Charmonium Spectroscopy

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Outline

• Introduction and experimental method
• The $\eta_c(1S)$
• The $\eta_c(2S)$
• The $h_c(^1P_1)$
• States above the $D\bar{D}$ threshold
  - The $X(3872)$
• Electromagnetic form factors of the proton in the timelike region
• Conclusions
Ever since its discovery in 1974 the charmonium system has been considered a powerful tool for the understanding of the strong interaction, and this is why it has often been called the positronium of QCD.

$$\alpha_s \approx 0.3 \quad \beta^2 \approx 0.2$$

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

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

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.
The antiproton beam momentum is varied in small steps (≤ 150 KeV/c) around the resonance under study and a scan across the resonance is made. The formation of charmonium is detected through $l^+l^-$, $\gamma\gamma$ and hadronic final states. The resonance parameters ($M_R$, $\Gamma_R$, $B_{in}\times B_{out}$) are extracted from the excitation curve using a maximum likelihood fit.

$$\sigma_{BW} = \frac{(2J+1)}{4} \frac{\pi}{k^2} \frac{B_{in}B_{out}\Gamma_R^2}{(E - M_R)^2 + \Gamma_R^2} \quad \nu = L_0\{ \epsilon \int dE f(E, \Delta E)\sigma_{BW}(E) + \sigma_{bck} \}$$
Experimental Requirements

• Precise knowledge of energy scale to make accurate measurement of masses (calibration at $\psi'$ mass, now known to better than 10 KeV)
• High beam momentum resolution (charmonium states are narrow) $\Delta p/p = 10^{-5} \div 10^{-4}$, in E835 $\Delta p/p = 2 \times 10^{-4}$
• Precise knowledge of beam momentum distribution
• High luminosity !!! (cross sections are small) (maximum E835 luminosity $5 \times 10^{31}$ cm$^{-2}$s$^{-1}$).
The charmonium spectrum
Despite the recent measurements by E835 not much is known about the ground state of charmonium:
- the error on the mass is still bigger than 1 Mev
- recent measurements give larger widths than previously expected

A large value of the $\eta_c$ width is difficult to explain in terms of simple quark models. Also unusually large branching ratios into channels involving multiple kaons and pions have been reported.

A precision measurements of the $\eta_c$ mass, width and branching ratios is of the utmost importance, and it can only be done in by direct formation in $\bar{p}p$. 
The $\eta_c(1^1S_0)$

$M(\eta_c) = 2979.9 \pm 1.0$ MeV

$\Gamma(\eta_c) = 25.5 \pm 3.3$ MeV

T. Skwarnicki – Lepton Photon 2003

D. Bettoni - Charmonium
The $\eta_c\ (1^1S_0)$

- Two photon channel $\eta_c \rightarrow \gamma\gamma$ (weak branching ratio $BR(\eta_c \rightarrow \gamma\gamma) = 3 \times 10^{-4}$).
- Hadronic decay channels, with branching ratios which are larger by several orders of magnitude.
  - $\eta_c \rightarrow \pi^+\pi^-K^+K^-$
  - $\eta_c \rightarrow 2(K^+K^-)$
  - $\eta_c \rightarrow 2(\pi^+\pi^-)$
  - $\eta_c \rightarrow K\bar{K}\pi$
  - $\eta_c \rightarrow \eta\pi\pi$
  - ...
- $\eta_c \rightarrow p\bar{p}$
**Expected properties of the $\eta_c(2^1S_0)$**

- The mass difference $\Delta'$ between the $\eta'_c$ and the $\psi'$ can be related to the mass difference $\Delta$ between the $\eta_c$ and the $J/\psi$:
  \[
  \Delta' = \frac{\alpha_s(M_{\psi'})}{\alpha_s(M_{J/\psi})} \frac{M_{\psi'}^2}{M_{J/\psi}^2} \frac{\Gamma(\psi' \rightarrow e^+e^-)}{\Gamma(J/\psi \rightarrow e^+e^-)} \Delta \approx 65 \text{ MeV}
  \]

- Various theoretical predictions of the $\eta'_c$ mass have been reported:

- Total width ranging from a few MeV to a few tens of MeV:
  $\Gamma(\eta'_c) \approx 5 \div 25 \text{ MeV}$

- Decay channels similar to $\eta_c$. 
\( \eta_c(2^1S_0) \) History

- Crystal Ball candidate
  \[ M(\eta_c') = (3594 \pm 5) \text{ MeV} / c^2 \]
  \[ \Gamma(\eta_c') \leq 8 \text{ MeV} (95 \% \text{ C.L.}) \]

- Not seen by E760/E835 in \( \bar{p}p \) annihilation

- Not seen by LEP in \( \gamma \gamma \) collisions
The Belle collaboration has recently presented a 6$\sigma$ signal for $B \rightarrow K K_S K \pi$ which they interpret as evidence for $\eta_c'$ production and decay via the process:

$$B \rightarrow K \eta'_c; \quad \eta'_c \rightarrow K_S K^+ \pi^-$$

with:

$$M(\eta'_c) = 3654 \pm 6 \pm 8 \text{ MeV}/c^2$$

$$\Gamma(\eta'_c) < 55 \text{ MeV}/c^2$$

in disagreement with the Crystal Ball result, but reasonably consistent with potential model expectations. (DPF 2002).

\[
\begin{align*}
M &= 2978 \pm 2(\text{stat}) \text{ MeV} \\
\Gamma &= 22 \pm 20(\text{stat}) \text{ MeV} \\
M &= 3654 \pm 6(\text{stat}) \text{ MeV} \\
\Gamma &= 15 \pm 24(\text{stat}) \text{ MeV}
\end{align*}
\]
\[ \gamma \gamma \rightarrow \eta_c(2^1S_0) \]

\[ M(\eta_c) = 3637.7 \pm 4.4 \text{ MeV} \]

\[ \Gamma(\eta_c) = 19 \pm 10 \text{ MeV} \]

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The $\eta_c(2^1S_0)$ mass

$$M(\eta_c) = 3637.7 \pm 4.4 \text{ MeV}$$

Is there a problem?

1. Quark models predict $M(\psi') - M(\eta_c') \approx 50-90 \text{ MeV}$
   (GI model predicts 53 MeV $\Rightarrow M(\eta_c') = 3633 \text{ MeV}$)

2. Coupled channel mechanism
   shifts $\Delta M(2^3S_1) =$ mass $-118 \text{ MeV}$ vs $\Delta M(1^3S_1) = -48 \text{ MeV}$

   $\Rightarrow$ need more precise measurements
   need to include coupled channel effects

S. Godfrey – QWG03
In PANDA we will be able to identify the $\eta_c'$ in the following channels:

- **two photon decay channel** $\eta_c' \rightarrow \gamma\gamma$. This will require a substantial increase in statistics and reduction in background with respect to E760/E835: lower energy threshold, better angular and energy resolution, increased geometric acceptance.

- **The real step forward** will be to detect the $\eta_c'$ through its **hadronic decays**, such as $K^+K^-$ and $\Phi\Phi$.

- $\eta_c' \rightarrow p \bar{p}$
The $h_c(^1P_1)$

Precise measurements of the parameters of the $h_c$ are of extreme importance in resolving a number of open questions:

- **Spin-dependent component of the $q \bar{q}$ confinement potential.** A comparison of the $h_c$ mass with the masses of the triplet $P$ states measures the deviation of the vector part of the $q \bar{q}$ interaction from pure one-gluon exchange.

- **Total width and partial width to $\eta_c + \gamma$** will provide an estimate of the partial width to gluons.

- **Branching ratios for hadronic decays to lower $c \bar{c}$ states.**
Expected properties of the $h_c(1^P_1)$

- Quantum numbers $J^{PC} = 1^+$.  
- The mass is predicted to be within a few MeV of the center of gravity of the $\chi_c(3P_{0,1,2})$ states

$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

- The width is expected to be small $\Gamma(h_c) \leq 1$ MeV.
- The dominant decay mode is expected to be $\eta_c + \gamma$, which should account for $\approx 50\%$ of the total width.
- It can also decay to $J/\psi$:
  
  $J/\psi + \pi^0$ violates isospin  
  $J/\psi + \pi^+\pi^-$ suppressed by phase space and angular momentum barrier
A signal in the $h_c$ region was seen by E760 in the process:

$$\bar{p}p \rightarrow h_c \rightarrow J/\psi + \pi^0$$

Due to the limited statistics E760 was only able to determine the mass of this structure and to put an upper limit on the width:

$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2 \text{ MeV} / c^2$$

$$\Gamma(h_c) < 1.1 \text{ MeV} (90\% CL)$$
E835 has performed a search for the $h_c$, in the attempt to confirm the E760 results and possibly add new decay channels. Data analysis is still under way in various decay channels:

- $h_c \rightarrow \eta_c + \gamma \rightarrow (\gamma \gamma) + \gamma$
- $h_c \rightarrow \eta_c + \gamma \rightarrow (\Phi \Phi) + \gamma \rightarrow (4K) + \gamma$
- $h_c \rightarrow J/\psi + \pi^0 \rightarrow (e^+e^-) + (\gamma \gamma)$
The $h_c(^1P_1)$

$^1P_1$ vs $^3P_{cog}$ mass - distinguish models

- In QM triplet-singlet splittings test
  - the Lorentz nature of the confining potential
  - Relativistic effects

- Important validation of
  - Lattice QCD calculations
  - NRQCD calculations

- Observation of $^1P_1$ states is an important test of theory

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Wide variation of theoretical predictions:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Approach</th>
<th>( n=1 ) ( c\bar{c} ) (MeV)</th>
<th>( n=1 ) ( b\bar{b} ) (MeV)</th>
<th>( n=2 ) ( b\bar{b} ) (MeV)</th>
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<tbody>
<tr>
<td>GI85 [14]</td>
<td>a</td>
<td>8</td>
<td>2</td>
<td>2</td>
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<tr>
<td>MR83 [15]</td>
<td>b</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>LPR92 [16]</td>
<td>c</td>
<td>4</td>
<td>2</td>
<td>1</td>
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<tr>
<td>OS82 [17]</td>
<td>d</td>
<td>10</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>MB83 [18]</td>
<td>e</td>
<td>(-5)</td>
<td>(-2)</td>
<td>(-2)</td>
</tr>
<tr>
<td>GRR86 [19]</td>
<td>f</td>
<td>(-2)</td>
<td>(-1)</td>
<td>(-1)</td>
</tr>
<tr>
<td>IO87 [20]</td>
<td>g</td>
<td>(24.1 \pm 2.5)</td>
<td>(3.73 \pm 0.1)</td>
<td>(3.51 \pm 0.02)</td>
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<tr>
<td>GOS84 ( \eta_s = 1 ) [21]</td>
<td>h</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>GOS84 ( \eta_s = 0 ) [21]</td>
<td>h</td>
<td>17</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>PJF92 [22]</td>
<td>i</td>
<td>(-20.3 \pm 3.7)</td>
<td>(-2.5 \pm 1.6)</td>
<td>(-3.7 \pm 0.8)</td>
</tr>
<tr>
<td>HOOS92 [23]</td>
<td>j</td>
<td>(-0.7 \pm 0.2)</td>
<td>(-0.18 \pm 0.03)</td>
<td>(-0.15 \pm 0.03)</td>
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<tr>
<td>PTN86 [25]</td>
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<td>(-0.4)</td>
<td>(-0.3)</td>
</tr>
<tr>
<td>PT88 [26]</td>
<td>j</td>
<td>(-1.4)</td>
<td>(-0.5)</td>
<td>(-0.4)</td>
</tr>
<tr>
<td>SESAM98 [31]</td>
<td>k</td>
<td>–</td>
<td>(~-1)</td>
<td>–</td>
</tr>
<tr>
<td>CP-PACS00 [33]</td>
<td>l</td>
<td>(1.7-4.0)</td>
<td>(1.6-5.0)</td>
<td>–</td>
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</tbody>
</table>

Wide variation in predictions indicates need for experimental data.
It is extremely important to identify this resonance and study its properties. To do so we need:

- High statistics: the signal will be very tiny
- Excellent beam resolution: the resonance is very narrow
- The ability to detect its hadronic decay modes.

The search and study of the $h_c$ is a central part of the experimental program of the PANDA experiment at GSI.
Charmonium States above the $D \bar{D}$ threshold

The energy region above the $D \bar{D}$ threshold at 3.73 GeV is very poorly known. Yet this region is rich in new physics.

- The structures and the higher vector states ($\psi(3S)$, $\psi(4S)$, $\psi(5S)$ ...) observed by the early $e^+e^-$ experiments have not all been confirmed by the latest, much more accurate measurements by BES. It is extremely important to confirm the existence of these states, which would be rich in $D \bar{D}$ decays.

- This is the region where the first radial excitations of the singlet and triplet $P$ states are expected to exist.

- It is in this region that the narrow $D$-states occur.
The D states

- $^3D_J$ masses - test spin dependent splittings
- There is still some question about the Lorentz structure of the potential
  - Vector 1-gluon exchange + scalar confinement
  - Vector 1-gluon exchange + colour electric confinement
  - + more complicated structures
- Because the D waves are larger they will feel the long-range spin-dependent potential more than the P waves.
- Observation of $^3D_J$ would be important in understanding the Lorentz structure of the confining potential

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The D wave states

• The charmonium “D states” are above the open charm threshold (3730 MeV) but the widths of the $J=2$ states $^3D_2$ and $^1D_2$ are expected to be small:

\[ ^1,^3D_2 \rightarrow \bar{D}D \] forbidden by parity conservation

\[ ^1,^3D_2 \rightarrow \bar{D}D^* \] forbidden by energy conservation

• Only the $\psi(3770)$, considered to be largely $^3D_1$ state, has been clearly observed
The D wave states

• The only evidence of another D state has been observed at Fermilab by experiment E705 at an energy of 3836 MeV, in the reaction:

\[ \pi Li \rightarrow J/\psi \pi^+ \pi^- + X \]

• This evidence was not confirmed by the same experiment in the reaction \( pLi \rightarrow J/\psi \pi^+ \pi^- + X \) and more recently by BES
The \( \text{X}(3872) \)

New state discovered by Belle in \( B^\pm \rightarrow K^\pm (J/\psi \pi^+ \pi^-) \), \( J/\psi \rightarrow \mu^+ \mu^- \) or \( e^+ e^- \)

\[ M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV} \]
\[ \Gamma < 2.3 \text{ MeV (90 \% C.L.)} \]

\( \text{X}(3872) \) seen also by CDF

\[ M = 3871.4 \pm 0.7 \pm 0.4 \text{ MeV} \]
What is the X(3872) ?

1. The mass of the state is right at the $D^0 \bar{D}^{0*}$ threshold, this suggests a loosely bound $D^0 \bar{D}^{0*}$ molecule. "Molecular Charmonium"

2. $^{13}D_2$ state. Because D-states have negative parity, spin 2 states cannot decay to $D \bar{D}$. They are narrow as long as below the $D \bar{D}^*$ threshold.

P predict \[
\frac{BR(\psi(1^3D_2) \rightarrow \gamma\gamma J/\psi)}{BR(\psi(1^3D_2) \rightarrow \pi^+\pi^- J/\psi)} \sim 3
\]

BUT \[
\frac{BR(X(3872) \rightarrow \gamma\chi_c^0)}{BR(X(3872) \rightarrow \pi^+\pi^- J/\psi)} < 0.89 \quad (90\% \text{ CL})
\]

Most models predict the $\psi(1^3D_2)$ mass $\sim$70 MeV lower than X(3872) mass. At the same time they reproduce the $\Upsilon(1^3D_2)$ very well. No models can accommodate $\psi(3770)$ and X(3872) in the same $1^3D_J$ triplet. Can coupled channel effects and $\psi(1^3D_1)$- $\psi(2^3S_1)$ mixing change this ?

3. A Charmonium Hybrid

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Belle hep-ex/0309032
It is extremely important to identify all missing states above the open charm threshold and to confirm the ones for which we only have a weak evidence. This will require high-statistics, small-step scans of the entire energy region accessible at GSI.
The electromagnetic form factors of the proton in the time-like region can be extracted from the cross section for the process:
\[ \bar{p}p \rightarrow e^+e^- \]
First order QED predicts:
\[
\frac{d\sigma}{d(\cos\theta^*)} = \frac{\pi \alpha^2 \hbar^2 c^2}{2xs} \left[ |G_M|^2 (1 + \cos^2 \theta^*) + \frac{4m_p^2}{s} |G_E|^2 (1 - \cos^2 \theta^*) \right]
\]
Data at high \( Q^2 \) are crucial to test the QCD predictions for the asymptotic behavior of the form factors and the spacelike-timelike equality at corresponding values of \( Q^2 \).
Predictions of nucleon form factors are applicable up to high $Q^2$ in both the spacelike and timelike regions.

- Perturbative QCD and analyticity relate timelike and spacelike form factors, predicting a continuous transition and spacelike-timelike equality at high $Q^2$.

- At high $Q^2$ PQCD predicts:

$$F_1(Q^2) \propto \frac{\alpha_s^2(Q^2)}{Q^4} \quad F_2(Q^2) \propto \frac{\alpha_s^2(Q^2)}{Q^6}$$

$F_1$ and $F_2$ are the Dirac and Pauli form factors respectively.

- PQCD and analyticity predict:

$$\left| \frac{G_M^n}{G_M^p} \right|^2 \approx \left( \frac{q_d}{q_u} \right)^2 = 0.25$$

There are several unexpected features in the existing data which deserve further experimental investigation:

- Threshold $Q^2$ dependence.
- High $Q^2$ predictions.
- Resonant structures.
The main background sources for the form factor analysis come from the following reactions:

- \( \psi + X \) inclusive events, with \( \psi \to e^+e^- \) and \( X \) undetected, \( \sigma'_{\psi X} < 1.6 \times 10^{-2} \) pb

- Photon conversions and \( \pi^0 \) Dalitz decays from:
  - \( \bar{p}p \to \pi^0\pi^0 \)
  - \( \bar{p}p \to \pi^0\gamma \)
  - \( \bar{p}p \to \gamma\gamma \)
  \( \sigma_p < 3.1 \times 10^{-3} \) pb

- Hadronic two-body final states, mainly \( \bar{p}p \to \pi^+\pi^- \)
  \( \sigma_h < 4.3 \times 10^{-3} \) pb
E835 measurement of $\sigma(\bar{p}p \rightarrow e^+e^-)$

<table>
<thead>
<tr>
<th>$s$ (GeV$^2$)</th>
<th>$L$ (pb$^{-1}$)</th>
<th>$N$</th>
<th>$\sigma_{\text{acc}}$ (pb)</th>
<th>$\sigma_{\text{back}}$ (pb)</th>
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<tbody>
<tr>
<td>11.63</td>
<td>32.86</td>
<td>32</td>
<td>$1.61^{+0.34+0.17}_{-0.29-0.10}$</td>
<td>$&lt;2.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>12.43</td>
<td>50.50</td>
<td>34</td>
<td>$1.11^{+0.23+0.12}_{-0.19-0.07}$</td>
<td>$&lt;1.5 \times 10^{-2}$</td>
</tr>
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</table>
Measurement of the Form Factor

\[ \sigma_{acc} = \int_0^{2\pi} d\phi \int_{-|\cos\theta^*|_{\text{max}}}^{+|\cos\theta^*|_{\text{max}}} d\sigma \frac{d\sigma}{d\Omega} d(\cos\theta^*) \]

\[ = \frac{\pi\alpha^2}{2\beta_p s} \left[ A \left| G_M \right|^2 + \frac{4m_p^2}{s} B \left| G_E \right|^2 \right] \]

E835 statistics not sufficient to measure the angular distribution (and thus determine \( G_E \) and \( G_M \) separately. Calculate \( G_M \) under two hypotheses:

• (a) \( G_E = G_M \)
• (b) \( G_E \) contribution negligible
The dashed line is the PQCD fit:

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

| \( s \) (GeV²) | \( 10^2 \times |G_M| \) (a) | \( 10^2 \times |G_M| \) (b) |
|---------------|-----------------|-----------------|
| 11.63         | 1.74 +0.18+0.11 | 1.94 +0.20+0.12 |
|               | −0.16−0.07      | −0.17−0.08      |
| 12.43         | 1.48 +0.15+0.08 | 1.63 +0.17+0.09 |
|               | −0.13−0.05      | −0.14−0.05      |

- (a) \( G_E = G_M \)
- (b) \( G_E \) contribution negligible
Form Factor Measurement in Panda

In Panda we will be able to measure the proton timelike form factors over the widest $q^2$ range ever covered by a single experiment, from threshold up to $q^2=30$ GeV$^2$, and reach the highest $q^2$.

• At low $q^2$ (near threshold) we will be able to measure the form factors with high statistics, measure the angular distribution (and thus $G_M$ and $G_E$ separately) and confirm the sharp rise of the FF.

• At the other end of our energy region we will be able to measure the FF at the highest values of $q^2$ ever reached, 30 GeV$^2$, which is 2.5 larger than the maximum value measure by E835. Since the FF decrease $\sim 1/s^5$, to get comparable precision to E835 we will need $\sim 80$ times more data.

• In the E835 region we need to gain a factor of at least 10-20 in data size to be able to measure the electric and magnetic FF separately.
## Form Factor Measurement in Panda

<table>
<thead>
<tr>
<th>$s$ (GeV$^2$)</th>
<th>factor</th>
<th>$\sigma$ (pb)</th>
<th>$\sigma_{bck}$ (pb)</th>
<th>$\int Ldt$ (pb$^{-1}$)</th>
<th>days</th>
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<tr>
<td>12.43</td>
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<td>1.11</td>
<td>0.015</td>
<td>50</td>
<td>5</td>
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<tr>
<td>15</td>
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<td>0.370</td>
<td>?</td>
<td>150</td>
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<td>?</td>
<td>550</td>
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<td>30</td>
<td>82</td>
<td>0.014</td>
<td>?</td>
<td>4100</td>
<td>410</td>
</tr>
</tbody>
</table>

- Values of cross sections at various energies assuming $1/s^5$ scaling.
- The same angular acceptance as E835 is assumed.
- Integrated luminosities and running times required to achieve the same accuracy as E835-II.
- Backgrounds need to be evaluated at the higher energies. The major background component, $J/\psi+X$, increases with energy!
Summary

The measurement of the e.m. form factors of the proton in the timelike region has considerable physics interest. In order to make the measurement in Panda we need:

• High statistics, in order to measure $G_E$ and $G_M$ separately, and in order to be able to carry out the measurement at the highest $q^2$ values.

• Excellent electron ID capability (at least as good as E835)

• Excellent background rejection (mainly from $\pi^0\pi^0$, $\pi^0\gamma$, $\gamma\gamma$ and $\pi^+\pi^-$).
Conclusions

• The B-factories have proven very effective in providing new results in charmonium (and bottomonium).
• Over the next few years more data will come from BaBar, Belle, Cleo-C, BES.
• Charmonium production from Tevatron, DESY, LHC.
• Still $\bar{p}p$ annihilation is unbeatable for
  - high-precision measurements, in particular of narrow resonances (e.g. $h_c(^1P_1)$)
  - systematic scans of extended energy regions (e.g. region above $D\bar{D}$ threshold)
• Measurement of the proton time-like form factors over the widest $q^2$ range ever covered by a single experiment