Paola Gianotti
Istituto Nazionale di Fisica Nucleare

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

14th International Workshop on Meson Production, Properties and Interaction
KRAKÓW, POLAND
2nd - 7th June 2016

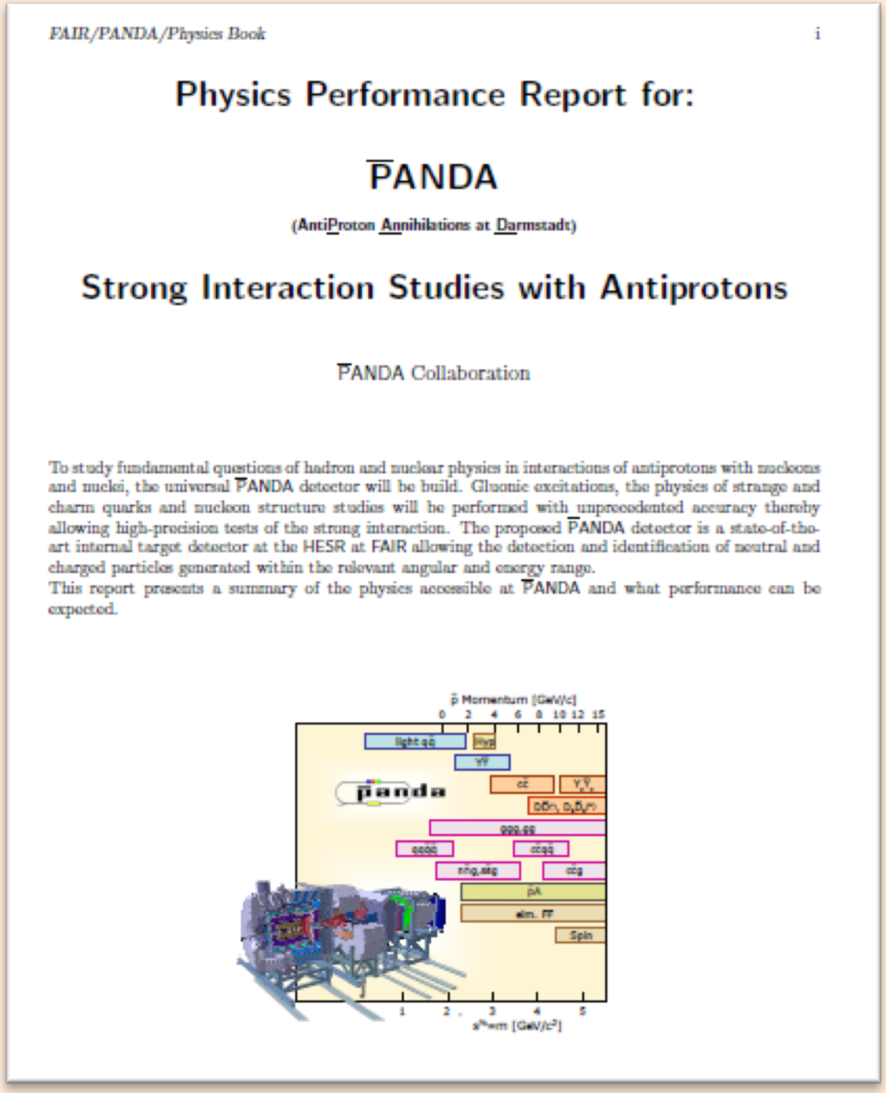
Outline

- Hadron spectroscopy with antiprotons;
- Meson spectroscopy:
  - Low energy sector;
  - Charmonium energy range;
- Baryon spectroscopy;
- e.m. reactions.

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

- HADRON SPECTROSCOPY
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - OPEN CHARM
  - (MULTI)STRANGE BARYONS
- NUCLEON STRUCTURE
  - ELECTROMAGNETIC FORM FACTORS
  - TMDs
  - GPDs, TDAs
- HYPERNUCLEAR PHYSICS
- HADRONS IN THE NUCLEAR MEDIUM

$$\sqrt{s} = 2 \div 5.5\ GeV$$



FAIR/PANDA/Physics Book i

Physics Performance Report for:

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

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

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

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\bar{\text{P}}$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 $\bar{\text{P}}$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 $\bar{\text{P}}$ANDA and what performance can be expected.

ArXiV:0903.3905

Physics scope

One of the open problems in the Standard Model is a full understanding of Quantum Chromodynamics (QCD).

QCD describes well phenomena at high energies (perturbative regime).

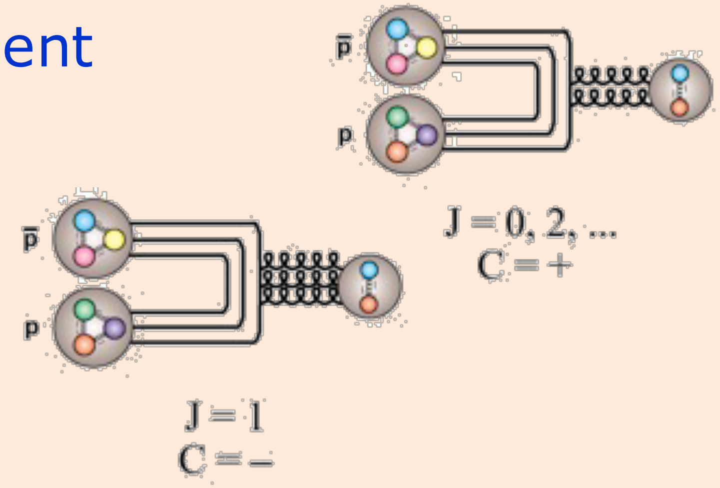
At low energies, QCD becomes a strongly coupled theory, many aspects of which are not understood.

$\bar{\text{P}}$ANDA will study $\bar{p}p$ and $\bar{p}A$ annihilations, providing unique and decisive measurements on a wide range of QCD aspects

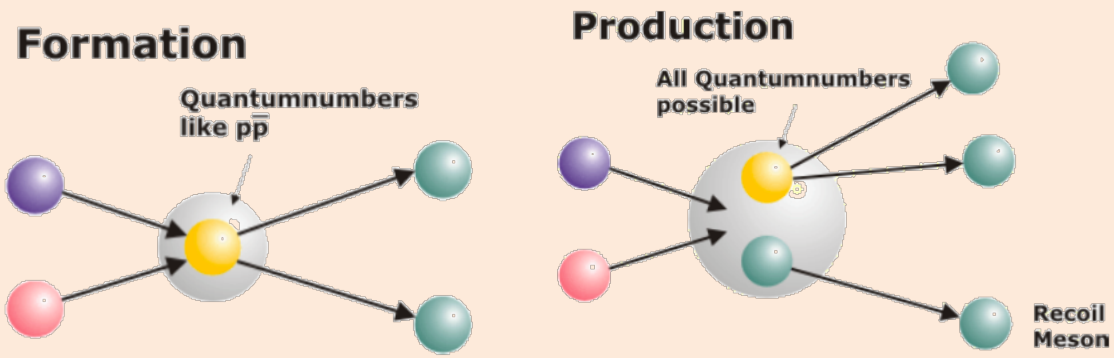
$\bar{p}p$ Anihilation

$\bar{p}p$ annihilation is a Gluon-Rich environment

Direct resonant formation of states with all non-exotic quantum numbers.
$\Rightarrow$ excellent precision in mass and width measurement



Access to both exotic and non-exotic quantum numbers via production and formation reactions



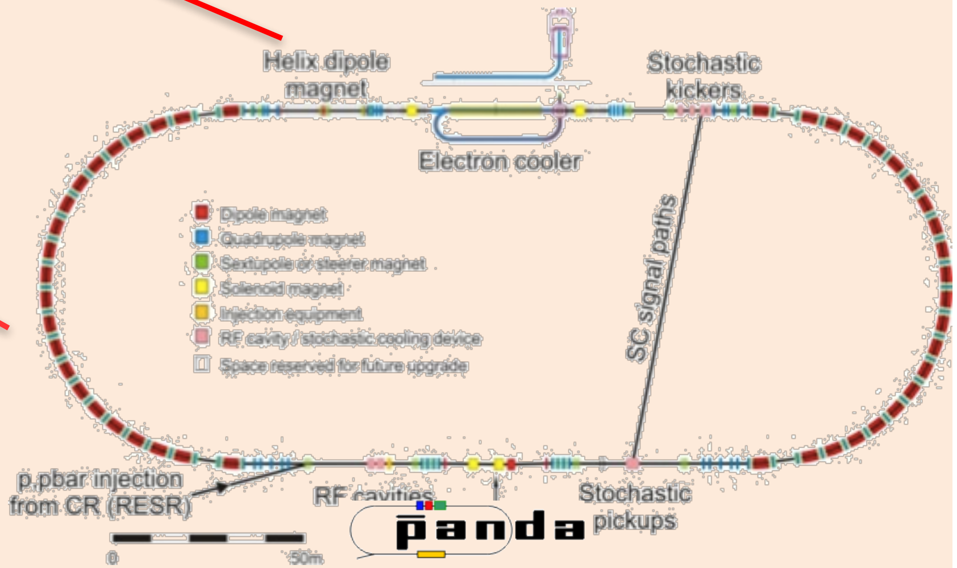
Versatility of physics program
if coupled to universal detector

Uniqueness of $\bar{p}$ probe
no other $\bar{p}$ facility in this energy range in the world

Facility for Antiproton and Ion Research

Antiproton production

- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce p on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR

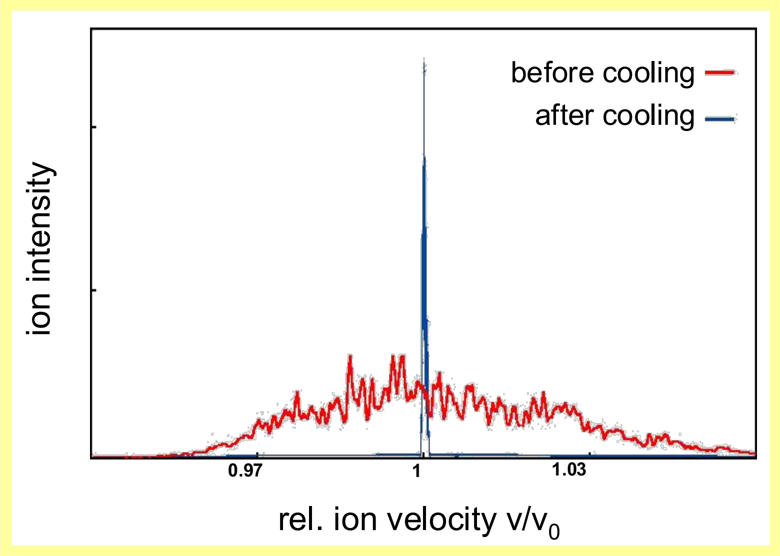


HESR: Storage ring for $\bar{p}$

- Injection of $\bar{p}$ at 3.7 GeV/c
- Slow synchrotron (1.5-15 GeV/c)
- Luminosity up to L~ 2×10^{32} $cm^{-2}s^{-1}$
  10^{31} for MSV0-3
- Beam cooling (stochastic & electron)

Antiproton power

$\bar{p}$-beams can be cooled ⇒ Excellent resonance resolution



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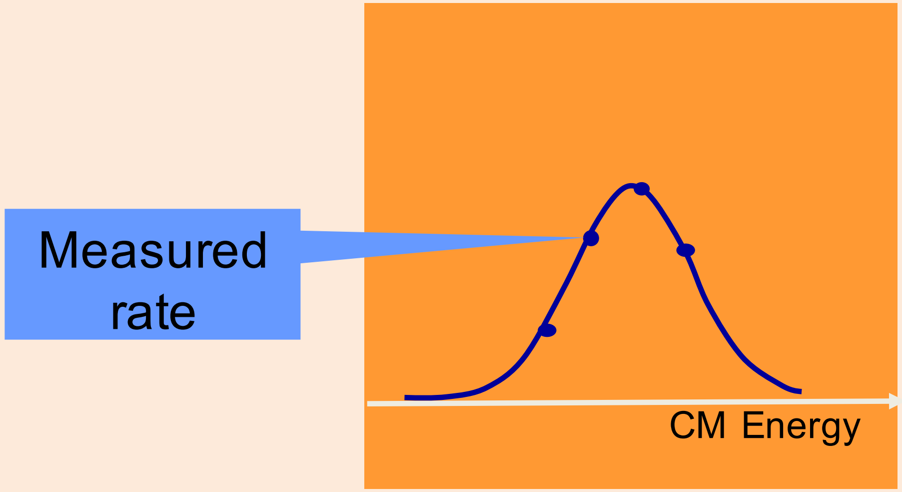

The production rate of a certain final state ν

Antiproton power

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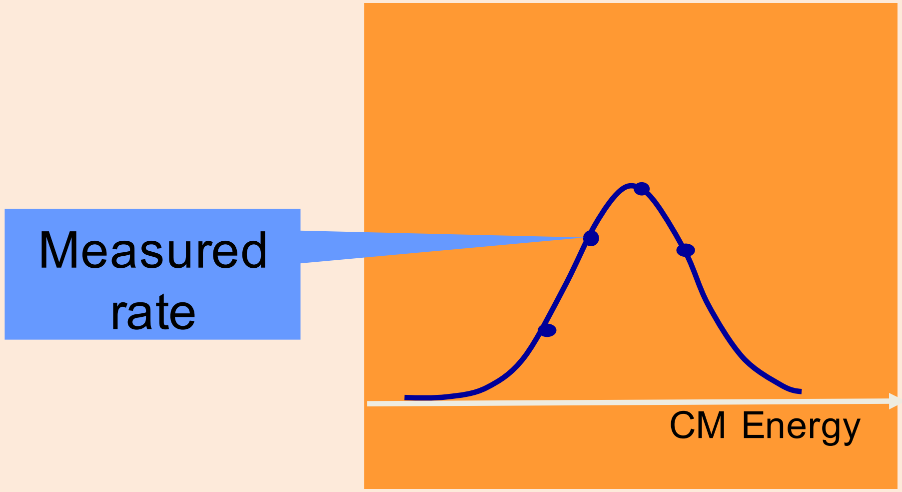

The production rate of a certain final state ν is a convolution of the

Antiproton power

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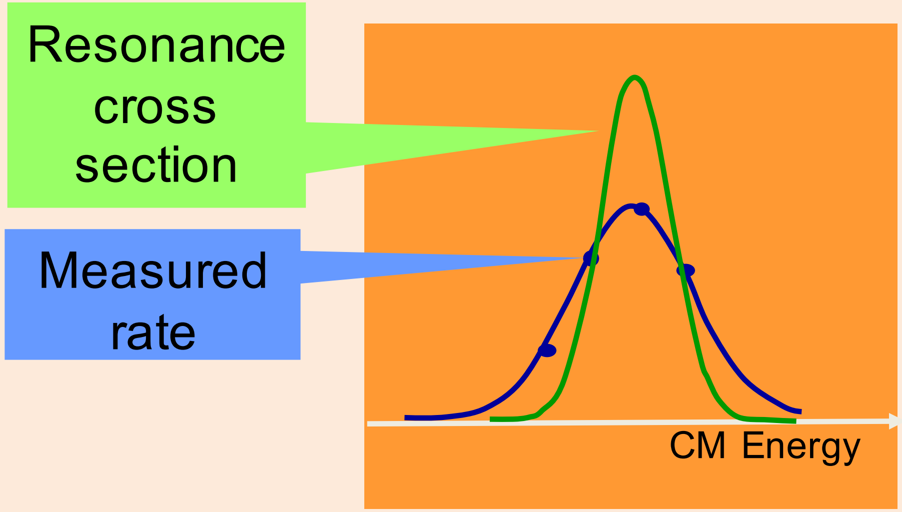
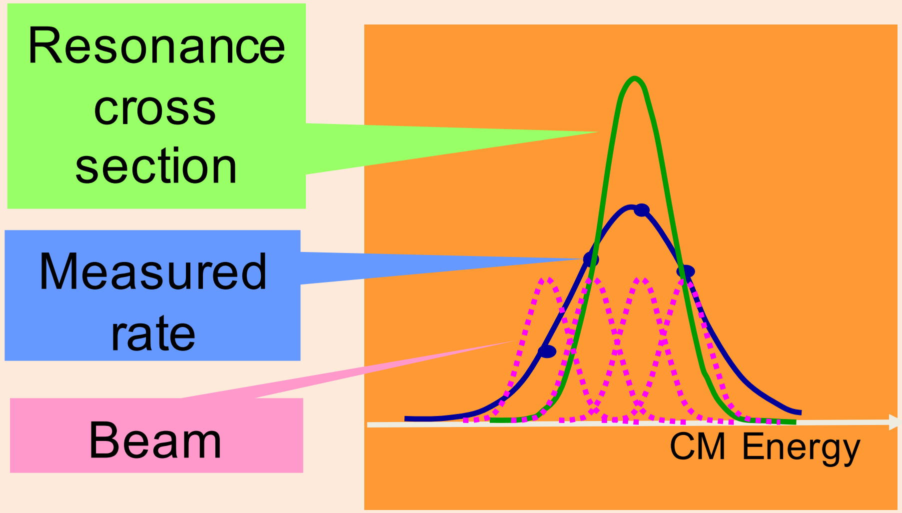


The production rate of a certain final state $\boldsymbol{\nu}$ is a convolution of the BW cross section

Antiproton power

p̅-beams can be cooled ⇒ Excellent resonance resolution



The production rate of a certain final state **ν** is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

Antiproton power

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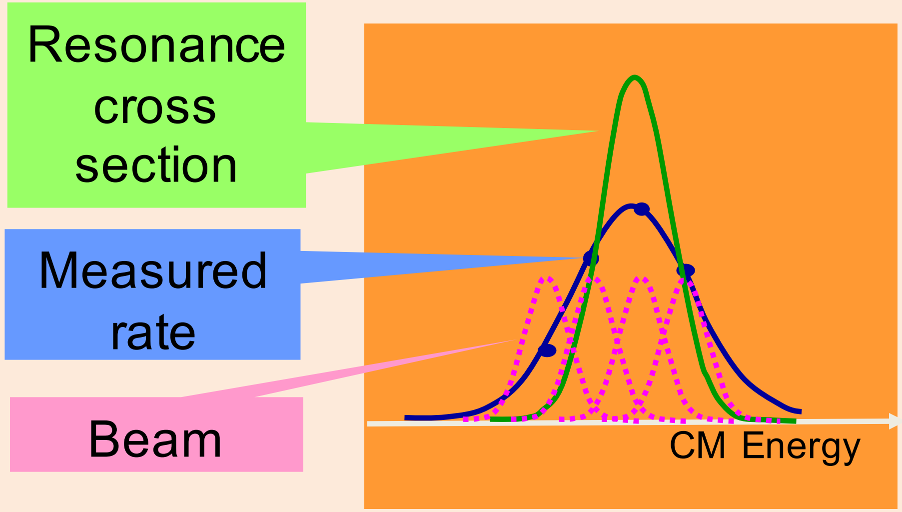
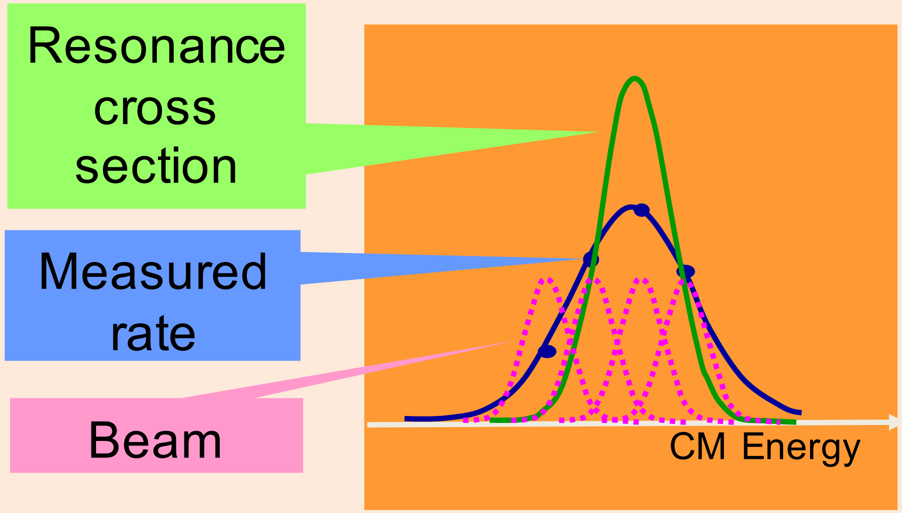


The production rate of a certain final state **ν** is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

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

Antiproton power

$\bar{p}$-beams can be cooled $\Rightarrow$ Excellent resonance resolution



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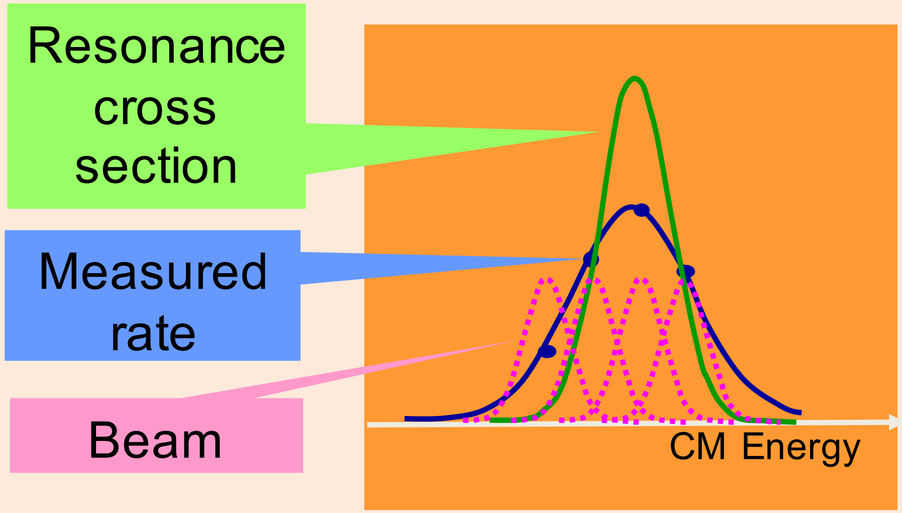
The resonance mass M_R, total width Γ_R are products of branching ratios into the initial and final state $B_{in}B_{out}$ and can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

Antiproton power

p̅-beams can be cooled ⇒ Excellent resonance resolution



Typical mass resolution

- e^+e^-: ~ MeV
- Fermilab: 240 KeV
- HESR: down to 50 KeV

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Comparison with other techniques

- e^+e^-
  - direct formation limited to $J^{PC} = 1^{--}$
  - limited mass and width resolution for non vector states
  - sub-MeV widths very difficult or impossible
  - high L not accessible
- high-energy (several TeV) hadroproduction
  - high combinatorial background makes discovery of new states very difficult
  - width measurements limited by detector resolution
- B decays (both for e^+e^- and hadroproduction)
  - limited J^{PC}
  - C cannot be determined since not conserved in weak decay

Antiproton power

- e^+e^- interactions:

- $\bar{p}p$ reactions:

Antiproton power

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
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- $\bar{p}p$ reactions:

  - all $q\bar{q}$ states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-5}$)

Antiproton power

$e^+e^- \to \psi(2S) \to \gamma\chi_{1,2} \to \gamma\gamma J/\psi \to \gamma\gamma e^+e^-$

$\bar{p}p \to \chi_{1,2} \to \gamma J/\psi \to \gamma e^+e^-$

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Antiproton power

$e^+e^- \rightarrow \psi(2S)$
$\rightarrow \gamma\chi_{1,2}$
$\rightarrow \gamma\gamma J/\psi$
$\rightarrow \gamma\gamma e^+e^-$

$\bar{p}\,p \rightarrow \chi_{1,2}$
$\rightarrow \gamma J/\psi$
$\rightarrow \gamma e^+e^-$

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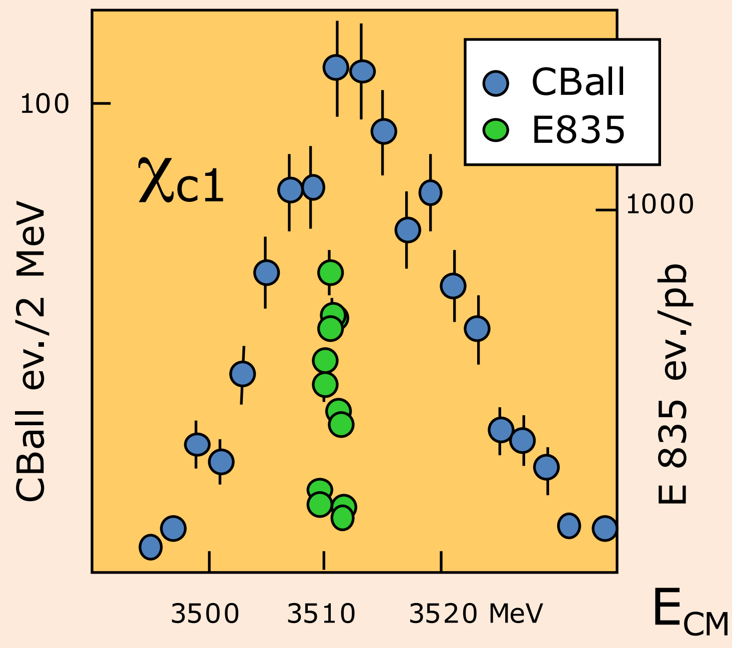

Antiproton power

$e^+e^- \rightarrow \psi(2S) \rightarrow \gamma\chi_{1,2} \rightarrow \gamma\gamma J/\psi \rightarrow \gamma\gamma e^+e^-$

$\bar{p}p \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$

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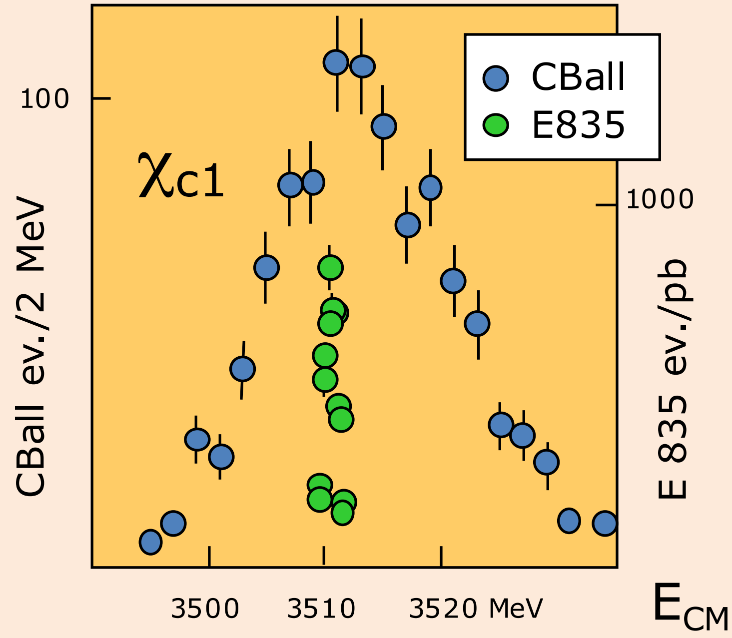
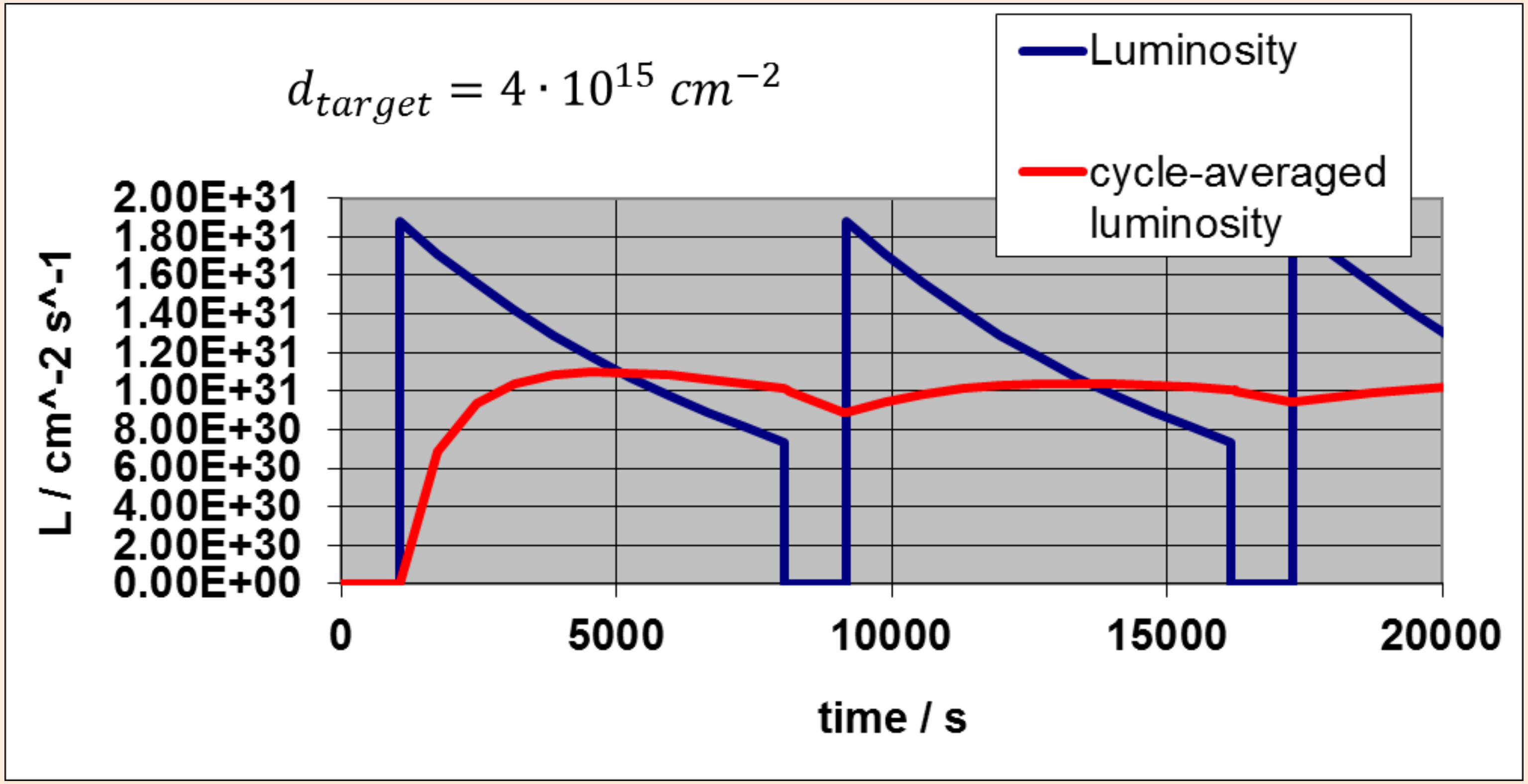


$Br(\bar{p}p \rightarrow \eta_c) = 1.2\ 10^{-3}$

$Br(e^+e^- \rightarrow \psi') \cdot Br(\psi' \rightarrow \gamma\eta_c) = 2.5\ 10^{-5}$

HESR in the MSV

- The intensity in the HESR in the MSV0-3 is limited to 10^{10} p-bars due to the cooling and injection efficiencies (RESR will not be present and its work will be done in the HESR).
- This means for P̄ANDA:
  1. Lower intensity
  2. Lower duty cycle



The low energy range

In the last 20 years many steps forward in the field were possible thanks to the variety of facilities available all over the world.

Main non-$q\bar{q}$ candidates	
$f_0(980)$	4q state, molecule
$f_0(1500)$	0^{++} glueball candidate
$f_0(1370)$	0^{++} glueball candidate
$f_0(1710)$	0^{++} glueball candidate
$\eta(1410)$; $\eta(1460)$	0^{-+} glueball candidate
$f_1(1420)$	hybrid, 4q state
$\pi_1(1400)$	hybrid candidate 1^{-+}
$\pi_1(1600)$	hybrid candidate 1^{-+}
π (1800)	hybrid candidate 0^{-+}
$\pi_2(1900)$	hybrid candidate 2^{-+}
$\pi_1(2000)$	hybrid candidate 1^{-+}
$a_2'(2100)$	hybrid candidate 1^{++}
$\phi(2170)$	hybrid candidate 1^{--}, 4q state

Nowadays confirmation of predictions, together with unexpected results, are still coming out mainly from $e^+ e^-$ collider.

$Y_S(2175)$

The Y_S [X](2175) [or ϕ(2170) on PDG] was first observed by BABAR in the process $e^+e^- \to \phi(1020) f_0(980)$ and identified as a 1^{--} state

M = (2.175±0.010±0.015) GeV, Γ = (58±16±20) MeV.

Then was confirmed by BES in the decay $J/\Psi \to \eta\phi f_0(980)$

with M = (2.186±0.010±0.006) GeV and Γ = (65±25±17) MeV.

We performed a preliminary study for this channel looking to the following reaction: $\bar{p}p \to Y_S(2175) + X$ with X being a π^0 or $\pi^+\pi^-$

$$\hookrightarrow \phi\pi^+\pi^-, \phi\pi^0\pi^0$$

assuming different hypotheses for the signal cross-section and the decay B.R.

This is an example of "meson production" for which we can investigate different decay channels.

Light meson spectroscopy

Assuming cross sections of about 10 nb for glueball/hybrid candidates important topics of the $\bar{\text{P}}$ANDA light hadron spectroscopy program can be addressed:

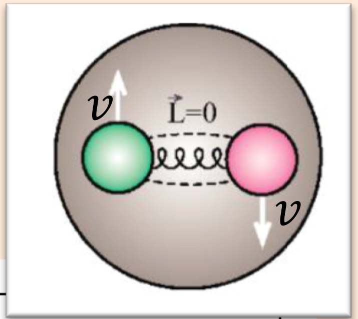
- with an integrated luminosity of about 2 pb^{-1} /channel;
- for new resonances, which do not require a Partial Wave Analysis, results can be obtained with data samples of 0.1 pb^{-1}.

Data samples of 2 pb^{-1} recorded in the low and high energy region, will allow to start first spin-parity analyses for spectroscopy.
These corresponds to 5 days with a Luminosity of 10^{31} cm^{-2} s^{-1} that is foreseen for the PANDA Day-1.

$\bar{\text{P}}$ANDA will collect high statistics on many channels in the low energy sector

Charmonium States

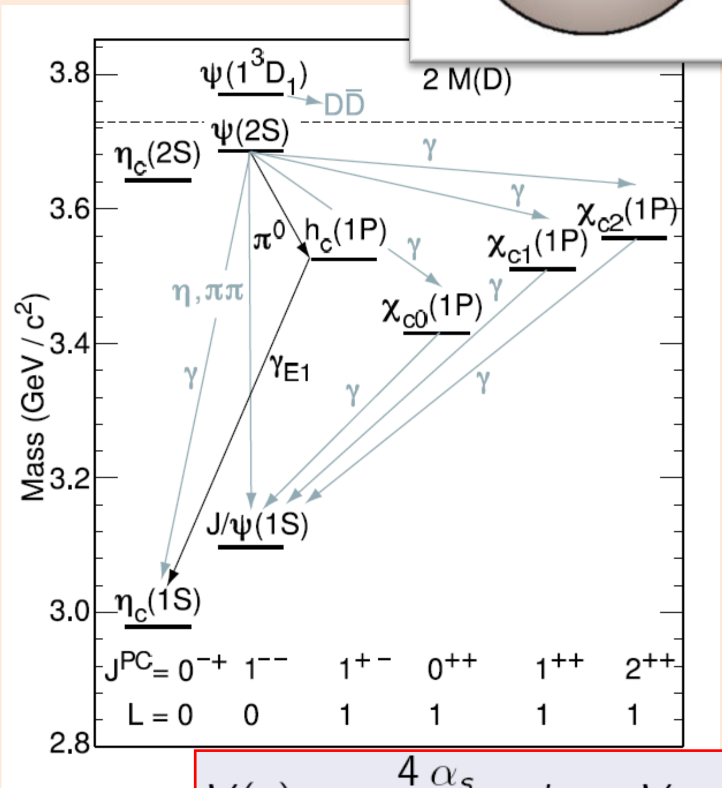
Study of charmonium states plays a crucial role in understanding QCD.



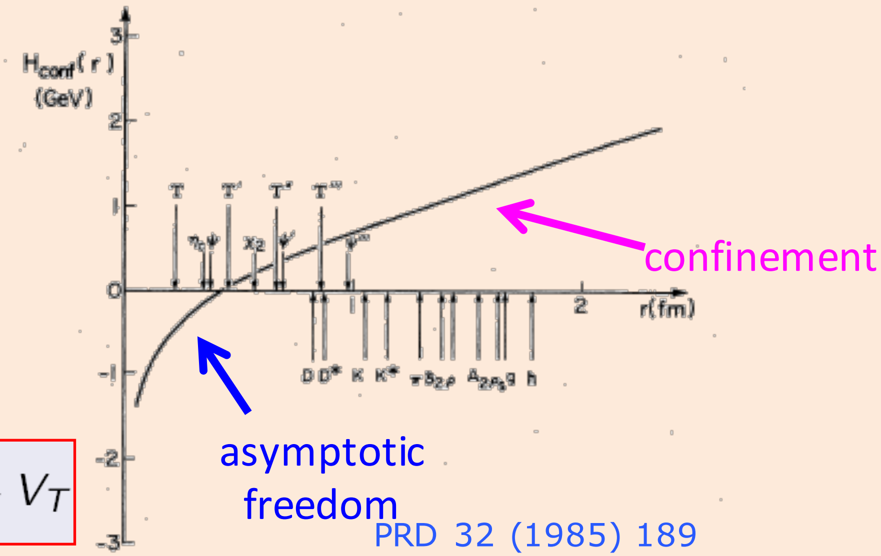
The system is non relativistic: $v_c^2 \approx 0.3$

The mass scale is perturbative: $m_c \approx 1.5GeV$

The structure of separated energy scales makes charmonium an ideal probe of (de)confinement.
Charmonium probe the perturbative, non perturbative transition regime.



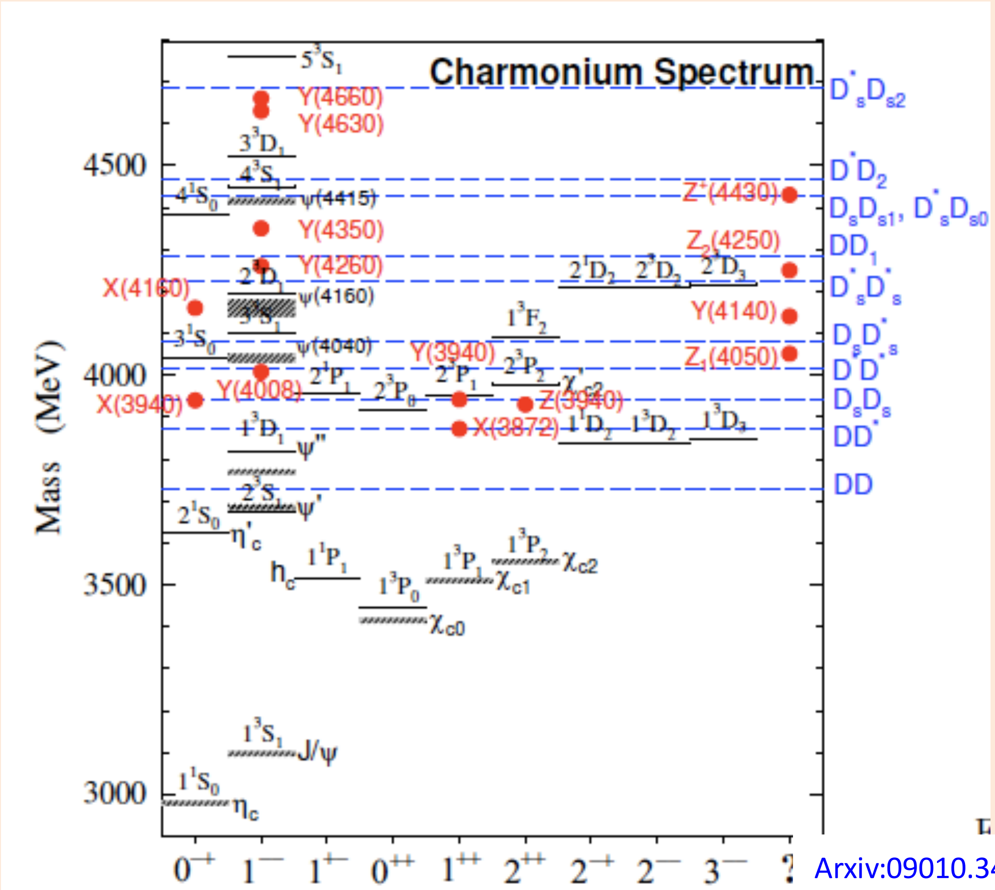
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr + V_{LS} + V_{SS} + V_T$$



PRD 32 (1985) 189

XYZ Mesons

Without entering into the details of each state some general consideration can be drawn.



Arxiv:09010.3409v2 [hep-th]

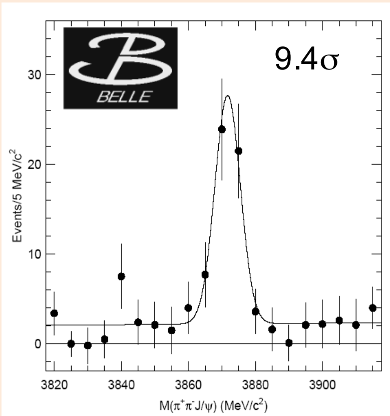
- masses are barely known;
- often widths are just upper limits;
- few final states have been studied;
- statistics are poor;
- quantum number assignment is possible for few states;
- some resonances need confirmation…

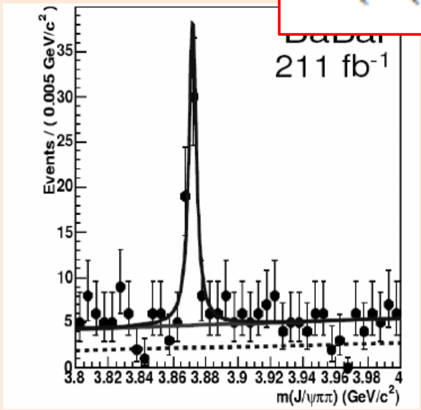
There are problems of compatibility Theory - Experiment

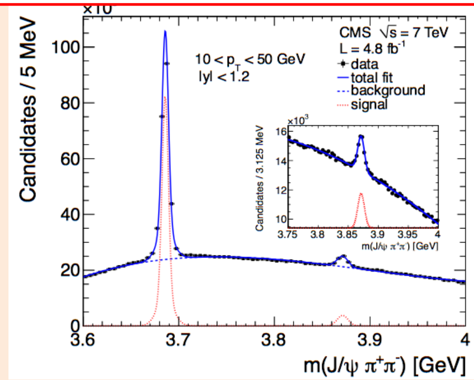
X(3872)

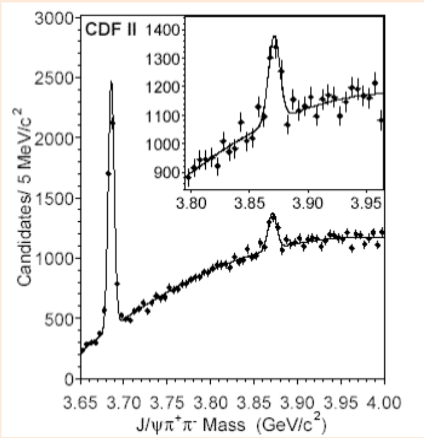
Discovered in 2003 by Belle (+ CDF, D0, BaBar, LHCb …) in $B^+ \to X K^+$; $X \to J/\psi \pi^+\pi^-$ is the big brother of the new "charmonium like" states.

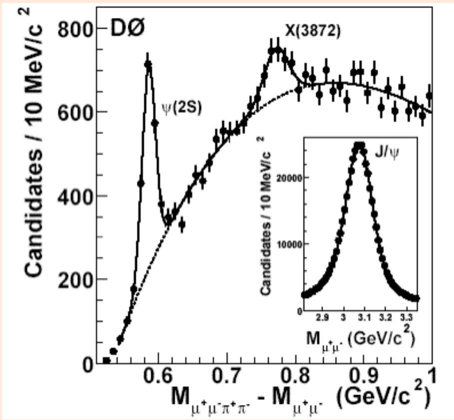
$$M(X(3872)) = 3871.95 \pm 0.48(\text{stat}) \pm 0.12(\text{syst})\ \text{MeV}/c^2$$

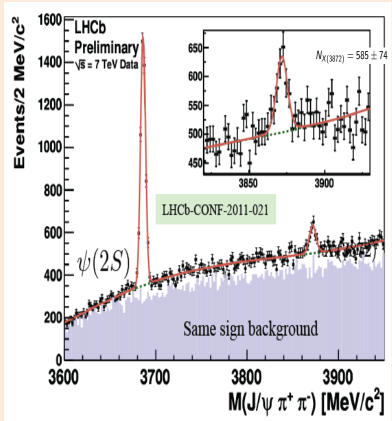












X(3872) has been observed in several decay channels

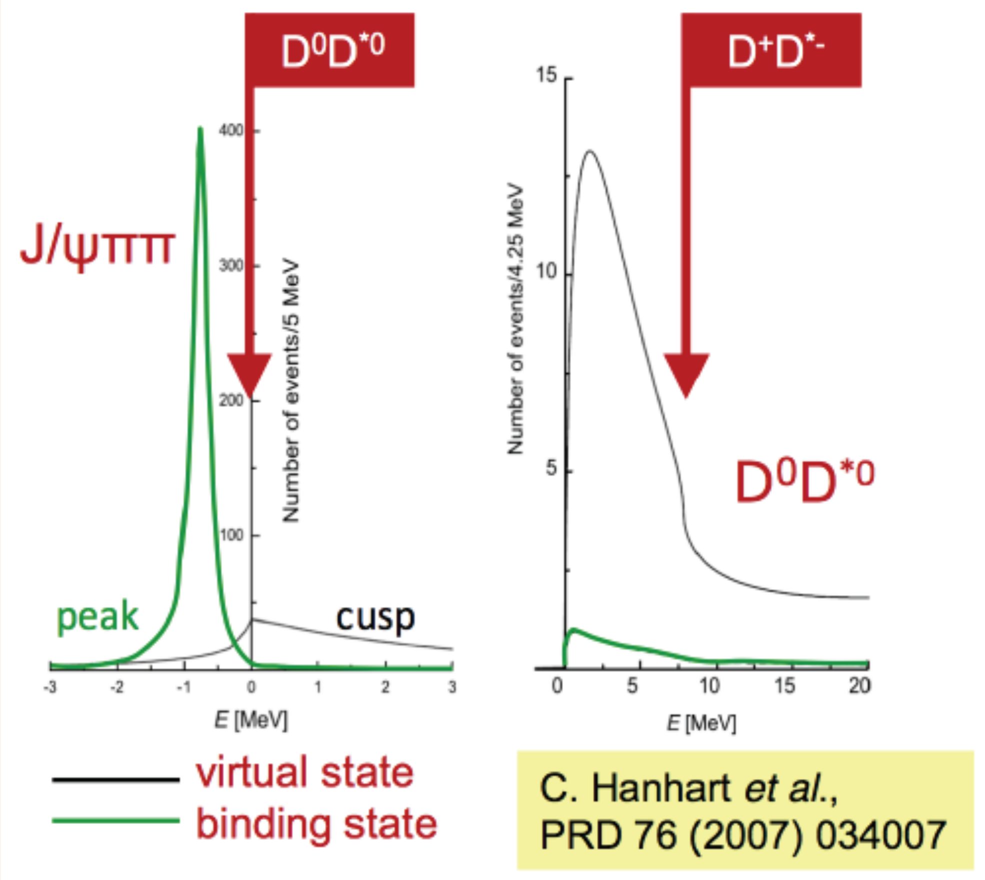
$J/\psi\pi^+\pi^-$, $D^{*0}\bar{D}^0$, $J/\psi\gamma$, $J/\psi\omega$

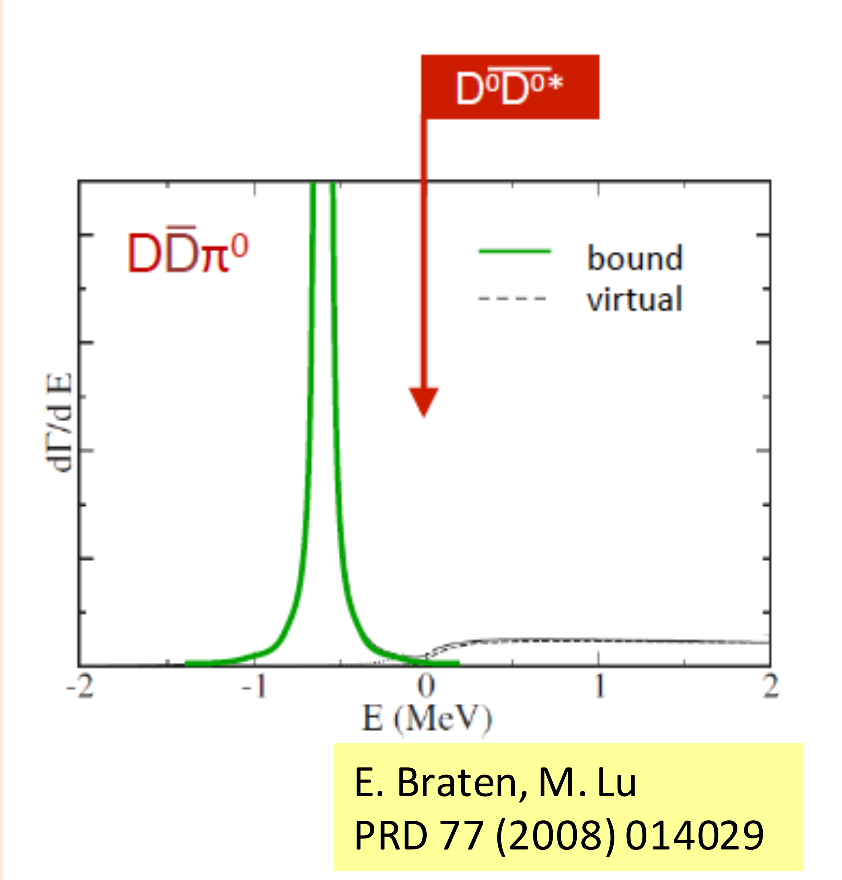
Interpretations oscillate:

- charmonium state;
- $D^*\bar{D}^0$ molecule;
- tetra-quark state.

X(3872) Lineshape

Being close to the $D\bar{D}^*$ threshold there are different hypotheses on the resonance shape.





By measuring the resonance lineshape it is possible to disentangle different model predictions, clarifying particle nature

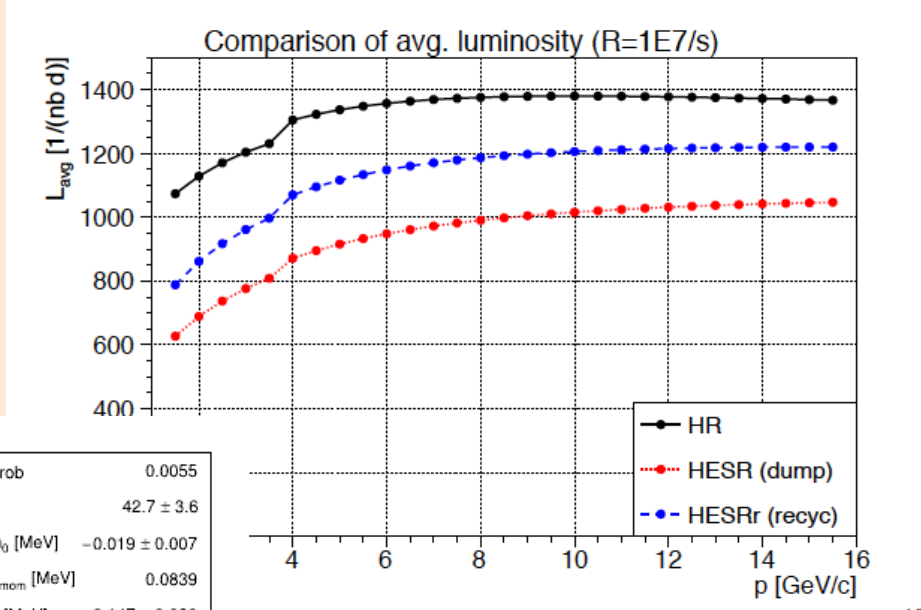
→ Lineshape only accessible at P̄ANDA

X(3872) @ $\bar{\text{P}}$ANDA

[By K.Götzen, GSI Darmstadt]

Thanks to the precise HESR momentum definition, widths of known states can be precisely measured with an energy scan.
Assuming for X(3872):

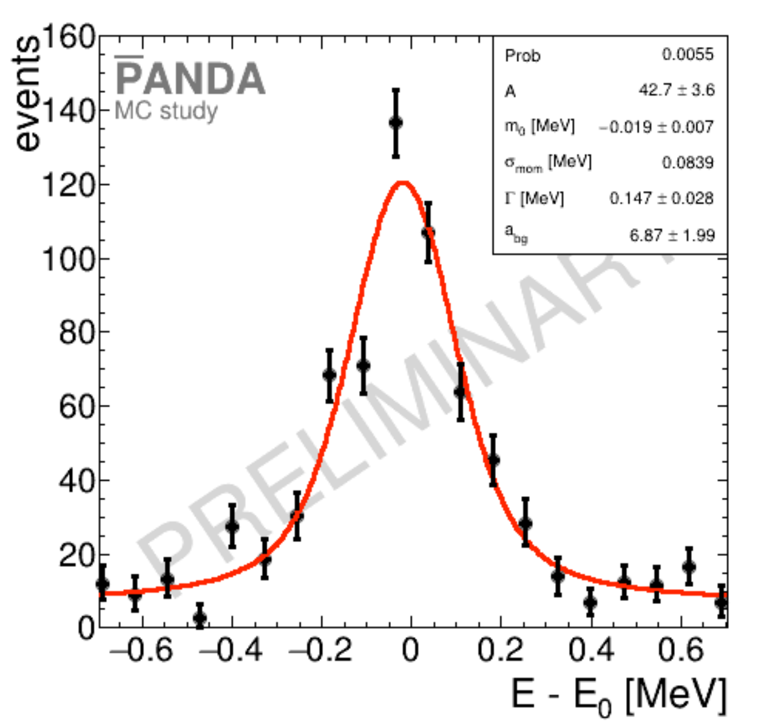
$\sigma_{peak}(\bar{p}p \to X)$	100 nb (U.L. 169nb)
$\sigma(\bar{p}p \to J/\psi\pi^+\pi^-)$ non- res @3.872 GeV	1.2 nb [PRD 77 (2008) 097501]
$\sigma(\bar{p}p \to \text{inelastic})$	46 mb



ΔE = 84 KeV [dp/p = $0.5 \cdot 10^{-5}$]

$X \to J/\psi\pi^+\pi^-$ [2.2÷ 6.6 %]

Overall eff. ~20%

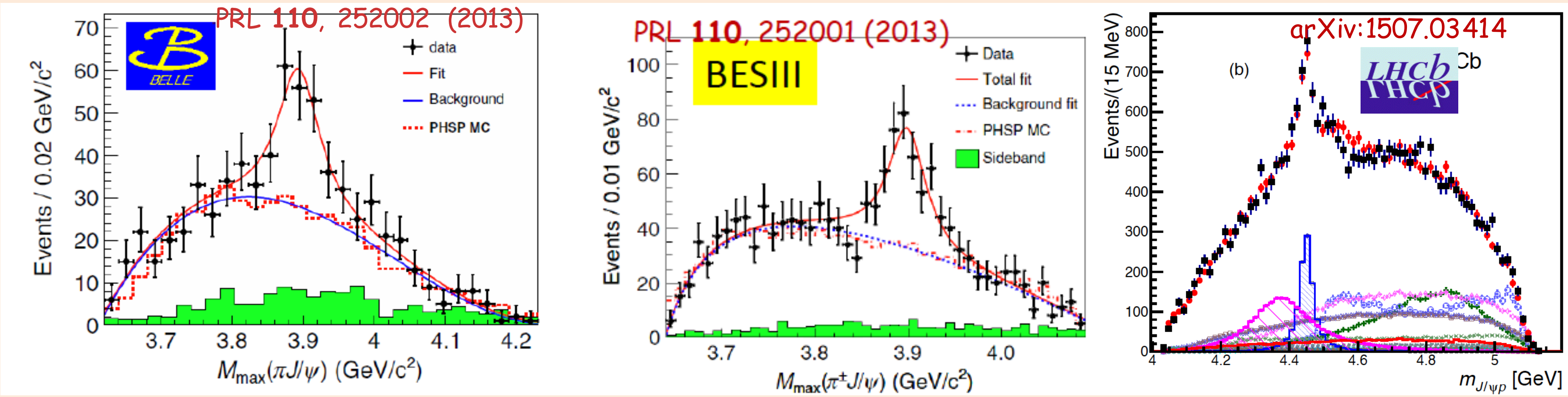


Injected width $\Gamma = 130$ keV
20 points each one require 2 days data taking

Multi-quark states

The first has been the $Z^+(4430)$ observed in the invariant mass $\Psi'\pi^\pm$ by Belle, followed by other states in the bottomomium energy range.
BESIII collaboration discovered an other charged charmonium-like axial meson $Z^+_c \rightarrow J/\Psi\pi^\pm$ (M= 3899±6 MeV, Γ = 46±22 MeV), confirmed by Belle and CLEO. The simplest quantum numbers $J^P = 1^+$, with positive G-parity.
LHCb has observed 2 five-quark states in the $J/\Psi p$ invariant mass. Quantum numbers are still open.

particle	decay	collaboration
$Z^+(4430)$	$\psi(2S)\ \pi^+$	Belle, LHCb
$Z^+(4050)$ $Z^+(4250)$	$\chi_{c1}\ \ \pi^+$	Belle, unconfirmed
$Z_c^+(3900)$	$J/\psi\ \ \pi^+$	BESIII, Belle, CLEOc
$Z_c^+(4020)$	$h_c(1P)\ \pi^+$	BESIII preliminary
$Z_c^+(4025)$	$(D^*\ D^*)^+$	BES III preliminary
$P_C^+(4450)$ $P_C^+(4380)$	$J/\psi\ \ p$	LHCb



$Z^{\pm}$ states @ P̄ANDA

[By M.Pelӓzeus, Bochum univ]

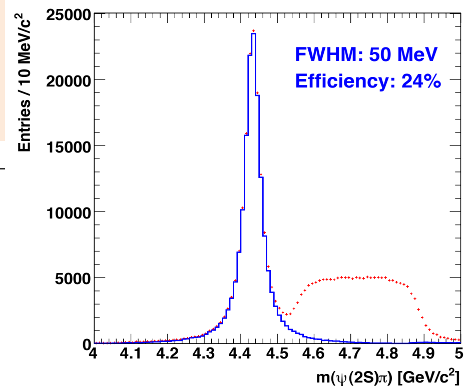
P̄ANDA can study the $Z^{\pm}$ states in both production and formation experiments.

In the production experiment, the $Z^{\pm}$ would be produced, e.g., in the reaction

$$\bar{p}p \rightarrow Z^{\pm}\pi^{\mp}$$ p_{beam} = 15 GeV/c

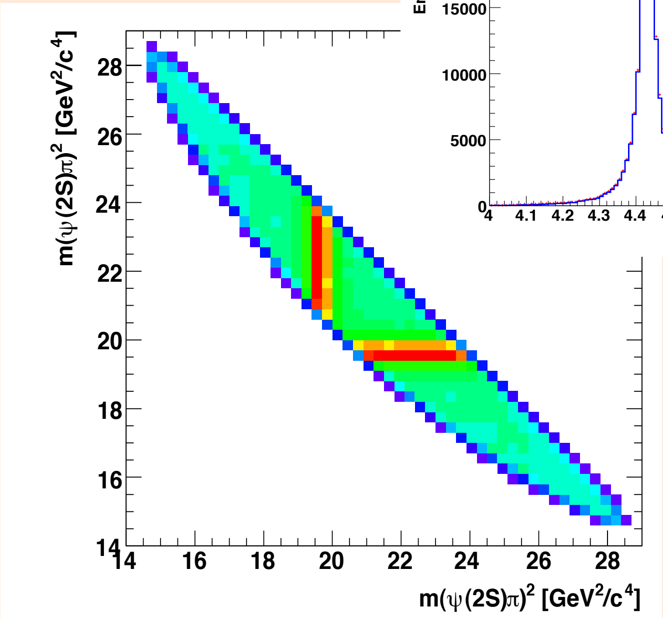
The subsequent decay chain could then be: $Z^{+}(4430) \rightarrow \psi(2S)\pi^{+} \rightarrow J/\psi\pi^{+}\pi^{-}\pi^{+} \rightarrow e^{+}e^{-}\pi^{+}\pi^{-}\pi^{+}$

The reconstruction efficiency for the $Z^{+}(4430)$ channel has been studied in Monte Carlo calculations and is ~ 24%.



In formation mode $Z^{\pm}$ states can be produced by using a deuterium target:

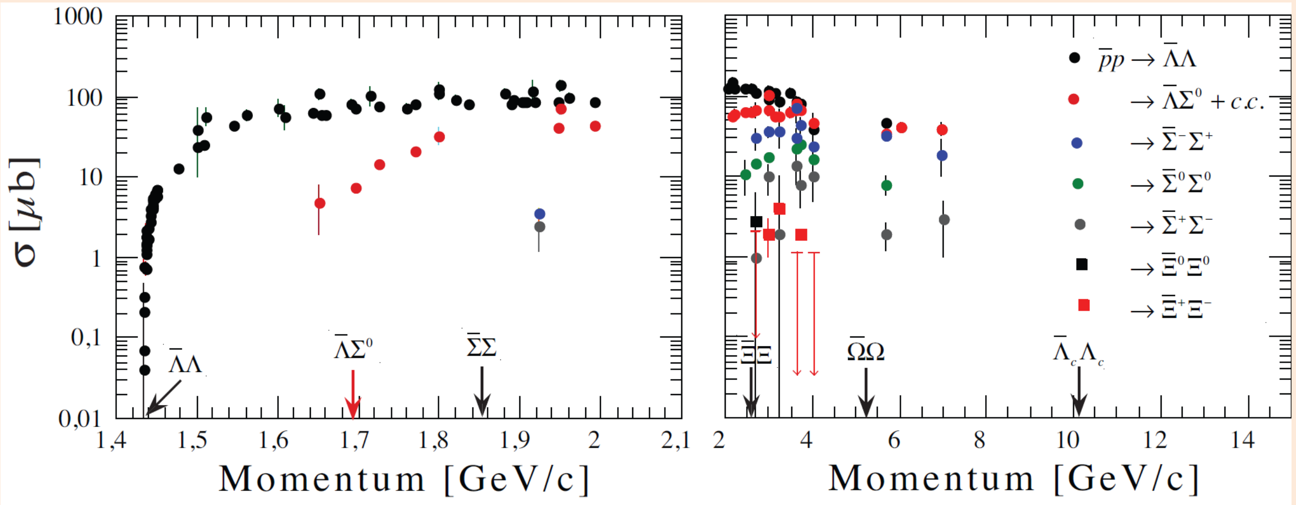
$$\bar{p}d \rightarrow Z^{-}p_{spectator}$$ p_{beam} = 9.5 GeV/c

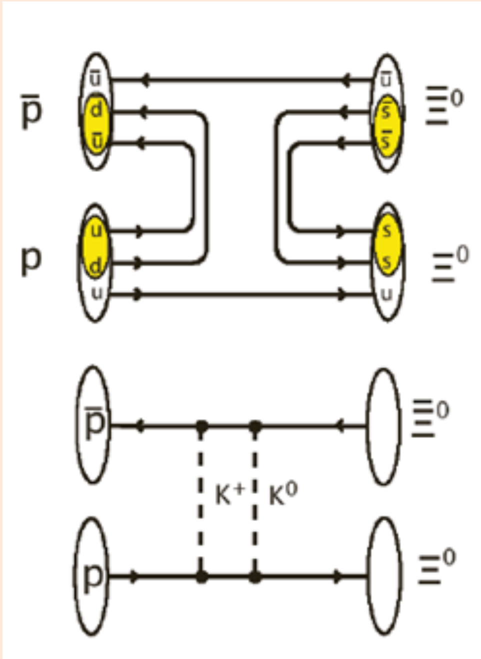


The reconstruction efficiency for this channel studied in Monte Carlo reactions is ~ 35%.

Baryon spectroscopy

The knowledge of the excitation spectrum of strange baryons, in particular those with double or triple strangeness, is poor. P̄ANDA is an ideal environment to study the excitation spectrum of Ξ and Ω baryons.





- Which are the relevant degrees of freedom?
- $m_S \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV
- Test of QCD at the transition

Prospects for PANDA

- New baryon states?
- Properties of already known states
- Symmetries in observed spectrum

Baryons in $\bar{\text{P}}$ANDA

- Large cross section σ for $\bar{p}p \rightarrow \bar{Y}Y$
  - $\bar{p}p \rightarrow \bar{\Xi}\Xi \approx \mu b$
  - $\bar{p}p \rightarrow \bar{\Omega}\Omega \approx 0.002 \div 0.06\ \mu b$
- No extra mesons in final state needed for strangeness or charm conservation
- Symmetry in hyperon and antihyperon
- $\bar{\text{P}}$ANDA detector versatile

Prospects for $\bar{\text{P}}$ANDA

S=2 hyperons (Ξ)
S=0 baryons (N)
S=1 hyperons (Λ)

S=3 hyperons (Ω)

Charmed (Λ_c, Σ_c)
Hidden charm ($N_{c\bar{c}}$)

$\bar{\text{P}}$ANDA is a Strangeness Factory

Prospects for PANDA

The parity-violating weak decay of hyperons gives access to spin observables even for unpolarised beam/target. These observables give insight in the production mechanism of hyperons (e.g. the role of spin in strangeness and charm production).
Unique to P̄ANDA: the study of these observables and especially the hyperon-antihyperon spin correlations.

Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate (with $0.5*10^{31}$ $cm^{-1}s^{-1}$)
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	28 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^{o}$	~40	30	30 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$	~2	20	1.5 s^{-1}
12	$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$	~0.002	30	~4 h^{-1}
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^{-}\Lambda_c^{+}$	~0.1	35	~2 day^{-1}

- High event rates for Λ and Σ
- Low background for Λ and Σ
- Ω channel feaseble
- Λ_C requires high luminosity

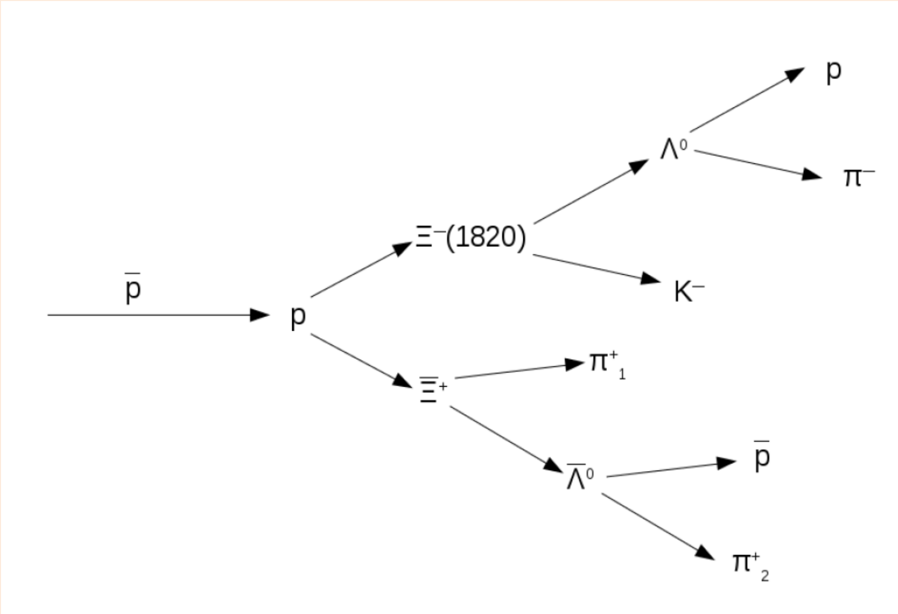
P̄ANDA is a Strangeness Factory

Feasibility study of $\bar{p}p \to \bar{\Xi}^{+}\Xi^{*-}$

[By J.Pütz, FZ Jülich]

Simulation input parameters:

- p_{beam} = 4.6 GeV/c
- $\sigma = 1\ \mu b$
- Consider $\Xi^{*-}(1820) \to \Lambda K$ decay, with a B.R. = 30%
- Lumi 10^{31} cm^{-2} s^{-1}

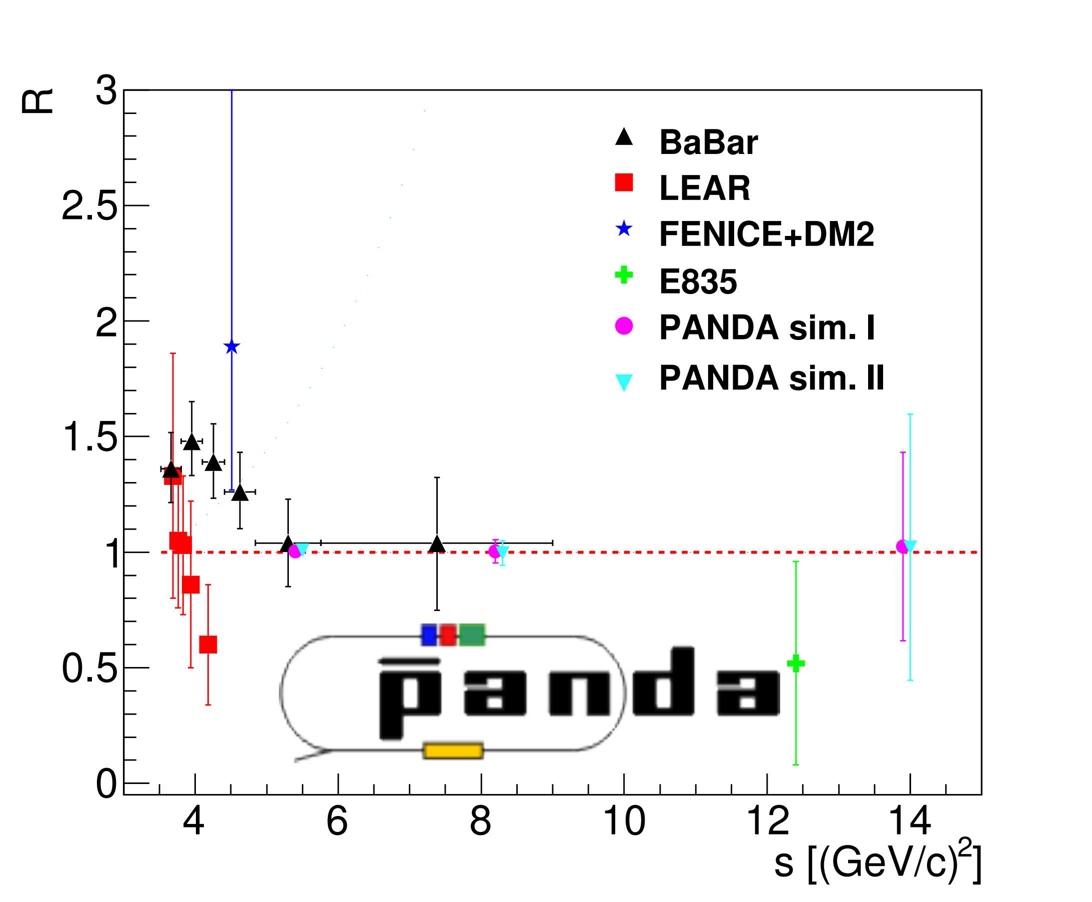


Results:

- ~ 30% inclusive efficiency for $\Xi^{*-}(1820)$
- ~ 5% exclusive efficiency for $\bar{\Xi}^{+}\Xi^{*-}(1820)$
- Low level of background
- ~ 5000 inclusive events/day

Proton Electromagnetic Form Factors in the Timelike Region

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



Measurement of effective form factor over wide q^2 range (30 GeV^2)

Individual measurement of $|G_E|$ and $|G_M|$ and their ratio R

First measurement of form factors with muons.

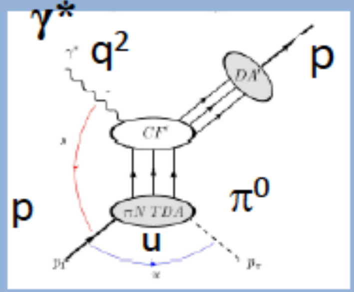
Measurement of form factors in unphysical region $\bar{p}p \to e^+e^-\pi^0$

Longer range goal: measurement of phase of $|G_E|$ and $|G_M|$ via polarisation observables.

Transition Distribution Amplitudes

$e^- p \rightarrow e^- p \pi^0$ Bwd

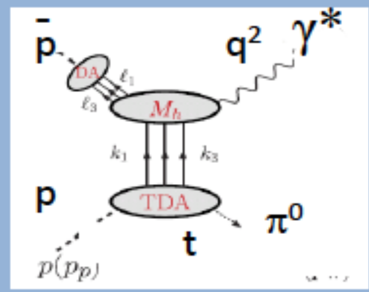
electroproduction



Large q^2
small u

Transition Distrib.
Amplitudes

$\bar{p}p \rightarrow e^+ e^- \pi^0$ Fwd/bwd



Large q^2
small t or u

Transition Distrib.
Amplitudes

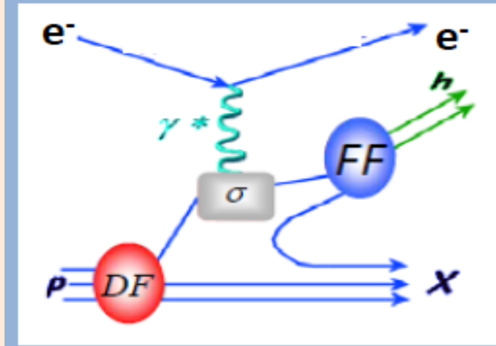
$$\bar{p}p \rightarrow e^+e^-\pi^0, e^+e^-\rho^0, e^+e^-\eta, \ldots$$

- Describe the transition between two particles
- Explore pionic components in the nucleon wave function
- Transverse picture of the pion cloud
- Universality: the same TDA could be measured in different kinematics or different reactions
- Test of Factorisation
- Matter – Antimatter asymmetry

TDAs in TL region can only be measured at $\bar{P}$ANDA

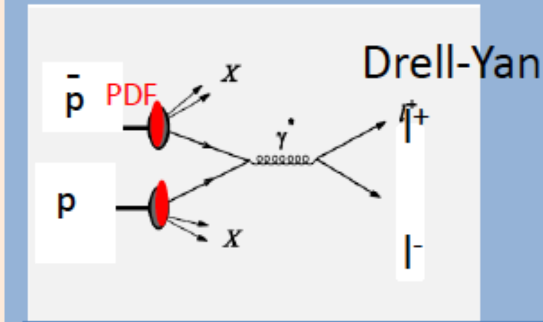
Drell-Yan Processes

$e^- p \to e^- h X$ SIDIS



Parton Distribution Functions

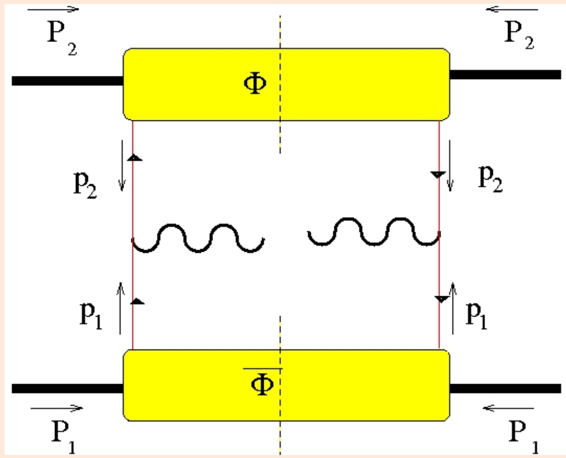
$\bar{p}p \to \mu^+\mu^- X / e^+e^- X$



Parton Distribution Functions

PDFs are convoluted with the fragmentation functions

Handbag diagram: $s >> M_h^2$



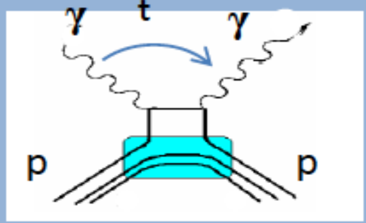
@ FAIR unique energy range
up to $s \sim 30$ GeV^2 with P̄ANDA
up to $s \sim 200$ GeV^2 with PAX

@ much higher energies
→ big contribution from sea-quarks

@$p\bar{p}$ annihilation each valence quark contribute to the diagram

Hard Exclusive Processes and $\bar{p}p$ Generalized Distribution Amplitudes

$\gamma p \to \gamma p$ Wide Angle Compton Scattering

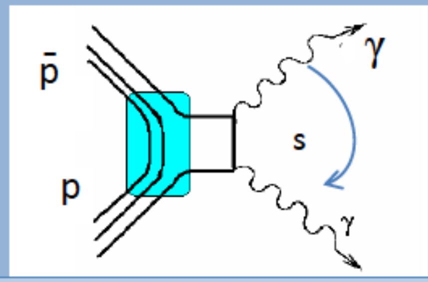


Large p_t

Generalized Parton Distributions

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

Large p_t



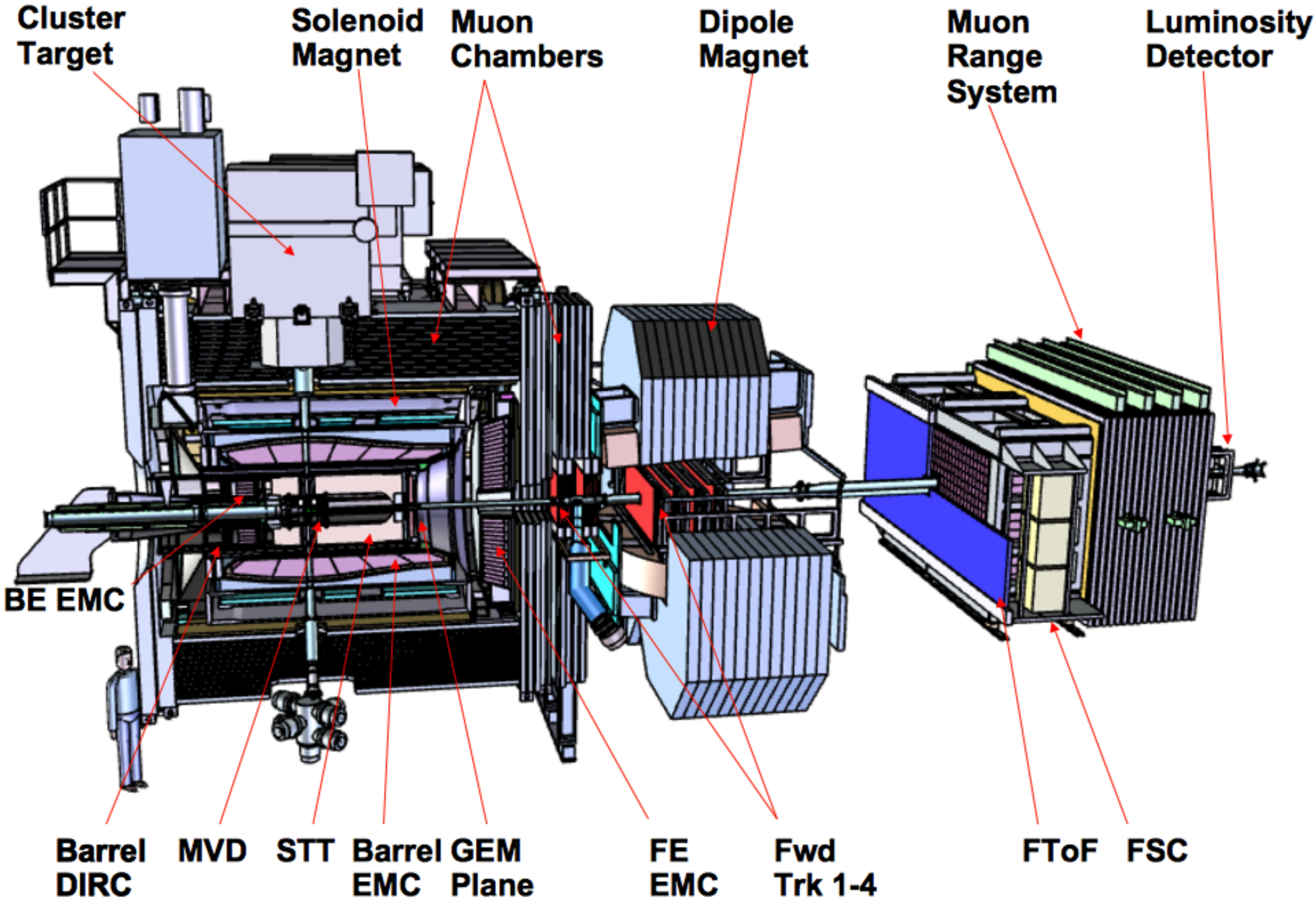
Generalized Distrib. Amplitudes

Timelike wide-angle Compton scattering can be measured at $\bar{\text{P}}$ANDA

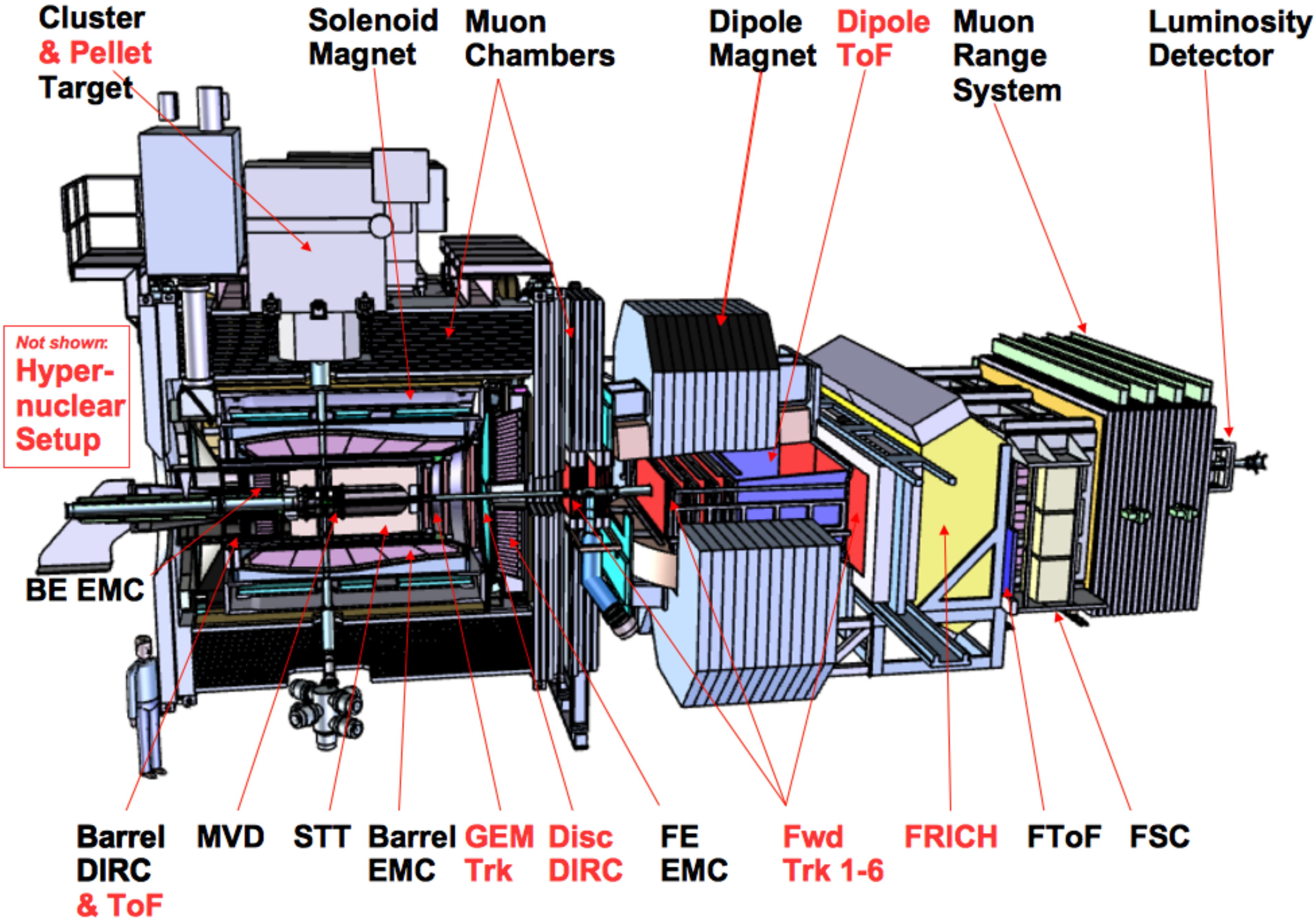
S/B~1 for (25% efficiency)
S/B~2 for (50% efficiency)

Further studies are required for precise predictions

Start Setup

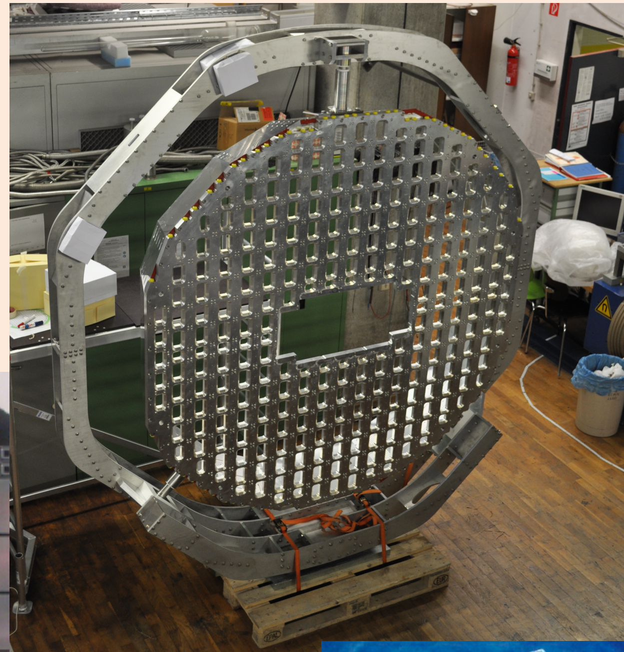

Cluster Target
Solenoid Magnet
Muon Chambers
Dipole Magnet
Muon Range System
Luminosity Detector
BE EMC
Barrel DIRC
MVD
STT
Barrel EMC
GEM Plane
FE EMC
Fwd Trk 1-4
FToF
FSC

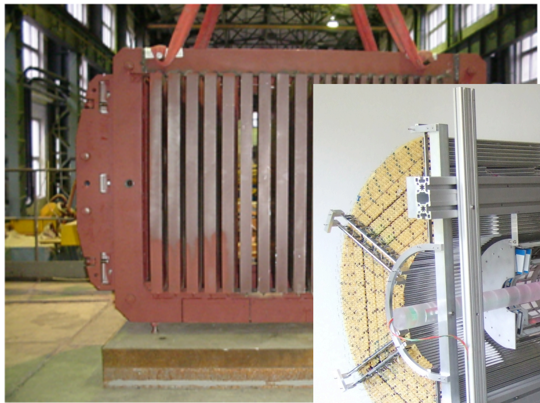
Full Setup

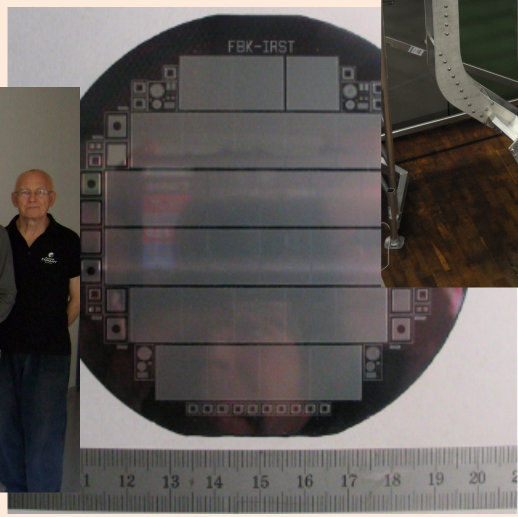

Cluster
& Pellet
Target
Solenoid
Magnet
Muon
Chambers
Dipole
Magnet
Dipole
ToF
Muon
Range
System
Luminosity
Detector
Not shown:
Hyper-
nuclear
Setup
BE EMC
Barrel
DIRC
& ToF
MVD
STT
Barrel
EMC
GEM
Trk
Disc
DIRC
FE
EMC
Fwd
Trk 1-6
FRICH
FToF
FSC

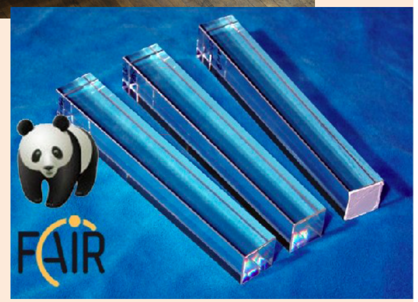
Conclusions

- Hadron spectroscopy is experiencing a new renascence;
- New high quality measurements are coming from e^+-e^- colliders and LHC experiments reveling unexpected properties of hadrons;
- All over the world there is lack of antiproton beams that in the past showed unique capabilities in the field;
- It is urgent to have an high-quality antiproton beam to contribute;
- The $\bar{\text{P}}$ANDA detector coped to the HESR will be the perfect combination of tools to make a break-through!



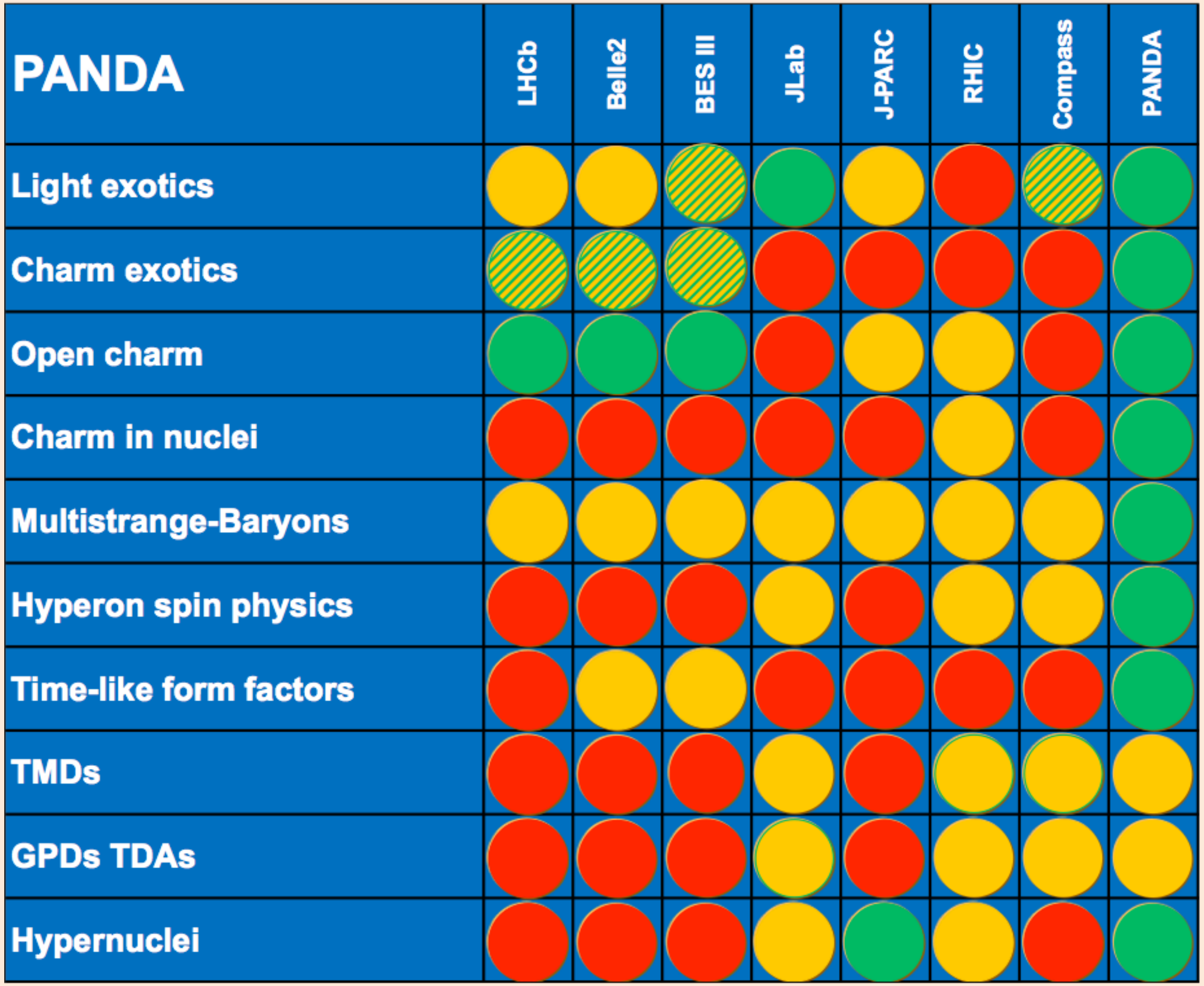






P̄ANDA Physics Competitiveness

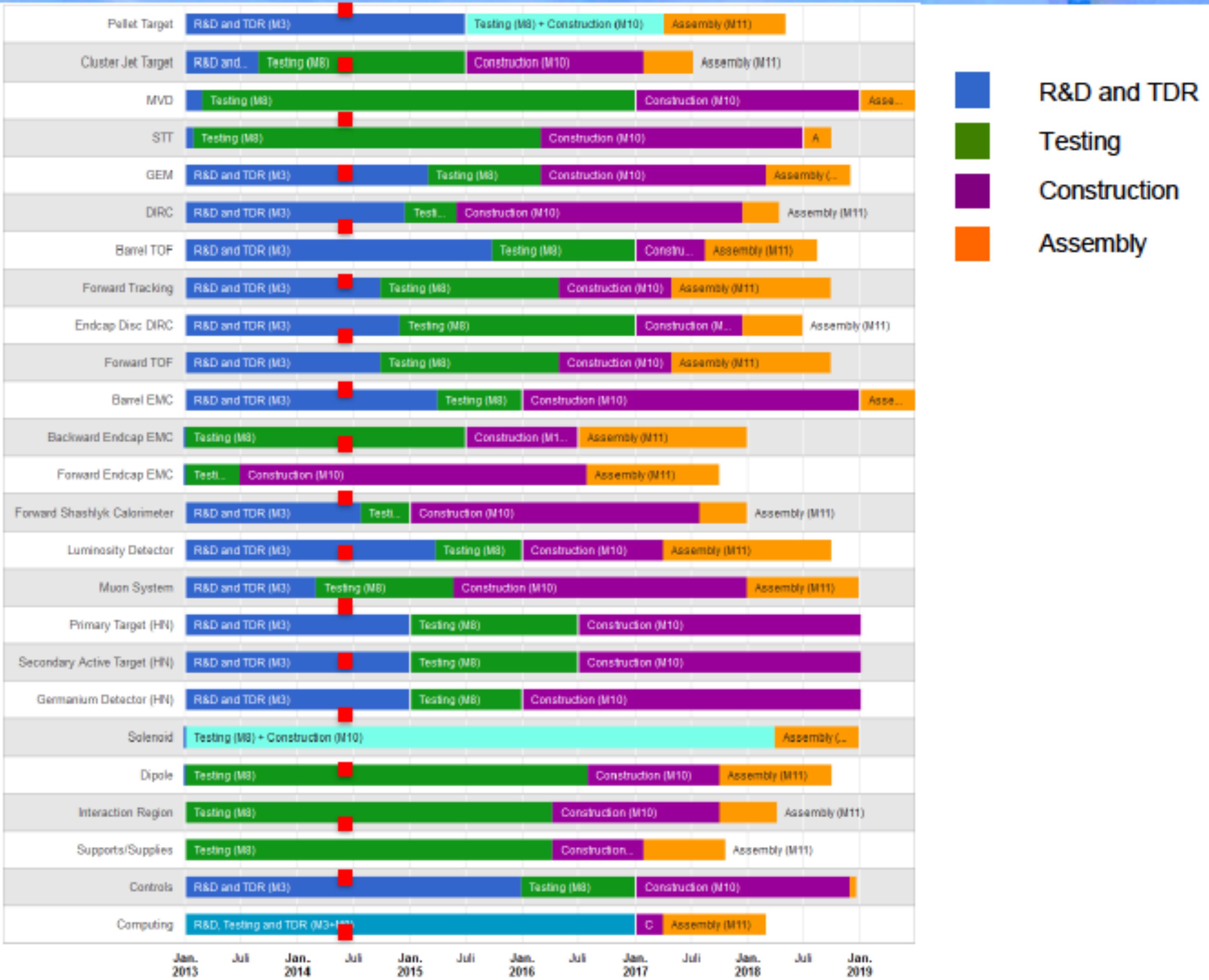
excellent — limited (e.g. accept., resol., quantum numbers, ...) — impossible



TDR status

System	Submission Expected	M3 (Approval) Expected
Target Spectrometer EMC		08/08/2008
Solenoid		05/21/2009
Dipole		05/21/2009
Micro Vertex Detector (MVD)		02/26/2013
Straw Tube Tracker (STT)		01/29/2013
Cluster Jet Target		08/28/2013
Muon System		09/22/2014
Forward Shashlyk Calorimeter	17/6/2015	*1/2016*
Luminosity Detector	*3/2016*	*9/2016*
Forward TOF	*3/2016*	*9/2016*
Forward Tracking	*3/2016*	*9/2016*
Barrel DIRC	*6/2016*	*12/2016*
Hypernuclear Setup	*6/2016*	*12/2016*
Pellet Target	*6/2016*	*12/2016*
Planar GEM Trackers	*9/2016*	*3/2017*
Barrel Time of Flight (TOF)	*9/2016*	*3/2017*
Controls	*6/2017*	*12/2017*
DAQ	*6/2017*	*12/2017*
Endcap Disc DIRC	*6/2017*	*12/2017*
Computing	*9/2017*	*3/2018*
Silicon Lambda Disks	tba	tba
Forward RICH	tba	tba
tba: to be announced		Status 3/11/2015
For the items “Interaction Region”, “Supports” and “Supplies” no TDRs are planned, only specification documents.		

Timeline of the PANDA Systems



Jim Ritman

Run-Plan: first 2 years