Antiproton Physics (Overview of the $\bar{P}$ANDA Physics Program)

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International School of Nuclear Physics,
From Quarks and Gluons to Hadrons and Nuclei
Erice, Italy, 16-24 September 2011

Outline

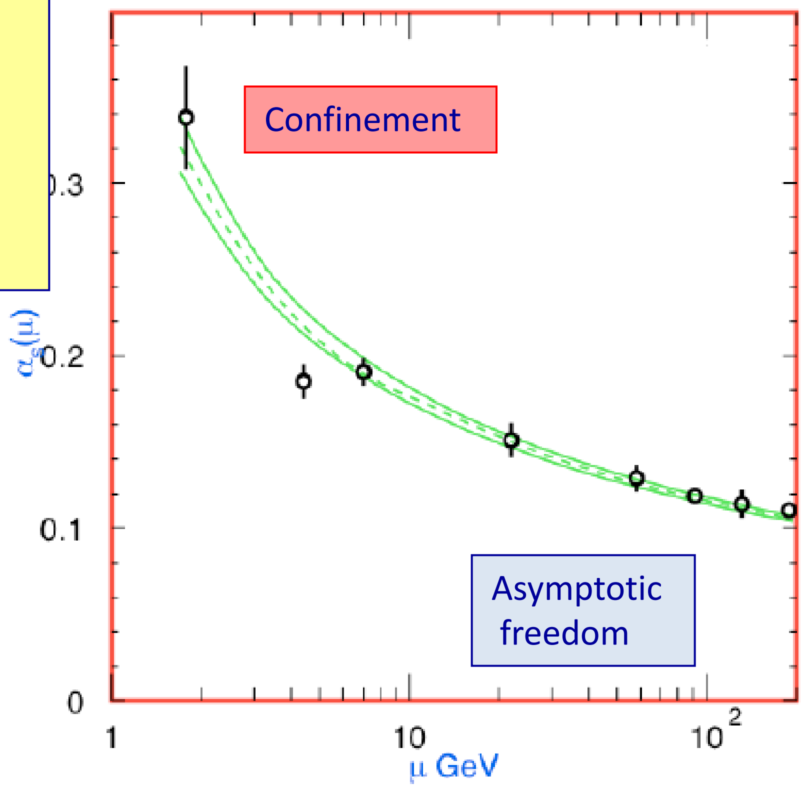
- The strong interaction and QCD
- $\overline{\text{P}}$ANDA at FAIR
  - Experimental Setup
  - The $\overline{\text{P}}$ANDA Physics Program
  - Physics Performance
- Summary and Outlook

QCD

The modern theory of the strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non abelian gauge group SU(3). It is part of the Standard Model.

At high energies, where the strong coupling constant α_s becomes small and perturbation theory applies, QCD is well tested.

In the low-energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood.



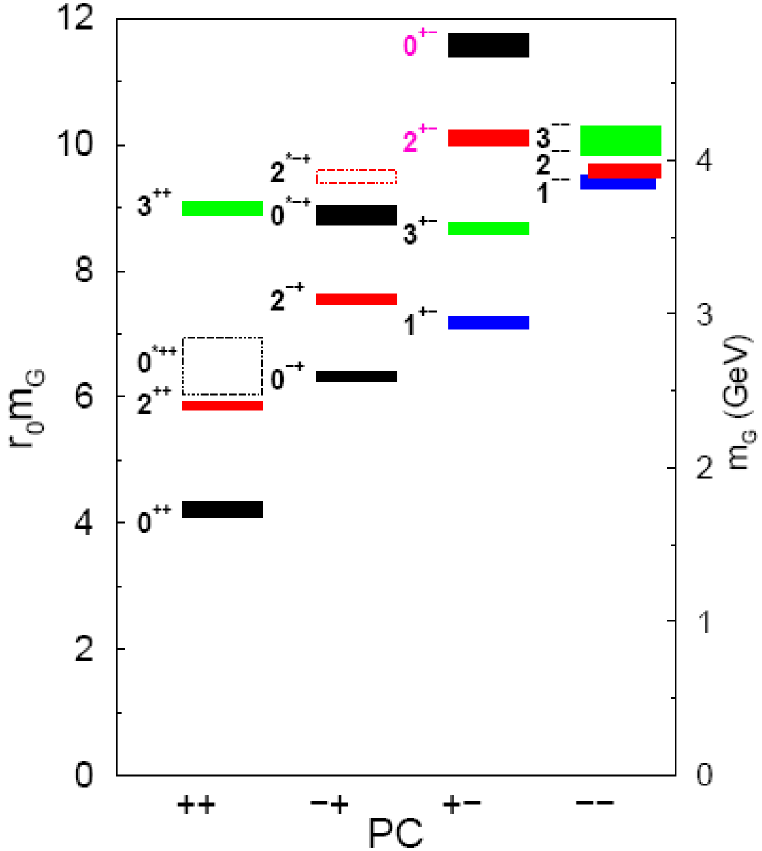
Theoretical Approaches to non-perturbative QCD

- Potential models. Bound systems of heavy quarks can be treated in the framework of non-relativistic potential models, with forms which reproduce the asymptotic behaviour of QCD. Masses and widths are obtained by solving Schrödinger's equation.
- Lattice QCD (LQCD)
  - The QCD equations of motions are discretized on a 4-dimensional space-time lattice and solved by large-scale computer simulations.
  - Enormous progress in recent years (e.g. gradual transition from quenched to unquenched calculations).
  - Ever increasing precision, thanks also to sinergies with EFT.
- Effective Field Theories (EFT)

  They exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective lagrangians that are equivalent to QCD for the problem at hand.
  - With quark and gluon degrees of freedom (e.g. Non Relativistic QCD or NRQCD)
  - With hadronic degrees of freedom (e.g. Chiral Perturbation Theory).

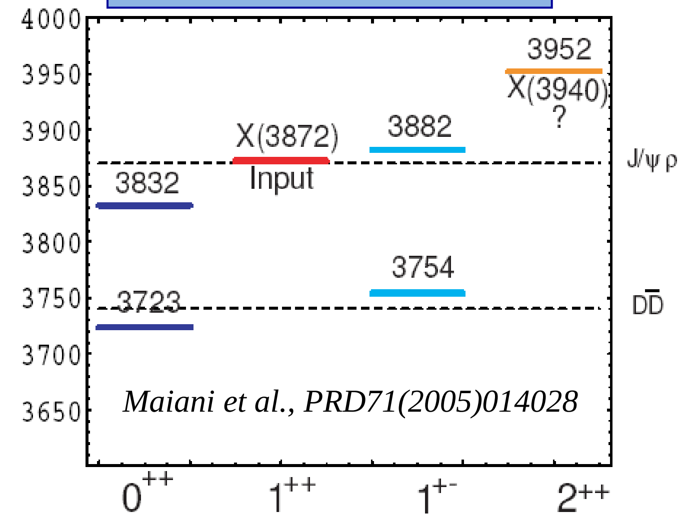
Examples of Theory Calculations

LQCD Glueball Spectrum

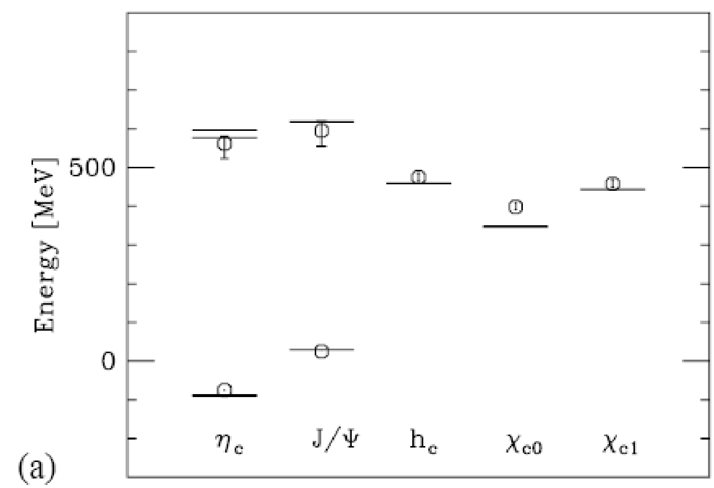


Morningstar und Peardon, PRD60 (1999) 034509

Four quark for the X(3872)



LQCD + NRQCD
Charmonium Spectrum



Experimental Measurements

- Spectroscopy of QCD bound states. Precision measurement of particle spectra to be compared with theory calculations. Identification of the relevant degrees of freedom.
  - light quarks, $c\bar{c}$, $b\bar{b}$
  - D meson
  - baryon
- Search for new forms of hadronic matter: hybrids, glueballs, multiquark states ...
- Hadrons in nuclear matter. Origin of mass.
- Hypernuclei.
- Study of nucleon structure.
  - Form Factors
  - GDAs
- Spin physics.

Experimental Techniques

e^+e^- collisions

direct formation
two-photon production
initial state radiation (ISR)
B meson decay
(BaBar, Belle, BES, CLEO(-c), LEP ...)

+ low hadronic background
+ high discovery potential
- direct formation limited to vector states
- limited mass and width resolution for non vector states

$\bar{p}p$ annihiliation

(LEAR, Fermilab E760/E835, $\bar{\text{P}}$ANDA)

- high hadronic background
+ high discovery potential
+ direct formation for all (non-exotic) states
+ excellent mass and width resolution for all states

Hadroproduction

(CDF, D0, LHC)

Electroproduction

(HERA)

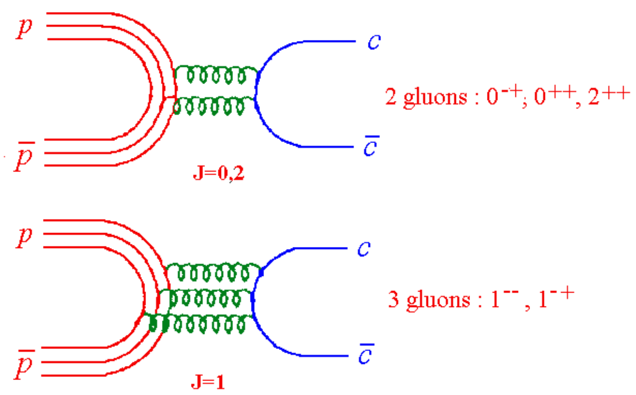
$\bar{p}p$

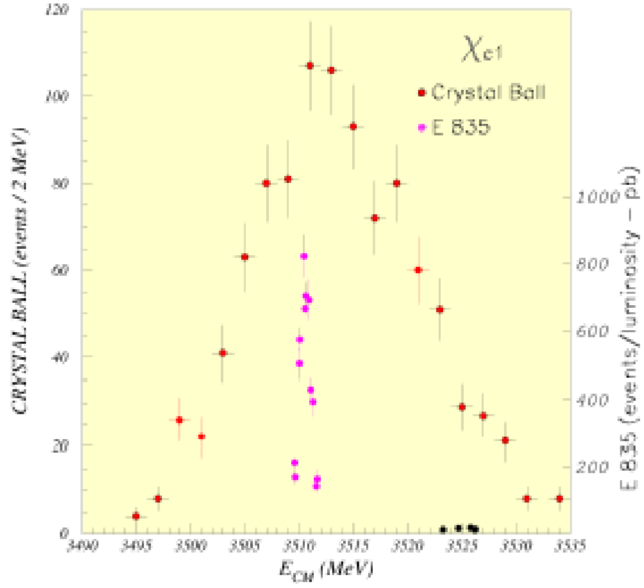
Experimental Technique

Highlights from Fermilab

$\bar{p}p$ 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.

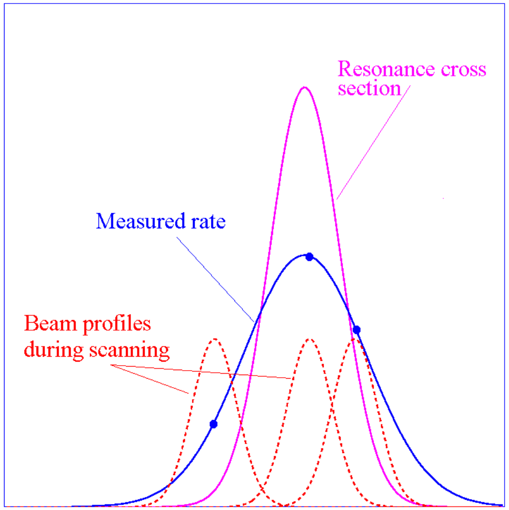
Experimental Method

The cross section for the process:

$\bar{p}p \rightarrow R \rightarrow$ final state

is given by the Breit-Wigner formula:

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

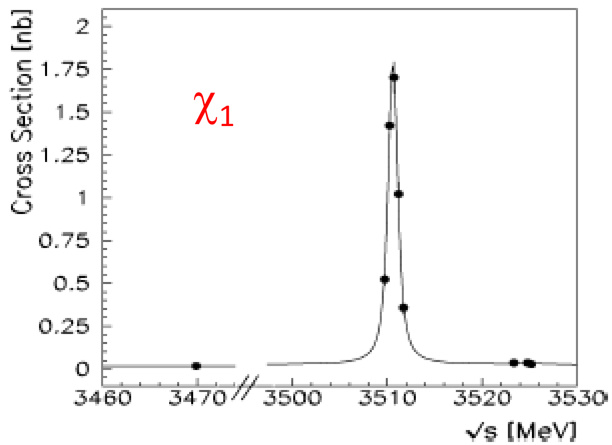


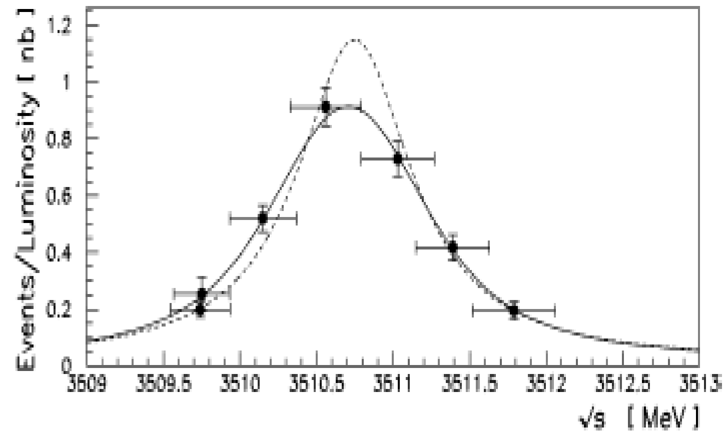
The production rate ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

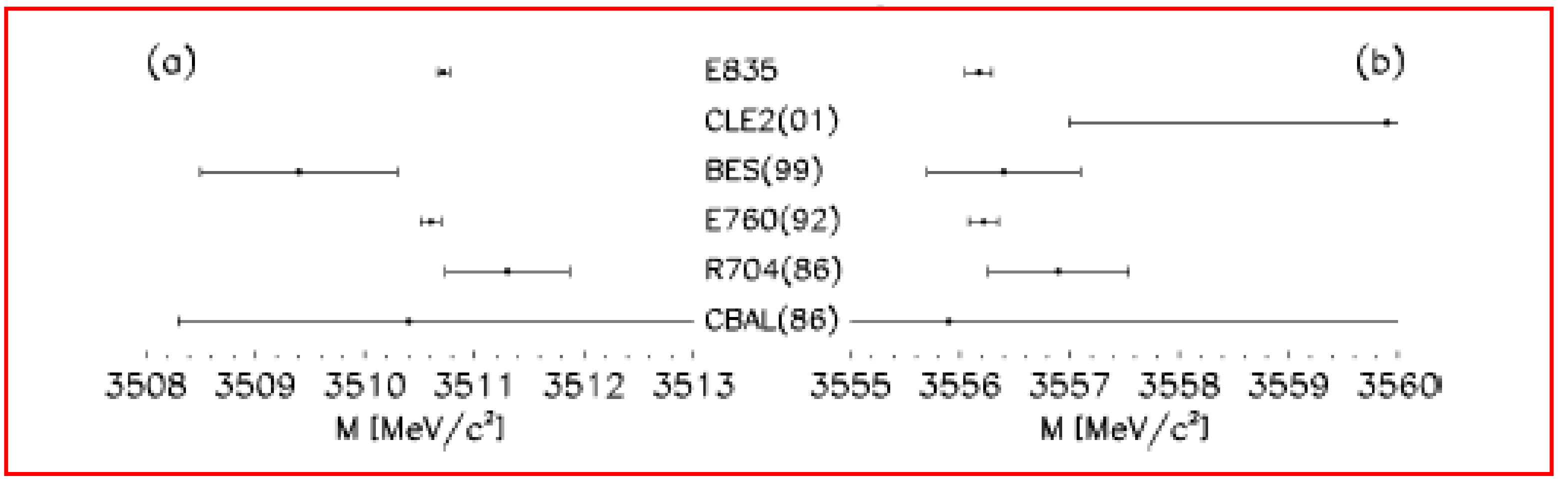
$$\nu = L_0 \left\{ \varepsilon \int dE f(E, \Delta E) \sigma_{BW}(E) + \sigma_b \right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy *E*.

Example: χ_{c1} and χ_{c2} scans in Fermilab E835







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

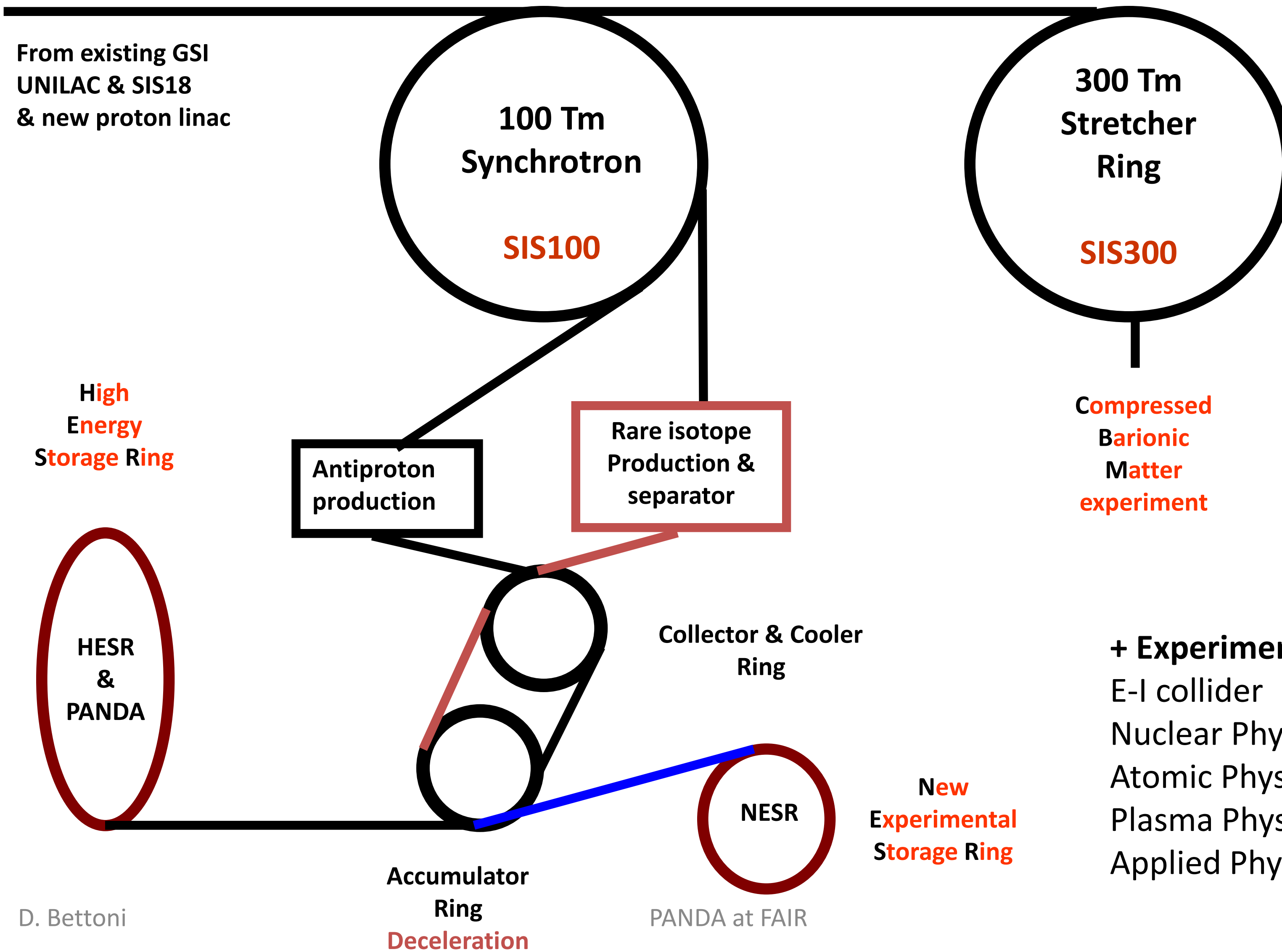
Experimental Setup

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

Physics Performance

FAIR at a glance
Facility for Antiproton and Ion Research

The FAIR Complex



+ Experiments:
E-I collider
Nuclear Physics
Atomic Physics
Plasma Physics
Applied Physics

High-Energy Storage Ring

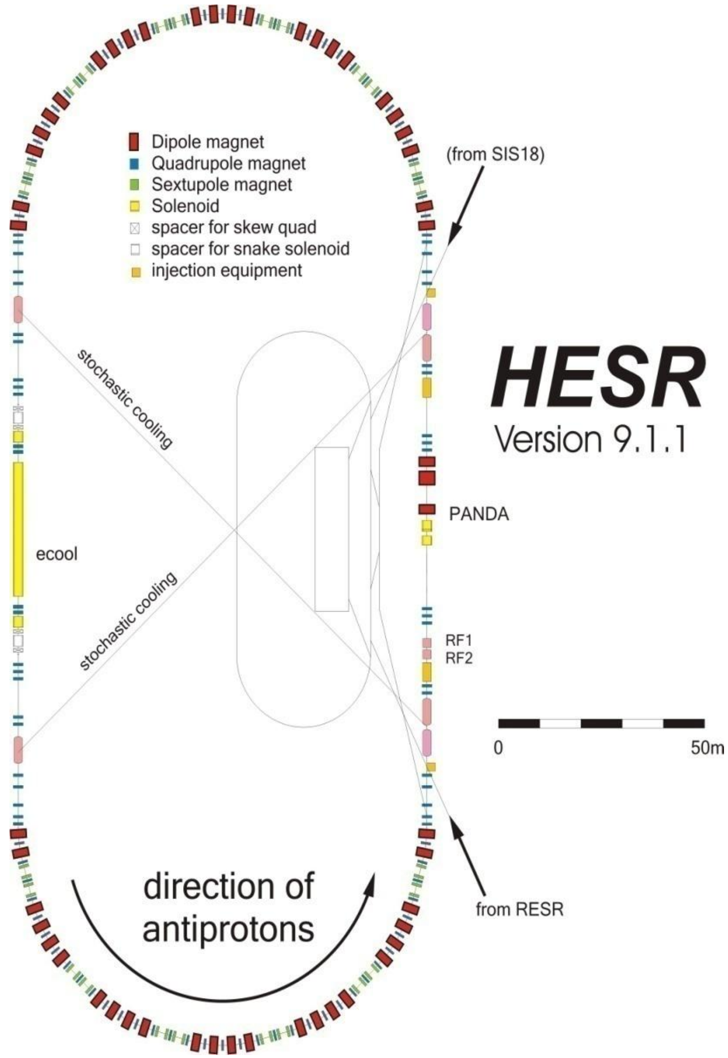
- Production rate $2x10^7$/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = $5x10^{10}$ $\bar{p}$
- Internal Target

High resolution mode

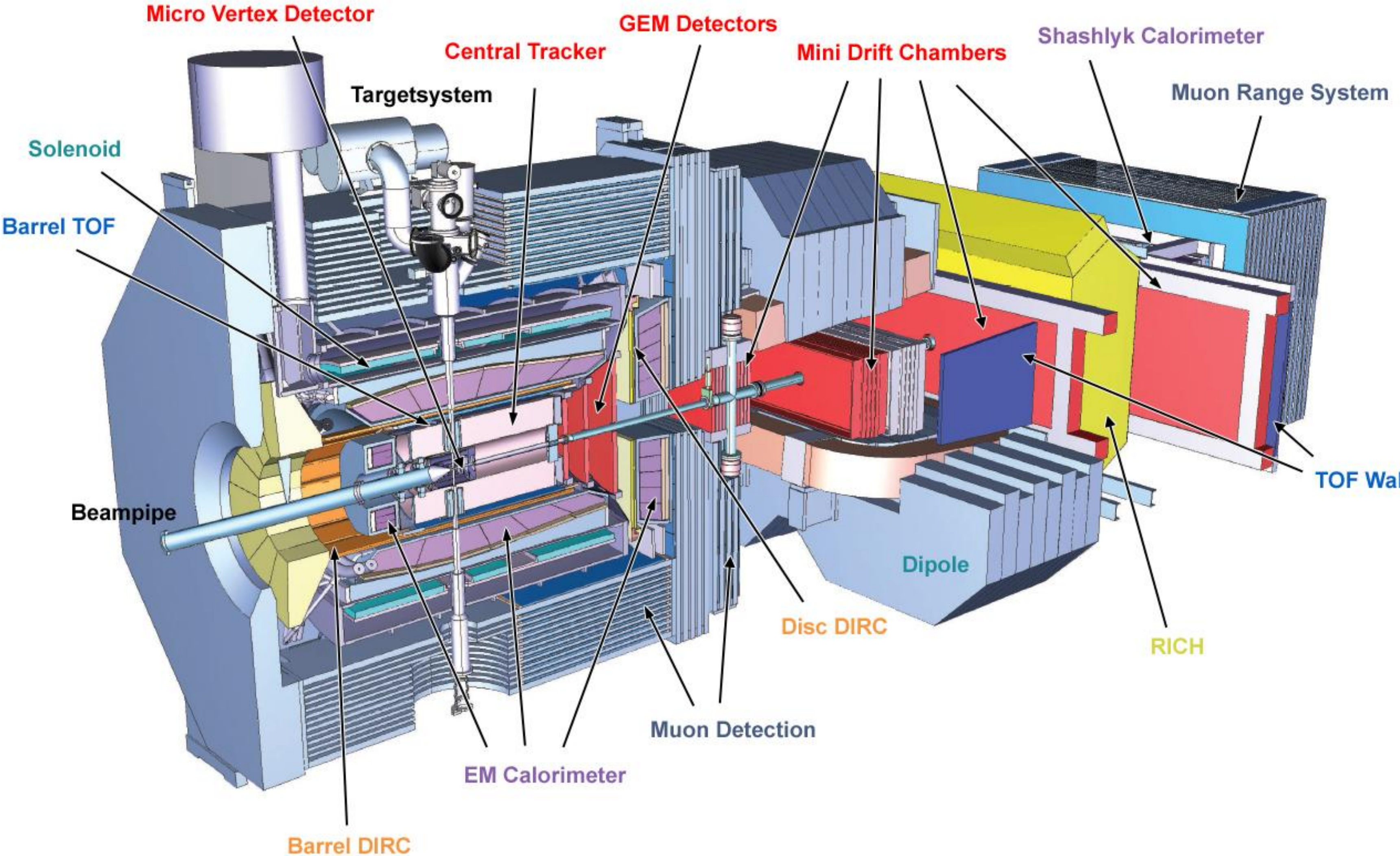
- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

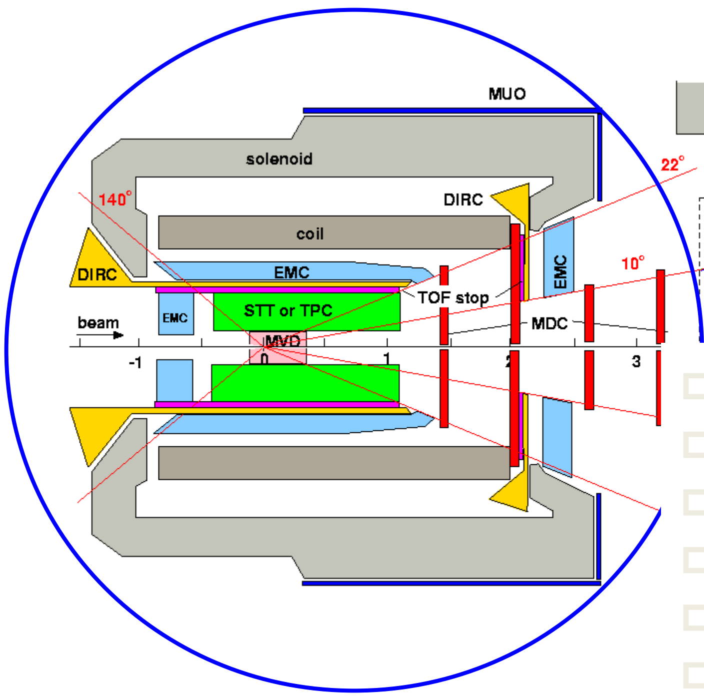
- Lumin. = 2 x 10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)

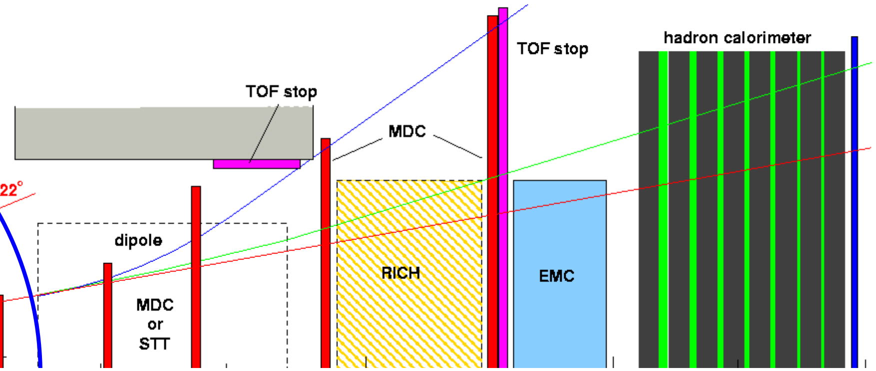


$\overline{\text{P}}$ANDA Detector



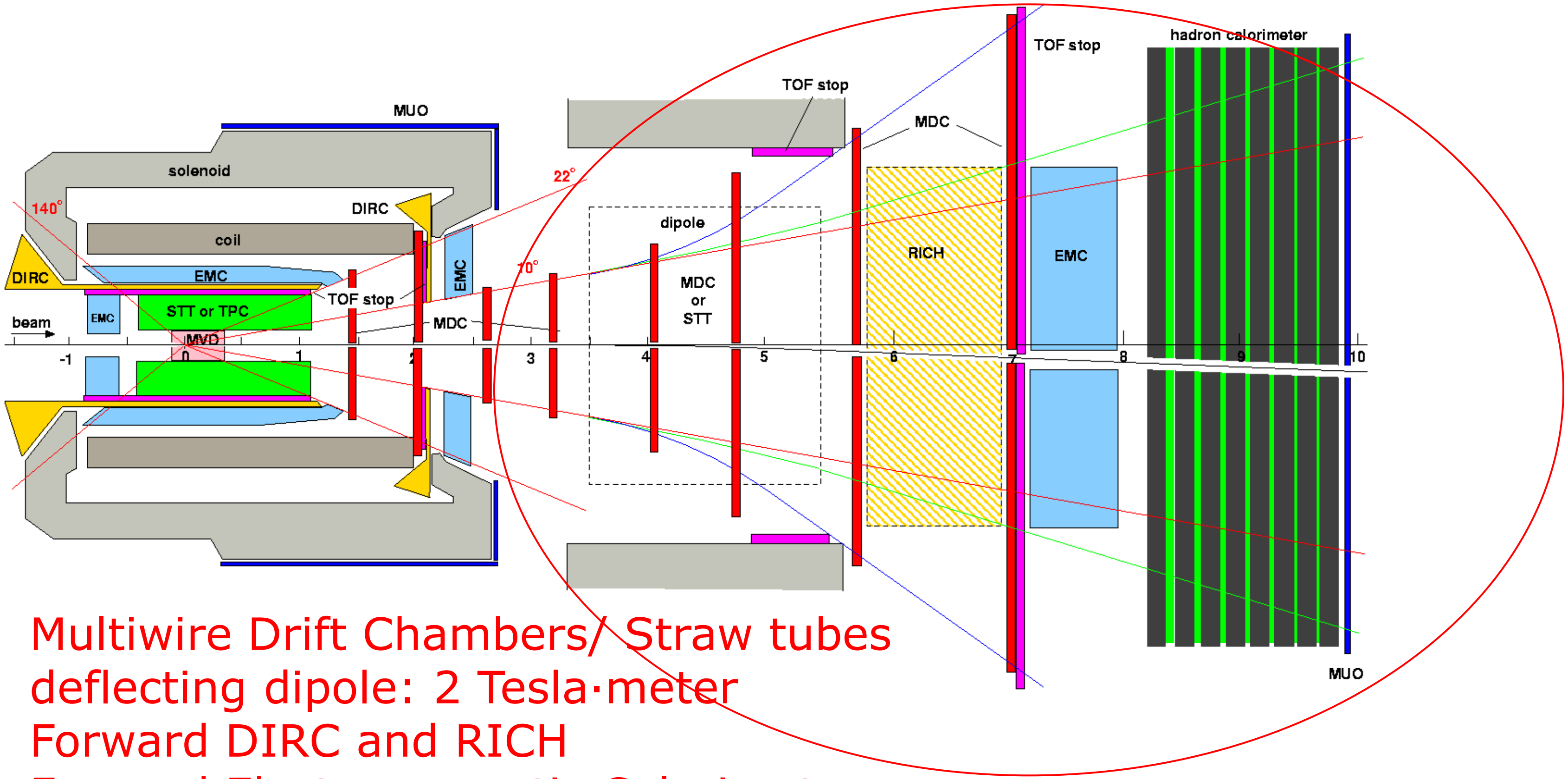
Target Spectrometer





- p of momentum from 1.5 up to 15 GeV/c
- 2 Tesla solenoid
- proton pellet target or gas jet target
- Micro Vertex Detector
- Inner Time of Flight detector
- Tracking detector: Straw Tubes
- DIRC
- Electromagnetic Calorimeter
- Muon counters
- Multiwire Drift Chambers

Forward Spectrometer



- Multiwire Drift Chambers/ Straw tubes
- deflecting dipole: 2 Tesla·meter
- Forward DIRC and RICH
- Forward Electromagnetic Calorimeters
- Time of Flight counters
- Hadron Calorimeter

PANDA Collaboration

> 430 Scientists

56 Institutions

16 Countries

U Basel
IHEP Beijing
U Bochum
U Bonn
U & INFN Brescia
IFIN Budapest
U & INFN Catania
U Cracow
GSI Darmstadt
TU Dresden
JINR Dubna
(LIT,LPP,VBLHE)
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
U Frankfurt
LNF-INFN Frascati
U & INFN Genoa
U Glasgow
U Gießen
KVI Groningen
IKP Jülich I + II
U Katowice
IMP Lanzhou
U Mainz
U & INFN Milano
Politecnico di Milano
U Minsk
TU München
U Münster
BINP Novosibirsk
LAL Orsay
U & INFN Pavia
IHEP Protvino
PNPI Gatchina
U of Silesia, Katowice
U Stockholm
KTH Stockholm
U & INFN Torino
Politechnico di Torino
U Oriente, Torino
U & INFN Trieste
U Tübingen
U & TSL Uppsala
U Valencia
SMI Vienna
SINS Warsaw
U Warsaw

$\overline{\text{P}}$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

FAIR/PANDA/Physics Book i

Physics Performance Report for:

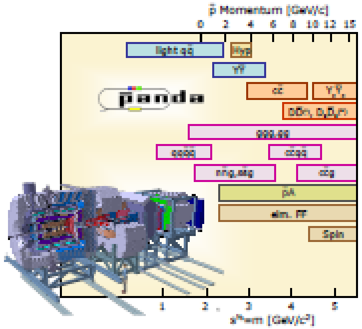
$\overline{\text{P}}$ANDA

(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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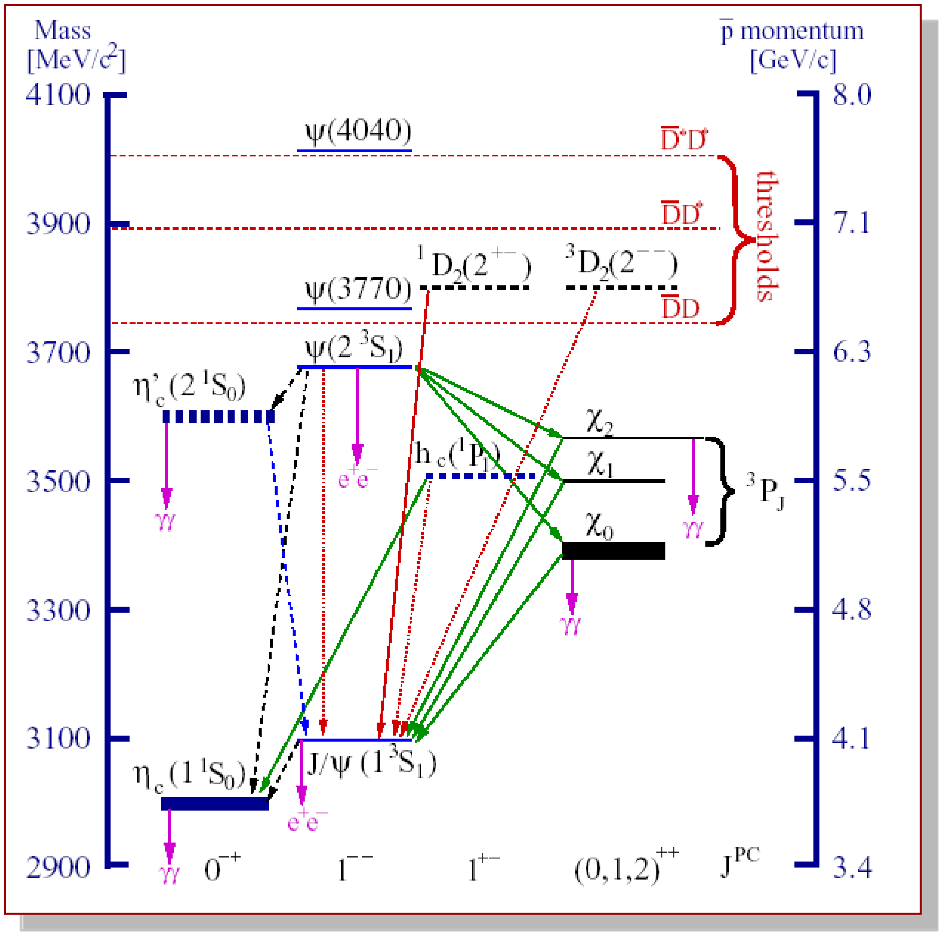
QCD Bound States

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)
  - $\eta_c(1S)$
  - $\eta_c(2S)$ (small splitting from $\psi(2S)$)
- 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 2×10^{32}cm^{-2}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 2×10^{32}cm^{-2}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/ψ+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 $\bar{c}c$ system.

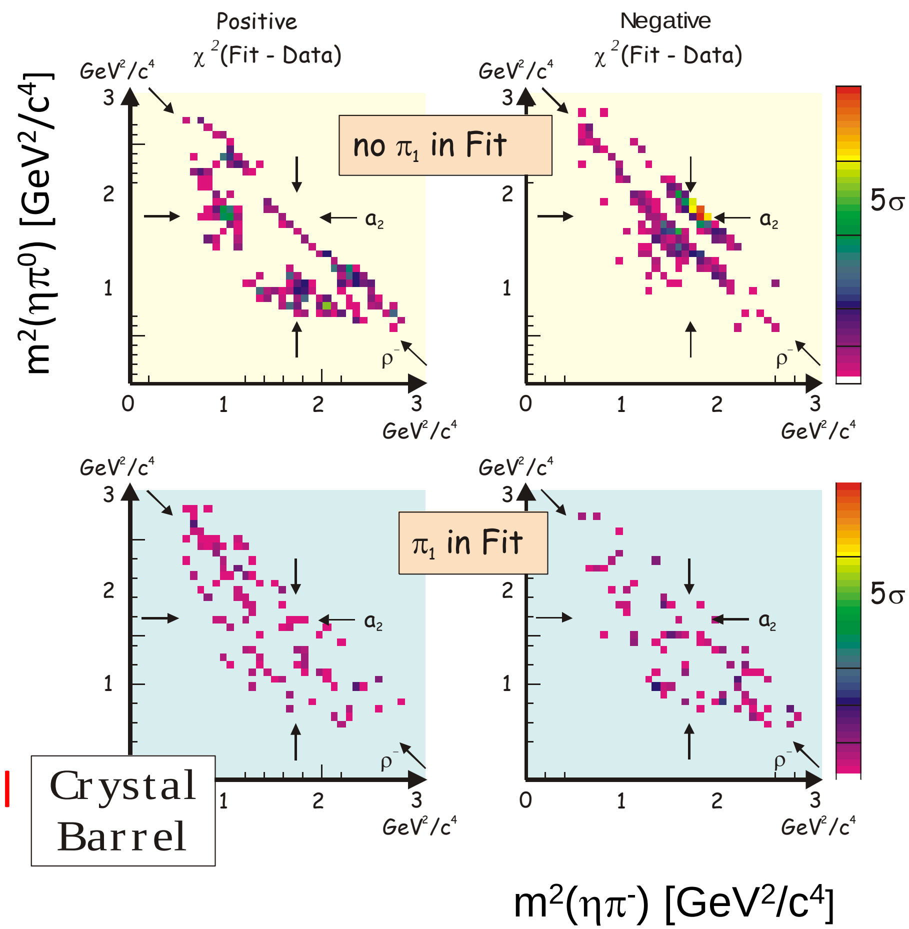
Hybrids and Glueballs

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 ($J^{PC}=0^{++}$).



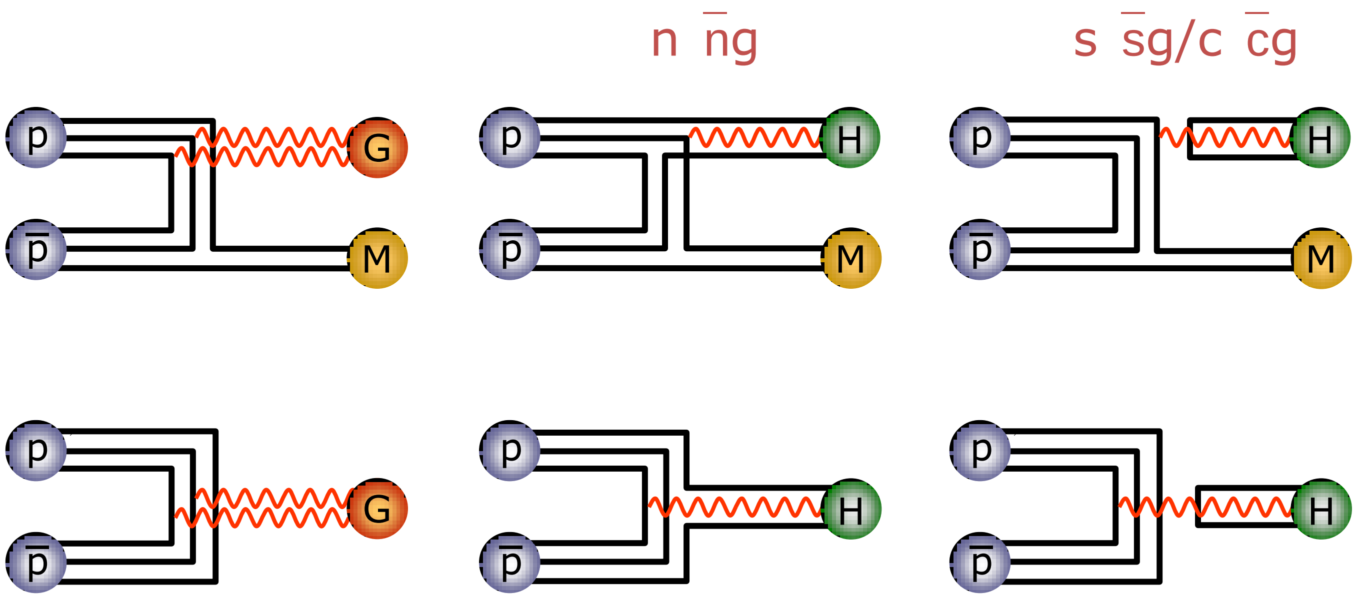
Hybrids and Glueballs in $\bar{p}p$ Annihilation

Production

all J^{PC} available

Formation

only selected J^{PC}

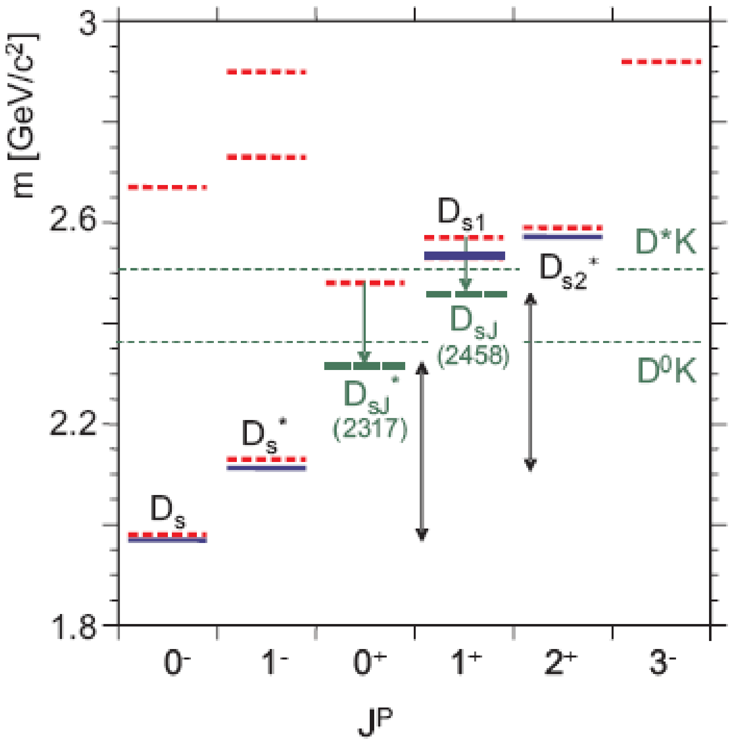


Gluon rich process creates gluonic excitation in a direct way

- $c\bar{c}$ 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.

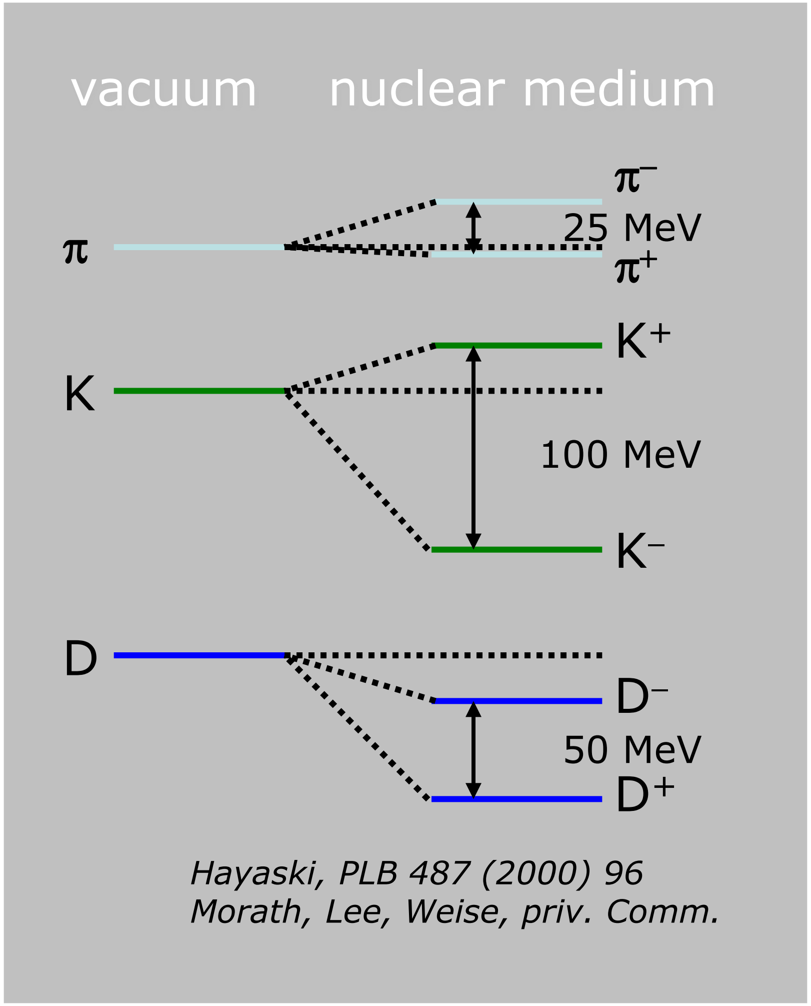
Non-perturbative QCD Dynamics

In the quark picture hyperon pair production either involves the creation of a quark-antiquark pair or the knock out of such pairs out of the nucleon sea. Hence, the creation mechanism of quark-antiquark pairs and their arrangement to hadrons can be studied by measuring the reactions of the type $\bar{p}p \rightarrow \bar{Y}Y$, where Y denotes a hyperon. By comparing several reactions involving different quark flavours the OZI rule, and its possible violation, can be tested for different levels of disconnected quark-line diagrams separately.

Furthermore the parity violating weak decay of most ground state hyperons introduces an asymmetry of the decay particles and gives access to spin degrees of freedom for these processes. A systematic investigation of these reactions will bring new information on single and multiple strangeness production and its dependence on spin observables.

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)



Charmonium in Nuclei

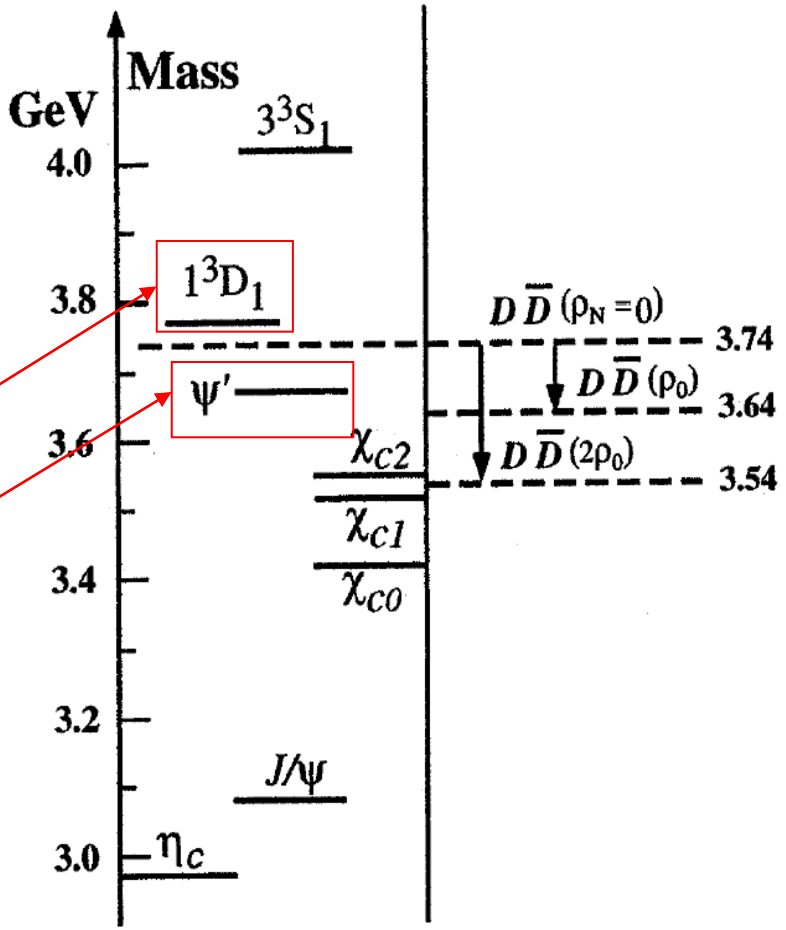
- Measure J/ψ and D production cross section in $\bar{p}$ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

  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)

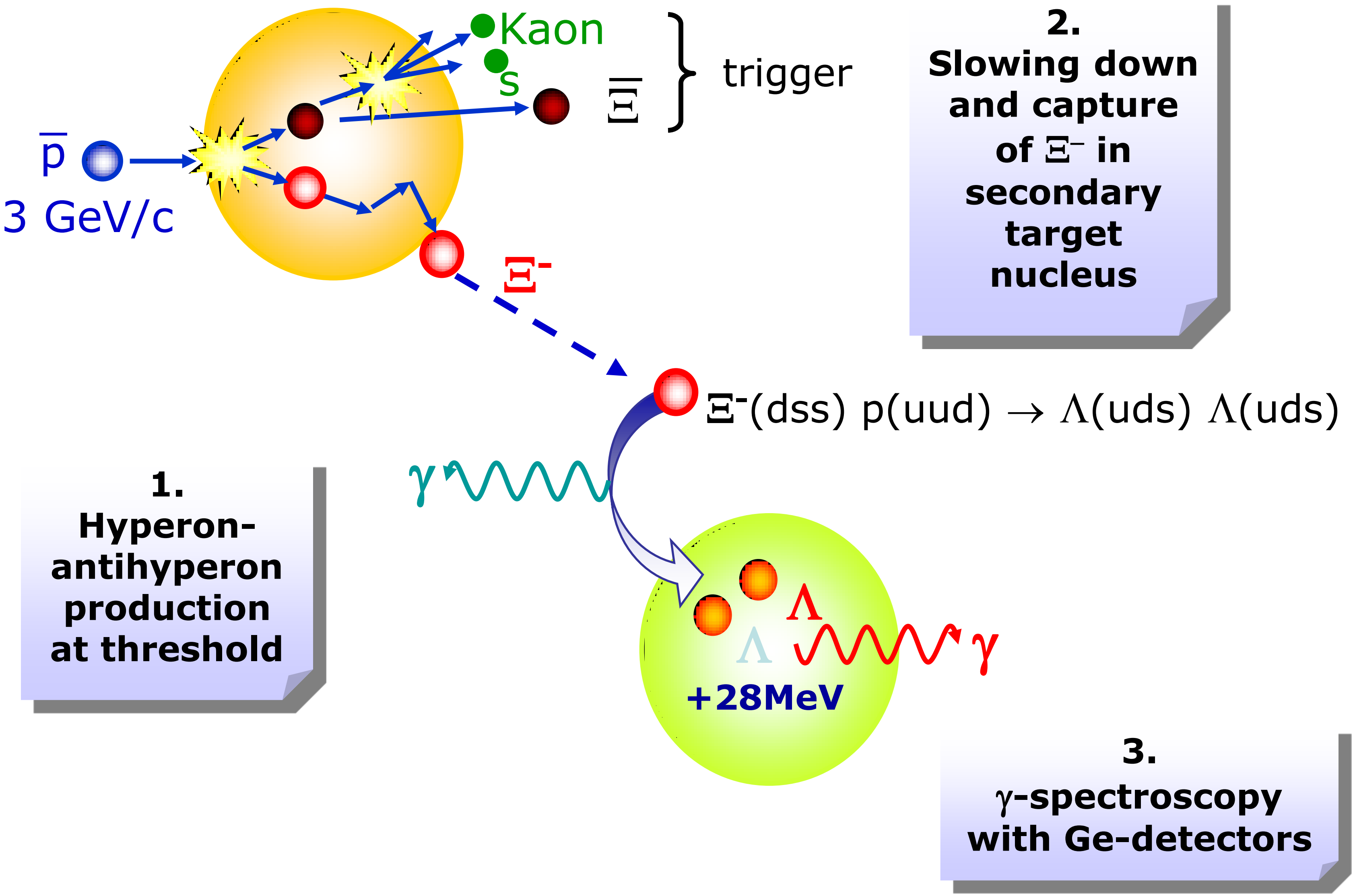


Hypernuclear Physics

Hypernuclei, systems where one (or more) nucleon is replaced by one (or more) hyperon(s) (Y), allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness.

- Probe of nuclear structure and its possible modifications due to the hyperon.
- Test and define shell model parameters.
- Description in term of quantum field theories and EFT.
- Study of the YN and YY forces (single and double hypernuclei).
- Weak decays ($\Lambda \rightarrow \pi N$ suppressed, but $\Lambda N \rightarrow NN$ and $\Lambda\Lambda \rightarrow NN$ allowed $\Rightarrow$ four-baryon weak interaction)
- Hyperatoms
- Experimentally: in 50 years of study 35 single, 6 double hypernuclei established

Production of Double Hypernuclei



Nucleon Structure Using Electromagnetic Processes

- The electromagnetic form factors of the proton in the time-like region can be extracted from the cross section for the process:

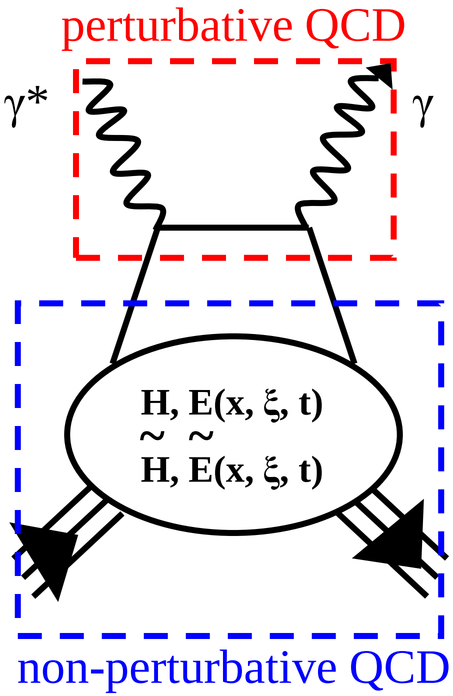
$$\bar{p}p \rightarrow e^+e^-$$

  - Moduli of form factors using angular distribution
  - Extend q^2 range
  - Improve accuracy of measurement

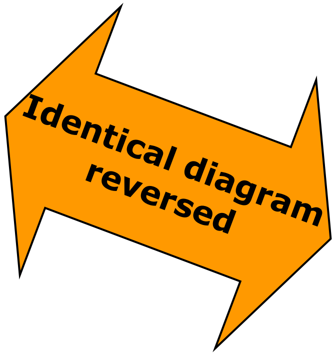
  (talks by Yue Ma and Dmitry Khaneft on thursday)
- Hard Scattering Processes ($\bar{p}p \rightarrow \gamma\gamma$)

  (test of factorization)
- Transverse parton distribution functions in Drell-Yan production.

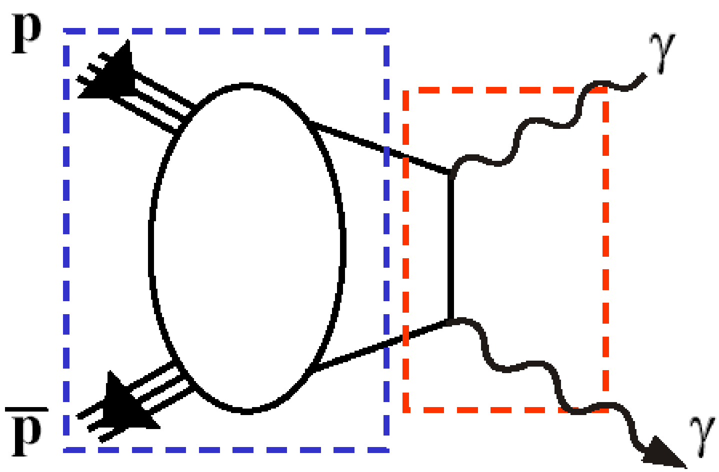
Hard Scattering Processes and $\bar{p}p \to \gamma\gamma$



Wide angle Compton scattering
factorisation into hard amplitude
(calculable in perturbative QCD)
and soft amplitude
(information on parton distributions)

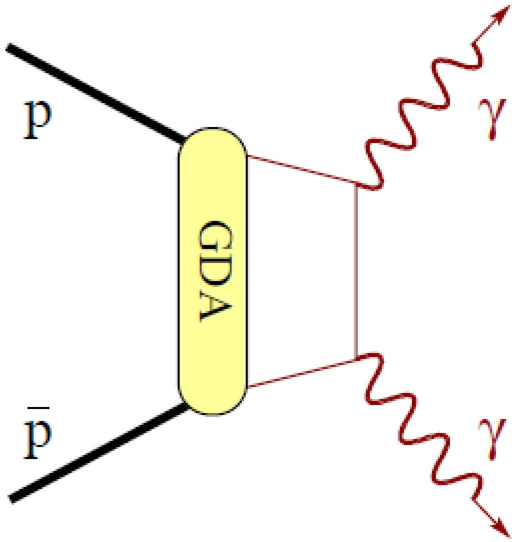


Crossed Diagram
$pp \to \gamma\gamma$
clear experimental signature
both baryons in ground state
$\sigma \approx 2.5$pb @ s ≈ 10 GeV^2
$L = 2 \cdot 10^{32}$ cm^{-2} s$^{-1} \to 10^3$ events per month



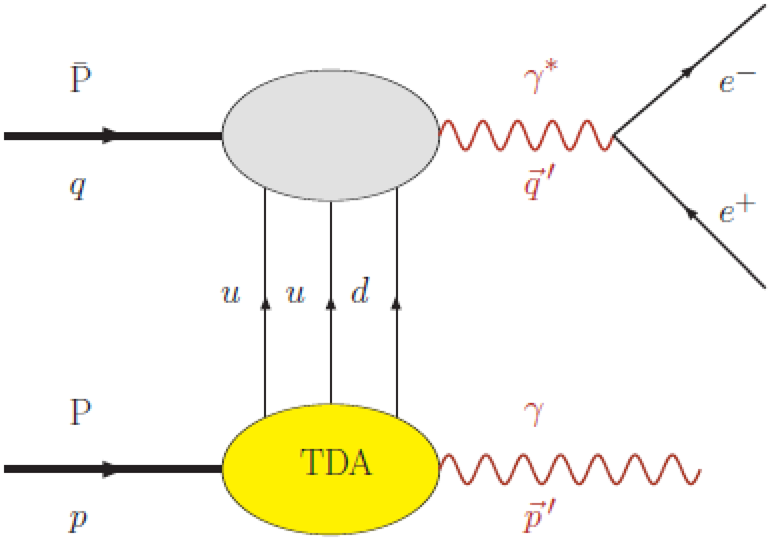
Other Timelike Processes in $\bar{\text{P}}$ANDA

$\bar{p}p \to \gamma\gamma$



Handbag approach
Test of Factorisation

$\bar{p}p \to e^{+}e^{-}\gamma$



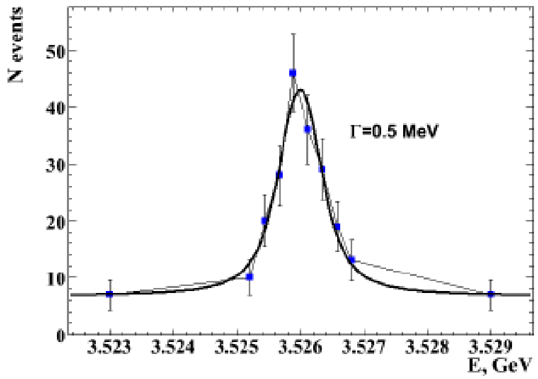
Determine TDA
(Transition Distribution Amplitude)
Measure FF in unphysical region

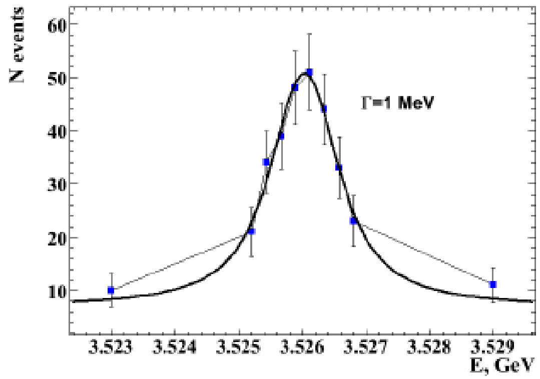
Physics Simulations

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

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

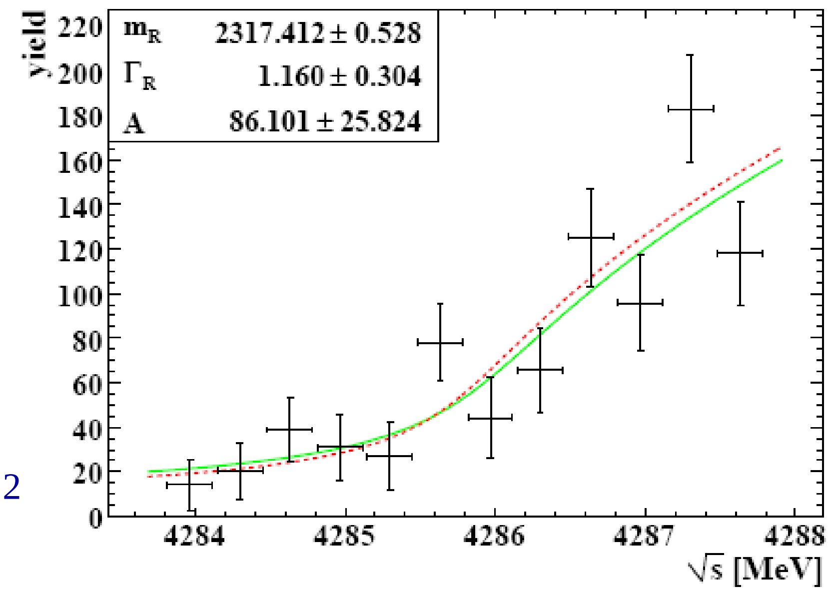
The production cross section around threshold depends on the total width.

input

$$\int \mathcal{L}dt = 126\ pb^{-1} (14\ \text{days})$$
$$S/B = 1/3$$
$$\Gamma = 1\ MeV$$
$$m = 2317.30\ MeV/c^2$$

output

$$\Gamma = (1.16 \pm 0.30)\ MeV$$
$$m = (2317.41 \pm 0.53)\ MeV/c^2$$



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.