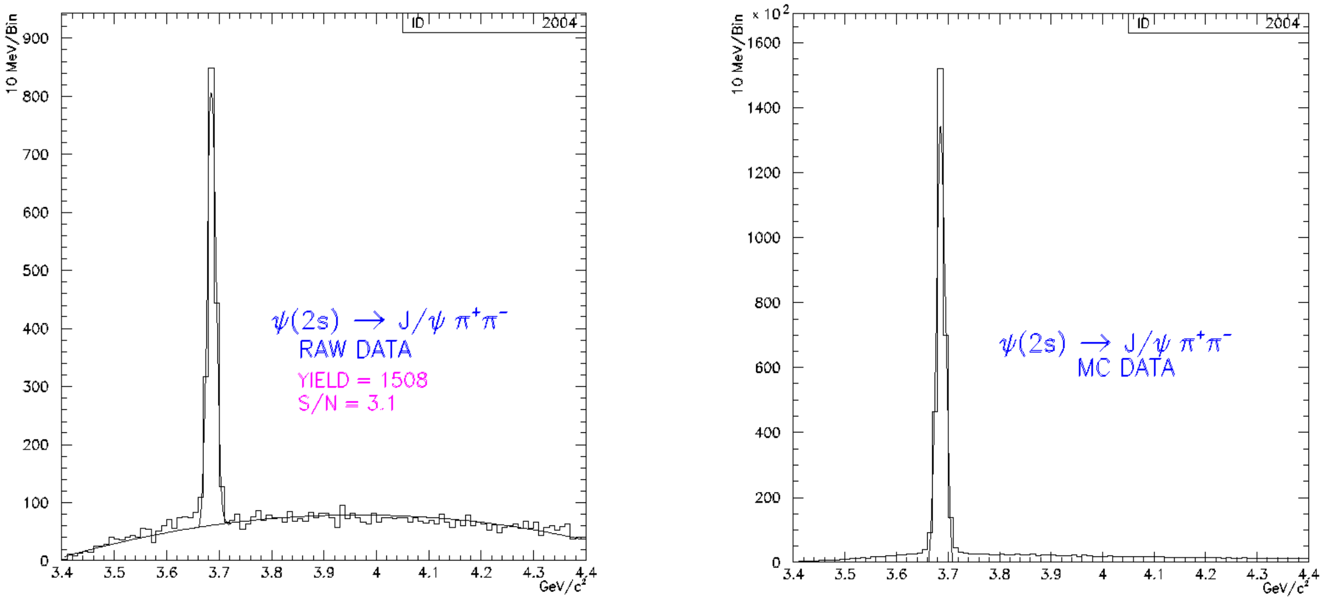
  ⋆ $E_{c\bar{c}}$: Energy of the charmomium state

  ⋆ $E_\gamma$: Energy of the incident photon.



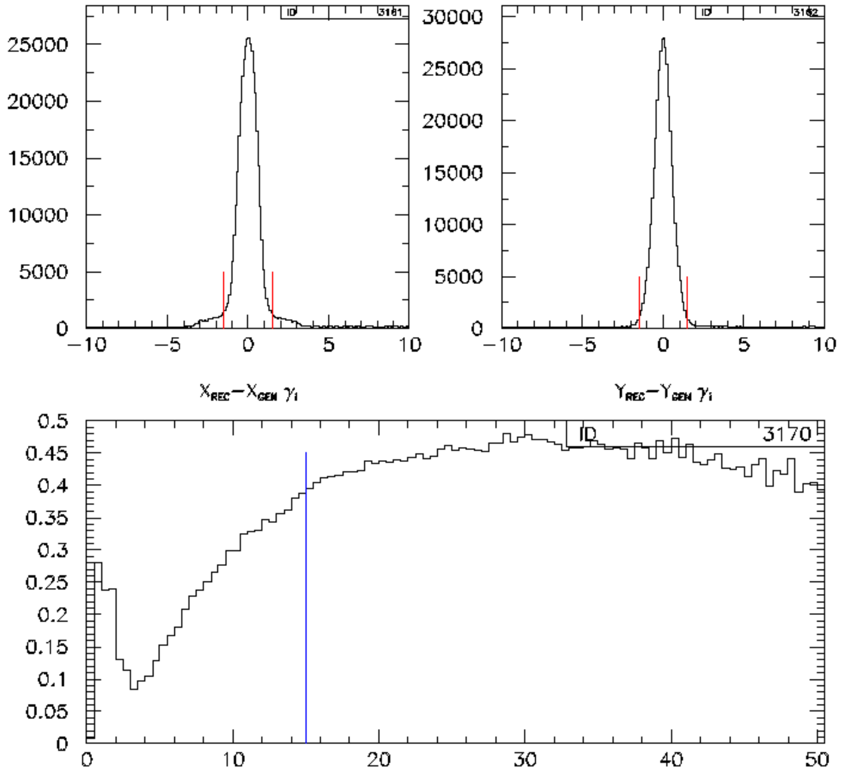
♡ Inelastic Case $\Longrightarrow$ Color Explicity Conserved

# $\psi(2S) \to J/\psi\pi^+\pi^-$ Sample




| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ [$MeV$] | OBS. EVENTS | $S/N$ |
|---|---|---|---|
| **$\psi(2S) \to J/\psi\pi^+\pi^-$ RAW DATA** | | | |
| $3.686 \pm 0.169 \times 10^{-3}$ | $7.9 \pm 0.26 \times 10^{-3}$ | $1499 \pm 43$ | 2.62 |
| **$\psi(2S) \to J/\psi\pi^+\pi^-$ MC ELASTIC** | | | |
| $3.686 \pm 0.23 \times 10^{-3}$ | $8.0 \pm 0.20 \times 10^{-4}$ | $206300 \pm 6683$ | $\epsilon_{ff} = 13.75\%$ |
| **$\psi(2S) \to J/\psi\pi^+\pi^-$ MC INELASTIC** | | | |
| $3.686 \pm 0.33 \times 10^{-4}$ | $9.8 \pm 0.42 \times 10^{-4}$ | $79560 \pm 239$ | $\epsilon_{ff} = 5.3\%$ |

## $\chi_c \rightarrow J/\psi + \gamma$ : $\epsilon_{ff}(\gamma \leftarrow \chi_c)$

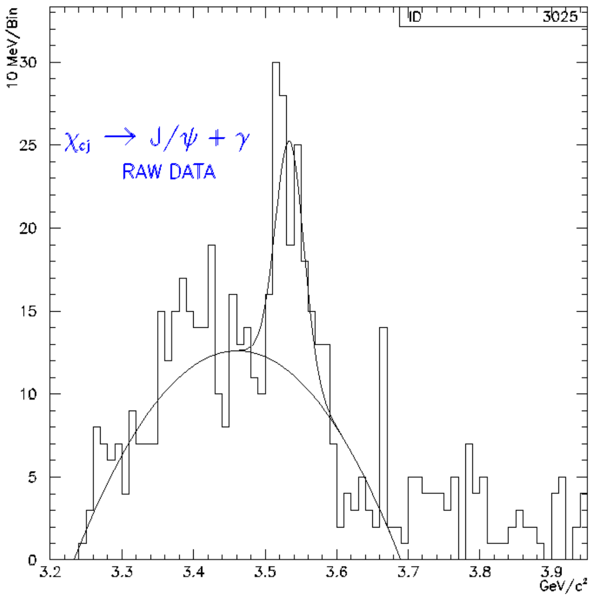


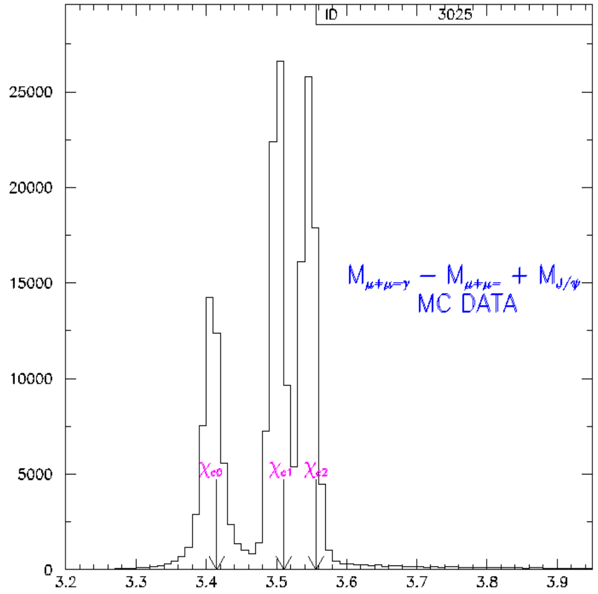

$\star$ Cuts applied for find $\chi_{cj} \rightarrow J/\psi\gamma$

1) Number of Blocks at IE $\geq 2$
2) $E_\gamma \geq 2$ GeV
3) $E_{CBlck}/E_\gamma \geq 30$ %
4) Fiducial for IE

## Non Corrected Candidates

$\chi_{cj} \to J/\psi\gamma$ (RAW) $\chi_{cj} \to J/\psi\gamma$ (MC)

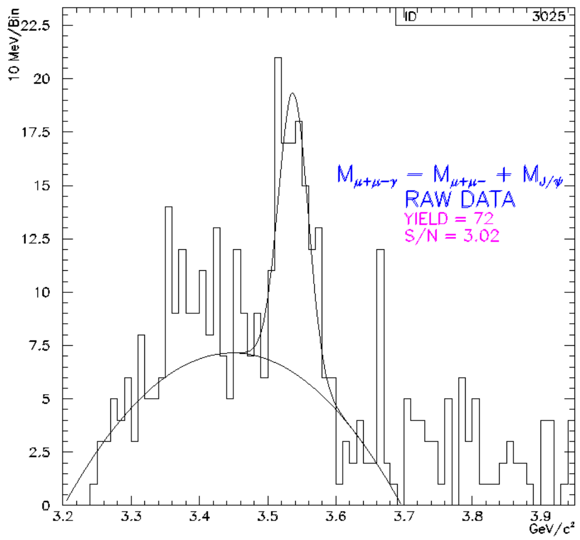


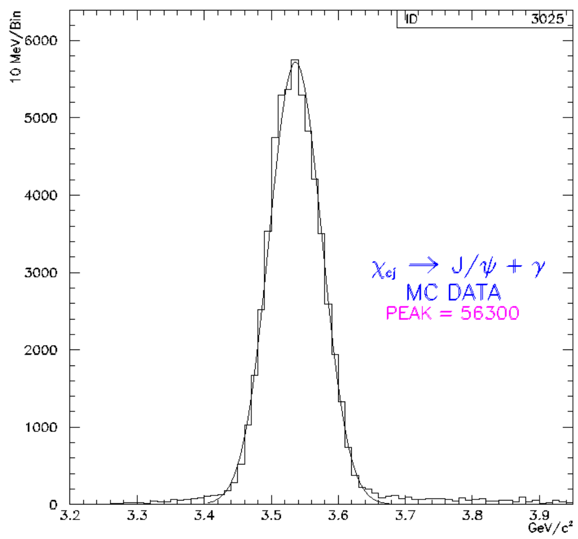

| $\chi_{cj} \to J/\psi\gamma$ RAWDATA | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ [$MeV$] | Obs. Events | $S/N$ |
| $3.534 \pm 0.467 \times 10^{-2}$ | 20 | $69.08 \pm 13.9$ | 0.42 |

# Corrected Samples

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




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

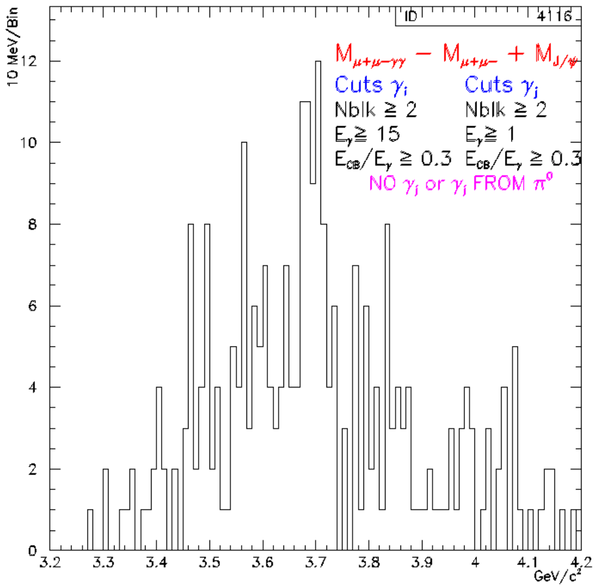


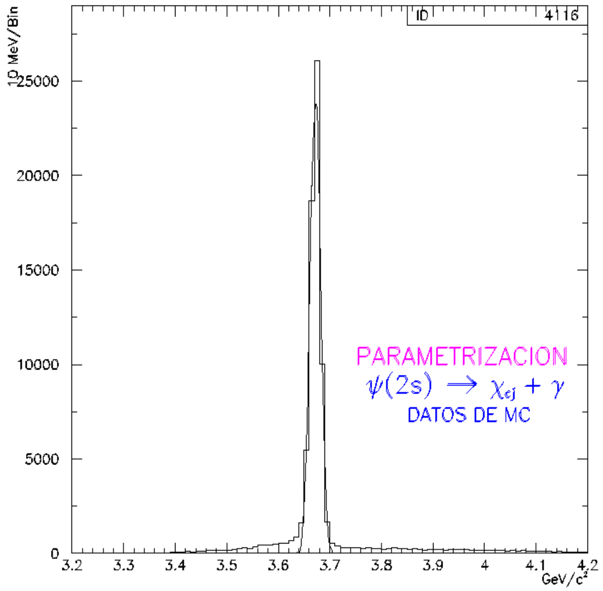

| $\chi_{cj} \to J/\psi\gamma$ (RAW DATA) | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ [$MeV$] | Obs. Events | $S/N$ |
| $3.537 \pm 0.46 \times 10^{-2}$ | $21 \pm 0.3 \times 10^{-2}$ | $77.8 \pm 12.82$ | 4.8 |
| $\chi_{cj} \to J/\psi\gamma$ (ELASTIC MC DATA) * | | | |
| $3.536 \pm 0.24 \times 10^{-3}$ | $38.8 \pm 0.24 \times 10^{-3}$ | $24930 \pm 159$ | $\epsilon_{ff} = 1.6\%$ |
| $\chi_{cj} \to J/\psi\gamma$ (INELASTIC MC DATA) * | | | |
| $3.536 \pm 0.21 \times 10^{-3}$ | $39.6 \pm 0.17 \times 10^{-3}$ | $31320 \pm 239$ | $\epsilon_{ff} = 2\%$ |

* $\chi_{c1} \to J/\psi\gamma$ and $\chi_{c2} \to J/\psi\gamma$ were generated

# $\psi(2S) \rightarrow \chi_{cj}\gamma$ RAW $\qquad$ $\psi(2S) \rightarrow \chi_{cj}\gamma$ MC

## Non Corrected Candidates

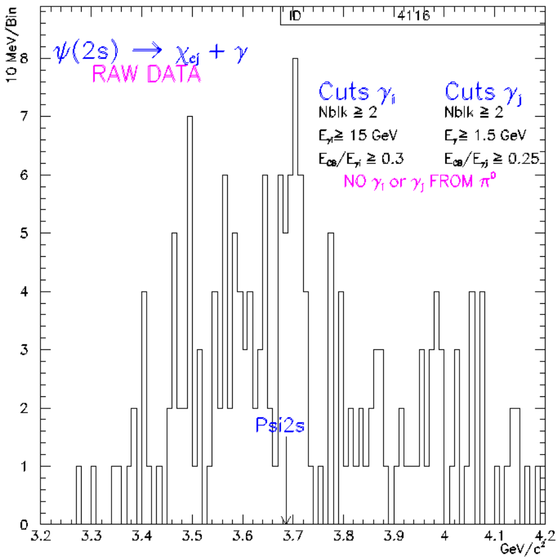


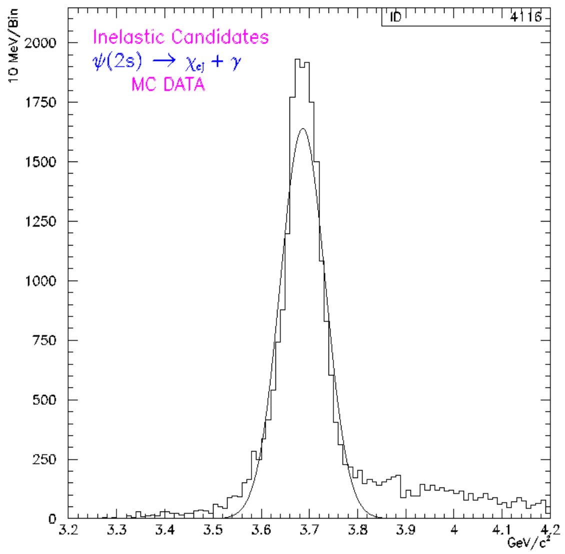




| $\psi(2S) \rightarrow \chi_{cj}\gamma$ RAW DATA | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ [$MeV$] | Obs. Events | $S/N$ |
| $3.694 \pm 0.47 \times 10^{-2}$ | 22 | $43.73 \pm 8.37$ | 0.88 |
| $\psi(2S) \rightarrow \chi_{cj}\gamma$ MC DATA | | | |
| $3.672 \pm 0.19 \times 10^{-4}$ | 10 | $\sim 62100$ | $\epsilon_{ff} = 1.5\%$ |

# $\psi(2S) \rightarrow \chi_{cj}\gamma \; (j = 0, 1, 2)$

## Corrected Candidate Sample

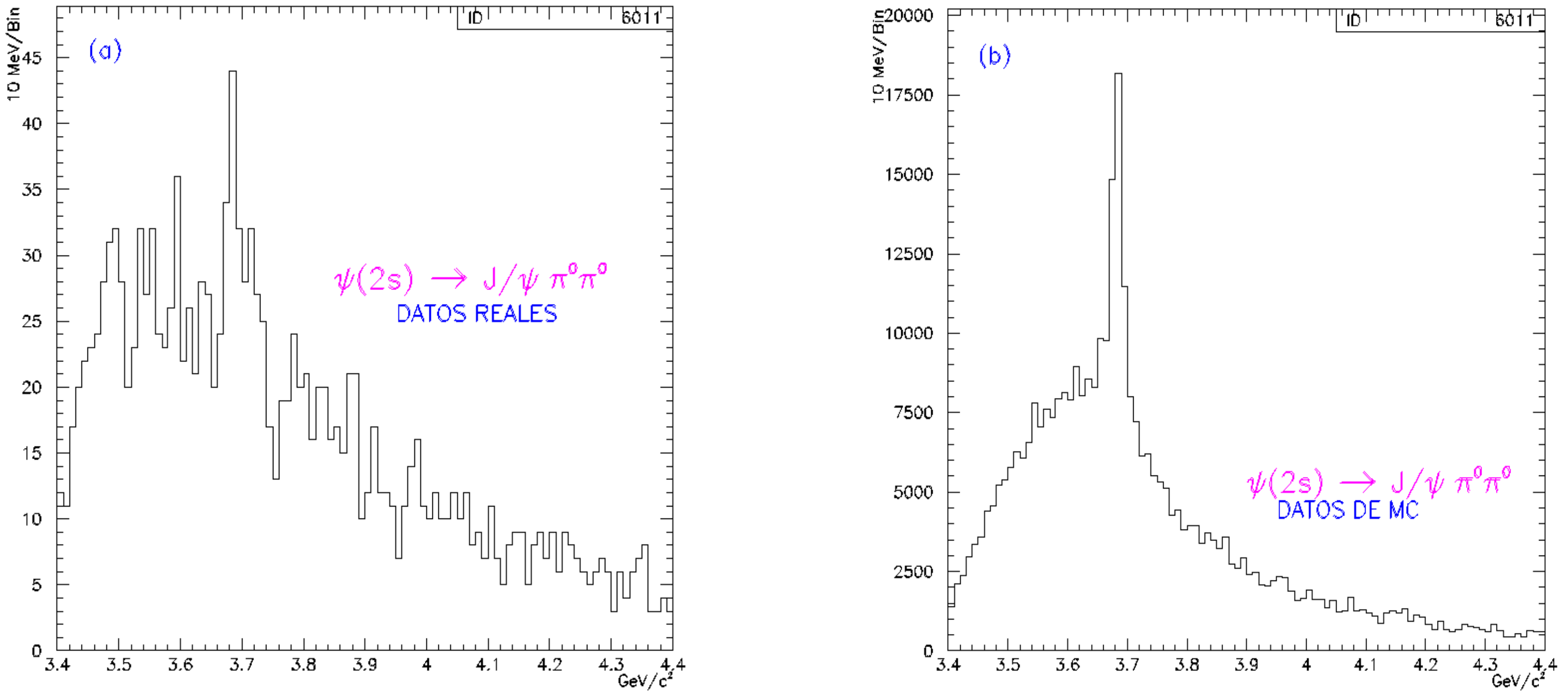



| $\psi(2S) \rightarrow \chi_{cj}\gamma$ **RAW DATA** | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ $[MeV]$ | Obs. Events | $S/N$ |
| $3.698 \pm 0.49 \times 10^{-2}$ | | $12.2 \pm 5.5$ | 1.07 |
| $\psi(2S) \rightarrow \chi_{cj}\gamma$ **ELASTIC MC DATA** | | | |
| $3.689 \pm 0.4 \times 10^{-3}$ | $32.2 \pm 0.34 \times 10^{-3}$ | $18560 \pm 174$ | $\epsilon_{ff} = 0.51\%$ |
| $\psi(2S) \rightarrow \chi_{cj}\gamma$ **INELASTIC MC DATA** | | | |
| $3.688 \pm 0.2 \times 10^{-3}$ | $36.8 \pm 0.32 \times 10^{-3}$ | $20410 \pm 155$ | $\epsilon_{ff} = 0.57\%$ |

# $\psi(2S) \to J/\psi\pi^0\pi^0$

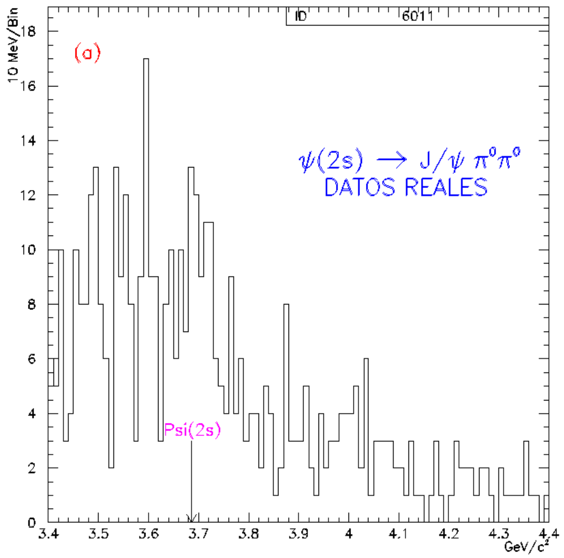
## Non Corrected Candidate Sample

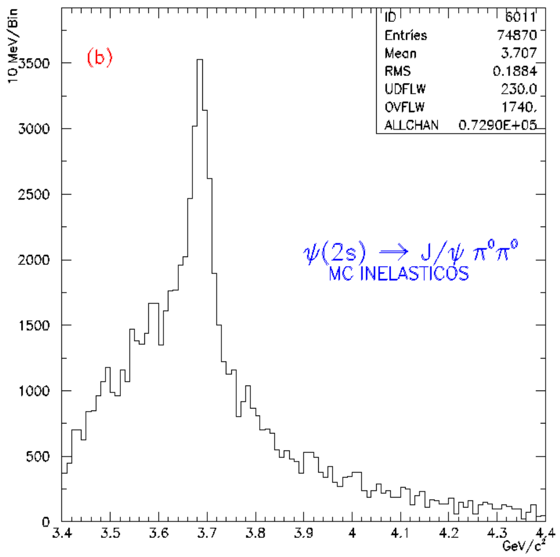



| $\psi(\mathbf{2S}) \to \mathbf{J}/\psi\pi^0\pi^0$ (RAW DATA) | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV$/c^2$] | $\sigma$ [$MeV$] | Obs. Events | $S/N$ |
| $\sim 3.695$ | | $\sim 55$ | 1.11 |
| $\psi(\mathbf{2S}) \to \mathbf{J}/\psi\pi^0\pi^0$ (MC DATA) | | | |
| $\sim 3.681$ | 11 | $\sim 11800$ | $\epsilon_{ff} = 0.3\%$ |

# Corrected Samples

## $\psi(2S) \to J/\psi\pi^0\pi^0$ (RAW DATA) | $\psi(2S) \to J/\psi\pi^0\pi^0$ (MC DATA)




| $\psi(2S) \to J/\psi\pi^0\pi^0$ RAW DATA | | | |
|---|---|---|---|
| $M_{\psi(2S)}$ [GeV/$c^2$] | $\sigma$ [$MeV$] | Obs. Events | $S/N$ |
| $\sim 3.687$ | | $\sim 56$ | |
| $\psi(2S) \to J/\psi\pi^0\pi^0$ ELASTIC MC DATA | | | |
| $3.684 \pm 0.3 \times 10^{-3}$ | $33.3 \pm 0.44 \times 10^{-3}$ | $26800 \pm 275$ | $\epsilon_{ff} = 0.89\%$ |
| $\psi(2S) \to J/\psi\pi^0\pi^0$ INELASTIC MC DATA | | | |
| $3.683 \pm 0.2 \times 10^{-3}$ | $25 \pm 0.4 \times 10^{-3}$ | $12390 \pm 126$ | $\epsilon_{ff} = 0.41\%$ |

# CONCLUSIONS

- Associated $J/\psi$ photoproduction, as $\chi_c$ and $\psi(2s)$, seems to be not negligible.
- Understand the mixed ratio between the $\chi_c$'s.
- Study how to apply other selection based on $P_T^2$ distribution and the beam energy in order to reduce the $Ela \Leftrightarrow Inel$ contamination.
- Working on reconstruction efficiencies to measure final ratio.