PANDA at the GSI

- Introduction
- The FAIR-Project and the PANDA-Detector
- Physics Program of the PANDA-Collaboration
  - – Hadron Spectroscopy
  - – Merits of Antiproton Physics
  - – Processes at large $p_\perp$
  - – Properties of Hadrons in Matter
  - – Double Λ-Hypernuclei
  - – Options
- Conclusions

(Thanks to D. Bettoni, G.Boca, P.Kroll, R.Mayer, J.Ritman, B.Seitz)

Introduction: Overview on $\bar{p}$-induced Reactions

High Energy:

$\bar{p}p$-Colliders (CERN, Fermilab)

- Discovery of Z^0, $W^{\pm}$
- Discovery of t-Quark

Medium Energy:

Conventional $\bar{p}$-beams (LBL, BNL, CERN, Fermilab, KEK, ...)

$\bar{p}$-Storage Rings (LEAR (CERN); Antiproton Accumulator (Fermilab))

- $\bar{p}$-N interaction
- Meson Spectroscopy (u, d, s, c)
- $\bar{p}$-nucleus Interaction
- Hypernuclei
- Antihydrogen

Low Energy (Stopped $\bar{p}$'s):

Conventional $\bar{p}$-beams

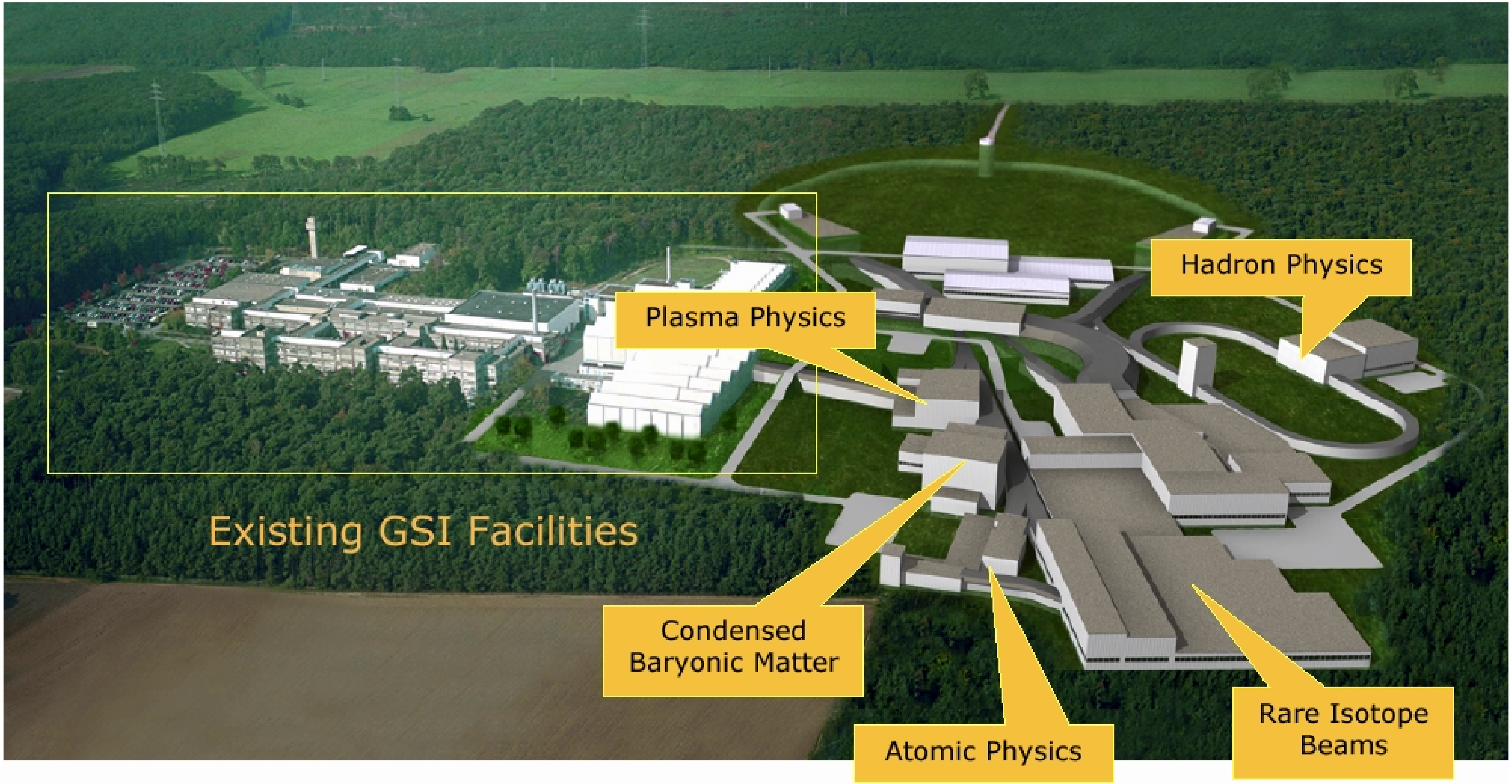
$\bar{p}$-Storage Rings (LEAR, AD (CERN))

- $\bar{p}$-Atoms ($\bar{p}$He)
- $\bar{p}$/p-mass ratio
- Antihydrogen

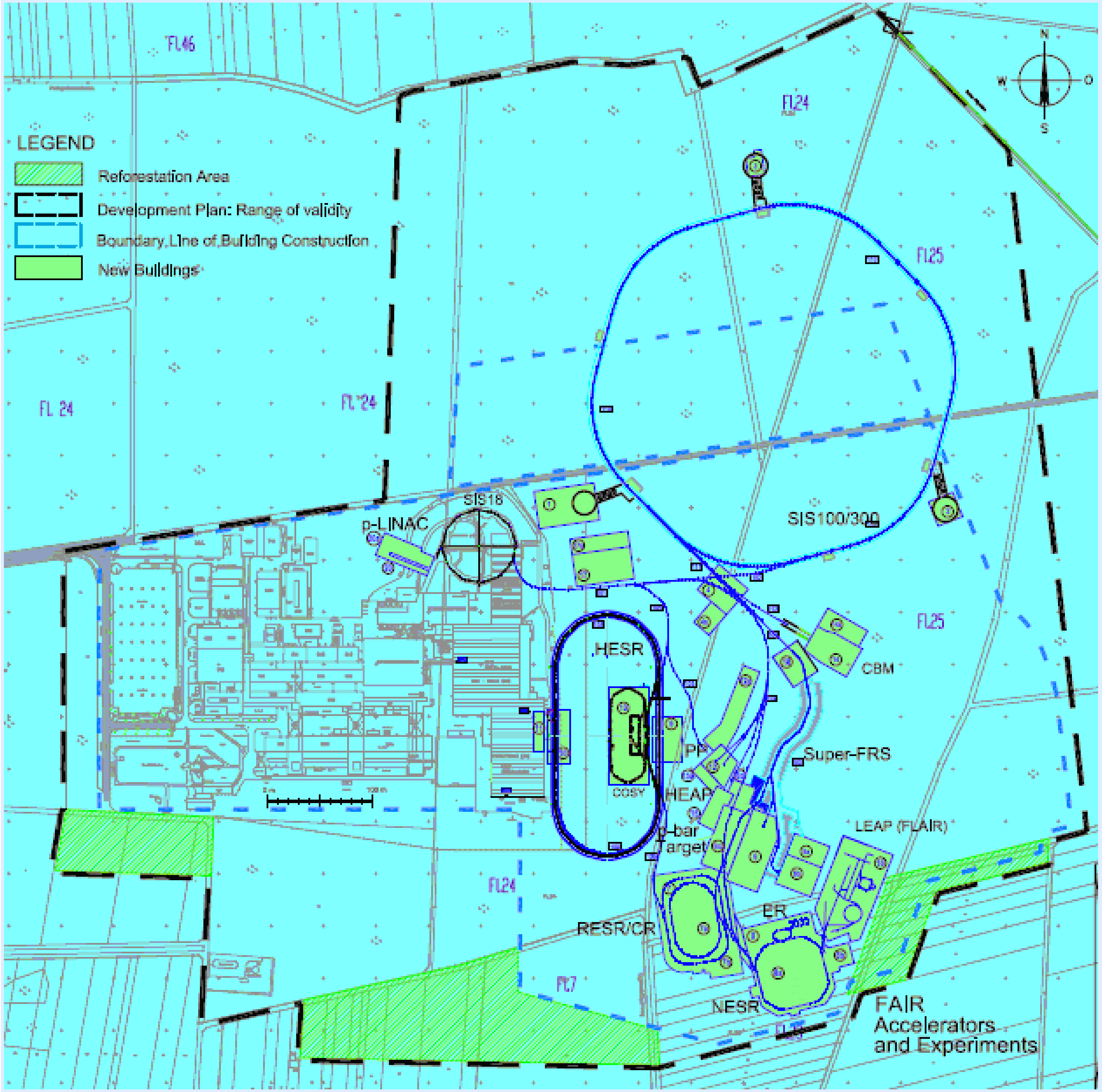
FAIR-Project

Higher $\bar{p}$-energies ($\leq$ 15 GeV)
Cooled $\bar{p}$-beams
Much higher luminosities

GSI now and in the Future



HESR at FAIR



FAIR

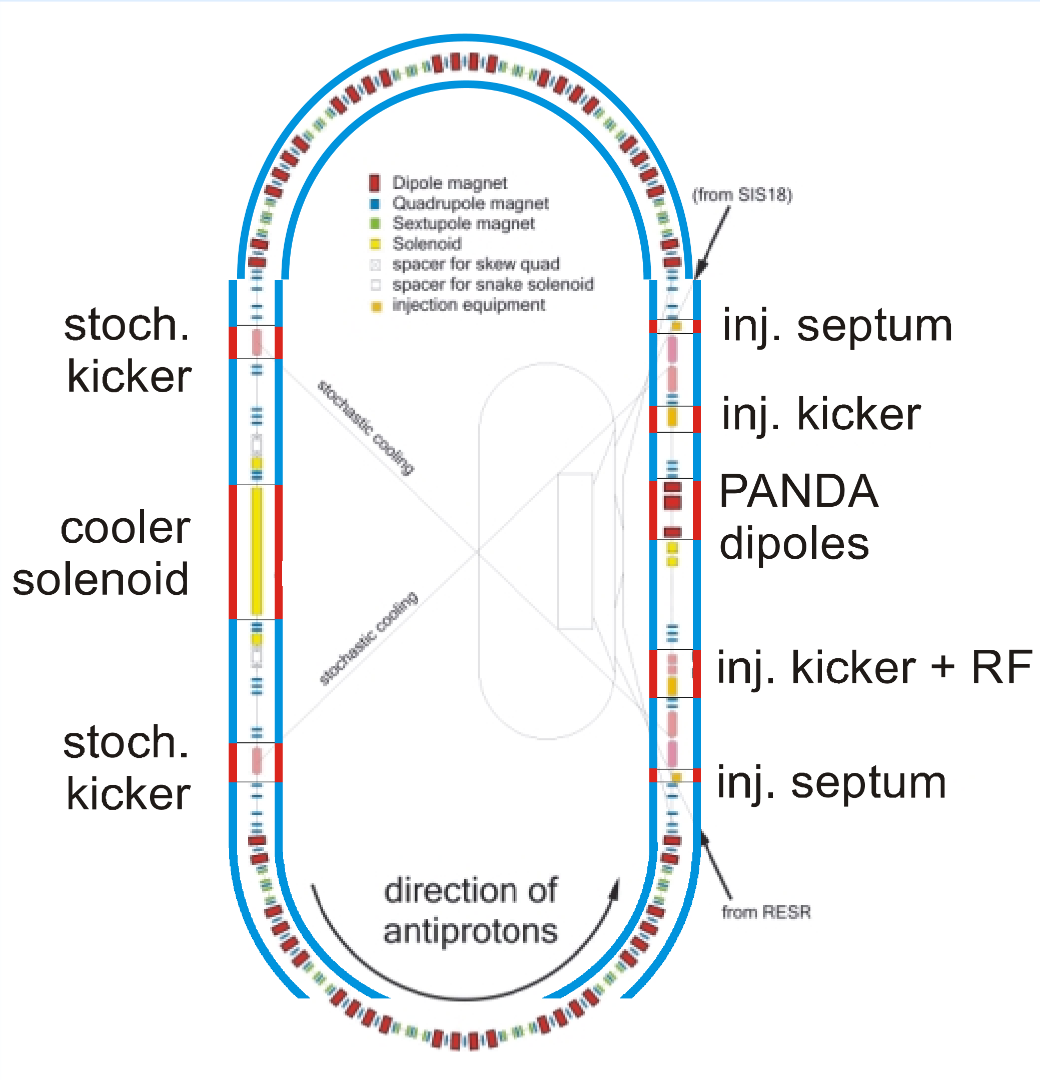
Facility for **A**ntiproton and **I**on **R**esearch

HESR

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

Antiproton Physics at high Energies

HESR: System Design

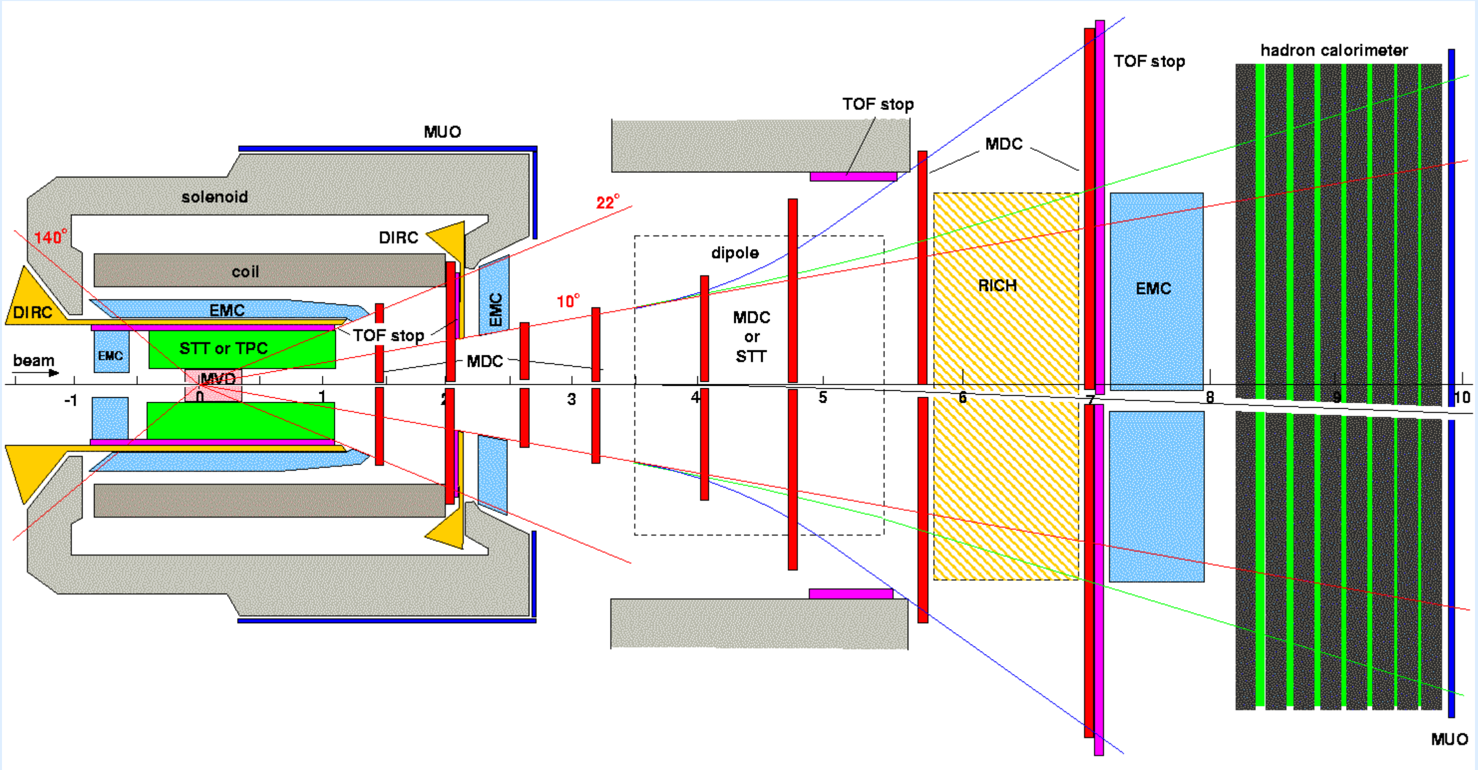


- Circumference 574 m
- Momentum (energy) range
  1.5 to 15 GeV/c (0.8-14.1 GeV)
- Injection of (anti-)protons from RESR at 3.8 GeV/c
- Acceleration rate 0.1 GeV/c/s
- Electron cooling up to 8.9 GeV/c
  (4.5 MeV electron cooler)
- Stochastic cooling above
  3.8 GeV/c

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}

The PANDA Detector



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

R & D – Work

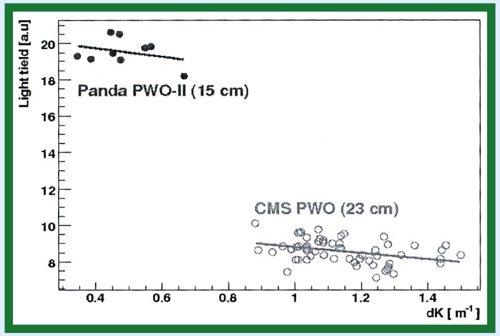
Example: E.-M. Calorimeter (Pb WO_4/PWO)

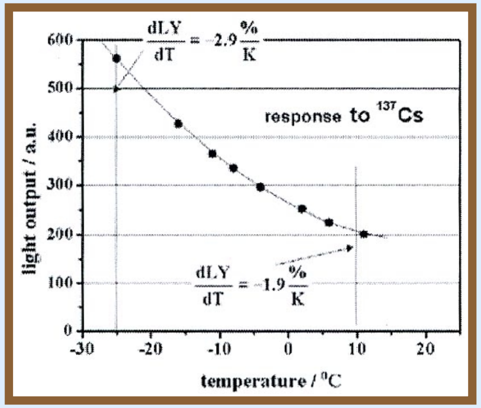
Requirements: Fast Response

Good energy resolution, even at low energies

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

Better material → Increase of light yield ≈ 100%

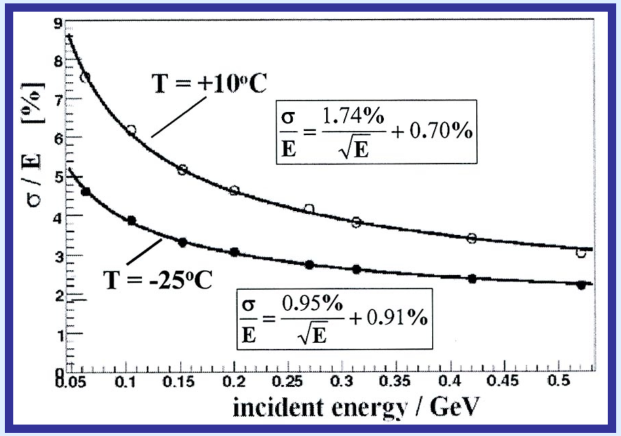




Operation of crystals at –25°C

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)

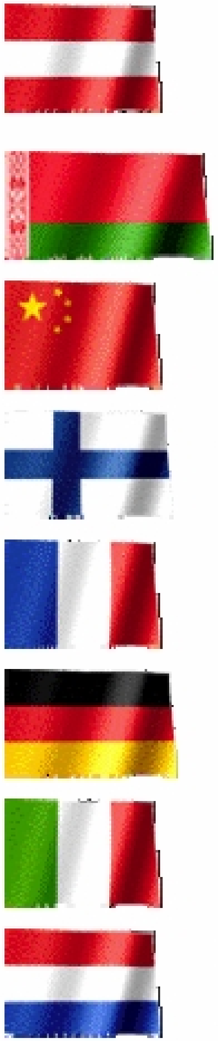
Signals comparable to Photo-Multiplier Readout

➥ Operation in high magnetic fields

R & D – Work

- Prototypes for Vertex-Detector / Tracker options in preparation
- Design of the other subdetectors in progress
- Crude simulation studies done
- Final simulation based on GEANT4 far advanced

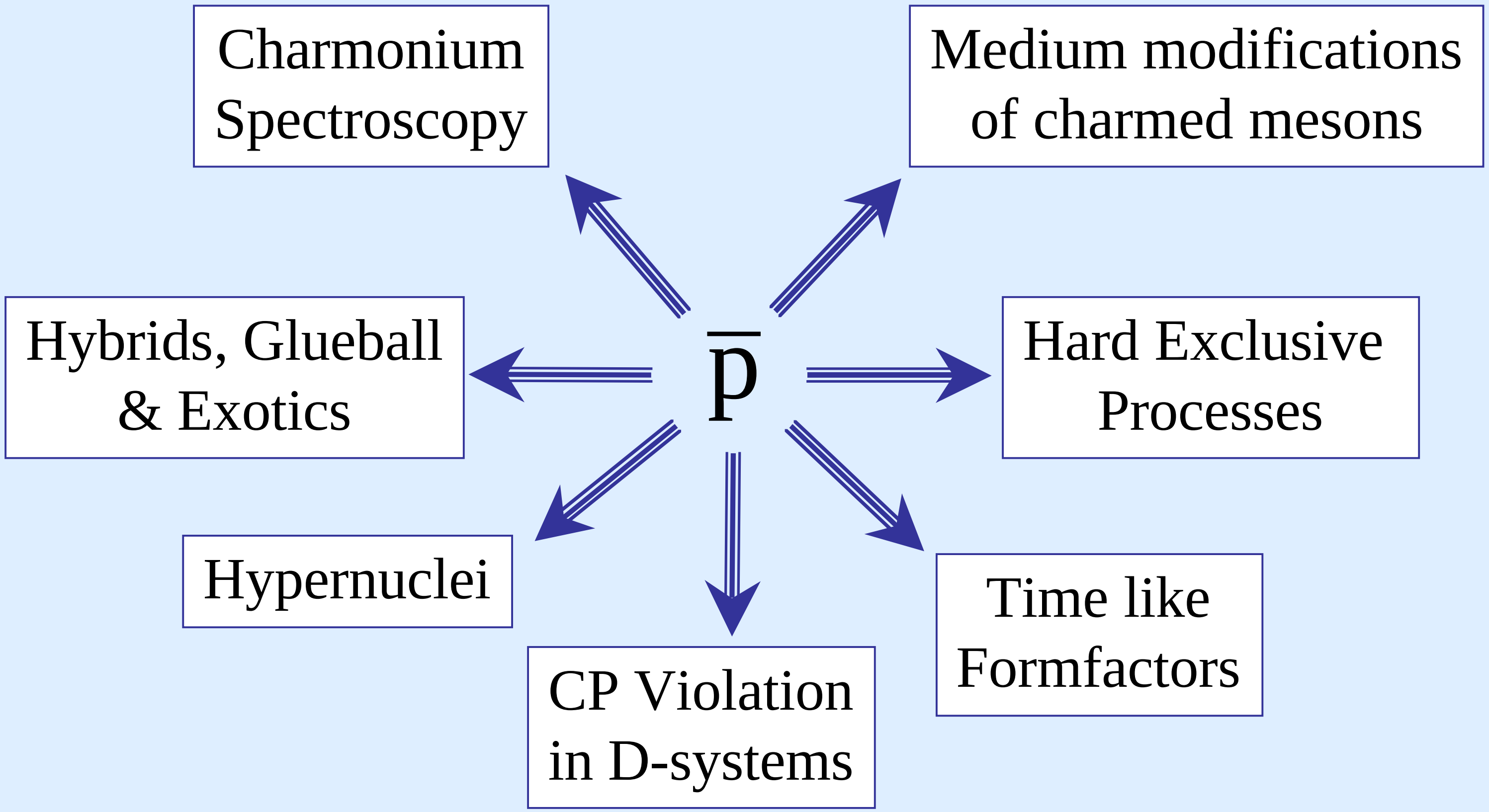
PANDA Collaboration



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

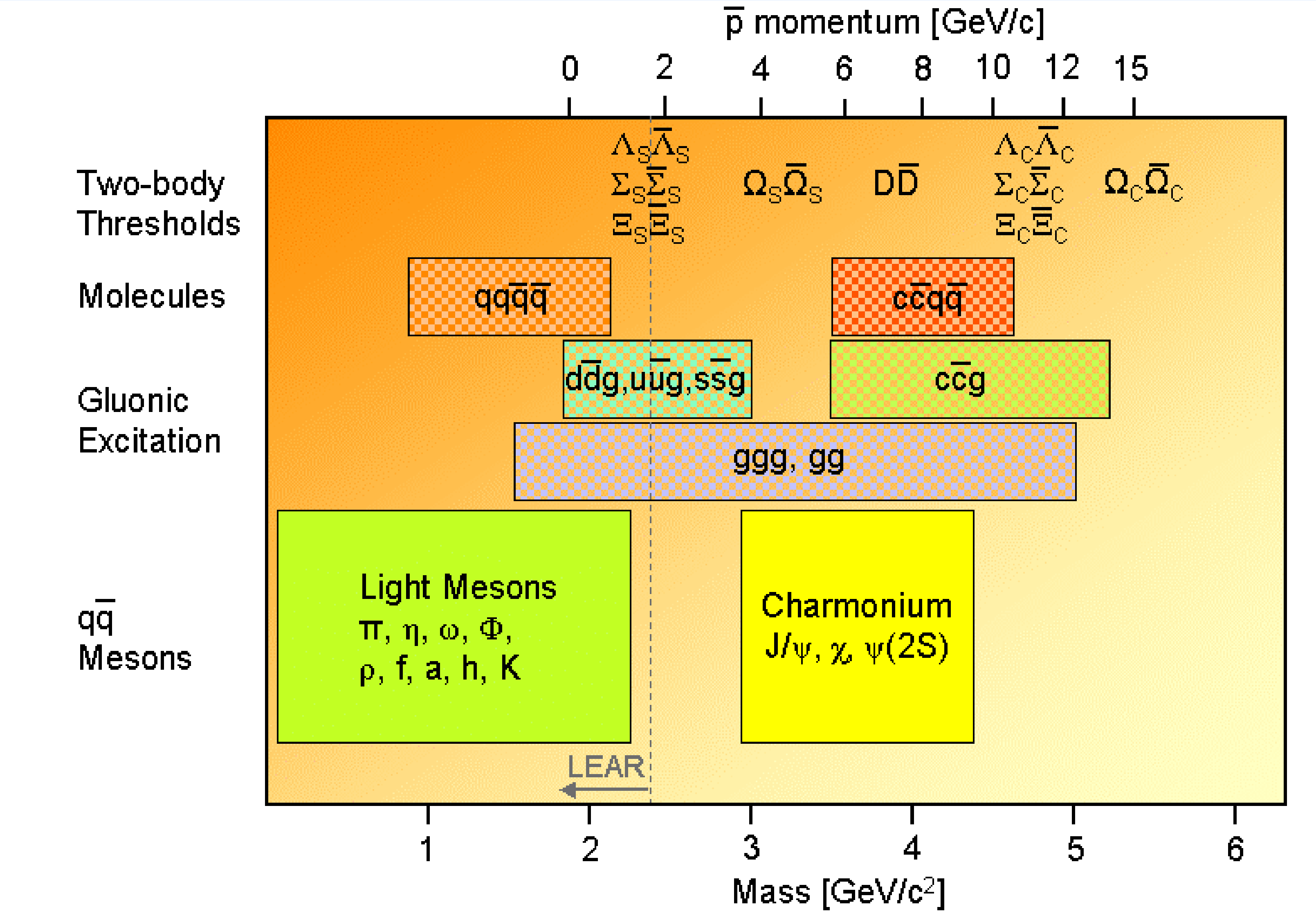
15 countries – 47 institutes – 370 scientists

Physics Program of PANDA



PANDA – Hadron Spectroscopy Program

QCD systems to be studied with PANDA



PANDA – Hadron Spectroscopy Program

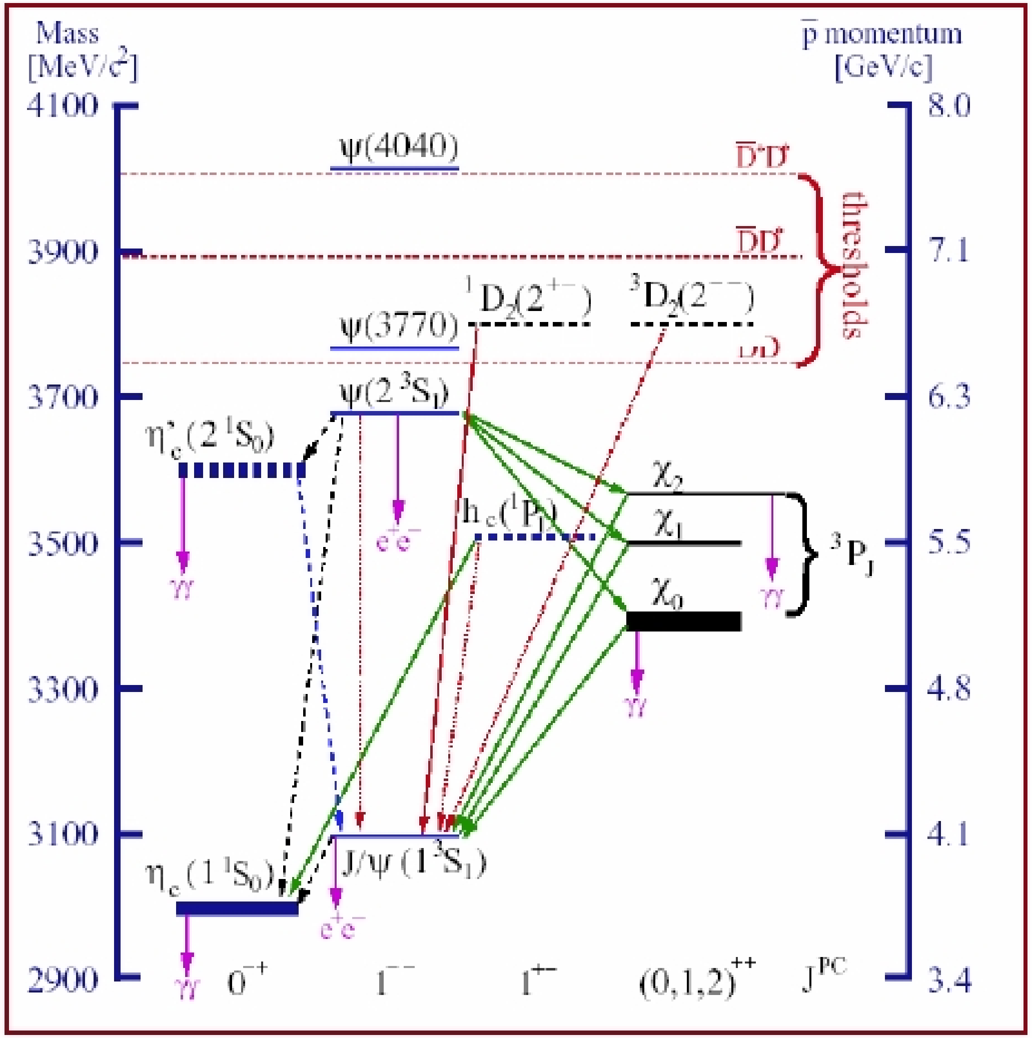
Production Rates (1-2 $(fb)^{-1}/y$)

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

Charmonium Spectroscopy



- 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

Charmonium Spectroscopy

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

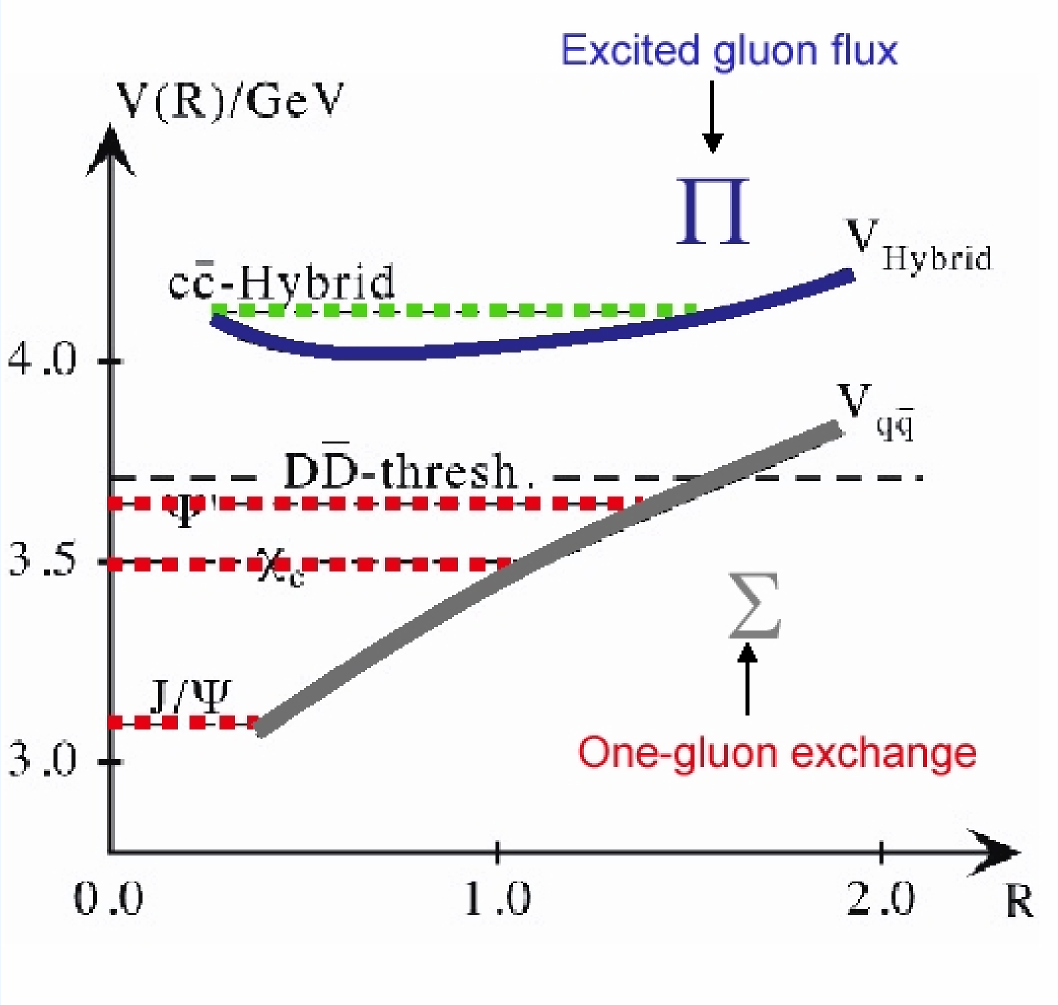
$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

States above the DD threshold

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

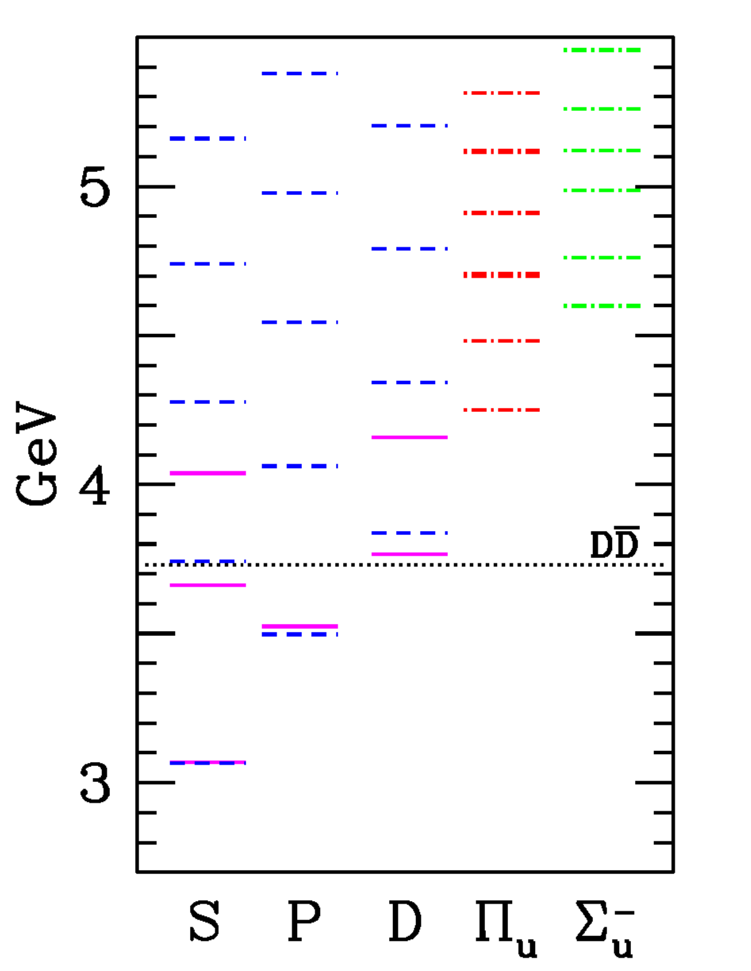
Nature of the new X(3872)/ X(3940), Y(3940) and Z(3940)

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)

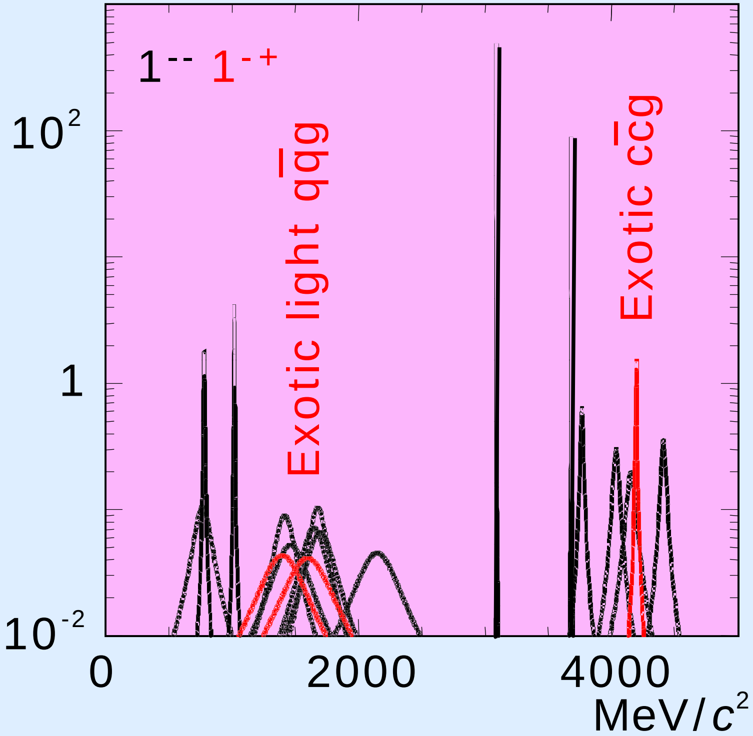
Charmonium Hybrids



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

Decay modes:
J/ψω; D*D̄

Small overlap with cc̄-states



PANDA – Hadron Spectroscopy Program

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.

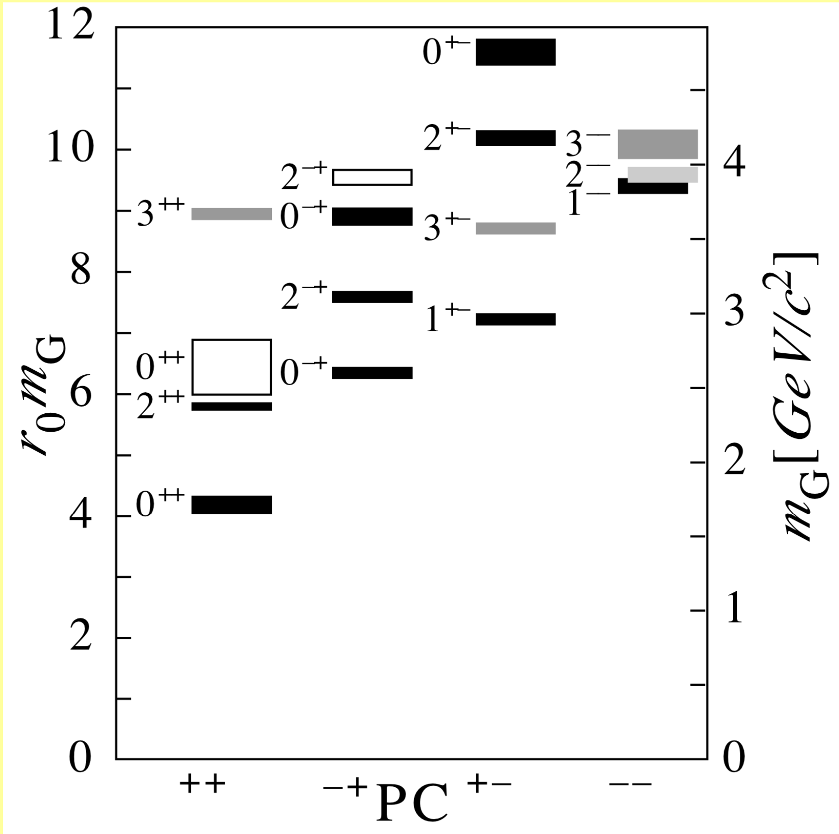
$J^{PC} = 2^{+-}$ (4.3 GeV/c^2)

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

Open Charm States

New observations

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

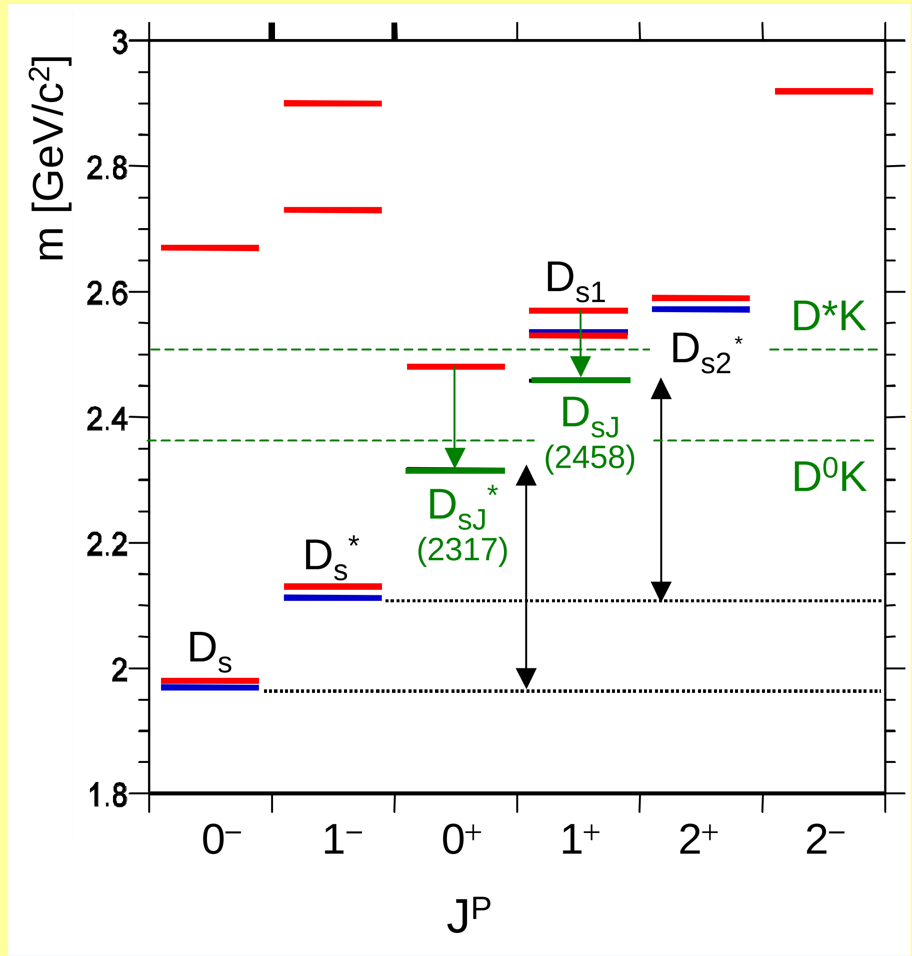
- Potential model
- Old measurements
- New observations

(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: $\bar{p}p \rightarrow \chi_{1,2}$

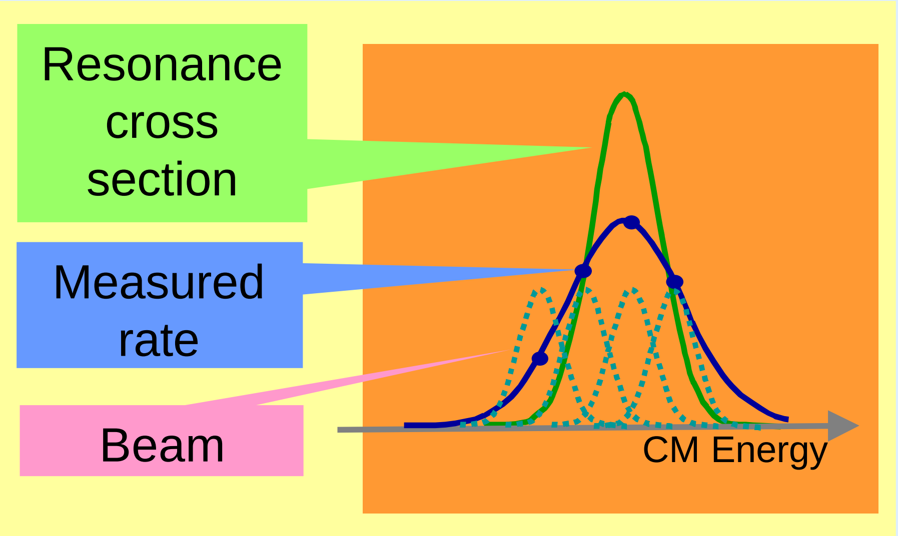
$\quad\quad \hookrightarrow \gamma J/\psi$

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

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

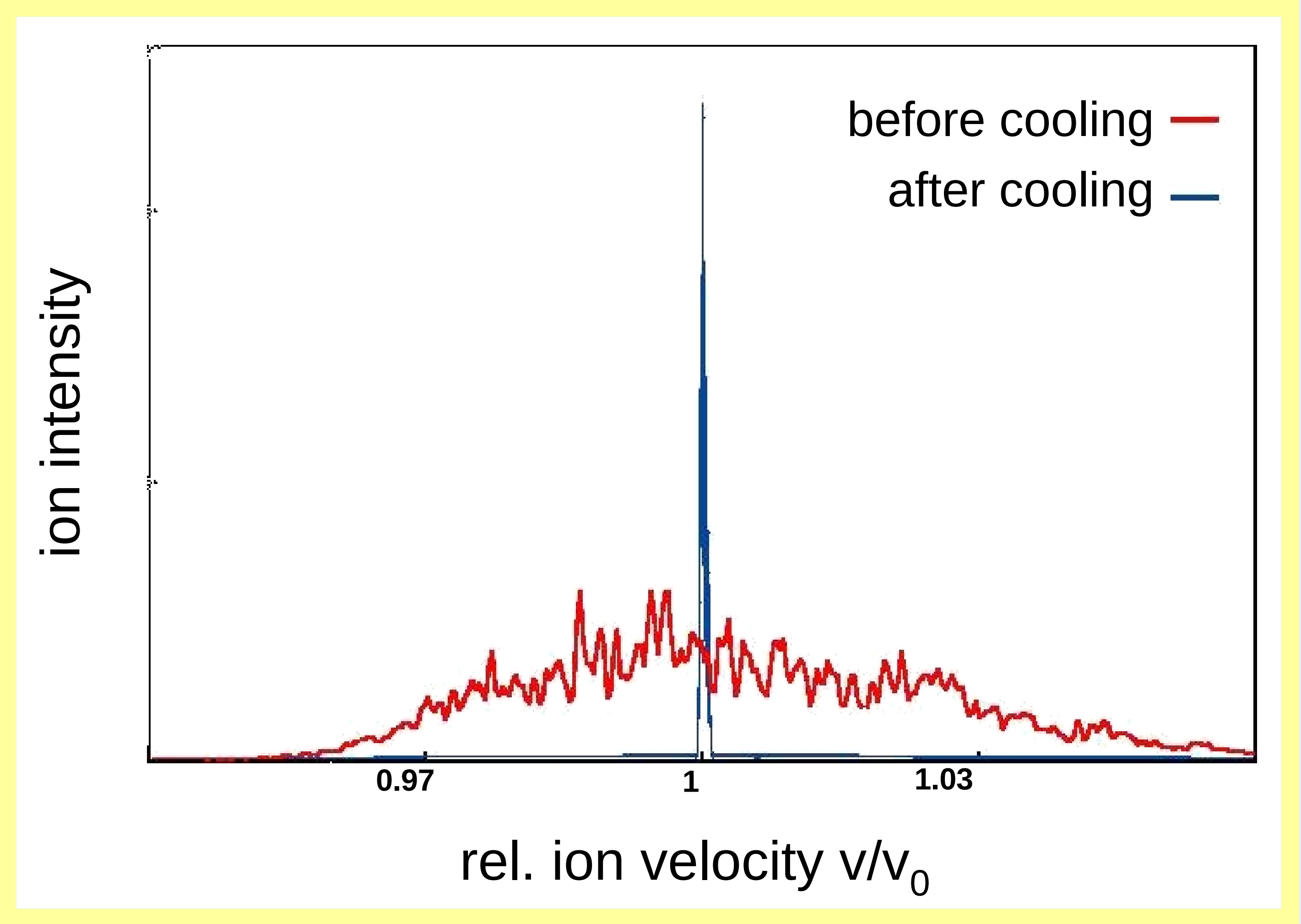
$$e^+e^- \rightarrow J/\psi \quad , \quad e^+e^- \not\rightarrow \chi_{1,2}$$

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



Merits of Antiprotons (2)

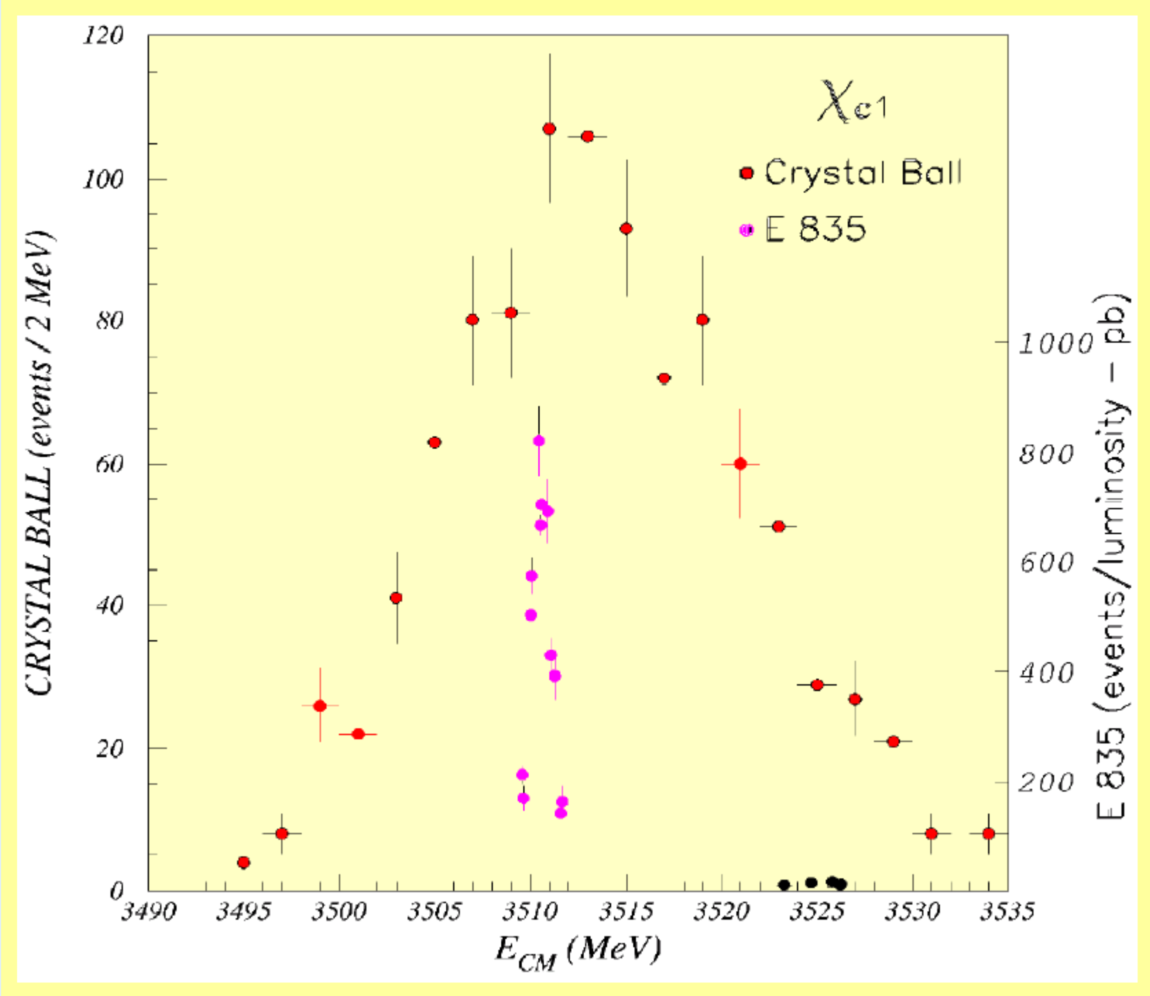
p̄-beams can be cooled → Excellent beam momentum resolution



High Resolution of M and Γ

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

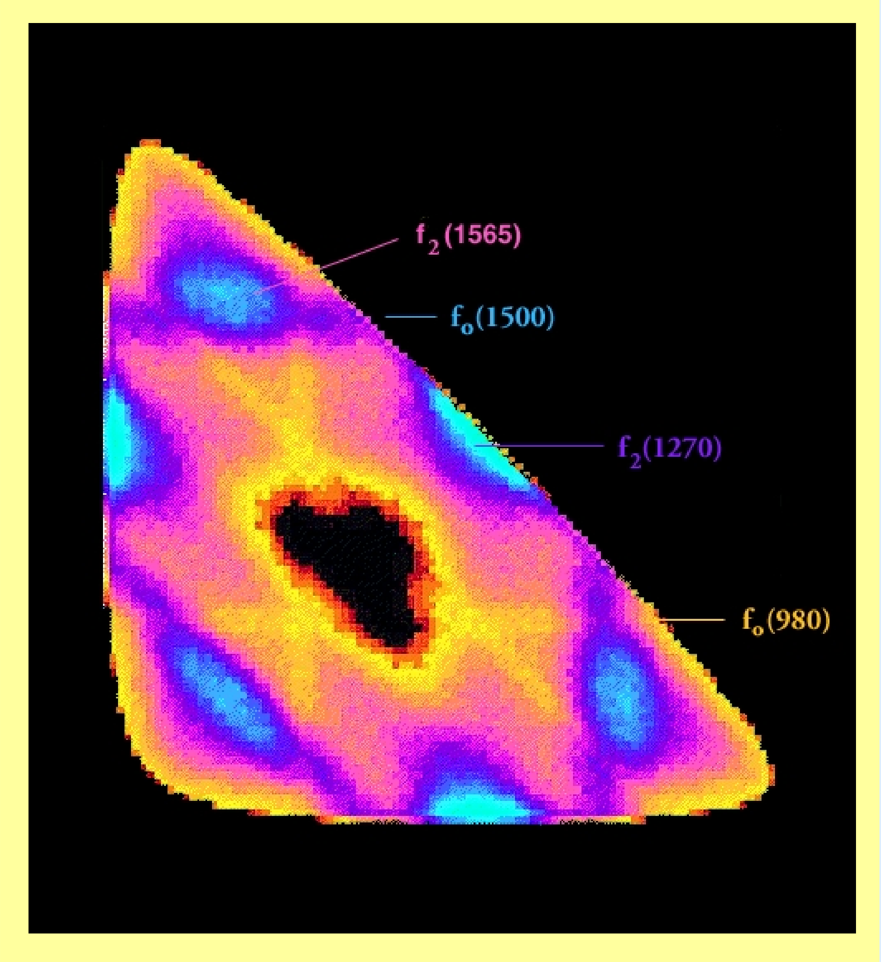
⇒ $\Delta p/p \sim 10^{-5}$ needed



Merits of Antiprotons (3)

$\bar{p}p$-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

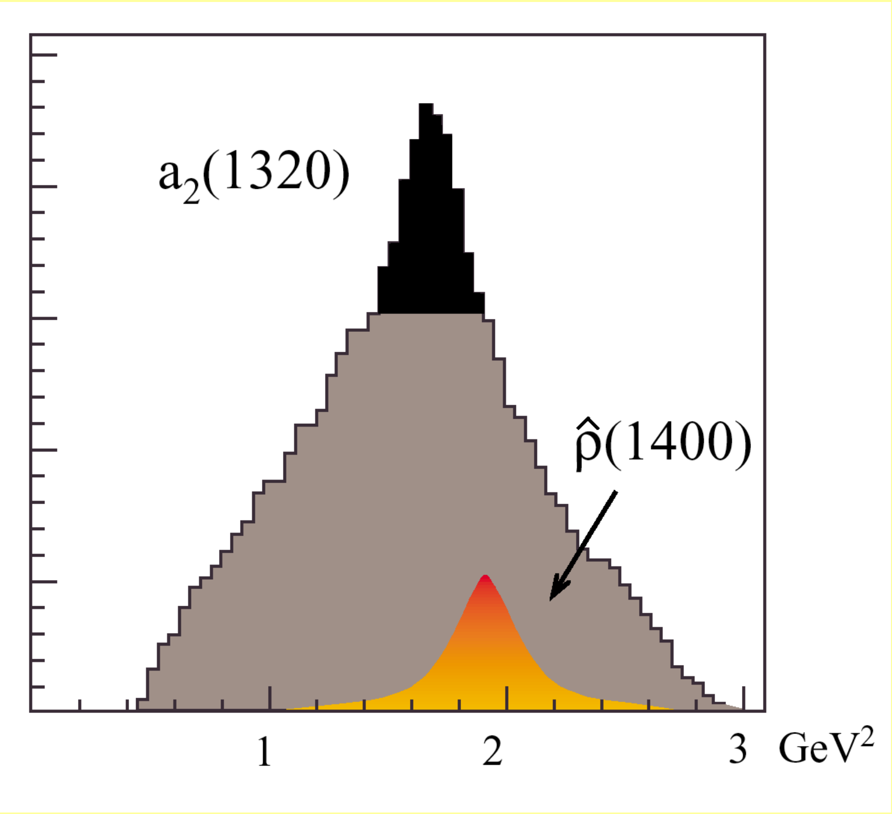


Low final state multiplicities: Clean spectra, Good for PWA analyses

Merits of Antiprotons (4)

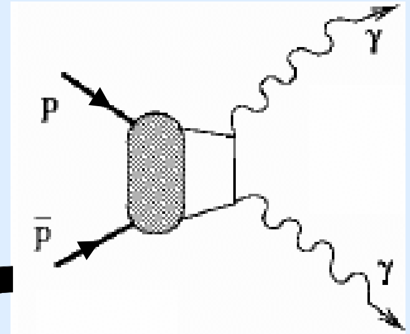
High probability for production of exotic states

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



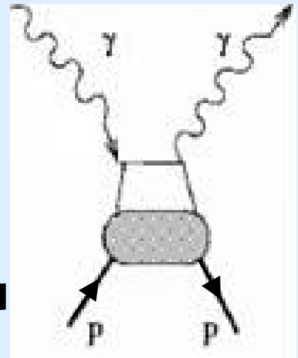
Processes at large $p_\perp$

Annihilation into two Photons:



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

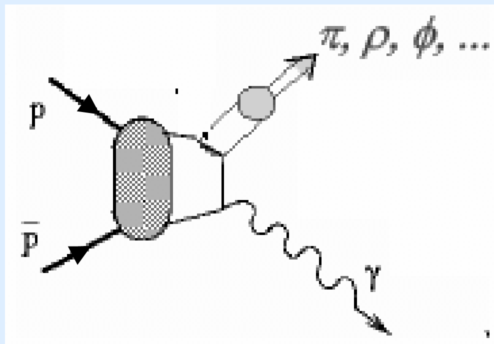
Prediction (from) : 15pb

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

Problem: Background from ;

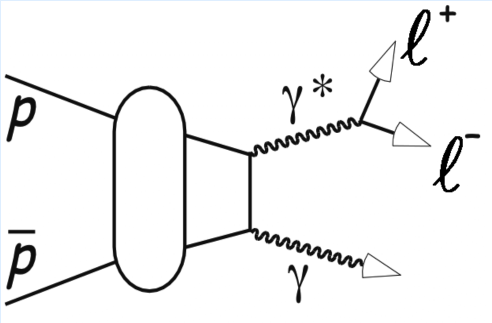
Related processes: $\bar{p}p \to \gamma + \pi, \rho, \omega, \phi$

Timelike GPD´s

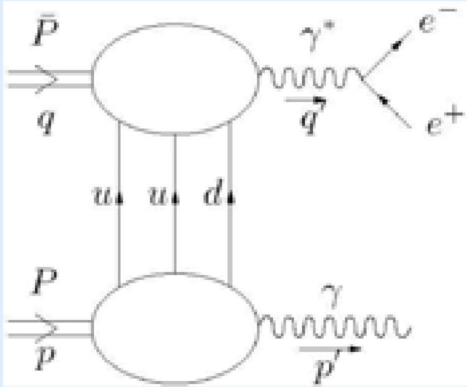


Processes at large $p_\perp$

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

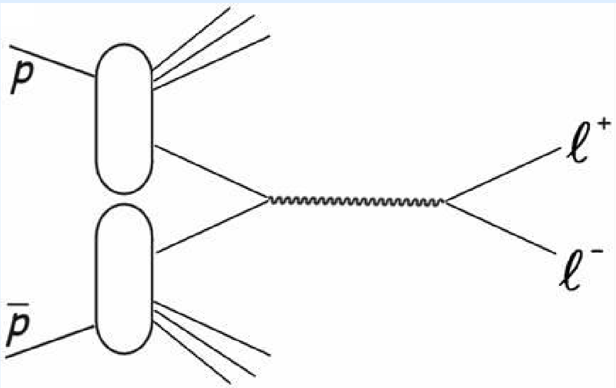


or



Comparison between predictions and data ⟶ Check of Factorisation

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



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

Boer-Mulders-Function

Time like Proton Form-Factor

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

Assumption: $|G_E| = |G_M|$

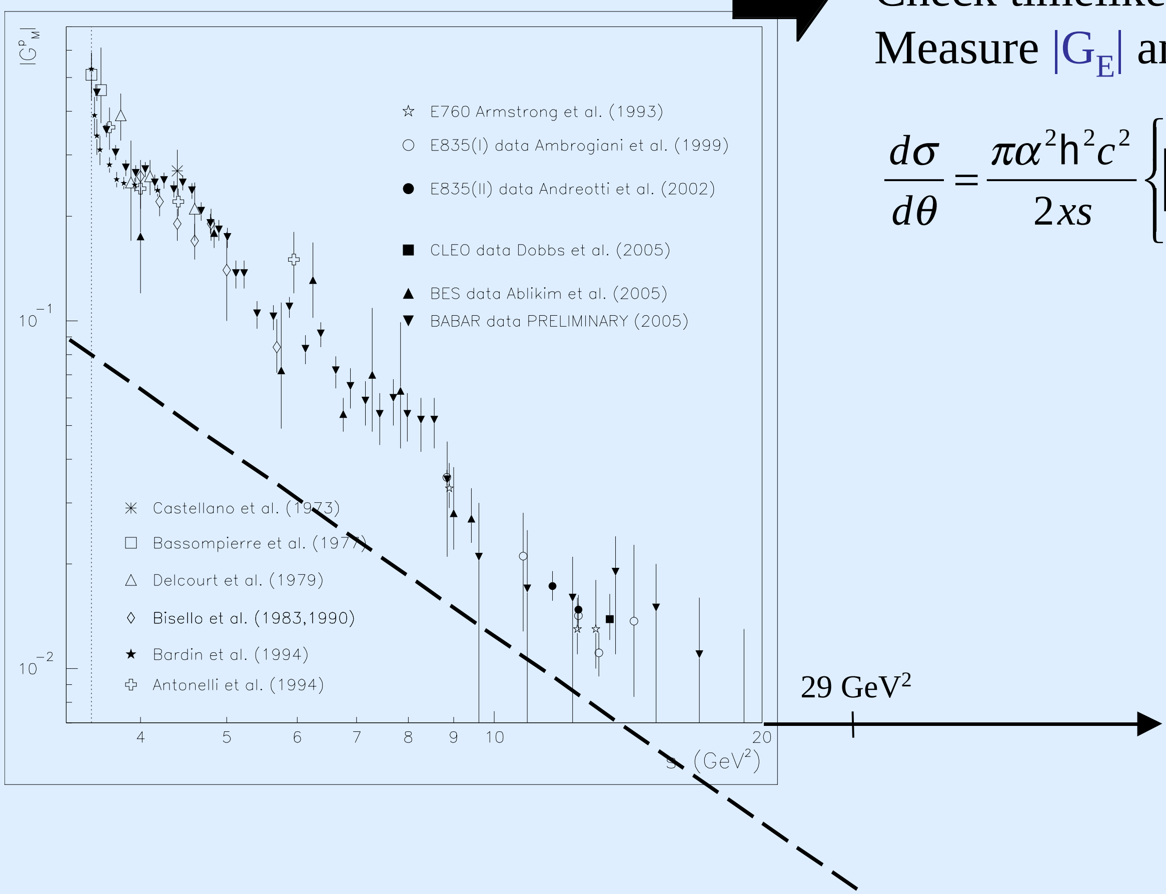
PANDA: Much wider angular acceptance and higher statistics

Measure for higher Q^2

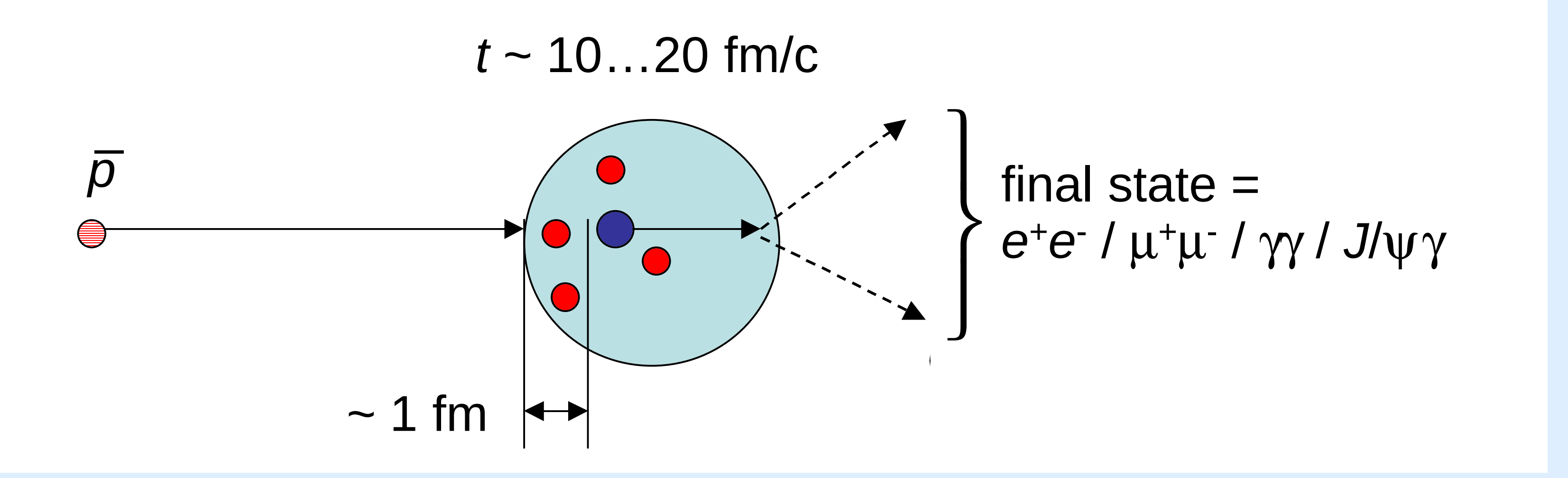
Check timelike/spacelike equality

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

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



Properties of Hadrons in Matter



p̄´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:

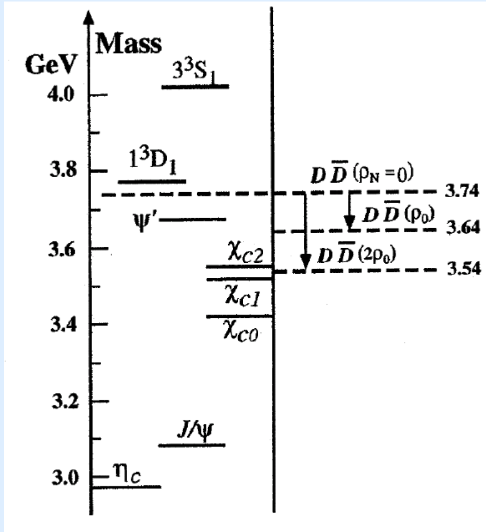
- Fermi motion of nucleons (≈ 200 MeV)
- Collisional broadening of states (≈ 20 MeV)

} 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

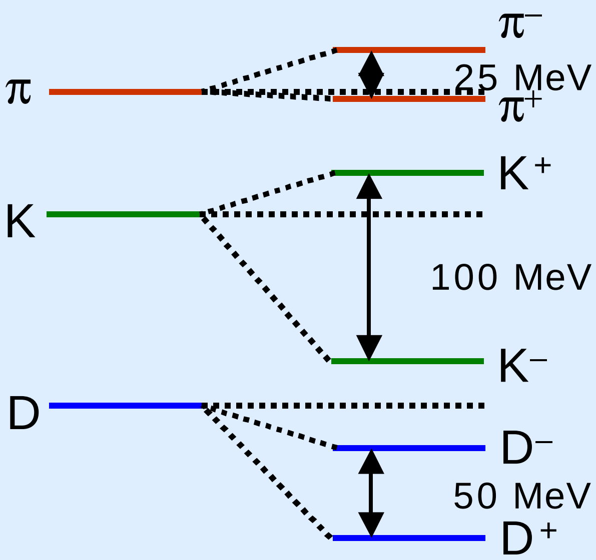
Properties of Hadrons in Matter



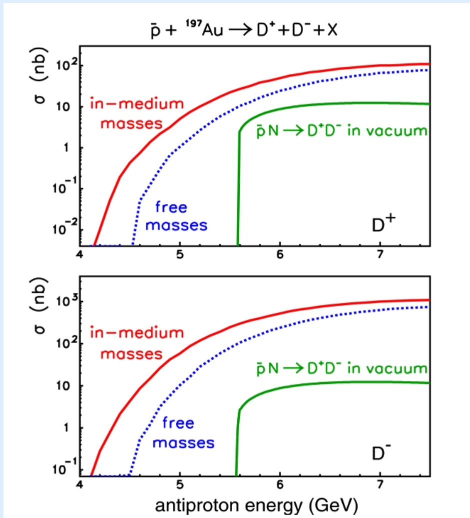
Predictions:

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.

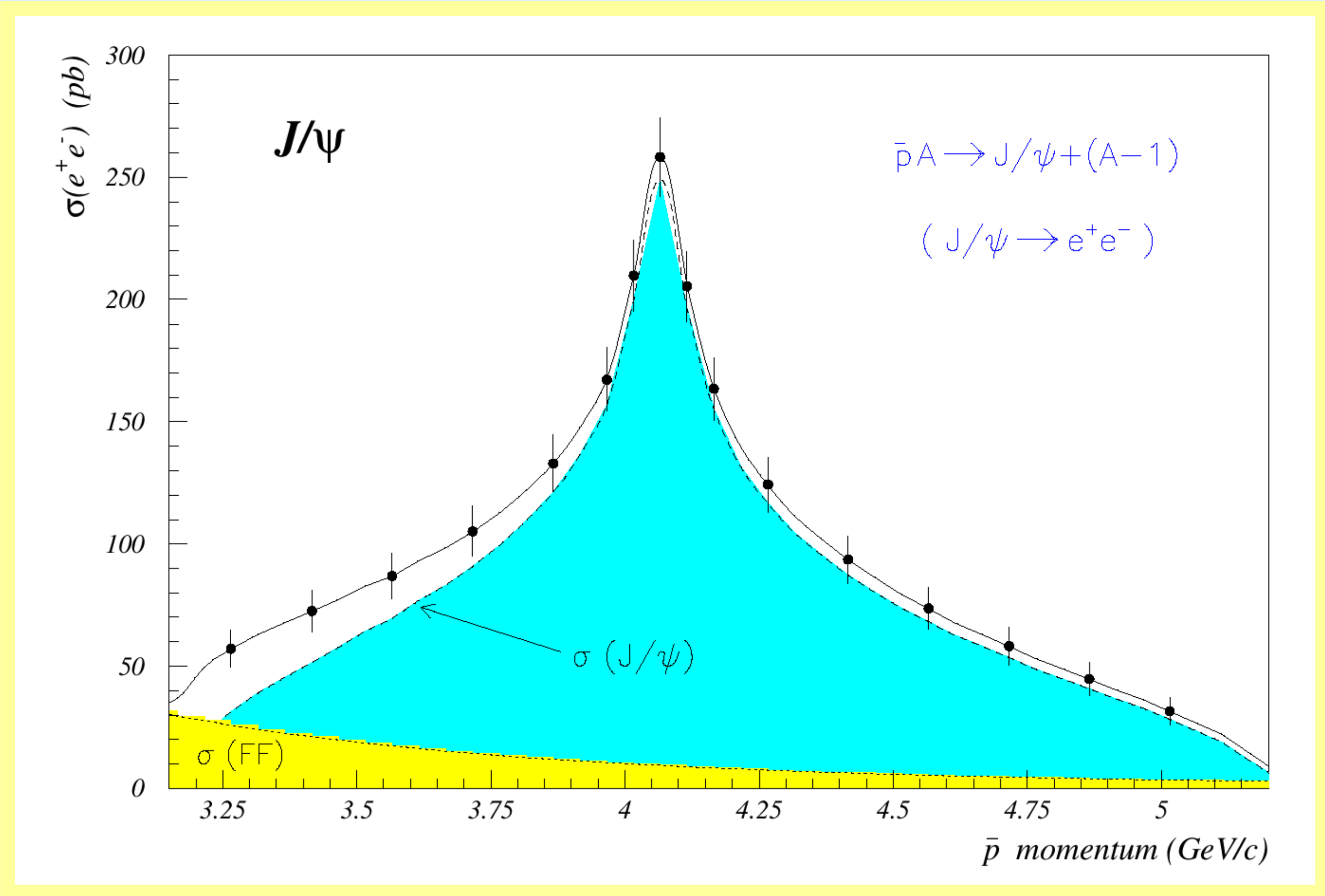


Calculation: A. Sibirtsev et al.,
Eur. Phys. J A6 (1999) 351

J/ψ, χ Absorption in Nuclei

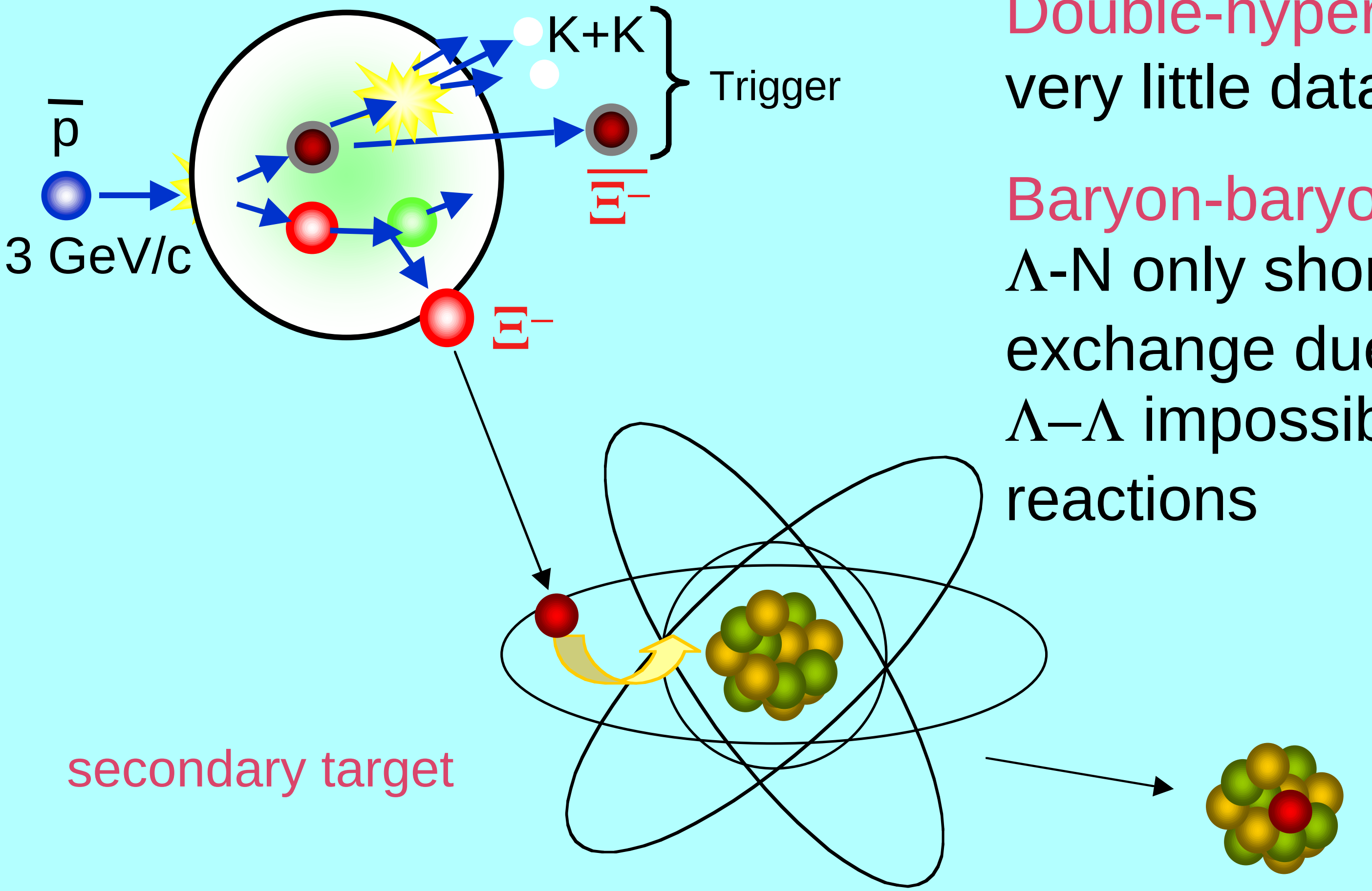
J/ψ absorption cross section in nuclear matter

$\bar{p} + A \rightarrow J/\psi + (A-1)$ → $\sigma_{tot}\,(J/\psi\ N)$ *Important for QGP*



Double Λ-Hypernuclei

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



Double-hypernuclei: very little data

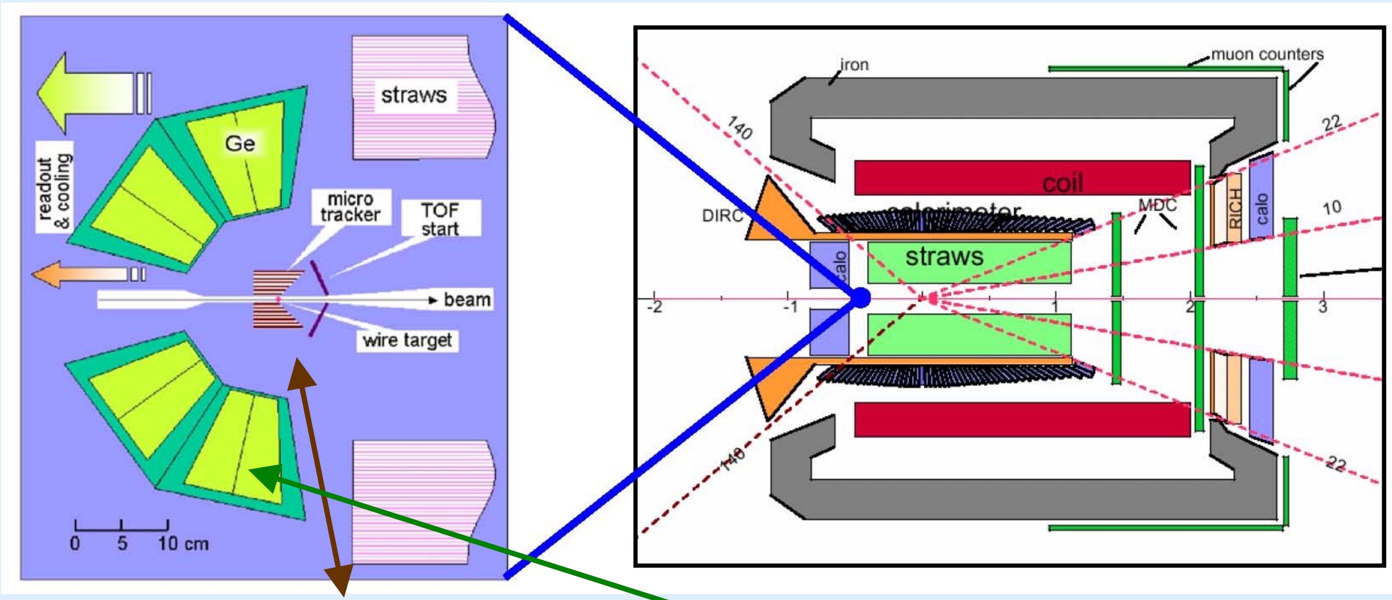
Baryon-baryon interactions:
Λ-N only short ranged (no 1π exchange due to isospin)
Λ–Λ impossible in scattering reactions

Ξ^-(dss) **p**(uud) ⇒ Λ(uds) Λ(uds)

Double Λ-Hypernuclei: Detector Requirements

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)

Physics Program / Further Options

– 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

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

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

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

Prediction (SM) ≈ $2x10^{-5}$ HESR: 1 year of beamtime

– CP-Violation in charmed region

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

Direct CP-Violation (SCS)

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

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

Time Schedule of the Project

2005 (Jan 15)	Technical Proposal (TP) with milestones. Evaluation and green light for construction.
2005 (May)	Project starts (mainly civil infrastructure).
2005-2008	Technical Design Report (TDR) according to milestones set in TP.
2006	High-intensity running at SIS18.
2009	SIS100 tunnel ready for installation.
2010	SIS100 commissioning followed by Physics.
2011-2013	Step-by-step commissioning of the full facility.

Running Strategy

- Many of the discussed experiments can be performed simultaneously running different triggers in parallel

- Spectroscopy and Structure functions

  1st step: Overview of physics / Determination of yet unknown rates
  Production experiments at selected energies

  2nd step: Scan experiments in fine steps

- Dedicated Runs for Hadron Properties in Matter and Hypernuclei

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