Search for Glueballs and Hybrids in Antiproton-Proton Annihilations

Ulrich Wiedner
Ruhr-Universität Bochum
Experiment: look for Gluon-rich Processes

Double pomeron exchange?

WA 79, WA 102

MARK III, DM2, BES

ASTERIX, Crystal Barrel, OBELIX, E835
Self Interaction of Color Fields

- NO electric charges
  - NO electromagnetic interaction

- color charges
  - color (= strong) interaction
Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

**FERMIONS**

<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2, 3/2, 5/2, ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c²</td>
</tr>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>0.000511</td>
</tr>
<tr>
<td>$\nu_{\mu}$ muon neutrino</td>
<td>$&lt;0.002$</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
</tr>
<tr>
<td>$\nu_{\tau}$ tau neutrino</td>
<td>$&lt;0.02$</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.777</td>
</tr>
</tbody>
</table>

**Quarks** spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of h, which is the quantum unit of angular momentum, where $h = 6.626 \times 10^{-34}$ kg m²/s. Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is $1.602 \times 10^{-19}$ coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in acquiring a potential difference of one volt. Masses are given in GeV/c² (fermions) or eV/c² (photons), where 1 GeV = $1.602 \times 10^{-19}$ kg. The mass of the proton is $938.27$ GeV/c² = $1.675 \times 10^{-27}$ kg.

**BOSONS**

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass GeV/c²</td>
</tr>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.4</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.4</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.187</td>
</tr>
</tbody>
</table>

**Strong (color)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$ gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Color Charge

Each quark carries one of three colors of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electricity and magnetism interact with charged particles, strong interactions involve charged particles that interact by exchanging gluons, leptons, photons, and $W$ and $Z$ bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons, they are confined in color neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color confined constituents. As color charged particles (quarks and gluons) move apart, the energy in the color force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons, those are the particles we can observe. Two types of hadrons have been observed in nature: mesons qq and baryons qq.

Residual Strong Interaction

The strong binding between quarks and neutrons to form hadrons is due to residual strong interactions between their color charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Properties of the Interactions

- **Gravitational**
- **Weak**
- **Electromagnetic**
- **Strong**

**MOSIONS qq**

Mesons are bosons, hadrons. There are about 160 types of mesons.

--

**Baryons**

Baryons are fermion hadrons. There are about 120 types of baryons.

--

Matte and Antimatter

For every particle type, there is a corresponding antimatter type, denoted by a bar over the particle symbol (e.g., $\bar{e} = \gamma - e^-$ = charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some especially neutral bosons (e.g., $\gamma$, $\nu$, and $\bar{\nu}$) do not have antimatter pairs, but $K^0$ and $\bar{K}^0$ are their own antiparticles.

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Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no numerical scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

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The Particle Adventure

Visit the award-winning web feature The Particle Adventure at http://ParticleAdventure.org

This chart has been made possible by the generous support of:

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- U.S. National Science Foundation
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- Stanford Linear Accelerator Center
- AIP Center for Physics of Fundamental Interactions of Particles and Fields

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http://CPEPweb.org
<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong Residual</th>
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</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td></td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td></td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td></td>
<td>Graviton</td>
<td>W⁺, W⁻, Z⁰</td>
<td>γ</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength relative to electromag</td>
<td>10⁻¹⁸ m 3·10⁻¹⁷ m</td>
<td>10⁻⁴¹</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>for two u quarks at:</td>
<td></td>
<td>10⁻⁴¹</td>
<td>10⁻⁴</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td></td>
<td>10⁻³⁶</td>
<td>10⁻⁷</td>
<td>1</td>
<td>Not applicable to quarks</td>
</tr>
</tbody>
</table>

See Residual Strong Interaction Note
Basic underlying theory is known: QCD … but

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<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>$W^+$</td>
<td>$W^-$</td>
<td>$Z^0$</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>Strength relative to electromagnetic for two u quarks at:</td>
<td>$10^{-18}$ m</td>
<td>$10^{-41}$</td>
<td>$0.8$</td>
<td>$1$</td>
<td>Not applicable to quarks</td>
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<tr>
<td>for two protons in nucleus</td>
<td>$3 \times 10^{-17}$ m</td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>$1$</td>
<td>Not applicable to hadrons</td>
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<td>Quarks, Gluons</td>
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<tr>
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<td>Graviton (not yet observed)</td>
<td>W⁺ W⁻ Z⁰</td>
<td>Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td>Strength relative to electromag for two u quarks at:</td>
<td>10⁻¹⁸ m</td>
<td>10⁻⁴¹</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td>10⁻¹⁷ m</td>
<td>10⁻⁴¹</td>
<td>10⁻⁴</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>10⁻⁻³⁶</td>
<td>10⁻⁻⁷</td>
<td>10⁻⁻⁷</td>
<td>1</td>
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See Residual Strong Interaction Note

Residual

Hadrons

Mesons

Not applicable to quarks

Not applicable to hadrons

20
Positronium

Charmonium

Dissociation energy

Singlet Triplet Triplet

Relative energy (eV)

Singlet Triplet Singlet Triplet

Relative energy (MeV)

L = 0

Singlet Triplet Singlet Triplet

L = 1

Singlet Triplet Singlet Triplet

Singlet Triplet Singlet Triplet

Bound states

DD threshold

\[ \eta_c \]

\[ \psi \]

\[ \psi' \]

\[ \psi'' \]

\[ h_c \]

\[ \chi_0 \]

\[ \chi \]

\[ \chi_1 \]

\[ \chi_2 \]

\[ 2^3S_1 \]

\[ 2^3P_0 \]

\[ 2^3P_1 \]

\[ 2^3P_2 \]

\[ 2^1P_1 \]

\[ 1^3S_1 \]

\[ 1^3S_0 \]

\[ 2^1S_1 \]

\[ 2^3S_1 \]

\[ 2^3P_1 \]

\[ 2^3P_0 \]
X and Y mesons

\[ X(3872) \]
\[ B \rightarrow K \pi^+ \pi^- J/\psi \]

\[ Y(4260) \]
\[ e^+ e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- J/\psi \]

\[ Y(3940) \]
\[ B \rightarrow K \omega J/\psi \]

\[ M(\pi^+ \pi^- J/\psi) - M(J/\psi) \]

\[ Y(4350) \& Y(4660) \]
\[ e^+ e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- J'/\psi \]

\[ X(3940) \]
\[ e^+ e^- \rightarrow DD^* J/\psi \]

\[ X(4160) \]
\[ e^+ e^- \rightarrow D^* D J/\psi \]

\[ X(4100) \]
\[ e^+ e^- \rightarrow D^* D J/\psi \]

\[ Y(4140) \]
\[ B \rightarrow K \phi J/\psi \]

\[ Y(4630) \]
\[ e^+ e^- \rightarrow \gamma_{ISR} \Lambda_c \Lambda_c \]

\[ X(3872) \]
\[ M(\pi^+ \pi^- J/\psi) - M(J/\psi) \]

\[ M(\omega J/\psi) \]

\[ M(\pi^+ \pi^- J') \]

\[ Y(4008)? \]
\[ e^+ e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- J'/\psi \]

\[ X(3872) \]
\[ Y(4140) \]
\[ CDF \]

\[ M(DD^*) \]

\[ M(D^* D J) \]

\[ M(\phi J/\psi) \]

\[ M(\Lambda_c \Lambda_c) \]
$Z^+ (4430)$ - a new state of matter (tetraquark?) decaying into $\pi^+\psi'$

$$M = (4.433 \pm 0.004 \text{ (stat)} \pm 0.001 \text{ (syst)}) \text{ GeV}$$

$$\Gamma = (0.044^{+0.017}_{-0.011} \text{ (stat)}^{+0.030}_{-0.011} \text{ (syst)}) \text{ GeV}$$

$$\mathcal{B}(B \rightarrow KZ(4430) \times \mathcal{B}(Z \rightarrow \pi^+\psi') = (4.1 \pm 1.0 \text{ (stat)} \pm 1.3 \text{ (syst)}) \times 10^{-5}$$

PRL 100, 142001 (2008)
arXiv:0708.1790 [hep-ex]
Belle-BaBar comparison

Not applied efficiency correction to the data and applying the $K^*$ veto

Both Belle and $BaBar$ data are re-binned (to calculate $\chi^2$) and side-band subtracted.

The $BaBar$ data are normalized to the Belle sample.

The data distributions are statistically consistent ($\chi^2 = 54.7/58$)
NEW results on Z(4430)$^+$ from Dalitz plot fit

The results of the DP fit in its slices with Z:

Confidence Level of the fit WITH Z(4430)$^+$ is 36%

Significance of Z is 6.4$\sigma$
Parameters of the new EXOTIC $Z^{+}_{1,2} \rightarrow \pi^{+}\chi_{c1}$ states and Mass($\pi^{+}\chi_{c1}$) distribution are the same order as obtained for other, possibly exotic X,Y,Z states.

No discrimination between $J=0$ or 1

\[
\begin{align*}
M_1 &= (4051 \pm 14^{+20}_{-41}) \text{ MeV/c}^2, \\
\Gamma_1 &= (82^{+21+47}_{-17-22}) \text{ MeV,} \\
M_2 &= (4248^{+44+180}_{-29-35}) \text{ MeV/c}^2, \\
\Gamma_2 &= (177^{+54+316}_{-39-61}) \text{ MeV,}
\end{align*}
\]

with the product branching fractions of
\[
\begin{align*}
\mathcal{B}(\bar{B}^0 \rightarrow K^- Z^+_1) \times \mathcal{B}(Z^+_1 \rightarrow \pi^+ \chi_{c1}) &= (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5}, \\
\mathcal{B}(\bar{B}^0 \rightarrow K^- Z^+_2) \times \mathcal{B}(Z^+_2 \rightarrow \pi^+ \chi_{c1}) &= (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.
\end{align*}
\]
S. Olsen’s conclusion at the Charmed Exotic Workshop (2009):

- **$Z(4430)^+$** signal in $B \rightarrow K \pi \psi'$ persists with a more complete amplitude analysis.
  - signif. $\sim 6\sigma$, product $Bf \sim 3 \times 10^{-5}$ (with large errors)

- No significant contradiction with the BaBar results
  - signif. $= 2 \sim 3\sigma$, Product $Bf < 3 \times 10^{-5}$

- **$Z_1(4050)$ & $Z_2(4250)$**, seen in $B \rightarrow K \pi \chi_{c1}$, have similar properties (i.e. $M$ & $\Gamma$) & product $Bf$'s
  - signif. (at least one $Z^+$)$>10\sigma$; (two $Z^+$ states)$>5\sigma$
PANDA: $\bar{p}p \rightarrow Z^+(4430) + \pi^-$
PANDA: $\bar{p}p \rightarrow Z^+(4430) + \pi^-$

$\rightarrow \psi(2S)\pi^+ \rightarrow J/\psi \pi^+\pi^-$
PANDA: $\bar{p}d \rightarrow Z^{-}(4430) + p$

$\psi(2S)\pi^{-} \rightarrow J/\psi \pi^{+}\pi^{-}$

FWHM: 11.2 MeV

Efficiency: 35%
$X(3872)$

$B \rightarrow KX; \ p\bar{p}$

$X \rightarrow \pi^+\pi^- J/\psi$

$X \rightarrow \pi^+\pi^-\pi^0 J/\psi$

$X \rightarrow \gamma J/\psi; \ X \rightarrow \gamma\psi(2S)$

$X(3875) \rightarrow D^0\bar{D}^0\pi^0$

$J^{PC} = 1^{++}$

$M = 3871.4 \pm 0.6$

$\Gamma < 2.3$

$> 10 \sigma$

DD* molecule

threshold effect

tetraquark
\[ B \rightarrow KY \]
\[ Y \rightarrow \omega J/\psi \]

\[ J^{PC} = J^{P+} \]
\[ M = 3943 \pm 17 \]
\[ \Gamma = 87 \pm 34 \]

8 \sigma

Observed decay mode: J/\psi + \omega is huge (> 7 MeV)
Decay of charmonium hybrids

Lattice results*

What is the nature of these states?

Quarkonia? Molecules? Hybrids?
PANDA antiproton physics has advantages:
PANDA antiproton physics has advantages:

Production vs. Formation
PANDA antiproton physics has advantages:

Production vs. Formation

Produktion experiments:

all quantum numbers possible

\[ J = L + S \]

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

\[ C = (-)^{L+S} \]
PANDA antiproton physics has advantages:

**Production vs. Formation**

Produktion experiments:
- All quantum numbers possible

Formation experiments:
- Identical quantum numbers

\[ J^P_C = (L + S) \]
\[ P = (-)^{L+1} \]
\[ C = (-)^{L+S} \]
PANDA antiproton physics has advantages:

Production vs. Formation

Produktion experiments:
- all quantum numbers possible

Formation experiments:
- identical quantum numbers

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

Discovery potential
PANDA antiproton physics has advantages:

Production vs. Formation

Production experiments:
- All quantum numbers possible

Formation experiments:
- Identical quantum numbers

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

- Discovery potential
- Precision physics
Formation experiments cannot produce exotic $J^{PC}$. 
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Production experiments can produce exotic $J^{PC}$. 
Formation experiments cannot produce exotic $J^{PC}$.

Production experiments can produce exotic $J^{PC}$.

Signal in production but no signal in formation
Formation experiments cannot produce exotic $J^{PC}$.

Production experiments can produce exotic $J^{PC}$.

Signal in production but no signal in formation

very interesting
$\bar{p}p \rightarrow \pi^0\pi^0\pi^0$ Dalitz plot

700000 events = 6×700000 entries
Production of $\chi_{1,2}$

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

$\chi_{1,2} \rightarrow \gamma (\gamma J/\psi)$

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

Reconstruction of invariant mass:
detector resolution dependent
Production of $\chi_{1,2}$

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

$\gamma \chi_{1,2}$

$\gamma (\gamma J/\psi)$

$\gamma \gamma (e^+e^-)$

Reconstruction of invariant mass:
detector resolution dependent
Production of $\chi_{1,2}$

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

$\chi_{1,2}$

$\gamma (\gamma J/\psi)$

$\gamma \gamma (e^+e^-)$

Reconstruction of invariant mass:
detector resolution dependent

Formation of $\chi_{1,2}$

$\bar{p}p \rightarrow \chi_{1,2}$

$\gamma J/\psi$

$\gamma (e^+e^-)$

Rate measurement (beam energy dependent):
detector resolution “independent”
Production of $\chi_{1,2}$

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

$\chi_{1,2} \rightarrow \gamma (\gamma J/\psi)$

$\gamma (e^+e^-)$

Reconstruction of invariant mass: detector resolution dependent

Formation of $\chi_{1,2}$

$\bar{p}p \rightarrow \chi_{1,2}$

$\gamma J/\psi$

$\gamma (e^+e^-)$

Rate measurement (beam energy dependent): detector resolution “independent”

$\sigma_m$ (beam) = 0.5 MeV

$J^{PC} = 1^{--}$

E 760 (Fermilab)
Production of $\chi_{1,2}$

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

$\gamma (\gamma J/\psi)$

$\gamma (e^+e^-)$

Reconstruction of invariant mass:
detector resolution dependent

Formation of $\chi_{1,2}$

$\bar{p}p \rightarrow \chi_{1,2}$

$\gamma J/\psi$

$\gamma(e^+e^-)$

Rate measurement (beam energy dependent):
detector resolution “independent”

$\sigma_m$ (beam) = 0.5 MeV

$J^P C = 1^{--}$

$J = 0, 2, ...$

$C = +$

$J = 1$

$C = -$
The width of the XYZ states cannot be determined in decays (limited detector resolution) but in scanning experiments with antiprotons.
**X(3872) → π⁺π⁻ J/ψ in BaBar**

**recent results**

**BABAR**: PRD 77,111101 (2008) [413 fb⁻¹]

$B^+ → X(3872)K^+$

413 fb⁻¹

8.6σ

$B^0 → X(3872)K^0_S$ 413 fb⁻¹

2.3σ

$\delta M_X = M(X \text{ from } B^±) - M(X \text{ from } B^0)$

\[ = (2.7 \pm 1.6 \pm 0.4) \text{ MeV} \]

$$R = \frac{BR(B^0 → X(3872)K^0)}{BR(B^± → X(3872)K^±)} = 0.41 \pm 0.24 \pm 0.05$$


S. Olsen @ charmed exotics workshop 2009
$M(X(3872))$ $\pi^+\pi^-J/\psi$ mode only

$<M_X> = 3871.46 \pm 0.19$ MeV

$\delta m = -0.35 \pm 0.41$ MeV
Resonance scan

Measure rate of final state under study:

\[ R_i = L_0 \cdot \sigma(p_i) \cdot K (\Delta p/p, |p_i - p_R|) \]

(K takes overlap between beam and resonance into account)
- 40k $J/\psi \omega$ events at $\Upsilon(3940)$
  - $J/\psi \rightarrow l^+l^-$, $\omega \rightarrow \pi^+\pi^-\pi^0$
- selection
  - PID: $p(l^+)>0.2$, $p(l^-)>0.85$
  - PID: $p(\pi^+)>0.2$, $m(\gamma\gamma) \in [115;150]$ MeV
  - 6C fit: beam, $J/\psi$ and $\pi^0$ mass constraint
  - mass windows
    - $m(e^+e^-) \in [3.07;3.12]$ GeV
    - $m(\pi^+\pi^-\pi^0) \in [750;810]$ MeV
  - $J/\psi \omega$ cand. w/ biggest CL $>0.1$
  - veto on $\Psi(2S) \rightarrow J/\psi \pi^+\pi^-$
    - $m(J/\psi \pi^+\pi^-) \in [3.6725;3.7]$ GeV

Reconstruction efficiency: 16.5%
Product of branching ratios:
$BR(\Upsilon(3940) \rightarrow J/\psi \omega) \times 10.7\%$
Assume: int. lum. 8pb-1/day
  cross sec. of 1nb
Expect $BR(\Upsilon(3940) \rightarrow J/\psi \omega) \times 140$ evts/day
$\bar{p}d \rightarrow \pi^- \pi^0 \eta + p$

spectator ($<100$ MeV/c)

$m^2(\eta\pi^-)$ vs $m^2(\eta\pi^-)$ [GeV/c$^2$]$^2$

- $\hat{\rho}(1400)$
- $a_2(1320)$
- $\rho^-(770)$

52,576 events
\[ \bar{p}d \rightarrow \pi^- \pi^0 \eta + \rho \]

spectator
\(<100 \text{ MeV}/c\)

\(\rho\) Amplitude and Interference

\(m^2(\eta\pi^-)\) vs. \([\text{MeV}/c^2]^2]\)

- \(a_2(1320)\)
- \(\rho^-(770)\)
Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)^{L=1}$
Mass: $1400 \pm 30$ MeV
Width: $310 \pm 70$ MeV
Quantum numbers: $J^{PC} = 1^{-+}$

not possible from $q\bar{q}$
Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)_{L=1}$
Mass: $1400 \pm 30$ MeV
Width: $310 \pm 70$ MeV
Quantum numbers: $J^{PC} = 1^{--}$

not possible from $q\bar{q}$
Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)_{L=1}$
Mass: $1400 \pm 30$ MeV
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Quantum numbers: $J^{PC} = 1^{--}$

not possible from $q\bar{q}$
Properties of the $\pi_1(1400)$

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Mass: $1400 \pm 30$ MeV
Width: $310 \pm 70$ MeV
Quantum numbers: $J^{PC} = 1^{--}$

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\end{align*}
\]

Previous indications of this resonance:

$\pi^- p \to (\pi^0\eta)n$  
(GAMS/CERN, 100 GeV/c, 1988)

$\pi^- p \to (\pi^0\eta)n$  
(VES/Serpukhov, 100 GeV/c, 1993)

$\pi^- p \to (\pi^0\eta)n$  
(E852/Brookhaven, 18 GeV/c, 1997))

$M: 1300 - 1400$ MeV/c$^2$, $\Gamma: 150 - 400$ MeV
Exotic production in $p\bar{p}$:
What is the nature of these states?

Quarkonia? Molecules? Hybrids?
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Quarkonia? Molecules? Hybrids?

➡️ Wait for PANDA
Glueballs
Glueballs → Creation of Mass
A few % of the proton mass is generated due to the Higgs mechanism.
Glueballs $\rightarrow$ Creation of Mass

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**HOW ???????**

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Glueballs
Glueballs, closed fluxtubes and $\eta(1440)$
Ludvig Faddeev, Antti Niemi and Ulrich Wiedner
Phys.Rev.D70:114033, 2004
The glueball spectrum
QCD systems
QCD systems

[Diagram showing various physics systems and their interactions, including QCD, mesons, antiprotons, and molecules.]
QCD systems
String Theory

AdS/CFT

AdS/QCD

Semi-Classical QCD / Wave Equations

Boost Invariant 3+1 Light-Front Wave Equations

J = 0, 1, 1/2, 3/2 plus L

Holography

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

Goal: First Approximant to QCD
Counting rules for Hard Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space

Conformal behavior at short distances
+ Confinement at large distance

J = 0, 1, 1/2, 3/2 plus L

Integrable!

Holography

PANDA Workshop
Turin June 17, 2009

Novel Anti-Proton QCD Physics

Stan Brodsky
SLAC
Electromagnetic Processes: $\bar{p}p \rightarrow \gamma\gamma$

Handbag diagram separates a soft part described by GPDs from a hard $q\bar{q}$ annihilation process

Predicted rates*: several thousand / month or above

Exp. problem: Background channels like $\pi^0\gamma$ or $\pi^0\pi^0$ 5× - 100× stronger.

Study of Drell-Yan processes might contribute to the knowledge of parton distribution functions (polarized nuclear targets?).
How to Calculate Meson Spectra from String Theory

Johanna Erdmenger

Max-Planck-Institut für Physik, München

work in collaboration with J. Babington, Z. Guralnik, I. Kirsch (HU Berlin), R. Apreda, J. Große (HU Berlin/MPI München), N. Evans (Southampton)

AdS/CFT Correspondence

(Maldacena 1997, AdS: Anti de Sitter space, CFT: conformal field theory)

- Duality Quantum Field Theory ⇔ Gravity Theory
- Arises from String Theory in a particular low-energy limit
- Duality: Quantum field theory at strong coupling
  ⇔ Gravity theory at weak coupling
- Works for large $N$ gauge theories at large 't Hooft coupling $\lambda$

Conformal field theory in four dimensions
  ⇔ Supergravity Theory on $AdS_5 \times S^5$
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Comparison with experimental results

D4/D8/D8 brane model – spontaneous breaking of $SU(N_f) \times SU(N_f)$

Sakai+Sugimoto 12/2004

vector and axial vector mesons
(obtained from gauge field fluctuations as described by the DBI action)

meson mass ratio:

Experiment:

$$\frac{m_{a_1}^2}{m_{\rho}^2} = \frac{(1230\text{MeV})^2}{(776\text{MeV})^2} = 2.51$$

Stringy model:

$$\frac{m_{a_1}^2}{m_{\rho}^2} = 2.4$$

($\rho : C = -1, a_1 : C = +1$)

In the model of Sakai+Sugimoto, it is also possible to have $N_f > 1$. 

23
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Glueball Mass Spectrum from Supergravity

Csaba Csáki† and John Terning
Theoretical Physics Group
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720
and
Department of Physics
University of California, Berkeley, CA 94720

TABLE III. Masses of the first few 0^{++} glueballs in QCD$_4$, in GeV, from supergravity compared to the available lattice results. The first column gives the lattice result [7,16,17], the second the supergravity result for $a = 0$ while the third the supergravity result in the $a \to \infty$ limit. The change from $a = 0$ to $a = \infty$ in the supergravity predictions is tiny. Note, that for the excited state the supergravity calculation came before the lattice results.

<table>
<thead>
<tr>
<th>state</th>
<th>lattice, $N = 3$</th>
<th>supergravity $a = 0$</th>
<th>supergravity $a \to \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^{++}</td>
<td>1.61 ± 0.15</td>
<td>1.61 (input)</td>
<td>1.61 (input)</td>
</tr>
<tr>
<td>0^{++}</td>
<td>2.48 ± 0.18</td>
<td>2.55</td>
<td>2.56</td>
</tr>
<tr>
<td>0^{++}</td>
<td>-</td>
<td>3.46</td>
<td>3.48</td>
</tr>
<tr>
<td>0^{++}</td>
<td>-</td>
<td>4.36</td>
<td>4.40</td>
</tr>
</tbody>
</table>
The PANDA Detector
PANDA Collaboration

At present a group of 420 physicists from 54 institutions and 16 countries


http://www.gsi.de/panda

Spokesperson: Ulrich Wiedner (Bochum)
The PANDA EMC

Partners:
Sweden (Uppsala, Lund, KTH Stockholm, Stockholm), KVI, Basel, Germany (Bochum, Giessen, GSI)
The Forward EMC is more challenging than the CMS-EMC:

- γ energies between 0.01 - 15 GeV
- very high count rates (up to 500 kHz)

absorbed energy dose:
- @14GeV (innermost)
  11.9 mJ/h
- @6GeV (innermost)
  5.7 mJ/h

J. Zhong, Bochum

M. Kotulla, Giessen
The PANDA-EMC will be better:

**light yield**

*CMS-ECAL*

Present quality for PANDA 2007/8

@-25°C: 90p.e./MeV, 18%QE

For APD-readout: A = 2cm², 70%QE 150p.e./MeV

To be considered:
- light collection in tapered crystals
- radiation damage
- uniformity due to surface treatment

R. Novotny, Giessen

**cooling**
Hardware activities
Cost: 1 g antimatter:

1 P€ \( (10^{15} \text{ €}) \)

Cost: FAIR:

1 B€ \( (10^9 \text{ €}) \)
Thank you for your attention!