PANDA experiment: antiproton physics at FAIR

AntiProton ANnihilations at DArmstadt

Overview on:

- The FAIR project
- The PANDA physics program
  - focus on hadronic spectroscopy:

    - charmonium
    - exotic states
    - baryonic resonances
    - hypernuclei
- The PANDA detector
- Perspectives

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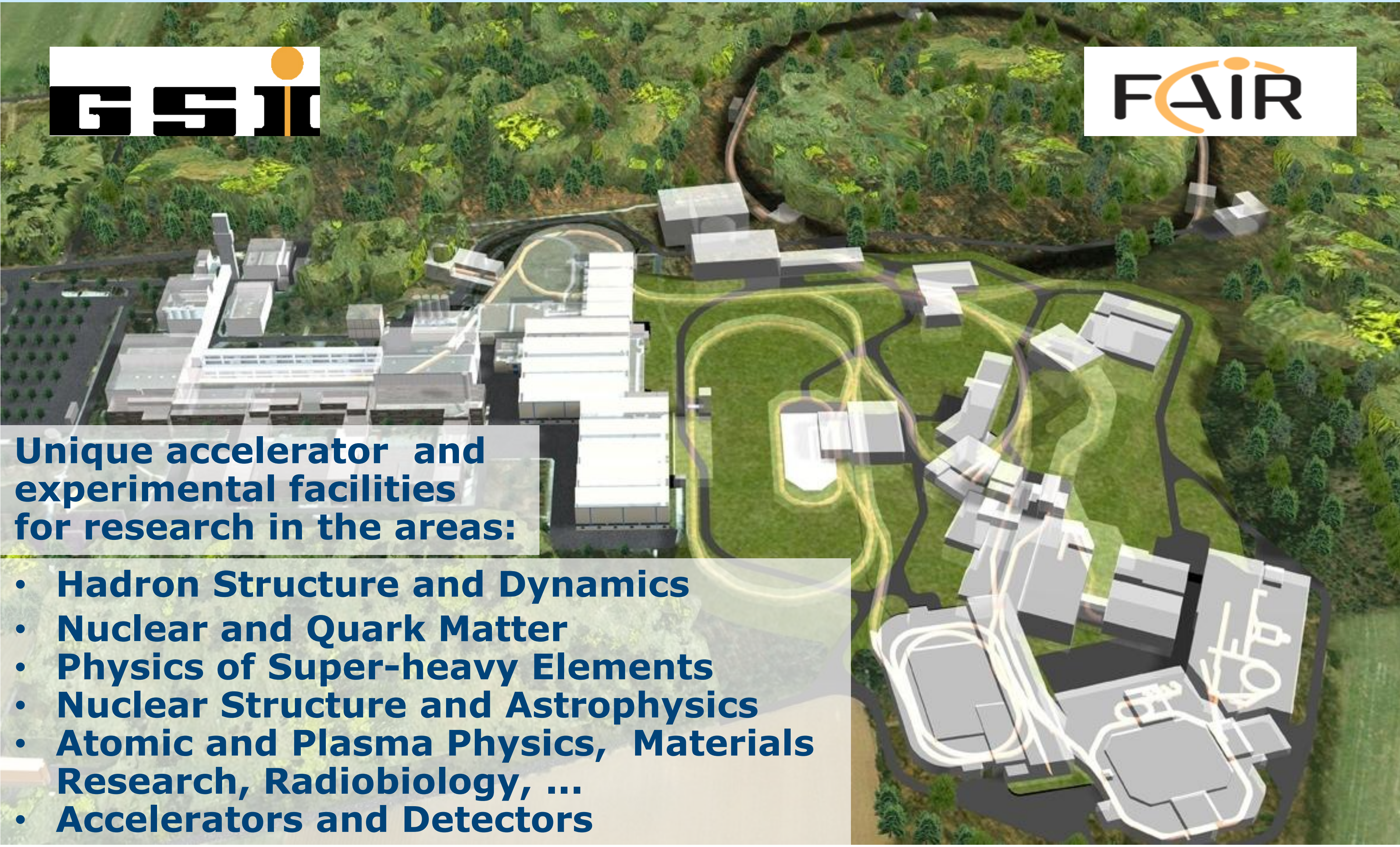
INFN Sezione di Pavia
on behalf of the PANDA Collaboration

From GSI to FAIR



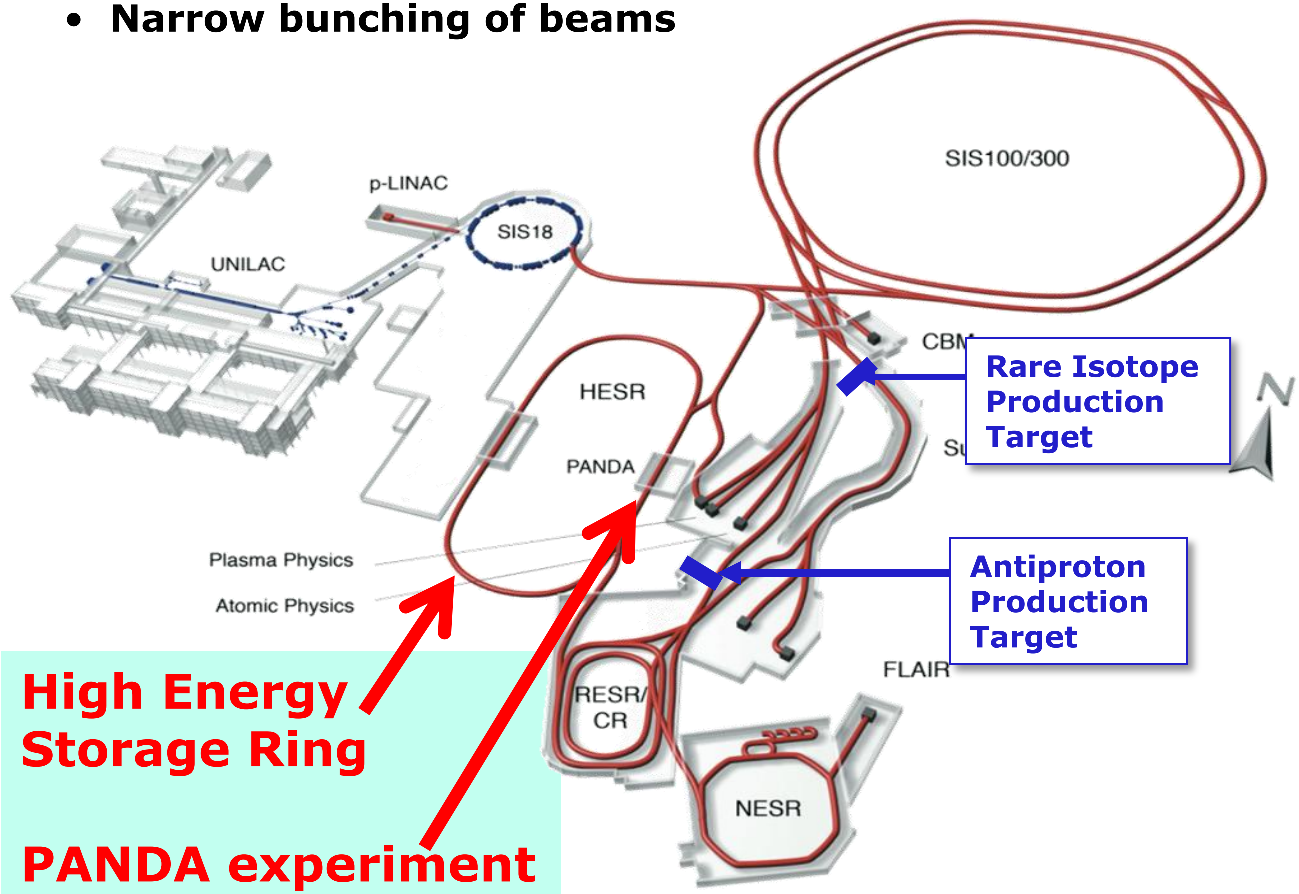
Unique accelerator and experimental facilities for research in the areas:

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

The FAIR Complex
Facility for Antiproton and Ion Research

Key Technologies

- Beam cooling
- Rapidly cycling superconducting magnets
- Narrow bunching of beams



Primary Beams

- **All elements** up to Uranium
- Factor 100-**1000** over present intensity
- **50ns bunching**

Secondary Beams

- **Rare isotope beams** up to a factor of **10 000** in intensity over present
- Low and high energy **antiprotons**

Storage and Cooler Rings

- Rare isotope beams
- e^-– Rare Isotope collider
- 10^{11} stored and cooled antiprotons for **Antimatter** creation

High Energy Storage Ring

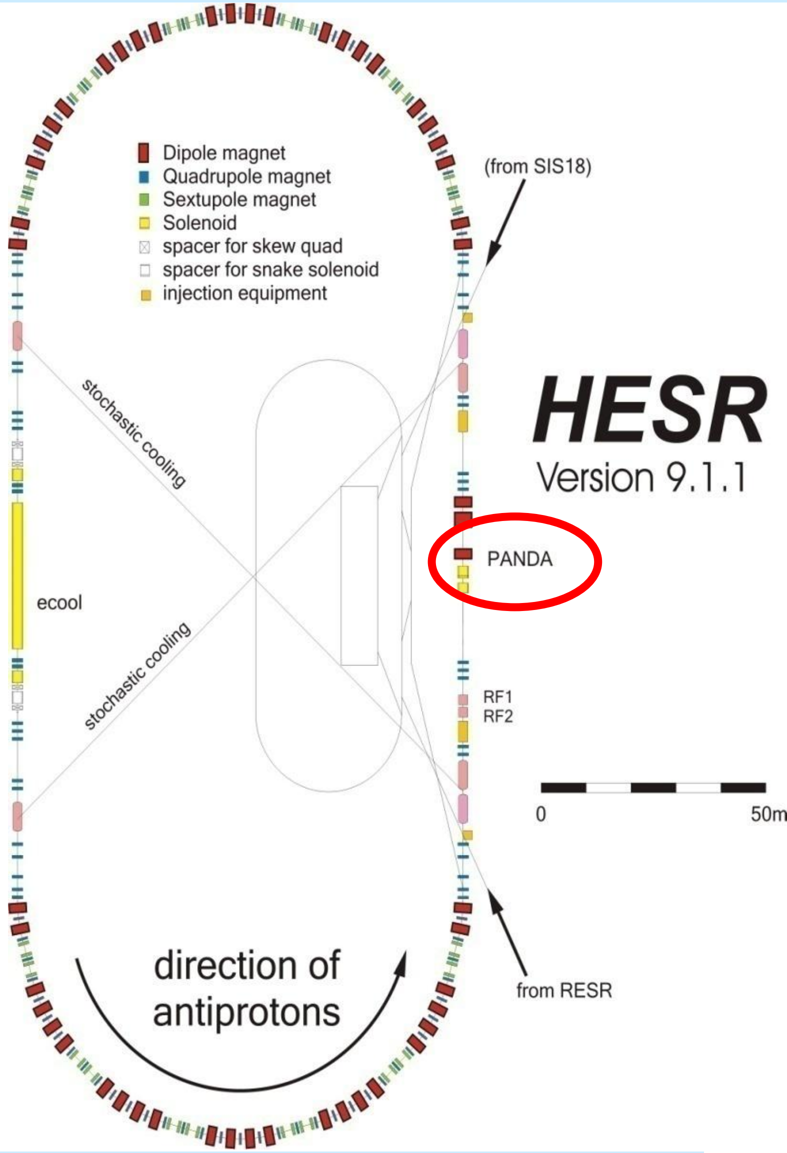
- **Production rate 2×10^{7}/sec**
- **P_{beam} = 1.5 - 15 GeV/c**
  ($2.25 < \sqrt{s} < 5.47$ GeV)
- **N_{stored} = 5×10^{10} antiprotons**
- **Internal Target**

High resolution mode

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

High luminosity mode

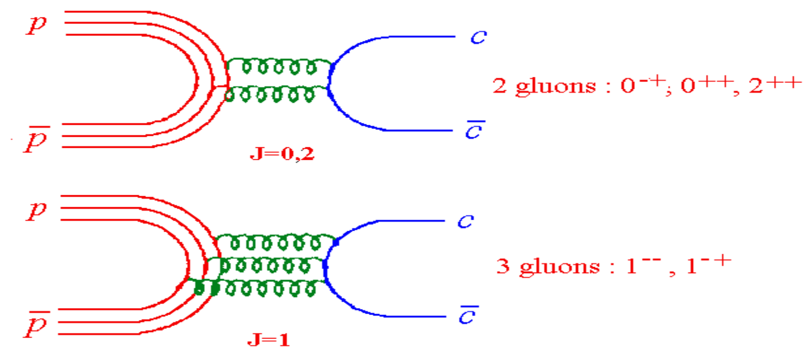
- Lumin. = 2×10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



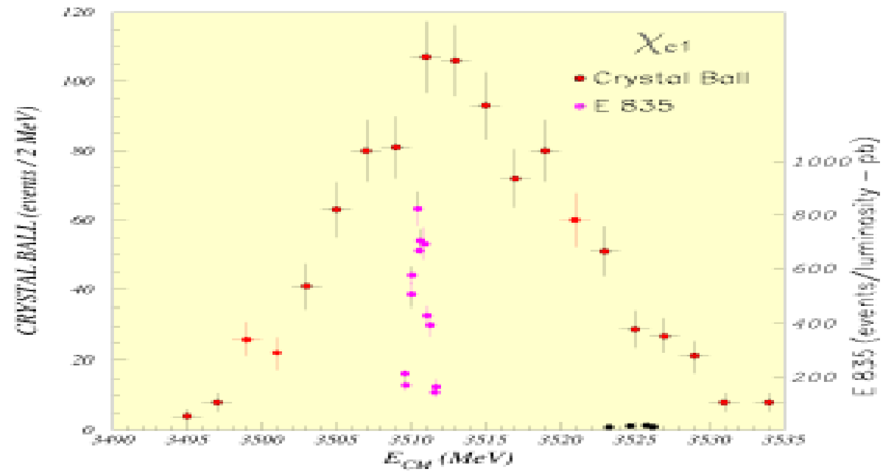
Antiproton-proton annihilation

In $p\bar{p}$ annihilation it is possible to access in formation all non-exotic quantum numbers:
0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}
(not just 1^{--} like in e^+e^-)

ex. charmonium formation



In the formation experiments, 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.



Typical resolution: e^+e^- Crystal Ball: ~ 10 MeV
$\bar{p}p$ Fermilab: 240 keV
$\bar{p}p$ PANDA: ~100 keV

A highly diversified physics program

PANDA will continue and extend the successful physics program performed in the past at facilities like LEAR at Cern and the antiproton accumulator ring at Fermilab

- **QCD BOUND STATES** → charmonium spectroscopy, exotic states, strange and charmed baryons, hypernuclear physics, open charm physics, D physics
- **NON PERTURBATIVE QCD DYNAMICS**
- **HADRONS IN THE NUCLEAR MEDIUM**
- **NUCLEON STRUCTURE**
- **ELECTROWEAK PHYSICS**

FAIR/PANDA/Physics Book i

Physics Performance Report for:

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

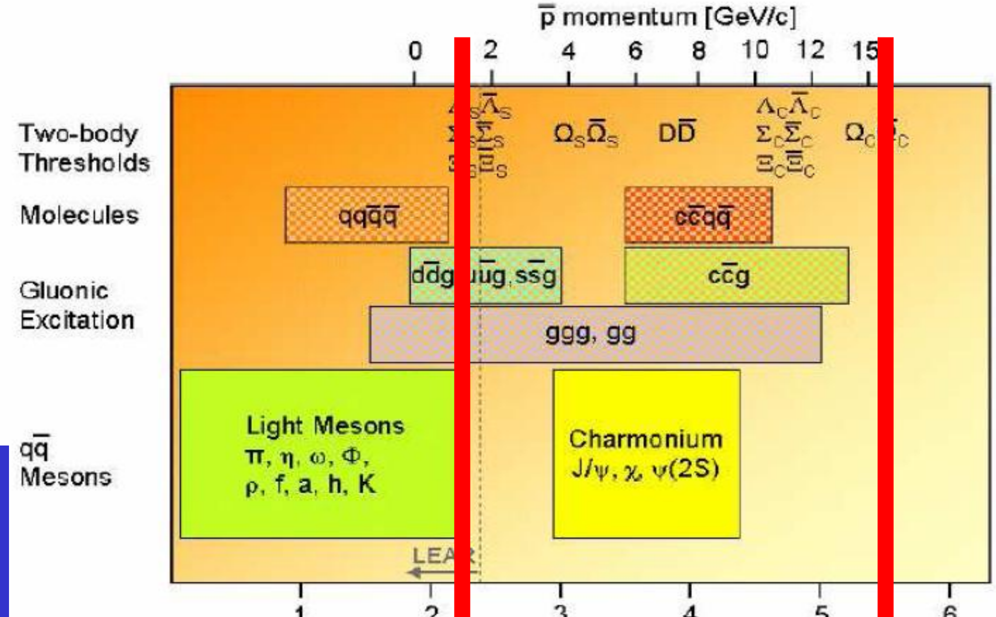
(AntiProton Annihilations at Darmstadt)

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.

Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons
Mar 2009, 216 pages
www-panda.gsi.de/archive/public/panda_pb.pdf
arxiv.org/abs/0903.3905v1



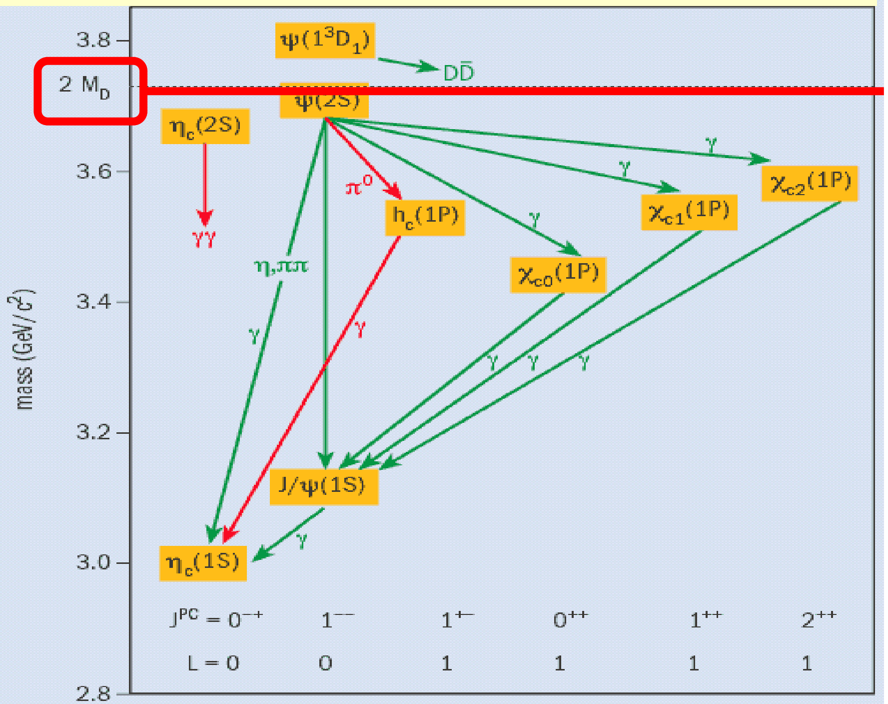
$2.25 < \sqrt{s} < 5.47$ GeV

Charmonium spectroscopy

$e^+ e^-$ Storage Rings
J/Y(3100), Y'(3700), Y"(3770),
SPEAR, DORIS, BES, CLEO-c, KEDR

B Factories
B->[cc]X allowed to find h_c 1S, 2S
CLEO, BABAR, BELLE

pp annihilation
many J^{PC} quantum numbers become accessible in formation: R704, LEAR (CERN), E760, E835 (FNAL)



Main issues

Below D$\bar{D}$ threshold (3.73 GeV)

All 8 states observed, some (precision) measurements still missing:

- **h_c (e.g. width)**
- **η_c(1S)**
- **η_c(2S) (small splitting from ψ(2S))**

Useful high precision measurements!

Above D$\bar{D}$ threshold (3.73 GeV)

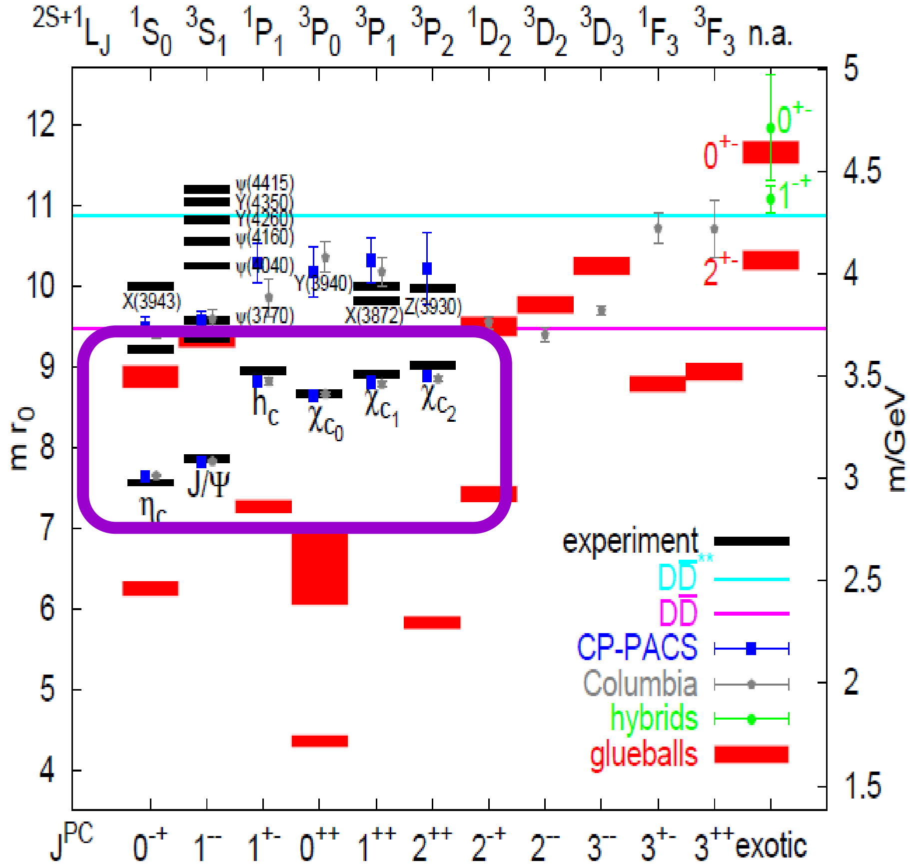
The region above open charm threshold must be explored in great detail:

- **find missing D states**
- **explain newly discovered states ($c\bar{c}$ or other)**
- **confirm vector states seen**

Useful high statistics measurements!

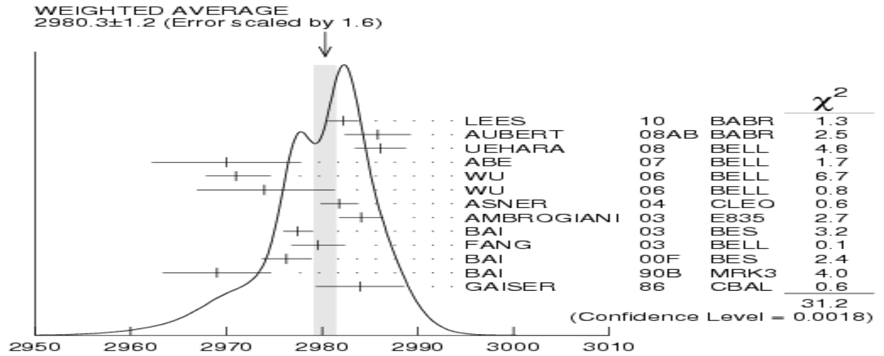
Charmonium-like states below $D\bar{D}$ threshold

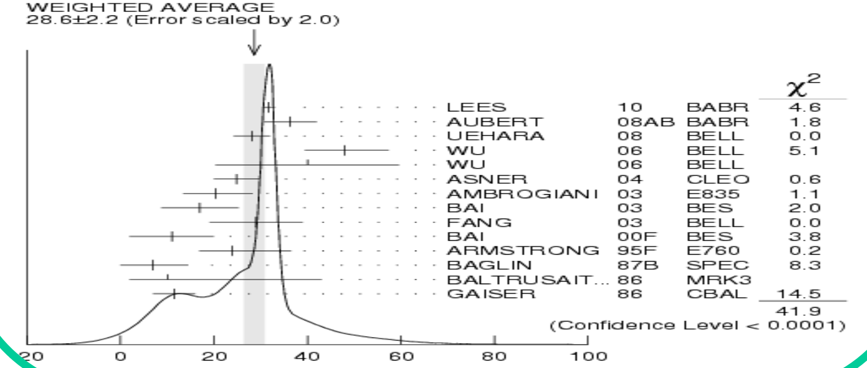
8 states well established, but width and mass of some of them (η_c , $\eta_c(2S)$, h_c) still have large errors.
More precise measurements are needed to better compare with theory.



G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610-5617

η_c mass and width (PDG 2010)

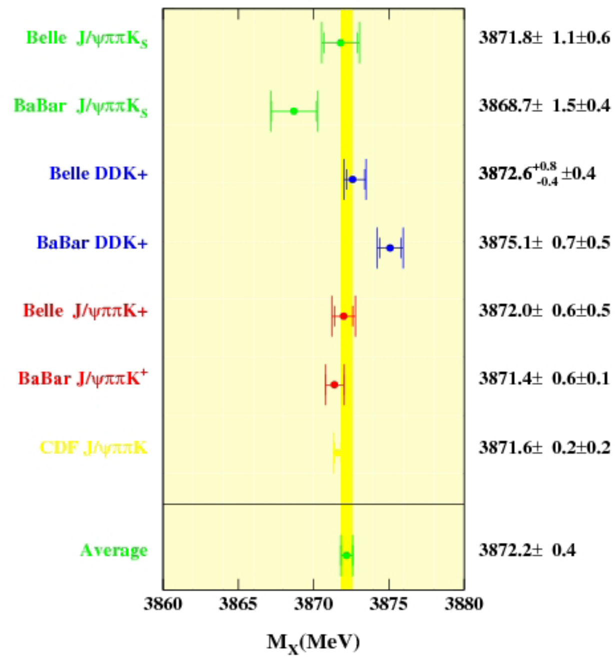




Charmonium-like states above $D\bar{D}$ threshold

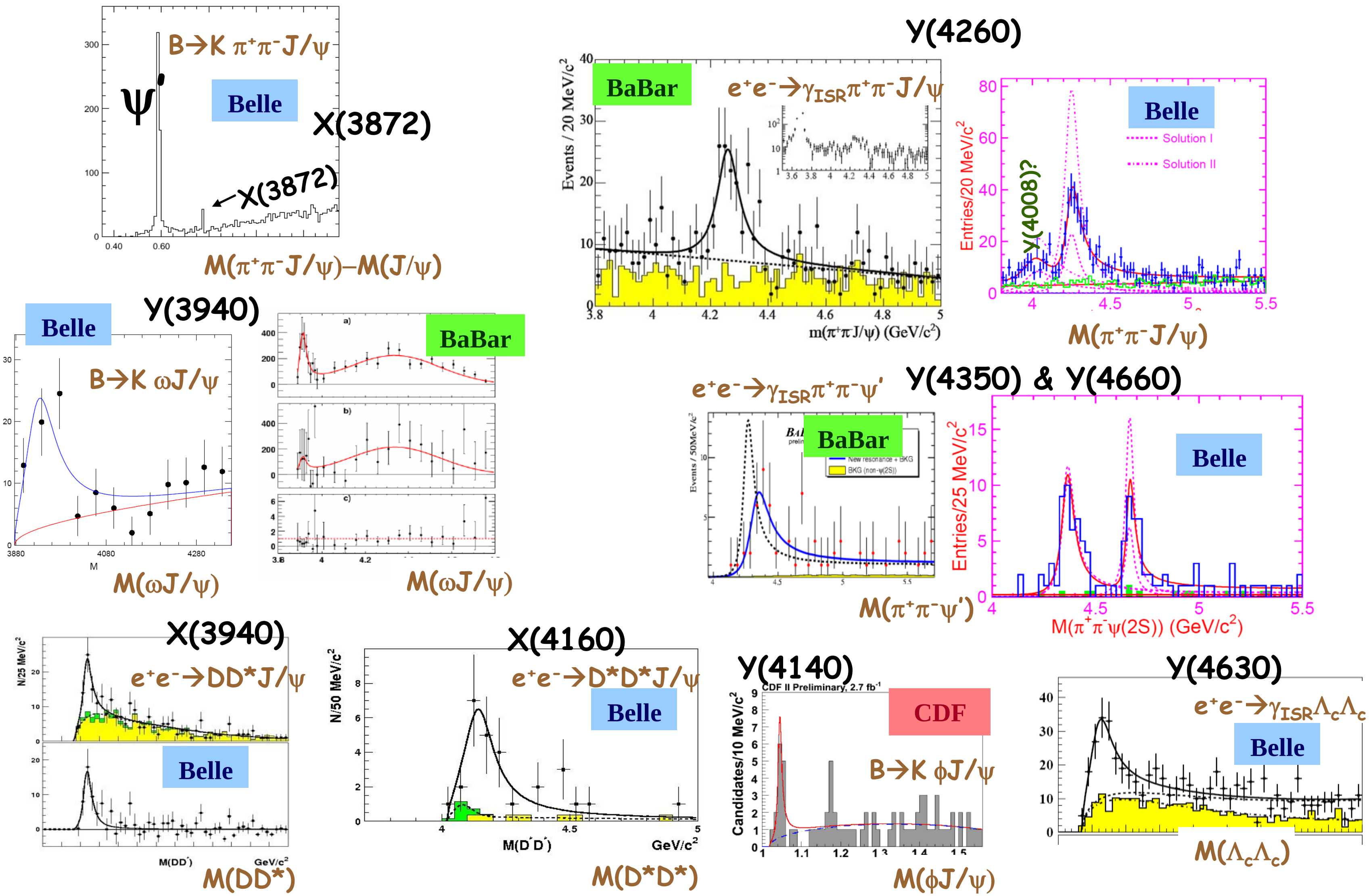
state	decay	J^{PC}
X(3872)	$J/\psi\ \pi^+\ \pi^-$	1^{++} or 2^{-+}
X(3940)	$J/\psi\ X$	?
X(3945) [or Y(3940)]	$J/\psi\ \omega$	$??^{+}$
$X(4050)^{\pm}$	$\chi_{c1}\ \pi^+$	?
X(4140)	$J/\psi\ \phi$	$??^{+}$
X(4160)	$J/\psi\ X$	?
$X(4250)^{+}$	$\chi_{c1}\ \pi^+$	?
X(4260) [or Y(4260)]	$J/\psi\ \pi^+\ \pi^-$	1^{--}
X(4350)	$J/\psi\ \phi$	$??^{+}$
X(4360) [or Y(4360)]	$\psi(2S)\ \pi^+\ \pi^-$	1^{--}
$X(4430)^{+}$ [or Z(4430)]	$\psi(2S)\ \pi^+$	?
X(4660)	$\psi(2S)\ \pi^+\ \pi^-$	1^{--}

Besides the ψ excited states, since the discovery of the X(3872) in 2003 a large number of charmonium-like states (decaying in J/ψ) **have been observed, not predicted by potential model. Their quantum numbers are mostly unknown, their interpretation still debated**



Measured mass of the X(3872) particle.

Charmonium-like states above $D\bar{D}$ threshold



Charmonium puzzle

PDG Live
particle data group

from the 2010 Review of Particle Physics.
Please use this **CITATION**: K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).

$c\bar{c}$ MESONS

$\eta_c(1S)$	$0^+(0^{-+})$	• $\chi_{c2}(2P)$	$0^+(2^{++})$	• $X(4350)$	$0^+(?^{?+})$
$J/\psi(1S)$	$0^-(1^{--})$	• $X(3940)$	$?^?(?^{??})$	• $X(4360)$	$?^?(1^{--})$
$\chi_{c0}(1P)$	$0^+(0^{++})$	• $X(3945)$	$0^+(?^{?+})$	$\psi(4415)$	$0^-(1^{--})$
$\chi_{c1}(1P)$	$0^+(1^{++})$	$\psi(4040)$	$0^-(1^{--})$	• $X(4430)^{\pm}$	$?(?^?)$
$h_c(1P)$	$?^?(1^{+-})$	• $X(4050)^{\pm}$	$?(?^?)$	• $X(4660)$	$?^?(1^{--})$
$\chi_{c2}(1P)$	$0^+(2^{++})$	• $X(4140)$	$0^+(?^{?+})$		
$\eta_c(2S)$	$0^+(0^{-+})$	$\psi(4160)$	$0^-(1^{--})$		
$\psi(2S)$	$0^-(1^{--})$	• $X(4160)$	$?^?(?^{??})$		
$\psi(3770)$	$0^-(1^{--})$	• $X(4250)^{\pm}$	$?(?^?)$		
$X(3872)$	$0^?(?^{?+})$	$X(4260)$	$?^?(1^{--})$		

• — OMITTED FROM SUMMARY TABLE

Charmonium at PANDA

- **$p\bar{p}$ annihilation up to 5.5 GeV**
- 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.
- At 2×10^{32} cm^{-2}s^{-1} (assuming 6 months/year data taking)
  Total integrated luminosity 1.5 fb^{-1}/year.
- **Improvements with respect to Fermilab E760/E835:**
  - **Up to 10 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**
  - $J/\psi+X$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$
  - $\gamma\gamma$
  - 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.

Charmonium-like channels simulation with PANDA

SIMULATION OF PHYSICS CHANNELS

Goal:

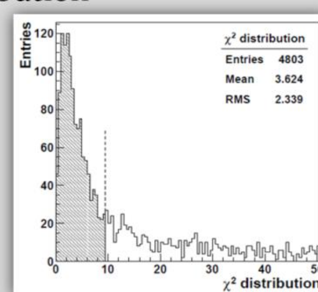
Study the performances of the designed PANDA Central Tracker through the analysis of physics events (**I.M. resolution studies**) and demonstrate that the detector setup can fulfil the physics case

Method:

1. Events generation, no background
2. Track reconstruction
3. Pattern recognition: information from all the Central Tracker subdetectors (MVD, STT, GEM) joined to obtain a global track
4. Track fitting of the global track (helix fit)
5. Kalman filter recursive method in order to improve the momentum resolution of the reconstructed tracks
6. Particle identification
7. Candidate selection (invariant mass cuts)
8. Invariant mass distribution
9. Four constraints (4C) kinematic fit

$$\sum_i^{n_d} p_i^\mu - p_C^\mu = 0$$

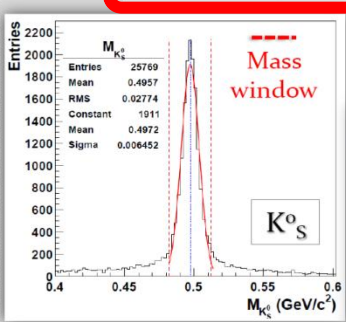
applied to the events passing the χ^2 test ($\chi^2 < 9.5$)



Preliminary results:

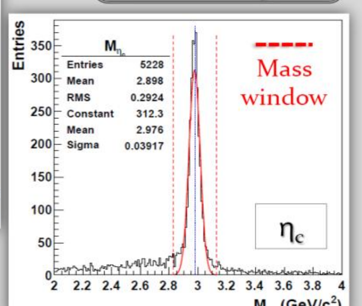
$\bar{p}p \to \eta_c(2979) \to K_S^0 K^+ \pi^-$

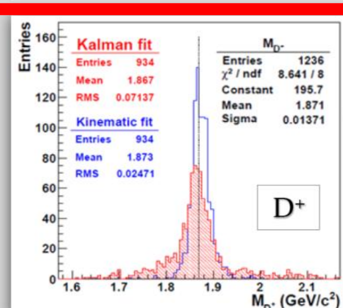
$\bar{p}p \to \Psi(3770) \to D^+D^- \to (K^-2\pi^+) + (K^+2\pi^-)$



Resolution: (1.31 ± 0.02) %

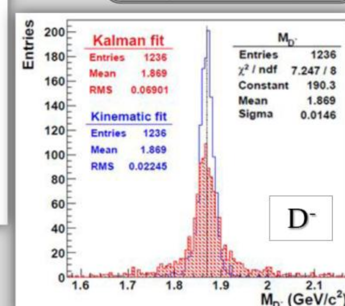
Resolution: (1.26 ± 0.03) %





Resolution: (0.73 ± 0.03) %

Resolution: (0.78 ± 0.02) %



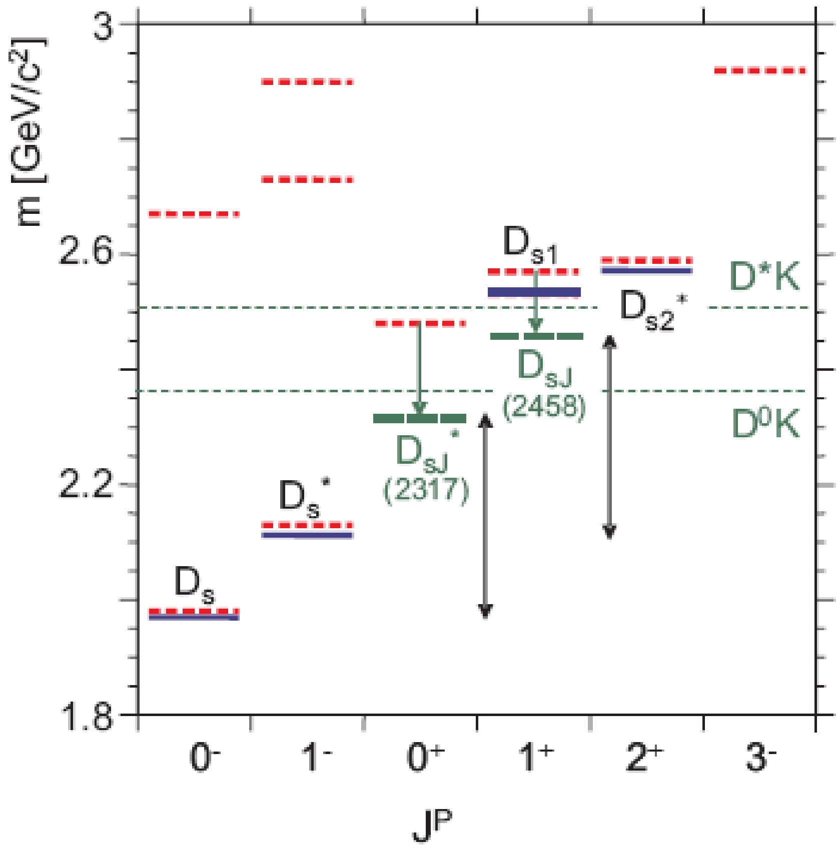
… a lot of simulation of physics channels in progress…

For example, see in this conference:

S.Costanza, poster "A StrawTube detector as Central Tracker for the PANDA experiment"

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.



Exotic states

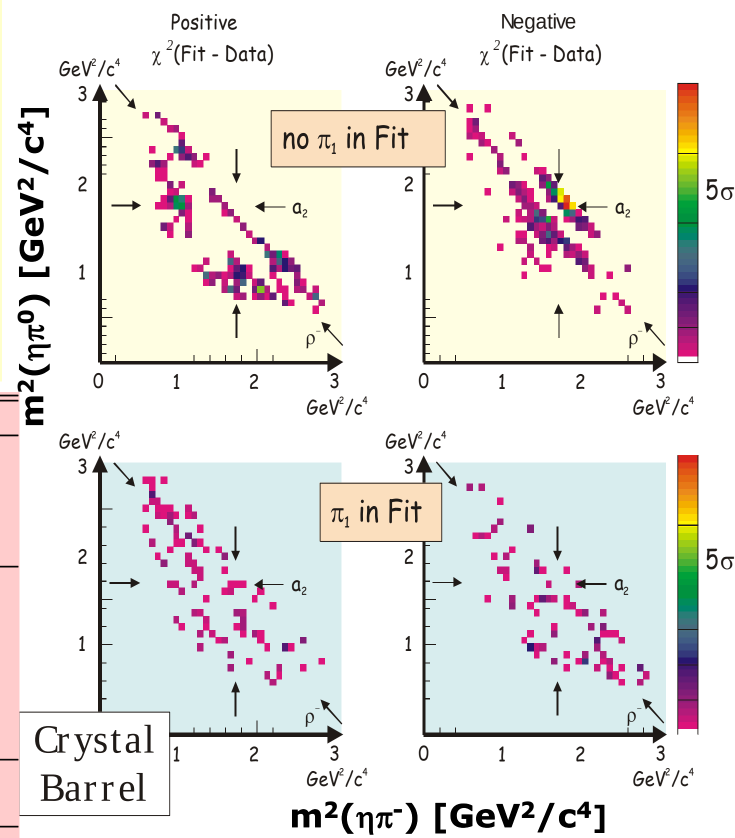
The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

Glueballs (gg, ggg), Hybrids ($q\bar{q}g$), Multiquarks ($q\bar{q}q\bar{q}$)

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.

Narrow state at 1500 MeV/c² seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).

Experiment	Exotic	J^{PC}	Mass $[MeV/c^2]$		Width $[MeV/c^2]$		Decay
E852	$\pi_1(1400)$	1^{-+}	1359	$^{+16}_{-14}\ ^{+10}_{-24}$	314	$^{+31}_{-29}\ ^{+9}_{-66}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1400	$\pm20\pm20$	310	$\pm50\ ^{+50}_{-30}$	$\eta\pi$
Crystal Barrel	$\pi_1(1400)$	1^{-+}	1360	±25	220	±90	$\eta\pi$
Obelix	$\pi_1(1400)$	1^{-+}	1384	±28	378	±58	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1593	$\pm8\ ^{+29}_{-47}$	168	$\pm20\ ^{+150}_{-12}$	$\rho\pi$
E852	$\pi_1(1600)$	1^{-+}	1597	$\pm10\ ^{+45}_{-10}$	340	$\pm40\pm50$	$\eta'\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1590	±50	280	±75	$b_1\pi$
Crystal Barrel	$\pi_1(1600)$	1^{-+}	1555	±50	468	±80	$\eta'\pi$
E852	$\pi_1(1600)$	1^{-+}	1709	$\pm24\pm41$	403	$\pm80\pm115$	$f_1\pi$
E852	$\pi_1(1600)$	1^{-+}	1664	$\pm8\pm10$	185	$\pm25\pm28$	$\omega\pi\pi$
E852	$\pi_1(2000)$	1^{-+}	2001	$\pm30\pm92$	333	$\pm52\pm49$	$f_1\pi$
E852	$\pi_1(2000)$	1^{-+}	2014	$\pm20\pm16$	230	$\pm32\pm73$	$\omega\pi\pi$
E852	$h_2(1950)$	2^{+-}	1954	±8	138	±3	$\omega\pi\pi$



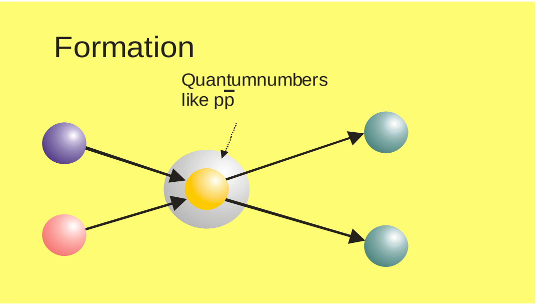
Search for exotic states

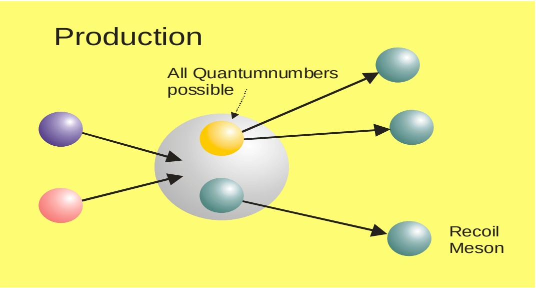
In the search for exotic mesons, antiproton acts as a filter:

All **non exotic** states are accessible in **formation** ($J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}$)

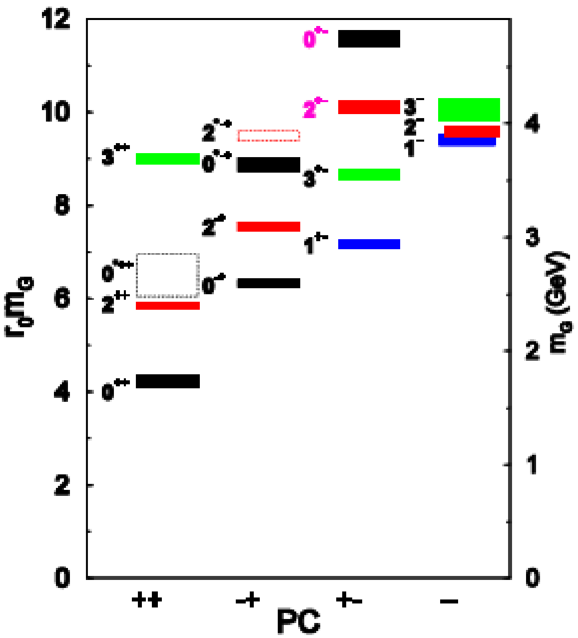
Exotic states with quantum numbers not allowed in $\bar{q}q$ ($J^{PC} = 0^{+-}, 1^{-+}, \ldots$) are possible in **associated production** ($p\bar{p} \to \pi H_c$) (σ is hundreds of pb)

Exotic states are possible in **production**





Charm hybrids candidates in the range 3-5 GeV :
likely narrow, since open charm decays are forbidden or suppressed below the DD^*_J threshold



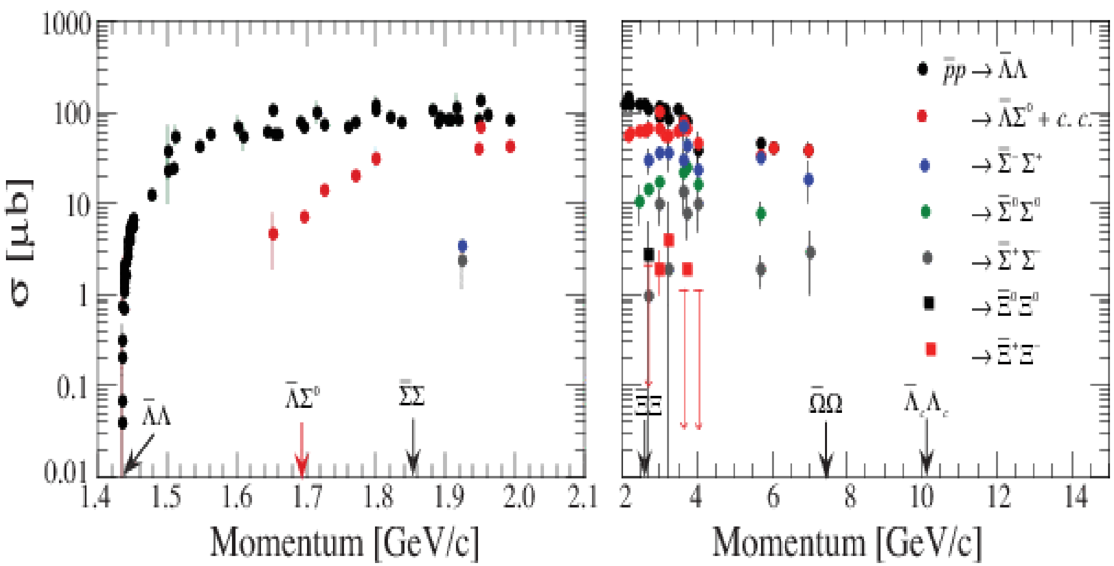
Examples of channels that PANDA can investigate

$$p\bar{p} \to \tilde{\eta}_{c0,1,2}\eta \to \chi_{c1}\pi^0\pi^0\eta$$
$$p\bar{p} \to \tilde{h}_{c0,1,2}\eta \to J/\psi\pi^0\pi^0\eta$$
$$p\bar{p} \to \tilde{\psi}\eta \to J/\psi\omega[\pi^0 \text{ or } \eta]$$
$$p\bar{p} \to [\tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1}]\eta \to DD^{\star}\eta$$

Strange and charmed baryons

Little is known of excited states of Λ , Σ and even less of Ξ and Ω. Do they follow the SU(3) predictions ?

Essentially no data exist on production cross section of $p\bar{p} \rightarrow$ (strange baryon) (strange antibaryon) above 2 GeV/c $\bar{p}$ momentum.



J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

			Decuplet members			
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
$3/2^+$	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

Baryon spectroscopy with PANDA

In PANDA: $p\bar{p} \rightarrow \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}, \bar{\Lambda}\Sigma, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}, \Lambda_c\bar{\Lambda}_c, \Xi_c\bar{\Xi}_c, \Omega_c\bar{\Omega}_c$

Example:

$pp \rightarrow \bar{\Xi}\Xi$ cross section up to 2 μb

→ sizeable population of excited Ξ states

→ analysis of their various decay modes

e.g. $\Xi\pi$, $\Xi\pi\pi$, $\Lambda\bar{K}$, $\Sigma\bar{K}$, $\Xi\eta$ ...

One year of data taking with PANDA ≈ 1-2 fb^{-1}

Final state	Cross section	# rec. events
$\bar{\Lambda}\Lambda$	50 μb	10^{10}
$\bar{\Xi}\Xi$	2 μb	10^{8}
$\bar{\Lambda}_c\Lambda_c$	20 nb	10^{7}
$\bar{\Omega}_c\Omega_c$	0.1 nb	10^{5}

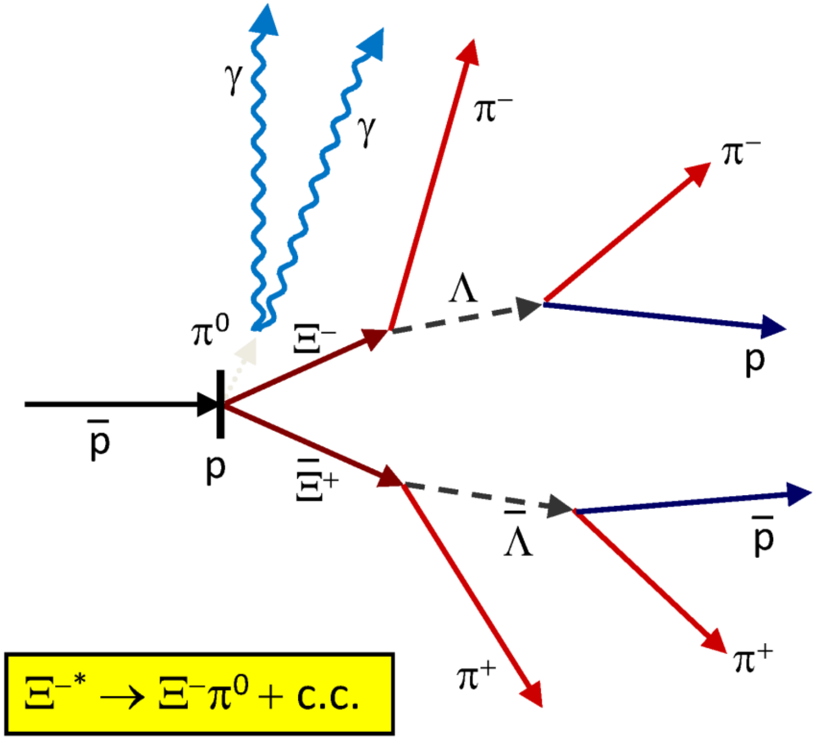


Figure 4.42: Schematic illustration of the investigated $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-\pi^0$ reaction with the considered decay branches. The reaction is characterised by four delayed decay vertices.

Hypernuclear physics

In hypernuclei one (or more) Λ substitute one (or more) nucleon. A whole new set of states can exist containing an extra degree of freedom : strangeness.

The lighter single strangeness (Λ–hypernuclei) energy levels are predicted in the frame of the shell model, where the Λ particle is subject to an effective single particle potential. Heavier Λ–hypernuclei and $\Lambda\Lambda$–hypernuclei are described by more complicated models.

Experimental situation : ~35 Λ–hypernuclei established since 50 years ago
Only 6 $\Lambda\Lambda$–hypernuclei

- 1963: Danysz et al. $^{10}_{\Lambda\Lambda}Be$ (emulsion)
- 1966: Prowse $^{6}_{\Lambda\Lambda}He$ (emulsion. Dalitz criticises the interpretation)
- 1991: KEK-E176 $^{13}_{\Lambda\Lambda}B$ (or $^{10}_{\Lambda\Lambda}Be$, emulsion counter hybrid experiment)
- 2001: BNL-E906 $^{4}_{\Lambda\Lambda}H$
- 2001: KEK-E373 $^{6}_{\Lambda\Lambda}He$
- 2001: KEK-E373 $^{10}_{\Lambda\Lambda}Be$

$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$

$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$

produce $\Xi^- \bar{\Xi}$ at threshold in $\bar{p}p \rightarrow \Xi^- \bar{\Xi}$

use a secondary target where Ξ^- is captured in a hyperatom and then interacts in nucleus

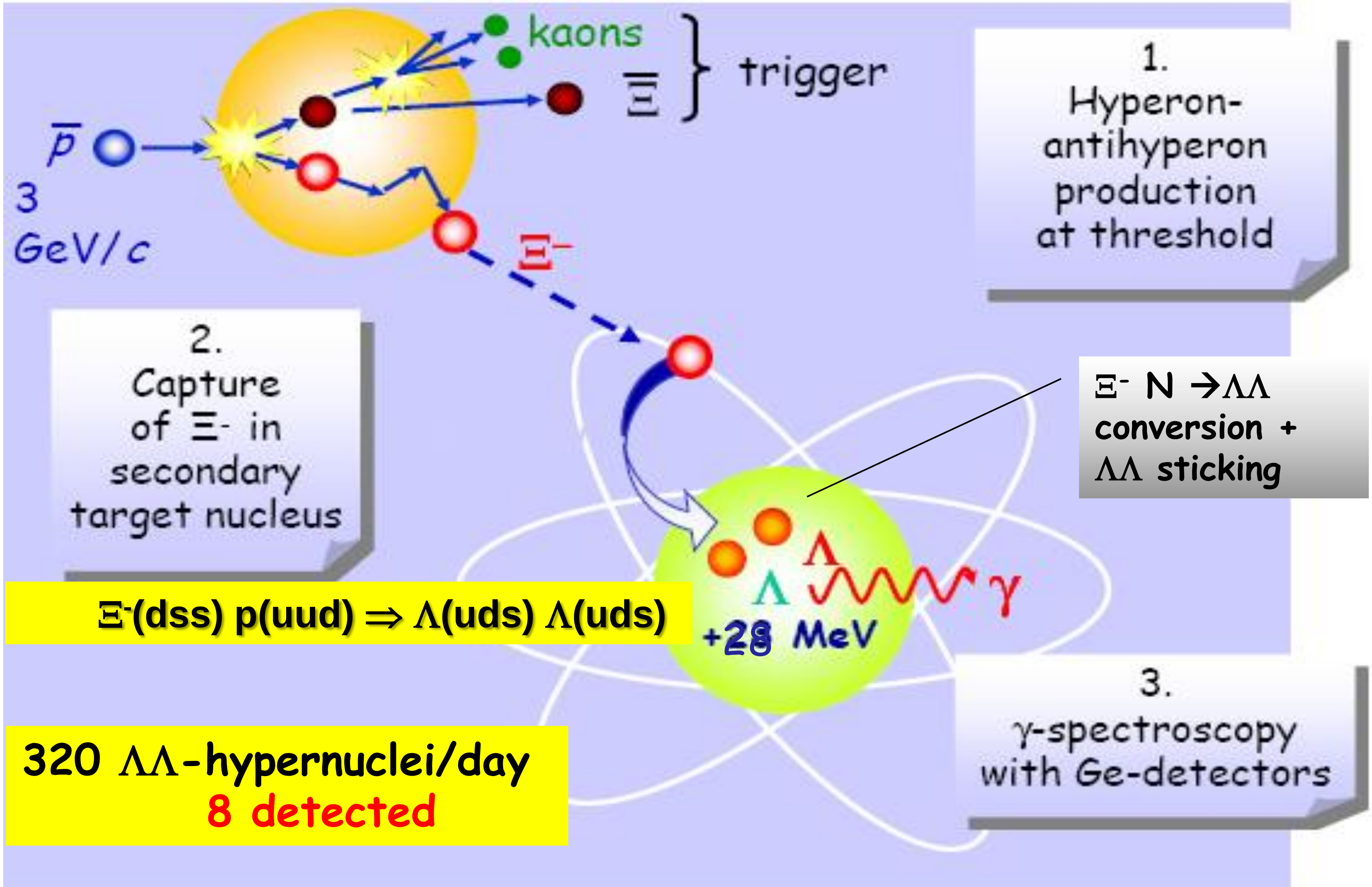
$$\Xi^- + {}^{A}Z \rightarrow {}^{A+1}{}_{\Lambda\Lambda}(Z-1)^* \rightarrow {}^{A+1}{}_{\Lambda\Lambda}(Z-1) + \gamma(\text{'s}) \text{ detected in apparatus}$$

$$\hookrightarrow {}^{A+1}(Z+1) + \pi^-\pi^-$$

detect γ with high resolution germanium detector in coincidence with tag.

$^{A+1}{}_{\Lambda\Lambda}(Z-1)$ subequently decays via pionic cascade into normal nucleus.

Double Λ-Hypernuclei in PANDA



$\Xi^-(dss)\ p(uud) \Rightarrow \Lambda(uds)\ \Lambda(uds)$

320 ΛΛ-hypernuclei/day
8 detected

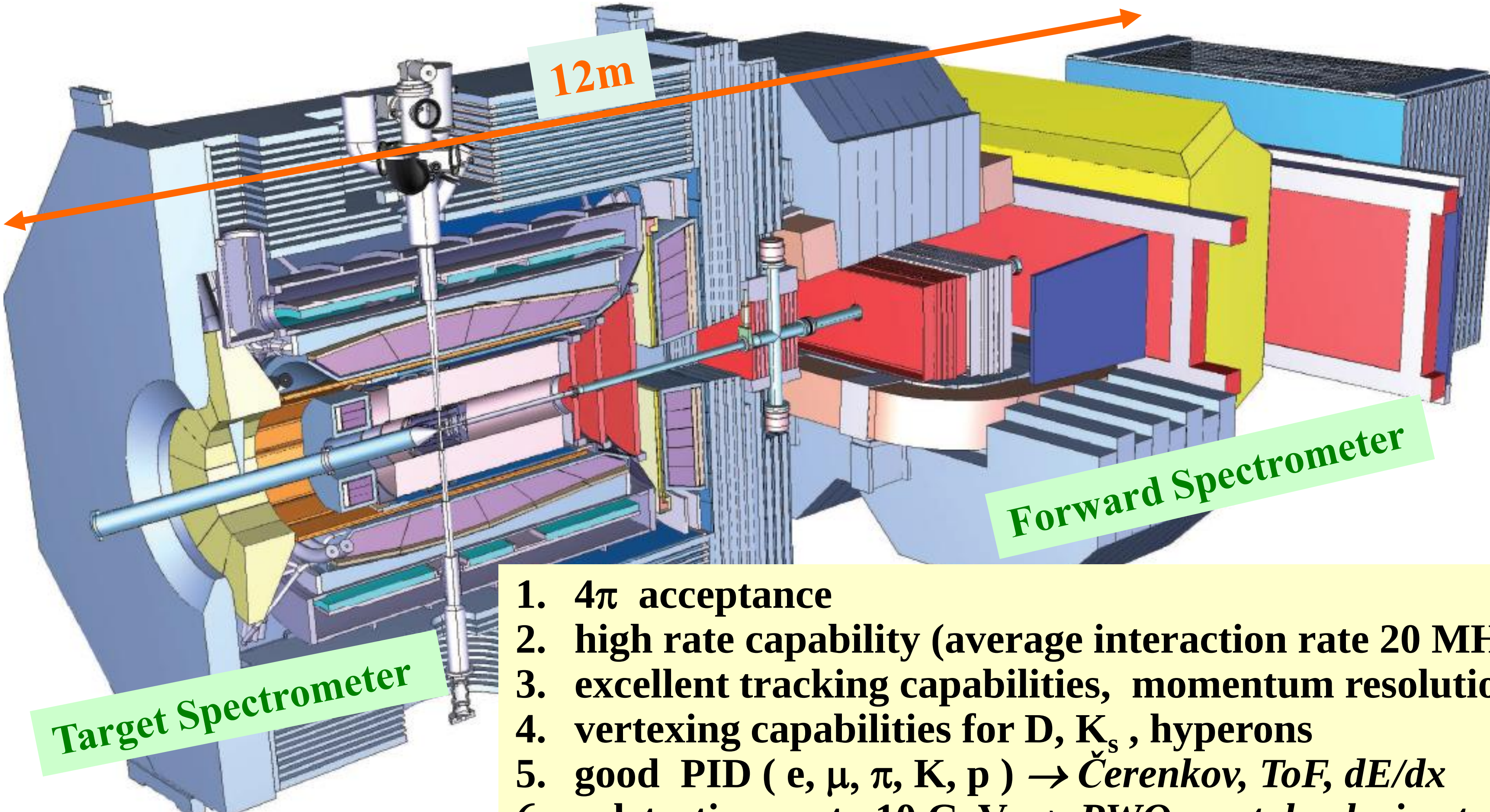
PANDA Production Rates

With 1-2 fb^{-1}/year, PANDA should collect:

Final State	cross section	# reconstructed events/year
$\eta_c \to K^0_S K^\pm \pi^\mp$	$10\,nb$	10^7
$\Lambda\bar{\Lambda}$	$50\,\mu b$	10^{10}
$\Xi\bar{\Xi}(\to_{\Lambda\Lambda}A)$	$2\,\mu b$	$10^8(10^5)$
$\psi(3770) \to D\bar{D}$	$3\,nb$	10^7
$J/\psi(\to e^+e^-,\mu^+\mu^-)$	$630\,nb$	10^9
$\chi_2(\to J/\psi + \gamma)$	$3.7\,nb$	10^7
$\Lambda_c\bar{\Lambda}_c$	$20\,nb$	10^7
$\Omega_c\bar{\Omega}_c$	$0.1\,nb$	10^5
$\sigma_T(p\bar{p})$	$70\,mb$	

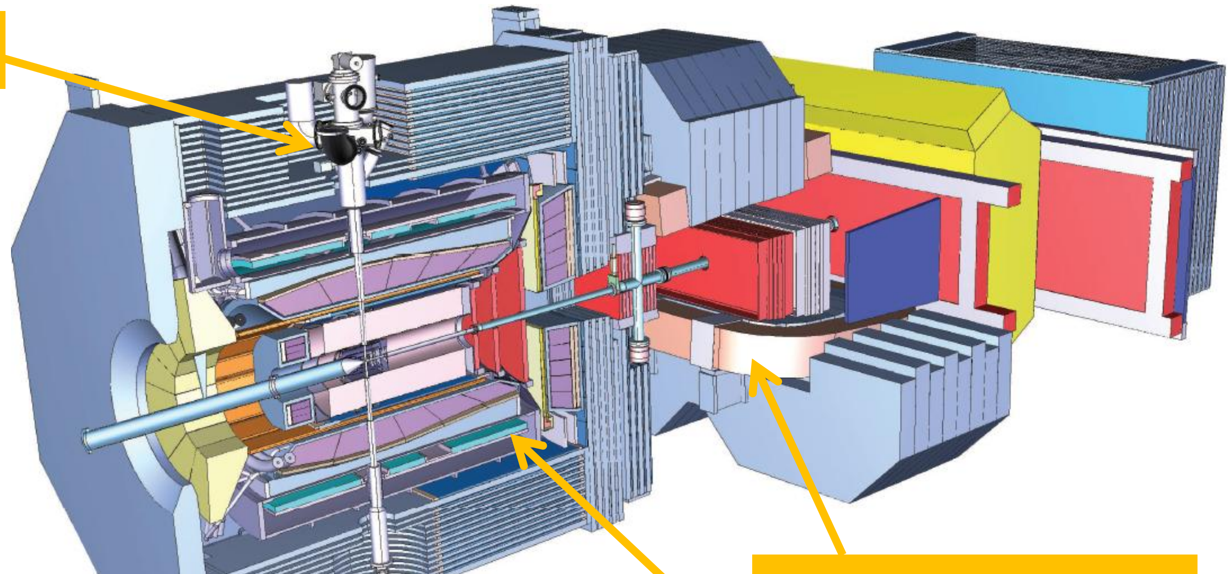
Common Feature : Low multiplicity events
Moderate particle energies

PANDA: detector requirements



1. 4π acceptance
2. high rate capability (average interaction rate 20 MHz)
3. excellent tracking capabilities, momentum resolution 1%
4. vertexing capabilities for D, K_s , hyperons
5. good PID (e, μ, π, K, p) → *Čerenkov, ToF, dE/dx*
6. γ detection up to 10 GeV → *PWO crystal calorimeter*
7. flexible and modular design (for hypernuclear physics)
8. continuous data acquisition, intelligent software trigger

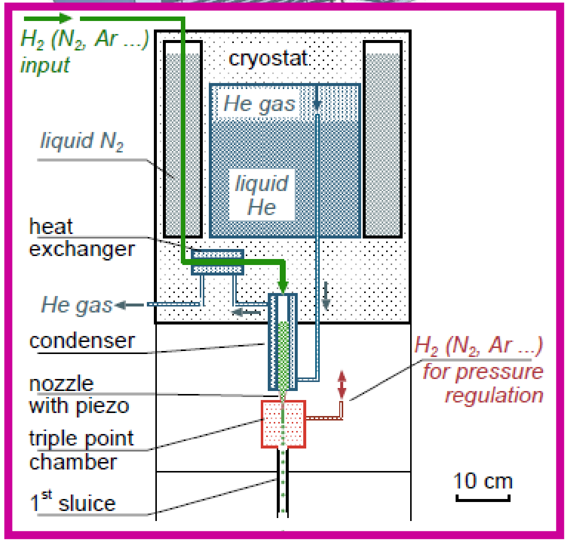
Target system

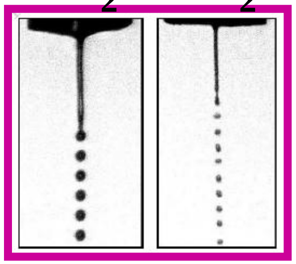


- **Requirements**
  - **Proton Target**
  - **$5 \cdot 10^{15}$ cm^{-2}** for maximum luminosity

- **Pellet Target**
  - Frozen droplets ∅ 20μm
  - also possible: D_2, N_2, Ne, ...
  - Status: $\rho \sim 5 \cdot 10^{15}$

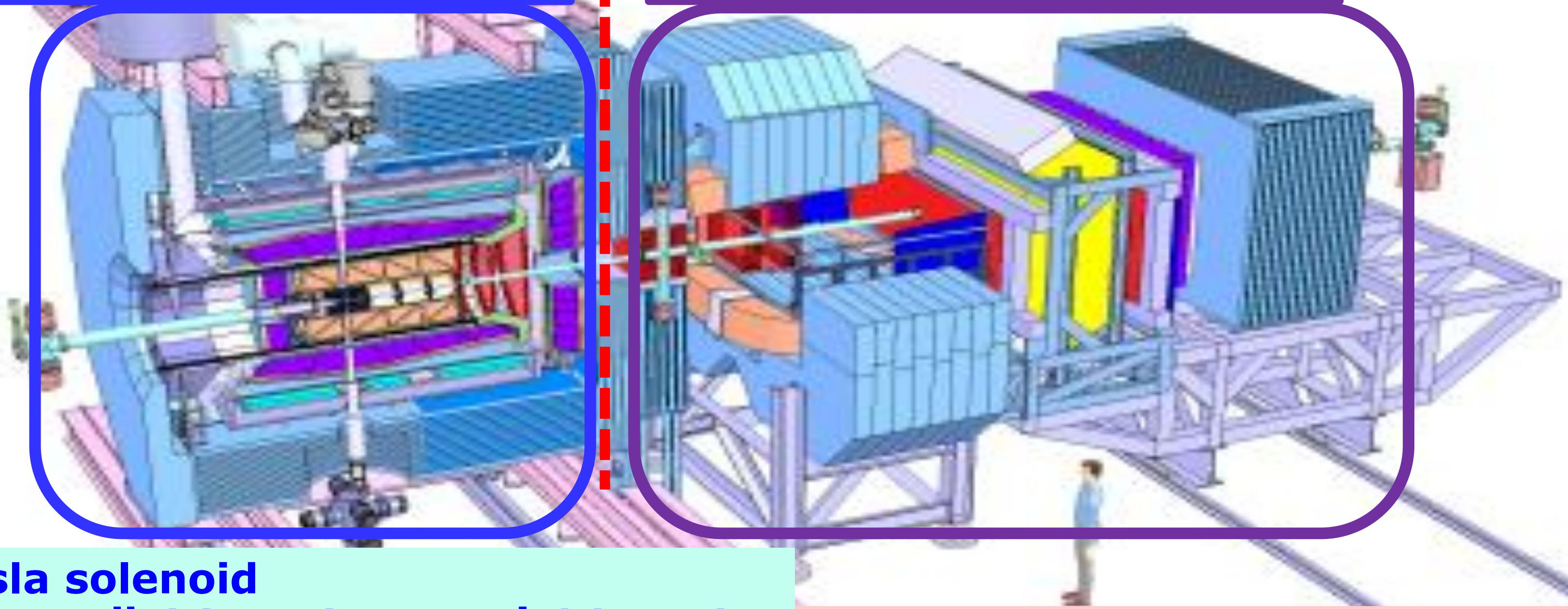
- **Cluster Jet Target**
  - Dense gas jet
  - also possible: D_2, N_2, Ne, ...
  - Status: $\rho \sim 8 \cdot 10^{14}$





Target and forward spectrometer

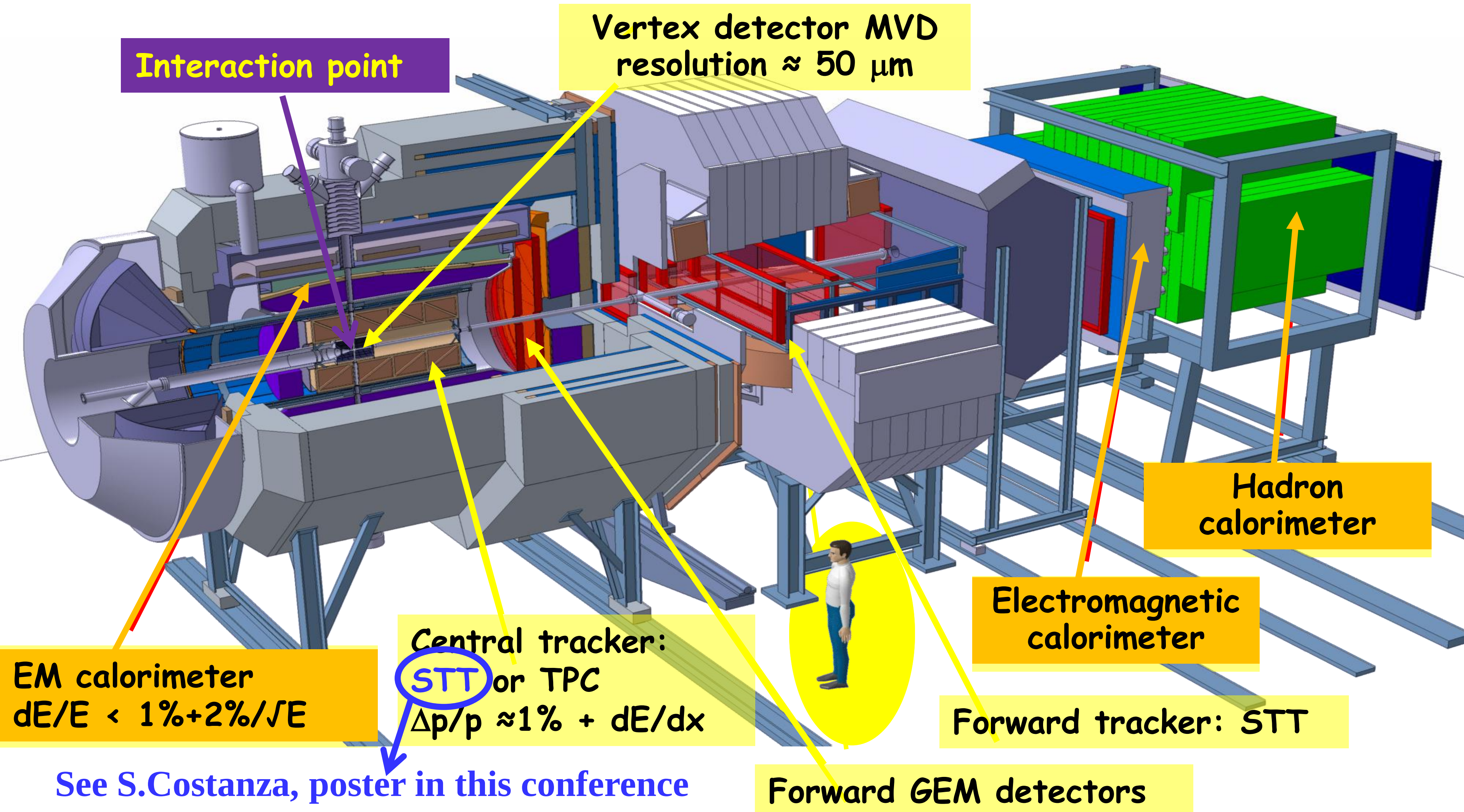
Target spectrometer | **Forward spectrometer**



2 Tesla solenoid
proton pellet target or gas jet target
Micro Vertex Detector
Inner Time of Flight detector
Tracking detector: Straw Tubes/TPC
GEM detectors
DIRC Cherenkov detector
Electromagnetic Calorimeter
Muon counters

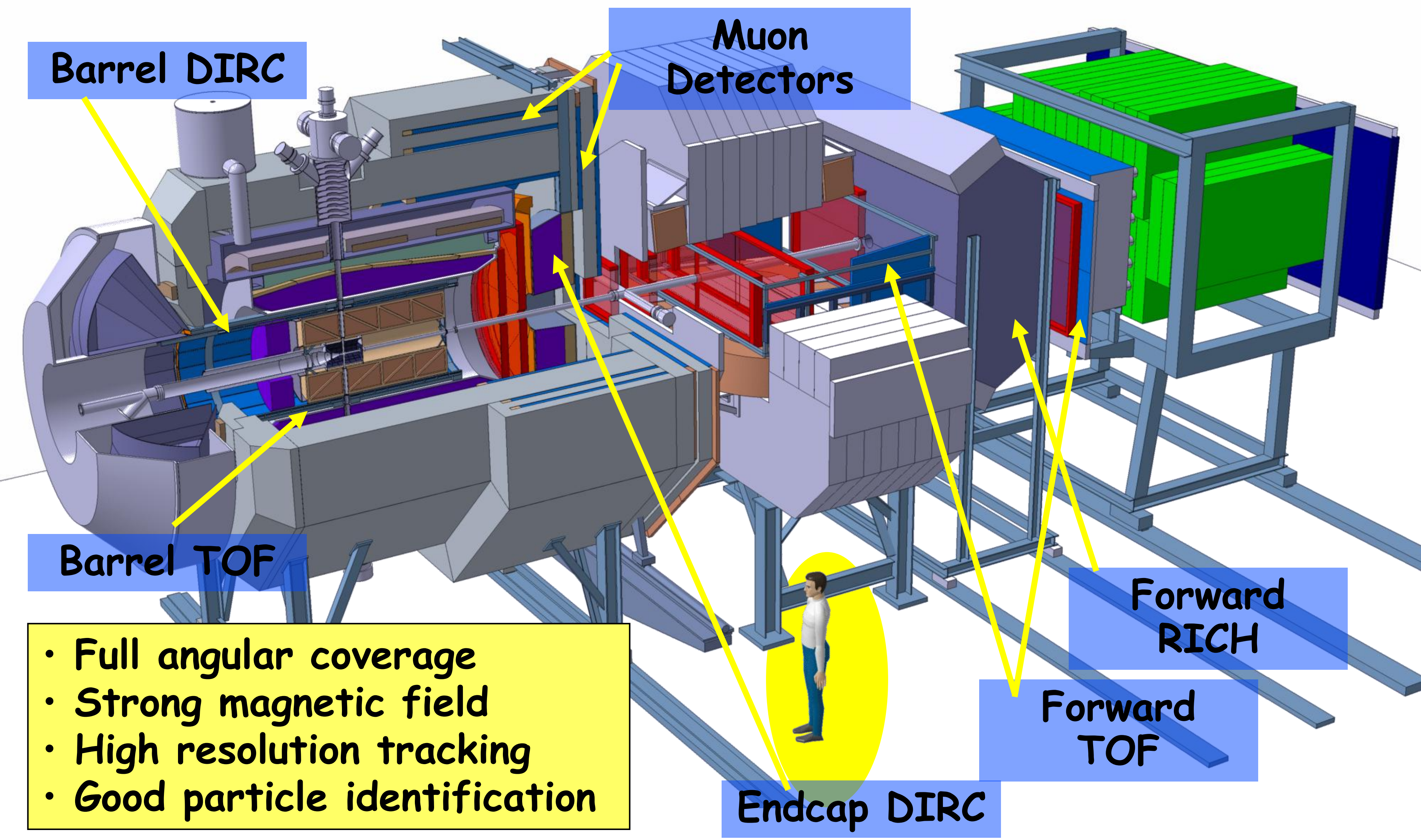
Forward drift chambers (straw tubes)
Deflecting dipole: 2 Tesla·meter
Forward RICH Cherenkov detector
Forward EM Calorimeters
Time of Flight counters
Hadron Calorimeter

Tracking system



See S.Costanza, poster in this conference

Particle identification system



- Full angular coverage
- Strong magnetic field
- High resolution tracking
- Good particle identification

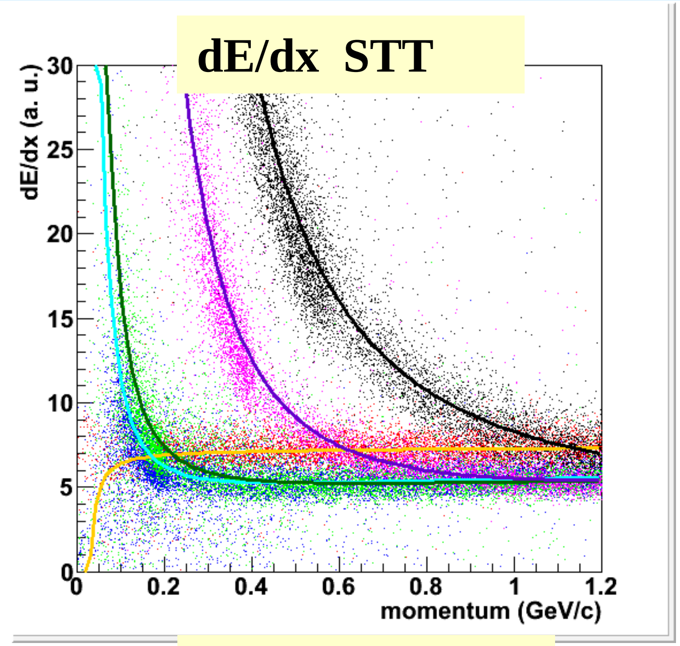
Particle identification

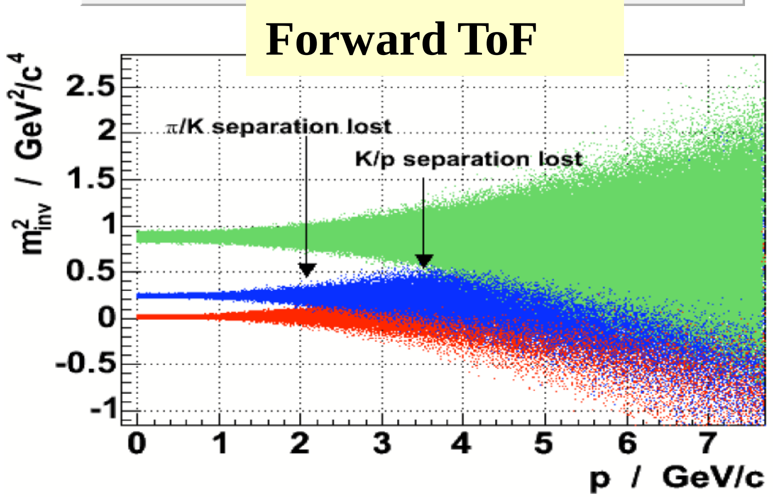
PANDA PID Requirements

- **Particle identification essential tool**
- **Momentum range**
  200 MeV/c – 10 GeV/c
- **Different processes for PID needed**

PID Processes

- **Čerenkov radiation: p > 1 GeV**
- **Energy loss: p < 1 GeV (TPC or STT)**
- **Time of flight**
- **Electromagnetic showers**





PANDA Collaboration

> 430 Scientists
56 Institutions
16 Countries

Reasonable time schedule:
first antiproton beam in 2016
PANDA fully installed at HESR in 2017

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

Summary

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).

The antiproton-induced reactions have unique features:

- Nearly all states can be directly produced
- High cross sections guarantee high statistics.

This will allow $\overline{\text{P}}$ANDA to carry out a number of measurements:

SPECTROSCOPY
High-resolution charmonium spectroscopy in formation experiments
Study of exotic states (hybrids, glueballs, multiquark)
Study of strange and charmed baryons
Open charm physics
Hypernuclear physics
Study of hadrons in nuclear matter

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

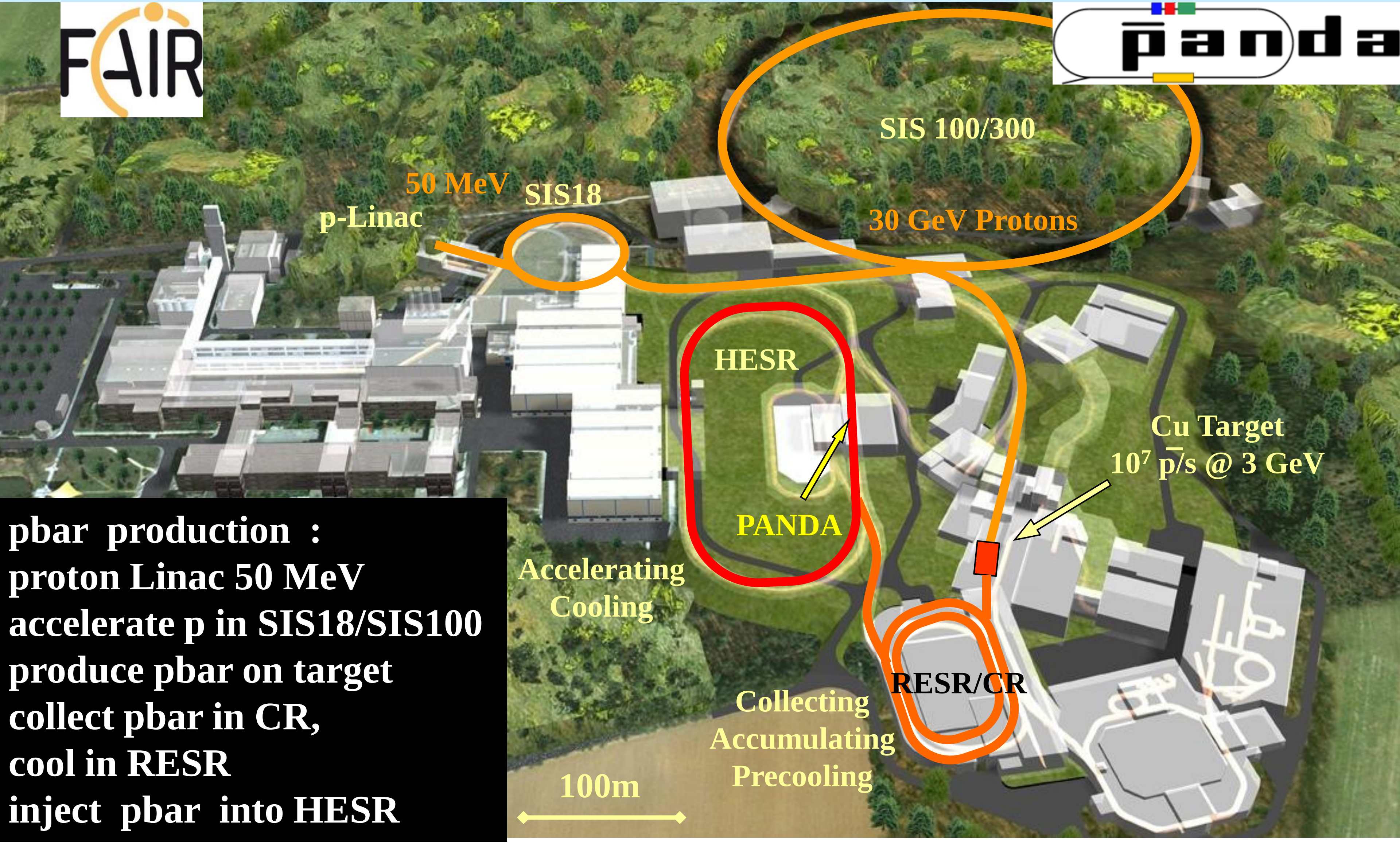
(not described here)

Thanks to *Alberto Rotondi, Gianluigi Boca, Diego Bettoni, Fulvio Piccinini, Daniela Calvo, Paola Gianotti, Lia Lavezzi, Susanna Costanza*

Backup slides

BACKUP SLIDES

Antiproton production at FAIR



pbar production :
proton Linac 50 MeV
accelerate p in SIS18/SIS100
produce pbar on target
collect pbar in CR,
cool in RESR
inject pbar into HESR

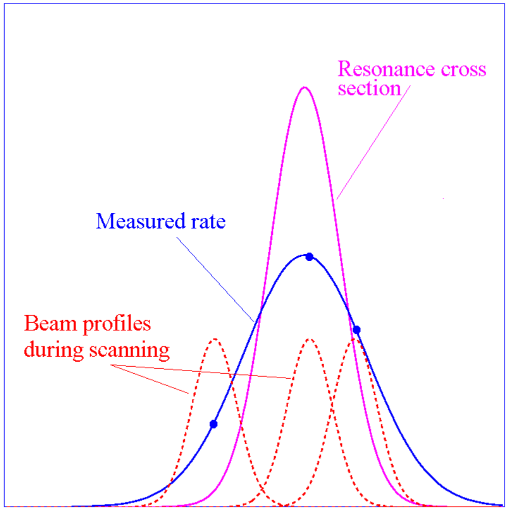
Antiproton physics: experimental method

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 $f(E,\Delta E)$:

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

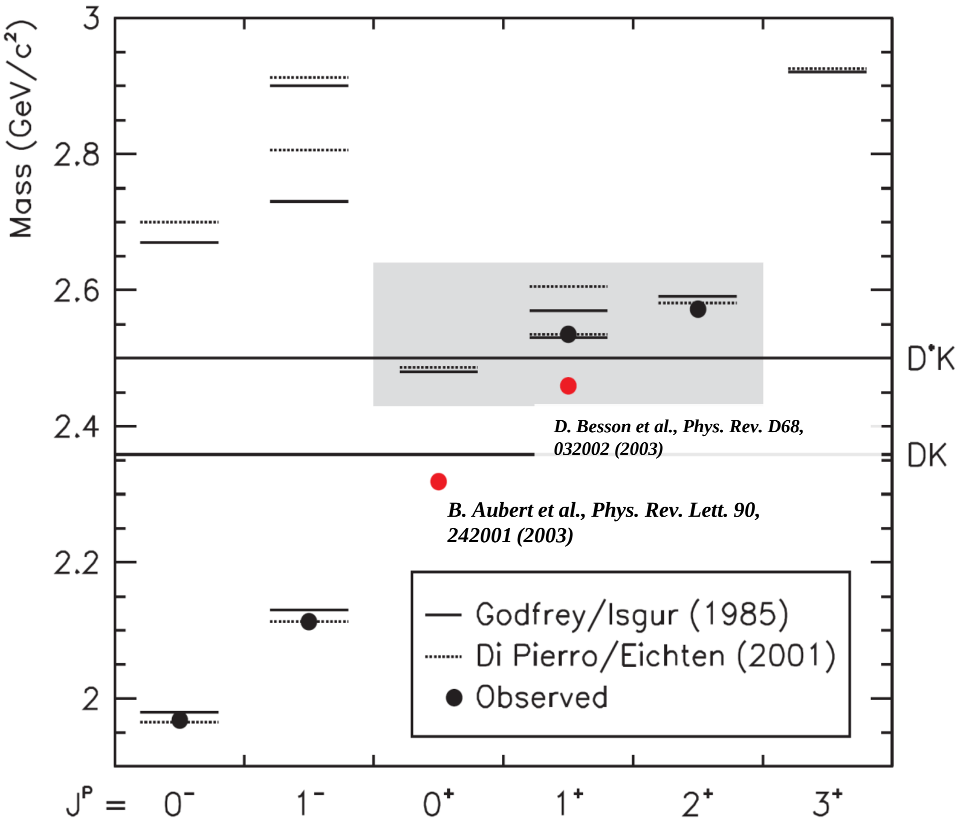
The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

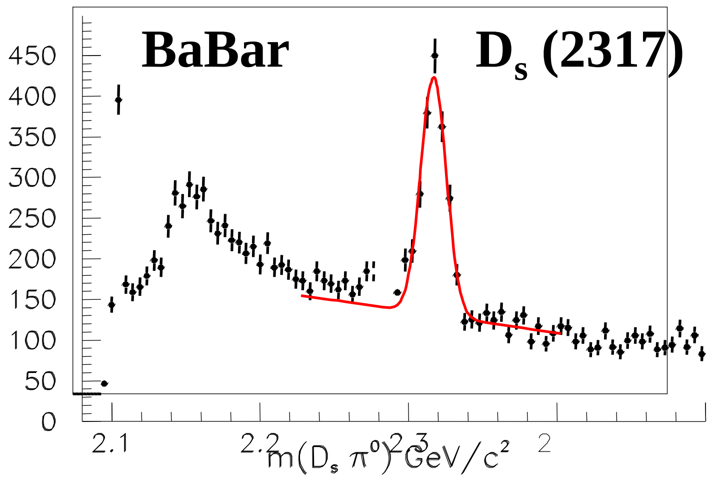
QCD bound states: open charm states

$D_s(2317) \rightarrow D_s \pi^0$ $\Gamma < 3.8$ MeV , $J^P = 0^+$

$D_s(2460) \rightarrow D^*_s(2112) \pi^0$ $\Gamma < 3.5$ MeV , $J^P = 1^+$

not predicted by the quark model





width of these states important to discriminate among different models

QCD bound states: open charm states

$D_s(2317) \rightarrow D_s \pi^0$ $\Gamma < 3.8$ MeV

$D_s(2460) \rightarrow D^*_s(2112)\, \pi^0$ $\Gamma < 3.5$ MeV

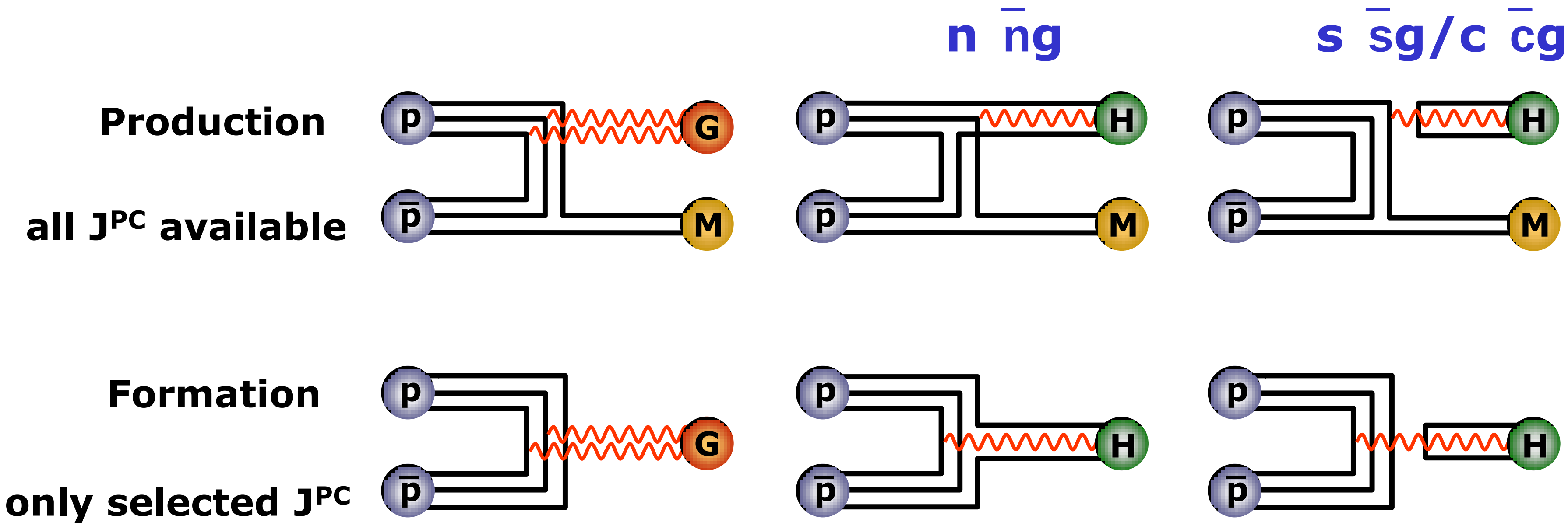
It is possible to measure the width of these states in reactions like

$$p\bar{p} \rightarrow D_s(2317)\, \bar{D}_s$$

inclusive (missing mass) or exclusive in $D_s \pi^0$

exploit very good beam momentum for excitation function measurement near threshold and width extraction. Resolution possible down to 100 KeV

Hybrids and glueballs in antiproton annihilation



Gluon rich process creates gluonic excitation in a direct way

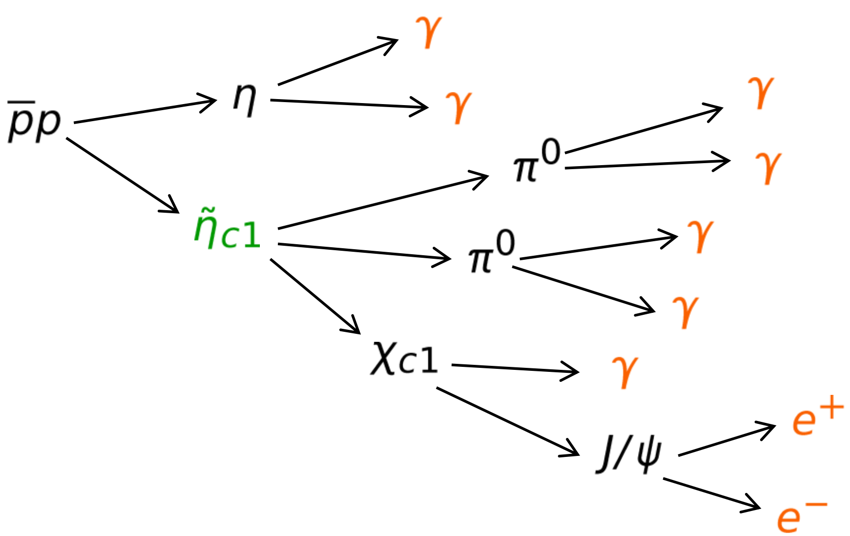
- $c\bar{c}$ requires the quarks to annihilate (no rearrangement)
- yield comparable to charmonium production
- even at low momenta large exotic content has been proven
- Exotic quantum numbers can only be achieved in production mode

Charmed hybrids in PANDA

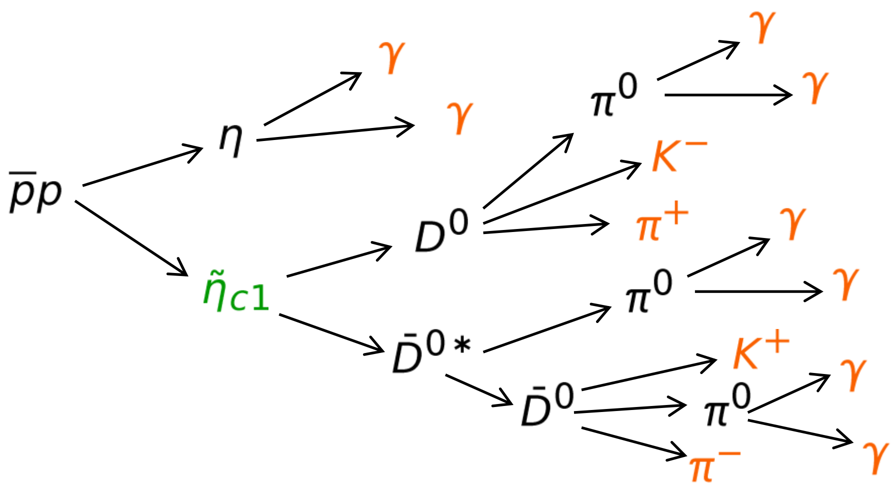
From LQCD calculations, $\tilde{\eta}_{c1}$ with m ~ 4.3GeV/c², $J^{PC} = 1^{-+}$

Reconstruction possible in PANDA in exclusive channels like

$\bar{p}p \to \tilde{\eta}_{c1}\eta \to \chi_{c1}\pi^0\pi^0\eta$

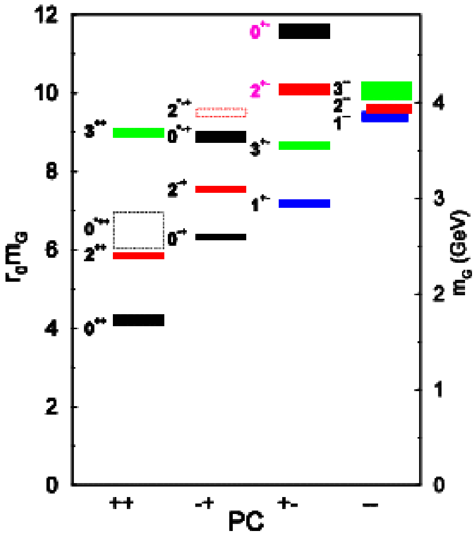


$\bar{p}p \to \tilde{\eta}_{c1}\eta \to D^0\bar{D}^{0*}\eta$



thanks to the good calorimeter (γ identification) and detector charged particle identification

Glueballs



LQCD theoretical predictions

Decay channels

ϕϕ and ϕη

preferred for glueball masses < 3.6 GeV

or

J/ψ η and J/ψ ϕ

for masses > 3.6 GeV

Oddballs should be narrower states (they don't mix with ordinary meson states) and therefore more easily detectable.

LEAR investigated glueball low mass region in pp collisions at rest, at Cern in the '90s.

PANDA is a unique opportunity to study also higher mass states.

Glueballs in PANDA

Examples of possible decay channels i $\bar{\text{p}}$anda

Light glueballs , $f_2(2000 - 2500)$:

$$p\bar{p} \rightarrow \phi\phi$$
$$p\bar{p} \rightarrow \phi\eta$$
$$p\bar{p} \rightarrow K^*\bar{K}^*$$
$$p\bar{p} \rightarrow \rho\rho$$

Heavy oddballs, $b_{0,2}(4000–5000)$:

$$p\bar{p} \rightarrow DD^*\,\eta$$
$$p\bar{p} \rightarrow DD^*\,\pi^0$$

Charmed baryons in PANDA

- **kinematic limit: $\sqrt{s}$ = 5.5 GeV**
- **moderate excitation energies only accessible in Λ_c and Σ_c**
- **ground state Ω_c just reached**
- **higher limit in $\bar{p}d \rightarrow \bar{D}Y_c$ but small cross section**

Baryon	M_{max} [GeV]	E^*_{max} [GeV]
Ξ	4.15	2.83
Ω	3.80	2.13
Λ_c	3.19	0.90
Σ_c	3.19	0.73
Ξ_c	3.00	0.53
Ω_c	2.78	0.08

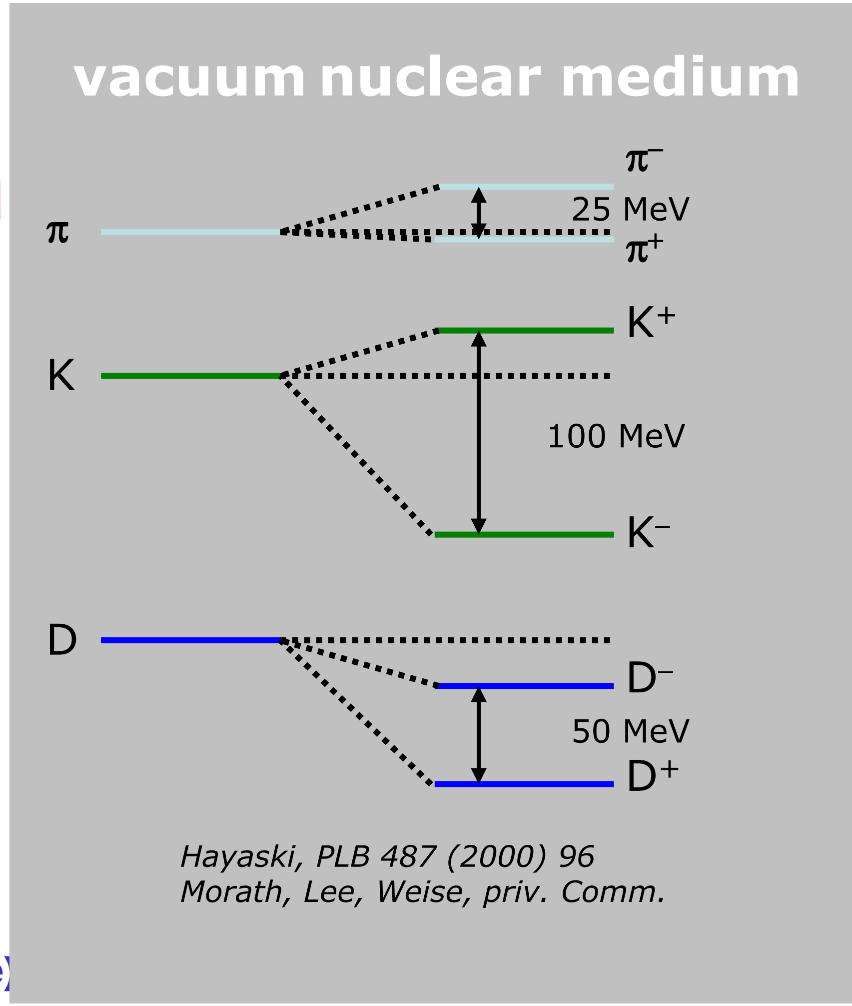
Charmed baryons in PANDA

- **detection of charmed baryons very ambitious:**
- **short decay length ~few 10 μm**
- **many decay channels < few %**
- **like to have ≥ 2 charged prompt particles plus strangeness tagging → hyperon in final state ($\Lambda_c/\Sigma_c \rightarrow \Lambda$, $\Xi_c \rightarrow \Xi$, $\Omega_c \rightarrow \Omega$)**
- **maybe only required on either baryon or antibaryon side**

Baryon	cτ [μm]	mode	b.f. [%]
Λ_c^+	60	$\Lambda\pi^+\pi^+\pi^-$	2.6 ± 0.7
Σ_c	0	$\Lambda_c^+\pi$	~100
Ξ_c^+	132	$\Xi^-\pi^+\pi^+$	?
Ξ_c^0	34	$\Xi^-\pi^+$ $\Xi^-\pi^+\pi^+\pi^-$	? ?
Ξ_c'	0	$\Xi_c\gamma$	~100
Ω_c^0	21	$\Omega^-\pi^+$ $\Omega^-\pi^+\pi^+\pi^-$	? ?

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

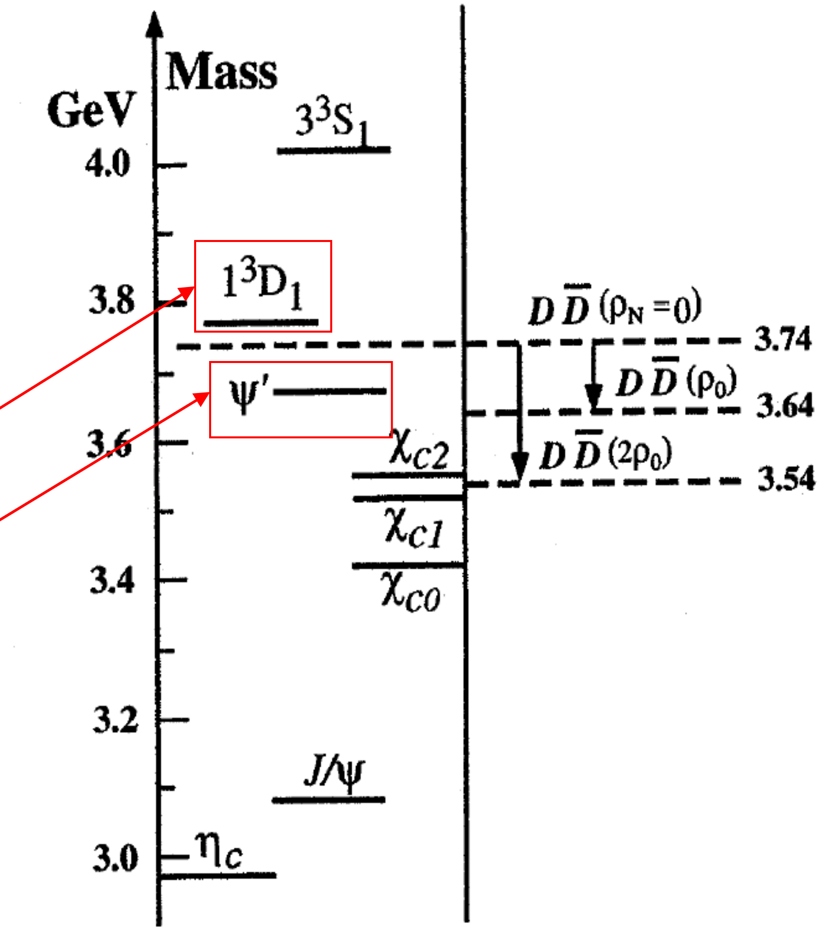
- Measure J/ψ and D production cross section in $\bar{p}$ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

  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)

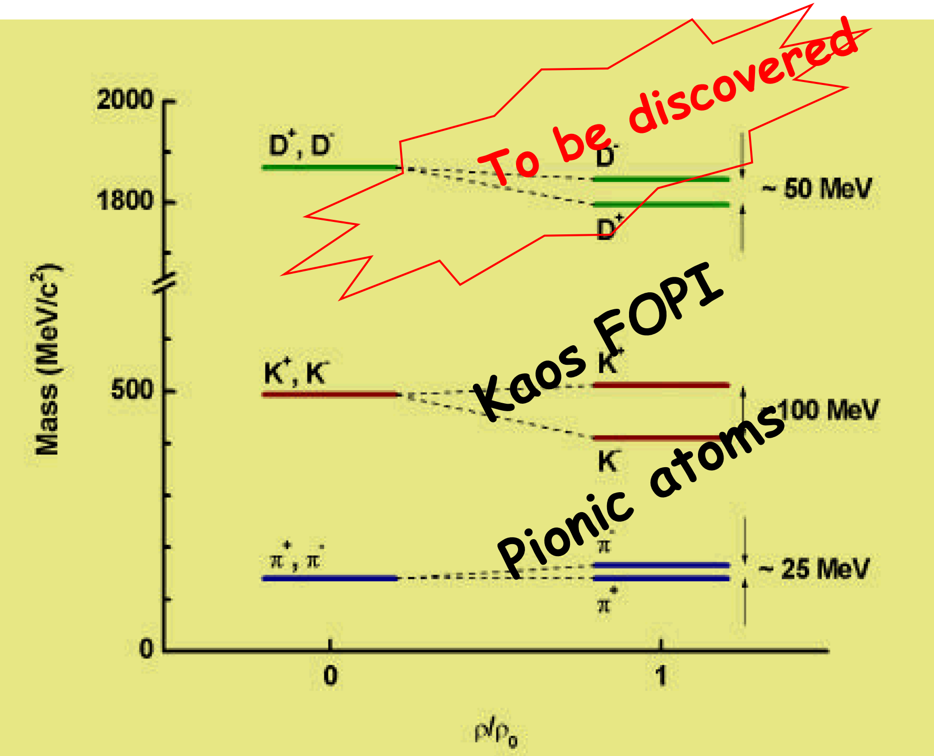


Charmed hadrons in nuclear matter

Test of qq and $q\bar{q}$ potentials

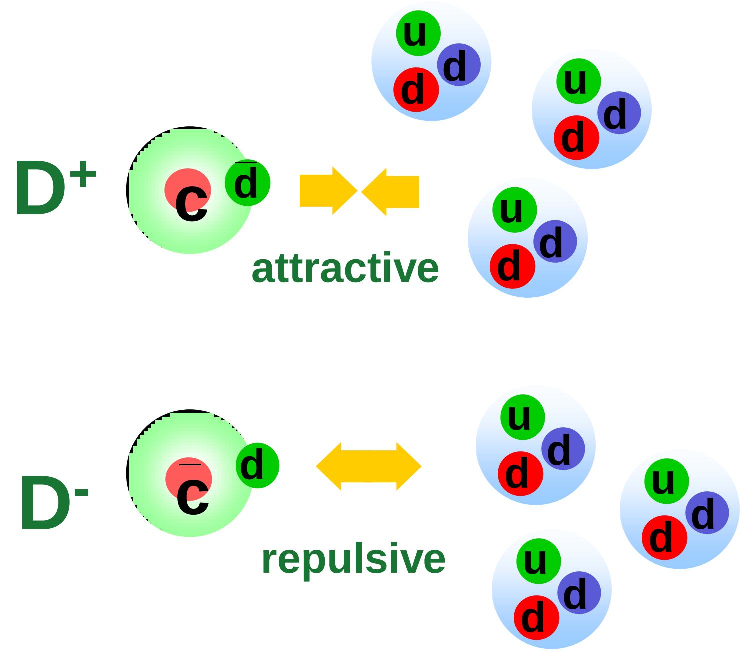
Mass splittings because charge conjugation symmetry broken at $n_B \neq 0$

Problem: to select "clean" decay modes!



K^- ($\bar{s}u$): $m_s/m_u \approx 40$

D^+ ($c\bar{d}$): $m_c/m_d \approx 200 \Rightarrow$ Quark atom



Electroweak physics

CP violation measurement possible for hyperons and the Λ_c in the self-analysing non-leptonic decay (for instance : $\Lambda \rightarrow p\,\pi^-$)

$$dP/d\cos\theta = \tfrac{1}{2}\,(1 + P\alpha\cos\theta)$$

where P is the polarization of the hyperon. If CP is conserved $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$

CP asimmetry parameter

$$\mathcal{A} = (\alpha_\Lambda + \alpha_{\bar{\Lambda}}) / (\alpha_\Lambda - \alpha_{\bar{\Lambda}})$$

PDG 2010 : $\mathcal{A}_\Lambda$ = 0.012   0.021

PANDA with 580 evt/s can improve this limit and can also measure asymmetry for $\Xi^0 \rightarrow \Lambda\pi^0$, $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda^+_c \rightarrow \Lambda\pi^+$

CP violation and mixing measurement in the charm sector in $\bar{p}p \rightarrow D\bar{D}$ possible with flavour tagging.

Charm rare decays and lepton flavour violation :

$D^0 \rightarrow \mu\, e$; $D \rightarrow \mu\, \pi\, e$ with flavour tagging.

Backup slides

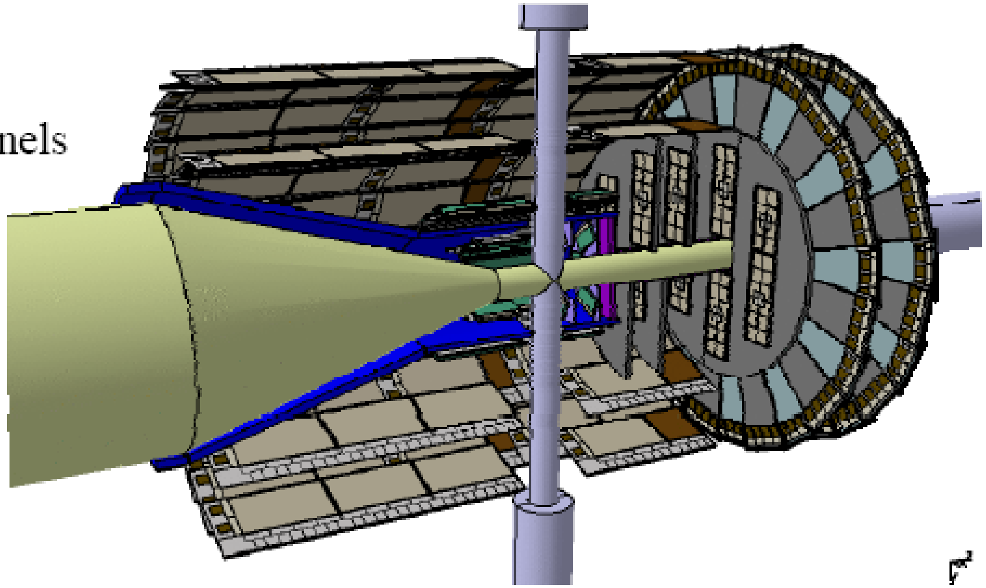
Micro Vertex Detector

Micro Vertex Detector

- 4 barrels and 6 disks
- Inner layers:
  hybrid pixels (100x100 μm^2)
  - 140 module, 12M channels
- Outer layers:
  silicon strip detectors
  - double sided strips
  - 400 modules, 200k channels
- Mixed forward disks
- Continuous readout

Requirements

- $c\tau(D^{\pm}) \sim 312\ \mu m$
  $c\tau(D_s^{\pm}) \sim 147\ \mu m$
- Vertex resolution ~ 50 µm



G.Boca GSI, Germany & U. Pavia, Italy

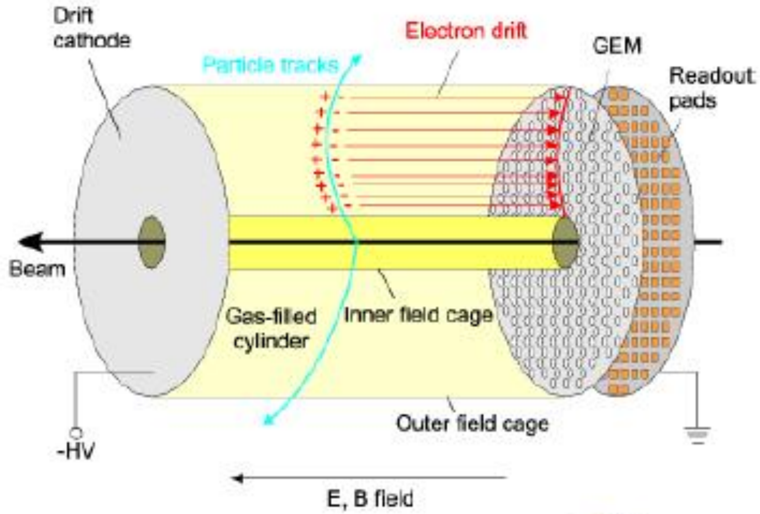
Central tracker detector

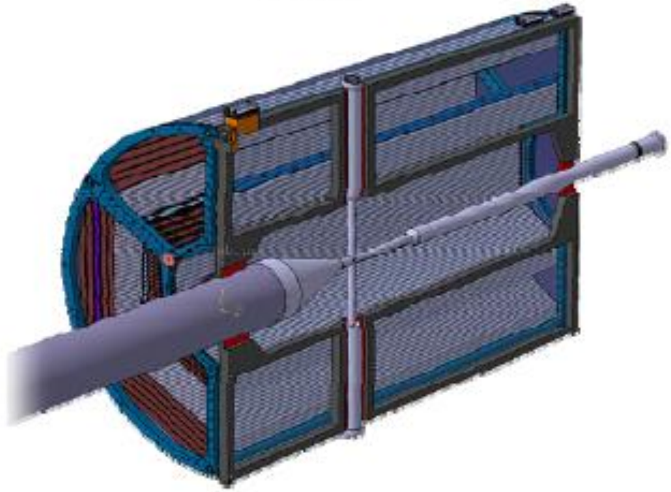
- Design figures:
  - $\sigma_{r\varphi} \sim 150\mu m$, $\sigma_z \sim 1mm$
  - $\delta p/p \sim 1\%$ (with MVD)
  - Material budget ~ 1% X_0

2 Alternatives:

- **Time Projection Chamber**
  - Continuous sampling
    GEMs readout plane
    (Ion feedback suppression)
    Online tracklet finding

- **Straw Tube Tracker**
  - about 4000 straws
  - 27 µm thin mylar tubes, 1 cm Ø
  - Stability by 1 bar overpressure





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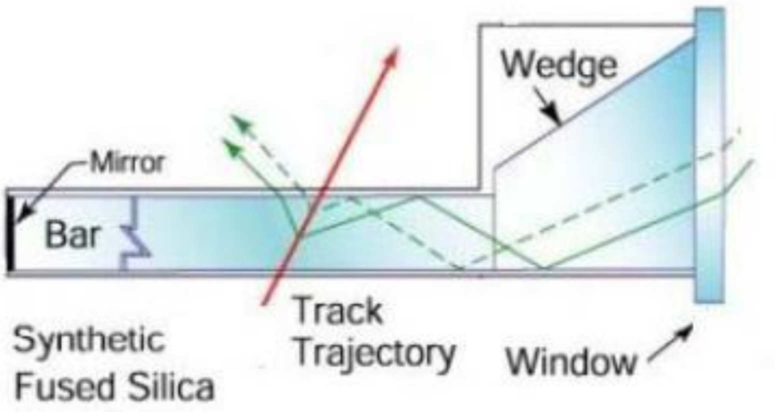
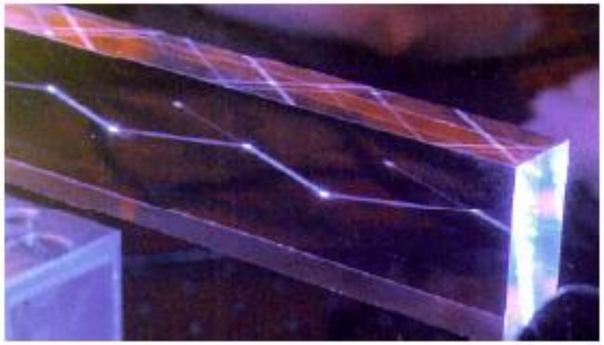
Cherenkov Detectors

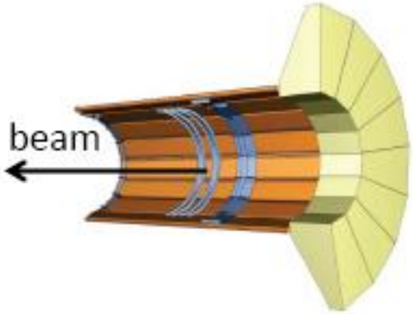
DIRC = Detection of Internally Reflected Cherenkov Light

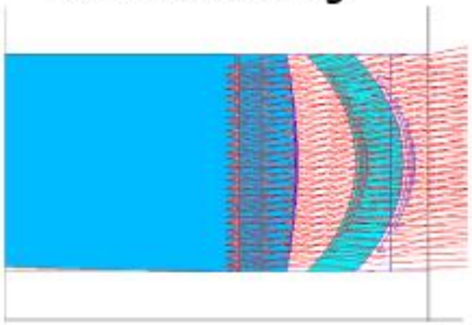




PANDA DIRC

- Lens focussing
- shorter radiator
- no water tank
- compact pixel readout (CP-PMTs or APDs)





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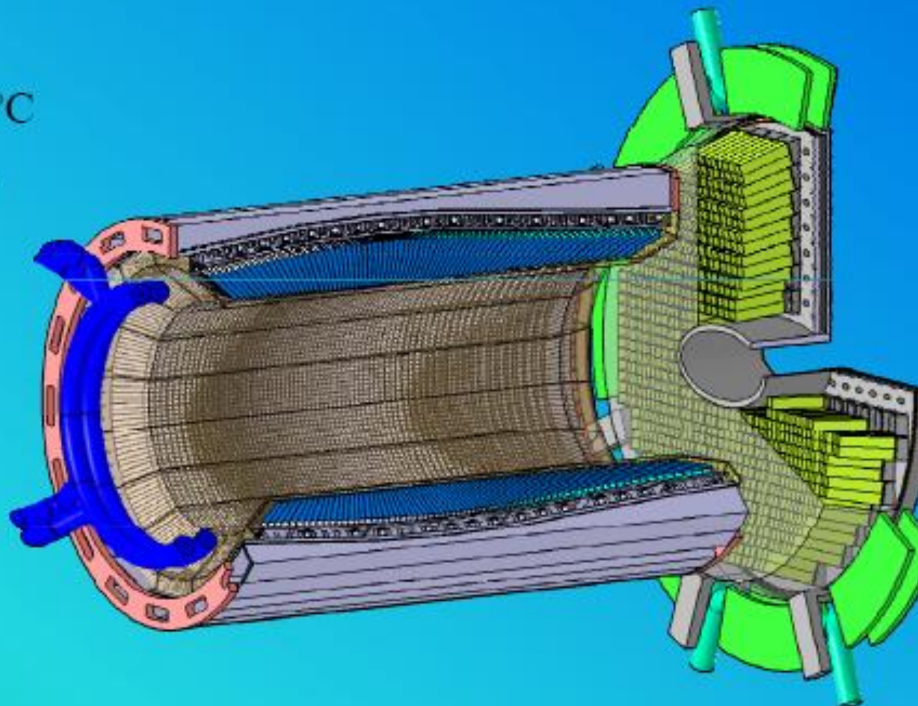
EM Calorimeters

PANDA PWO Calorimeters

- PWO is dense and fast
- Increase light yield:
  - improved PWO II
  - operation at -25°C
- Challenges:
  - temperature stable to 0.1°C
  - control radiation damage
  - low noise electronics
- Delivery of crystals started

Forward Endcap
- 4000 PWO crystals
- High occupancy in center
- LAAPD readout



Barrel Calorimeter
- 11000 PWO Crystals
- LAAPD readout, 2 x 1cm^2
- $\sigma(E)/E \sim 1.5\%/\sqrt{E}$ + const.

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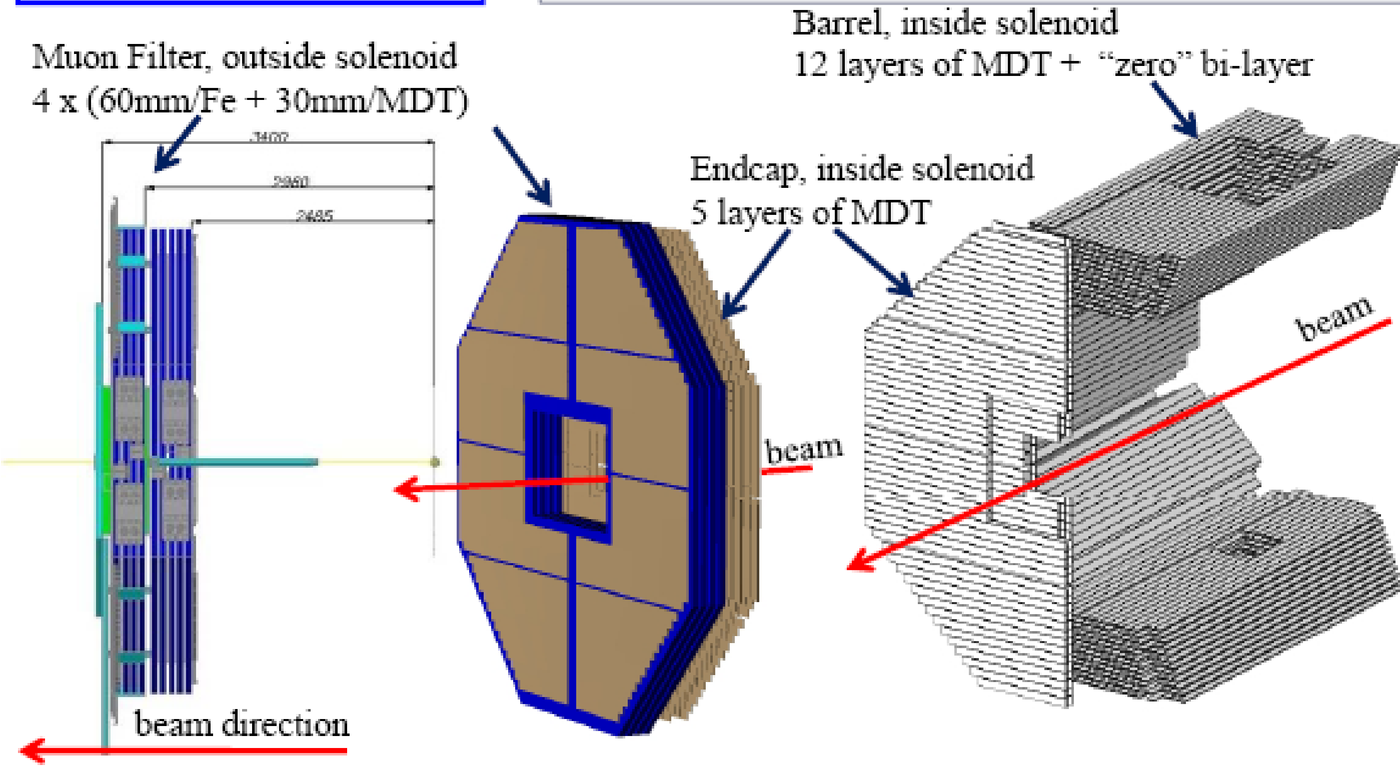
Muon detectors

Proportional tubes : anode signal and induction signal on 1 cm strips

Outside the solenoid
"Muon Filter", 4 layers

Inside the solenoid
Barrel: 12 layers inside the yoke + 1 bi-layer ("zero" bi-layer) in before iron
Endcap: 5 layers + "zero" bi-layer before iron

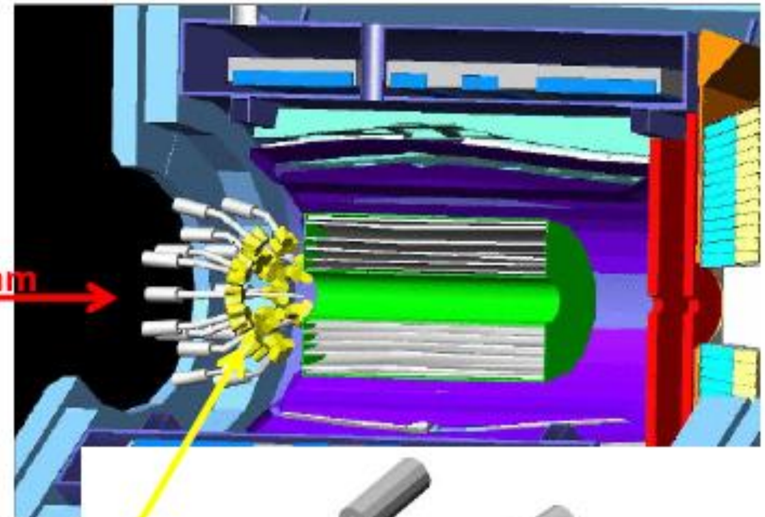


Hypernuclear detector

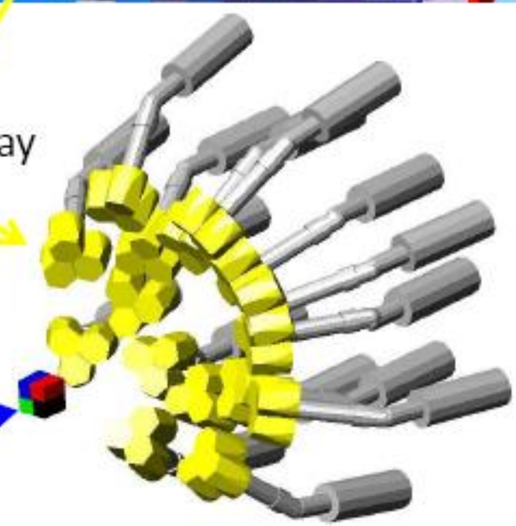
Hypernuclear Detector

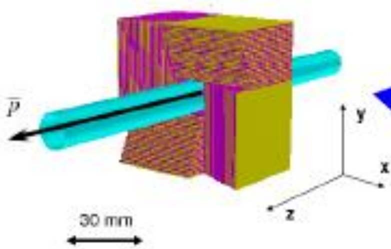
- Active silicon target to produce and stop the $\Xi\bar{\Xi}$ pair and detect the hypenuclei decay products
- Germanium γ array detector, with 15 clusters of 3 gemanium

- Forseen 2 KeV γ enery resolution, 1.3 MeV π energy resolution



Germanium array





active target

DAQ/Trigger

DAQ

- no hardware trigger, continuous data taking ;
- flexibility required to select different physics channels;
- average interaction rate $2x10^7$;
- average required bandwidth 120 – 140 GB/s;
- signals detected autonomously by each sub-detector and preprocessed, time stamp is associated to each hit bunch;
- data concentrators receive hits from subdetectors, provide point-to-point communication via optical links, buffering and online manipulation ;
- programmable computing nodes (FPGA, Digital Signal Processors) perform data feature extraction, association of data fragments to events, event selection;
- necessary a precise time distribution system (SODA).

G.Boca GSI, Germany & U. Pavia, Italy

Timescale of PANDA