Hadron Physics with Antiprotons

– Introduction

– HESR/PANDA - Project at GSI (→ W. Henning)

– Merits of experiments with antiprotons

– Physics Program

    Charmonium Spectroscopy (→ D. Bettoni)

    Heavier Glueballs and charmed Hybrids (→ K. Peters)

    Hadrons in Nuclear Matter (→ W. Henning)

    Double Hypernuclei (→ J. Pochodzalla)

    Further Options:

    Low energy beams, Open Charm production, CP-Violation, Inverted Deeply Virtual Compton Scattering (→ P. Kienle, Poster H. Koch, S. Ganzhur)

– Status of the Project

– Conclusions

Introduction

Open problems in non-perturbative QCD

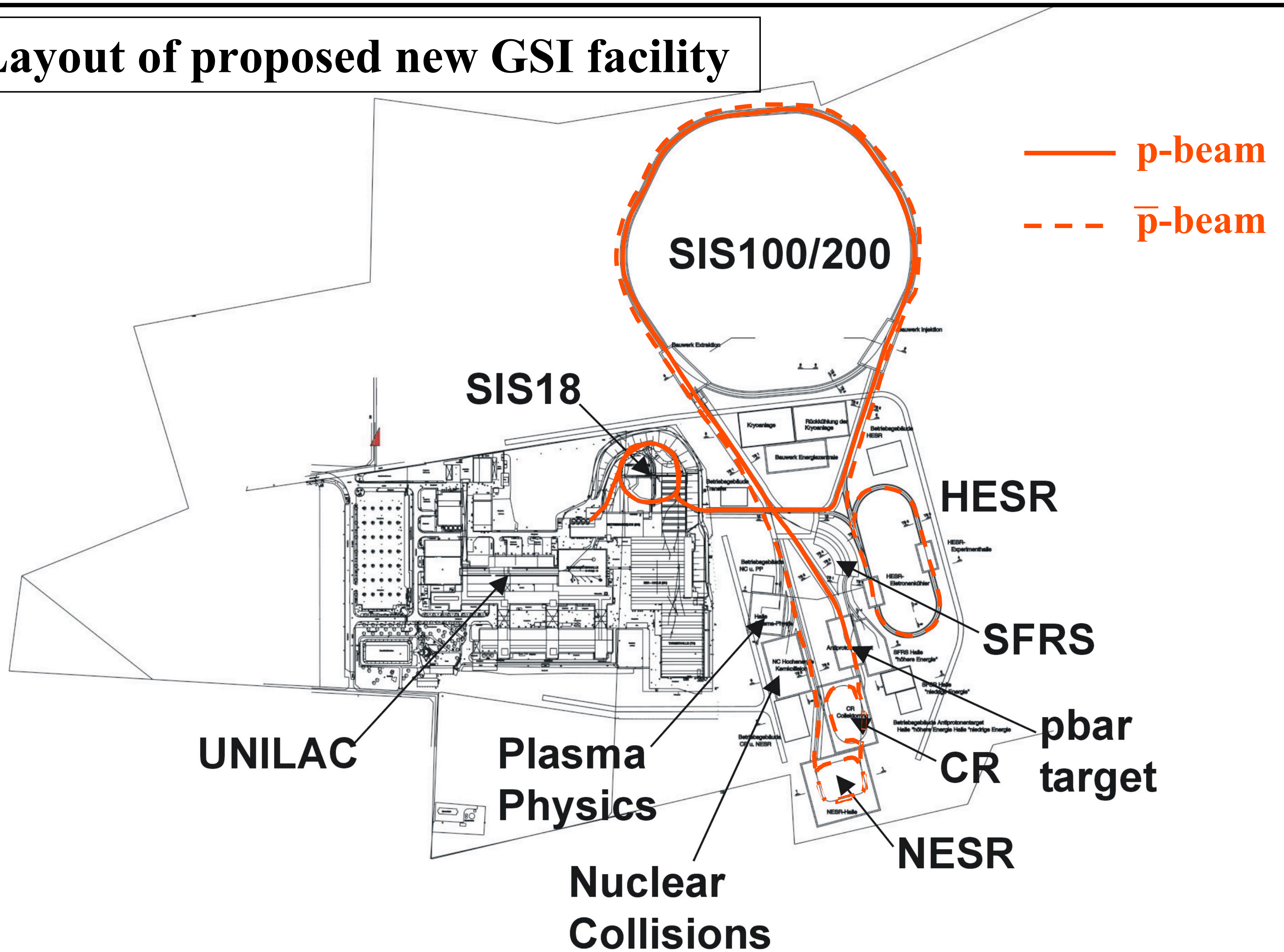
Confinement

Violation of chiral symmetry

Masses of Hadrons

Important : Gluonic degrees of freedom

Layout of proposed new GSI facility



HESR (High Energy Storage Ring)

$\bar{p}$ production with 29 GeV p-beam

$\bar{p}$ production rate : 10^7/s

$\bar{p}$-stored in the HESR, Fixed Target ($E_{CM} \leq 5.5$ GeV)

$\bar{p}$-momentum : 1.5-15 GeV/c

$N_{\bar{p}\text{-stored}}$: $5 \bullet 10^{10}$

<u>High luminosity mode</u>

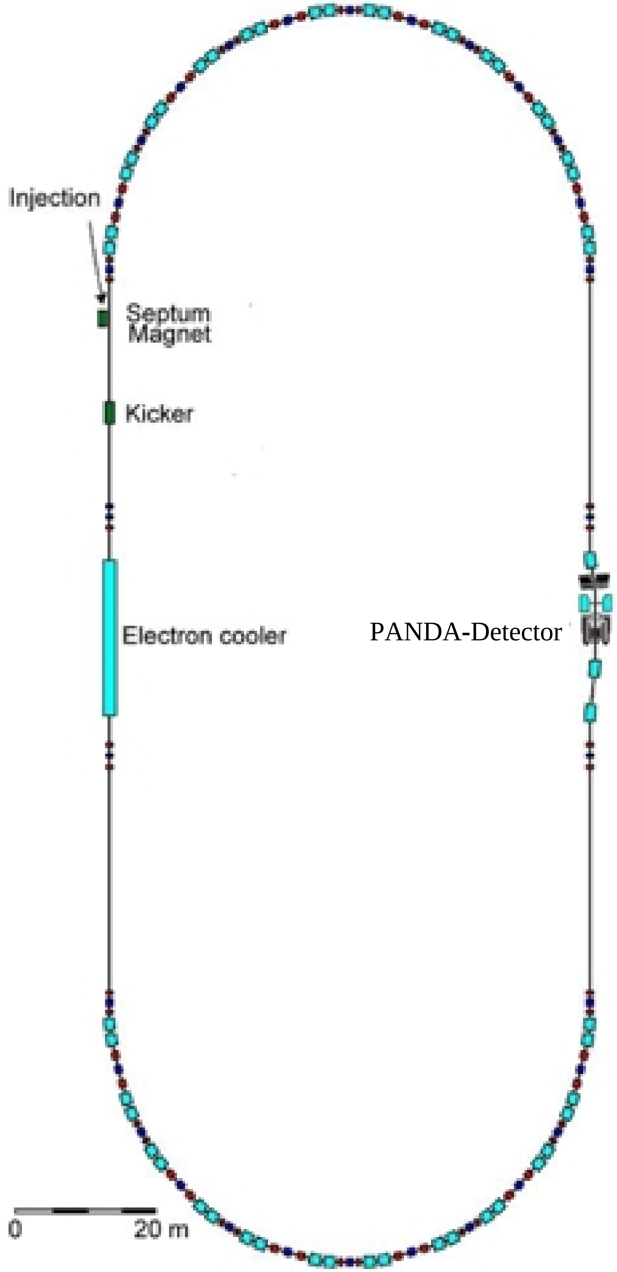
$L \approx 2 \bullet 10^{32}$ cm^{-2}s^{-1}

$\delta p/p \approx 10^{-4}$ (stochastic cooling)

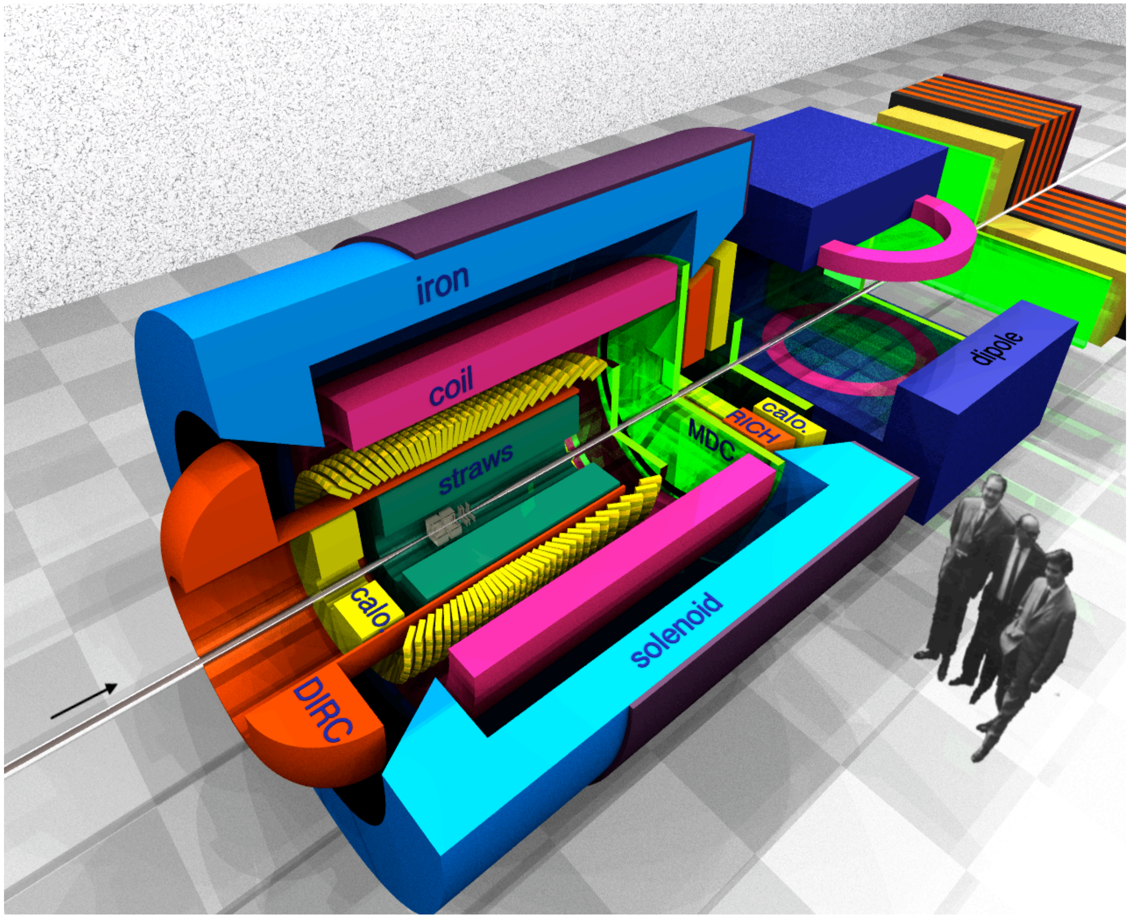
<u>High resolution mode</u>

$L \approx 10^{31}$ cm^{-2}s^{-1}

$\delta p/p \approx 10^{-5}$ (e^-- cooling)



The PANDA detector



Detector features:

- tracking of charged particles
- measurement and identification of γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
- high rate capability
- sophisticated and fast trigger scheme

PANDA – Detector

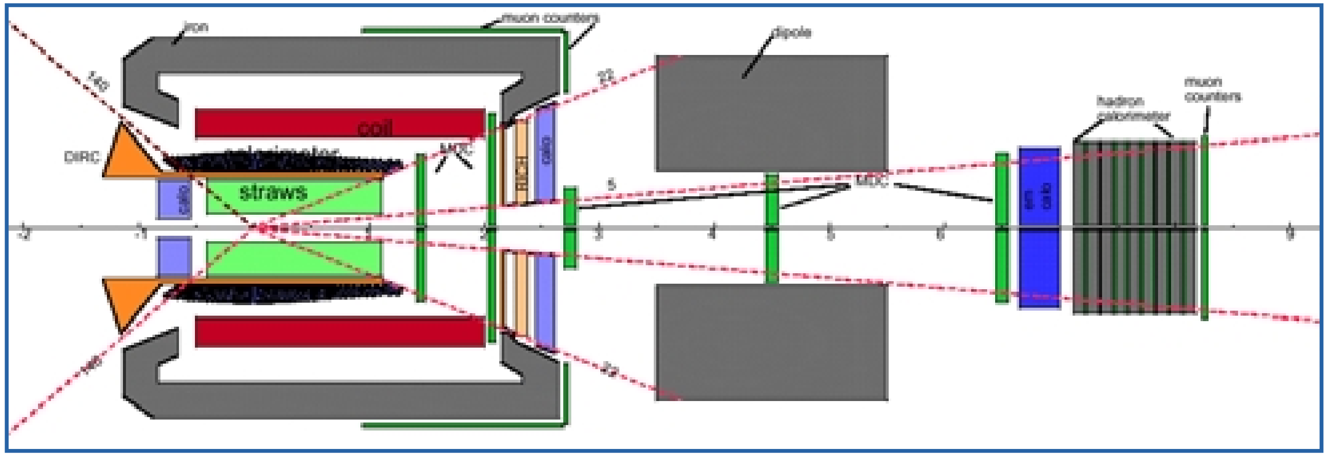
Detector requests

– Nearly full solid angle for charged particles and Gammas

– High rate capability

– Good particle identification (e, μ, π, K, p)

– Efficient trigger on e, μ, K, D



General purpose detector

– Target: Jet/Pellet/Wire

– Tracking: Pixels (MVD) / Straws / Mini-Drift-Chambers (MDC)

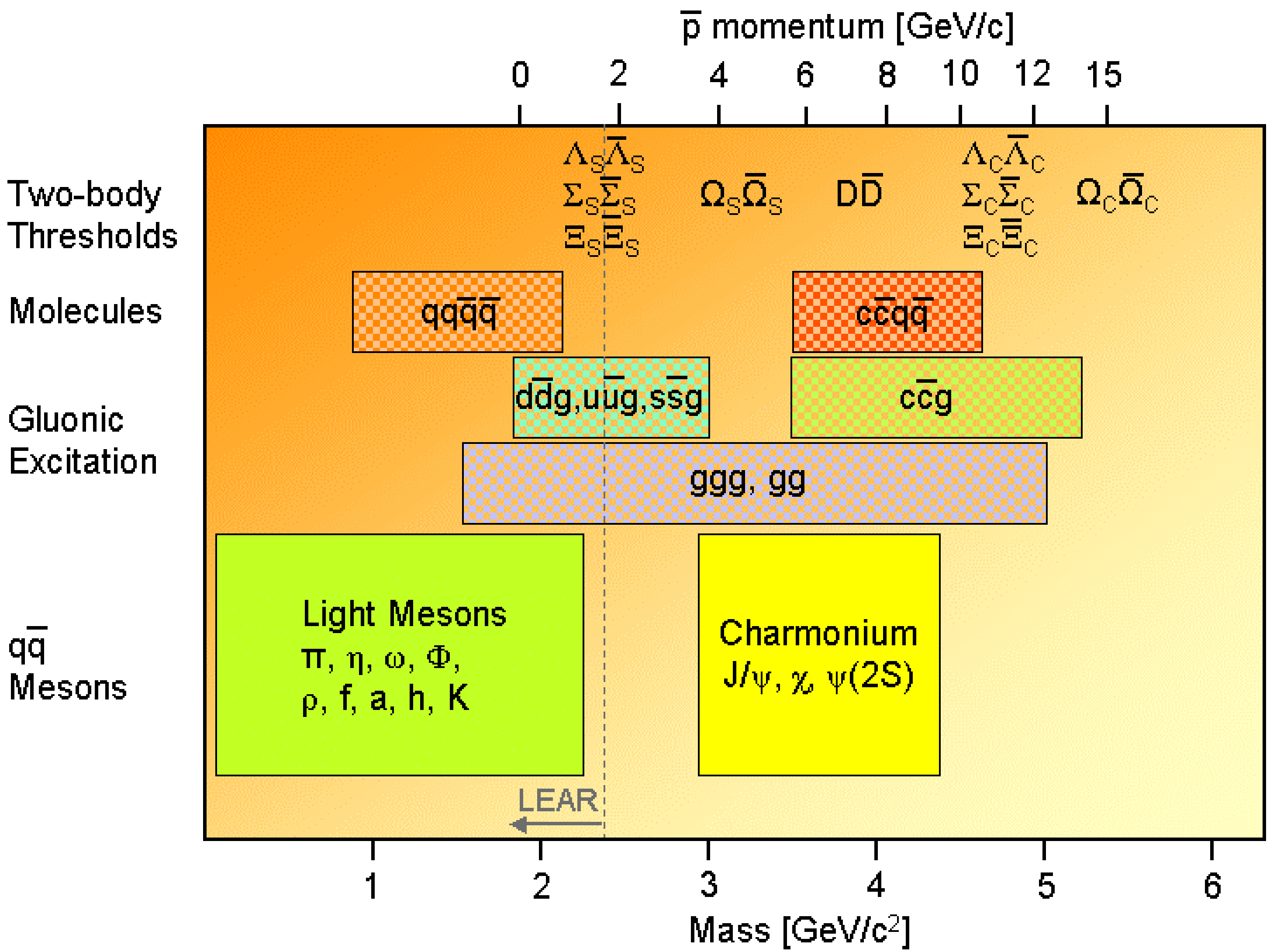
– E.M. Calorimeter: $PbWO_4$, APD-Readout

– Muons: Plastic Scint. Strips

– PID: Aerogel Cerenkov (ACC) / DIRC

– Trigger: High $p_\perp$ electrons/muons / Multiplicity jump (K^0_S, Λ, …)
Secondary vertex (D's,…) / Invariant masses / Global kinematical conditions

QCD systems to be studied at HESR



Review of Particle Physics 2000

$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I = 1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I = 0$	$\bar{s}u$, $\bar{s}d$ $I = 1/2$
$1\ ^1S_0$	0^{-+}	π	η, η'	**K**
$1\ ^3S_1$	1^{--}	ρ	ω, ϕ	**K*(892)**
$1\ ^1P_1$	1^{+-}	**b_1(1235)**	**h_1(1170)**, h_1(1380)	**K_{1B}**†
$1\ ^3P_0$	0^{++}	**a_0(1450)***	**f_0(1370)***, **f_0(1710)***	**K_0*(1430)**
$1\ ^3P_1$	1^{++}	**a_1(1260)**	**f_1(1285)**, **f_1(1420)**	**K_{1A}**†
$1\ ^3P_2$	2^{++}	**a_2(1320)**	**f_2(1270)**, **f_2'(1525)**	**K_2*(1430)**
$1\ ^1D_2$	2^{-+}	**π_2(1670)**	η_2(1645), η_2(1870)	**K_2(1770)**
$1\ ^3D_1$	1^{--}	**ρ(1700)**	**ω(1650)**	**K*(1680)**‡
$1\ ^3D_2$	2^{--}			**K_2(1820)**
$1\ ^3D_3$	3^{--}	**ρ_3(1690)**	**ω_3(1670)**, **ϕ_3(1850)**	K_3*(1780)
$1\ ^3F_4$	4^{++}	**a_4(2040)**	**f_4(2050)**, f_4(2220)	**K_4*(2045)**
$2\ ^1S_0$	0^{-+}	**π(1300)**	**η(1295)**, **η(1440)**	K(1460)
$2\ ^3S_1$	1^{--}	**ρ(1450)**	**ω(1420)**, **ϕ(1680)**	**K*(1410)**‡
$2\ ^3P_2$	2^{++}		f_2(1810), **f_2(2010)**	K_2*(1980)
$3\ ^1S_0$	0^{-+}	**π(1800)**	η(1760)	K(1830)

[blue box] contributions from LEAR experiments

HESR / PANDA

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

Merits of experiments with Antiprotons

– High cross sections

↳Facilitates search for rare particles (Glueball Groundstate)

– Most particles can be directly created in formation processes regardless of their J^{PC} quantum numbers ($\bar{c}c$-spectroscopy)

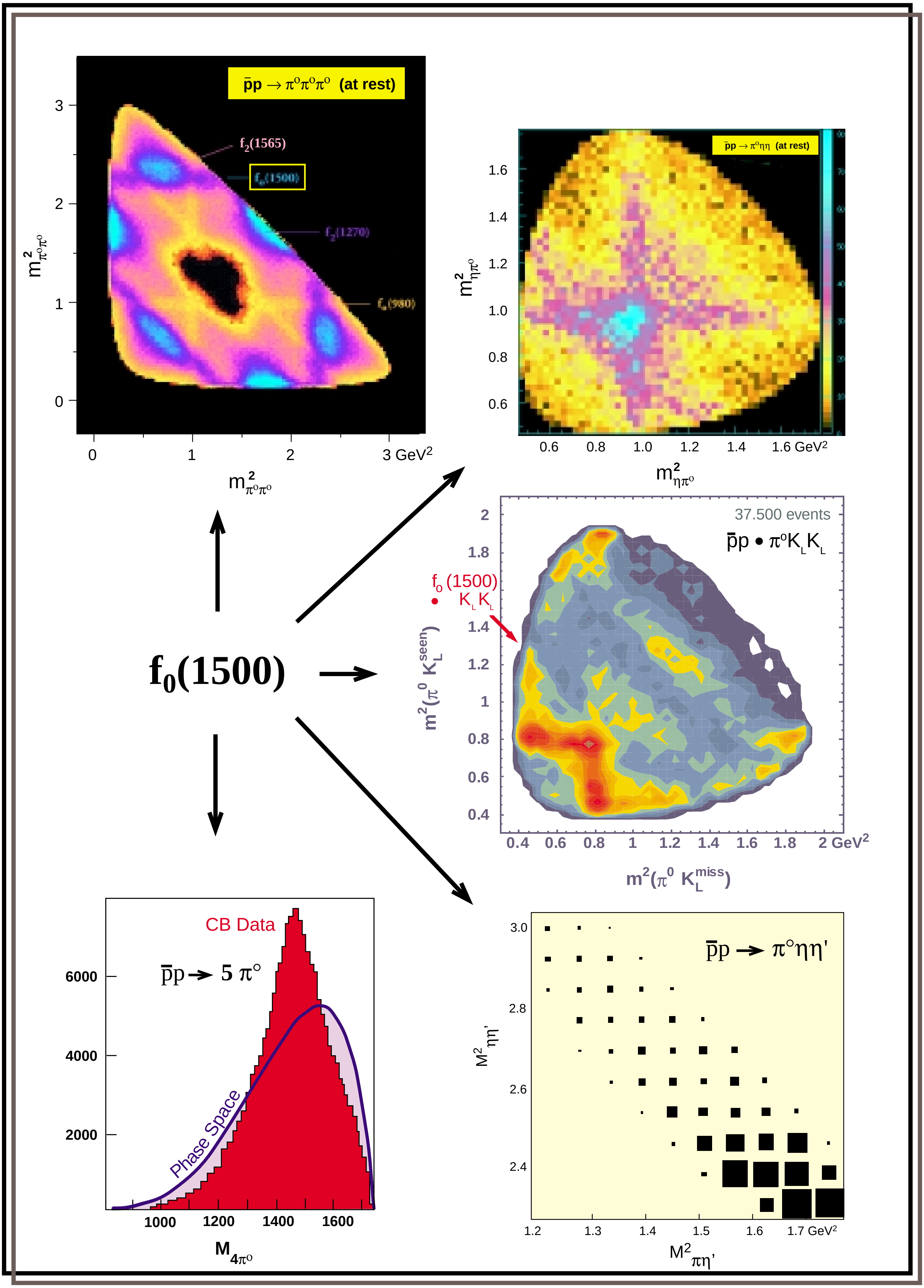
– Exotic states are produced with rates similar to $\bar{q}q$, qqq-systems (Glueball-, Hybrid candidates)

– (Cooled) beams have small $\Delta p/p$ and small emittances

↳Clean experimental conditions

– $\bar{p}$-induced reactions ($\leq$ 15 GeV) have low particle multiplities

↳Reconstruction of full events, Reliable PWA


p̄p → π°π°π° (at rest)
f2(1565)
f0(1500)
f2(1270)
f0(980)
m²π°π°
0
1
2
3 GeV²
p̄p → π°ηη (at rest)
m²ηπ°
0.6
0.8
1.0
1.2
1.4
1.6 GeV²
f0(1500)
37.500 events
p̄p • π°KLKL
f0 (1500) • KLKL
m²(π0 KL seen)
m²(π0 KL miss)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2 GeV²
CB Data
p̄p → 5 π°
Phase Space
6000
4000
2000
1000
1200
1400
1600
M4π°
p̄p → π°ηη'
M²ηη'
M²πη'
3.0
2.8
2.6
2.4
1.2
1.3
1.4
1.5
1.6
1.7 GeV²

Merits of experiments with Antiprotons

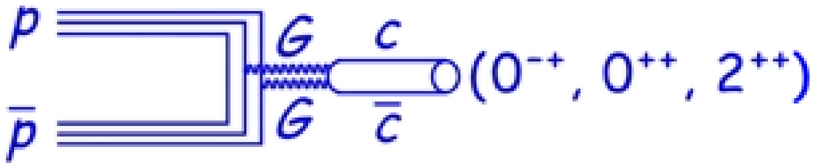
Charmonium - States

e^+e^-- collisions:

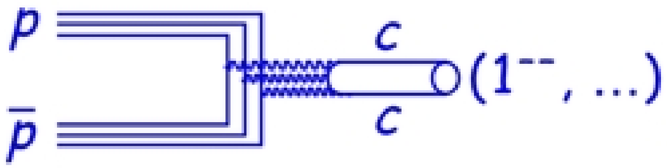
Only 1^{--} -states are directly formed
(Well measured, $e^- e^+$ energy scans)
The other states only visible through
secondary reactions,
e.g.: $e^+e^- \to \psi' \to \chi + \gamma$ (moderate mass resolution)

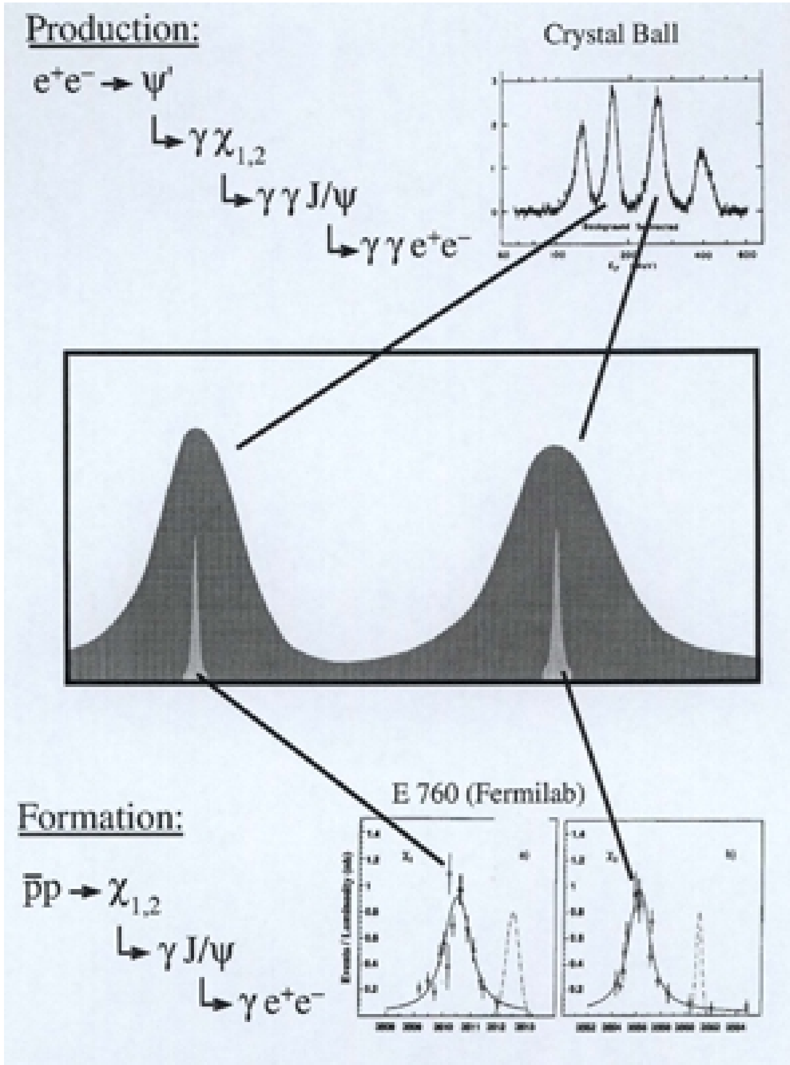
$p\bar{p}$ - collisions:

All states can be directly formed (Very good mass resolution, scans with $\bar{p}$)



or





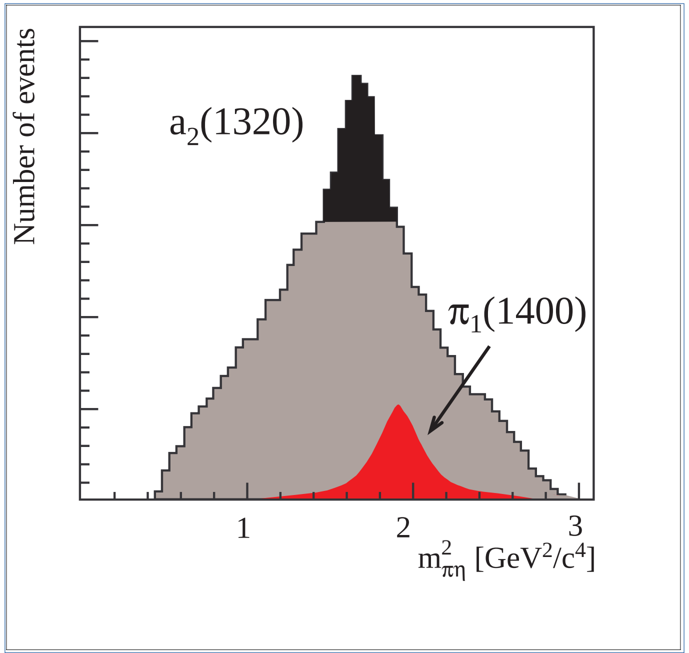
Merits of experiments with Antiprotons

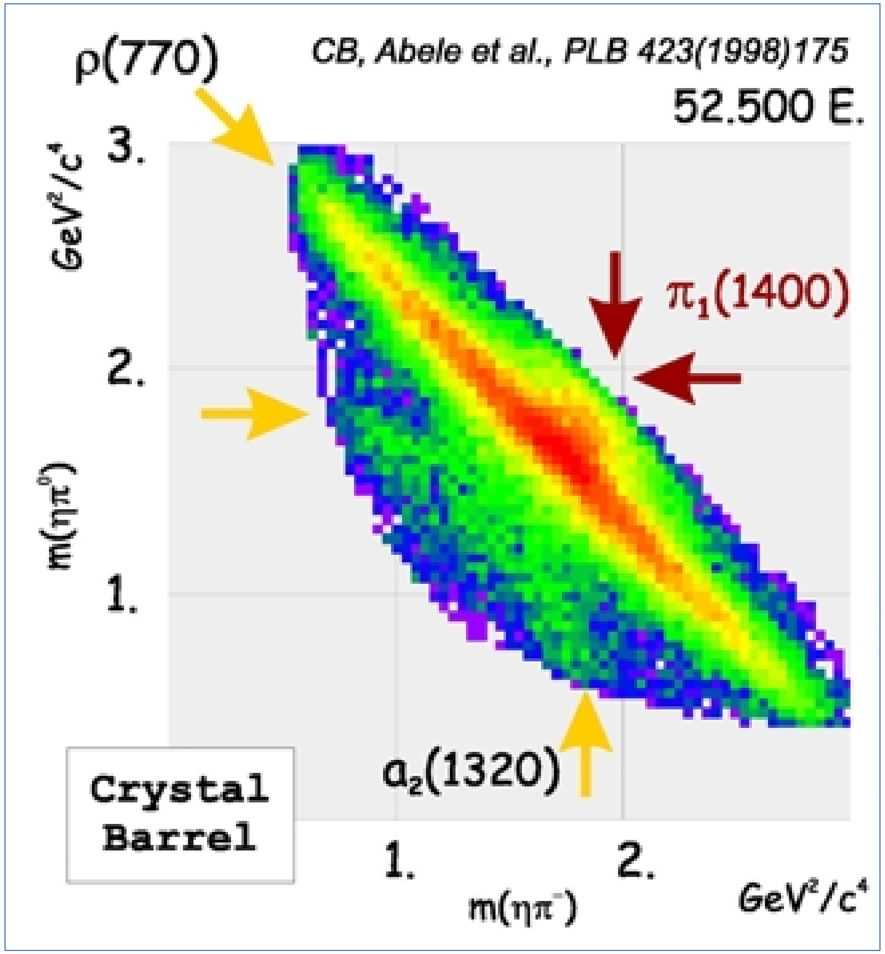
LEAR : Spin Exotics

$\bar{p}_{Stop}\, d \rightarrow X(1^{-+}) + \pi + p,\ X(1400) \rightarrow \eta\pi^0, \eta\pi^-;\ X(1600) \rightarrow \pi\eta'$ (Established by BNL; First hints: VES, GAMS)

General observations

- High Statistics data needed
- Exotics couple to $\bar{p}p$ with a strength similar to $q\bar{q}$-states





Properties of the $\hat{\rho}(1400)$

Decay: $(\eta\pi)_{L=1}$

Mass: 1400 ± 30 MeV

Width: 310 ± 70 MeV

Quantum Numbers: $J^{PC} = 1^{-+}$ (I =1)

not possible from $q\bar{q}$

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-)^{L+1}$$

$$C = (-)^{L+S}$$

Previous indications of this resonance:

$\pi^- p \rightarrow (\pi^\circ\eta)n$ (GAMS/CERN, 100 GeV/c, 1988)

$\pi^- p \rightarrow (\pi^\circ\eta)n$ (VES/Serpukhov, 100 GeV/c, 1993)

$\pi^- p \rightarrow (\pi^\circ\eta)n$ (E852/Brookhaven, 18 GeV/c, 1997)

M: 1300 – 1400 MeV, G: 150 – 400 MeV

A second exotic particle ($J^{PC}=1^{-+}$)

Crystal Barrel:

$$\bar{p}p \longrightarrow \pi^+\pi^-\eta'$$

$\pi_1(1600)$: $M = 1563 \pm 30$ MeV/c^2
$\Gamma = 195 \pm 50$ MeV/c^2

preliminary, LEAP2000 conference

BNL (E852):

$$\pi^- p \longrightarrow \rho\pi^- p$$

$\pi_1(1600)$: $M = 1593 \pm 8$ MeV/c^2
$\Gamma = 168 \pm 20$ MeV/c^2

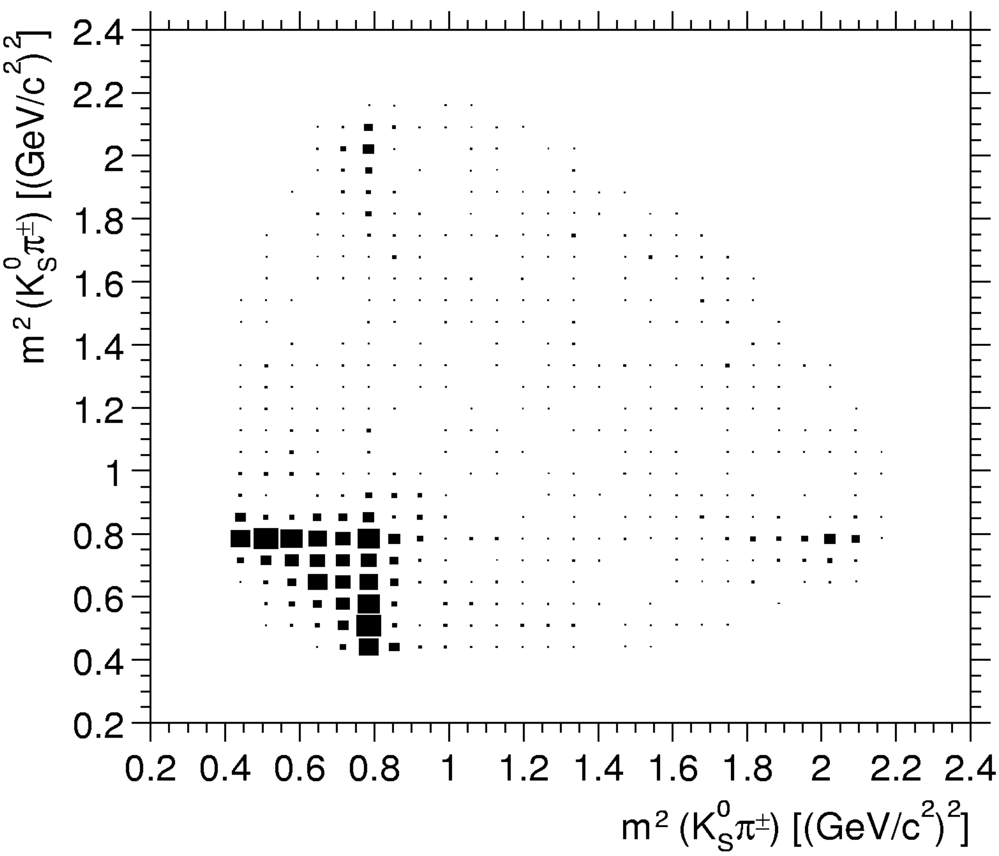
Phys. Rev. Lett. 81 (1998) 5760

Fit of Dalitz plot

preliminary, Joerg Reinhardt, Bonn

ρ	$(\pi\pi)_S$	$a_2(1320)$	$a_0(1450)$	π_1 (1585,160)	$\ln L$
22.72	77.28	-	-	-	164.2
18.68	80.78	0.53	-	-	158.31
33.75	40.35	0.01	25.9	-	134.1
24.26	64.0	1.23	2.39	8.04	126.63
22.72	77.28	-	-	-	164.2
18.68	80.78	0.53	-	-	158.31
27.15	64.7	1.33	-	6.82	127.83
24.26	64.0	1.23	2.39	8.04	126.63
				(1567.7,158.2)	
26.93	64.5	1.28	-	7.08	127.28
				(1563,195.0)	
23.64	61.3	1.24	3.76	10.1	125.86

Meson production in D_s decays with BABAR



~ 900 events in 1 year of running

New Results from CLEO

$B \rightarrow J/\psi\phi K$

Phys. Rev. Lett. 84, 1393 (2000)

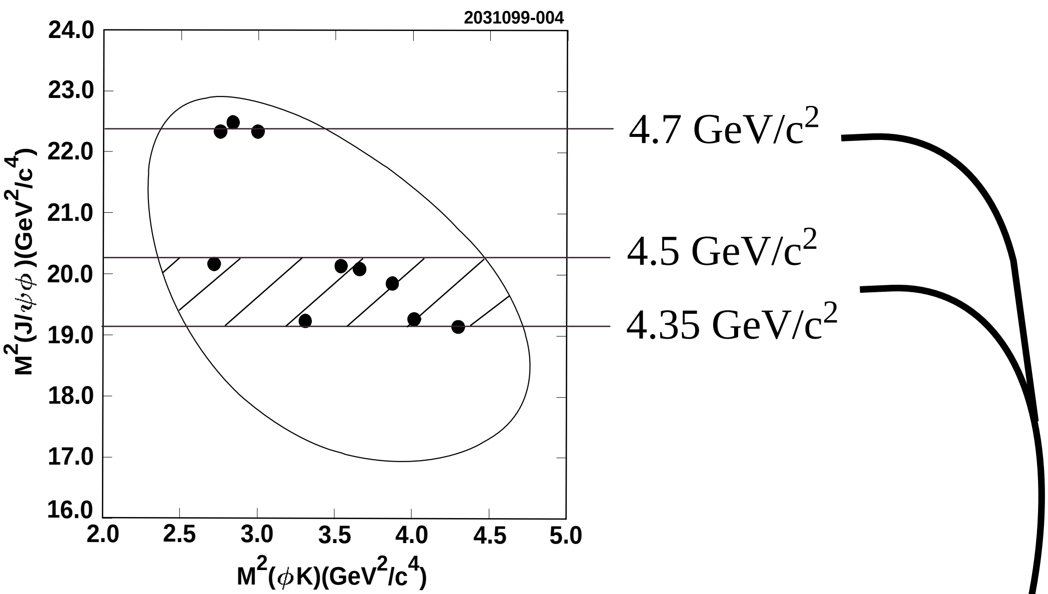


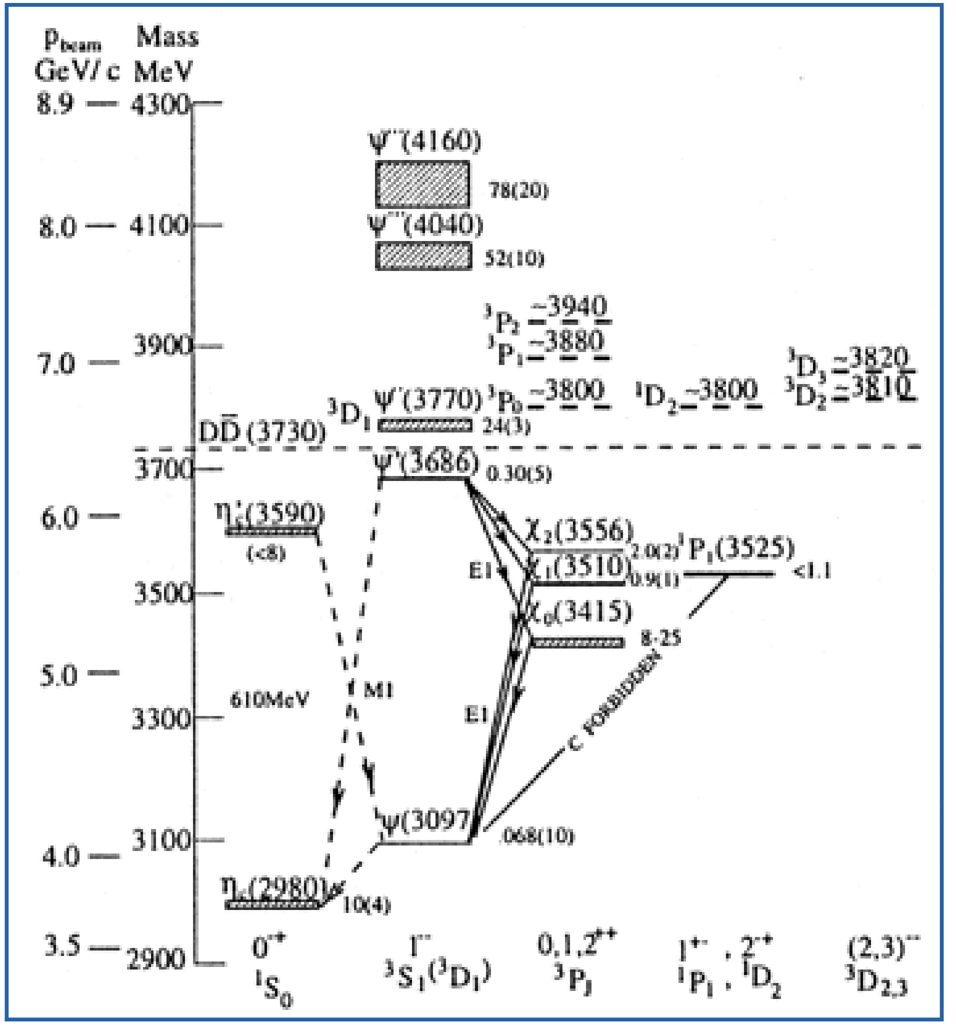
FIG. 4. Dalitz plot for the 10 $B \rightarrow J/\psi\,\phi K$ candidates in data. The kinematic boundary is represented by solid line.

Indications for a $J/\psi\phi$ resonances?

BABAR can expect ~300 events within 5 years.

Physics Program / Charmonium Spectroscopy

$c\bar{c}$ - system (QCD) ≙ e^+e^--system (QED)



Energies/Energy splittings/Widths of states

↳ Details of $Q\bar{Q}$-interactions

Confinement Potential

Exclusive Decays

↳ Mixing of perturbative/non-pert. effects

Physics Program / Charmonium Spectroscopy

Experimental situation

R704 (CERN/ISR) / E760/835 (Fermilab)

↳ Discovery of h_c ($^1P_1$) - state

Very precise values for masses and withs of χ_c, η_c-states

Measurement of previously unknown branching ratios

Determination of α_s (m_c)

But : Severe limitations (Non magnetic detector, beamtime, beam momentum reproducibility, ...)

Many questions left open:

– η_c‘ (Cball) not yet established (Spin-Spin-Interaction)

– $^1P_1$ (E760) unconfirmed

– D-wave states (some of them very narrow) and radially P-states not fully understood (Structure of states)

– Angular distributions of radiative decays not understood (Mixing of pert./non-pert. Effects)

e.g. $J/\psi \to \rho\pi^0; \eta_c, \chi_{co} \to B\bar{B}$ (Hadron helicity non conserving process)

$J/\psi \to \pi^+\pi^-, \omega\pi^0, \rho\eta$ (G– parity violating decays)

$\psi' \to \gamma + \pi, \eta \ldots$ (Radiative ψ' – decays)

$\chi_{cJ} \to \rho\rho, \phi\phi, \rho\eta, \rho\eta', \eta'\eta'$ (Higher Fock state contributions)

Physics Program / Charmed Hybrids

Charmed Hybrids : $(c\bar{c}g)$

Predictions: (LQCD, Bag-Model, Flux-Tube-Model,…)

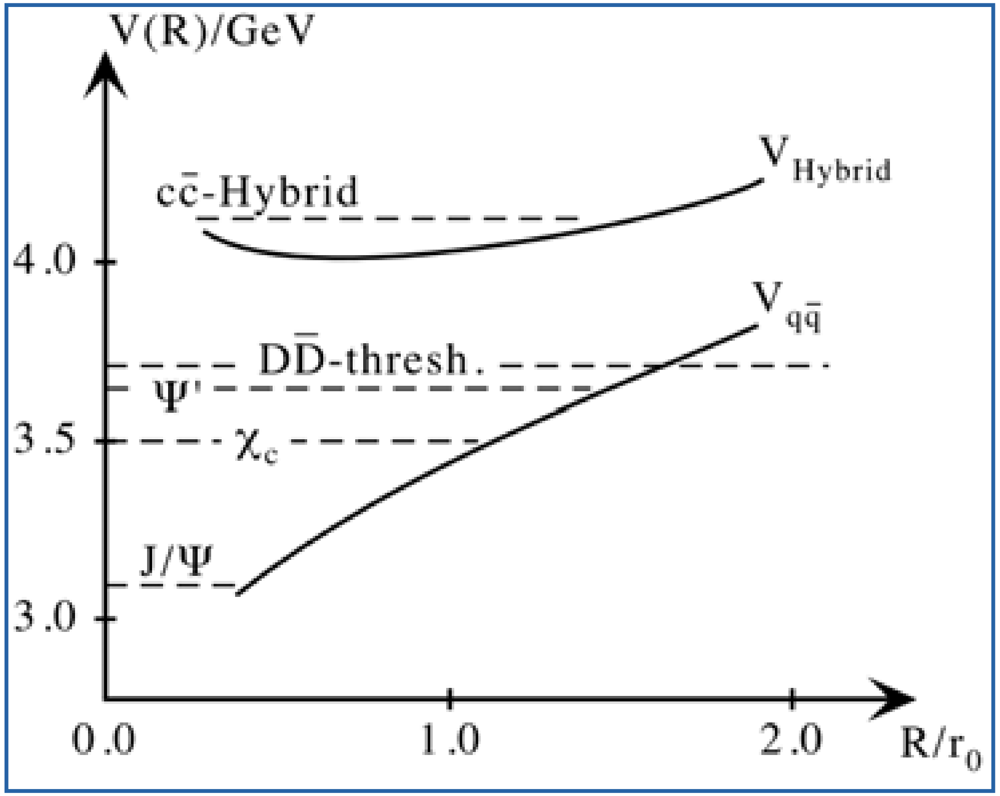
Masses

Lowest energy states: 3.9-4.5 GeV/c^2

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

Widths

Could be narrow in some cases (≈MeV)



Physics Program / Charmed Hybrids

High chances to find charmed hybrids

Less mixing than in $(q\bar{q}g)$-sector

Measuring program at HESR

States with non exotic q.-n.:

$\bar{p}$-scan: $\bar{p}p \to (c\bar{c}g)$ 3.9 - 4.3 GeV/c^2 ; J/ψ-trigger)
$\bar{p}p \to (c\bar{c}g)$ (4.3 - 5.0 GeV/c^2 ; D-trigger),
$\approx 10^4$ $(c\bar{c}g) \to J/\psi + \eta$ per day (Decay channel selects q.-n.)

States with exotic q.-n.:

Production experiment: $\bar{p}p \to (c\bar{c}g) + \pi^0(\eta)$
$\hookrightarrow J/\psi + \omega, \phi, \gamma$

$\approx 10^2$ $(c\bar{c}g)$ per day, PWA of Dalitz-Plots (see LEAR)

In addition: Measuring program on light hybrids $\approx$ 2 GeV/c^2, Scan- and production mode
Favorite channels: $\bar{p}p \to (c\bar{c}g) \to f_1(1285)\pi, K_1\bar{K}, \ldots$
Large cross sections (μb), Complementary to Hall D

Physics Program / Heavier Glueballs

Glueballs (gg)

Predictions:

Masses:

1.5-5.0 GeV/c^2 (Ground state found? ; Candidates for further states?)

Quantum numbers:

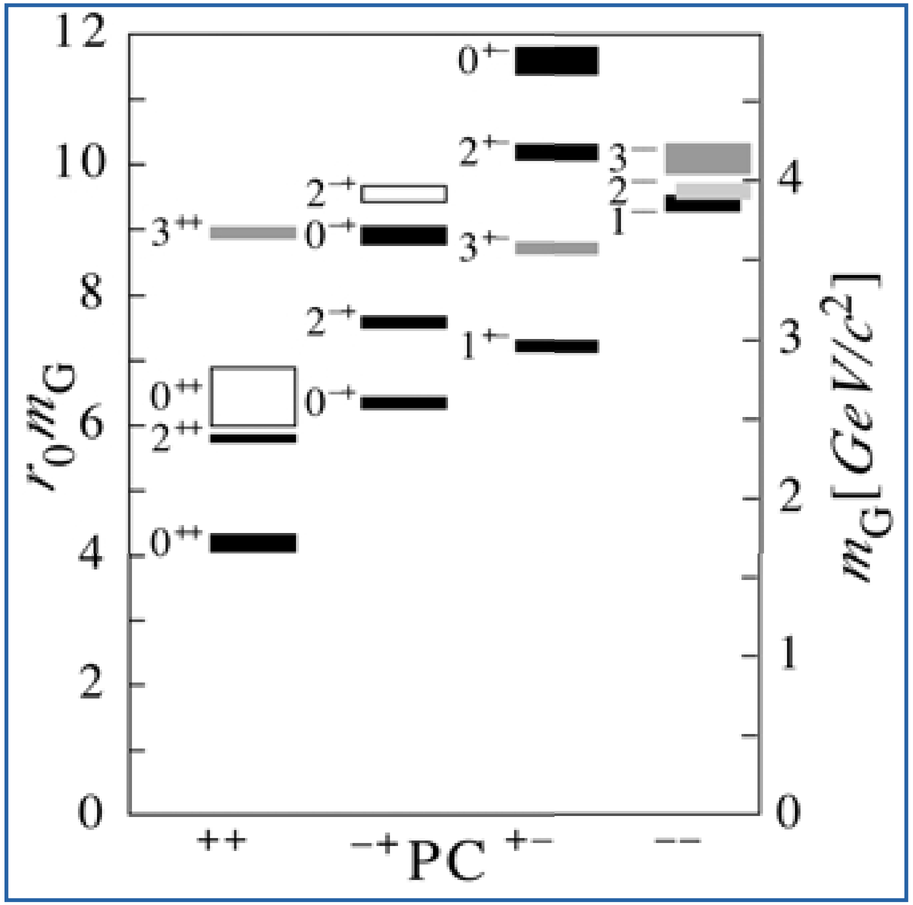
Several spin exotics (oddballs), e.g.

$J^{PC} = 2^{+-}$ (4.3 GeV/c^2)

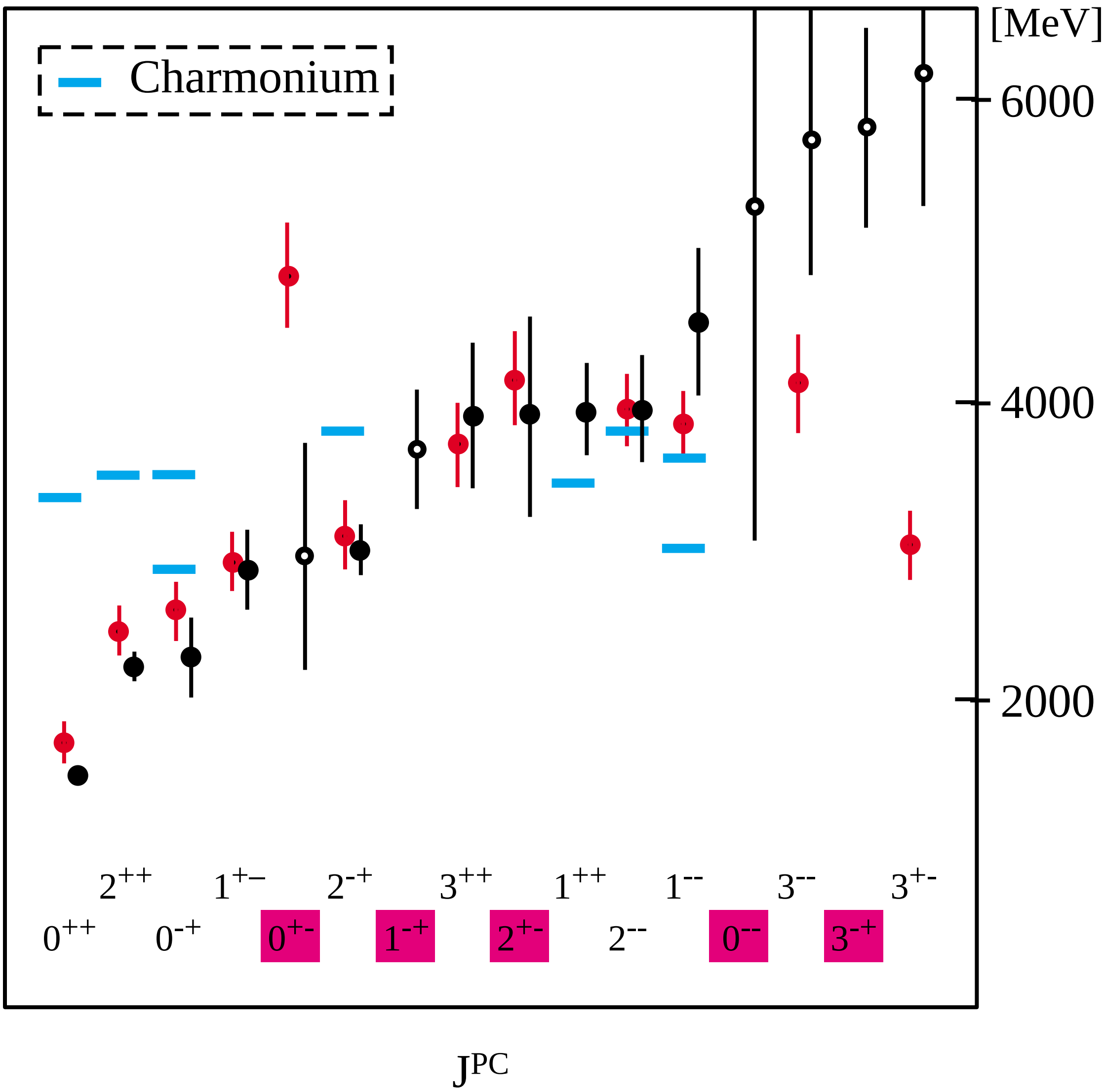
Widths: ≥ 100 MeV/c^2

– Decay into two lighter glueballs often forbidden because of q.-n.

– No mixing effects for oddballs



Charmonium States and Predicted Glueballs



● UKQCD Collaboration, G. S. Bali et al., Phys. Lett. B309 (1993) 378.

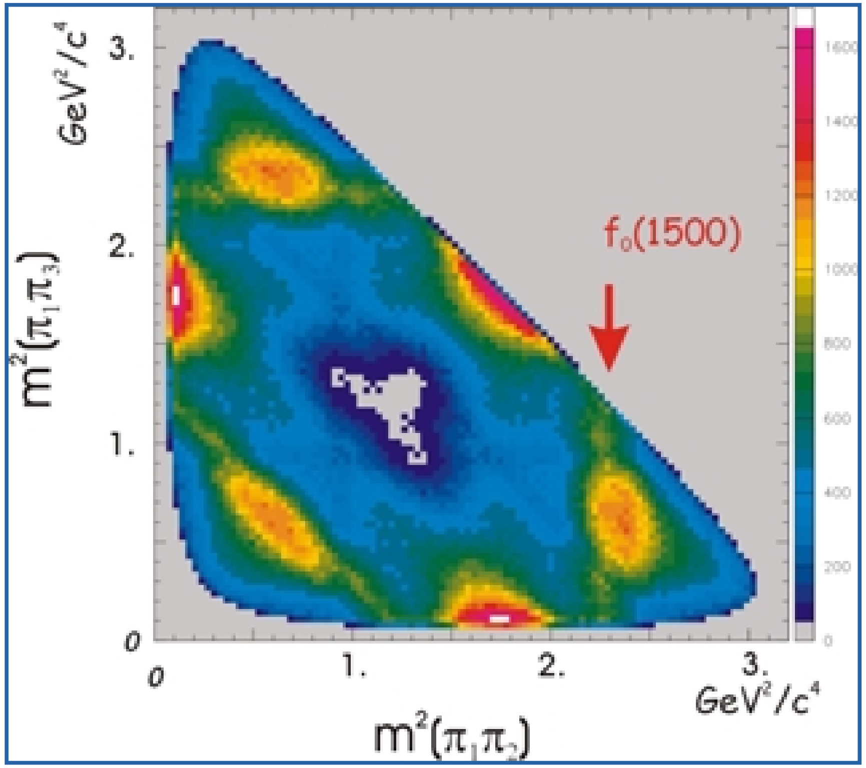
● C. Morningstar, M. Peardon; Phys. Rev. D 60 (1999) 034509

Physics Program / Heavier Glueballs

Production cross section:

Maybe high in $\bar{p}p$-annihilation (see $f_0(1500)$)

Comparable to $q\bar{q}$-systems (! μb)



Experimental program at HESR

$\bar{p}$-scan for non-exotics: $\bar{p}p \to (gg) \to \phi\phi, \phi\eta$

(Most reasonable channels, easily distinguishable, low l - waves (simple PWA))

Production exp. for exotics: $\bar{p}p \to (gg) + \pi$

Reasonable measuring times

Physics Program / Measurements in the Charm Region

Spin non-exotic states $X: \bar{p}p \rightarrow X$ ($\bar{p}$-scan)

X: Heavier $q\bar{q}$-mesons $\rightarrow$ $n\pi + mK, \ldots$

Heavier Glueballs $\rightarrow$ $\phi\phi$, $\phi\eta, \ldots$

Charmed Hybrids $\rightarrow$ $J/\psi\eta, \ldots$

Spin-exotic states (# $q\bar{q}$) $Y: \bar{p}p \rightarrow Y + \pi$, $\eta, \ldots$ (Production mode)

Y: Oddballs $\rightarrow$ $\eta\pi$, $\phi\phi, \ldots$

Charmed Hybrids $\rightarrow$ $\chi(\pi\pi)_S, \ldots$ (e.g. groundstate)

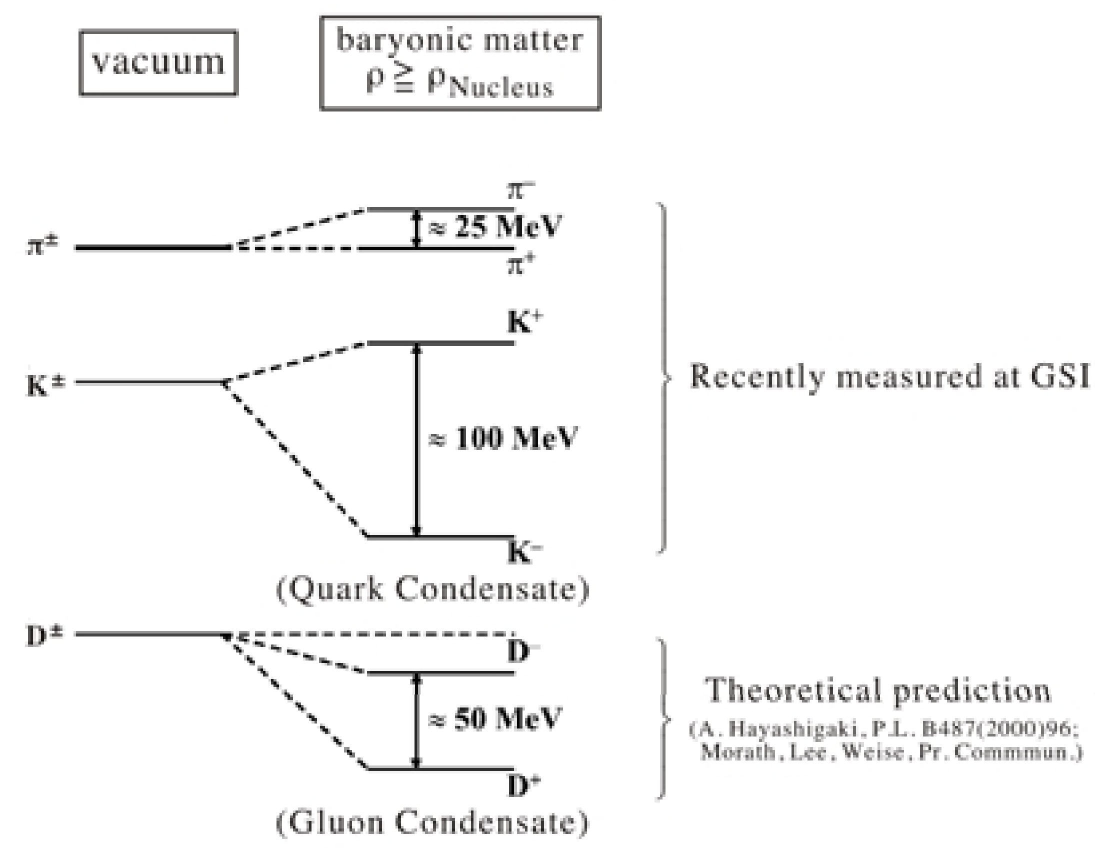
Physics Program / Hadrons in Nuclear Matter

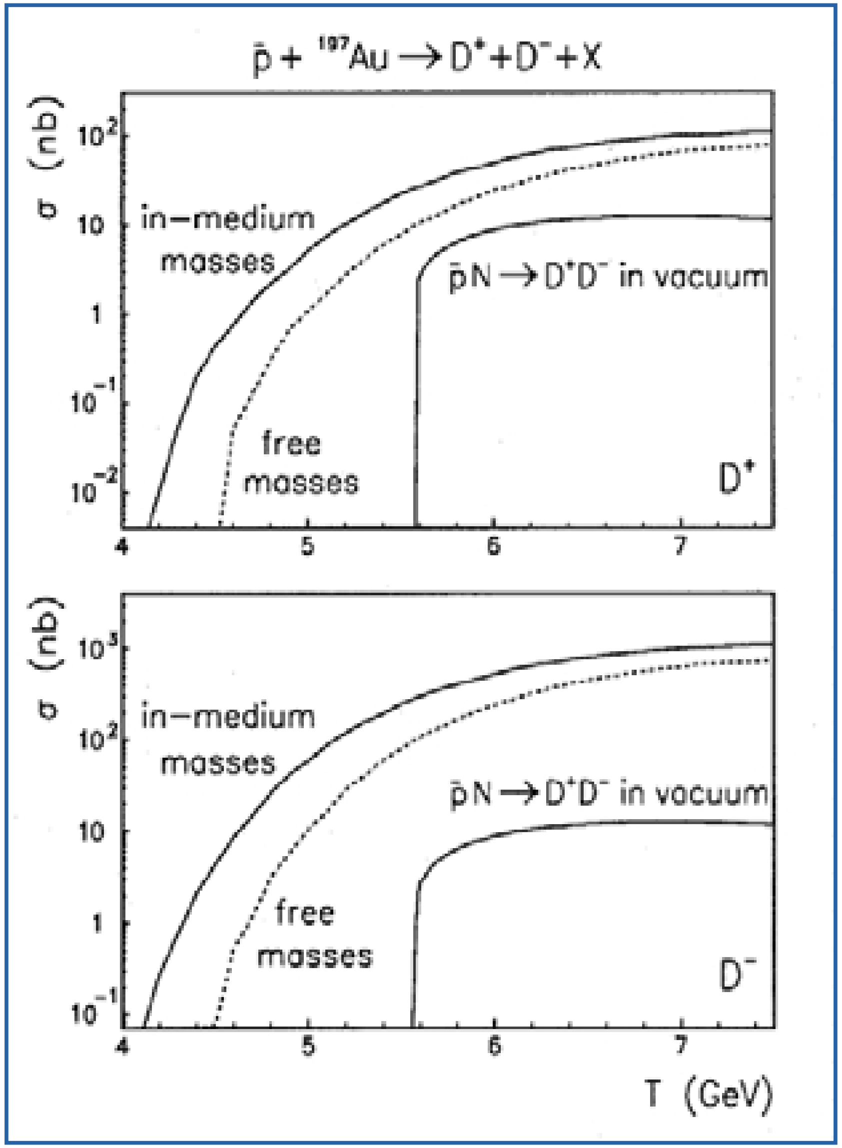
1) Effective masses of hadrons in the nuclear medium

– $^{206}Pb(d, {}^{3}He)$, Q-Value

– K^+, K^--Production in heavy ion collisions

Excitation spectra → $(m_K)_{Eff.}$





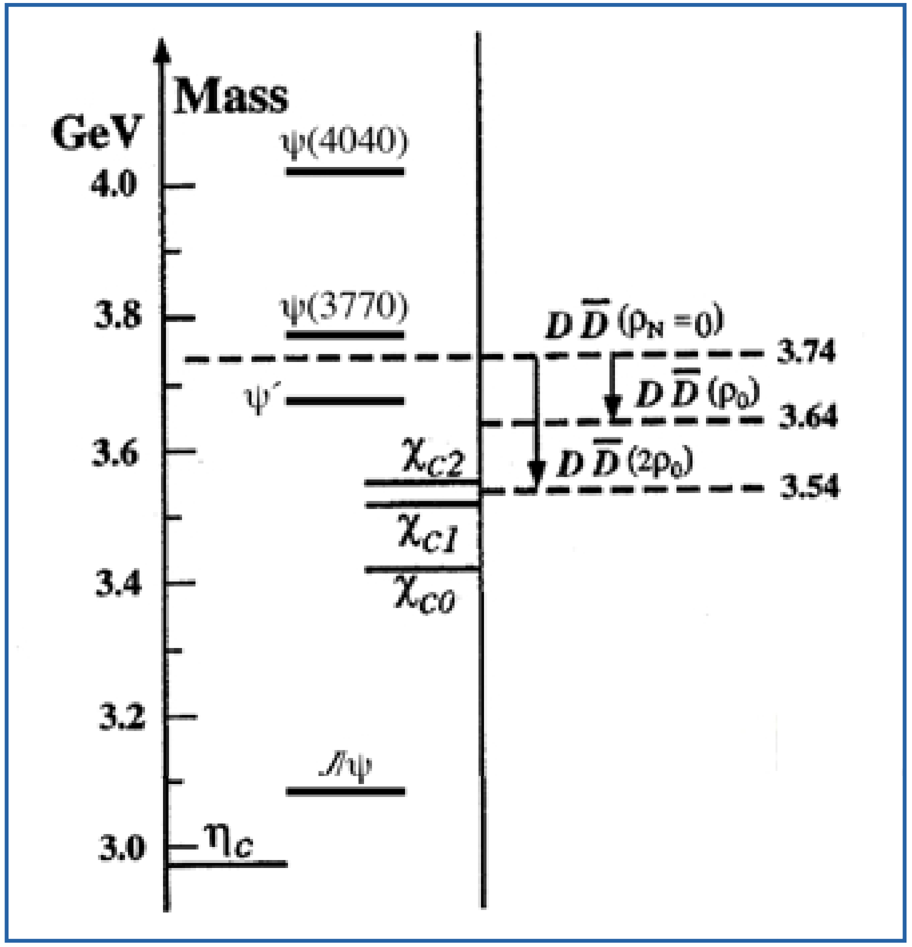
Physics Program / Hadrons in Nuclear Matter

Effective D-masses in nuclear medium

– Dramatically increased $D\bar{D}$-decay rate of ψ'- and χ_{C2}-states in nuclear medium

↳Substantial increase of widths (0.3 MeV → ?; 2.0 MeV → ?)

– Increased width of ψ(3770) (24 MeV → ?)

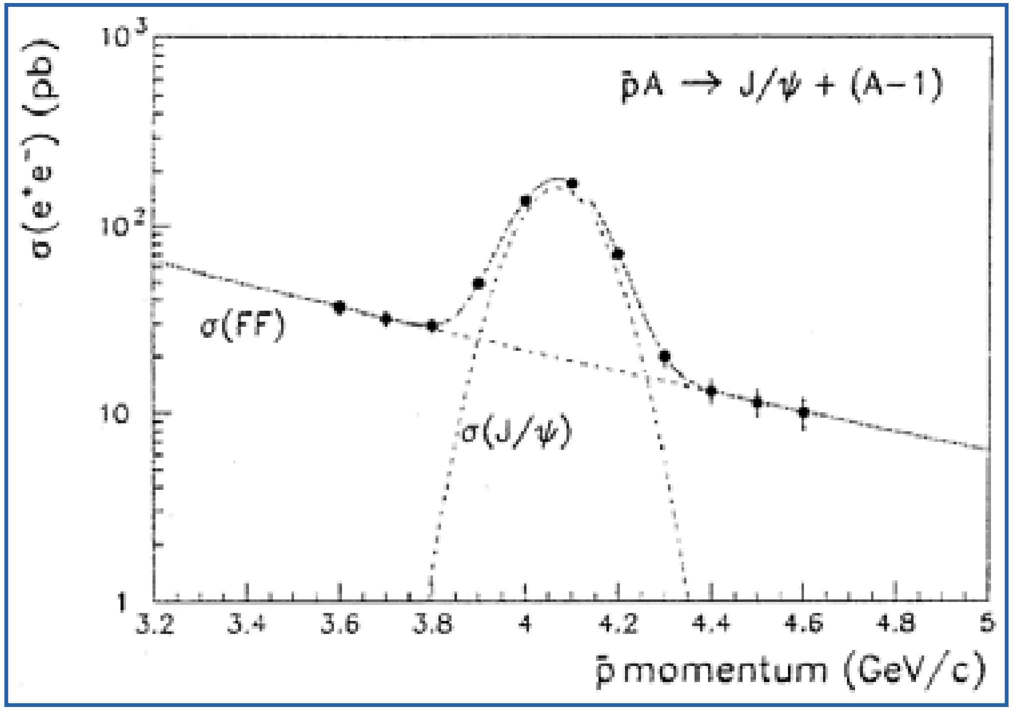


Physics Program / Hadrons in Nuclear Matter

2) J/ψ - nucleon absorption cross section

Important for J/ψ - suppression in QGP

Proposed reaction:
$\bar{p}$(3.4-4.6 GeV/c) + A → J/ψ + (A-1)



Furthermore:

– $c\bar{c}$ - dissociation to open charm in the presence of nucleons:
$\bar{p}d \rightarrow D^- + \Lambda_c^+$

– Elastic J/ψ - nucleon cross sections (Low momenta)
$\bar{p}d \rightarrow J/\psi + \gamma + n$

Physics Program / Double Hypernuclei

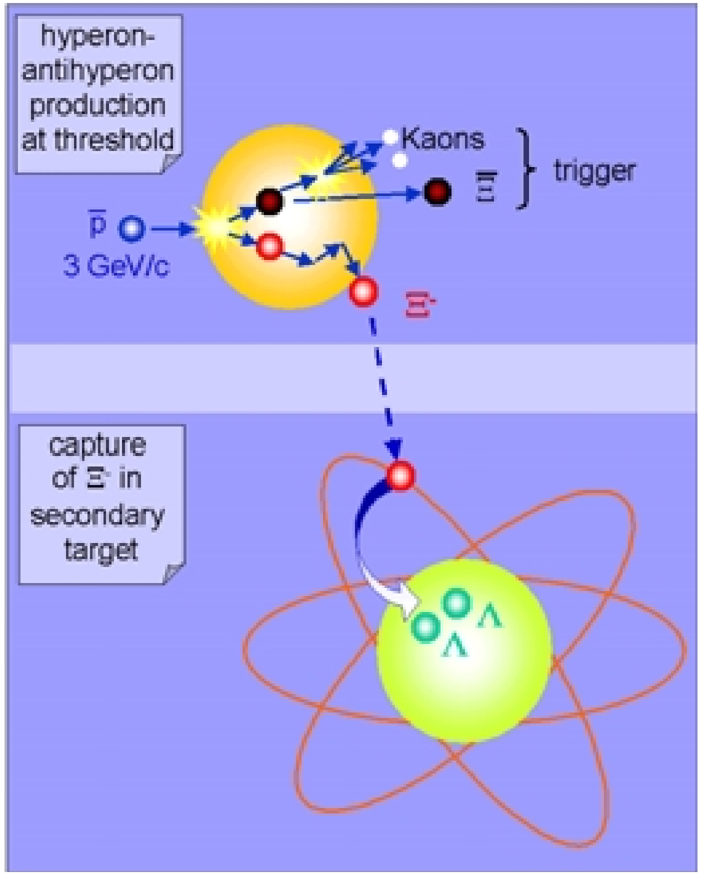
3) Strange Baryons in Nuclear Field

Hypernuclei = Third dimension of the nuclear chart

Production of Double Λ-Hypernuclei:

$$\bar{p}(2.6\,\mathrm{GeV/c}) + A \rightarrow \Xi^-{}_{(\mathrm{slow})} + \underbrace{\bar{\Xi}(KK\ldots)}_{\mathrm{Trigger}}\,;\; \Xi^-{}_{(\mathrm{slow})} + A' \rightarrow {}_{\Lambda\Lambda}A'$$

Active, secondary target (→ A')



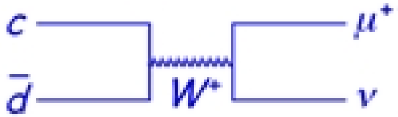
Physics Program / Further Options

– Baryon Spectroscopy

New states, Quantum numbers and decay rates

– Rare D-decays

Example: $D^+ \to \mu^+ \nu (BR \sim 10^{-4})$



$\Gamma \sim f_0^2 \sim |\psi(0)|^2$

Sensitive Test of LQCD, $\cdots$

– Direct CP-Violation in Λ, $\bar{\Lambda}$-decays

Compare angular decay asymmetries $(\alpha, \bar{\alpha})$ for $\Lambda \to p\pi^- / \bar{\Lambda} \to \bar{p}\pi^+$

$$A \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

Prediction (SM) $\approx 2 \times 10^{-5}$

HESR: 1 year of beamtime

Physics Program / Further Options

CP-Violation in charmed region

$D^0/\overline{D}^0 -$ Mixing $(r) < 10^{-8}$ (SM) HESR : $\Delta r/r \sim 10^{-4}$

Direct CP-Violation (SCS)

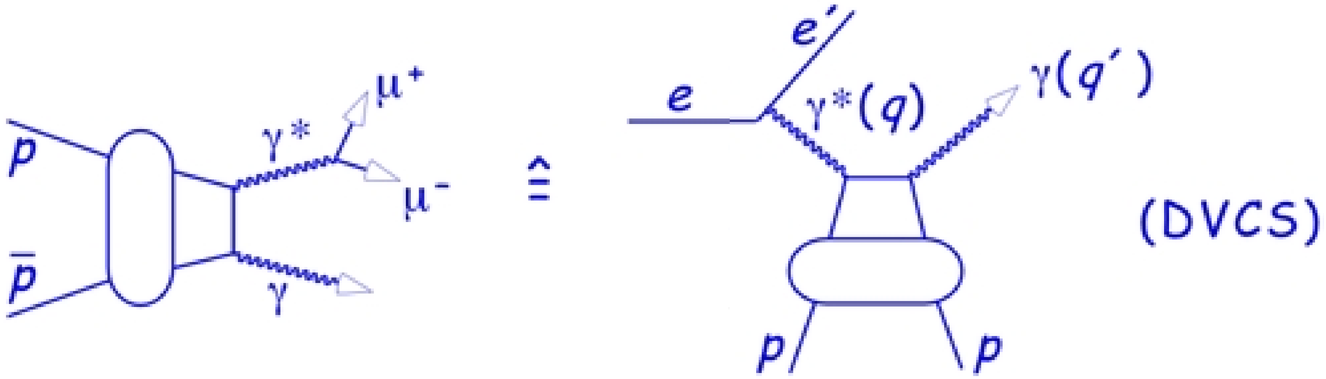
Compare $D^+ \to K^+\overline{K}^{0*} / D^- \to K^- K^{0*}$ Asymmetries A (SM) $< 10^{-3}$

HESR $=$ $\Delta A/A \approx 10^{-4} - 10^{-3}$

Physics Program / Further Options

Study of reversed Deeply Virtual Compton Scattering (DVCS)

$\bar{p} + p \rightarrow \gamma^* + \gamma \rightarrow l^+ l^- + \gamma \rightarrow$ Nucleon structure functions



Low energy p̄-physics

– p̄p-annihilation process
– Antiprotonic atoms
– Antihydrogen

Status of the Project

May 1999 : LOI for HESR (www.ep1.rub.de/gsi/part1.ps.gz)
Jan. 2001 : Start of Detector simulations (Geant 4)
Nov. 2001 : Conceptual Design Report (www.gsi.de/GSI-Future)
Review by an International Committee of the „Deutsche Wissenschaftsrat“
July 2002 : First Meeting of the PANDA collaboration
(35 Institutions, 160 scientists so far)
Nov. 2002 : Very positive vote of the „Deutsche Wissenschaftsrat“
Start of R&D work for the PANDA detector
Jan. 2003 : Promise for funding of the project by the German Ministery for Research and Technology

Conclusion

– HESR will deliver cooled high quality antiproton beams with energies up to 15 GeV

– Antiproton induced reactions exhibit unique features

  – High statistics data
  – Low multiplicity events
  – Symmetric production of particles and antiparticles
  – High production rates for gluonic hadrons
  – Many states can be directly formed

– Rich and unique Physics Program with emphasis on charmed particles

  – Precision charmonium spectroscopy
  – Search for charmed hybrids and heavier Glueballs
  – J/ψ-Nucleon interactions
  – Effective masses of hadrons in nuclear matter
  – CP-violation in the charm sector
  – Low energy $\bar{p}$ - physics, including Antihydrogen experiments