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The Charm of Excited Glue
Charmonium in $e^+e^-$ and $pp$ collisions
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Charmonium in $e^+e^-$ and $p\bar{p}$ collisions

BESII
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BESII  PANDA
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BESII  PANDA
Outline

Motivation

• Strong QCD – what, why?
• Why charmonium?
• How do we understand charmonium?

Electron-positron

• BESII
• $\psi'$ radiative decays
• Angular distributions

Proton-antiproton

• Formation vs. production
• PANDA
• $\eta_c$ simulation
• Charmonium hybrid search

Relating cross sections to decay widths
Strong QCD

- pQCD has been extremely successful at large momentum transfer.
- Asymptotic freedom

- At fm-scales the strong coupling makes QCD difficult
- Gluon self-interaction
- Confinement
- Mass generation
The Proton

Deep inelastic scattering
Deeply virtual Compton scattering

Mass:
2% from Higgs Mechanism.
(MS mass)

We do not understand the origin of 98% of the visible mass of the universe.

We think we have the right equation - QCD
We can find the right answer – experiment
We do not know the steps in between
We might encounter this kind of physics again
Experiment

- Spectroscopy
- Production mode
- Decay channels
- Angular distributions (Partial Wave Analyses)

Phenomenology

- Quark model
- Flux-tube model
- Bagmodel
- Potential models
- Perturbative approaches
- Chiral perturbation
- Coupled channels
- Lattice QCD
Gluonic excitations

Most known states can be identified within the constituent quark model as mesons or baryons.

QCD allows for anything colour-neutral. Searched for decades for glueballs and hybrids.

Observations in the light quark sector: \( f_0(1500), f_0(1710) \)
• Scalar overpopulation
  Glueballs?

Hybrid calculations in the flux-tube model, lattice QCD, bag-model, constituent gluon model. **Spin-exotic hybrids** \( 1^+, 0^+, 2^+ \)

• Exotic quark. \( 1^-+ \)
  Hybrids?

\( \pi_1(1400) \) E852(\( \pi p \)) Crystal Barrel(\( pp \))

\( \pi_1(1600) \) E852(\( \pi p \)) Crystal Barrel(\( pp \))

• Difficult to identify in the light quark sector, many overlapping states which mix. Disentangle what is what.
Why charmonium?

\[ m_u \approx 1.5 - 4 \text{ MeV}/c^2 \]

\[ m_d \approx 4 - 8 \text{ MeV}/c^2 \]

\[ m_s \approx 80 - 130 \text{ MeV}/c^2 \]

\[ m_c \approx 1.15 - 1.35 \text{ GeV}/c^2 \]

\[ m_b \approx 4.1 - 4.4 \text{ GeV}/c^2 \]

\[ m_t \approx 174.3 \text{ GeV}/c^2 \]

- **Up, down, strange quark:**
  - Very light, relativistic, most energy and mass comes from the strong force. Nonperturbative. Very difficult!

- **Charmquark:**
  - Semi-relativistic, half-perturbative
  - Somewhat less difficult!

- **Topquark:**
  - Heavy, decays quickly through weak interactions. Nonrelativistic.

- **Bottomquark:**
  - Already done but it only got us so far.
Charmonium

- Positronium of QCD
- Described by a Coulomb + linear confining potential

In a Schrödinger equation
- Spin-dependent term perturbative
- EM and 3P0 strong decays
- Narrow states
- Little mixing
Charmonium at the B-factories – alphabet states
Stable even above strong decay thresholds.

16 February. 2007

A. Lundborg, IKP Uppsala
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BESII
Why electron-positron?

\[ \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = R \]

The vector charmonium system is well scanned in high precision electron positron experiments.

You tune the energy to where there is a resonance and you have a charmonium factory.

- Easy initial state
- Partial Wave Analysis
- Well-defined energy

\[ 1^- = J/\psi(c\bar{c}), \psi'(c\bar{c}), \Upsilon(b\bar{b}) \]
Beijing Electron Positron Spectrometer II - BESII

Electrons and positrons colliding in the middle of a modular detector.

\[ 14 \times 10^6 \psi'(c\bar{c}) \]
Radiative decay

\[ \bar{c} \gamma \rightarrow \gamma K^+ K^- \]

\[ \psi' \rightarrow \gamma \pi^+ \pi^- \]

Only 0++ and 2++ resonances can be reached from conservation of quantum numbers.

\[ J = L + S \]
\[ P = (-)^{L+1} \]
\[ C = (-)^{L+S} \]

Gluon-rich

Glueball spectrum from lattice QCD.
Event selection

- Photon
- Separation between tracks
- Regions we trust

First event selection requirements

Exactly two MDC tracks (extra non-MDC tracks are allowed).
The MDC tracks have one track fit.
The MDC tracks have single charge.
The MDC tracks have good helix fits (BES notation mfit=2).
The total charge is zero.
The MDC tracks must have momentum between 0 and 3 GeV/c.
The total number of muon hits < 5 (section 1.3).
At least one charged particle must have $E < 1$ GeV energy deposit in the SC.

At least one good photon in the barrel calorimeter.
The most energetic photon is considered as the real one.
The selected photon must have a good quality as defined below.

Photon quality

A good photon has a shower counter hit.
A good photon is in the barrel shower counter.
A good photon has energy larger than 0.05 GeV/$c^2$.
A good photon leaves a track somewhere within the first 12 layers out
of 24 (BES notation track not equal to 6).
A good photon is separated from charged tracks with more than 15 degrees
in the xy-plane.
A good photon has $\cos \theta > 0.8$ between the shower in the BSC and the
track pointing to the target.

Compton back-to-back photon requirements

$|\cos \theta_+| < 0.8$ and $|\cos \theta_-| < 0.8$

$(x_p + x_n) + 6(\frac{\sqrt{p \cdot p_{MC}}}{p_{MC}} + \frac{\sqrt{p \cdot p_{MC}}}{p_{MC}}) - 2^2 > 5^2$ (section 2.1)

Total muon track quality less than 3 (section 1.3).
$p_{tot} > 0.01$ and $p_{ID} > p_{otherID}$ (section 1.4).
QED background

Muon rejection
Less than three muon chamber hits

Electron reduction

\[(\chi_p^2 + \chi_m^2) + 6(\sqrt{(\frac{E_{cal.}}{P_{MDC}})_p^2 + (\frac{E_{cal.}}{P_{MDC}})_m^2} - 2)^2 > 5^2\]

From dE/dx

Leptonic misidentification

| Signal            | Expect   | Sim.    | $\gamma \pi^+\pi^- (|\cos \theta_{\pm}| < 0.65)$ | $\gamma K^+K^-$ |
|-------------------|----------|---------|-----------------------------------------------|-----------------|
| Bhabha            | $3.6 \cdot 10^6$ | $3.6 \cdot 10^6$ | $16\pm4$ ($3\pm1.7$)                         | $2.0\pm1.4$     |
| $\psi \rightarrow e^+e^-$ | 103 740  | 107 500 | $1\pm1$ ($0$)                                | $0$             |
| Radiative muonic  | 110 806  | 332 418 | $68\pm5$ ($15\pm2$)                         | $0.7\pm0.5$     |
| $\psi \rightarrow \mu^+\mu^-$ | 102 200  | 315 720 | $0$ ($0$)                                    | $0$             |
Particle identification

\[ \chi_{pid}^2(pID) = \chi_{TOF}^2(pID) + \chi_{dE/dx}^2(pID). \]

Kinematic fit

Input: \((p_x, p_y, p_z)_{\pi^+, \pi^-}\) and \((\theta, \phi, E)_{\gamma}\).
three invariant masses, energy and momentum conservation.
Output: three fourmomenta - \(\rightarrow\) 4C-fit

Overall event identification

\[ \chi_{tot}^2 = \chi_{pid+}^2 + \chi_{pid-}^2 + \chi_{4C-fit}^2. \]

\[ p_{tot} = P \chi^2(\chi^2, NDOF). \]

\[ p_{tot} > 0.01 \text{ and } p_{ID} > p_{other}. \]

16 February. 2007  A. Lundborg, IKP Uppsala
A lot of work

Iterations

Data analysis

Tests

Simulations
<table>
<thead>
<tr>
<th>Signal</th>
<th>Expected</th>
<th>Sim.</th>
<th>$\gamma\pi^+\pi^-$</th>
<th>$\gamma K^+K^-$</th>
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<td>$\psi' \to J/\psi^0\pi^0, J/\psi \to \pi^+\pi^-\pi^0$</td>
<td>52 601</td>
<td>78 960</td>
<td>0 (0)</td>
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<td>2 534</td>
<td>50 000</td>
<td>136 (72)</td>
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<td>Includes $\pi\pi$</td>
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<tr>
<td>$\psi' \to K^+K^-\pi^0$</td>
<td>&lt; 414</td>
<td>100 000</td>
<td>&lt;0.74 (0.53)</td>
<td>&lt;23.7</td>
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<td>$J/\psi\pi^+\pi^-, J/\psi \to e^+e^-$</td>
<td>263 173</td>
<td>337 903</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$\gamma\chi_c2, \chi_c2 \to \gamma J/\psi, J/\psi \to \rho^\pm\pi^\mp$</td>
<td>2 309</td>
<td>15 400</td>
<td>1.6 (0.9)</td>
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<td>$J/\psi\pi^0\pi^0, J/\psi \to \gamma f_0(1710) \to \gamma K^+K^-$</td>
<td>1 120</td>
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<td>3 462</td>
<td>20 000</td>
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</table>

**Background channels**

- Added explicitly according to BESII PWA.
- Average between BESII and CLEO-c BR.
- Unknown BR. Fitted to data.

**Background in KK**

- Total except $\pi^+\pi^-\pi^0$ | 9.3 (5.2) | 34.7 |
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<th>$\sigma$</th>
<th>$f_{c}(1270)$</th>
<th>$f_{c}(1500)$</th>
<th>$f_{c}(1710)$</th>
<th>$f_{c}(1810)$</th>
<th>$f_{c}(2020)$</th>
<th>$f_{c}(2030)$</th>
<th>$f_{c}(2150)$</th>
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</table>
Mass resolution is at least a factor of 10 below resonance mass and convolution effects are negligible.

<table>
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<tr>
<th>$m[GeV/c^2]$</th>
<th>$\Gamma[MeV]$</th>
<th>$J^{PC}$, $x=y$</th>
<th>Eff</th>
<th>Mass resolution</th>
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<tr>
<td>1.2741</td>
<td>185.1</td>
<td>$2^{++}$, 0.35,-0.19</td>
<td>13.84%</td>
<td>$8.1 \pm 0.1 \text{ MeV/c}^2$</td>
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<td>1.2741</td>
<td>185.1</td>
<td>$2^{++}$, -0.36,-0.25</td>
<td>14.16%</td>
<td>$8.1 \pm 0.1 \text{ MeV/c}^2$</td>
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<td>1.714</td>
<td>140</td>
<td>$0^{++}$</td>
<td>15.45%</td>
<td>$9.7 \pm 0.2 \text{ MeV/c}^2$</td>
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<tr>
<td>2.197</td>
<td>201</td>
<td>$0^{++}$</td>
<td>15.87%</td>
<td>$9.9 \pm 0.2 \text{ MeV/c}^2$</td>
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</table>

**Comparison**

- **Red** without resolution convolution.
- **Blue dotted** with resolution 10 MeV.
Signal shape $f_2(1270)$

Mass dependent width

$$\frac{d\sigma}{dm} \propto |T|^2 \frac{PQ}{m_{\psi}}$$

$$T = \frac{Q^l}{BW_{\text{prop}}}$$

$$BW_{\text{prop}} = m_0^2 - m^2 - im_0 \Gamma_{\text{total}}(m)$$

$$\Gamma_{\text{total}}(m) = \Gamma_0 \frac{m_0}{m} \frac{BR(X \rightarrow \pi\pi)}{BR(X \rightarrow \pi\pi) + BR(X \rightarrow K\bar{K})} \left[ \frac{Q_{\pi}(m)}{Q_{\pi}(m_0)} \right]^{2l+1} + \theta BR(X \rightarrow K\bar{K}) \left[ \frac{Q_K(m)}{Q_K(m_0)} \right]^{2l+1}$$

Convention is to use Blatt Weisskopf dampening.

Blue – D-wave mass dep width.
Red – D-wave constant width.
Cyan – D-wave Blatt Weisskopf.
Dotted – s-wave constant width.

With Blatt Weisskopf damping

$$\sigma \propto \frac{QP}{|BW_{\text{prop}}|^2} Q^{2l} B^2_l(Q)$$

$$B_2 = \sqrt{\frac{13}{Q^4 + 2Q^2Q_0^2 + 9Q_0^4}}$$

$$Q_0 = 0.197321/R \text{ GeV/c}$$

$$R = 3.4 \text{ fm centrifugal barrier radius}$$


L. Haibo. Study of $\chi_c$ and $f_2(1270)$ states in $\psi(2s) \rightarrow 5\gamma s$, August 1998. Presentation at the BES physics workshop, CCAS.
$\psi' \rightarrow \gamma \pi^+ \pi^-$

Structure function approach.

1000 data events
800 bg reduced

Data - Dots with error bars
Continuum – Blue filled histogram
Continuum + $\pi^+\pi^-\pi^0$ – Green filled histogram
Continuum + $\pi^+\pi^-\pi^0$ + Lund Charm + $K^+K^-\pi^0$
(upper limit 90% confidence level) – White histogram
**Systematic errors**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\pi\pi$</th>
</tr>
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<tbody>
<tr>
<td>Number of $\psi'$ [1]</td>
<td>4%</td>
</tr>
<tr>
<td>Charged tracks</td>
<td>4%</td>
</tr>
<tr>
<td>Photon ID [22]</td>
<td>2%</td>
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<tr>
<td>Trigger [25]</td>
<td>&lt;0.5%</td>
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<tr>
<td>Kinematic fit [23]</td>
<td>6%</td>
</tr>
<tr>
<td>Eff. variation with (x,y)</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>Lower fit</th>
<th>Upper fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$(1270)</td>
<td>6.7%</td>
<td>4.9%</td>
</tr>
<tr>
<td>$f_0$(1500)</td>
<td>23%</td>
<td>50%</td>
</tr>
<tr>
<td>$f_0$(1710)</td>
<td>44%</td>
<td>30%</td>
</tr>
<tr>
<td>$f_4$(2050)</td>
<td>18%</td>
<td>28%</td>
</tr>
<tr>
<td>$f_0$(2200)</td>
<td>19%</td>
<td>98%</td>
</tr>
</tbody>
</table>

**Log likelihood fit with RooFit**

- $f_2$(1270)
- $f_0$(1500)
- $f_0$(1710)
- $f_4$(2050)
- $f_0$(2200)

**BESI [17]**

| $BR(\psi' \rightarrow \gamma f_2(1270) \rightarrow \gamma \pi^+\pi^-)$ | $(1.2 \pm 0.3) \times 10^{-4}$ |
| $BR(\psi' \rightarrow \gamma f_0(1500) \rightarrow \gamma \pi^+\pi^-)$ | $-$ |
| $BR(\psi' \rightarrow \gamma f_0(1710) \rightarrow \gamma \pi^+\pi^-)$ | $(2.0 \pm 0.9) \times 10^{-5}$ |
| $BR(\psi' \rightarrow \gamma f_4(2050) \rightarrow \gamma \pi^+\pi^-)$ | $-$ |
| $BR(\psi' \rightarrow \gamma f_0(2200) \rightarrow \gamma \pi^+\pi^-)$ | $-$ |

**From data**

| $BR(\psi' \rightarrow \gamma f_2(1270) \rightarrow \gamma \pi^+\pi^-)$ | $(2.2 \pm 0.1^{+0.2}_{-0.2}) \times 10^{-4}$ |
| $BR(\psi' \rightarrow \gamma f_0(1500) \rightarrow \gamma \pi^+\pi^-)$ | $(1.5 \pm 0.7^{+0.9}_{-0.4}) \times 10^{-5}$ |
| $BR(\psi' \rightarrow \gamma f_0(1710) \rightarrow \gamma \pi^+\pi^-)$ | $(2.4 \pm 0.6^{+0.7}_{-1.1}) \times 10^{-5}$ |
| $BR(\psi' \rightarrow \gamma f_4(2050) \rightarrow \gamma \pi^+\pi^-)$ | $(2.8 \pm 0.9^{+0.8}_{-0.6}) \times 10^{-5}$ |
| $BR(\psi' \rightarrow \gamma f_0(2200) \rightarrow \gamma \pi^+\pi^-)$ | $(4.6 \pm 1.0^{+4.5}_{-1.0}) \times 10^{-5}$ |
Data - Dots with error bars
Continuum – Blue filled histogram
Continuum + π⁺π⁻π⁰ – Green filled histogram
Continuum + π⁺π⁻π⁰ + lundcharm + K⁺K⁻π⁰
(90% confidence level) – White histogram

<table>
<thead>
<tr>
<th>BR(ψ' → γf₂(1270) → γK⁺K⁻)</th>
<th>PDG06=BESI[17]</th>
<th>From data</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.9 ± 1.0) × 10⁻⁶</td>
<td></td>
<td>(1.9 ± 0.6⁺¹⁻⁰.⁶) × 10⁻⁵</td>
</tr>
<tr>
<td>BR(ψ' → γf₂(1525) → γK⁺K⁻)</td>
<td>-</td>
<td>(6.9 ± 4.4⁺⁴⁻¹.⁴) × 10⁻⁶</td>
</tr>
<tr>
<td>BR(ψ' → γf₀(1710) → γK⁺K⁻)</td>
<td>(3.0 ± 1.5) × 10⁻⁵</td>
<td>(3.1 ± 0.6⁺¹⁻⁰.⁷) × 10⁻⁵</td>
</tr>
</tbody>
</table>
What does this mean?

<table>
<thead>
<tr>
<th></th>
<th>BES PWA</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2(1270) \rightarrow \pi^+\pi^-$</td>
<td>24±5%</td>
<td>28±4%</td>
</tr>
<tr>
<td>$f_0(1500) \rightarrow \pi^+\pi^-$</td>
<td>22±20%</td>
<td>&gt;5±4%</td>
</tr>
<tr>
<td>$f_0(1710) \rightarrow \pi^+\pi^-$</td>
<td>9±5%</td>
<td>14±13%</td>
</tr>
<tr>
<td>$f_4(2050) \rightarrow \pi^+\pi^-$</td>
<td>-</td>
<td>9±5%</td>
</tr>
<tr>
<td>$f_2(1270) \rightarrow K^+K^-$</td>
<td>-</td>
<td>60±38%</td>
</tr>
<tr>
<td>$f_2'(1525) \rightarrow K^+K^-$</td>
<td>4±4%</td>
<td>3±3%</td>
</tr>
<tr>
<td>$f_0(1710) \rightarrow K^+K^-$</td>
<td>6±4%</td>
<td>7±3%</td>
</tr>
</tbody>
</table>

$\frac{BR(\psi' \rightarrow h.f.s.)}{BR(J/\psi \rightarrow h.f.s.)} \equiv \frac{BR(\psi' \rightarrow ggg)}{BR(J/\psi \rightarrow ggg)} \leq \frac{BR(\psi' \rightarrow e^+e^-)}{BR(J/\psi \rightarrow e^+e^-)} \leq \frac{(7.35 \pm 0.18) \times 10^{-3}}{(5.04 \pm 0.05) \times 10^{-3}} \approx (14.6)\%$


\[ c\bar{c} \rightarrow \gamma gg \rightarrow \gamma (q\bar{q})_{L_z=0} \]

*Coupling 0++ and 2++ same

$f_0(1710)$ and $f_2'(1525)$

\[ \frac{BR(\psi \rightarrow \gamma 0^+)}{BR(\psi \rightarrow \gamma 2^+)} = \frac{2}{7} \]

- Very strong $f_2(1270)$
- Branching ratios of $f_0(1710)$
- Signal from $f_0(1500)$
- Not a strong $f_2'(1525)$
- Enhancement near 2 GeV / $c^2$
Compare $f_2(1270)$ and $f_2'(1525)$

$$f_2(1270) = \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}|$$

$$f_2'(1525) = |s\bar{s}|$$

**Perturbative SU(3) flavour symmetry Isospin coupling**


\[
R = \frac{\Gamma(\psi' \rightarrow \gamma f_2'(1525))}{\Gamma(\psi' \rightarrow \gamma f_2(1270))} = 0.5
\]

\[
R = \frac{(6.9 \pm 4.4^{+4.1}_{-2.1}) \times 10^{-6} \times 2 \times 1/0.888}{(2.2 \pm 0.1^{+0.2}_{-0.2}) \times 10^{-4} \times 3/2 \times 1/0.847} \approx 4\%
\]

\(J/\psi\), 20–30%
In first order pQED the radiative transition
\[ \psi' \rightarrow \gamma X(2^{++}) \rightarrow \gamma(0^-0^-) \]
is an E1 transition (L=0->L=1)
With relativistic corrections it turns into a mixture of E1, M2, E3 (parity changing).
A0, A1, A2= helicity amplitudes,
The distribution depends on the real parameters x=A1/A0 and y=A2/A0.

\[
W(\theta_\gamma, \theta_M, \phi_M) = \\
3x^2 \sin^2 \theta_\gamma \sin^2 2\theta_M \\
+ (1 + \cos^2 \theta_\gamma) \left[ (3 \cos^2 \theta_M - 1)^2 + \frac{3}{2} y^2 \sin^4 \theta_M \right] \\
+ \sqrt{3} x \sin 2\theta_\gamma \sin 2\theta_M \left[ 3 \cos^2 \theta_M - 1 - \frac{\sqrt{6}}{2} y \sin^2 \theta_M \right] \cos \phi_M \\
+ \sqrt{6} y \sin^2 \theta_\gamma \sin^2 \theta_M (3 \cos^2 \theta_M - 1) \cos 2\phi_M.
\]

---


X. Shi and C. Yuan. Measurement of the polarization for \( \psi(2s) \rightarrow \gamma \chi_{c2} \). BES analysis memo, Beijing, China, 2004.
\[ W(\theta_\gamma, \theta_M, \phi_M) = \]
\[ 3x^2 \sin^2 \theta_\gamma \sin^2 2\theta_M \]
\[ + (1 + \cos^2 \theta_\gamma) \left[ (3 \cos^2 \theta_M - 1)^2 + \frac{3}{2} y^2 \sin^4 \theta_M \right] \]
\[ + \sqrt{3} x \sin 2\theta_\gamma \sin 2\theta_M \left[ 3 \cos^2 \theta_M - 1 - \frac{\sqrt{6}}{2} y \sin^2 \theta_M \right] \cos \phi_M \]
\[ + \sqrt{6} y \sin^2 \theta_\gamma \sin^2 \theta_M (3 \cos^2 \theta_M - 1) \cos 2\phi_M. \]
Almost symmetric in $x$

\[
W(\theta_\gamma, \theta_M, \phi_M) = \\
3x^2 \sin^2 \theta_\gamma \sin^2 2\theta_M \\
+(1 + \cos^2 \theta_\gamma) \left[(3 \cos^2 \theta_M - 1)^2 + \frac{3}{2} y^2 \sin^4 \theta_M\right] \\
+\sqrt{3}x \sin 2\theta_\gamma \sin 2\theta_M \left[3 \cos^2 \theta_M - 1 - \frac{\sqrt{6}}{2} y \sin^2 \theta_M\right] \cos \phi_M \\
+\sqrt{6} y \sin^2 \theta_\gamma \sin^2 \theta_M (3 \cos^2 \theta_M - 1) \cos 2\phi_M.
\]
Angular acceptance from simulation

\[ \cos \theta_\gamma \]

\[ \cos \theta_M \]

Endcaps

Close to photon higher momentum
Background reduced angular fit

Scaled continuum and scaled 3pi background is included into the logL-fit as opposite sign contributions.

M. Ablikim et al. Partial wave analysis of $\psi' \rightarrow \pi^+\pi^-\pi^0$. Physics Letters B, 619:247.

<table>
<thead>
<tr>
<th>Mass region</th>
<th>Data</th>
<th>$3\pi$</th>
<th>Con.</th>
<th>$x$</th>
<th>$y$</th>
<th>Corr.</th>
<th>log $L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m_{\pi\pi} - m_{f_2}</td>
<td>&lt; \Gamma_{f_2}$</td>
<td>263</td>
<td>11.3</td>
<td>18.4</td>
<td>0.25±0.06</td>
<td>-0.28±0.07</td>
</tr>
<tr>
<td>$</td>
<td>m_{\pi\pi} - m_{f_2}</td>
<td>&lt; \Gamma_{f_2}$</td>
<td>263</td>
<td>11.3</td>
<td>18.4</td>
<td>-0.29±0.06</td>
<td>-0.28±0.07</td>
</tr>
<tr>
<td>$m_{\pi\pi} - m_{f_2} &lt; 0.75\Gamma_{f_2}$</td>
<td>227</td>
<td>8.4</td>
<td>15.4</td>
<td>0.34±0.06</td>
<td>-0.27±0.08</td>
<td>0.366</td>
<td>-94.5</td>
</tr>
<tr>
<td>$m_{\pi\pi} - m_{f_2} &lt; 0.75\Gamma_{f_2}$</td>
<td>227</td>
<td>8.4</td>
<td>15.4</td>
<td>-0.38±0.06</td>
<td>-0.28±0.08</td>
<td>-0.262</td>
<td>-93.3</td>
</tr>
<tr>
<td>$m_{\pi\pi} - m_{f_2} &lt; 0.5\Gamma_{f_2}$</td>
<td>172</td>
<td>5.6</td>
<td>15.4</td>
<td>0.20±0.09</td>
<td>-0.26±0.08</td>
<td>0.529</td>
<td>-80.8</td>
</tr>
<tr>
<td>$m_{\pi\pi} - m_{f_2} &lt; 0.5\Gamma_{f_2}$</td>
<td>172</td>
<td>5.6</td>
<td>15.4</td>
<td>-0.26±0.09</td>
<td>-0.25±0.09</td>
<td>-0.430</td>
<td>-80.9</td>
</tr>
<tr>
<td>Positive solution</td>
<td>$\sigma_x$</td>
<td>$\sigma_y$</td>
<td>$\rho$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------</td>
<td>------------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC simulation</td>
<td>0.18</td>
<td>0.05</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-resonant events (Fit region variation)</td>
<td>0.14</td>
<td>0.02</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misidentified background (With/without bg red.)</td>
<td>0.11</td>
<td>0.01</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative solution</td>
<td>$\sigma_x$</td>
<td>$\sigma_y$</td>
<td>$\rho$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC simulation</td>
<td>0.18</td>
<td>0.05</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-resonant events (Fit region variation)</td>
<td>0.12</td>
<td>0.03</td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misidentified background (With/without bg red.)</td>
<td>0.10</td>
<td>0.00</td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>0.24</td>
<td>0.06</td>
<td>-0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$\rho = \sum_i \frac{\rho_i \sigma_{xi} \sigma_{yi}}{\sigma_x \sigma_y}$$

Systematic errors
### Positive solution

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>0.20 ± 0.09 ± 0.25</td>
</tr>
<tr>
<td>(y)</td>
<td>-0.26 ± 0.08 ± 0.05</td>
</tr>
<tr>
<td>(\rho_{\text{stat}})</td>
<td>0.53</td>
</tr>
<tr>
<td>(\rho_{\text{sys}})</td>
<td>0.44</td>
</tr>
</tbody>
</table>

### Negative solution

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(x)</td>
<td>-0.26 ± 0.09 ± 0.24</td>
</tr>
<tr>
<td>(y)</td>
<td>-0.25 ± 0.09 ± 0.06</td>
</tr>
<tr>
<td>(\rho_{\text{stat}})</td>
<td>-0.43</td>
</tr>
<tr>
<td>(\rho_{\text{sys}})</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

### Experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(x)</th>
<th>(y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESII [31]</td>
<td>0.89 ± 0.02</td>
<td>0.46 ± 0.02</td>
</tr>
<tr>
<td>Crystal Ball [28]</td>
<td>0.88 ± 0.13</td>
<td>0.04 ± 0.19</td>
</tr>
<tr>
<td>MARK III [15]</td>
<td>0.96 ± 0.07</td>
<td>0.06 ± 0.08</td>
</tr>
</tbody>
</table>

- **Low \(E\) \(\gamma\)** \(x = \sqrt{3}, y = \sqrt{6}\)
- **High \(E\) \(\gamma\)** \(x = 0, y = 0\)
- **Krammer** \(x = 0.68, y = 0.45\)
- **Close** \(x = \sqrt{3}/2, y = 0\)
AGNES LUNDBORG

The Charm of Excited Glue
Charmonium in $e^+e^-$ and $p\bar{p}$ collisions

PANDA
Why proton-antiproton

\[ 1^{-} = \psi \text{ in } (c\bar{c}) \]

Formation
The two particles fuse into the intermediate state.
Resolution depends on the beam quality.

Production
The state is reached through decays or nonresonant production.
For example charmonium or B-decays.
Resolution depends on the detector.

The vector charmonium system is well scanned in high precision electron positron experiments.
Scanning mode

Discovery in production and precision measurement in scanning. Measured shape = Resonance convoluted with beam shape. Narrow beam can give a fine scanning by step-wise changing the beam energy.

Important for: cross section shape measurements
Precision measurements on mass and widths both at resonance-energies and two-meson thresholds.
Typical resolution in production

Crystall Ball e+e- \( \chi_{c1} \) \( \Gamma < 8 \text{ MeV} \)
Resolution of nonvector charmonium depends on the detector.
Also valid at B-factories and current e+e- charmonium factories (BES, CLEO-c)

Typical resolution in formation

Proton-antiproton E835
Energy spread in beam
\( \sqrt{s} \approx 0.4 \text{ MeV} \)
PDG \( \Gamma_{\chi_{c1}} \approx 0.91 \text{ MeV} \)
Accessible physics

Two body thresholds

Molecules

Gluonic Excitations

Hybrids

Hybrids + Recoil

Glueballs

Glueballs + Recoil

$q\bar{q}$ Mesons

$\bar{p}$ Momentum [GeV/c]

Mass [GeV/c$^2$]
PANDA detector at FAIR

Uppsala involved in:
• Physics simulations
  Agnes, Elin, Frida, Sophie, Robert, Kajsa.
• EMC
  Frida, Sophie, Inti.
• Pellet target
  Örjan, Florian, Inti, Gunnar, Carl-Johan, Zahnkui, Matthias, Jonas.
• Electron-cooling
  TSL.

16 February. 2007
A. Lundborg, IKP Uppsala
$p\bar{p} \rightarrow \eta_c \rightarrow \gamma\gamma$

Measured at E835 about 50 pb in the region $|\cos\theta| < 0.25$

Major background sources

$p\bar{p} \rightarrow \pi^0\pi^0$

$p\bar{p} \rightarrow \pi^0\gamma$

Event selection

• Exactly two neutral tracks.
• No charged tracks.
• No pion candidates

$|m_{\gamma\gamma} - m_{\eta_c}| < 25$ MeV

• Invariant mass energy window

$|E_{\gamma\gamma} - E_{pp}|_{CM} < 0.4$ GeV

• Momentum of candidate < 0.4 GeV/c
• Opening angle $> 178.5^\circ$
• Momentum angle $|\cos\theta| < 0.25$

$\eta_c$ efficiency 10%\
$\# Signal = 5 \pm 1$

$\# Background$

16 February. 2007
A. Lundborg,
Gluon-rich environment – glueballs, hybrids

\[ \bar{p} \rightarrow \pi^0, \eta \]

Lowest energy charmonium hybrid (spin-exotic)

\[ J^{PC} = 1^{--} \quad M = 4.1 - 4.4 \, GeV \]

\[ \Gamma = O(20) \, MeV \]

[F.E. Close, Phys. Rev. 1998]
[UKQCD, McNeile, Phys. Rev. D56(2002)\]
A possible charmonium hybrid channel:

\[ p \bar{p} \rightarrow \psi_g \pi^0 / \eta \]

Nonrelativistic decay: charmquarks stay as they are. Gluonic excitation goes into a light scalar.

Sensitive to mass of the hybrid.

\[ \psi_g \rightarrow \chi_c + (\pi^0 \pi^0)_s \]

\[ 1^{-+} \rightarrow 1^{++} + 0^{++} (L = 1) \]

[UKQCD, McNeile, Phys. Rev. D56 (2002)]

Final state:
7 photons! 1 lepton pair!
We need:
1 Excellent calorimeter with full angular range coverage.

\[ e^+ e^- / \mu^+ \mu^- \] Good experimental tag!
For the given hybrid decay channel the EMC is in focus, 7150 crystals

$20 \chi_0, PbWO_4$

- Exotic - finding in production and not formation
- High detection efficiency over full phase space
- 2 cm iron plate in forward magnet 2% event loss
- 10 MeV threshold 1.5% event loss, 20 MeV 6% event loss
- 91.5% coverage of the muon detectors
- Minimise material before the EMC, event detection $\sim e^{-49x/9}$
- Outlook: new framework, but also open charm decays
AGNES LUNDBORG

The Charm of Excited Glue

Charmonium in $e^+e^-$ and $p\bar{p}$ collisions

BESII  PANDA
Cross sections for associated charmonium production?

Complicated QCD process
only one theoretical guideline
for only one channel (PCAC)


T. Barnes and X. Li. Associated charmonium production in low energy $p\bar{p}$

Only one measurement (E760):

$$\sigma(p\bar{p} \rightarrow J/\psi\pi^0) \approx 0.1 \text{ nb}$$

100 – 1000 events / day
Annihilation background
$$\approx 10^7 / s$$

R. Cester. Formation of $c\bar{c}$ states from antiproton-proton annihilations in the
Fermilab accumulator (E760). In Physics at SuperLEAR, number 124 in Inst.
Use experimental data

$\bar{c}c \rightarrow \bar{p}p + m$ known amplitude $A$

extrapolate $A$ to $\bar{p}p \rightarrow \bar{c}c + m$

It’s a kinematical extrapolation, not very far..

We know this decay width...

We want to know this cross section.

\[ \Gamma_{\psi \rightarrow m\bar{p}p} = \frac{1}{256\pi} \frac{1}{|p_p\cdot m\bar{p}|} \sum |\mathcal{M}|^2 A_D \]

\[ \frac{d\sigma}{dt}_{p\bar{p} \rightarrow m\bar{p}p} = \frac{1}{256\pi} \frac{1}{|p_p\cdot m\bar{p}|^2} s^{-1} \sum |\mathcal{M}|^2 \]
Cross sections
1 nb-10 pb
10-10000 events/day at PANDA

Results

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma_{p\bar{p} \rightarrow m\Psi}^{max}$ [pb]</th>
<th>$E_{cm}^{max}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow \pi^0 J/\psi$</td>
<td>420 ± 40</td>
<td>4.28</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta J/\psi$</td>
<td>1520 ± 140</td>
<td>4.57</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \rho^0 J/\psi$</td>
<td>&lt; 450</td>
<td>4.80</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \omega J/\psi$</td>
<td>1900 ± 400</td>
<td>4.80</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta' J/\psi$</td>
<td>3300 ± 1500</td>
<td>4.99</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \phi J/\psi$</td>
<td>280 ± 90</td>
<td>5.06</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \pi^0 \psi'$</td>
<td>55 ± 8</td>
<td>5.14</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta \psi'$</td>
<td>33 ± 8</td>
<td>5.38</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \rho^0 \psi'$</td>
<td>38 ± 17</td>
<td>5.59</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \omega \psi'$</td>
<td>46 ± 22</td>
<td>5.60</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \phi \psi'$</td>
<td>&lt; 28</td>
<td>5.84</td>
</tr>
</tbody>
</table>

Enhanced isoscalar production could be an artefact of the constant matrix element approximation.

Outlook:
• C=+ states are produced from gg rather than ggg.
• Resonances (form-factors).
Summary

• Charmonium spectroscopy, decay and production can probe QCD: semi-relativistic, semi-perturbative.

• Glueballs in e+e- at BES.
  \[ e^+ e^- \rightarrow \psi' \rightarrow \gamma X \rightarrow \gamma \pi^+ \pi^- , \gamma K^+ K^- \]

• Simulation of \( p\bar{p} \rightarrow \eta_c \rightarrow \gamma\gamma \) at PANDA gave a signal-to-background ratio of at least 5 with an efficiency of 10%.

• Proton-antiproton can give “all” quantum numbers in formation → beam width limits resolution, not detector.

• Hybrids in the future experiment PANDA. EMC important. Full phase space coverage and little material.

• Relate decay widths to cross section ~10 -10000 events per day.