Physics Goals of PANDA

- Introduction
  - The PANDA Project
  - PANDA and HESR
  - Status of the PANDA Project
- Physics Program of PANDA
  - Hadron Spectroscopy
  - Merits of Antiproton Physics
  - Properties of Hadrons in Matter
  - Double Λ-Hypernuclei
  - Nucleon Structure
  - Options
- Conclusions

The PANDA Project

Study $\bar{p}p$-reactions (Fixed target) in the $\bar{p}$-momentum range from 1.5 - 15 GeV/c,
Fixed energy / Beam scan mode
Targets: Hydrogen (unpolarized), Nuclear Targets

Typical reactions:

$$\bar{p}p \rightarrow \rho_0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0$$

$$\bar{p}p\,(3.1\ \mathrm{GeV}) \rightarrow J/\psi \rightarrow e^+ e^-$$

$$\bar{p}p \rightarrow J/\psi + \pi \rightarrow e^+ e^- + \pi$$

$$\bar{p}p \rightarrow D\bar{D} \rightarrow K\bar{K}\pi\, K\bar{K}\pi;\ \ D\bar{D} + \pi$$

} Hadron Spectroscopy up to the Charm-Region (Conventional $q\bar{q}$ and exotic states)

$$\bar{p}p \rightarrow \gamma^{(*)}\gamma,\ e^+e^-$$

} Nucleon Structure

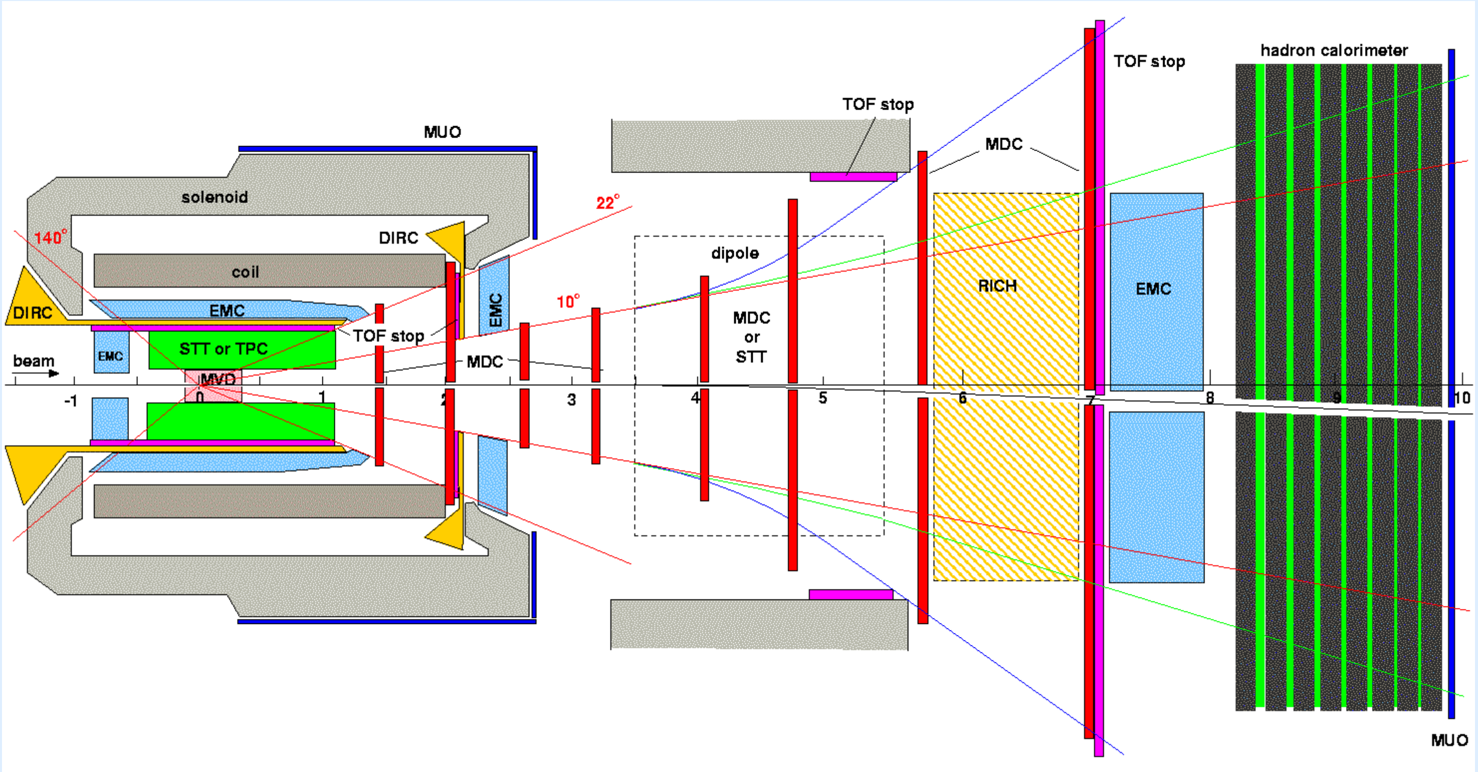
$$\bar{p}A \rightarrow J/\psi + (A-1)$$

} Properties of Hadrons in Matter

$$\bar{p}A \rightarrow \Xi\bar{\Xi} + X;\ \Xi A' \rightarrow_{\Lambda\Lambda} A''$$

} Double Λ-Hypernuclei

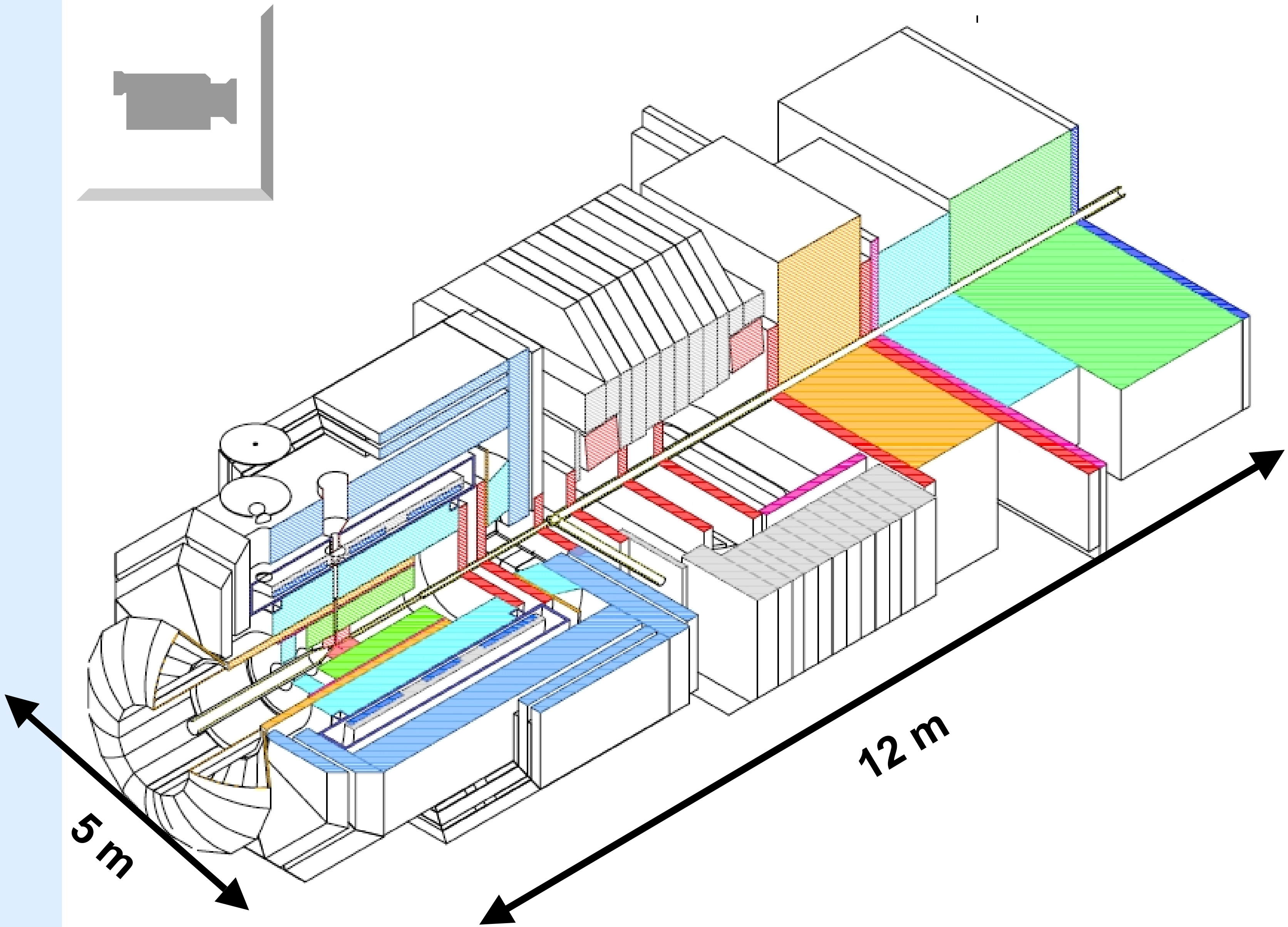
The PANDA Detector (1)



Detector requirements

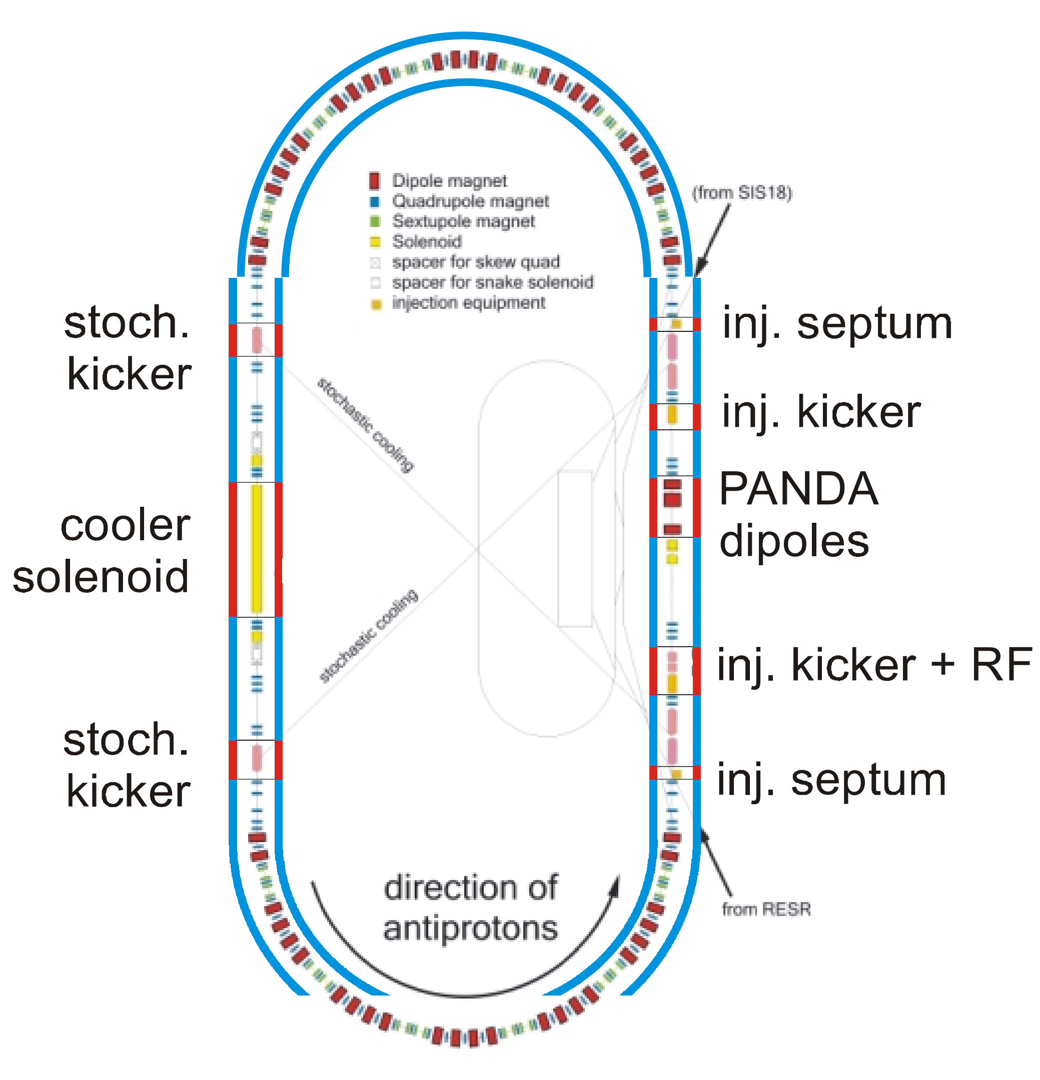
- full angular acceptance and angular resolution for charged particles and γ, π^0
- particle identification (π, K , e, μ) in the range up to ~ 8 GeV/c
- high momentum resolution in a wide energy range
- high rate capabilities, especially in interaction point region and forward detector : expected interaction rate ~ 10^7/s
- precise vertex reconstruction for fast decaying particles

The PANDA Detector (2)



PANDA and HESR

High Energy Storage Ring (HESR), proposed by P.K.

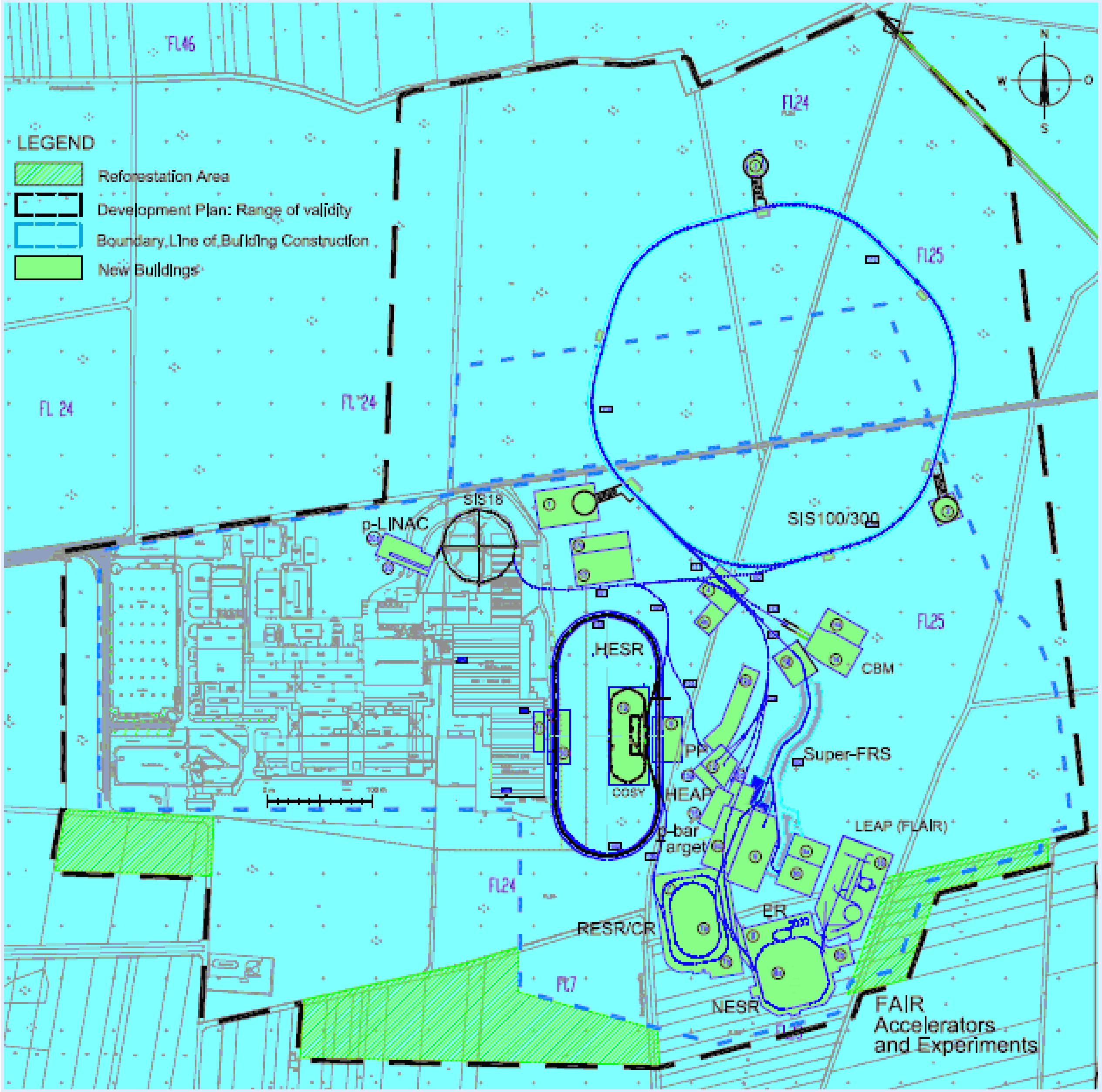


- Circumference 574 m
- Momentum (energy) range
  1.5 to 15 GeV/c (0.8-14.1 GeV)
- Injection of (anti-)protons from RESR at 3.8 GeV/c
- Acceleration rate 0.1 GeV/c/s
- Electron cooling up to 8.9 GeV/c
  (4.5 MeV electron cooler)
- Stochastic cooling above
  3.8 GeV/c

HESR: Parameters

Experiment Mode	High Resolution Mode	High Luminosity Mode
Momentum range	1.5 – 8.9 GeV/c	1.5 – 15.0 GeV/c
Target	Pellet target with $4*10^{15}$ cm^{-2}	
Number of stored Antiprotons	$1*10^{10}$	$1*10^{11}$
Luminosity	$2*10^{31}$ cm^{-2} s^{-1}	$2*10^{32}$ cm^{-2} s^{-1}
rms-emittance	1 mm mrad	
rms-momentum resolution	10^{-5}	10^{-4}

HESR at FAIR

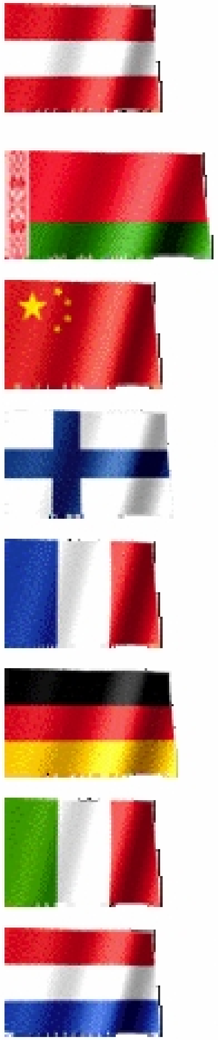


FAIR
Facility for **A**ntiproton and **I**on **R**esearch

HESR
High **E**nergy **S**torage **R**ing

Antiproton Physics at high Energies

Status of the PANDA Project (1)

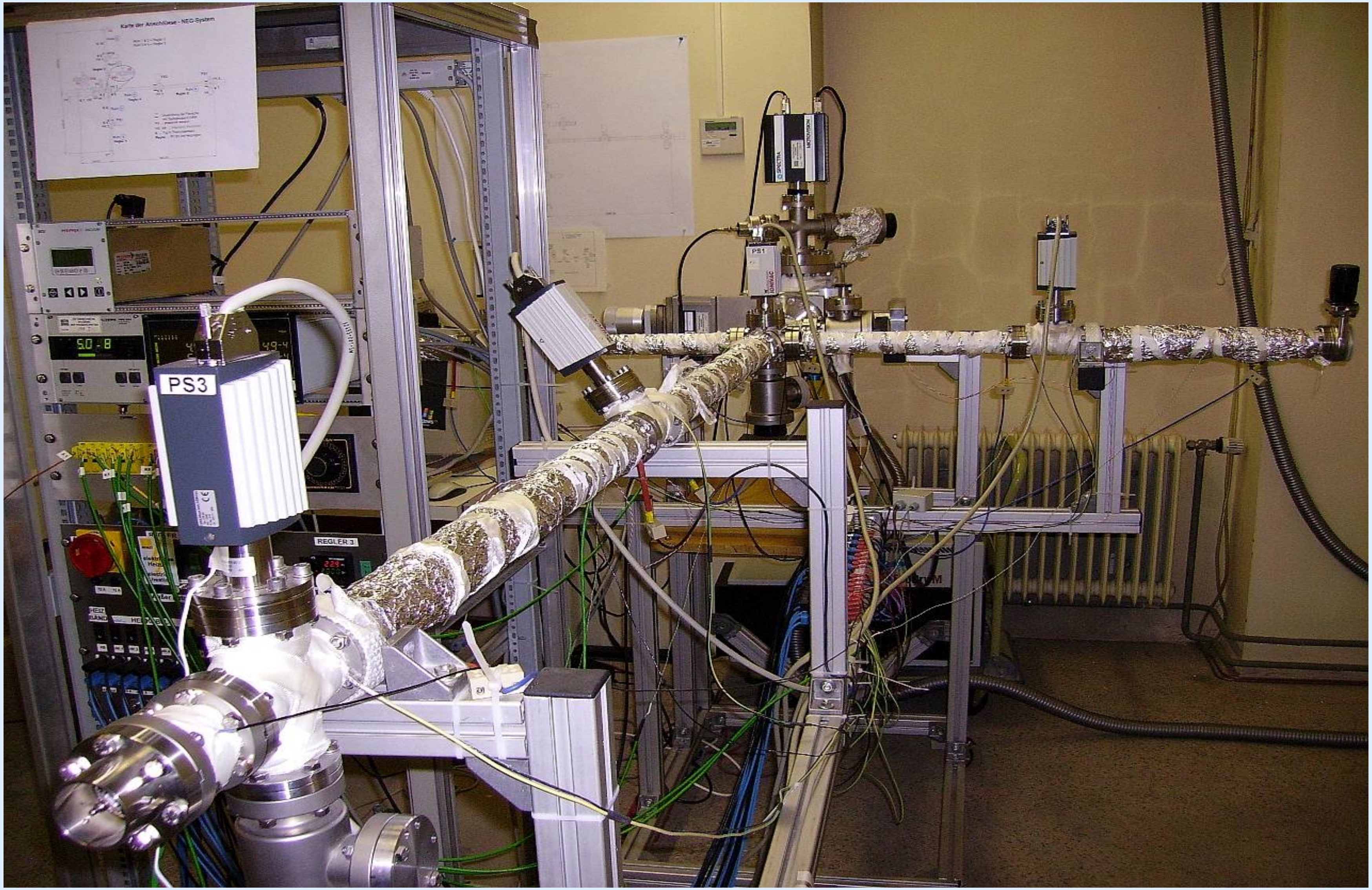


Universität Basel, IHEP Beijing, Ruhr-Universität Bochum, Universität Bonn, Università di Brescia + INFN, Università di Catania, University of Silesia, University Cracow, GSI Darmstadt, TU Dresden, JINR Dubna, JINR Dubna, University Edinburgh, Universität Erlangen, Northwestern University, INFN Sezione di Ferrara, Universität Frankfurt, LNF-INFN Frascati, INFN Sezione di Genova,Università di Genova, Universität Gießen, University of Glasgow, KVI Groningen, Institute of Physics Helsinki, FZ Jülich - IKP I, FZ Jülich - IKP II, IMP Lanzhou, Universität Mainz, Università di Milano, TU München, Universität Münster, BINP Novosibirsk, IPN Orsay, Università di Pavia, PNPI Gatchina St. Petersburg, IHEP Protvino, Stockholm University , Università di Torino, Università de Piemonte, Università di Trieste + INFN, Universität Tübingen, Uppsala Universitet, TSL Uppsala, Universidad de Valencia, Stefan Meyer Institut für subatomare Physik, Vienna, SINS Warschau

15 countries – 47 institutes – 370 scientists

Status of the PANDA Project (2)

Example: Simulation of the PANDA interaction region with NEG-coated beam pipes at SMI



Status of the PANDA Project (3)

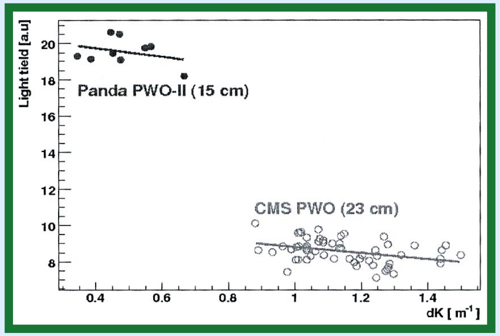
Example: E.-M. Calorimeter (Pb WO_4/PWO)

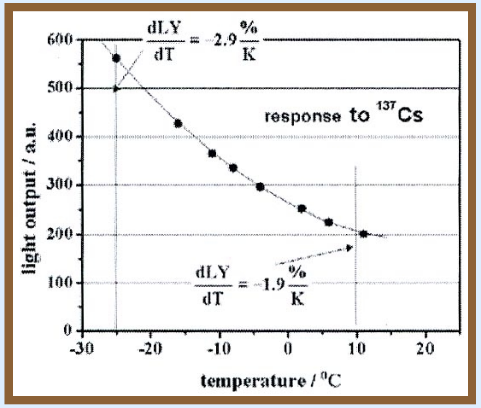
Requirements: Fast Response

Good energy resolution, even at low energies

Development of new crystals (PWO (CMS) → PWO II)

Better material → Increase of light yield ≈ 100%

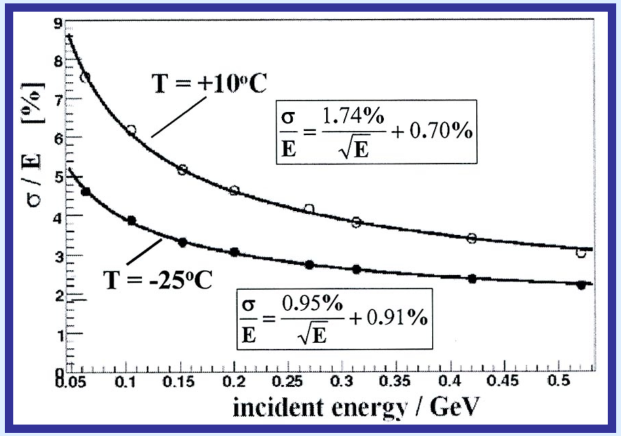




Operation of crystals at –25°C

Reduction of thermal quenching → Increase of light yield by ≈ 400%

➥



Best PWO energy resolution, ever measured

Development of Large Area APD's (together with Hamamatsu Photonics)

Signals comparable to Photo-Multiplier Readout

➥ Operation in high magnetic fields

PANDA – Hadron Spectroscopy Program (1)

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

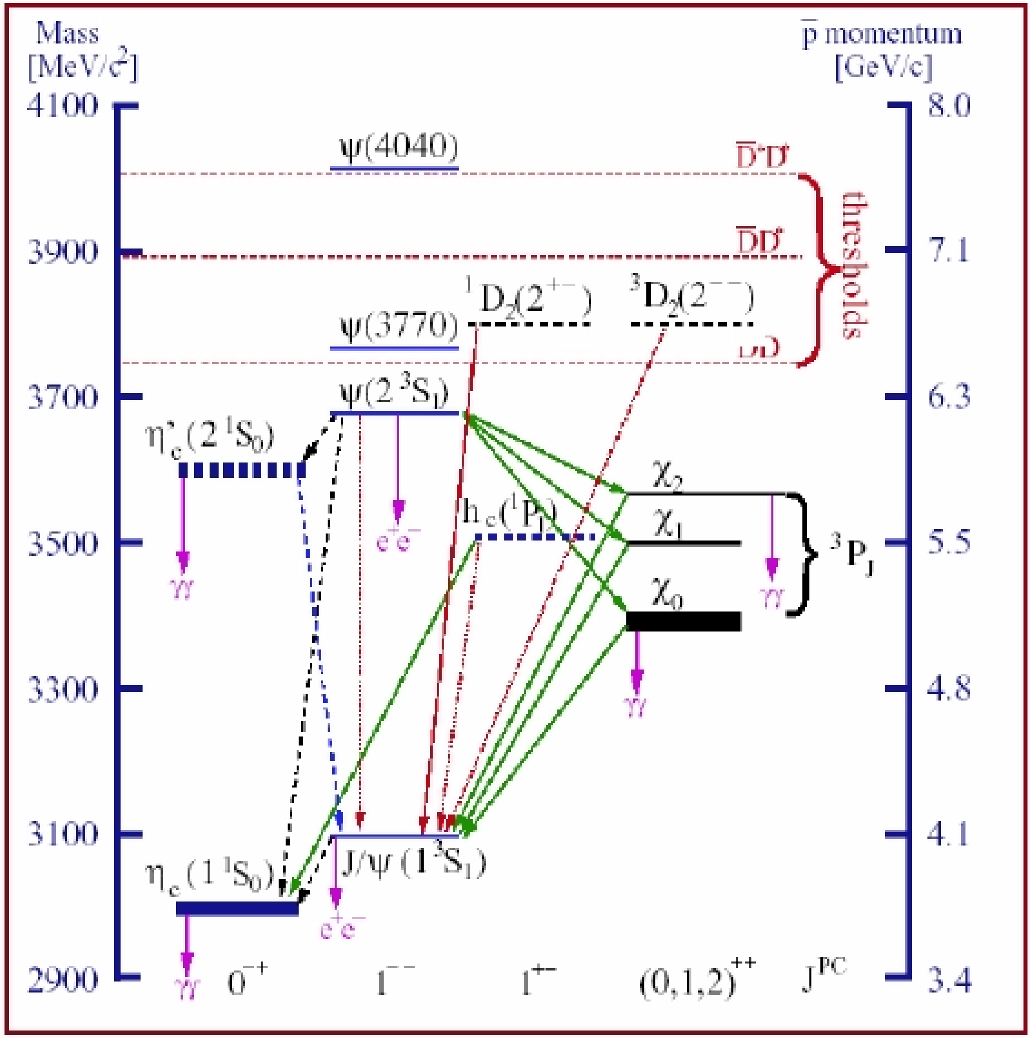
Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}\ (\rightarrow_{\Lambda\Lambda} A)$	2μb	10^{8} (10^{5})
$D\bar{D}$	250nb	10^{7}
$J/\psi\ (\rightarrow e^+e^-, \mu^+\mu^-)$	630nb	10^{9}
$\chi_2\ (\rightarrow J/\psi + \gamma)$	3.7nb	10^{7}
$\Lambda_c\bar{\Lambda}_c$	20nb	10^{7}
$\Omega_c\bar{\Omega}_c$	0.1nb	10^{5}

Common Feature : Low multiplicity events
Moderate particle energies

For Pairs : Charge symmetric conditions
Trigger on one, investigate the other

PANDA – Hadron Spectroscopy Program (2)

Charmonium Spectroscopy (Many Inputs from P.K.)



- powerful tool for understanding QCD
- high c-Quark mass allows to apply non-relativistic potential models with correct asymptotic behaviour
- free parameters to be determined by experiment

PANDA – Hadron Spectroscopy Program (3)

Experiments $c\bar{c}$:

η_c (1^1S_0)

experimental error on M > 1 MeV
Γ hard to understand in simple quark models

η_c' (2^1S_0)

Recently seen by Belle, BaBar, Cleo

Crystal Ball result way off

$h_c(^1P_1)$

Spin dependence of QQ potential
Compare to triplet P-States
LQCD ←→ NRQCD

$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

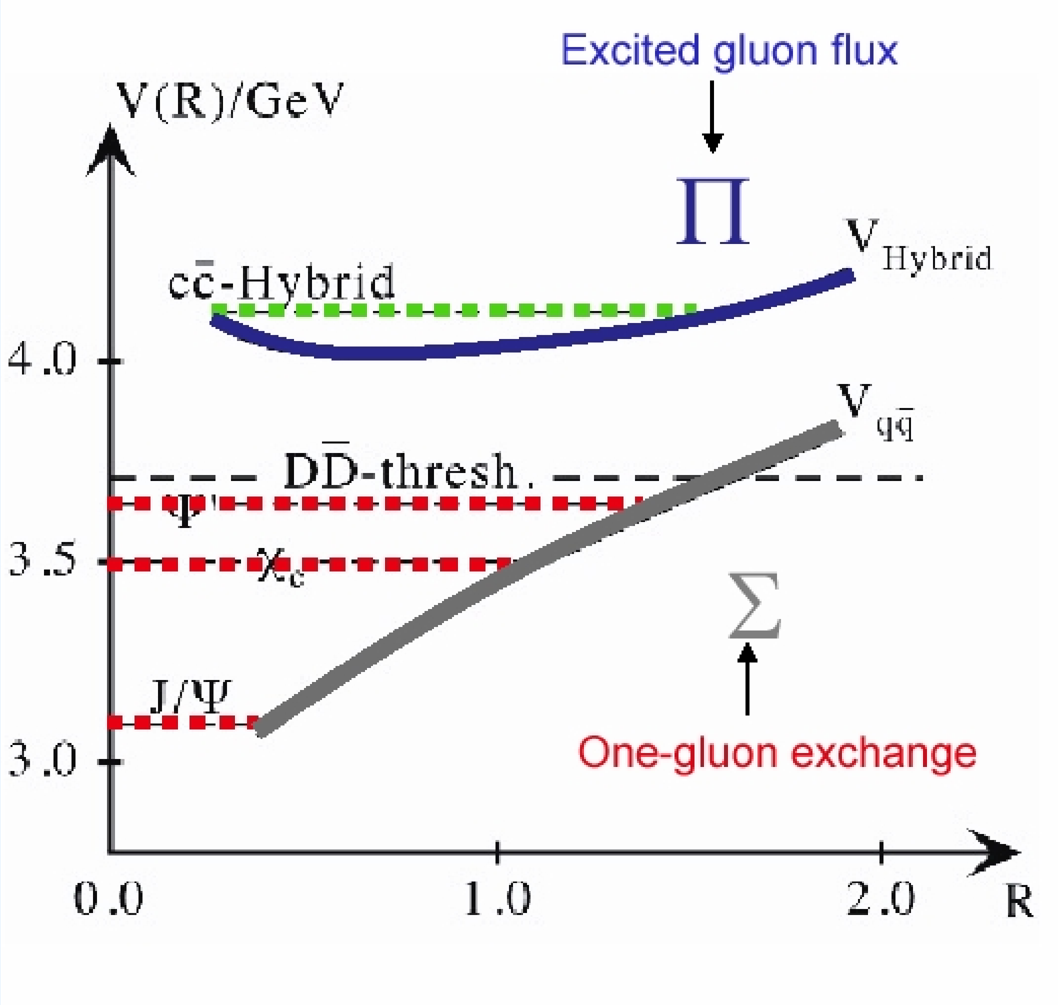
States above the DD threshold

Higher vector states not confirmed Ψ(3S), Ψ(4S)
1st radial excitation of P wave states
Narrow D wave states, only Ψ(3770) seen
Sensitive to long range Spin-dependent potential

Nature of the new X(3872), X(3940), Y(3940) and Z(3940)

PANDA – Hadron Spectroscopy Program (4)

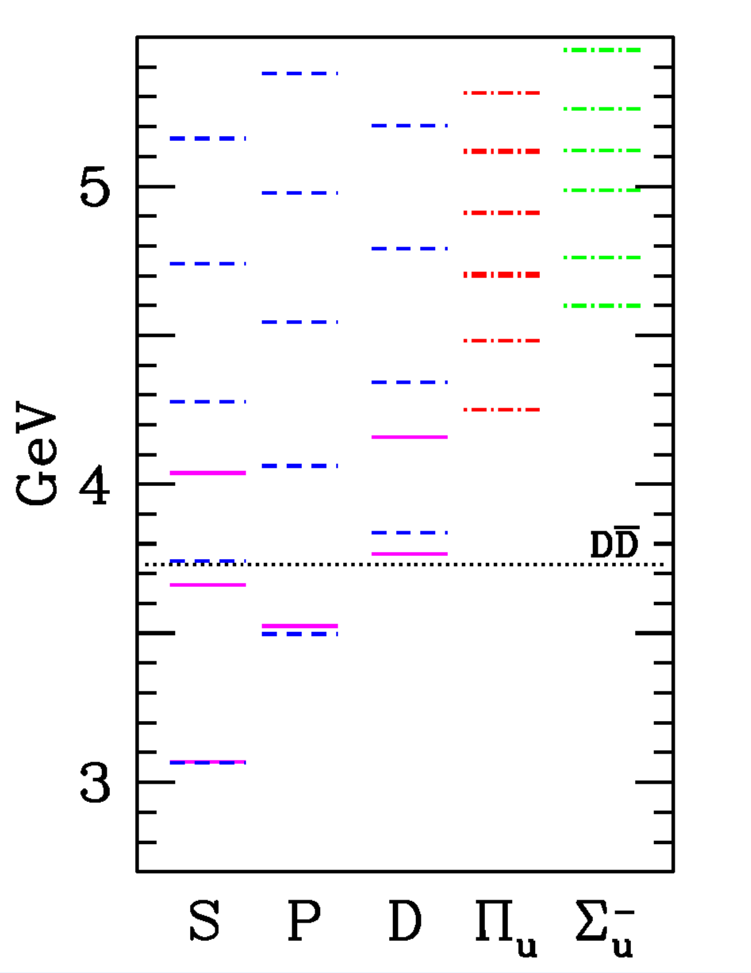
Charmonium Hybrids



- Hybrids predicted in various QCD models (LQCD, bag models, flux tubes...)
- Some charmonium hybrids predicted to be narrow (exotic quantum numbers)
- Production cross section similar to other charmonia (~150pb)

PANDA – Hadron Spectroscopy Program (5)

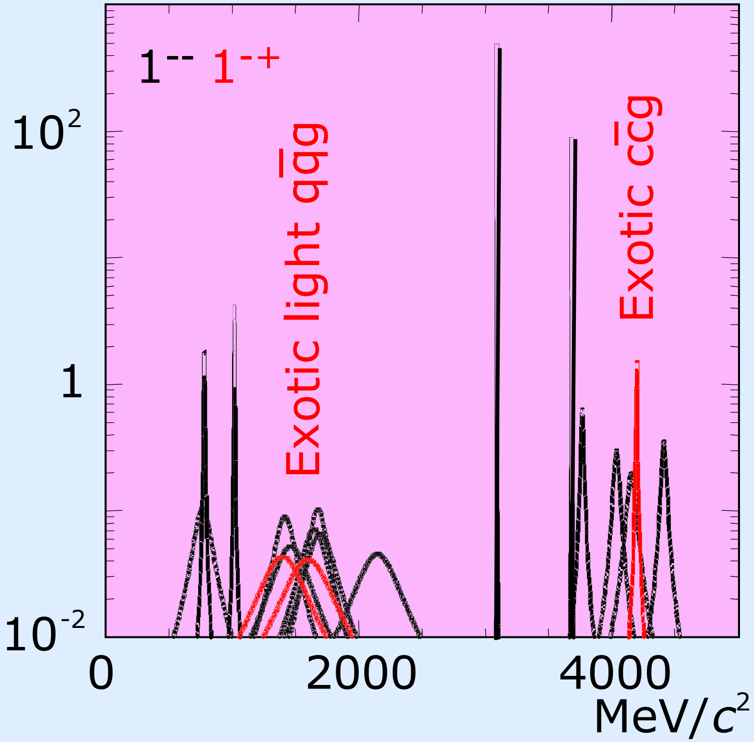
Charmonium Hybrids



42] K. Juge, J. Kuti, and C. Morningstar, Phys. Rev. Lett. 90, 161601 (2003).

Decay modes:
$J/\psi\omega$; $D^*\bar{D}$

Small overlap with $c\bar{c}$-states

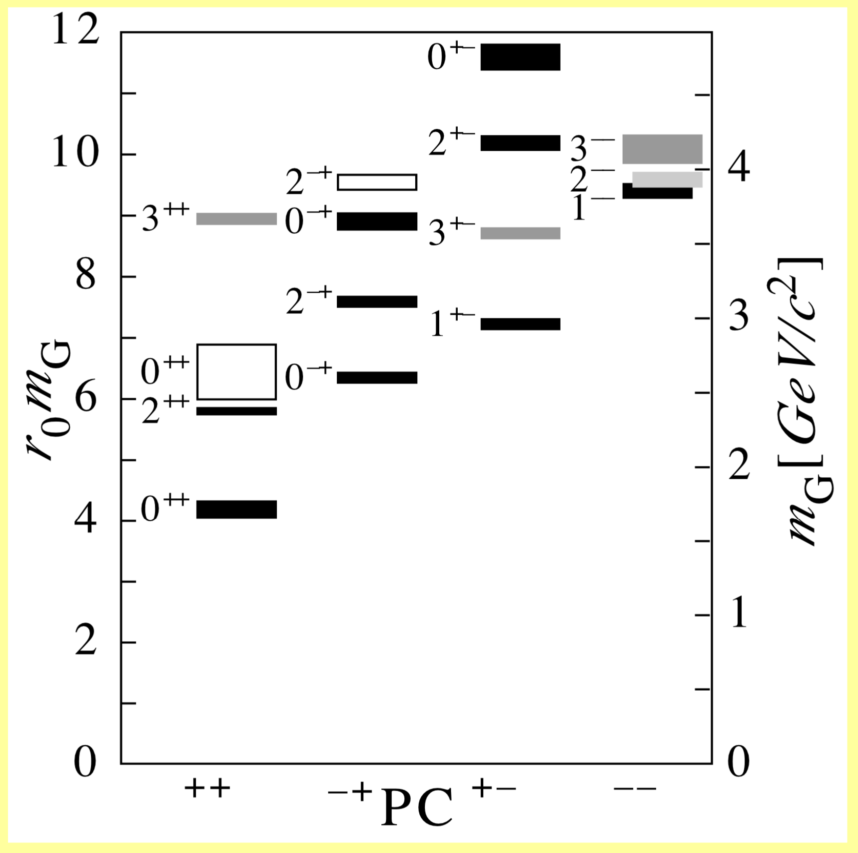


PANDA – Hadron Spectroscopy Program (6)

Glueballs (gg)

Predictions:

- Masses:
  - 1.5-5.0 GeV/c^2 (Ground state found? ;
  - Candidates for further states?)
- Quantum numbers:
  - Several spin exotics (oddballs), e.g.
  - $J^{PC} = 2^{+-}$ (4.3 GeV/c^2)
- Widths: ≥ 100 MeV/c^2
  - – Decay into two lighter glueballs often forbidden because of q.-n.
  - – No mixing effects for oddballs
- Decays: φφ, φη, ηπ



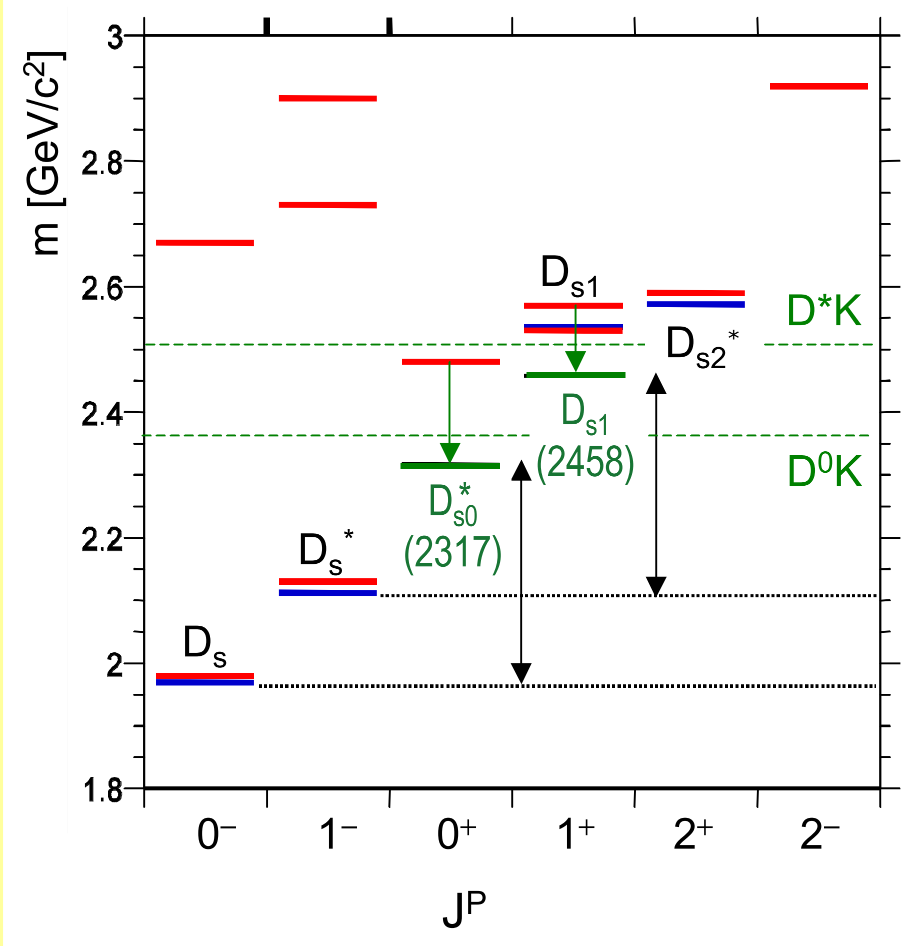
PANDA – Hadron Spectroscopy Program (7)

Open Charm States

New observations

The $D_S^{\pm}$ spectrum |cs> + c.c. was not expected to reveal any surprises, but ...

- Potential model
- Old measurements
- New observations
(BaBar, CLEO-c, Belle)



Or these are molecules ?

Most recent state (BaBar):

$D_{sJ}(2680)^+ \longrightarrow D^0 K^+$

Merits of Antiprotons (1)

In $\bar{p}p$-annihilation **all mesons** can be formed

Example: $\bar{p}p \to \chi_{1,2}$

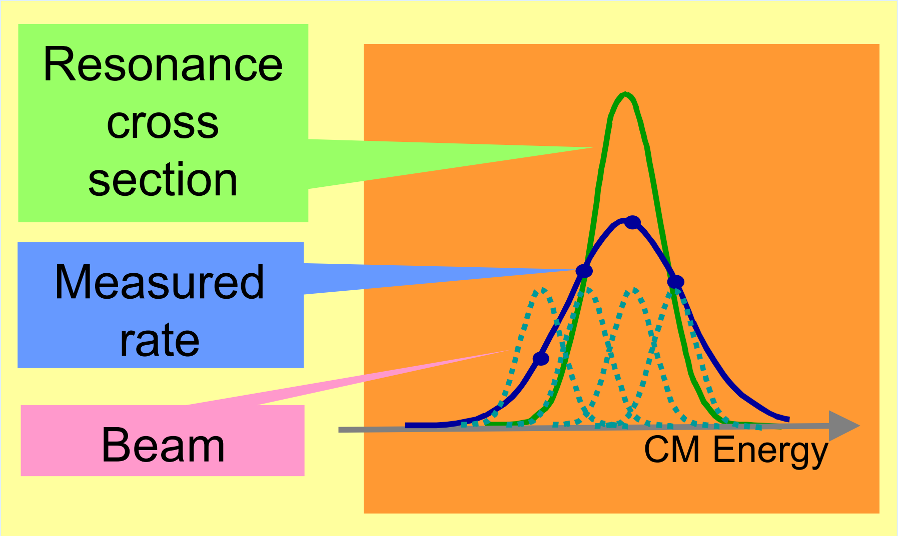
$\hookrightarrow \gamma\, J/\psi$

$\hookrightarrow \gamma e^+e^-$

In contrast: In e^+e^--annihilation only $J^{PC} = 1^{--}$ can be formed

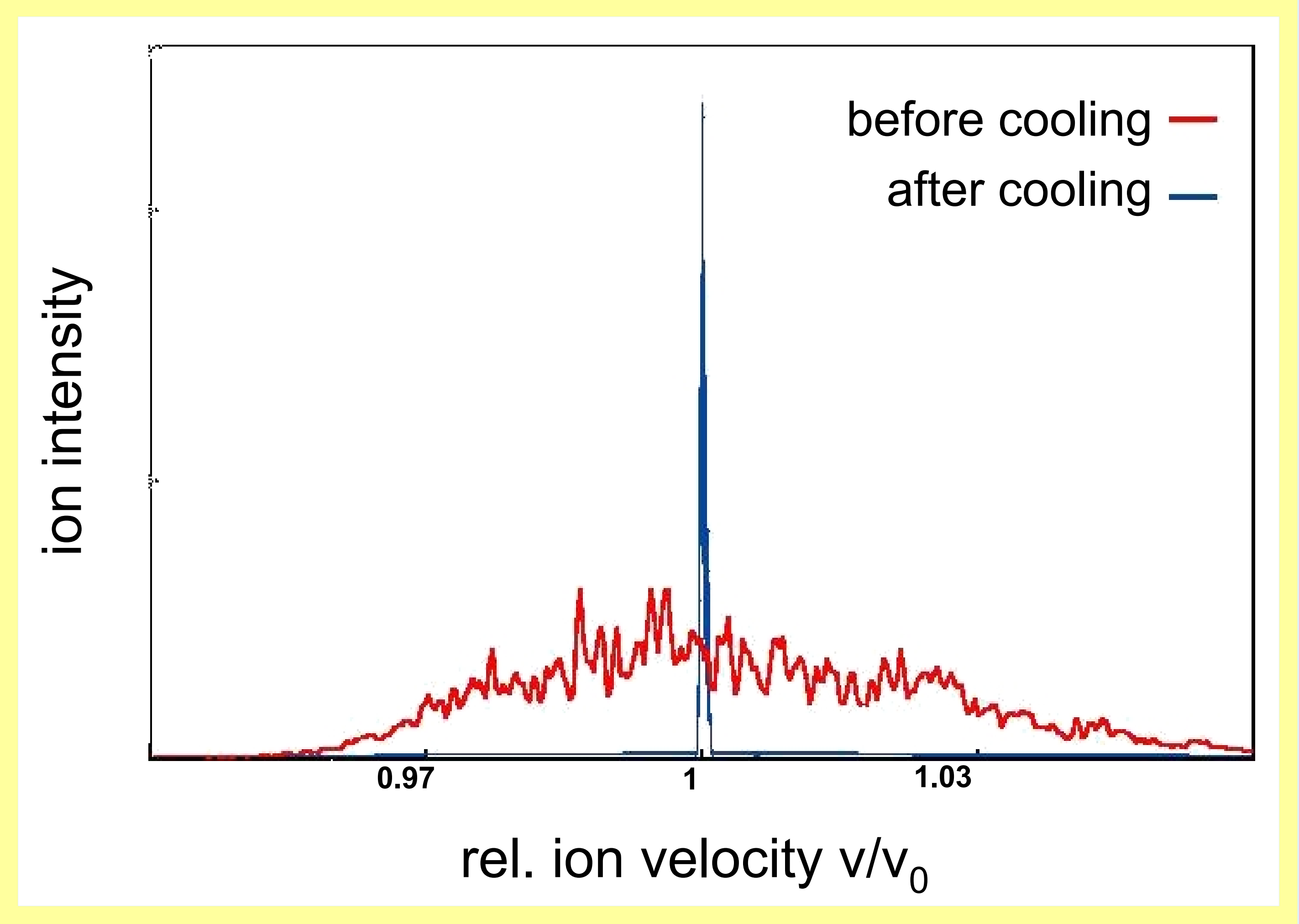
$$e^+e^- \to J/\psi \quad , \quad e^+e^- \not\to \chi_{1,2}$$

Resolution of the mass and width is only limited by the (excellent) beam momentum resolution



Merits of Antiprotons (2)

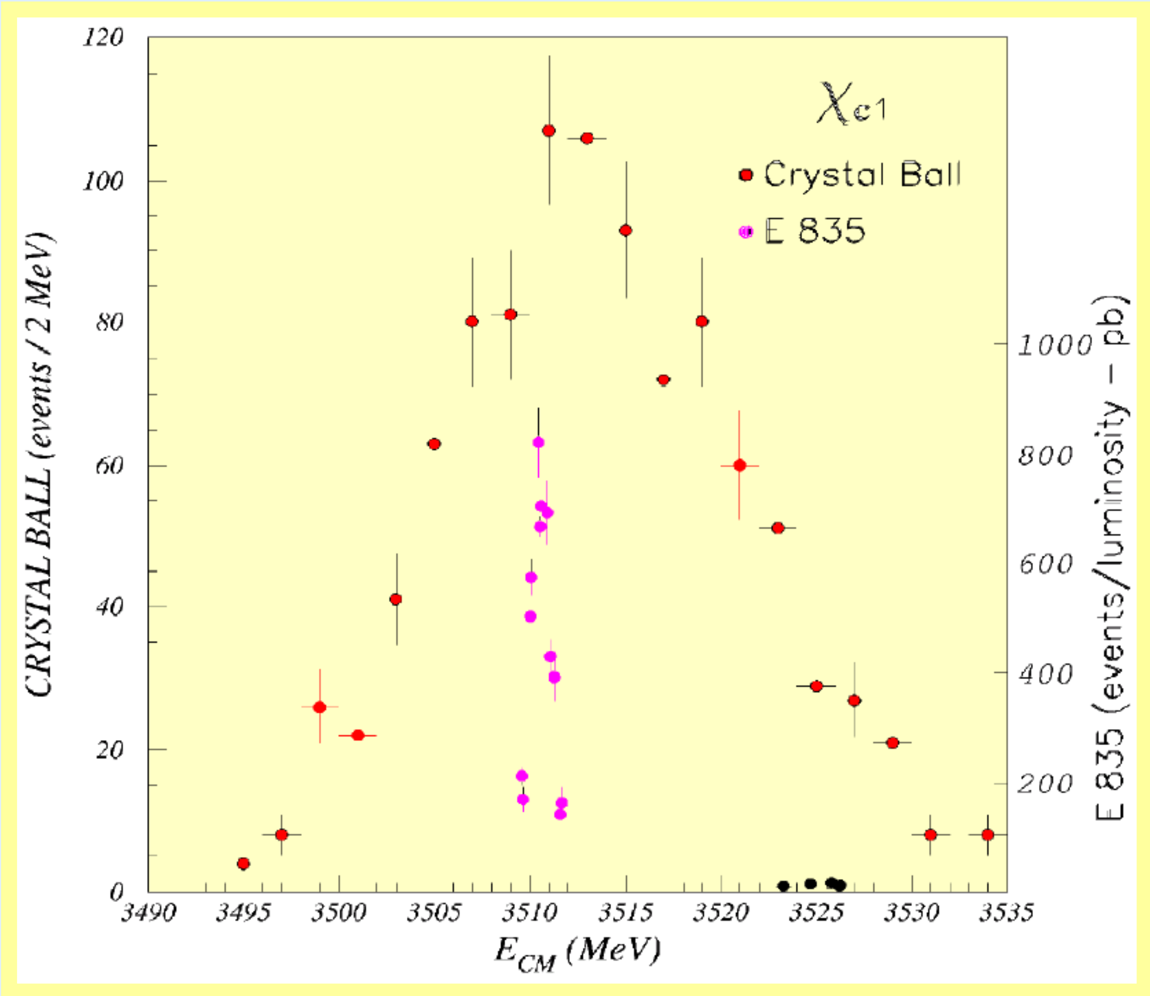
$\bar{p}$-beams can be cooled → Excellent beam momentum resolution



Merits of Antiprotons (3)

- Crystal Ball: typical resolution ~ 10 MeV
- Fermilab: 240 keV
- PANDA: ~20 keV

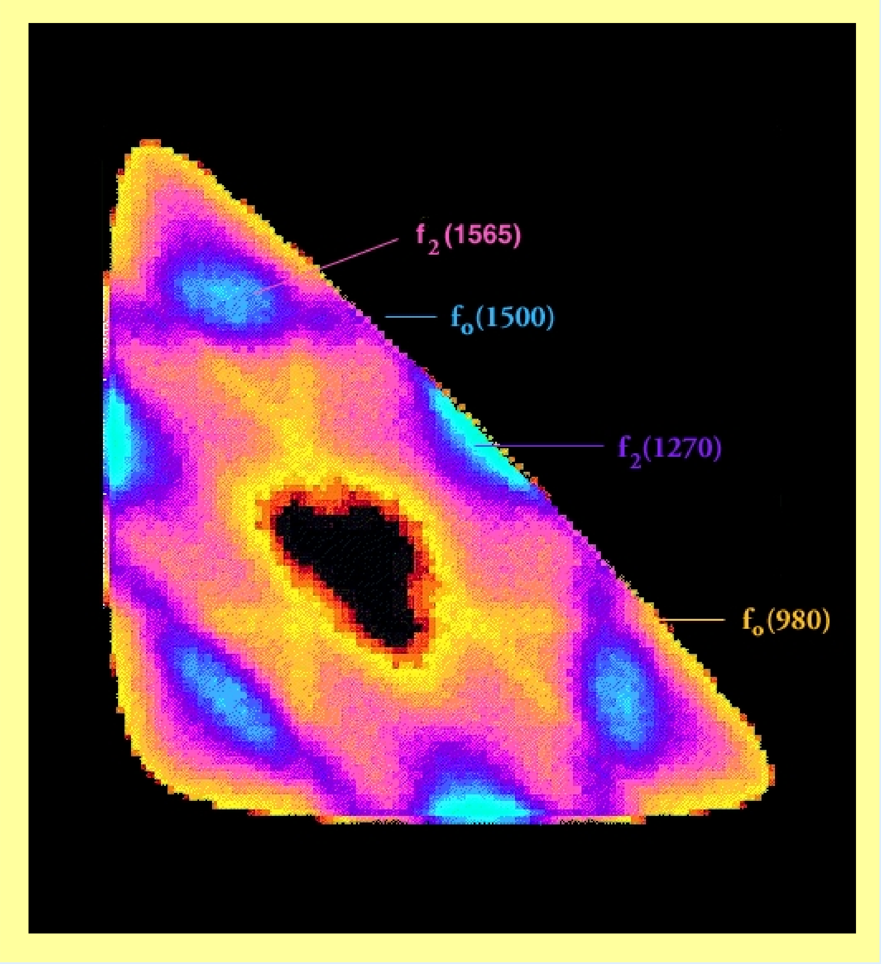
$\Rightarrow \Delta p/p \sim 10^{-5}$ needed



Merits of Antiprotons (4)

$\bar{p}p$-cross sections high $\rightarrow$ Data with very high statistics

Example: $\bar{p}p \rightarrow \pi^0\pi^0\pi^0$ (LEAR) $\rightarrow f_0(1500)$ = best candidate for Glueball ground state

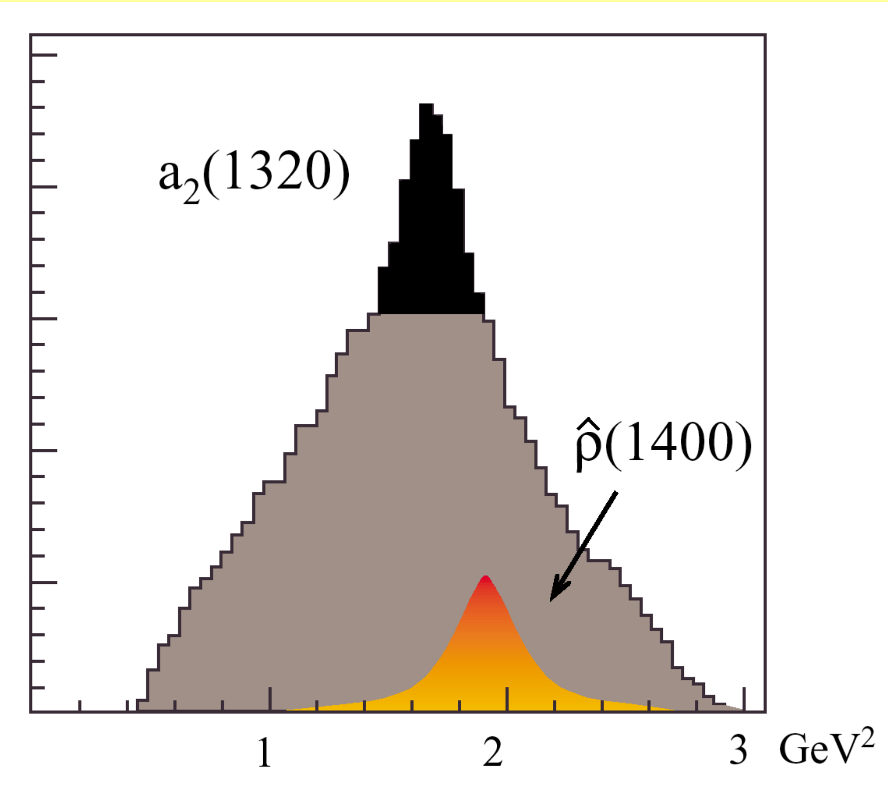


Low final state multiplicities: Clean spectra, Good for PWA analyses

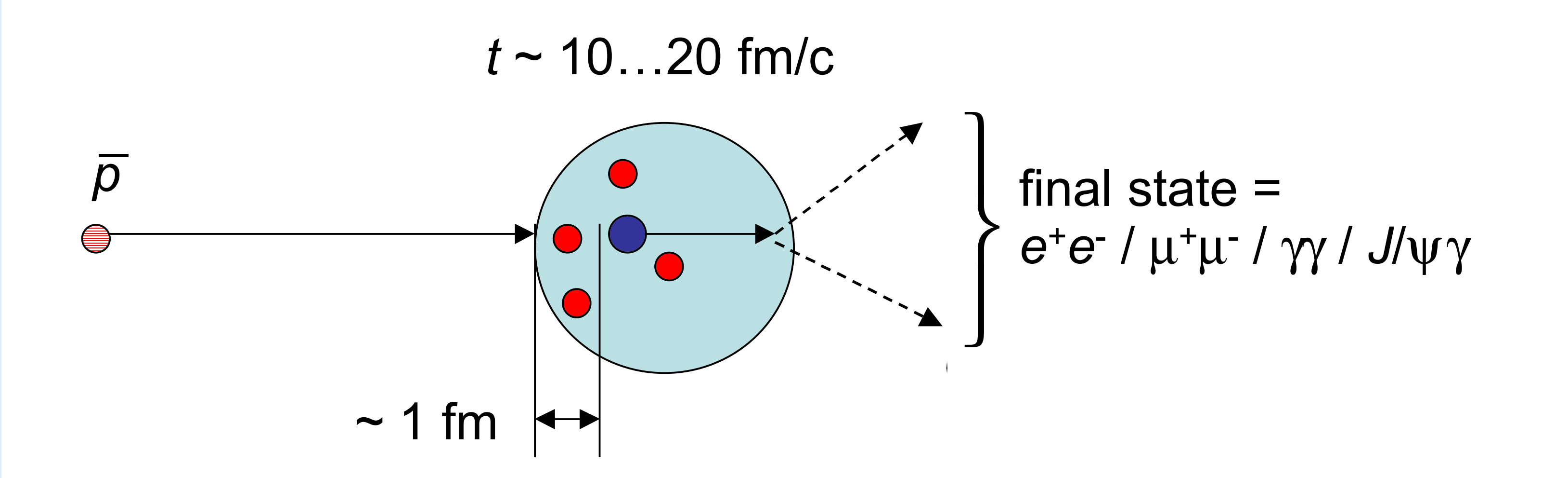
Merits of Antiprotons (5)

High probability for production of exotic states

Example: $\bar{p}p \rightarrow \eta\pi^0\pi^0$: $\hat{\rho}(1400)$ **($J^{PC} = 1^{-+}$)** = candidate for Hybrid ground state



Properties of Hadrons in Matter (1)



$\bar{p}$´s interact with p within 1 fm

At appropiate $E_{CM}(\bar{p}p)$ J/ψ, ψ', χ_c –systems are formed ($\beta \approx 0.8 - 0.9$)

Effects to be considered:

- Fermi motion of nucleons (≈ 200 MeV)
- Collisional broadening of states (≈ 20 MeV)

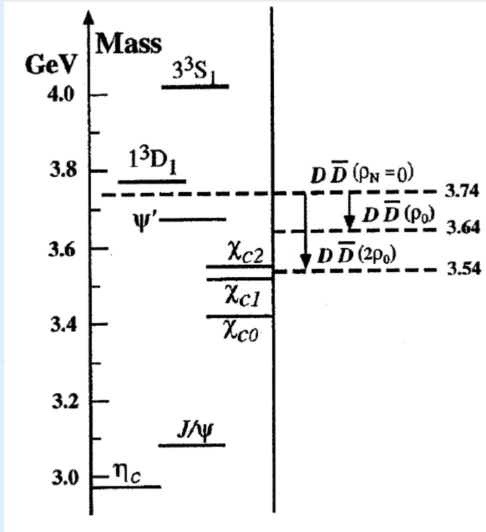
} Trivial

- Mass shifts and broadening of $c\bar{c}$-states in matter
- Mass shifts and modifications of spectral functions of open charm states ($D^{\pm}$)

} Chiral dynamics, Partial restoration of chiral symmetry in hadronic environment

P.K., see also talks of T. Yamazaki and N. Herrmann

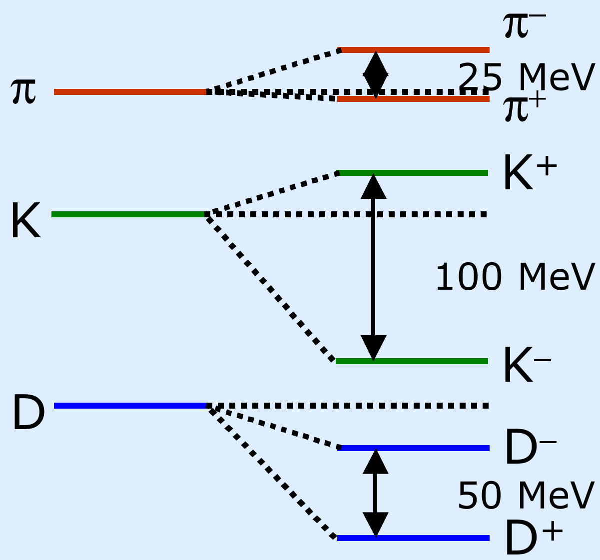
Properties of Hadrons in Matter (2)



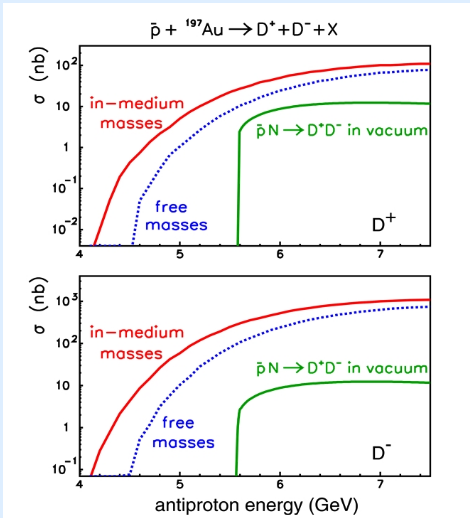
Predictions:

1) Hidden charm states ($c\bar{c}$):
Small mass shifts: 10 - 100 MeV (Gluon Condensate)
Sizeable width changes

2) Open charm states ($Q\bar{q}$):



Hayaski, PLB 487 (2000) 96
Morath, Lee, Weise, priv. Comm.



Calculation: A. Sibirtsev et al.,
Eur. Phys. J A6 (1999) 351

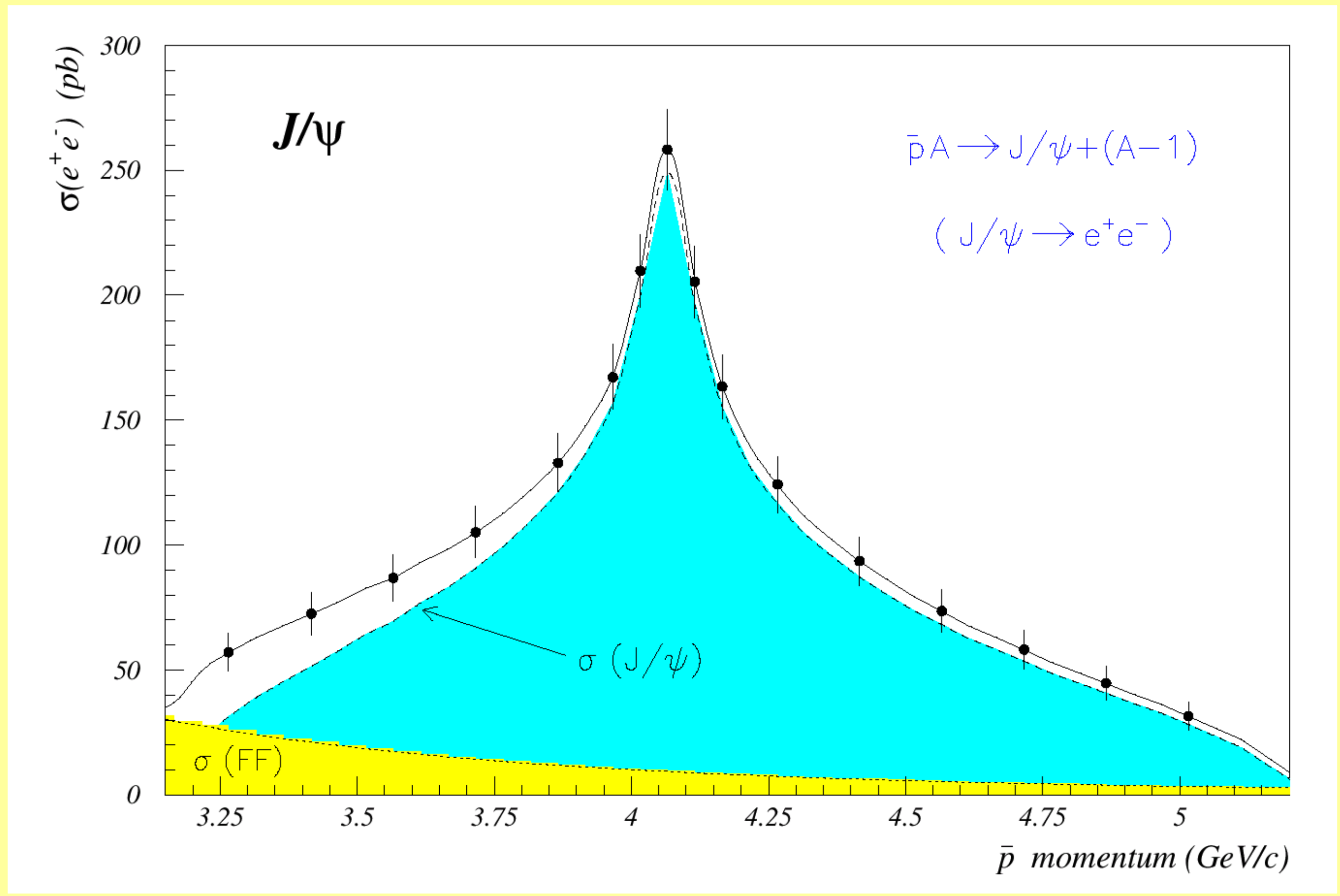
Properties of Hadrons in Matter (3)

J/ψ absorption cross section in nuclear matter

$\bar{p} + A \rightarrow J/\psi + (A-1)$

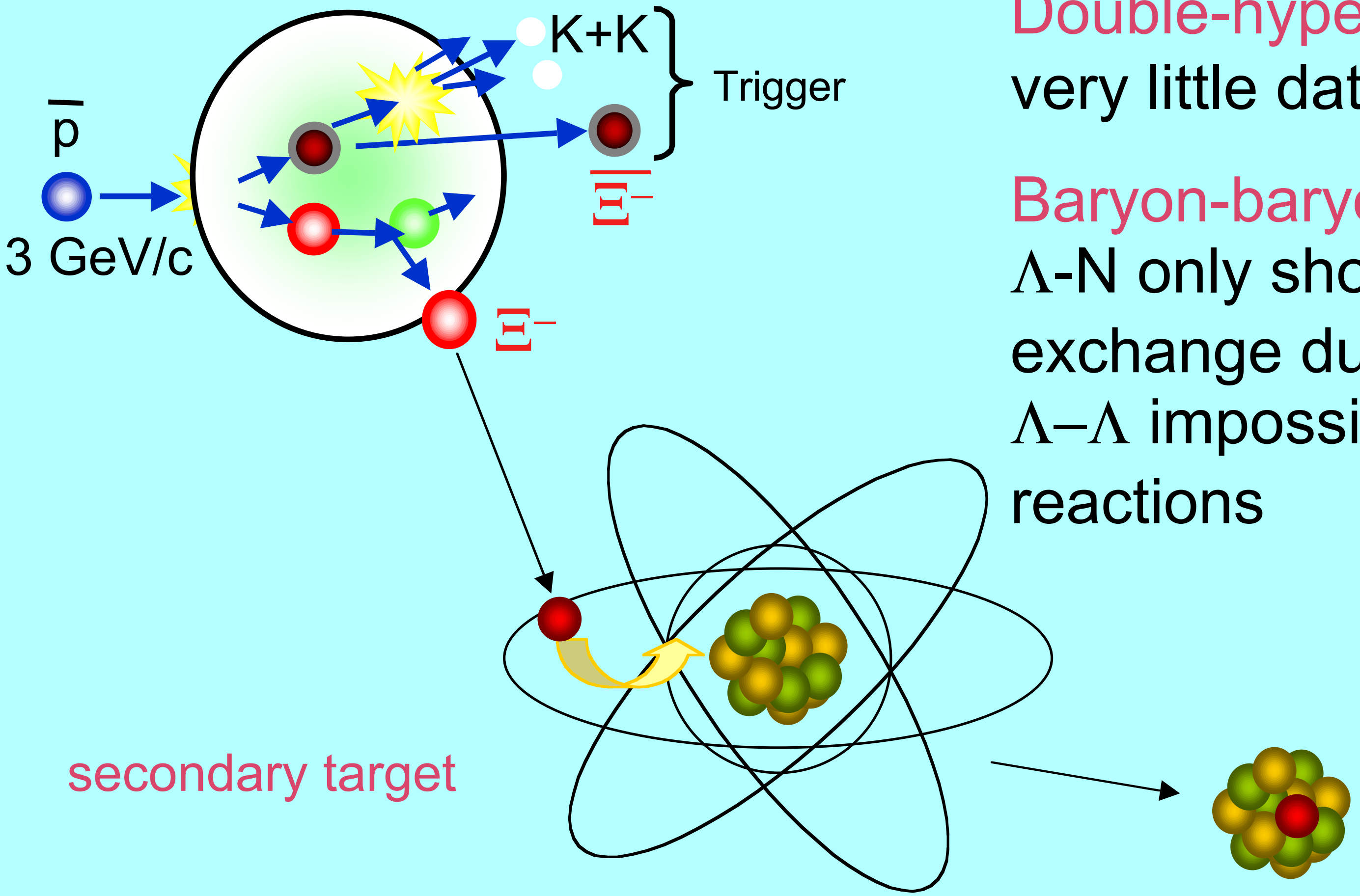
→ $\sigma_{tot}\,(J/\psi\ N)$

Important for QGP



Double Λ-Hypernuclei (1)

Hypernuclei open a 3rd dimension (strangeness) in the nuclear chart



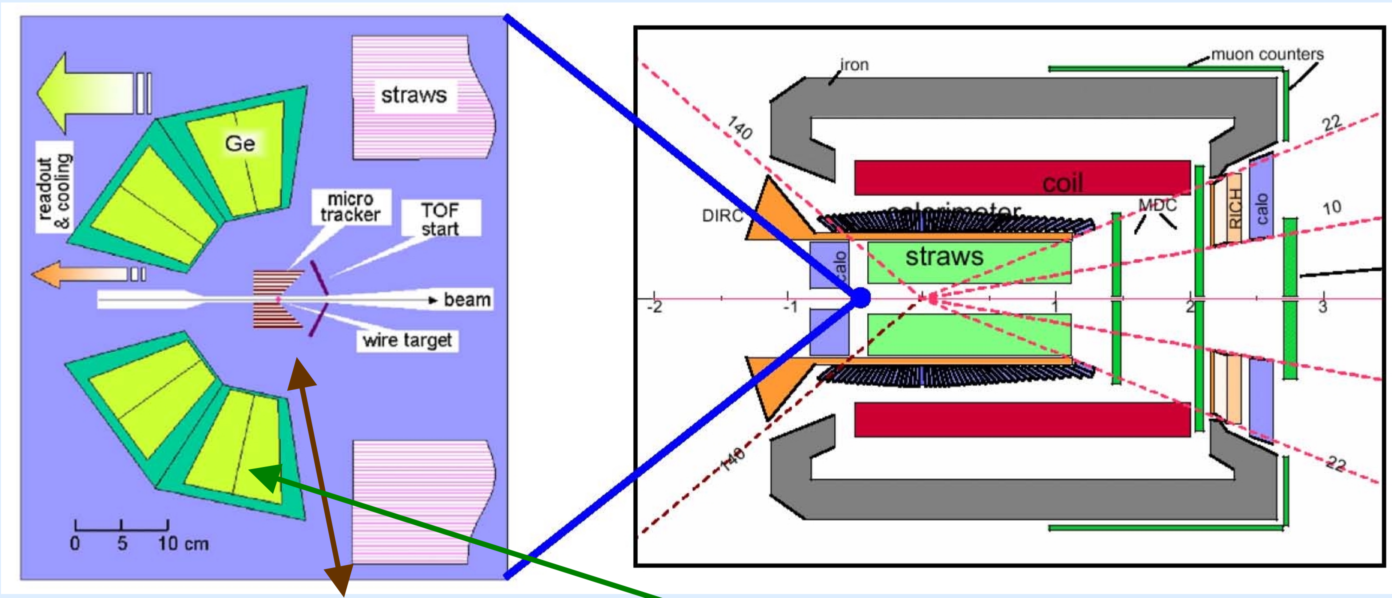
Double-hypernuclei:
very little data

Baryon-baryon interactions:
Λ-N only short ranged (no 1π exchange due to isospin)
Λ–Λ impossible in scattering reactions

Ξ^-(dss) **p**(uud) ⇒ Λ(uds) Λ(uds)

Double Λ-Hypernuclei (2)

Current state of the art γ detection resolution : 2 KeV (KEK E419)
Current state of the art p detection resolution : ΔE = 1.29 MeV Finuda Collaboration, PLB622: 35-44, 2005

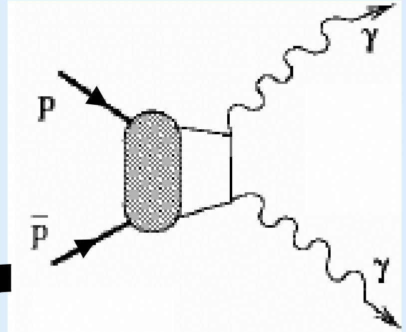


Solid state detector (diamond or silicon)
compact : thickness ~ 3 cm
high rate capability
high resolution
capillar (2D) or pixel (3D)

position sensitive Germanium γ detector (like Vega or Agata)

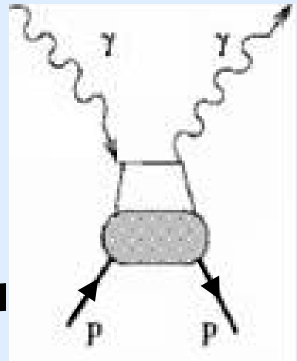
Nucleon Structure (1)

Annihilation into two Photons: $\bar{p}p \rightarrow \gamma\gamma$



Intermediate energies: Dominance of handbag diagram for $s \approx 10$ GeV^2; $|t| \approx s(\theta\approx 90°)$

Timelike GPD´s



Wide Angle Compton Scattering

Spacelike GPD´s

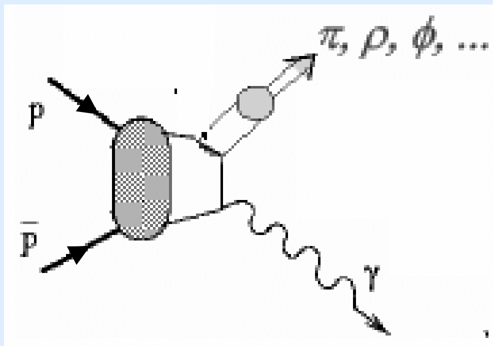
Prediction (from $\gamma\gamma \rightarrow p\bar{p}$): ≈ 15pb ($\sqrt{s}$ = 3.6 GeV)

Simulation: Several thousand events/month ($|\cos\theta_\gamma|$) < 0.6

Problem: Background from $\pi^0\gamma$(420 pb) ; $\pi^0\,\pi^0$ (17500 pb)

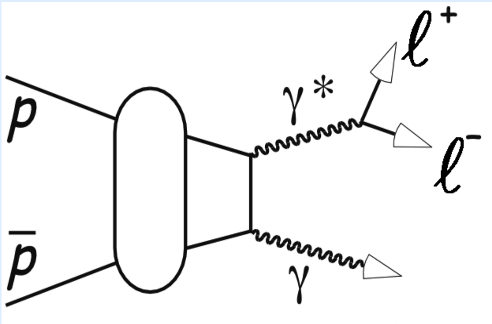
Related processes: $\bar{p}p \rightarrow \gamma + \pi, \rho, \omega, \phi$

Timelike GPD´s

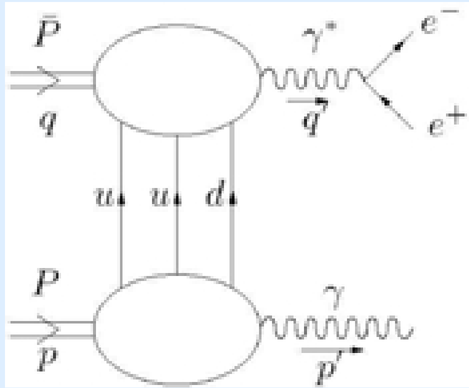


Nucleon Structure (2)

Annihilation to: $\bar{p}p \rightarrow \gamma\gamma^{*}(\rightarrow \ell^{+}\ell^{-})$

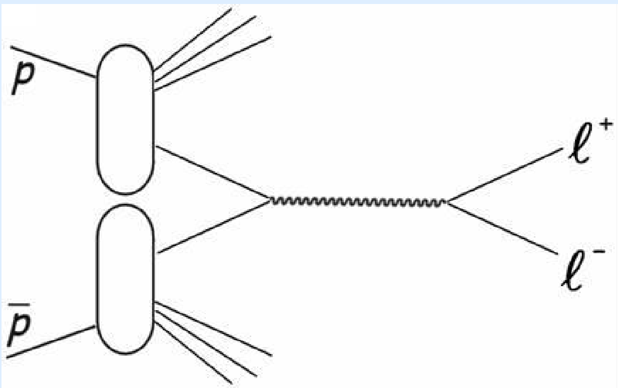


or



Comparison between predictions and data ⟶ Check of Factorisation

Contribution to Parton Distribution Functions: DY-Dilepton-Production:



$$\Rightarrow \int d\vec{k}_{\perp} h_1^{\perp}\left(x_1, \vec{k}_{\perp}\right) \bar{h}_1^{\perp}\left(x_2, \vec{k}_{\perp}\right)$$

Boer-Mulders-Function

Nucleon Structure (3)

Timelike Proton Form Factor

Present situation: $|G_M|_{timelike} \approx 2xG_{M\ spacelike}$

Assumption: $|G_E| = |G_M|$

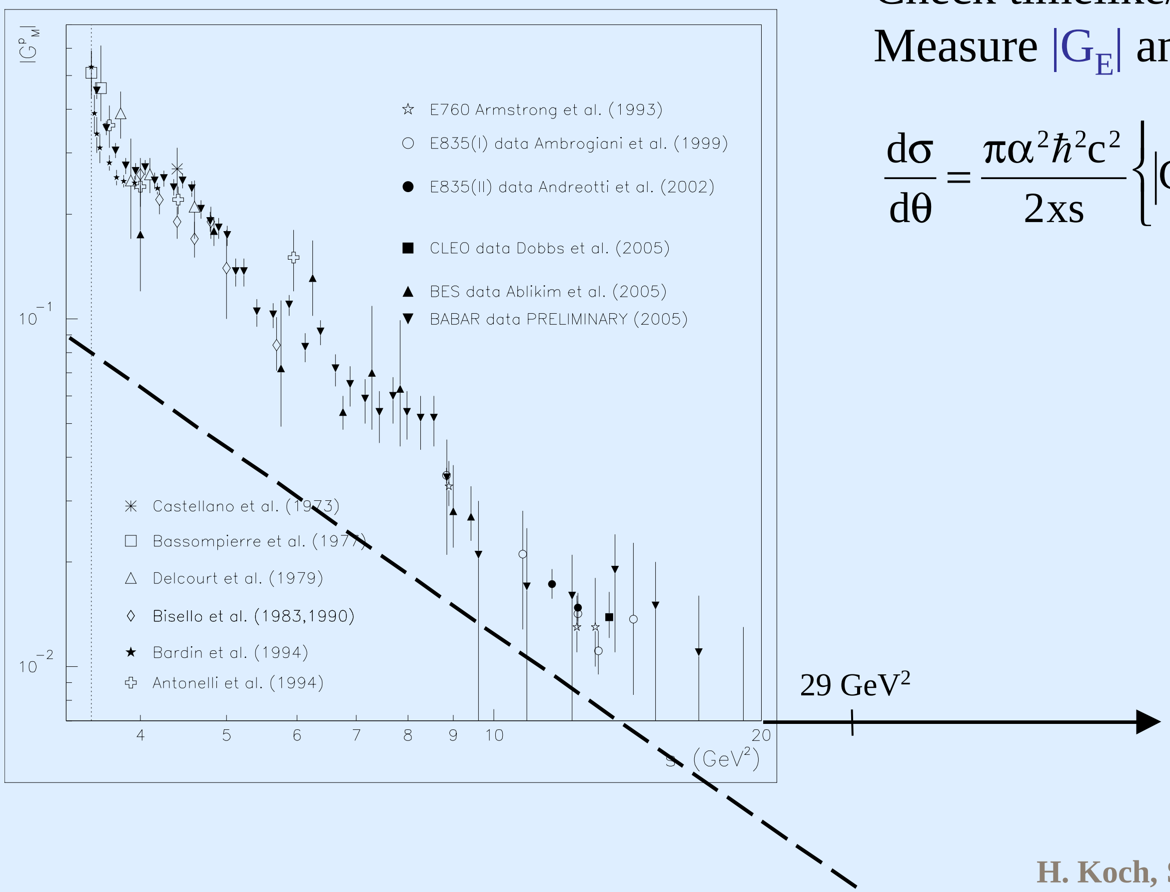
PANDA: Much wider angular acceptance and higher statistics

Measure for higher Q^2

Check timelike/spacelike equality

Measure $|G_E|$ and $|G_M|$ separately:

$$\frac{d\sigma}{d\theta} = \frac{\pi\alpha^2\hbar^2c^2}{2xs}\left\{|G_M^2|(1+\cos^2\theta^*) + \frac{4m_p^2}{s}|G_E^2|(1-\cos^2\theta^*)\right\}$$



Physics Program / Further Options (1)

– Baryon Spectroscopy

New states, Quantum numbers and decay rates

Multi – Strangeness Channels	Threshold $\left[GeV/c^2\right]$	$p_{Lab}\left[GeV/c\right]$	$\sigma\left(\bar{p}p \to B\bar{B}\right)$
$\Delta\bar{\Delta}$	2.23	1.43	$100\mu b$
$\Lambda\bar{\Sigma}$	2.31		
$\Sigma\bar{\Sigma}$	2.39		$10\mu b$
$\Lambda\bar{\Sigma}(1385)$	2.50	2.20	
$\Lambda\bar{\Lambda}(1405)$	2.52		
$\Lambda\bar{\Lambda}(1520)$	2.64		
$\Xi\bar{\Xi}$	2.64	2.62	$2\mu b$
$\Xi\bar{\Xi}(1530)$	2.85		
$\Omega\bar{\Omega}$	3.35	4.93	$200nb$
Charmed Channels			
$\Lambda_c\bar{\Lambda}_c$	4.57	10.1	$20nb$
$\Lambda_c\bar{\Sigma}_c$	4.74	11.0	
$\Sigma_c\bar{\Sigma}_c$	4.91	11.9	$10nb$
$\Xi_c\bar{\Xi}_c$	4.93	12.0	$0.1nb$
$\Xi_c^*\bar{\Xi}_c^*$	5.33	14.1	
$\Omega_c\Omega_c$	5.33	14.1	$0.1nb$

Physics Program / Further Options (2)

– Strangeness in Nuclei (Essential input by P.K.)

Use $\bar{p}$p-annihilation in nuclei to search for [ppK$^-$], [ppnK$^-$], ..., [$\bar{p}^3$He], ..., [$\bar{\Lambda}$ (A-1)]-systems

– Direct CP-Violation in $\Lambda, \bar{\Lambda}$-decays

Compare angular decay asymmetries $(\alpha, \bar{\alpha})$ for $\Lambda \to p\pi^- / \bar{\Lambda} \to \bar{p}\pi^+$

$$A \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

Prediction (SM) ≈ 2×10^{-5} HESR: 1 year of beamtime

– CP-Violation in charmed region

$D^0 / \bar{D}^0 -$ Mixing $(r) < 10^{-8}$ (SM) HESR : $\Delta r / r \sim 10^{-4}$

Direct CP-Violation (SCS)

Compare $D^+ \to K^+ \bar{K}^{0*} / D^- \to K^- K^{0*}$ Asymmetries A (SM) $< 10^{-3}$

HESR $=$ $\Delta A / A \approx 10^{-4} - 10^{-3}$

Conclusions

- Enormous impact in particle physics of $\bar{p}$-induced reactions
- $\bar{p}$-induced reactions have unique features
  - Nearly all states can be directly produced
  - High cross sections guarantee high statistics data
- $\bar{p}$-beams can be cooled very effectively
- The planned $\bar{p}$-experiments at FAIR will contribute to a further understanding of the non-perturbative sector of QCD
- The impact of Paul Kienle to Fair and particularly to the Antiproton Project was enormous as far as physics ideas and technical developments were concerned.
  Without his constant help and new ideas the project would not have prospered so well.

Some Selected Topics

Case Studies:
Y(4260)
X(3872)
Z(3930)
X(3940)
Y(3940).
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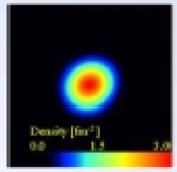
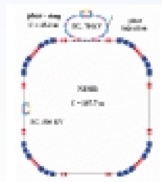
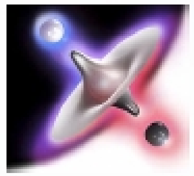
- Antiprotons for Charm Physics
- Kaonic Nuclear Clusters – Production with Antiproton Annihilation



- Mesons and Antiprotons in Nuclear Media
- Anti Deuteron Beams for Charm in Nuclei?

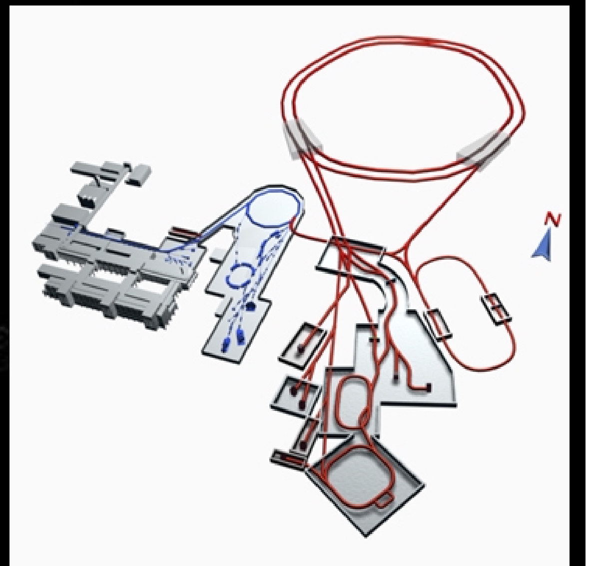


- Can we breed Anti Helium?



- Fundamental Symmetries and Antihydrogen

THE LORD OF THE RINGS



one ring to rule them all. one ring to find them. one ring to bring them all and in the darkness bind them