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

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Outline

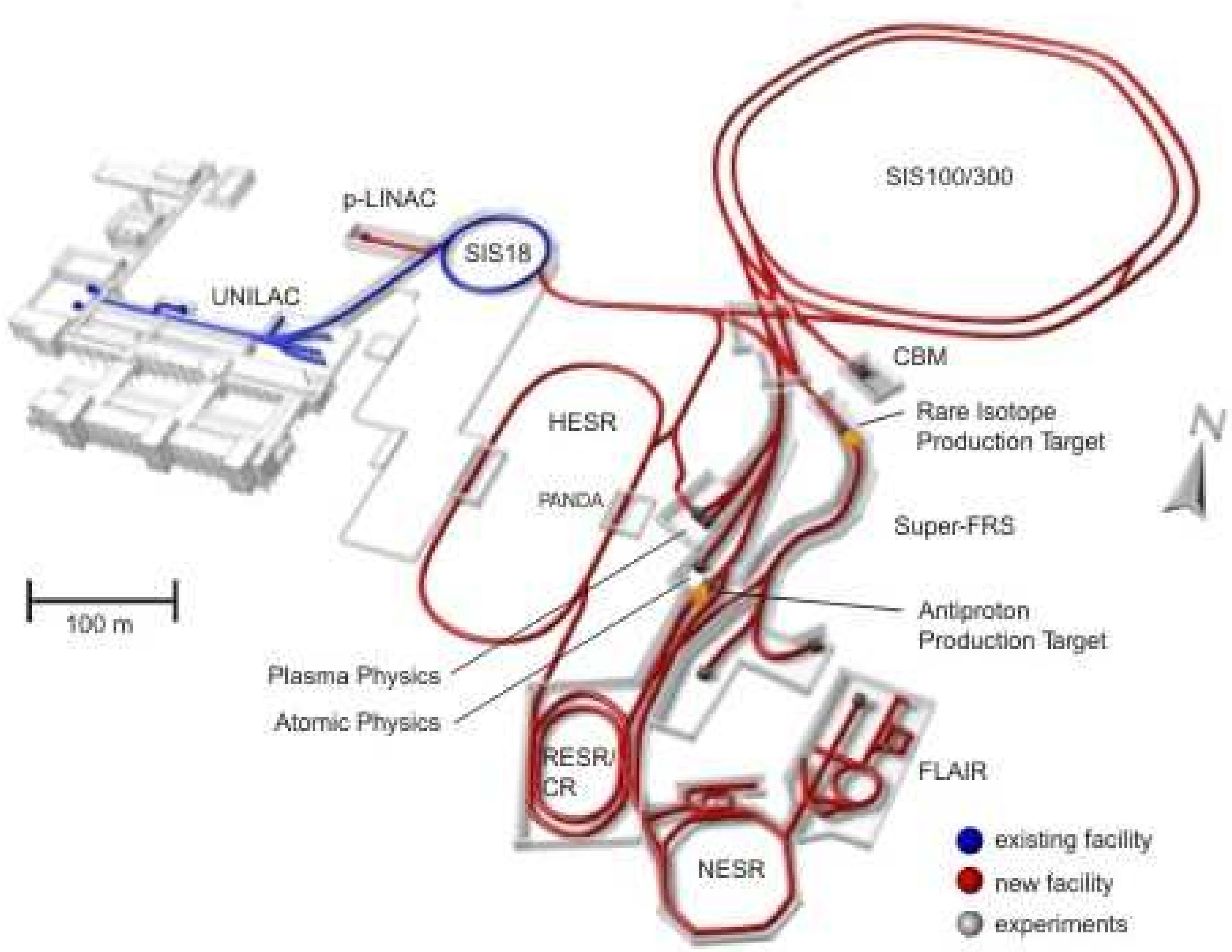
- Introduction
  - The FAIR facility
  - Experimental Method
- The $\overline{\text{P}}$ANDA experiment
  - Experimental Setup
  - The $\overline{\text{P}}$ANDA Physics Program
- Physics Performance
- Summary and Outlook

GSI Helmholtz Center and FAIR

Unique Accelerator and Experimental Facilities for Forefront Research in the Areas:

- **Hadron Structure and Dynamics**
- **Nuclear and Quark Matter**
- **Physics and Chemistry of Super-heavy Elements**
- **Nuclear Structure and Astrophysics**
- **Atomic Physics, Plasma Physics, Materials Research, Radiobiology, ...**
- **Accelerators and Detectors**

The FAIR Complex



High-Energy Storage Ring

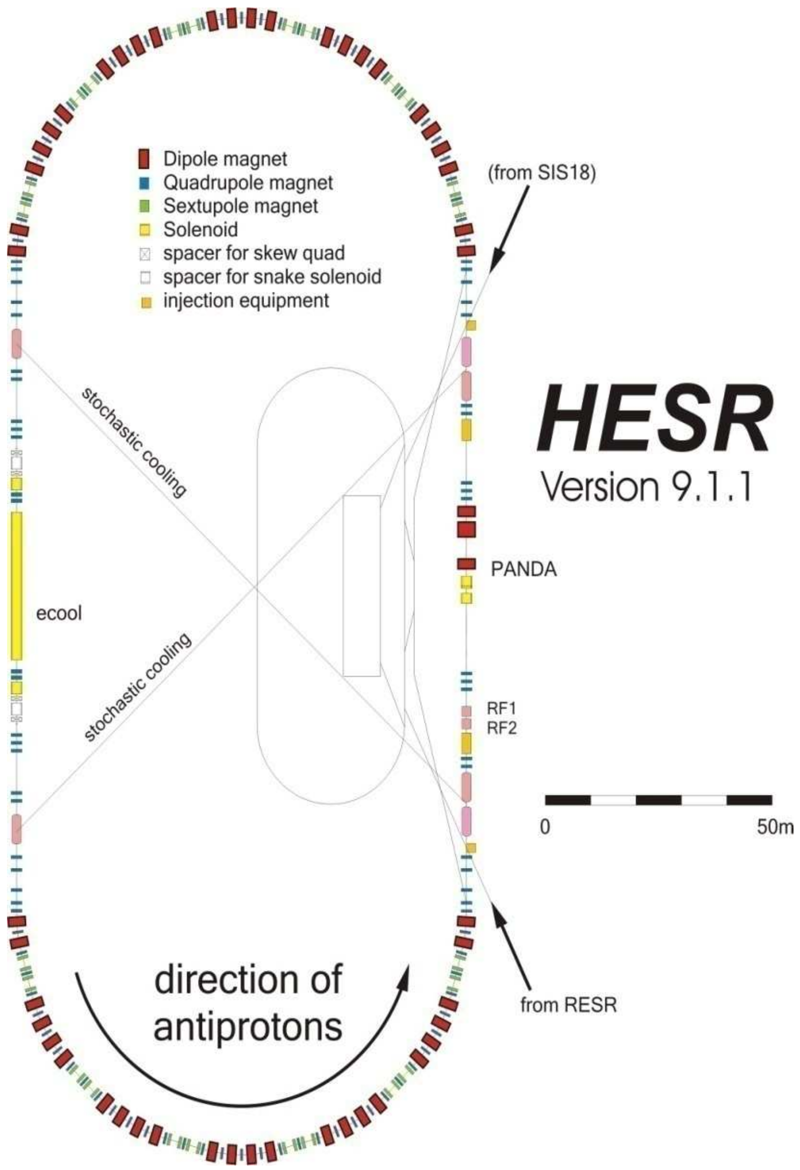
- Production rate $2x10^7$/sec
- P_{beam} = 1.5 – 14.5 GeV/c
- N_{stored} = $5x10^{10}$ $\bar{p}$
- Internal Target

High resolution mode

- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

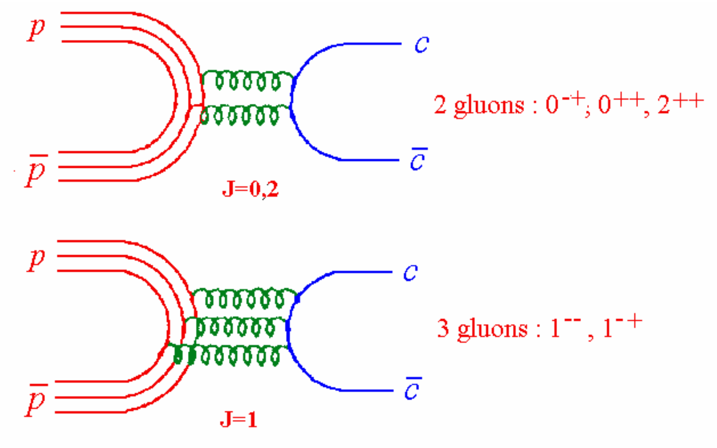
High luminosity mode

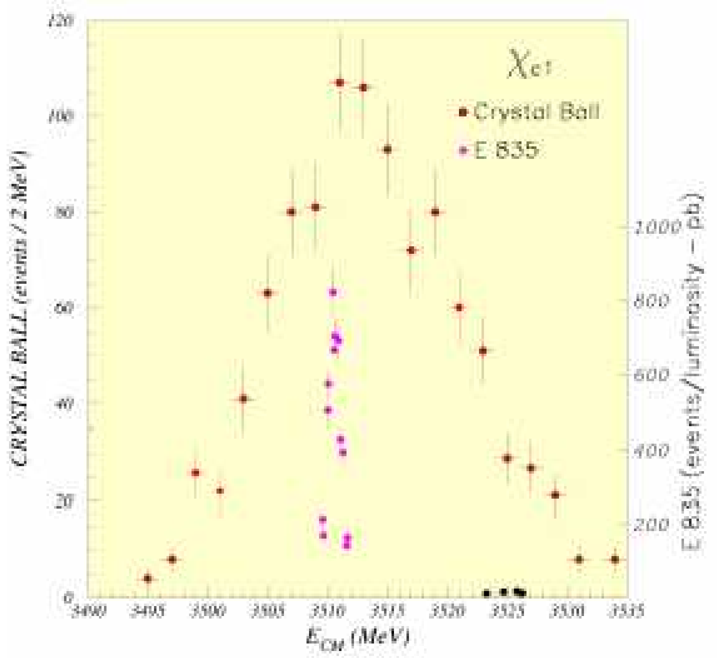
- Lumin. = 2 x 10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



$\bar{p}p$ Annihilation

In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all non-exotic quantum numbers.





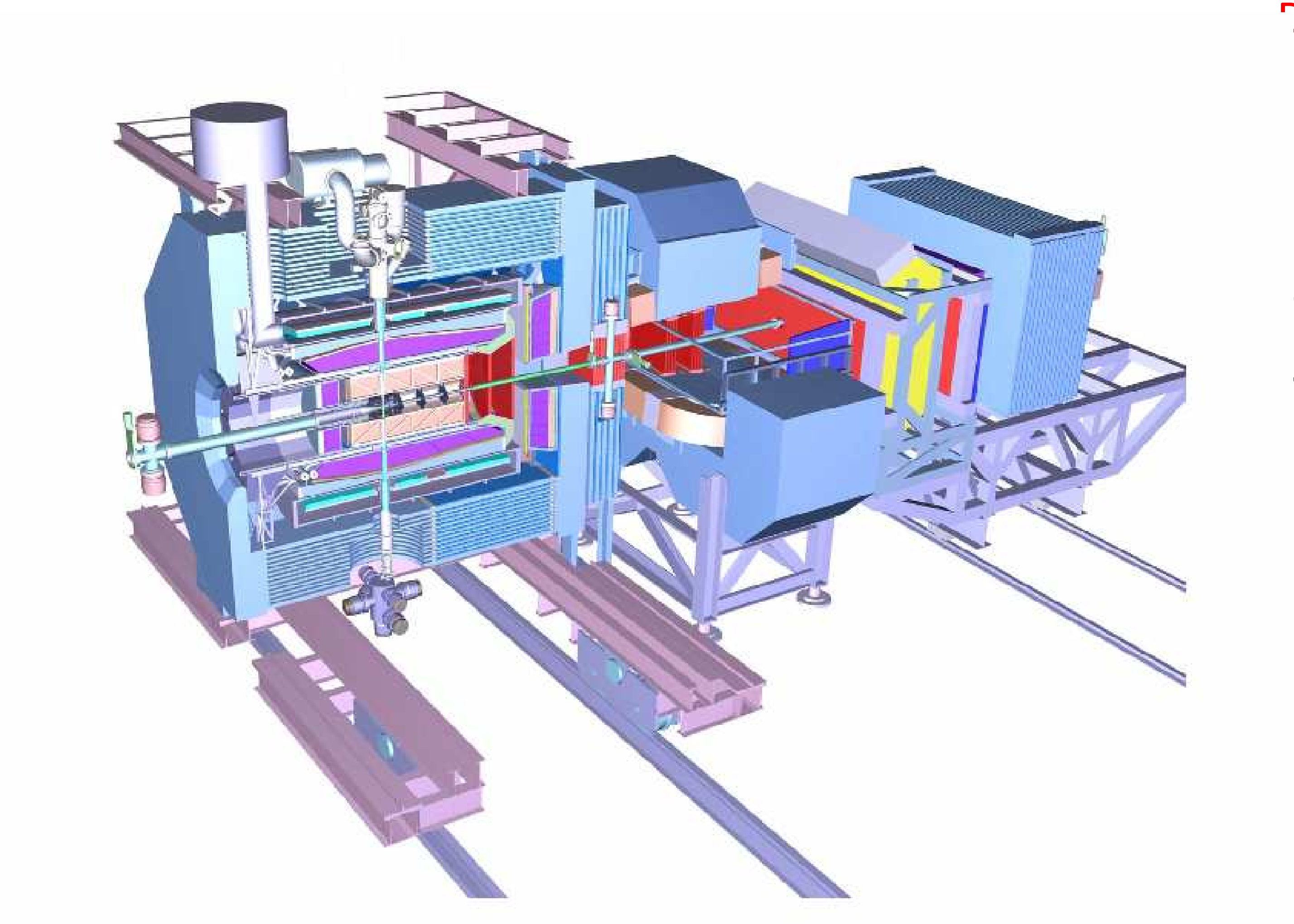
The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

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

Experimental Setup

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

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



Detector Requirements

(Nearly) 4π solid angle coverage (partial wave analysis)
High-rate capability (2×10^7 annihilations/s)
Good PID (γ, e, μ, π, K, p)
Momentum resolution (≈ 1 %)
Vertex reconstruction for D, K^0_s, Λ
Efficient trigger
Modular design
Pointlike interaction region
Lepton identification
Excellent calorimetry
- Energy resolution
- Sensitivity to low-energy photons

PANDA Collaboration

At present a group of **410 physicists** from 53 institutions of 16 countries

Austria – Belaruz - China - France - Germany –India - Italy – Netherlands Poland – Romania - Russia – Spain - Sweden – Switzerland - U.K. – U.S.A..

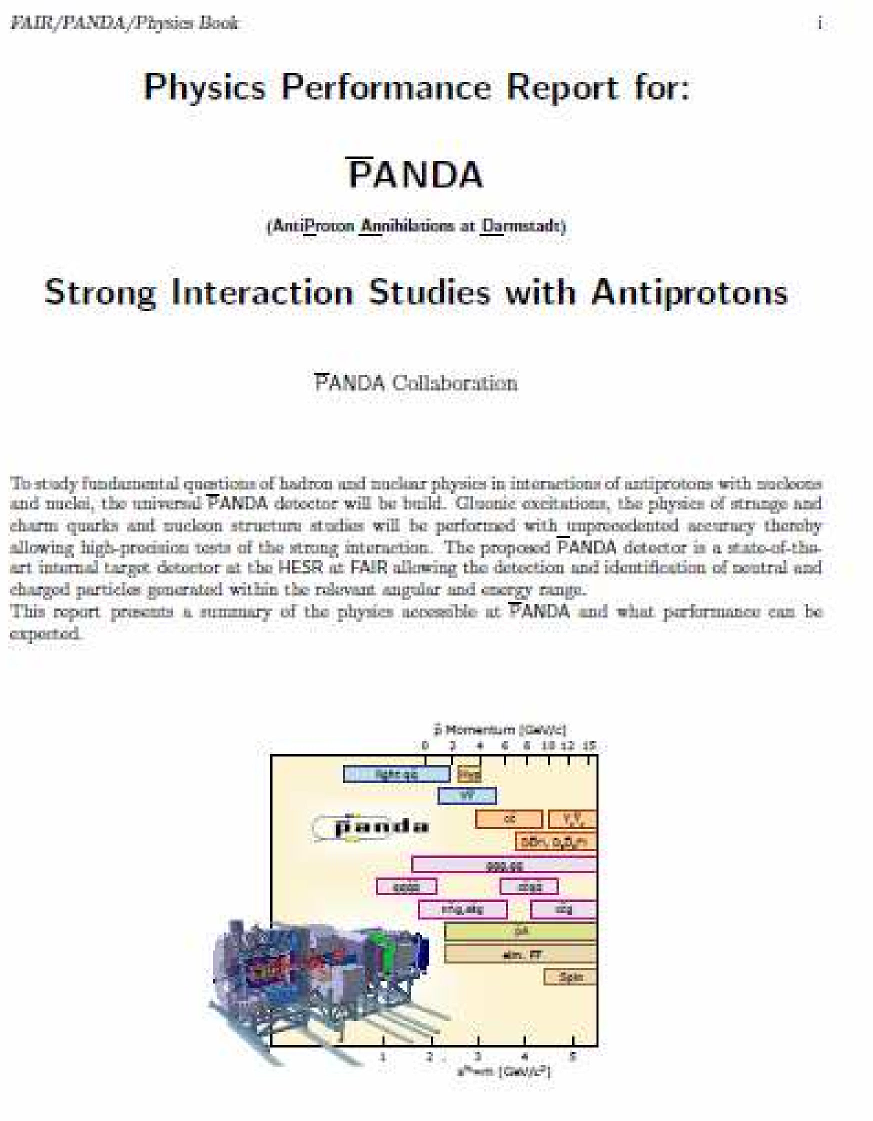
Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, Chicago, Cracow, IFJ PAN Cracow, Cracow UT, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow, TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, Piemonte_Orientale, IHEP Protvino, PNPI St. Petersburg, KTH Stockholm, Stockholm, U Torino, INFN Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, SMI Wien

http://www.gsi.de/panda

Recent Activities

- Electromagnetic Calorimeter TDR written
- Crystals funded
- Dipole magnet and forward Čerenkov funded
- Magnet TDR written
- Tracking TDR in progress
- First version of $\overline{\text{P}}$ANDA Physics Book completed.

  ArXiV:0903.3905.


FAIR/PANDA/Physics Book i

Physics Performance Report for:

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

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

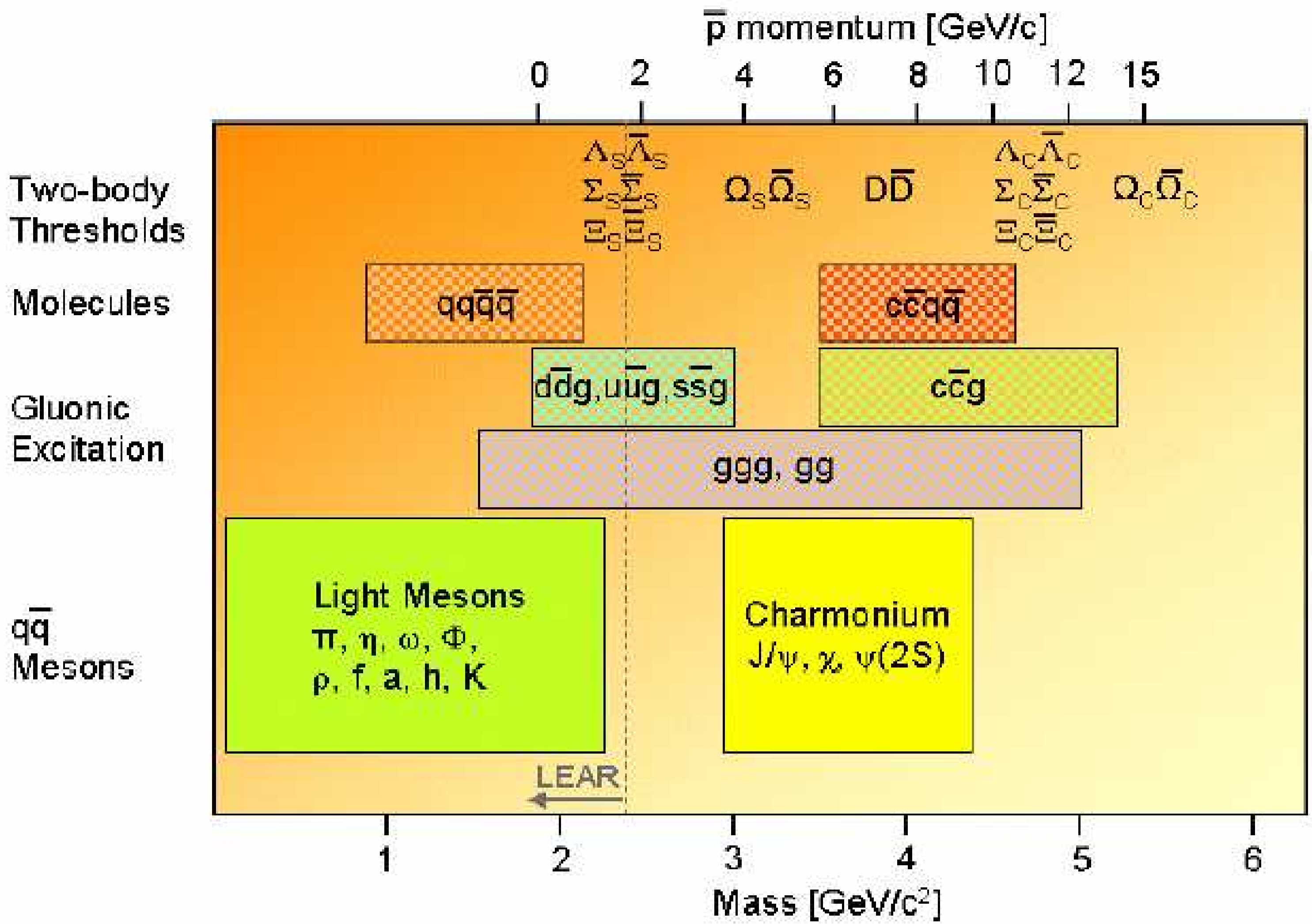
$\overline{\text{P}}$ANDA Collaboration

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.

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

- QCD BOUND STATES
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - HEAVY-LIGHT SYSTEMS
  - STRANGE AND CHARMED BARYONS
- NON PERTURBATIVE QCD DYNAMICS
- HADRONS IN THE NUCLEAR MEDIUM
- NUCLEON STRUCTURE
  - GENERALIZED DISTRIBUTION AMPLITUDES (GDA)
  - DRELL-YAN
  - ELECTROMAGNETIC FORM FACTORS
- ELECTROWEAK PHYSICS

QCD Systems to be Studied in $\bar{P}$ANDA

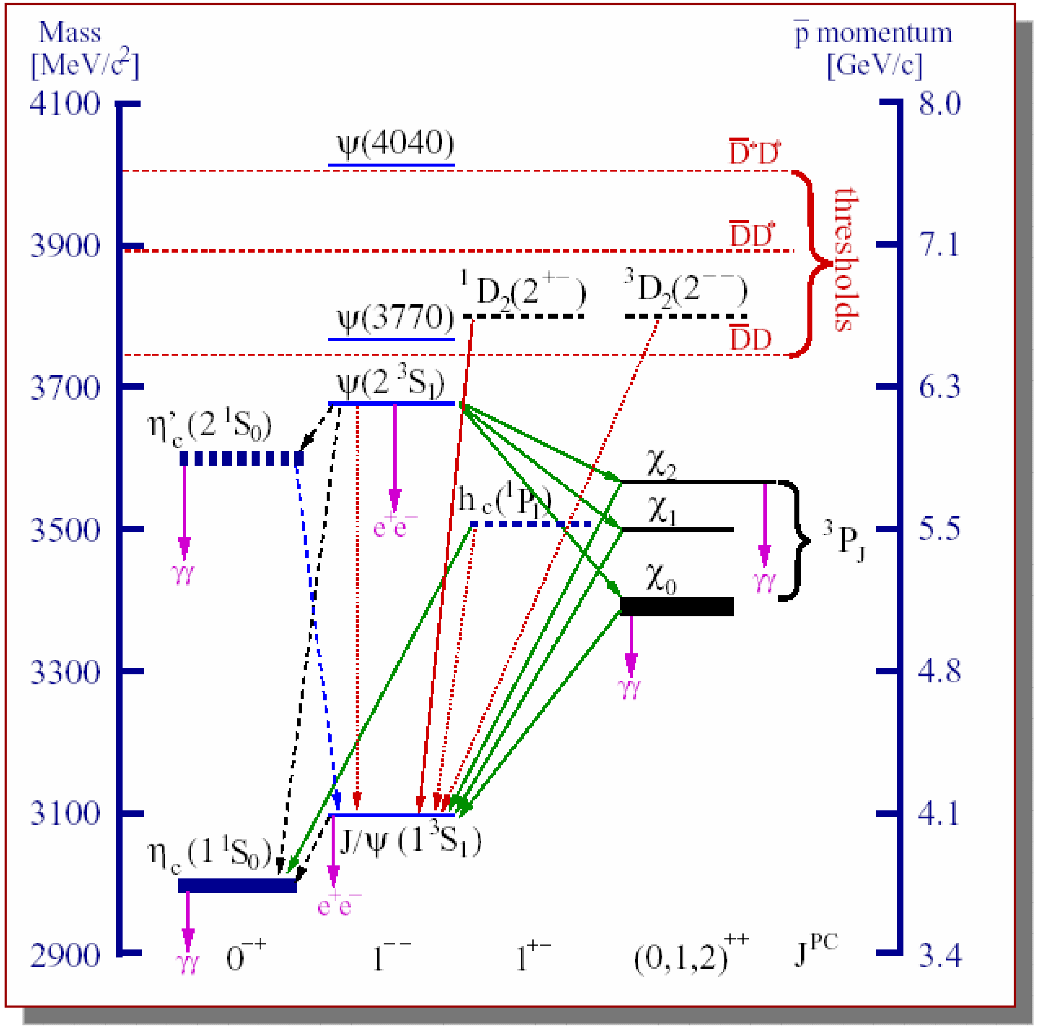


QCD Bound States

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 Spectroscopy
- Gluonic Excitations
- Heavy-Light Systems
- Strange and Charmed Baryons

Charmonium Spectroscopy



Main issues

- All 8 states below threshold observed, some (precision) measurements still missing:
  - h_c (e.g. width)
  - η_c(1S)
  - η_c(2S) (small splitting from ψ(2S))
- The region above open charm threshold must be explored in great detail:
  - find missing D states
  - explain newly discovered states ($c\bar{c}$ or other)
  - confirm vector states seen in R

Charmonium at $\bar{\text{P}}$ANDA

- At $2\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) $\Rightarrow 10^4 \div 10^7$ $(c\bar{c})$ states/day.
- Total integrated luminosity 1.5 fb^{-1}/year (at $2\times10^{32}\text{cm}^{-2}\text{s}^{-1}$, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs 2×10^{-4} (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).
- Fine scans to measure masses to ≈ 100 KeV, widths to ≈ 10 %.
- Explore entire region below and above open charm threshold.
- Decay channels
  - $J/\psi+X$, $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\bar{D}$

•Precision measurement of known states
•Find missing states (e.g. D states)
•Understand newly discovered states

Get a complete picture of the dynamics of the $c\bar{c}$ system.

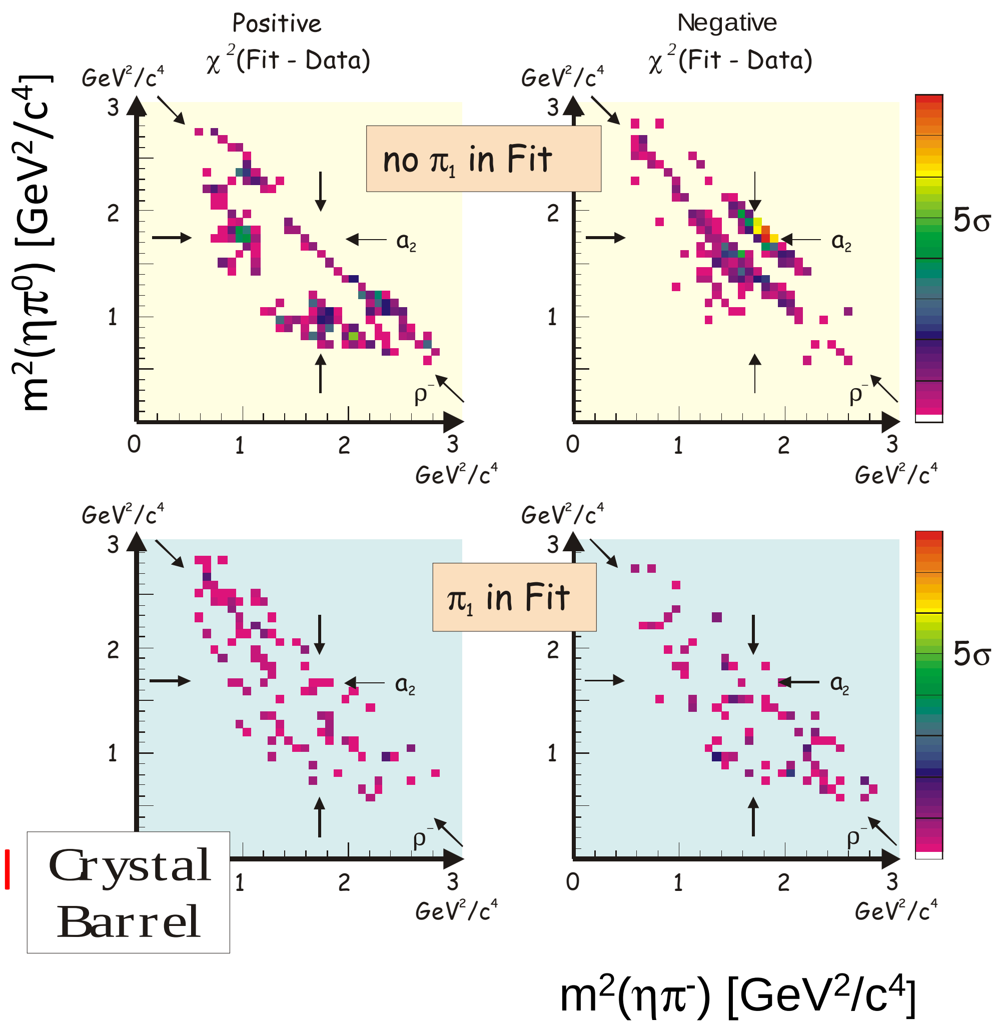
Hybrids and Glueballs

The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

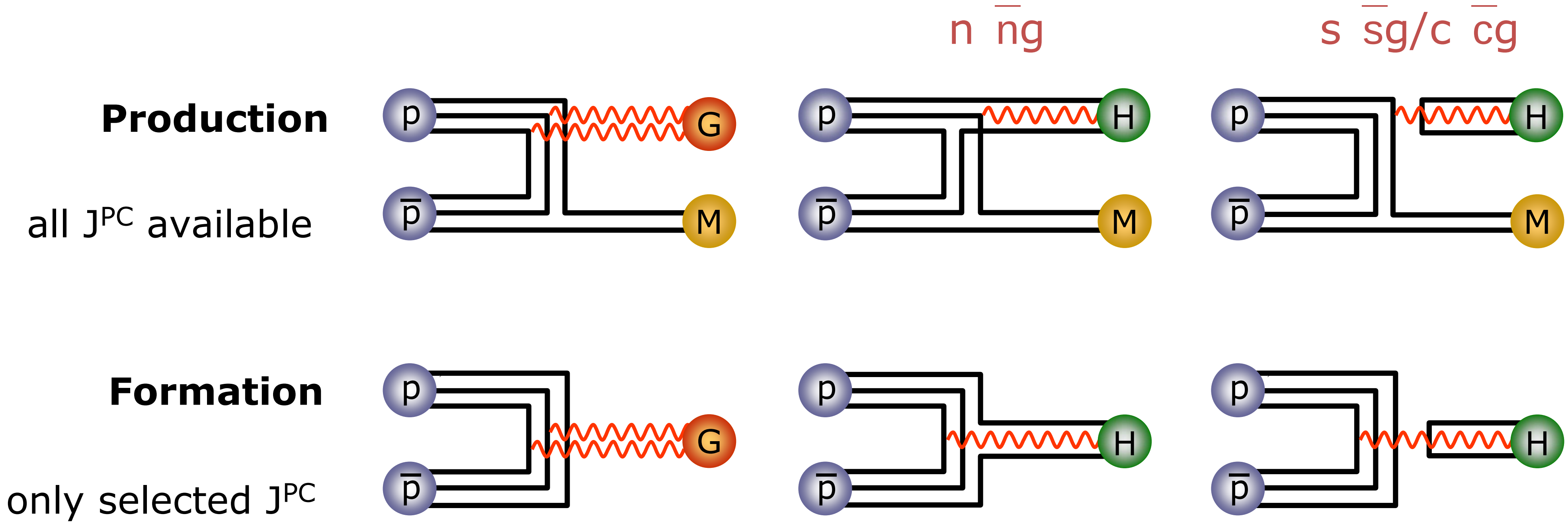
Glueballs states of pure glue

Hybrids $q\bar{q}g$

- Spin-exotic quantum numbers J^{PC} are powerful signature of gluonic hadrons.
- In the light meson spectrum exotic states overlap with conventional states.
- In the $c\bar{c}$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously.
- $\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC}=1^{-+}$.
- $\pi_1(2000)$ and $h_2(1950)$
- Narrow state at 1500 MeV/c^2 seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).



Hybrids and Glueballs in $\bar{p}p$ Annihilation

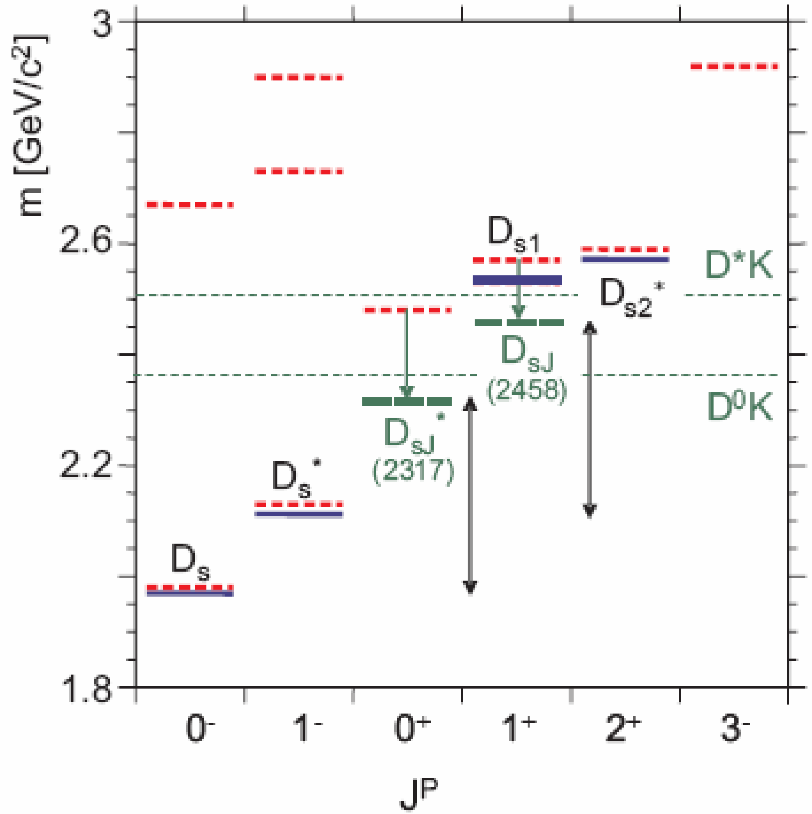


Gluon rich process creates gluonic excitation in a direct way

- $c\bar{c}$ requires the quarks to annihilate (no rearrangement)
- yield comparable to charmonium production
- even at low momenta large exotic content has been proven
- Exotic quantum numbers can only be achieved in production mode

Open Charm Physics

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



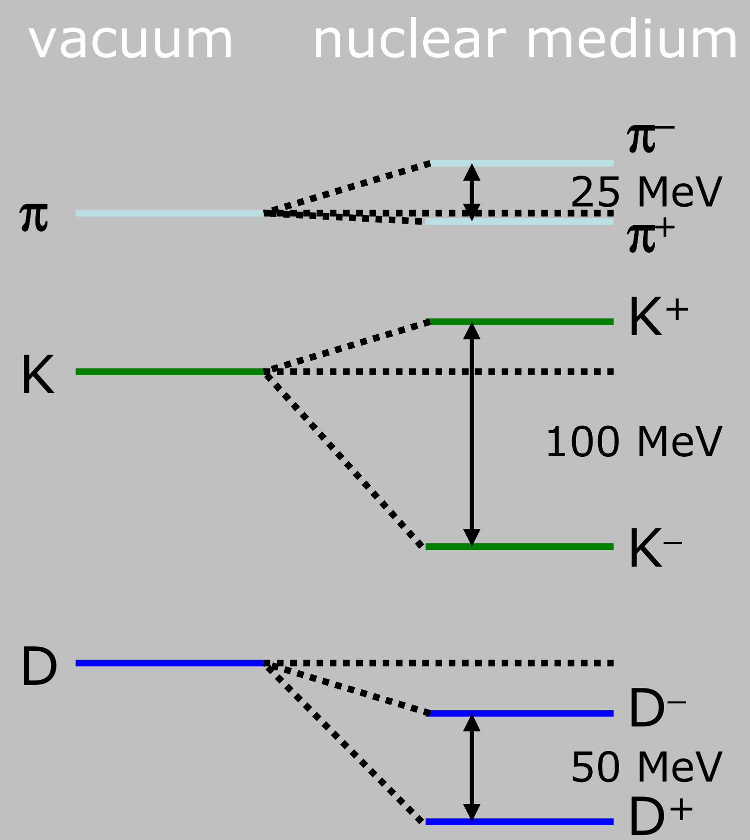
Baryon Spectroscopy

An understanding of the baryon spectrum is one of the primary goals of non-perturbative QCD. In the nucleon sector, where most of the experimental information is available, the agreement with quark model predictions is astonishingly small, and the situation is even worse in the strange baryon sector.

- In $\bar{p}p$ collisions a large fraction of the inelastic cross section is associated to channels with a baryon-antibaryon pair in the final state.
- This opens up the opportunity for a comprehensive baryon spectroscopy program at PANDA.
- Example: $\bar{p}p \rightarrow \bar{\Xi}\Xi$ cross section up to 2 μb, expect sizeable population of excited Ξ states. In PANDA these excited states can be studied by analyzing their various decay modes e.g. $\Xi\pi$, $\Xi\pi\pi$, $\Lambda\bar{K}$, $\Sigma\bar{K}$, $\Xi\eta$ ...
- Ω baryons can also be studied, but cross sections lower by approximately two orders of magnitude.

Hadrons in Nuclear Matter

- Partial restoration of chiral symmetry in nuclear matter
  - Light quarks are sensitive to quark condensate
- Evidence for mass changes of pions and kaons has been deduced previously:
  - deeply bound pionic atoms
  - (anti)kaon yield and phase space distribution
- $(c\bar{c})$ states are sensitive to gluon condensate
  - small (5-10 MeV/c^2) in medium modifications for low-lying $(c\bar{c})$ (J/ψ, η_c)
  - significant mass shifts for excited states: 40, 100, 140 MeV/c^2 for χ_{cJ}, ψ', $\psi(3770)$ resp.
- 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)



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

Charmonium in Nuclei

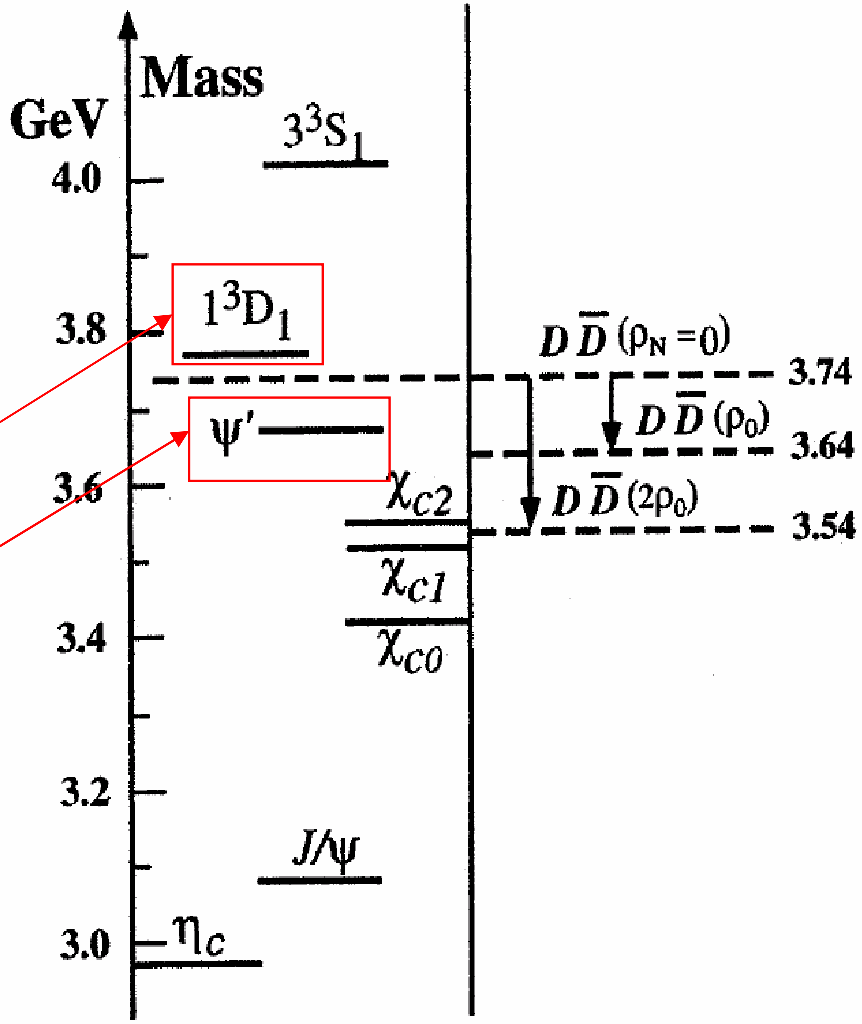
- Measure J/ψ and D production cross section in $\bar{p}$ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

ψ(1D) 20 MeV → 40 MeV

ψ(2S) .28 MeV → 2.7 MeV

⇒Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton ($c\bar{c}$) or hadronic decays (D)



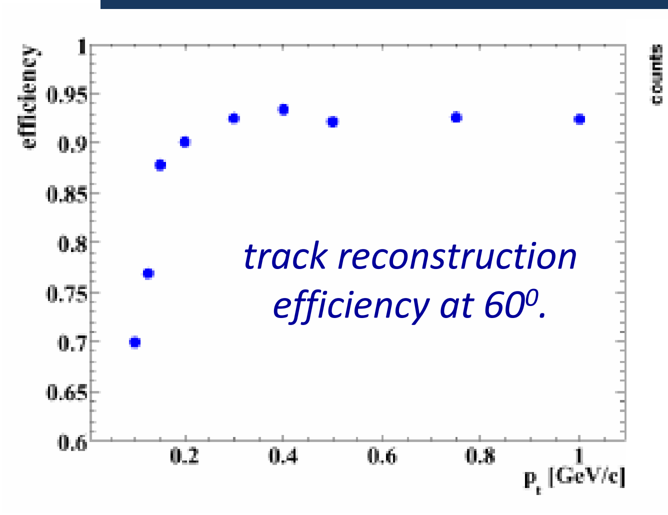
Physics Performance

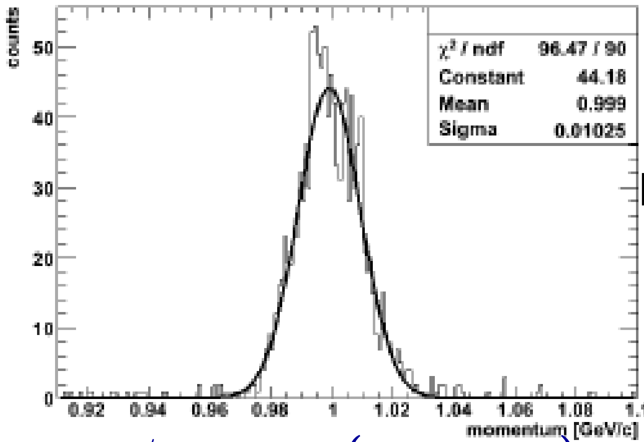
Monte Carlo Simulations

- Event generators with accurate decay models for the individual physics channels as well as for the relevant background channels (e.g. Dual Parton Model, UrQMD, ...).
- Particle tracking through the complete $\overline{\text{P}}$ANDA detector by using the GEANT4 transport code.
- Digitization which models the signals of the individual detectors and their processing in the frontend electronics.
- Reconstruction and identification of charged and neutral particles, providing lists of particle candidates for the physics analysis.

  Kalman Filter for charged particle tracking.
- High-level analysis tools which allow to make use of vertex and kinematical fits and to reconstruct decay trees.

Monte Carlo Performance

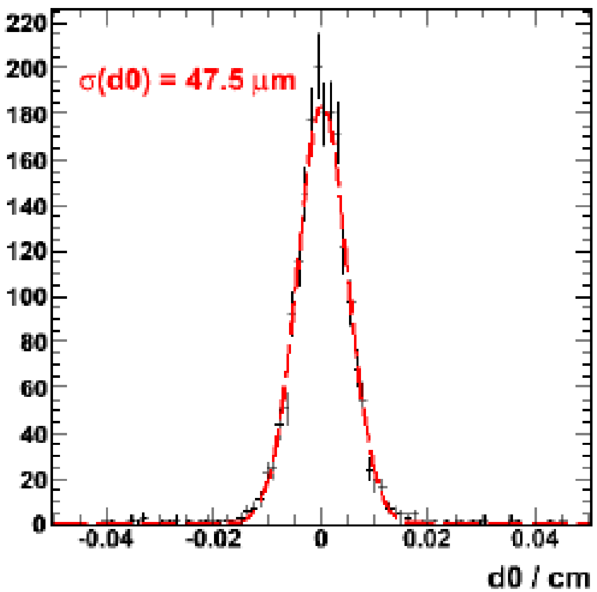


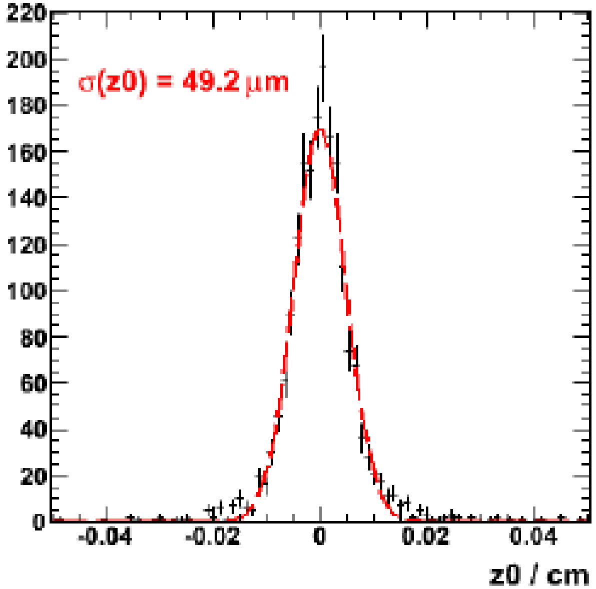


$$\sigma_p / p = 1\% \left(1\, GeV\ \pi\right)$$

Energy thresholds in the Calorimeters

	Central ($PbWO_4$)	Forward (Shashlik)
single crystal	3 MeV	8 MeV
Cluster	10 MeV	15 MeV
Max	20 MeV	10 MeV

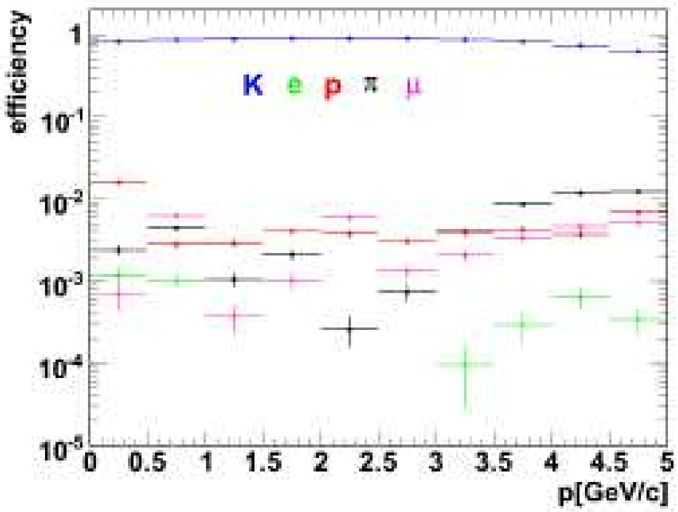




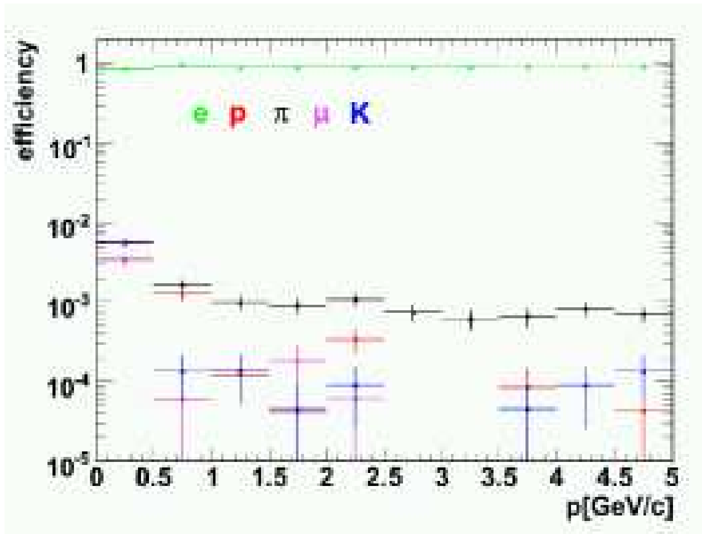
Particle ID

Particle ID:
- dE/dx
  - MVD,STT
- Calorimeter information
- DIRC counter
- Muon detector

	VeryLoose	Loose	Tight	VeryTight
e	20 %	85 %	99 %	99.8 %
μ	20 %	45 %	70 %	85 %
π	20 %	30 %	55 %	70 %
K	20 %	30 %	55 %	70 %
p	20 %	30 %	55 %	70 %



K VeryTight Efficiency and contamination

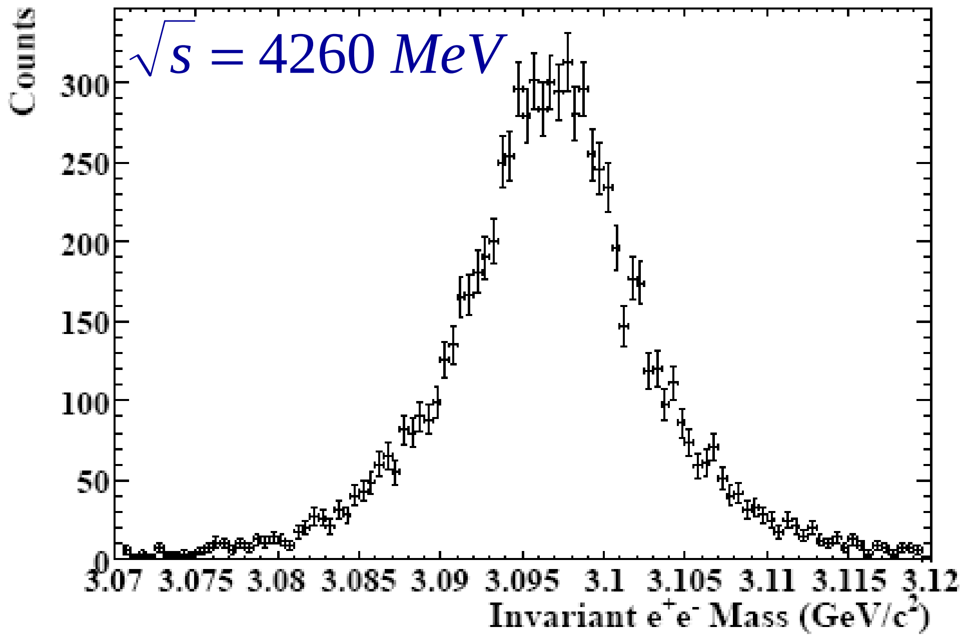


e VeryTight Efficiency and contamination

Charmonium Decays to J/ψ

$$\bar{p}p \rightarrow \bar{c}c \rightarrow J/\psi + X,\ J/\psi \rightarrow e^+e^-,\ (\mu^+\mu^-)$$

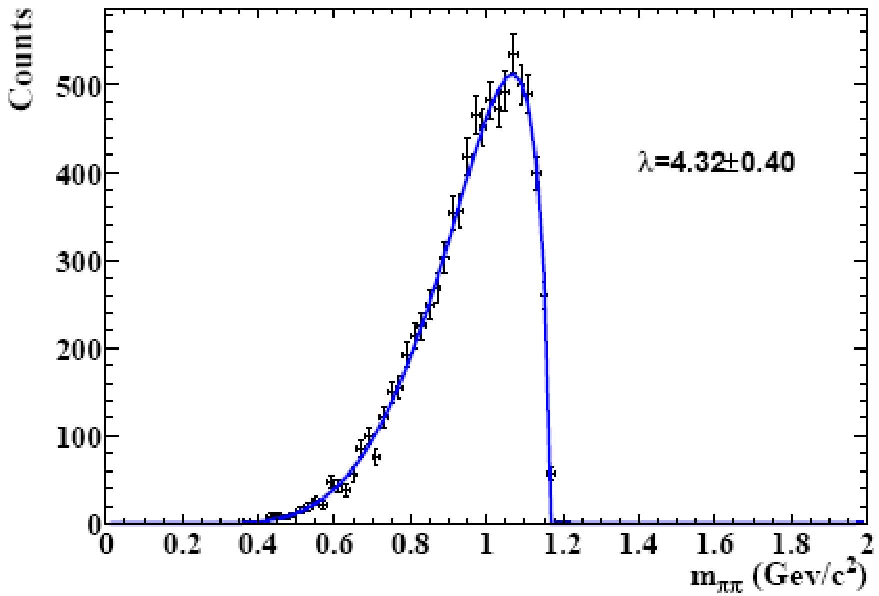
- Tagged by lepton pair with invariant mass equal to $M(J/\psi)$.
- Main background source: misidentified $\pi^+\pi^-$ pairs.
- Electron analysis:
  - two electron candidates: one Loose one Tight.
  - kinematic fit to J/ψ hypothesis with vertex constraint.
  - $P(fit) > 0.001$.
- Additional cuts for exclusive final states:
  - $\bar{p}p \rightarrow J/\psi\pi^+\pi^-$
  - $\bar{p}p \rightarrow J/\psi\pi^0\pi^0$
  - $\bar{p}p \rightarrow \chi_{c1,c2}\gamma \rightarrow J/\psi\gamma\gamma$
  - $\bar{p}p \rightarrow J/\psi\gamma$
  - $\bar{p}p \rightarrow J/\psi\eta$



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

- J/ψ selection
- two pion candidates (VeryLoose)
- vertex fit to $J/\psi \pi^+ \pi^-$

$$\frac{dN}{dm_{\pi\pi}} \propto PHSP \cdot \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2$$



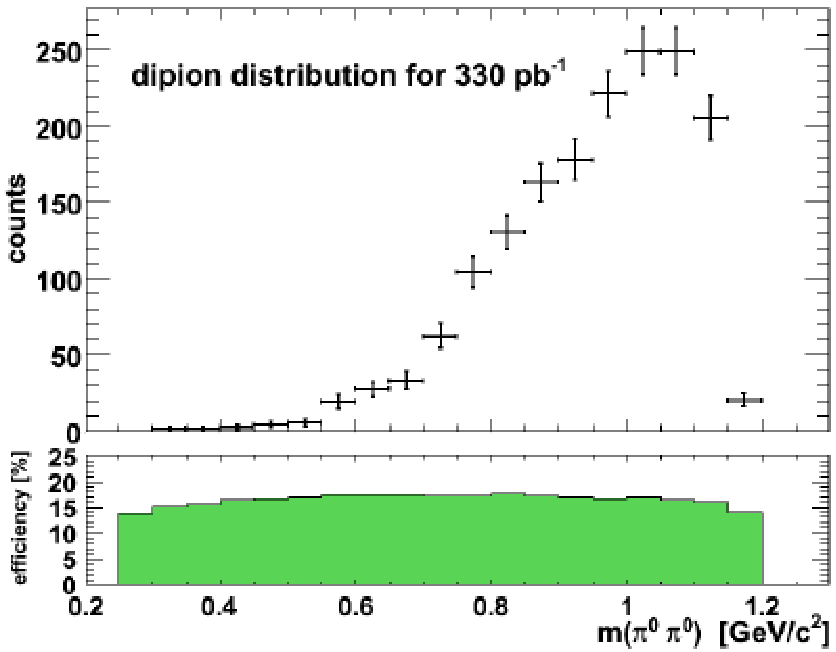
$\sqrt{s}$ [GeV]	Eff [%]	RMS [MeV]
3.526	27.52	3.7
3.686	30.90	5.7
3.872	32.07	8.3
4.260	32.58	13.4
4.600	30.60	18.5
5.000	29.70	24.3

Main background process:

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

Estimated background cross section < 10 pb

$\bar{p}p \to J/\psi\, \pi^0 \pi^0 \to e^+ e^- \pi^0 \pi^0$



Main background process:

$\bar{p}p \to \pi^+ \pi^- \pi^0 \pi^0$

Estimated S/B 25

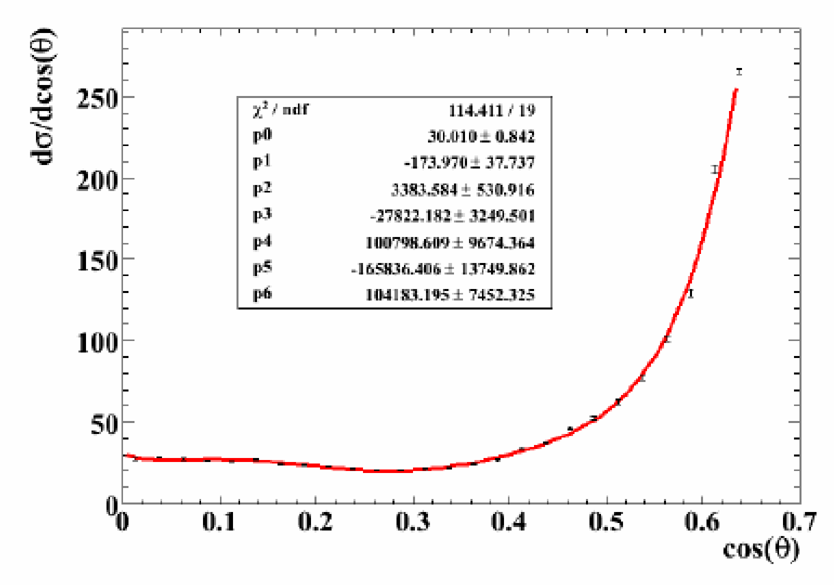
channel	assumed σ	efficiency	
$\bar{p}p \to J/\psi\pi^0\pi^0 \to e^+e^-4\gamma$	30 pb	16.9 %	n_{rec}= 40 events / day
background reactions:			
$\bar{p}p \to \pi^+\pi^-\pi^0\pi^0 \to \pi^+\pi^-4\gamma$	50 μb	1 / 250M	S/B= 25
$\bar{p}p \to J/\psi\eta\pi^0 \to e^+e^-4\gamma$	<30 pb	0 / 20K	S/B> 10^3
$\bar{p}p \to J/\psi\omega\pi^0 \to e^+e^-5\gamma$	<10 pb	4 / 20K	S/B> 10^3

$h_c \rightarrow \eta_c \gamma \rightarrow 3\gamma$

$E_\gamma = 503\ MeV$

$\Gamma_{p\bar{p}} B_{\eta_c \gamma} = 10\ eV \quad \Rightarrow \quad \sigma_p = 33\ nb$

- Pair 2 γs to form η_c mass ($\gamma_1\gamma_2$).
- 4C fit to h_c candidate.
- $N_\gamma = 3$.
- CL (4C fit) > 10^{-4}.
- $0.4\ GeV < E_\gamma < 0.6\ GeV$.
- $|\cos\theta| < 0.6$.
- $M(\gamma_1\gamma_3), M(\gamma_2\gamma_3) > 1\ GeV$.



Channel	σ (nb)	number of events
$\bar{p}p \rightarrow h_c \rightarrow 3\gamma$		20 k
$\bar{p}p \rightarrow \pi^0\pi^0$	31.4	1.3 M
$\bar{p}p \rightarrow \pi^0\gamma$	1.4	100 k
$\bar{p}p \rightarrow \pi^0\eta$	33.6	1.3 M
$\bar{p}p \rightarrow \eta\eta$	34.0	1.3 M
$\bar{p}p \rightarrow \pi^0\eta'$	50.0	100 k

$h_c \to \eta_c\gamma \to 3\gamma$

Cut	h_c	$\pi^0\gamma$	$\pi^0\pi^0$	$\pi^0\eta$	$\eta\eta$	$\pi^0\eta'$
preselection	0.70	0.43	0.14	$8.2 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$	$8.5 \cdot 10^{-2}$
$3\ \gamma$	0.47	0.31	$1.3 \cdot 10^{-2}$	$7.5 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$	$8.7 \cdot 10^{-3}$
$CL > 10^{-4}$	0.44	0.30	$9.9 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$7.2 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$
E_γ [0.4;0.6] GeV	0.43	0.12	$3.9 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$2.8 \cdot 10^{-4}$	$2.3 \cdot 10^{-3}$
$\lvert\cos(\theta)\rvert < 0.6$	0.22	$9.2 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$	$7.0 \cdot 10^{-5}$	$7.5 \cdot 10^{-4}$
$m_{12}^2, m_{23}^2 > 1.0\,\mathrm{GeV}$	$8.1 \cdot 10^{-2}$	0	0	0	0	0

signal efficiency 8.2 %

Channel	S/B ratio
$\bar{p}p \to \pi^0\pi^0$	> 94
$\bar{p}p \to \pi^0\gamma$	> 164
$\bar{p}p \to \pi^0\eta$	> 88
$\bar{p}p \to \eta\eta$	> 87
$\bar{p}p \to \pi^0\eta'$	> 250

In high-luminosity mode ($L = 2\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) expect 20 signal events/day.

$h_c \to \eta_c\gamma \to \phi\phi\gamma \to 4K\gamma$

Channel	N of events	
$\bar{p}p \to h_c \to \phi\phi\gamma$	20 k	
$\bar{p}p \to K^+K^-K^+K^-\pi^0$	6.2 M	σ~345 nb
$\bar{p}p \to \phi K^+K^-\pi^0$	200 k	σ~60 nb
$\bar{p}p \to \phi\phi\pi^0$	4.2 M	σ< 3 nb
$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$	5 M + 15 M	σ~30 μb
	100 k	

DPM estimate

- ϕ candidates: K pairs in appropriate mass window.
- 4C fit to beam-momentum
- CL (4C) > 0.05
- η_c invariant mass [2.9, 3.06] GeV .
- E_γ [0.4, 0.6] GeV
- ϕ mass [0.99, 1.05] GeV
- no π^0 in event

Selection criteria	signal	$4K\pi^0$	$\phi K^+K^-\pi^0$	$\phi\phi\pi^0$	$K^+K^-\pi^+\pi^-\pi^0$
pre-selection	0.51	$9.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$	$4.9 \cdot 10^{-2}$	$9.0 \cdot 10^{-6}$
$CL > 0.05$	0.36	$1.5 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$7.0 \cdot 10^{-3}$	$4.0 \cdot 10^{-8}$
$m(\eta_c), E_\gamma$	0.34	$4.1 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	0
$m(\phi)$	0.31	$4.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	0
$no\ \pi^0(30\,MeV)$	0.26	$2.7 \cdot 10^{-6}$	$4.5 \cdot 10^{-5}$	$9.2 \cdot 10^{-4}$	0
$no\ \pi^0(10\,MeV)$	0.24	$1.8 \cdot 10^{-6}$	$3.0 \cdot 10^{-5}$	$7.1 \cdot 10^{-4}$	0

signal efficiency 24 %

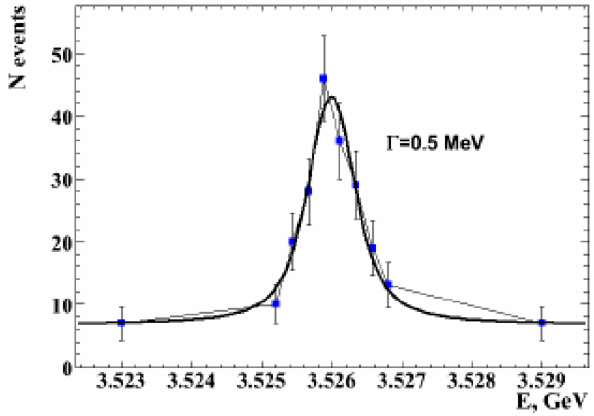
In high-luminosity mode
(L = 2×10^{32}cm^{-2}s^{-1}) expect
92 signal events/day.

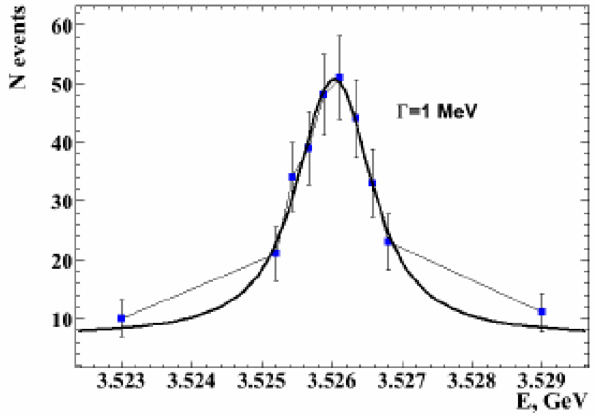
channel	Signal/Background
$\bar{p}p \to K^+K^-K^+K^-\pi^0$	8
$\bar{p}p \to \phi K^+K^-\pi^0$	8
$\bar{p}p \to \phi\phi\pi^0$	> 10
$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$	> 12

Sensitivity to h_c Width Measurement

$$p\bar{p} \rightarrow h_c \rightarrow \eta_c + \gamma \rightarrow K^+K^-K^+K^-\gamma$$

$$\nu_i = [\varepsilon \times \int Ldt]_i \times [\sigma_{bkgd}(E) + \frac{\sigma_p \Gamma_R^2/4}{(2\pi)^{1/2}\sigma_i} \times \int \frac{e^{-(E-E')^2/2\sigma_i^2}}{(E'-M_R)^2 + \Gamma_R^2/4} dE'],$$





signal efficiency ε=0.24

each point corresponds to 5 days of data taking

Likelihood function:

$$\mathcal{L} = \prod_{j=1}^{N} \frac{\nu_j^{n_j} e^{-\nu_j}}{n_j!}.$$

$\Gamma_{R,MC}$, MeV	$\Gamma_{R,reco}$, MeV	$\Delta\Gamma_R$, MeV
1	0.92	0.24
0.75	0.72	0.18
0.5	0.52	0.14

$\bar{p}p \rightarrow \bar{D}D$

- Charmonium states above open charm threshold
- Charm spectroscopy
- Search for hybrids decaying to $\bar{D}D$
- Rare D decays (and CP violation)

Main issue: separation of charm signal from large hadronic background

$$\bar{p}p \rightarrow D^+D^- \quad D^+ \rightarrow K^-\pi^+\pi^+ \qquad \sqrt{s} \rightarrow \psi(3770)$$

$$\bar{p}p \rightarrow D^{*+}D^{*-} \quad D^{*+} \rightarrow D^0\pi^+ \quad D^0 \rightarrow K^-\pi^+ \qquad \sqrt{s} \rightarrow \psi(4040)$$

Cross section estimates: Breit-Wigner, with $\bar{p}p$ BR scaled from ψ

$$\sigma\left(\bar{p}p \rightarrow \psi(3770) \rightarrow D^+D^-\right) = 2.8\ nb$$

$$\sigma\left(\bar{p}p \rightarrow \psi(4040) \rightarrow D^{*+}D^{*-}\right) = 0.9\ nb$$

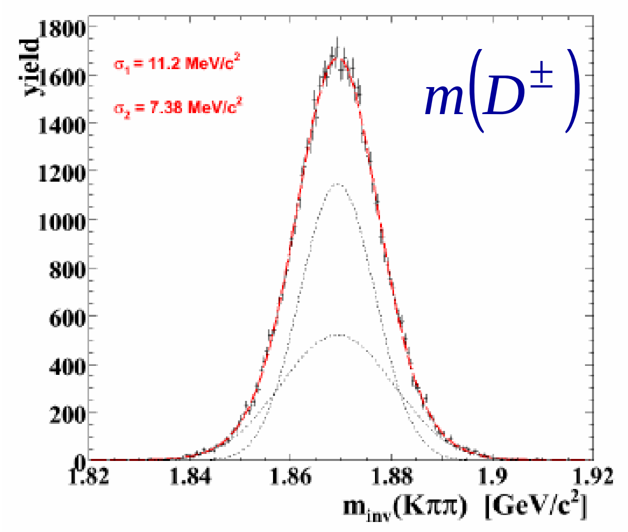
channel	D^+D^-	$D^{*+}D^{*-}$
decay	$D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$ (9.2 %)	$D^{*+} \rightarrow D^0\pi^+$ (67.7 %) $D^0 \rightarrow K^-\pi^+$ (3.8 %)
R	4×10^{-10}	1×10^{-11}

Event Selection

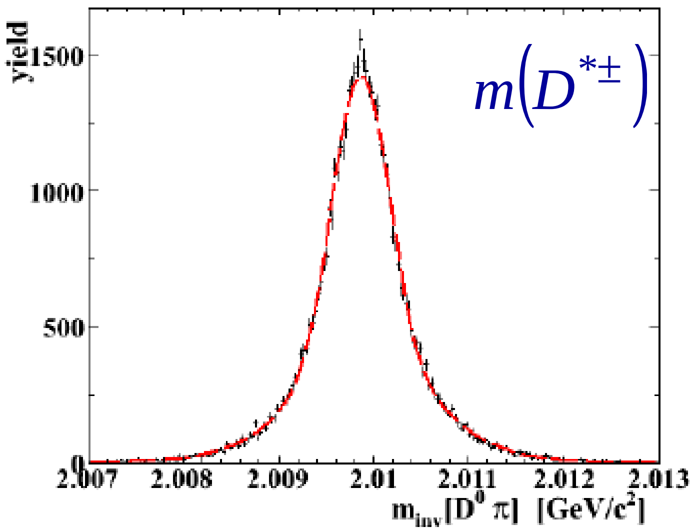
- Loose mass window cut before vertex fitting $\Delta m = \pm 0.3\ GeV/c^2$.
- Minimum 6 charged tracks.
- All decay particles must form a common vertex.
- 4C kinematic fit to constrain beam energy and momentum: $CL > 5\times 10^{-2}$.
- K/π selection Loose ($LH > 0.3$).
- Only one combination per event.

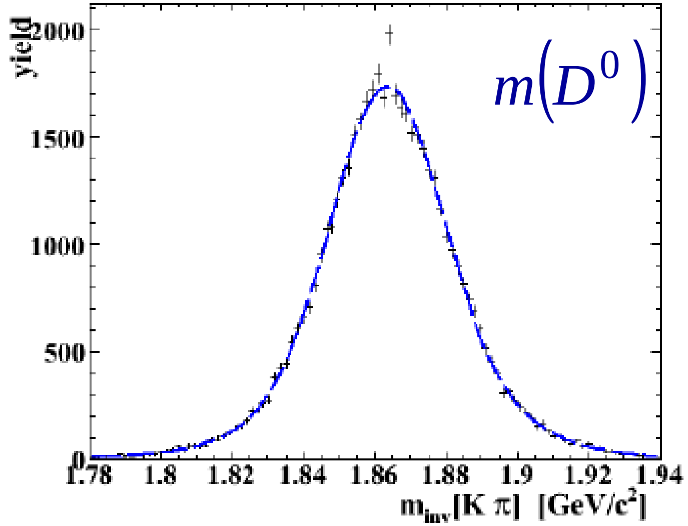
Signal Efficiency

$\bar{p}p \rightarrow D^{+}D^{-}$



$\bar{p}p \rightarrow D^{*+}D^{*-}$





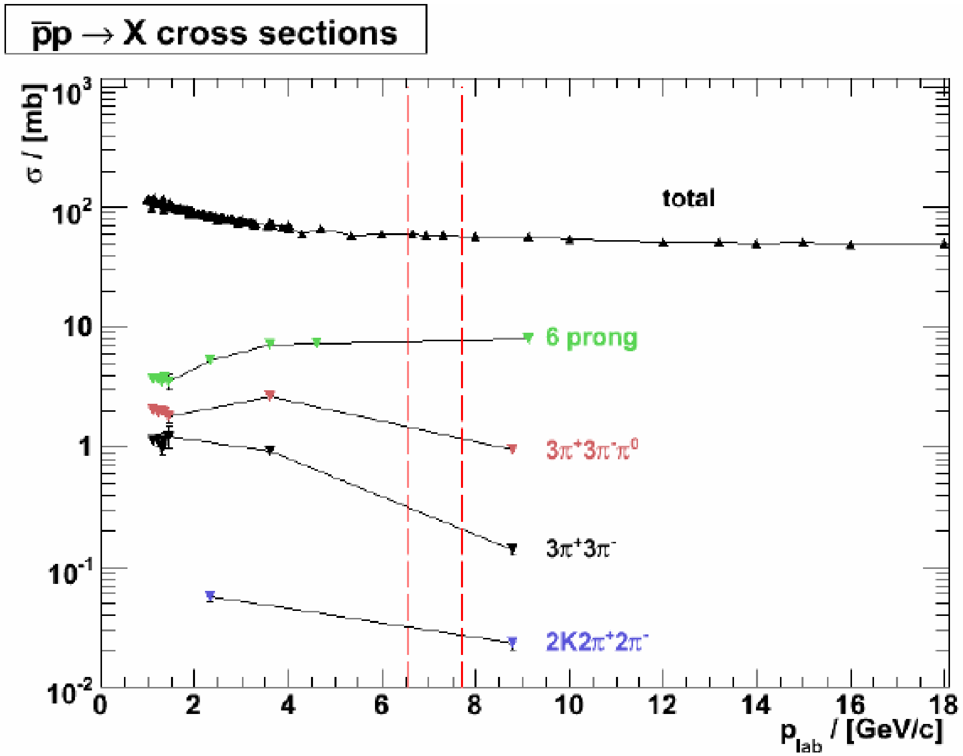
after 5C fit (D^0 mass constraint)

overall efficiency
$\varepsilon(signal)$ = 40 %

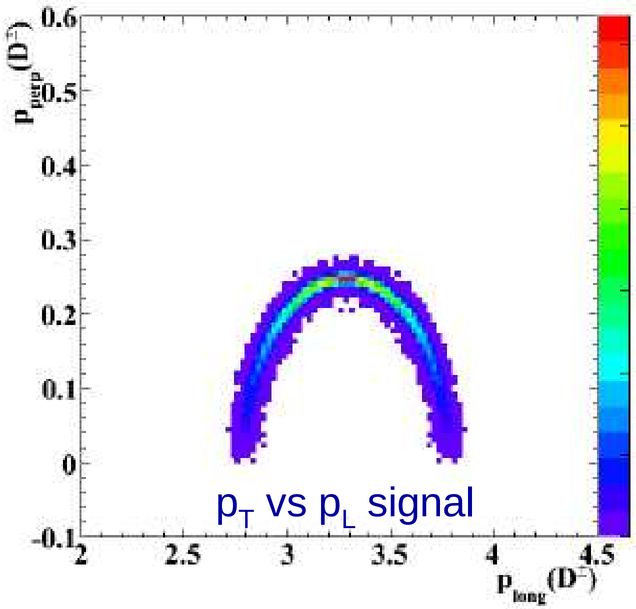
overall efficiency $\varepsilon(signal)$ = 27.4 % (4C fit)
overall efficiency $\varepsilon(signal)$ = 24.0 % (5C fit)

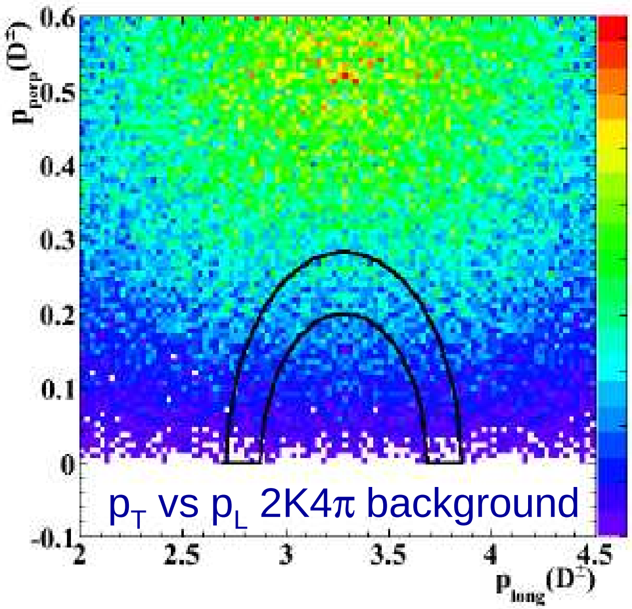
Background Studies

channel	D^+D^-	$D^{*+}D^{*-}$	Ratio to $\overline{p}p$
DPM	100 M	-	-
$3\pi^+3\pi^-\pi^0$	50 M	43 M	2.5×10^{-2}
$3\pi^+3\pi^-$	10 M	14 M	5×10^{-3}
$K^+K^-2\pi^+2\pi^-$	1 M	10 M	5×10^{-4}

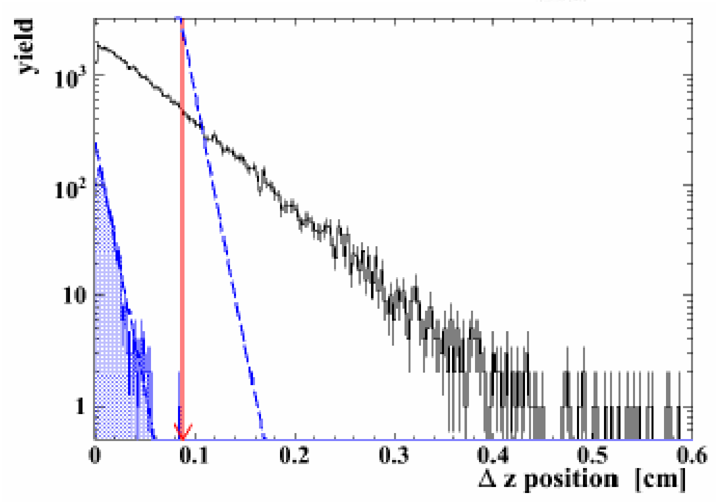


$2K4\pi$ Background





Two-dimensional cut on $D^{\pm}$ momentum reduces $2K4\pi$ background by factor *26*.



Cut on Δz of $D^{\pm}$ decay vertex:
$\Delta z > 0.088$ *cm* $S/B = 1$ $\varepsilon(signal) = 7.8$ *%*

For the $D^{*+}D^{*-}$ channel the analysis gives $S/B = 1/3$. An additional cut on the Δz of the D^0 decay vertex gives $S/B=3/2$, bringing the signal efficiency from *24 %* to *12.7 %*.

Non Strange Background

selection	efficiency			signal/background	
selection	D^+D^-	$3\pi^+3\pi^-$	$3\pi^+3\pi^-\pi^0$	$\frac{D^+D^-}{3\pi^+3\pi^-}$	$\frac{D^+D^-}{3\pi^+3\pi^-\pi^0}$
preselection	0.43	$5.4 \cdot 10^{-3}$	$9.6 \cdot 10^{-4}$	-	-
4C-fit	0.40	$1.4 \cdot 10^{-6}$	$4.2 \cdot 10^{-7}$	0.02	0.015
$D^\pm$ momentum	0.40	$< 1.1 \cdot 10^{-8}$	$< 3.6 \cdot 10^{-9}$	> 2.7	> 1.8
K LH > 0.3	0.23	$< 1.8 \cdot 10^{-9}$	$< 1.7 \cdot 10^{-9}$	> 6.4	> 2.9

selection	efficiency			signal/background	
selection	$D^{*+}D^{*-}$	$3\pi^+3\pi^-$	$3\pi^+3\pi^-\pi^0$	$\frac{D^{*+}D^{*-}}{3\pi^+3\pi^-}$	$\frac{D^{*+}D^{*-}}{3\pi^+3\pi^-\pi^0}$
preselection	0.27	$5.0 \cdot 10^{-7}$	$7.5 \cdot 10^{-8}$	-	-
5C-fit	0.24	$5.0 \cdot 10^{-11}$	$7.5 \cdot 10^{-12}$	≥ 10	≥ 14

Measurement of the $D^*_{s0}(2317)$ Width

inclusive $D_s(2317)$ reconstruction:

$\bar{p}p \rightarrow D_s^{\pm} D_{s0}^{\mp *}(2317)$

$D_s^{\pm} \rightarrow \phi\pi^{\pm}$, $\phi \rightarrow K^+K^-$

$D_{s0}^{\mp *}(2317) \rightarrow$ anything: → ε_{signal}, $\varepsilon_{background}$, S/B

The production cross section around threshold depends on the total width.

input

$$\int L\,dt = 126\ pb^{-1} (14\ \text{days})$$

$$S/B = 1/3$$

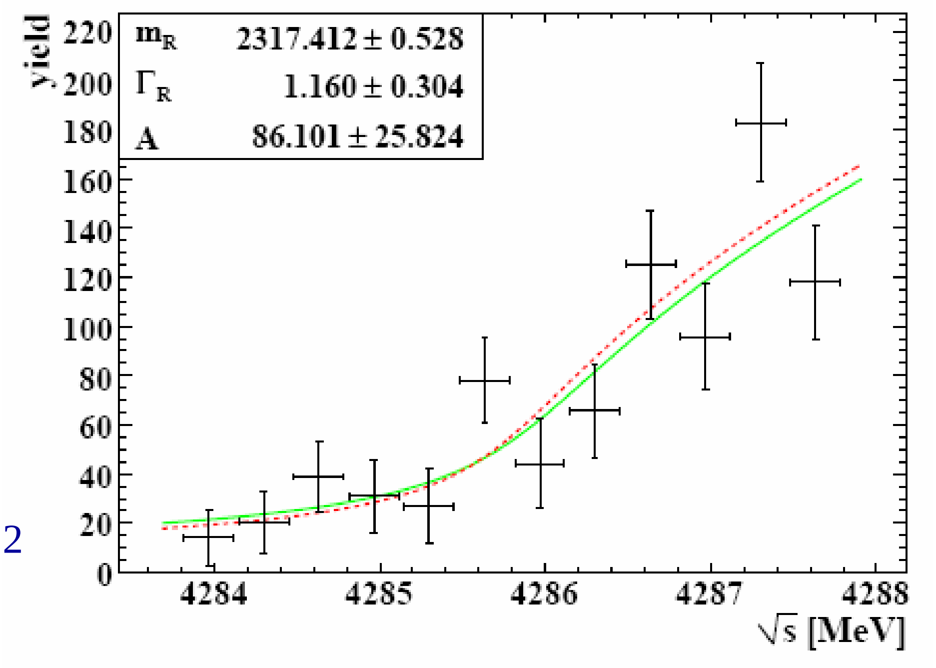
$$\Gamma = 1\ MeV$$

$$m = 2317.30\ MeV/c^2$$

output

$$\Gamma = (1.16 \pm 0.30)\ MeV$$

$$m = (2317.41 \pm 0.53)\ MeV/c^2$$



Charmonium Hybrids Simulation

- Charmonium hybrid ground state
  - expected to be spin-exotic $J^{PC} = 1^{-+}$
  - mass prediction: 4.1 – 4.4 GeV/c^2
- In this analysis:
  - assume M = 4.29 MeV/c^2, Γ = 20 MeV
  - produced in $\bar{p}p$ with recoil particle $\bar{p}p \to \tilde{\eta}_{c1}\eta$ at 15 GeV
  - decay modes

$$\tilde{\eta}_{c1} \to \chi_{c1}\pi^0\pi^0 \quad \tilde{\eta}_{c1} \to D^0\overline{D}^{*0}$$

  - assume signal cross section to be of the same order of magnitude as

$$\bar{p}p \to \psi(2S)\eta \quad (33 \pm 8)\ pb \quad \left(\sqrt{s} = 5.38 GeV\right)$$

$\chi_{c1}\pi^0\pi^0$ selection

- 200k events at 15 GeV/c
- $\psi_g \rightarrow \chi_{c1}\pi^0\pi^0$, $\chi_{c1} \rightarrow J/\psi\gamma$, $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$, $\eta \rightarrow \gamma\gamma$
- Selection criteria
  - PID: $p(e) > 0.85$, $p(\mu) > 0.85$
  - 9C fit: beam, $J/\psi, \pi^0, \eta$, χ_{c1} mass constraint
  - $m(l^+l^-) \in [3.3;3.7]\mathrm{GeV}/c^2$
  - $m(J/\psi\gamma) \in [3.49;3.53]\mathrm{GeV}/c^2$
  - $m(\gamma\gamma) \in [0.115;0.15]\ \mathrm{GeV}/c^2$, $\in [0.47;0.61]\ \mathrm{GeV}/c^2$
- Accept only $\psi_g\eta$ candidate with highest confidence level per event, minimum CL > 0.1 %
- MC truth match for signal mode

$\chi_{c1}\pi^0\pi^0$ channel

Reaction $\bar{p}p \to$	σ	$\mathcal{B}$
$\tilde{\eta}_{c1}\eta$	33 pb	$0.82\,\% \times \mathcal{B}(\tilde{\eta}_{c1} \to \chi_{c1}\pi^0\pi^0)$
$\chi_{c0}\pi^0\pi^0\eta$		$0.03\,\%$
$\chi_{c1}\pi^0\eta\eta$		$0.32\,\%$
$\chi_{c1}\pi^0\pi^0\pi^0\eta$		$0.81\,\%$
$J/\psi\pi^0\pi^0\pi^0\eta$		$2.26\,\%$

Reaction $\bar{p}p \to$	Events
$\tilde{\eta}_{c1}\eta$	$8 \cdot 10^4$
$\chi_{c0}\pi^0\pi^0\eta$	$8 \cdot 10^4$
$\chi_{c1}\pi^0\eta\eta$	$8 \cdot 10^4$
$\chi_{c1}\pi^0\pi^0\pi^0\eta$	$8 \cdot 10^4$
$J/\psi\pi^0\pi^0\pi^0\eta$	$8 \cdot 10^4$

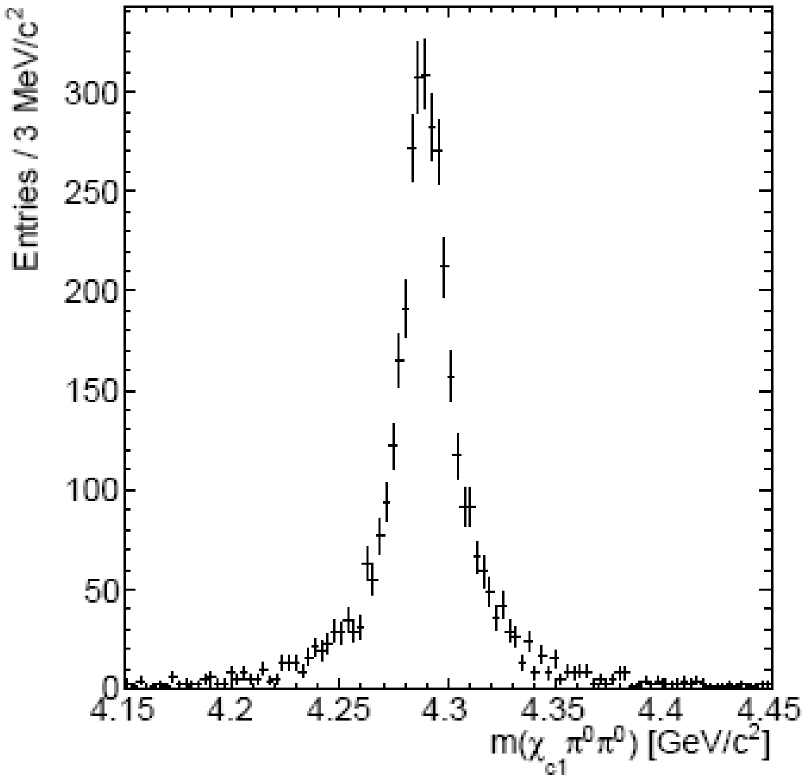
Reconstruction efficiency
6.83 % for $J/\psi \to e^+e^-$

$$\tilde{\eta}_{c1} \quad signal \quad width\,(FWHM)$$

$$30 \quad MeV$$

Expected events per day

$$N = 0.16 \times \mathrm{B}\left(\tilde{\eta}_{c1} \to \chi_{c1}\pi^0\pi^0\right)$$



$\chi_{c1}\pi^0\pi^0$ background studies

Reaction $\bar{\mathrm{p}}\mathrm{p} \rightarrow$	$\eta_{e^+e^-}$ $[10^3]$	$S/N_{e^+e^-}$ $[10^3]$
$\chi_{c0}\pi^0\pi^0\eta$	5.33	$10.1\,\mathcal{R}$
$\chi_{c1}\pi^0\eta\eta$	26.6	$4.57\,\mathcal{R}$
$\chi_{c1}\pi^0\pi^0\pi^0\eta$	> 80	$> 5.53\,\mathcal{R}$
$J/\psi\pi^0\pi^0\pi^0\eta$	9.98	$0.25\,\mathcal{R}$

$$R = \frac{\sigma_S \mathrm{B}\left(\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0\right)}{\sigma_B}$$

S/N ≈ 250-10100 R depending on J/ψ background channel
very low background contamination expected if

$$\sigma_B \approx \mathrm{O}\left(\sigma_S \mathrm{B}\left(\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0\right)\right)$$

$D^0 \overline{D}^{0*}\eta$ Decay mode

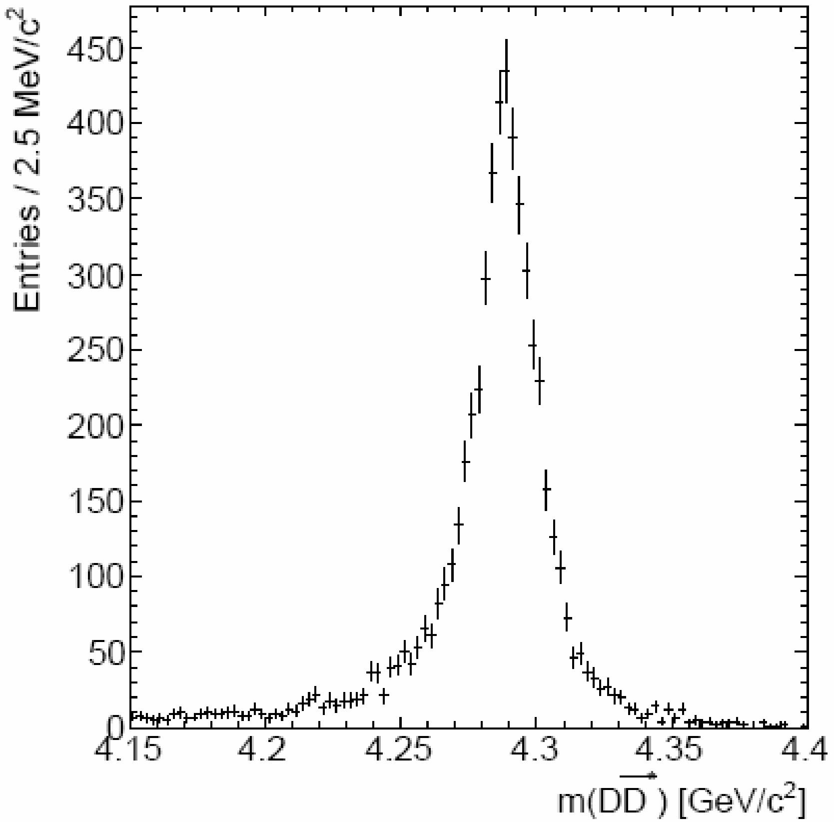
Reaction $\overline{p}p \rightarrow$	$\mathcal{B}$
$\tilde{\eta}_{c1}\eta$	$0.47\% \times \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\overline{D}^{*0})$
$D^0\overline{D}^{*0}\eta$	$3.2\% \times \mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^0\pi^0) = 0.16\%^*$
$D^0\overline{D}^{*0}\pi^0$	1.17%

Signal reconstruction efficiency *5.17 %*

background rejection > 1.6×10^5

$$\frac{S}{N} > \frac{\mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\overline{D}^{*0}) \times 0.47\,\% \times 5.17\,\%}{(0.16\,\% + 1.17\,\%) \times 5 \cdot 10^{-6}} = \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\overline{D}^{*0}) \times 2.9 \cdot 10^3, \qquad (4.17)$$

$$N = \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\overline{D}^{*0}) \times 0.077.$$



$Y(3940) \rightarrow J/\psi\omega \rightarrow e^+e^-\pi^+\pi^-\pi^0$

- 40k $J/\psi\omega$ events at Y(3940)
- $J/\psi \rightarrow e^+e^-/\mu^+\mu^-$, $\omega \rightarrow \pi^+\pi^-\pi^0$ with correct angular distribution (omega_dalitz decay model in EvtGen), $\pi^0 \rightarrow \gamma\gamma$
- Selection criteria
  - PID p(e) > 0.85, p(μ) > 0.85, p(π) > 0.2
  - 6C fit: beam, J/ψ and π^0 mass constraint
  - Mass windows - $m(\pi^+\pi^-\pi^0) \in [0.750; 0.810]$ GeV/c^2,
    - $m(\gamma\gamma) \in [0.115; 0.150]$ GeV/c^2
    - $m(l^+l^-) \in [3.07; 3.12]$ GeV/c^2
- Accept only $J/\psi\omega$ candidate with highest confidence level per event, minimum CL = 0.1 %
- Veto on $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
  - $m(J/\psi\pi^+\pi^-) \in [3.6725; 3.7]$ GeV/c^2 rejected
- Signal modes: truth match

Reaction $\overline{p}p \to$	σ	$\mathcal{B}$
$Y \to J/\psi\omega$	σ_S	$5.2\,\% \times \mathcal{B}(Y \to J/\psi\omega)$
$\pi^+\pi^-\pi^0\rho^0$	$149\,\mu b^*$	$100\,\%$
$\pi^+\pi^-\pi^-\rho^+$	$198\,\mu b^*$	$100\,\%$
$\pi^+\pi^-\omega$	$23.9\,\mu b^*$	$100\,\%$
$\psi(2S)\pi^0$	$55\,pb$	$3.73\,\%$
$Y \to J/\psi\rho\pi$	σ	$5.9\,\% \times \mathcal{B}(Y \to J/\psi\rho\pi)$

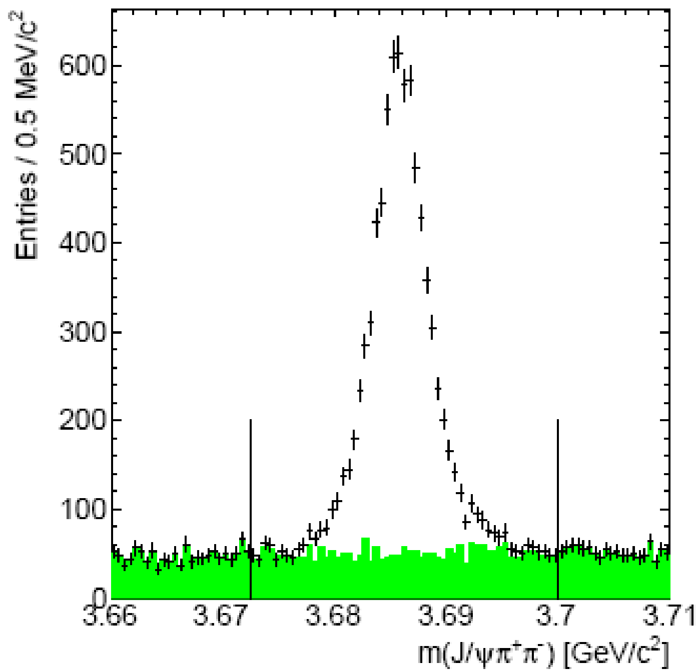
Reaction $\overline{p}p \to$	Events	Filter eff.
$J/\psi\omega$	$2 \cdot 10^4$	100%
$\pi^+\pi^-\pi^0\rho^0$	$8.49 \cdot 10^6$	0.77%
$\pi^+\pi^-\pi^-\rho^+$	$8.49 \cdot 10^6$	0.81%
$\pi^+\pi^-\omega$	$9.9 \cdot 10^6$	9.15%
$J/\psi\pi^-\rho^+$	$2.5 \cdot 10^5$	100%
$J/\psi\pi^0\rho^0$	$2.5 \cdot 10^5$	100%
$\psi(2S)\pi^0$	$1.6 \cdot 10^5$	100%

Reconstruction efficiency
14.7 % for $J/\psi \to e^+e^-$

Expected number of reconstructed events per day

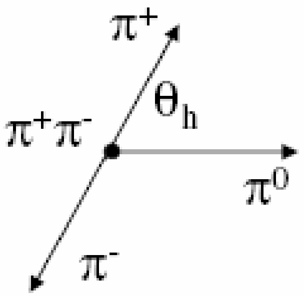
$$N = 119 \times \sigma_S \mathcal{B}(Y \to J\psi\omega)\text{nb}^{-}$$

$$(\mathcal{L} = 2 \cdot 10^{32} cm^{-2} s^{-1})$$



$J/\psi\omega$ background studies

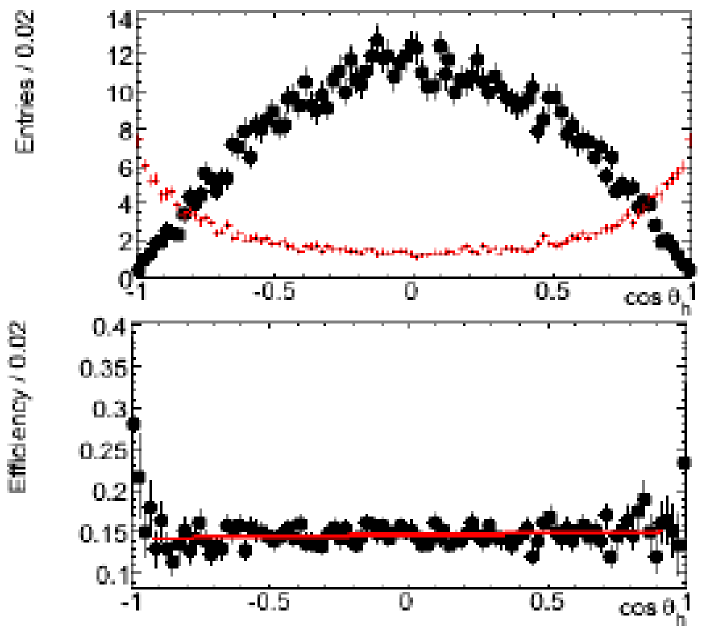
$J/\psi\omega$ ($\omega \to \pi^+\pi^-\pi^0$) and
$J/\psi\rho\pi$ ($\rho \to \pi\pi$)
Exploit angular distribution
helicity angle θ_h



- Signal events: ~$\sin\theta_h$
- efficiency ~ 1

- different angular distribution for background $\rho \to \pi\pi$
  observed θ_h distrib. for backgr. independent of ρ ang. distr.

Reaction	$\eta_{e^+e^-}$	$S/N_{e^+e^-}$
$\pi^+\pi^-\pi^0\rho^0$	$> 1.1 \cdot 10^9$	$> 56.5\,\tilde{\sigma}/\,\mathrm{nb}$
$\pi^+\pi^-\pi^-\rho^+$	$> 1.05 \cdot 10^9$	$> 40.6\,\tilde{\sigma}/\,\mathrm{nb}$
$\pi^+\pi^-\omega$	$> 1.08 \cdot 10^8$	$> 34.6\,\tilde{\sigma}/\,\mathrm{nb}$
$\psi(2S)\pi^0$	$3.33 \cdot 10^3$	$24.8\,\tilde{\sigma}/\,\mathrm{pb}$
$J/\psi\pi^-\rho^+$	25	$4.90\,\mathcal{BR}$
$J/\psi\pi^0\rho^0$	22.1	$7.65\,\mathcal{BR}$



$\bar{p}A \rightarrow J/\psi X$

Motivation:

- understand J/ψ suppression as signature for QGP
- investigate J/ψ-nucleon interaction

Method:

- measure systematic A dependence in J/ψ production in $\bar{p}A$
- scan $\bar{p}$ momentum across J/ψ resonance
- determine $\sigma_{\bar{p}A \rightarrow J/\psi X} \propto A^{-\alpha}\ \sigma_{\bar{p}p \rightarrow J/\psi}$ $\qquad \sigma_{J/\psi N}$

simulation studies:

Signal channels:

- 4.05 GeV/c $\overline{p}\ {}^{40}Ca \rightarrow J/\psi\ X \rightarrow e^+e^-\ X$ 80 k events
- 4.05 GeV/c $\overline{p}\ {}^{40}Ca \rightarrow J/\psi\ X \rightarrow \mu^+\mu^-\ X$ 80 k events

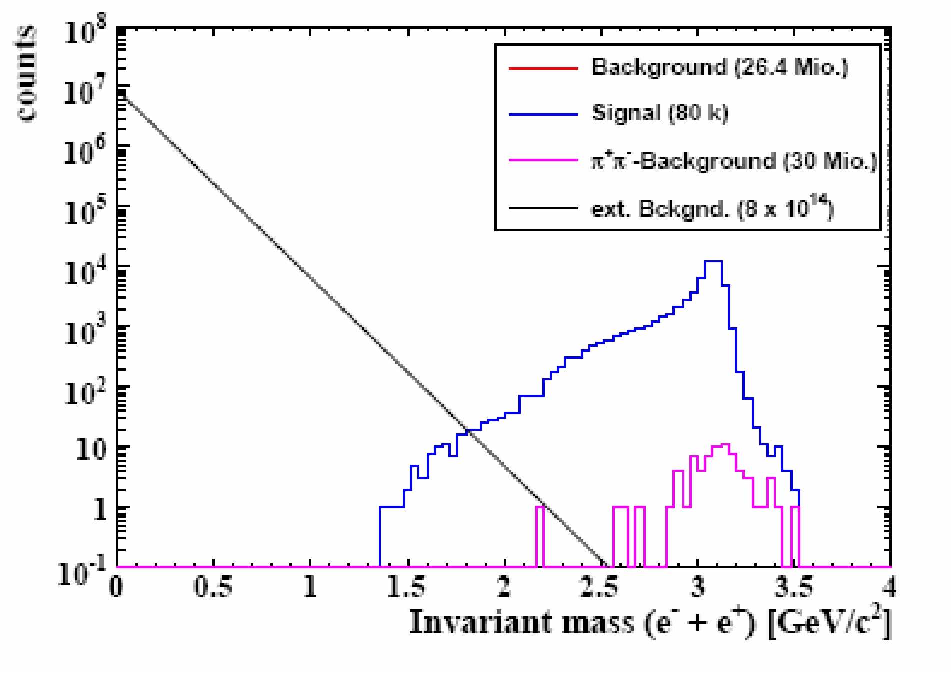
Background channels: e^+e^- / $\mu^+\mu^-$ analysis

- 4.05 GeV/c $\overline{p}\ {}^{40}Ca$ UrQMD 26.4 M events
- 4.05 GeV/c $\overline{p}$ ‚p' $\rightarrow \pi^+\pi^-$ 30 M events
  ‚p' $\equiv$ Fermi smeared

$\overline{p}$ momentum „on resonance", no scan, no systematic errors

cut	fraction accepted		
	signal	background	
		UrQMD	$\pi^+\ \pi^-$
$\sqrt{v_x^2 + v_y^2} < 1\,\mathrm{mm}$	0.77	$3.8 \cdot 10^{-8}$	$4.1 \cdot 10^{-6}$
$P_z(e^+) + Pz(e^-) > 2.0\,\mathrm{GeV}/c$	0.77	$2.3 \cdot 10^{-7}$	$4.9 \cdot 10^{-6}$
$\Phi(e^+, e^-) > 2.5\,\mathrm{rad}$	0.77	$1.5 \cdot 10^{-7}$	$4.9 \cdot 10^{-6}$
$[P_\perp(e^+) + P_\perp(e^-)] > 1$ GeV/c & $\left|\arctan\left(\frac{P_\perp(e^+)}{P_\perp(e^-)}\right) - 45^\circ\right| < 15^\circ$	0.73	$3.8 \cdot 10^{-8}$	$2.8 \cdot 10^{-6}$
combined ($IM_{e^+e^-} > 2.0\,\mathrm{GeV}/c^2$)	0.73	$< 3.8 \cdot 10^{-8}$	$2.4 \cdot 10^{-6}$

Required rejection factor of the order of 10^6 achieved !!!



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 ($\sqrt{s} \approx 5.5$ GeV). This will allow $\bar{\text{P}}$ANDA to carry out the following measurements:

SPECTROSCOPY

- High-resolution charmonium spectroscopy in formation experiments
- Study of gluonic excitations (hybrids and glueballs) and other exotica (e.g. multiquark)
- Study of hadrons in nuclear matter
- Open charm physics
- Hypernuclear physics

NUCLEON STRUCTURE

- Proton Timelike Form Factors
- Crossed-Channel Compton Scattering
- Drell-Yan

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

The simulations show that the final states of interest can be detected with good efficiency and that the background situation is under control.