PANDA experiment at the future FAIR facility (Darmstadt, Germany)

D. Melnychuk, NCBJ

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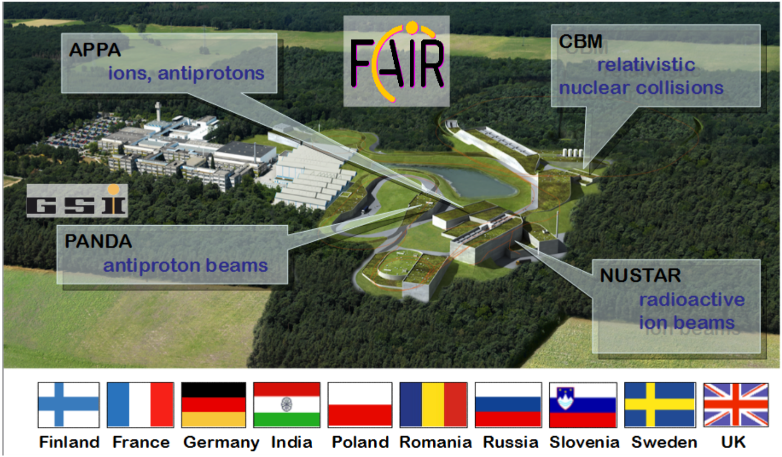
Plan

- FAIR facility
- Overview of physics program
- Overview of detector

FAIR project

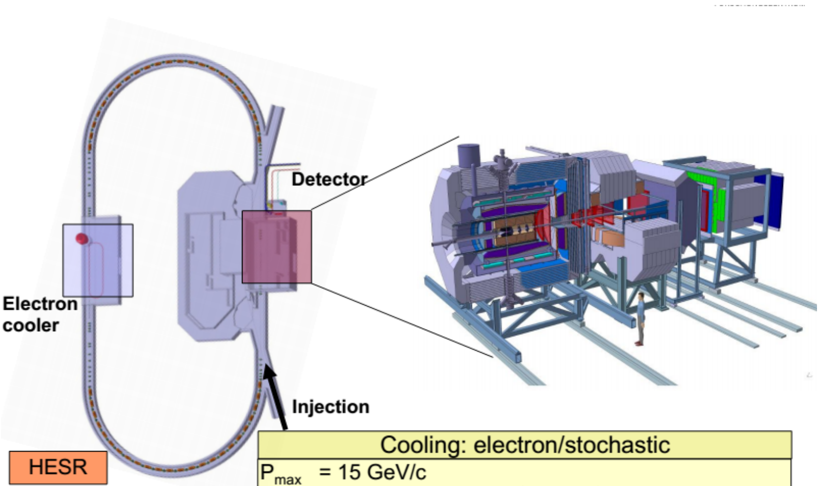


Total cost - 1.008,66 MEuro, Poland - 23.74 MEuro.

Construction site

Soil reinforcement

HESR



Cooling: electron/stochastic

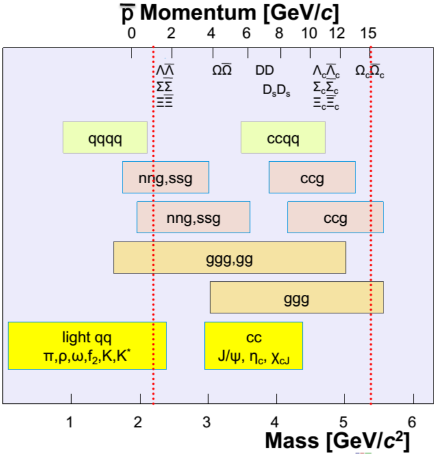
P_{max} = 15 GeV/c

High resolution: $L = 2 \cdot 10^{31}$ cm^{-2} s^{-1} $\delta p/p < 4\times10^{-5}$

High luminosity: $L = 2 \cdot 10^{32}$ cm^{-2} s^{-1} $\delta p/p < 10^{-4}$

Up to 10^{11} stored antiprotons. Annihilation rate up to $2 \cdot 10^{7}\ s^{-1}$.

PANDA experiment



Physics program of the PANDA experiment:

- Charmonium spectroscopy
- Search for exotic states (hybrids and glueballs)
- Hadrons in nuclear matter
- Physics of open charm
- Physics of hypernuclei
- Electromagnetic processes

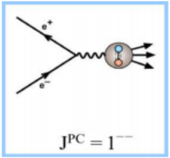
Fixed target experiment with antiproton beam of 1.5 - 15 GeV/c momentum from HESR synchrotron.

History

- Idea of experiment arises in 2003.
- Letter of intent in 2004 (http://www-panda.gsi.de/archive/public/panda_loi.pdf).
- Technical progress report in 2005 (http://www-panda.gsi.de/archive/public/panda_tpr.pdf).
- Physics performance report with detailed description of intended scientific program in 2009 (http://arxiv.org/abs/0903.3905v1).
- Technical design report of detector subcomponents (EMC - 2008, Magnet - 2009, MVD, Straw Tube Tracker - 2012)
- Current estimate of first physics run - 2018.

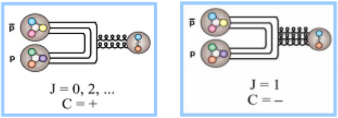
Why antiprotons?

- Gluon rich process
- Gain ~ 2 GeV in annihilation (low momentum transfer)
- B = 0 system
- All fermion-antifermion quantum numbers accessible (compared to e^+e^-)
- Very high mass resolution in *formation reactions*
- High angular momentum accessible (high L states)



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

Formation:



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

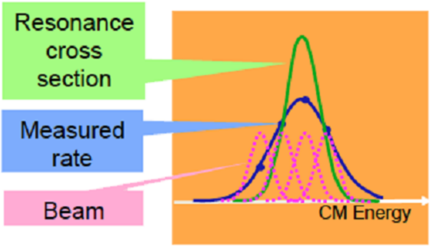
Why antiprotons?

The cross section for the process:
$p\bar{p} \longrightarrow R \longrightarrow$ final state
is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

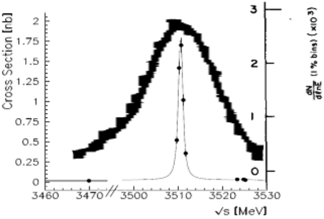
The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = \mathcal{L}\{\epsilon \int dE\, f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\}$$



The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the center of mass energy E.

Why antiprotons?



Gaiser et al., Phys. Rev. D34 (1986) 711 CrystalBall (SLAC):
3512.3 ± 4 MeV/c²
Andreotti et al., Nucl. Phys. B717 (2005) 34-47 (E835):
3510.641 ± 0.074 MeV/c²

Production:

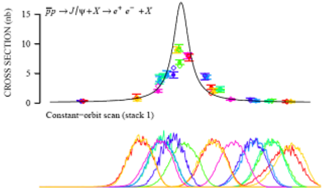
$$e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_{1,2} \rightarrow \gamma(\gamma J/\psi) \rightarrow \gamma\gamma e^+e^-$$

Invariant mass reconstruction depends on the detector resolution ≈ 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 ≈ 240 keV

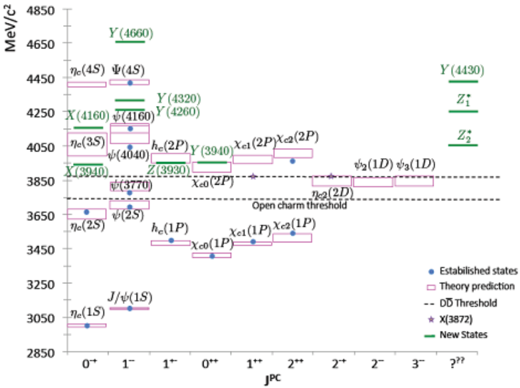
PANDA ≈ 50 keV

Interpretation of many states depends on width of states

QCD bound states

The study of QCD bound states is of fundamental importance for a better, quantitative understanding of QCD.
Particle spectra can be computed within the framework of non-relativistic potential models, effective field theories and Lattice QCD.
Precision measurements are needed to distinguish between the different approaches and identify the relevant degrees of freedom.

- Charmonium
- Exotic excitations
- Heavy-light systems
- Strange and charmed baryons



- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; some precision masses and widths still missing; there are no additional states.

- Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$.
Several exotic hypotheses about their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

- These result mainly from Belle and *BABAR* , with significant contributions also from CDF, D0, CLEO, LHCb, ATLAS, CMS and BES

Exotic QCD states (X,Y,Z)

- conventional quarkonium

- quarkonium hybrids

- quarkonium tetraquarks
  - compact tetraquark
  - meson molecule
  - diquark-onium
  - hadro-quarkonium

Eric Braaten - Charm 2013

Exotic QCD states (X,Y,Z)

quarkonium tetraquarks

- compact tetraquark
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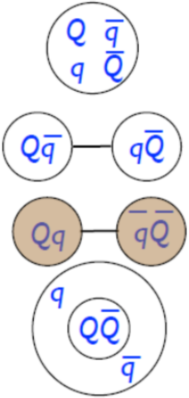

- Born-Oppenheimer tetraquark! arXiv:1305.6905

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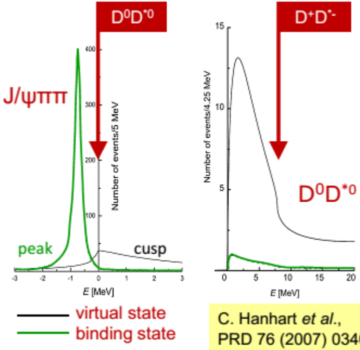
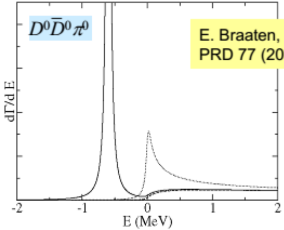
How PANDA can contribute?

- $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $\chi_c\gamma \rightarrow J/\psi\gamma\gamma$, $J/\psi\gamma$, $J/\psi\eta$, $\eta_c\gamma$
- Direct formation in $\bar{p}p$: line shapes !

X(3872)



C. Hanhart *et al.*, PRD 76 (2007) 034007



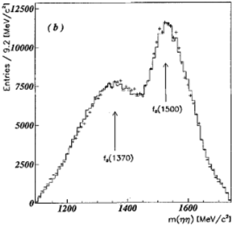
E. Braaten, M. Lu, PRD 77 (2008) 014029

Compare lineshapes in different final states!

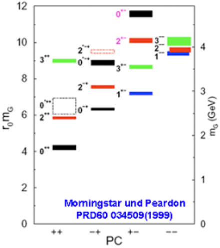
- Narrow state at 1500 MeV/c^2 seen by Crystal Barrel best candidate for glueball ground state ($J^{PC} = 0^{++}$)
- Non exotic gg/ggg-system are complicated to be identified (mixing with the nearby $\bar{q}q$ states).
- Detailed predictions of mass spectrum from LQCD.

C.Amsler et al., [Crystal Barrel], Phys Lett B 342, 433 (1995)

- Exotic heavy glueballs:
  - $m(0^{+-})$=4140(50)(200) MeV
  - $m(2^{+-})$=4340(70)(230) MeV
- Width unknown but there is a good probability to see glueballs in charm channels



Crystal Barell Collaboration
C. Amsler, Phys Lett B 355 (1995)

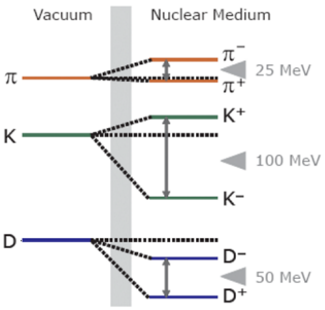


Morningstar und Peardon
PRD60 034509(1999)

Hadrons in nuclear matter

One of the fundamental questions of QCD is the generation of MASS.
The light hadron masses are large than the sum of the constituent quark masses. Spontaneous chiral symmetry breaking seems to play a decisive role in the mass generation of light hadrons. How can we check this?

- Since density increase in nuclear matter is possible a partial restoration of chiral symmetry.
- Evidence for mass changes of pions and kaons has been observed.
- $c\bar{c}$ states are sensitive to gluon condensate:
  - Small (5-10 MeV/c^2 in medium modifications for low-lying $c\bar{c}$ (J/ψ and η_c)
  - Significant mass shifts for excited states: 40, 100, 140 MeV/c^2 for χ_{cJ}, ψ' and $\psi(3770)$ respectively (S.Lee, Phys. Rev. C67, 038202 (2003)).
- D mesons are the QCD analog of the H-atom.
  - chiral symmetry to be studied on a single light quark
  - theoretical calculations disagree in size and sign of mass shift (50 MeV/c^2 attractive - 160 MeV/c^2 repulsive) (Phys. Rev. B487, 96 (2000) - Eur. Phys. J A7, 279 (2000)).

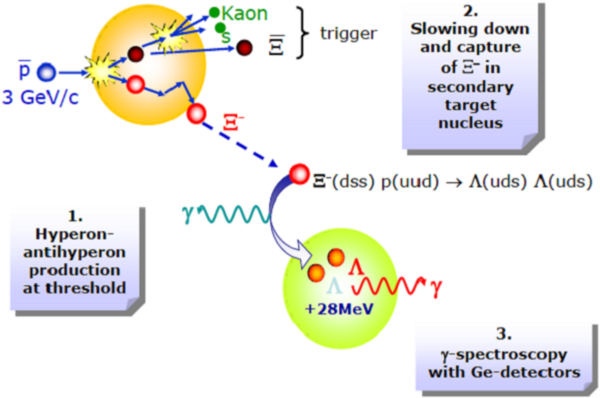


Hypernuclear physics

Hypernuclei, system where one (or more) nucleon is replaced by one (or more) hyperon(s) (Y), allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness.

- Probe of nuclear structure and its possible modifications due to the hyperon
- Test and define shell model parameters
- Description in term of quantum field theories and EFT
- Study of the YN and YY forces (single and double hypernuclei)
- Weak decays ($\Lambda \to \pi N$ suppressed, but $\Lambda N \to NN$ and $\Lambda\Lambda \to \Lambda$N allowed: four baryon weak interact)
- Hyperatoms
- Experimentally: in 50 years of study 35 single and 6 double hypernuclei established.

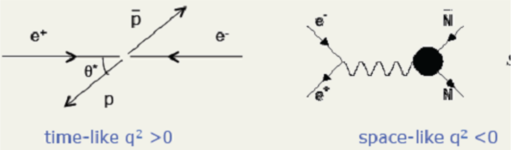
Hypernuclear physics



- $\bar{p}p \rightarrow \Xi^-\bar{\Xi}^+$ and $\bar{p}n \rightarrow \Xi^-\bar{\Xi}^0$ followed by re-scattering of the Ξ^- within the primary target nucleus.
- After stopping the Ξ^- in an external secondary target, the formed Ξ hypernuclei will be converted into double Λ hypernuclei.

Nucleon form factor

The simplest structure functions of the nucleon are form factors.

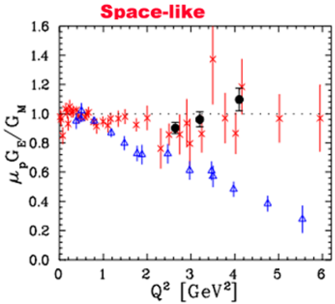


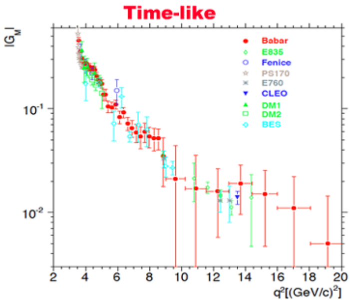
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2 (1+\cos^2\theta^*) + \frac{4m_N^2}{s} |G_E(s)|^2 \sin^2\theta^* \right]$$

Most experiments could not determine $|G_M|$ and $|G_E|$ (the magnetic and electric form factors respectively) separately from the analysis of the angular distributions, but extracted $|G_M|$ using the arbitrary assumption $|G_E| = |G_M|$

Nucleon form factor

Existing results on the proton form factor



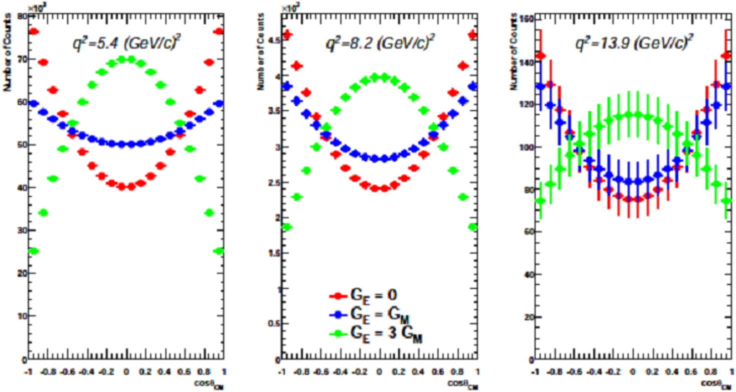


Older Rosenbluth separation data (crosses), most recent JLab Rosenbluth separation data (filled circles), and polarization transfer data (triangles).

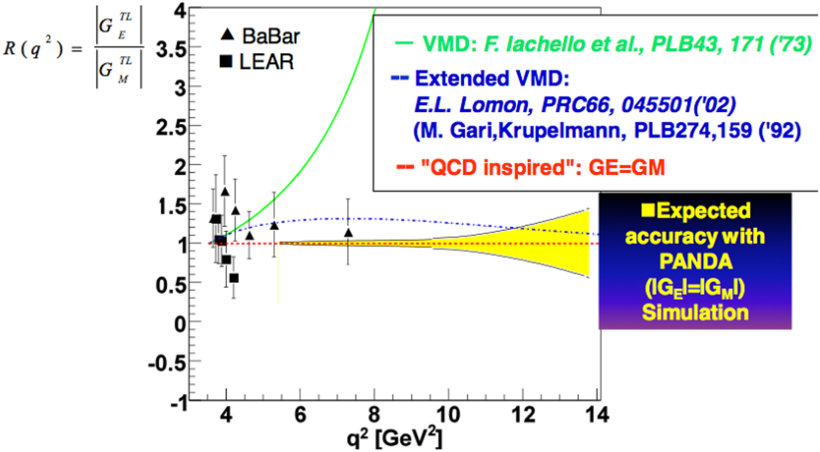
- $|G_E|$ and $|G_M|$ in the time like region can be determined by the reactions $\bar{p}p \rightarrow e^+e^-$
- Presently statistics is limited: no real separation $|G_E|/|G_M|$
- G_E in the time like region is today unknown
- Extraction of the ratio $R = |G_E|/|G_M|$

$p\bar{p} \to e^+e^-$ angular distribution

- $\sim$ 120 days, $\mathcal{L}$=2×10^{32} cm^{-2}s^{-1}, $\mathcal{L}_{int}$=2 fb^{-1}
- Statistical errors only
- $R = |G_E|/|G_M|$ will be determined with good precision for q^2 values less than 15 (GeV/c)^2

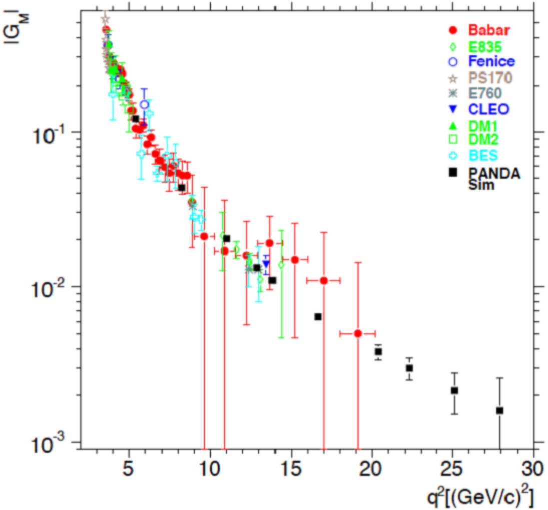


Time-like form factor of the proton

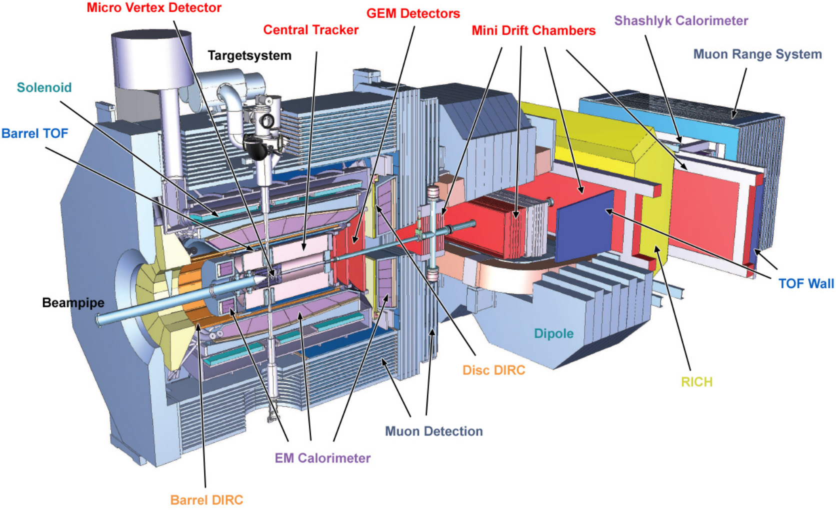


Measurement of the $R = |G_E|/|G_M|$ ratio at $\bar{\text{P}}$ANDA can be done with unprecedent precision compared to BABAR and LEAR.

Time-like magnetic form factor of the proton

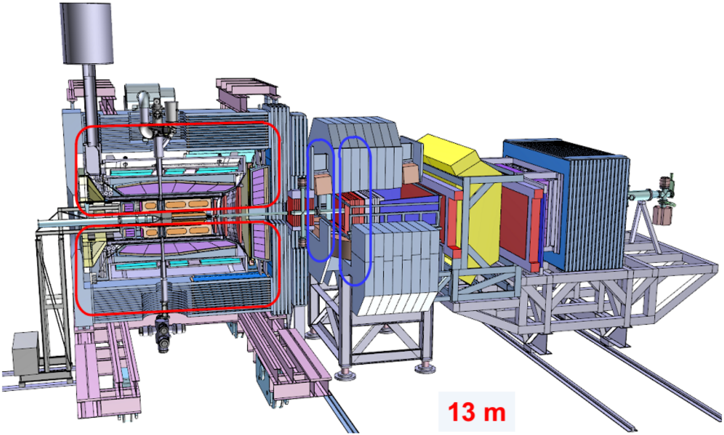


Panda detector



Detector requirements

4π coverage	(partial wave analysis)
High rates	(2×10^7 annihilation/s)
Good PID	(γ, e, μ, π, K, p)
Good momentum resolution	($\sim$ 1 %)
Vertexing for D, K^0_S, Λ	(cτ = 123 μ m for D^0)
No hardware trigger	(raw data rate $\sim$ TB/s)
Modular structure	(Hypernuclear physics)

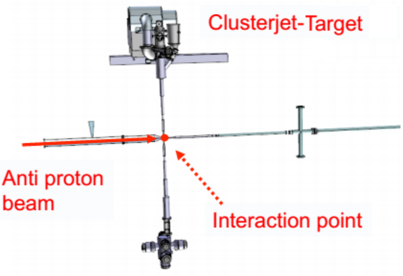


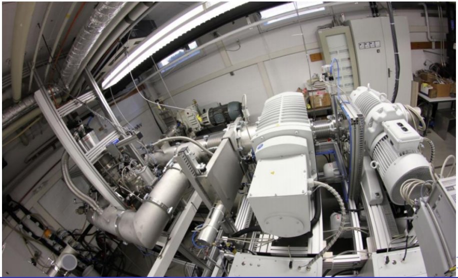
Detector is divided into:

- Target spectrometer with superconducting solenoid magnet (2 *Tesla*)
- Forward spectrometer with large aperture dipole magnet (2 $Tesla \cdot m$).

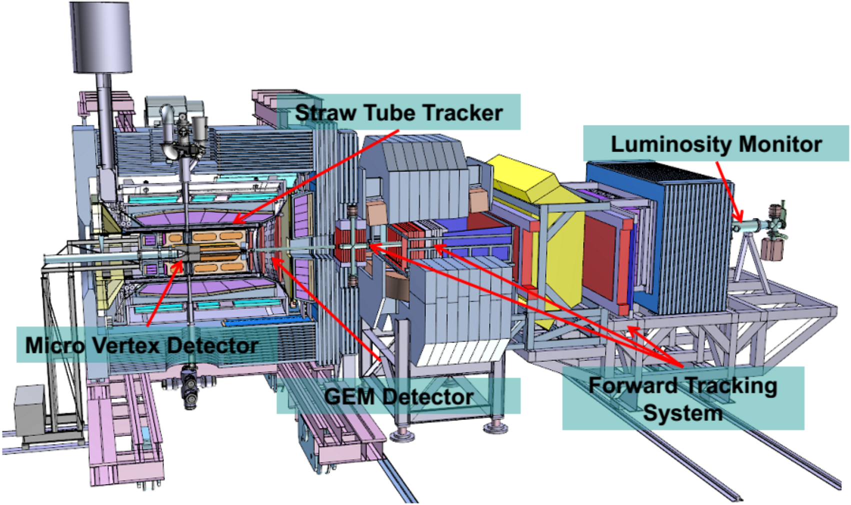
Target

The cluster-jet beam for the internal target in the HESR is produced by expansion of pre-cooled gas in a convergent-divergent Laval-type nozzle with micron-sized throat into vacuum. During the passage of the gas through the nozzle the gas adiabatically cools down and forms a supersonic stream of atoms or molecules. Under appropriate conditions, depending on the type of gas, condensation can take place and nano-particles, the so-called clusters, are created. In prototype of cluster jet target the record of density $2 \times 10^{15} cm^{-2}$ reached.



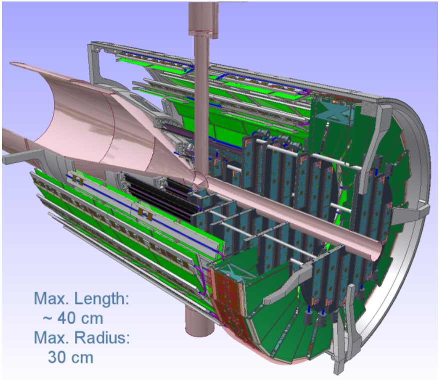


Tracking


Straw Tube Tracker
Luminosity Monitor
Micro Vertex Detector
GEM Detector
Forward Tracking System

MVD

The concept of the MVD is based on radiation hard silicon pixel detectors with fast individual pixel readout circuits and silicon strip detectors. The layout foresees a four layer barrel detector with an inner radius of 2.5 cm and an outer radius of 13cm. The two innermost layers will consist of pixel detectors and the outer two layers will consist of double sided silicon strip detectors. Six detector wheels arranged perpendicular to the beam will achieve the best acceptance for the forward part of the particle spectrum.

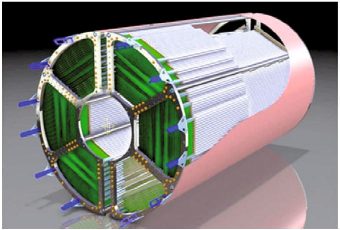


- Small pixel cells ($100 \times 100\ \mu m^2$, 10^7 channels)
- Dedicated ASIC for untriggered data readout (ToPix)
- Double-sided silicon micro-strip detectors in the outer parts of the MVD facilitate the readout of a much larger area with significantly fewer channels.
- ToT to extract some energy information.
- PID capability via dE/dX.

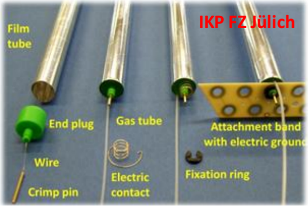
STT

This detector will consist of aluminised Mylar tubes called straws, which will be self supporting by the operation at 1 bar overpressure. The straws are to be arranged in planar layers which are mounted in a hexagonal shape around the MVD.

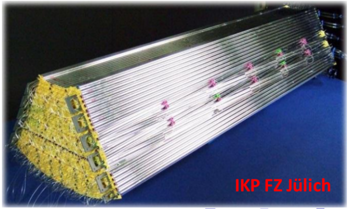
- 4636 straw tubes
- 23-27 radial layers
- Ar/CO_2 gas mixture (200 ns drift time)
- Position resolution ($\sigma_{r\phi} \sim 150\mu m$, $\sigma_z \sim 2-3mm$)
- Momentum resolution $1-2\%$
- Two concepts of readout (Amplitude sampling vs amplitude via Time-over-Threshold)



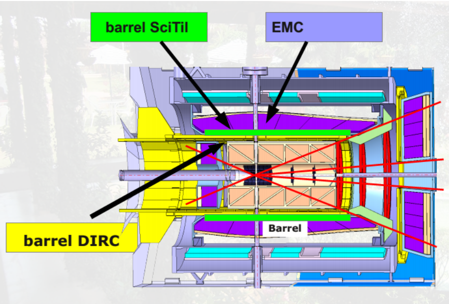
Straw components

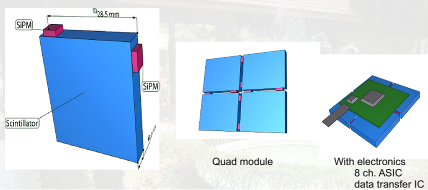


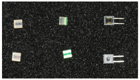
Full hexagon sector



SciTil



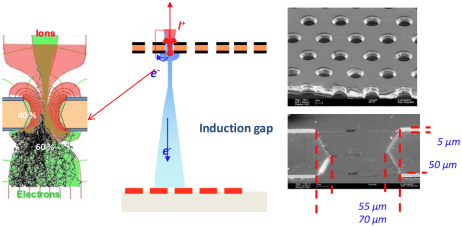


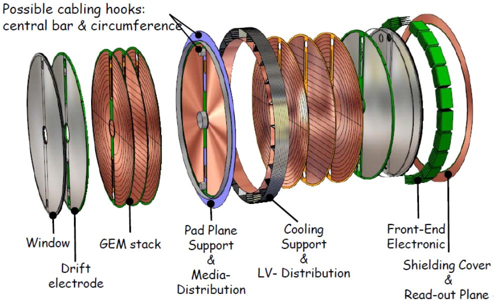


- At the high interaction rate in the presence of multiple pile-ups the fast detector can assign accurate time stamps to tracks $\Rightarrow$ SciTil.
- Conversion of γ's in DIRC can be detected.
- Contribution to PID with time-of-flght.
- Silicon Photomultiplier as a photon detector is small, fast, has high rate capability and can work in magnetic field.
- Time resolution around 100 ps can be achieved.

GEM

- Gaseous micro-pattern detector based on GEM foils are chosen due to high rate capability to sustain up to $3 \times 10^4 cm^{-2} s^{-1}$ particles expected in most forward direction.
- 3 GEM station will cover particles emitted at angles $5^\circ - 22^\circ$.
- Required position resolution $\sim 100 \mu m$.

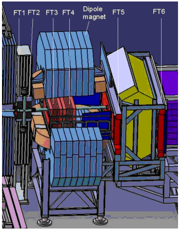


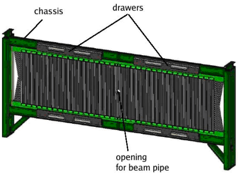


Forward tracker

The Forward Tracker (FT) is designed for momentum analysis of charged particles deflected in the field of the PANDA dipole magnet. Three pairs of planar tracking stations: one pair (FT1, FT2) in front, the second (FT5, FT6) behind the dipole magnet and the third pair (FT3, FT4) inside the magnet gap in order to track low momentum particles hitting the magnet yoke.

- Each tracking station consists of four double-layers: the first and the fourth one contain vertical straws (0°) and the two intermediate double-layers contain straws inclined at $+5^\circ$ and -5°, respectively.
- The FT is based on 10 mm in diameter straw tube detectors of the type proposed for the Central Tracker.
- In order to minimize the aging effects, usage of 90% Ar + 10% CO_2 gas mixture is considered.
- With position resolution of $\sigma = 0.1mm$ per detection layer the momentum resolution better than 1 % is expected.





Electromagnetic calorimeter

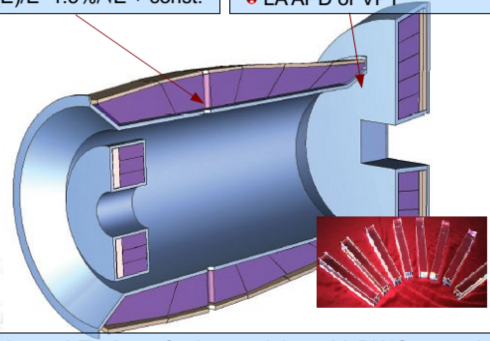
PANDA PWO Crystals
- PWO is dense and fast
- Low γ threshold is a challenge
- Increase light yield:
  - improved PWO II (2xCMS)
  - operation at -25°C (4xCMS)
- Challenges:
  - temperature stable to 0.1°C
  - control radiation damage
  - low noise electronics

Large Area APDs

5x5 mm² 10x10 mm² and 7x14 mm²

Barrel Calorimeter
- 11000 PWO Crystals
- LAAPD readout, 2x1cm²
- σ(E)/E~1.5%/√E + const.

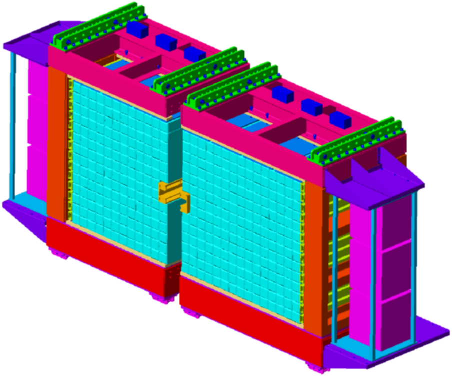
Forward Endcap
- 4000 PWO crystals
- High occupancy in center
- LA APD or VPT

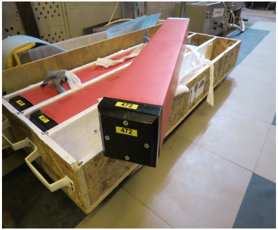


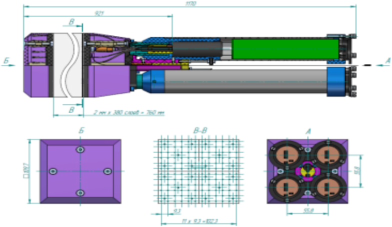
Backward Endcap for hermeticity, 560 PWO crystals

Shashlyk calorimeter

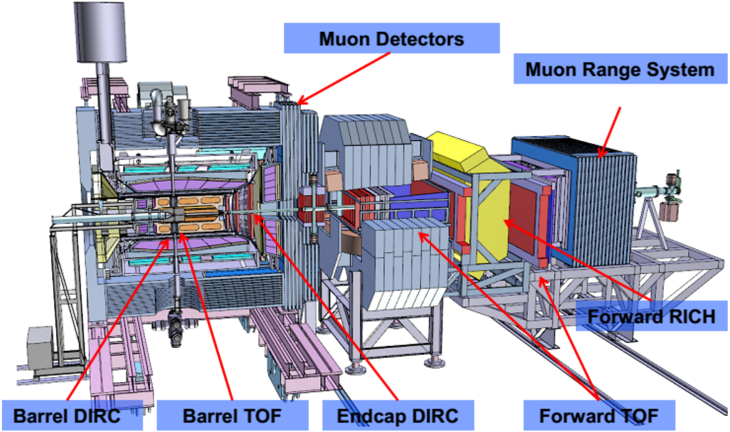
The detection is based on lead-scintillator sandwiches read out with wavelength shifting fibres passing through the block and coupled to photo-multipliers (27 $\times$ 14 modules).







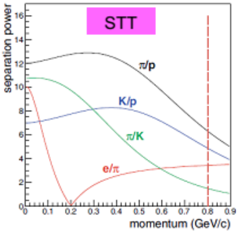
PID

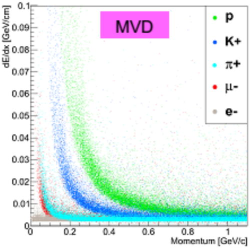


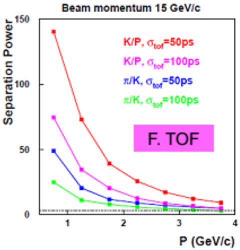
Muon Detectors
Muon Range System
Forward RICH
Barrel DIRC
Barrel TOF
Endcap DIRC
Forward TOF

PID

- Cherenkov radiation : above ~ 0.8 GeV/c
- Energy loss measurements: below ~ 0.8 GeV/c
- Time of flight
- Muon detectors: primary muons selection from pions and decay muons
- EMC: electromagnetic showers for e and γ

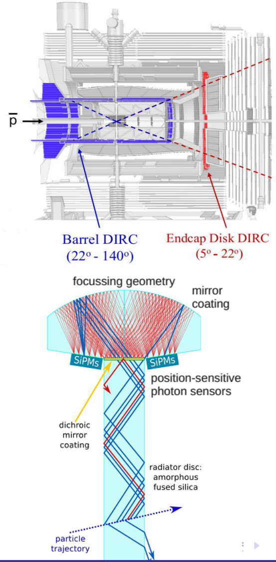




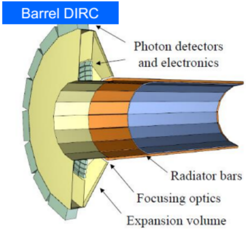


DIRC (Detection of Internally Reflected Cherenkov light)

- PANDA PID requirement: more than 3σ π/K separation in the momentum range 0.5-5 GeV/c
- DIRC detector is based on principle that charged particles propagated in medium with $\beta > 1/n$ emit cherenkov photons on a cone with opening angle $\cos\theta_c = 1/\beta n(\lambda)$
- Photons exit radiator bars through focusing elements into expansion volume and are imaged on photon detector array.
- Observed hit patterns of Cherenkov photons (x,y,t) determine PID likelihoods for $e/\mu/\pi/K/p$
- Two DIRC detectors in PANDA: Barrel DIRC similar to Babar DIRC with several improvements (fast photon timing, focusing system) and Disk DIRC



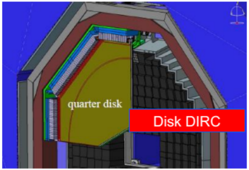
DIRC

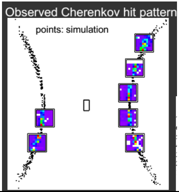


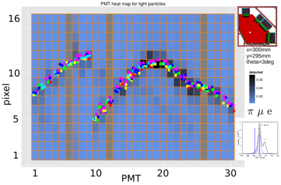
- 22° - 140 ° polar angle
- 80 radiator bars, syntetic fused silica 1.7x3.3x250 cm^3
- Double lens system
- 30 cm oil-filled
- ~ 15 kchannels MCP-PMTs

Single photon Cherenkov angle resolution: 8-9 mrad
Number of photoelectrons per track > 20

- 5°-22°
- Octagonal disk, 2 m diameter, 2 cm thick
- Four identical pieces with polished and reflecting sides
- Dichroic mirrors on rim
- 432 small focusing guides image photons on digital SiPM or MCP PMTs





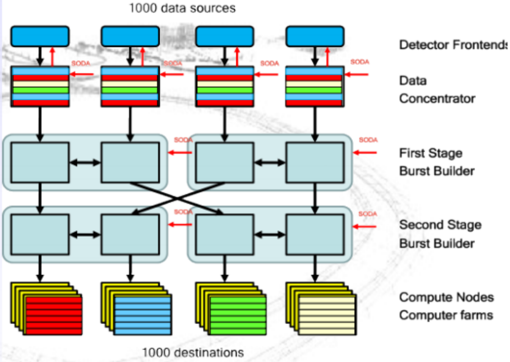


DAQ

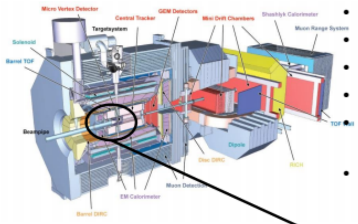
Self triggered readout

- Components:
  - Time distribution system
  - Intelligent frontends
  - Powerful compute nodes
  - High speed network
- Data Flow:
  - Data reduction
  - Local feature extraction
  - Data burst building
  - Event selection
  - Data logging after online reconstruction

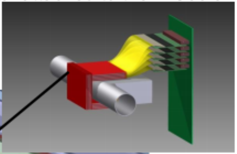
→ **Programmable Physics Machine**

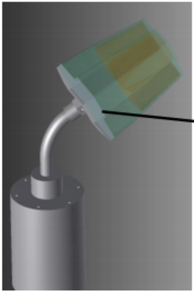


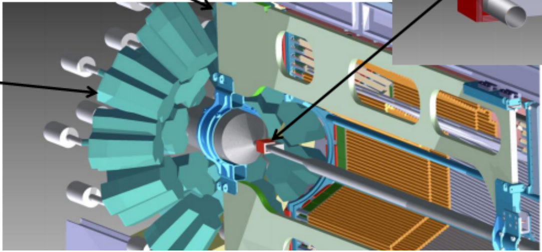
Hypernuclear setup



- $\Lambda\Lambda$ hypernuclei study: $\overline{p} + {}^{12}C \Rightarrow \Xi^{-} + \overline{\Xi}$
- Backward End Cap EMC and MVD will be removed
- Dedicated beam pipe system
- Wire target into the beam pipe
- Secondary active target (Si strips + Be,B,C absorbers)
- HPGe encapsulated crystal attached to the X-Cooler







Collaboration

More than 520 physicists from 67 institutions in 17 countries

Aligarh Muslim University
U Basel
IHEP Beijing
U Bochum
Magadh U, Bodh Gaya
BARC Mumbai
IIT Bombay
U Bonn
IFIN-HH Bucharest
U & INFN Brescia
U & INFN Catania
NIT, Chandigarh
AGH UST Cracow
JU Cracow
U Cracow
IFJ PAN Cracow
GSI Darmstadt

Karnatak U, Dharwad
TU Dresden
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
Birla IT&S, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
IIT Guwahati

IIT Indore
Jülich CHP
Saha INP, Kolkata
U Katowice
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U Mainz
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ITEP Moscow
MPEI Moscow
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U Stockholm
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Suranree University
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Politechnico di Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
NCBJ Warsaw
TU Warsaw

Thank you for your attention!