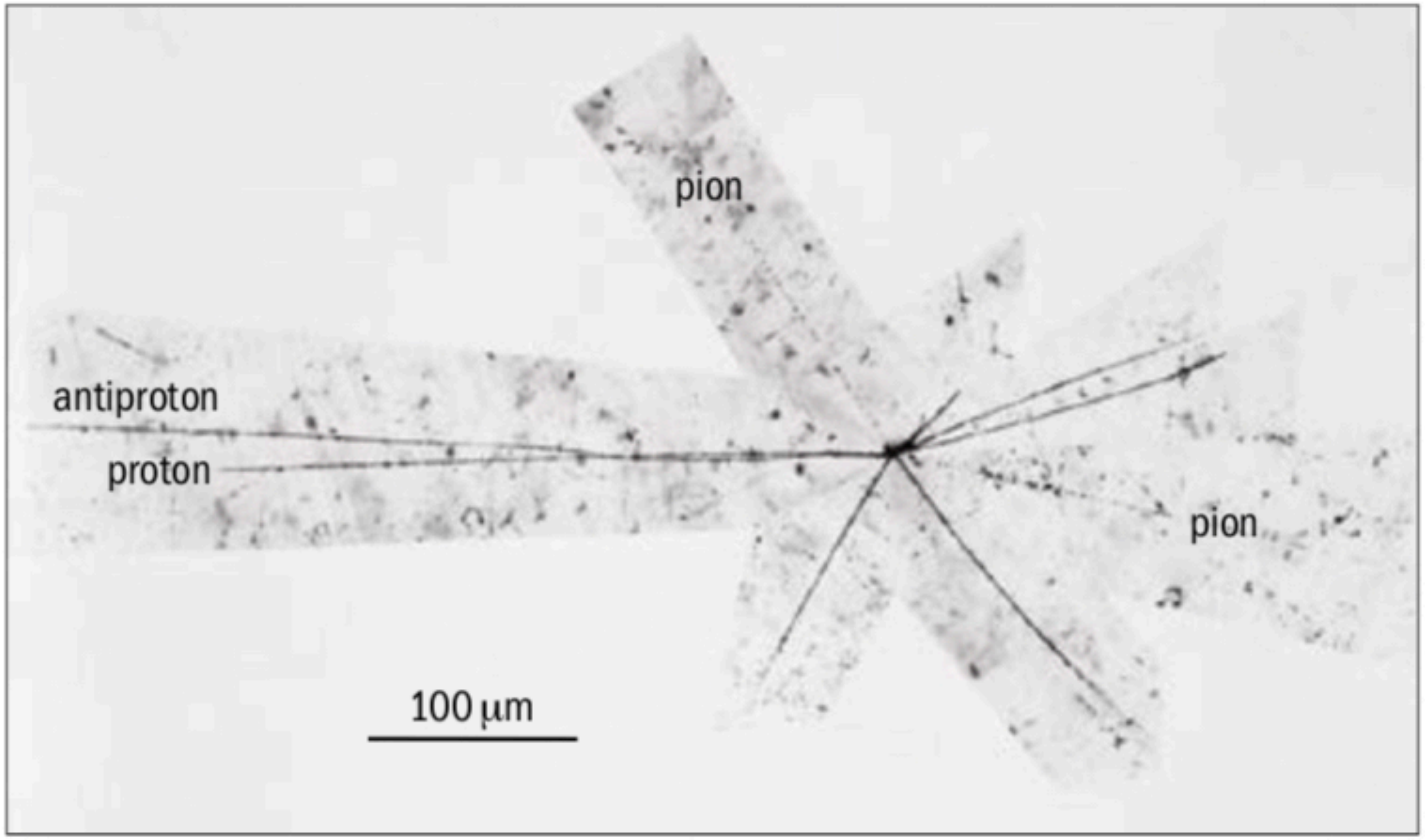
Low energy antinucleon-proton annihilation

Claude Amsler

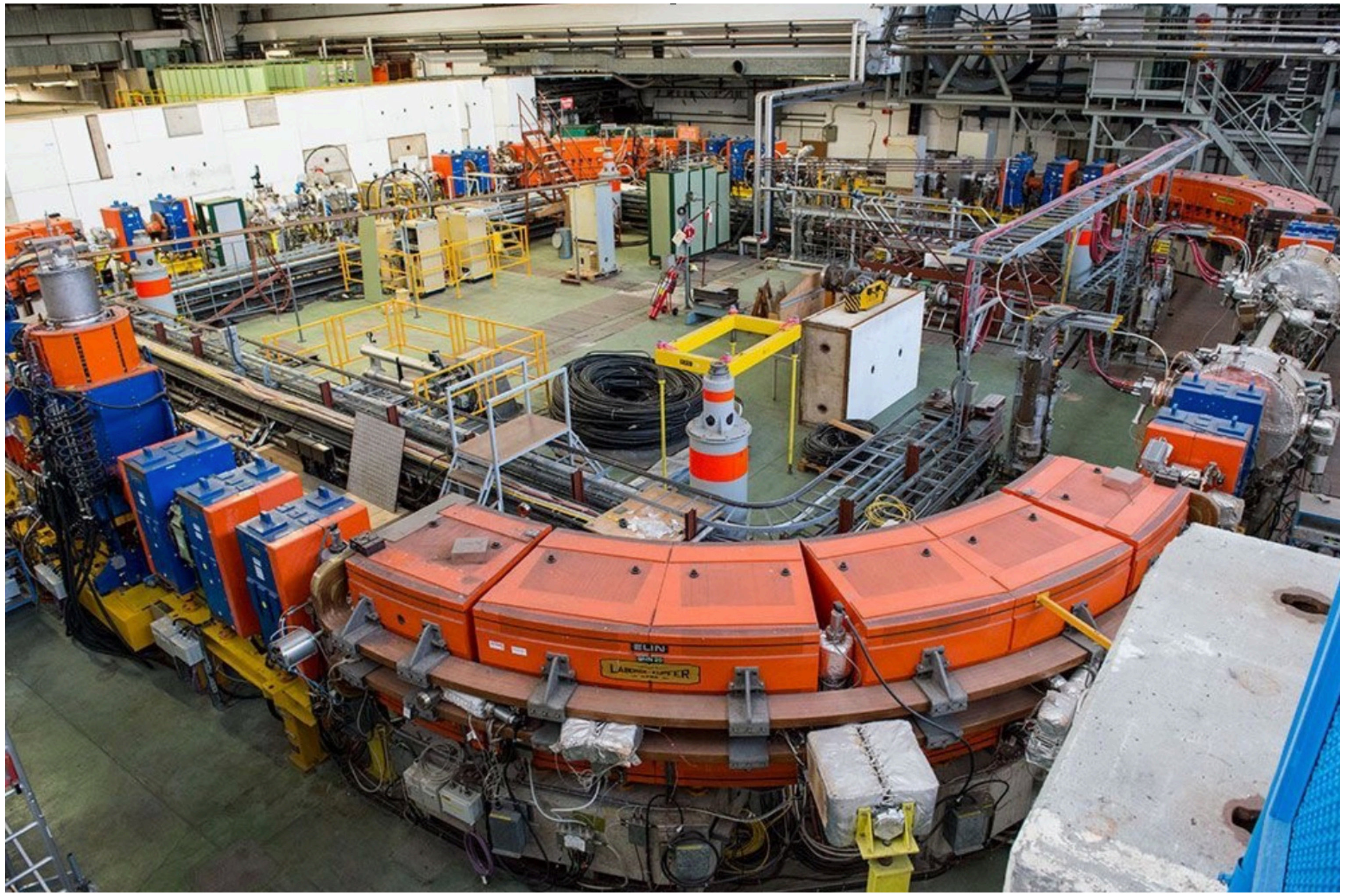


1956, Bevatron, Berkeley

O Chamberlain et al. *1956* Nuov. Cim. *3 447*

Count rate: 1 antiproton/15 min)

Low Energy Antiproton Ring in the CERN South Hall (LEAR, 1983-1996)



$\bar{p}$ {
- 3.5 GeV/c from AA into PS, decelerated to 600 MeV/c in PS, sent to LEAR
- 100 — 1940 MeV/c (5.3 — 1217 MeV)
- extraction (1 hour spill), $\Delta p/p < 10^{-3}$, 10^6/s

Total of 35 experiments, 15 on annihilation mostly with stopping antiprotons ("annihilation at rest")

ASTERIX, Crystal Barrel, OBELIX: 350 publications, 6 new mesons (today established)

Global features of proton-antiproton annihilation at rest

Charged annihilation products : known from bubble chamber data (~1970, CERN & Brookhaven)

Prong (charged)	%
0	4.1 (+0.2-0.6)
2	43.2 (+0.9-0.7)
4	48.6 (+0.9-0.7)
6	4.1 (+0.2-0.2)

contain ~7% η , ~6 % K

and ~60% of all annihilations have $> 1\pi^0$

were studied by Crystal Barrel

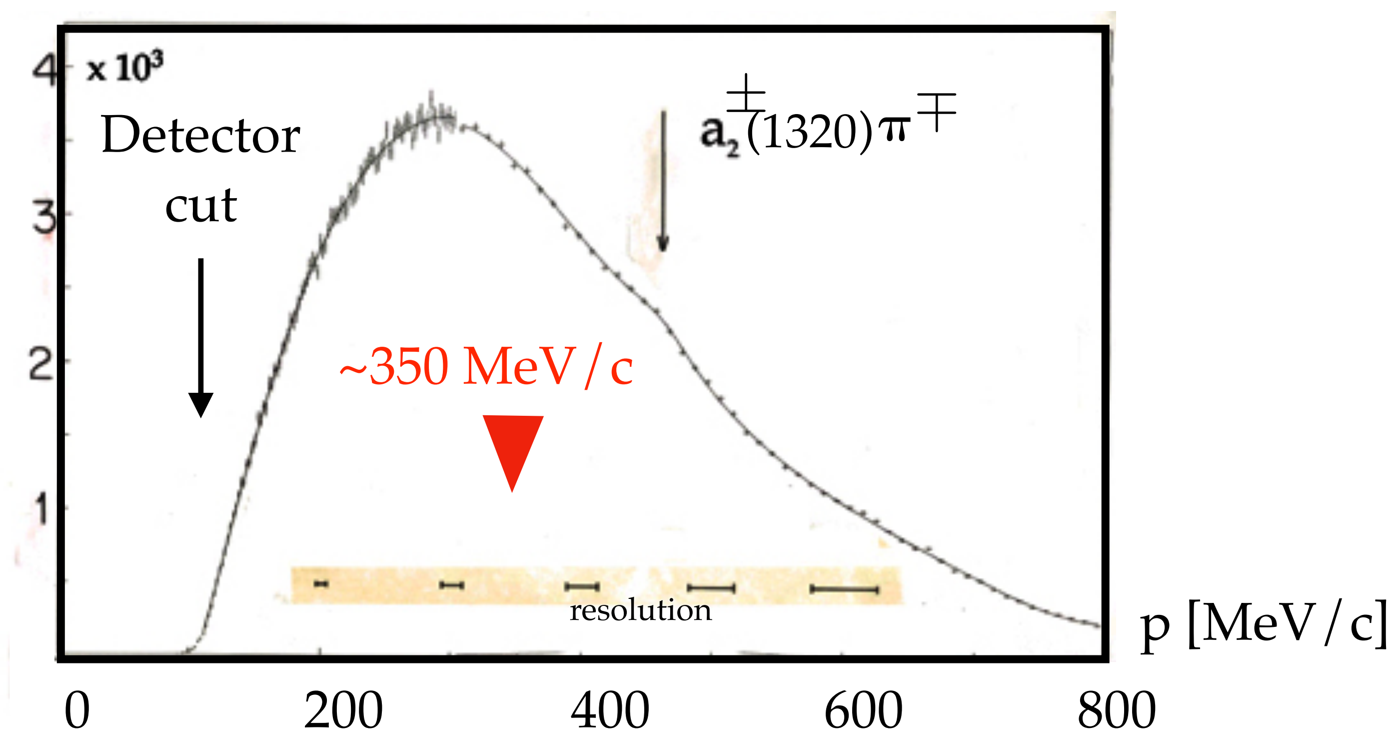
Pion multiplicity:

$$< n(\pi^0) >= 2.0 \pm 0.2$$
$$< n(\pi^\pm) >= 3.0 \pm 0.2$$

Inclusive charged pion spectrum $\bar{p}p$ at rest

(ASTERIX)

Phys. Lett. 152B (1985) 135



(Similar in flight at low energy)

- Fireball, pions emitted statistically from the hot gas

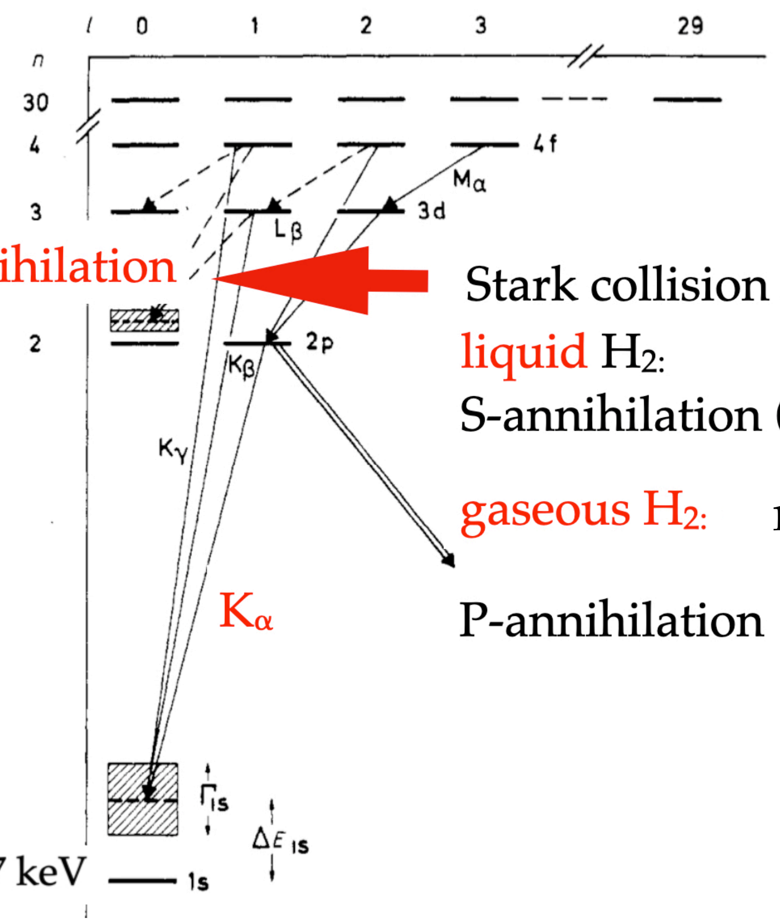
More complicated:
mostly via intermediate resonances:

Mechanism? e.g. $2\pi^+2\pi^-\pi^0 : \omega\rho^0, \omega f_2(1270), \rho 3\pi \ldots$

- From the annihilation rates in various channels:

Clear evidence for quark and antiquark interactions, but the exact mechanism is unclear

Stopping antiprotons in hydrogen:



capture: n = 30

Annihilation

Stark collision effect in liquid H_2:
S-annihilation (L=0) between the proton and the antiproton

gaseous H_2: more L = 1

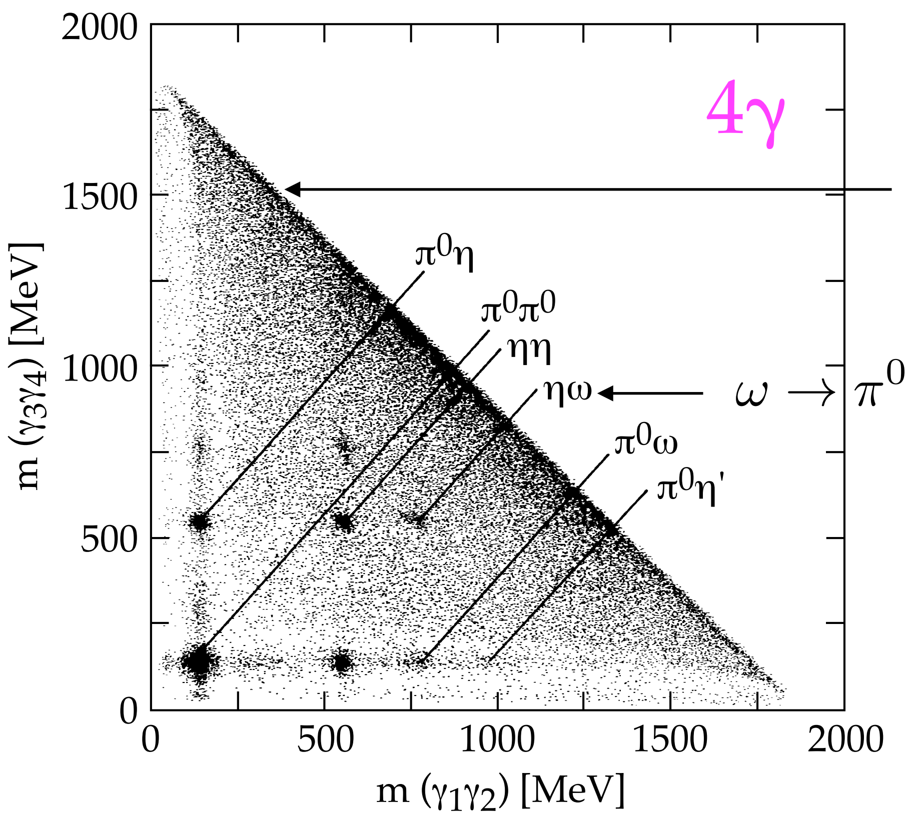
K_α

P-annihilation : pure L=1

ASTERIX
Phys. Lett. 157B (1985) 333

K_α 9.37 keV

Mechanism: annihilation at rest into two neutral mesons (Crystal Barrel): quarks!!



$$\omega = \frac{1}{2}(d\bar{d} + u\bar{u}),\ \rho^0 = \frac{1}{2}(d\bar{d} - u\bar{u})$$

$$\eta = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin(\theta_i - \theta_P) - s\bar{s}\cos(\theta_i - \theta_P)$$

$$\eta' = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\underbrace{\cos(\theta_i - \theta_P)}_{\Delta} + s\bar{s}\sin(\theta_i - \theta_P)$$

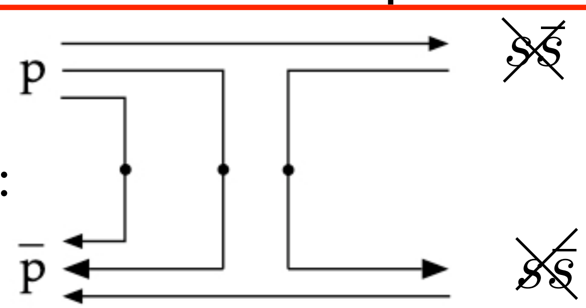
ignore by the OZI rule

$\theta_i = 35.3°$ ideal mixing angle

θ_P: pseudoscalar mixing angle

Annihilation probability (branching fractions): 10^{-3} - 10^{-4}

no $s\bar{s}$ in the $\bar{p}p$ system:



From K, π, η, η' masses:
From $\gamma\gamma$ production in e+e- collisions

$$\theta_P = -10^0 \rightarrow -20^0$$

<u>Prediction, for example:</u>

$$\frac{B(\eta\eta)}{B(\eta\eta')} = \frac{(\sin^2\Delta)^2}{2(\sin\Delta\cos\Delta)^2} = \frac{\tan^2\Delta}{2}$$

(add phase space factors)

Ratio from data	θ_p (deg)
$\pi^0\eta/\pi^0\eta'$	-18.1 ± 1.6
$\eta\eta/\eta\eta'$	-17.7 ± 1.9
$\omega\eta/\omega\eta'$	-21.1 ± 1.5
$\eta\rho^0/\eta'\rho^0$	$-25.4 \pm^{5.0}_{2.9}$

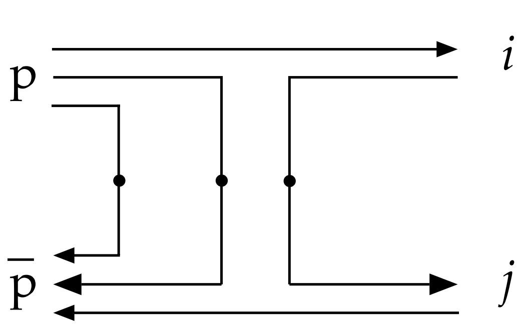
Consistent results which agree with $\theta_P = -10^0 \rightarrow -20^0$

Sign of quark dynamics

From data: pseudoscalar mixing angle

Which graph contributes?

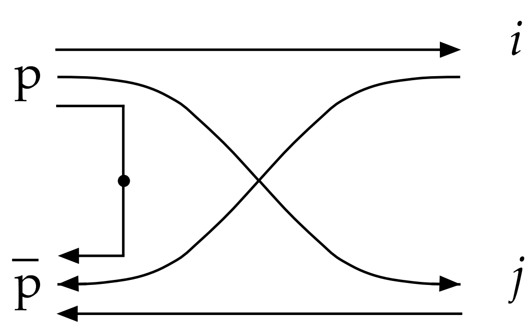
$i, j = u\bar{u}$ or $d\bar{d}$



A

Annihilation

no $u\bar{u}, d\bar{d}$



R

Rearrangement

no $d\bar{d}, d\bar{d}$

- If A dominates: less consistent θ_P, contribution from R

  and $\rho^0\rho^0 = \omega\omega$ if A dominates

Data: $\rho^0\rho^0 = (1.2 \pm 1.2) \times 10^{-3}$

$\omega\omega = (3.32 \pm 0.34) \times 10^{-2}$

contribution from R or statistics?

Sign of quark dynamics but A or R?

Could profit from more precise data…

- Several charged two-body processes are not understood

Violation of the OZI rule

As before, now for vector mesons:

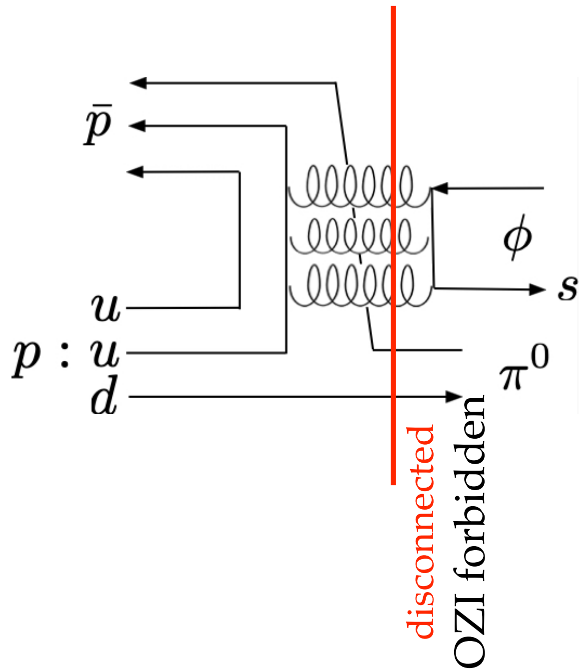
$$\phi = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\sin(\theta_i - \theta_V) - s\bar{s}\cos(\theta_i - \theta_V)$$

$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\cos(\theta_i - \theta_V) + s\bar{s}\sin(\theta_i - \theta_V)$$

θ_V : vector mixing angle

From K^*, ρ, ω, ϕ masses: θ_V is close to $\theta_i = 35.3°$

decoupling $\phi \simeq -s\bar{s}$ $\omega \simeq \frac{1}{\sqrt{2}}(d\bar{d} + u\bar{u})$



Assuming no $s\bar{s}$ in the nucleon: OZI rule suppresses ϕ production

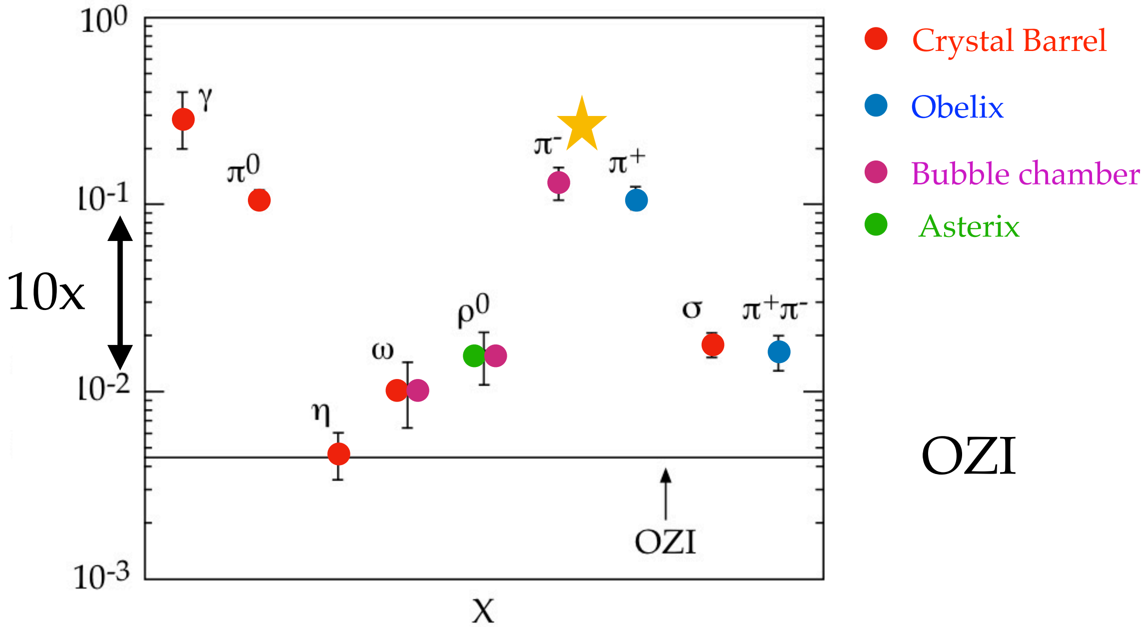
e.g. $\phi\pi^0$

Apart from phase space factors $\frac{B(\phi X)}{B(\omega X)} = \tan^2(\theta_V - \theta_i)$ $= 5 \times 10^{-3}$

e.g. $\omega\pi^0$ because $\phi \simeq -s\bar{s}$

OZI violation!

$X\phi/X\omega, X = \gamma, \pi^0 ...$

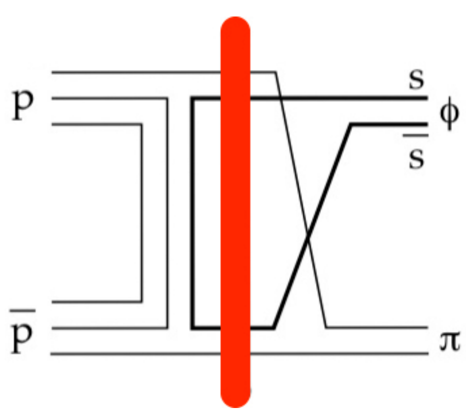


Very large OZI violation at rest with almost any ϕX in liquid H_2 (and low energy $\bar{p}n$, $n\bar{p}$) ★

Very large $\gamma\phi$

OZI

Possible explanation (among others): $sq\bar{s}\bar{q}$ tetraquark states?



No violation of OZI rule

close to $N\bar{N}$ threshold, candidates near $2m_p$...:

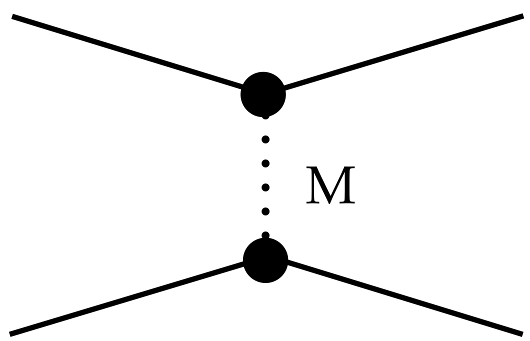
e.g. C(1480) in $\pi^- p \to Cn, C \to \phi\pi^0$, $\omega\pi^0$ not seen

or $\phi(2170) \to \phi\pi\pi$ well established meson

Bound states and resonances of $N\bar{N}$ systems

Bound states and resonances ("baryonium") are predicted in the $N\bar{N}$ system due to the attractive short range force.

$N\bar{N}$ potential =
NN potential x G-parity of exchanged meson M



Isospin I:

$\bar{p}p$: $I = 0$ and 1

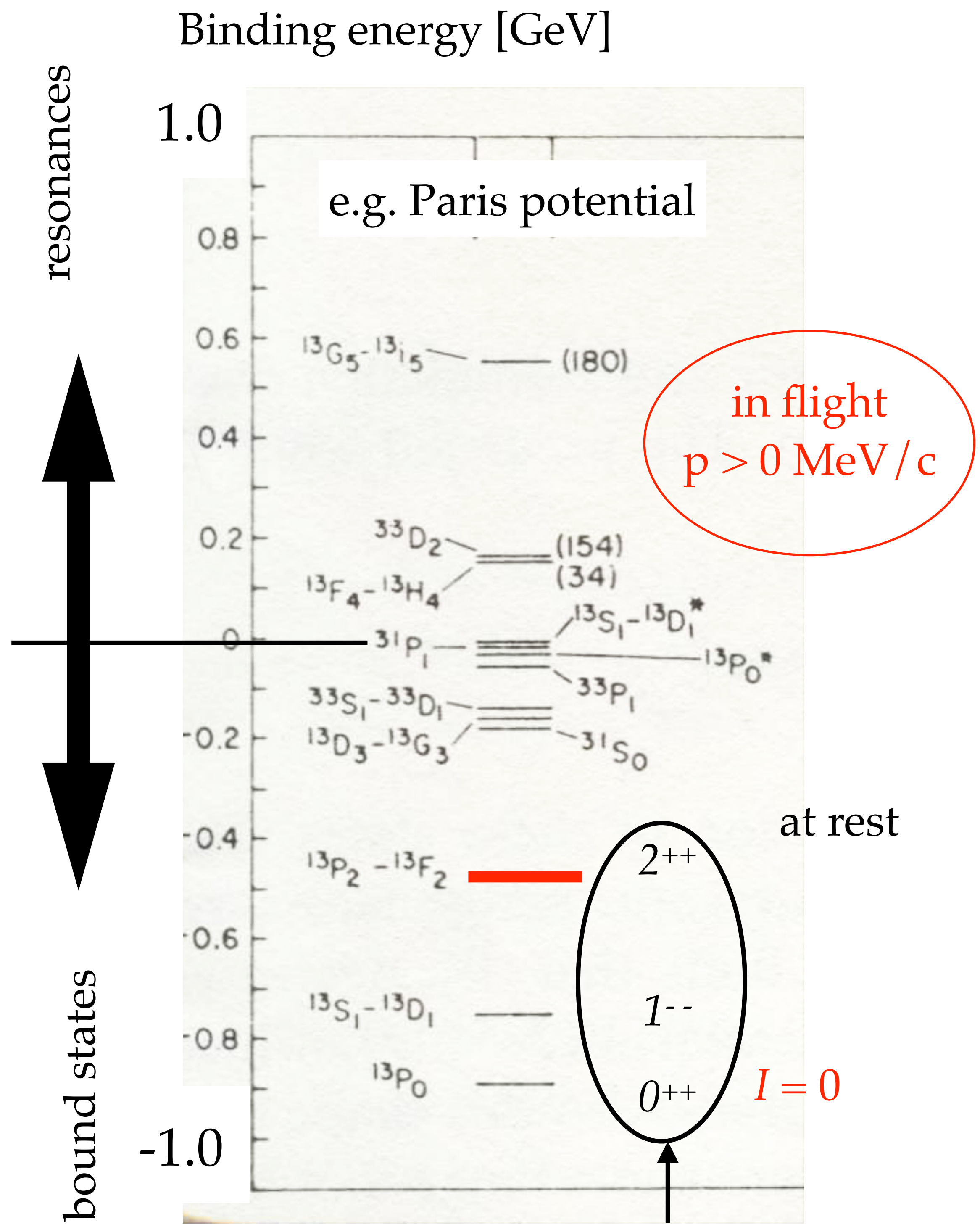
$\bar{p}n$ or $\bar{n}p$: $I = 1$ only

Short distance central force is attractive for ω and σ

for both $\bar{p}p$ isospin $I = 0$ and 1

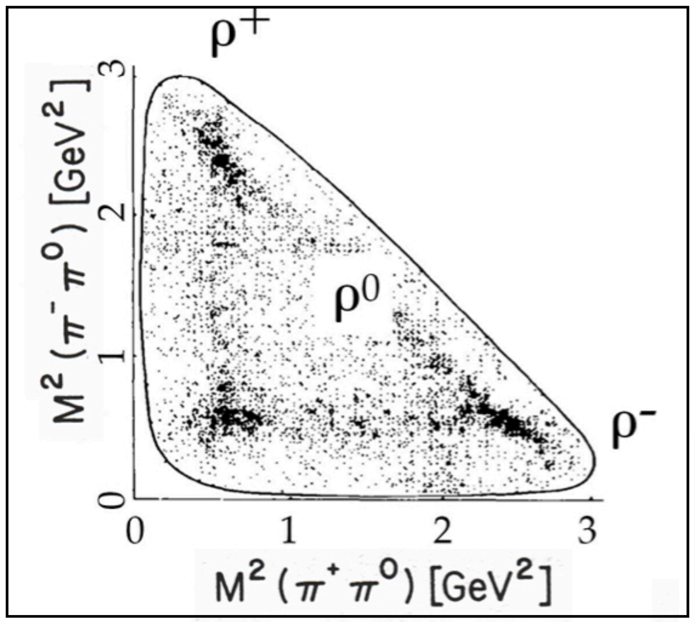
ρ contributes repulsion in $I = 1$

Deeply bound: isospin 0 (charge neutral states)

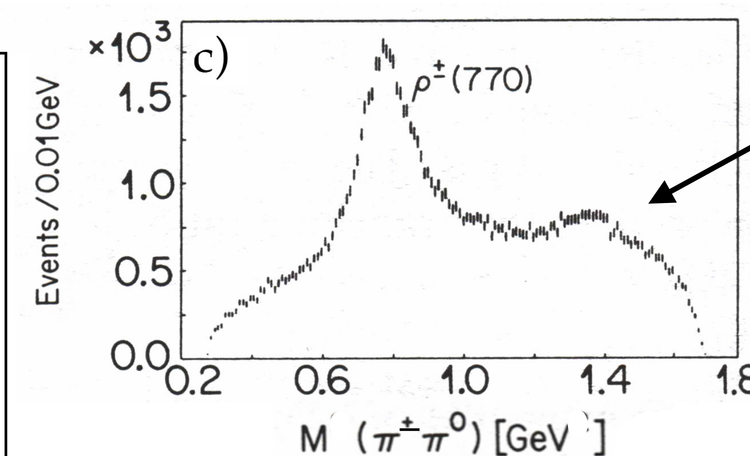


Importance of P-wave (*L*=1) annihilation, an example $\bar{p}p \to \pi^+\pi^-\pi^0$ stopping $\bar{\text{p}}$

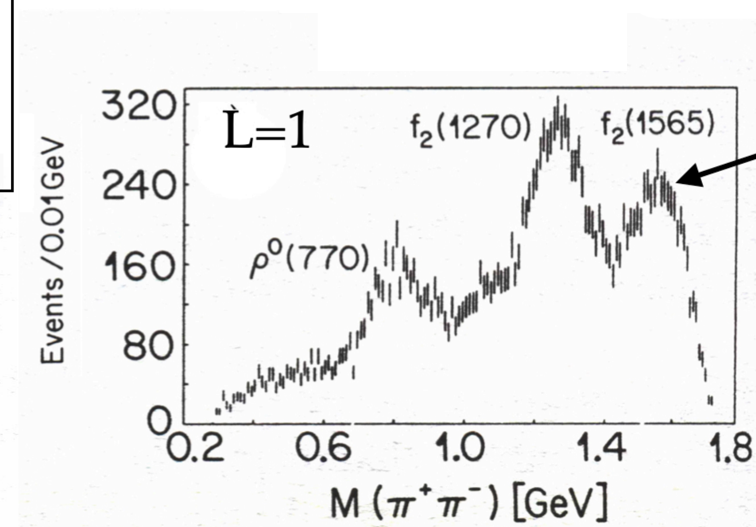
liquid hydrogen (BBC)



ASTERIX (gas)



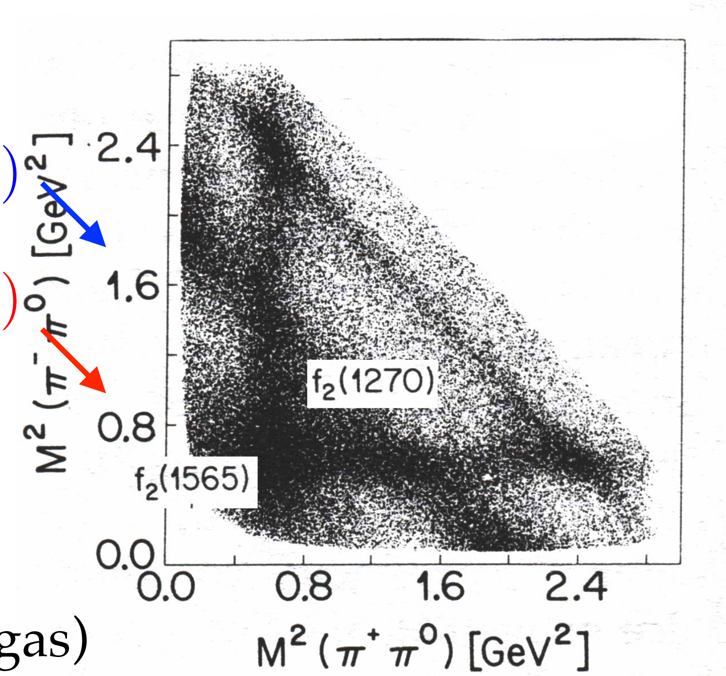
no charged mode



neutral mode: $I = 0$

$f_2(1270)$

$f_2(1565)$



ASTERIX (gas)

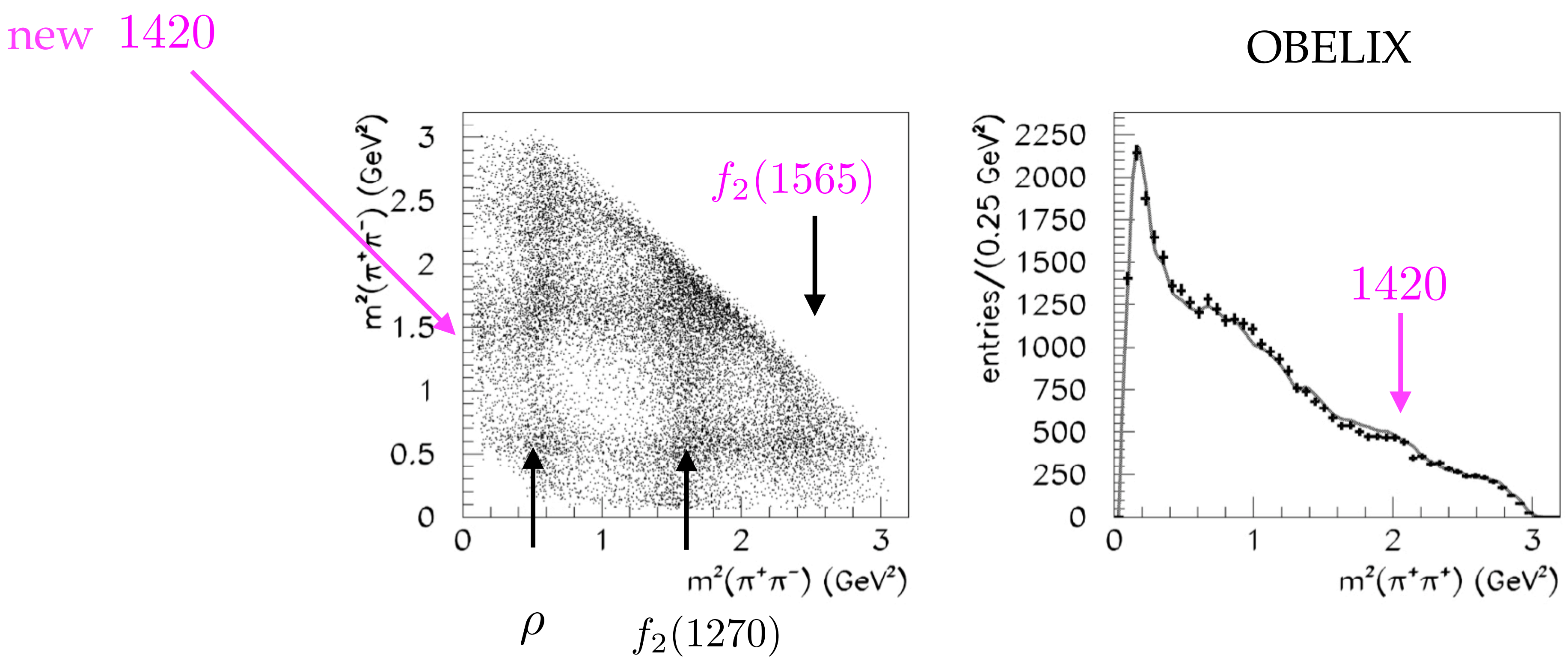
2^{++}, neutral, m=1565, Γ=134 MeV,
new, no space left in the 2^{++} $q\bar{q}$ nonet!

Well established state , observed by several experiments

Is this $f_2(1565)$ the predicted bound state? $\bar{p}p \to 2^{++}$ (baryonium) π^0 ?

→ $L = 1$ can also be reached with annihilation at low momenta, below ~200 MeV/c

Benefit of in flight annihilation, an example using antineutrons: $\bar{p}p \to \bar{n}n$, $\bar{n}p \to \pi^+\pi^-\pi^+$



A. Filippi *et al.*, Phys. Lett. B495 (2000) 284

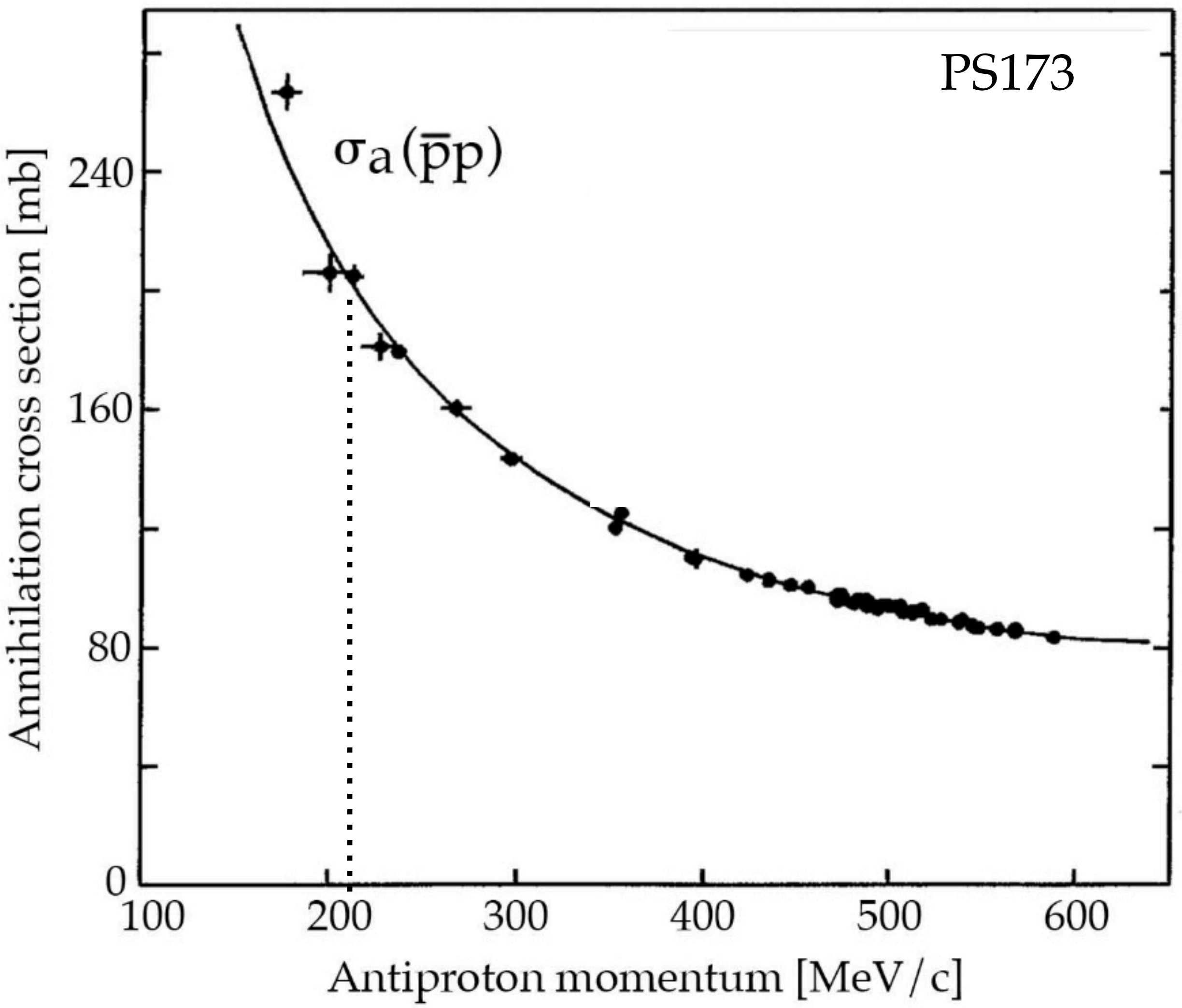
$$M = 1420 \pm 20, \Gamma = 100 \pm 10 \text{ MeV} \qquad J^P = 0^+$$

Doubly charged, hence not a quark-antiquark state (tetraquark?)

Low energy annihilation cross section on the proton

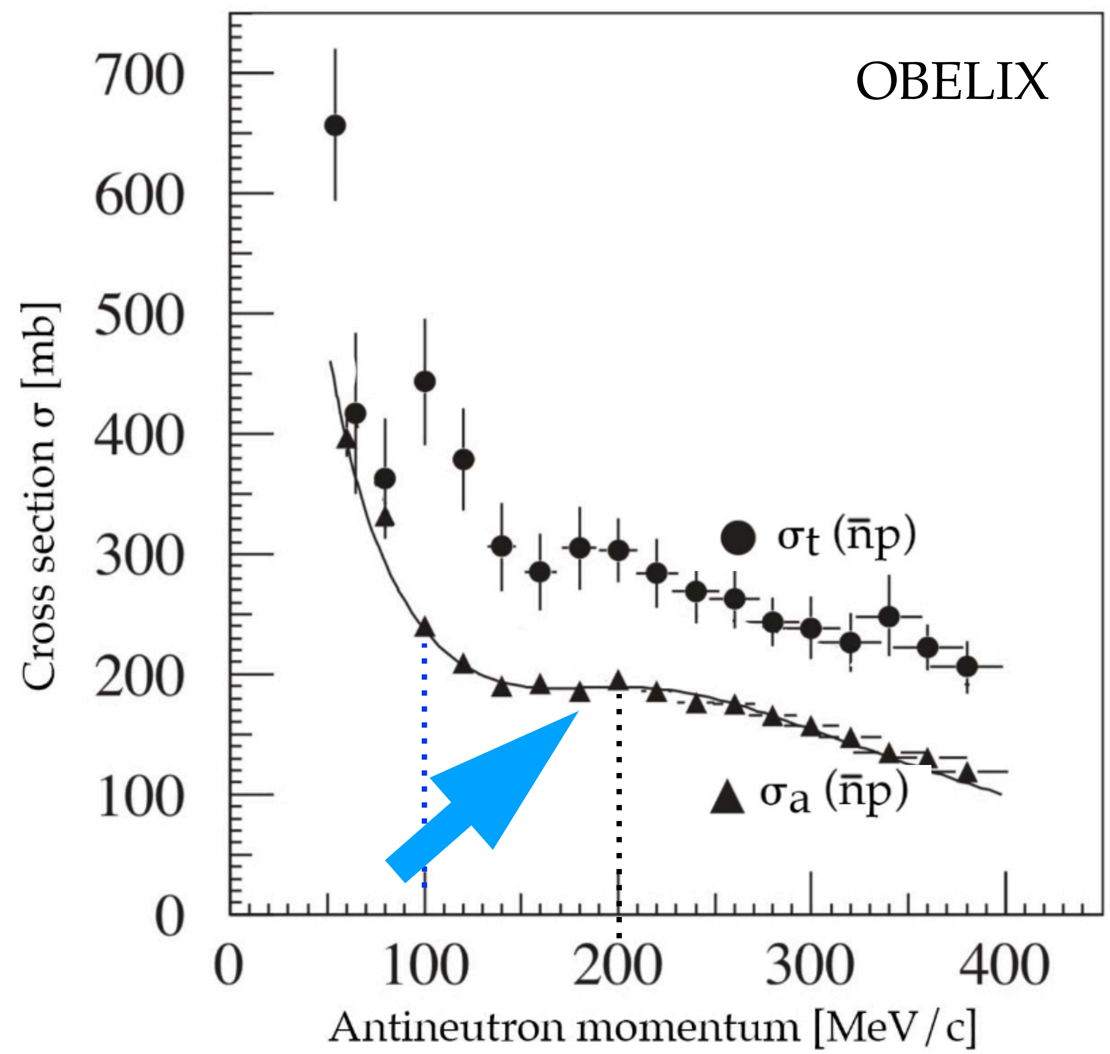
No low energy data: resonances below 200 MeV/c?

Antiprotons



W. Bruckner *et al.*, Z. Phys. A335 (1990) 217

Antineutrons



T. Bressani, A. Filippi, Phys. Rep. 383 (2003) 213

- *P*-wave strong (attraction)
- $\sigma(\bar{n}p) \simeq \sigma(\bar{p}p)$ (~200MeV/c)

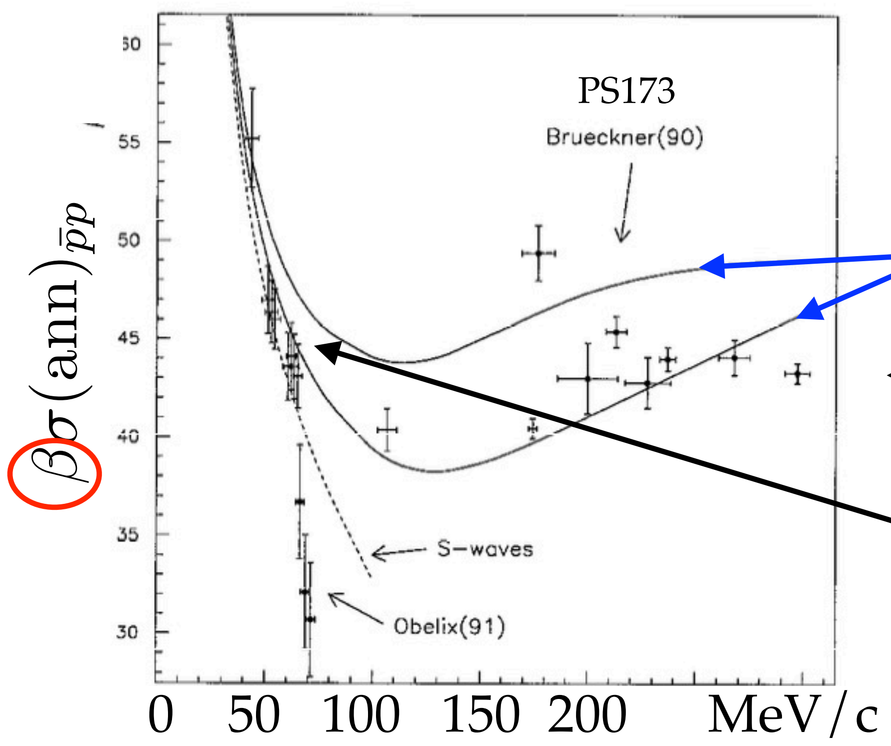
→ $I = 1$ dominance

$\sigma(\bar{n}p) < \sigma(\bar{p}p)$ @ very low energy

➡ strong attraction in $I = 0$

Status of antiproton-proton annihilation cross section:

OBELIX Physics Letters B 369 (1996) 77-85



$$\sigma(\text{ann})_{\bar{p}p} \neq \frac{1}{\beta}$$ absorption law for finite range potential

Modified by attractive Coulomb force ? Steeper

Not clear: also steeper for antineutron annihilation in nuclei

(A. Filippi's talk?)

PS 173: flat?

Disagreement between OBELIX data

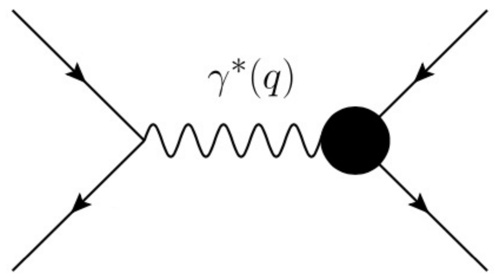
Difficult experiment at LEAR: > 43 MeV/c
OBELIX with high pressure target

Needs a low energy beam with narrow momentum byte:

300 MeV/c <-> 47 MeV
100 MeV/c <-> 5.2 MeV

Electromagnetic form factor of the proton (in the time-like region)

$\bar{p}p \to e^+e^-$



$$\sigma_{p\bar{p}}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{|G_E|^2}{2\tau}\right] \qquad \tau = \frac{q^2}{4m_p^2}$$

q^2 = is the mass² of the virtual photon = s
= energy² in c.m.s

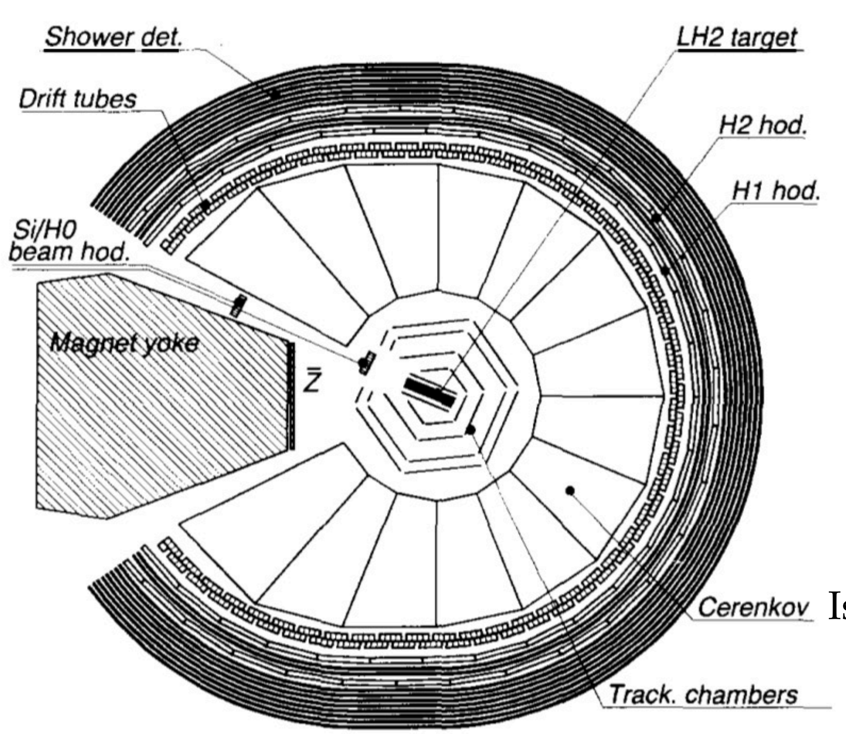
(C = Coulomb correction)

Sensitive to VDM:
vector mesons near threshold

Measurement of the differential cross section as a function q^2 gives

$$|G_M|, |G_E|$$

$\bar{p}p \to e^+e^-$ PS170 at LEAR

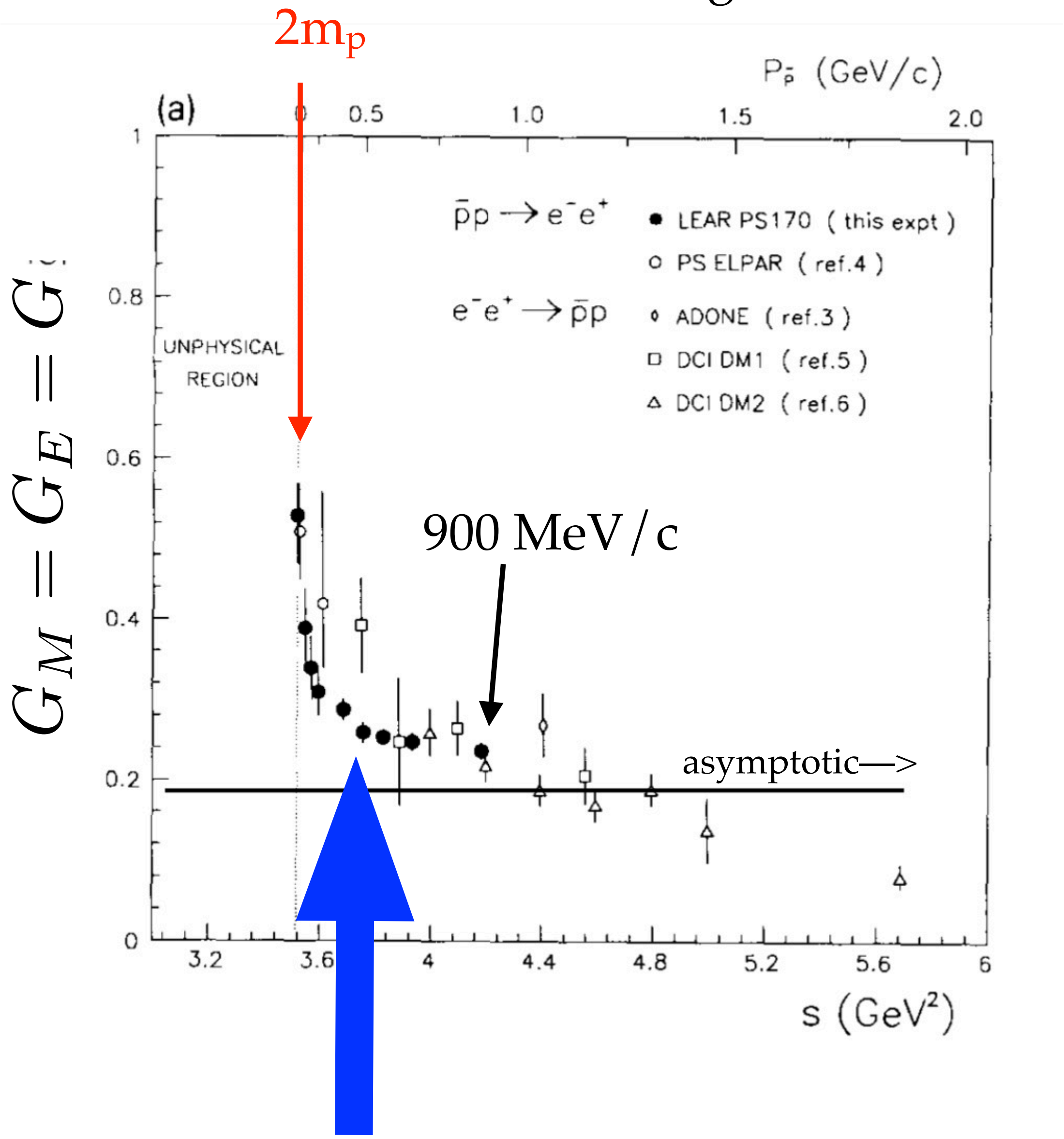


Isobutane

NIM A259 (1987) 376

Nucl. Phys. B411 (1994) 3

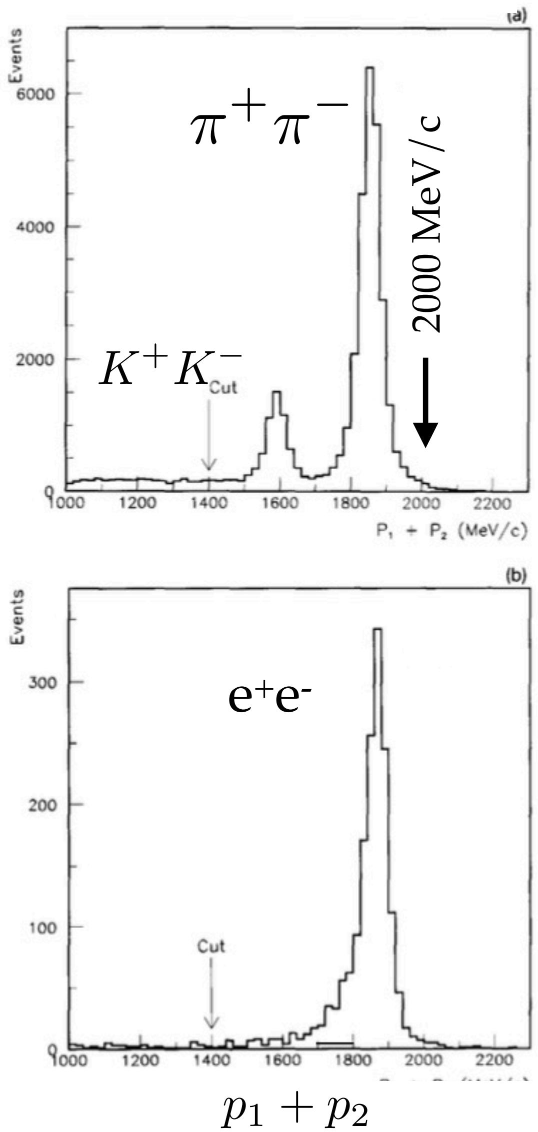
900 - 300 MeV/c beam, long hydrogen target
Branching ratio at rest: $(3.58 \pm 0.10) \times 10^{-7}$



Low, see next slide

Small number of events:
assume $G_M = G_E = G$ (strictly true at 2m$_p$)

Background

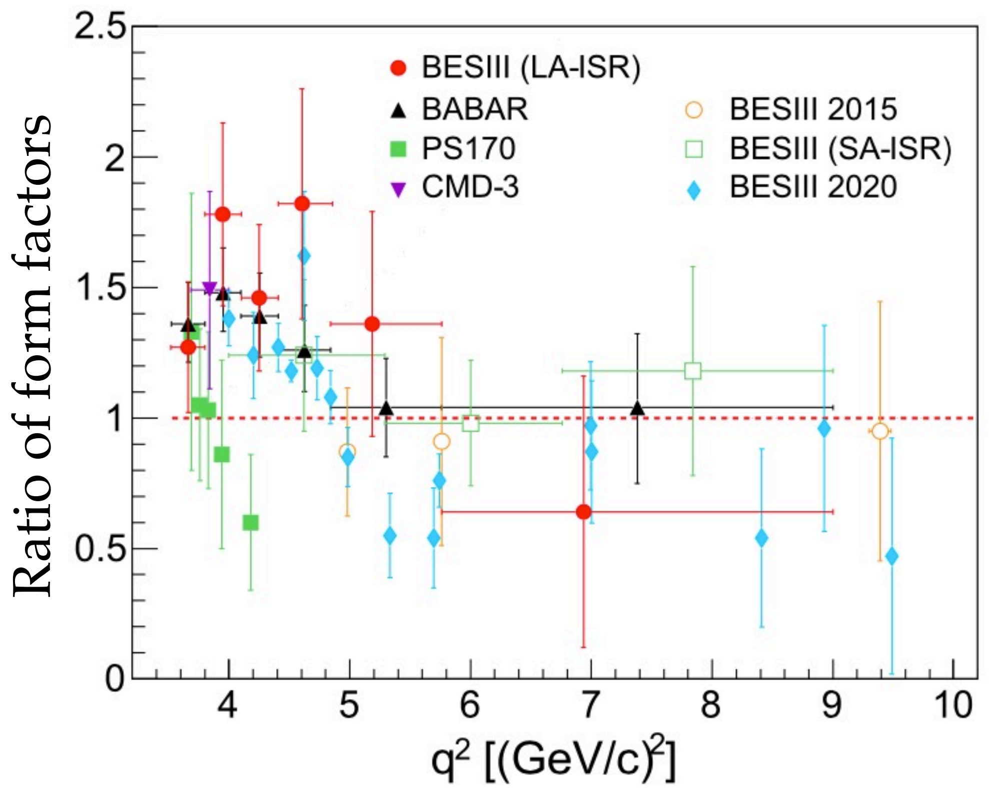


Normalisation on cross section for

$$\bar{p}p \to K^+K^-, \pi^+\pi^-$$

$$\frac{\sigma(e^+e^-)}{\sigma(\pi^+\pi^-)} = \mathrm{O}(10^{-5})$$

Compare BES3 (2021) with PS170

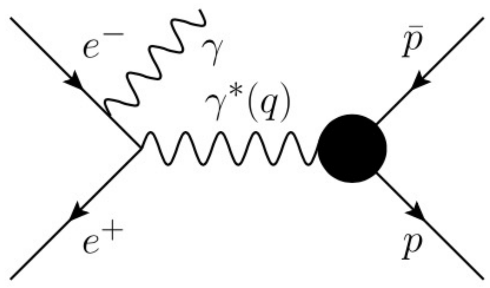


Physics Letters B 817 (2021) 136328

Time reversed reaction

$e^+e^- \to \bar{p}p\,\gamma$

Initial state radiation



Ratio of form factors:

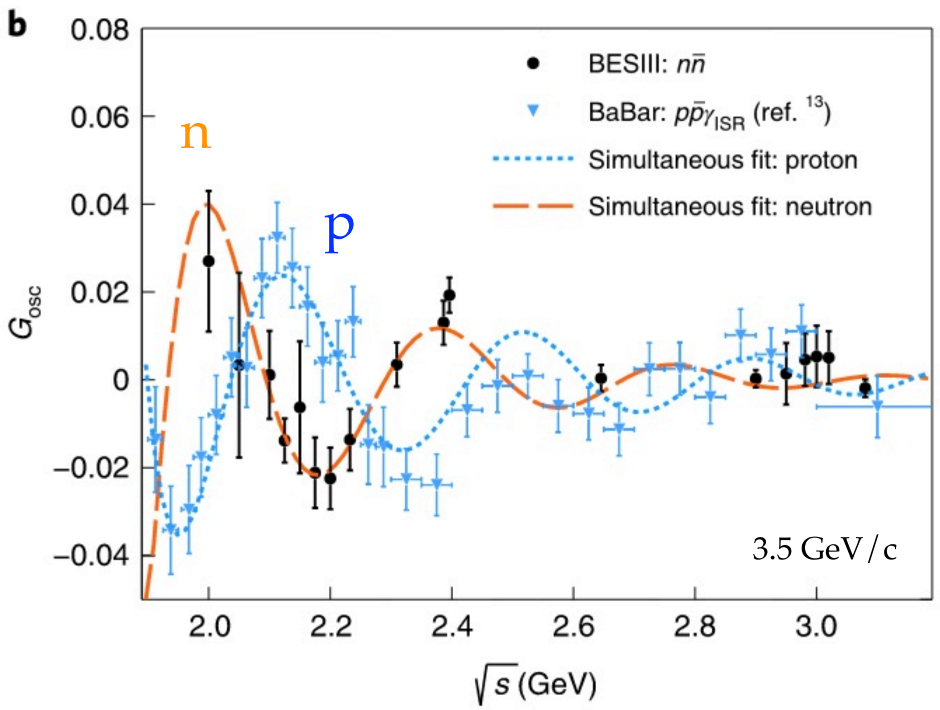
- > 1, enhancement at low momentum transfer!??
- PS 170 is much steeper ($\bar{p}$p final state interaction?)

Nucl. Phys. A 929 (2014) 102-118

?

Important to re-measure at low energy but difficult experiment:

- Electron identification
- ELENA: 100 keV = 13.7 MeV/c only, needs a DC beam
- AD extraction at 100 MeV/c (or higher), PS170: up to 900 MeV/c
- Up to 3.5 GeV/c: observe the oscillation of the formfactor (BES3)



Summary

Data are needed for:

Annihilation in flight

at low momenta with the motivations to investigate:

- the predicted existence of resonances close to the $2M_N$ threshold (p ~< 300 MeV/c),
- the peculiar behaviour of the annihilation cross section close to threshold,
- with antineutrons the presence of resonances and also to disentangle the I=1 component (threshold for antineutron production with $\bar{p}p \rightarrow \bar{n}n$: 100 MeV/c),
- the formfactor of the proton/antiproton in the timelike region (possibly up to 3.5 GeV/c).

Annihilation at rest:

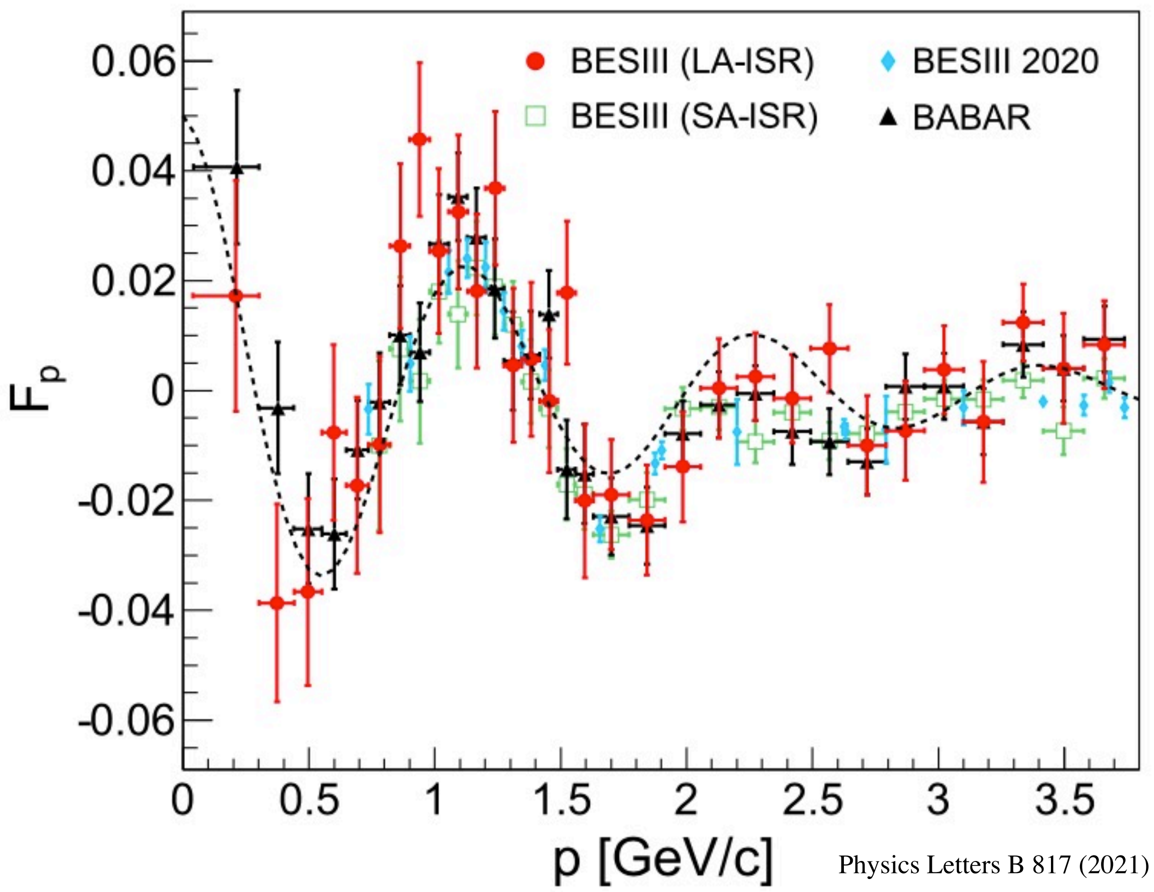
- proton-antiproton annihilation has been studied extensively, however the details of the mechanism (e.g. quarks) are not understood, mostly an issue for theorists (?), although more accurate data on branching fractions would be desirable,
- urgent: nuclear physics studies at rest (Pontecorvo reactions, sexaquarks… see the other talks at this workshop).

Requires a DC beam, the higher the momenta, the better!

see e.g. C.A.: - Rev. Mod. Phys. Rev. Mod. Phys. 70 (1998) 1293
- Trento Workshop (2019), https://arxiv.org/abs/1908.08455
- Ann. Rev. of Nucl. and Part. Sci. 451 (1991) 219 (with F. Myhrer)
- J.M. Richard: Frontiers in Physics 8 (2020)


Backup

Incidentally, at higher momentum transfer: BES3



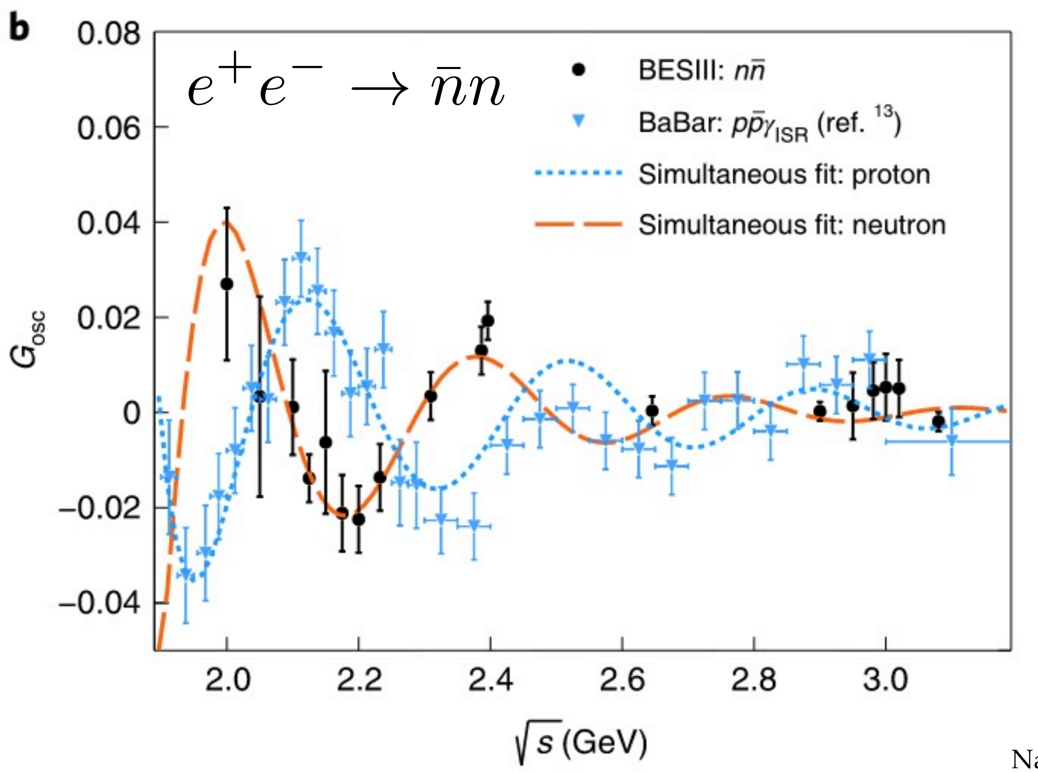
Physics Letters B 817 (2021) 136328

Divide by smooth function:

$$|G_{\text{eff}}| = \frac{\mathcal{A}}{(1+q^2/m_a^2)[1-q^2/q_0^2]^2}, \quad q_0^2 = 0.71\ (\text{GeV}/c)^2$$

$$\mathcal{A} = 7.7 \text{ and } m_a^2 = 14.8\ (\text{GeV}/c)^2$$

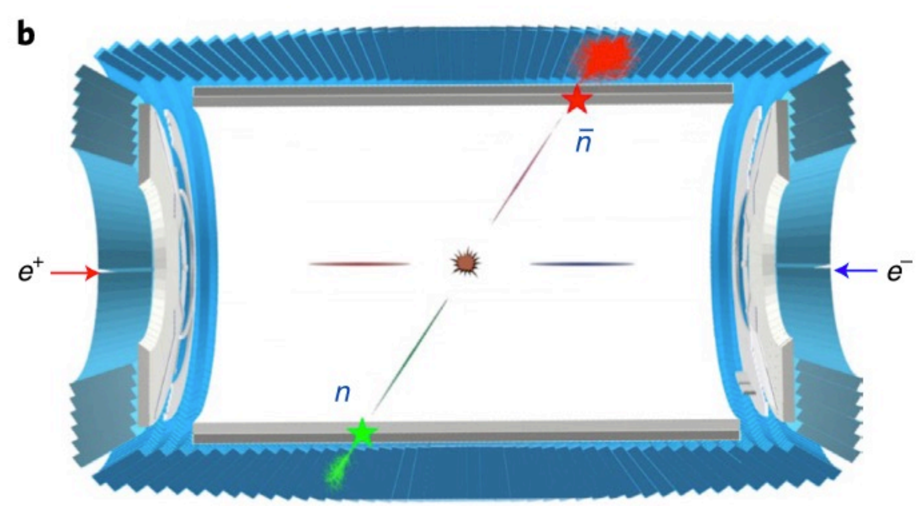
Oscillation is due either to unknown resonances or rescattering in the final state ???



Nature 17 (2021) 1200

Formfactor of the neutron by BES3!

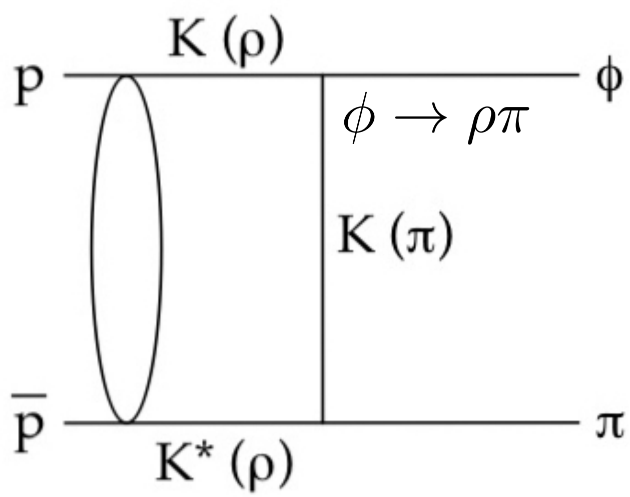
Oscillation phase shifted



Dream of the reverse reaction!

Violation of OZI rule

Rescattering

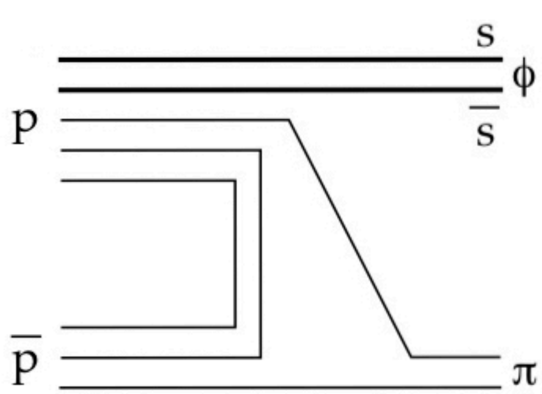


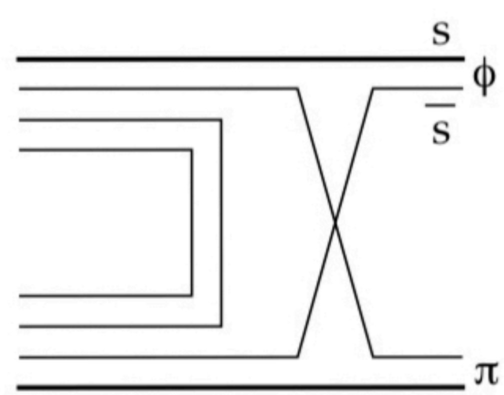
Constructive interference between $K^*\bar{K}$ and $\rho\rho$ → large $\phi\pi$ Go96

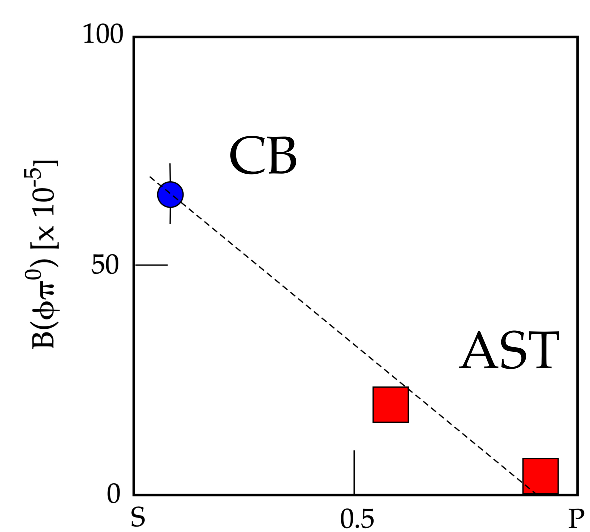
Strange sea quarks in the nucleon:

Deep inelastic scattering with muons: $s\bar{s}$ spins parallel and opposite to nucleon spin El95

$s\bar{s}$ spins parallel opposite to $p\bar{p}$ $^3S_1$ (as needed for the spin 1 ϕ)







wavefunction does not match

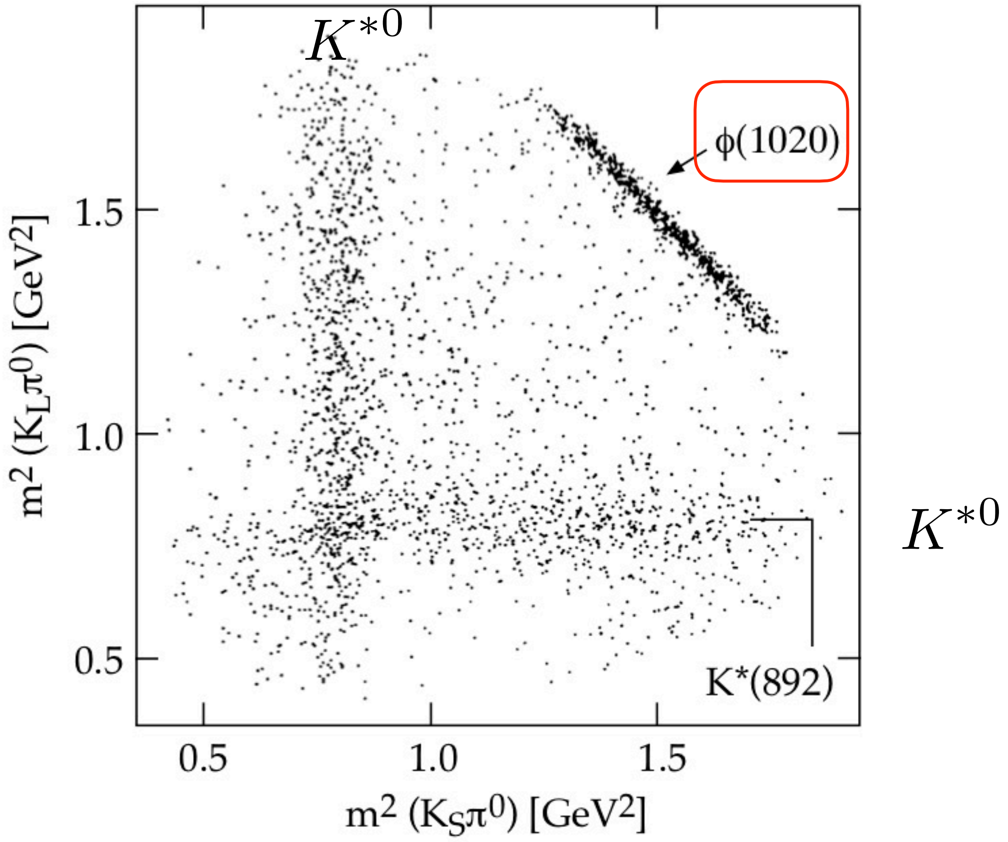
OK

Decreases with P wave (1P1)

OZI violation also seen with antineutrons

Crystal Barrel @ rest

$\phi\pi^0 : \bar{p}p \to K_S K_L \pi^0 \to 3\pi^0 + \text{miss}K_L$

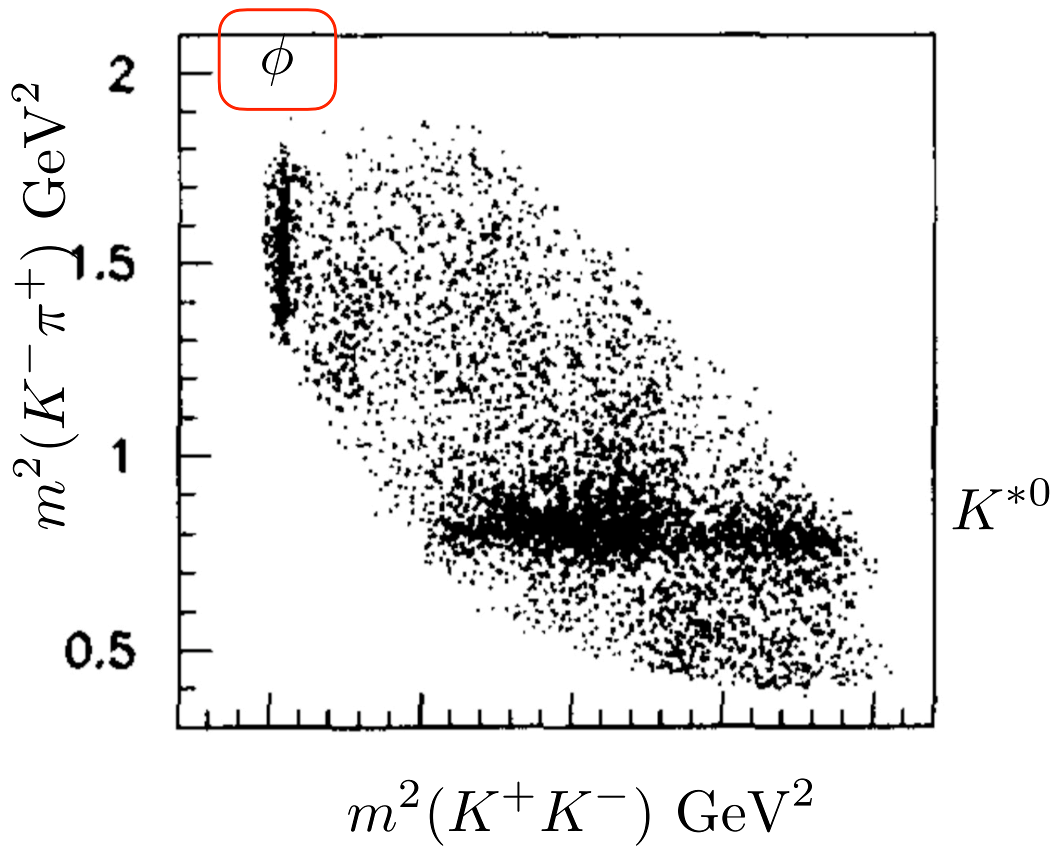


Compare with $\omega\pi^0 : \bar{p}p \to \omega\pi^0 \to \gamma 2\pi^0$

C. Amsler *et al.*, Phys. Lett. B319 (1993) 373

OBELIX, $\bar{\text{n}}$ momentum < 405 MeV/c

$\phi\pi^+ : \bar{n}p \to K^+K^-\pi^+$



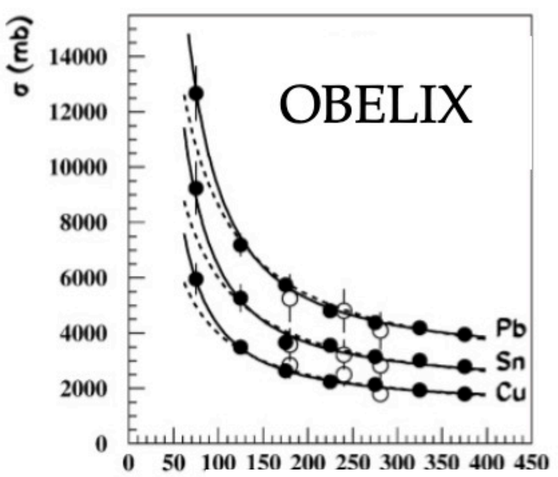
$\omega\pi^+ : \bar{n}p \to \pi^+\pi^-\pi^0\pi^+$

A. Filippi, *et al.*, Nucl. Phys. A655 (1999) 453
T. Bressani, A. Filippi, Phys. Rep. 383 (2003) 213

Behaviour of annihilation at low energy not $1/\beta$

Surprising antineutron-nucleus annihilation:

M. Astrua et al. / Nuclear Physics A 697 (2002) 209–224



MeV/c

$$\sigma_{ann}(\bar{n}) = A^{\frac{2}{3}}(a + b/p_{\bar{n}})$$

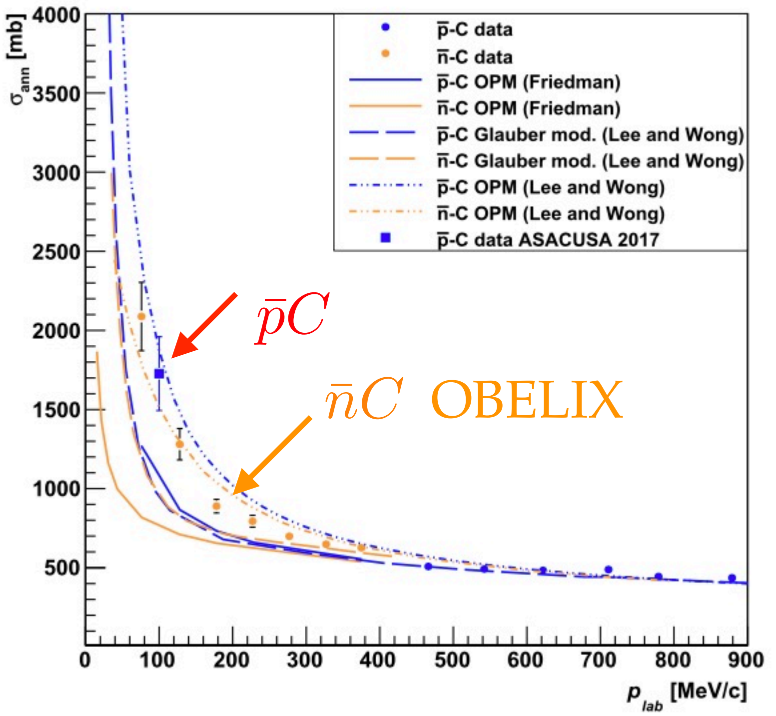
$1/\beta$ expected (dashed)

Better fit (full curve):

$$\sigma_{ann}(\bar{n}) = A^{\frac{2}{3}}(a + b/p_{\bar{n}} + c/p_{\bar{n}}^2)$$

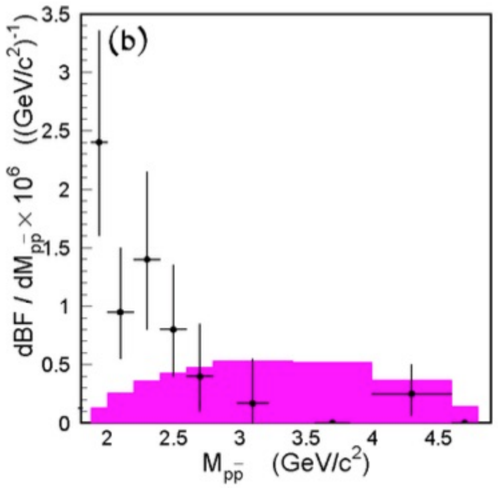
L. Venturelli measurement $\bar{p}C$

H. Aghai-Khozani et al. / Nuclear Physics A 970 (2018) 366–378

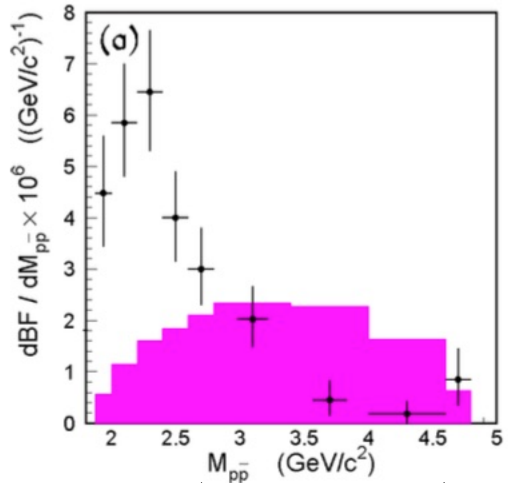


$1/\beta^2$ for both $\overline{\text{p}}$ and $\overline{\text{n}}$?

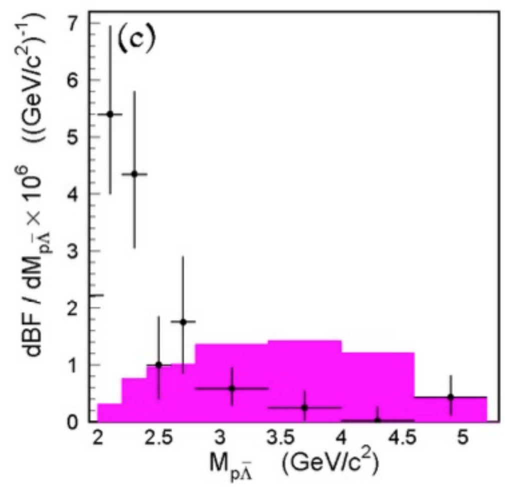
Enhancements near proton-antiproton thresholds (1876 MeV)



$B^0 \to p\bar{p}K_S$



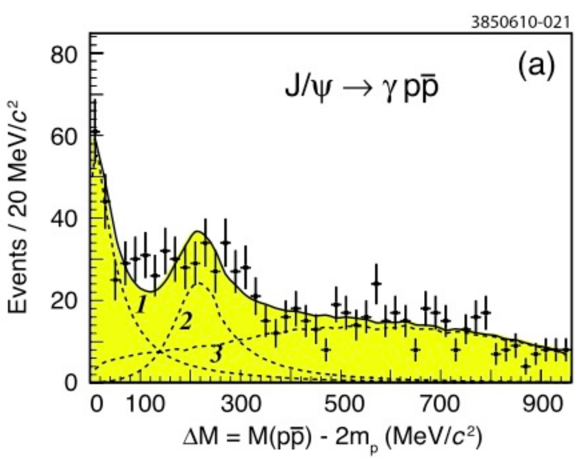
$B^+ \to p\bar{p}K^+$



$B^0 \to p\bar{\Lambda}\pi^-$

B-decays (BELLE) Wang 05

Charmless decays

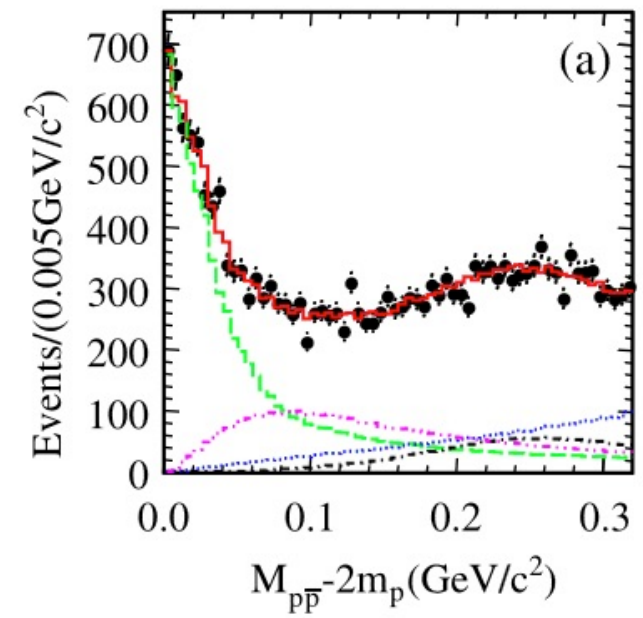


$J/\psi \to \gamma p\bar{p}$

CLEO (Alexander 10) BES3 (Ablikim 12D)

1837 ± 13 MeV 1832^{+32}_{-26} MeV

below threshold 0^{-+}



Lots of activities near thresholds (general remark)

Are these baryonium states or the manifestation of the final state interaction between the proton and the antiproton?

Total of 35 experiments, 15 on annihilation mostly with stopping $\bar{p}$

(“annihilation at rest”)

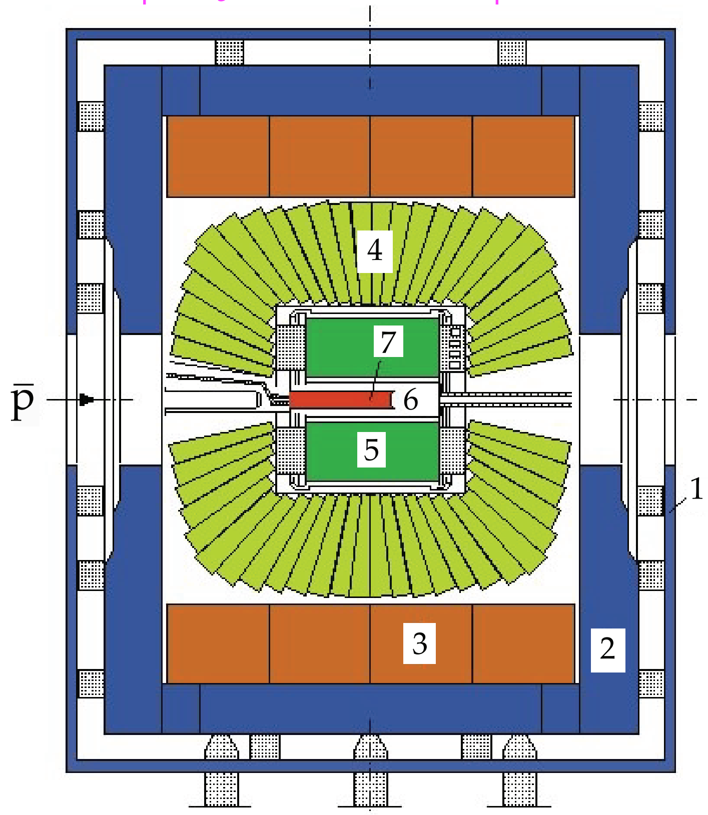
PS170 Precision Measurements of the Proton Electromagnetic Form Factors in the Time-like Region and Vector Meson Spectroscopy
PS171 Study of Proton-Antiproton Interactions at Rest in a H_2 Gas Target at LEAR (ASTERIX)
PS173 Measurement of Antiproton-Proton Cross-Sections at Low Antiproton Momenta
PS177 Study of the Fission Decay of Heavy Hypernuclei
PS179 Study of the Interaction of Low-Energy Antiprotons with H_2,He_3,He_4,Ne-Nuclei Using a Streamer Chamber in Magnetic Field
PS182 Investigations on Baryonium and Other Rare pp Annihilation Modes Using High-Resolution π^0 Spectrometers
PS183 Search for Bound NN States Using a Precision Gamma and Charged Pion Spectrometer at LEAR
PS184 Study of Antiproton-Nucleus Interaction with a High Resolution SPESII Magnetic Spectrometer
PS186 Nuclear Excitations by Antiprotons and Antiprotonic Atoms
PS187 A high statistics study of antiproton interactions with nuclei
PS197 The Crystal Barrel: Meson Spectroscopy at LEAR with a 4π Detector
PS201 Study of antiproton and antineutron annihilations at LEAR with OBELIX, a large acceptance and high resolution detector based on the Open Axial Field Spectrometer
PS202 JETSET: Physics at LEAR with an Internal Gas Jet Target and an Advanced General Purpose Detector
PS203 Antiproton Induced Fission and Fragmentation
PS208 Decay of Hot Nuclei at Low Spins Production by Antiproton-Annihilation in Heavy Nuclei

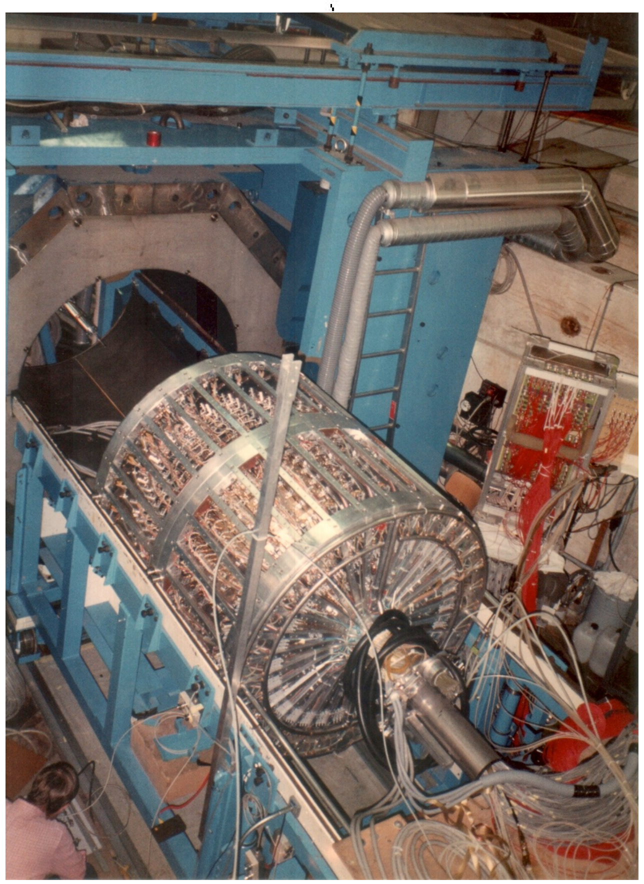
Antiproton-proton annihilation at rest mostly by
ASTERIX, Crystal Barrel, OBELIX

350 publications

This talk deals mostly with some of their results

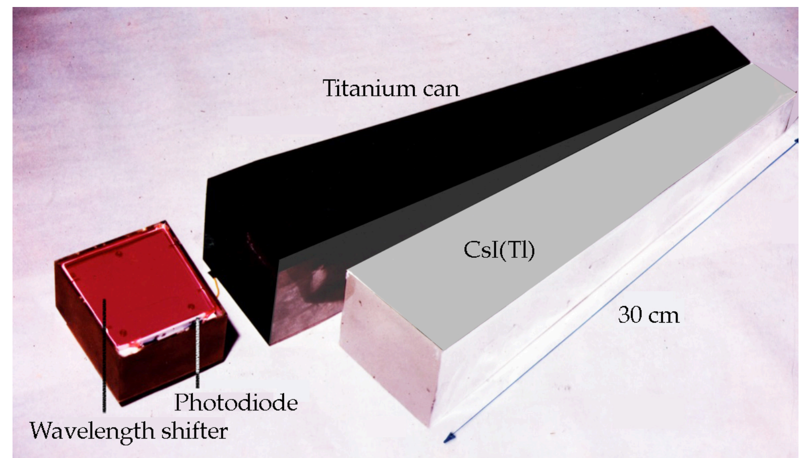
Crystal Barrel





Annihilation at rest in liquid, but with multiple photon detection ($\leq 10\gamma$)

- 15 kGauss
- 1380 CsI (Tl) crystals (97% x 4π)



- Jet drift chamber for charged products

CO_2/isobutane

- Emphasis on meson spectroscopy: new mesons discovered:

  $f_0(1370), \pi_1(1400), \eta(1410), a_0(1450), f_0(1500), \eta_2(1645)$

  with large data samples -> T-matrix analyses

- Annihilation into 2 and 3 mesons
- Radiative annihilation

ASTERIX

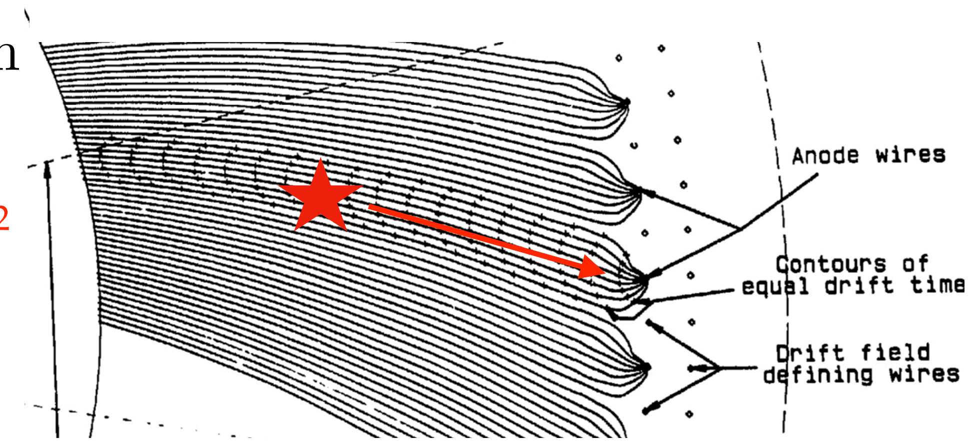
Solenoid 8kG (DM1 from LAL-Orsay)

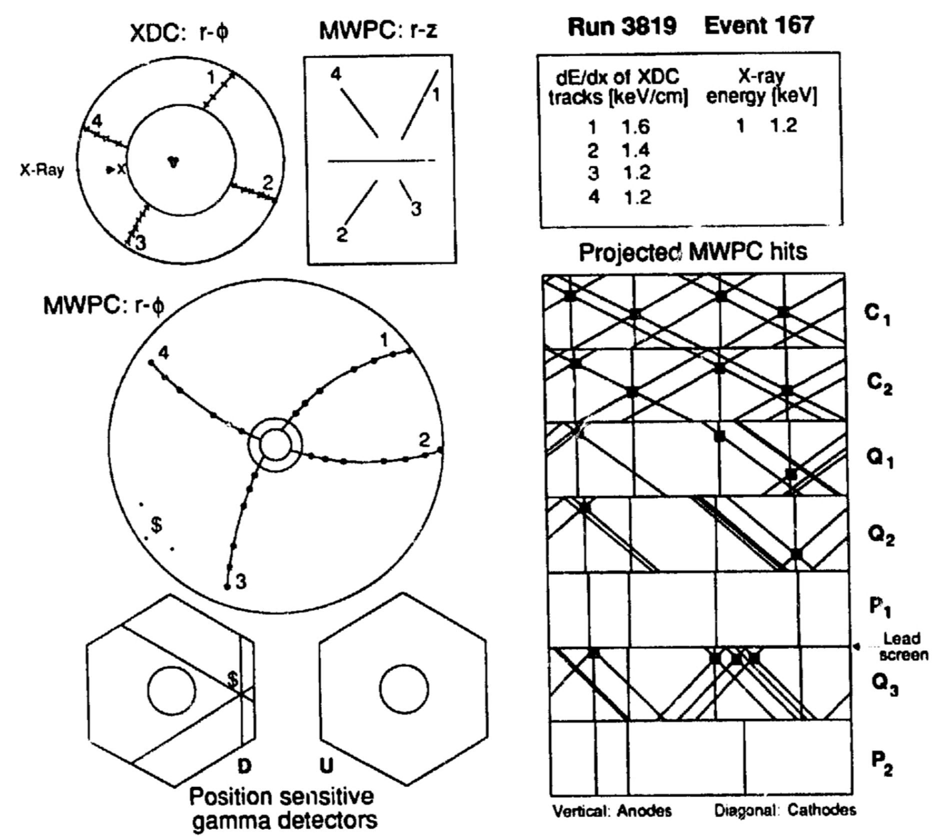
105 MeV/c $\bar{p}$, H_2 gas at NTP

argon/ethane X-ray drift chamber (>1 keV)

6 μm

H_2



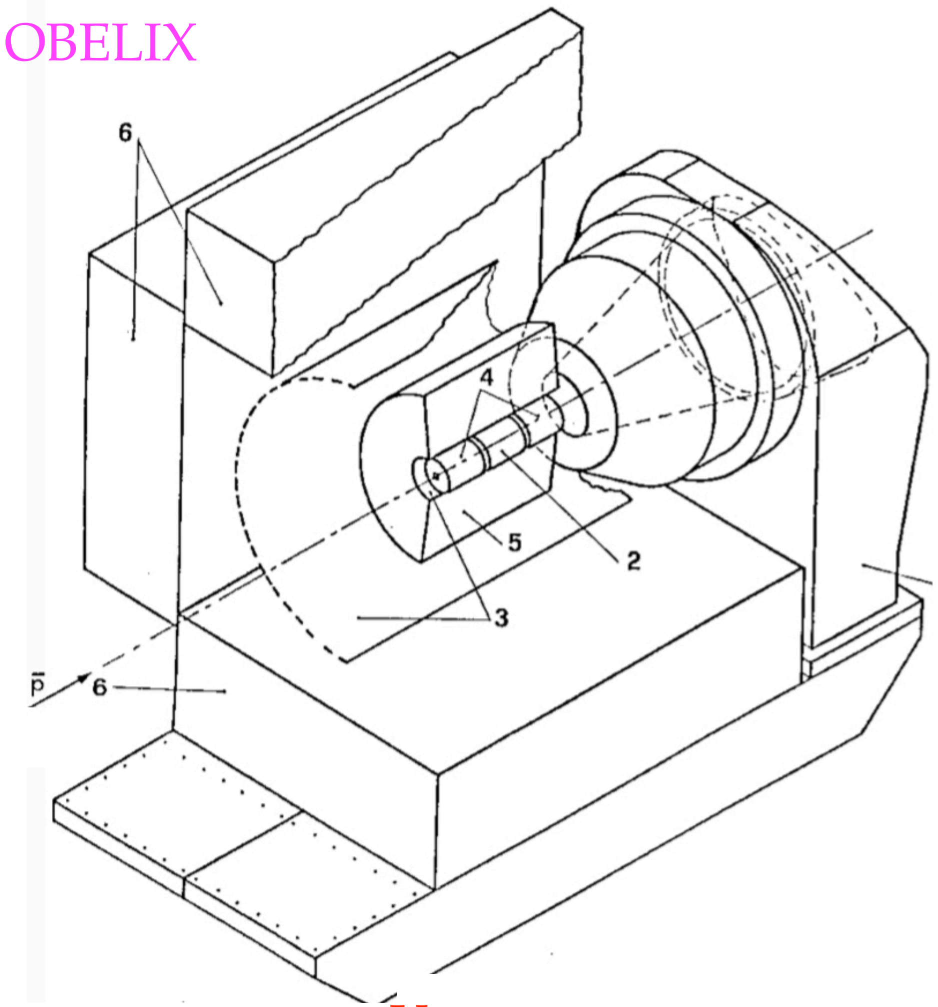


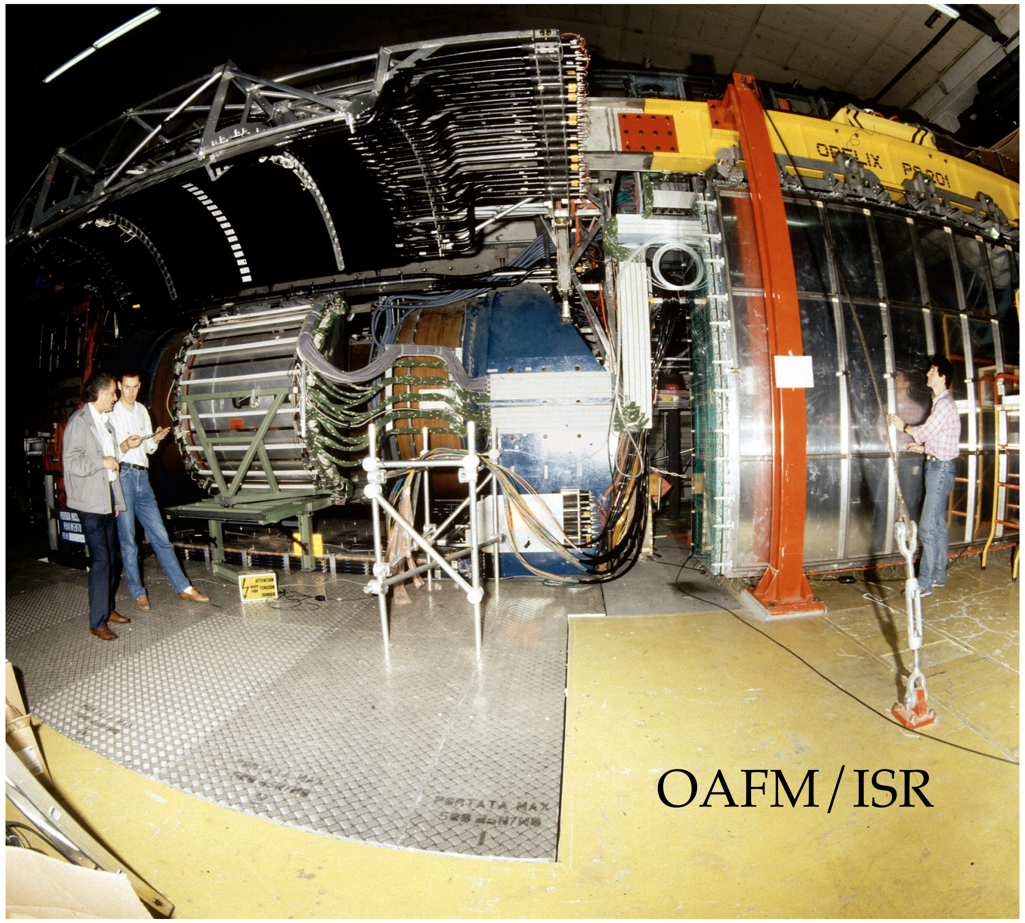
4 prong event

7 MWPC cathode strips

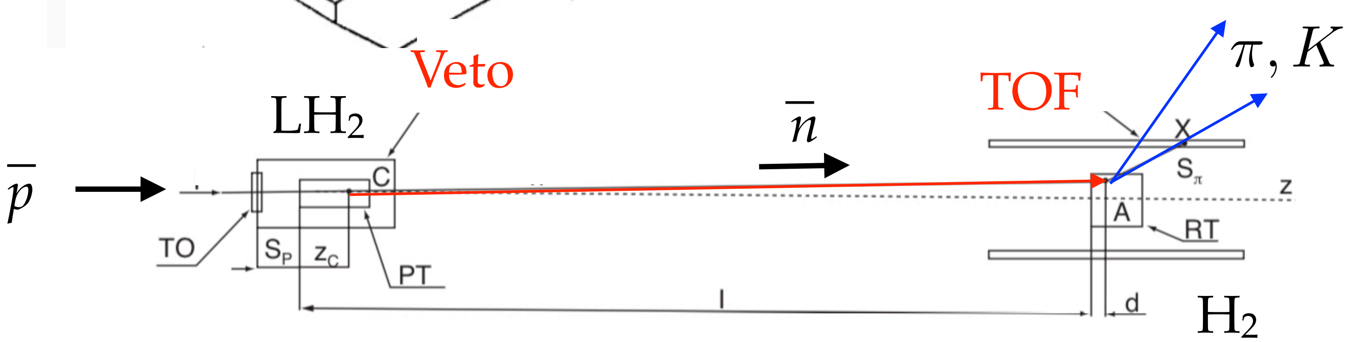
limited γ capability with Pb converter

OBELIX





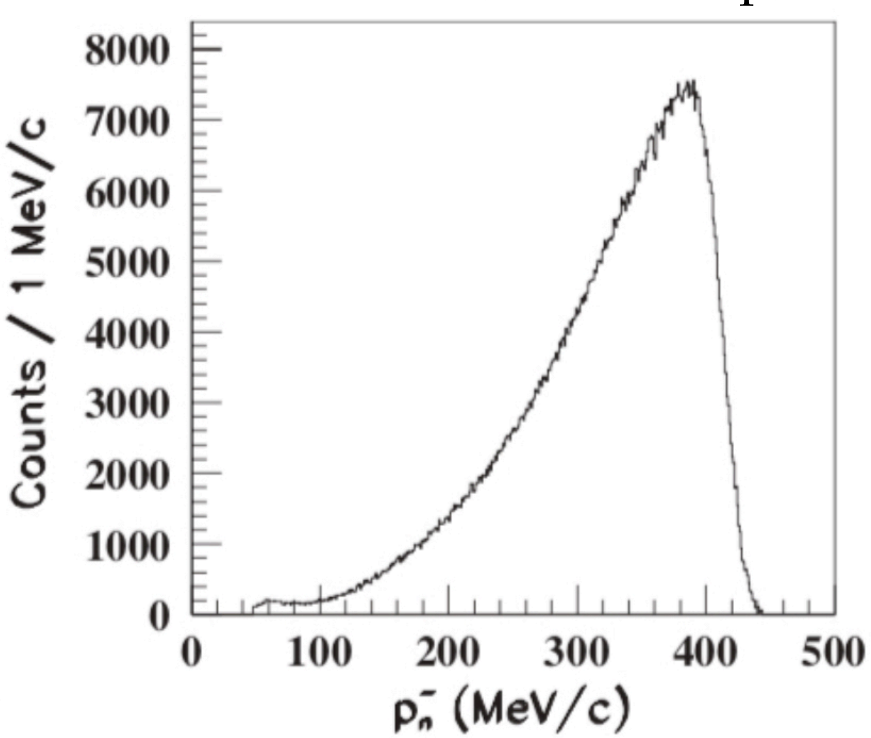
low flux (~40 $\overline{n}$/10^6 $\overline{p}$)



Antineutron beam < 400 MeV/c

$\bar{p}p \to \bar{n}n$ 412 MeV/c antiprotons

(minimum is 98 MeV/c = AD energy 😡)



T. Bressani, A. Filippi, Phys. Rep. 383 (2003) 213