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

Ralf Kliemt

Helmholtz-Institut Maiz, GSI Darmstadt

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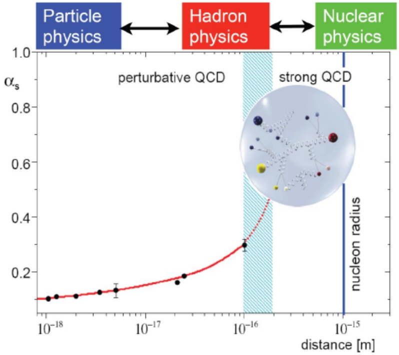
Outline

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 Non-Perturbative 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? $\longrightarrow$ 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?

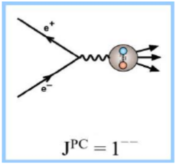
Why Antiprotons?

e^+e^- Reaction

- 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...)

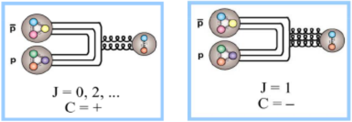
$p\bar{p}$ Annihilation

- Direct Formation of hadronic states
- Precision limited by beam parameters but high hadronic background
- All non-exotic J^{PC} available
- (→ LEAR, Fermilab E760/E835, $\overline{\text{P}}$ANDA)



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

Formation:



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

Beam Scan – Experimental Method

Breit-Wigner resonance cross section:

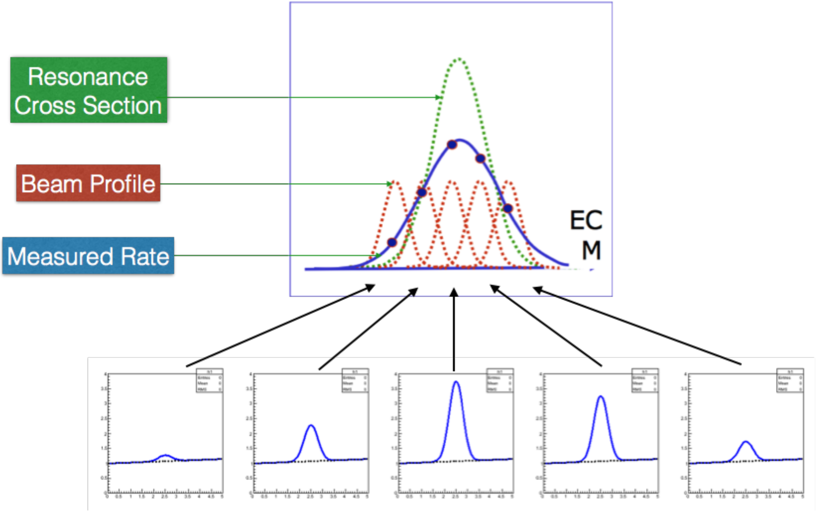
$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

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

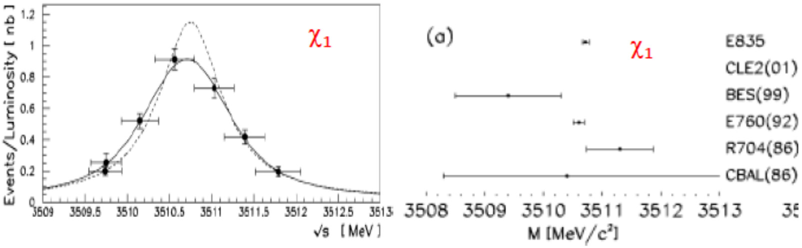
$$\nu \sim \mathcal{L}\left\{\epsilon \int f(E,\Delta E)\sigma_{BW}(E)dE + \sigma_b\right\}$$

→ 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.

Beam Scan – Experimental Method



Example: χ_1 scan at Fermilab E835



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

FAIR/PANDA/Physics Book i

Physics Performance Report for:

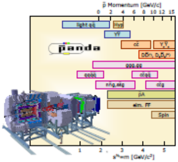
$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

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

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.



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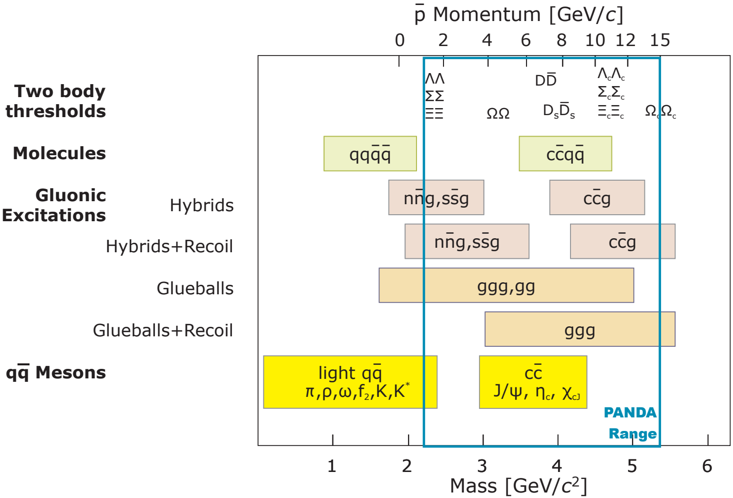
Hadron Spectroscopy:
- Charmonium
- Gluonic Excitations
- Open Charm
- Strange and Charmed Baryons

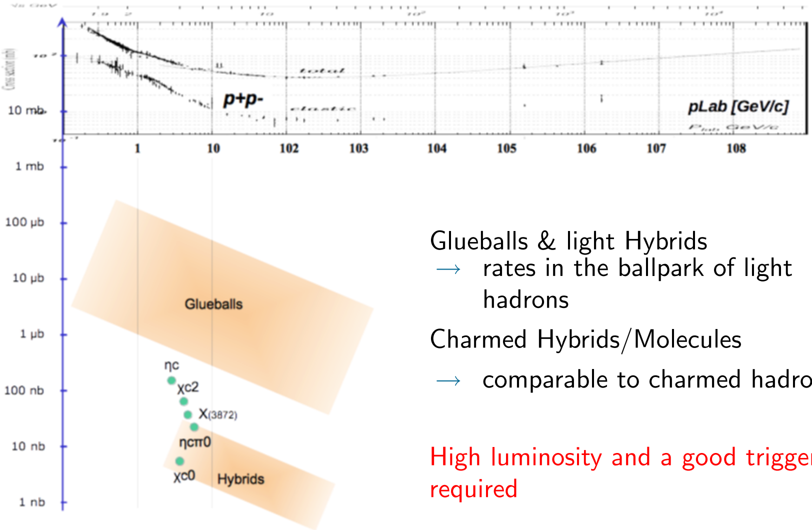
Nucleon Structure:
- Generalized Distribution Amplitudes (GDA)
- Drell-Yan
- Electromagnetic Formfactors

Hypernuclear Physics
Hadrons in Nuclear Medium

Energy Range



Expected Cross Sections

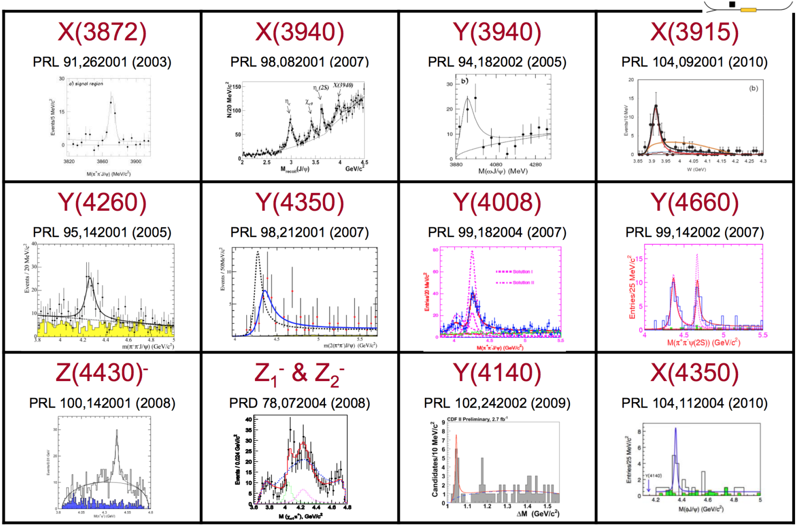


Glueballs & light Hybrids
→ rates in the ballpark of light hadrons

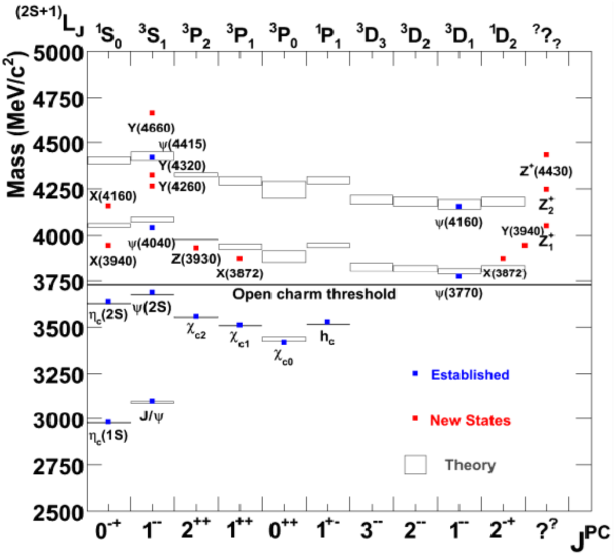
Charmed Hybrids/Molecules
→ comparable to charmed hadrons

High luminosity and a good trigger required

Charmonium


X(3872)
PRL 91,262001 (2003)
X(3940)
PRL 98,082001 (2007)
Y(3940)
PRL 94,182002 (2005)
X(3915)
PRL 104,092001 (2010)
Y(4260)
PRL 95,142001 (2005)
Y(4350)
PRL 98,212001 (2007)
Y(4008)
PRL 99,182004 (2007)
Y(4660)
PRL 99,142002 (2007)
Z(4430)-
PRL 100,142001 (2008)
Z1- & Z2-
PRD 78,072004 (2008)
Y(4140)
PRL 102,242002 (2009)
X(4350)
PRL 104,112004 (2010)

Charmonium



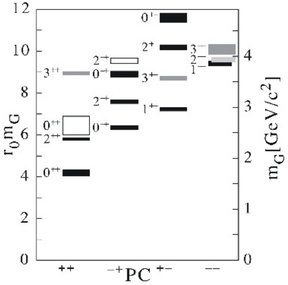
(2S+1)LJ
1S0 3S1 3P2 3P1 3P0 1P1 3D3 3D2 3D1 1D2 ??
Mass (MeV/c2)
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
Y(4660)
ψ(4415)
Y(4320)
Y(4260)
X(4160)
Z+(4430)
Z2+
ψ(4160)
Y(3940)
Z1+
ψ(4040)
X(3940)
Z(3930)
X(3872)
X(3872)
Open charm threshold
ψ(3770)
ηc(2S)
ψ(2S)
χc2
χc1
χc0
hc
Established
J/ψ
ηc(1S)
New States
Theory
0-+ 1-- 2++ 1++ 0++ 1+- 3-- 2-- 1-- 2-+ ??
JPC

Charmonium at $\overline{\rm P}$ANDA

- At $2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ accumulate $8\mathrm{pb}^{-1}/\mathrm{day}$ (assuming 50% overall efficiency). It means 10^4-10^7 $(\mathrm{c\bar{c}})$ states/day.
- Total integrated luminosity $1.5\mathrm{fb}^{-1}/\mathrm{year}$ (at $2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, assuming 6 months/year data taking).
- Fine scans to measure masses to $\sim 100\mathrm{keV}$ 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 $\mathrm{c\bar{c}}$ system.

Exotic States

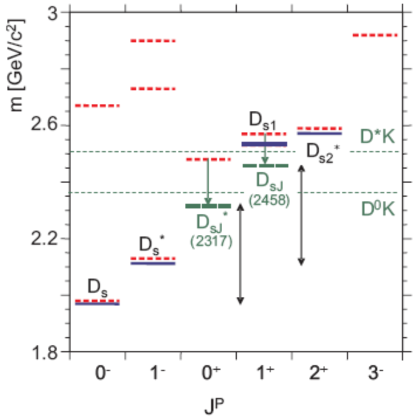
- Spin-exotic quantum numbers J^{PC}
- States overlap strongly in light meson spectrum
- $c\bar{c}$ spectrum less dense populated



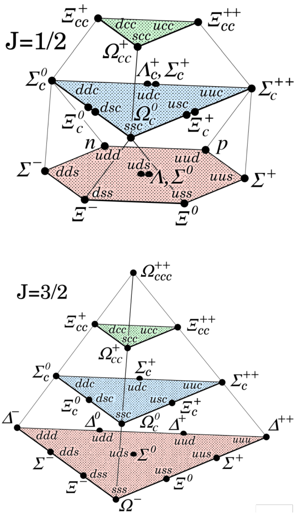
$Q\text{-}\overline{Q}$	Conventional Quarkonium
$Q\text{-}g\text{-}\overline{Q}$	Quarkonium Hybrid
$gg,\ ggg$	Glueballs
$(Qq\overline{Q}\overline{q})$	Tetraquark
$(Q\overline{q})\text{–}(q\overline{Q})$	Meson Molecule
$(Qq)\text{–}(\overline{Q}\overline{q})$	Diquark-onium
$q\text{–}(Q\overline{Q})\text{–}\overline{q}$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

Open Charm

- New narrow states $\mathrm{D_{sJ}}$ 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 $\mathrm{D\overline{D}}$ 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:

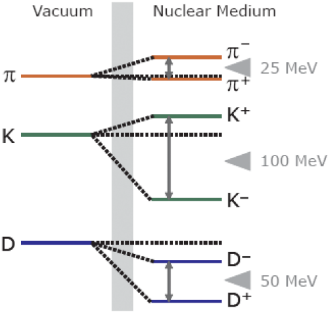
- Narrow widths of resonances
- Rich spectrum of states
- J^{PC} quantum numbers not yet all measured
- Testing ground for HQET

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?

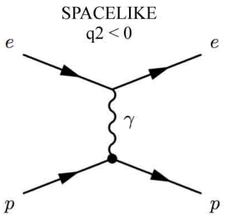
$\rightarrow$ Partial chiral symmetry restoration in nuclear medium

- 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

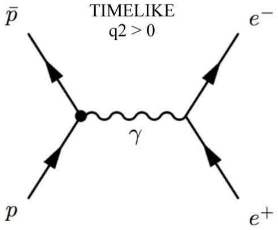


Nucleon Structure / Electromagnetic Form Factors

scattering:



annihilation:



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

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

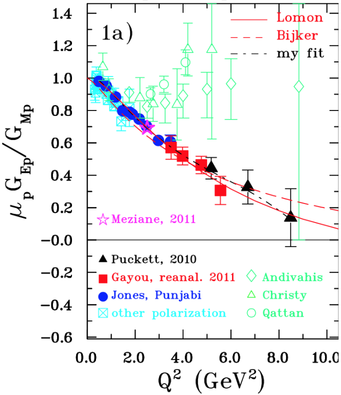
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta C}{4s}(|G_M(s)|^2(1+\cos^2\theta^*) + \frac{4m_N^2}{s}|G_E(s)|^2\sin^2\theta^*)$$

Electromagnetic Form Factors

SPACELIKE ($q^2 < 0$)

many high precision measurements

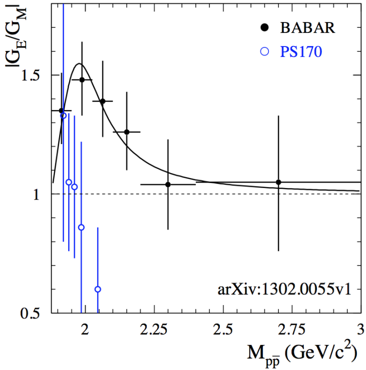
Rosenbluth separation / polarization transfer



TIMELIKE ($q^2 > 0$)

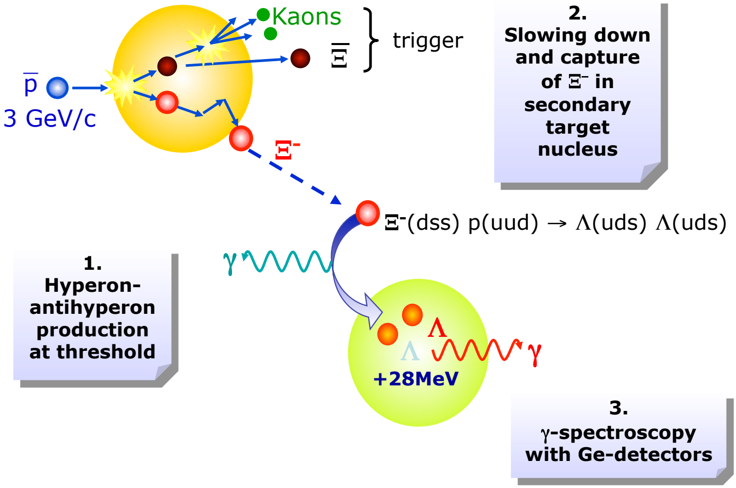
few low precision measurements

cross section (angular distribution)



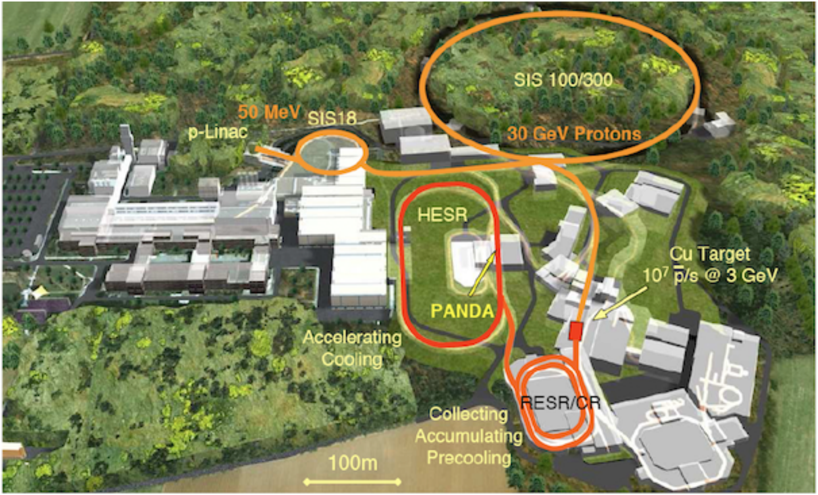
Hypernuclear Physics

Replacing nucleons in an atom with hyperons.
$\rightarrow$ New nuclear degree of freedom strangeness



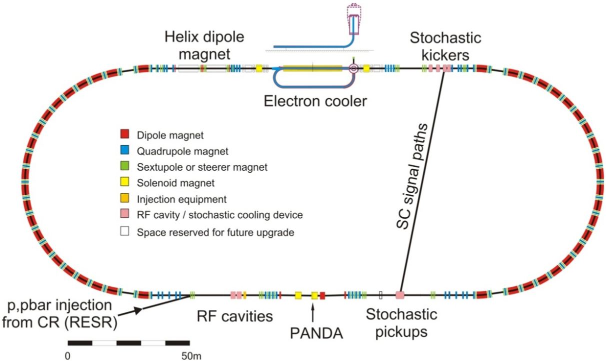
FAIR

(Aug. 2014)



* The discussion about the RESR construction is ongoing

Antiprotons



High Resolution Mode

$N_{\text{stored}} = 10^{10}\ \overline{\text{p}}$
$\rightarrow L = 10^{31}\text{cm}^{-2}\text{s}^{-1}$
Beam momentum resolution:
$\Delta p/p \sim 10^{-5}$ (electron cooling)

High Luminosity Mode

$N_{\text{stored}} = 10^{11}\ \overline{\text{p}}$
$\rightarrow L = 2 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$
Beam momentum resolution:
$\Delta p/p \sim 10^{-4}$ (stochastic cooling)

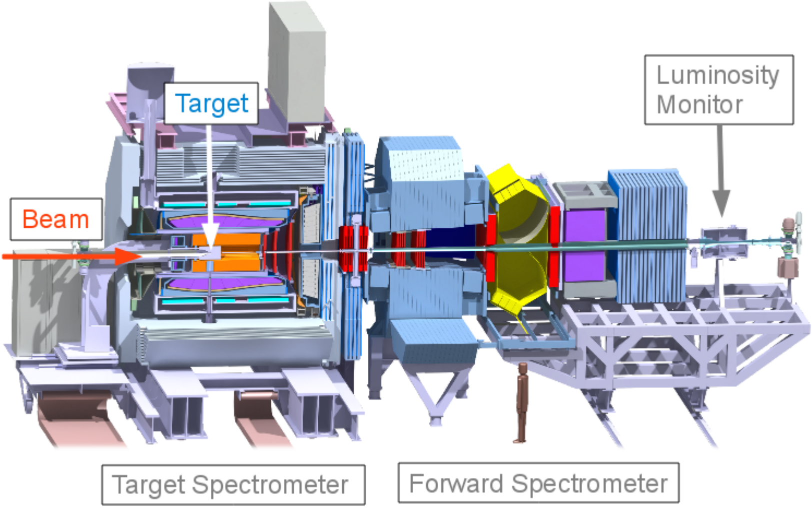
$\overline{\text{p}}$ momentum: $1.5 - 15$ GeV/c

Antiproton Experiments

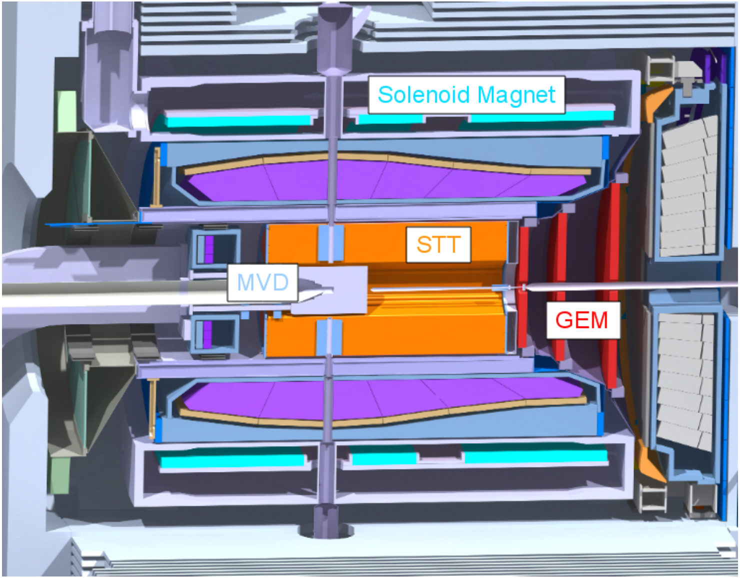
Experiment	Years	Intensity ($\overline{p}$/s)	Momentum [GeV/c]	Resolution $\Delta p/p$
LEAR (CERN)	1983–1996	$2 \cdot 10^6$	0.06–1.94	10^{-3}
FermiLab (45% polarized)	1985–2011	$2 \cdot 10^6$ 10^4	< 8.9	10^{-4}
$\overline{\text{P}}$ANDA	2018–...	$2 \cdot 10^7$	1.5–15	10^{-5}

$\overline{\text{P}}$ANDA the successor of those experiments with better features.

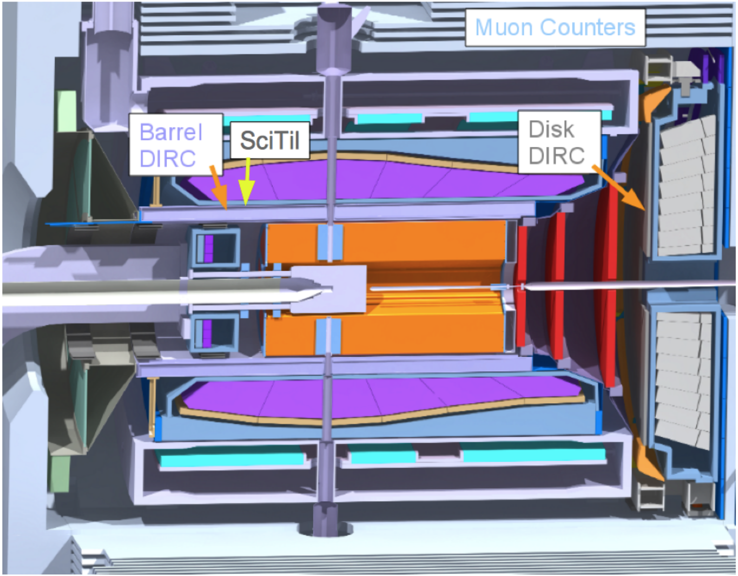
Detector Overview



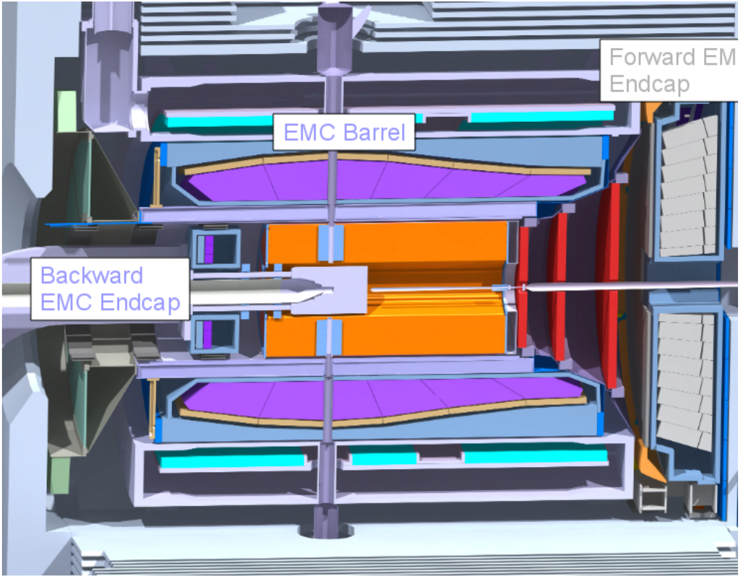
Tracking



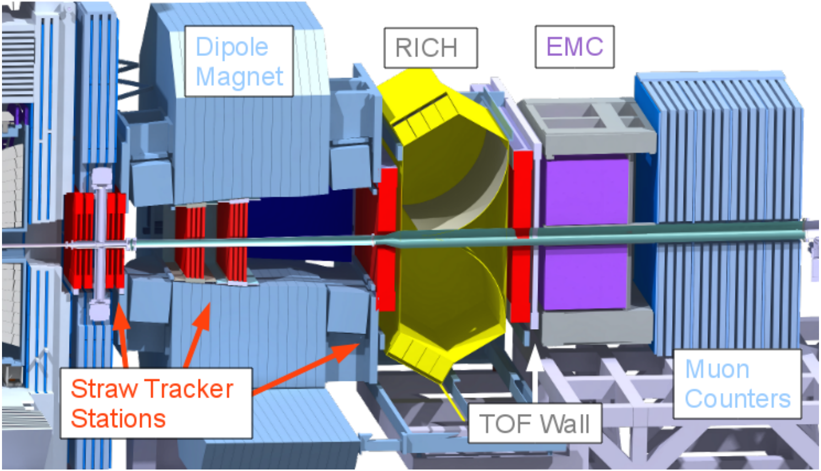
PID Detectors



Electromagnetic Calorimetry



Forward Spectrometer



Target

Luminosity Considerations

- Goal: $2 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$
- With 10^{11} stored $\overline{p}$ and 50 mb: $4 \cdot 10^{15}\text{cm}^{-2}$ target density

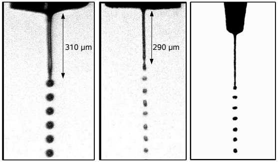
Cluster Jet Target

- Continuos development
- Nozzle improvement
- Better alignment by tilt device
- $\sim 2 \cdot 10^{15}\text{cm}^{-2}$ achieved

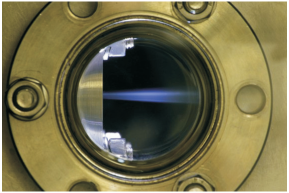
Pellet Target

- $> 4 \cdot 10^{15}\text{cm}^{-2}$ feasible
- Prototype underway
- Pellet tracking (prototype)

Hydrogen Droplets:



Hydrogen Cluster Jet:



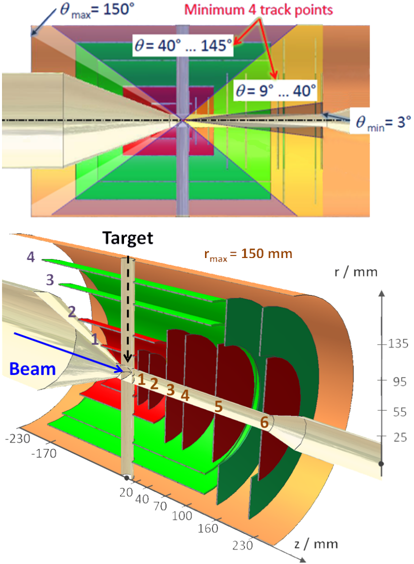
Micro Vertex Detector

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

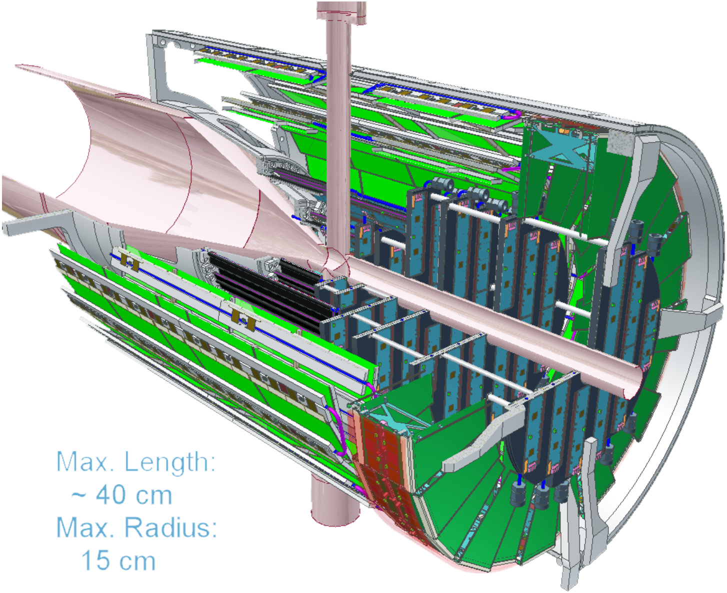
- 4 barrels and 6 disks
- Hybrid Pixels:
  - $100 \times 100 \mu\text{m}^2$
  - Thinned sensor wafers
- Strip sensors
  - Double sided
  - Rectangles and trapezoids
- Custom Readout: ToPix & PASTA

Challenges:

- Low material budget
- Radiation hardness



Micro Vertex Detector



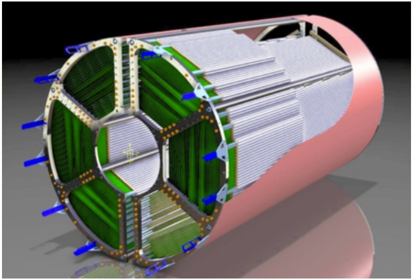
Straw Tube Tracker

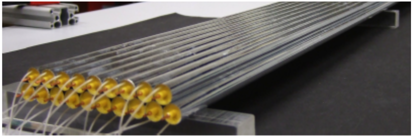
Detector Layout

- 4600 straws in 21-27 layers
  8 layers skewed at $\sim 3°$
- Tubes $\varnothing 1\text{cm}$, $27\mu\text{m}$ thin Al-mylar
- $R = 150\text{mm}–420\text{mm}$, $l = 1.5\text{m}$
- Self-supporting double-layers
  $\sim 1\text{bar}$ overpressure Ar/CO_2
- Readout with ASIC, TDC, FADC

Material Budget

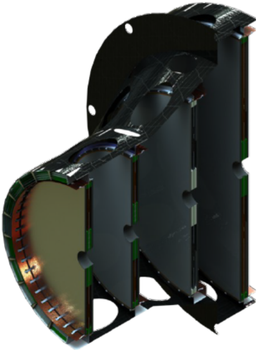
- $0.05\%\ \text{X}/\text{X}_0$ per layer
- Total $1.3\%\ \text{X}/\text{X}_0$

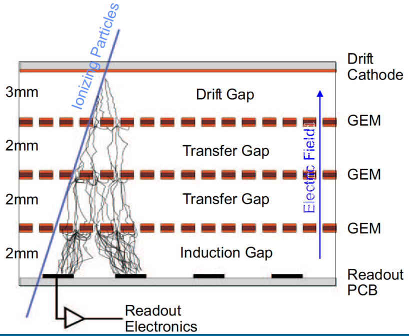


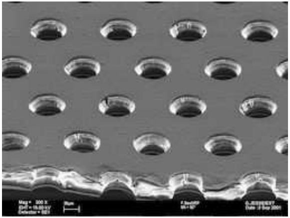


Gas Electron Multiplier (GEM) Tracker

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

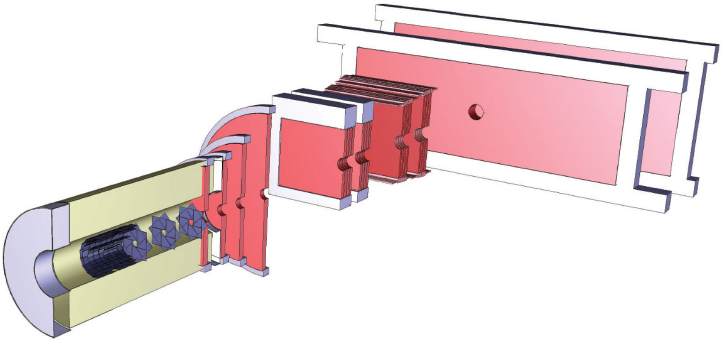




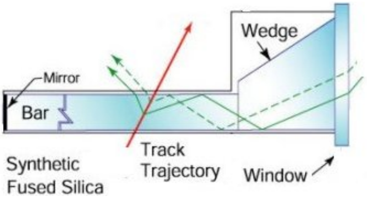


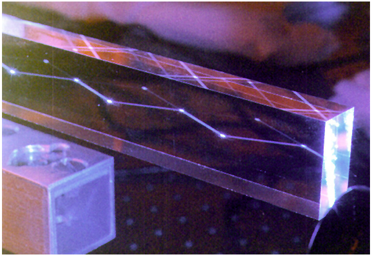
Forward Tracker

- Cover $0^\circ < \Theta < 5^\circ - 10^\circ$
- 3 stations of 2 chambers before, inside and behind dipole
- Double layer straw tube design
- Tubes $\varnothing 1\text{cm}$, $27\mu\text{m}$ thin Al-mylar, Stability by 1 bar overpressure
- 3 projections per chamber: 0°, $+5^\circ$, -5°

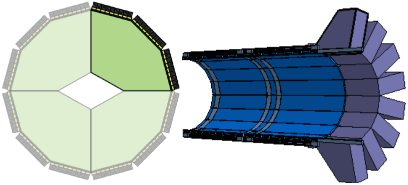


DIRC – Detection of Internally Reflected Cherenkov light





- SiO_2 Radiator with $n = 1.47$
- Readout at bar ends & disc rims
- Complex patterns
  $\rightarrow$ Sophisticated reconstruction algorithms



EMC

Barrel Calorimeter

- 11000 PWO Crystals
- LAAPD readout, $2 \times 1\text{cm}^2$
- $\sigma(E)/E[\%] \sim 1.5\sqrt{E} + \text{const}$

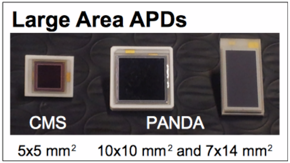
Forward Endcap

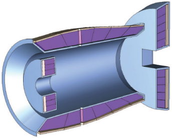
- 4000 PWO crystals
- High occupancy in center
- LA APD or VPT

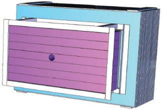
Backward Endcap

- for hermeticity
- 560 PWO crystals

Forward EMC shashlyk behind dipole

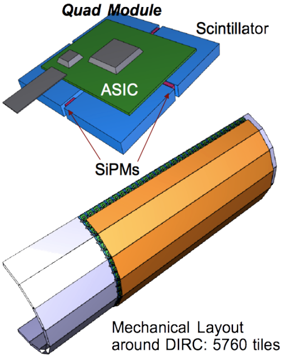


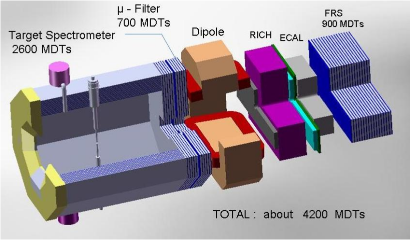




Time of Flight & Muon Detection

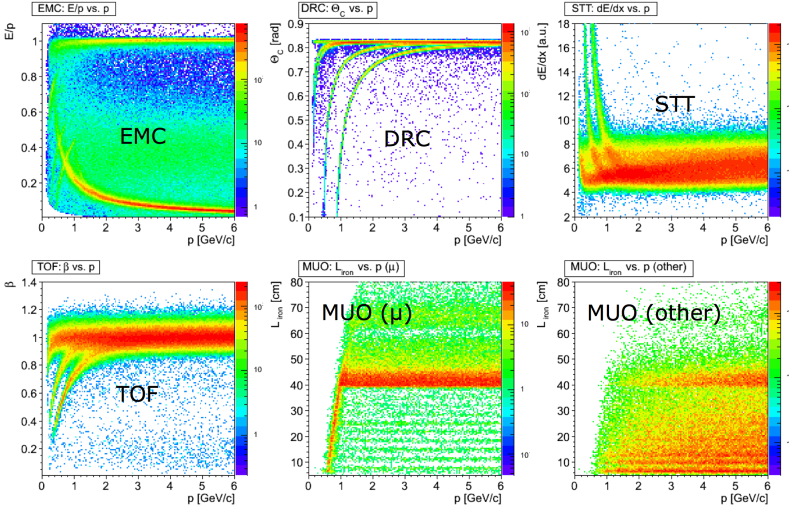
- Scintillator tiles $3 \times 3 \times 0.5\ \mathrm{cm}^3$
- Time resolution goal: $100\ \mathrm{ps}$



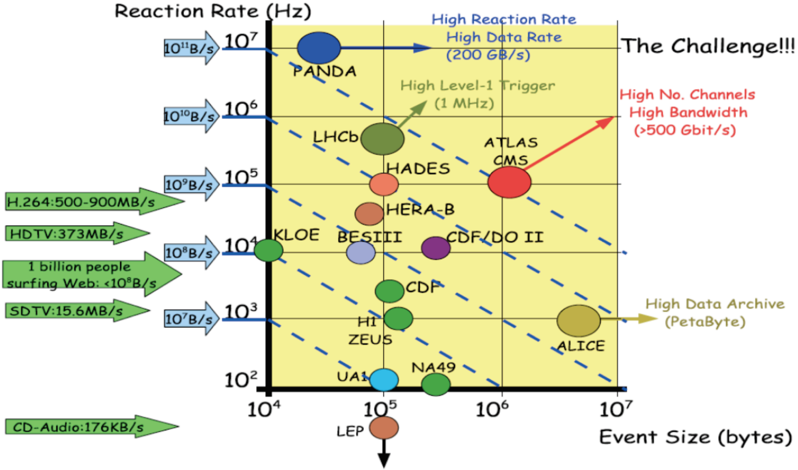


- Drift tubes with wire & cathode strip readout
- Barrel: 12+2 layers in yoke
- Endcap: 5+2 layers
- Muon Filter: 4 layers
- Forward: 16+2 layers

PID (Simulations)



Data Rates

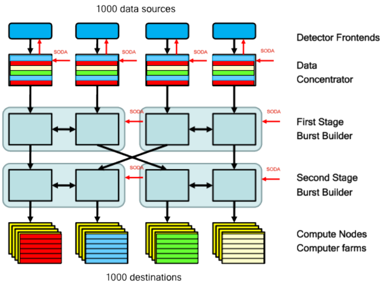


Reaction Rate (Hz)
10^11B/s
10^10B/s
10^9B/s
10^8B/s
10^7B/s
10^7
10^6
10^5
10^4
10^3
10^2
H.264:500-900MB/s
HDTV:373MB/s
1 billion people surfing Web: <10^8B/s
SDTV:15.6MB/s
CD-Audio:176KB/s
PANDA
High Reaction Rate
High Data Rate
(200 GB/s)
The Challenge!!!
High Level-1 Trigger
(1 MHz)
High No. Channels
High Bandwidth
(>500 Gbit/s)
LHCb
ATLAS
CMS
HADES
HERA-B
KLOE
BESIII
CDF/DO II
CDF
H1
ZEUS
High Data Archive
(PetaByte)
ALICE
NA49
UA1
LEP
10^4
10^5
10^6
10^7
Event Size (bytes)

Data Acquisition

Continuos Readout

- Self triggered
- Intelligent frontends
- Powerful computing nodes
- High speed network



Data Flow

- Data reduction
- Local feature extraction / online reconstruction
- Event selection: "Software Trigger" → Studies on Trigger Algorithms under development now

Summary & Outlook

In Short

- Antiprotons provide a unique access
- Rich hadron physics program
- Accelerator & detector on track

Timeline

- R&D on many components going to be finished
- Now starting to build first detector components
- First Constructions in Jülich
- 2018 Finishig installation & commissioning accelerator and detector components
- 2019 Commissioning with beam & first data

Thanks for your attention.

The PANDA collaboration: $\sim$ 520 Members, 69 Institutes, 18 Countries

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK