HELMHOLTZ
GEMEINSCHAFT
Helmholtz-Institut Mainz

The $\bar{\text{P}}$ANDA Experiment at FAIR

Alicia Sanchez Lorente
on behalf of the PANDA Collaboration

FAIRNESS Workshop,
Garmisch-Partenkirchen, 14. -19. February 2016

Outline

- QCD and the strong Interaction
- PANDA at FAIR
  - PANDA Physics Program
    - Nucleon structure E.M. processes
    - Meson spectroscopy
      - light mesons
      - charmonium
      - exotic states
        - glueballs
        - hybrids
        - molecules/multiquarks
      - open charm
    - Baryon/antibaryon production
    - Charm in nuclei
    - Strangeness physics
      - Hyperatoms
      - S = -2 nuclear system
        - Ξ^- nuclei
        - $\Lambda\Lambda$ hypernucle
  - Experimental Setup

- Summary and Outlook

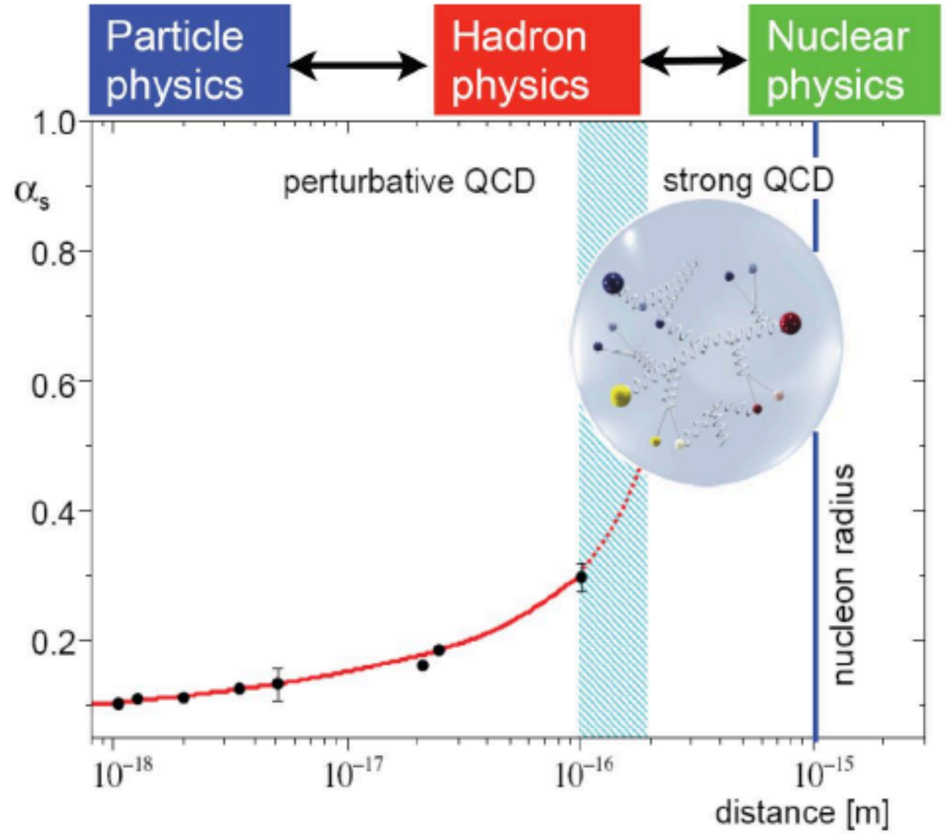
QCD and the strong Interaction

- Standard Model:
  Quantum Chromo Dynamics (QCD)
  based on SU(3) group theory

- Running coupling constant

- Asymptotic Freedom at high energies.
  Perturbative QCD, well understood

- Confinement at lower energies.
  Perturbation theory fails.
  Other approaches needed



Approaches to the non-Pertubative QCD

Potential Models
Non-relativistic treatment of heavy quark bound systems. Think of hydrogen and positronium prototypes and the Schrödinger equation.

Lattice QCD
Equations of motion are *discretized* on a 4-dimensional space-time lattice and solved by large-scale *computer simulations*. It had an enormous progress in the recent years and an ever increasing precision.

Effective Field Theories (EFT)
Effective Lagrangians using symmetries and hierarchies of scale *tailored for the problem at hand*. With quark and gluon degrees of freedom (e.g. Non relativistic QCD, NRQCD) as well as with hadronic degrees of freedom (e.g. Chiral Perturbation Theory).

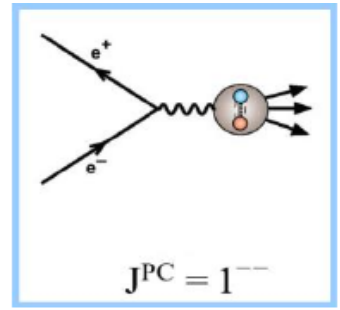
Open-Questions, what can we learn ?

- Confinement : Why are there no free quarks?
- Exotics : Are there other color-neutral objects?
  - hybrids, glueballs, multi-quark states
- Hadron Spectroscopy Compare to theoretical model predictions
  Partial Wave Analysis to identify relevant degrees of freedom
- Hadrons in Matter How do masses and widths behave inside nuclei?
- Nucleon What is its structure?
- Spin What are the degrees of freedom?

Why Antiprotons?

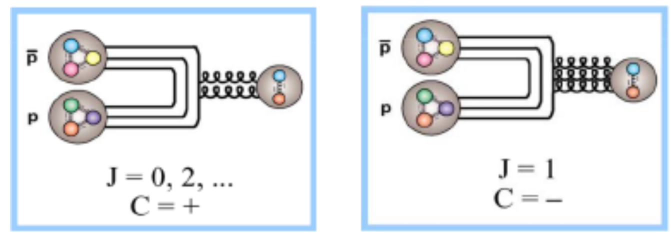
e^+e^- Collisions

- Hadrons via direct formation & initial state radiation
- Low hadronic background but precision mainly limited by detector resolution
- Initial state limited to $J^{PC} = 1^{--}$ (BaBar, Belle, BES, CLEO(-c), LEP...)



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

Formation:

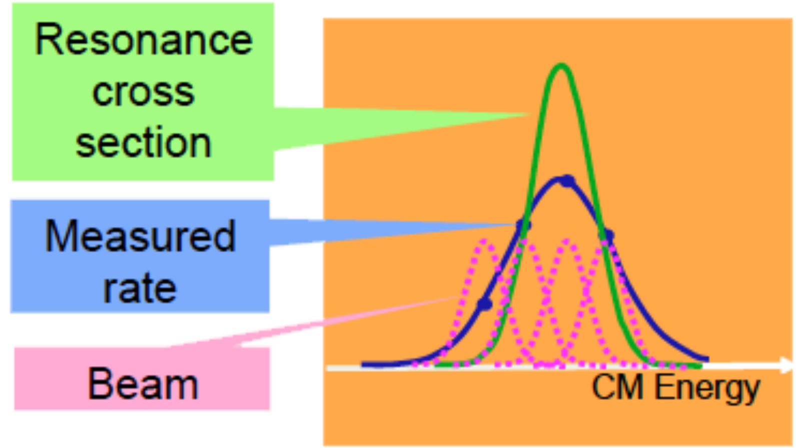


All J^{PC} allowed for ($\bar{q}q$) accessible in $\bar{p}p$

$\bar{p}p$ Annihilation

- Large luminosities with thin targets (stored $\bar{p}$)
- Direct Formation of hadronic states
- Measurement precision limited by beam parameters
- High hadronic background
- All non-exotic J^{PC} available (LEAR, Fermilab E760/E835, PANDA)

Beam Scan – Experimental Methods



Breit-Wigner resonance cross section:

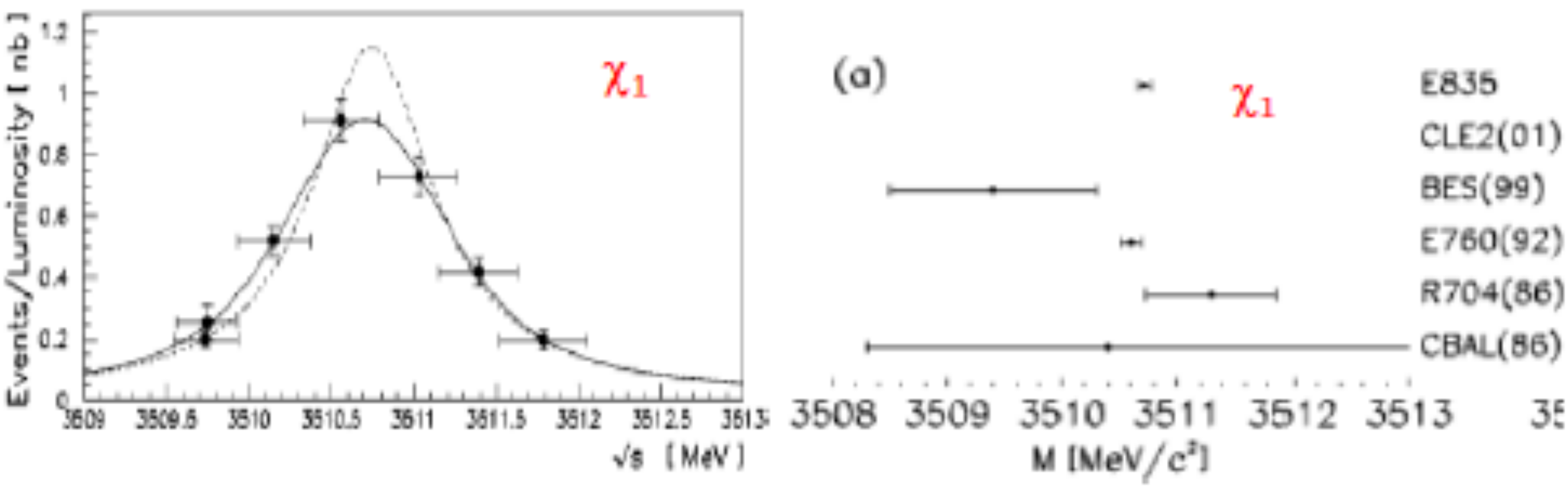
$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

Reaction rate ν is convolution of cross section and beam energy distribution function $f(E,\Delta E)$

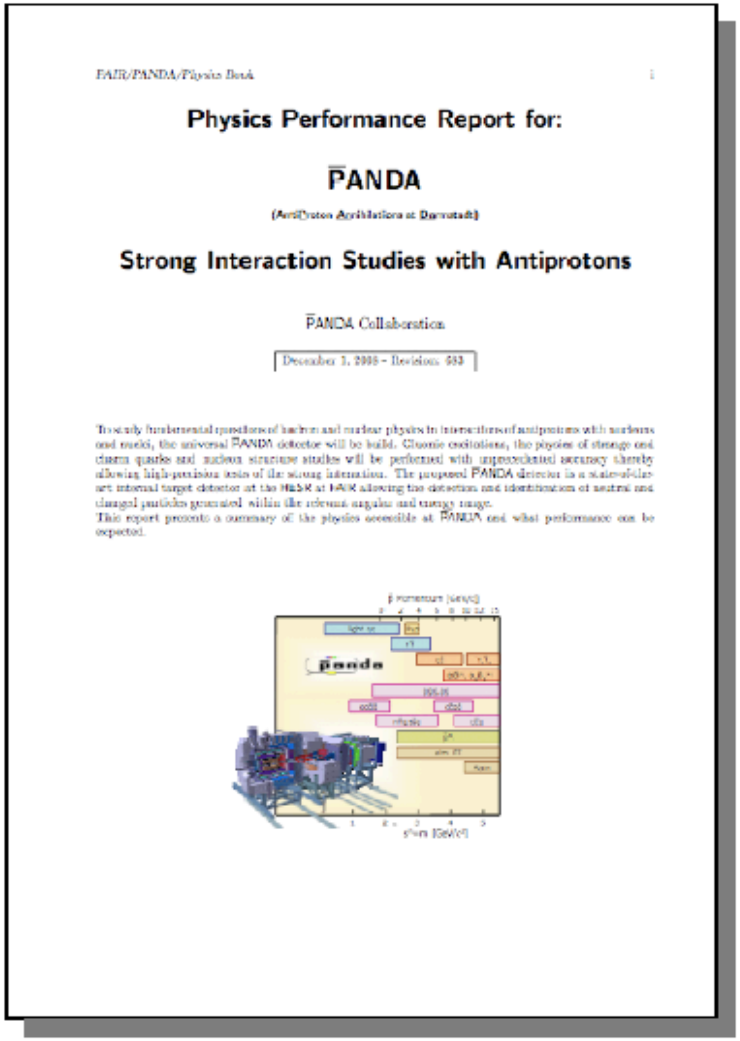
$$\nu \sim \mathcal{L}\left\{\epsilon\int f(E,\Delta E)\sigma_{BW}(E)dE+\sigma_b\right\}$$

→ Mass M_R, width Γ_R and branching ratio product $B_{in}B_{out}$ can be extracted by scanning the line shape with the beam.

Example : X_1 scan at Fermilab E835



Physics Performance Report for PANDA



FAIR/PANDA/Physics Book

Physics Performance Report for:

$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

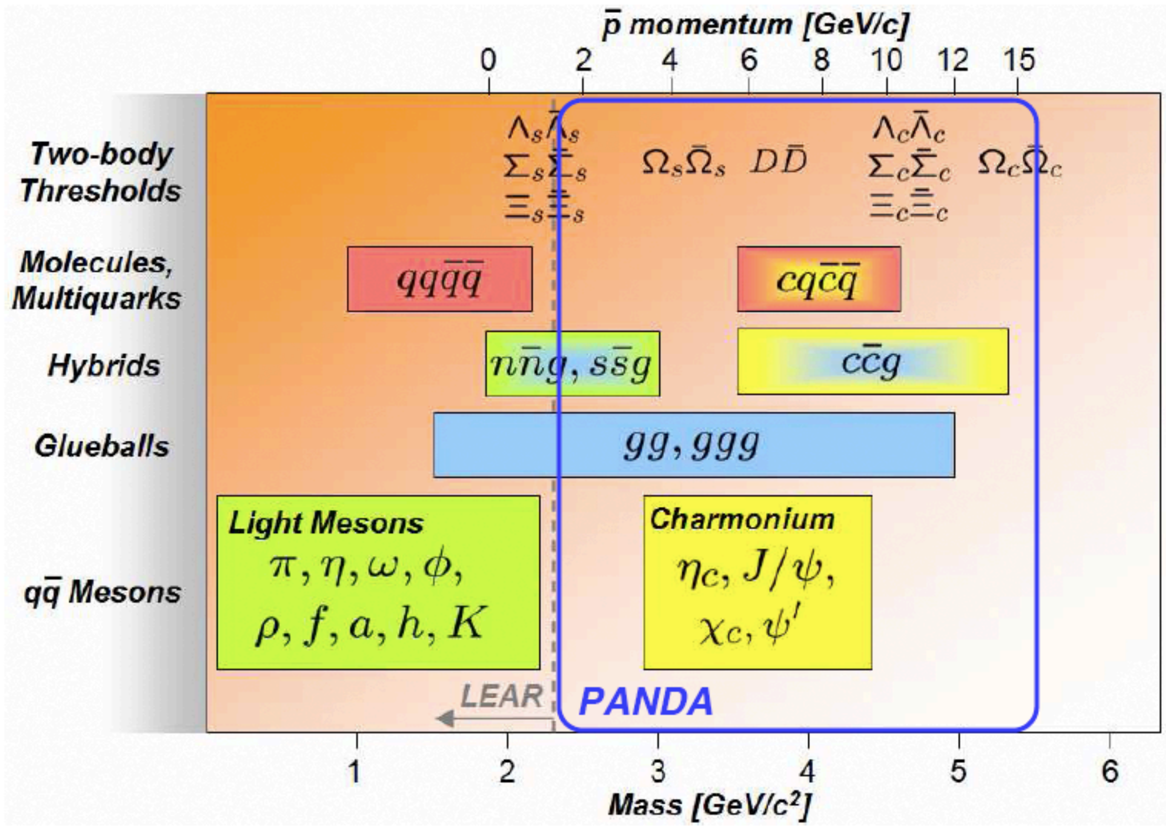
$\overline{\text{P}}$ANDA Collaboration

December 1, 2008 – Revision: [illegible]

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA 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 $\overline{\text{P}}$ANDA 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 $\overline{\text{P}}$ANDA and what performance can be expected.

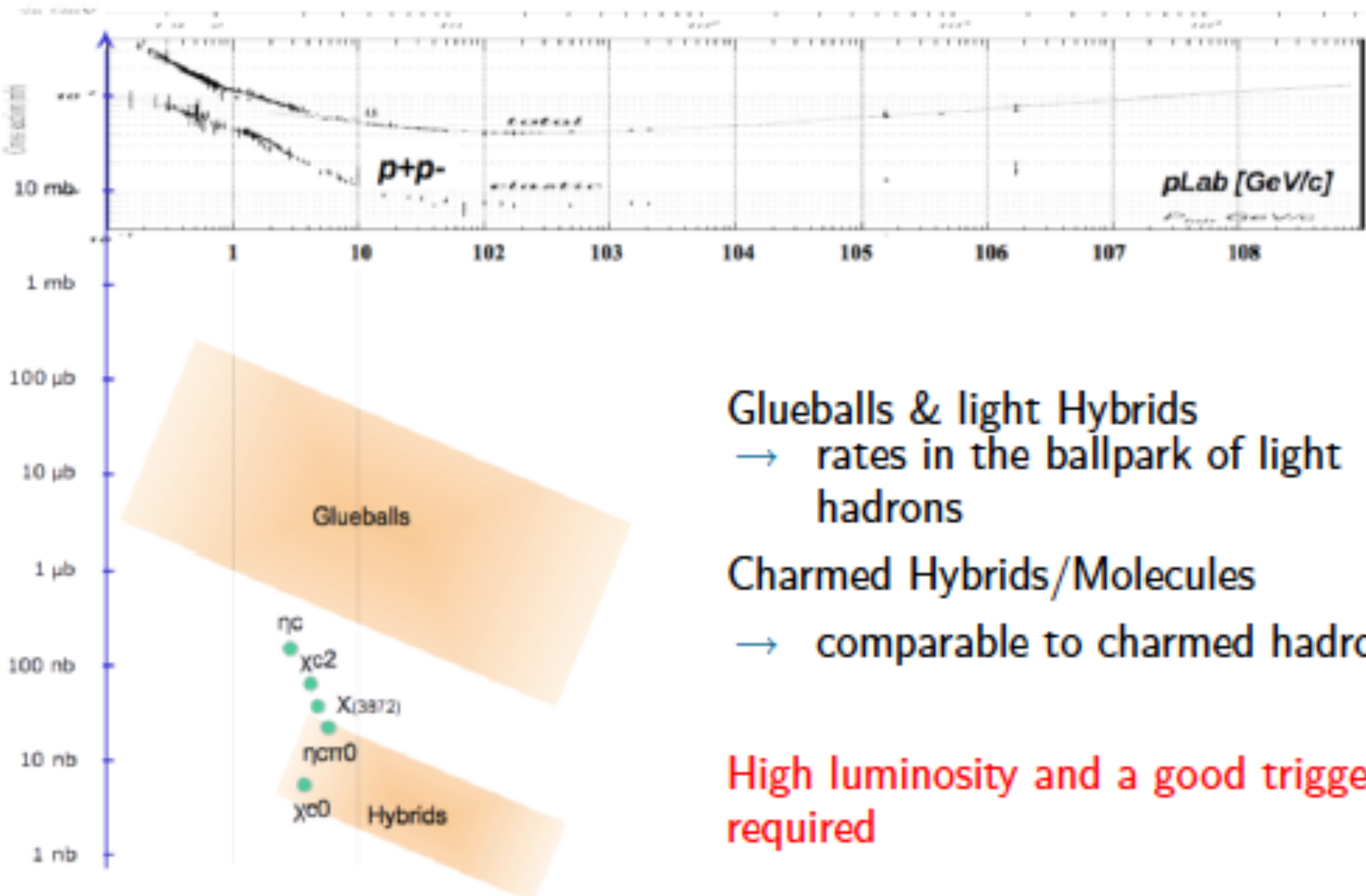
- A big effort has been made to create the **PHYSICS PERFORMANCE REPORT FOR PANDA**
- Detailed description of the intended scientific program.
- More than 20 channels have been studied in detail to determine the experimental sensitivity
  http://arxiv.org/abs/0903.3905v1

The $\bar{\text{P}}$ANDA Physics Program



- QCD bound states:
  - - Charmonium
  - - Exotic excitations
  - - Heavy-light systems
  - - Strange and charmed baryons
- Hadrons in the nuclear medium
- Hypernuclear physics
- Nucleon structure
  - - Generalized distribution amplitudes
  - - Drell-Yan
  - - Electromagnetic form factors
- Electroweak physics

Expected Cross Section

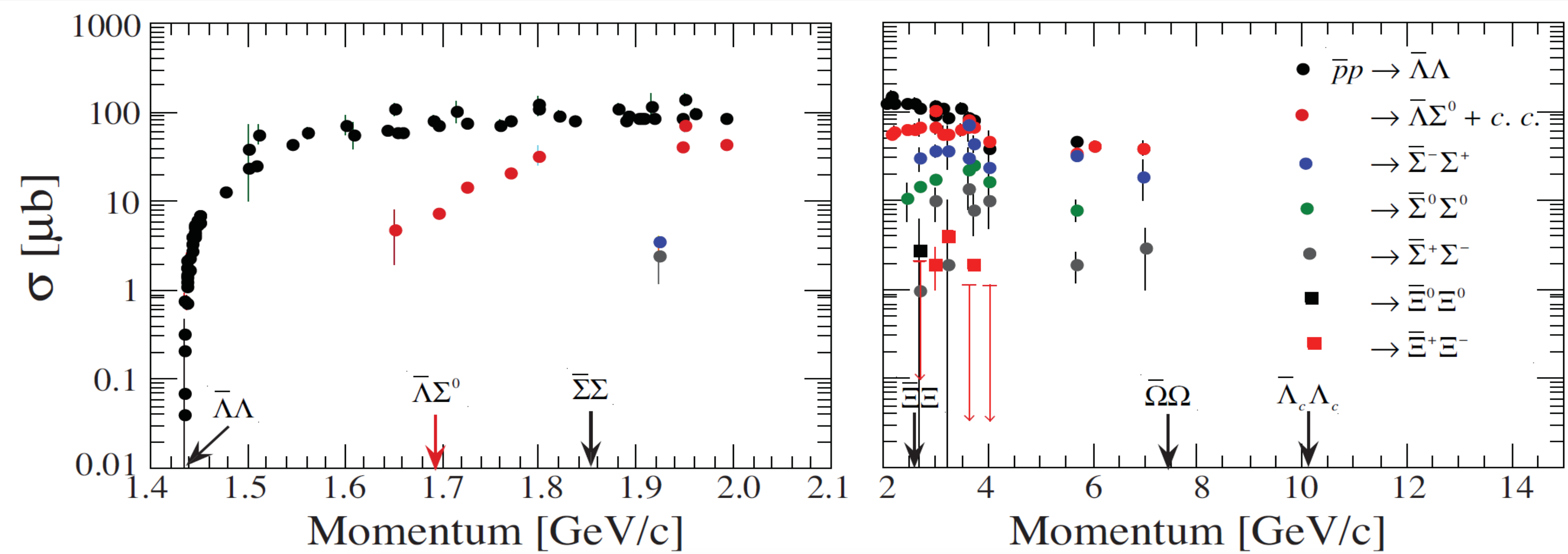


Glueballs & light Hybrids
→ rates in the ballpark of light hadrons

Charmed Hybrids/Molecules
→ comparable to charmed hadrons

High luminosity and a good trigger required

$\bar{\text{P}}$ANDA – a Factory for strange *and* charmed $Y\bar{Y}$-Pairs



Production Rates (1-2 (fb)$^{-1}$/y)

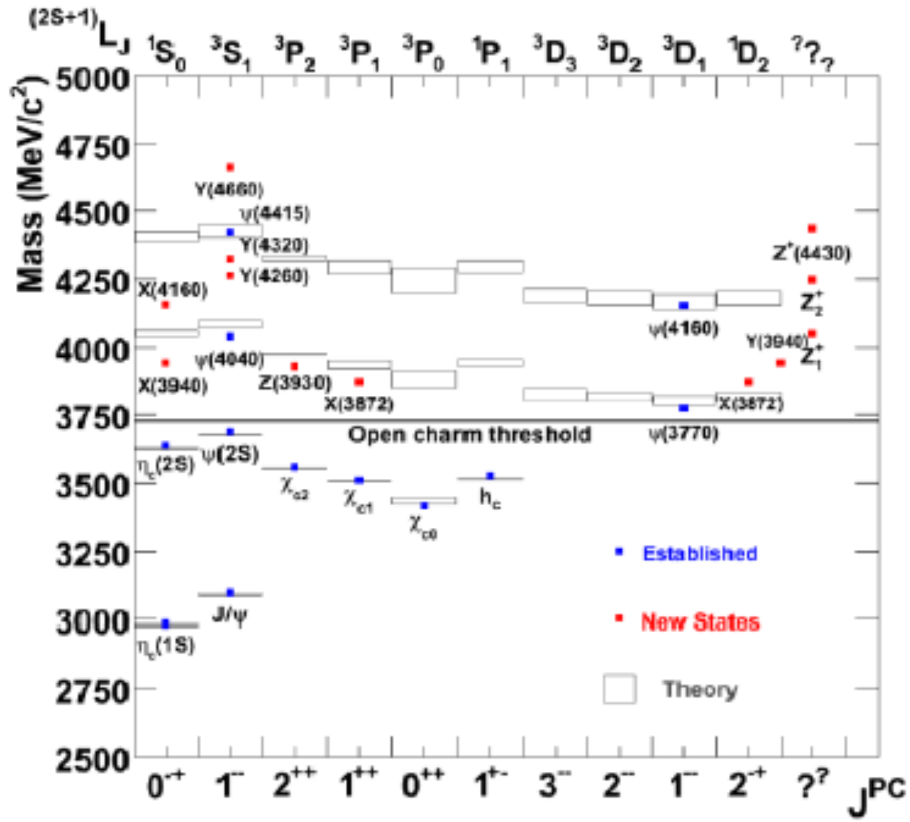
Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$ ($\to_{\Lambda\Lambda}$ A)	2μb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\to e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\to$ J/ψ + γ)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

The Charmonium Spectrum

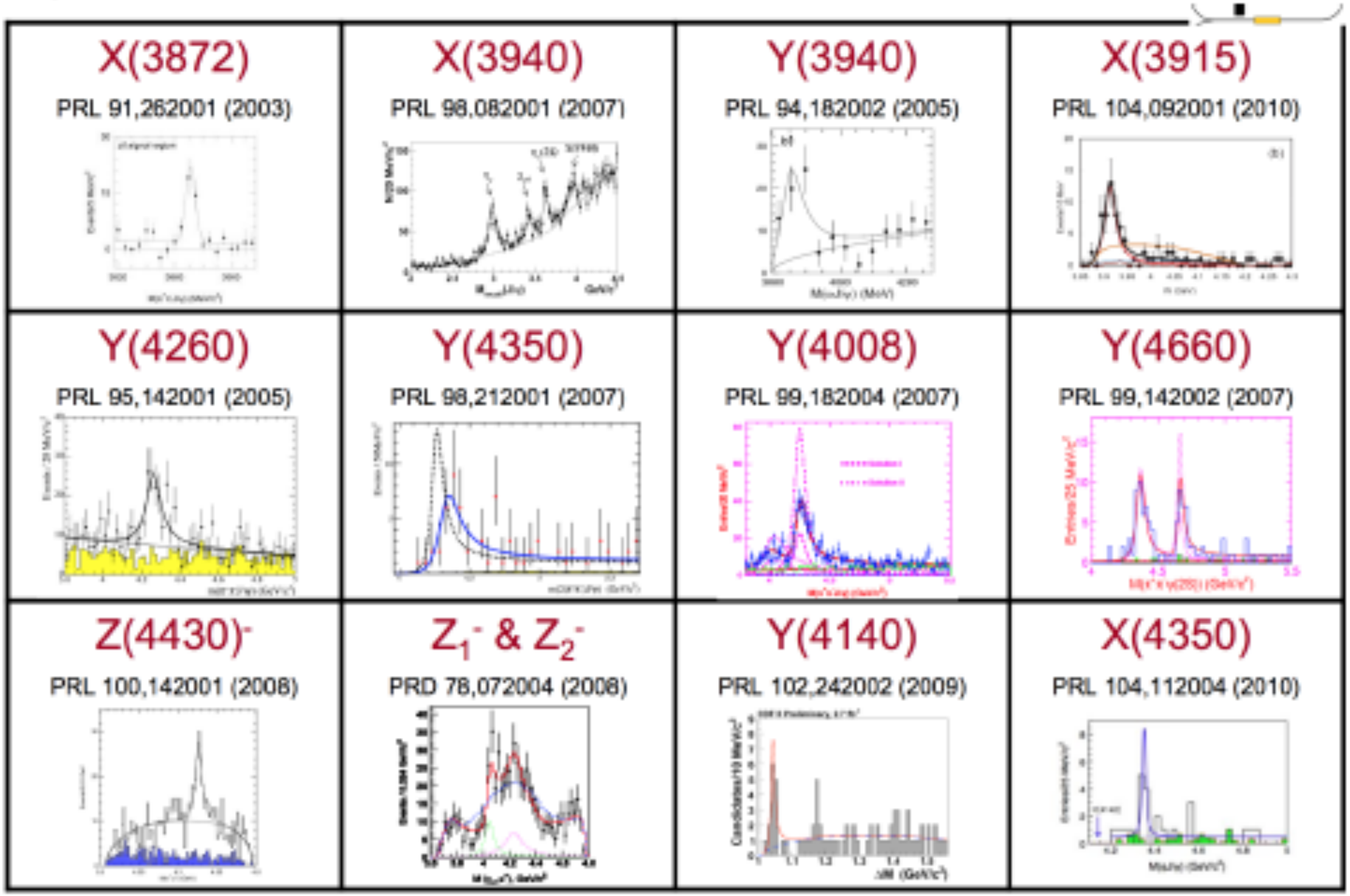
new „XYZ“ states (Belle, BaBar, CLEO, CDF, D0, LHCb …)

- masses are poorly known;
- often widths are just upper limits;
- few final states have been studied;
- statistics are poor;
- quantum number assignment is possible for few states;
- some resonances need confirmation…

- new degrees of freedom: molecules, tetraquarks, gluonic excitations?
- open questions below $D\bar{D}$ threshold widths, branching
- conventional states above $D\bar{D}$
- high L states: access in $\bar{p}p$ but not in e^+e^-



The XYZ States

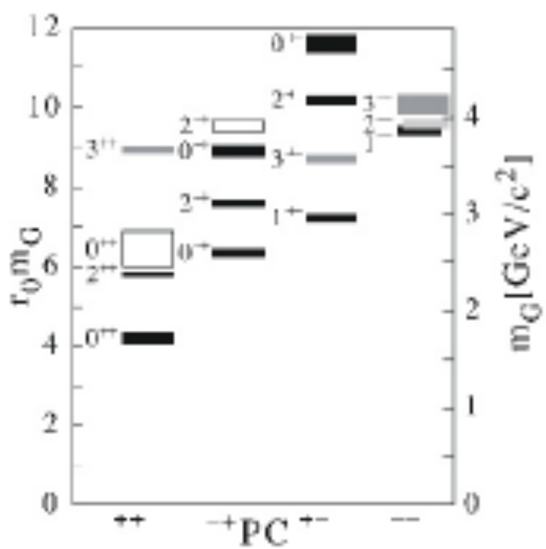


Charmonium in PANDA

- At $2 \cdot 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ accumulate $8 \mathrm{pb}^{-1}$/day (assuming 50% overall efficiency). It means 10^4-10^7 ($c\bar{c}$) states/day.
- Total integrated luminosity $1.5 \mathrm{fb}^{-1}$/year (at $2 \cdot 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$, assuming 6 months/year data taking).
- Fine scans to measure masses to ~100 KeV and widths to $\sim 10\%$
- Explore entire region below and above open charm threshold, finding missing states and understanding newly discovered states
- Typical decay channels:
  - $J/\psi + X$; $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\overline{D}$
- Get a complete picture of the dynamics of the $c\bar{c}$ system.

Excited States

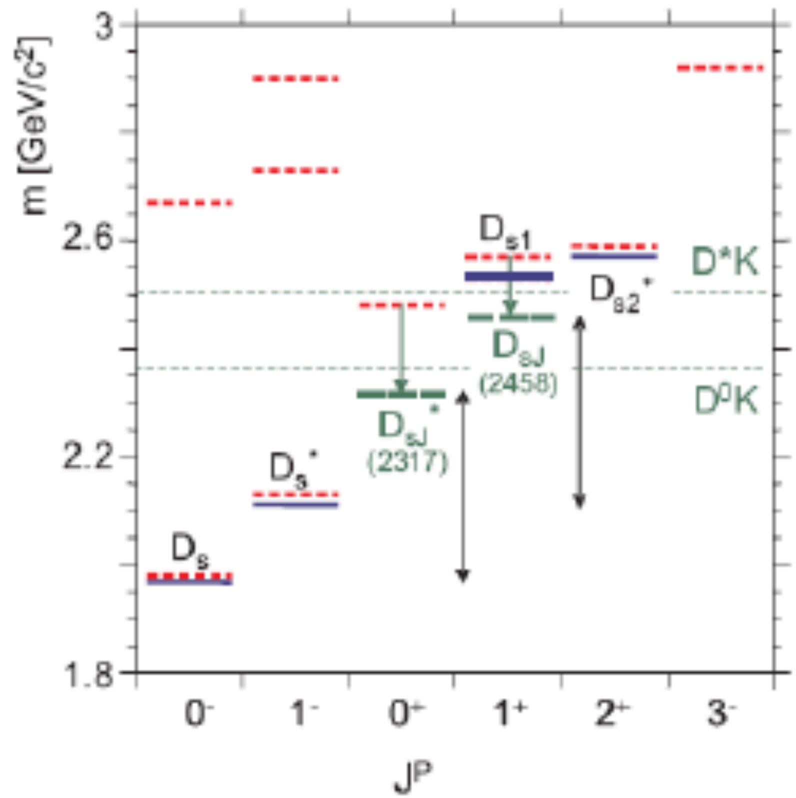
- Spin-exotic quantum numbers J^{PC}
- States overlap strongly in light meson spectrum
- $c\bar{c}$ spectrum less dense populated



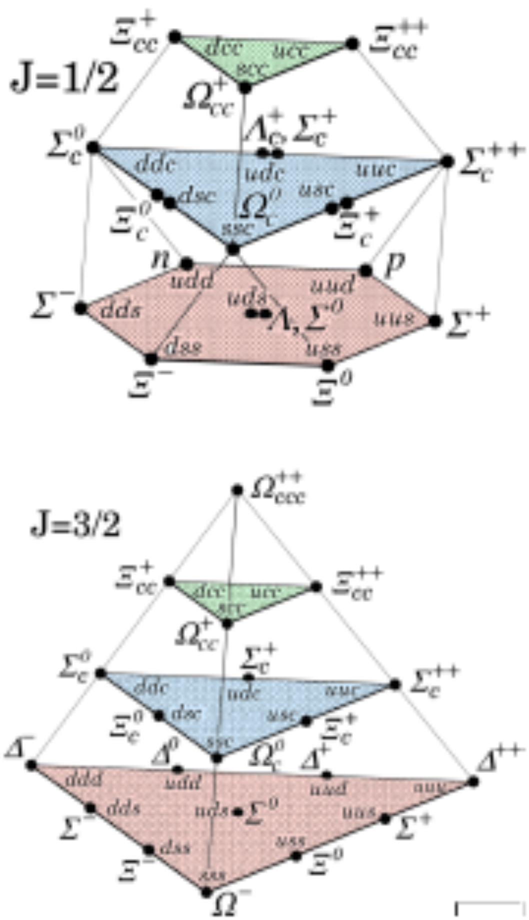
$Q\text{-}\overline{Q}$	Conventional Quarkonium
$Q\text{-}g\text{-}\overline{Q}$	Quarkonium Hybrid
gg, ggg	Glueballs
$(Qq\overline{Q}\overline{q})$	Tetraquark
$(Q\overline{q})\text{–}(q\overline{Q})$	Meson Molecule
$(Qq)\text{–}(\overline{Q}\overline{q})$	Diquark-onium
$q\text{–}(Q\overline{Q})\text{–}\overline{q}$	Hadro-quarkonium

Open Charm

- New narrow states D_{sJ} recently discovered at B factories do not fit theoretical calculations.
- At full luminosity and beam momenta larger than 6.4 GeV/c $\overline{\text{P}}$ANDA will produce large numbers of $D\overline{D}$ pairs.
- Despite small signal/ background ratio $(5 \cdot 10^{-6})$ background situation favourable because of limited phase space for additional hadrons in the same process.



Baryon Spectroscopy



Baryon spectroscopy in $\overline{\text{P}}$ANDA:

- Measurements and models don't agree
- Large cross-section, no extra mesons
- 4π particle acceptance
- Displaced vertex tagging

N and Δ baryons:

- Missing resonances
- Hardly any progress since 2 decades

Charmed baryons:

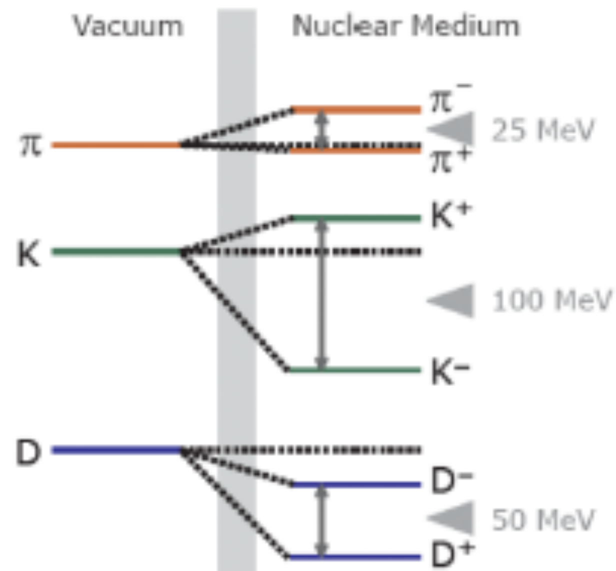
- Narrow widths of resonances
- Rich spectrum of states
- J^{PC} quantum numbers not yet all measured
- Testing ground for HQET

In-Medium Effects

How is mass generated in QCD? Mesons are much heavier than constituent quark mass sum. Spontaneous chiral symmetry breaking would be an explanation. How to verify?

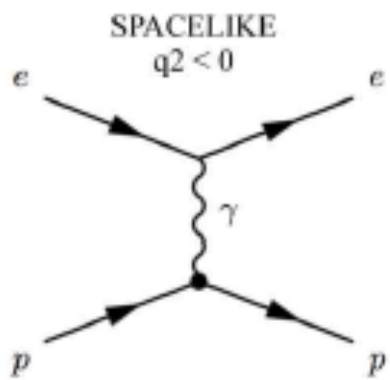
$\rightarrow$ Partial chiral symmetry restoration in nuclear medium

- Mass changes seen for π & K
- significant shifts expected in excited $c\bar{c}$ states, e.g. χ_{cJ}, ψ' and $\psi(3770)$
- D mesons analog to H-atom $\rightarrow$ chiral symmetry studied for single light quark
- Predictions are controversial in size and sign of D mass shifts

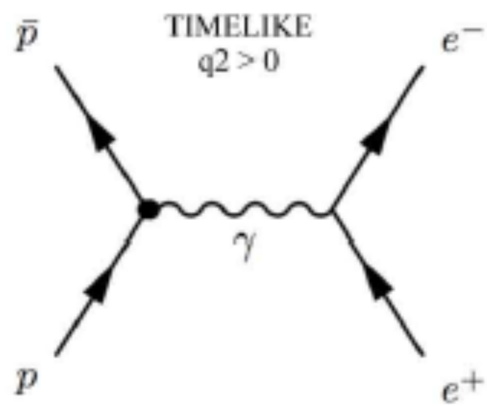


Nucleon Structure / Electromagnetic From Factors

scattering:



annihilation:



- Time-like region interesting
- Both $|G_M|$ & $|G_E/|G_M|$ accessible

- Channel: $p\overline{p} \rightarrow l^+l^-$
- $\overline{\mathrm{P}}$ANDA will contribute with precision to $|G_E/|G_M|$

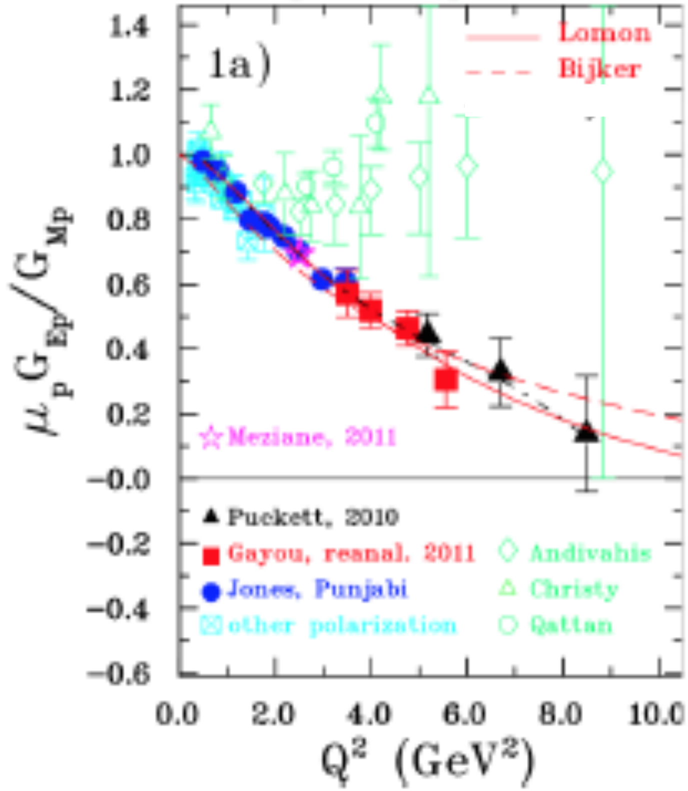
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta C}{4s}(|G_M(s)|^2(1+\cos^2\theta^*) + \frac{4m_N^2}{s}|G_E(s)|^2\sin^2\theta^*)$$

Electromagnetic Form Factors

SPACELIKE ($q^2 < 0$)

many high precision measurements

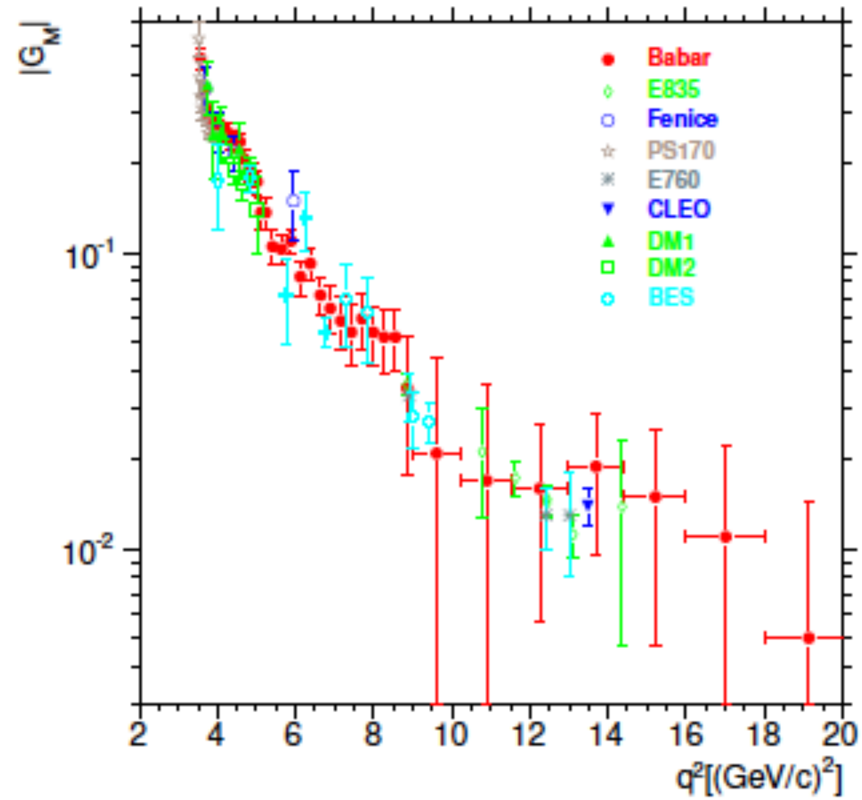
Rosenbluth separation / polarization transfer



TIMELIKE ($q^2 > 0$)

few low precision measurements

cross section (angular distribution)



The Present Nuclear Chart

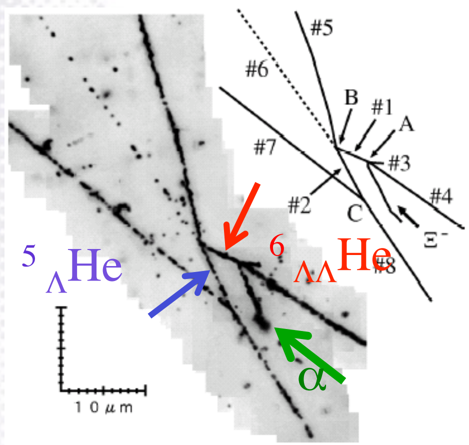
Present limitations

only single Λ-hypernuclei close to valley of stability

only very few ΛΛ-hypernuclei events

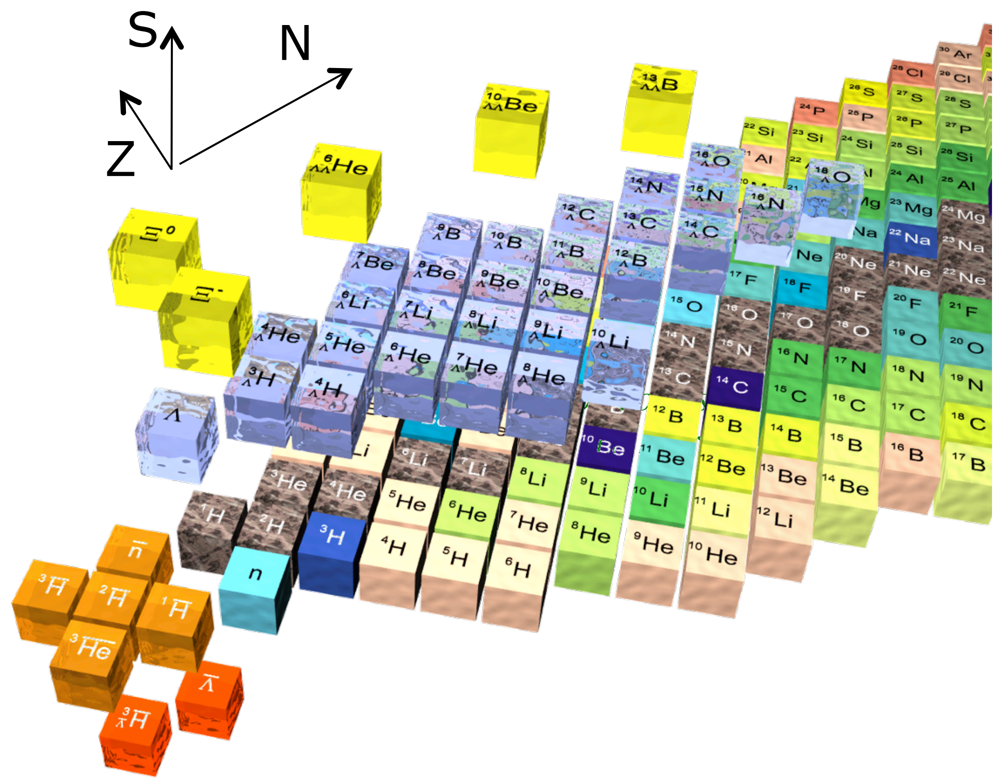
Study of ΛΛ Hypernuclei offers additional information about the Y-Y interaction ($\Delta B_{\Lambda\Lambda} \sim B_{\Lambda\Lambda} - 2\,B_{\Lambda}$)

Nagara event



$^{12}C + \Xi \Rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$

${}^{6}_{\Lambda\Lambda}He \Rightarrow {}^{5}_{\Lambda}He + p + \pi$



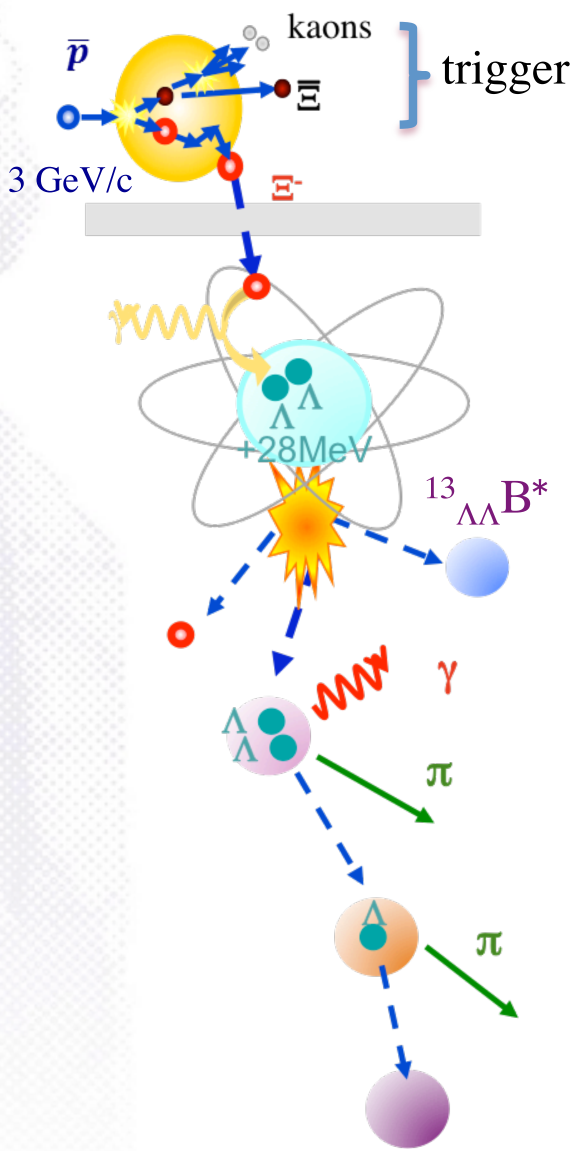
number of baryons N+Z+Y

element = total charge (not number of protons)

$^{B}_{Y}X$

(number of) hyperons Y

Hypernuclear Physics



$\bar{p} + {}^{12}C \rightarrow \Xi^- + \Xi^+ + X$

in a primary target

$\Rightarrow$ Slowing down, capture and conversion of Ξ

($\Xi^- + p \rightarrow \Lambda + \Lambda + 28MeV$)

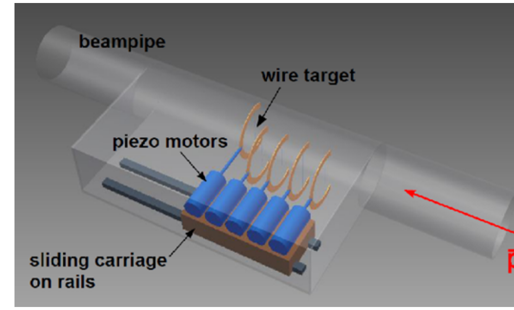
in a secondary active target.

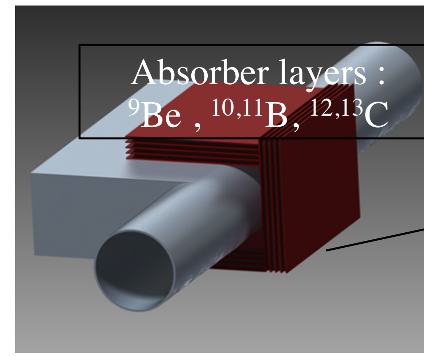
$\Rightarrow$ Statistical decay of slightly excited hypernuclei

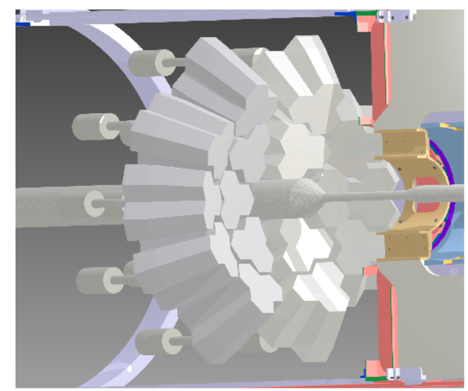
$\Rightarrow$ Electromagnetic transition to g.s

$\Rightarrow$Sequential mesonic decay

Need of a devoted detector setup



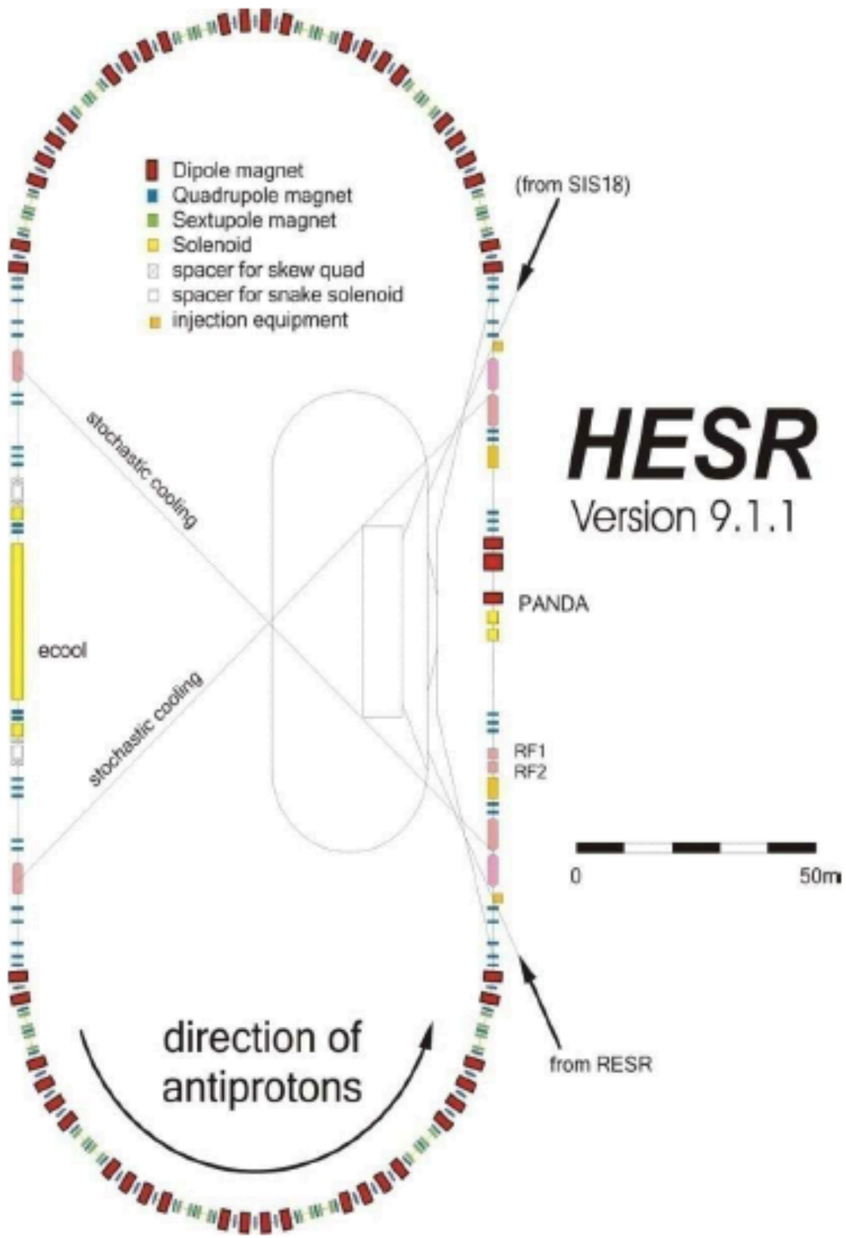




Facility for Antiprotons and Ion Research

* The discussion about the RESR construction is ongoing

High Energy Storage Ring (HESR)

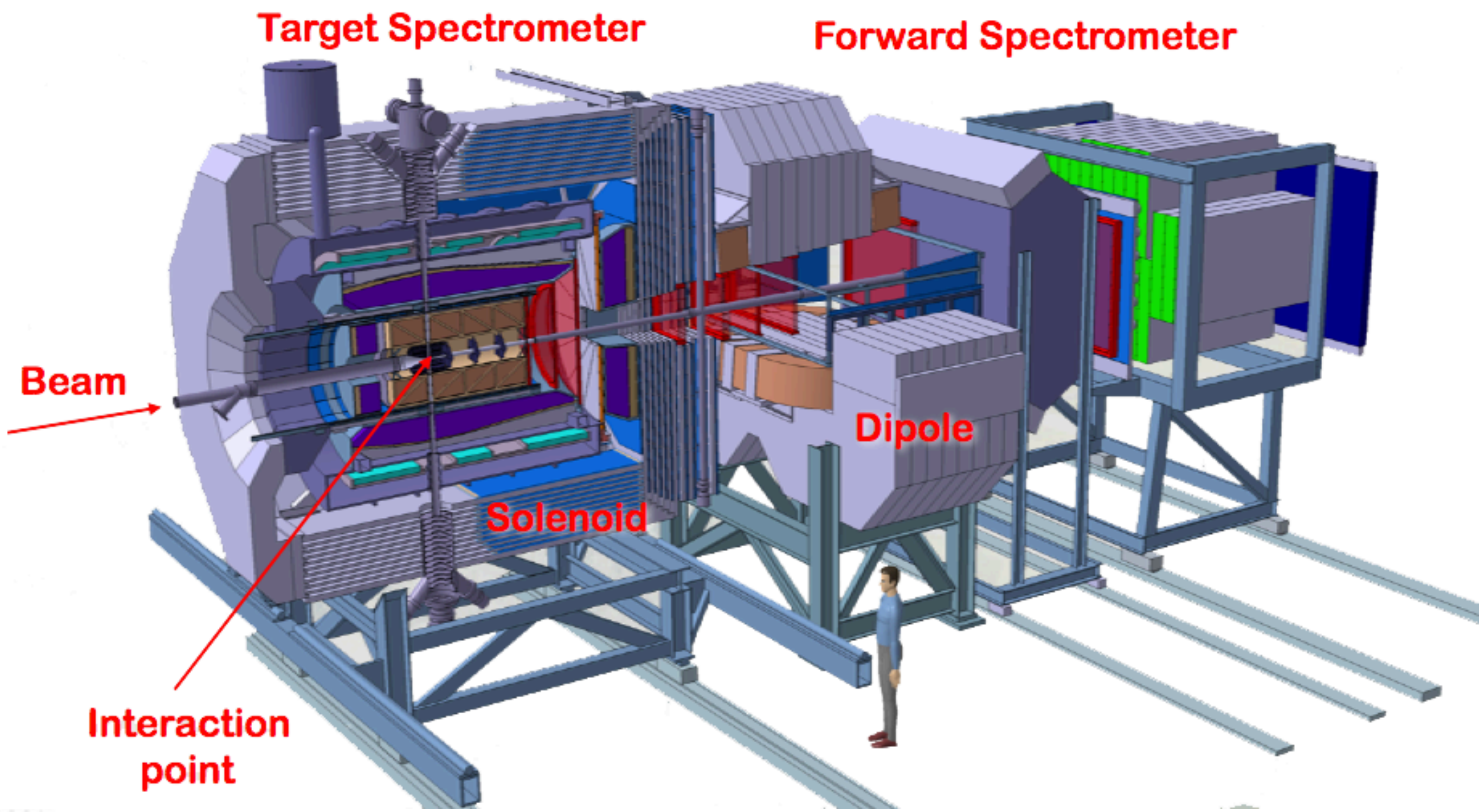


- $\bar{p}$ beam momentum: 1.5 – 15 GeV/c
- Internal Target
- Antiproton production rate : 2 10^7 /sec
- N_{stored} = up to 10^{11} p

- High resolution mode
  - e^- cooling $1.5 \leq p \leq 8.9$ GeV/c
  - 10^{10} antiprotons stored
  - Luminosity up to $2 \cdot 10^{31}$ $cm^{-2}s^{-1}$
  - $\Delta p/p \leq 4 \cdot 10^{-5}$

- High luminosity mode
  - Stochastic cooling $p \geq 3.8$ GeV/c
  - 10^{11} antiprotons stored
  - Luminosity up to $2 \cdot 10^{32}$ $cm^{-2}s^{-1}$
  - $\Delta p/p \leq 2 \cdot 10^{-4}$

The PANDA Spectrometer



- 4π coverage
- good PID
- high rates and momentum res.
- vertexing for D, Λ and K^0_s
- efficient trigger (no hardware trigger)
- modular design

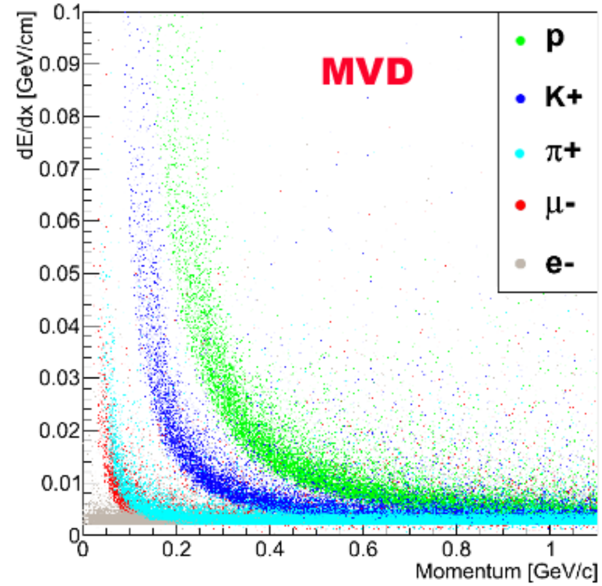
QCD bound states
Non-perturb. QCD
Hadrons in nuc. matter
Electro. Processes
Electroweak physics
Hypernuclear Physics

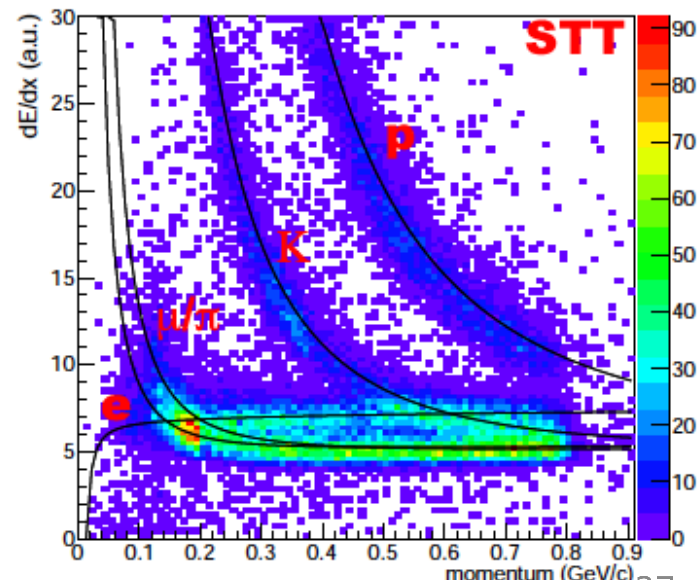
The $\bar{\text{P}}$ANDA Detector : PID

PID Requirements and Capabilities

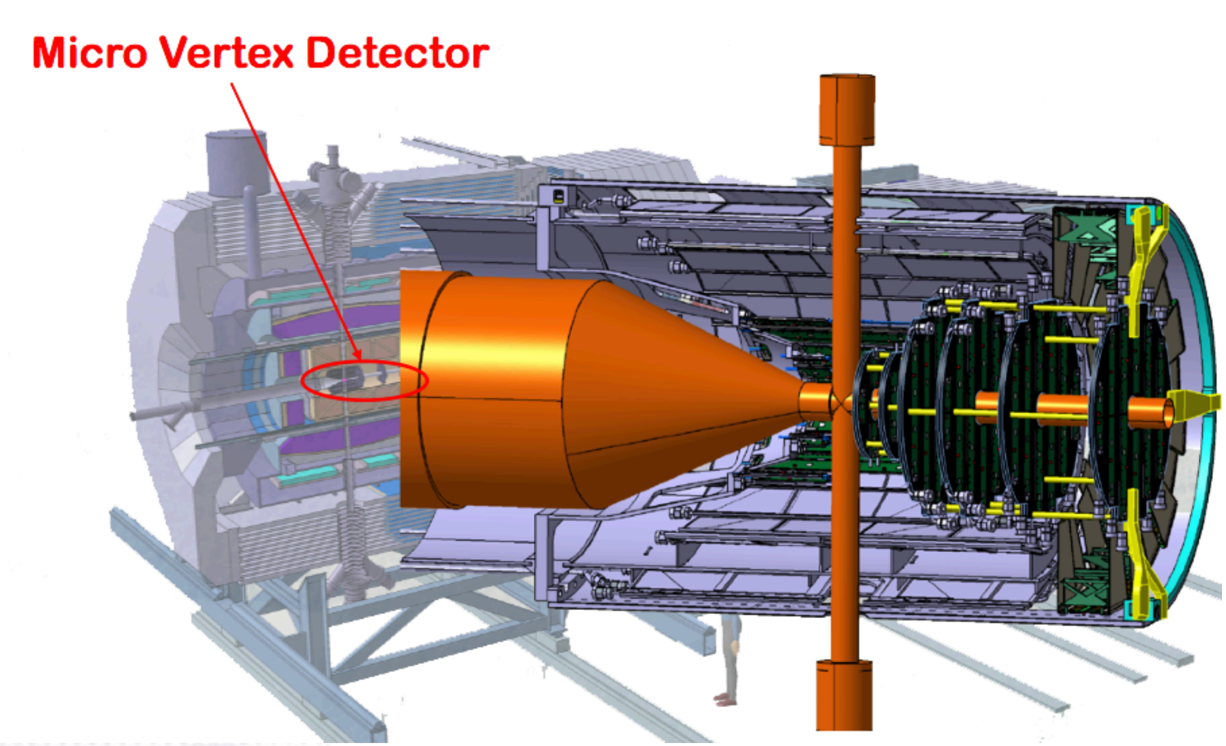
- separate charged π, *K, p, e,*
- momentum range: 200 MeV/c - 10 GeV/c

- **π, K, p below 1 GeV**: energy loss (Micro Vertex Detector, Trackers)
- **π, K, p above 1 GeV**: Cherenkov (barrel DIRC, disc DIRC, RICH)
- **π, K, p up to 4 GeV**: Time of Flight (TOF detectors)
- **e and γ** : electromagnetic showers (EMC); (: few MeV to 10 GeV)
- **μ:** showers (Muon detectors)





The $\bar{P}$ANDA Detector

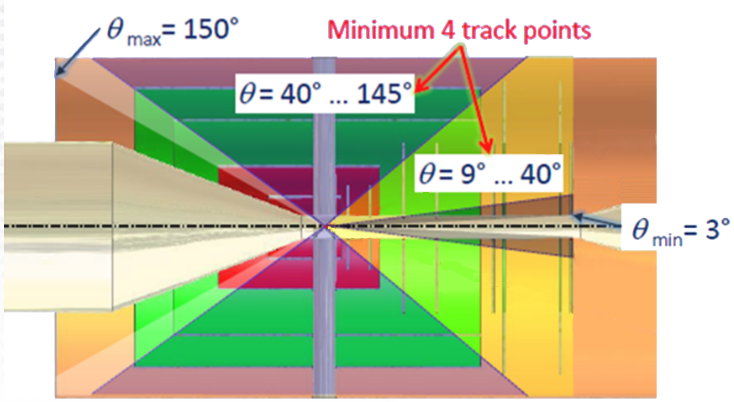


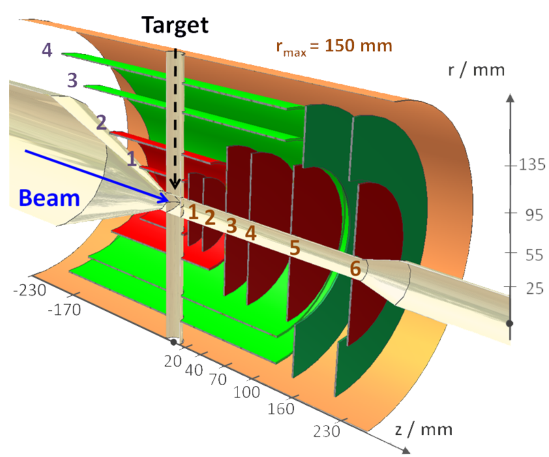
Technical Design Report:
`panda-wiki.gsi.de/Mvd/MvdPublic`

- 4 barrels and 6 disks
- Hybrid Pixels:
  - $100 \times 100 \mu m^2$
  - Thinned sensor wafers
- Strip sensors
  - Double sided
  - Rectangles and trapezoids
- Custom Readout: ToPix & PASTA

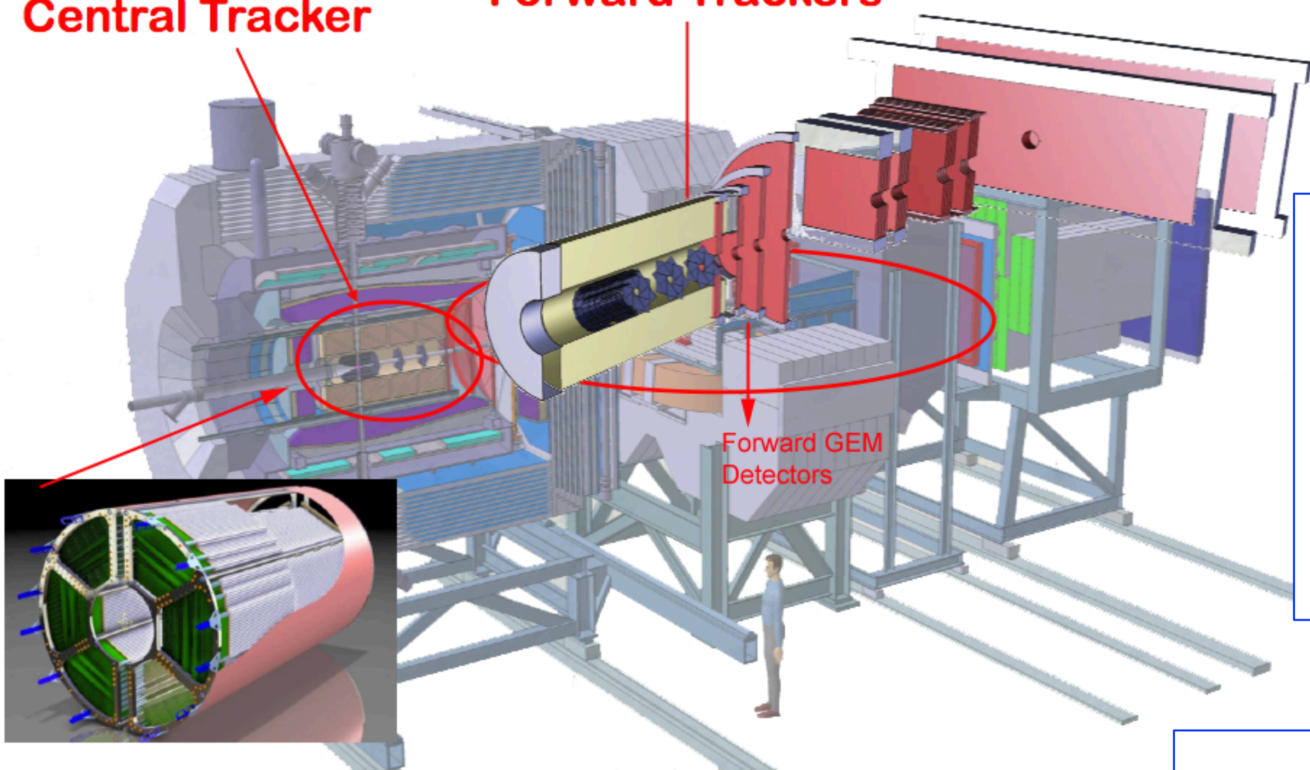
Challenges:

- Low material budget
- Radiation hardness





The $\bar{\text{P}}$ANDA Detector



Forward Tracker

- Cover 0° < Θ< 5° -- 10°
- 3 stations of 2 chambers before, inside and behind dipole
- Double layer straw tube design
- Tubes ⦸1cm, 27µm thin Al-mylar, Stability by 1 bar overpressure
- 3 projections per chamber: 0°, +5°, -5°

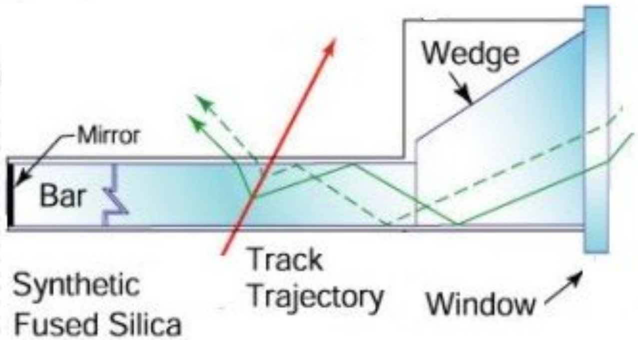
Straw Tube Tracker

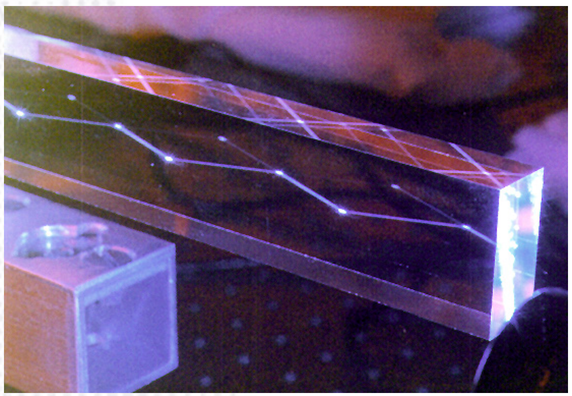
- 4600 straws in 21-27 layers
  8 layers skewed at ~3°
- Tubes ⦸1cm , 27 µm thin Al-mylar
- R = 150mm --420mm , l = 1.5m
- Self-supporting double-layers
  ~1bar overpressure Ar/CO2
- Readout with ASIC, TDC,FADC

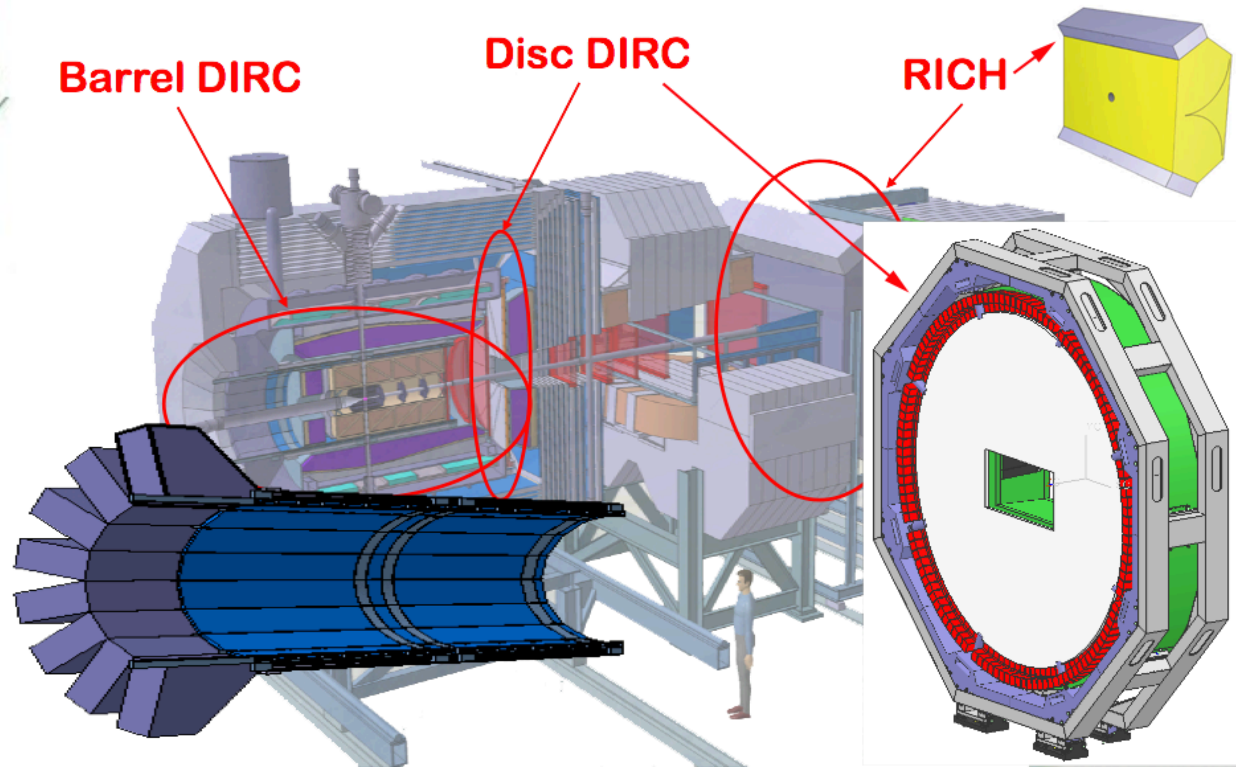
Gas Electron Multiplier (GEM)

- 3-4 stations with 4 projections each: radial, concentric, x, y
- Large area GEM foils (CERN)
  (50m Kapton, 2 – 5 µm copper coating)
- ADC readout for cluster centeroids
  (~ 35000 channels)
- Challenge: Minimize Material

The $\bar{\text{P}}$ANDA Detector



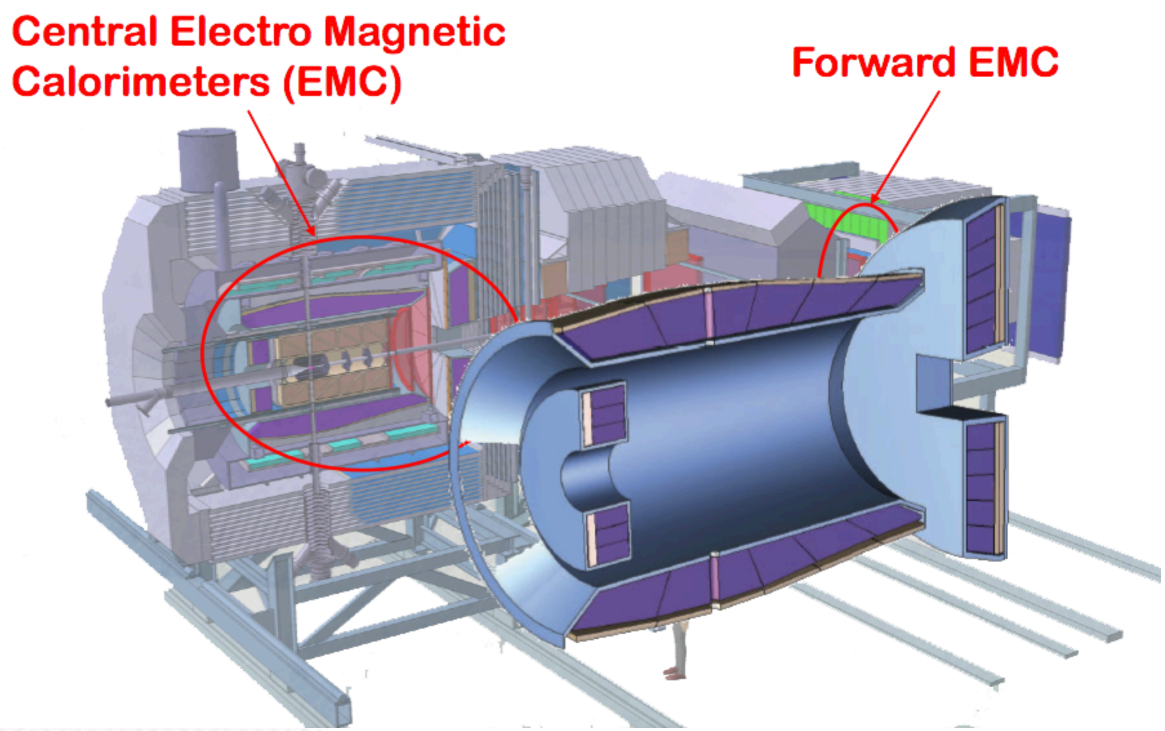




DIRC – Detection of Internally Reflected Cherenkov light

- SiO2 Radiator with n = 1.47
- Readout at bar ends & disc rims
- Complex patterns
  →Sophisticated reconstruction algorithms

The $\bar{\text{P}}$ANDA Detector



Barrel Calorimeter

- 1000 PWO Crystals
- LAAPD readout, 2 x 1 cm^2
- $\sigma(E)/E[\%] \sim 1.5\ E^{1/2} + const$

Forward Endcap

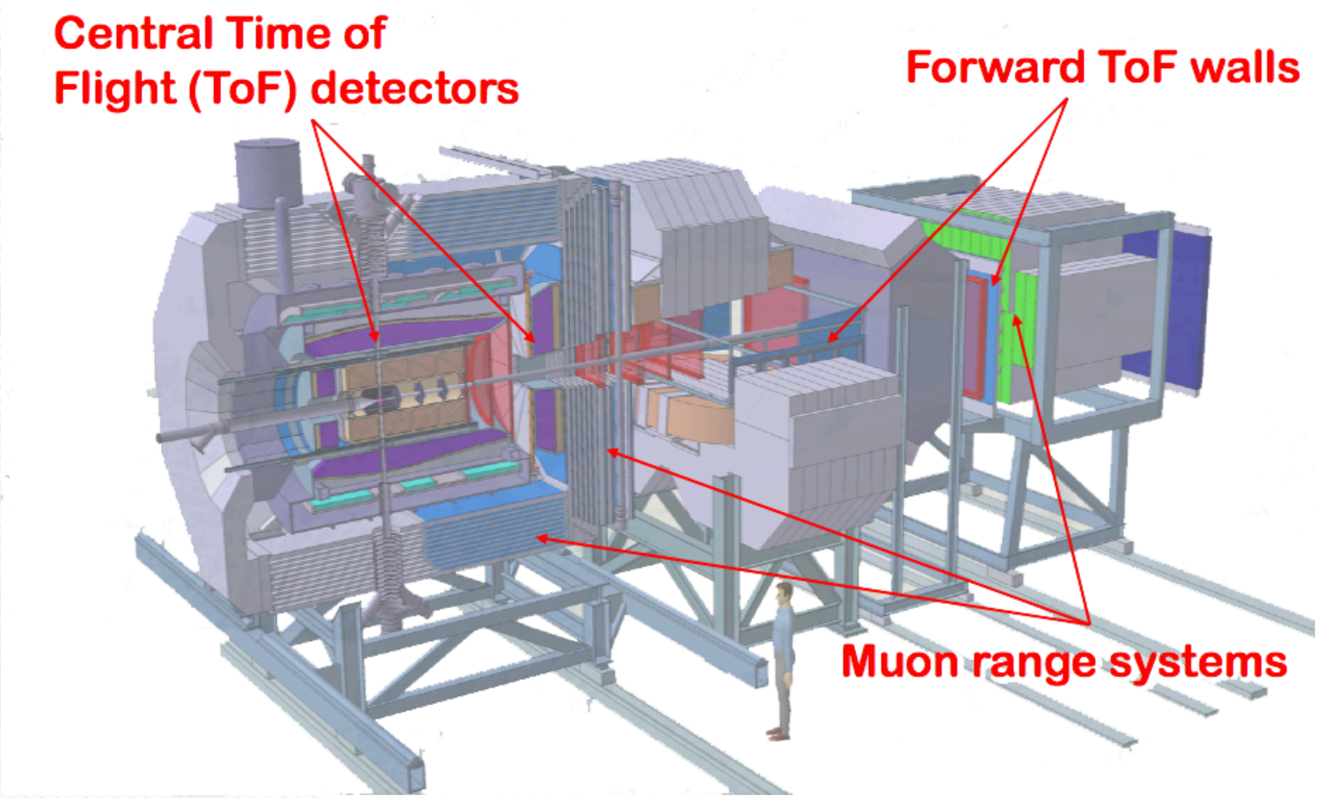
- 4000 PWO crystals
- High occupancy in center
- LA APD or VPT

Backward Endcap

- for hermeticity
- 560 PWO crystals

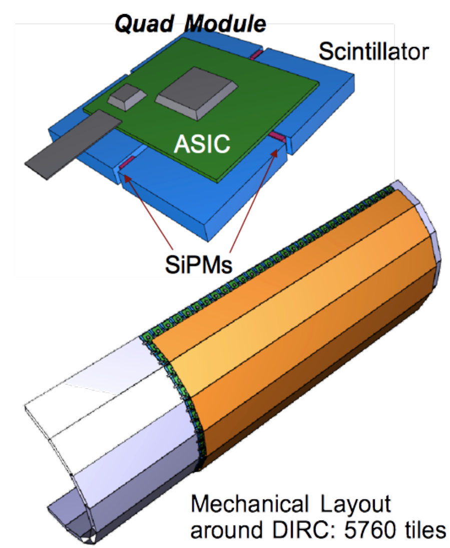
Forward EMC shashlyk behind dipole

The $\bar{P}$ANDA Detector



TOF Barrel

- Scintillator tiles 3x3x0.5 cm ^{3}
- Time resolution goal: 100 ps

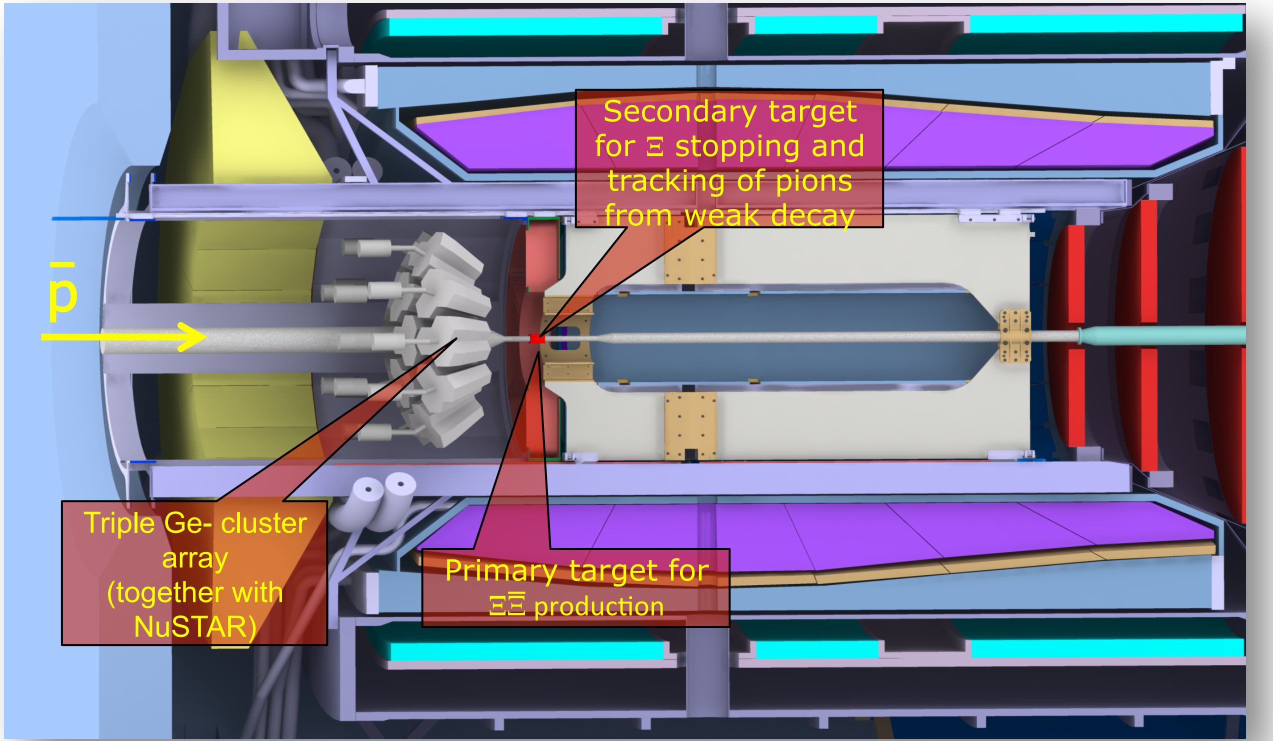


Muon detectors

- Drift tubes with wire & cathode strip readout
- Barrel: 12+2 layers in yoke
- Endcap: 5+2 layers
- Muon Filter: 4 layers
- Forward: 16+2 layers

Hypernuclear Detector Setup

- **Integration in the PANDA spectrometer**
  - Space constraints
  - High magnetic field
  - Large hadronic background



- **Physics Performance**
  - **The primary target** :

production of slow momentum Ξ^-

  - **The Secondary Active target** :

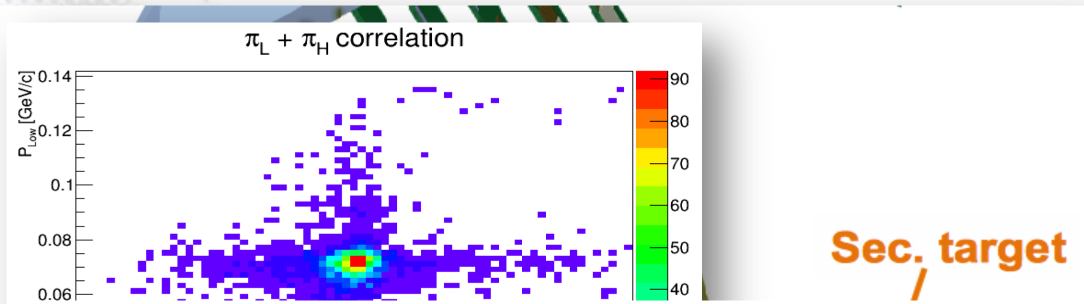
Stopping of Ξ^- , and detection of charged decay products (monoenergetic π^-)

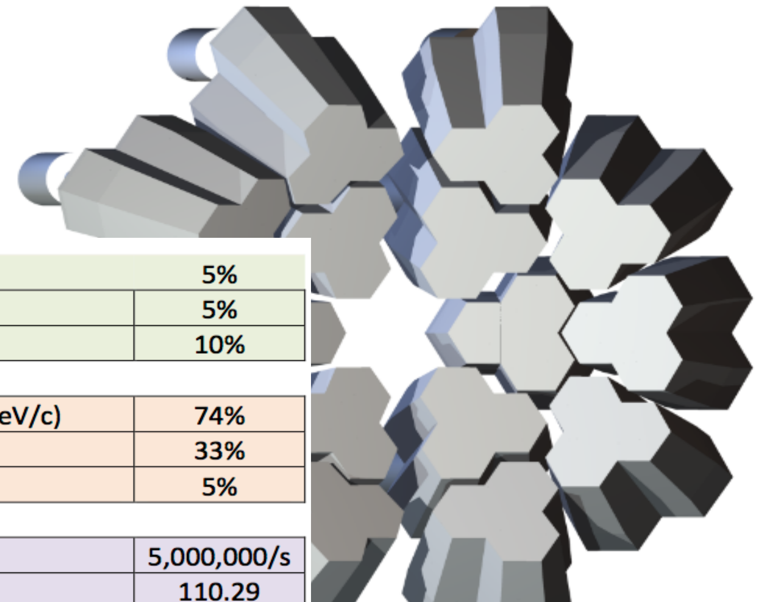
  - **The HPGe Array** : high precision γ detection

Status and expected count rate

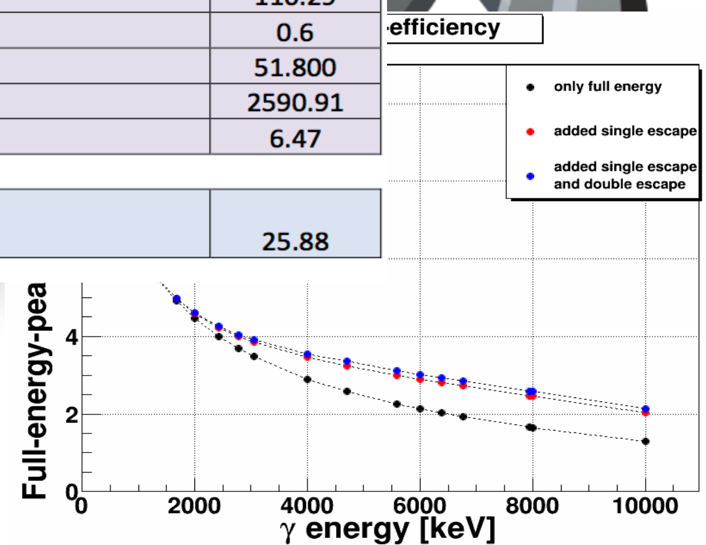
- Primary and Secondar active target

HPGe Cluster Array





Process :	Capture and conversion for Xi	5%
	Main channels (which hypernucleus is produced)	5%
	weak decay probability	10%
Detection:	Pion tracking efficiency for pion mom (higher than 100MeV/c)	74%
	Double Pion tracking efficiency	33%
	Gamma Efficiency	5%
Counting rates:	Counting rate at PANDA	5,000,000/s
	Xi-Production per second	110.29
	Stopped Xis per second	0.6
	Stopped Xis per day	51.800
	Double hypernuclei (DHP) production per day	2590.91
	Detected DHP per month	6.47
Measurement period (4 months)	detected single gamma transitions (11LLBe)	25.88



Summary and Outlook

- The HESR at the GSI FAIR facility will deliver $\bar{p}$ beams of unprecedented quality with momenta up to 15 GeV/c. This allow $\overline{\text{P}}$ANDA to carry out the following measurements:

  - QCD bound states: charmonium, exotic excitations, heavy-light systems, strange and charmed baryons
  - Non perturbative QCD dynamics
  - Hadrons in the nuclear medium
  - Hypernuclear physics
  - Nucleon structure: generalized distribution amplitudes, Drell-Yan, electromagnetic form factors.

- The performance of the detector and the sensitivity to the various physics channels have been estimated reliably by means of detailed Monte Carlo simulations: acceptance, resolution, signal/background

THANKS FOR YOUR ATTENTION