Precision spectroscopy of charmonium-like (exotic) XYZ states at PANDA/FAIR

K. Götzen, R. Kliemt, Frank Nerling*, K. Peters
*Frankfurt University, GSI Darmstadt
on behalf of the PANDA Collaboration

XIIIth Quark Confinement and the Hadron Spectrum, Maynooth, Ireland, Aug 1wt – 6th 2018

Outline

• Introduction
  ➢ Motivation, PANDA physics programme
  ➢ Advantage of anti-protons

• Energy scans of very narrow resonances
  ➢ The puzzle of the X(3872) & handle for clarification
  ➢ Prospects for PANDA, performance study

• Summary & outlook
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

- Hadron spectroscopy
  - Light mesons
  - Charmonium
  - Exotic states: glue-balls, hybrids, molecules / multi-quarks
- (Anti-) Baryon production
- Nucleon structure
- Charm in nuclei
- Strangeness physics
  - hypernuclei
  - S = -2 nuclear system

\[ \begin{align*}
\text{mass [GeV/c}^2]\end{align*} \]

\[ \begin{align*}
\text{p momentum [GeV/c]} \end{align*} \]
Precision spectroscopy of (exotic) XYZ states at PANDA
High Resolution (HR) mode:
• Luminosity up to $2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
• $\Delta p/p = 2 \times 10^{-5}$

High Luminosity (HL) mode:
• Luminosity up to $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
• $\Delta p/p = 1 \times 10^{-4}$

PANDA Experiment, Detector
Some Advantages of Anti-Protons

• Access to all fermion-antifermion quantum numbers \((not in e^+e^-)\)

• Access to states of high spin \(J\)

Formation:

only \(J^{PC} = 1^-\)

all \(q\bar{q}\) \(J^{PC}\)
Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers (*not in e⁺e⁻*)
- Access to states of high spin J
- Precise mass resolution in formation reactions

Formation:

\[ e^+ + e^- \rightarrow \text{hadronic state} \]

- Only J^{PC} = 1^{--}
- All q\bar{q} J^{PC}

Beam profile

Resonance Cross Section

Measured Rate

E_{cms}
Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers \((not in e^+e^-)\)
- Access to states of high spin \(J\)
- Precise mass resolution in formation reactions

\[ E760/835@Fermilab \approx 240 \text{ keV} \]
\[ \text{PANDA@FAIR} \approx 50 \text{ keV} \]

BES (IHEP): 3510.3 ± 0.2 MeV/c²

Andreotti et al., Nucl. Phys. B717 (2005) 34:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c²
Experimental Review of the X(3872)

- The first unexpected states
  - and the most intriguing one

- First observed by Belle in 2003
  - $X(3872) \rightarrow J/\psi \pi \pi$
  - very narrow state with $J^{PC} = 1^{++}$

- Both, Belle & BaBar report signal in
  - $X(3872) \rightarrow D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)
Experimental Review of the X(3872)

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- Both, Belle & BaBar report signal in
  - $X(3872) \rightarrow D^0\bar{D}^*0$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

- Mass: $m(X) - m(\bar{D}^*0) - m(D^0)$ = $-0.12 \pm 0.19$ MeV/c²
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2$ MeV (90% c.l., 2011)

Intriguing Analogon

"binding energy" of $-0.12 \pm 0.19$ MeV?
**Experimental Review of the X(3872)**

- The first unexpected states
  - and the most intriguing one

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  - \(X(3872) \rightarrow J/\psi \pi \pi\)
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**For clarification:** Precision measurement of \(\Gamma_{X(3872)}\) in the sub-MeV range needed!

Intriguing Analagon

```
1.8 GeV   2 GeV
D         D*
PION      PION
1 GeV     1 GeV
n         p
```

"binding energy" of -0.12±0.19 MeV ?
Molecular Picture

- Here only interested in $X(3872) \rightarrow J/\psi \, \rho^0$

\[ \sigma(E) = C \cdot \frac{\Gamma_{\pi^+ \pi^- J/\psi}(E)}{|D(E)|^2} \]

(assuming line-shape as in $B$ decays)

\[
D(E) = \begin{cases} 
E - E_f - \frac{g_1 k_1}{2} - \frac{g_2 k_2}{2} + i \frac{\Gamma(E)}{2}, & E < 0, \\
E - E_f - \frac{g_2 k_2}{2} + i \left( \frac{g_1 k_1}{2} + \frac{\Gamma(E)}{2} \right), & 0 < E < \delta, \\
E - E_f + i \left( \frac{g_1 k_1}{2} + \frac{g_2 k_2}{2} + \frac{\Gamma(E)}{2} \right), & E > \delta,
\end{cases}
\]

- $\Gamma(E) = \Gamma_{\pi^+ \pi^- J/\psi}(E) + \Gamma_{\pi^+ \pi^- \pi^0 J/\psi}(E) + \Gamma_0$

\[ \Gamma_{\pi^+ \pi^- J/\psi}(E) = \int_{2m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\rho}{(m-m_\rho)^2 + \Gamma_\rho^2 / 4} \]

\[ \Gamma_{\pi^+ \pi^- \pi^0 J/\psi}(E) = \int_{3m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m-m_\omega)^2 + \Gamma_\omega^2 / 4} \]

Flatte energy $E_f$ determines state to be bound or virtual [Hanhardt et al., PRD 76 (2007) 034007]
Line-shapes for different $E_f$

Scattering length $D^0D^{0*}$:

$$a = -\frac{\sqrt{2\mu_2\delta + 2E_f/g + i\Gamma(0)/g}}{\left(\sqrt{2\mu_2\delta + 2E_f/g}\right)^2 + \Gamma(0)^2/g^2}$$

$\text{Re}(a) > 0$ : bound state
$\text{Re}(a) < 0$ : virtual state

Examples always scaled to same $f_{\text{max}}$

$E_f = -14.0 \text{ MeV}$
$E_f = -10.0 \text{ MeV}$
$E_f = -7.0 \text{ MeV}$
$E_f = -5.0 \text{ MeV}$

Examples with: $f_\rho = 0.00047, f_\omega = 0.00271, g = 0.137, \Gamma_0 = 1.0 \text{ MeV}$

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05/08/2018
Energy scan of the X(3872)
Initial Remarks

• Nature of X(3872)
  - Need line-shape and width to understand structure
  - PANDA: Fine scan around nominal mass
    => energy-dependent cross-section

• Analysis goals
  - Sensitivity of $\Gamma$ measurement (conventional BW)
  - Sensitivity for virtual/bound state (molecular picture)

• Analysis strategy
  - Analysis of $X(3872) \rightarrow J/\psi(\ell^+\ell^-) \rho^0(\pi^+\pi^-)$ channel only
  - Geant based sim/reco => signal + background efficiencies $\varepsilon_S$ and $\varepsilon_B$
  - MC scan simulation with assumption for cross-sections, and integrated luminosities, BRs

• Three accelerator modes
  - HL (high lumi) and HR (high resolution), P1 (initial Phase-1, reduced lumi/resol.)
Reconstruction Part
## Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>BR((J/\psi \rightarrow e^+ e^-))</td>
<td>5.97 %</td>
</tr>
<tr>
<td>BR((J/\psi \rightarrow \mu^+ \mu^-))</td>
<td>5.96 %</td>
</tr>
<tr>
<td>BR((\rho^0 \rightarrow \pi^+ \pi^-))</td>
<td>100%</td>
</tr>
<tr>
<td>BR((X \rightarrow J/\psi \rho^0))</td>
<td>5 % (UL: 6.6%)</td>
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### Branching Fractions

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>(\sigma_{\text{peak}}(p\bar{p} \rightarrow X))</td>
<td>([20,30,50,75,100,150] \text{nb})</td>
</tr>
<tr>
<td>(\sigma(pp \rightarrow J/\psi \pi^+\pi^- \text{ non-res}))</td>
<td>1.2 nb [theory]</td>
</tr>
<tr>
<td>(\sigma(pp \rightarrow \text{inelastic}) @ 3.872 \text{ GeV})</td>
<td>46 mb [CERN-HERA-84-01 (1984)]</td>
</tr>
</tbody>
</table>

### Cross sections

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>(L_{\text{HL}} (3.872 \text{ GeV}))</td>
<td>13683 (nb·d)^{-1}</td>
</tr>
<tr>
<td>(L_{\text{HR}} (3.872 \text{ GeV}))</td>
<td>1368 (nb·d)^{-1}</td>
</tr>
<tr>
<td>(L_{P1} (3.872 \text{ GeV}))</td>
<td>1170 (nb·d)^{-1}</td>
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</table>

### Luminosities

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>(\Delta E_{\text{abs}} \text{ (energy prec. w/ calibration)})</td>
<td>168 keV (dp/p = 10^{-4})</td>
</tr>
<tr>
<td>(\Delta E_{\text{rel}} \text{ (relative energy positioning)})</td>
<td>1.7 keV (dp/p = 10^{-6})</td>
</tr>
<tr>
<td>(\Delta E_{\text{mom}} \text{ (HL)})</td>
<td>168 keV (dp/p = 10^{-4})</td>
</tr>
<tr>
<td>(\Delta E_{\text{mom}} \text{ (HR)})</td>
<td>34 keV (dp/p = 2·10^{-5})</td>
</tr>
<tr>
<td>(\Delta E_{\text{mom}} \text{ (P1)})</td>
<td>84 keV (dp/p = 5·10^{-5})</td>
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Kinematic Distributions
(after 4C fit applied)

Signal

Generic bkgd

Non-resonant J/ψ

Numbers of generated events of the different signal & bkgd types:

<table>
<thead>
<tr>
<th>Event type</th>
<th>Description</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( pp \rightarrow J/\psi \rho^0 \rightarrow e^+e^-\pi^+\pi^- )</td>
<td>( \approx 10^7 = 9.58 \cdot 10^9 ) generated</td>
</tr>
<tr>
<td></td>
<td>( \bar{p}p \rightarrow J/\psi \rho^0 \rightarrow \mu^+\mu^-\pi^+\pi^- )</td>
<td>( \approx 10^7 = 8.87 \cdot 10^9 ) generated</td>
</tr>
<tr>
<td>II</td>
<td>( pp \rightarrow J/\psi \pi^+\pi^- \rightarrow e^+e^-\pi^+\pi^- ) (non-res)</td>
<td>100 000</td>
</tr>
<tr>
<td></td>
<td>( \bar{p}p \rightarrow J/\psi \pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^- ) (non-res)</td>
<td>99 000</td>
</tr>
<tr>
<td>III</td>
<td>DPM ( J/\psi \rightarrow e^+e^- ) pre-filter</td>
<td>98 000</td>
</tr>
<tr>
<td></td>
<td>DPM ( J/\psi \rightarrow \mu^+\mu^- ) pre-filter</td>
<td>100 000</td>
</tr>
</tbody>
</table>
Final Selection Results
(after final selection and 4C fit)

PANDA MC simulation

\[ \frac{J/\psi \rightarrow \mu^+\mu^-}{\text{counts / 3.2 MeV/c}^2} \]

\[ m_{\text{fit}}(\mu^+\mu^-) \text{ [GeV/c}^2] \]

\[ \frac{J/\psi \rightarrow e^+e^-}{\text{counts / 4.0 MeV/c}^2} \]

\[ m_{\text{fit}}(e^+e^-) \text{ [GeV/c}^2] \]

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

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

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>( \epsilon_S ) [%]</th>
<th>( \epsilon_{B,\text{gen}} ) ( \times 10^{-10} )</th>
<th>( \epsilon_{B,\text{NR}} ) [%]</th>
<th>( \epsilon_S ) [%]</th>
<th>( \epsilon_{B,\text{gen}} ) ( \times 10^{-10} )</th>
<th>( \epsilon_{B,\text{NR}} ) [%]</th>
<th>S:N_{\text{comb}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-selection</td>
<td>19.1</td>
<td>1150</td>
<td>17.3</td>
<td>24.2</td>
<td>29300</td>
<td>21.8</td>
<td>1 : 1087</td>
</tr>
<tr>
<td>Final selection</td>
<td>12.2</td>
<td>1.0</td>
<td>2.8</td>
<td>15.2</td>
<td>4.5</td>
<td>3.0</td>
<td>2.7 : 1</td>
</tr>
</tbody>
</table>
Energy scan part
Yield Extraction

Simulated extraction of energy-dependent yield:

- Fit signal in $J/\psi$ mass
  - Removes generic background
  - NR background still present

- Requires sufficiently large $J/\psi$ mass window
• Softened selection for $\mu^+\mu^-$ (only to define reasonable PDF's)
  - Muon PID($\mu^\pm$) > 0.8
  - $m_{\text{fit}}(\mu^+\mu^-) + m_{\text{fit}}(\pi^+\pi^-) > 3.65$ GeV/c$^2$

• **Signal**: Double-Gauss

• **Background**: Parabola
Scan Procedure Principle (Example)

20 $E_{\text{cms}}$ scan point within ±0.4 MeV window around nominal mass

Repeat many times ...

PRELIMINARY

HR
$\Gamma_0 = 130$ keV
$\Gamma_{\text{fit}} = 120 \pm 20$ keV

PRELIMINARY

Mean = 2.0 keV
RMS = 25.5 keV
Sensitivities Breit-Wigner $\Gamma$ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $\text{rms}_{\text{fit}}/\Gamma_{\text{fit}}$ in [%]

Sensitivity

\[
\frac{\Delta \Gamma_{\text{meas}}}{\Gamma_{\text{meas}}} = \frac{\text{RMS}}{\text{Mean} + \Gamma_0}
\]

(Breit-Wigner case)

$\sigma_s = 50 \text{ nb}$

$\rightarrow 20\% @ \Gamma = 50 \ldots 120 \text{ keV}$

HR     HL
Sensitivities Breit-Wigner $\Gamma$ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $\text{rms}_{\text{fit}}/\tilde{\Gamma}_{\text{fit}}$ in [%]

\[ \frac{\Delta \Gamma_{\text{meas}}}{\Gamma_{\text{meas}}} = \frac{\text{RMS}}{\text{Mean} + \Gamma_0} \] (Breit-Wigner case)

**Sensitivity**

![Graph showing sensitivity vs $\Gamma_0$ in keV with P1, HR, and HL modes, and a threshold of $\sigma_s = 50$ nb at 3σ level.](image)

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Sensitivities Breit-Wigner $\Gamma$ (40 x 2d)

- Extract standard deviation from toy MC fits
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Sensitivity

$$\frac{\Delta \Gamma_{\text{meas}}}{\Gamma_{\text{meas}}} = \frac{\text{RMS}}{\text{Mean} + \Gamma_0}$$

(Breit-Wigner case)

PANDA MC study

$\sigma_s = 50 \text{ nb}$

$\Delta \Gamma_{\text{meas}}/\Gamma_{\text{meas}} [%]$ vs $\Gamma_0 [\text{keV}]$

$\Gamma_{\text{min}} (3\sigma \text{ sign.}) [\text{keV}]$ vs $\sigma_s [\text{nb}]$
Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual and bound state be distinguished? → integrate mismatch region:

\[ P_{\text{mis}} = \frac{N_{\text{mis-id}}}{N_{\text{MC}}} \] (Molecule case)

**Sensitivity**

**PANDA**

**MC study**

**virtual**

**mismatch**

**bound**

\[ \text{input} = E_{f,0} \text{ [MeV]} \]

\[ \text{output} = E_{f,\text{meas}} \text{ [MeV]} \]

**PRELIMINARY**

\[ \text{HR} \]

\[ \sigma = 50 \text{ nb} \]

\[ \sigma_s = 50 \text{ nb} \]

\[ E_{f,0} = -9.0 \text{ MeV} \]

\[ N_{\text{mis}} = 71 \]
Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual and bound state be distinguished? → integrate mismatch region:

\[ P_{\text{mis}} = \frac{N_{\text{mis-id}}}{N_{\text{MC}}} \]  (Molecule case)

PANDA MC study

- virtual mismatch
- bound mismatch

\[ \sigma_s = 50 \text{ nb} \]

\[ P_{\text{mis}} [\%] \]

\[ E_{f,0} [\text{MeV}] \]

\[ E_{f,\text{meas}} [\text{MeV}] \]

\[ E_{f,0} [\text{MeV}] \]

\[ E_{f,\text{meas}} [\text{MeV}] \]

\[ \text{output} = E_{f,\text{meas}} \]

\[ \text{input} = E_{f,0} \]
Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
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Sensitivity

\[ P_{\text{mis}} = \frac{N_{\text{mis-id}}}{N_{\text{MC}}} \] (Molecule case)

**PANDA**

MC study

output = \( E_{f,\text{meas}} \) [MeV]

\[ -11.0 \rightarrow -10.5 \rightarrow -10.0 \rightarrow -9.5 \rightarrow -9.0 \rightarrow -8.5 \rightarrow -8.0 \rightarrow -7.5 \rightarrow -7.0 \]

input = \( E_{f,0} \) [MeV]

\[ -10.0 \rightarrow -9.5 \rightarrow -9.0 \rightarrow -8.5 \rightarrow -8.0 \rightarrow -7.5 \rightarrow -7.0 \]

**PANDA**

MC study

\[ \sigma_s = 50 \text{ nb} \]

\[ P_{\text{mis}}(10\%) \]

\[ -10.0 \rightarrow -9.5 \rightarrow -9.0 \rightarrow -8.5 \rightarrow -8.0 \rightarrow -7.5 \rightarrow -7.0 \]
Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can **virtual** and **bound** state be distinguished? \( \rightarrow \text{integrate mismatch region:} \)

\[
P_{\text{mis}} = \frac{N_{\text{mis-id}}}{N_{\text{MC}}} \quad \text{(Molecule case)}
\]

### Sensitivity

**10% \( P_{\text{mis}} \), bound as virtual state**

**10% \( P_{\text{mis}} \), virtual as bound state**

**PANDA MC study**

- P1 mode
- HR mode
- HL mode
Summary & Conclusions

• Feasibility study for resonance energy scans at PANDA
  ➢ Lineshape and width measurements for X(3872)
  ➢ Achievable performance quantified

• Scenario studied exemplarily: 40 x 2d data taking

• Determined sensitivity for BW width measurement
  ➢ Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50 \ldots 120$ keV
  ➢ HR mode performs better for smaller widths

• Determined sensitivity for molecular line-shape measurement
  ➢ Possible to distinguish bound/virtual state
  ➢ $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  ➢ Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  ➢ HL mode performs better over investigated range

... about to be submitted to EPJ A
Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
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  - Sub-MeV resolution on $|E_f - E_{f,\text{th}}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated range

PANDA will be the facility to study QCD -- hadron structure and spectroscopy
Thank you for your attention!

The PANDA collaboration:
~ 500 Members, 72 Institutes, 20 Countries

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK, ... (to be updated/completed)
Backup
Facility for Antiproton and Ion Research
Facility for Antiproton and Ion Research
Facility for Antiproton and Ion Research

Official ground breaking in summer 2017

Same area now

[Courtesy: I. Lehmann, FAIR]
Schedule

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Pre-Commissioning

Design

Construction

Installation

Commissioning

PANDA Hall assumed available Q4/2021

Physics

Installation

Physics

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Precision spectroscopy of (exotic) XYZ states at PANDA

05/08/2018
Status of TDRs and Construction

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Precision spectroscopy of (exotic) XYZ states at PANDA

05/08/2018
Collaboration

UniVPM Anconca
U Basel
IHEP Beijing
U Bochum
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
U Cracow
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Gießen
U Glasgow
BITS Pilani KKBGC,
Goa
KVI Groningen
Sadat Patel U, Gujart
Gauhati U, Guwahati
FH Iserlohn
FZ Jülich
IMP Lanzhou
INFN Legnaro
U Lund
HI Mainz
U Mainz
INP Minsk
ITEP Moscow
MPEI Moscow
BARC Mumbai
U Münster
BINP Novosibirsk
Novosibirsk State U
Novosibirsk STU
IPN Orsay
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
U of Sidney
PNPI St. Petersburg
KTH Stockholm
U Stockholm
Soranaree University
SVNIT Surat-Gujarat
South Guarat U,
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