Status of PANDA @ FAIR

Newport News, May 16, 2017

Klaus Peters
GSI/U Frankfurt
**Production** all exotic and non-exotic quantum numbers accessible with a recoil
- high discovery potential
- associated, access to all quantum numbers (exotic)

**Formation** all non-exotic quantum numbers accessible
- not only limited to $J^{PC} = 1^-$ as $e^+e^-$ colliders
- precision physics of known states
- resonant, high statistics, extremely good precision in mass and width

antiproton probe unique and decisive
Discovery of the $Z^+(3900)$

Discovery of the $Z_c^{+/-}(3900)$ in the $J/\psi \pi^{+/-}$ invariant mass spectrum in the decay $Y(4260) \rightarrow J/\psi \pi^{+}\pi^{-}$

Observation of the $Z_c^{+/-}(4025)$ in the $h_c\pi^{+/-}$ and $\bar{D}^*D^*$ invariant spectrum in $Y(4260/4360)$ decays

BES3

Belle

2013
# New Charmonium-like Discoveries

<table>
<thead>
<tr>
<th>Meson</th>
<th>Date</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>PRL 91,262001 (2003)</td>
<td></td>
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<tr>
<td>X(3940)</td>
<td>PRL 98,082001 (2007)</td>
<td></td>
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<tr>
<td>Y(3940)</td>
<td>PRL 94,182002 (2005)</td>
<td></td>
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<tr>
<td>X(3915)</td>
<td>PRL 104,092001 (2010)</td>
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<tr>
<td>Y(4260)</td>
<td>PRL 95,142001 (2005)</td>
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</tr>
<tr>
<td>Y(4350)</td>
<td>PRL 98,212002 (2007)</td>
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<tr>
<td>Y(4008)</td>
<td>PRL 99,182004 (2007)</td>
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<tr>
<td>Y(4660)</td>
<td>PRL 99,142002 (2007)</td>
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<tr>
<td>Z(4430)</td>
<td>PRL 100,142001 (2008)</td>
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<tr>
<td>Z₁⁻ &amp; Z₂⁻</td>
<td>PRD 78,072004 (2008)</td>
<td></td>
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<tr>
<td>Y(4140)</td>
<td>PRL 102,242002 (2009)</td>
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<tr>
<td>X(4350)</td>
<td>PRL 104,112004 (2010)</td>
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*Fact is that charmonium is very complicated and guides us into a terra incognita.*
Frontiers

- Complexity Frontier
- Intensity Frontier
- Energy Frontier
- Precision Frontier
Complexity

REALITY

SIMPLICITY

Energy Frontier

Intensity Frontier

Precision Frontier

Complexity Frontier
Charmonium

S-States
\( \eta_c(nS) \psi(nS) \)

radial excitations

P,D,F,... States

high angular momentum

Several golden ways to heaven

Charmonium states diagram

PANDA@FAIR / K. Peters
Charmonium – other degrees of freedom?

K.J. Juge, J. Kuti, C. Morningstar
hep-lat 9709131

Different “potential”
Eliminating Conventional States

remove the leading term
by selecting quantum numbers

e.g. for hybrids

impossible for $q\bar{q}$

$J^P C$ exotic

Gluonic Magnetic Electric

$^1S_0, 0^-$
$1^{++}$
$1^-$

$^3S_1, 1^-$
$0^+$
$0^-$
$1^+$
$1^{--}$
$2^+$
$2^-$

$= \sum_i(q\bar{q})_i \sum_j g_j$
### Table: \( \pi_1(1600) \) and \( \rho \pi \) in 1997 and COMPASS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass</th>
<th>Width</th>
<th>Decay</th>
<th>Citation</th>
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<tbody>
<tr>
<td>E852</td>
<td>1359 (+16-14) (+10-24)</td>
<td>314 (+31-29) (+9-66)</td>
<td>( \eta \pi )</td>
<td>PR D60, 092001</td>
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<tr>
<td>Crystal Barrel</td>
<td>1400 (+20-20) (+20-20)</td>
<td>310 (+50-50) (+50-30)</td>
<td>( \eta \pi )</td>
<td>PL B423,175</td>
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<tr>
<td>Crystal Barrel</td>
<td>1360 (+25-25)</td>
<td>220 (+90-90)</td>
<td>( \eta \pi )</td>
<td>PL B446,349</td>
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<tr>
<td>Obelix</td>
<td>1384 (+28-28)</td>
<td>378 (+58-58)</td>
<td>( \rho \pi )</td>
<td>EPJ C35, 21</td>
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<tr>
<td>E852</td>
<td>1593 (+8-8) (+29-47)</td>
<td>168 (+20-20) (+150-12)</td>
<td>( \rho \pi )</td>
<td>PR D65, 072001</td>
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<tr>
<td>E852</td>
<td>1597 (+10-10) (+45-10)</td>
<td>340 (+40-40) (+50-50)</td>
<td>( \eta' \pi )</td>
<td>PRL 86, 3977</td>
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<tr>
<td>Crystal Barrel</td>
<td>1590 (+50-50)</td>
<td>280 (+75-75)</td>
<td>( b_1 \pi )</td>
<td>PL B563,140</td>
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<tr>
<td>E852</td>
<td>1709 (+24-24) (+41-41)</td>
<td>403 (+80-80) (+115-115)</td>
<td>( f_1 \pi )</td>
<td>PL B595,109</td>
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<tr>
<td>E852</td>
<td>1664±8±10</td>
<td>185±25±28</td>
<td>( (b_1 \pi)^- )</td>
<td>submitted to PRL</td>
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<tr>
<td>E852</td>
<td>( \cong 1700 )</td>
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<tr>
<td>E852</td>
<td>2001±30±92</td>
<td>333±52±49</td>
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<tr>
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<td>230±32±73</td>
<td>( (b_1 \pi)^- )</td>
<td>submitted to PRL</td>
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<td>h_2(1950)</td>
<td>E852</td>
<td>1954±8 (stat.)</td>
<td>138±3 (stat.)</td>
<td>( (b_1 \pi)^0 )</td>
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</table>
Our Mission
Study strongly interacting matter on (almost) all scales

Nuclear Structure & Astrophysics
(rare isotope beams)

Hadron Physics
(stored and cooled
15 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(anti-protons & highly stripped ions)

Dense Bulk Plasmas
/ion beam bunch compression
& petawatt-laser/

Materials Science & Radiation Biology
/ion & anti-proton beams/

Accelerator Physics
HESR – Storage Ring for Antiprotons

Parameters of HESR

- Injection of $p$ at 3.7 GeV
- Slow synchrotron (1.5-14.5 GeV/c)
- Storage ring for internal target operation
- Luminosity up to $L \sim 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Beam cooling (stochastic & electron)

Energy resolution $\sim 50$ keV
- Resonance scan
tune $E_{CM}$ to probe resonance
get precise mass and width
Accessible Hadrons at PANDA

Phase Space Coverage

Two body thresholds

Molecules

Gluonic Excitations

Hybrids

Hybrids+Recoil

Glueball

Glueball+Recoil

q¯q Mesons

light q¯q

π, p, η, f₂, K, K*

conventional charmonium

exotic charmonium

Accessible Hadrons at PANDA
Planning Activities – almost finished
Civil Engineering

Existing only SIS 18

600,000 cbm > 1 Mio tons of concrete
35,000 tons of steel

New

Beamline $\Sigma$ 3.2 km thereof
Syncrotron 1.1 km
Modularized Start Version (MSV)

Cost about 1.6 billion by 2018
(1 billion 2005 Euros)

Modules
M0: SIS100
M1: APPA
M1: CBM/HADES
M2: NUSTAR
M3: PANDA, NuSTAR, APPA
Construction Site (almost today)
\( \bar{p}p \) cross sections

- Crystal Barrel
- PS185
- E760/E835

\( \sqrt{s} \) GeV

Cross section (mb)

\( 10^{-1} \)  \( 10 \)  \( 10^2 \)  \( 10^3 \)  \( 10^4 \)

\( P_{lab} \) GeV/c

Jetset

Obelix

\( \bar{p}p \)

elastic

total

pp cross sections – exclusive final states

Many orders of magnitude light quark background

Example X(3872)
peak ~50 nb (E. Braaten)
$D\bar{D}\pi/\psi\pi\pi$ ~10:1
→ $\psi\pi\pi$ 250 pb (ee and $\mu\mu$)
→ $D\bar{D}\pi$ 500 pb (multiple channels)

$L=2\cdot10^{31}$, duty $\epsilon=0.5$
$\int(L\cdot\epsilon) = 0.86$ pb$^{-1}$/d
→ 2 d/point
→ peak (~400 ev. $\psi\pi\pi$/~800 ev. $D\bar{D}\pi$)
x 20 points → 40 days
PANDA Physics Programme

**Spectroscopy**
- New narrow XYZ: Search for partner states
- Production of exotic QCD states: Glueballs & hybrids

**HEP underlying elementary processes**
- Generalized parton distributions:
  - Orbital angular momentum
  - Drell Yan process:
    - Transverse structure, valence anti-quarks
  - Time-like form factors:
    - Low and high E, e and µ pairs

**Nucleon Structure**
- Bound States of Strong Interaction
  - Hypernuclear physics:
    - Double Λ hypernuclei
    - Hyperon interaction
  - Hadrons in nuclei:
    - Charm and strangeness in the medium

**Astrophysics**
- Strange n-stars

**Strangeness**
- Strange baryons:
  - Spectroscopy
  - Polarization

**HEP interference of coupled channels**

**Nuclear Physics**
- HI collisions comparing QGP to elementary reactions

**Generalized parton distributions**
- Orbital angular momentum
- Drell Yan process:
  - Transverse structure, valence anti-quarks
- Time-like form factors:
  - Low and high E, e and µ pairs

**Hadrons in nuclei:**
- Charm and strangeness in the medium
Previous measurements of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

A lot of data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold.

Very scarce data bank above 4 GeV.

Only a few bubble chamber events.

No data on $\bar{p}p \rightarrow \bar{\Omega}\Omega$ nor $\bar{p}p \rightarrow \bar{\Xi}\Xi$.

Octet $\Xi$ states: no partner of most $N^*$ states.

Decuplet $\Xi$ and $\Omega$ states: no partner of $\Delta^*$ states.

PDG note on $\Xi$ resonances:

“... nothing of significance on $\Xi$ resonances has been added since our 1988 edition.”

PANDA is a strangeness factory.
## Prospects for PANDA

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

Even with conservative cross section estimates, $\Omega / \Lambda_c$ channels are feasible
New efficiency studies using sophisticated MC framework underway.

Gain a factor of 100 with inclusive measurement
Nucleon Electromagnetic Final States

Background Suppression ~ $10^{-8}$
The effective FF can be measured up to $q^2 \sim 30 \text{ GeV}^2$ but no individual determination of $G_E$ and $G_M$ so far.

<table>
<thead>
<tr>
<th>$s$ [(GeV/c)$^2$]</th>
<th>4 - 9.5</th>
<th>5 - 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R =</td>
<td>G_E</td>
<td>/</td>
</tr>
<tr>
<td>21 scan points</td>
<td>L=2 fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>= 552 pb$^{-1}$ (2015)</td>
<td>2.10$^{32}$ cm$^{-1}$ s$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

with transverse polarized target

\[
\left( \frac{d\sigma}{d\Omega} \right)_0 A_{1,y} \propto \sin 2\Theta \text{Im}(G_M G^*_E)
\]
Hypernuclear Physics @ PANDA

Limiting factor
charged particle load on central detector \((0.6-1.0) \cdot 10^7\)
\(L=(3-5) \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}\)
\(\bar{p} \text{ re-storage} < 6 \cdot 10^6\)

\[\Xi^{-}(dss)p(uud) \rightarrow \Lambda(uds)\Lambda(uds)\]

Minimum 8 months full running
# Degas HPGe Array

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Array type</td>
<td>Composite Ge detector array</td>
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<tr>
<td>Energy range (keV)</td>
<td>50-5000</td>
</tr>
<tr>
<td>Noise threshold (keV)</td>
<td>15</td>
</tr>
<tr>
<td>Energy resolution (at 1.3 MeV)</td>
<td>2.3 keV</td>
</tr>
<tr>
<td>Full energy γ-detection efficiency (at 1 MeV)</td>
<td>16%</td>
</tr>
<tr>
<td>Effective full energy efficiency after prompt flash blinding</td>
<td>14%</td>
</tr>
<tr>
<td>P/T-value</td>
<td>34%</td>
</tr>
<tr>
<td>Time resolution (at 1.3 MeV)</td>
<td>10 ns</td>
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<tr>
<td>Overload recovery time</td>
<td>100 ns/MeV</td>
</tr>
<tr>
<td>Relative background suppression</td>
<td>5</td>
</tr>
</tbody>
</table>

Half sphere EB Clusters based
Straw Tube Tracker

Detector Layout
4600 straws in 21-27 layers,
of which 8 layers skewed at ~3°
Tube made of 27 µm thin Al-mylar, ø=1cm
R_{in} = 150 mm, R_{out} = 420 mm, l=1500 mm
Self-supporting straw double layers
at ~1 bar overpressure (Ar/CO₂)
Readout with ASIC+TDC or FADC

Material Budget
Max. 26 layers,
0.05 % X/X₀ per layer
Total 1.3% X/X₀

Project Status
3000 Straws produced
Readout prototypes and beam tests
Ageing tests: up to 1.2 C/cm²
Electromagnetic Calorimeter (TS)

PANDA PWO Crystals
- PWO is dense and fast
- Low γ threshold is a challenge
- Increase light yield
  - improved PWO II (2xCMS)
  - operation at -25°C (4xCMS)
Challenges
- temperature stable to 0.1°C
- control radiation damage
- low noise electronics
Delivery of crystals 54%

Barrel Calorimeter
- 11000 PWO Crystals
- LAAPD readout, 2x1cm²
- $\sigma(E)/E \sim 1.5%/\sqrt{E} + \text{const.}$

Forward Endcap
- 4000 PWO crystals
- High occupancy in center
- LA APD and VPTT

Backward Endcap
- for hermeticity, 530 PWO crystals

Large Area APDs
- CMS
- PANDA 7x14 mm²
Electromagnetic Calorimeter (TS)

Crystals
1st lot of crystals delivered
New producer Crytur
Test production in 2016 (~100 pc)

APD/Preamp/VPTT
Screening of 30000 APDs ongoing
ASIC preamp design finalized
VPTT (Forward) characterized

Assembly
Forward-EMC full completion ‘til 2018
Backward-EMC prototype-tests successful
Barrel-EMC: alveoles produced
1st slice in construction
**Barrel DIRC**

- **Baseline design**
  - DIRC: Detection of Internally Reflected Cherenkov light pioneered by BaBar
  - Cherenkov detector with SiO₂ radiator
  - Detected patterns give β of particles

- **Optimization and challenges**
  - Focusing by lenses/mirrors
  - More compact design
  - Magnetic field → MCP PMT
  - Fast readout to suppress BG
  - Plates as more economic radiator

- **Project status**
  - Baseline and Plate design verified
  - Awaiting approval of TDR

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**Diagram**

- **Electronics**
- **Photon detectors**
- **Radiator bars**
- **Focusing optics**

**Images**

- Baseline
- Bars & prism
- Plates

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PANDA@FAIR / K. Peters
Barrel DIRC (beam tests)

Test beam campaign at CERN T9
2 periods: 3+2 weeks May-July
ToF ref. at multi-hadron beam
Readout with TRB3/PADIWA

Measurement program
Focusing by various lenses
Prism as expansion volume
Bars as baseline radiator
Plate radiator as alternative

Simulated separation of π/p at test-beam
Status of TDRs and Construction
**PANDA Phases**

**Phase 0**
Currently PANDA detectors are being built. They will be used in other excellent experiments until the experimental hall is available.

**Phase 1**
First physics experiments with the PANDA start setup using antiprotons

**Phase 2**
Experiments using the full setup

**Phase 3**
Experiments beyond MSV (needs RESR)
Goal: Hyperon structure, extend our understanding of the nucleon

How: Hyperon Dalitz decay Transition FF

well connected to the PANDA physics program

Role of ρ-baryon coupling (VMD?)

- Only few measurements of radiative decays:
  - e.g. $\Sigma^0(\ast) \rightarrow \Lambda\gamma$ $\Lambda(1520) \rightarrow \Lambda\gamma$
  - $Y \rightarrow \Lambda e^+e^-$ never measured!
- Proposed reaction:
  - $pp(A) \rightarrow Y$ (any) $X \rightarrow \Lambda e^+e^- X$

Tag with $\Lambda \rightarrow \pi\rho$ BR $\sim 10^{-5}$
Phase 0: Backward EMC @ MAMI

Magnetic Moment of the $\Delta(1232)$ by
- $e\, p \rightarrow e\, p\, \pi^0\, \gamma$
- Additional calorimeter for $\pi^0$ and $\gamma$ detection
- Virtual photon flux higher in e-production
- $S_{11}$-Resonance

Electron-Muon-Universality (Proton Radius Puzzle)
- $e\, p \rightarrow e\, p\, l^+l^-$ below/above $\mu^+\mu^-$ pair threshold
- Additional calorimeter for forward angles

Multi-$\pi^0$-Production
- $e\, p \rightarrow e\, p\, \pi^0\, \pi^0$ etc.
- Unknown transition amplitudes, calibration and commissioning of calorimeter
Phase-0: Preparation for Data Analysis

Mandate from our Science Council: prepare for the future!

- R&D / Q&A of analysis software → fast start asa data is available
- We have already two software packages
  - PAWIAN – quite feature loaded – monolithic but partly expandable, ready to use for many cases
  - ComPWA – new bottom-up development after a design requirements process – module based and fully open by design, but only a few cases implemented (from Nov 11 - Sep 12 → 12 page Document)
- Goal: further developments and perform 2018/19 a data challenge → double blind feasibility study for various light quark channels
  - create blinded data with one package and one group and analyze it with a different software from a different group
  - this will help us debugging the software and adding important features for the ease of the process
PANDA Schedule

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<tbody>
<tr>
<td>Phase 0</td>
<td>PANDA Phase 0</td>
<td>Pre-Commissioning</td>
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<td>Start Setup</td>
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<td>Design</td>
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<td>Installation</td>
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<td>Phase 3: RESR</td>
<td>PANDA Phase 3: RESR</td>
<td>Physics</td>
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PANDA Hall assumed available Q4/2021
Start-Setup (Phase-1)
Full Setup (Phase-2)

Clustering & Pellet Target
Solenoid Magnet
Muon Chambers
Dipole Magnet
DipoleToF
Muon Range System
Luminosity Detector

Hyper nuclear Setup
not shown

Barrel
DIRC &ToF
MVD
STT
Barrel
EMC
GEM I & II
Fwd
ToF
FE
EMC
Disk
DIRC
Fwd Trk I & II
Fwd
RICH
Fwd
ToF
Fwd
Shashlyk
PANDA Collaboration

more than 450 physicists from more than 60 institutions in 19 countries
Thank you
High signal rates and high background rejection for excited double strange baryons

\[ \bar{p}_{\text{beam}} = 4.6 \text{ GeV/c} \]

Consider the \( \Xi^*(1820) \rightarrow \Lambda K \) decay,
assume \( \text{BR} = 100\% \) and \( \sigma = 1 \mu \text{b} \)

Simplified MC framework
Day-1 luminosity: \( 10^{31} \text{cm}^{-2}\text{s}^{-1} \)

Results

~30\% inclusive efficiency for \( \Xi^*(1820) \)

~5\% exclusive efficiency for \( \Xi^+\Xi^- (1820) \)

Low background level \( \rightarrow \) ~15000 exclusive events / day
\( \bar{p}p \rightarrow J/\psi \pi^0 \rightarrow e^+ e^- \gamma \gamma \)

\( \pi N \) TDA’s provide information on the nucleon’s pion cloud

Validity of factorization?

Simulation results for 4 months at \( L = 2 \times 10^{32} \)

Biggest background is \( J/\psi \pi^0 \pi^0 \) S/B > 15

after selecting \( N_\gamma \ (E_\gamma > 20 \text{ MeV}) < 4 \)

arXiv:1610.02149