Status of $J/\psi\pi^+\pi^-$, $J/\psi\gamma$ and $\chi_{1,2}\gamma$ analysis

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Outline

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$\bar{p}p \to Y(4260) \to J/\psi\pi^+\pi^- \to e^+e^-\pi^+\pi^-$

Y(4260)

Y(4260) was observed for the first time by BaBar in ISR events. (Ref. Phys. Rev. Lett. 95, 142001).
The quantum numbers of this state are $J^{PC} = 1^{--}$.
One possible interpretation of this state is an hybrid.
The idea is to study this state through its decay in $J/\psi\pi^+\pi^-$.

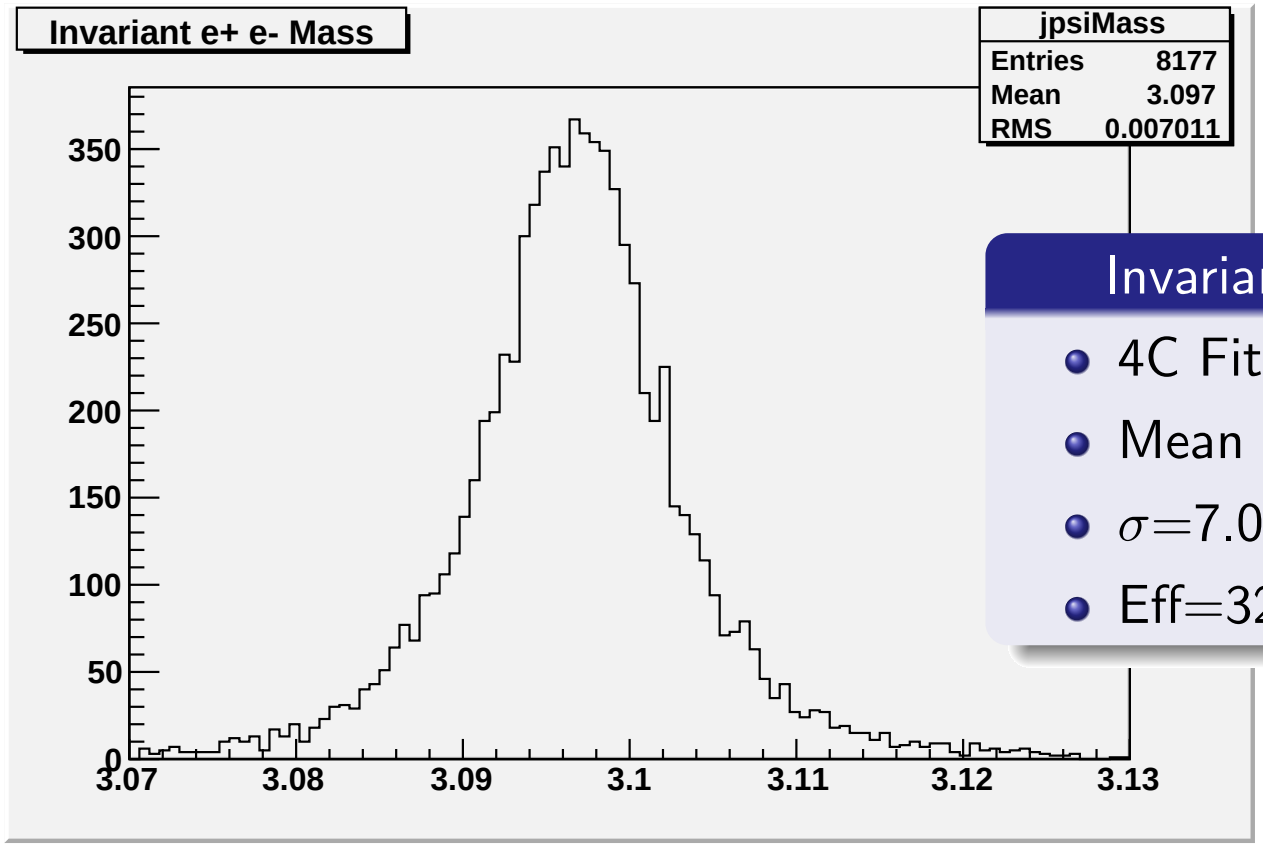
25.000 events generated for $\bar{p}p \to Y(4260) \to J/\psi\pi^+\pi^- \to e^+e^-\pi^+\pi^-$

no phase space decay model used

$Y(4260) \to J/\psi\pi^+\pi^- \to e^+e^-\pi^+\pi^-$

- Release 0.15.3
- Detectors: MVD, STT, EMC, DIRC, DCH, MUO, GEM
- List for Electrons: 1 ElectronLHCombinedLoose, 1 ElectronLHCombinedTight
- List for Pions: PionLHCombinedVeryLoose
- fittingAlgoritgm: TreeFitter
- CL>0.1%
- J/ψ Mass window=[2.5,3.5]GeV

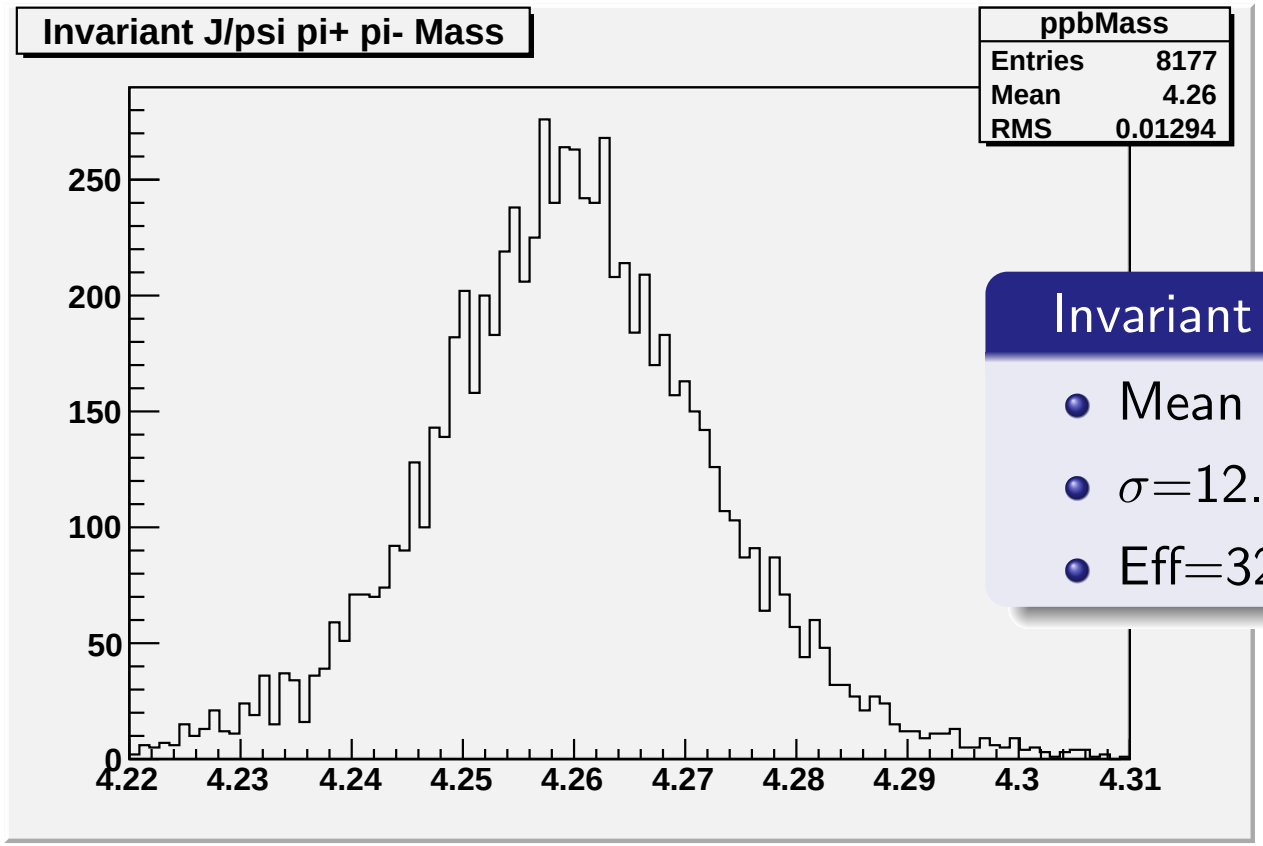
Invariant e^+e^- mass



Invariant e^+e^- mass

- 4C Fit
- Mean Value=3.097 GeV
- σ=7.01 MeV
- Eff=32.71%

Invariant $J/\psi\pi^+\pi^-$ mass



Invariant $J/\psi\pi^+\pi^-$ mass

- Mean Value=4.260 GeV
- σ=12.94 MeV
- Eff=32.71%

Invariant Dipion Mass of Y(4260) candidates

The choice is motivated by observations from $\psi(2S) \to J/\psi\pi^+\pi^-$.
Parametrization of the dipion invariant mass is given by:

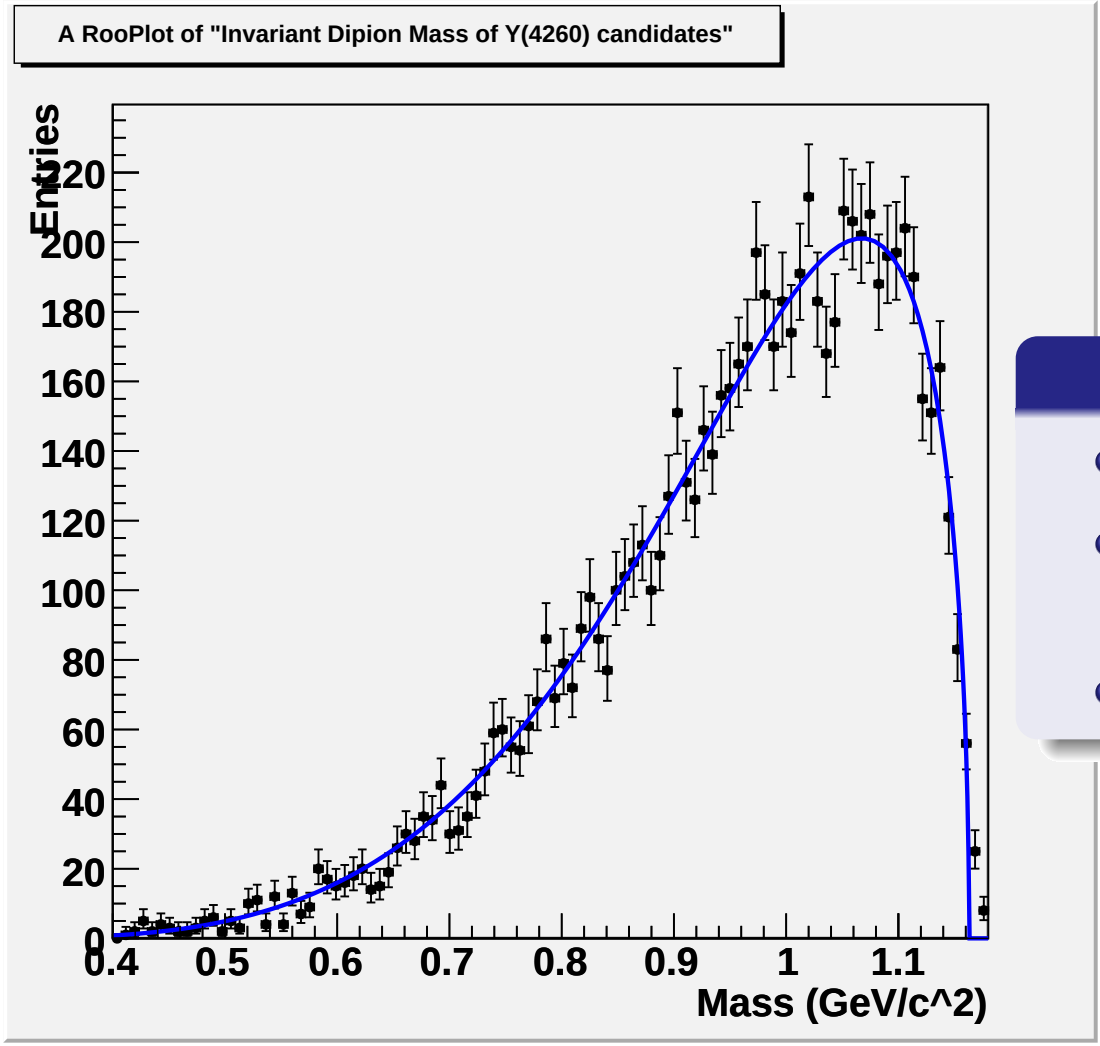
$$\frac{d\Gamma}{dm_{\pi\pi}} \propto PHSP \cdot \left(m^2_{\pi\pi} - \lambda m^2_{\pi\pi}\right)^2 \tag{1}$$

with

$$PHSP = \sqrt{\frac{(m^2_{\pi\pi} - 4m^2_{\pi\pi})\left[M^4_{\psi} + M^4_{\psi,} + m^4_{\pi\pi} - 2\left(M^2_{\psi} m^2_{\pi\pi} + M^2_{\psi,} m^2_{\pi\pi} + M^2_{\psi} + M^2_{\psi,}\right)\right]}{4M^2_{\psi,}}} \tag{2}$$

Ref. T.N.Pham, B.Pire and T.N. Truong, Phys. Lett. B61 (1976) 183

Invariant Dipion Mass of Y(4260) candidates



Dipion Invariant Mass

- Simulation: $\lambda = 4.0$
- Fit Result: $\lambda = 4.0 \pm 0.20$
- $\chi^2/ndf = 1.17$

Background: $\bar{p}p \longrightarrow \pi^+\pi^-\pi^+\pi^-$

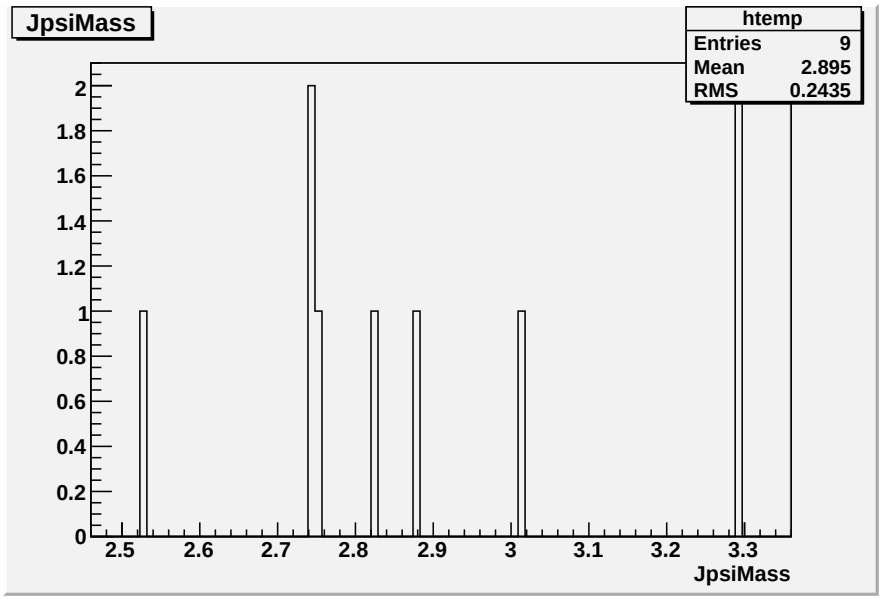
The major background of this channel come from $\bar{p}p \longrightarrow \pi^+\pi^-\pi^+\pi^-$

7.584.000 million events analyzed

Apply the same selection of signal events to background events

$\sigma(\bar{p}p \longrightarrow Y(4260) \approx 60pb$ (E835) (Ref: Matteo Negrini PhD Thesis)

$\sigma(\bar{p}p \longrightarrow \pi^+\pi^-\pi^+\pi^-) \approx 0.046mb$ (Ref: Flaminio CERN-HERA 79.03)



9 events pass the selection, in the region [2.4,3.4] GeV/c^2

0 events in the region [3.07,3.13] GeV/c^2

0 events peak exactly at the J/ψ mass

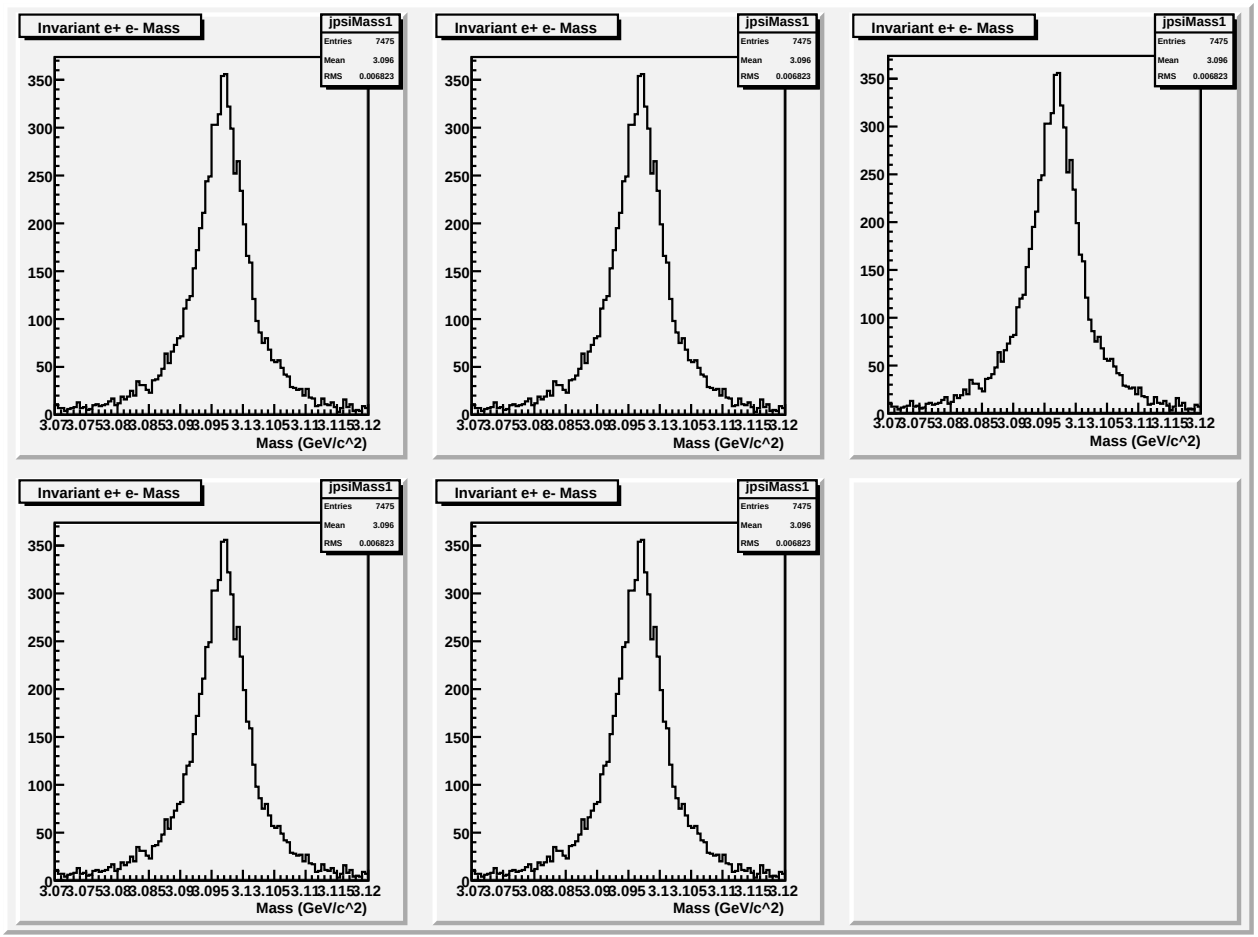
$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

- Same cut as Y(4260) selection
- Phase Space Model used
- 20.000 events generated
- Energies analyzed: h_c, $\psi(2S)$, X(3872), 4.600 GeV, 5.000 GeV

$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

The invariant e^+e^- masses reconstructed are:



$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

Summary data:

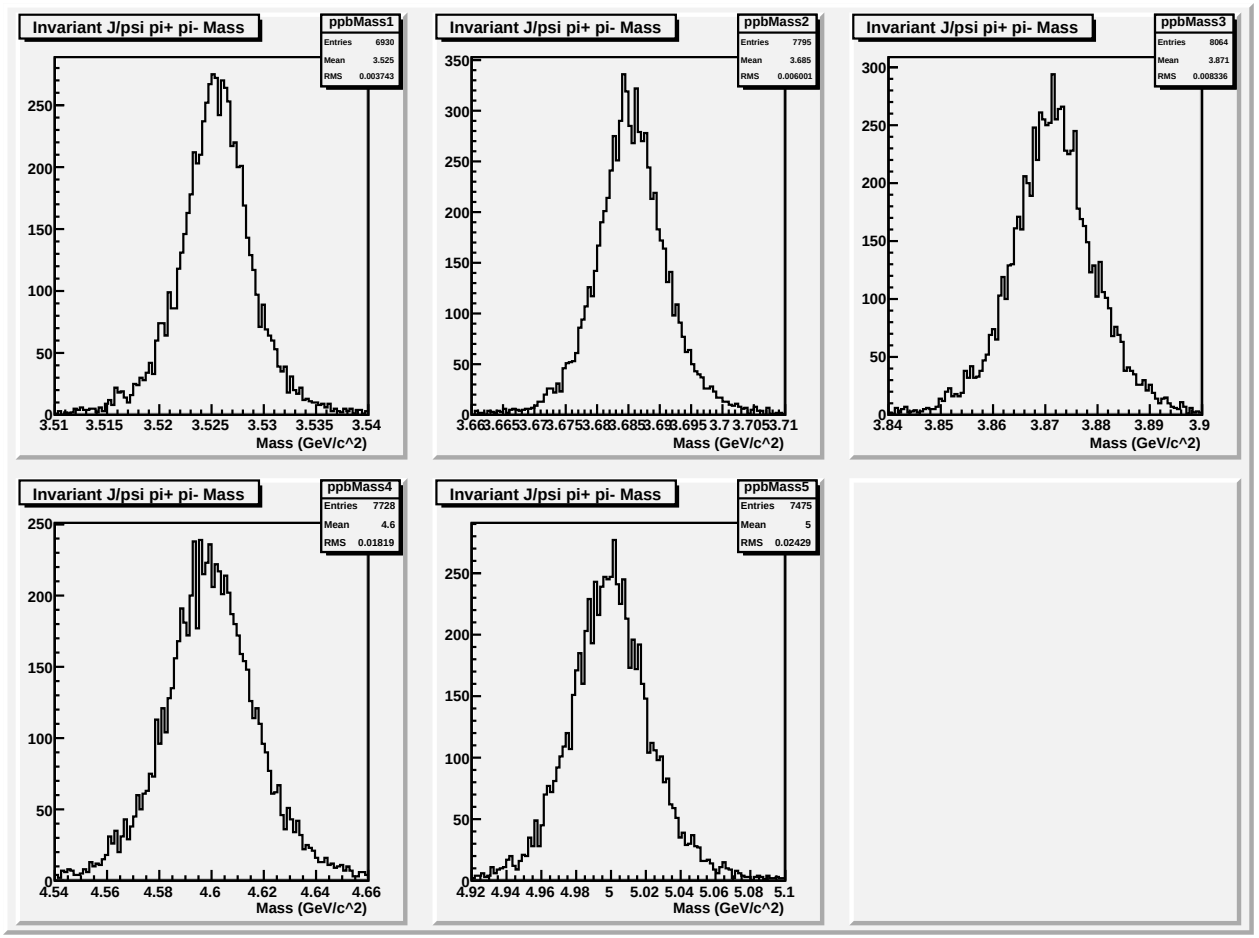
Mean Value $= 3.097\ GeV$

$E_{CM}(GeV)$	Eff(%)	$\sigma(MeV)$
3.526	27.72	2.45
3.686	31.18	3.30
3.872	32.26	4.25
4.600	30.91	5.67
5.000	29.90	6.39

Table: Invariant e^+ e^- mass

$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

The invariant $J/\psi\pi^+\pi^-$ masses reconstructed are:



$\bar{p}p \longrightarrow J/\psi\pi^+\pi^- \longrightarrow e^+e^-\pi^+\pi^-$ at different energies

Summary data:

$E_{CM}(GeV)$	Mean (GeV)	Eff(%)	$\sigma(MeV)$
3.526	3.525	27.72	3.74
3.686	3.685	31.18	6.00
3.872	3.871	32.26	8.34
4.600	4.600	30.91	18.47
5.000	5.000	29.90	24.29

Table: Invariant $J/\psi\pi^+\pi^-$ mass

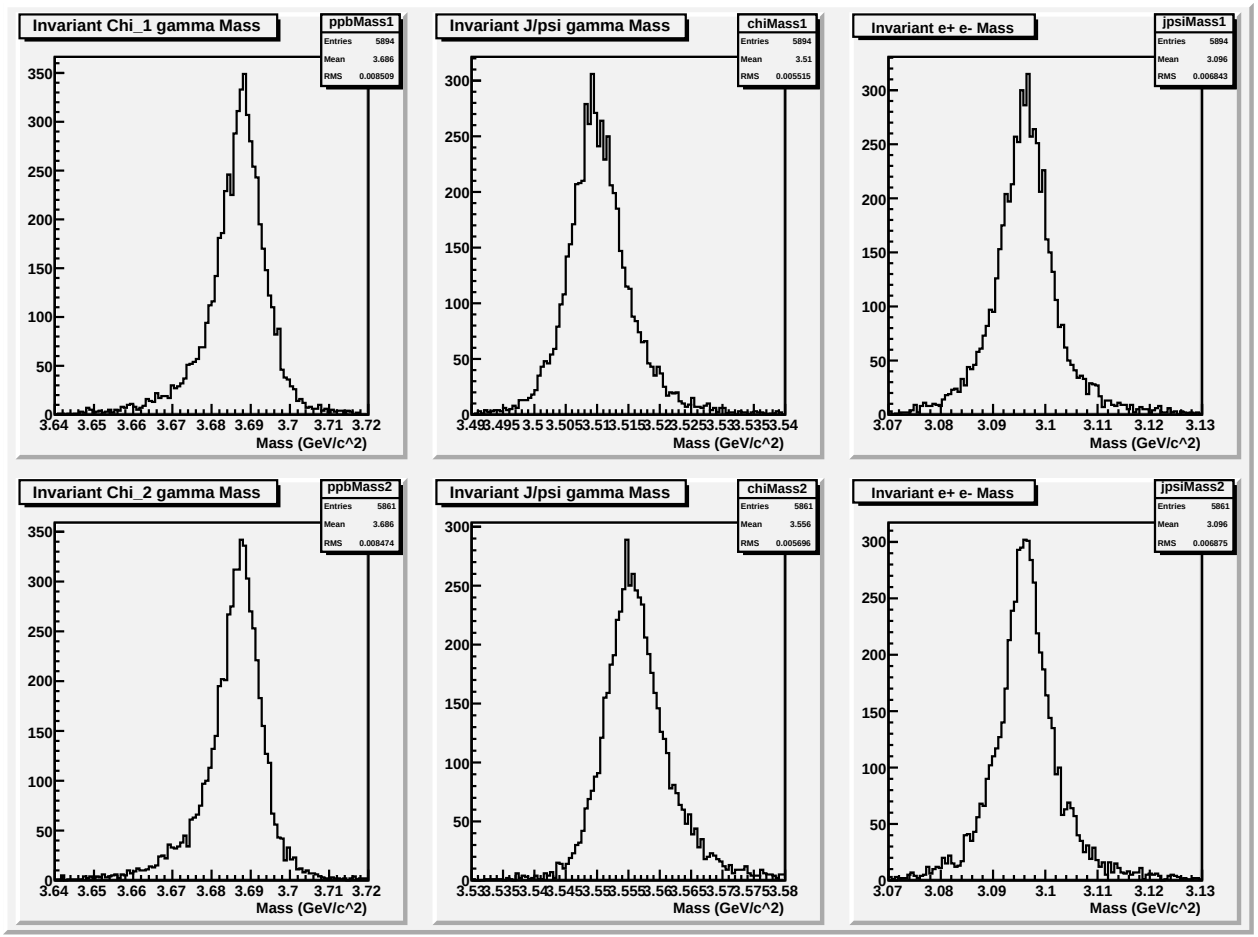
$\bar{p}p \to \chi_{1,2}\gamma \to J/\psi\gamma\gamma \to e^+e^-\gamma\gamma$

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

- List for Electrons: 1 ElectronCombinedLHLoose and 1 ElectronCombinedLHTight
- List for Photons: Calor Neutral with Energy$\in$[30MeV,15GeV]
- fittingAlgorith: TreeFitter
- J/ψ mass window: [2.5,3.5] GeV
- χ_1, χ_2 mass window: [3.3,3.7] GeV
- CL>0.1%
- Study done at energies: $\psi(2S), X(3872), Y(4260)$
- 20.000 events generated
- Phase Space Model

$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at $\psi(2S)$

The reconstructed masses of $\psi(2S)$, $\chi_{1,2}$ and J/ψ are:



$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at $\psi(2S)$

Summary of the data:

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_1\gamma$	3.686	8.51
$J/\psi\gamma$	3.510	5.52
e^+e^-	3.096	6.98

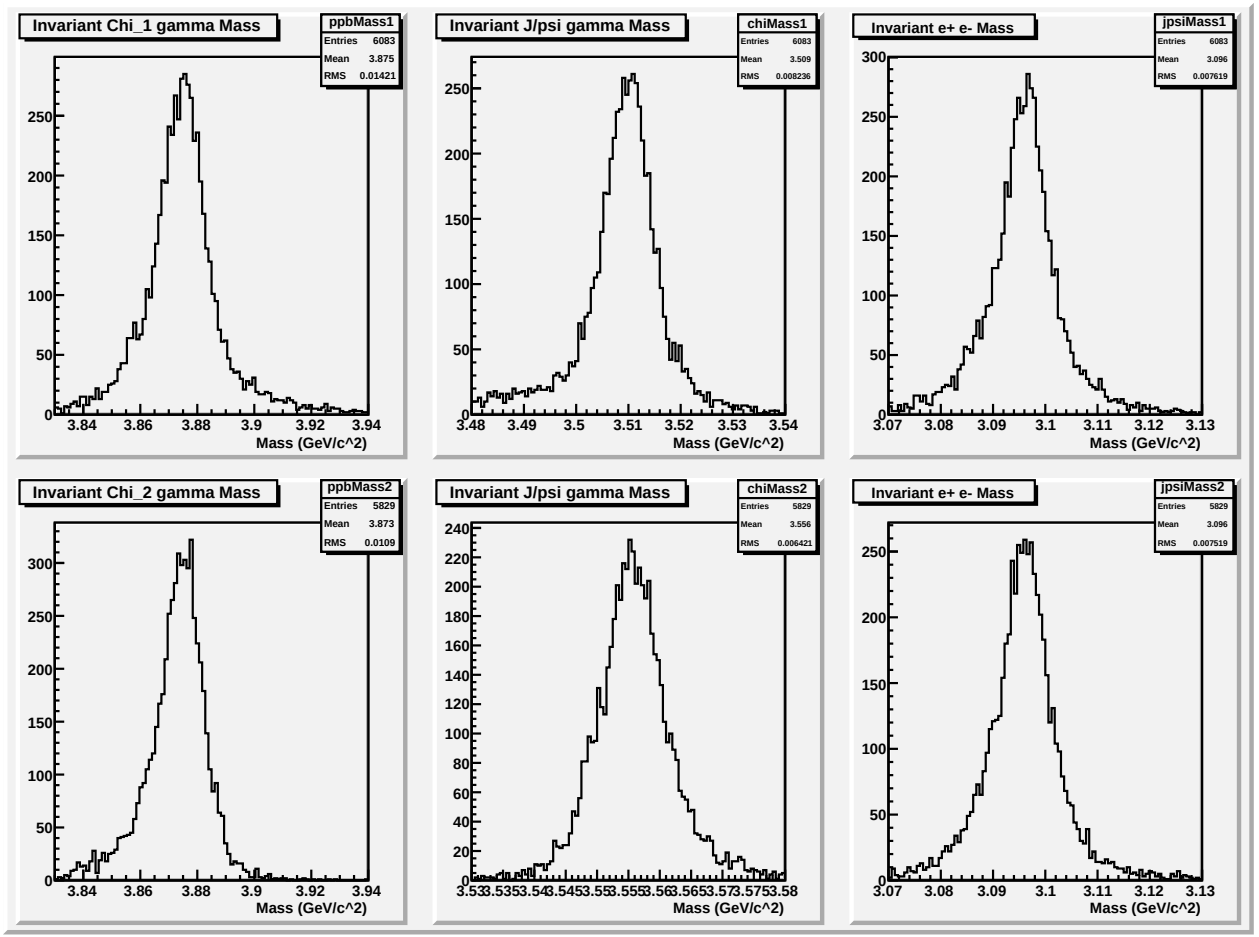
Table: Result for χ_1. Efficiency 29.47%

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_2\gamma$	3.686	8.47
$J/\psi\gamma$	3.556	5.54
e^+e^-	3.097	7.19

Table: Result for χ_2. Efficiency 29.31%

$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at X(3872)

The reconstructed masses of X(3872), $\chi_{1,2}$ and J/ψ are:



$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at X(3872)

Summary of the data:

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_1\gamma$	3.875	14.21
$J/\psi\gamma$	3.509	8.24
e^+e^-	3.096	7.92

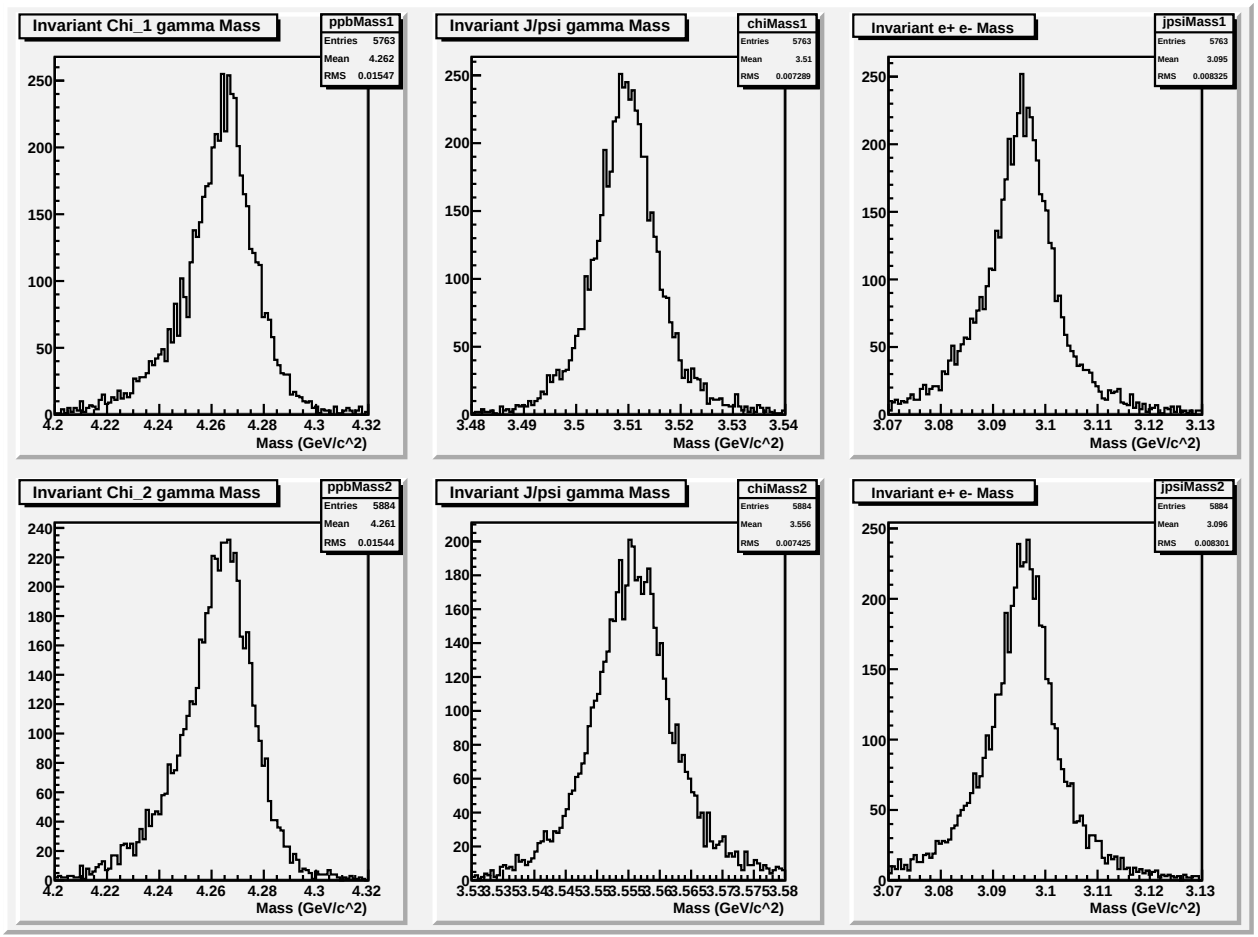
Table: Result for χ_1. Efficiency 30.42%

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_2\gamma$	3.873	10.79
$J/\psi\gamma$	3.556	6.42
e^+e^-	3.096	7.81

Table: Result for χ_2. Efficiency 29.15%

$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at Y(4260)

The reconstructed masses of Y(4260), $\chi_{1,2}$ and J/ψ are:



$\bar{p}p \longrightarrow \chi_{1,2}\gamma \longrightarrow J/\psi\gamma\gamma \longrightarrow e^+e^-\gamma\gamma$ at Y(4260)

Summary of the data:

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_1\gamma$	4.262	15.47
$J/\psi\gamma$	3.510	7.29
e^+e^-	3.095	8.55

Table: Result for χ_1. Efficiency 28.82%

Invariant Mass	Mean (GeV)	$\sigma(MeV)$
$\chi_2\gamma$	4.262	15.06
$J/\psi\gamma$	3.556	7.43
e^+e^-	3.096	8.51

Table: Result for χ_2. Efficiency 29.42%

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

Isabella Garzia

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 $\bar{c}c$ bound state.

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

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:

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

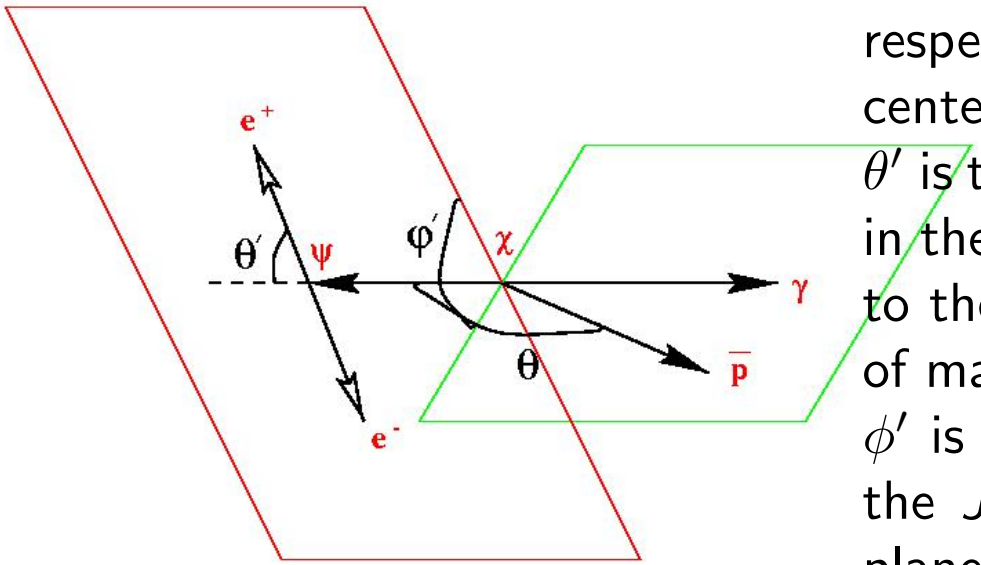
Angular distribution of the χ_{cJ} states

- 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



θ is the polar angle of the J/ψ with respect to the antiproton in the $\bar{p}p$ 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

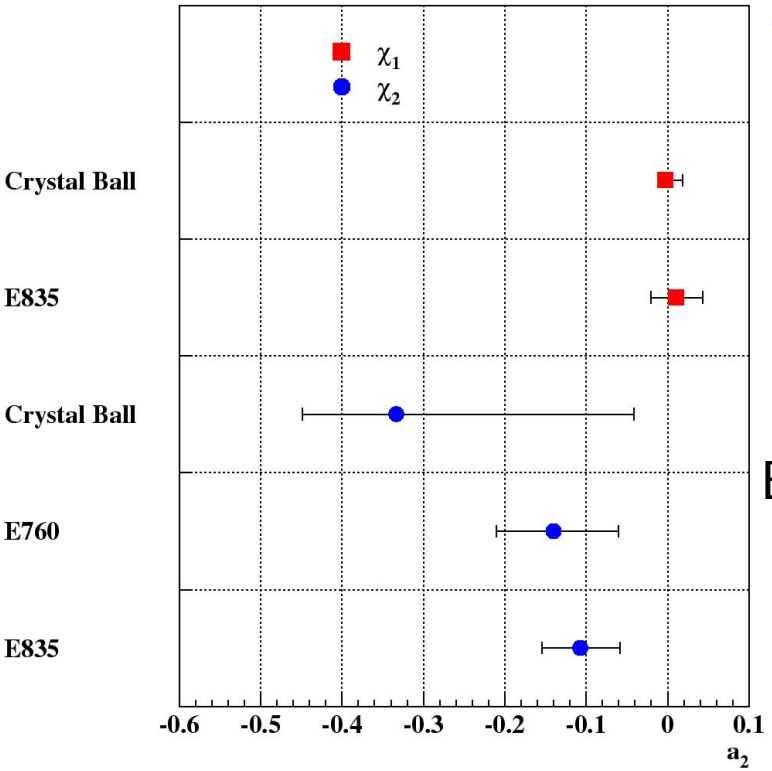
$\bar{p}p \to \chi_1 \to J/\psi\gamma \to e^+e^-\gamma$

- Production amplitudes: $B_0 = 0$
- Decay Amplitudes: a_2

$\bar{p}p \to \chi_2 \to J/\psi\gamma \to e^+e^-\gamma$

- Production amplitudes: B_0^2
- Decay Amplitudes: a_2, a_3

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:

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

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

χ_{c1} and χ_{c2} angular distributions

$\bar{p}p \to \chi_1 \to J/\psi\gamma \to e^+e^-\gamma$

- $a_2 = 0.002 \pm 0.032 \pm 0.004$

$\bar{p}p \to \chi_2 \to J/\psi\gamma \to e^+e^-\gamma$

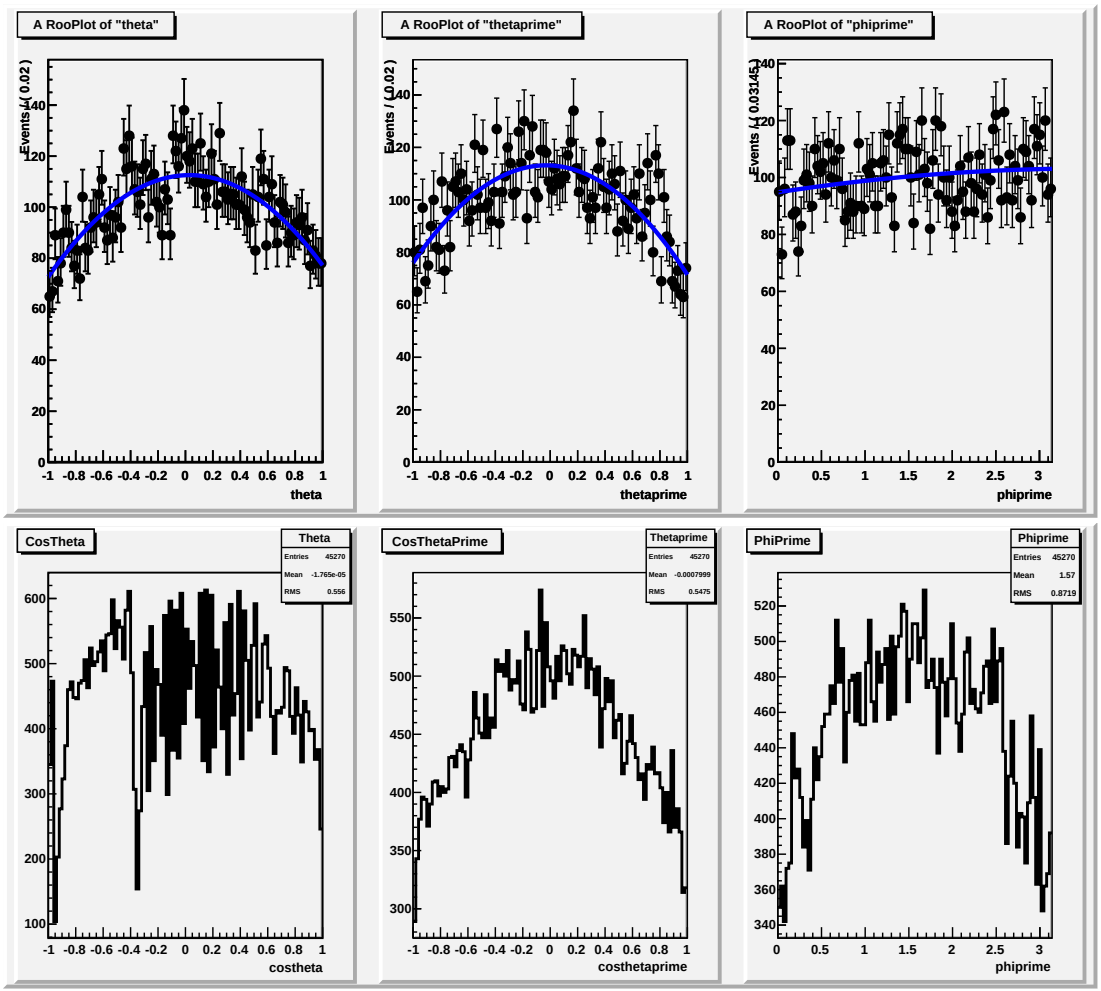
- $B_0^2 = 0.16^{+0.09}_{-0.10} \pm 0.01$
- $a_2 = -0.076^{+0.054}_{-0.050} \pm 0.009$
- $a_3 = 0.020^{+0.055}_{-0.044} \pm 0.009$

While the value of $a_2(\chi_2)$ agrees well with the predictions of a simple theorical model, the value of $a_2(\chi_1)$ is lower than expected (for $\kappa_c = 0$) and the ratio between the two, which is indipendent of κ_c is $\approx 2\sigma$ away from the prediction.
This could indicate the presence of competing mechanisms, lowering the value of the M2 amplitude at the χ_1.
Further, high statistics measurements of these angular distributions are needed to solve this question

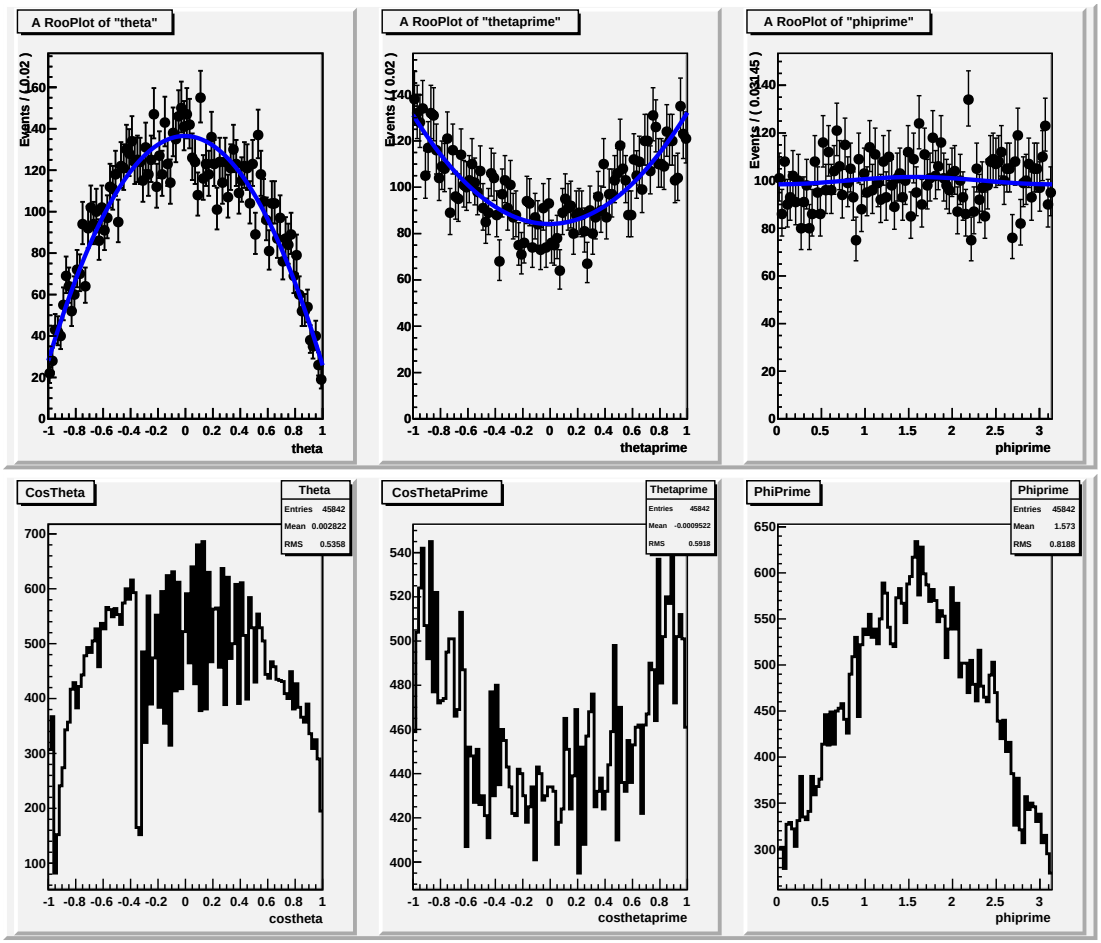
$\bar{p}p \to \chi_{1,2} \to J/\psi\gamma \to e^+e^-\gamma$

- List for Electrons: 1 ElectronCombinedLHLoose and 1 ElectronCombinedLHTight
- List for Photons: Calor Neutral with Energy$\in$[30MeV,15GeV]
- fittingAlgorith: TreeFitter
- J/ψ mass window: [2.7,3.4] GeV
- CL>0.1%
- 100.000 events generated
- No Phase Space Model Used

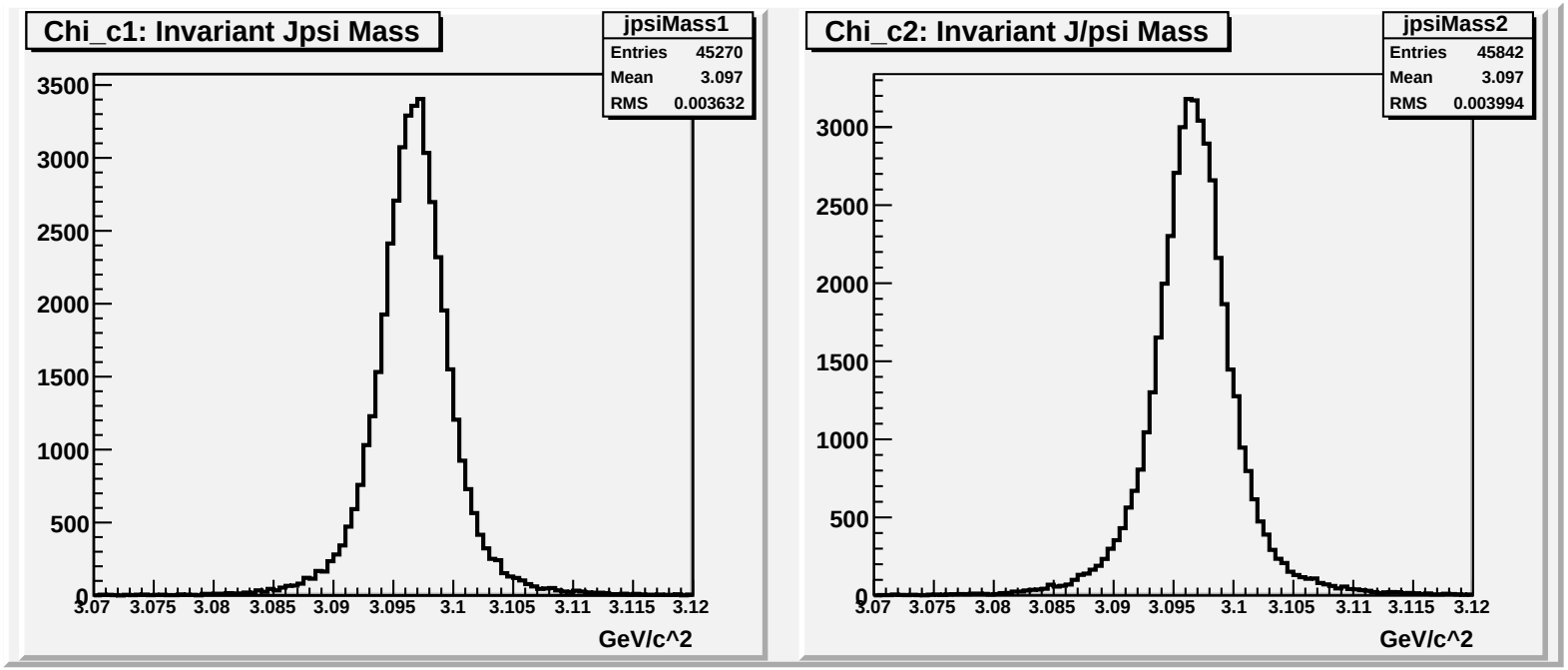
Angular distribution of $\bar{p}p \to \chi_1 \to J/\psi\gamma \to e^+e^-\gamma$



Angular distribution of $\bar{p}p \longrightarrow \chi_2 \longrightarrow J/\psi\gamma \longrightarrow e^+e^-\gamma$



Invariant e^+e^- mass



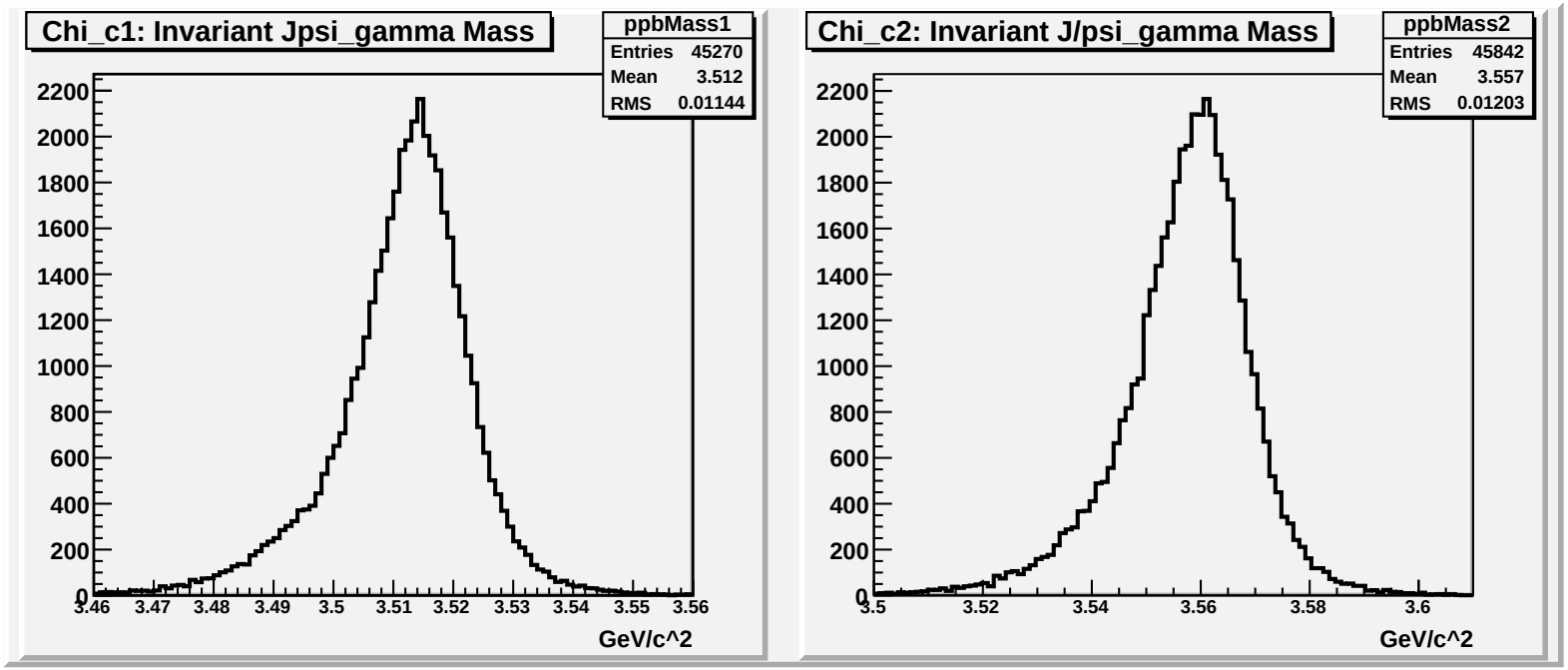
Result for χ_1

- Mean = 3.097 GeV
- Sigma = 3.63 MeV
- Eff = 45.27%

Result for χ_2

- Mean = 3.097 GeV
- Sigma = 3.99 MeV
- Eff = 45.84%

Invariant $J/\psi\gamma$ mass



Result for χ_1

- Mean = 3.512 GeV
- Sigma = 11.44 MeV
- Eff = 45.27%

Result for χ_2

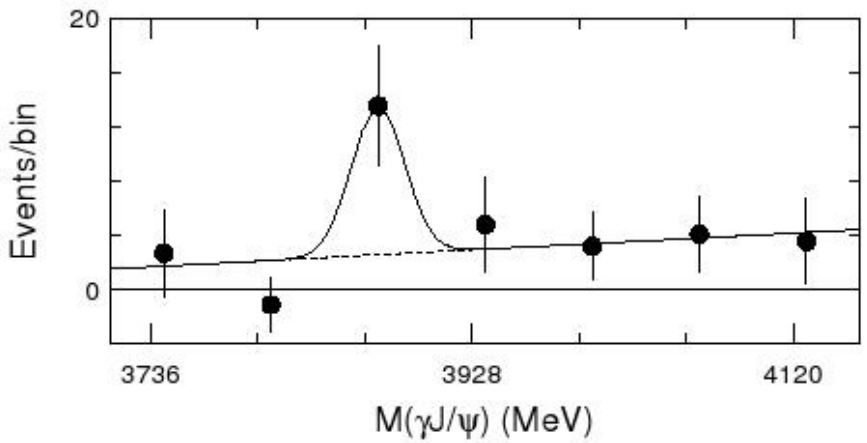
- Mean = 3.557 GeV
- Sigma = 12.03 MeV
- Eff = 45.84%

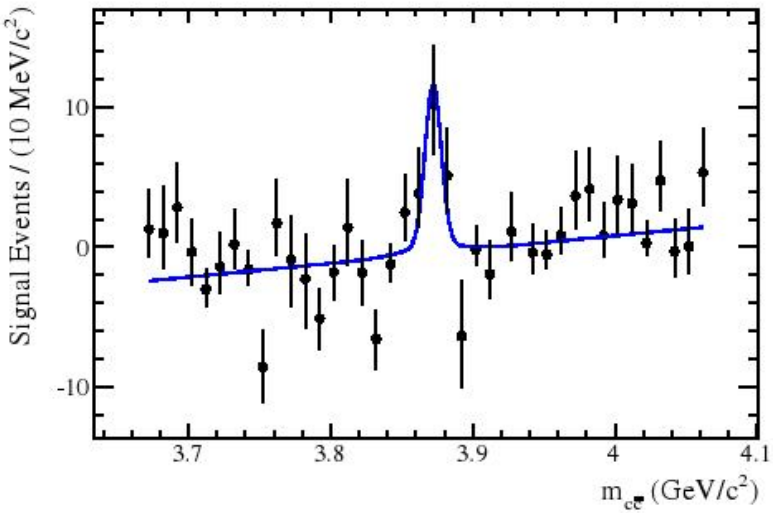
$\bar{p}p \to X(3872) \to J/\psi\gamma \to e^+e^-\gamma$

Isabella Garzia

Decay of X(3872) into $J/\psi\gamma$

Belle and BaBar saw $J/\psi\gamma$ decay of X(3872) in B decays ($B \to J/\psi\gamma K$)





Belle Result: (Ref: hep-ex/0505037)

$B(B \to X(3872)K^+, X \to J/\psi\gamma) = (1.8 \pm 0.6 \pm 0.1) \cdot 10^{-6}$

BaBar Result: (Ref: PRD 74, 071101 (2006))

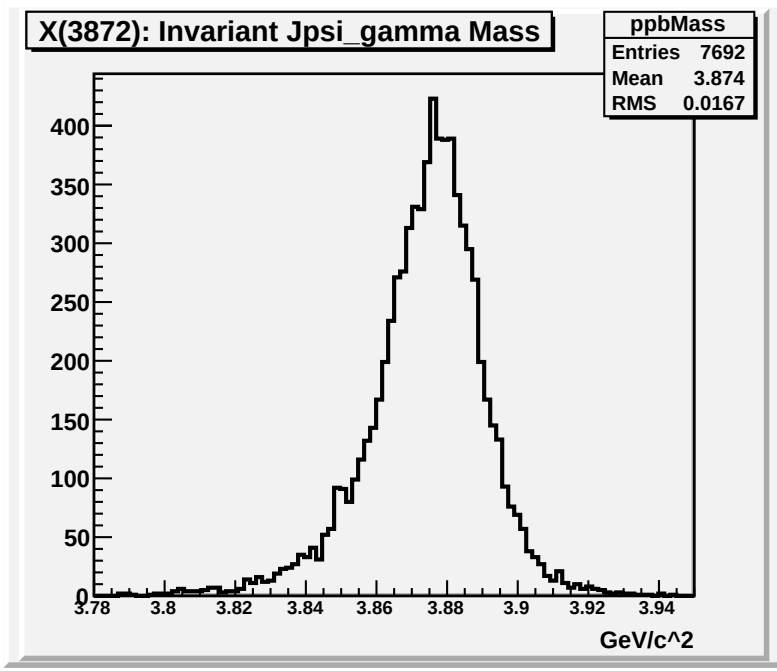
$B(B \to X(3872)K^+, X \to J/\psi\gamma) = (3.3 \pm 1.0 \pm 0.3) \cdot 10^{-6}$

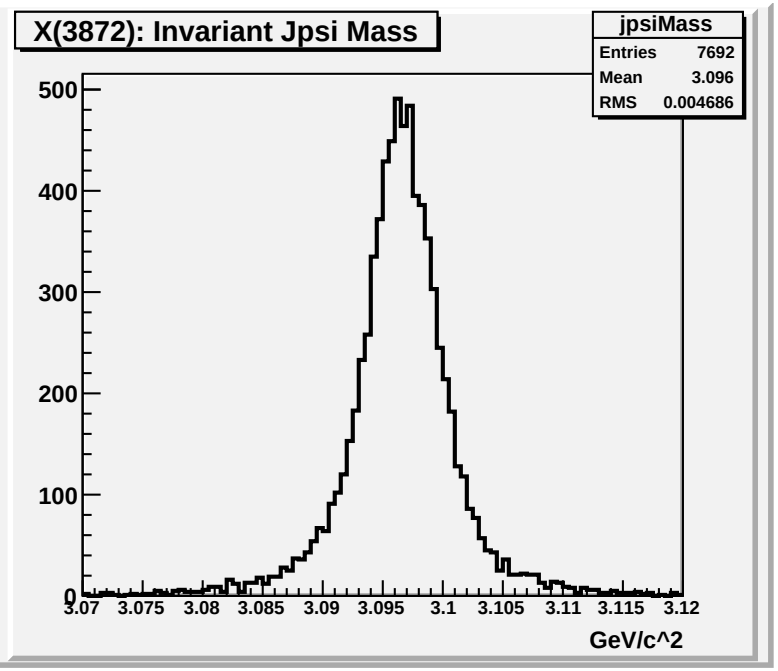
Never seen $\bar{p}p \to X(3872) \to J/\psi\gamma$

$\bar{p}p \to X(3872) \to J/\psi\gamma \to e^+e^-\gamma$

- List for Electrons: 1 ElectronCombinedLHLoose and 1 ElectronCombinedLHTight
- List for Photons: Calor Neutral with Energy$\in$[30MeV,15GeV]
- fittingAlgorith: TreeFitter
- J/ψ mass window: [2.7,3.4] GeV
- CL>0.1%
- 20.000 events generated
- Phase Space Model Used

$X(3872) \to J/\psi\gamma \to e^+e^-\gamma$





Invariant $J/\psi\gamma$ mass

- Mean = 3.874 GeV
- Sigma = 16.70 MeV
- Eff = 38.46%

Invariant e^+e^- mass

- Mean = 3.096 GeV
- Sigma = 4.69 MeV
- Eff = 38.46%

Background: $\bar{p}p \longrightarrow \pi^+\pi^-\pi^0$

1.964.000 events analyzed

Apply the same selection of signal events to background events

$\sigma(\bar{p}p \longrightarrow \pi^+\pi^-\pi^0) \approx 0.29mb$ (Ref: Flaminio CERN-HERA 79.03)

9 events pass the selection

0 events peak at the J/ψ mass after PID cuts

Summary

- In the release 0.15.3 all these channels are well simulated.
- The new angular distribution models implemented seem to work very well.
- The background analyzed demonstrates that the signal channels could be well identified.

To do:

- Correct the angular distribution of $\chi_{1,2}$ for the acceptance of the detector
- Study the background for the $\chi_{1,2}$ radiative decays

Thanks for the attention!

Backup slides

Backup slides

Angular Distribution for the decay of $\chi_{1,2}$ into $J/\psi\gamma$

The angular distribution of the process can be written as:

$$W(\theta, \theta', \phi') = \sum_i K_i \left(B_{|\lambda(\bar{p})-\lambda(p)|}, A_{|\lambda(J/\psi)-\lambda(\gamma)|}\right) T_i(\theta, \theta', \phi') \qquad (3)$$

where:

- the coefficients K_i depend upon the helicity amplitudes
- T_i are functions of the observed angles θ, θ', ϕ'
- $B_{|\lambda(\bar{p})-\lambda(p)|}$ parametrize the dynamics of the formation process
- $A_{|\lambda(J/\psi)-\lambda(\gamma)|}$ parametrize the dynamics of the decay processes.
- The index $\lambda(\bar{p}) - \lambda(p)$ is equal to the projection of the χ_c spin on the $\bar{p}$ direction
- The index $\lambda(J/\psi) - \lambda(\gamma)$ is the projection of the χ_c spin on the J/ψ direction

Connection of helicity and multipole amplitude

The helicity amplitudes A_k are linear combinations of the multipole amplitudes a_i.

$$\left(\begin{array}{l} A_0 = \frac{1}{\sqrt{2}} a_1 - \frac{1}{\sqrt{2}} a_2 \\ \\ A_1 = \frac{1}{\sqrt{2}} a_1 + \frac{1}{\sqrt{2}} a_2 \end{array} \right)_{\chi_1, J=1}$$

$$\left(\begin{array}{l} A_0 = \sqrt{\frac{1}{10}} a_1 + \sqrt{\frac{1}{2}} a_2 + \sqrt{\frac{6}{15}} a_3 \\ \\ A_1 = \sqrt{\frac{3}{10}} a_1 + \sqrt{\frac{1}{6}} a_2 - \sqrt{\frac{8}{15}} a_3 \\ \\ A_2 = \sqrt{\frac{6}{10}} a_1 - \sqrt{\frac{1}{3}} a_2 + \sqrt{\frac{1}{15}} a_3 \end{array} \right)_{\chi_2, J=2}$$

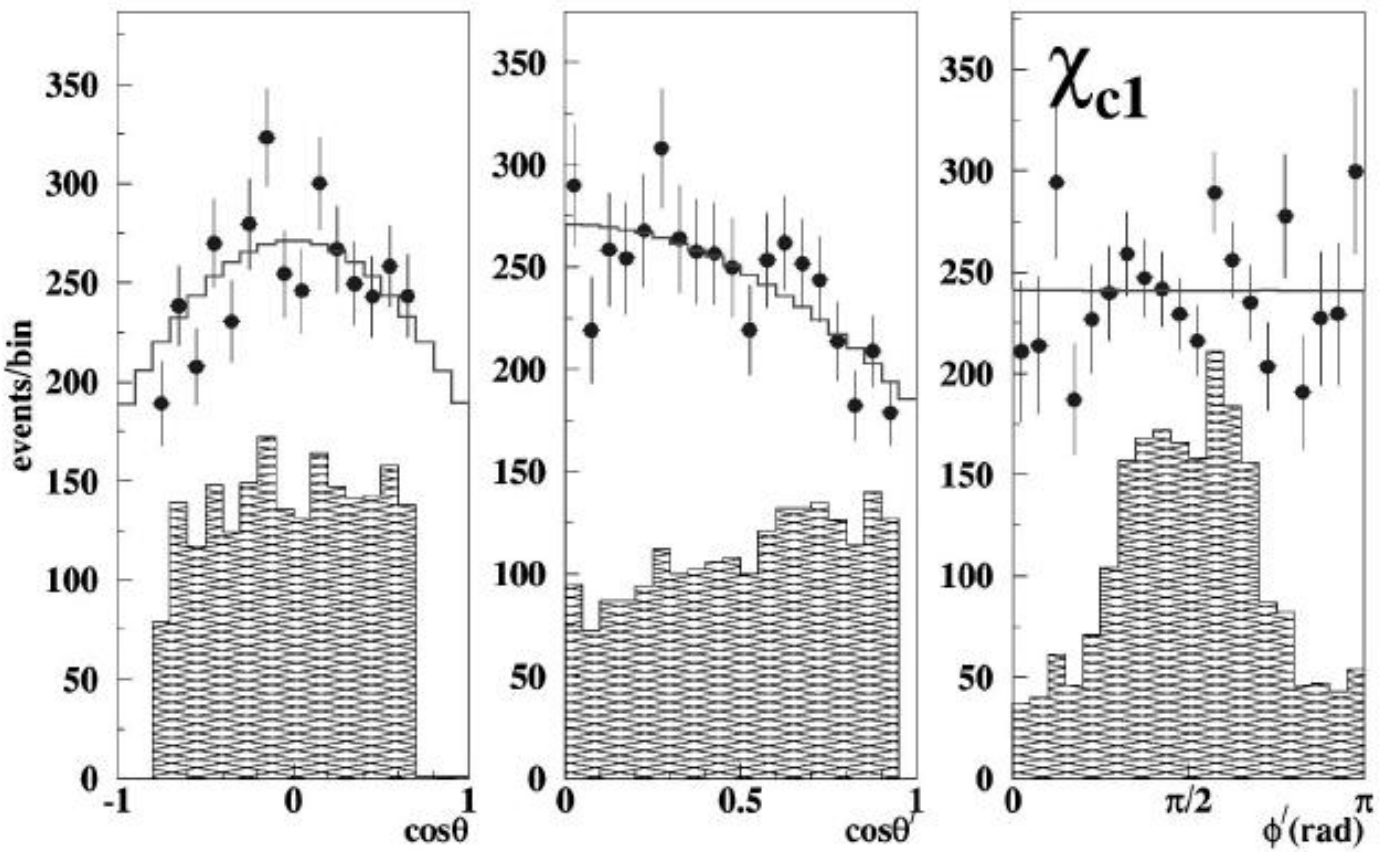
K_i and T_i for the χ_1

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

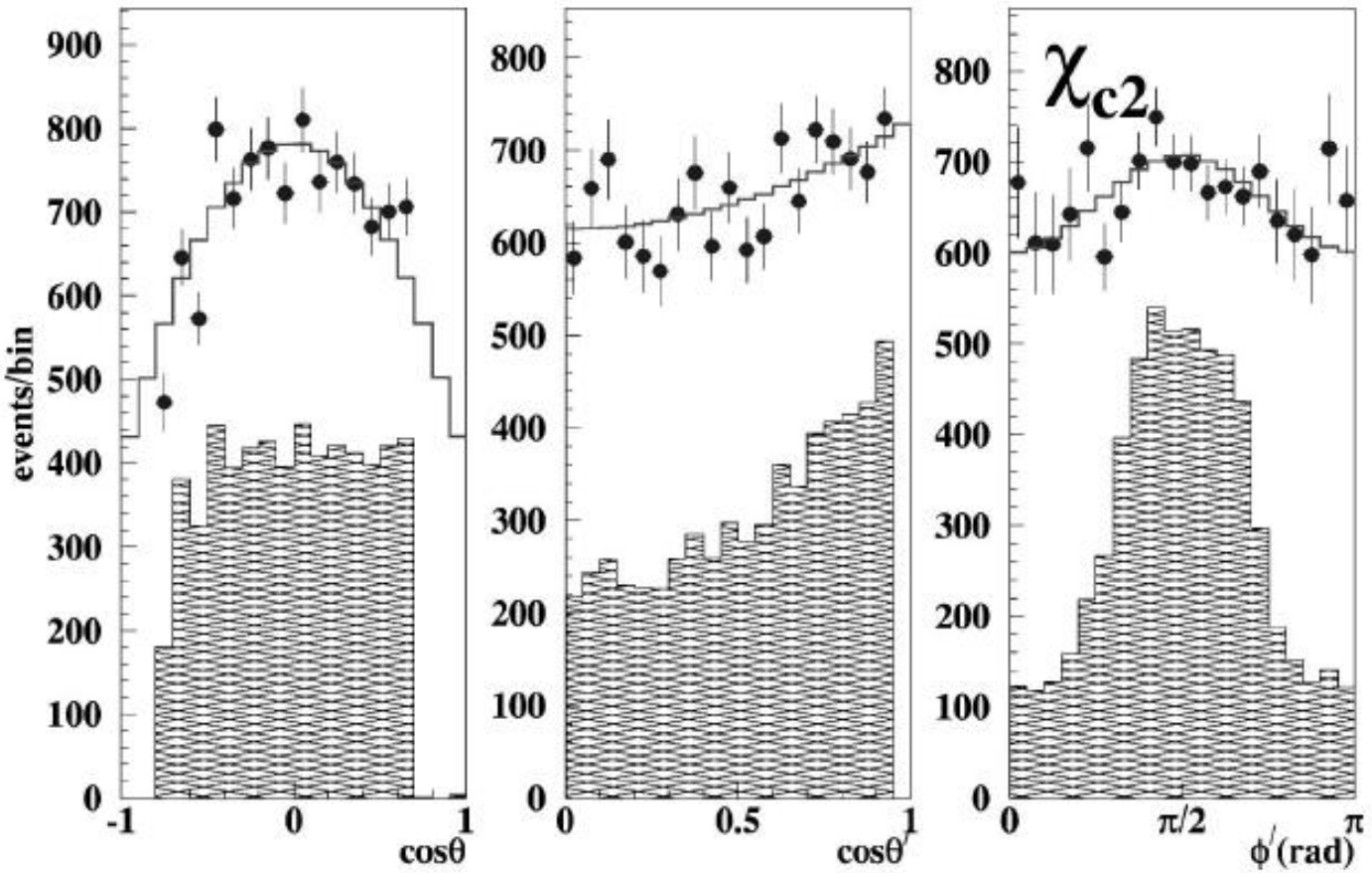
K_i and T_i for the χ_2

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	$\cos^2\theta\sin 2\theta\sin 2\theta'\cos\phi'$	$-\frac{1}{4\sqrt{3}}(5R - 3)\left(3A_0A_1 + \sqrt{\frac{3}{2}}A_1A_2\right)$

Angular distribution of $\bar{p}p \to \chi_1 \to J/\psi\gamma \to e^+e^-\gamma$ from E835



Angular distribution of $\bar{p}p \to \chi_2 \to J/\psi\gamma \to e^+e^-\gamma$ from E835



Angular distribution of $\bar{p}p \to \chi_1 \to J/\psi\gamma \to e^+e^-\gamma$ from E835

If $a_2 = 0$ the projections of the angular distributions reduce to:

$$\overline{W}(cos\theta) \sim 1 - \frac{1}{3}cos^2\theta$$

$$\overline{W}(cos\theta') \sim 1 - \frac{1}{3}cos^2\theta'$$

Angular distribution of $\bar{p}p \to \chi_2 \to J/\psi\gamma \to e^+e^-\gamma$ from E835

If $a_2 = 0$ and $B_0^2 = 0$ the projections of the angular distributions reduce to:

$$\overline{W}(cos\theta) \sim 1 - \frac{1}{3}cos^2\theta$$

$$\overline{W}(cos\theta') \sim 1 + \frac{1}{13}cos^2\theta'$$

$$\overline{W}(\phi') \sim 1 - \frac{8}{71}cos2\phi'$$