Hadron Physics Experiments with Antiprotons

- Introduction
- Basic Facts about Antiprotons
- Historical Survey
- Production of Antiprotons and Antiproton Beams
- Antiproton-Nucleon Interactions
- Discovery of the TOP-Quark
- Discovery of the Intermediate Vector Bosons $W^{\pm}$, Z^0
- Charmonium Spectroscopy
- LEAR Results
- Future Prospects

Basic Facts about $\bar{p}(\bar{n})$'s (1)

– Properties

Antiparticles of Protons (Neutrons)

CPT-Symmetry: $q_{\bar{q}} = -q_q$; $m_{\bar{p}(\bar{n})} = m_{p(n)}$; $\mu_{\bar{p}(\bar{n})} = -\mu_{p(n)}$; $S = \frac{1}{2}\hbar$; $I = \frac{1}{2}$; $\tau_p = \tau_{\bar{p}}$

Experimental results (PDG):

$$\left|q_p + q_{\bar{p}}\right|/e \quad < 6 \cdot 10^{-8} (\text{C.L.} = 90\%)$$

$$\left|m_p - m_{\bar{p}}\right|/m_p < 6 \cdot 10^{-8} (\text{C.L.} = 90\%)$$

$$\left|\frac{q_{\bar{p}}}{m_{\bar{p}}}\right| / \left|\frac{q_p}{m_p}\right| \quad < 0.999\,999\,999\,91 \pm 0.000\,000\,000\,09$$

$$\left|\mu_p + \mu_{\bar{p}}\right|/\mu_p = (-2.6 \pm 2.9) \mathrm{x} 10^{-3}$$

$$\tau_{\bar{p}} \; > 1.3 \mathrm{x} 10^{6}\,\mathrm{y}\; (\bar{p} \to e^{-}\gamma)$$

$$(\tau_{\bar{p}} > 10^{17}\,\mathrm{y}\,;\ \text{Cosmological Limit})$$

Basic Facts about $\bar{p}(\bar{n})$'s (2)

– $\bar{p}(\bar{n})$ - Interactions

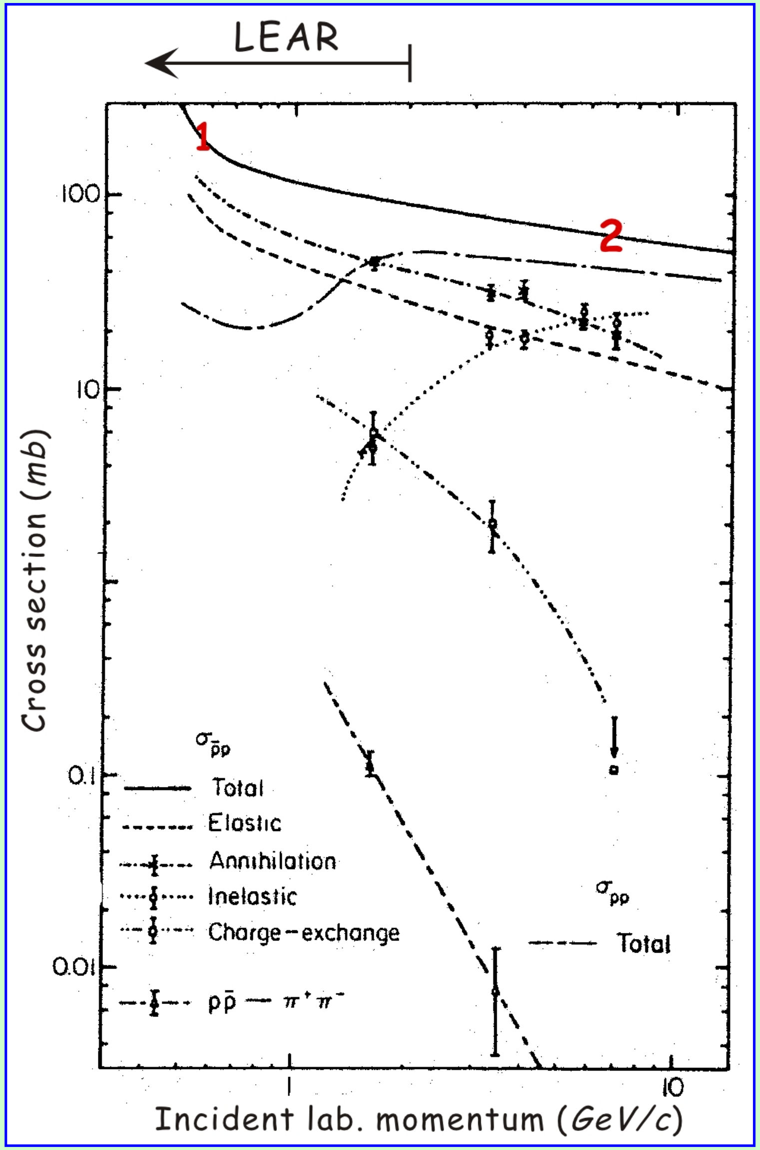
Interactions with protons (neutrons)

- Elastic scattering , e.g. $\bar{p} + p \rightarrow \bar{p} + p$
- Charge exchange , e.g. $\bar{p} + p \rightarrow \bar{n} + n$
- Inelastic scattering, e.g. $\bar{p} + p \rightarrow \bar{p} + p + \pi^+ + \pi^-$
- Annihilation , e.g. $\bar{p} + p \rightarrow \pi^+\pi^-\pi^0\pi^0$

  (Dominant al low energies)

Rich of resonances

Basic Facts about $\bar{p}(\bar{n})$'s (3)



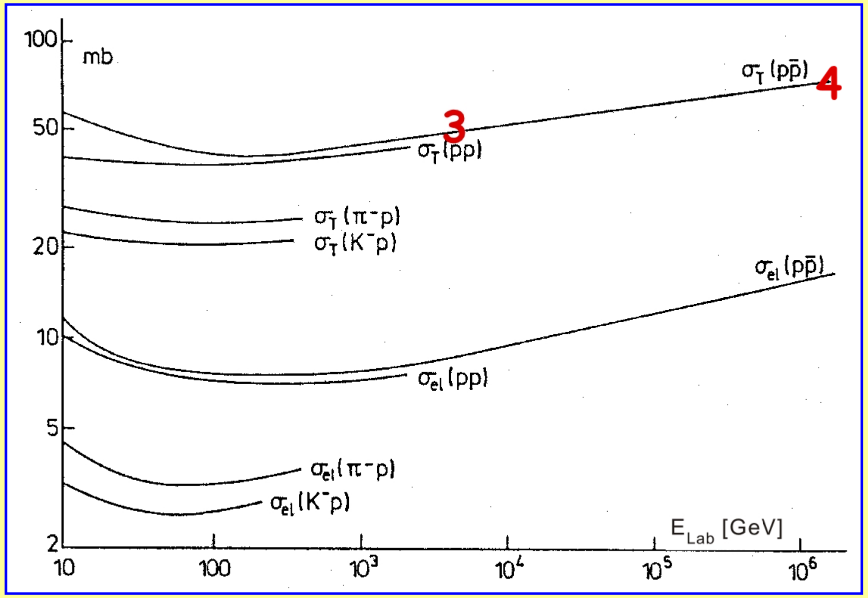
Low and medium energy antiprotons

① $\bar{p}p$-atoms as initial state

Final states: Only Annihilation (2π, 3π, $\rho\pi$, $f_2\pi$, ..)

② Prediction measurements in the $c\bar{c}$-system

Rare process (nb)



High energy antiprotons (SPSC, Tevatron)

③ Discovery of $W^{\pm}$, Z^0

Rare process (nb): Drell-Yan-Production

④ Discovery of t-quark

Rare process (pb): Pair ($t\bar{t}$)-Production

Basic Facts about $\bar{p}(\bar{n})$'s (4)

– Interactions with nuclei

Similar processes as in $\bar{p}p(n)$ interactions $\rightarrow$ Intranuclear cascade

– Particular situation for very low energy $\bar{p}$'s:

Formation of $\bar{p}$-atoms $\xrightarrow{\text{X - rays, ...}}$ Low excited or ground state $\rightarrow$ Annihilation from atomic state
(Natural trap for $\bar{p}$'s)

– Special Features of Antiprotons

– Cooled $\bar{p}$-beams (Low emittance)

– Low energy antiprotons can be trapped in e.-m. bottles
(Storage of antiprotons for larger times)

Physics with Antiprotons (Antineutrons): Historical Overview (1)

Before 1955:	Interest to test Dirac‘s Theory for complex particles First weak evidences for antiprotons in cosmic ray events (Cloud Chamber, Photographic Emulsions)
Nov. 1955:	Chamberlain, Segrè, Wiegand, Ypsilantis Bevatron, Berkeley: Production of antiprotons and first experiments After 3 years of measurement: $\Delta m_{\bar{p}} / m_{\bar{p}} \leq 2\%$ J^P = ?, but indirect evidence for $1/2^+$ Annihilation observed, Multiplicities determined Production in pairs confirmed Cross sections for $\bar{p}N$ and $\bar{p}A$-collisions, Angular distributions First purified beams (Be-absorber; Wien-Filter) $\bar{p} + p \rightarrow n + \bar{n}$ (Detection of Antineutrons)

Physics with Antiprotons (Antineutrons): Historical Overview (2)

1956 - 1981: $\bar{p}$-physics ($\lesssim$ 30 GeV/c) on fixed targets
(BNL, Argonne, CERN, Serpukhov, KEK, ...)
Secondary beams of low intensity, ill defined energy, large contamination by negatively charged meson inspite of separation techniques
Detectors: Bubble Chambers + Electronic Detectors

➥ Cross sections
New Mesons : $\omega(782)$, $f_1(1285)$, $K_1(1270)$, $E/\eta(1440)$
Antiprotonic Atoms

Physics with Antiprotons (Antineutrons): Historical Overview (3)

1980: Antiproton Accumulator @ CERN (AA)
Use of stochastic Cooling Techniques $\rightarrow$ Availability of high intensity, high quality $\bar{p}$-beams @ 3.5 GeV/c

1981 - 1996: Experiments with high energy antiprotons ($\rightarrow$ 315 GeV) in the SPSC @ CERN
- ➥ Measurement of cross sections and inclusive quantities (Multiplicities, $p_\perp$-, Rapidity-distributions, ...) up to $\sqrt{s} \approx 630$ GeV

Highlight: Discovery of W^+, Z^0

1981 - 1983: Experiments with medium energy antiprotons ($\rightarrow$ 30 GeV) at ISR @ CERN
- ➥ Measurement of cross sections

Highlight: Formation of $c\bar{c}$-states: $\bar{p}p \rightarrow c\bar{c}$

1983 - 1996: Low energy antiproton ring (LEAR) @ CERN ($p_{\bar{p}}^{max}$ = 1.940 GeV/c)
➥ Extremely rich physics program:
- – Details of $\bar{p}(\bar{n})p$-scattering, Polarisation Observables
- – Meson-Spectroscopy:
  Detection of new states:
  $f_0(1500)$ (Glueball?); $a_0(1450)$, $f_0(1370)$; $E/\eta(1450)$; ...
- – Inelastic Reactions:
  $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ (Detailed investigation)

Physics with Antiprotons (Antineutrons): Historical Overview (4)

– Exotic atoms:

$\bar{p}p$-atoms: $\bar{p}p$-scattering length

$\bar{p}A$-atoms: Best value for $\mu_{\bar{p}}$, ...

High precision spectroscopy in the $\bar{p}$-He-system

Neutron densities in the nuclear periphery

– T(CP)-violation in the $K^0/\overline{K}^0$-system

– $m_{\bar{p}}/m_p$ with extreme precision (E.-M. Traps)

– Discovery of (hot) Antihydrogen ($\overline{H}$)

1986-Today: High energy antiprotons at Fermilab ($\sqrt{s} \approx 1.8$ TeV)

↪ Test of perturbative QCD

Asymptotic $\bar{p}p$/pp-reactions

Inclusive measurements

Highlight: Discovery of the Top-Quark

Constraints for the Higgs-Mass

1986 - 2001: Medium Energy Antiproton at Fermilab ($p_{\bar{p}} \leq 8$ GeV/c)

↪ Precision spectroscopy in the $c\bar{c}$-system

Physics with Antiprotons (Antineutrons): Historical Overview (5)

2001-Today: Antiprotons Decelerator (AD) @ CERN

↪ Formation of (cold) Antihydrogen Atoms
High precision experiments on $\bar{p}$-He-atoms

Future: Facility for Antiproton and Ion Research (FAIR) @ GSI/Germany
Japan Hadron Facility (JAERI-KEK)

Production of Antiprotons and Antiproton Beams (1)

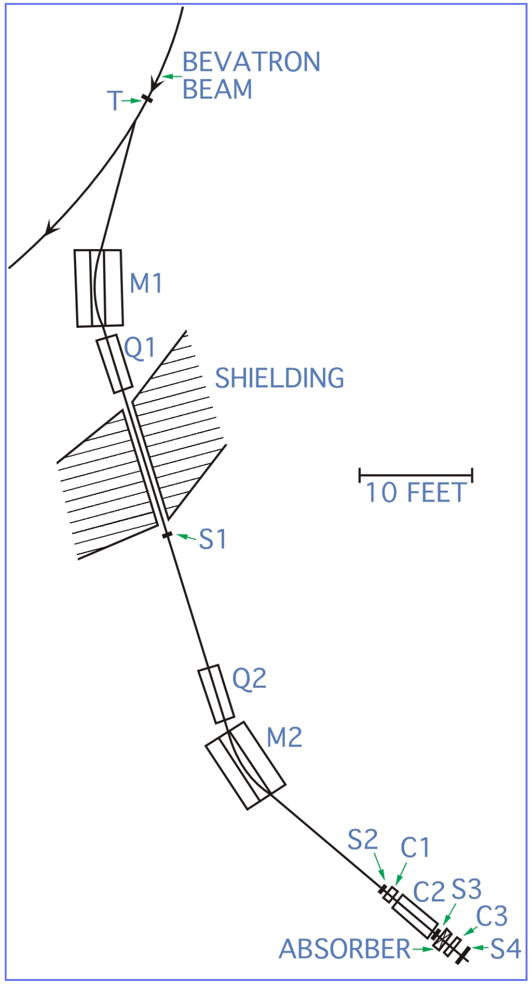
Conventional $\bar{p}$-beams:

Typical Example (Bevatron Set up)

$p(6.2\ \mathrm{GeV}) + Cu \rightarrow p + p + p + \bar{p} + X$

Threshold (p): 5.63 GeV

Threshold (A): 4.30 GeV (25 MeV Fermi Energy)



T : Production target (Cu)

$p_{beam} = 1.19\ \mathrm{GeV/c};\ \beta_{\bar{p}} = 0.78;\ \beta_{\pi^-} = 0.99\ \left(N_{\pi^-} / N_{\bar{p}} \approx 50000\right)$

S_1, S_2 : TOF – Counters ($\bar{p}$'s : 51ns; π's = 40ns) $\rightarrow \beta$

C_1 : Cerenkov – Counter for pions ($\beta > 0.79$)

C_2 : Cerenkov – Counter : $0.75 \leq \beta \leq 0.78$

M1, M2 : Dipole Magnets $\rightarrow p_{\bar{p}}$

Mass ($\bar{p}$) from $p = mc\beta\gamma;\ \gamma = \dfrac{1}{\sqrt{1-\beta^2}}$

$\hookrightarrow\ \Delta m_{\bar{p}} / m_{\bar{p}} \approx 5\%$

Production of Antiprotons and Antiproton Beams (2)

After Bevatron era:

Higher p-energies (26 GeV) $\Rightarrow$ Higher $\bar{p}$-rates ($\approx 10^2$-10^5/s)

↪ Cross section measurements in the μb, nb-regime

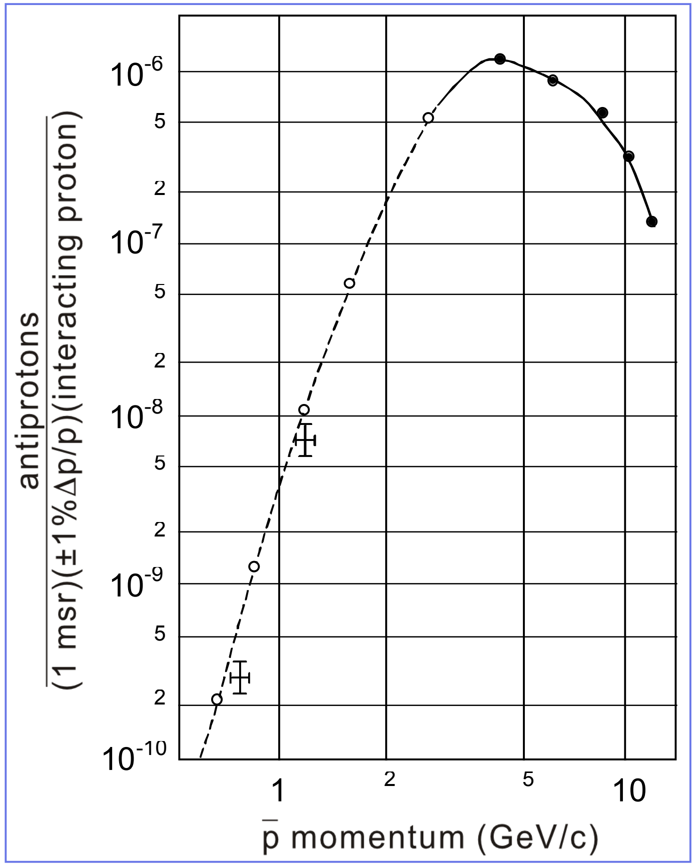
Use of separator techniques:

Electrostatic separators (≈ 1970) for lower $\bar{p}$-energies
HF-separators (s.c.) at higher energies

Deflection of particles with same momentum, but different mass, Spatial separtion of $\bar{p}/\pi^-/e^-$

Low energy beams (200 MeV/c):

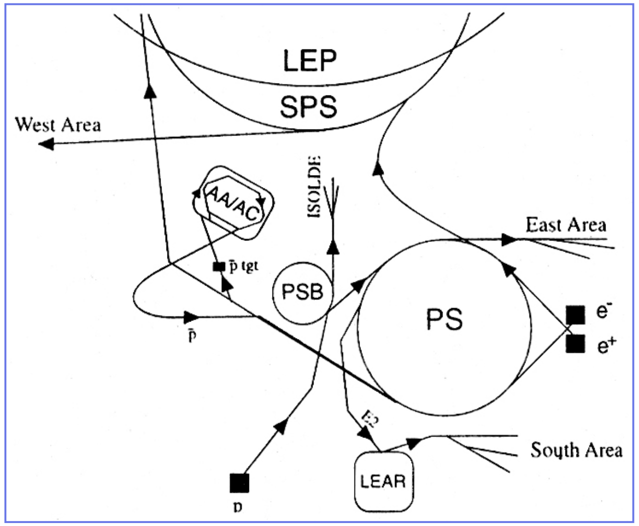
Degradation of the $\bar{p}$-beams of higher energy by absorbers (Dramatic loss of $\bar{p}$'s)



Production of Antiprotons and Antiproton Beams (3)

Cooled $\bar{p}$-beams:

Production of Antiprotons



AA/AC: @ CERN

Production Target: 50 mm Ir (∅ 3 mm)

$L_{coll} = L_{abs} \approx 50$ mm

Focusing of antiprotons: Magnetic Horn, Li-Lense

$\bar{p}$-intensity limited by several factors, e.g. thermal shock in the target

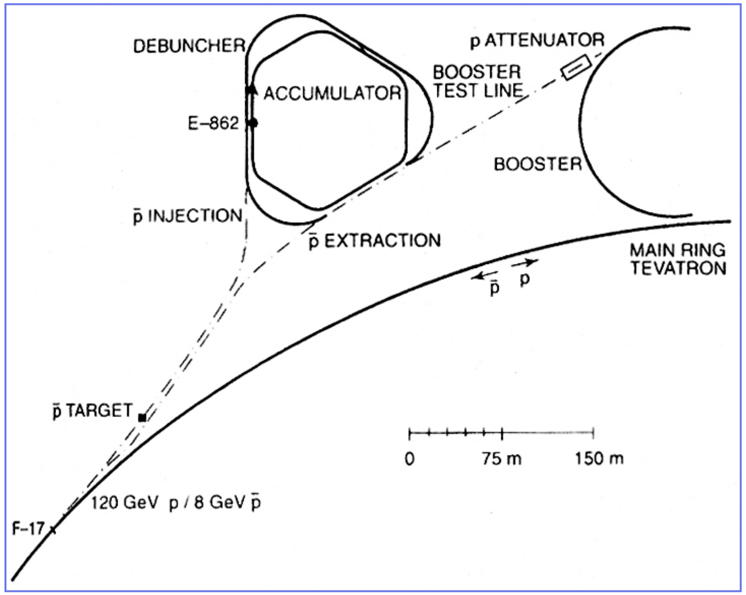


TABLE II. Comparison of CERN and Fermilab antiproton sources: for Fermilab the upgrading program quoted in Church and Marriner (1993) has been anticipated; for CERN the measured yield with magnetic horn has been used.

Machine		CERN Antiproton Collector	Fermilab debuncher
Production momentum (GeV/c)		26	120
Collection momentum (GeV/c)		3.5	9
$\bar{p}$/sr/GeV/c/Interacting p		0.013	0.25
Acceptances	A_h (π mm mrad)	200	25
	A_v (π mm mrad)	200	25
	$\Delta p/p \times 10^{-3}$	60	40
$\sqrt{A_h A_v} \times \Delta p/p$ (π mm mrad $\times 10^{-3}$)		12×10^3	10^3
Yield ($\bar{p}/p$)		3.5×10^{-6}	14×10^{-6}
Protons per pulse		1.5×10^{13}	0.5×10^{13}
Antiprotons per pulse		5×10^7	7×10^7

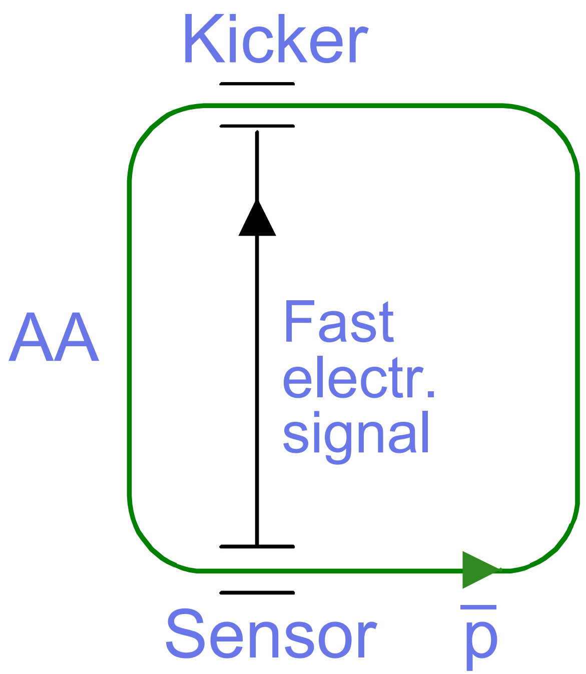
Production of Antiprotons and Antiproton Beams (4)

Accumulation of Antiprotons: AA (1980)

10^7 $\bar{p}$'s occupy ≈ 50 % of the AA phase-space valume

➥ Beam cooling needed in order to store 10^{11} $\bar{p}$'s (necessary for SPSC-experiments)

Stochastic Cooling
(van de Meer 1968; Test in ICE @ CERN)



After 1988: AC (Antiproton Collector)-Ring,
Concentric with AA: Debunching and Recooling

Production of Antiprotons and Antiproton Beams (5)

Experiments with high energy antiprotons: Acceleration of $\bar{p}$'s in PS ($\rightarrow$ 26 GeV), Transfer to SPSC, Acceleration up to 315 GeV.

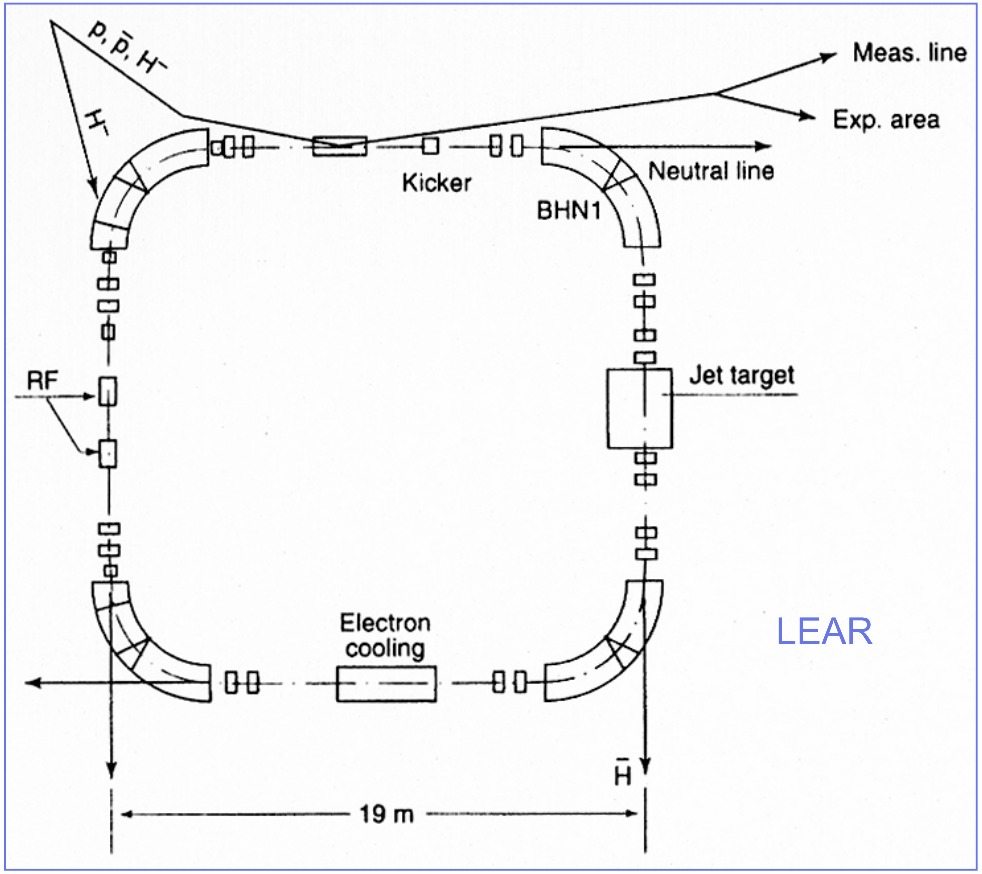
Experiments with low energy antiprotons: (Loss free) Deceleration of p's in PS (600 MeV/c), Transfer to LEAR (Low Energy Antiproton Ring) (1983-1996)

Pure, high intensity ($\leq 10^7$/s) $\bar{p}$-beams with small emittances

$200 \text{ MeV/c} \leq p_{\bar{p}} \leq 1940 \text{ MeV/c}$

Experiments with stopped antiprotons no problem: $\bar{p}$ of 200 MeV/c are easily produced and stopped in a target

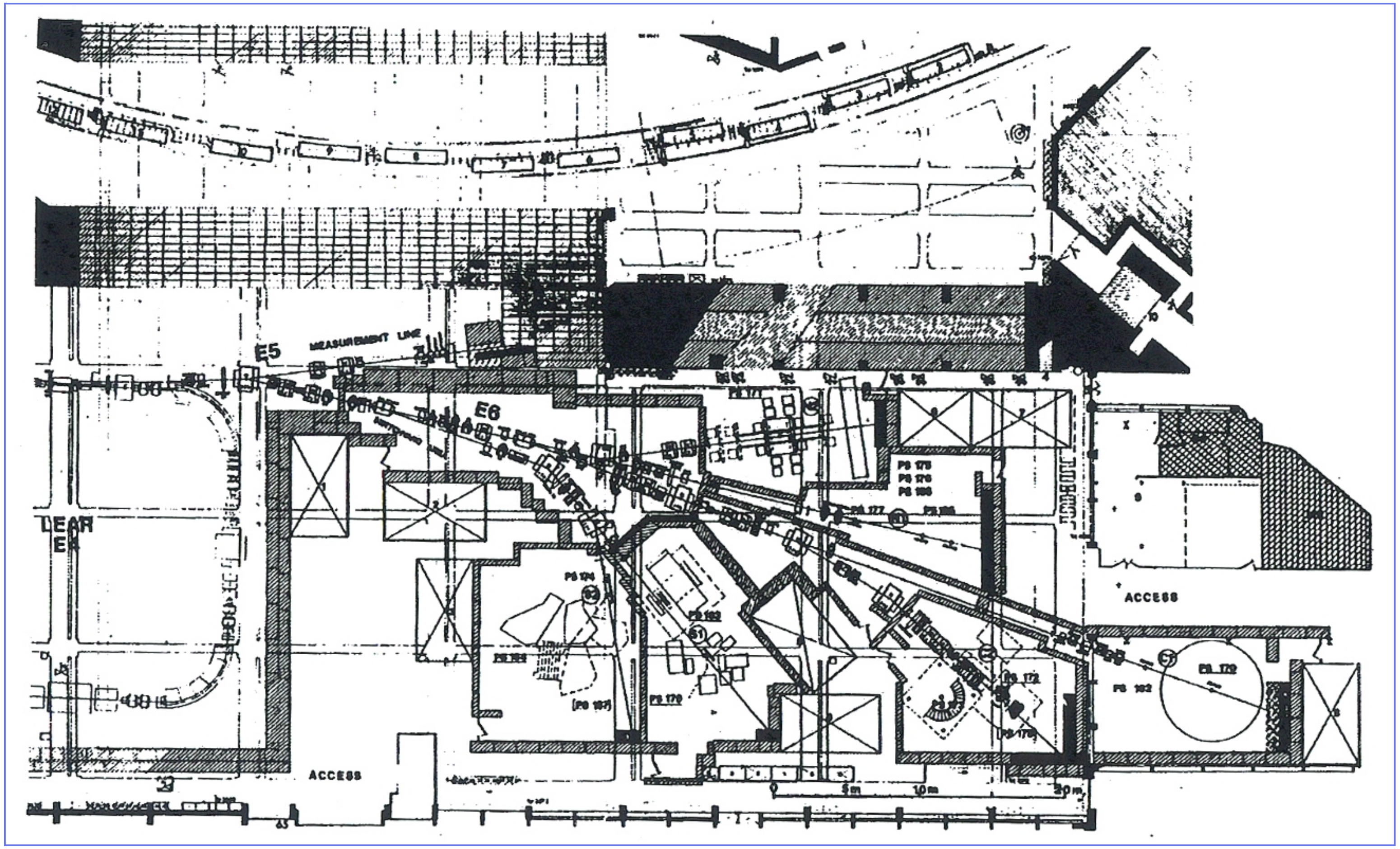
Special case: Trap experiments



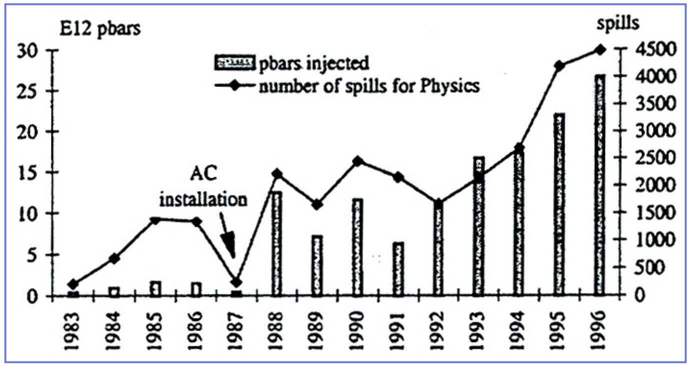
LEAR

Production of Antiprotons and Antiproton Beams (6)

$\bar{p}$-Beams @ LEAR



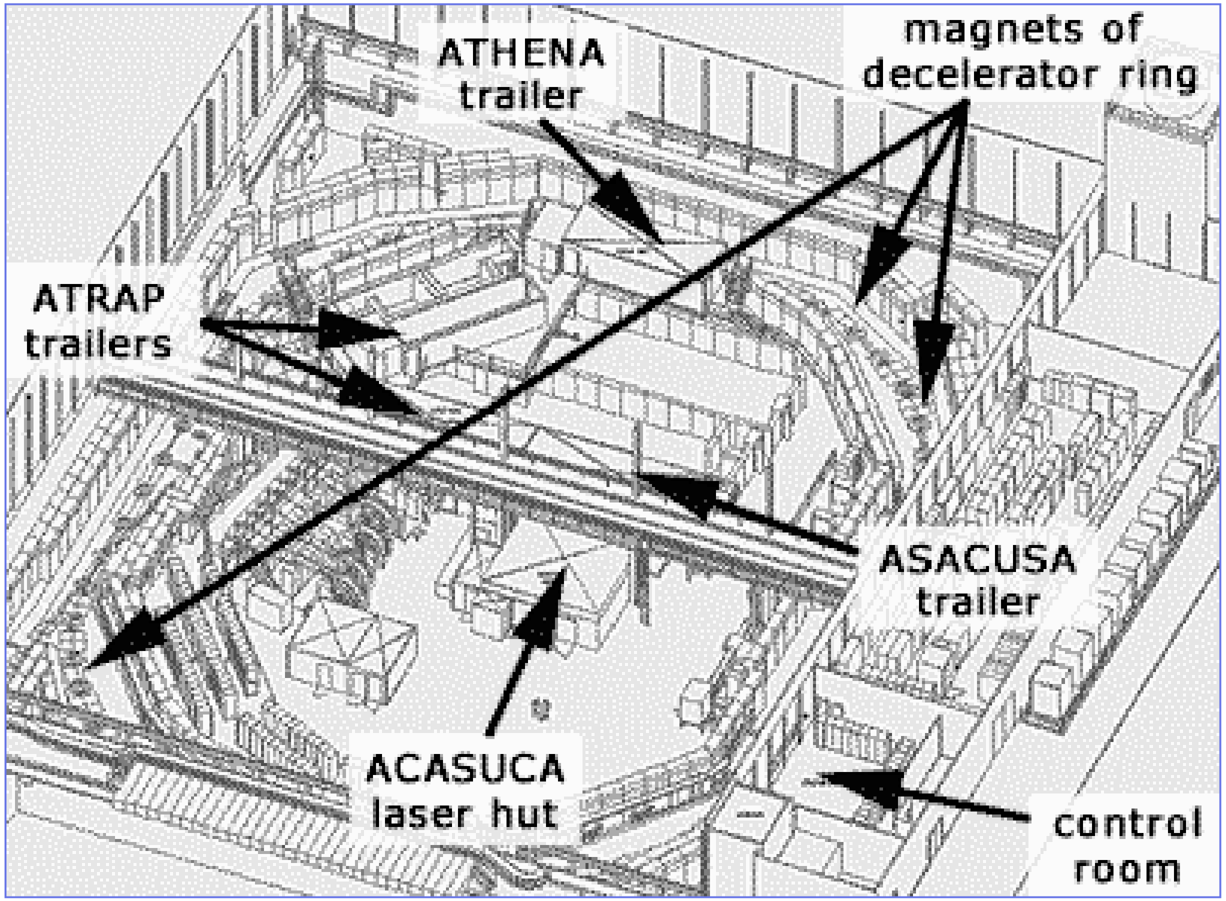
Performance of LEAR



Production of Antiprotons and Antiproton Beams (7)

Antiproton-Decelerator at CERN (AD) (2001 - Today)

Refurbished version of AC with electron cooling



Pulsed machine, only usable
for special kinds of experiments

Delivers pulsed $\bar{p}$-beams down
to 100 MeV/c
$\approx 10^7$ $\bar{p}$'s in a pulse of 0.2 - 0.5 μs
Cycle time ≈ 1 min

$\bar{p}(\bar{n})$-N-Interactions (1)

Interactions in flight $(200\ \mathrm{MeV/c} \leq p_{\bar{p}}^{Lab} \leq 10^6\ \mathrm{GeV/c})$

Investigations of

– Total cross section σ_{Tot}
– Elast. cross section: σ_{el}, $d\sigma_{el}/dt$, ρ-Parameter
– Charge exchange: $\bar{p}p \rightarrow \bar{n}n$

} Comparison with p(n)N-processes

– Inelastic Interaction (without annihilation),
e.g. $\bar{p}p \rightarrow N^*N^* \rightarrow N\pi N\pi$, ... (Baryon-Resonances)
– Annihilation,
e.g. $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$, $X\pi$, $X\pi\pi$ (X = Meson-Resonances)

} Inclusive/exclusive Data

(not existent in NN-interactions; Relevant for low energies)

– Special inelastic channels (Very high energy):

$$\bar{p}p \rightarrow W^{\pm},\ Z^0 + X$$

$$\bar{p}p \rightarrow t\bar{t} + X$$

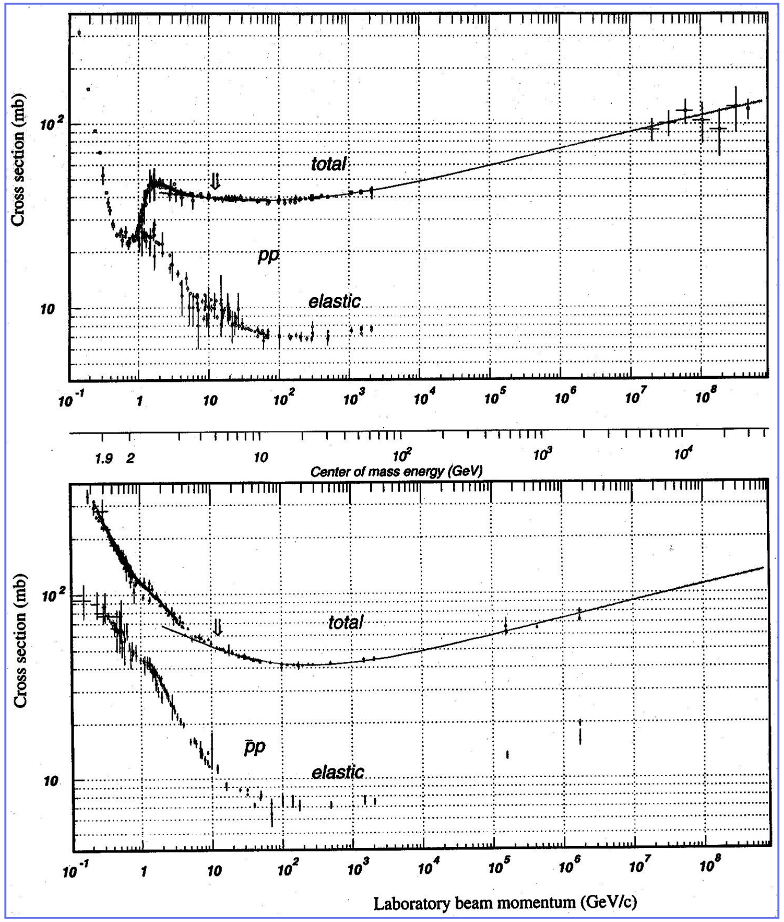
$\bar{p}(\bar{n})$-N-Interactions (2)

Characteristic Features

Total Cross Section

Low energy: σ_{Tot} ($\bar{p}$p) > σ_{Tot} (pp) (Annihilation!)

High energy: σ_{Tot} ($\bar{p}$p) ≈ σ_{Tot} (pp) (Pomeranchuk)
Regge-Description



Elastic Cross Section

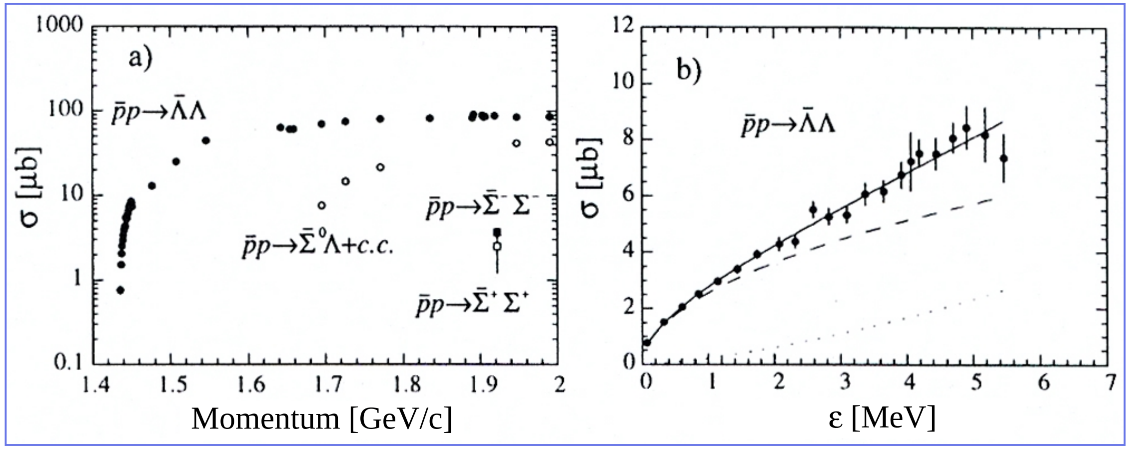
Mainly diffractive (∅ disc ≈ 1.3 fm)

p̄(n̄)-N-Interactions (3)

Inelastic Interactions

Low Energies :

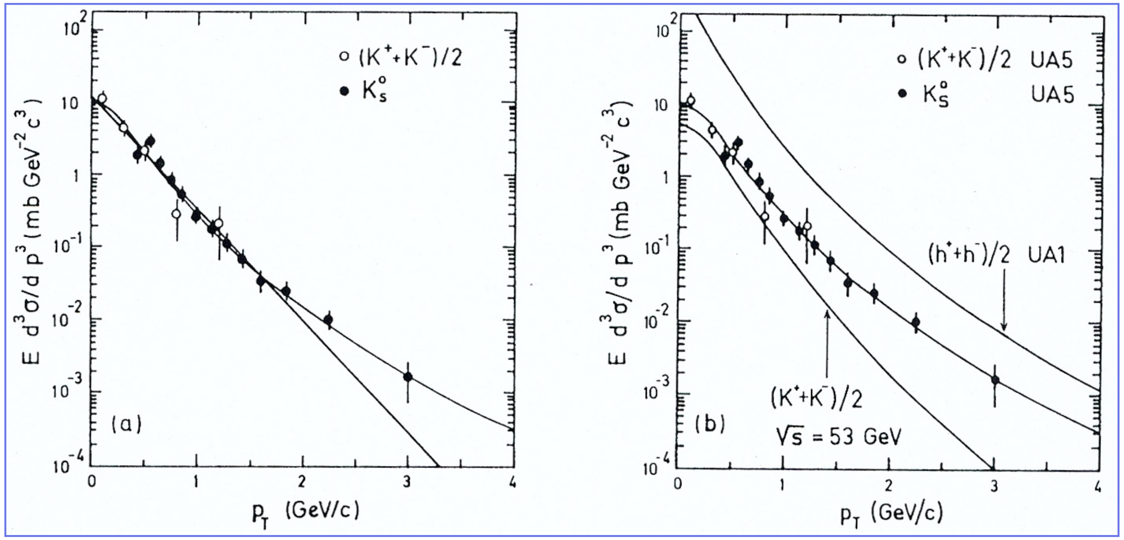
Baryon-Spectroscopy, e.g.



High Energies :

Only inclusive measurements (Multiplicities, Rapidity distributions, ...)

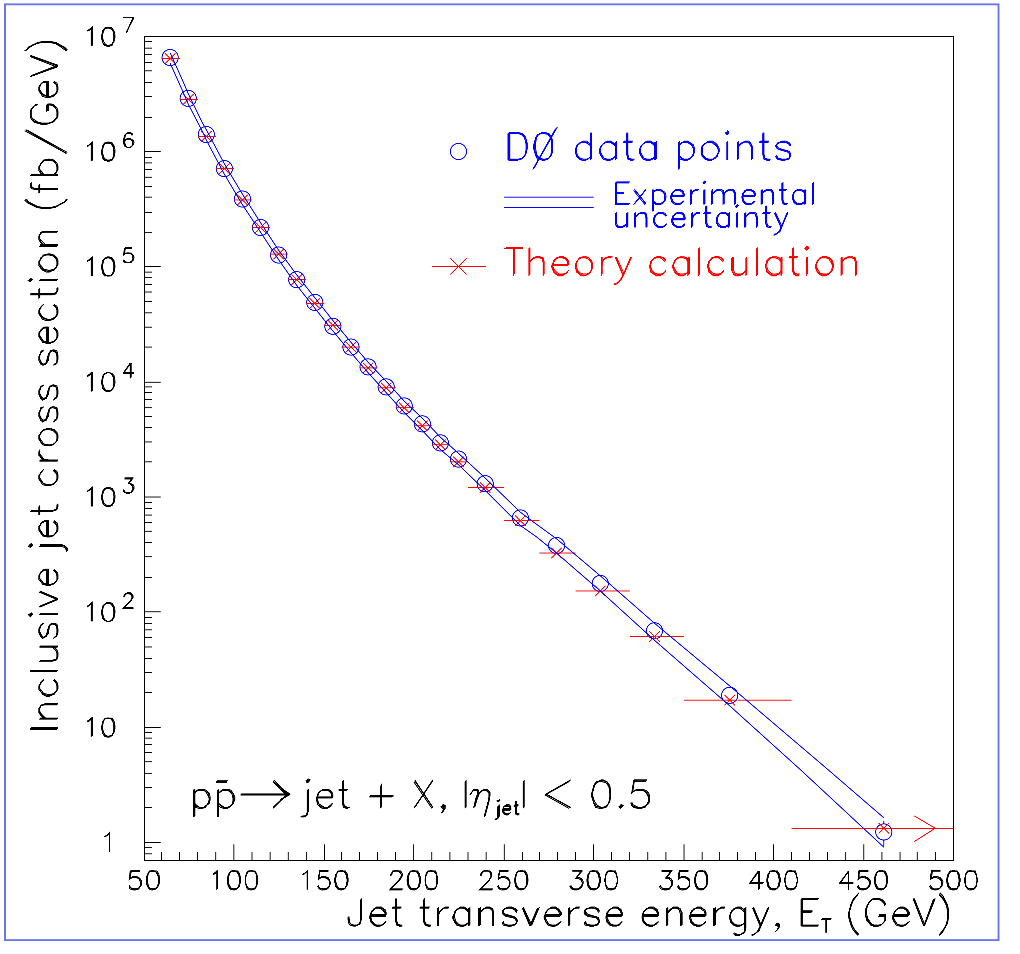
Bulk of events: Most particles forward/backward in CMS: $\langle p_t \rangle \approx 0.4$ GeV/c



$\bar{p}(\bar{n})$-N-Interactions (4)

High p_t-events: Formation of Jets

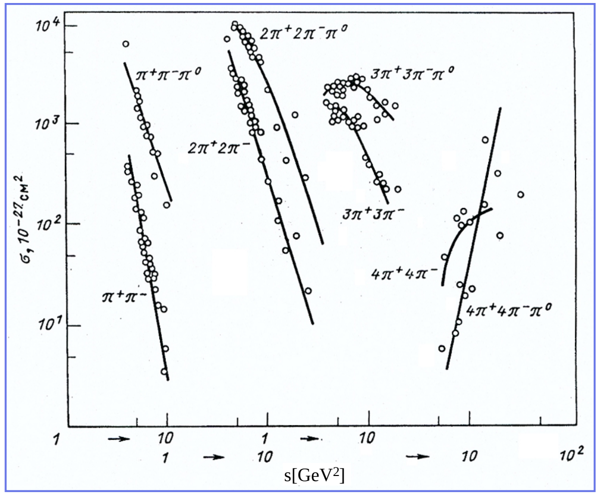
$\bar{p}p \rightarrow \text{Jet} + X, |\eta_{\text{Jet}}| < 0.5$



$\bar{p}(\bar{n})$-N-Interactions (5)

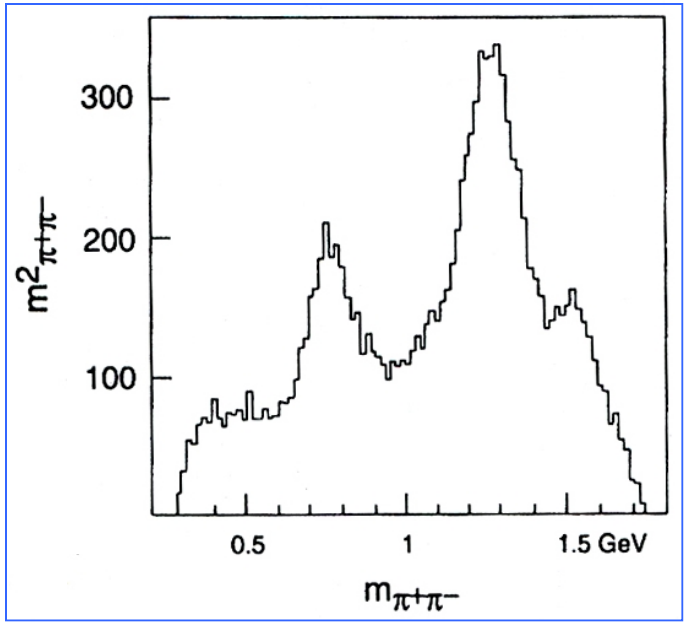
Annihilation

Annihilation cross sections drop quickly with energy
Mass production favored in comparison with energy production

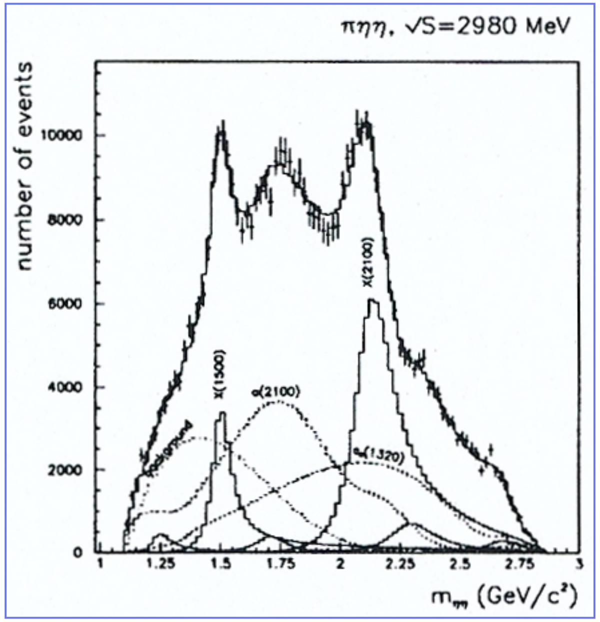


Source for Meson/Exotic-Spectroscopy

$\bar{n}$(100-380 MeV/c)p $\rightarrow \pi^+ \pi^- \pi^+$ (Obelix)



$\bar{p}$(6 GeV/c)p $\rightarrow \eta\eta\, \pi^0$ (E835)

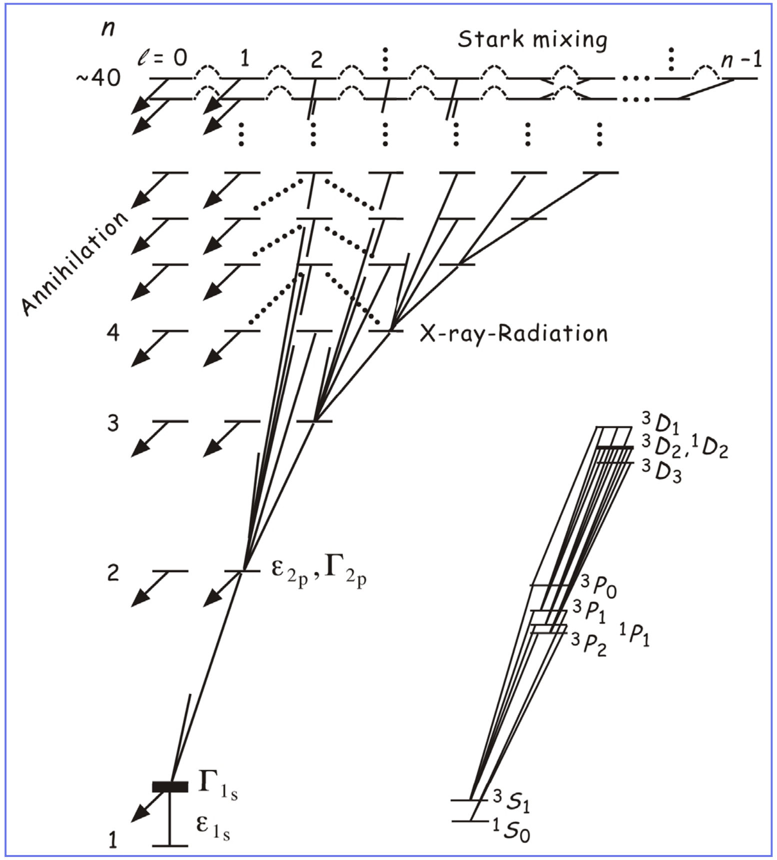


$\bar{p}(\bar{n})$-N-Interactions (6)

Special case: $\bar{p}$-Interactions at rest ($p_{\bar{p}} \approx 0$ MeV/c)

Low energy ($\leq$ 200 MeV/c) antiprotons are slowed down in a Hydrogen target (Bethe-Bloch) and finally form a $\bar{p}p(d)$-atom

Energy Level Scheme of $\bar{p}p$



Capture in atomic levels: n ≈ 30 - 40
Population of L-substates: $0 \leq L \leq n - 1$
Lifetime of states (→ μs)
Deexcitation: Collisions, Auger-, X-ray emission
Level mixing: Stark-Effect
Atom disappears via annihilation from s- and p-states mainly
Vacuum: Mainly annihilation from 2p-state
LH_2: Mainly annihilation from s-state
s-, p- levels are shifted (ε) and broadened (Γ) by strong interaction effects

$\bar{p}(\bar{n})$-N-Interactions (7)

Physics with stopped Antiprotons

Very rich possibilities, mostly explored at LEAR

– Low energy $\bar{p}p(n)$-interactions

Measurement of shifts and widths of atomic levels $\rightarrow$ Complex scattering lengths, ρ-parameter at threshold

– Meson/Exotics-Spectroscopy

$\bar{p}p$-annihilation at rest very rich source for most $q\bar{q}$-resonances ($\lesssim 1.7$ GeV/c^2)

Candidates for exotic states clearly seen: $f_0(1500)$, $\pi_1(1400)$, E/i(1400)

Unique possibility:

Observe the same annihilation process for different H_2-pressures

↪ Change of initial state distribution

↪ Helps identifiying J^{PC} of the resonances

– $\bar{p}p$-Annihilation = Rich source for K^0, $\overline{K}^0$, η, $K^{\pm}$, ...

↪ Precision Test of CP/T-Violation

↪ Test of chiral perturbation QCD

↪ Production of Hypernuclei

– Strangeness Content of Nucleon/Antinucleon

– Antiprotonic Atoms

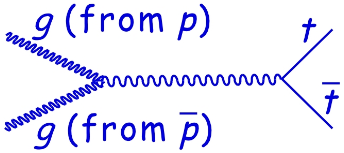
Discovery of the Top-Quark (1)

FNAL: 1995

Tevatron : $\sqrt{s} = 1.8$ TeV

Detectors : CDF, D∅

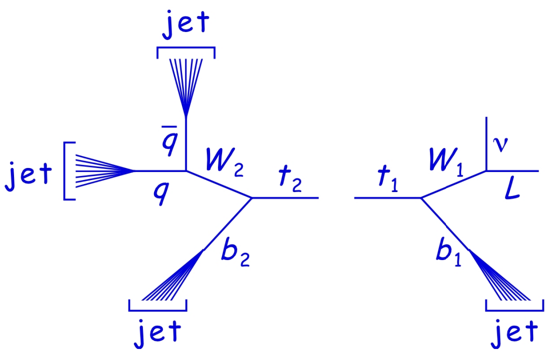
Dominant Production



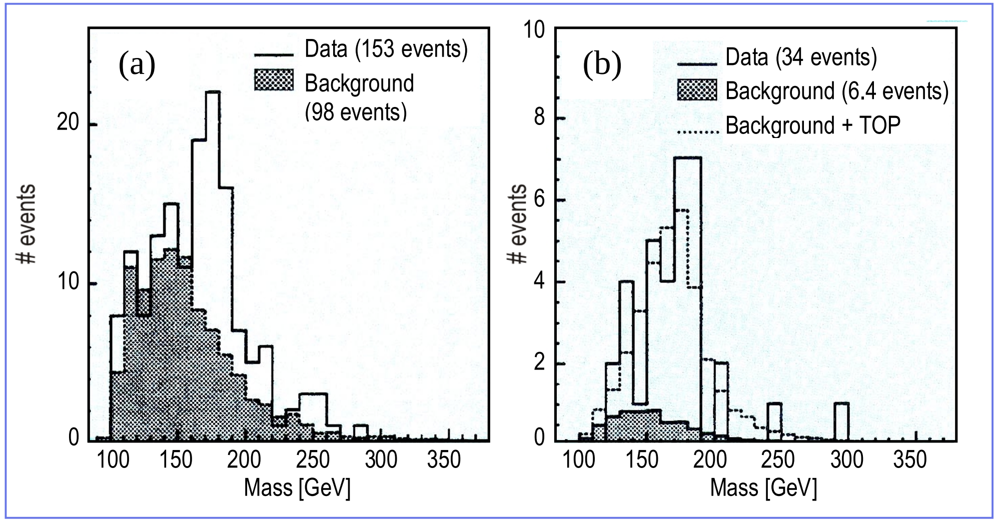
$\sigma \approx 4$ pb (High $p_\perp$)

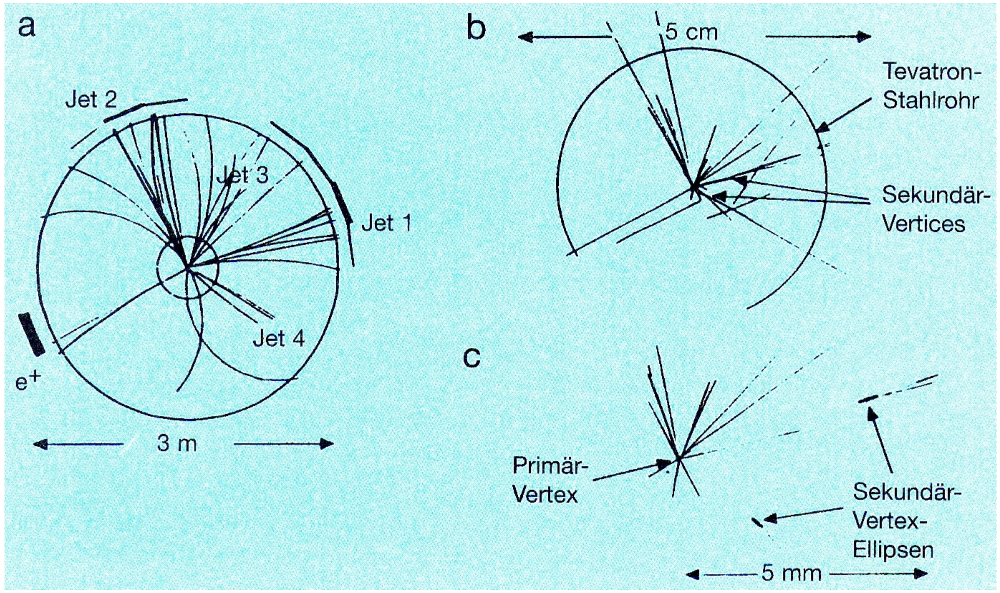
($\sigma_{Tot} \approx 60$ mb (10 o.m. bigger) ($< p_\perp > \approx 0.5$ GeV))

Dominant Decay



Trigger on high $p_\perp$ and secondary (b) vertex





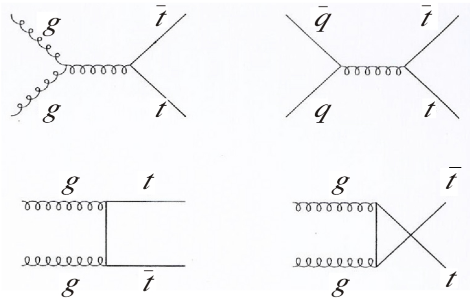
$\Rightarrow m_t = (174.3 \pm 5.1)$ GeV/c^2

$\sigma(\bar{p}p) \rightarrow t\bar{t})$ in agreement with SM-predictions

Discovery of the Top-Quark (2)

Production Mechanisms

SM: (a) Pair production $p\bar{p} \rightarrow t\bar{t} + X$

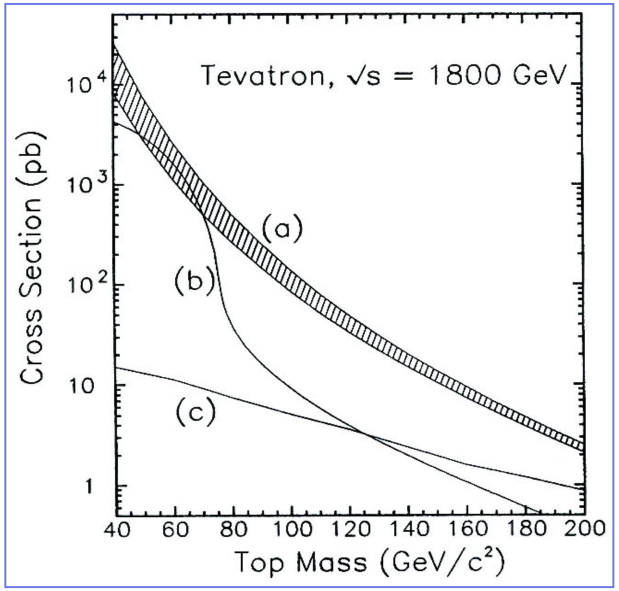


Dominant for $\sqrt{s}$ = 1.8 TeV and $m(t)$ = 175 GeV
Z, $\gamma \rightarrow t\bar{t}$ also possible, but small cross section

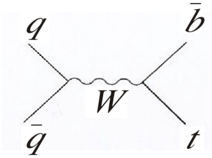
$\sigma(\bar{p}p \rightarrow t\bar{t} + X)$ ($\sqrt{s}$ = 1.8 TeV; m(t) = 175 GeV) ≈ 10pb

(≈ 10^{-10} x $\sigma_{inelast.}$)

Top-production cross sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. (a) $p\bar{p} \rightarrow t\bar{t}$ from Laenen, Smith, and van Neerveen (1994) (the band represents the estimated theoretical uncertainty), (b) sum of $t\bar{b}$ and $\bar{t}b$ from W decay (Drell-Yan), (c) sum of $t\bar{b}$ and $\bar{t}b$ from W-gluon fusion. See text for details.



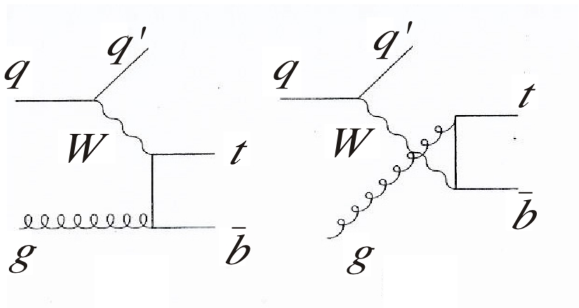
(b) Drell-Yan Production (Single t-production) $\bar{p}p \rightarrow W^{+} + X$
↪ $t\bar{b}$



Small cross section for $\sqrt{s}$ = 1.8 TeV ≈ 0.9pb

Discovery of the Top-Quark (3)

(c) W-Gluon-Fusion (Single t-production) $p\bar{p} \rightarrow t\bar{b} + X$



Small cross section for $\sqrt{s} = 1.8$ TeV ≈ 2.4pb

$\lceil \sigma_{pp} \rightarrow t\bar{t} + X$ ($\sqrt{s} = 14$ TeV ; LHC) ≈ 700pb $\rfloor$

Discovery of the Top-Quark (4)

Decay Modes

SM: $t \to W + b$ Dominant

$$\left.\begin{array}{l}\to W + c \\ \to W + d\end{array}\right\} \text{CKM unterdrückt}$$

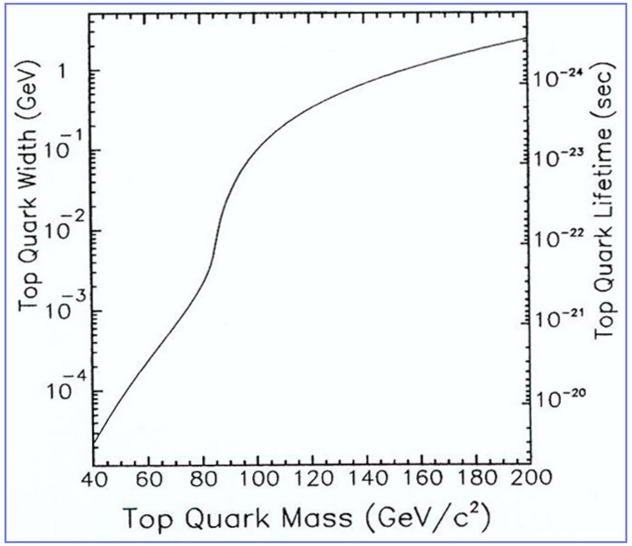
Very small rates:

$t \to q\gamma$ (FCNC)

$t \to qZ$ (")

$\vdots$

Lifetime of Top-Quark



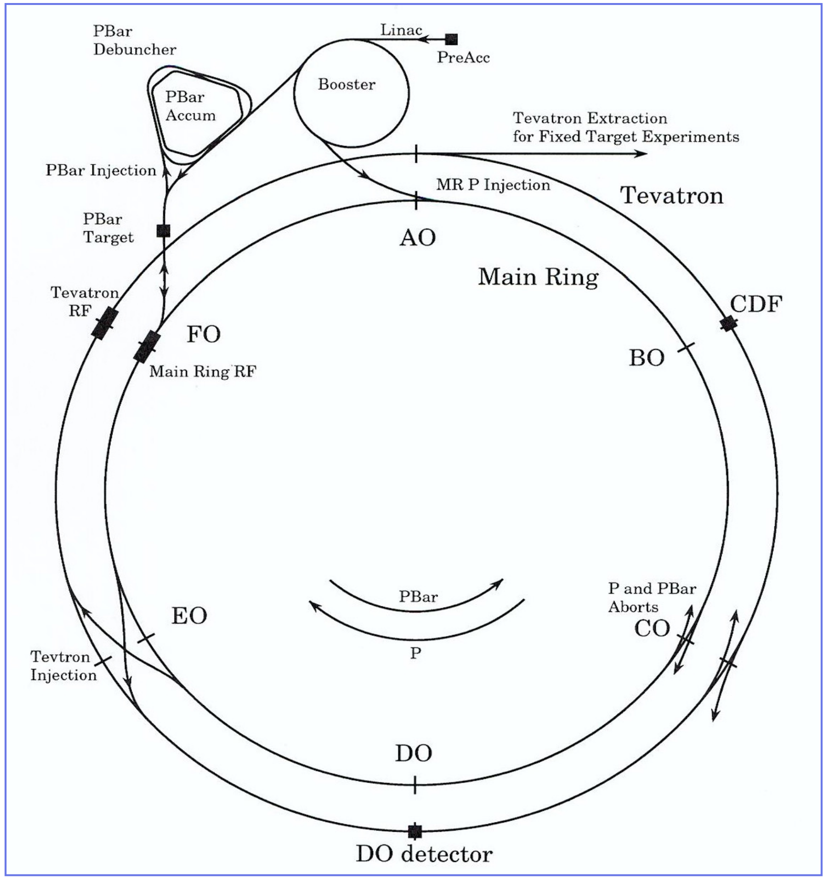
Decay modes in $p\bar{p} \to t\bar{t} + X$

Decay modes for a $t\bar{t}$ pair and their lowest-order branching ratios standard model decays

Decay mode	Branching ratio
$t\bar{t} \to q\bar{q}q\bar{q}b\bar{b}$	36/81
$t\bar{t} \to q\bar{q}e\nu b\bar{b}$	12/81
$t\bar{t} \to q\bar{q}\mu\nu b\bar{b}$	12/81
$t\bar{t} \to q\bar{q}\tau\nu b\bar{b}$	12/81
$t\bar{t} \to e\nu\mu\nu b\bar{b}$	2/81
$t\bar{t} \to e\nu\tau\nu b\bar{b}$	2/81
$t\bar{t} \to \mu\nu\tau\nu b\bar{b}$	2/81
$t\bar{t} \to e\nu e\nu b\bar{b}$	1/81
$t\bar{t} \to \mu\nu\mu\nu b\bar{b}$	1/81
$t\bar{t} \to \tau\nu\tau\nu b\bar{b}$	1/81

Discovery of the Top-Quark (5)

Run 1: $\bar{p}p$ (E_{CM} = 1.8 TeV); $L_{Peak} = 2 \times 10^{31}\ cm^{-2}s^{-1}$; $\int Ldt = 162 (pb)^{-1}$
(1992-96)

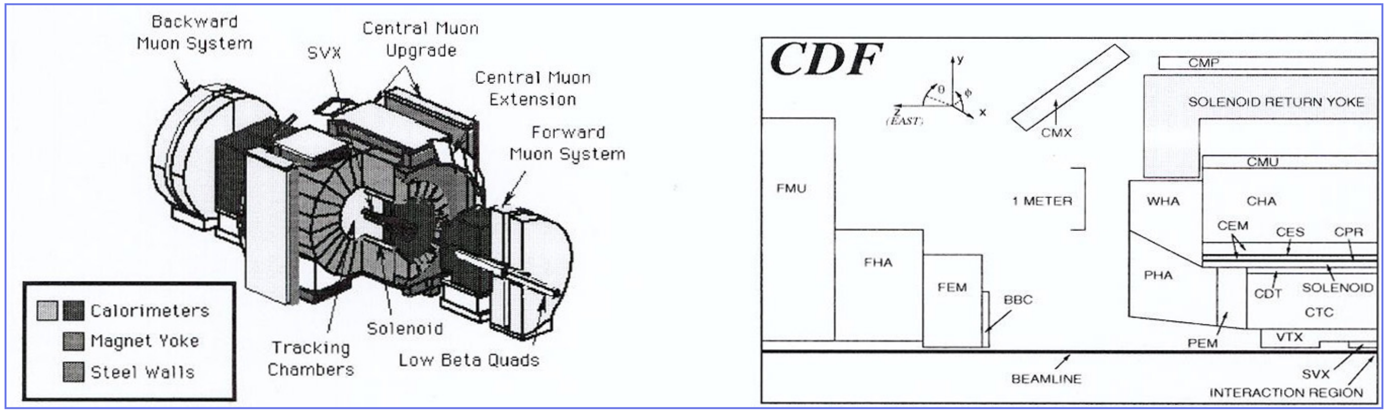


Run 2: Main Ring $\rightarrow$ Main Injector ($L \rightarrow 8 \times 10^{31}\ cm^{-2}s^{-1}$); Recycler ($L \rightarrow 2 \times 10^{32}$);
(2001$\rightarrow$) 1.8 TeV $\rightarrow$ 2.0 TeV

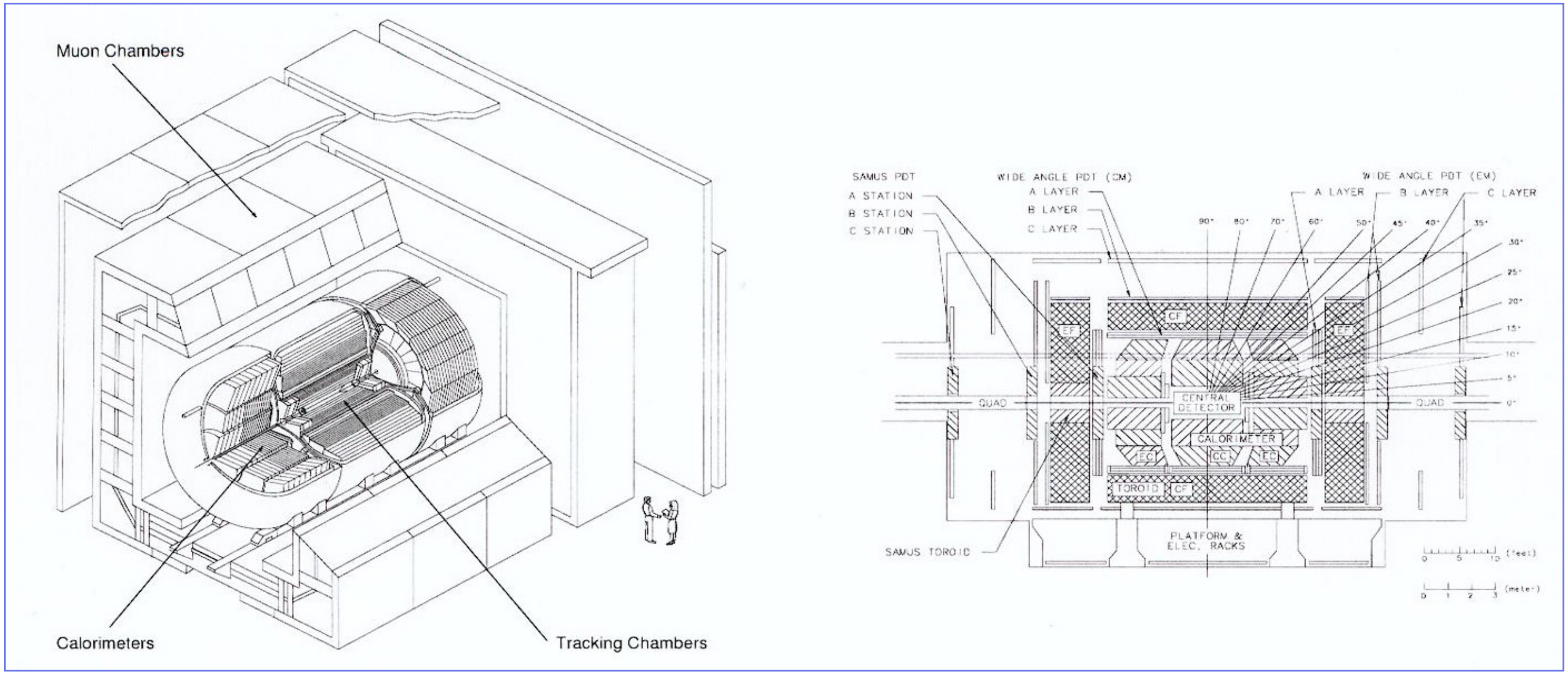
Detector Upgrades: DO: Central magnetic field; Si-Vertex-Det.; Scint. Fiber Tracker
CDF: Expanded Vertex Detector

Discovery of the Top-Quark (6)

CDF-Detector:



DO-Detector:



Discovery of the Top-Quark (7)

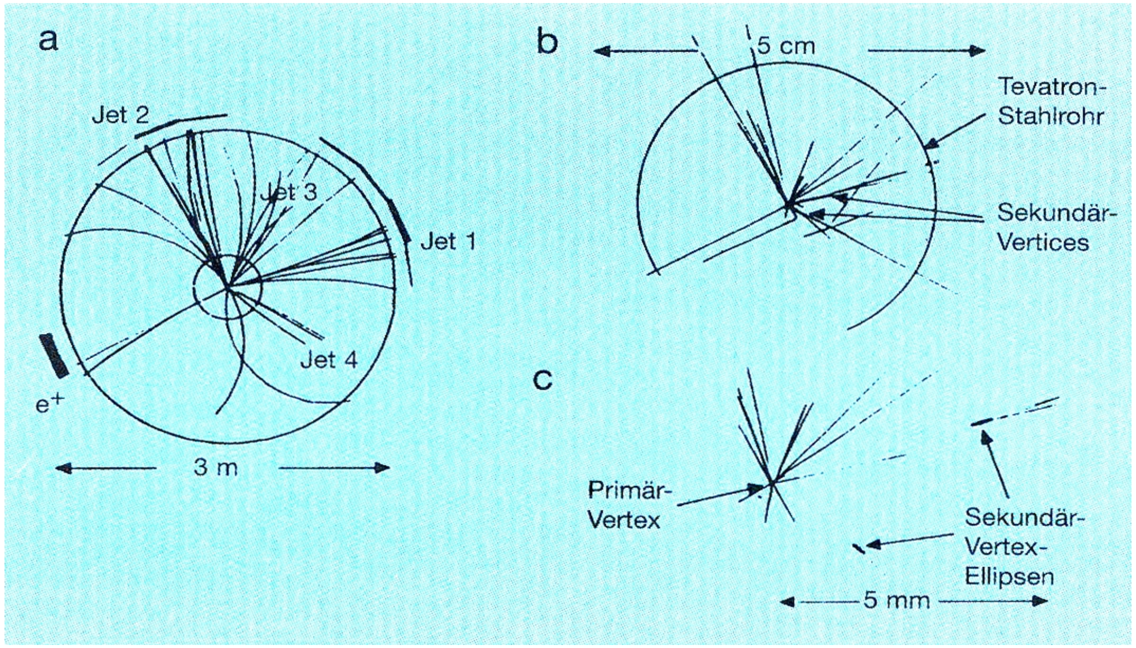
Lepton + Jets-Channel:

b-Jet, $\bar{b}$-Jet, Charged Lepton, Missing ν, q-Jet, $\bar{q}$-Jet

Cuts as above + topologial conditions (sphericity/aplanarity)

Observed events	Est. Background
34 (DVT)	9.2 ± 1.5
40 (SLT)	22.6 ± 2.8

Typical event:



Discovery of the Top-Quark (8)

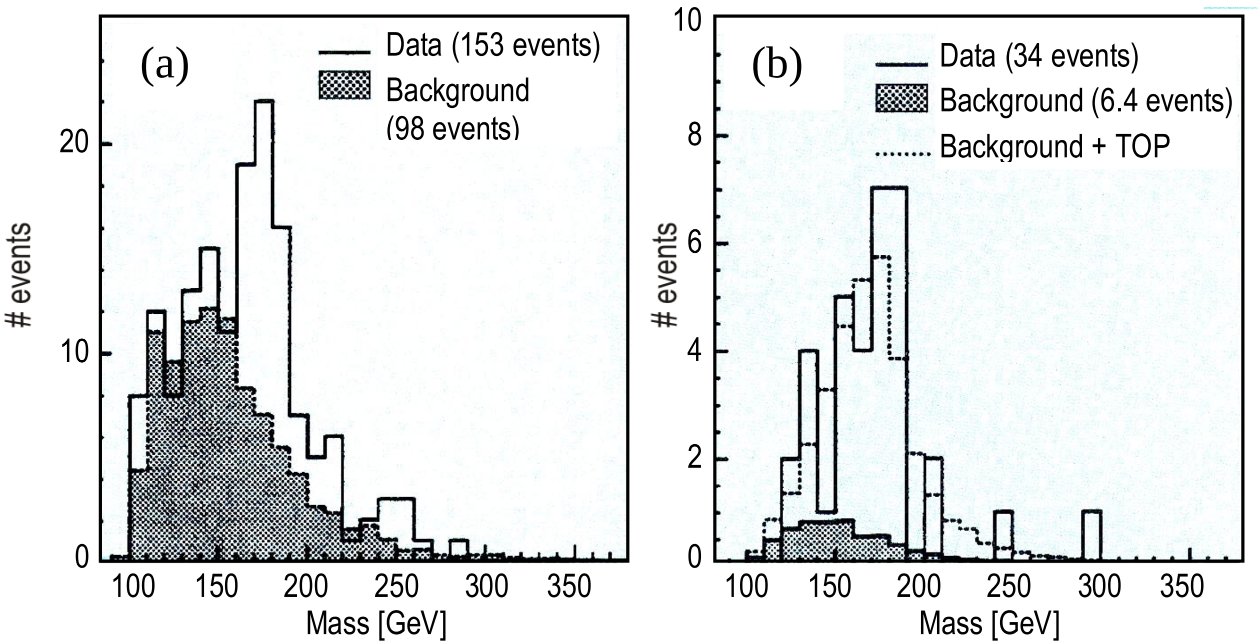
All Jet-Channels

b-Jet; $\bar{b}$-Jet; 2q-Jets; 2$\bar{q}$-Jets

Cuts as above + highly sophisticated topologies

Observed events	Est. Background
187 (DVT)	142 ± 12
157 (SLT)	120 ± 18

Resulting Spectra (CDF)

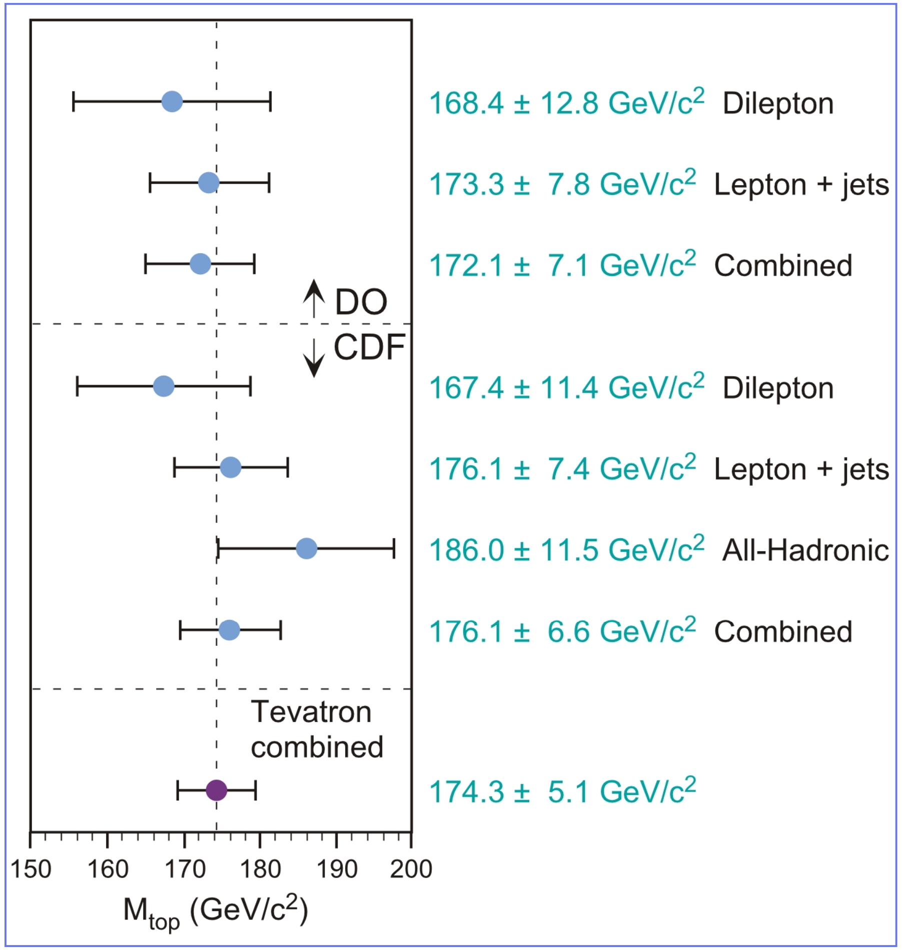


No *b*-Tag *b*-Tag

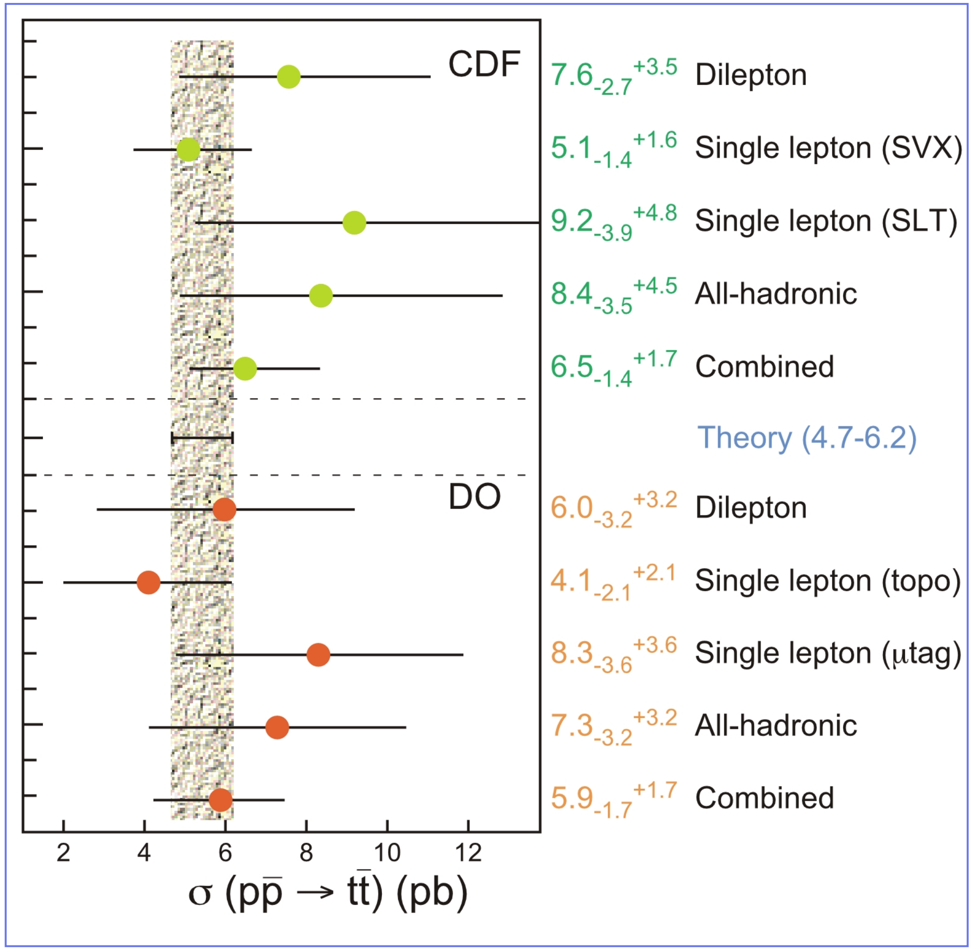
Discovery of the Top-Quark (9)

Mass : m_t

Tevatron Top Quark Mass Measurements



Production Cross Section : $\sigma_{t\bar{t}}$



Common Fit to data with m_t and $\sigma_{t\bar{t}}$ as free parameters

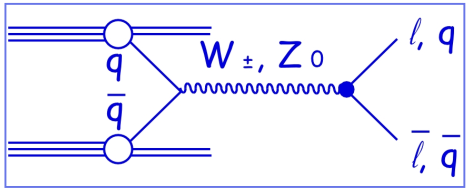
SM predictions well fulfilled. Also width in agreement with SM

Discovery of the Intermediate Vector Bosons $W^{\pm}$, Z^0 (1)

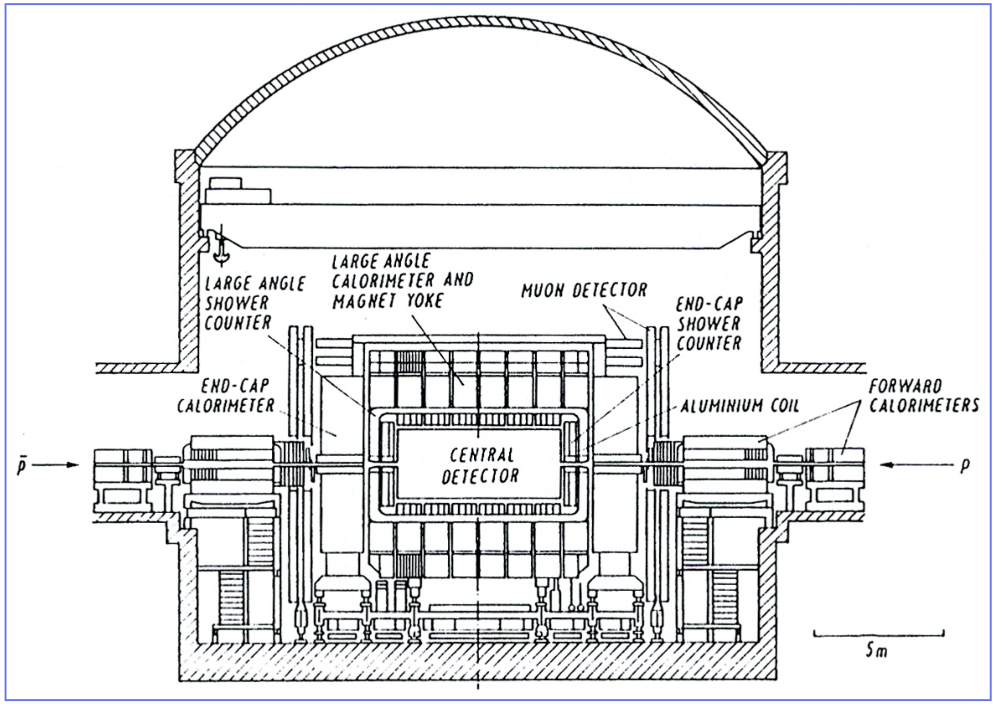
CERN (1983)

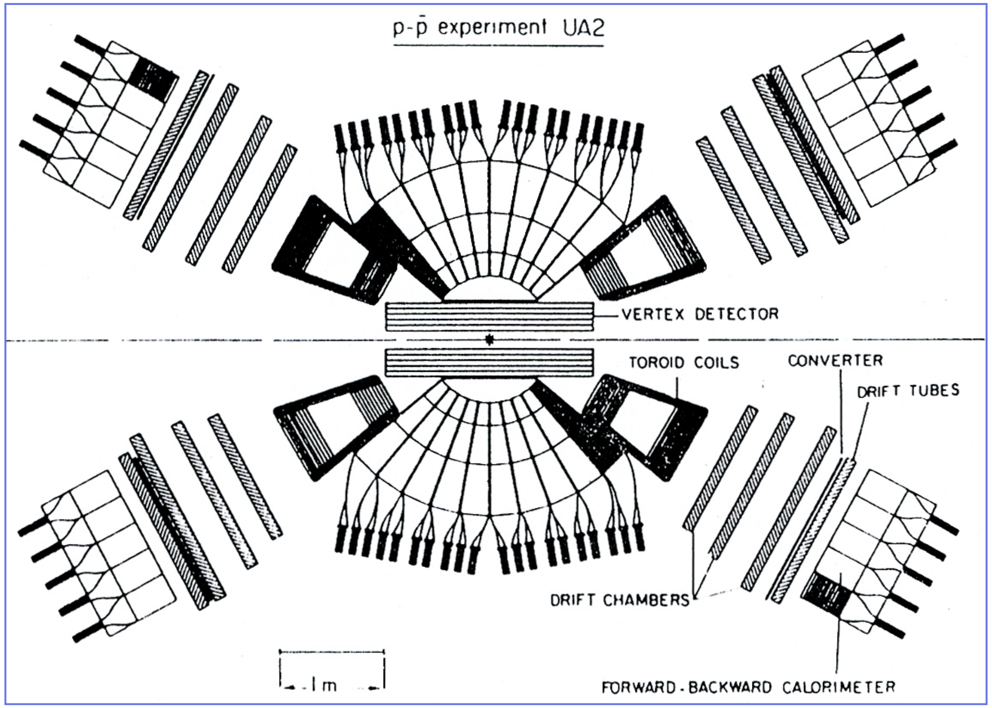
SPSC : $\sqrt{s}$ = 630 GeV
Detectors : UA1, UA2

Production/Decay
(Drell-Yan)

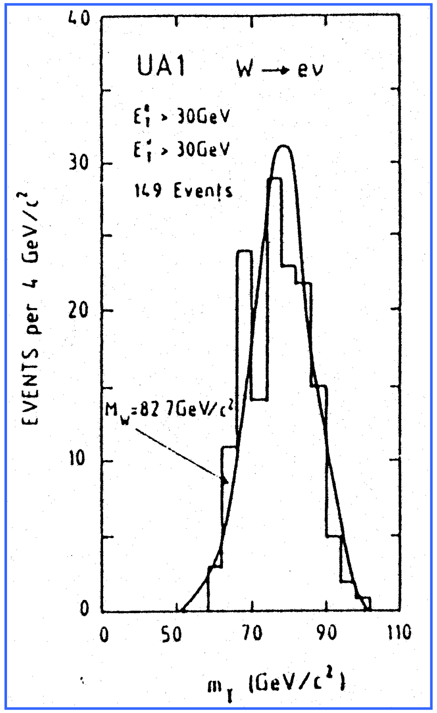


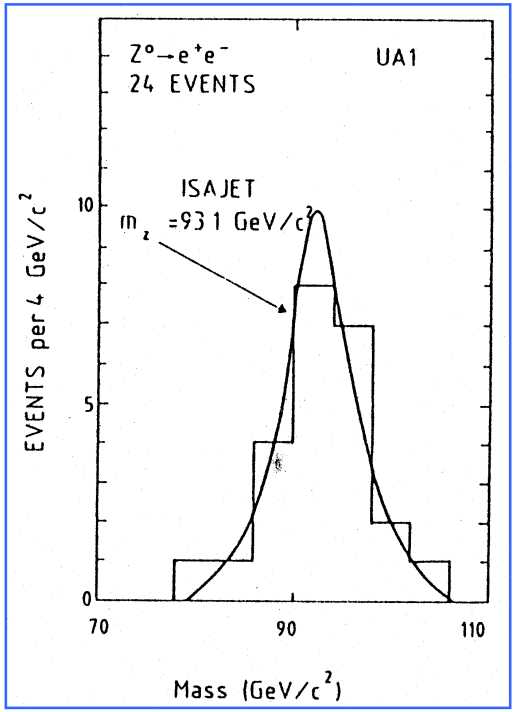
$\sigma \approx$ (1-5) nb (High $p_\perp$)
$\sigma_{Tot} \approx$ 50 mb (7 o.m. bigger) ($< p_\perp > \approx 0.4$ GeV)

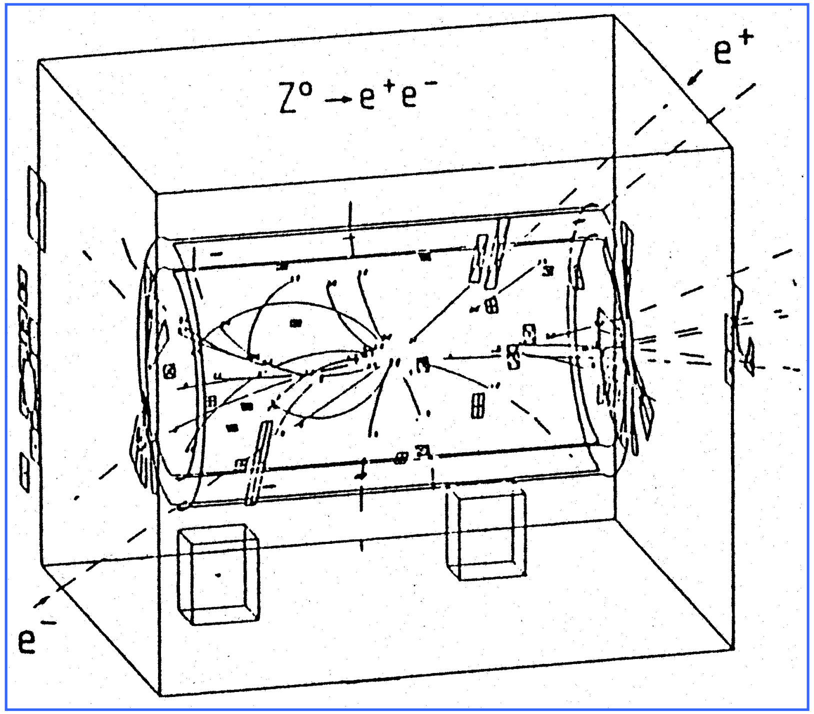




Discovery of the Intermediate Vector Bosons $W^{\pm}$, Z^0 (2)







$$m_{W^{\pm}} = \begin{array}{l} (80.2 \pm 0.6 \pm 0.5 \pm 1.3)\ \mathrm{GeV}/c^2\ (\mathrm{UA1}) \\ (82.7 \pm 1.0 \pm 2.7)\ \mathrm{GeV}/c^2\ (\mathrm{UA2}) \end{array} \qquad \Gamma_W \leq 5.4\ \mathrm{GeV}/c^2 \quad ; \quad J_P(W) = 1^-$$

$$m_{Z^0} = \begin{array}{l} (93.1 \pm 1.0 \pm 3.1)\ \mathrm{GeV}/c^2\ (\mathrm{UA1}) \\ (91.4 \pm 1.2 \pm 1.7)\ \mathrm{GeV}/c^2\ (\mathrm{UA2}) \end{array} \quad ; \quad \Gamma_{Z^0} = \begin{array}{l} (2.7\ {}^{+1.2}_{-1.0} \pm 1.3)\ \mathrm{GeV}/c^2\ (\mathrm{UA1}) \\ (2.7 \pm 2.0 \pm 1.0)\ \mathrm{GeV}/c^2\ (\mathrm{UA2}) \end{array}$$

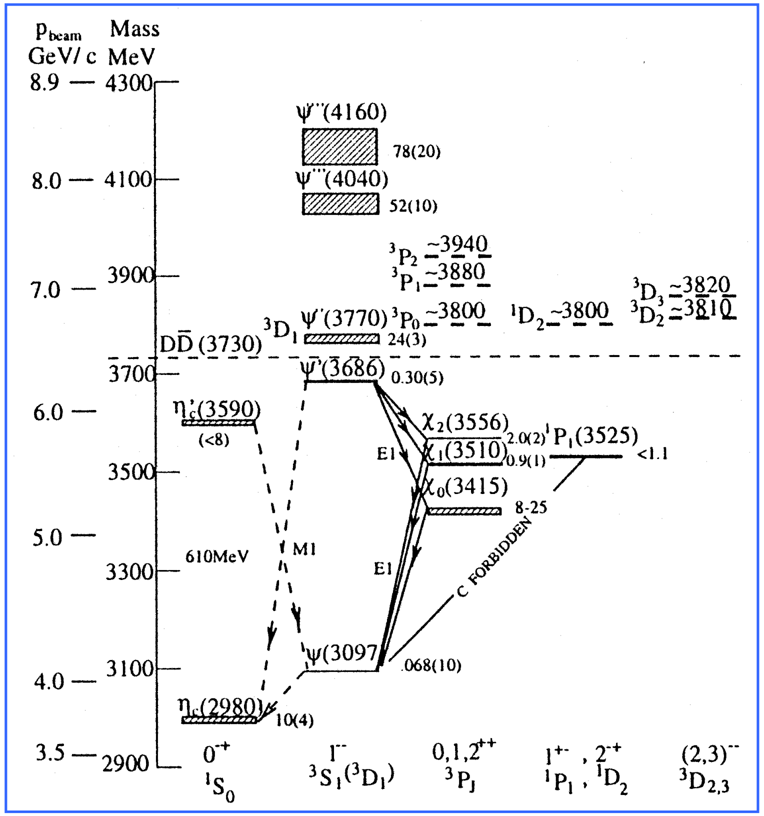
In the meantime: More data from from FNAL and LEP

↪ $m_{W^{\pm}} = (80.423 \pm 0.039)\mathrm{GeV}/c^2$; $\Gamma_{W^{\pm}} = (2.118 \pm 0.042)\mathrm{GeV}/c^2$
$m_{Z^0} = (91.1876 \pm 0.0021)\mathrm{GeV}/c^2$; $\Gamma_{Z^0} = (2.4952 \pm 0.0023)\mathrm{GeV}/c^2$

$c\bar{c}$-Spectroscopy (1)

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

e^+e^--collisions



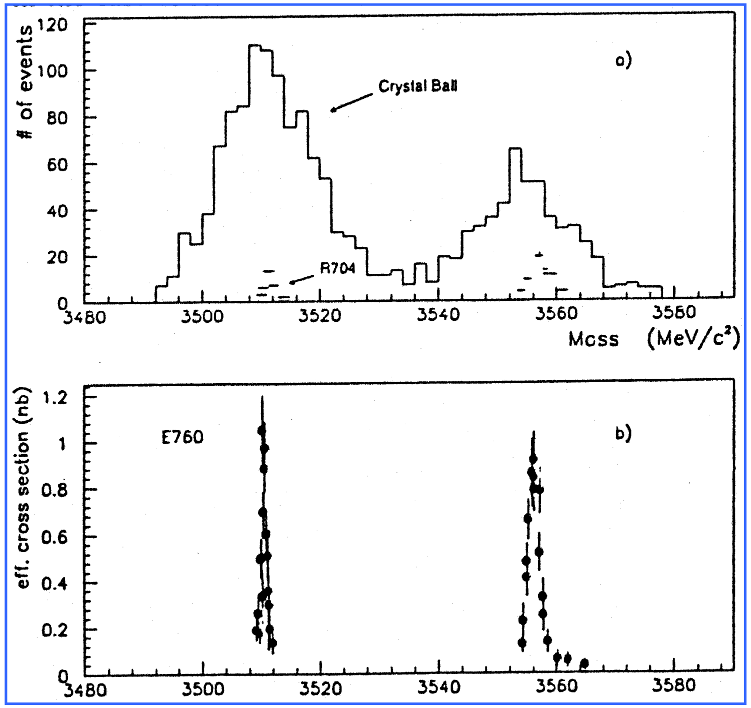
Drawback:

Only $J^{PC} = 1^{--}$ states are directly produced in e^+e^-

Other states are only visible in γ-transitions,

e.g. χ_1, χ_2, χ_0, η_c, η'_c, ...

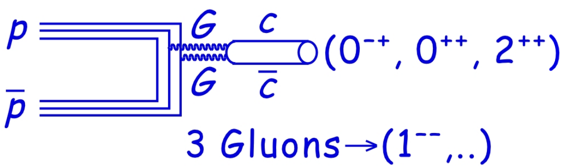
➥ Data with moderate mass resolution



$\bar{p}p$-collisions

All ($c\bar{c}$)-states can be directly formed

Production



Decay

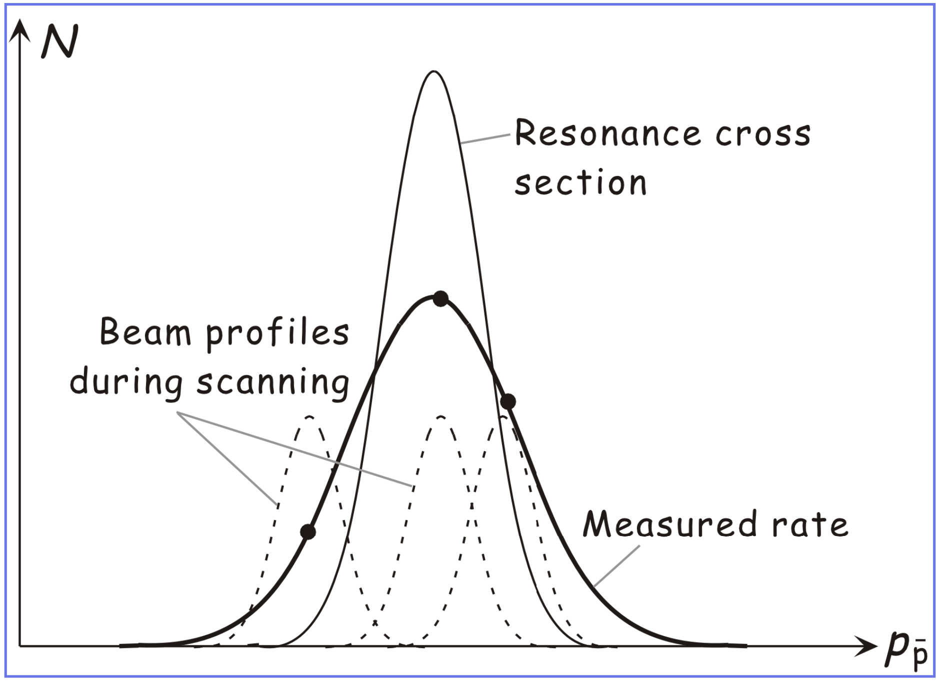
$(C\bar{C})_{g.s.} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, \phi\phi$

$(C\bar{C})_{exc.} \rightarrow (C\bar{C})_{g.s.} + \gamma$

$c\bar{c}$-Spectroscopy (2)

Experimental method

Scan with $\bar{p}$-beam with adjustable momenta (3.4 - 6.3 GeV/c)



$\sigma(\bar{p}p \to (c\bar{c}) \to e+e-, ..) \approx$ nb $\to$ pb

Background:

σ_{Tot} = 50mb $\to$ Trigger on e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$, ..

Resonance parameters from excitation curve

Critical:

Excellent knowledge of beam energy

Very good $\bar{p}$-beam energy resolution ($0 \approx 10^{-4}$)

Experiments:

CERN/ISR: R 704 (Demonstration of method)

Fermilab/$\bar{p}$-Cooler-Ring ($\leq$ 8 GeV/c): E 760, E 835

Many beautiful results

But: Much is to done

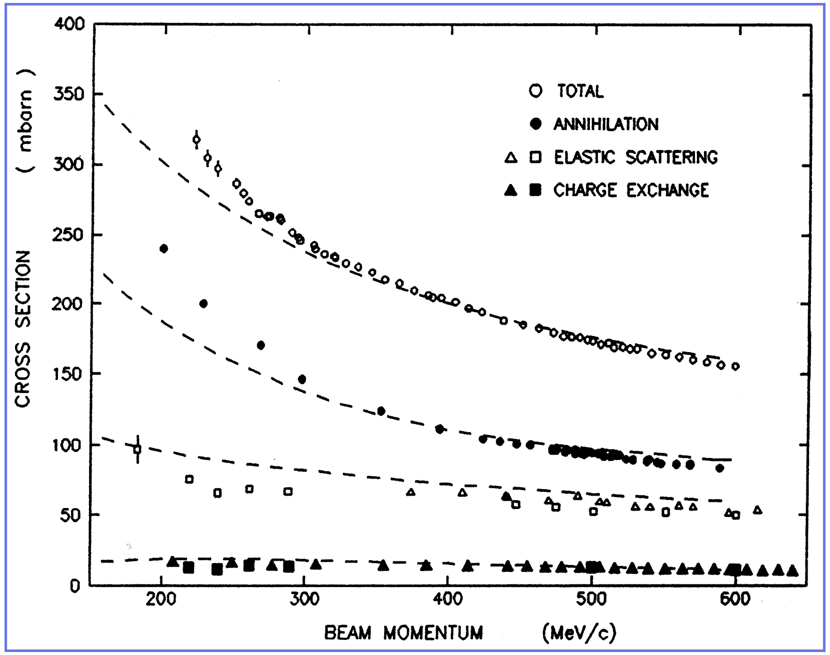
– Search for missing states

– Specific decay modes

⋮

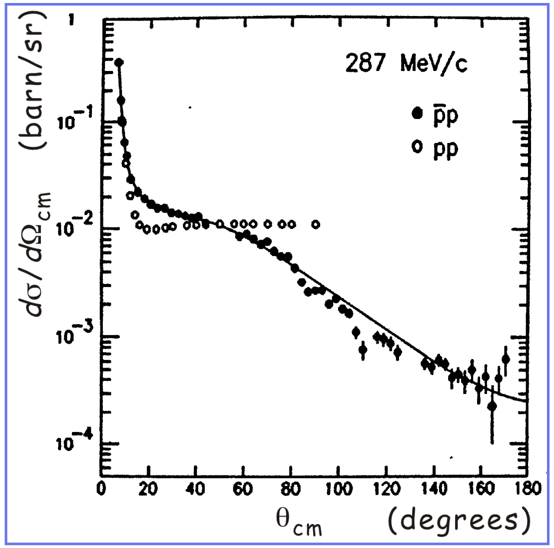
LEAR: Low and medium energy $\bar{p}p(n)$ - Reactions (1)

Total = Elastic + CEX + Annihilation cross section



No structures near threshold → No narrow Baryonium states

Elastic + CEX-scattering

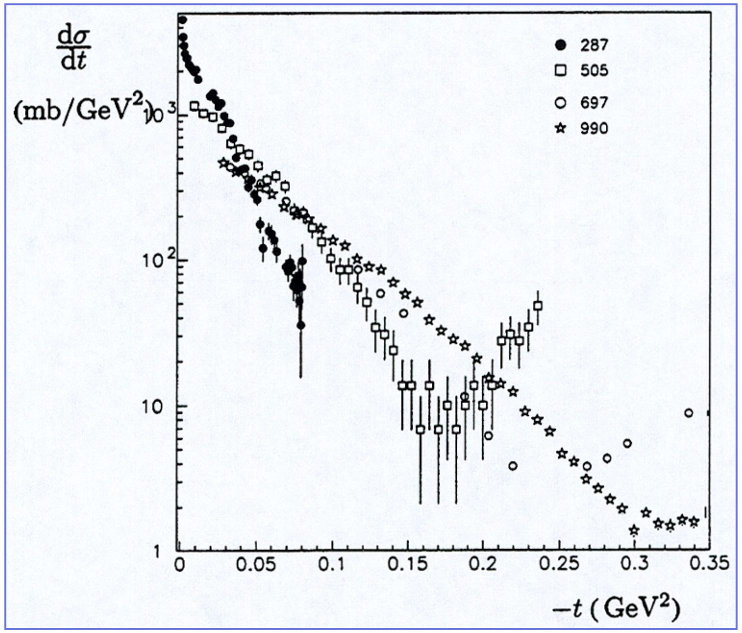


$\frac{d\sigma}{d\Omega}(\theta)$, Analyzing Power (θ), measured from 180(70)-1940 MeV/c

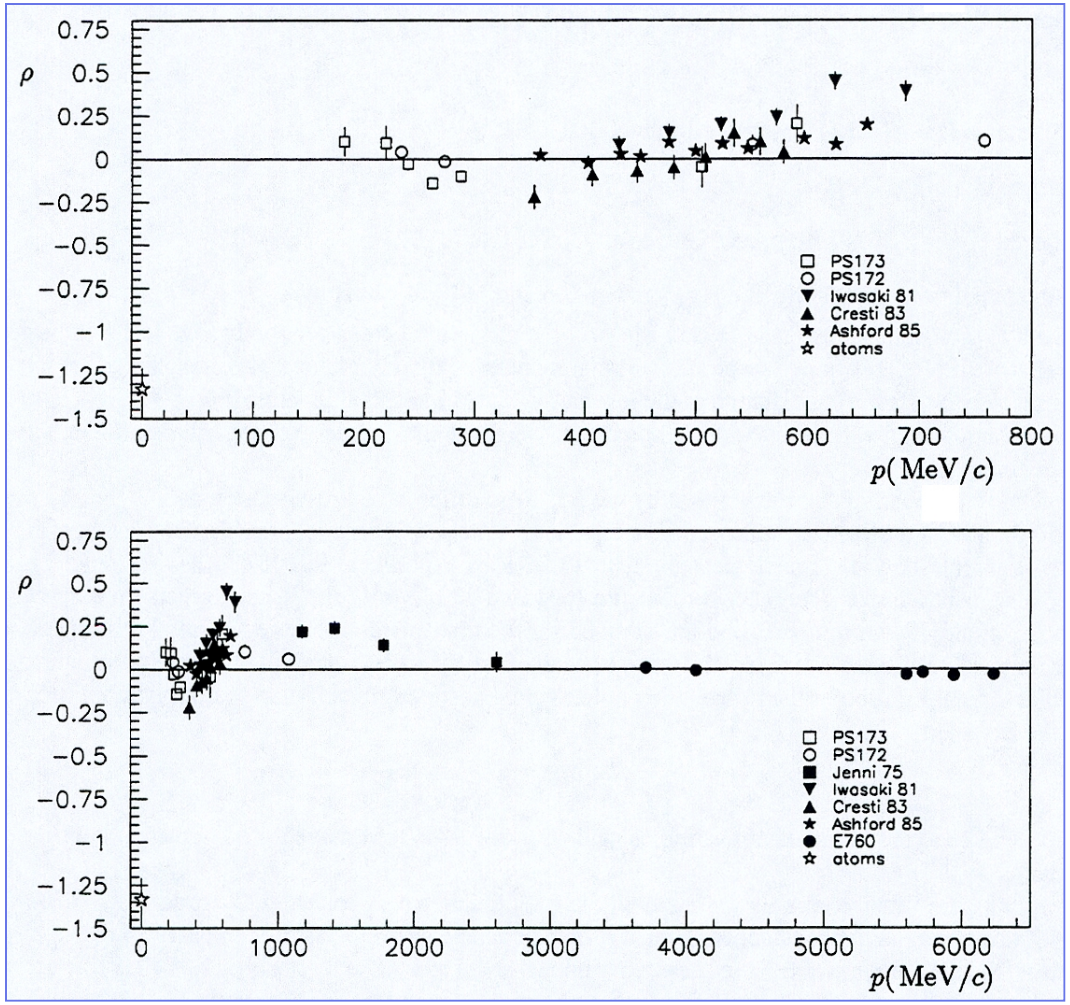
Forward peak like in diffractive scattering
Strong p-wave already at threshold
(Strong s-wave absorption, ≠ pp)

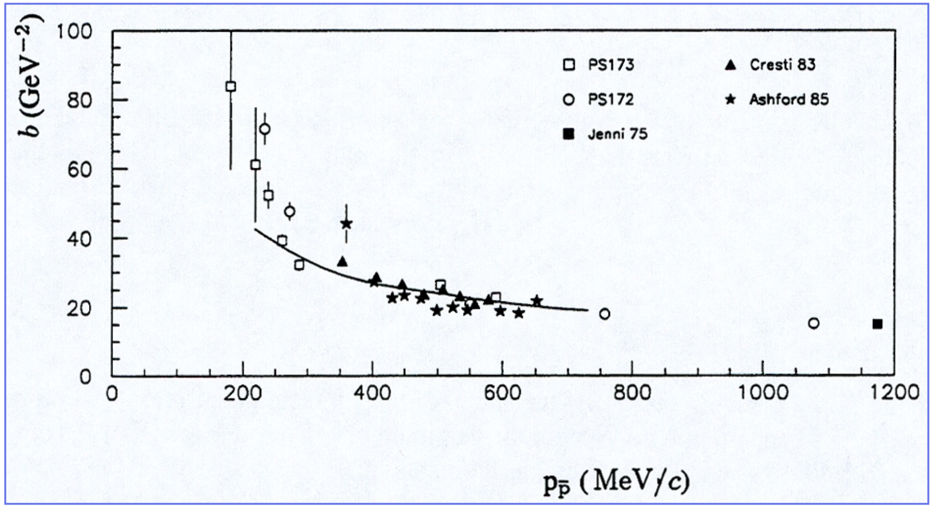
LEAR: Low and medium energy $\bar{p}p(n)$ - Reactions (2)

Elastic Scattering



$$f(t) = \frac{\sigma_{Tot}}{4\pi}(i+\rho)\exp(bt/2);\ \rho = (\mathrm{Re}\,T/\mathrm{Im}\,T)_{t\approx 0}$$





LEAR: Low and medium energy $\bar{p}p(n)$ - Reactions (3)

Interpretation of data (Elastic + CEX)

Often in terms of a potential-model

Real part (Long range): No problem, Meson-exchange picture (G-parity transformation from V_{NN})

Real part (Short range): Problem **!** Annihilation region

Several (phenomenological) ansaetze:

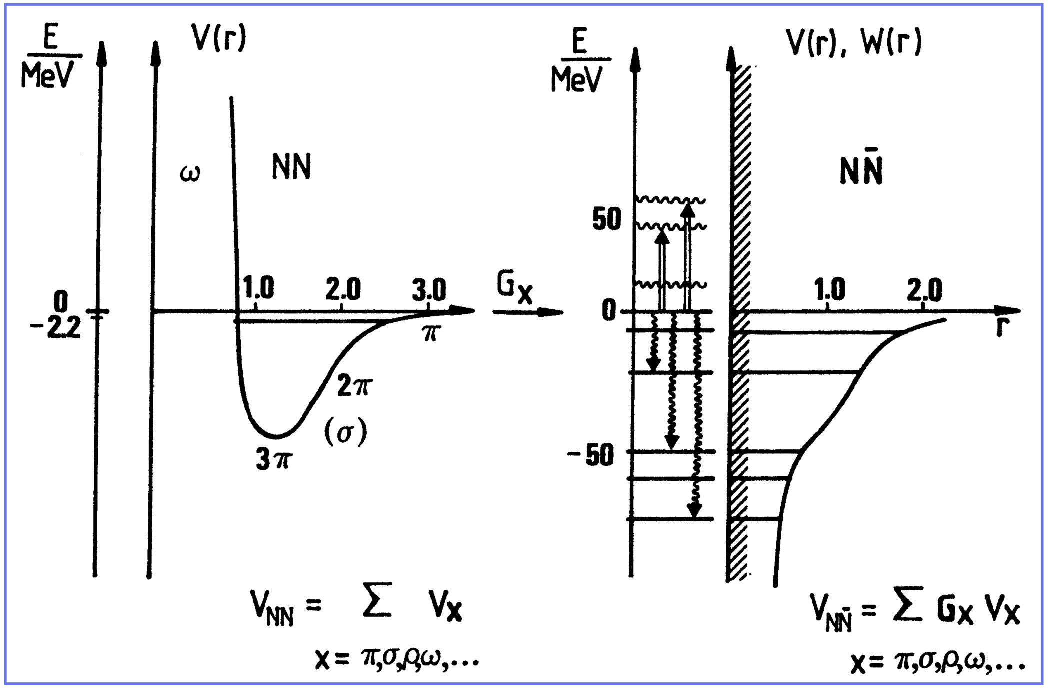
– $q\bar{q}$-interactions

– Cut-off parameters

Imaginary part: Short range strong absorption (annihilation)

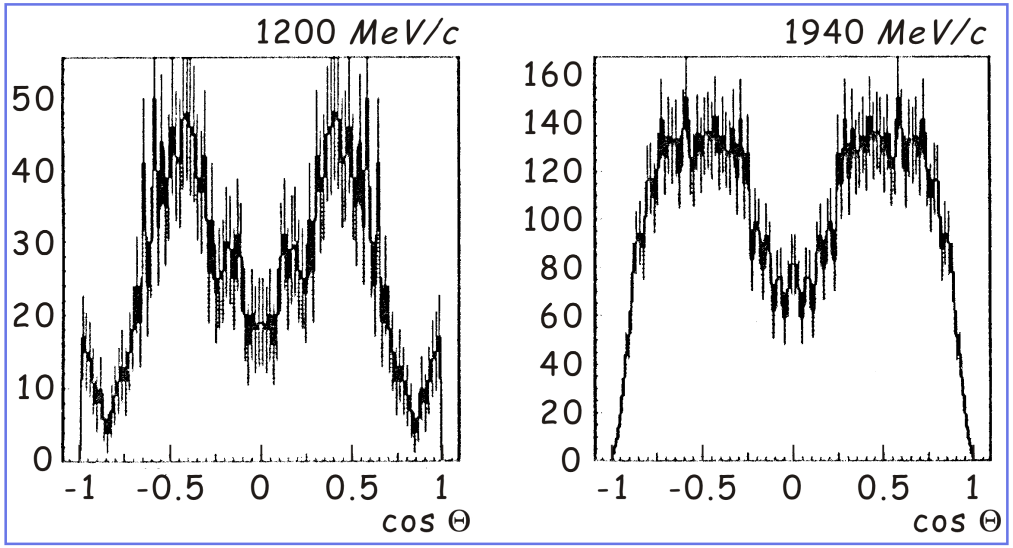
Resumee:

Good description of data, but not from first principles



LEAR: Low and medium energy $\bar{p}p(n)$ - Reactions (4)

Specific annihilation channels



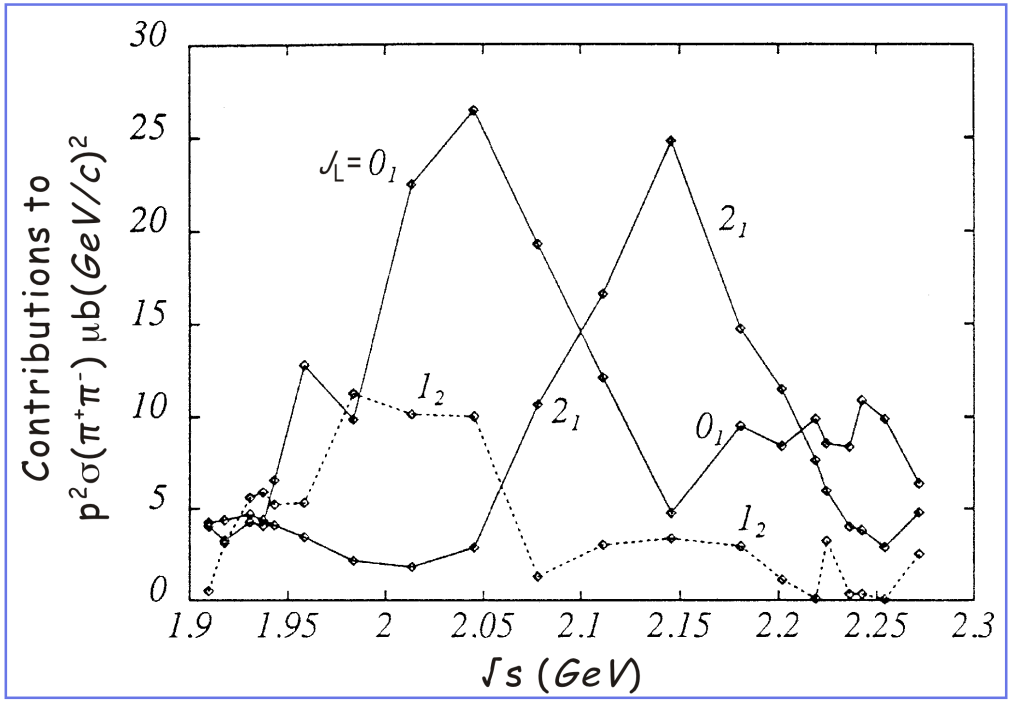
Few high statistics data in flight:

$\bar{p}p \rightarrow \pi^+\pi^-, \pi^0\pi^0$ (up to 20 $\bar{p}$-momenta)

Angular distributions change rapidly with $\bar{p}$-momentum

➥ Dominating partial waves

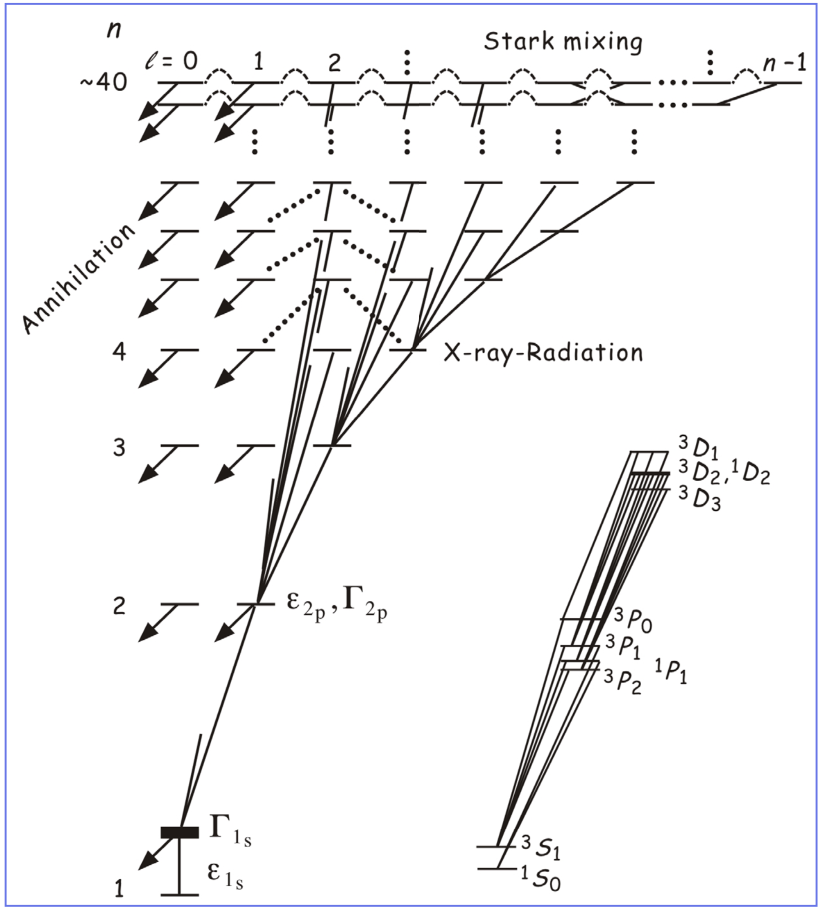
$(p_{\bar{p}} = 1940\ \mathrm{MeV/c} : L_{max} = 5)$



$\bar{p}p \rightarrow \underbrace{\omega\pi^0, \omega\eta, \omega\omega}_{\text{Unambiguous analysis}}, \pi^0\eta\eta$ (9 $\bar{p}$-momenta)

LEAR: Antiprotonic X-rays (1)

$\bar{p}$p(d) - System : Measurement of strong interaction effects (ε, Γ)



$$E_n = \mu c^2 \frac{\alpha^2}{2n^2}$$

Three problems:

– Energies of 2p-1s, 3d-2p-transitions small (≈ 10 keV, ≈ 2 keV)

– Yield of the 2p-1s-X-ray very small $(\Gamma^{x}_{2p-1s})/\Gamma^{ann.}_{2p} \approx 1\%$

– 2p-level only populated in dilute H_2-gas

Long list of experiments to search for $\bar{p}$p(d)-X-rays:

LH_2-Experiments: Failed

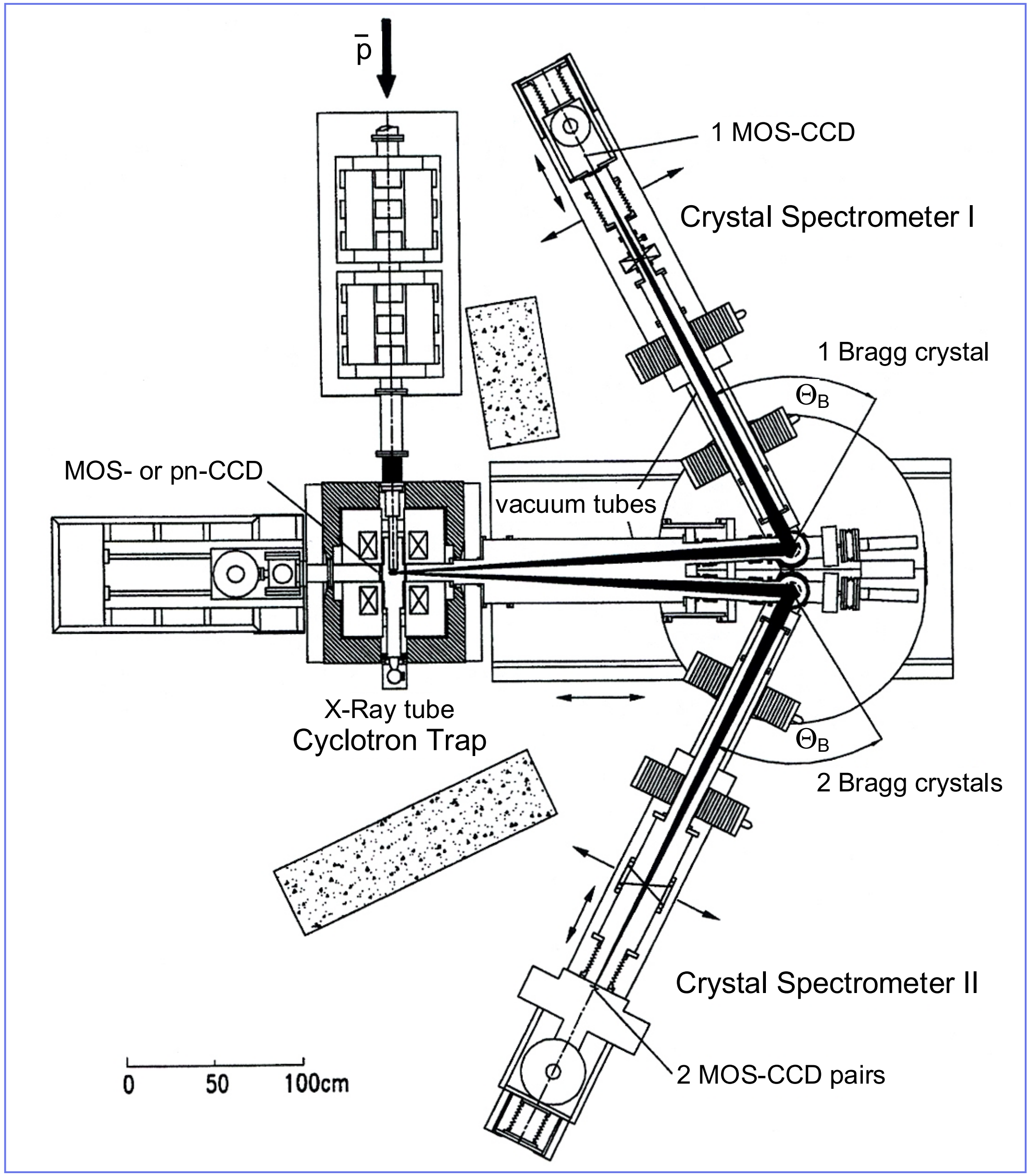
Asterix (H_2-gas, STP) → L_α+L_∞-lines, K_α-line (p$\bar{p}$)

Cold Gas Experiment (H_2-gas @ various densities) → L-Series ($\bar{p}$p, pd), K-series ($\bar{p}$p)

Inverse Cyclotron Trap: (H_2-gas of 20m bar) → Fine Structure of L-/and K-series

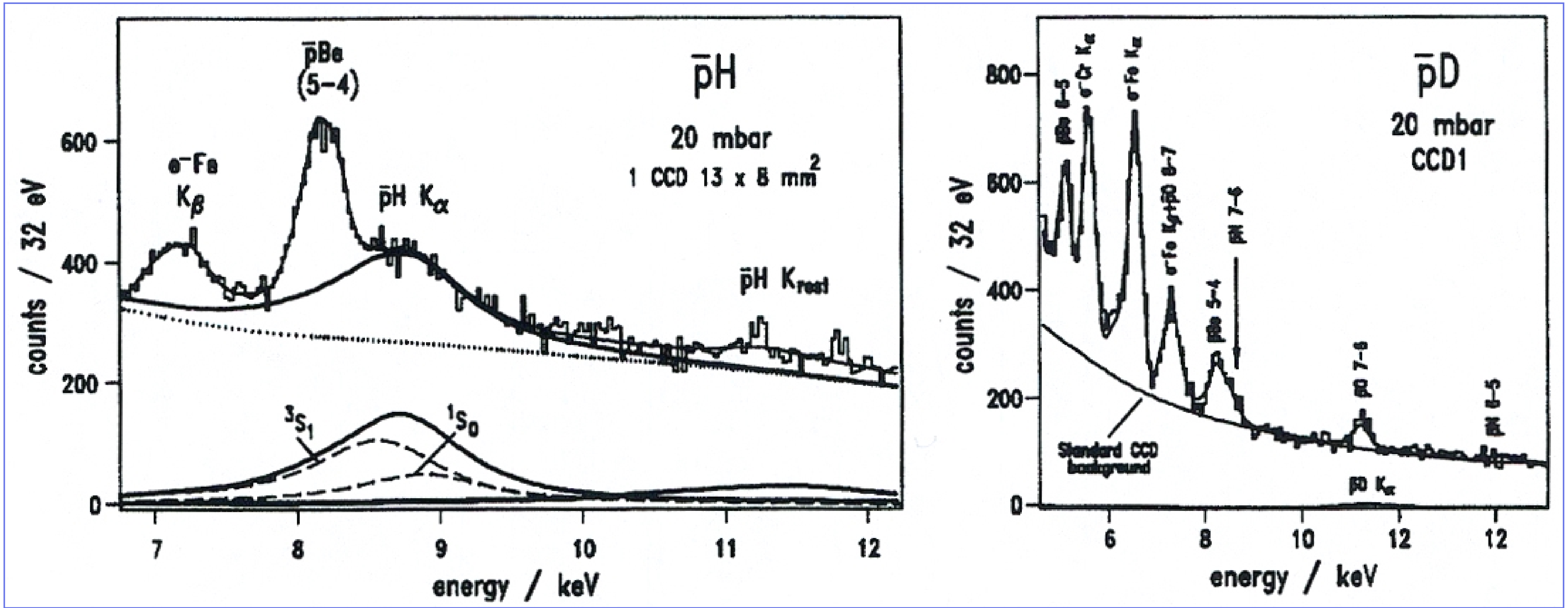
LEAR: Antiprotonic X-rays (2)

Inverse Cyclotron Trap



LEAR: Antiprotonic X-rays (3)

Inverse Cyclotron Trap



LEAR: Antiprotonic X-rays (4)

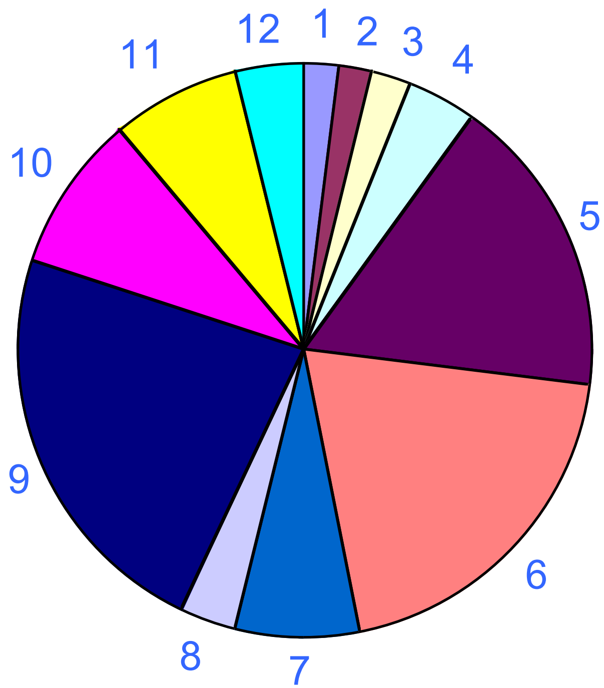
Inverse Cyclotron Trap

Strong interaction shifts and widths of antiprotonic hydrogen and deuterium atoms.

Antiprotonic hydrogen atoms	
Energy shift	**Energy width**
$\epsilon_{1S} = -730 \pm 30\,\mathrm{eV}$	$\Gamma_{1S} = 1060 \pm 80\,\mathrm{eV}$
$\epsilon(2^3P_2, 2^1P_1, 2^3P_1) = +4.0 \pm 5.8\,\mathrm{meV}$	$\Gamma(2^3P_2, 2^1P_1, 2^3P_1) = 30.5 \pm 2.0\,\mathrm{meV}$
$\epsilon(2^3P_0) = +139 \pm 20\,\mathrm{meV}$	$\Gamma(2^3P_0) = 120 \pm 25\,\mathrm{meV}$
	$\Gamma(2^1P_1) = 51 \pm 18\,\mathrm{meV}$
Mean 2P level widths	
using (3.72)	using (3.73)
$\Gamma_{2P} = 38.0 \pm 2.8\,\mathrm{meV}$	$\overline{\Gamma}_{2P} = 44 \pm 8\,\mathrm{meV}$
S-wave scattering length	**P-wave scattering volume, imag. part**
$a_o^{sc} = (0.88 \pm 0.04) - i(0.64 \pm 0.05)\,\mathrm{fm}$	$\mathcal{I}m\, a_1^{sc} = -(0.77 \pm 0.06)\mathrm{fm}^3$
ρ-parameter at threshold	
$\rho(E=0) = -1.38 \pm 0.12$	
Antiprotonic deuterium atoms	
Energy shift	**Energy width**
$\epsilon_{1S} = -1.05 \pm 0.25\,\mathrm{keV}$	$\Gamma_{1S} = 1.10 \pm 0.75\,\mathrm{keV}$
$\bar{\epsilon}_{2P} = 243 \pm 26\,\mathrm{meV}$	$\bar{\Gamma}_{2P} = 489 \pm 30\,\mathrm{meV}$

LEAR: Annihilation at Rest (1)

Global Picture



1	Kaons (2%)
2	$3\pi^+3\pi^-3\pi^0$ (2%)
3	$3\pi^+3\pi^-$ (2%)
4	$2\pi^+2\pi^-3\pi^0$ (4%)
5	$2\pi^+2\pi^-2\pi^0$ (17%)
6	$2\pi^+2\pi^-\pi^0$ (20%)
7	$2\pi^+2\pi^-$ (7%)
8	$\pi^+\pi^-4\pi^0$ (3%)
9	$\pi^+\pi^-3\pi^0$ (23%)
10	$\pi^+\pi^-2\pi^0$ (9%)
11	$\pi^+\pi^-\pi^0$ (7%)
12	Neutrals (4%)

Interpretation of Data

Hot gas model (T ≈ 100 MeV)

$$\frac{dN}{dE}(\pi^\pm) \text{ of } \bar{p}p \rightarrow \pi^\pm + X$$

Isospin statistical model (Pais)

$$\sigma(\bar{p}p \rightarrow n\pi) \propto n_{\pi^+}!\, n_{\pi^-}!\, n_{\pi^0}! \;(\, n = n_{\pi^+} + n_{\pi^-} + n_{\pi^0})$$

Threshold Dominance model (Vandermeulen), Valid up to 3.5 GeV/c

$$\text{BR (Non strange meson pair)} = \; p \cdot C_{ab} \exp\left[-A\left(E_{cm}^2 - (m_a + m_b)^2\right)^{1/2}\right]$$

➥ Production rate increases with higher masses of a, b
Annihilation prefers to produce mass, not energy

LEAR: Annihilation at Rest (2)

Particularly well measured: 2 Body Final States

Branching ratios B for $\bar{p}p$ annihilation at rest in liquid. See Amsler and Myhrer (1991) for annihilation in gaseous hydrogen. Further branching ratios from Dalitz plot analyses are listed in Table XIII below.

Channel	B				Reference
e^+e^-	3.2	±	0.9	10^{-7}	Bassompierre *et al.* (1976)
$\pi^0\pi^0$	6.93	±	0.43	10^{-4}	Amsler *et al.* (1992a)‡
	4.8	±	1.0	10^{-4}	Devons *et al.* (1971)
$\pi^+\pi^-$	3.33	±	0.17	10^{-3}	Armenteros and French (1969)
$\pi^+\pi^-$	3.07	±	0.13	10^{-3}	Amsler *et al.* (1993b)‡
$\pi^0\eta$	2.12	±	0.12	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\eta'$	1.23	±	0.13	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\rho^0$	1.72	±	0.27	10^{-2}	Armenteros and French (1969)
$\pi^\pm\rho^\mp$	3.44	±	0.54	10^{-2}	Armenteros and French (1969)
$\eta\eta$	1.64	±	0.10	10^{-4}	Amsler *et al.* (1993b)‡
$\eta\eta'$	2.16	±	0.25	10^{-4}	Amsler *et al.* (1993b)‡
$\omega\pi^0$	5.73	±	0.47	10^{-3}	Amsler *et al.* (1993b) [a]‡
	6.16	±	0.44	10^{-3}	Schmid (1991) [b]‡
$\omega\eta$	1.51	±	0.12	10^{-2}	Amsler *et al.* (1993b) [a]‡
	1.63	±	0.12	10^{-2}	Schmid (1991) [b]‡
$\omega\eta'$	0.78	±	0.08	10^{-2}	Amsler *et al.* (1993b)‡
$\omega\omega$	3.32	±	0.34	10^{-2}	Amsler *et al.* (1993b)‡
$\eta\rho^0$	4.81	±	0.85	10^{-3}	[c]
	3.87	±	0.29	10^{-3}	Abele *et al.* (1997a)‡
$\eta'\rho^0$	1.29	±	0.81	10^{-3}	Foster *et al.* (1968a)
	1.46	±	0.42	10^{-3}	Urner (1995)‡
$\rho^0\rho^0$	1.2	±	1.2	10^{-3}	Armenteros and French (1969)
$\rho^0\omega$	2.26	±	0.23	10^{-2}	Bizzarri *et al.* (1969)
K^+K^-	1.01	±	0.05	10^{-3}	Armenteros and French (1969)
K^+K^-	0.99	±	0.05	10^{-3}	Amsler *et al.* (1993b)‡
K_SK_L	7.6	±	0.4	10^{-4}	Armenteros and French (1969)
K_SK_L	9.0	±	0.6	10^{-4}	Amsler *et al.* (1995c)‡

[a]From $\omega\rightarrow\pi^0\gamma$.
[b]From $\omega\rightarrow\pi^+\pi^-\pi^0$.
[c]Average between Baltay *et al.* (1966), Espigat *et al.* (1972) and Foster *et al.* (1968a).
‡Crystal Barrel experiment.

LEAR: Annihilation at Rest (3)

Selection Rules for Two-Body-Annihilation Channels

$\bar{p}p$-System (Fermion-Antifermion)

$$P = (-1)^{L+1};\ C = (-1)^{L+S};\ G = (-1)^{L+S+I};\ I = 0,\ 1$$

$\hookrightarrow J^{PC}$ – atomic states:

$${}^1S_0 \triangleq 0^{-+},\ {}^3S_1 \triangleq 1^{--}$$

$${}^3P_2 \triangleq 2^{++},\ {}^3P_1 \triangleq 1^{++},\ {}^3P_0 \triangleq 0^{++},\ {}^1P_1 \triangleq 1^{+-}$$

Two Boson System

$$P = (-1)^{L};\ C = (-1)^{L+S};\ G = (-1)^{L+S+I}$$

Examples:

$\pi^0\pi^0,\ K_SK_S,\ \eta\eta$: L even $\rightarrow P = C = +1$

$\hookrightarrow J^{PC} = 0^{++},\ 2^{++}$

K_SK_L : $L = 1,\ P = C = -1$

$\hookrightarrow J^{PC} = 1^{--}$

Conservation of quantum numbers in annihilation process:

$\pi^0\pi^0$, ... only possible from ${}^3P_0$ and ${}^3P_2$

K_SK_L, ... only possible from ${}^3S_1$

LEAR: Annihilation at Rest (4)

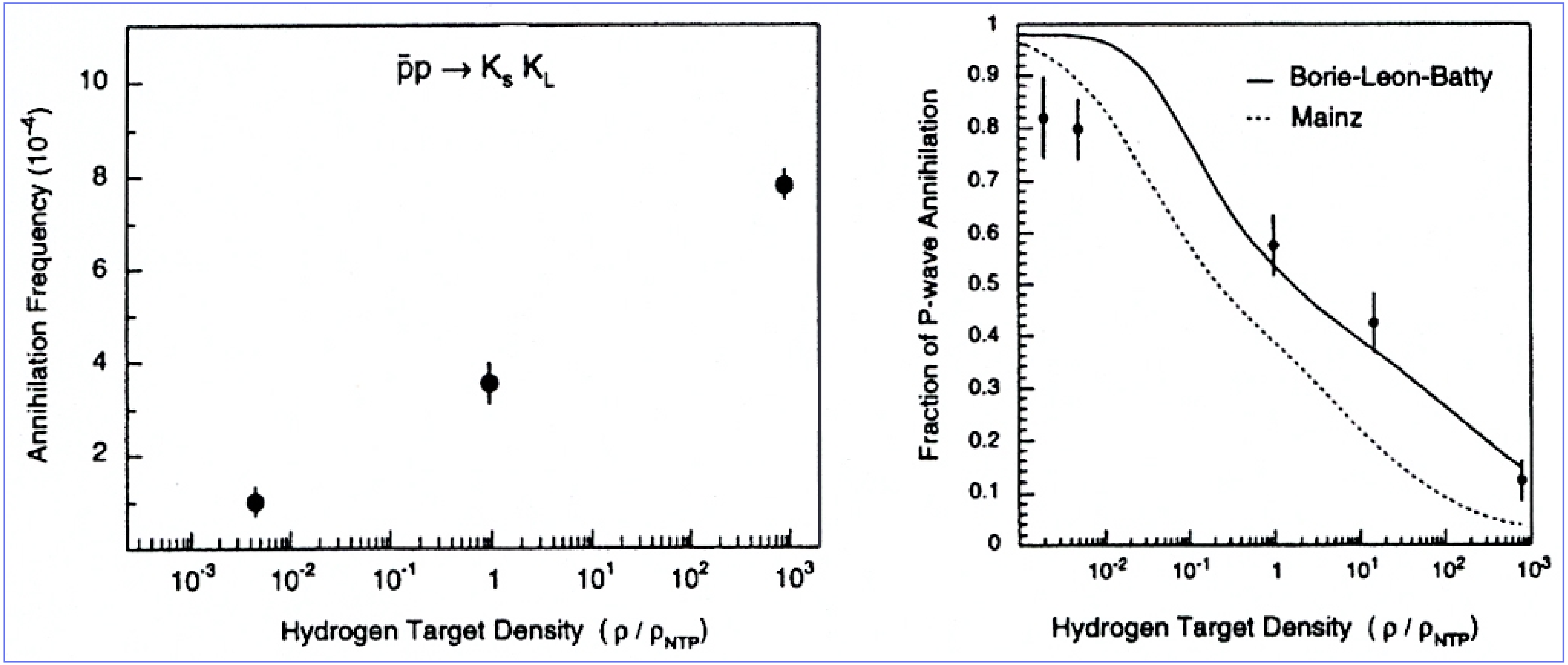
Selection Rules for Two-Body Channels

State	J^P	C	I	G	$2\pi^0$	$\pi^+\pi^-$	$K_1^0K_1^0+K_2^0K_2^0$	$K_1^0K_2^0-K_2^0K_1^0$
$^1S_0$	0^-	+1	0	+1	X	X	X	X
			1	–1	X	X		
$^3S_0$	1^-	–1	0	–1	X	Z	X	–
			1	+1	X	–		
$^1P_1$	1^+	–1	0	–1	X	X	X	X
			1	+1	X	X		
$^3P_0$	0^+	+1	0	+1	–	–	–	X
			1	–1	Z	Z		
$^3P_1$	1^+	+1	0	+1	X	X	X	X
			1	–1	X	X		
$^3P_2$	2^+	+1	0	+1	–	–	–	X
			1	–1	Z	Z		

Forbidden: X; G-Forbidden: Z; Allowed: –

LEAR: Annihilation at Rest (5)

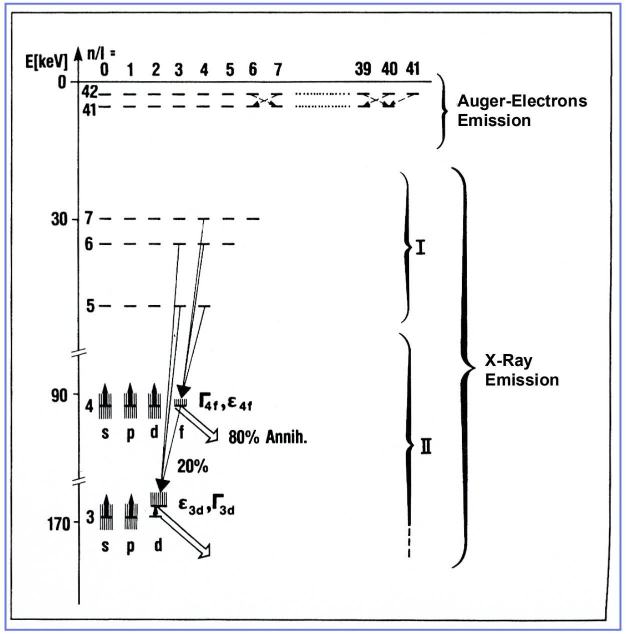
Determination of p-/s- state annihilation as function of H_2-pressure



LEAR: Antiprotonic Atoms (1)

Antiprotonic Atoms: $\bar{p}A$

Form easily in a nuclear target, X-rays much easier to observe than in $\bar{p}p$-system
(No Stark-Mixing, Higher Energies)



$$E_n = \mu c^2 \frac{(Z\alpha)^2}{2n^2} \;;\; r_n = \frac{\hbar^2}{\mu c^2} \cdot \frac{n^2}{Z}$$

Observation of X-rays:
– Capture Mechanism
– Properties of particles involved, e.g. $\mu_{\bar{p}}$
– Measurement of ε, Γ of last observable transition $\Rightarrow$ $\bar{p}$-nuclear interaction (ρ_N at nuclear surface)
– Study of annihilation products

Special case:

$\bar{p}$-He: Metastable states $\rightarrow$ High Resolution Laser Spectroscopy

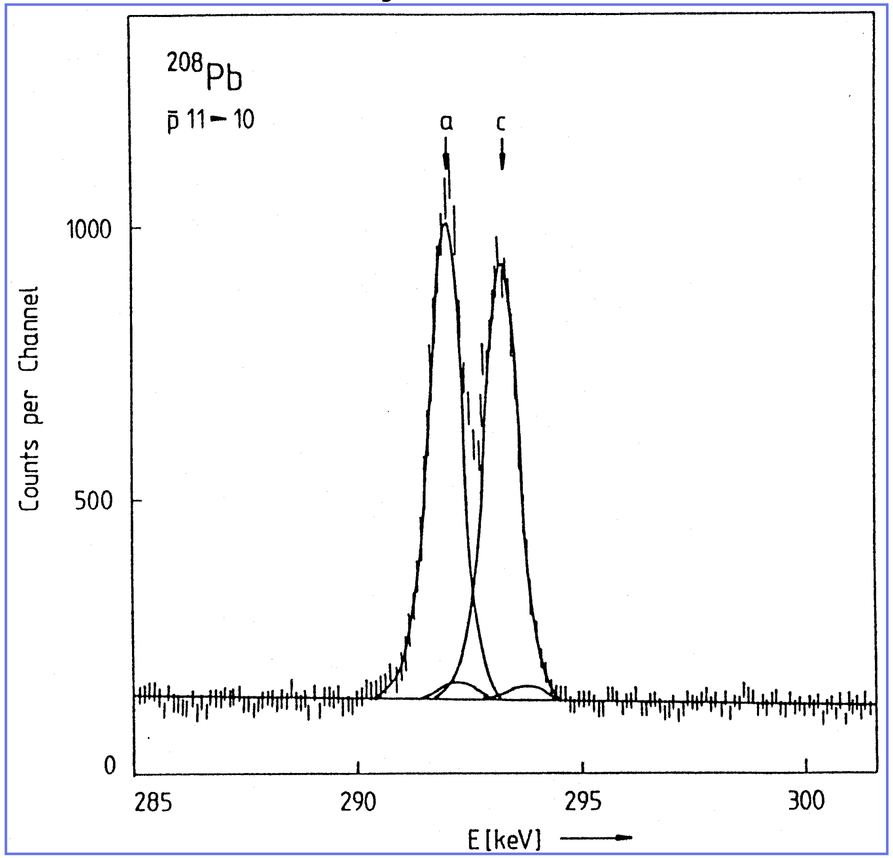
LEAR: Antiprotonic Atoms (2)

Antiprotonic Atoms: $\bar{p}A$

X-rays of transitions between various energy levels measured in many nuclei

Levels, not affected by strong $\Rightarrow m_{\bar{p}}, \mu_{\bar{p}}$

$\mu_{\bar{p}} = (2.8005 \pm 0.0090)\, \mu_{nm}$ (Best value)



Levels, affected by strong interaction $\Rightarrow (\varepsilon, \Gamma)_{S.I.}$ (last accessible level)

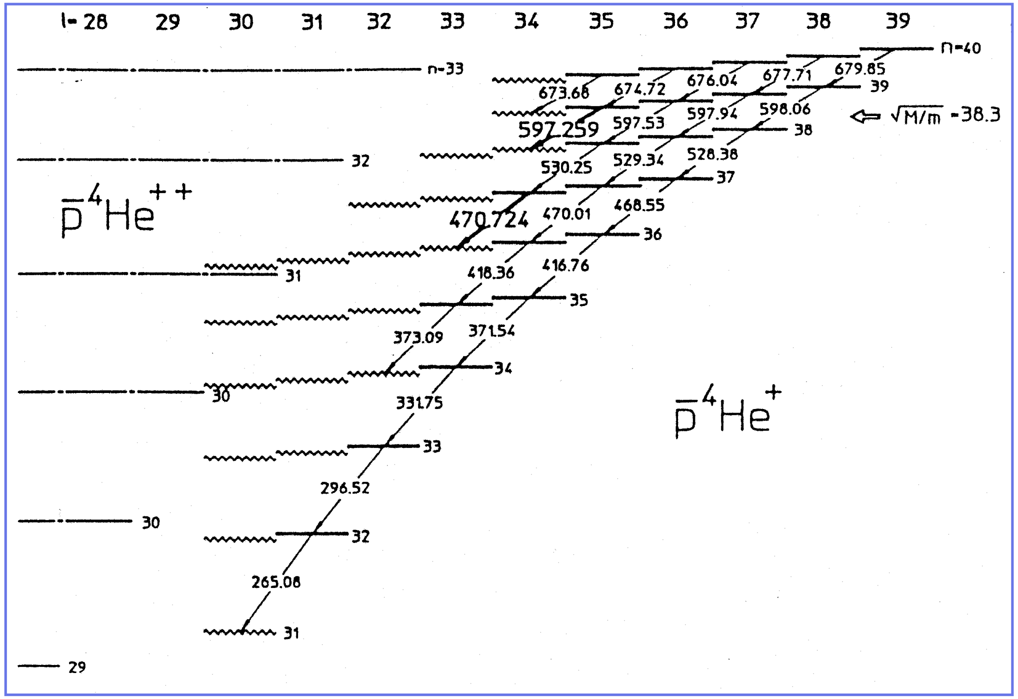
Interpretation:

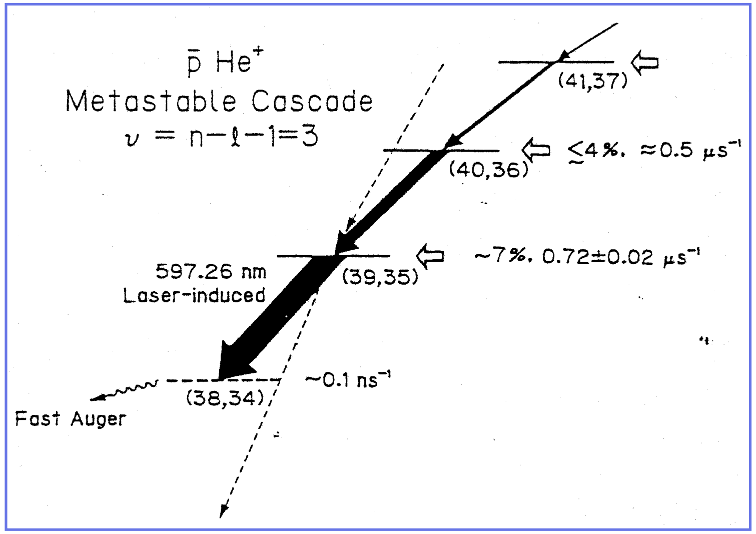
$$\varepsilon + i\,\Gamma\!/\!_2 \propto \int (a_{\bar{p}p} \cdot \rho_p + a_{\bar{p}n}\, \rho_n)\, |\psi|^2\, d\tau$$

Only nuclear surface contributes $\Rightarrow$ **Neutron halo established, e.g. t_n - t_p = 0.6 fm (^{172}Yb)**

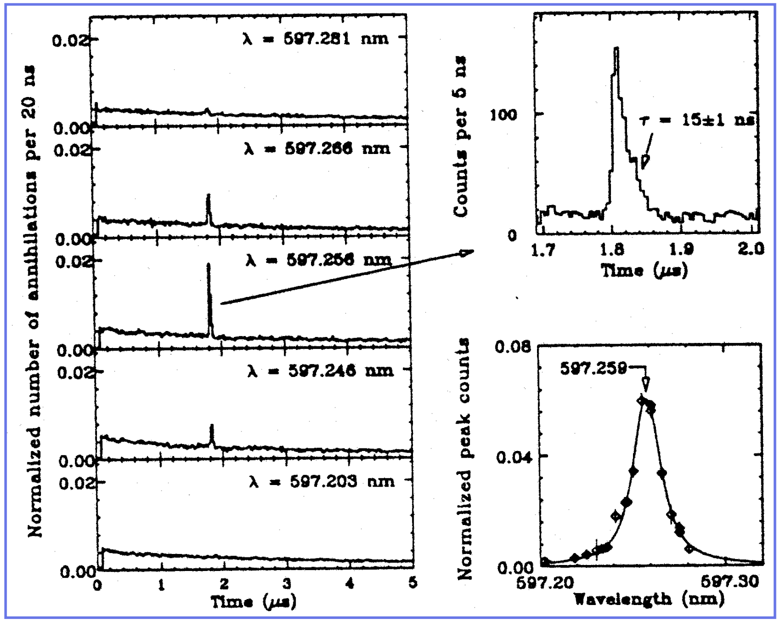
LEAR: $\bar{p}$He-Atoms

Metastable states ($\tau \approx \mu s$), deexcited by Laser-injection
$\Rightarrow$ Measurements on ΔE with extreme precision





Pulsed excimer-pumped tunable Dye-Laser Resonant enhancement of annihilation, $\Delta\lambda/\lambda_0 = 0.5$ ppm



$\Rightarrow$
- Very stringent test of calculations in the three-body Coulomb system
- $\left|\frac{m_{\bar{p}} - m_p}{m_p}\right| \leq 5\text{x}10^{-7}$
- $\left|\frac{q_{\bar{p}} - e}{e}\right| \leq 5\text{x}10^{-7}$

Future (AD): Increase of precision, $\mu_{\bar{p}}$

LEAR: $\bar{p}(\bar{n})$-A-Interactions (1)

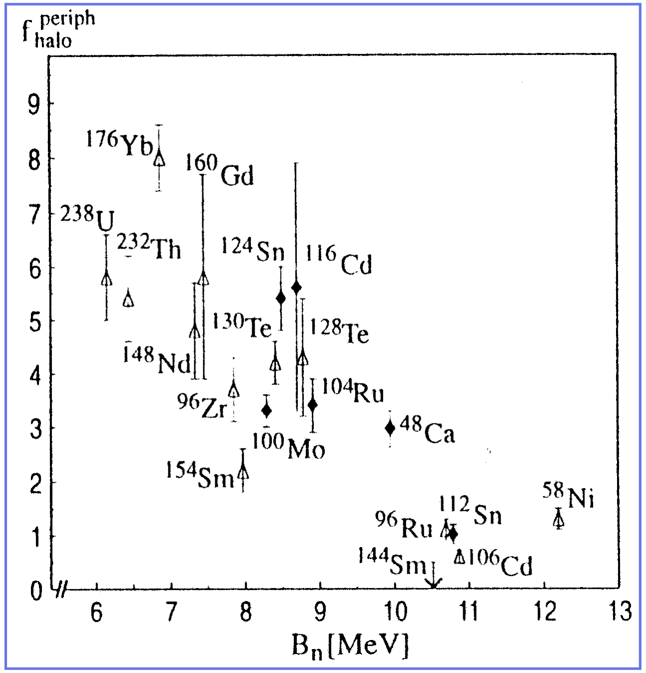
$\bar{p}_{stop}$:

Interaction only with nuclear periphery

Discrimination between $\bar{p}n$ and $\bar{p}p$ annihilations in single nucleon interactions (quite rare)

Identification of residual nuclei from γ-ray spectra $\rightarrow$ $N(\bar{p}n)/N(\bar{p}p)$

$$\text{Neutron Halo factor} = \frac{N(\bar{p}n)}{N(\bar{p}p)} \; \frac{Z}{N} \; \frac{Im(a_p)}{Im(a_n)}$$



Large for nuclei with low B_n

➥ **Neutron Halo**

$\bar{p}$ @ higher energies

Bulk annihilation, Heating of nuclei to ≥ 800 MeV, Soft heating ⇒ No dramatic density increase, No violent collective effects (High-Spins, Deformation), Formation of five pions in average (Δ-matter ?)

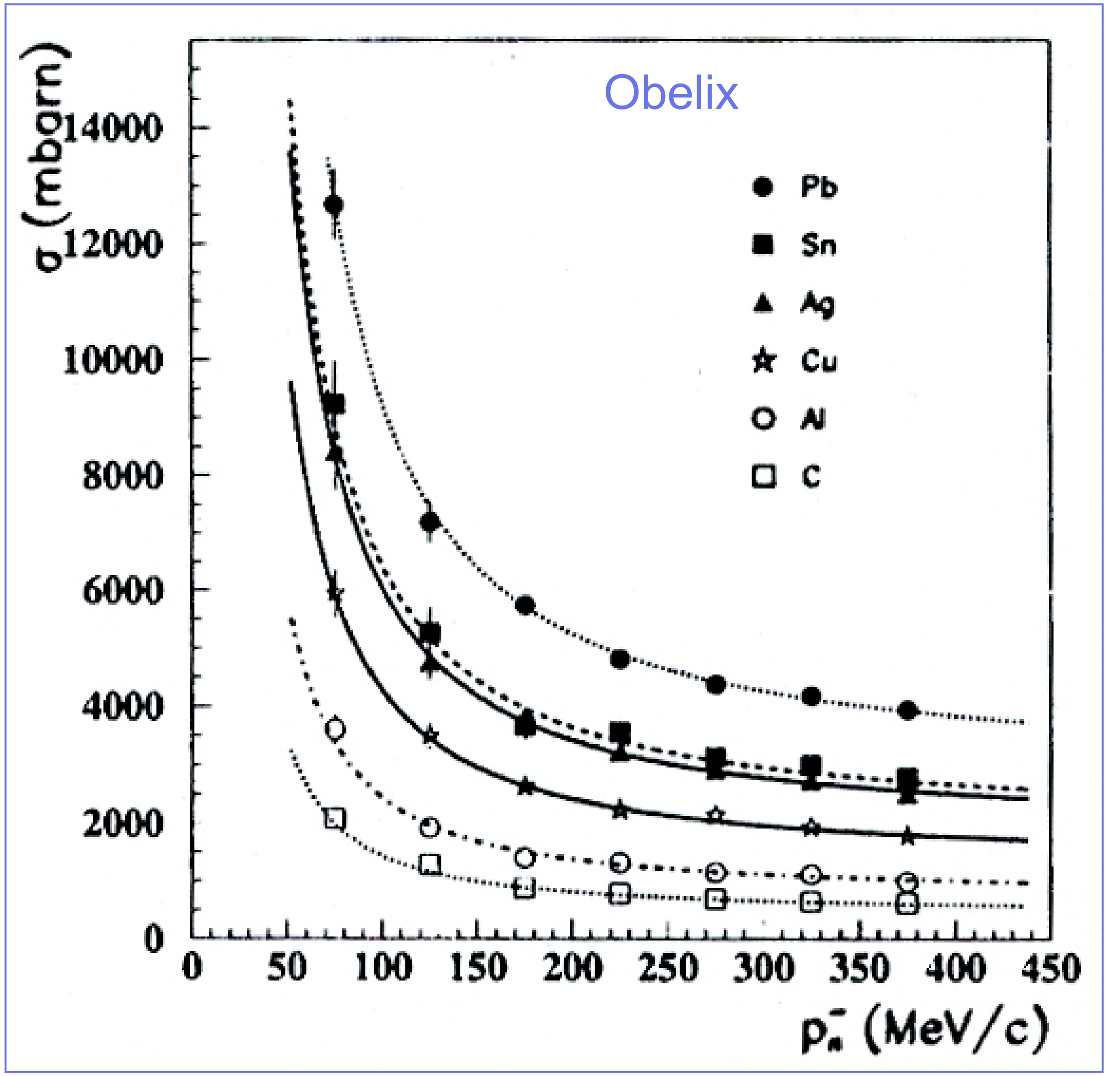
Experimental results:

1 GeV: Particle spectra in good agreeement with INC-calculations

8. GeV (ideal energy): INC-model works, Higher particle multiplicities than in π-induced reactions

LEAR: $\bar{p}(\bar{n})$-A-Interactions (2)

$\bar{n}$-A cross section measurement (50! - 400 MeV/c)



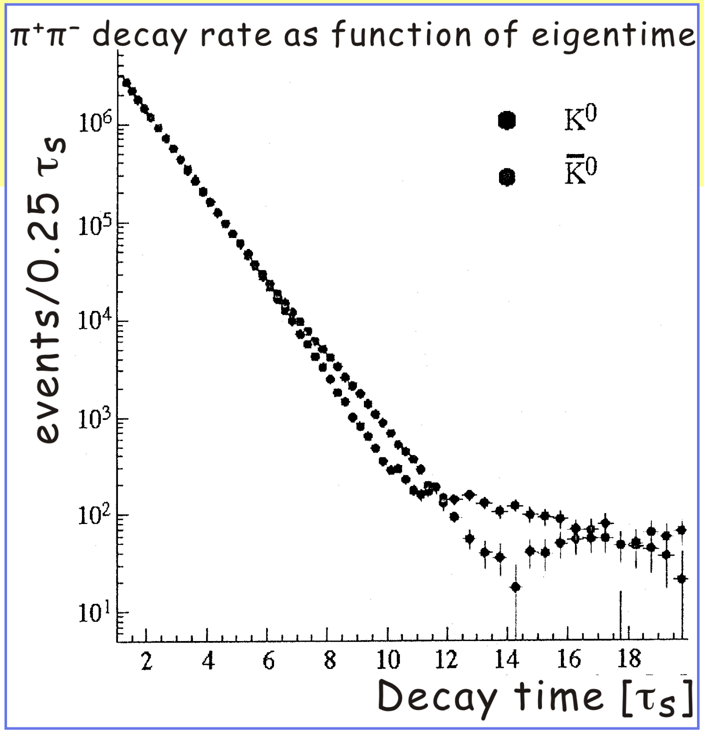
LEAR: CP/T/CPT - Tests (1)

CP-Lear: Investigation of CP-/T-/CPT-symmetries in the neutral Kaon system

– Measurement of time dependent decay asymmetries for the main K^0, $\overline{K}^0$-decay modes

– Tagging of Strangeness of K^0, $\overline{K}^0$ at production time $\left(\bar{p}p \to \begin{matrix} K^-\pi^+K^0 \\ K^+\pi^-\overline{K}^0 \end{matrix}\right)$

– Tagging of Strangeness of K^0, $\overline{K}^0$ at decay time
$0 \le t \le 20\tau_s (K^0 \to \pi^- e^+ \nu_e,\ \overline{K}^0 \to \pi^+ e^- \bar{\nu}_e,\ \Delta S = \Delta Q)$
(For semileptonic decay only)



$$K^0(t) = a_L^- |K_s\rangle e^{-i\gamma_s t} + a_s^- |K_L\rangle e^{-i\gamma_L t}$$

$$\overline{K}^0(t) = a_L^+ |K_s\rangle e^{-i\gamma_s t} - a_S^+ |K_L\rangle e^{-i\gamma_L t}$$

$$\gamma_{s,L} = m_{s,L} - \tfrac{i}{2}\Gamma_{s,L}$$

$$a_{s,L}^{\pm} = \tfrac{1}{\sqrt{2}}(1 \pm \varepsilon_{s,L})$$

$$\varepsilon_{s,L} = \varepsilon \pm \delta$$

$\varepsilon \ne 0$: T and CP violation

$\delta \ne 0$: T and CPT violation

Measurement of asymmetries $A(t) = \dfrac{R(\overline{K}^0 \to f) - R(K^0 \to f)}{R(\overline{K}^0 \to f) + R(K^0 \to f)}$ $f = \pi^+\pi^-,\ \pi^0\pi^0,\ \pi^+\pi^-\pi^0,\ \pi^0\pi^0\pi^0$

$\Rightarrow$ Parameters of CP-violation: $|\eta_{\pm}|$, ϕ_{+-} (Best Value **!**), $|\eta_{00}|$, ϕ_{00}, ...

LEAR: CP/T/CPT - Tests (2)

Semileptonic decay: $f = \pi e \nu_e$

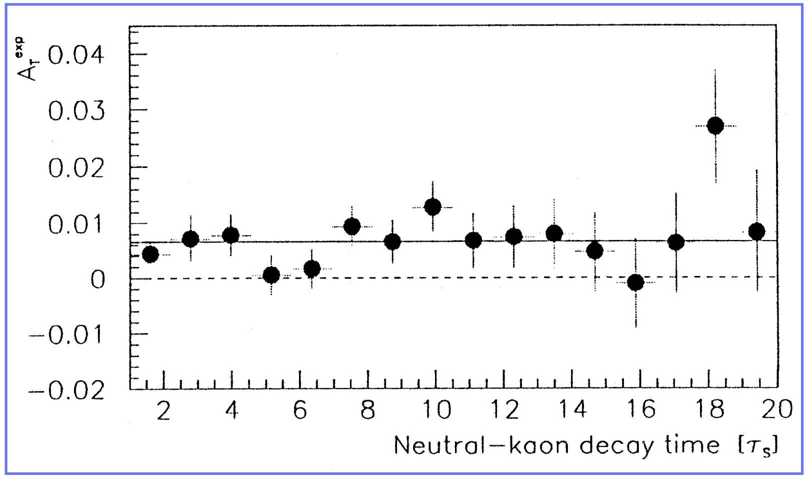
– Direct Test of T-violation ($\varepsilon \neq 0$?)

$$A_T(t) = \frac{R\left(\overline{K}^0 \to K^0(\pi^- e^+ \nu)\right) - R\left(K^0 \to \overline{K}^0(\pi^+ e^- \overline{\nu})\right)}{R\left(\overline{K}^0 \to K^0(\pi^- e^+ \nu)\right) + R\left(K^0 \to \overline{K}^0(\pi^+ e^- \overline{\nu})\right)}$$

$$= 4\,\mathrm{Re}(\varepsilon) \qquad (\text{for } t >> \tau_s)$$

Measurement: $4\,\mathrm{Re}(\varepsilon) = (6.2 \pm 1.4 \pm 1.0)\mathrm{x}10^{-3} \neq 0$ **!!**

i.e.: $\boxed{R(\overline{K}^0 \to K^0) > R(K^0 \to \overline{K}^0)}$



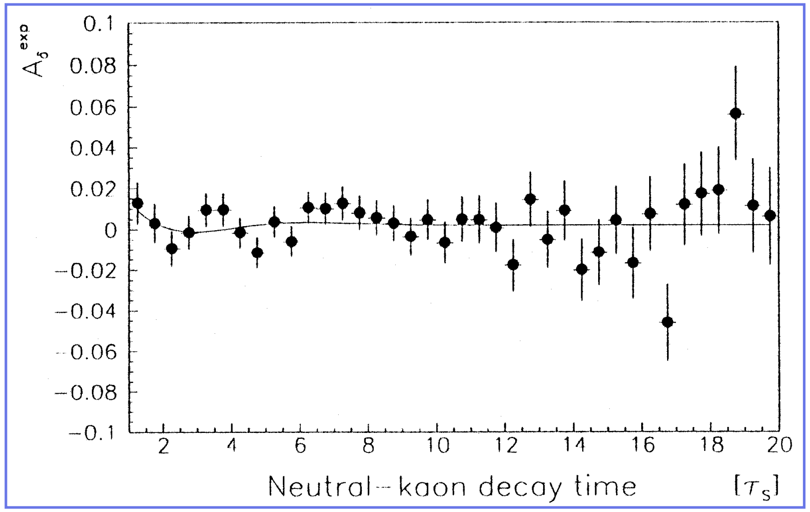
– Direct Test of CPT-violation ($\delta \neq 0$?)

$$A_\delta(t) = \frac{R\left(\overline{K}^0 \to \overline{K}^0(\pi^+ e^- \overline{\nu}_e)\right) - R\left(K^0 \to K^0(\pi^- e^+ \nu_e)\right)}{R\left(\overline{K}^0 \to \overline{K}^0(\pi^+ e^- \overline{\nu}_e)\right) + R\left(K^0 \to K^0(\pi^- e^+ \nu_e)\right)}$$

$$= 8\,\mathrm{Re}(\delta) \qquad (\text{for } t >> \tau_s)$$

Measurement: $\mathrm{Re}(\delta) = (24 \pm 28)\mathrm{x}10^{-5}$ **!!**

$\left(\mathrm{Im}\,\delta = (2.4 \pm 5.0)\mathrm{x}10^{-5},\ \text{Unit. Relat.}\right)$



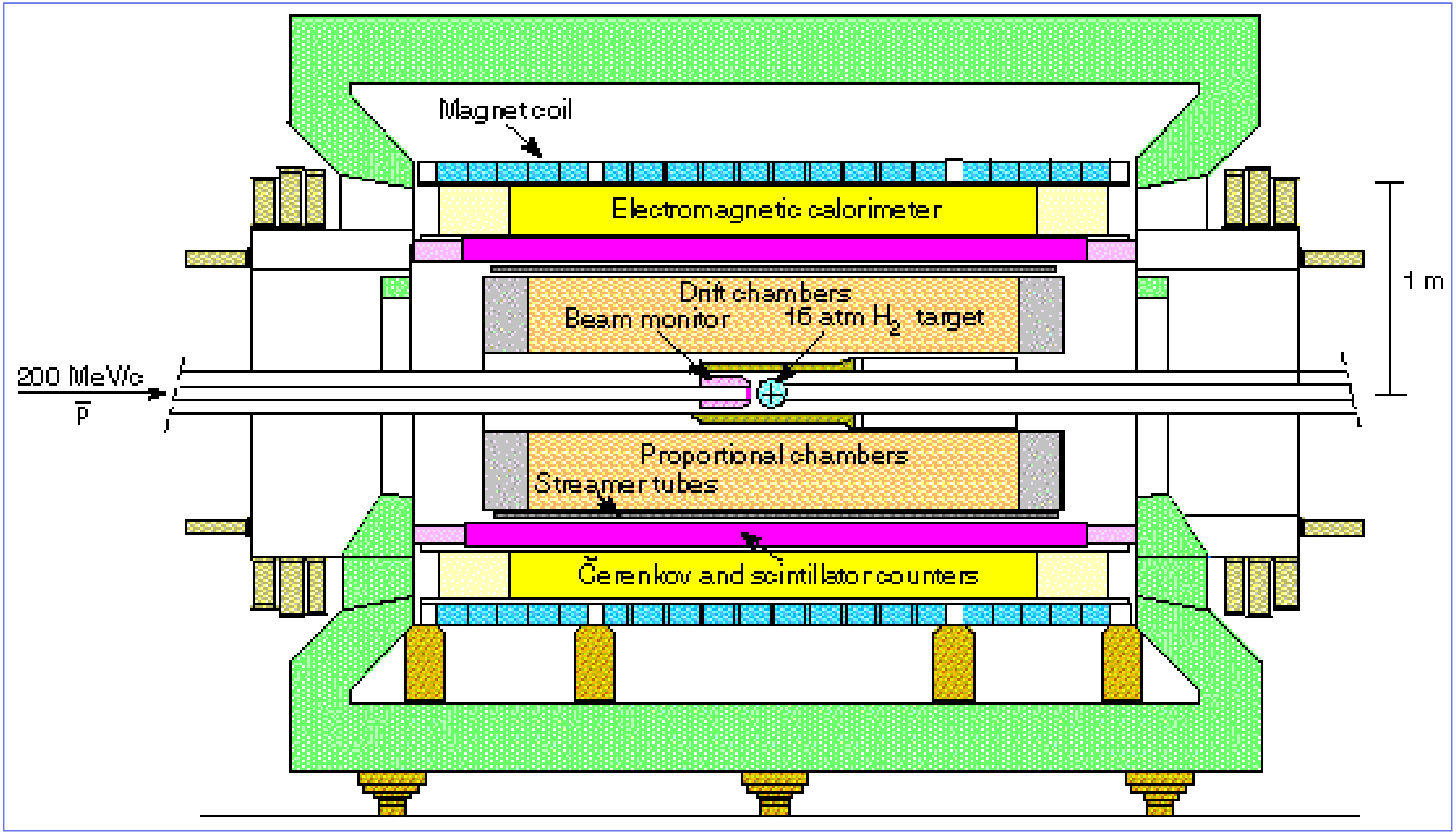
$\boxed{\text{CPT-Invariance proven}}$

➥ **!! CP-Invariance in K-decays due to T-violation !!**

(Furthermore: No violation of $\Delta S = \Delta Q$ in semilept. decays)

LEAR: CP/T/CPT - Tests (3)

CP-LEAR-Detector

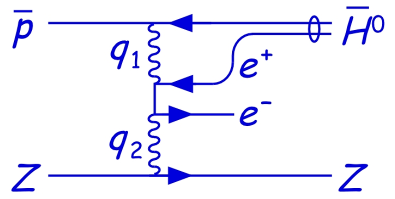


LEAR: Formation of (hot) Antihydrogen ($\overline{\mathrm{H}}$) in Flight

Idea: Brodsky, Munger, Schmitt

PS 210 (LEAR)

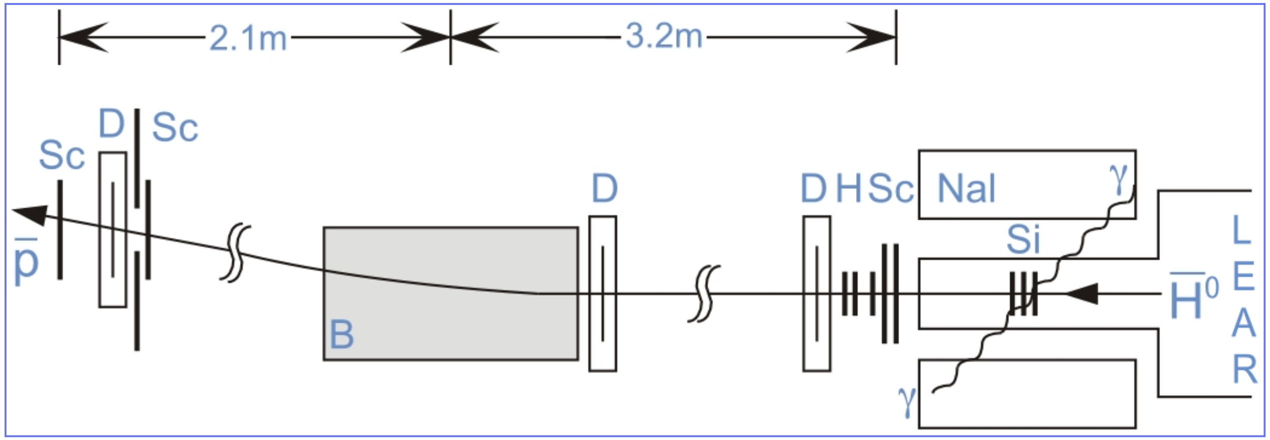
Production of $\overline{\mathrm{H}}$ in Coulomb field of Xe-(cluster) target (1.94 GeV/c antiprotons)



Stripping in Si-counter → e^+ (stopped → γγ (511 keV)) + $\bar{p}$ (Spectrometer)

11 events identified

(Background estimate: 2 ± 1)



E 862 (Fermilab)

Production of $\overline{\mathrm{H}}$ in H2-cluster target by 5.2-6.2 GeV/c antiprotons

67 events identified

Continuation @ AD: $\overline{\mathrm{H}}$-Formation at low energies

LEAR: Meson/Exotics-Spectroscopy (1)

Mesons: $q\bar{q}$
Exotics: Glueballs (gg, ggg), Hybrids ($\bar{q}qg$)
Multi quark-states ($\bar{q}\bar{q}qq$, ...)
(Exotic q.-n. combinations, like $J^{PC} = 1^{-+}$, ...)

$\bar{p}p$-annihilation:

– Production mode ($E_{\bar{p}}$ fixed)

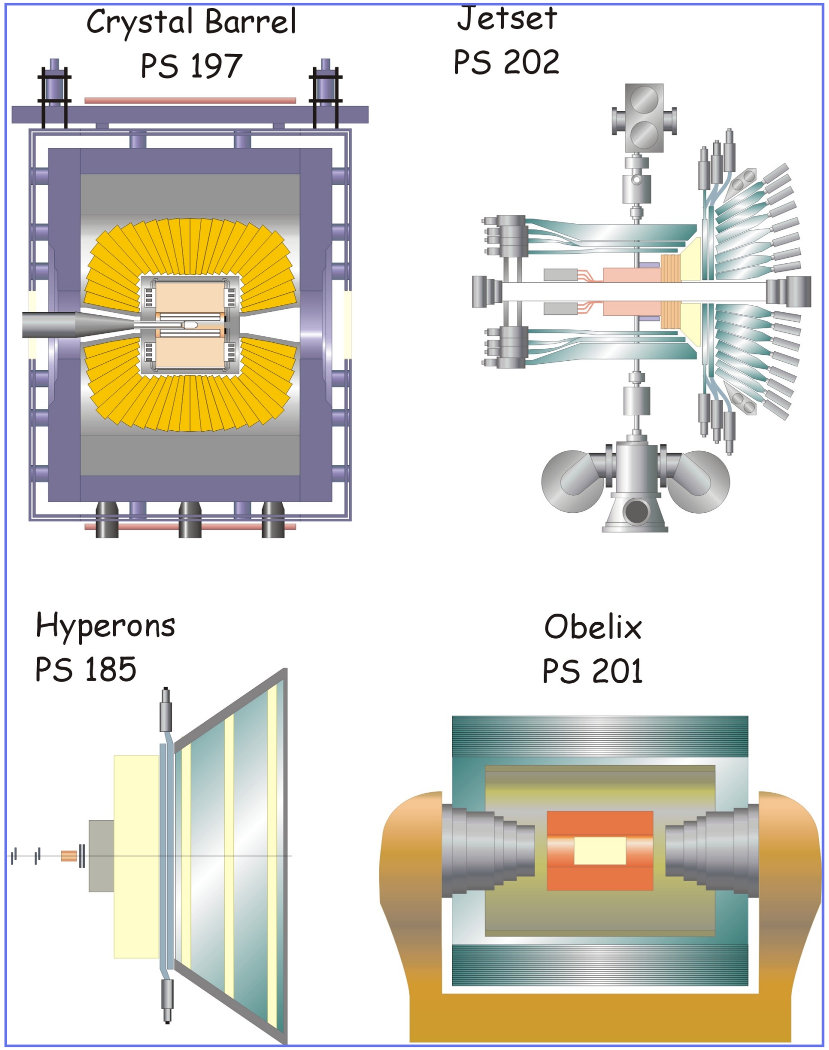
$$\text{e.g.}\quad \bar{p}p \to (\pi^+\pi^-)_\rho \pi^0$$
$$\to (\eta\eta)_{f_0(1500)} \pi^0$$
$$\to \left((\pi^+\pi^-)_\rho (\pi^+\pi^-)_\rho\right)_{f_0(1500)} \pi^0$$

$$\lceil \text{Unique feature}: \bar{p}_{stop} \to (\bar{p}p)_{atom} \text{ as initial state} \rfloor$$

– Formation mode ($E_{\bar{p}}$ variied)

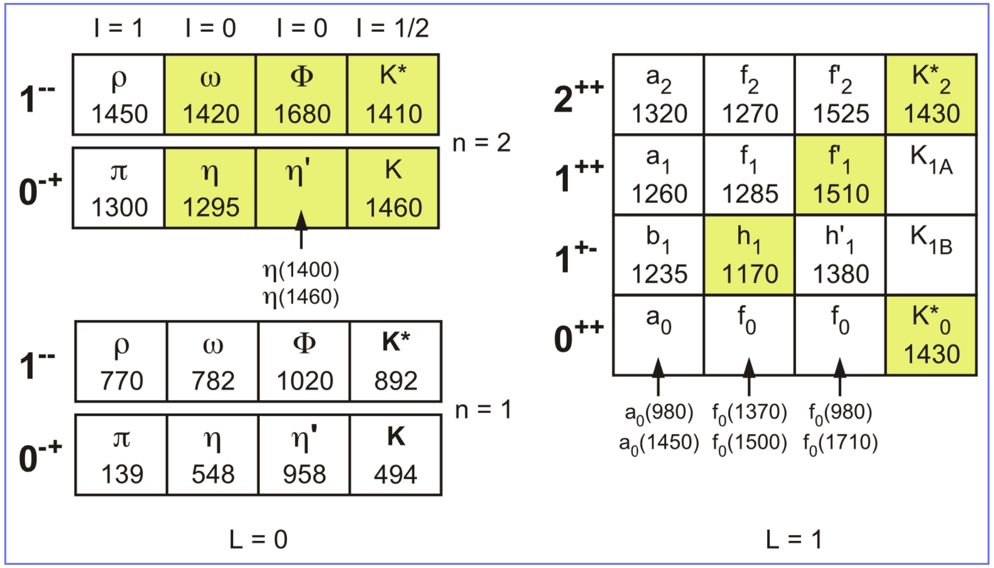
$$\text{e.g.}\quad \bar{p}p \to \xi(2220) \to \phi\phi \to K^+K^-K^+K^-$$

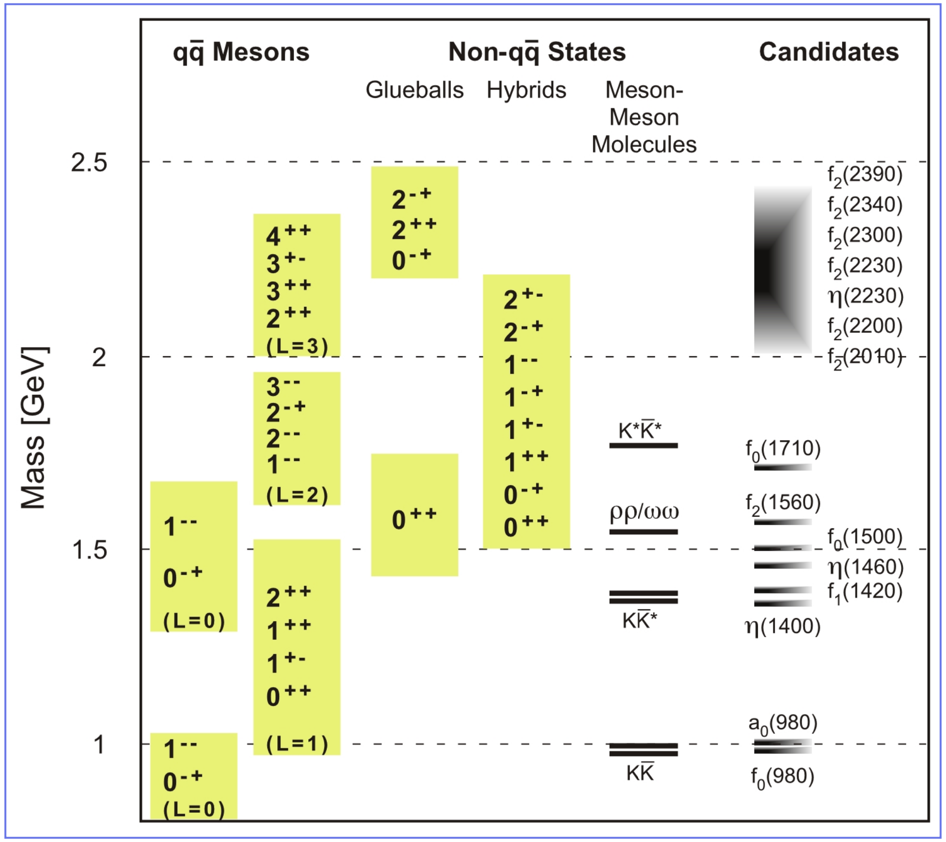
Mass/Width determination: Invariant masses
(Dalitz Plot)
J^{PC} determination: Partial wave analysis
(Angular distribution)
p_{max} LEAR) = 1.94 GeV/c ⇒ **Masses < 2.3 GeV/c²**



LEAR: Meson/Exotics-Spectroscopy (2)

$q\bar{q}$-States/Exotic States





Review of Particle Physics

$N^{2S+1}L_J$	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^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$K_{1B}^{\dagger}$
$1\ ^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$K_0^*(1430)$
$1\ ^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$K_{1A}^{\dagger}$
$1\ ^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$K_2^*(1430)$
$1\ ^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	$K_2(1770)$
$1\ ^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$K^*(1680)^{\ddagger}$
$1\ ^3D_2$	2^{--}			$K_2(1820)$
$1\ ^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	$K_3^*(1780)$
$1\ ^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	$K_4^*(2045)$
$2\ ^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	$K(1460)$
$2\ ^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$K^*(1410)^{\ddagger}$
$2\ ^3P_2$	2^{++}		$f_2(1810), f_2(2010)$	$K_2^*(1980)$
$3\ ^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	$K(1830)$

contributions from LEAR experiments

H. Koch, Hadron Physics, Varenna, June 2004

LEAR: Meson/Exotics-Spectroscopy (3)

Crystal Barrel Experiment

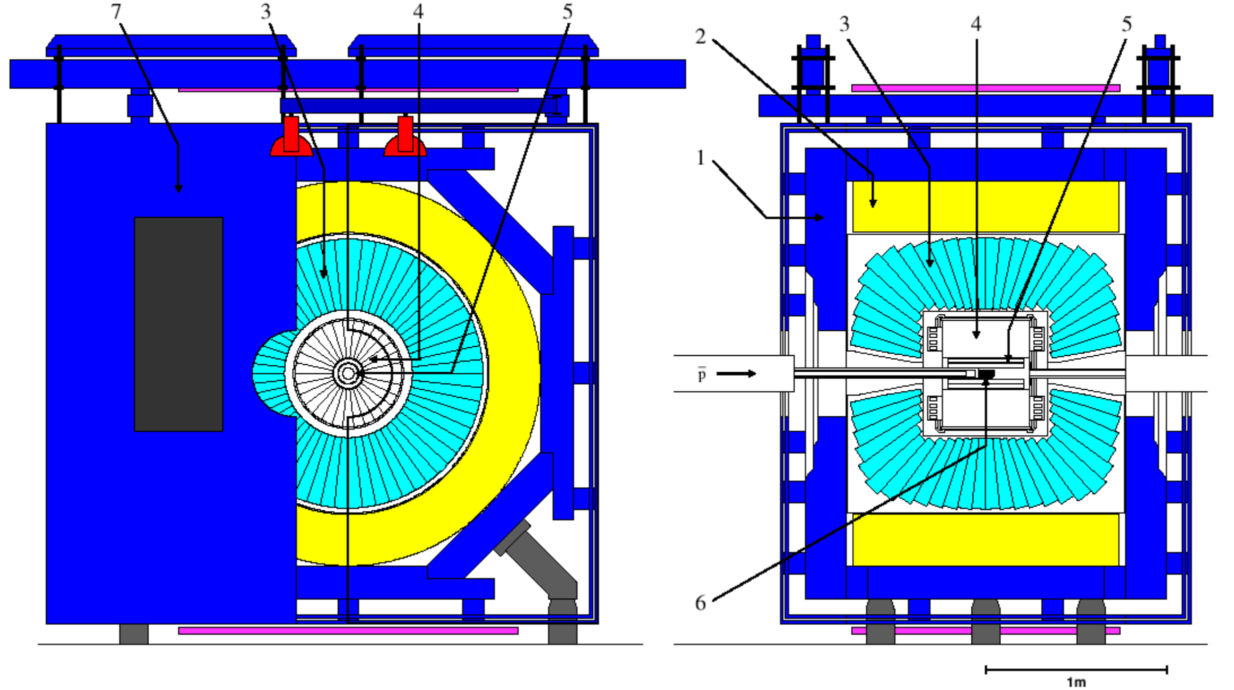
Not mentioned: Test of Quark Line Rule, Radiative Annihilations, Radiative ω, η'-decays, Limit for light gauge bosons, Strangeness in Nucleon/Antinucleon (ϕ/ω), Test of χPT; Scan of specific annihilation channels ($\pi^0\pi^0$, $\pi\omega$, ..., $\phi\phi$)

Strength of the experiment: Very good π^0, η, η'-identification ($\to 2\gamma$)

1380 CsI crystals ($\approx 4\pi$)

Experiments at rest and in flight

Target: Mainly LH_2

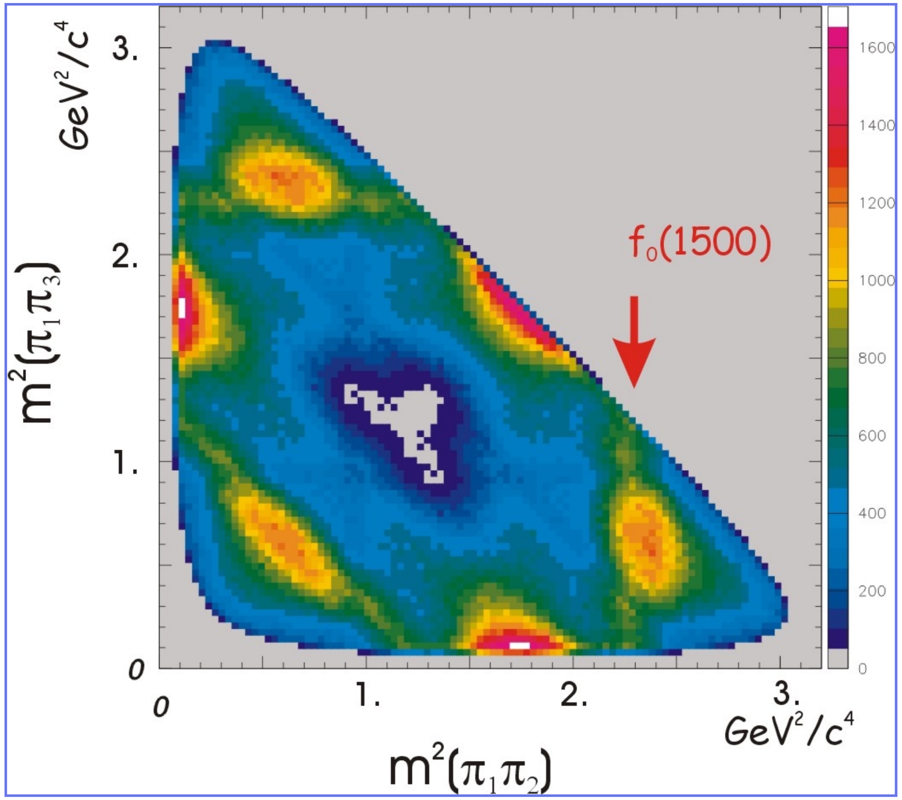


Overall layout of the Crystal Barrel Detector showing
(1) the magnet yoke, (2) the magnet coils,
(3) the CsI barrel, (4) the jet drift chamber, (5) the proportional wire chambers,
(6) the liquid hydrogen target, and (7) one half of the endplate.

LEAR: Meson/Exotics-Spectroscopy (4)

) $\bar{p}_{Stop}p \rightarrow 3\pi^0,\ 2\pi^0\eta,\ 2\eta\pi^0,\ 5\pi^0,\ \pi^0 K_L K_L,\ \pi^0\eta\eta'$

DP: $3\pi^0$ (712 000 events)



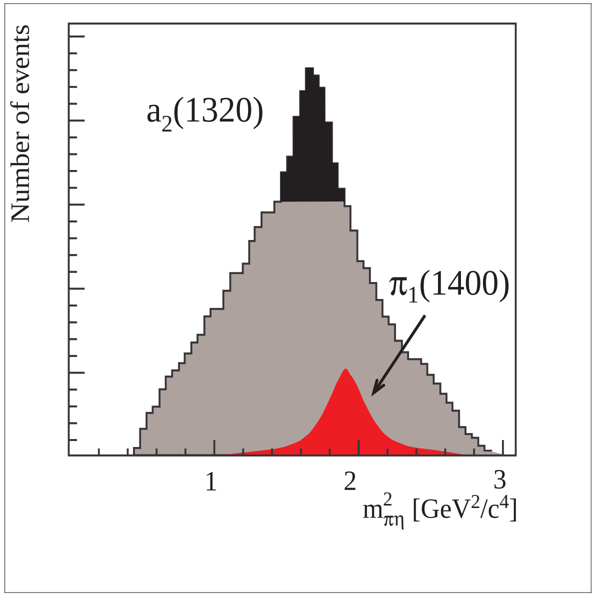
Contributing Resonances:
$a_0(980)$, $f_0(980)$, $f_2(1270)$, $a_2(1320)$, ...

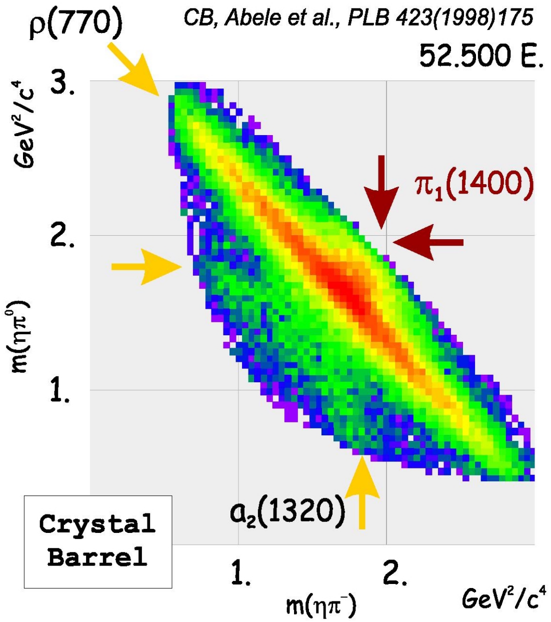
Firstly discovered:
$f_0(1500)$
$a_0(1450)$
$f_0(1370)$

Similar statistics:
$\pi^0\pi^0\eta$ (280 000 events),
$\pi^0\eta\eta$ (198 000 events),
$\pi^0 K_L K_L$ (48 000 events)

LEAR: Meson/Exotics-Spectroscopy (5)

2) $\bar{p}_{Stop} n \rightarrow \pi^0 \eta \pi^-$



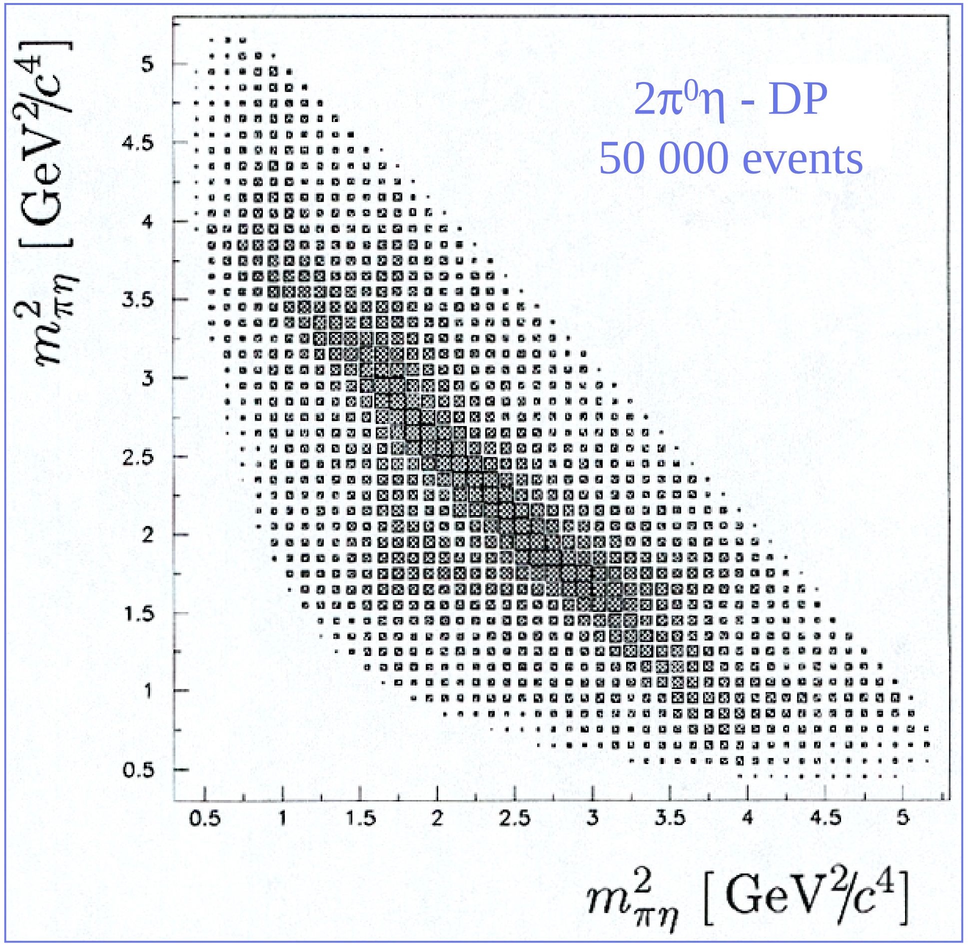


Resonances:
ρ^-, $a_2(1320)$, $\pi_1(1400)$
$\pi_1(1400)$: $J^{PC}=1^{-+}$ **!** (Exotic q.-n.)
$M \approx 1400$ MeV, $\Gamma \approx 300$ MeV

Firstly seen in
$\pi^- p \rightarrow \pi_1(1400) p$ (E 835/BNL)
$\hookrightarrow \eta\pi^-$

LEAR: Meson/Exotics-Spectroscopy (6)

3) $\bar{p}(1940\ \text{MeV}/c)p \rightarrow 3\pi^0,\ 2\pi^0\eta,\ 2\eta\pi^0$



Contributing Resonances:
$a_0(980)$, $f_0(980)$, $f_2(1270)$,
$a_2(1320)$, $f_0(1500)$

Further states needed:
$a_2(1660)$
$f_2(1650)$ $(\overset{?}{=}$ AX)
$f_J(2100)$

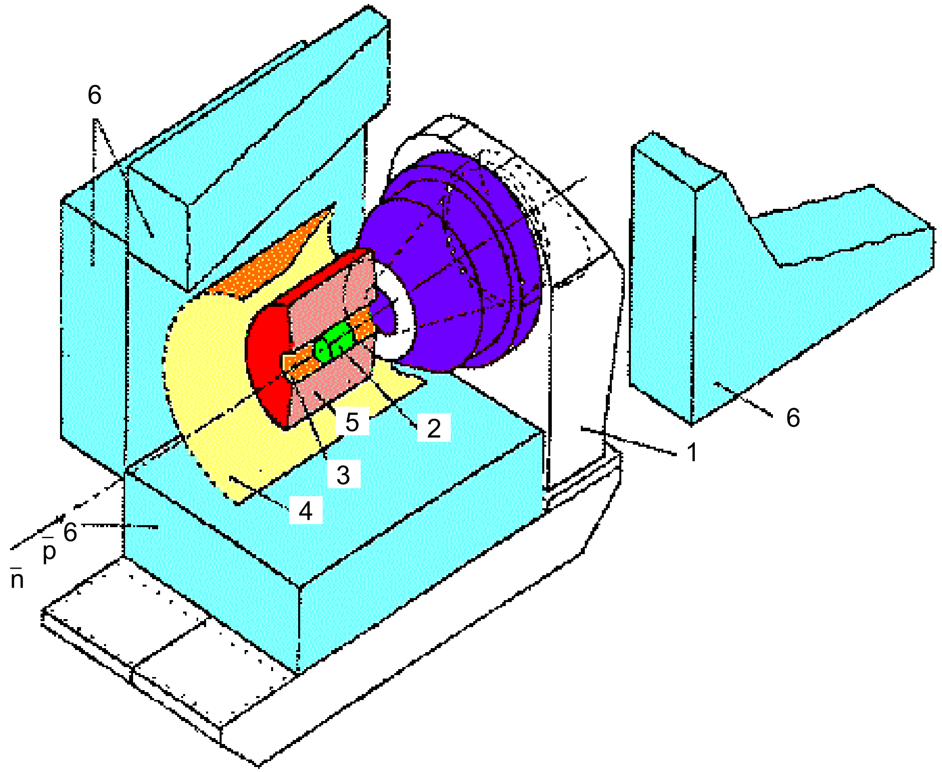
Resumee: Most of the known $(q\bar{q})$ resonances confirmed
Additional states found
➥ New input for a reinterpretation of $q\bar{q}$-Nonetts

LEAR: Meson/Exotics-Spectroscopy (7)

Obelix-Experiment

Not mentioned:
Precise determination of annihilation rates (pressure); Stopping Power of very low energy antiprotons (keV); Pontecorvo-Reactions; $\bar{p}$-He metastable states; ...

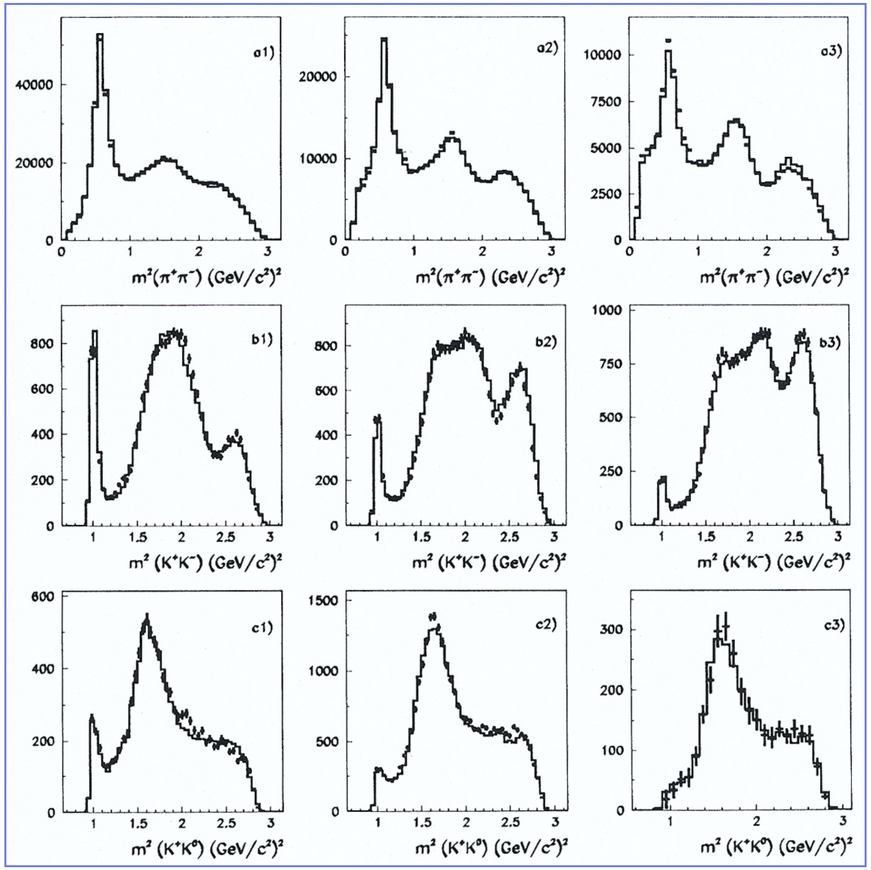
Strength of the experiment:
Good $K^{\pm}$ indentification
Variable target pressure
$\bar{n}p$-interactions



Overall layout of the Obelix Detector showing
(1) the open axial field magnet, (2) the spiral projection chamber,
(3) the (inner) time of flight detector, (4) the (outer) time of flight detector,
(5) the jet drift chamber, and (6) the gamma detector.

LEAR: Meson/Exotics-Spectroscopy (8)

) $\bar{p}_{Stop}p \rightarrow \pi^+\pi^-\pi^0;\ K^+K^-K^0;\ K^{\pm}K^0K^{\mp}$, (LH, NTP, LP)



Contributing Resonances:

$\phi(1020),\ K^*(892),\ \rho(770),\ \rho(1414),\ \rho(1620)\ (1^{--})$

$a_2(1320),\ f_2(1270),\ f'_2(1525),\ f_2(1565)\ (2^{++})$

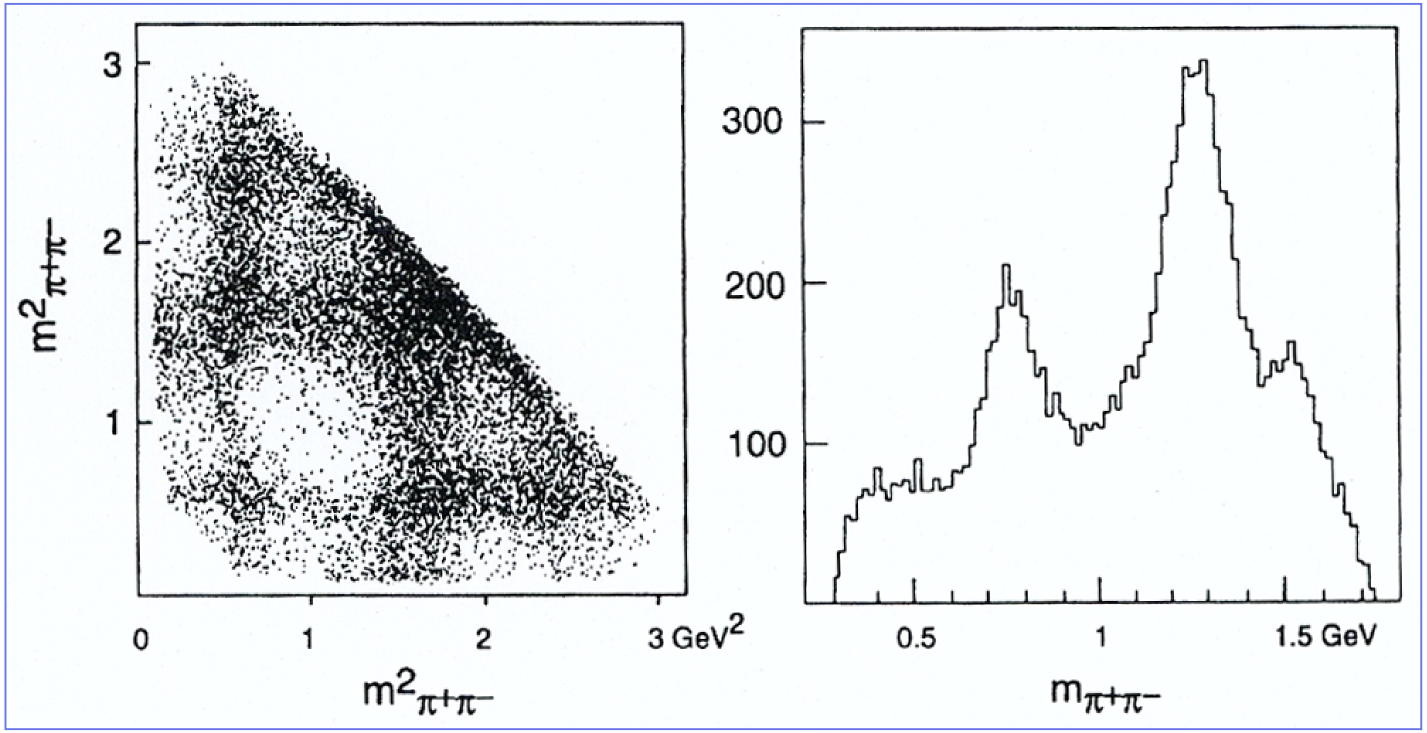
$K_0^*(1430),\ a_0(980),\ a_0(1300)\ (0^{++})$

$f_0(980),\ f_0(1540),\ f_0(1460)\ (0^{++})$

Confirmation of CB – results

LEAR: Meson/Exotics-Spectroscopy (9)

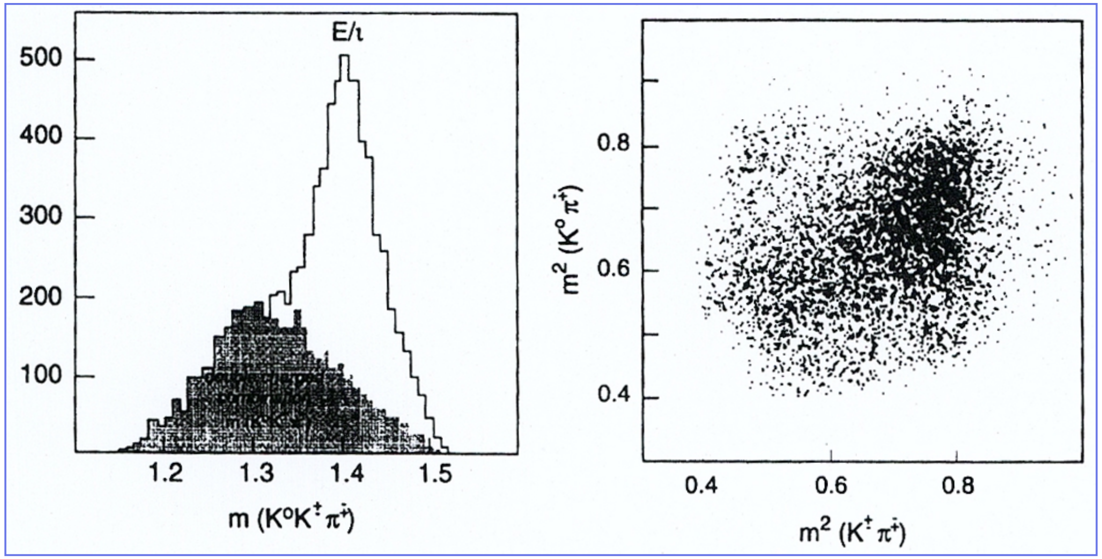
2) $\bar{n}(150-380\ \text{MeV}/c)p \rightarrow \pi^+\pi^-\pi^+$

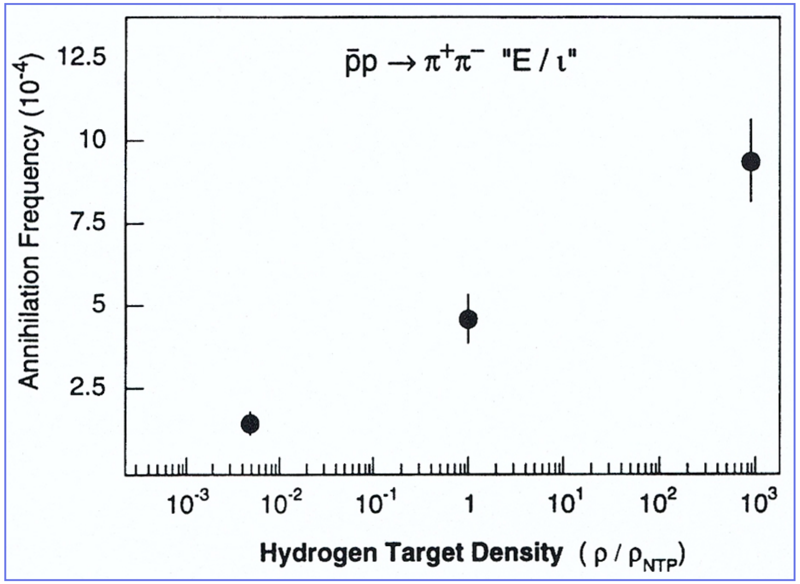


Contributing Resonances:
$\rho(770)$, $f_2(1270)$
$f_0(1520)$, $f_2(1565)$

LEAR: Meson/Exotics-Spectroscopy (10)

3) $\bar{p}p \rightarrow \pi^+\pi^-K^0K^\pm\pi^\mp$





Resonances: $E/i \rightarrow K^0K^\pm K^\mp, \quad J^{PC} = 0^{-+}$

$(\text{Two (?) states} \rightarrow a_0(980)\pi, K^*K)$

LEAR: Meson/Exotics-Spectroscopy (11)

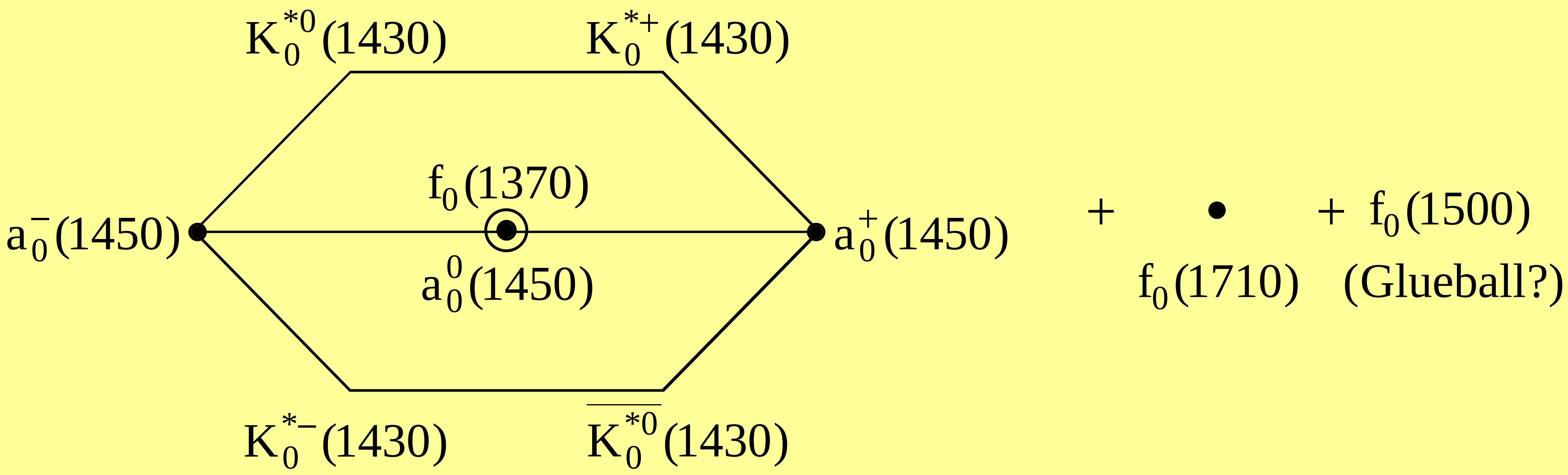
Discusion of scalar resonances (0^{++})

Many 0^{++}-states found:

$\sigma(600)$?, $a_0(980)$, $f_0(1370)$, $a_0(1450)$, $K_0^*(1430)$, $f_0(1500)$

Nature of these states ?

Possible Scenario:

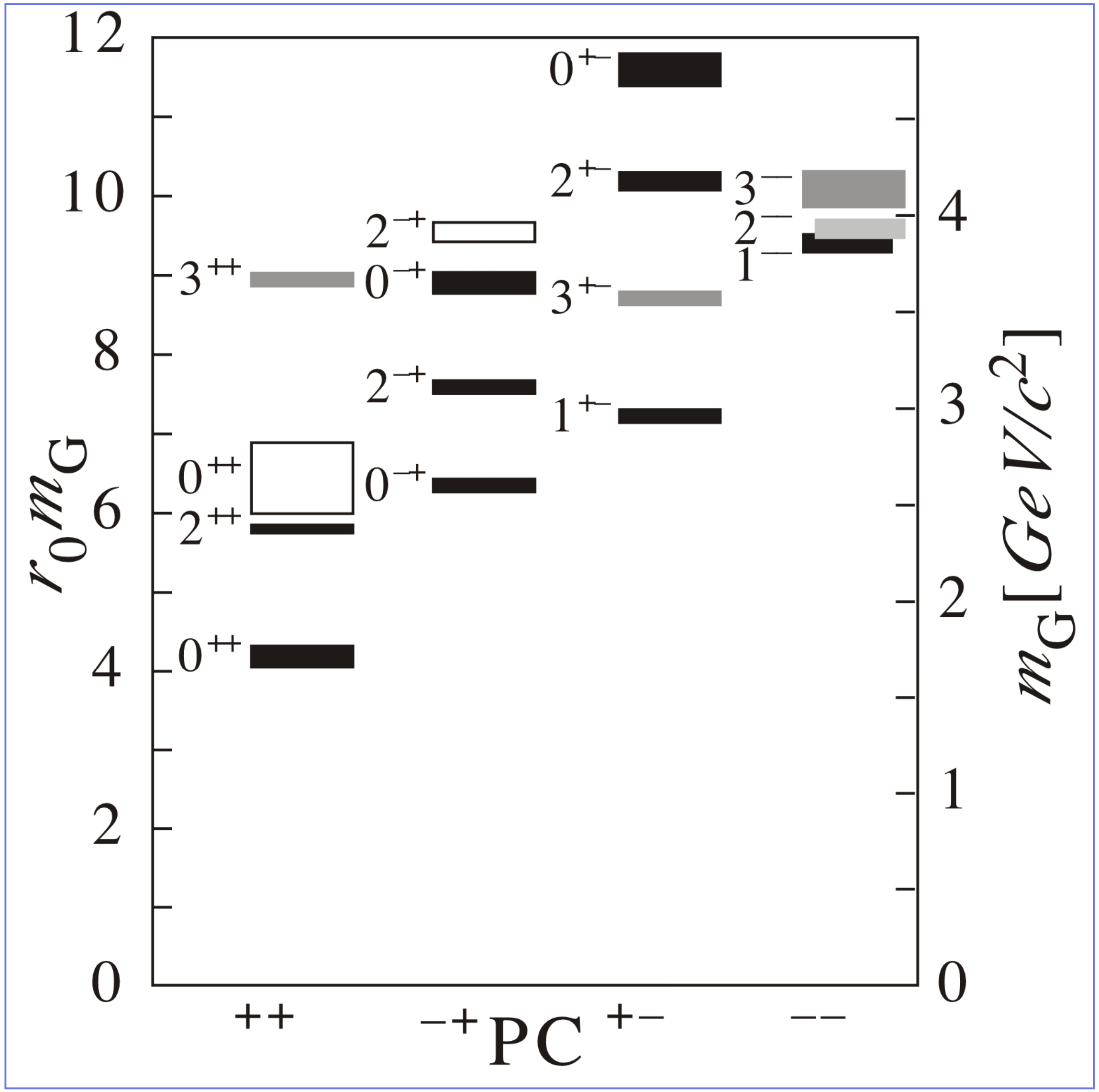


Consequences: $a_0(980)$, $f_0(980)$ = Multi-Quark-states
$\sigma(600)$: t-Channel Exchange

Further Scenarios also possible, Common to all: Supernumerary states

Situation not fixed, further experimental information needed, e.g. @ higher energies

LEAR: Meson/Exotics-Spectroscopy (12)



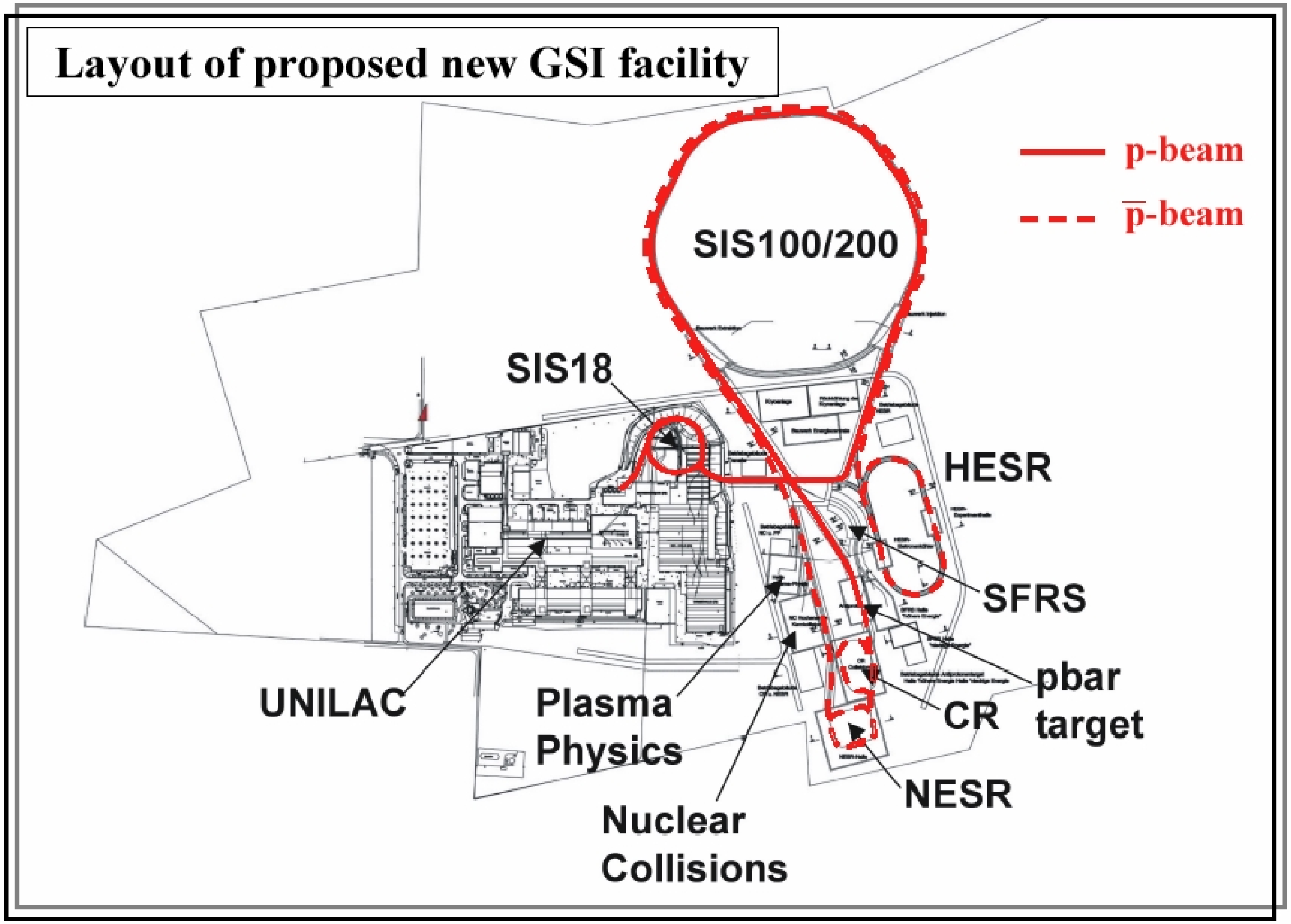
Lattice QCD:
Predicted Glueball Spectrum

Future Prospects (1)

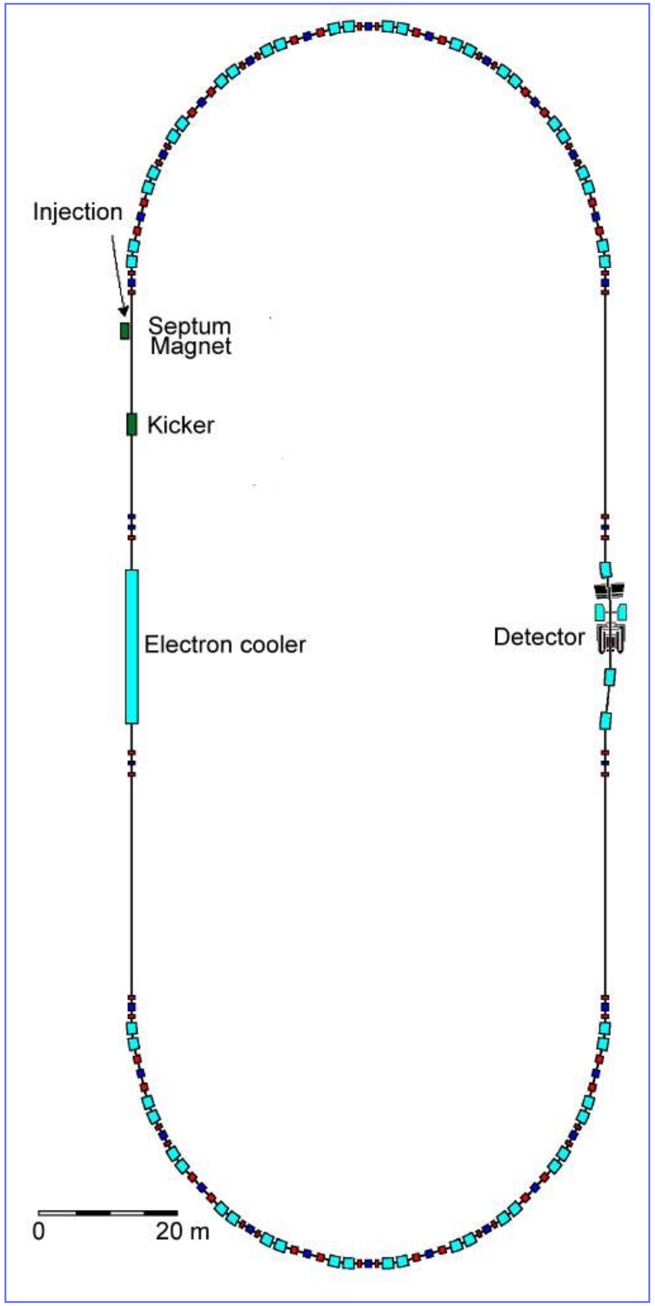
FAIR-Project at GSI/Darmstadt: Heavy Ions + Antiproton Physics
JAERI-KEK Hadron Facility: Emphasis on K-, ν-beams, Antiprotons in 2. stage

FAIR-Project

Production of Antiprotons up to 15 GeV/c



Future Prospects (2)



Physics Proposals involving Antiprotons:

Spectroscopy and $\bar{p}N/\bar{p}A$ reactions in the Charm Domain (PANDA)

Nucleon Structure Functions with/without Polarization (PAX, ASSIA)

Low energy $\bar{p}$-physics: FLAIR ($\bar{H}$-Spectroscopy, $\bar{p}$-He, ...)

:

PANDA – Detector

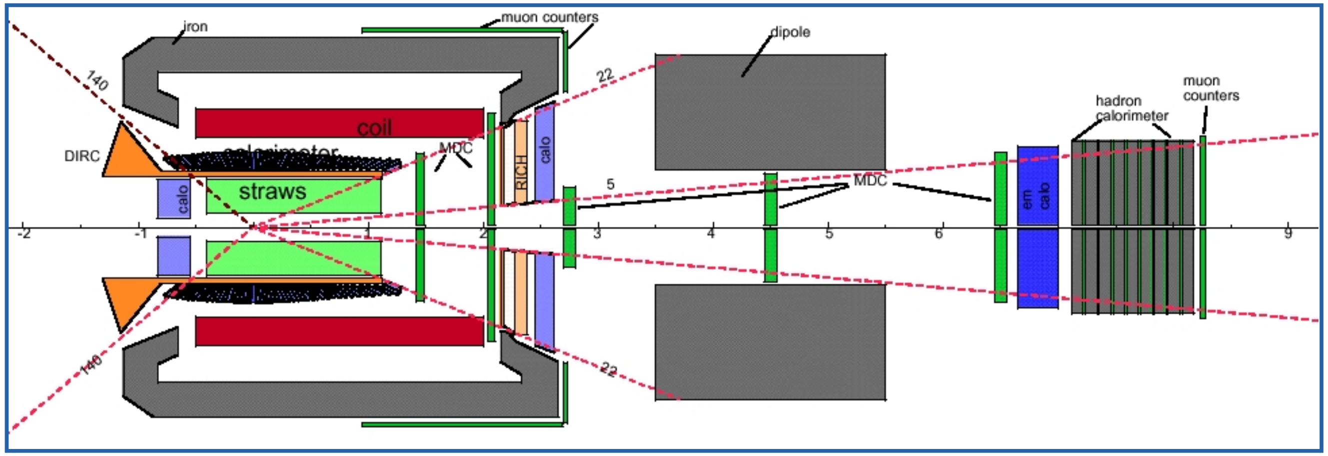
Detector requests

– 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

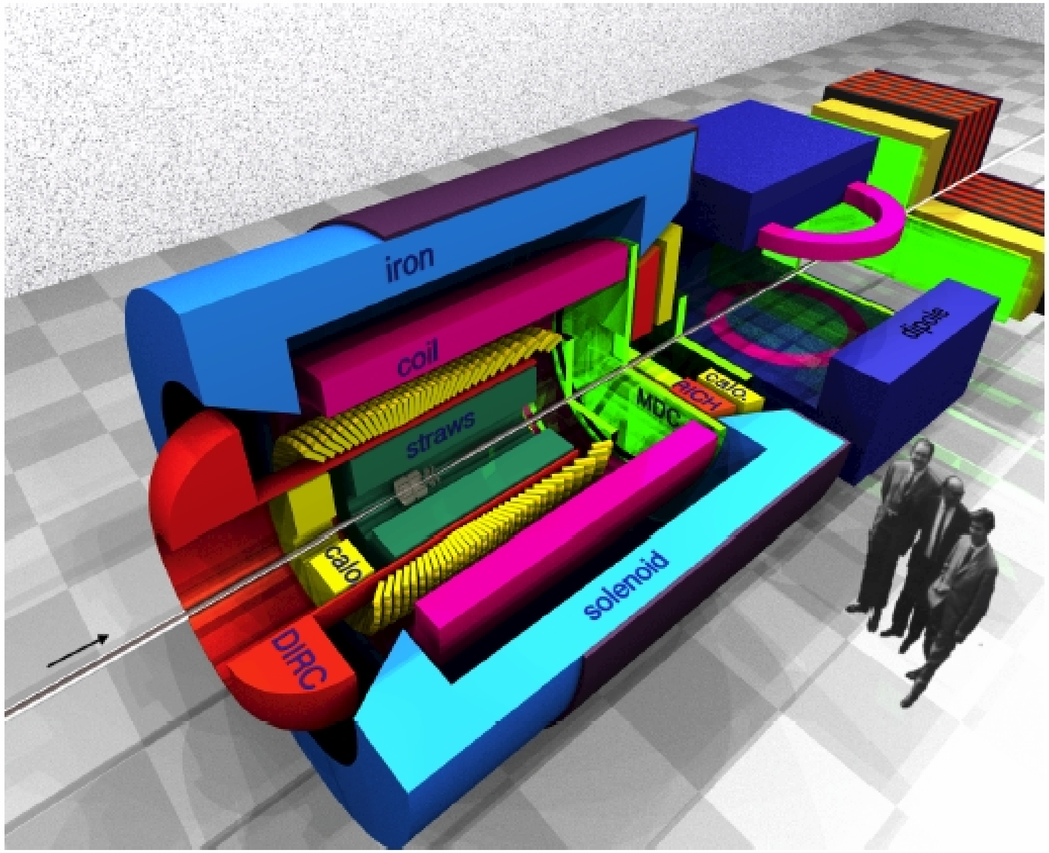
– Muons: Plastic Scint. Strips

– PID: Aerogel Cerenkov (ACC) / DIRC

– Trigger: High $p_\perp$ electrons/muons / Multiplicity jump (K_S, Λ, …)

Secondary vertex (D's,…) / Invariant masses / Global kinematical conditions

PANDA - Detector

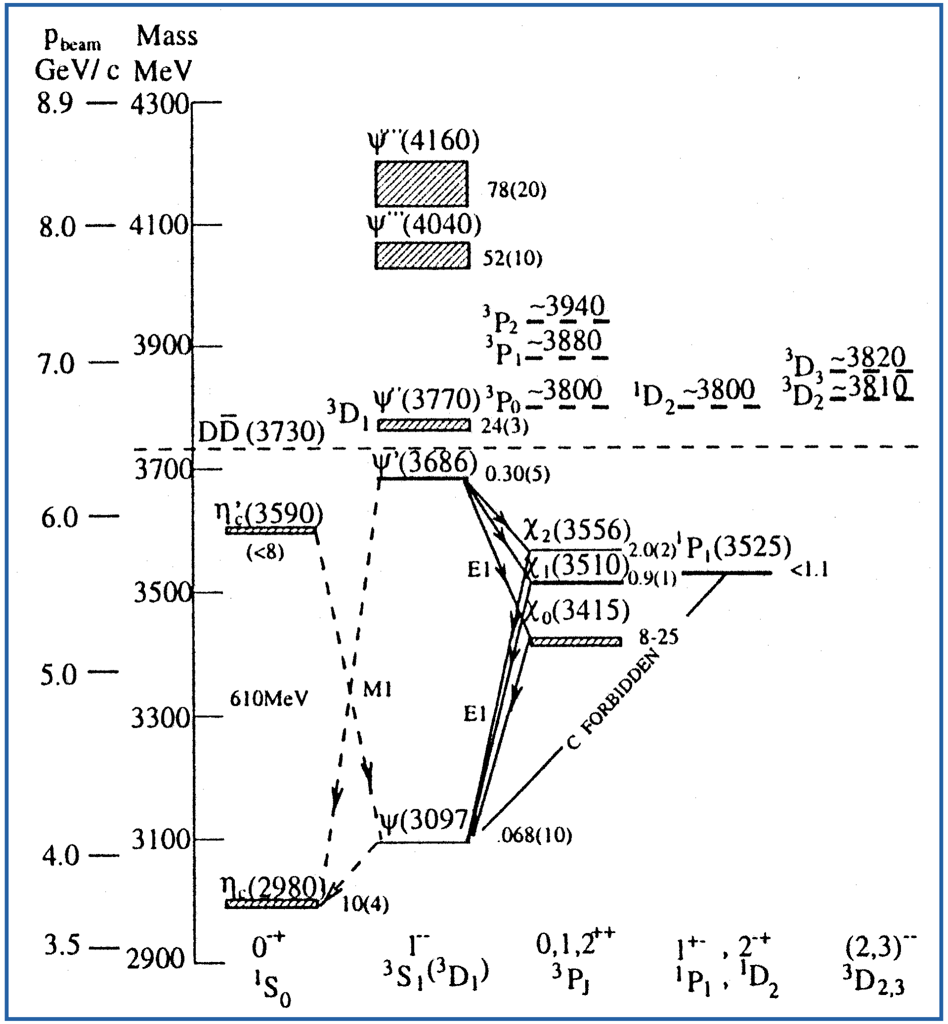


Detector features:

- 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 - Physics Program / Charmonium Spectroscopy (1)

$c\bar{c}$ - system (QCD) $\hat{=}$ 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

PANDA - Physics Program / Charmonium Spectroscopy (2)

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. $J/\psi \to \rho\pi^0; \eta_c, \chi_{co} \to B\overline{B}$ (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)

PANDA - Physics Program / Charmed Hybrids

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

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

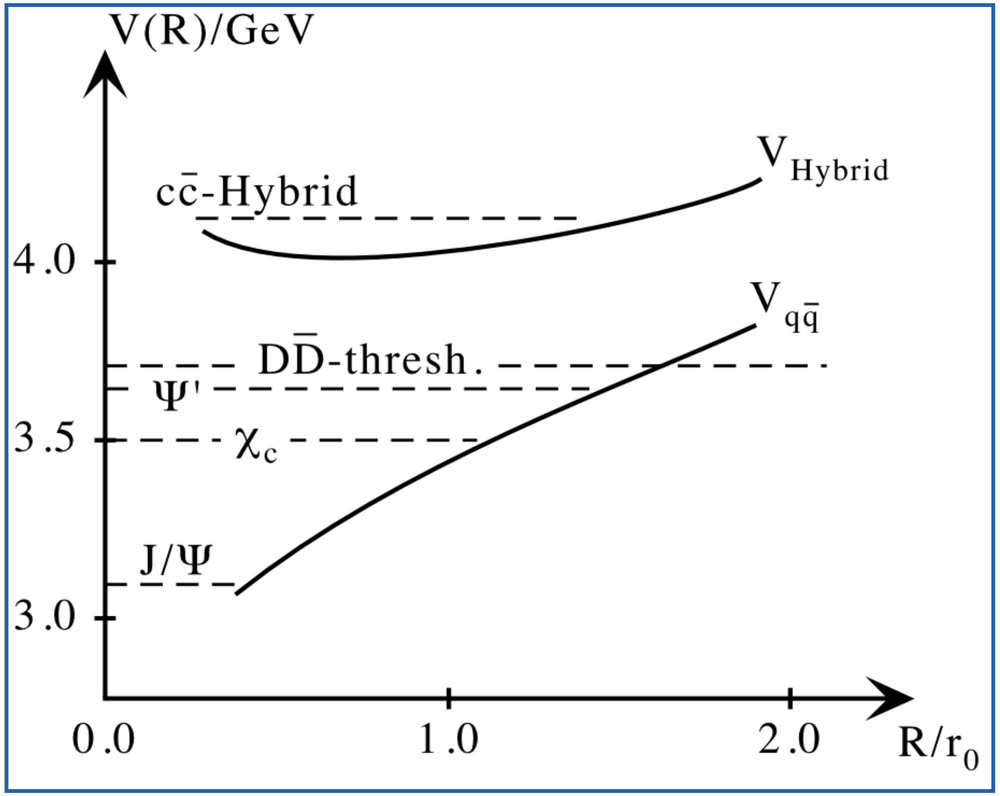
Masses

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)



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

States with exotic q.-n.:

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

$\approx 10^2$ ($c\bar{c}g$) 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: $\bar{p}p \rightarrow (c\bar{c}g) \rightarrow f_1(1285)\pi$, $K_1\bar{K}$, ...
Large cross sections (μb), Complementary to Hall D

Glueballs (gg)

Predictions:

Masses:

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

Quantum numbers:

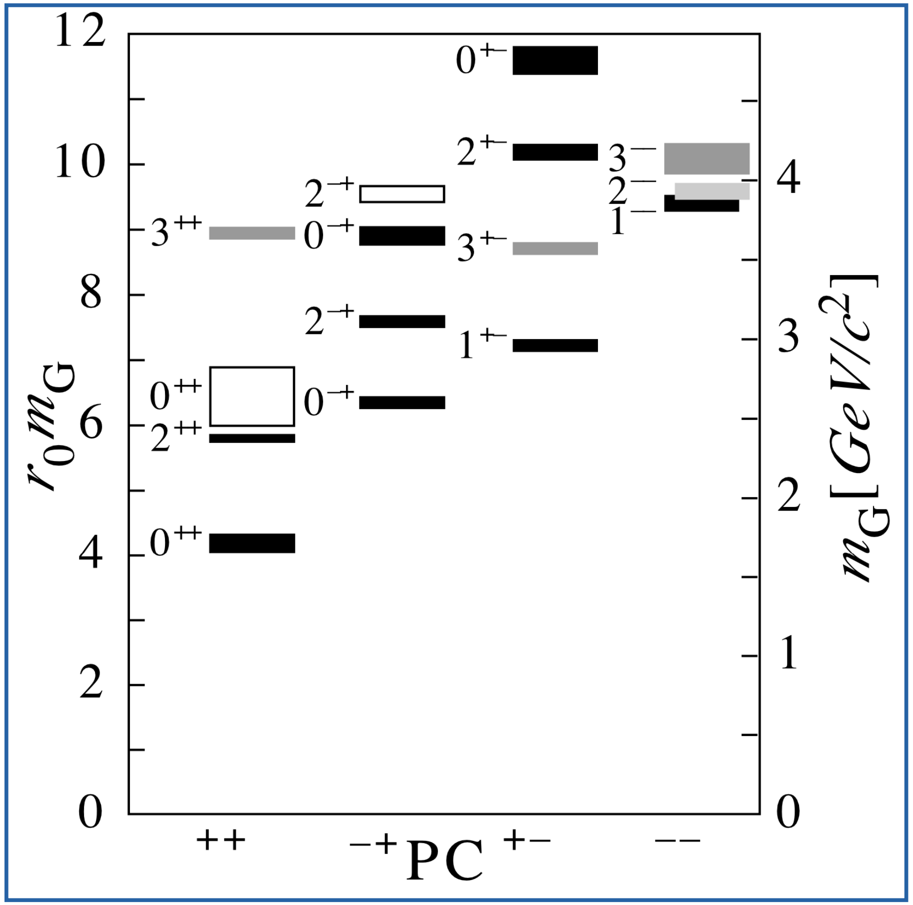
Several spin exotics (oddballs), e.g.

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

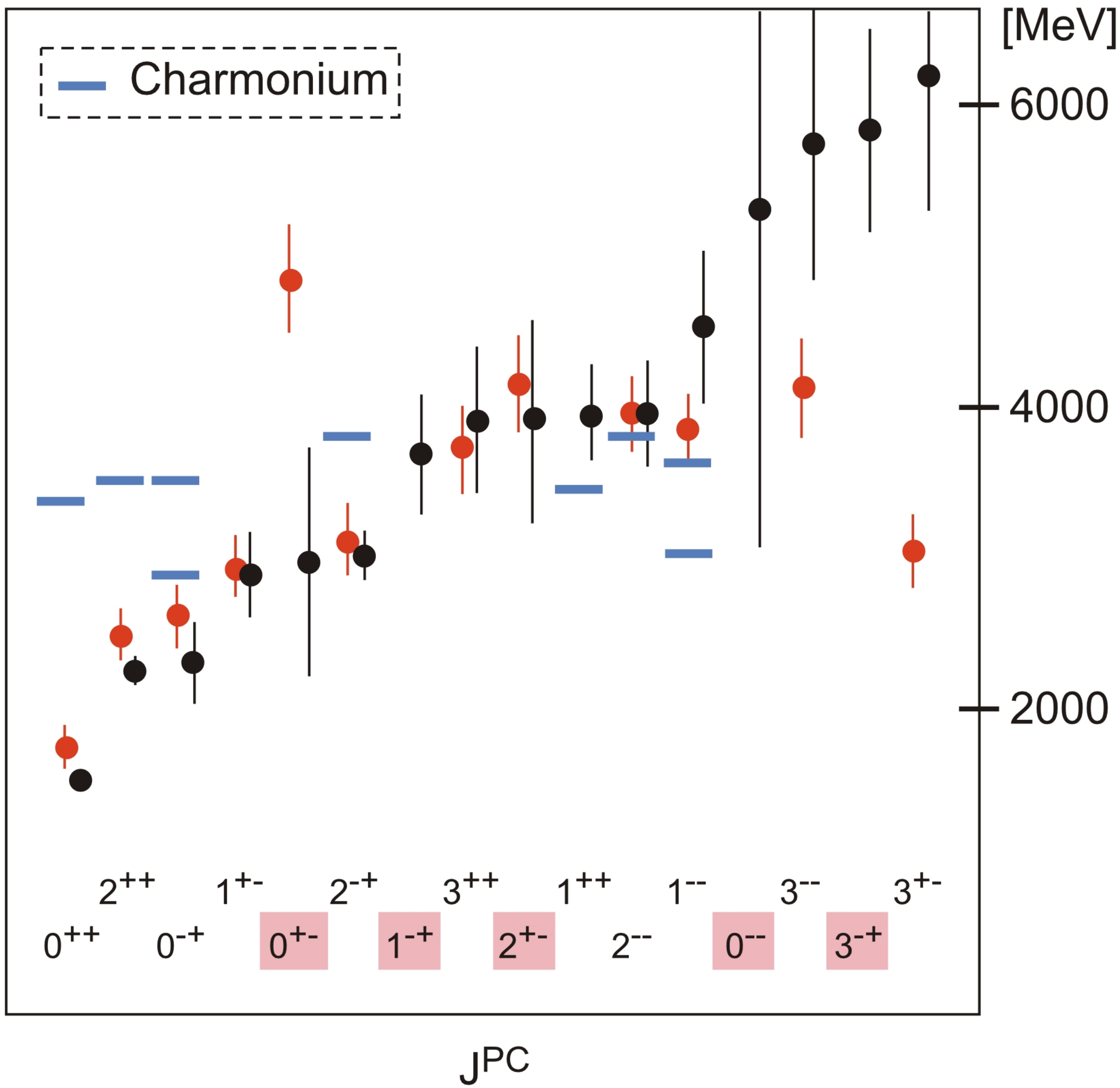
Widths: ≥ 100 MeV/c^2

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

– No mixing effects for oddballs



Charmonium States and Predicted Glueballs



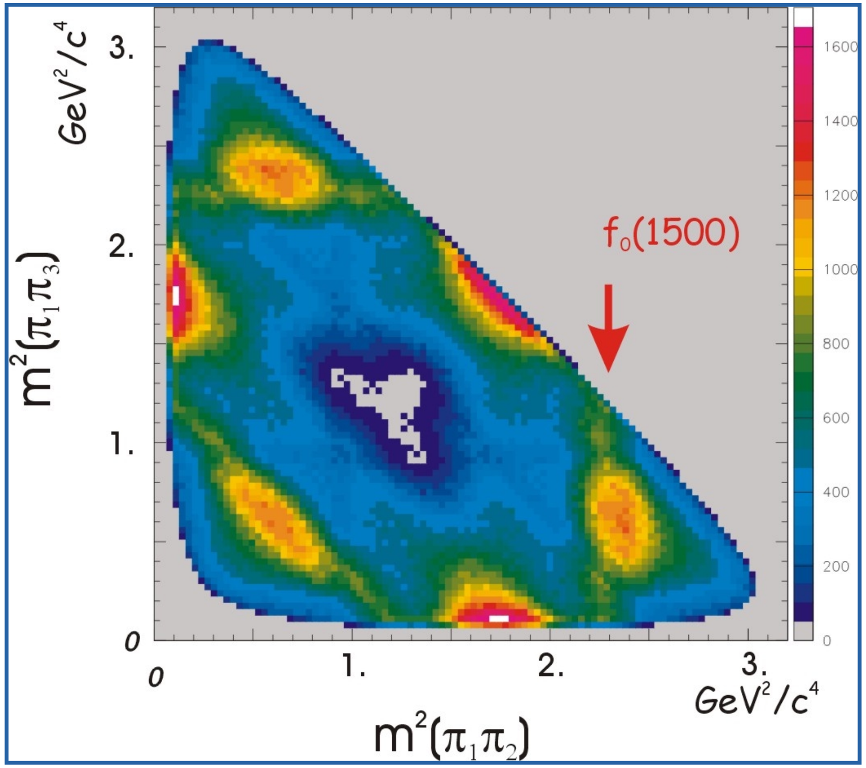
● UKQCD Collaboration, G. S. Bali et al., Phys. Lett B309 (1993) 378.
● C. Morningstar, M. Peardon; Phys. Rev. D 60 (1999) 034509.

PANDA - 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: $\bar{p}p \rightarrow (gg) \rightarrow \phi\phi, \phi\eta$

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

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

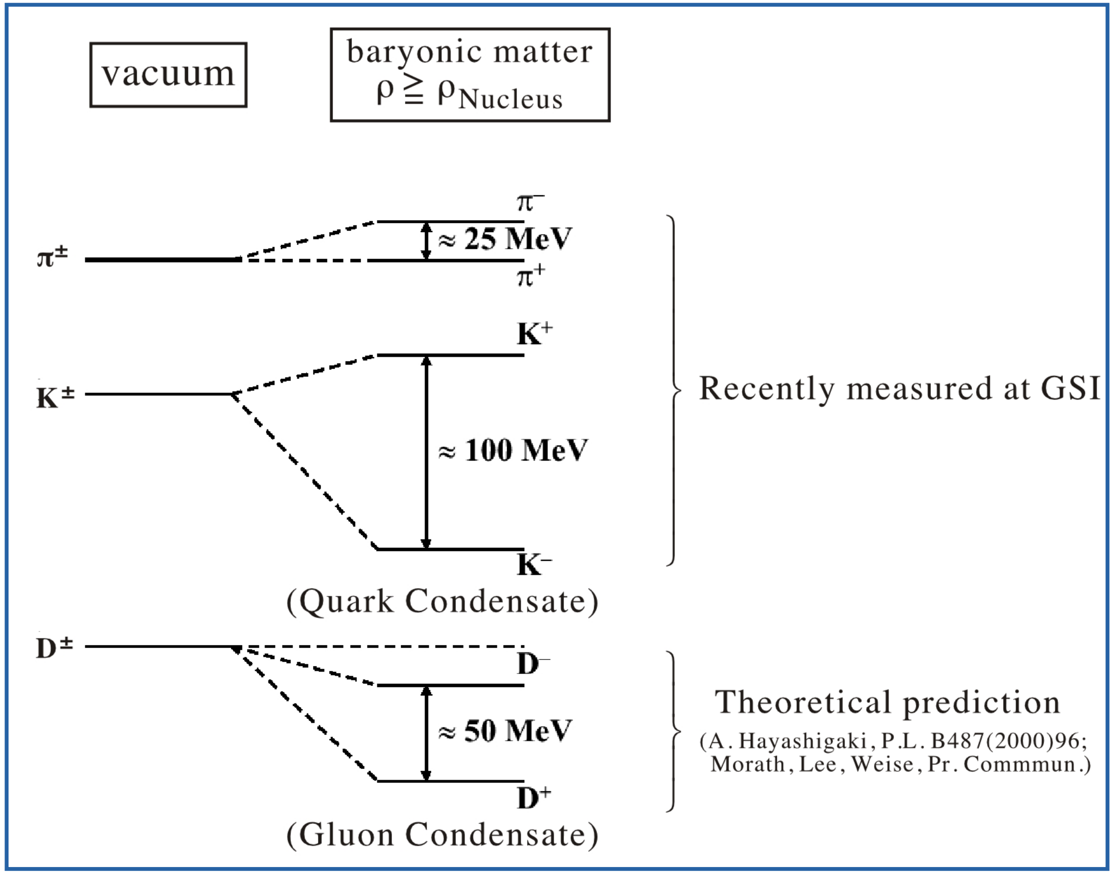
Reasonable measuring times

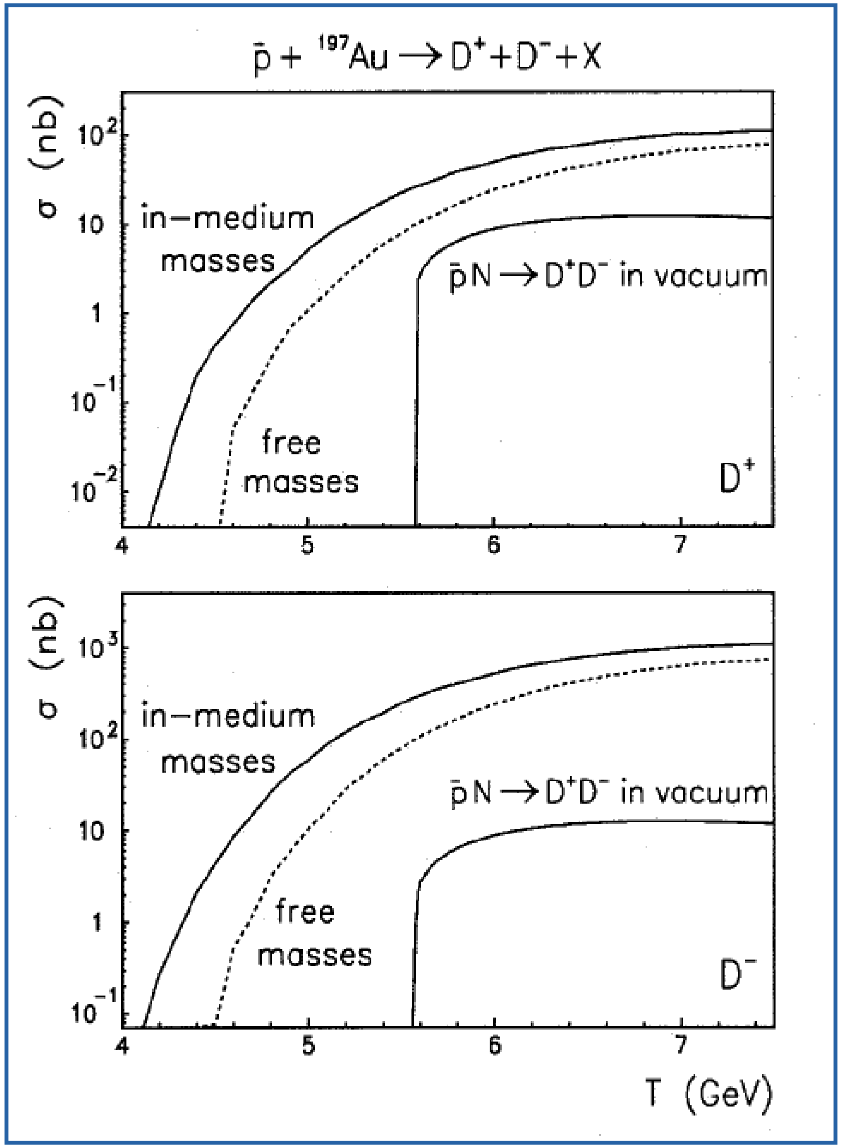
PANDA - Physics Program / Hadrons in Nuclear Matter

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 $\rightarrow (m_K)_{Eff.}$





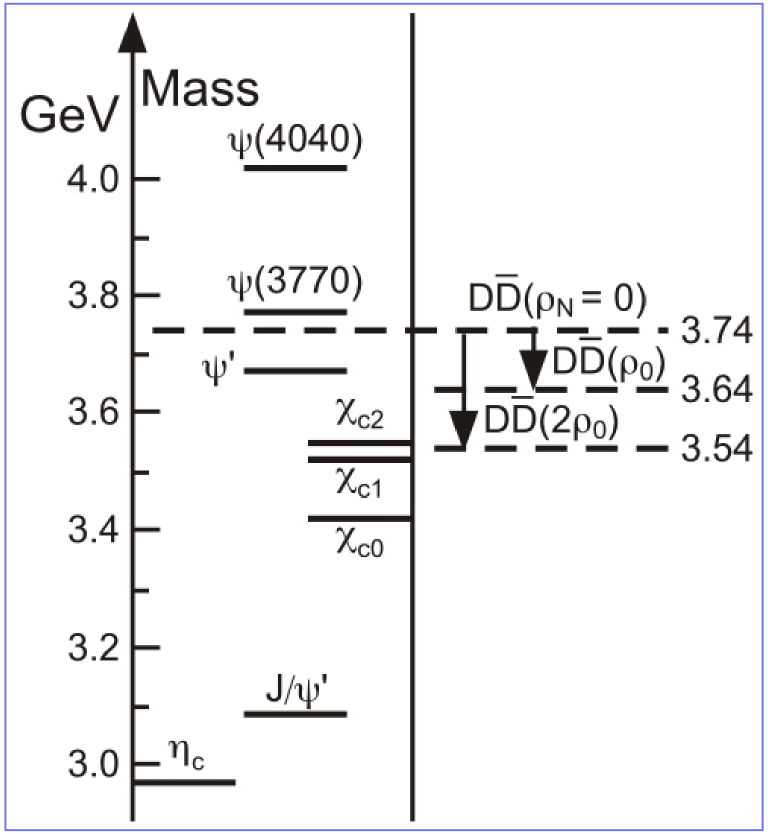
PANDA - Physics Program / Hadrons in Nuclear Matter

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 $\rightarrow$?; 2.0 MeV $\rightarrow$?)

– Increased width of $\psi(3770)$ (24 MeV $\rightarrow$?)

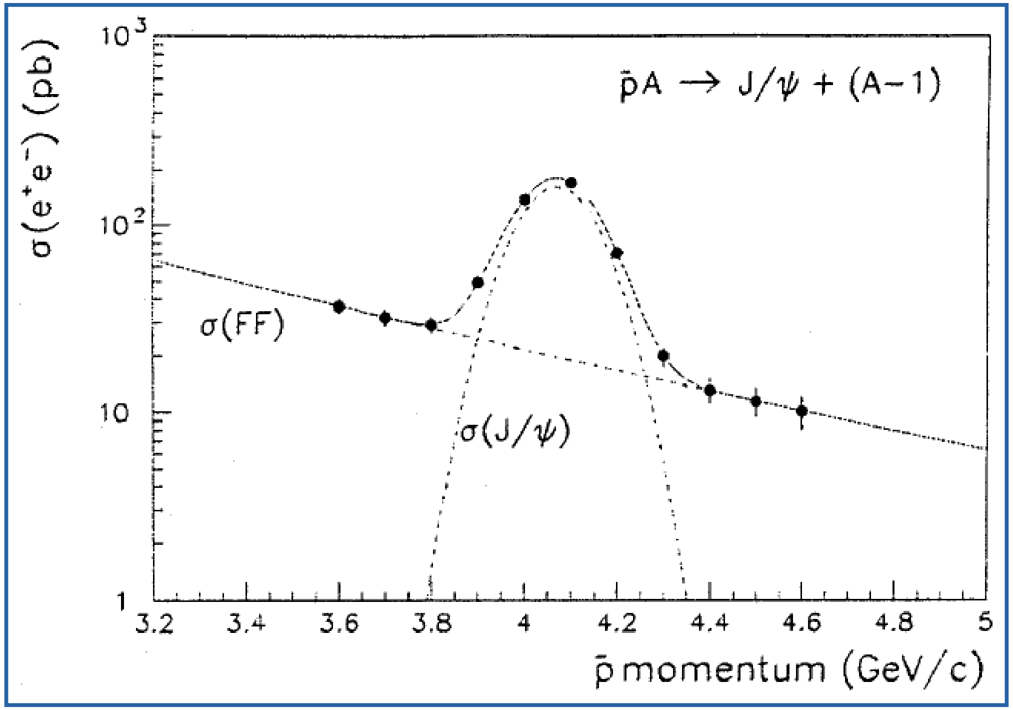


2) J/ψ - nucleon absorption cross section

Important for J/ψ - suppression in QGP

Proposed reaction:

$\bar{p}$(3.4-4.6 GeV/c) + A $\rightarrow$ J/ψ + (A-1)



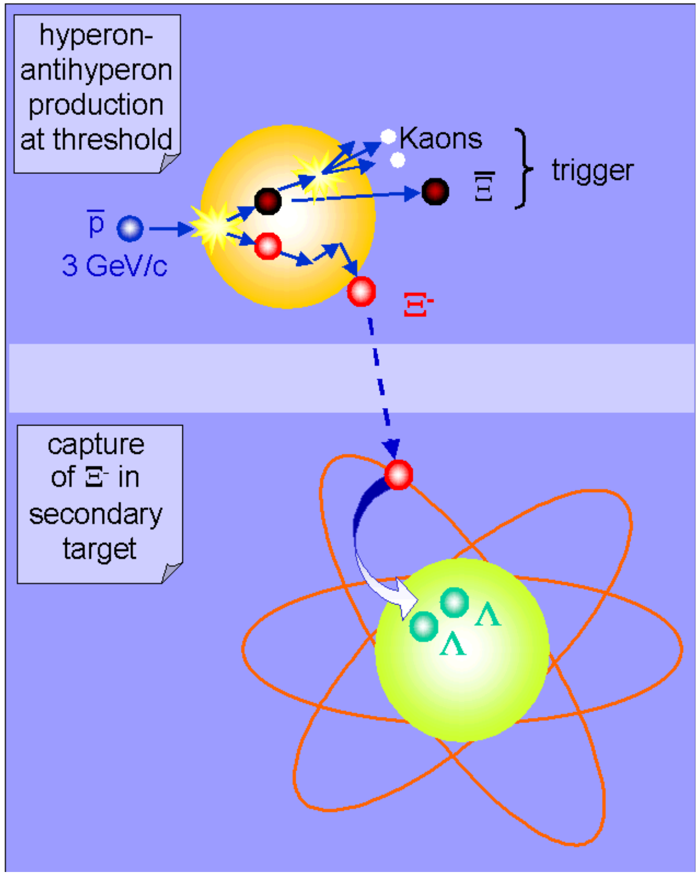
Furthermore:

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

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

3) Strange Baryons in Nuclear Field

Hypernuclei = Third dimension of the nuclear chart



Production of Double Λ-Hypernuclei:

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

Active, secondary target

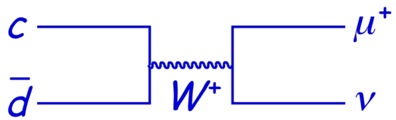
PANDA - Physics Program / Further Options

– 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 $\Lambda, \overline{\Lambda}$-decays

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

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

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

HESR: 1 year of beamtime

PANDA - 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)

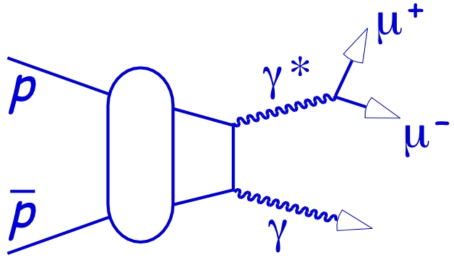
Compare $D^+ \to K^+\overline{K}^{0*}/D^- \to K^-K^{0*}$ Asymmetries $A\ (SM) < 10^{-3}$

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

PANDA - Physics Program / Further Options

Study of reversed Deeply Virtual Compton Scattering (DVCS)

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



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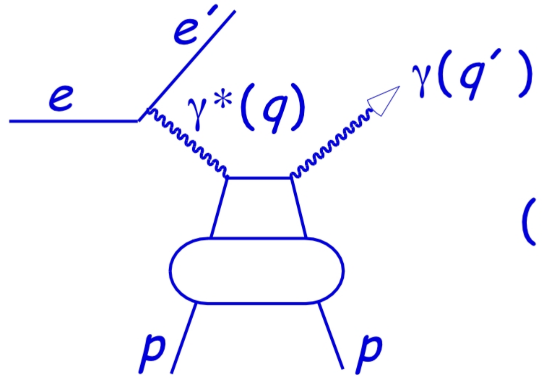


(DVCS)

Conclusions

– Physics with Antiprotons very fruitful in the past and in the future

Production of heavy particles ($W^{\pm}$, Z^0, t)

Copious and tagged production of particles (K^0, $\overline{K^0}$, η, η', Λ, Ξ, n, ...)

Study of resonant states up to the Charm Region with high statistics

Antiprotonic atoms and $\overline{\mathrm{H}}$

– Annihilation Process ideal source for the search for gluonic degrees of freedom

– Cooled Antiproton beams have unique features as far as precision experiments are concerned

– Bright Future ahead

Physics Program / Measurements in the Charm Region

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

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

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

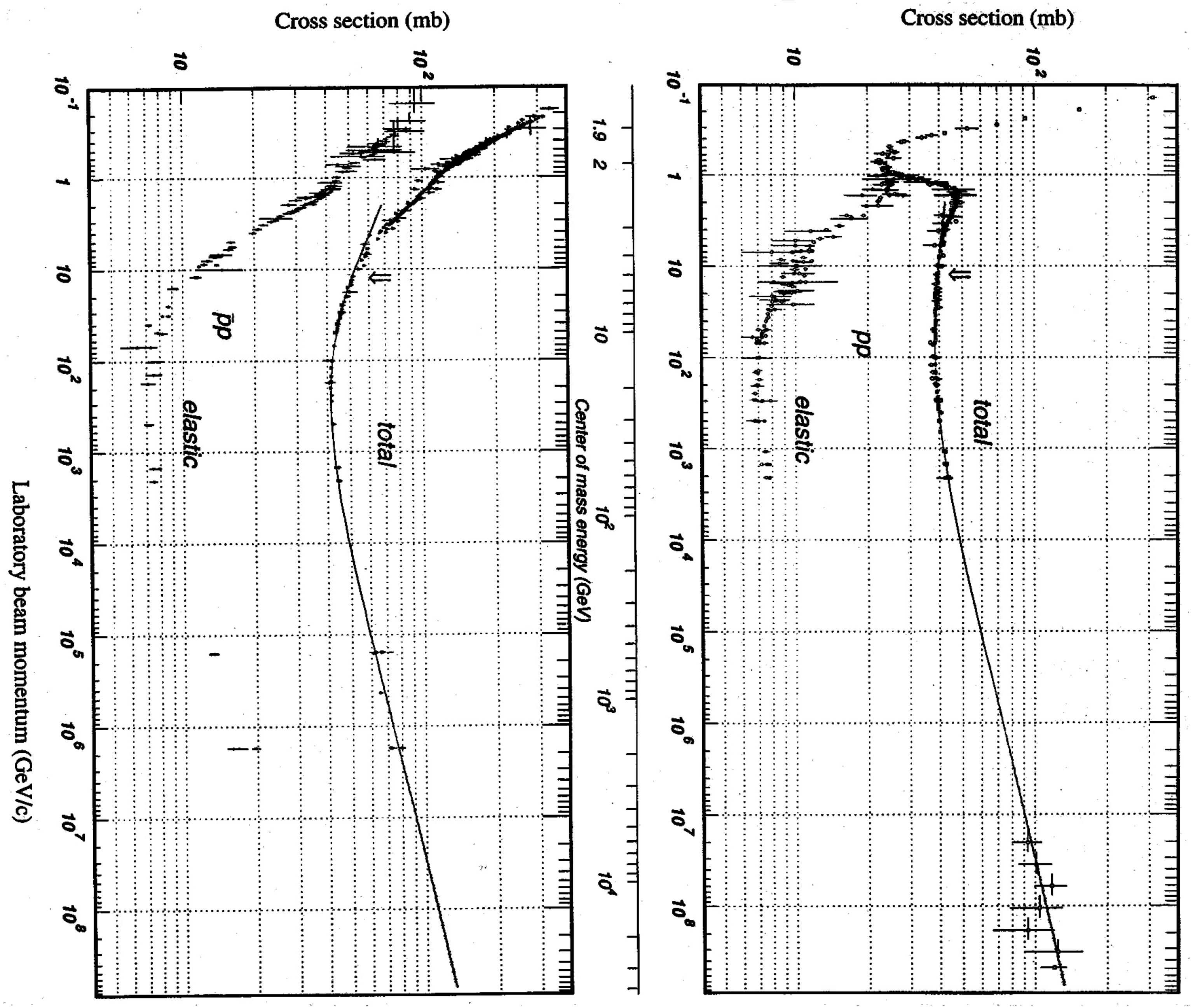
Charmed Hybrids $\rightarrow$ $J/\psi\eta, \ldots$

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)

Basic Facts about $\bar{p}$(n)'s



LEAR: Meson/Exotics-Spectroscopy

Meson-like states with exotic quantum number combination

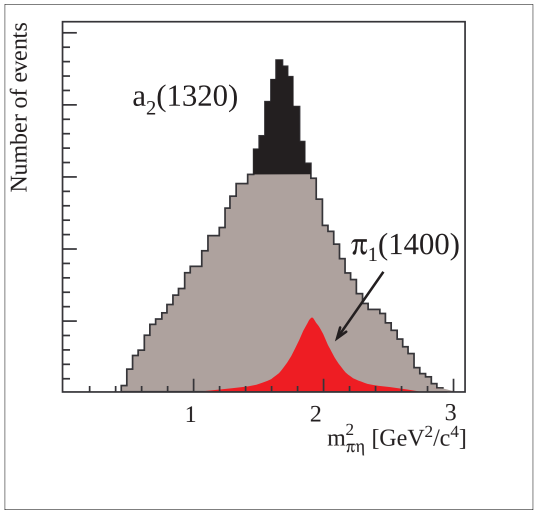
$\pi_1(1400)$ / $\pi_1(1600)$

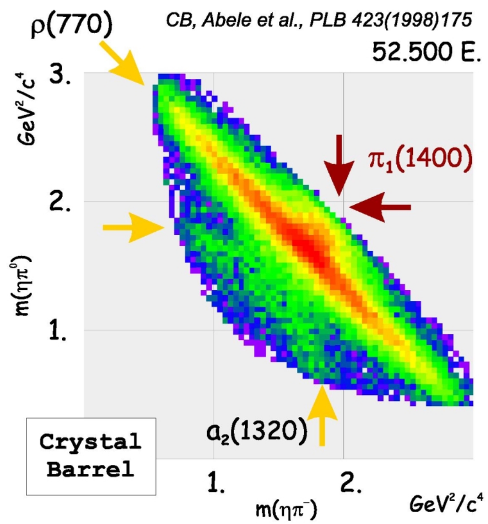
Production/Decays :

$\pi^- p \rightarrow \pi_1(1400)p$ (E835/BNL) and $\bar{p}n \rightarrow \pi_1(1400)\pi^0$ (Crystal Barrel/LEAR)
$\quad \hookrightarrow \eta\pi^- \qquad\qquad\qquad\qquad \hookrightarrow \eta\pi^-$

$\pi^- p \rightarrow \pi_1(1600)p$ (E835 BNL) and $\bar{p}p \rightarrow \pi_1(1600)\pi^+$ (Crystal Barrel/LEAR)
$\quad \hookrightarrow \pi^-\eta \qquad\qquad\qquad\qquad \hookrightarrow \pi^-\eta$

M ≈ 1400, 1600 MeV ; Γ ≈ 300 MeV ; J^{PC} = **1^{-+}** (Exotic Q.-N., At variance with naive Quark-model)





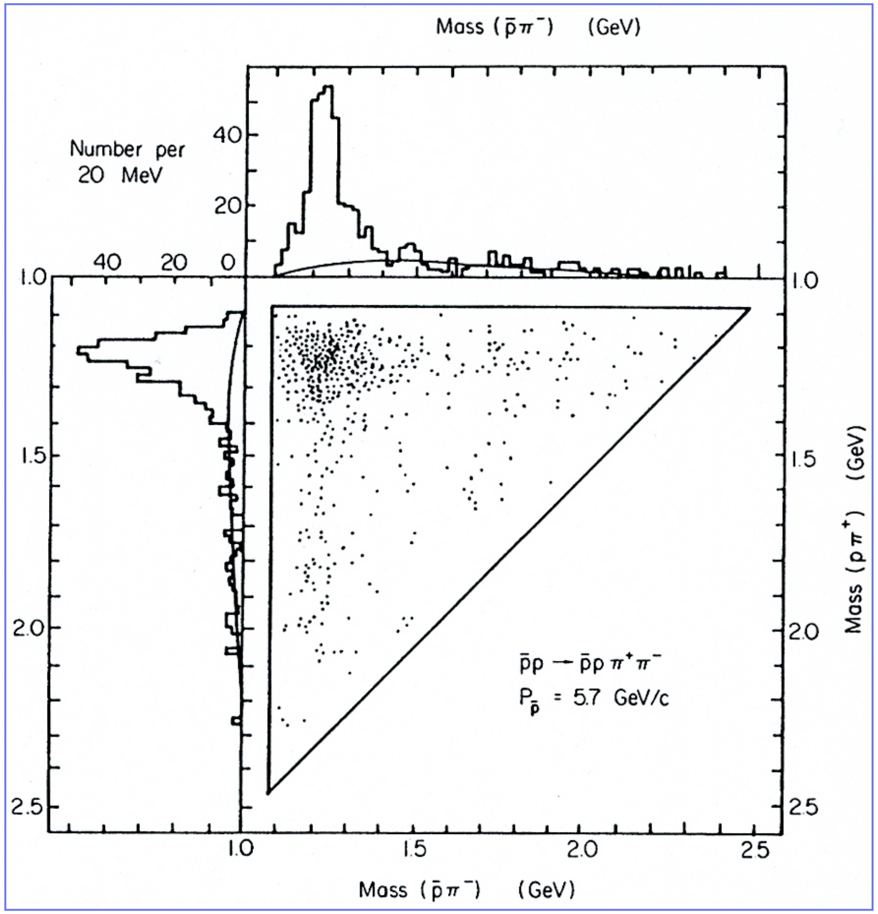
Exotic?
Exotic J^{PC}-combination

Hybrids?
Multi-Quark-states?

$\bar{p}(\bar{n})$-N-Interactions

Medium energies:

$\bar{p}(5.7\ \text{GeV/c})p \rightarrow \bar{p}p\pi^+\pi^-$



High energies (only inclusive measurements)

– Most particles go forward or backward in CMS
– $\langle p_t \rangle \approx 0.4$ GeV/c
– Leading particle effects

$\bar{p}(\bar{n})$-N-Interactions

Rapidity

Adequate variable to describe the p_L-distribution of particles ($\pi^{\pm}$, all charged, beam-, target particle)

Rapidity: $$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} = \ln\frac{E+p_L}{\sqrt{p_t^2+m^2}};\ p_L = (\vec{p}\cdot\vec{e});\ \vec{e} = \text{direction of beam}$$

$$\text{Lab}:\quad 0 \le y \lesssim 2\ln\frac{E_{CM}}{m}$$

$$\text{CMS}: -\ln\frac{E_{CM}}{m} \le y^* \le \ln\frac{E_{CM}}{m}$$

$$\text{Advantage}: y' = y + \ln(\gamma(\beta+1)) \qquad \text{Additive!}$$

$$\beta = \text{velocity of system' relative to system} \quad ; \quad \frac{\delta y}{\delta p_L} = \frac{1}{E}$$

Pseudorapidity

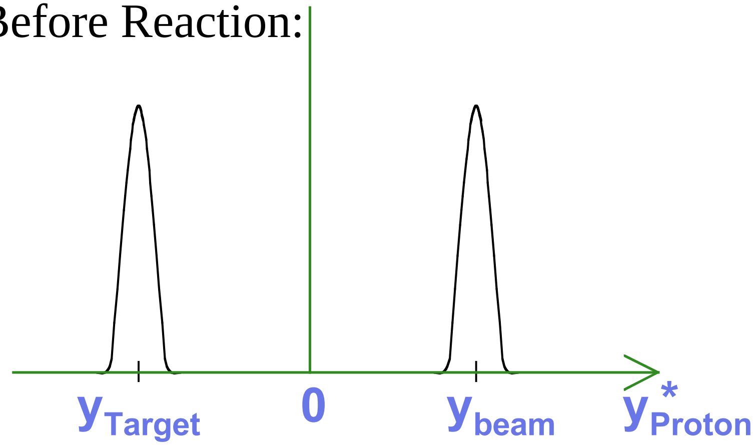
$$\eta^* = \frac{1}{2}\ln\frac{|\vec{p}|+p_L}{|\vec{p}|-p_L} = -\ln(\tan(\Theta^*/2))$$ Advantage: no measurement of particle momentum necessary

$$\hookrightarrow\ = y^* \text{ for } p_t^2 >> m^2;\ p_L \sim E;$$

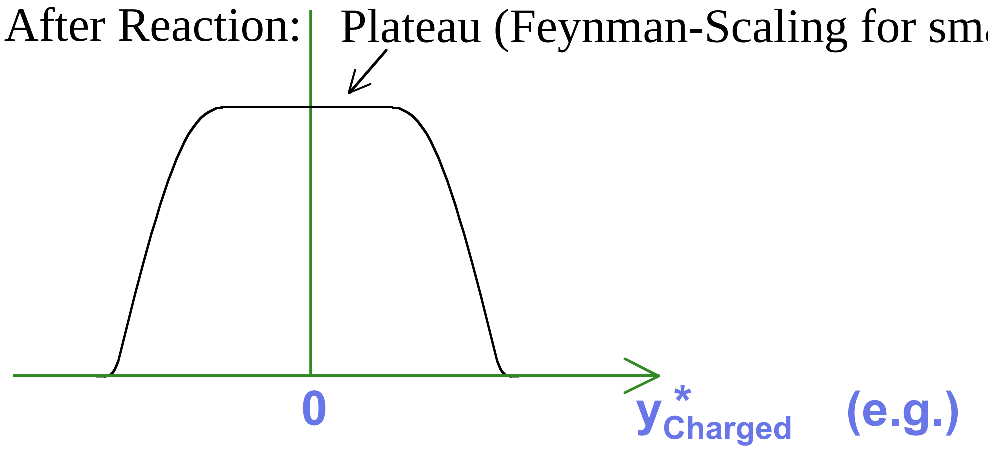
$$= y^* \text{ for } \gamma\text{'s } (m=0)$$

$\bar{p}(\bar{n})$-N-Interactions

Before Reaction:

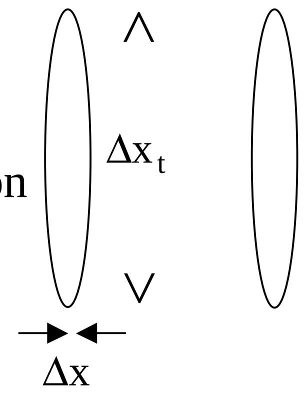


After Reaction:



(Qualitative) Explanation for low $<p_t>$: Relativistic Fireball Model

Relativistic
Lorentz Contraction



$$\Delta x_L \approx \frac{1}{m_\pi} \frac{2m_p}{\sqrt{s}}$$

$$\Delta x_t \approx \frac{1}{m_\pi}$$

$$\hookrightarrow \left.\begin{array}{l} < p_L > \approx \dfrac{1}{\Delta x_L} \approx \dfrac{m_\pi}{m_p} \dfrac{\sqrt{s}}{2} \\ < p_t > \approx \dfrac{1}{\Delta x_t} \approx m_\pi \end{array}\right\} \text{Experimentally verified}$$

$\bar{p}(\bar{n})$-N-Interactions

Data (UA5, …)

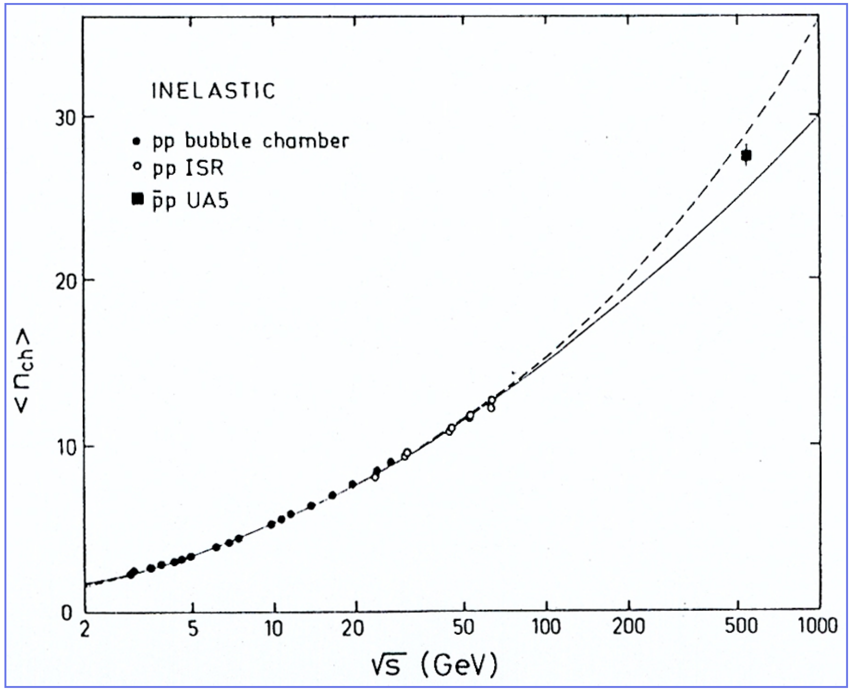
Multiplicities of a typical event @

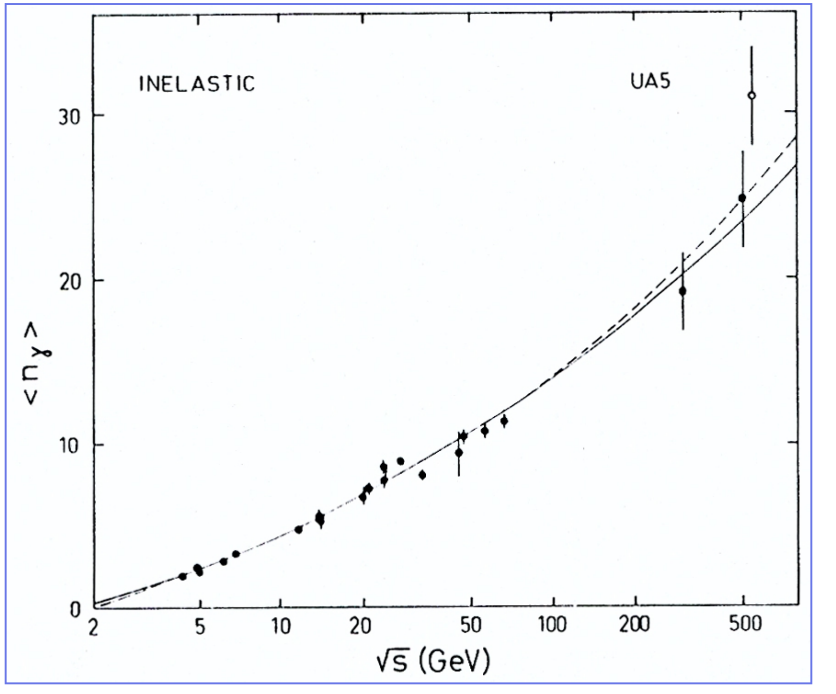
$$\sqrt{s} = 546/53\ \text{GeV}$$

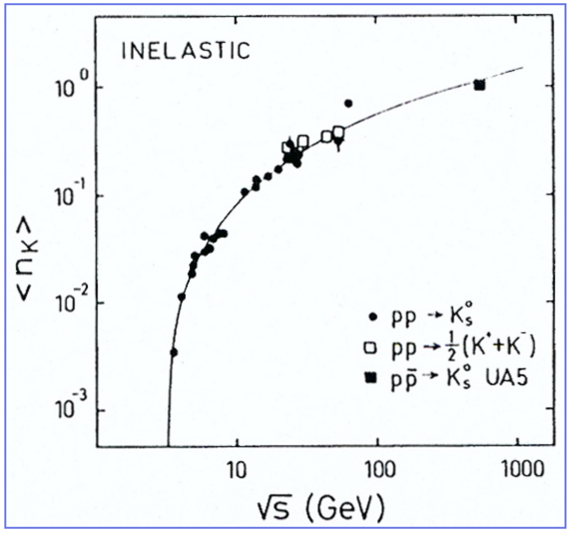
Particle type		$\sqrt{s}=546$ GeV $\langle n \rangle$	$\sqrt{s}=53$ GeV $\langle n \rangle$
All charged		28.4 ± 0.3	10.1
$K^+ + K^-$	*	2.24 ± 0.16	0.75
$K^0 + \overline{K^0}$	*	2.24 ± 0.16	0.7
all γ		33.0 ± 3.0	11.8
$p + \bar{p}$	*	1.45 ± 0.15	0.3
$n + \bar{n}$	*	1.45 ± 0.15	0.3
$\Lambda + \bar{\Lambda} + \Sigma^0 + \bar{\Sigma}^0$	*	0.53 ± 0.11	0.1
$\Xi^- + \bar{\Xi}^-$	*	0.10 ± 0.03	–
$\Xi^0 + \bar{\Xi}^0$	*	0.10 ± 0.03	–
$\Sigma^+ + \Sigma^- + \bar{\Sigma}^+ + \bar{\Sigma}^-$	*	0.27 ± 0.06	0.04
$e^+ + e^-$		0.41 ± 0.04	0.15
$\pi^+ + \pi^-$		23.9 ± 0.4	8.9
η	*	3.4 ± 1.1	1.1
γ (from η)		11.0 ± 3.5	3.4
$\pi^\pm$ (from η)		1.9 ± 0.6	0.6
$\pi^\pm$ (not from η)	*	22.0 ± 0.7	8.4
π^0 (not from η)	*	11.0 ± 0.4	4.2

p̄(n̄)-N-Interactions

Energy dependence of <n>:

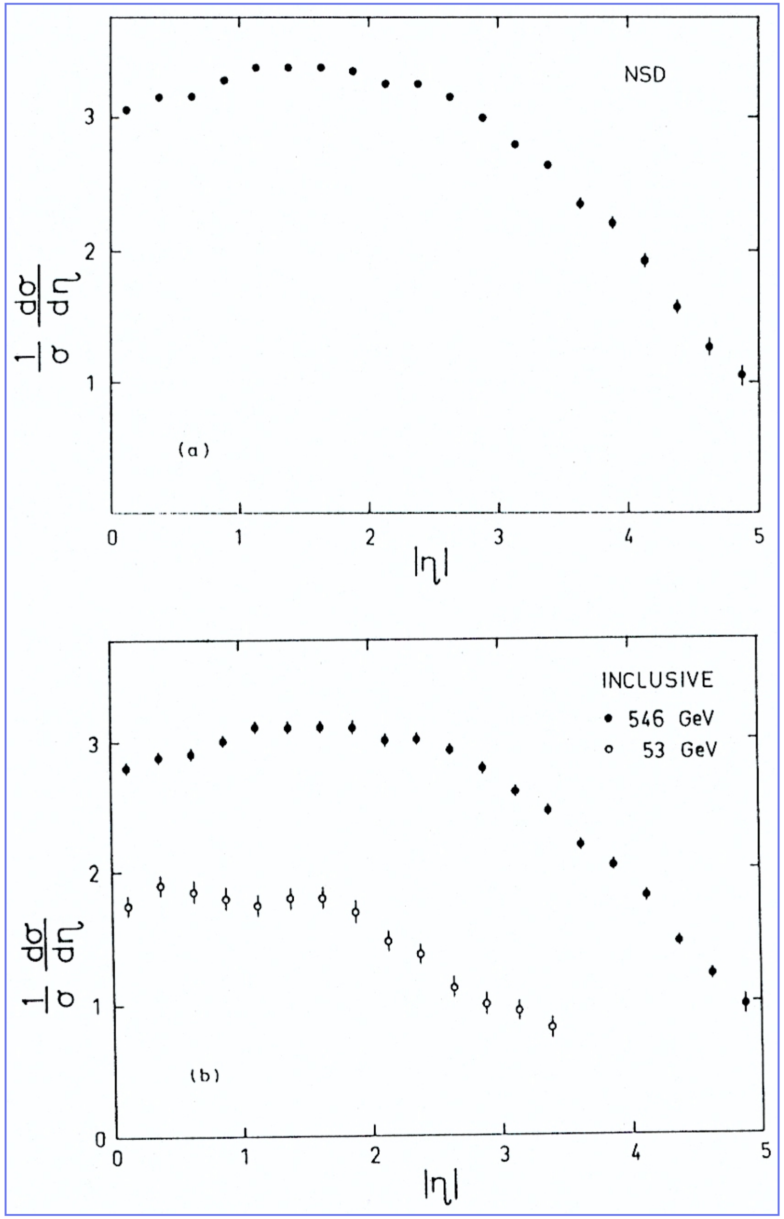






$\bar{p}(\bar{n})$-N-Interactions

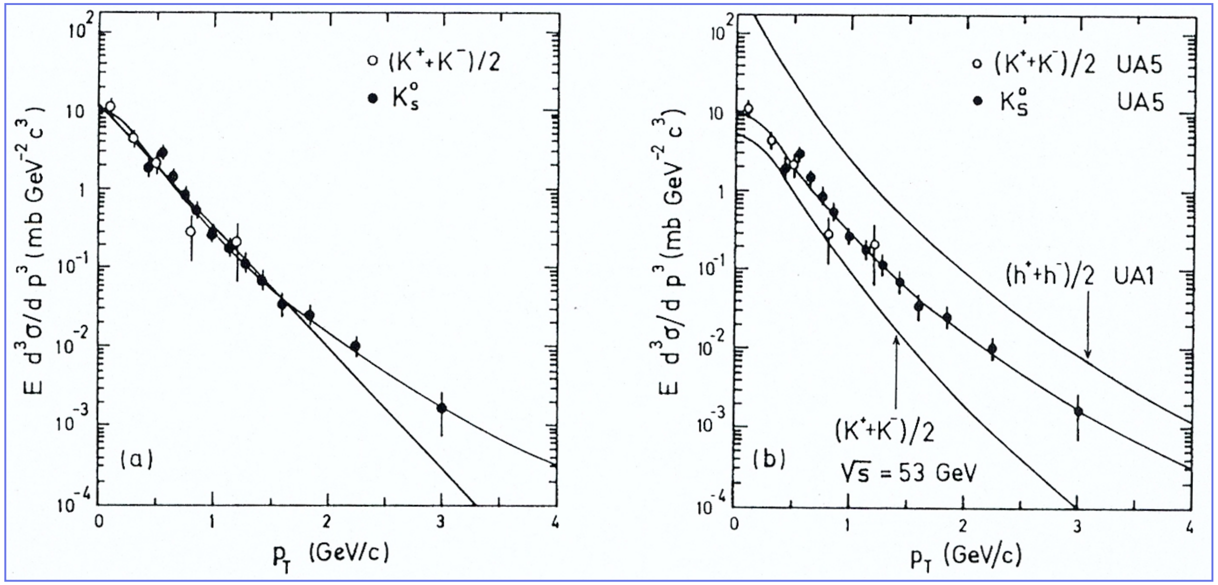
Rapidity Distributions



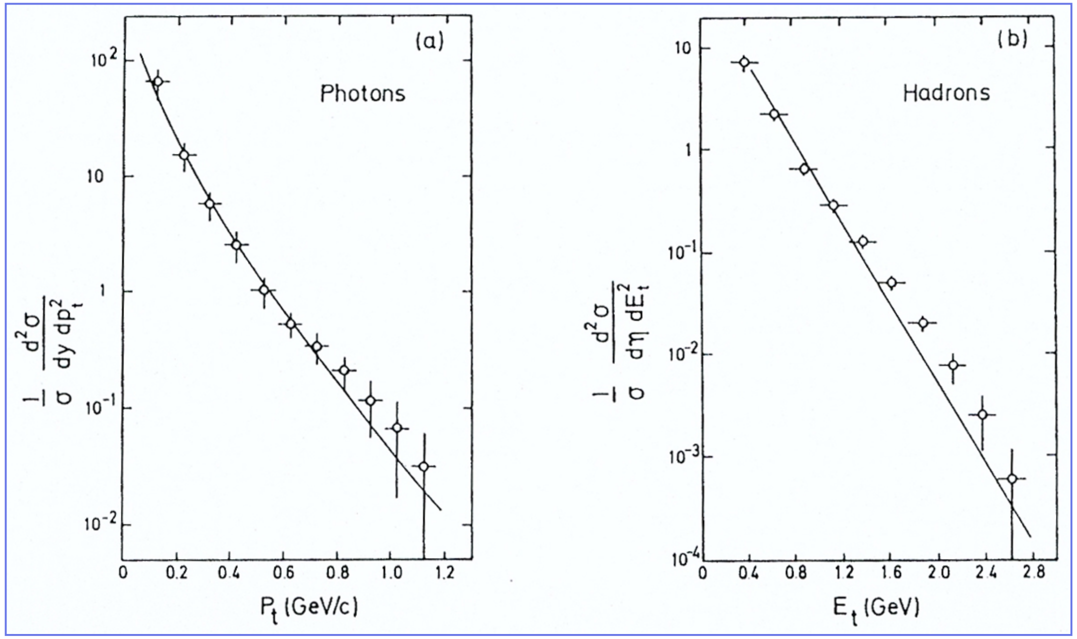
Feynman-Scaling for $|\eta| \leq 3$.

$\bar{p}(\bar{n})$-N-Interactions

p_t-Distributions



$\langle p_t \rangle_{Ch} = (0.42 \pm 0.02)$ GeV/c



$\langle p_t \rangle_{\gamma} = (0.20 \pm 0.02)$ GeV/c