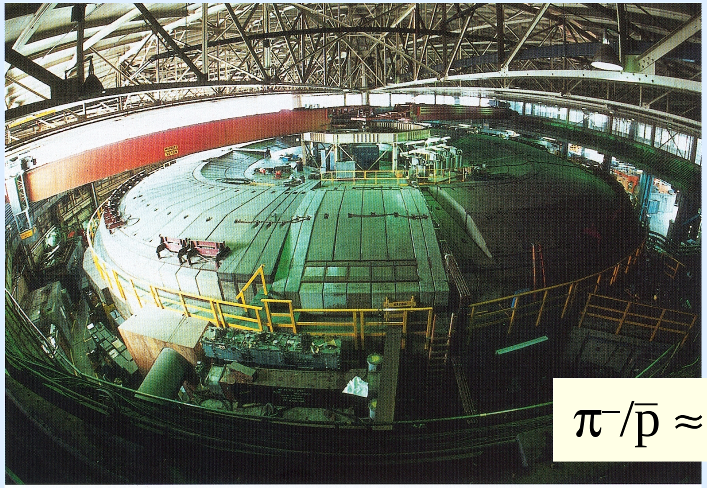
Hadron Spectroscopy with Antiprotons

- Historical Overview
- Spetroscopy with antiproton beams
  - Conventional beams
  - LEAR-era (Fixed $\bar{p}$-energy)
  - Fermilab/ISR-experiments ($\bar{p}$ scan)
- Future Project
  - PANDA @ FAIR/GSI
- Conclusions

Historical Overview (1)

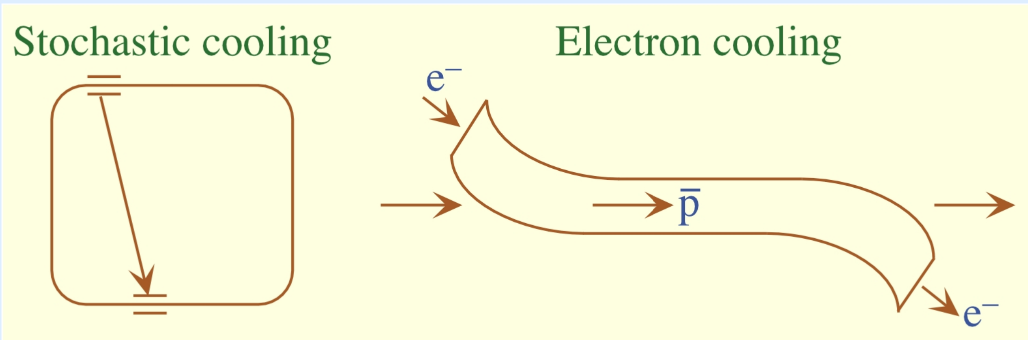
- Detection of Antiprotons/Antineutrons
  1955: Bevalac (p @ 6.2GeV), Cu- target



$\pi^-/\bar{p} \approx 50000$

- Conventional $\bar{p}$-beams
  1956-1981: BNL, Argonne CERN, Serpukhov, KEK, ...

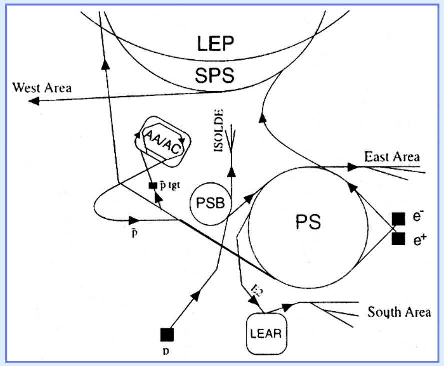
- Cooling of Antiprotons (1981/2)
  ICE, AA-rings @ CERN

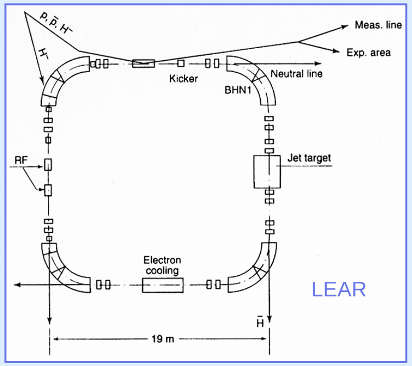


↳ Acceleration/Deceleration/Storage of antiprotons; Pure antiproton beams

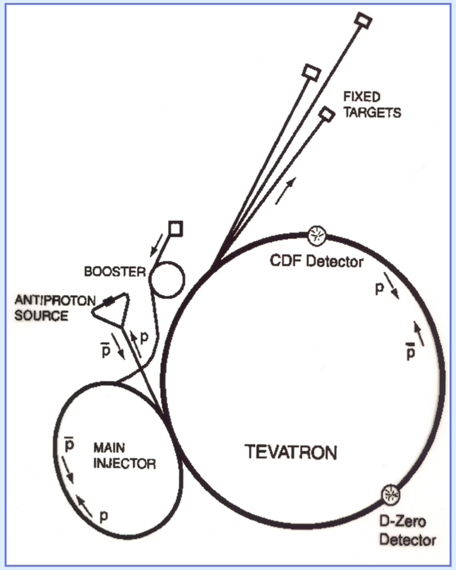
Historical Overview (2)

- SPSC/LEAR @ CERN
  1981-1996

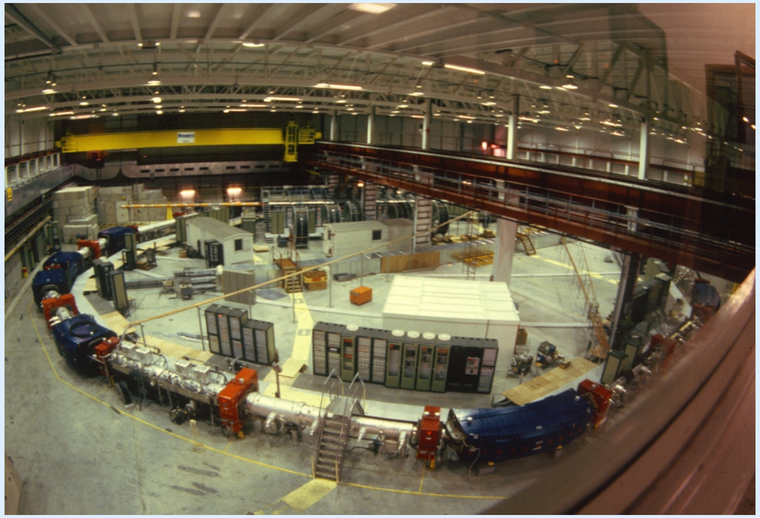




- Fermilab (Antiproton Source) / ISR @ CERN
  1986-2002 1981/83



- AD @ CERN
  2001-today

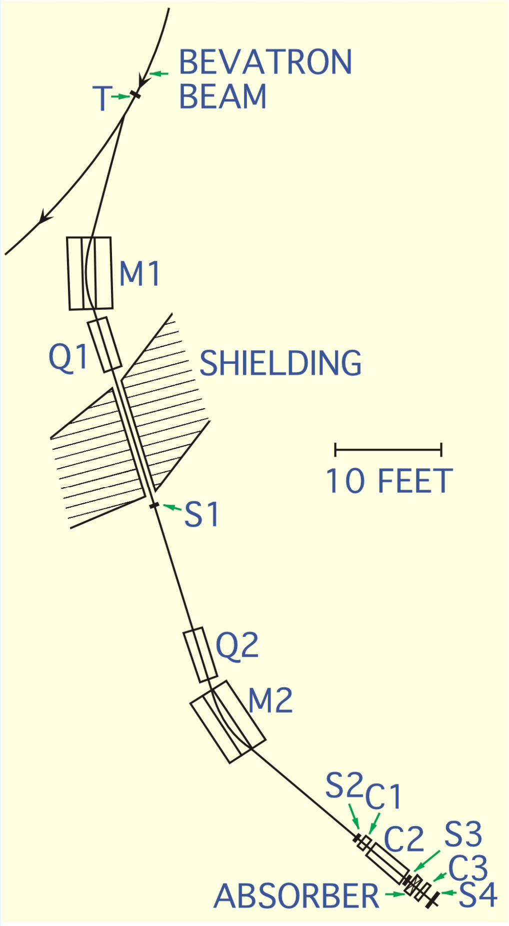


Only low energy antiprotons; Pulsed beam (low d.c.)

Spectroscopy with Antiproton Beams (1)

I) Conventional Beams

Typical example: Bevalac



Bevalac: $\pi^-/\bar{p} \approx 50000$

In general:

Large contaminations (π^-, K^-, ...)

Ill defined energy

Particle separators

Discovery of new mesons: ω(782), f_1(1285), E/η(1440)

Many properties (masses, q.-n., magn. mom., BR's) of already known mesons

Detectors: BC, Electronic detectors

Spectroscopy with Antiproton Beams (2)

II) LEAR era

$5 \leq E_{\bar{p}} \leq 1940 \mathrm{MeV}$
$N_{\bar{p}} \leq 10^6/\mathrm{s}$
Small beam spot
Small $\Delta p/p$

Typical reactions

$\bar{p}p \to \rho\pi^0 \quad \to (\pi^+\pi^-)\pi^0 \quad \to \pi^+\pi^-2\gamma$

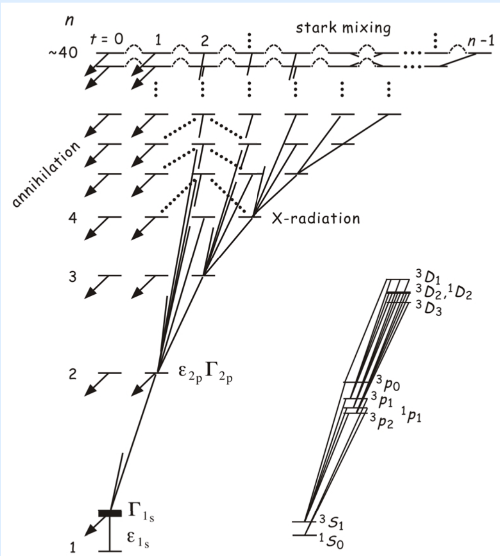
$\bar{p}p \to \omega\eta \quad \to (\pi^+\pi^-\pi^0)(\gamma\gamma) \quad \to \pi^+\pi^-4\gamma$

$\quad \to (\pi^+\pi^-\pi^0)(\pi^0\pi^0\pi^0) \to \pi^+\pi^-8\gamma$

$\bar{p}p \to f_0(1500)\pi^0 \to (\pi^0\pi^0)\pi^0 \quad \to 6\gamma$

Experiments with stopped antiprotons

Initial states = $\bar{p}p$-atom states



Few initial states ($^3S_1$, $^1S_0$, P-States)
Facilitates PWA
Population of states dependent on H_2-gas pressure (Day, Snow, Sucher)
Limitation: M(resonances) ≤ 1.6GeV

Experiments with $\bar{p}$'s in flight

Initial states = scattering states
More initial states
More involved PWA
(Tricks: Measure near threshold)
No limitation of M(resonances)

Spectroscopy with Antiproton Beams (3)

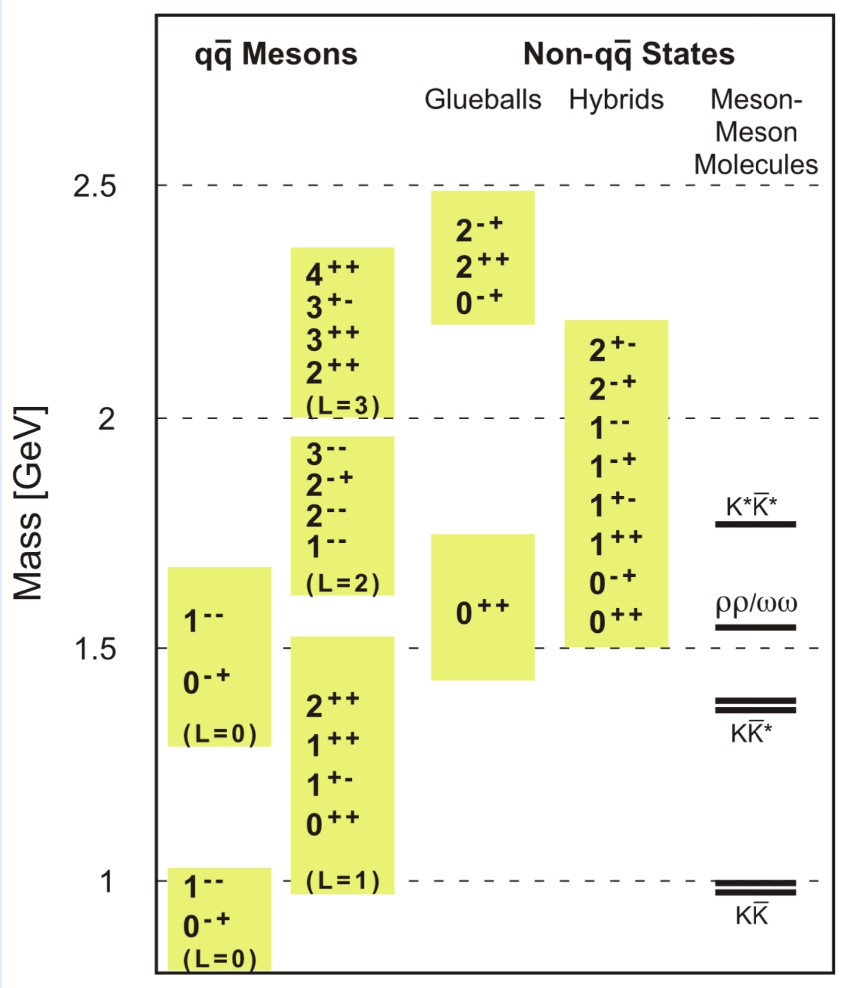
Situation in light quark spectroscopy

L = 0

J^{PC}	n	I = 1	I = 0	I = 0	I = 1/2
1^{--}	n = 2	ρ 1450	ω 1420	Φ 1680	K* 1410
0^{-+}	n = 2	π 1300	η 1295	η' (η(1400), η(1460))	K 1460
1^{--}	n = 1	ρ 770	ω 782	Φ 1020	K* 892
0^{-+}	n = 1	π 139	η 548	η' 958	K 494

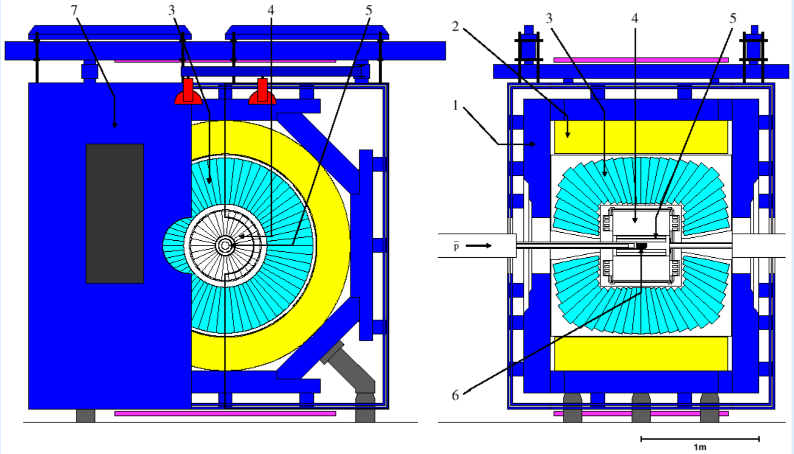
L = 1

J^{PC}				
2^{++}	a_2 1320	f_2 1270	f'_2 1525	K^*_2 1430
1^{++}	a_1 1260	f_1 1285	f'_1 1510	K_{1A}
1^{+-}	b_1 1235	h_1 1170	h'_1 1380	K_{1B}
0^{++}	a_0 ($a_0(980)$, $a_0(1450)$)	f_0 ($f_0(1370)$, $f_0(1500)$)	f_0 ($f_0(980)$, $f_0(1710)$)	K^*_0 1430

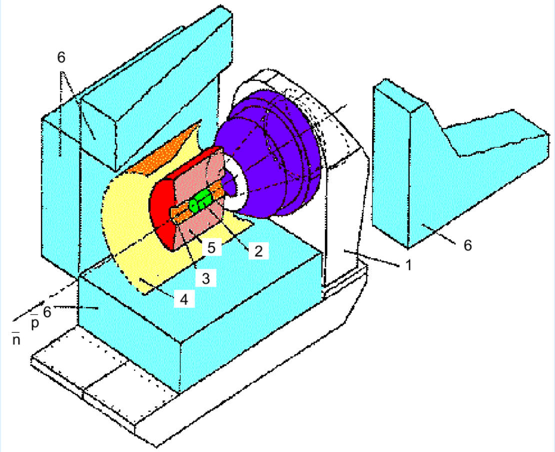


Spectroscopy with Antiproton Beams (4)

Crystal Barrel Detector (CB)



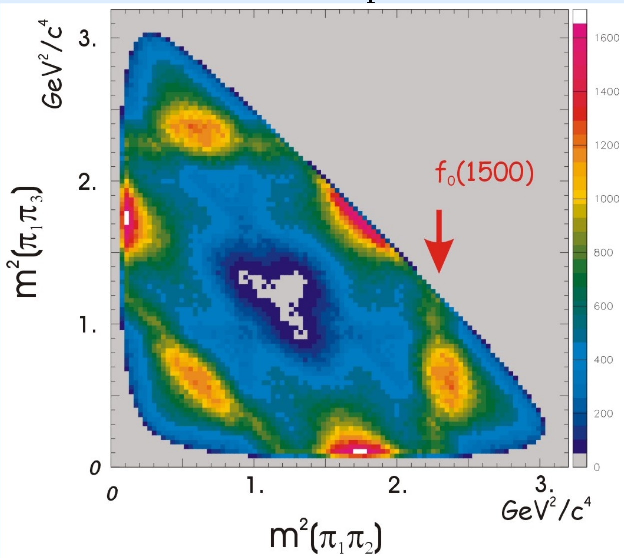
Obelix Detector (OX)



General remark: Nearly all known resonances clearly seen in data

Selected results:

Dalitz plot of $\bar{p}_{Stop}p \rightarrow 3\pi^0$ (CB)



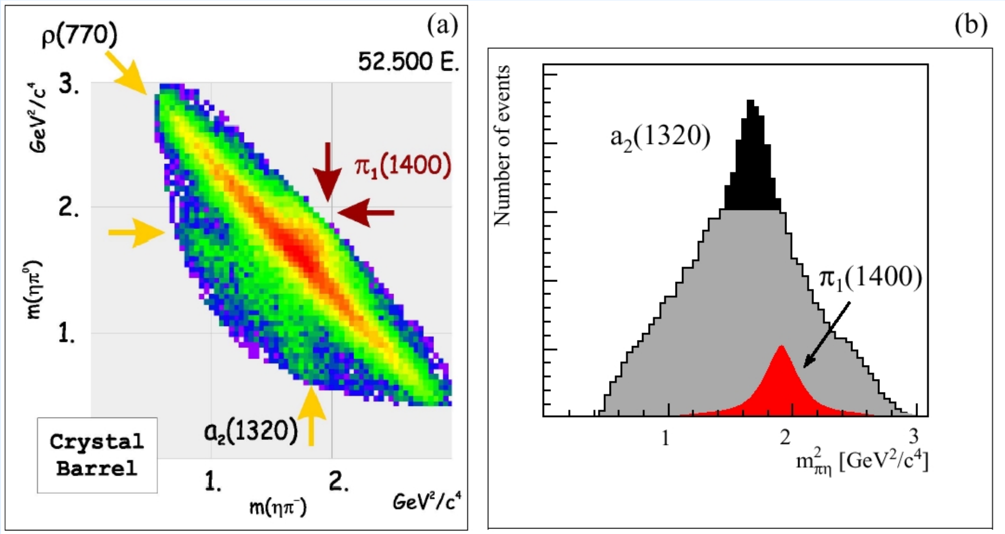
712000 events

$f_0(1500)$ firstly seen, Glueball ground state?

Spectroscopy with Antiproton Beams (5)

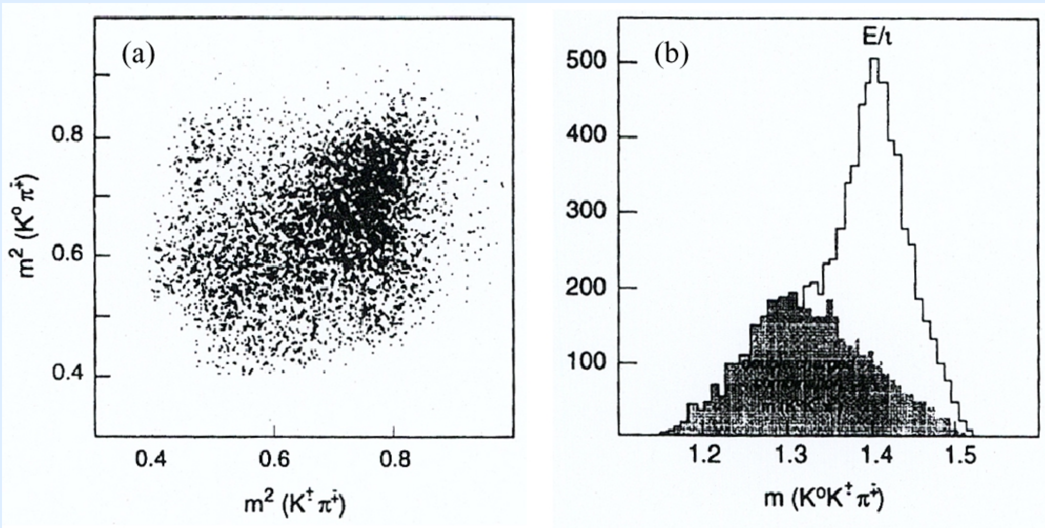
Dalitz plot of $\bar{p}_{Stop}n \rightarrow \pi^0\eta\pi^-$ (CB)

52000 events



Clear confirmation
of spin exotic state ($J^{PC} = 1^{-+}$!)
Not allowed for $q\bar{q}$-systems

Dalitz plot and invariant mass spectrum of $\bar{p}_{Stop}p \rightarrow \pi^+\pi^-K^0K^\pm\pi^\mp$ (OX)



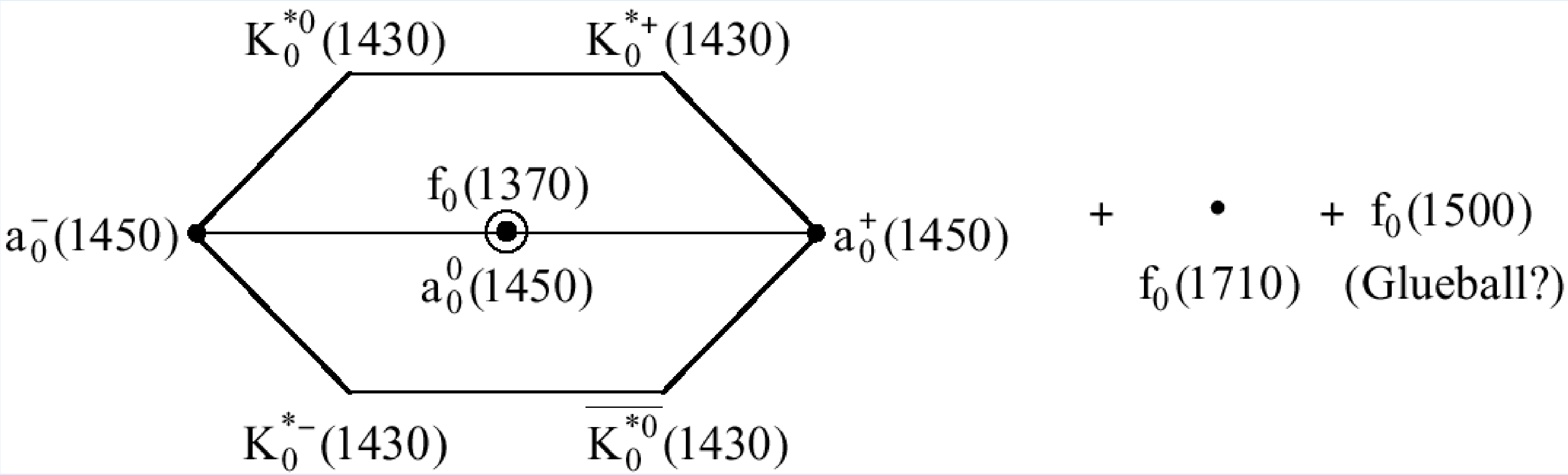
Clear confirmation of E/i(1440)
Glueball state?

Spectroscopy with Antiproton Beams (6)

Discussion of the $J^{PC} = 0^{++}$ nonet

Nine open slots, but twelve candidates

Possible scenario:



$a_0(980)$, $f_0(980)$: 4 quark states

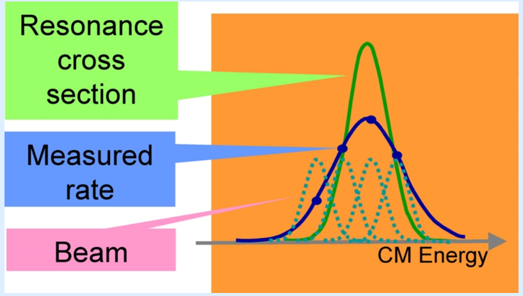
Spectroscopy with Antiproton Beams (7)

Direct production of all $c\bar{c}$-states:

$\bar{p}p \rightarrow (c\bar{c}) \rightarrow e^+e^-, \gamma\gamma$, hadrons (e⁺e⁻: only $J^{PC} = 1^{--}$ $c\bar{c}$-states)

High mass resolution:

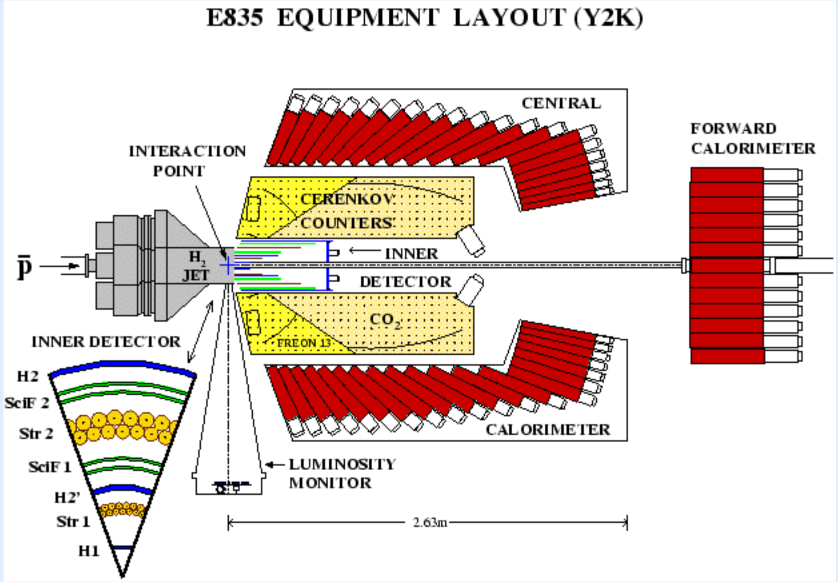
Only determined by energy spread of $\bar{p}$-beam, not by detection of decay particles



Mass resolution ≈ 240keV

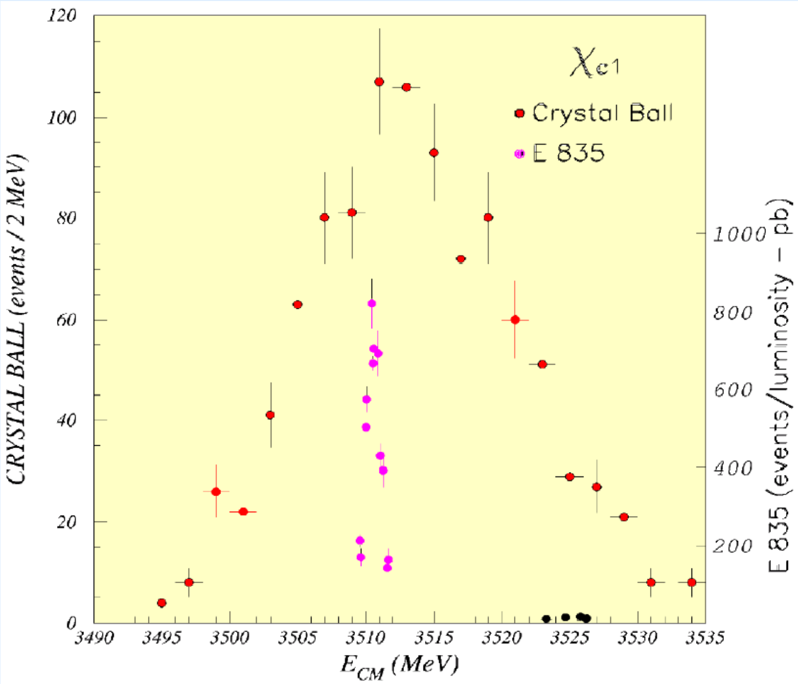
First survey experiments: R704 (ISR); E760/835 (Fermilab)

(No 4π-detector;
only parasitic running)



Spectroscopy with Antiproton Beams (8)

Selected results

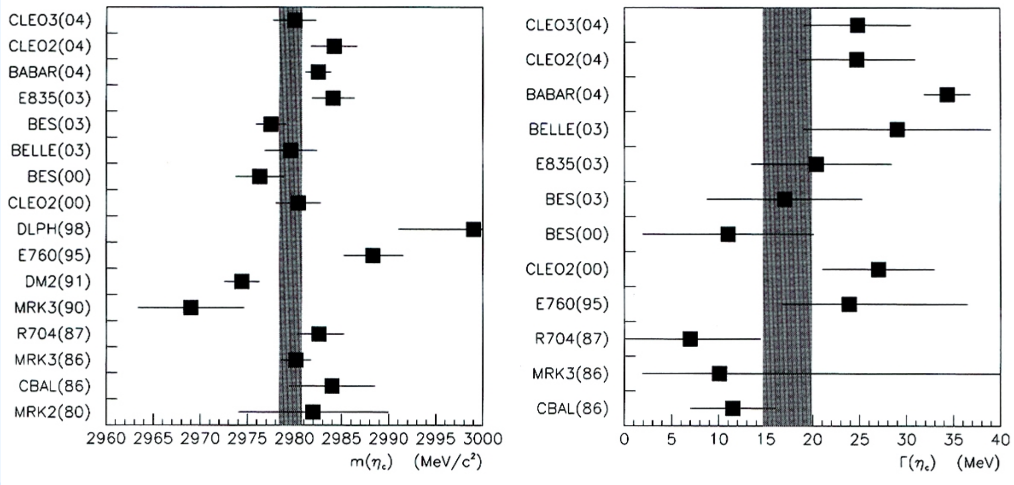


χ_{c1}-signals in Crystal Ball (e^+e^-) and E835 ($\bar{p}p$)

World averages of the masses and total widths of the χ_{cJ} states

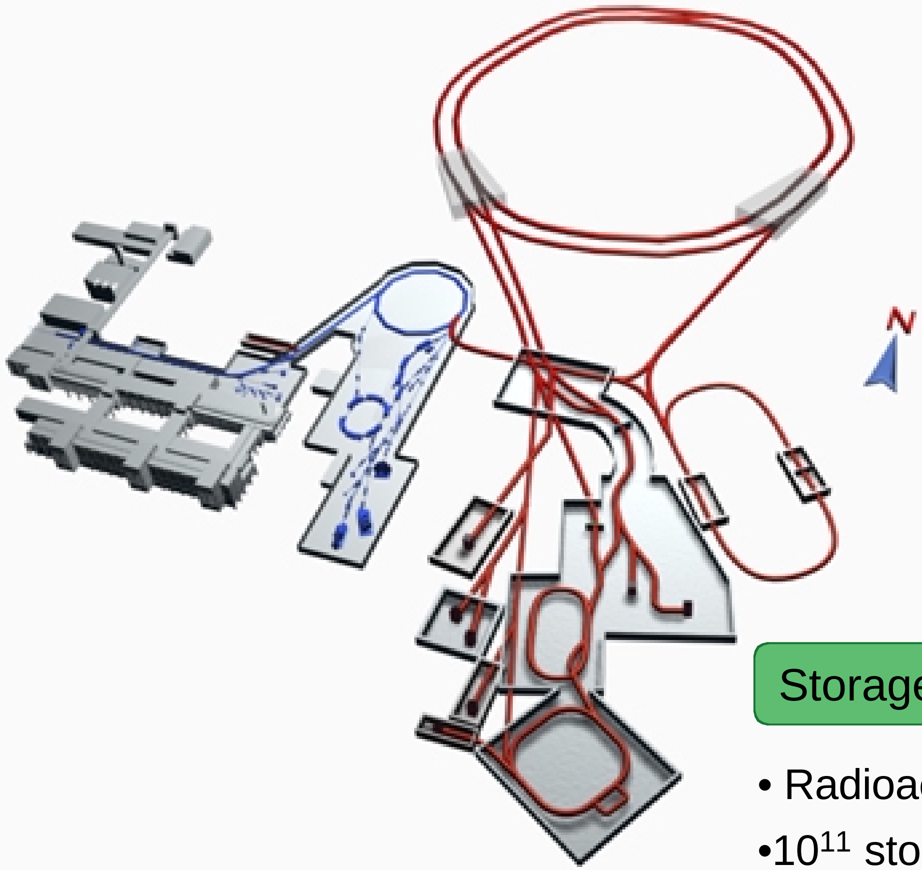
State	Mass (MeV/c^2)	Total width (MeV)
χ_{c0}	3415.19 ± 0.34	10.2 ± 0.9
χ_{c1}	3510.59 ± 0.10	0.88 ± 0.14
χ_{c2}	3456.26 ± 0.11	2.0 ± 0.18

η_c-mass and width



Future Perspectives (1)

FAIR-Project at GSI



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

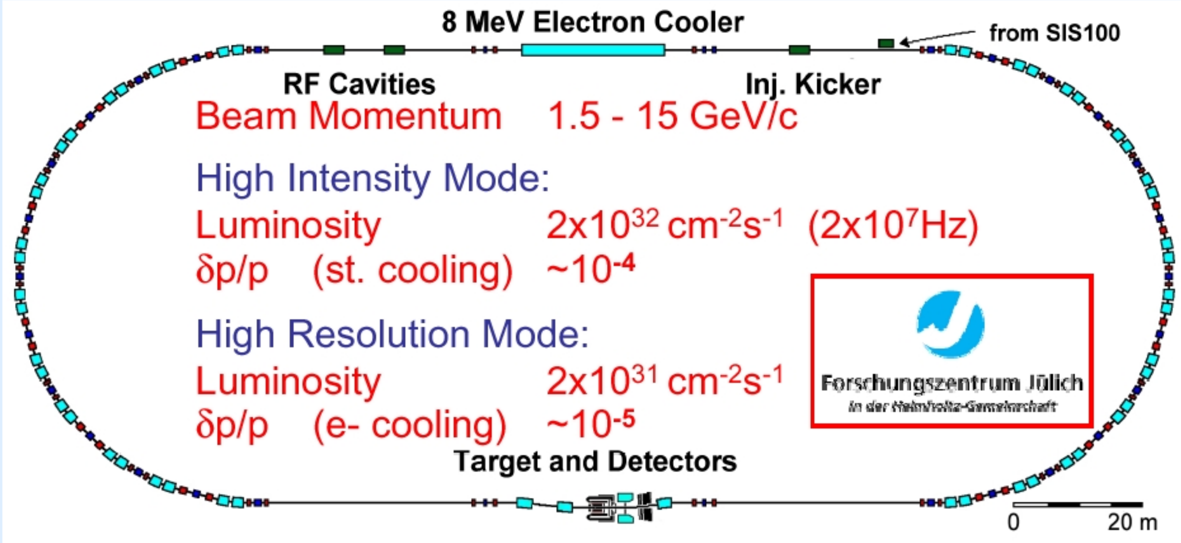
Storage and Cooler Rings

- Radioactive beams
- 10^{11} stored and cooled 1 - 15 GeV/c antiprotons

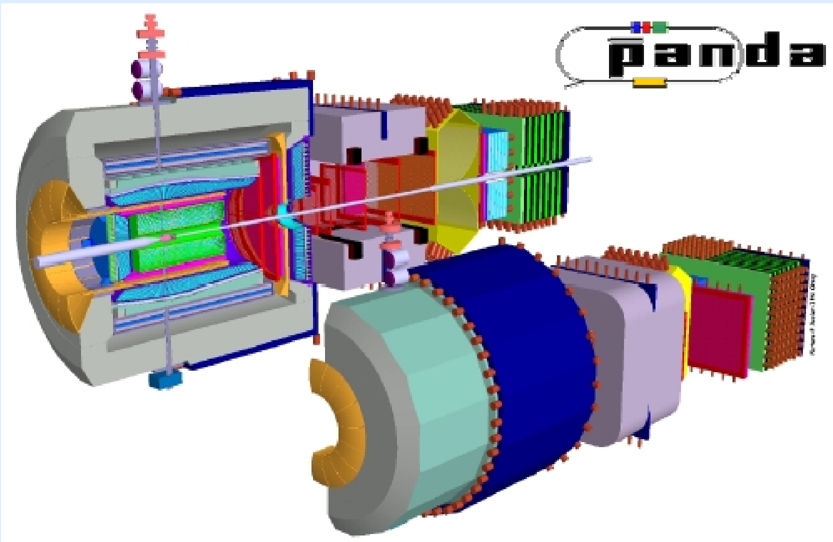
Future Perspectives (2)

Antiprotons at FAIR

HESR:



General Purpose Detector: PANDA



Formation: $\bar{p}$(scan)p → X → ...

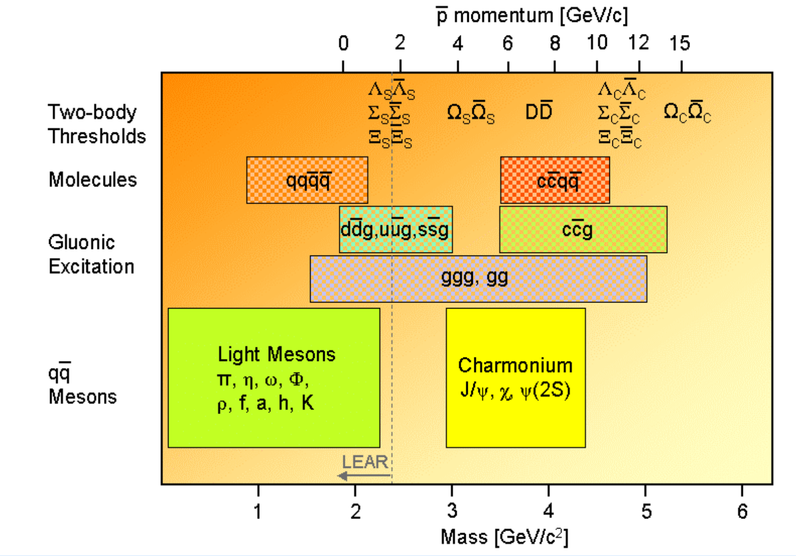
Production: $\bar{p}$(fixed)p → X + nπ + ...

PANDA-Collaboration:

370 scientists from 8 countries and 30 institutions

Future Perspectives (3)

QCD systems to be studied with PANDA



Rates

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

Final State	cross section	# reconstr. events/y
Meson resonance + anything	100µb	10^{10}
$\Lambda\bar{\Lambda}$	50µb	10^{10}
$\Xi\bar{\Xi}$ ($\rightarrow_{\Lambda\Lambda}$ A)	2µb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\rightarrow e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\rightarrow J/\psi + \gamma$)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

Common Feature : Low multiplicity events
Moderate particle energies

For Pairs : Charge symmetric conditions
Trigger on one, investigate the other

Future Perspectives (4)

Physics Program

Charmonium

Search for new states above D$\bar{D}$-threshold

Precision determination of masses and widths

(Extremly high masses resolution → 20keV)

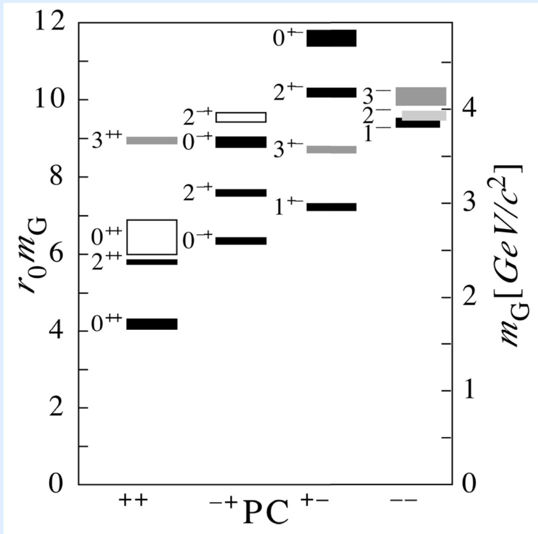
Production cross sections

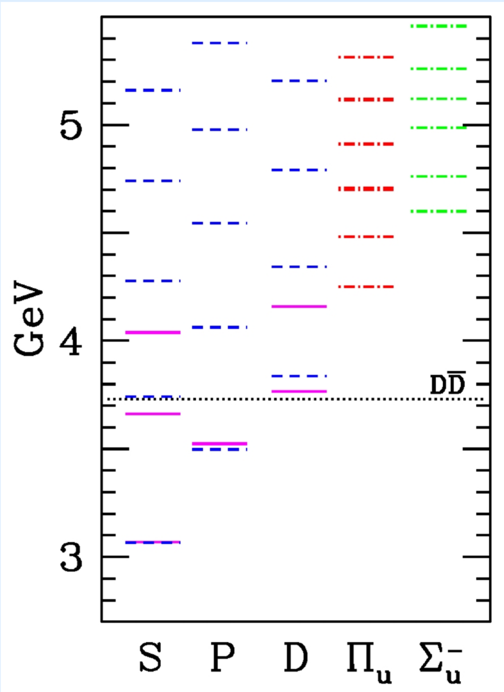
Decay branching ratios

Exotica

Glueballs, Charmed Hybrids, Multiquark states

Predictions for Glueballs





Prediction for Charmed Hybrids

Lowest energy states: 3.9 - 4.5GeV

Ground state: $J^{PC} = 1^{-+}$ (Spin exotic!)

Widths: Could by narrow in some cases (≈ MeV)

Future Perspectives (5)

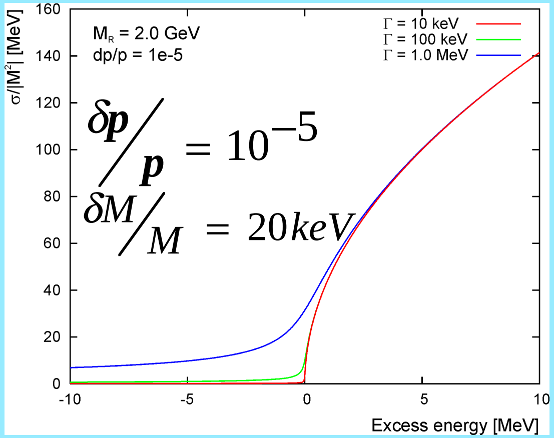
Open Charm Physics

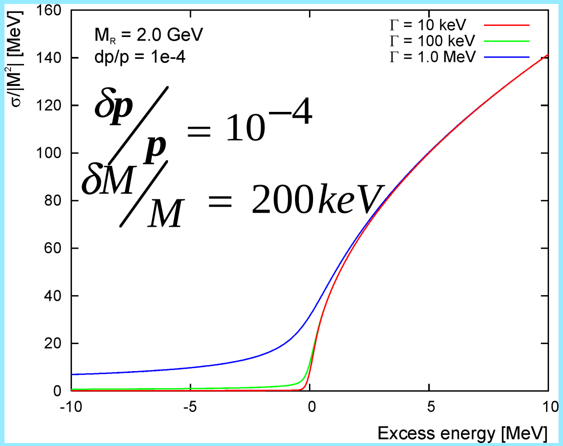
Widths of states

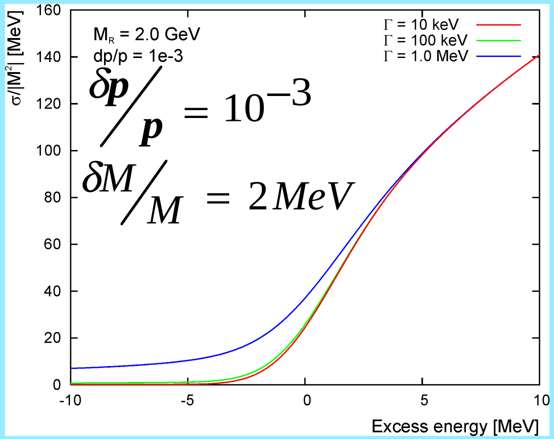
e.g.: $\bar{p}p \rightarrow D^*_{sJ}(2317)\ \overline{D^*_{sJ}(2317)}$

Depend on internal structure the width of D_{sJ}^* can be different:

- Current limit ~ 4.9 MeV
- χ-doubling ~ 10 keV
- Phenomenological ~ 130 keV
- D_sK – molecules ~ 200 keV

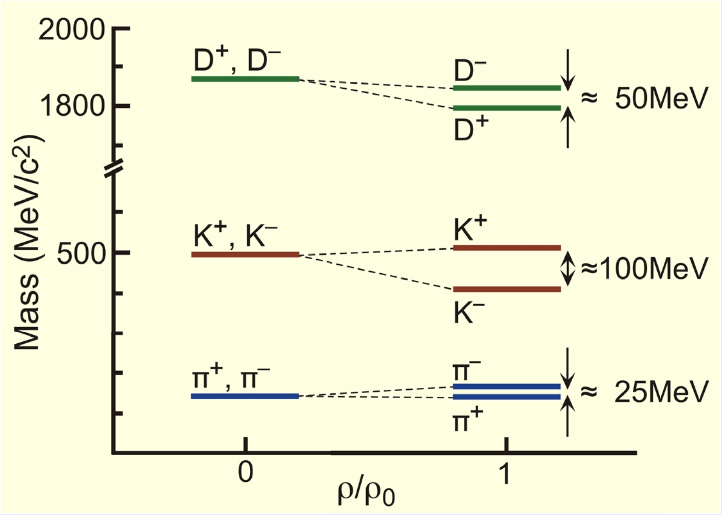






Future Perspectives (6)

Hadrons in matter



Hypernuclear Physics

$\bar{p}$(3GeV/c)p $\rightarrow$ Ξ^- (slow) $\overline{\Xi^-}$ (fast)

↳ Ξ^- p $\rightarrow$ $\Lambda\Lambda$ (inside nucleus)

Further Options

Baryon Spectroscopy

CP-Violation in D-decays

Deeply Virtual Compton Scattering (DVCS)

Proton FF in time-like region

Not discussed: Low energy $\bar{p}$-physics:
$\bar{H}$, Antiprotonic Atoms, $\bar{p}$ ^{4}He

Conclusions/Merits of Antiprotons for Spectroscopy

- All $q\bar{q}$-states can be formed directly (not only 1^{--})
  ↳ High mass resolution for all states

- $\bar{p}p$ cross sections high
  ↳ Data with high statistics

- High probability for production of exotic states
  Example: 1^{-+}-state in $p\bar{p}$-annihilation (LEAR)

- Low final state multiplicities
  ↳ Allows complete PWA