The ČPANDA Experiment

Diego Bettoni
INFN, Ferrara, Italy

Joint GSI/FAIR Scientific Councils
GSI 29 June 2015
The theory of the strong interaction, Quantum Chromodynamics (QCD) is well understood and tested only at high energies (perturbative regime).

At low energies QCD becomes a strongly coupled theory, many fundamental aspects of which are not understood.

PANDA will study $\bar{p}p$ and $\bar{p}A$ annihilations, providing unique and decisive measurements on a wide range of QCD aspects:

- Hadron spectroscopy
- Hadron structure
- Hadronic interactions (properties of hadrons in matter and hypernuclei).
\( \bar{p} p \) Annihilation

**Gluon- Rich Environment**

Direct resonant formation of states with all non-exotic quantum numbers. \( \Rightarrow \) excellent precision in mass and width measurement

Access to both exotic and non-exotic quantum numbers via production and formation reactions

**Versatility of physics program**
(if coupled to universal detector)

**Uniqueness of \( \bar{p} \) probe**
(no other \( \bar{p} \) facility in this energy range in the world)
Comparison with Other Techniques

• $e^+e^-$
  – direct formation limited to $J^{PC} = 1^-$
  – limited resolution for masses and widths for non vector states
  – sub-MeV widths very difficult or impossible
  – high L not accessible

• high-energy (several TeV) hadroproduction
  – high combinatorial background makes discovery of new states very difficult
  – width measurements limited by detector resolution

• B decays (both for $e^+e^-$ and hadroproduction)
  – limited $J^{PC}$
  – C cannot be determined since not conserved in weak decay
PANDA Physics Program

- HADRON SPECTROSCOPY
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - OPEN CHARM
  - (MULTI)STRANGE BARYONS
- NUCLEON STRUCTURE
  - ELECTROMAGNETIC FORM FACTORS
  - TMDs
  - GPDs, TDAs
- HYPERNUCLEAR PHYSICS
- HADRONS IN THE NUCLEAR MEDIUM

\[ \sqrt{s} = 2 \div 5.5 \text{ GeV} \]

ArXiv:0903.3905
Exotic Hadrons I: Hybrids and Glueballs

Production

- All $J^P_C$ available

Formation

- Only selected $J^P_C$

Sound theoretical predictions from models and LQCD
Gluon rich process creates gluonic excitation in a direct way
Access to both exotic and non-exotic quantum numbers
Highest precision for direct formation
Access to both light and charm energy range
UNIQUE to $\bar{P}$ANDA

D. Bettoni

PANDA at FAIR
Exotic Hadrons II: X, Y, Z

Need systematic approach with the capability to carry out high-precision measurements to map out completely the spectrum of these new states, in order to understand their nature: PANDA will be unique in achieving this.

350 X(3872)/day
820 Y(4260)/day
176 Z(3900)/day

PANDA is an X Y Z factory
Exotic Hadrons II: X, Y, Z

<table>
<thead>
<tr>
<th>State</th>
<th>m (MeV)</th>
<th>Γ (MeV)</th>
<th>J^{PC}</th>
<th>Process (mode)</th>
<th>Experiment (#σ)</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (3872)</td>
<td>3871.68±0.17</td>
<td>&lt; 1.2</td>
<td>1^{++}</td>
<td>$B \to K (\pi^+\pi^- J/\psi)$</td>
<td>Belle [37,38] (12.8), BABAR [39] (8.6)</td>
<td>2003</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$</td>
<td>CDF [40–42] (np), D0 [43] (5.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K (\omega J/\psi)$</td>
<td>Belle [44] (4.3), BABAR [45] (4.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K (D^0 \bar{D}^0)$</td>
<td>Belle [46,47] (6.4), BABAR [48] (4.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K (\gamma J/\psi)$</td>
<td>Belle [49] (4.0), BABAR [50,51] (3.6), LHCb [52] (&gt;10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K (\gamma\psi(2S))$</td>
<td>BABAR [51] (3.5), Belle [49] (0.4), LHCb [52] (4.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z_c(3900)^+</td>
<td>3883.9 ± 4.5</td>
<td>25 ± 12</td>
<td>1^{+-}</td>
<td>$pp \to (\pi^+\pi^- J/\psi) + ...$</td>
<td>BESIII [55] (np)</td>
<td>2013</td>
<td>NC!</td>
</tr>
<tr>
<td></td>
<td>3891.2 ± 3.3</td>
<td>40 ± 8</td>
<td>?^{--}</td>
<td>$Y(4260) \to \pi^- (D \bar{D}^*)^+$</td>
<td>BESIII [56] (8), Belle [57] (5.2)</td>
<td>2013</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4260) \to \pi^- (\pi^+ J/\psi)$</td>
<td>T. Xiao <em>al.</em> [CLEO data] [58] (&gt;5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z_c(4020)^+</td>
<td>4022.9 ± 2.8</td>
<td>7.9 ± 3.7</td>
<td>?^{--}</td>
<td>$Y(4260, 4360) \to \pi^- (\pi^+ h_c)$</td>
<td>BESIII [59] (8.9)</td>
<td>2013</td>
<td>NC!</td>
</tr>
<tr>
<td></td>
<td>4026.3 ± 4.5</td>
<td>24.8 ± 9.5</td>
<td>?^{--}</td>
<td>$Y(4260) \to \pi^- (D^* \bar{D}^*)^+$</td>
<td>BESIII [60] (10)</td>
<td>2013</td>
<td>NC!</td>
</tr>
<tr>
<td>Z_b(10610)^+</td>
<td>10607.2 ± 2.0</td>
<td>18.4 ± 2.4</td>
<td>1^{+-}</td>
<td>$\Upsilon(10860) \to \pi^- (\pi \Upsilon(1S, 2S, 3S))$</td>
<td>Belle [61,62,63] (&gt;10)</td>
<td>2011</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Upsilon(10860) \to \pi^- (\pi^+ h_b(1P, 2P))$</td>
<td>Belle [62] (16)</td>
<td>2011</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Upsilon(10860) \to \pi^- (B B^*)^+$</td>
<td>Belle [64] (8)</td>
<td>2012</td>
<td>NC!</td>
</tr>
<tr>
<td>Z_b(10650)^+</td>
<td>10652.2 ± 1.5</td>
<td>11.5 ± 2.2</td>
<td>1^{+-}</td>
<td>$\Upsilon(10860) \to \pi^- (\pi \Upsilon(1S, 2S, 3S))$</td>
<td>Belle [61,62] (&gt;10)</td>
<td>2011</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Upsilon(10860) \to \pi^- (\pi^+ h_b(1P, 2P))$</td>
<td>Belle [62] (16)</td>
<td>2011</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\Upsilon(10860) \to \pi^- (B^* B^*)^+$</td>
<td>Belle [64] (6.8)</td>
<td>2012</td>
<td>NC!</td>
</tr>
</tbody>
</table>
### Exotic Hadrons II: X, Y, Z

<table>
<thead>
<tr>
<th>State</th>
<th>$m$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment (#σ)</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_c(3915)$</td>
<td>3917.4 ± 2.7</td>
<td>28$^{+10}_{-9}$</td>
<td>0$^{++}$</td>
<td>$B \rightarrow K (\omega J/\psi)$</td>
<td>Belle [66] (8.1), BABAR [67,65] (19)</td>
<td>2004</td>
<td>OK</td>
</tr>
<tr>
<td>$\chi_c(2P)$</td>
<td>3927.2 ± 2.6</td>
<td>24±6</td>
<td>2$^{++}$</td>
<td>$e^+e^- \rightarrow e^+e^- (D\bar{D})$</td>
<td>Belle [68] (5.3), BABAR [69,45] (5.8)</td>
<td>2005</td>
<td>OK</td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>3942$^{+9}_{-8}$</td>
<td>37$^{+27}_{-17}$</td>
<td>?$^{++}$</td>
<td>$B \rightarrow K (\omega J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>Belle [70] (7.7), BABAR [45] (np)</td>
<td>2007</td>
<td>NC</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008$^{+121}_{-49}$</td>
<td>226±87</td>
<td>1$^{--}$</td>
<td>$B \rightarrow K (\pi^+\chi_c(1P))$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>Belle [71] (6.0)</td>
<td>2007</td>
<td>NC</td>
</tr>
<tr>
<td>$Z_1(4050)$</td>
<td>4051$^{+24}_{-11}$</td>
<td>82$^{+11}_{-55}$</td>
<td>?</td>
<td>$B \rightarrow K (\pi^+\chi_c(1P))$</td>
<td>Belle [72] (7.4)</td>
<td>2007</td>
<td>NC</td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4145.8 ± 2.6</td>
<td>18 ± 8</td>
<td>?$^{++}$</td>
<td>$B \rightarrow K^+ (\phi J/\psi)$</td>
<td>CDF [75,76] (5.0), BABAR [77] (1.9), LHCb [78] (1.4), CMS [79] (5.7)</td>
<td>2009</td>
<td>NC</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4156$^{+29}_{-25}$</td>
<td>139$^{+113}_{-65}$</td>
<td>?$^{++}$</td>
<td>$e^+e^- \rightarrow J/\psi (D\bar{D})$</td>
<td>Belle [73] (5.0), BABAR [74] (2.0)</td>
<td>2008</td>
<td>NC</td>
</tr>
<tr>
<td>$Z_2(4250)$</td>
<td>4248$^{+185}_{-145}$</td>
<td>177$^{+321}_{-72}$</td>
<td>?</td>
<td>$B \rightarrow K (\pi^+\chi_c(1P))$</td>
<td>BABAR [81,82] (8.0)</td>
<td>2005</td>
<td>OK</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4263$^{+8}_{-9}$</td>
<td>95±14</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$ $e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$</td>
<td>BABAR [83] (5.4), Belle [72] (15)</td>
<td>2007</td>
<td>NC</td>
</tr>
<tr>
<td>$Y(4274)$</td>
<td>4293 ± 20</td>
<td>35 ± 16</td>
<td>?$^{++}$</td>
<td>$B \rightarrow K^+ (\phi J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>CLEO [84] (11), CLEO [8] (5.1)</td>
<td>2008</td>
<td>NC</td>
</tr>
<tr>
<td>$X(4350)$</td>
<td>4350$^{+4.6}_{-5.3}$</td>
<td>13.3$^{+18.4}_{-10.0}$</td>
<td>0/2$^{++}$</td>
<td>$e^+e^- \rightarrow e^+e^- (\phi J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>BaBar [85] (np), Belle [57] (np)</td>
<td>2012</td>
<td>OK</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4361 ± 13</td>
<td>74±18</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow e^+e^- (\phi J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>BESIII [56] (np), Belle [57] (5.2)</td>
<td>2013</td>
<td>OK</td>
</tr>
<tr>
<td>$Z(4430)$</td>
<td>4458 ± 15</td>
<td>166$^{+37}_{-32}$</td>
<td>1$^{--}$</td>
<td>$B^0 \rightarrow (\pi^+\pi^- J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>BESIII [86] (5.3)</td>
<td>2013</td>
<td>NC</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>4634$^{+9}_{-11}$</td>
<td>92$^{+41}_{-32}$</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow e^+e^- (\phi J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>CDF [76] (3.1), LHCb [78] (1.0), CMS [79] (5.3), D0 [80] (np)</td>
<td>2011</td>
<td>NC</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664±12</td>
<td>48±15</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$ $e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td>BABAR [88] (np), Belle [89] (8.0)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>$Y(10860)$</td>
<td>10876 ± 11</td>
<td>55 ± 28</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$ $e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$</td>
<td>Belle [97,62,63] (&gt;10)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>$Y_b(10888)$</td>
<td>10888.4 ± 3.0</td>
<td>30.7$^{+8.9}_{-7.7}$</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$ $e^+e^- \rightarrow (\pi^+\pi^- J/psi)$</td>
<td>Belle [99] (2.3)</td>
<td>2008</td>
<td>NC</td>
</tr>
</tbody>
</table>

D.Bettoni

PANDA at FAIR
Open Charm

- QCD laboratory
- Intermediate case between heavy and light quarks
- Interesting spectroscopy
- Weak interactions

At PANDA full program requires high luminosity ($10^{32}\text{cm}^{-2}\text{s}^{-1}$).
Unique features at PANDA:
- width measurement of $D_{sJ}(2317)$ (30-100 KeV) (threshold scan)
- Access to high L (available in $\bar{p}p$, suppressed in B decays)
Strange and Charmed Hyperons

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?
Strange and Charmed Baryons

- Light quark (u, d) systems:
  - Highly non-perturbative interactions.
  - Relevant degrees of freedom are hadrons.

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV $\sim \Lambda_{\text{QCD}} \approx 200$ MeV.
  - Relevant degrees of freedom?
  - Probes QCD in the intermediate domain.

- Systems with charm
  - Scale: $m_c \approx 1300$ MeV.
  - Quark and gluon degrees of freedom more relevant.
  - By comparing strange and charmed hyperons we learn about QCD at two different energy scales.
Baryon Spectroscopy

- New baryon states?
- Properties of already known states.
- Symmetries in observed spectrum.

Baryons in PANDA

- Large cross section s for $\bar{p}p \rightarrow \bar{Y}Y$
  - $\bar{p}p \rightarrow \Xi\Xi \approx \mu b$
  - $\bar{p}p \rightarrow \Omega\Omega \approx 0.002 \div 0.06 \mu b$
- No extra mesons in final state needed for strangeness or charm conservation
- Symmetry in hyperon and antihyperon
- PANDA detector versatile

Prospects for PANDA

S=2 hyperons ($\Xi$)
S=0 baryons ($N$)
S=1 hyperons ($\Lambda$)

S=3 hyperons ($\Omega$)

Charmed ($\Lambda_c, \Sigma_c$)
Hidden charm ($N_{c\bar{c}}$)

D.Bettoni
PANDA at FAIR
Baryon Spectroscopy

New baryon states?
Properties of already known states.
Symmetries in observed spectrum.

Prospects for PANDA

S=2 hyperons (Ξ)
S=0 baryons (N)
S=1 hyperons (Λ)
S=3 hyperons (Ω)

Charmed (Λ_c, Σ_c)
Hidden charm (N_{cc̅})

PANDA is a Strangeness Factory

Baryons in PANDA

Large cross-sections for \( \bar{p}p \rightarrow YY \)
- \( \bar{p}p \rightarrow ΞΞ \approx \mu b \)
- \( \bar{p}p \rightarrow ΩΩ \approx 0.002 \div 0.06 \mu b \)
No extra mesons in final state needed for strangeness or charm conservation
Symmetry in hyperon and antihyperon
PANDA detector versatile
Spin Observables in Hyperon Production

The parity-violating weak decay of hyperons gives access to spin observables even for unpolarised beam/target. These observables give insight in the production mechanism of hyperons (e.g. the role of spin in strangeness and charm production). Unique to PANDA: the study of these observables and especially the hyperon-antihyperon spin correlations.

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>Reaction</th>
<th>$\sigma$ (µb)</th>
<th>Efficiency (%)</th>
<th>Rate (with $10^{31}$ cm$^{-1}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$</td>
<td>64</td>
<td>10</td>
<td>28 s$^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$</td>
<td>~40</td>
<td>30</td>
<td>30 s$^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$</td>
<td>~2</td>
<td>20</td>
<td>1.5 s$^{-1}$</td>
</tr>
<tr>
<td>12</td>
<td>$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$</td>
<td>~0.002</td>
<td>30</td>
<td>~4 h$^{-1}$</td>
</tr>
<tr>
<td>12</td>
<td>$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$</td>
<td>~0.1</td>
<td>35</td>
<td>~2 day$^{-1}$</td>
</tr>
</tbody>
</table>

- High event rates for $\Lambda$ and $\Sigma^*$.
- Low background for $\Lambda$ and $\Sigma^*$.
- $\Omega$ channel feasible.
- $\Lambda_c$ requires high luminosity.
Production of Double Hypernuclei

1. Hyperon-antihyperon production at threshold

2. Slowing down and capture of $\Xi^-$ in secondary target nucleus

3. $\gamma$-spectroscopy with Ge-detectors

- $\bar{p} \rightarrow \Xi^- + 28\text{ MeV}$
- $3\text{ GeV/c}$
- $1300\text{ Hz}$
- $5600 / \text{day}$
- $8000 / \text{month}$
- $80 / \text{month}$
- $\Xi^-(dss)p(uud) \rightarrow \Lambda(uds)\Lambda(uds)$
- D. Bettoni
- PANDA at FAIR
Production of Double Hypernuclei

$^{12}$C diamond target to produce $\Xi^-$

Trigger on $\Xi_{\text{bar}}$. $\Xi^-$ interacts with active target containing different nuclei. Detect decay products.

- High production rate;
- Many hypernuclear systems at the same time;
- High acceptance/resolution magn. spect. for neutral and charged;
- Ge-detectors for X-ray transitions;

$\Xi^-(dss)\ p(uud) \rightarrow \Lambda(uds) \ \Lambda(uds)$

2. Slowing down and capture of $\Xi^-$ in secondary target nucleus

1300 Hz

$\gamma$-spectroscopy with Ge-detectors

3. $\gamma$-spectroscopy with Ge-detectors

8000 / month

80 / month
Charmonium in Nuclei

Measure $J/\psi$ production cross section in $\bar{p}$ annihilation on nuclear targets.
⇒ $J/\psi$-nucleus dissociation cross section

- In PANDA the $J/\psi$ is produced at relatively low energies. The $c\bar{c}$ pair hadronized in a very short time.
- Measurement problematic in pA (need to go to $x_F \ll 0$)
- ALICE at high energies opposite situation wrt PANDA.

PANDA produces **charmonium in cold nuclear matter**, providing exclusive information complementary to hadroproduction and heavy ion experiments.
Proton Electromagnetic Form Factors in the Timelike Region

\[ \bar{p}p \rightarrow e^+e^- \quad \bar{p}p \rightarrow \mu^+\mu^- \]

Measurement of effective form factor over wide $q^2$ range (30 GeV$^2$)

Individual measurement of $|G_E|$ and $|G_M|$ and their ratio $R$

First measurement of form factors with muons.

Measurement of form factors in unphysical region $\bar{p}p \rightarrow e^+e^-\pi^0$

Longer range goal: measurement of phase of $|G_E|$ and $|G_M|$ via polarisation observables.
Proton Electromagnetic Form Factors in the Timelike Region

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

Measurement of effective form factor over wide $q^2$ range ($30 \text{ GeV}^2$)

Individual measurement of $|G_E|$ and $|G_M|$ and their ratio $R$

First measurement of form factors with muons.

Measurement of form factors in unphysical region $\bar{p}p \rightarrow e^+e^-\pi^0$

Longer range goal: measurement of phase of $|G_E|$ and $|G_M|$ via polarisation observables.
Drell-Yan Process at PANDA

PDFs are convoluted with the fragmentation functions.

@ FAIR unique energy range up to $s \sim 30\,\text{GeV}^2$ with PANDA

@ much higher energies → big contribution from sea-quarks

@ $pp\bar{p}$ annihilation each valence quark contribute to the diagram
Transition Distribution Amplitudes

1. Describe the transition between two particles
2. Explore pionic components in the nucleon wave function
3. Transverse picture of the pion cloud
4. **Universality**: the same TDA could be measured in different kinematics/reactions
5. Test of Factorisation
6. Matter – Antimatter asymmetry

- $e^- p \rightarrow e^- p \pi^0$ (Bwd)
- $\bar{p} p \rightarrow e^+ e^- \pi^0$ (Fwd/bwd)
- Large $q^2$, small $u$
- Large $q^2$, small $t$ or $u$
Transition Distribution Amplitudes

- Describe the transition between two particles
- Explore pionic components in the nucleon wave function
- Transverse picture of the pion cloud
- Universality: the same TDA could be measured in different kinematics/reactions
- Test of Factorisation
- Matter – Antimatter asymmetry

**TDAs in TL region can only be measured at PANDA**

\[ e^-p \rightarrow e^-p \pi^0 \] \hspace{1cm} Bwd
electroproduction

\[ \bar{p}p \rightarrow e^+e^-\pi^0 \] \hspace{1cm} \text{from/bwd}

\[ \gamma^* \rightarrow q^2 \text{small } u \]

\[ \bar{p}p \rightarrow e^+e^-\pi^0 \text{, } e^+e^-\rho^0 \text{, } e^+e^-\eta, \ldots \]
Hard Exclusive Processes and $pp \rightarrow \gamma \gamma$

Generalized Distribution Amplitudes (GDA)

The QCD factorization theorem allows us to calculate high energy cross sections separating short-distance process with long-distance non-perturbative functions.

Hard scale is defined by the large transverse momentum of the final state photon.
Hard Exclusive Processes and $pp \rightarrow \gamma \gamma$

Generalized Distribution Amplitudes (GDA)

Timelike wide-angle Compton scattering can be measured at $\bar{p}$ANDA

$S/B \sim 1$ for $\bar{p}p \rightarrow \gamma \gamma$ (25% efficiency)
$S/B \sim 2$ for $\bar{p}p \rightarrow \pi^0 \gamma$ (50% efficiency)

Further studies are required for precise predictions
### PANDA Physics Competitiveness

<table>
<thead>
<tr>
<th>PANDA</th>
<th>LHCb</th>
<th>Belle2</th>
<th>BES III</th>
<th>JLab</th>
<th>J-PARC</th>
<th>RHIC</th>
<th>Compass</th>
<th>PANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light exotics</td>
<td>yellow</td>
<td>yellow</td>
<td>green</td>
<td>yellow</td>
<td>red</td>
<td>green</td>
<td>green</td>
<td>green</td>
</tr>
<tr>
<td>Charm exotics</td>
<td>yellow</td>
<td>yellow</td>
<td>green</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
<tr>
<td>Open charm</td>
<td>green</td>
<td>green</td>
<td>green</td>
<td>green</td>
<td>green</td>
<td>green</td>
<td>green</td>
<td>green</td>
</tr>
<tr>
<td>Charm in nuclei</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
<tr>
<td>Multistrange-Baryons</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
</tr>
<tr>
<td>Hyperon spin physics</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
<tr>
<td>Time-like form factors</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
<td>yellow</td>
</tr>
<tr>
<td>TMDs</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
<tr>
<td>GPDs TDAs</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
<tr>
<td>Hypernuclei</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
<td>red</td>
</tr>
</tbody>
</table>

- **excellent**
- **limited (e.g. accept., resol., quantum numbers, ...)**
- **impossible**
Detector, Funding etc.

- Accelerator parts needed: in MSV0-3 we need p-linac, SIS18, SIS100, HEB, pbar-target/collector, CR and HESR. RESR for high luminosity ($10^{32}\text{cm}^{-1}\text{s}^{-2}$).
- TDR and funding: one more TDR submitted (FSC), expected approval Dec 2015. Approved TDRs cover 71% of costs. No major change in funding.
- Significant progress achieved in R&D and construction for magnet, EMC, FSC, luminosity monitor, MVD, STT, integration of inner detector components (MVD, STT, EMC), DAQ.
- Strategy in view of FAIR delay: keep physics program updated, to make sure we do excellent physics from day 1.
- All detector components ready by 2019. Installation will take two years.
Potential PANDA Run-Plan 1st year – 139 days net  @ $10^{31}$cm$^{-2}$s$^{-1}$

part of machine development approx. 7 days @ J/$\psi$ & $\psi(2S)$ peaks
• calibration/commissioning

30 days @ 1.64 GeV/c
• time-like form-factors
• light meson spectroscopy and $\Lambda\bar{\Lambda}$ bar physics

40 days @ 15 GeV/c
• survey of light and heavy exotics at max momentum (hybrids, tetraquarks)
• generic open charm production $>10\sigma$ (yields and angular distributions)

14 days @ 12 GeV/c
• $\Omega\bar{\Omega}$ and $\Lambda_c\bar{\Lambda}_c$ bar production and dynamics, excited $\Omega$s
• generic open and hidden charm production

25 days $p_{\text{bar}}A$ @ 2 GeV/c
• $p_{\text{bar}}$ and $\Lambda_{\text{bar}}$-potentials incl. calibration (N, Ne, Ar targets)

10 days $p_{\text{bar}}d$ @ 8 GeV/c
• $\Delta\Delta$ content of the deuteron and feasibility studies of $p_{\text{bar}}d$ for spectroscopy (d-target)

13 days @ 5.55 GeV/c
• $\chi_{c1}$ angular distribution
• excited $\Xi$s

7 days @ 3.75 GeV/c
• Investigate $Y(2175)$ and $\Phi\Phi$ resonances, T/PS-glueball search
Potential PANDA Run-Plan 2\textsuperscript{nd} year – 144 days net @ $10^{31}\text{cm}^{-2}\text{s}^{-1}$

14 days @ 3 GeV/c
- Ξ-Atoms with hypernuclear setup and Ge-Counter

7 days @ 3 GeV/c
- excited Λs

7 days @ 4.4 GeV/c
- ΞΞ\bar{Ξ} production and dynamics

36 days @ 5.73 GeV/c
- $\chi_{c2}$ angular distribution

80 days @ 6.99++ GeV/c
- $X(3872)$ scan

other options depending on PANDA results and the development of the field until 2020

60 days – 5.61 GeV/c
- $h_c$ width

30-80 days on various momenta
- detailed scans of potentially interesting signals
Potential PANDA Run-Plan – Overview first 2 years

- survey light and heavy exotics
- generic open charm production
- ΩΩbar and ΛcΛcbar production and dynamics
- excited Ωs generic open and hidden charm production
- ΔΔ content of the deuteron – feasibility of pbar-d meson spectroscopy
- Ξ(3872) scan
- χc2 angular distribution
- χc1 ang. distr. and excited Ξs
- ΞΞbar production and dynamics
- Y(2175) and ΦΦ - T/PS-glueball search
- Ξ-Atoms and excited Λs
- pbar and Λbar-potentials (N, Ne, Ar targets)
- time-like form-factors - meson spectroscopy - ΛΛbar physics
Minimal Detector for Start Physics

- **Target**
  - TDR approved

- **Charged track detection and momentum**
  - Magnets
    - TDR approved
  - MVD
    - TDR approved
  - STT Tracker
    - TDR approved
  - Forward tracker (2/6)
    - TDR 2016
  - Muon chambers
    - TDR approved

- **Photons and electrons**
  - Electromagnetic calorimeter
    - TDR approved
  - Shashlyk
    - TDR submitted

- **Particle ID**
  - Barrel DIRC
    - TDR 2016
  - Forward TOF
    - TDR 2016
Summary

• PANDA has developed a world class experimental program covering the three pillars of hadron physics:
  – hadron spectroscopy
  – hadron structure
  – hadron interaction
  These experimental programs present many synergies and can in most cases be carried out in parallel.

• PANDA is unique in combining the potential for the discovery of new physics with the ability to carry out precise, systematic measurements.

• This physics potential will remain intact, and even increase, with time. [The capabilities of PANDA are in fact timeless with respect to other competitors, C. Guaraldo, INFN]

• The collaboration, detector developments and funding are in good shape and we are on track to produce excellent physics at the beginning of the next decade.