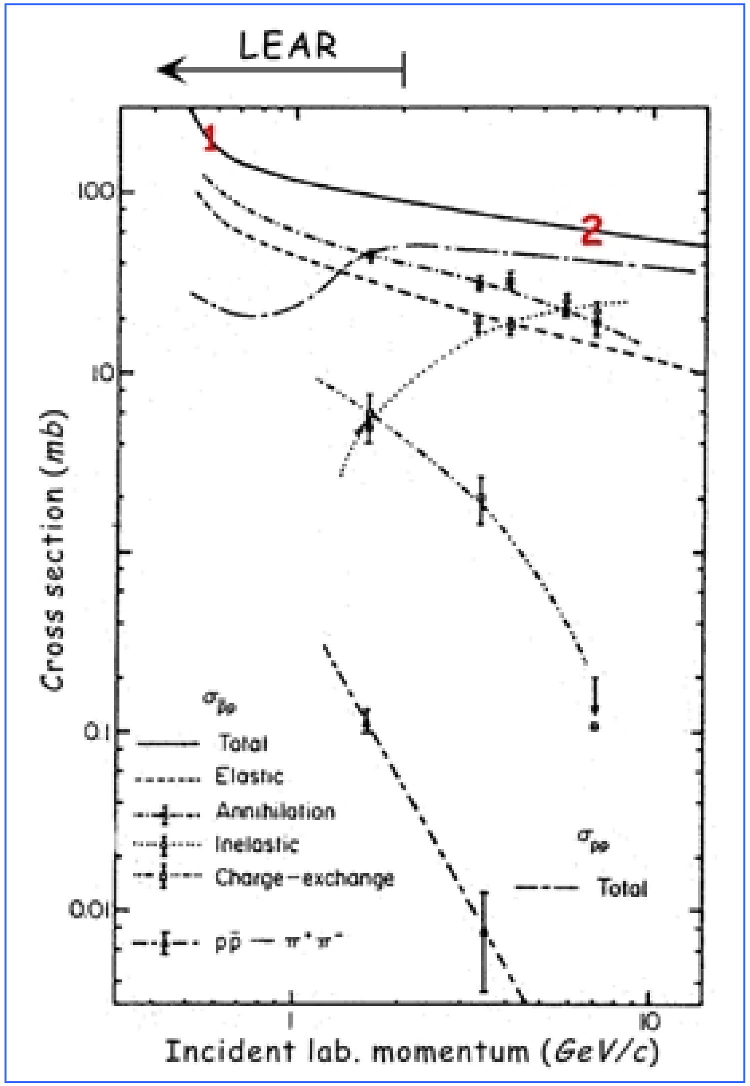
Physics with Antiprotons: From Antihydrogen to the Top-Quark

- General survey on $\bar{p}p$ - reactions / History
- From TeV to meV
  - Discovery of the Top-Quark
  - Discovery of $W^{\pm}, Z^0$
  - High precision measurements in the $(c\bar{c})$ - system
  - Physics at LEAR
    - Low and medium energy $\bar{p}N$ - interactions
    - Antiprotonic X-ray measurements
    - $\bar{p}$ - nucleus interactions
    - T/CP/CPT - tests
    - Meson/Exotics - Spectroscopy
    - Physics with trapped antiprotons
    - Antihydrogen
- Conclusions

Survey on $\bar{p}p$-reactions



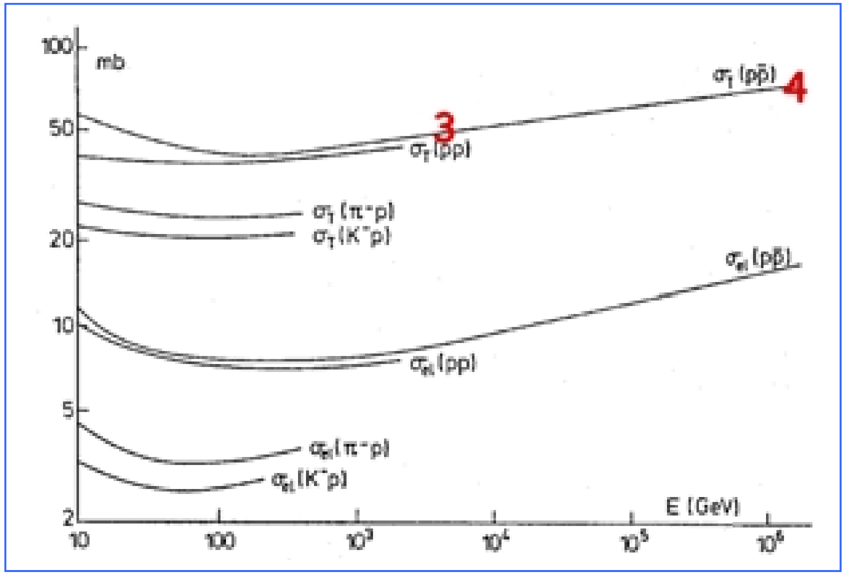
Low and medium energy antiprotons

① $\bar{p}p$-atoms as initial state

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

② Precision 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

Historical Survey on experiments with Antiprotons

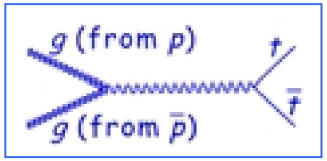
1955:	Discovery of the antiproton @ Bevatron/Berkeley	
1960-1990:	Experiments with conventional, secondary beams @ CERN, BNL, KEK, Serpukhov, ...	
	Bubble chamber experiments:	Very precise, but low statistics Several meson-resonances firstly seen in $\bar{p}p$-annihilation reactions, others confirmed
	Electronic detectors:	More data on rare channels, Discovery of $\bar{p}$-atoms Search for resonant and deeply bound $\bar{N}N$-states (Baryonium)
1972-1986:	Invention of stochastic cooling, ICE-Test facility, SPSC-Project/CERN	
1983-1984:	Formation of $c\bar{c}$-states at ISR	
1983:	Discovery of $W^{\pm}$, Z^{0} @ SPSC (*UA1*, *UA2* - Detectors)	
1984-1996:	LEAR: $\bar{N}N$ interaction, Meson/Exotics-spectroscopy, $\bar{p}$-Nucleus interactions, Exotic atoms ($\bar{p}p$, $\bar{p}He$), T/CP-violation in K^0, $\bar{K}^0$-decay, Trapped Antiprotons	
1985- :	Tevatron at FNAL	
1996-2000:	$c\bar{c}$-Spectroscopy at Fermilab	
1996-1997:	First $\bar{H}$ signal at LEAR and Fermilab	
1995:	Discovery of the top-quark at Fermilab	
2000:	Physics with AD	
?	HESR	

Discovery of the Top-Quark (FNAL, 1995)

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

Detectors : CDF, DØ

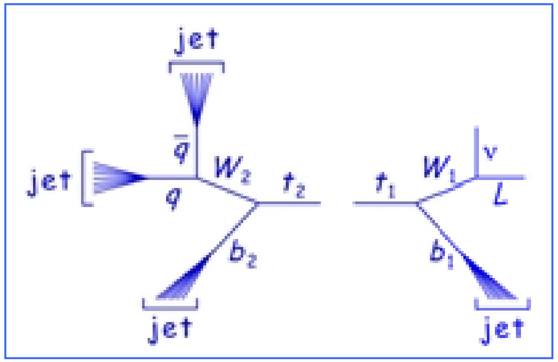
Production



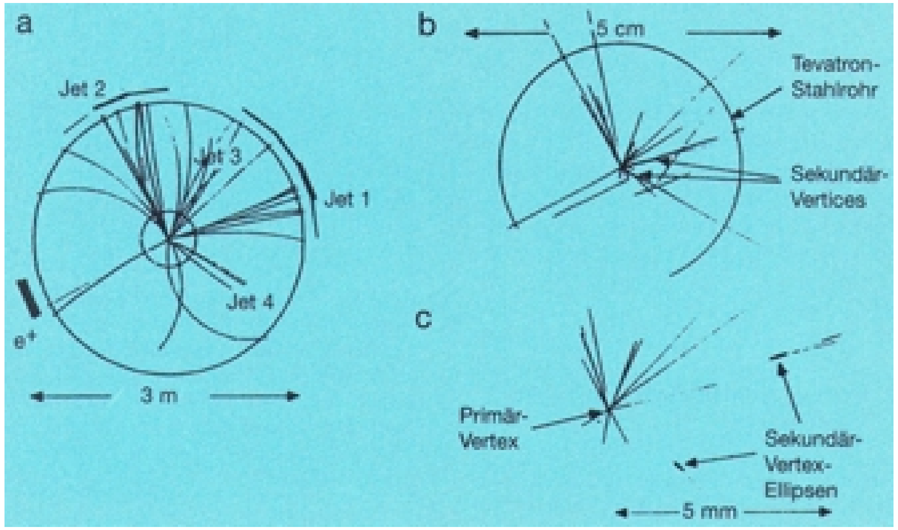
$\sigma \approx 4\ pb$ (High $p_\perp$)

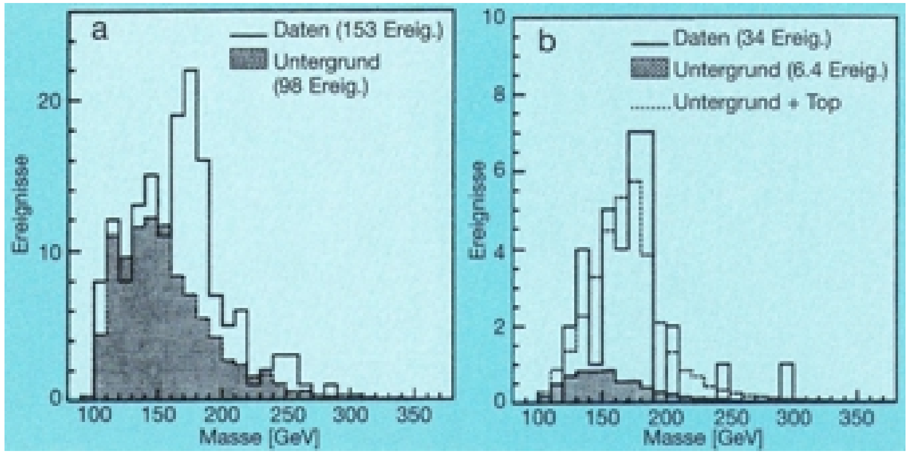
($\sigma_T \approx 60\ mb$ (10 o.m. bigger) ($< p_\perp > \approx 0.5\ GeV$))

Decay



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





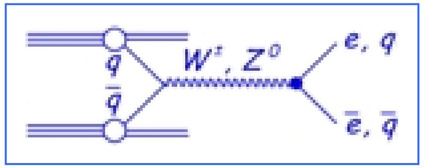
$\Rightarrow m_t = (174.3 \pm 5.1)\ GeV/c^2$

Discovery of the Intermediate Vector Bosons $W^{\pm}$, Z^0 (CERN, 1983)

SPSC: $\sqrt{s} = 630\ GeV$

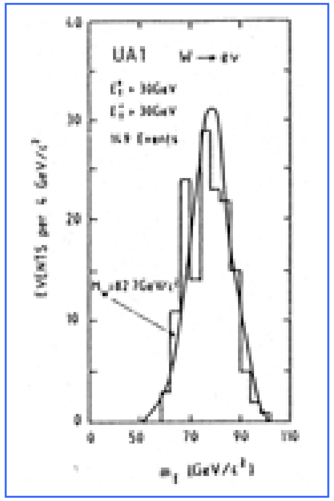
Detectors: *UA1, UA2*

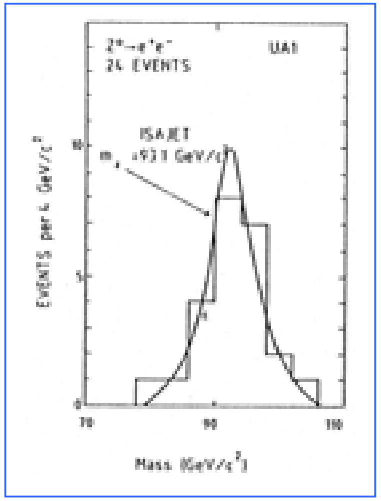
Production/Decay (Drell-Yan)

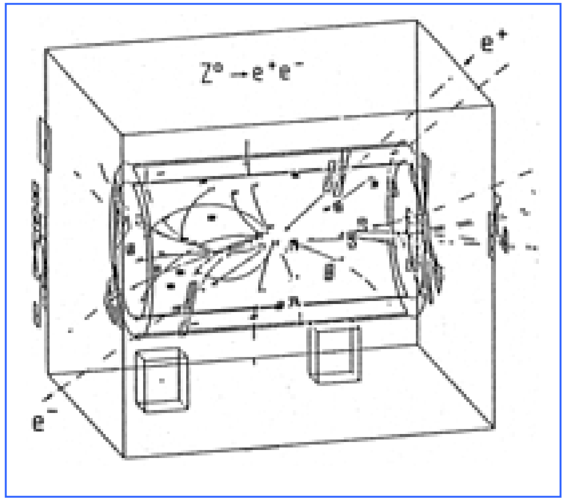


$\sigma \approx$ (1-5) *nb* (High $p_{\perp}$)

$\sigma_T \approx 50\ mb$ (7 o.m. bigger) ($< p_{\perp} > \approx 0.4\ GeV$)







$m_{W^{\pm}} =$ (80.2 ± 0.6 ± 0.5 ± 1.3) GeV/c^2 (*UA1*)
(82.7 ± 1.0 ± 2.7) GeV/c^2 (*UA2*)

$\Gamma_W \leq 5.4\ GeV/c^2$; $J^P(W) = 1^-$

$m_{Z^0} =$ (93.1 ±1.0 ± 3.1) GeV/c^2 (*UA1*)
(91.4 ± 1.2 ±1.7) GeV/c^2 (*UA2*)

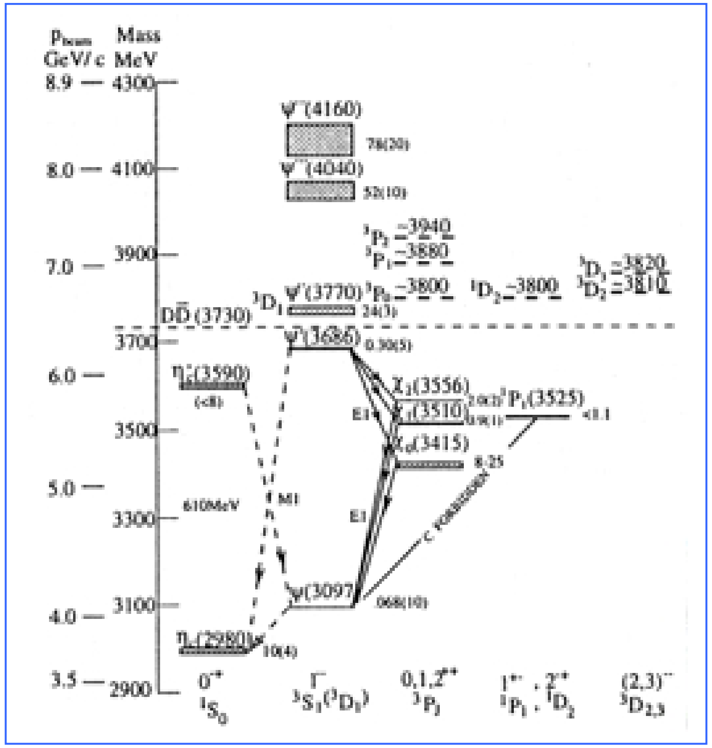
; $\Gamma_{Z^0} =$ $(2.7\ ^{+1.2}_{-1.0} \pm 1.3)\ GeV/c^2$ (*UA1*)
(2.7 ± 2.0 ± 1.0) GeV/c^2 (*UA2*)

FNAL- and LEP- data not considered

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

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

e^+e^-- collisions



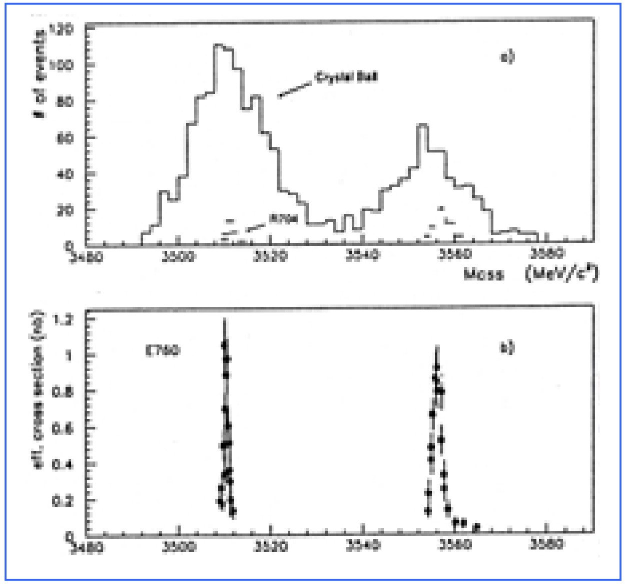
Drawback:

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

Other states are only visible in γ-transitions,

e.g. $\chi_1, \chi_2, \chi_0, \eta_c, \eta'_c$,..

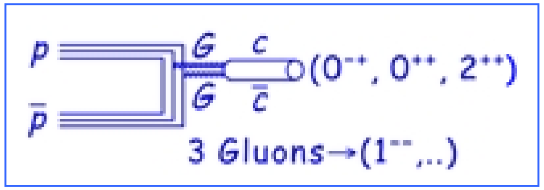
→ Data with moderate mass resolution



$\bar{p}\,p$ - collisions

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

Production



Decay

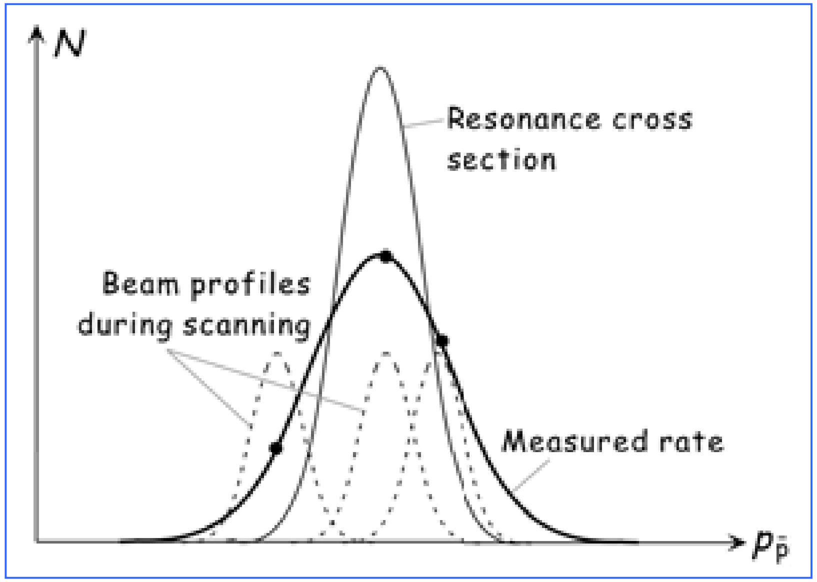
$(c\bar{c})_{g.s.} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, \phi\phi$

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

$c\bar{c}$-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:

$\sigma_{Tot} = 50mb \to$ 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 ($O \sim 10^{-4}$)

Experiments:

CERN/ISR: R 704 (Demonstration of method)

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

Many beautiful results

But: Much is to be done

- Search for missing states
- Specific decay modes

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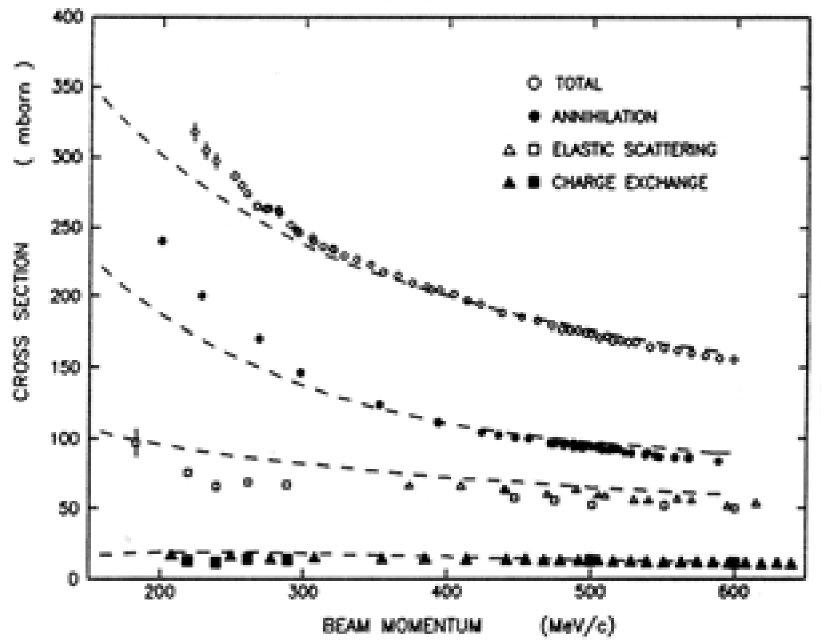
Low and medium energy $\bar{p}p\,(n)$ - Reactions (1)

Total = Elastic + CEX + Annihilation cross section

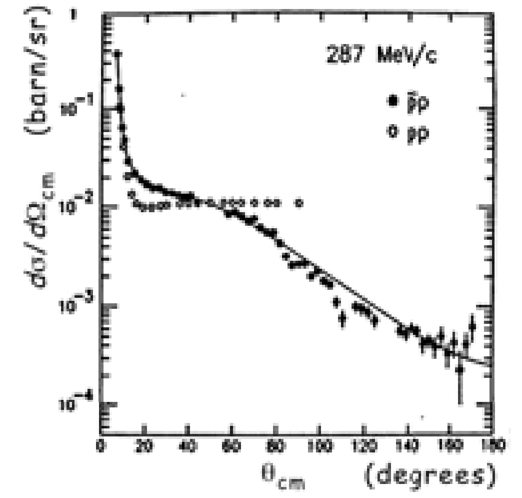
$\sigma_{Elast.} < 0.5\ \sigma_{Tot.} \rightarrow$ No diffractive scattering

(dominates for $p_{\bar{p}} \geq 3.5\ GeV/c$)

No structures near threshold $\rightarrow$ 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, $\neq pp$)

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

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})

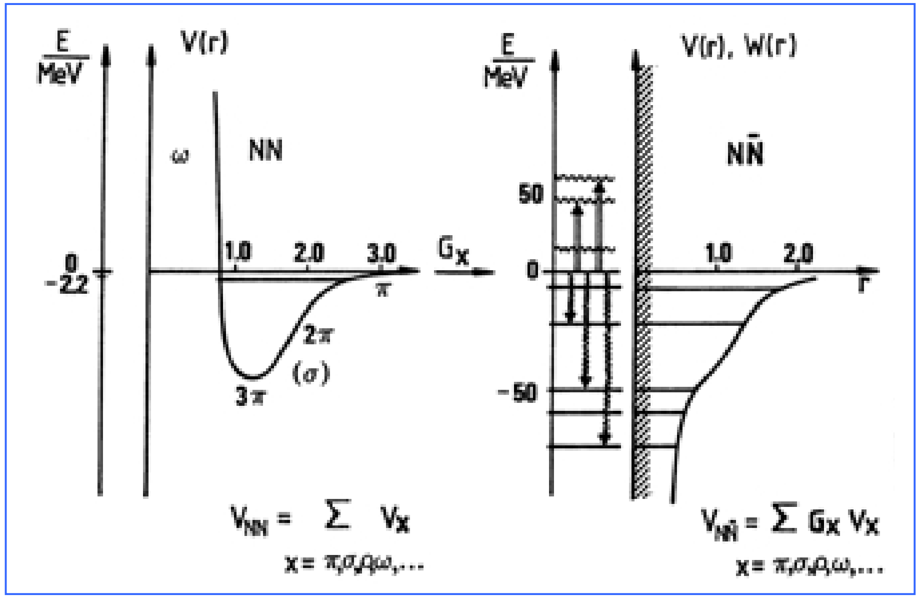
Real part (Short range): Problem ! Annihilation region
Several (phenomenological) ansaetze:
- $q\bar{q}$ - interactions
- Cut - off parameters

Imaginary part: Short range strong absorption (annihilation)

Resumee:

Good description of data, but not from first principles

→ No unambiguous statements on quark-distributions inside nucleon



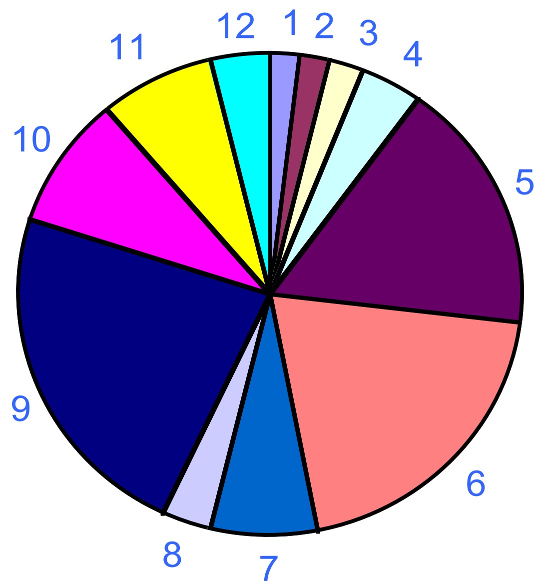
Low and medium energy $\bar{p}p(n)$ - Reactions (3)

Annihilation Reactions

Global picture:

$\sigma_{ann}(E)$, Multiplicities,

Dominant at threshold $\left((\bar{p}p)_{Atom}\right)$



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 ($T \approx 100$ 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 the higher the higher the mass of a, b
Annihilation prefers to produce mass, not energy

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

Specific annihilation channels

Many data at rest $\rightarrow$ BR's

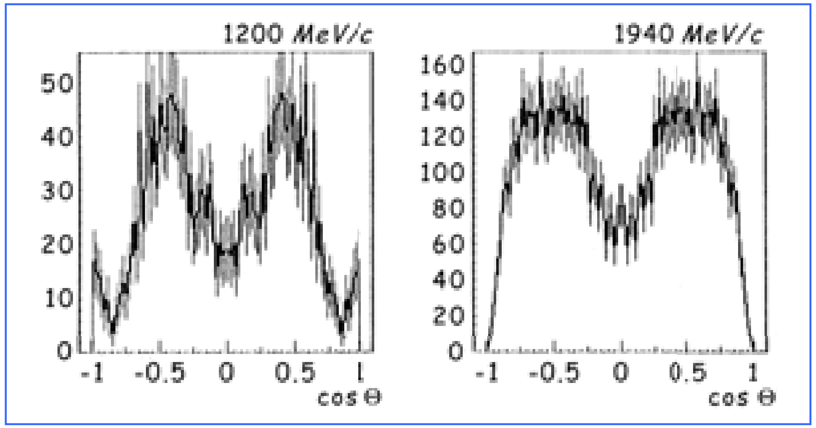
- Dynamical selection rules
- Strong OZI - violations

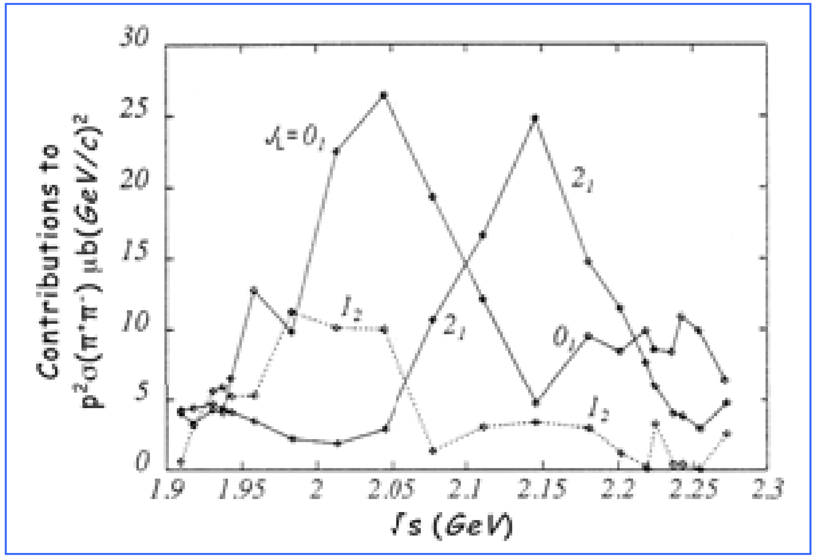
Few data in flight:

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

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

$\Rightarrow$ Dominating partial waves (Resonances in Formation processes)





Recent results:

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

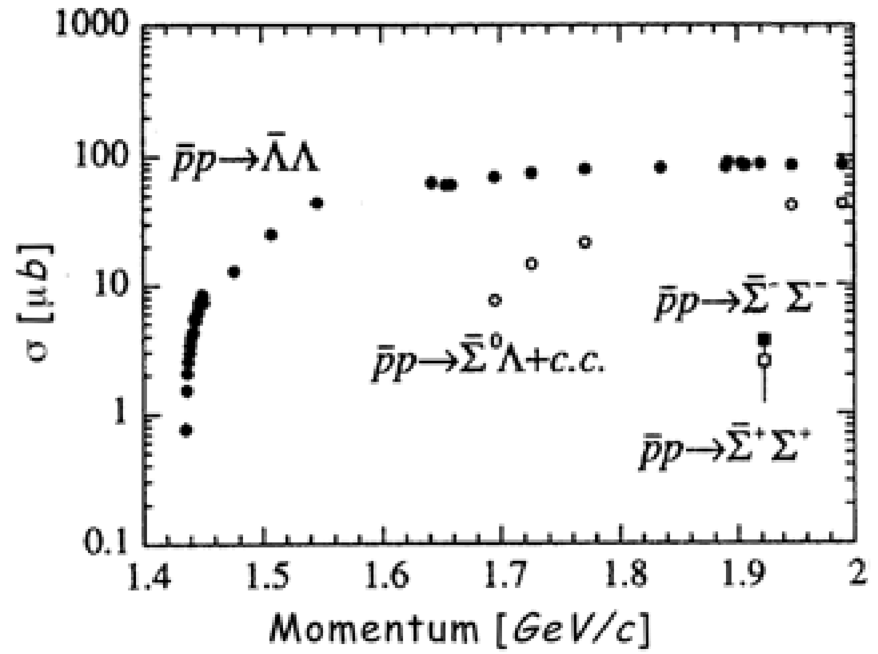
Low and medium energy $\bar{p}p\,(n)$ - Reactions (5)

Particularly well investigated: $\bar{p}p \rightarrow \Lambda\overline{\Lambda}, \overline{\Sigma}^0\Lambda, \overline{\Sigma}^-\Sigma^-, \overline{\Sigma^+}\Sigma^+$

Measured quantities:

$\sigma(p_{\bar{p}})$, $\dfrac{d\sigma}{d\Omega}$, Polarisations (Self analyzing decay),

Spin - Correlations, Spin Transfer



Total cross sections for the $\bar{p}p \rightarrow \Lambda\overline{\Lambda}, \overline{\Sigma}^0\Lambda$ and $\overline{\Sigma}^-\Sigma^-$- reactions

Observations:

- Strong p - wave contribution near threshold
- Λ and $\overline{\Lambda}$ spins are aligned to $S = 1$
  (Reflection of $s\bar{s}$ in the nucleon?)
- $\dfrac{d\sigma}{d\Omega}$ strongly forward peaked

Low and medium energy $\bar{p}p\,(n)$ - Reactions (6)

Interpretation of data

Only possible (yet) in terms of models (Highly non perturbative QCD-sector)

Meson/Baryon - exchange picture

Exchange of π, K, Baryons (Single or multiple)

Quark/Gluon - picture

Quark Line Rule

$SU(3)$ - Symmetry

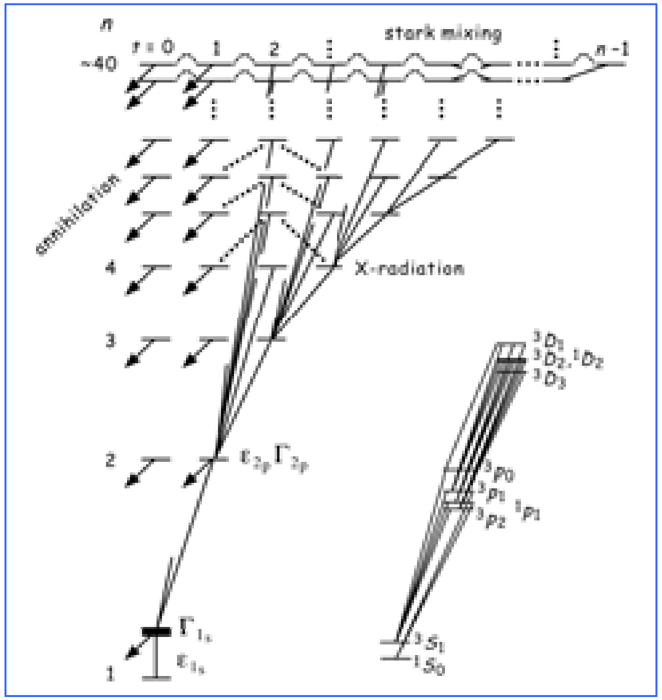
Quark Rearrangement/Quark Annihilation ($^3P_0$, $^3S_1$-Vertices)

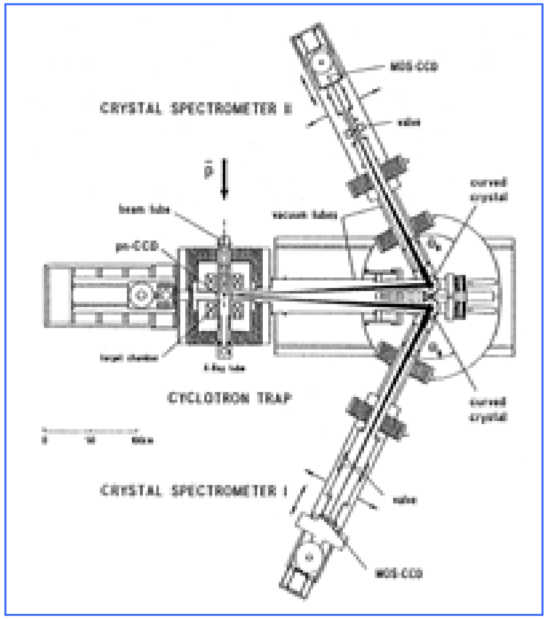
Polarized intrinsic Strangeness

⋮

Resumee: Data can be well described by models.
Observables sensitive on nucleon structure ($s\bar{s}$-content, Diquarks,...).
Differentiation between models needs more and better data.

Antiprotonic X-rays (1) - $\bar{p}p\,(d)$ – System





2→1 transition (≈ 10 keV): pn-CCD

3→2 transition (≈ 2 keV): Crystal Spectrom.

Shifts and widths due to strong interaction:

$$\left.\boxed{\begin{aligned}\varepsilon_{1s} &= (-730 \pm 20)\,eV\\ \Gamma_s &= (\;1122 \pm 57)\,eV\\ \Gamma_{2p} &= (\;34.0 \pm 2.9)\,eV\end{aligned}}\;\right\}\text{ spin averaged}$$

$$\Rightarrow a_s(\bar{p}p) = (-0.88 \pm 0.03) + i(0.67 \pm 0.04)\ fm$$

Separation of $2\,{}^3P_0$:

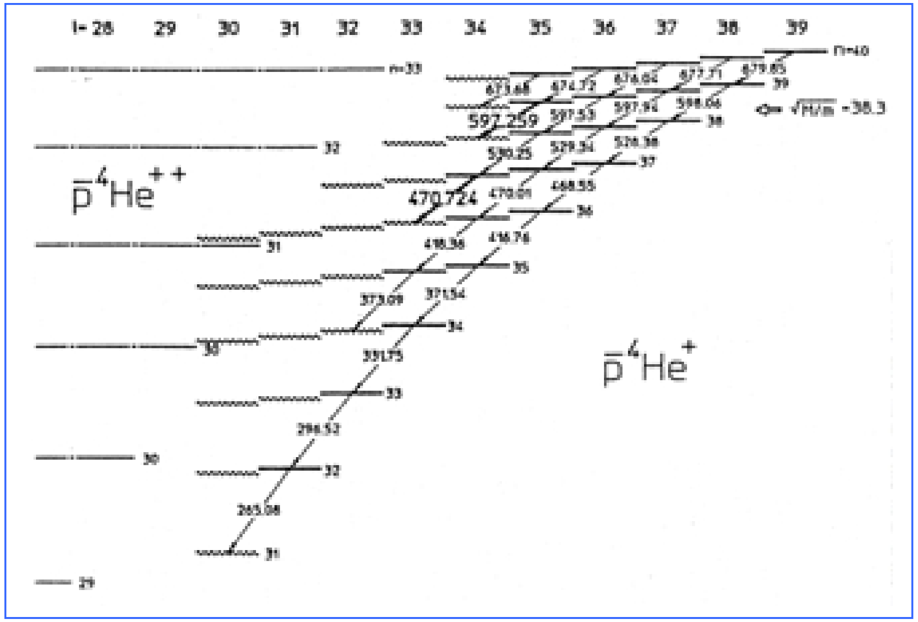
$$\left.\boxed{\begin{aligned}\varepsilon\,(2\,{}^3P_0) &= (140 \pm 30)\,meV\\ \Gamma\,(2\,{}^3P_0) &= (\;80 \pm 60)\,meV\end{aligned}}\;\right\}$$

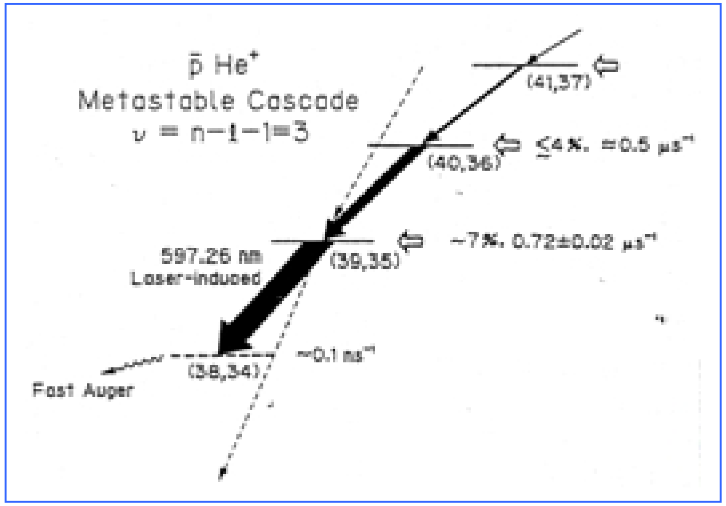
Sensitive on specific $\overline{N}N$ interaction

Antiprotonic X-rays (2) - $\bar{p}He$ – System

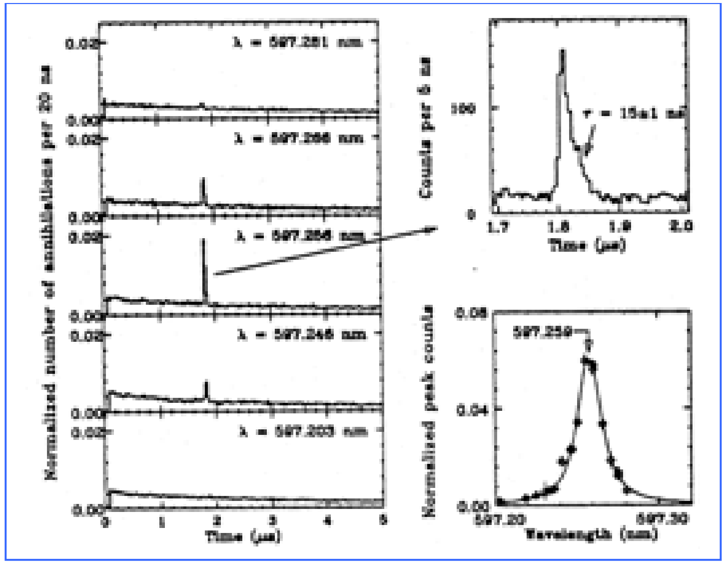
Metastable states ($\tau \approx \mu s$), deexcited by Laser-injection

$\Rightarrow$ Measurements on ΔE with extreme precision





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



$\Rightarrow$

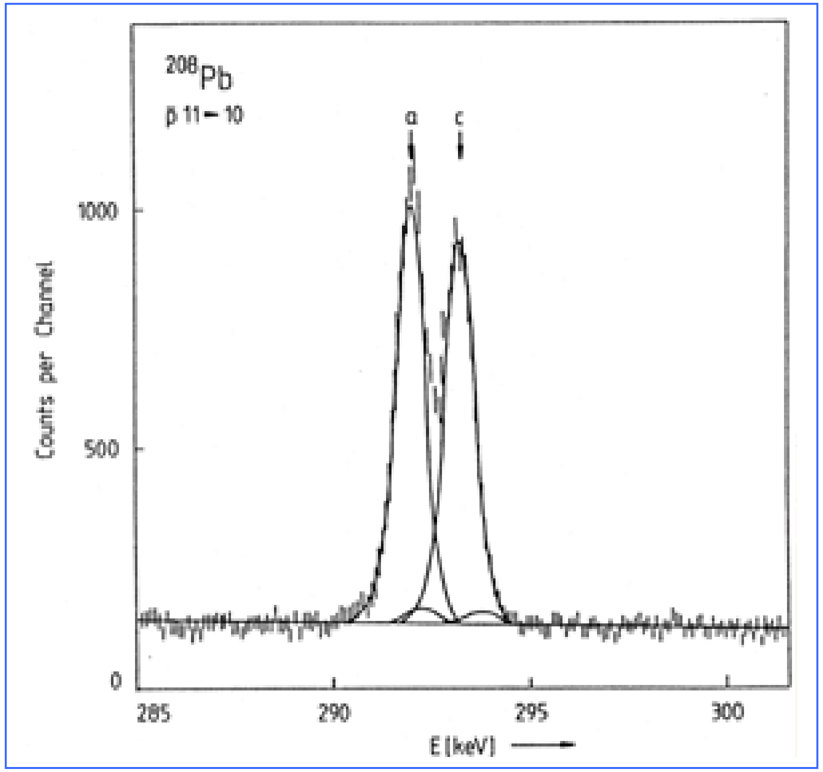
- Very stringent test of calculations in the three-body Coulomb system
- $\left|\dfrac{m_{\bar{p}} - m_p}{m_p}\right| \leq 5x10^{-7}$
- $\left|\dfrac{q_{\bar{p}} - e}{e}\right| \leq 5x10^{-7}$

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

Antiprotonic X-rays (3) - $\bar{p}$ – nucleus – System

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

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



$\mu_{\bar{p}}$ = (2.8005 ± 0.0090) μ_{nm} (Best value) $\Leftarrow$

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)

$\bar{p}$-induced nuclear reactions

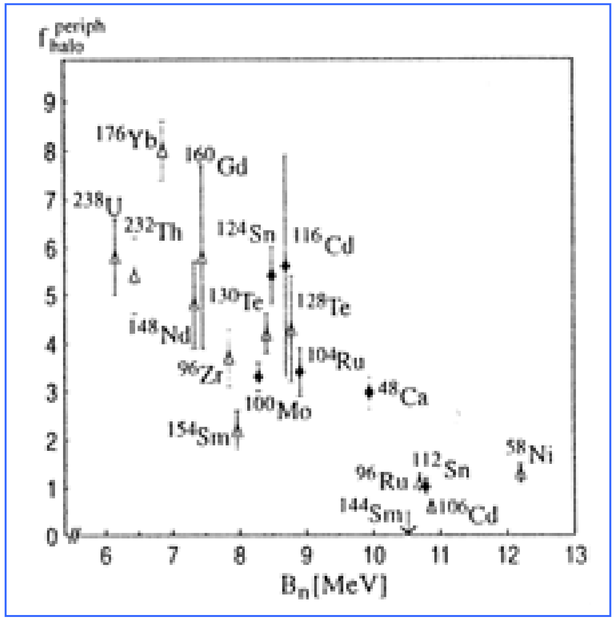
$\bar{p}_{stop}$:

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 $\rightarrow N(\bar{p}n)/N(\bar{p}p)$

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



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:

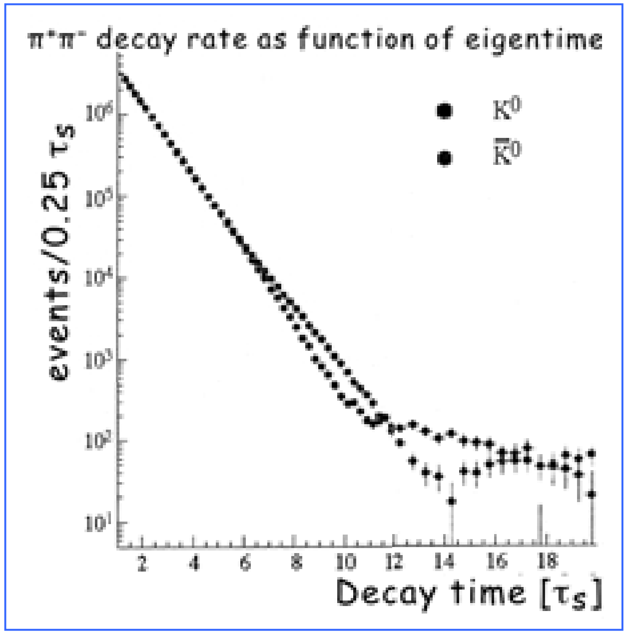
1 *GeV*: Particle spectra in good agreement with INC-calculations, Fission important, No Multi-Fragmentation

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

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, $\bar{K}^0$-decay modes
- Tagging of Strangeness of K^0, $\bar{K}^0$ at production time ($\bar{p}p \rightarrow \begin{matrix} K^-\pi^+K^0 \\ K^+\pi^-\bar{K}^0 \end{matrix}$)
- Tagging of Strangeness of K^0, $\bar{K}^0$ at decay time
  $0 \leq t \leq 20\tau_S$ ($K^0 \rightarrow \pi^- e^+ \nu_e$, $\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$, $\Delta S = \Delta Q$)
  (For semileptonic decays only)



$$K^0(t) = a_L^- \,|\, K_S \rangle e^{-i\gamma_S t} + a_S^- \,|\, K_L \rangle e^{-i\gamma_L t}$$

$$\bar{K}^0(t) = a_L^+ \,|\, K_S \rangle e^{-i\gamma_S t} - a_S^+ \,|\, K_L \rangle e^{-i\gamma_L t}$$

$$\gamma_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

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

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

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

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

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

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

CP/T/CPT - Tests (2)

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

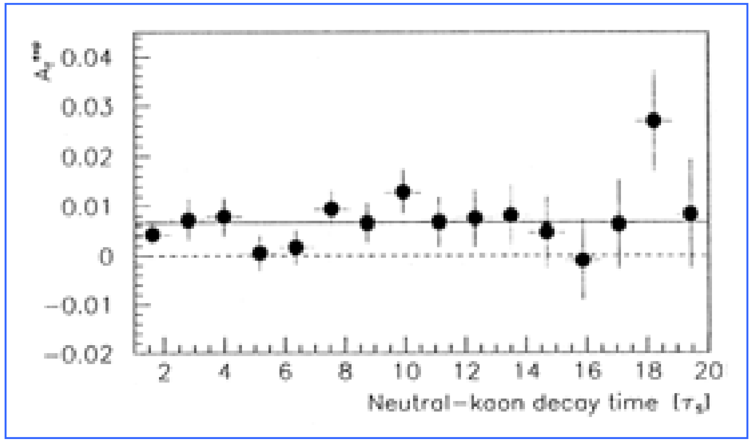
- Direct Test of T-violation ($\varepsilon \neq 0$?)

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

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

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

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



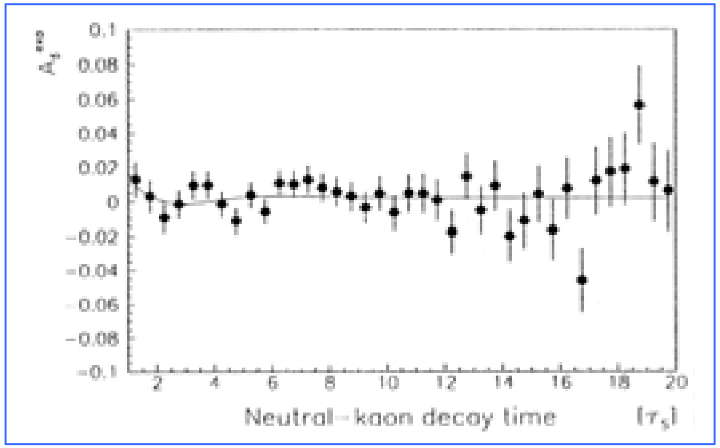
- Direct Test of CPT-violation ($\delta \neq 0$?)

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

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

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

($Jm\,\delta$ = (2.4 ± 5.0) $x10^{-5}$, Unit. Relat.)



CPT-Invariance proven

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

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

Meson/Exotics-Spectroscopy (1)

Mesons/Mesonic resonances: $q\bar{q}$

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)

e.g. $\bar{p}p \to (\pi^+\pi^-)_\rho \, \pi^0$

$\to (\eta\eta)_{f_0(1500)} \, \pi^0$

$\to \left((\pi^+\pi^-)_\rho (\pi^+\pi^-)_\rho\right)_{f_0(1500)} \pi^0$

⌈Unique feature: $\bar{p}_{stop} \to (\bar{p}p)_{atom}$ as initial state⌋

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

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

Mass/Width determination: Invariant masses

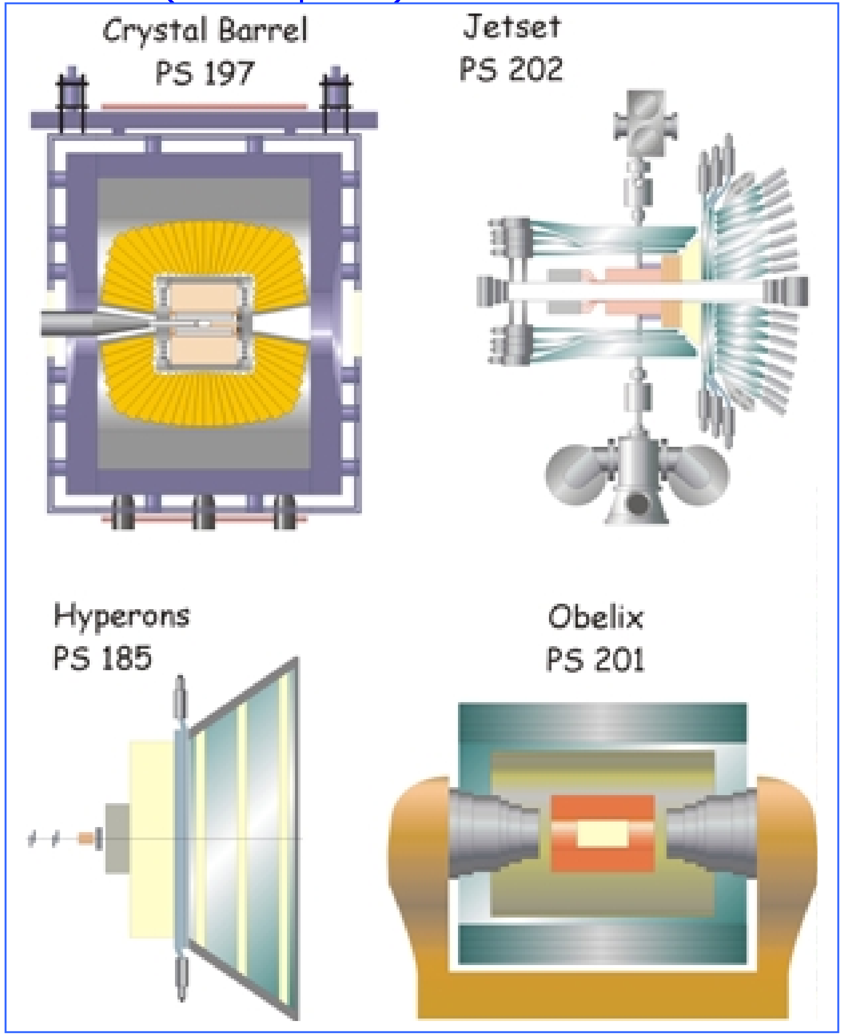
(Dalitz Plot)

J^{PC} determination: Partial wave analysis

(Angular distribution)

p_{max} (LEAR) = 1.94 $GeV/c \Rightarrow$ Masses < 2.3 GeV/c^2

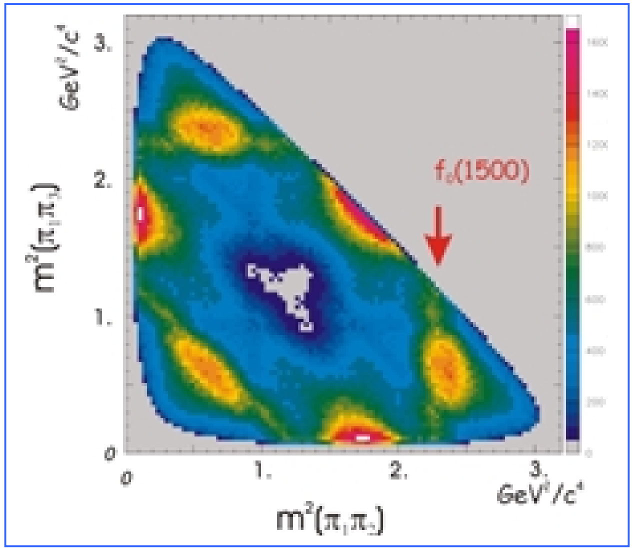
Asterix (1. LEAR period)



Meson/Exotics-Spectroscopy (2)

Experiments $\rightarrow$ High statistics and clean data, mostly on $\bar{p}_{stop}$

Results:



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

- Most of the already known light mesons very clearly seen
- Discovery of new states, particularly with $J^{PC} = 0^{++}$
- Confirmation of two states with exotic quantum numbers (1^{-+})
- at 1400 and 1600 MeV/c^2.

Clarification of the 0^{-+}-sector (1400-1500 MeV/c^2) (E/i)

$\bar{p}_{Higher\ momenta}$:

Fixed momentum: – Confirmation of results obtained with $\bar{p}_{stop}$

– Interesting structures at Fermilab (8 GeV/c)

$\bar{p}$ – scan: – High sensitivity scans in the $\bar{p}p$-threshold region

($\rightarrow$ No narrow Baryonium states above or below threshold)

– Coarse scans at a few higher momenta (Not finished)

} see before

Interpretation of results:

Evidence for exotic (gluonic) states

For further clarification more and accurate data @ higher energies needed.

Trapped Antiprotons

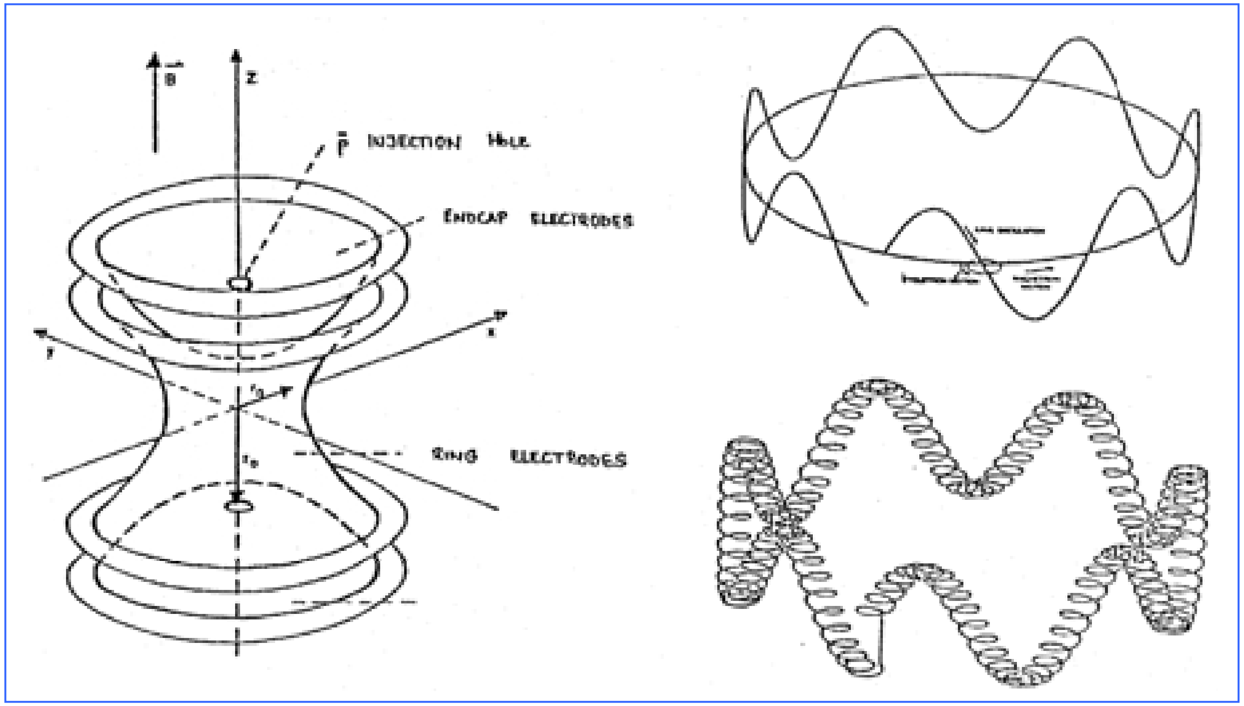
Low energy Antiprotons (5.4 *MeV*) are cooled down (*meV*) and trapped in magn./electr. field

Cyclotron/Magnetron rotations — Frequences
Axial oscillations — coupled

Cyclotron Frequency:

$$\hbar\omega_c = \frac{\hbar}{c} \cdot B \cdot \frac{e}{m_{\bar{p}}} \quad (\omega_c \approx 90\ MHz)$$

Resonance ($\omega_{HF} = \omega_c$) detected from change in axial oscillation (20 *MHz*)



Comparison between $\bar{p}$ and H^--ions:

$$\boxed{\left(\frac{e}{m}\right)_{\bar{p}} / \left(\frac{e}{m}\right)_{p} = 0.999\,999\,999\,1 \pm 0.000\,000\,000\,09}$$

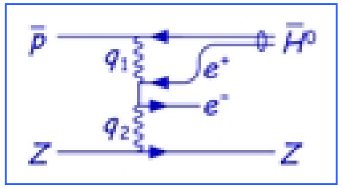
Formation and Investigation of $\bar{H}$ at AD: Simular technique

Formation of Antihydrogen ($\overline{H}$) in Flight

Idea: Munger, Brodsky, Schmitt

PS 210 (LEAR)

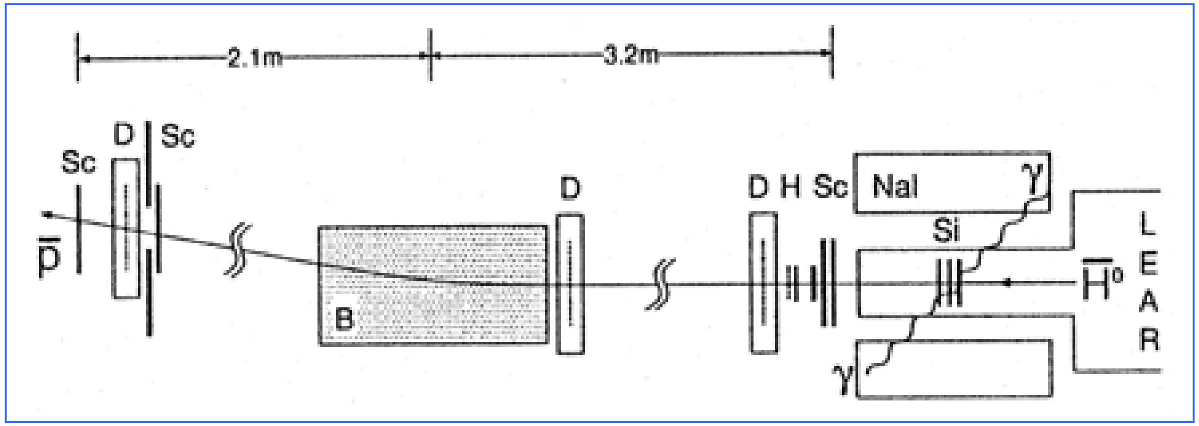
Production of $\overline{H}$ in Coulomb field of Xe-(cluster) target (1.94 GeV/c antiprotons)



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

11 events identified

(Background estimate: 2 ± 1)



E 862 (Fermilab)

Production of $\overline{H}$ in H_2-cluster target by 5.2-6.2 GeV/c antiprotons

67 events identified

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

Conclusions

$\bar{p}p$ reactions very useful for investigations in many areas of particle and nuclear physics

Annihilation process has no restrictions in quantum numbers and is gluon rich, so that conventional and exotic quark/gluon states are easily produced

Experiments with antiprotons are easily performed, as antiprotons can be cooled down (tiny primary vertex, detectable secondary vertices)

The physics with antiprotons has just started. Look ahead to HESR!