Hadron physics with PANDA:

Study of the strong interaction in the transition region between perturbative QCD and nuclear phenomena
Open questions to be addressed:

- Confinement: Why do we not observe free quarks?
- Hadron mass? The Higgs mechanism accounts for some percent of the nucleon mass. The rest is QCD.
- How are color neutral objects formed?
- Does non-standard hadron configurations exist?
- Structure of the nucleon?
- Spin degrees of freedom?

Physics with antiprotons:

- hadron spectroscopy
- hadron structure
- interaction of hadrons
Particle production in $\bar{p}p$ interaction

Formation:

\[ J = 0, 2, \ldots \]
\[ C = + \]

\[ J = 1 \]
\[ C = - \]

All $J^{PC}$ allowed for $(q\bar{q})$ are accessible in $\bar{p}p$

Only $J^{PC} = 1^{--}$ allowed in $e^+e^-$

\[ \chi_{1,2} \]

\[ e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_{1,2} \rightarrow \gamma(\gamma J/\psi) \rightarrow \gamma e^+e^- \]

Invariant mass reconstruction depends on the detector resolution $\approx 10$ MeV

Formation

\[ \bar{p}p \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^- \]

Resonance scan. Resolution depends on the beam resolution.

E760@Fermilab $\approx 240$ keV

PANDA $\approx 50$ keV
Many new and narrow states recently observed in
Charmonium region above $D\bar{D}$ threshold ($X,Y,Z$ states)

<table>
<thead>
<tr>
<th>State</th>
<th>$\Gamma$ [MeV]</th>
<th>Experiment</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>3 ± 2</td>
<td>Belle, BaBar, CDF, D0</td>
<td>$1^{+}, 2^{-}, D^0\bar{D}^*$ molecule, tetraquark</td>
</tr>
<tr>
<td>X(3930)</td>
<td>29 ± 10</td>
<td>Belle</td>
<td>$2^-$ $\chi_{c2}(2P)$</td>
</tr>
<tr>
<td>X(3940)</td>
<td>&lt; 52</td>
<td>Belle</td>
<td>$??$ $???$</td>
</tr>
<tr>
<td>X(3945)</td>
<td>40 ± 18</td>
<td>Belle, BaBar</td>
<td>$??^+ \eta_c(3S)$?</td>
</tr>
<tr>
<td>X(4160)</td>
<td>139±113</td>
<td>Belle</td>
<td>$??$ $???$</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>95 ± 9</td>
<td>BaBar, CLEO, Belle</td>
<td>$1^-$ Hybrid, threshold effect</td>
</tr>
<tr>
<td>Y(4360)</td>
<td>75 ± 14</td>
<td>BaBar, Belle</td>
<td>$1^-$ $???$</td>
</tr>
<tr>
<td>X(4660)</td>
<td>48 ± 15</td>
<td>BaBar, Belle</td>
<td>$1^-$ Threshold effect</td>
</tr>
</tbody>
</table>

Overpopulated region => Hints for exotics

Positronium - QED

Coulomb-like potential: $V(r) = -\frac{4}{3}\alpha_s(r)\frac{\hbar c}{r} + kr$ ; $k \approx 0.9$ GeV/fm

Works for lower part of the spectrum

Info on confinement potential and spin contributions

Unconfirmed/unobserved states

Charmonium - QCD
Open charm mesons

Hydrogen of QCD

\[ D^{*}\bar{s}o(2317), \Gamma < 3.8 \text{ MeV} \]

\[ \Delta\Gamma/\Gamma = 30\% \ (\Gamma = 1 \text{ MeV}) \]

\[ \bar{p}p \rightarrow D_s^{\pm}D_s^{*}(2317)^\pm \]

14 days threshold scan

\[ J^{PC} \text{ not allowed for } q\bar{q} \text{ possible} \]
Particle production in $\bar{p}p$ interaction

**Production:**

- **J$^{PC}$ not allowed for $(q\bar{q})$ possible**
- **Good hunting ground for exotics**

**Fluxtube Hybrids**

<table>
<thead>
<tr>
<th>$q\bar{q}$</th>
<th>Gluon</th>
<th>$1^-$ (TM)</th>
<th>$1^-$ (TE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$, $0^+$</td>
<td>$1^+$</td>
<td>$1^-$</td>
<td></td>
</tr>
<tr>
<td>$^3S_1$, $1^-$</td>
<td>$0^-$</td>
<td>$1^-$</td>
<td>$1^-$</td>
</tr>
</tbody>
</table>

**Light-quark sector:**

**Non-qq candidates**

<table>
<thead>
<tr>
<th>$f_0(980)$</th>
<th>$f_0(1500)$</th>
<th>$f_0(1370)$</th>
<th>$f_0(1710)$</th>
<th>$h(1410); h(1460)$</th>
<th>$f_1(1420)$</th>
<th>$\pi_1(1400)$</th>
<th>$\pi_1(1600)$</th>
<th>$\pi(1800)$</th>
<th>$\pi_2(1900)$</th>
<th>$\pi_1(2000)$</th>
<th>$a_2(2100)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4q state - molecule</td>
<td>$0^{++}$ glueball candidate</td>
<td>$0^{++}$ glueball candidate</td>
<td>$0^{++}$ glueball candidate</td>
<td>$0^+$ glueball candidate</td>
<td>hybrid, 4q state</td>
<td>hybrid candidate</td>
<td>hybrid candidate</td>
<td>hybrid candidate</td>
<td>hybrid candidate $2^{++}$</td>
<td>hybrid candidate</td>
<td>hybrid candidate $1^{++}$</td>
</tr>
</tbody>
</table>

- ☘️ most candidates observed in $\bar{p}p$ annihilation
- ☘️ $\approx$ equal population as into ordinary states
- ☘️ broad and overlapping states
Charmed-quark sector:

- Hybrid states are expected to be narrow
- Less crowded region
- Glueballs with exotic quantum numbers (0+,2+), "oddballs", predicted in this region

**Hybrids**

Exotic charm hybrid

Flux-tube model:

\[ J^{PC} = 1^{+-} \]

\[ M = 4.2 - 4.5 \text{ GeV} \]

\[ \Gamma < 50 \text{ MeV} \]

**Glueballs**

Oddballs

LatticeQCD:

\[ J^{PC} = 0^{++}, 2^{++} \]

\[ M = 4 - 5 \text{ GeV} \]

\[ \Gamma < 50 \text{ MeV} \]

Many open questions in meson spectroscopy:

- Charmonium singlet states poorly measured
- Where are the radial excitations of the S and P states?
- Where are the missing 1D states?
- What is the nature of the alphabet (X,Y,Z) states?
- Exotics

**Z(4430)** seen in B-decay from Belle:

\[ B \rightarrow \psi' \pi^\pm \]

**Z(4430):** charged and decays into \( c\bar{c} \)

Prime candidate for a multiquark state.
Statistics is needed for PWA analysis

\[ \bar{p}p \rightarrow \pi^0 \pi^0 \pi^0 \] Crystal Barrel@LEAR

700,000 events

- \( f_2(1565) \)
- \( f_0(1500) \)
- \( f_2(1270) \)
- \( f_0(980) \)

The self-analysing weak decay of hyperons give access to spin observables.

The spin of the \( \bar{\Lambda}/\Lambda \) is primarily carried by the \( \bar{s}/s \) quarks

\[ \Rightarrow \]

Spin degrees of freedom in \( \bar{s}s \) production accessible.

Same argument for \( \bar{\Lambda}_c\Lambda_c \)
Strange Baryon spectroscopy

\[ pp \to \Lambda \Lambda \]

\[ pp \to \Xi \Xi^- \]

\[ pp \to \Xi^- \Xi^+ \]

\[ pp \to \Xi^- \Xi^+ \]

\[ pp \to \Xi^- \Xi^+ \]

≈ equal ratio between baryonic final states and annihilation into mesons in \( pp \) interactions

Baryonic final states largely formed via exited states

\( S = 2 \)

\( S = 3 \)

Many missing states!

Löhring, Metsch, Petry EPJ A10 (2001) 395
Facility for Antiproton and Ion Research (FAIR)

Primary Beams

- 30 GeV protons $2(4) \times 10^{13}$ s$^{-1}$

Secondary Beams

- Antiproton production target $2 \times 10^7$ s$^{-1}$ @ 3.8 GeV/c

Storage and Cooler Ring

- $10^{11}$ stored and cooled 1.5 - 14.5 GeV/c antiprotons

High resolution mode

- $\delta p/p < 2 \times 10^{-3}$ (electron cooling)
- Luminosity = $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

High luminosity mode

- Luminosity = $2 \times 10^{35}$ cm$^{-2}$ s$^{-1}$
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)

Physics Performance Report for:

PANDA

(Antiproton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

PANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal PANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed PANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.

This report presents a summary of the physics accessible at PANDA and what performance can be expected.
Need a versatile tool ...

Pellet/cluster jet target  
$\approx 4 \times 10^{15}$ atoms/cm$^2$

Si pixel/strip detector  
$\sigma$(vertex) $\approx 50 \mu$m  
$dE/dx$

EMC: PWO crystals  
1 MeV - 10 GeV  
$\sigma(E)/\sqrt{E} < 2 \%$

EMC: Shashlyk  
$\sigma(E)/\sqrt{E} \approx 4 \%$

Straw tube tracker  
$\Delta p/p \approx 1\%$  
$dE/dx$

Drift chambers  
$\Delta p/p \approx 0.2\%$

GEM trackers

TARGET

Tracking

EMC

PID

RHIC  
$\pi/K/p > 2.8$ GeV/c

DIRC  
$\pi/K/p > 1$ GeV/c

ToF  
$\pi/K/p < 2.8$ GeV/c

Muon chambers
Strong and international collaboration:

≈ 500 scientists
53 institutions
17 countries

QCD is exciting!