Study of charmonium states formed in $\bar{p}p$ annihilations: results from Fermilab E835

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OUTLINE

- Introduction.
- Experimental Method.
- Results:
  - $\bar{p}p \to \chi_0 \to J/\psi+\gamma \to e^+e^-+\gamma$
  - $\bar{p}p \to \eta_c \to \gamma+\gamma$
  - $\bar{p}p \to \chi_2 \to \gamma+\gamma$
  - $\bar{p}p \to \chi_0 \to \gamma+\gamma$
  - search for $\bar{p}p \to \eta_c' \to \gamma+\gamma$
  - proton e.m. form factors (time-like)
  - $\bar{p}p \to \eta_c \to \phi\phi \to 4K$
- Summary and outlook.

Introduction

E835 studies the direct formation of $\bar{c}c$ states in $\bar{p}p$ annihilations. It is a fixed target experiment, in which the antiproton beam circulating in the Fermilab accumulator intersects a hydrogen gas jet target.

The charmonium system has often been called the *hydrogen atom of strong interactions.*

Non relativistic potential models + relativistic corrections + Perturbative QCD make it possible to calculate masses, widths and branching ratios to be compared with experiment.

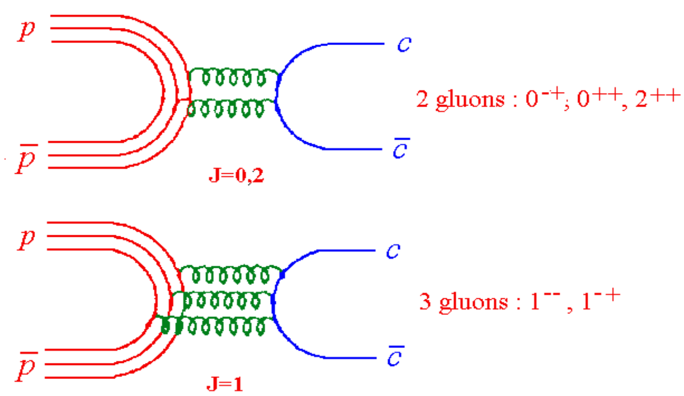
Why $\bar{p}p$?

In e^+e^- annihilations only states with the quantum number of the photon $J^{PC} = 1^{--}$ can be formed directly via the process $e^+e^- \to \gamma^* \to \bar{c}c$. States with $J^{PC} \neq 1^{--}$ are usually studied from radiative decays, e.g.

$$e^+e^- \to \psi' \to \chi + \gamma$$

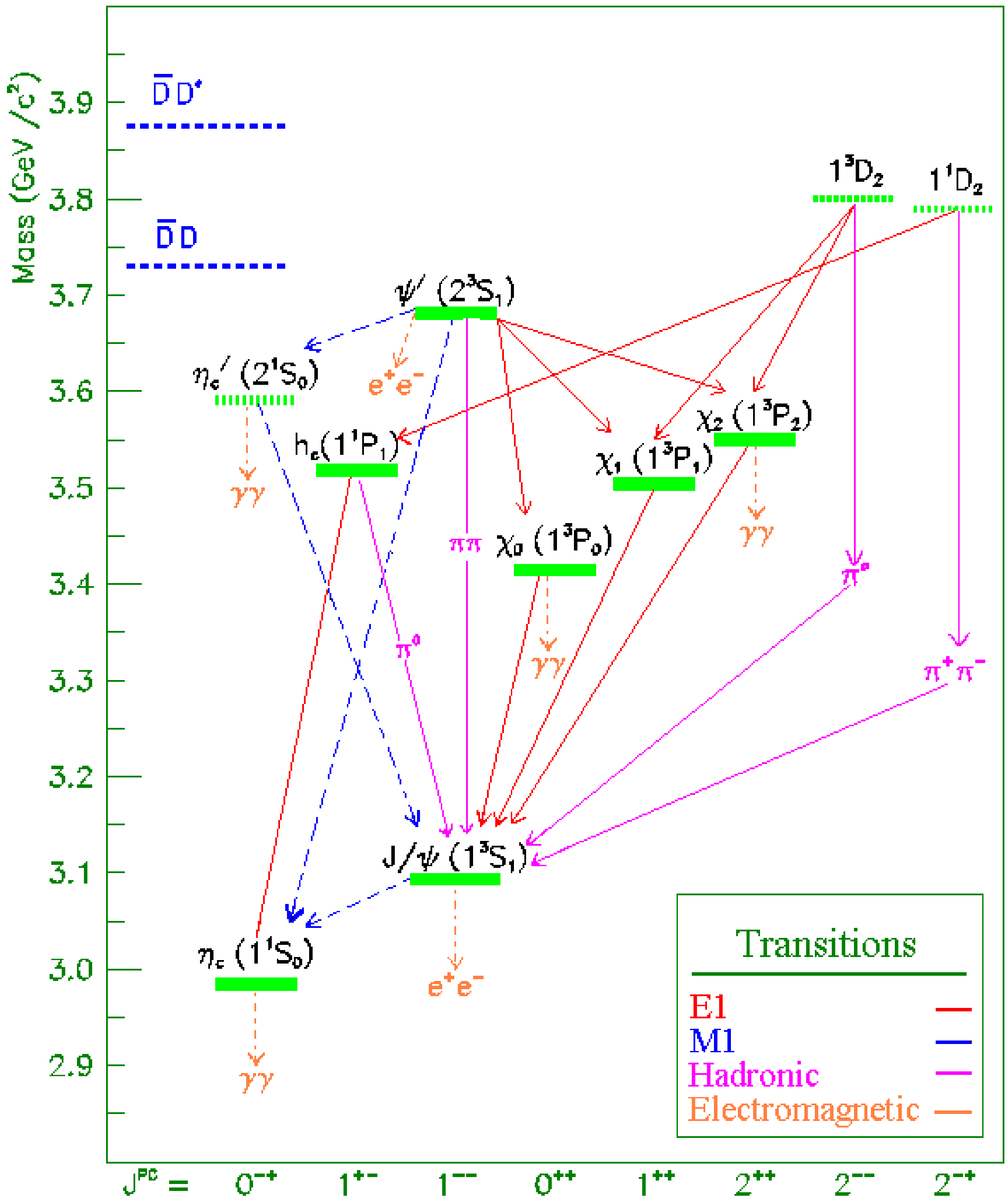
In this case the measurement accuracy (for masses and widths) is limited by the detector.

In $\bar{p}p$ annihilations all quantum numbers are directly accessible.



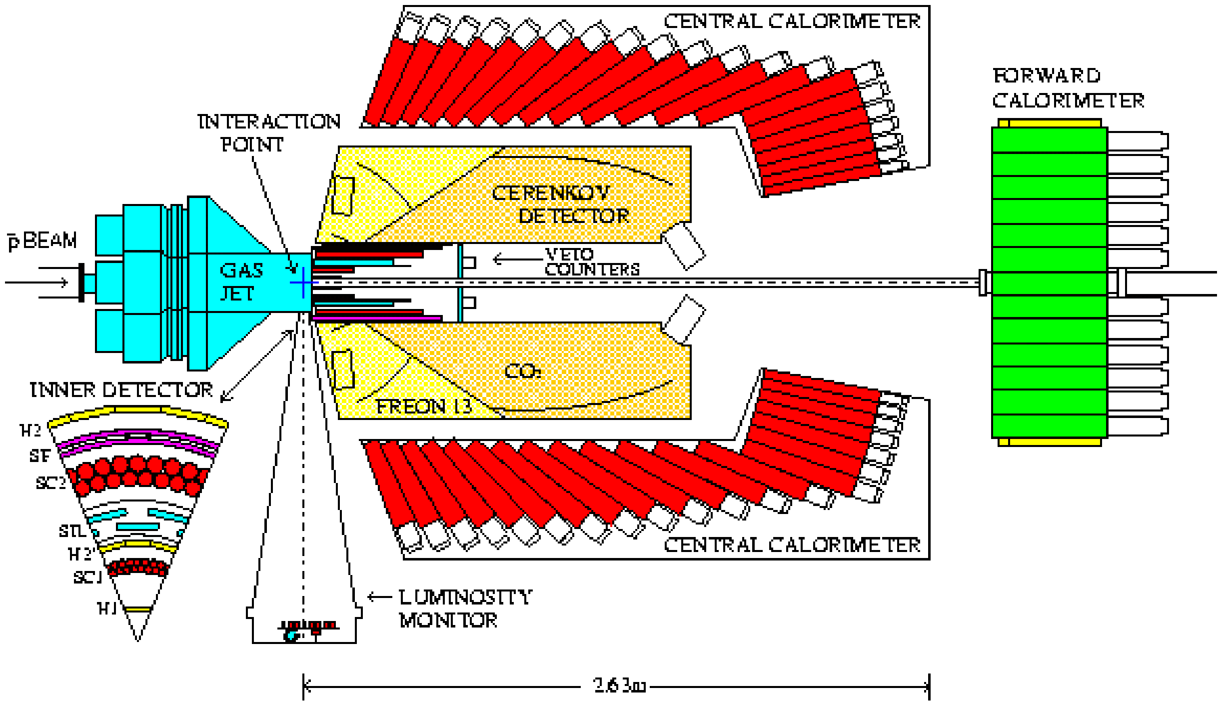
The resonance parameters are determined from the beam parameters and do not depend on the detector energy and momentum resolution.

CHARMONIUM SPECTRUM



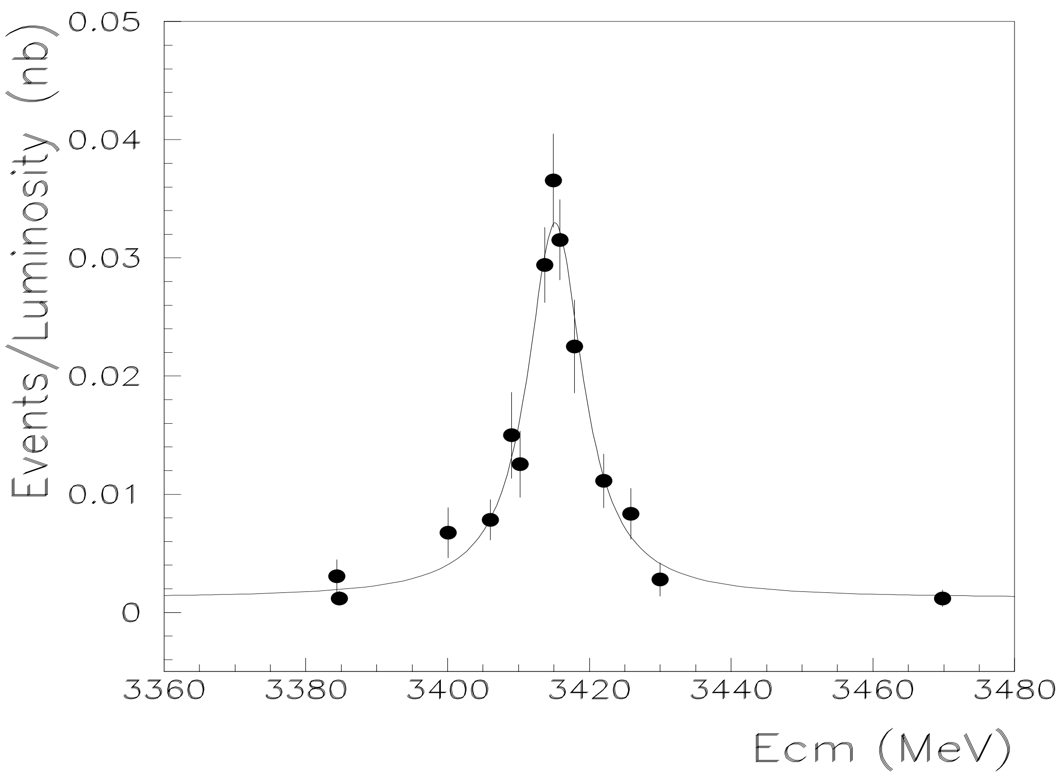
E835 DETECTOR

$$p\bar{p} \to c\bar{c} \to e^+e^-$$
$$p\bar{p} \to c\bar{c} \to J/\psi\ X \to e^+e^-X$$
$$p\bar{p} \to c\bar{c} \to \gamma\gamma$$
$$p\bar{p} \to multi \quad \gamma$$
$$p\bar{p} \to \phi\phi \to K^+K^-K^+K^-$$
$$p\bar{p} \to p\bar{p}$$



$\bar{p}p \rightarrow \chi_0 \rightarrow J/\psi + \gamma \rightarrow e^+e^- + \gamma$

PRELIMINARY



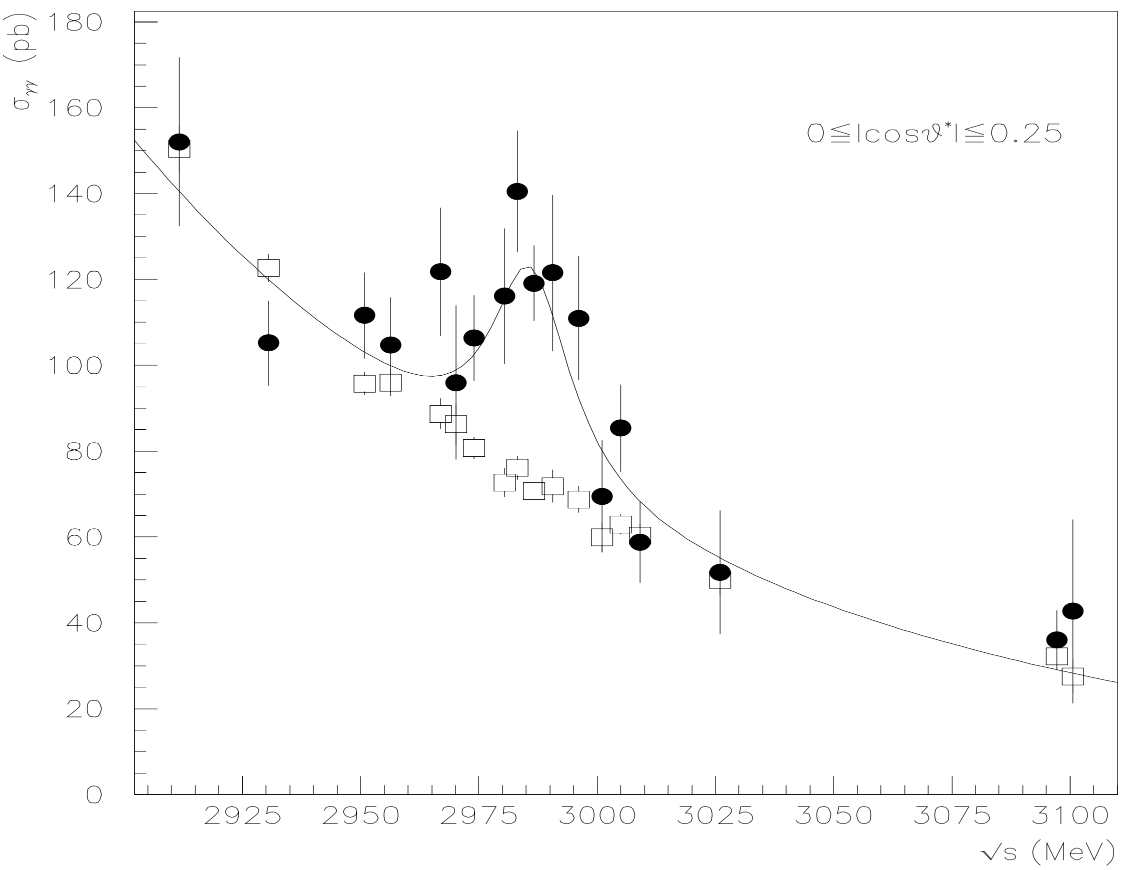
$$M(\chi_0) = 3414.97 \pm 0.42 \; MeV$$

$$\Gamma(\chi_0) = 9.78 \pm 1.15 \; MeV$$

$$B(\chi_0 \rightarrow \bar{p}p) = (5.86 \pm 0.39) \times 10^{-4}$$

$\eta_c(1^1S_0) \rightarrow \gamma\gamma$

PRELIMINARY



$$M(\eta_c) = 2985.4^{+2.1}_{-2.0}\, MeV$$

$$\Gamma(\eta_c) = 21.1^{+7.5}_{-6.2}\, MeV$$

$$B(\eta_c \rightarrow \overline{p}p) \times B(\eta_c \rightarrow \gamma\gamma) = (21.8^{+3.4}_{-3.3}) \times 10^{-8}$$

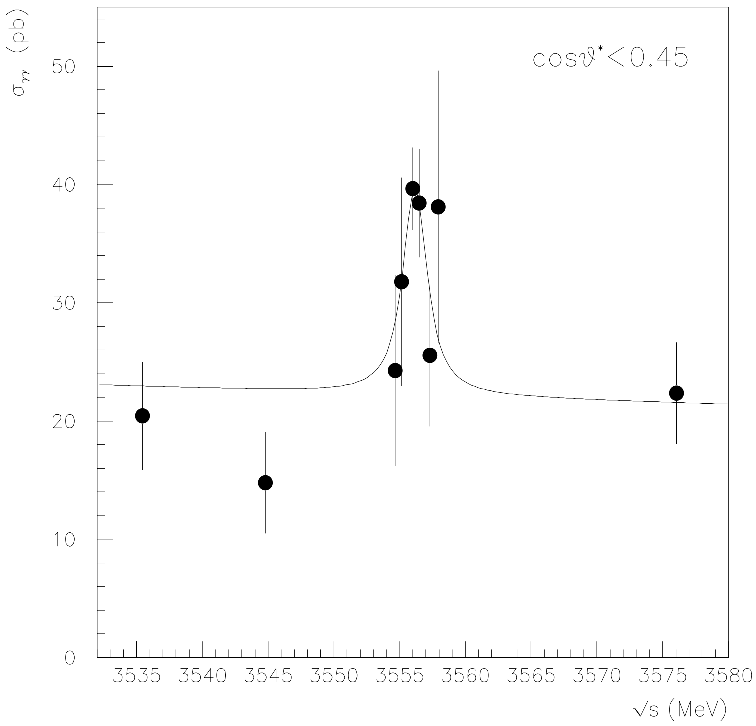
$$\Gamma(\eta_c \rightarrow \gamma\gamma) = 3.85^{+1.5}_{-1.2}\, KeV$$

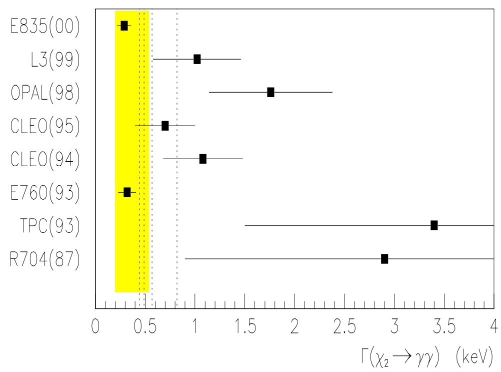
$$(with\, B(\eta_c \rightarrow \overline{p}p) = (12 \pm 4) \times 10^{-4})$$

$\chi_{c2} \to \gamma\gamma$

E835 has improved the measurement of the partial width to two photons of the χ_{c2} state:

$$\Gamma(\chi_{c2} \to \gamma\gamma) = 0.27 \pm 0.049 \pm 0.033 keV$$

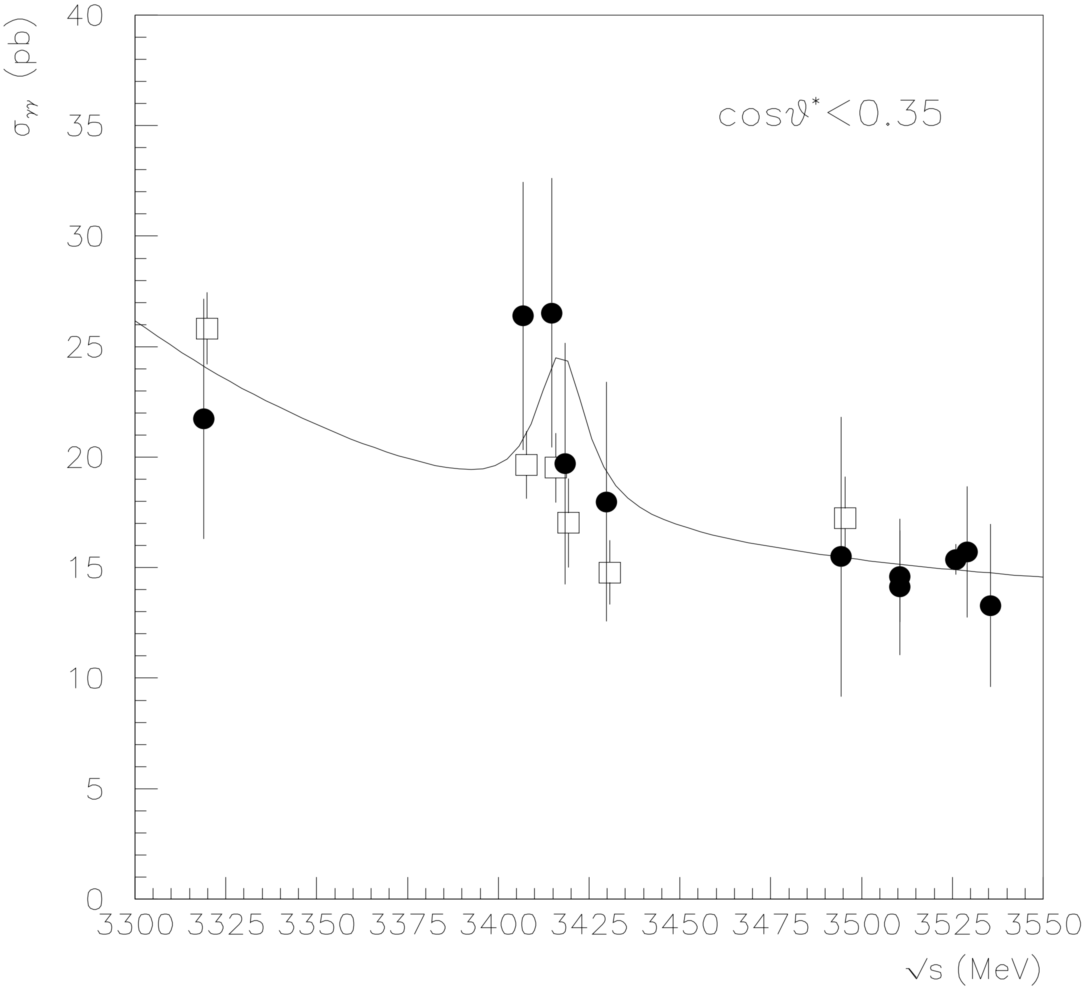




$\chi_{c0} \rightarrow \gamma\gamma$

The χ_{c0} state has also been studied through the two photons decay

Analysis of the χ_{c0} data is in progress

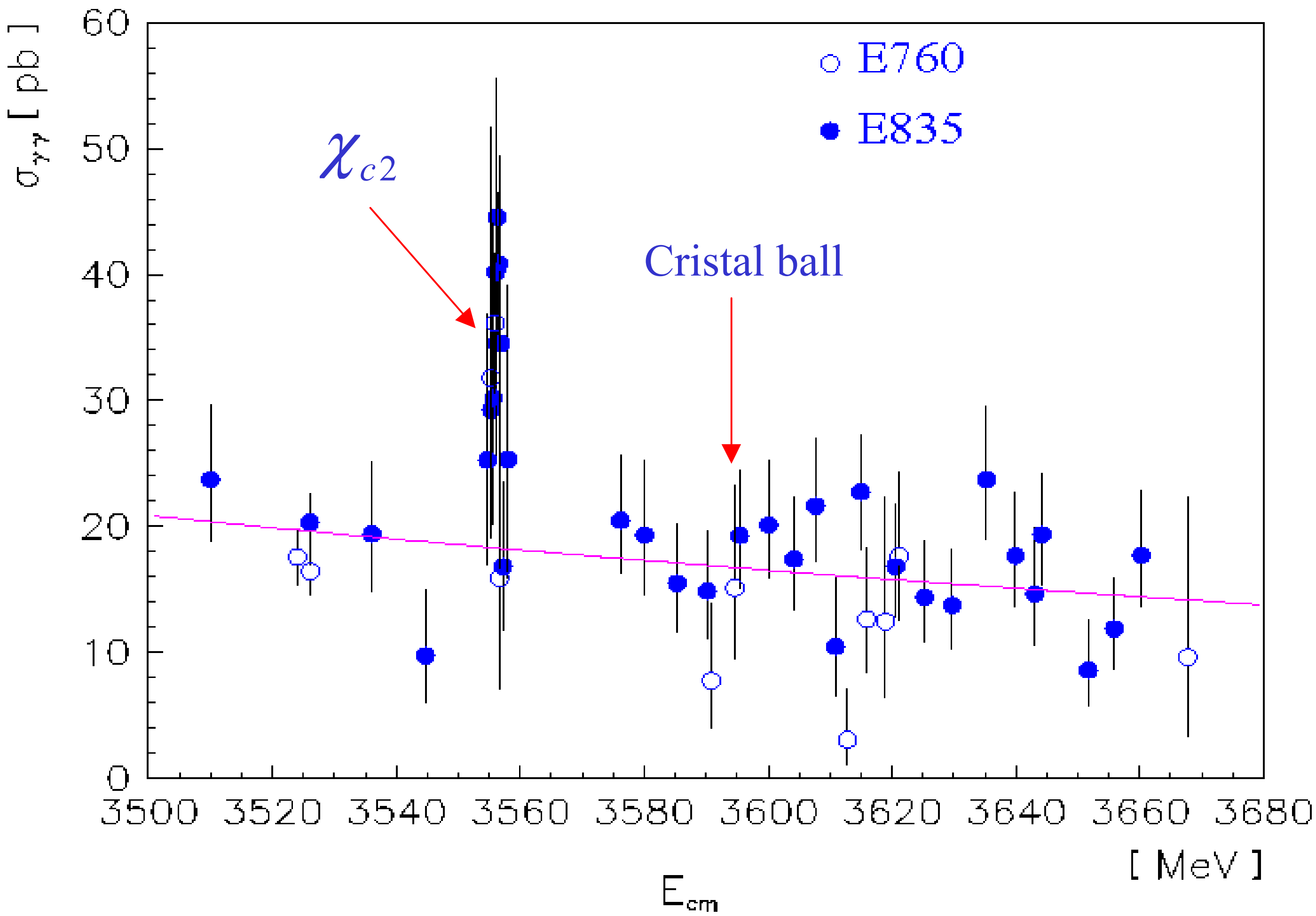


η_c' search

- E835 searched for the η_c' state in the region:

$$3576 < E(MeV) < 3660$$

- No evidence has been found



η'_c search

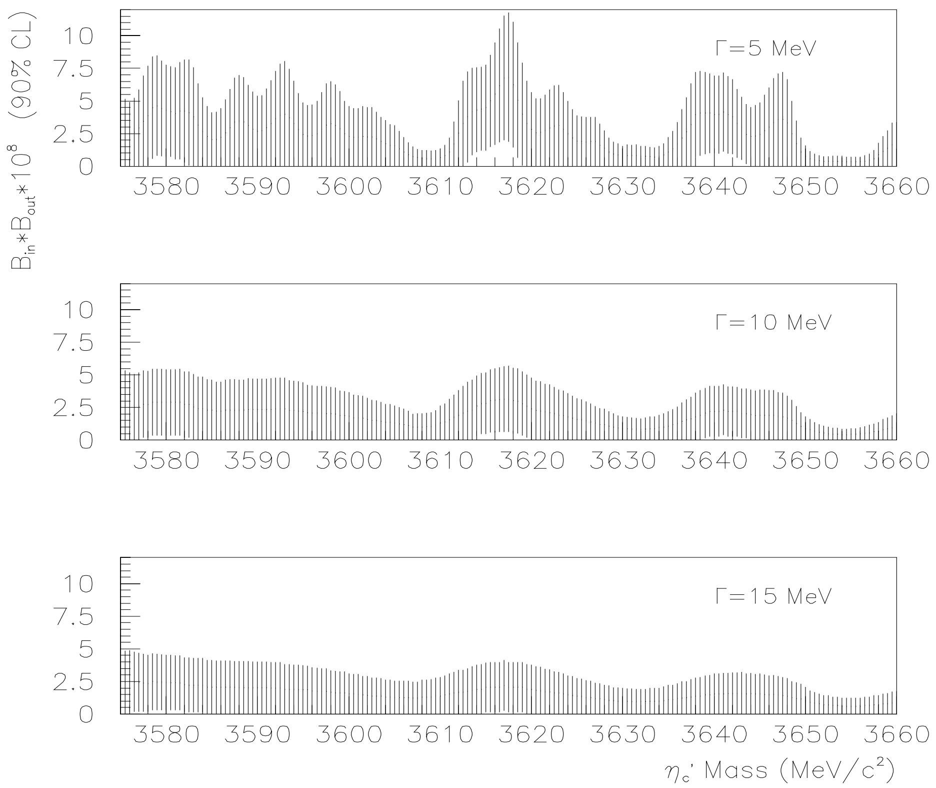
- We fit the data (maximum likelihood) with hypothesis of a spin 0 resonance plus a power law background, for three values of the total width

- According to our result we can set the upper limits:

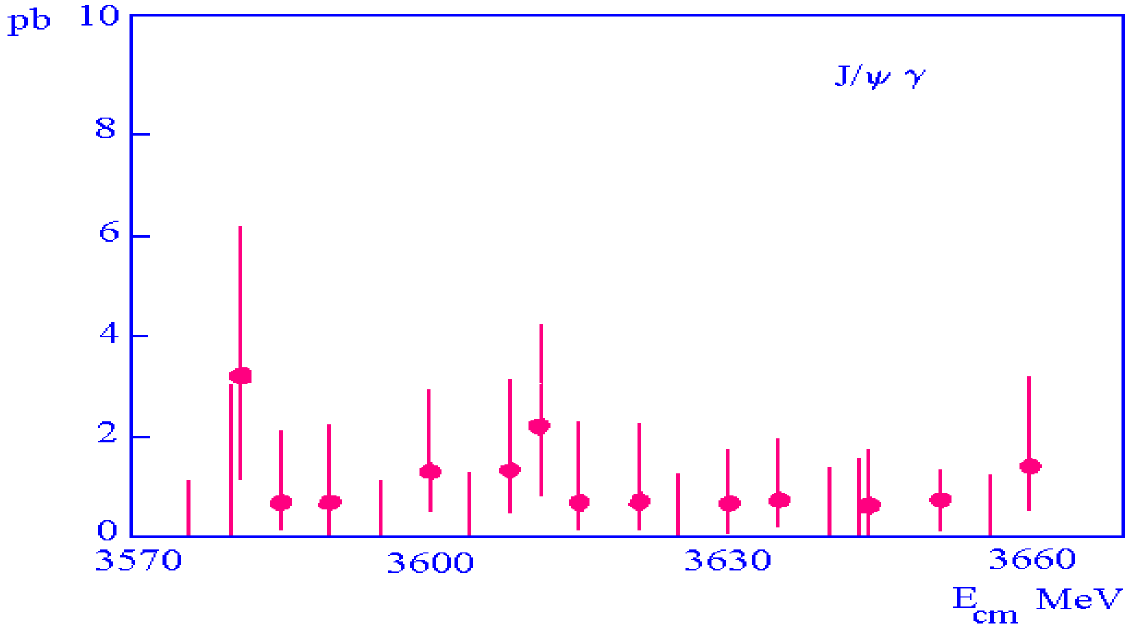
$$B.R.(\eta'_c \to \overline{p}p) \times B.R.(\eta'_c \to \gamma\gamma) < 12 \times 10^{-8} (\Gamma_{\eta'_c} = 5 MeV)$$

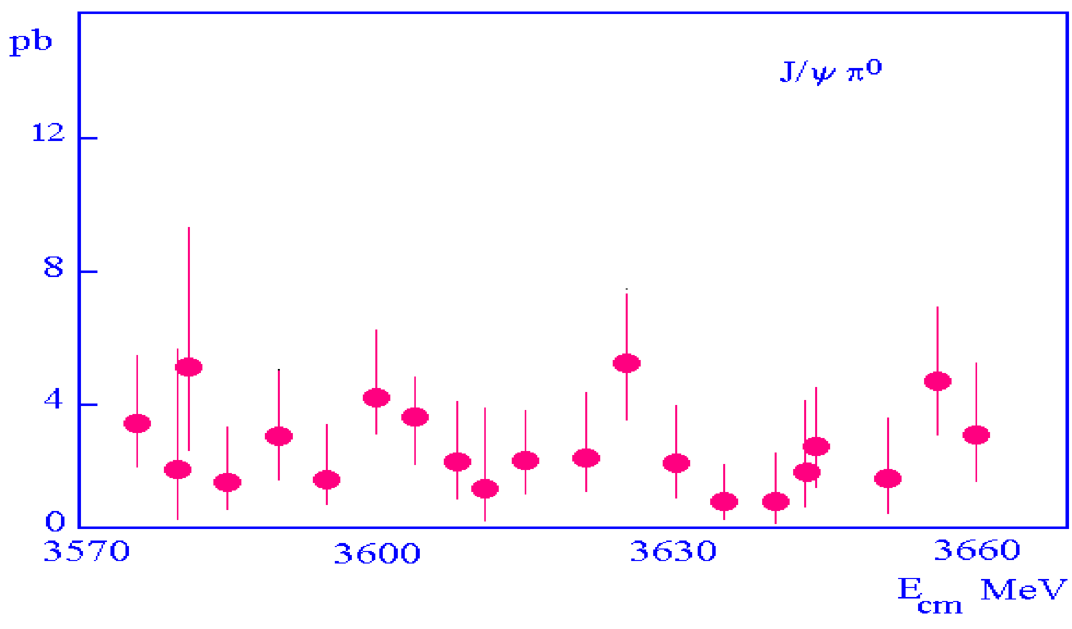
$$B.R.(\eta'_c \to \overline{p}p) \times B.R.(\eta'_c \to \gamma\gamma) < 6 \times 10^{-8} (\Gamma_{\eta'_c} = 10 MeV)$$

$$B.R.(\eta'_c \to \overline{p}p) \times B.R.(\eta'_c \to \gamma\gamma) < 6 \times 10^{-8} (\Gamma_{\eta'_c} = 15 MeV)$$



η_c' search in other channels

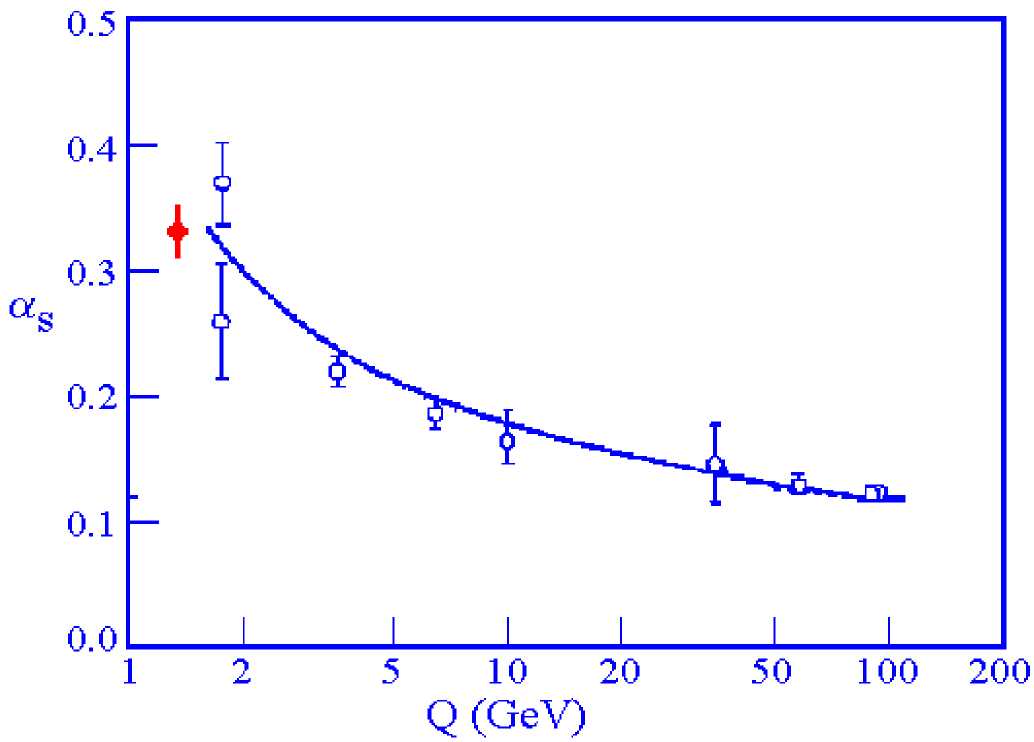




Determination of $\alpha_s(m_c)$

$$\frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\eta_c \to gg)} = \frac{8\alpha^2}{9\alpha_s^2} \cdot \frac{\left[1 - \frac{3.4}{\pi}\alpha_s\right]}{\left[1 + \frac{4.8}{\pi}\alpha_s\right]} \Rightarrow \alpha_s(m_c) = 0.33^{+0.06}_{-0.03}$$

$$\frac{\Gamma(\chi_2 \to \gamma\gamma)}{\Gamma(\chi_2 \to gg)} = \frac{8\alpha^2}{9\alpha_s^2} \cdot \frac{\left[1 - \frac{16}{3\pi}\alpha_s\right]}{\left[1 - \frac{2.2}{\pi}\alpha_s\right]} \Rightarrow \alpha_s(m_c) = 0.38 \pm 0.02$$



Proton e.m. form factors in the time-like region

The proton electromagnetic form factors in the timelike region can be extracted from the measurement of the cross section for the process:

$$\bar{p}p \rightarrow e^+e^-$$

First order QED predicts:

$$\frac{d\sigma}{d(\cos\theta^*)} = \frac{\pi\alpha^2\hbar^2c^2}{2xs}\left[|G_M|^2\left(1+\cos^2\theta^*\right)+\frac{4m_p^2}{s}|G_E|^2\left(1-\cos^2\theta^*\right)\right]$$

Background from $\pi^0\pi^0$, $\pi^0\gamma,\gamma\gamma$ and $\pi^+\pi^-$ has been carefully evaluated and is negligible.

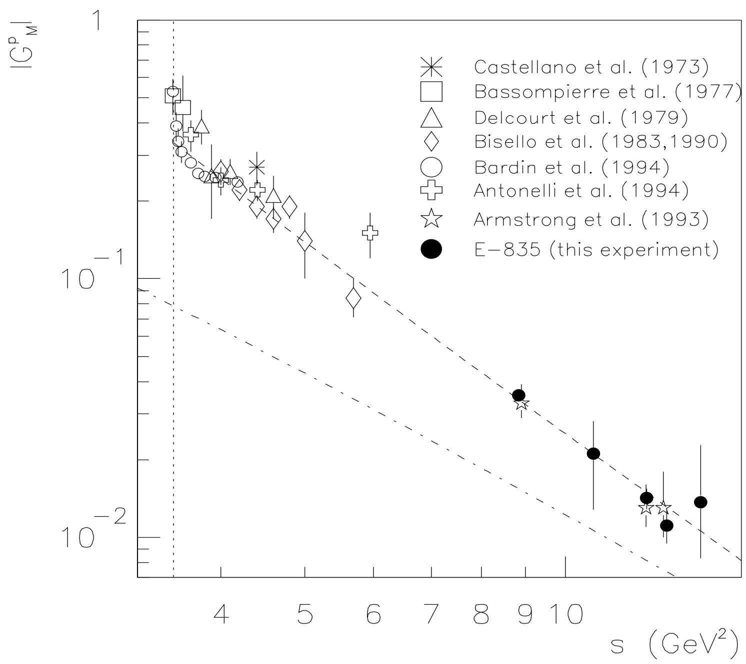
The form factors are extracted from the data under two separate hypotheses:

- |GE| = |GM|.
- Neglecting the term containing GE.

The data are well fitted by the PQCD predicted functional form:

$$\frac{|G_M|}{\mu_p} = \frac{C}{s^2 \ln^2\left(\frac{s}{\Lambda^2}\right)}$$

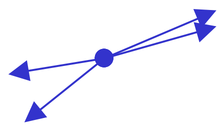
Proton Magnetic Form Factor



The dashed line is the PQCD fit.
The dot-dashed line represents the dipole behaviour of the form factor in the spacelike region for the same values of $|q|^2$.

$\eta_c \rightarrow \phi\phi \rightarrow 4K$

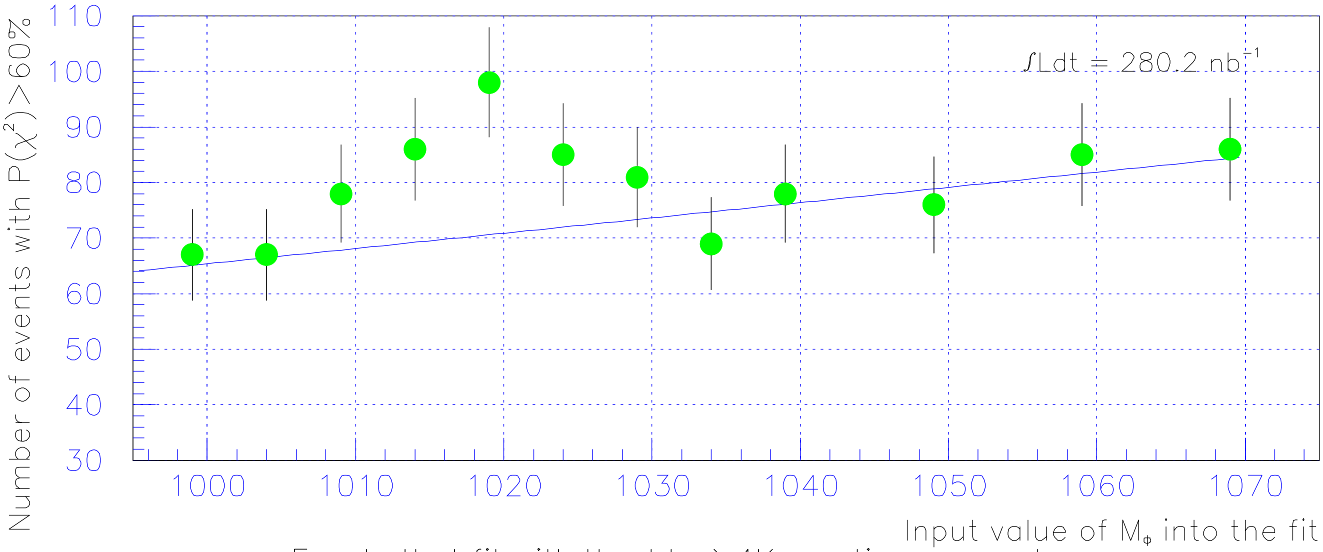
- This channel has a peculiar kinematics, so we can extract it in the huge hadronic background.



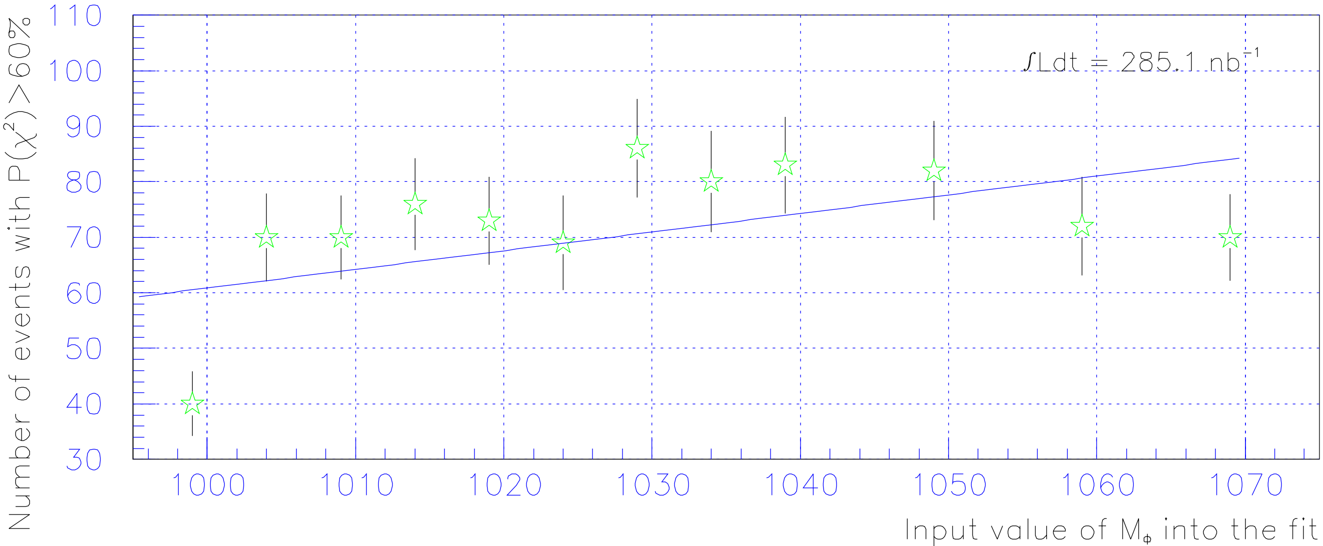
- Special trigger (using hodoscopes and SciFi detector): 4 tracks with the right kinematics.

- Event selection:
  - 4 charged tracks
  - cuts on $\Delta\varphi$, $\Delta\theta$ opening angle ($<25^{0}$)
  - cuts on calculated invariant mass
  - kinematic fit probability > 60%

Analysis of the $\Phi\Phi \longrightarrow 4K$ channel

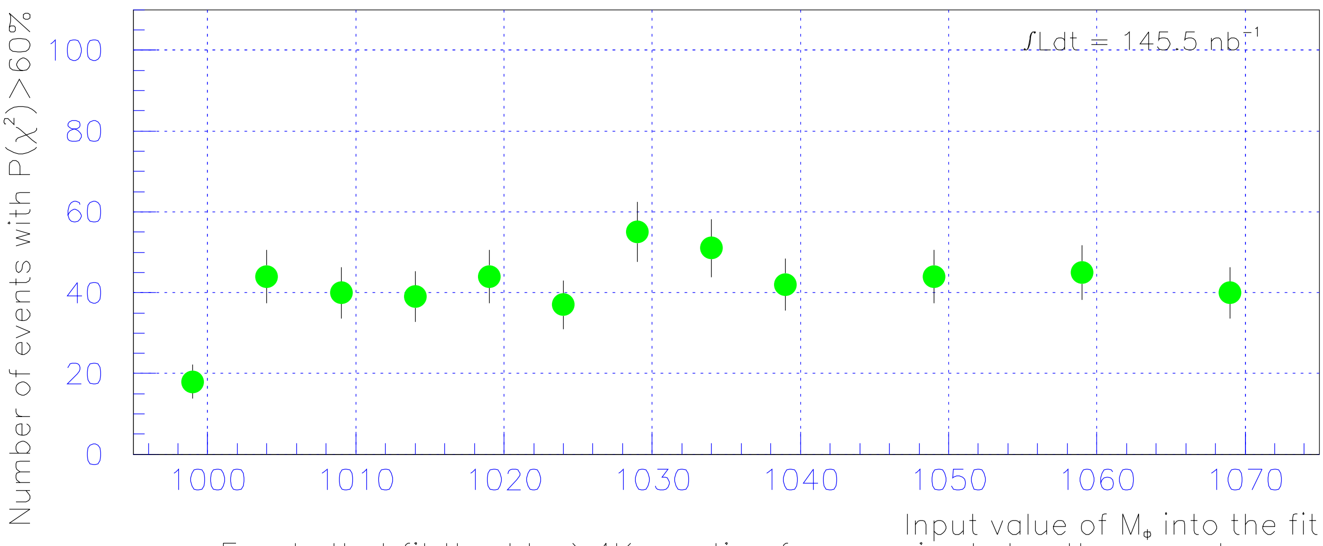


Events that fit with the $\Phi\Phi \longrightarrow 4K$ reaction, η_c peak energy

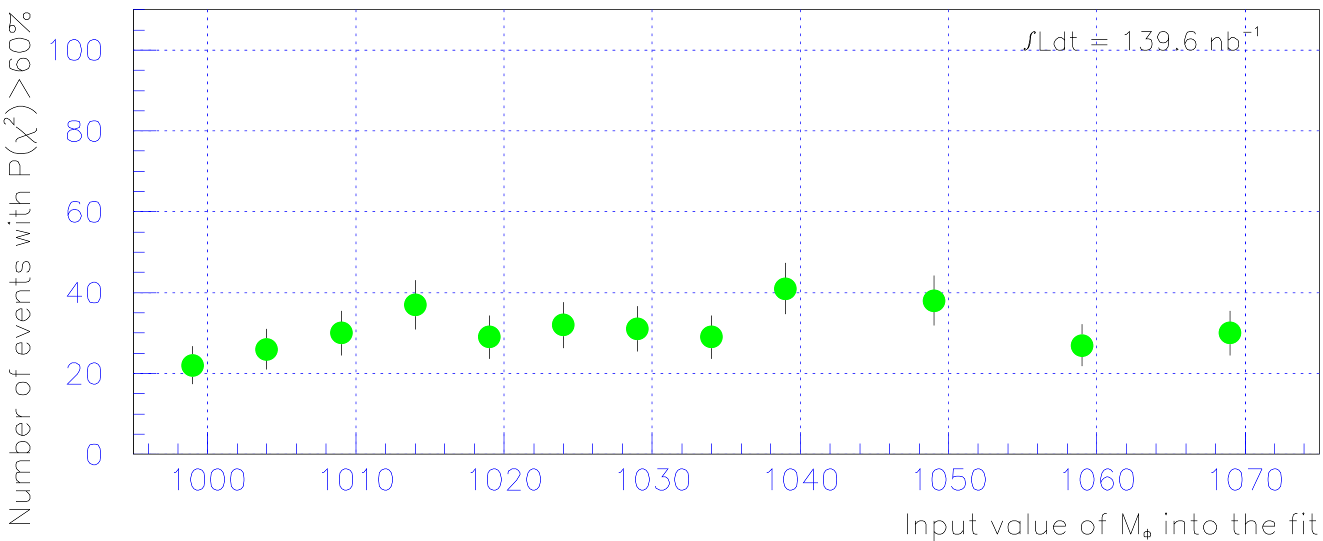


Events that fit with the $\Phi\Phi \longrightarrow 4K$ reaction, off resonance energies

Analysis of the data below and above the η_c peak energy



Events that fit the $\Phi\Phi \longrightarrow 4K$ reaction for energies below the η_c peak



Events that fit the $\Phi\Phi \longrightarrow 4K$ reaction for energies above the η_c peak

Conclusions and outlook

A lot of progress has been made in our knowledge of the charmonium spectrum.

ψ, ψ', χ_1, χ_2 very well measured.
χ_0, η_c well measured.

Nonetheless there is still a lot to be done:

1P1 needs further investigation.
new decay modes.
Still missing: η_c', D states.

The hadronic decay channels look promising.