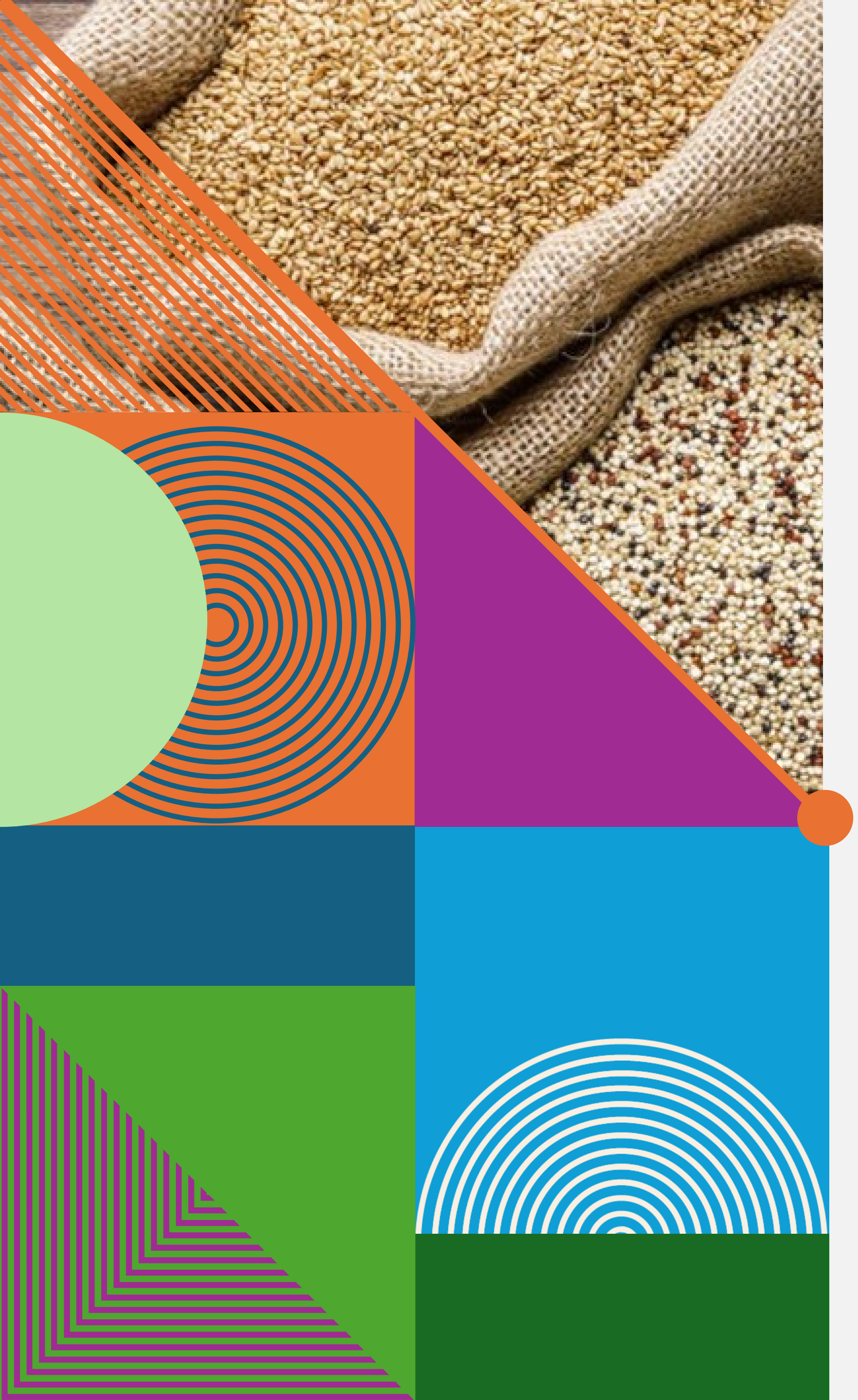

# A SACKFUL OF ANTINEUTRONS: A WISHLIST FOR THE SOLUTION OF A FEW OPEN PROBLEMS

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FuPhy24 Workshop

Vienna, April 9, 2024

# Outline of the talk

- Introduction: state-of-art measurements with low energy antineutrons as probes
  - $\bar{n}$ induced interactions and annihilation dynamics
  - Meson spectroscopy with antineutrons
- Puzzles (at least 4!)
  - Annihilation cross sections on nuclei: $\bar{n}$'s vs $\bar{p}$'s
  - The shape of $(\bar{n}p)$ elastic cross section
  - $I=0$ vs $I=1$ sources in $\bar{N}N$ annihilation
  - The CEX cross section at very forward angles
- Open issues (… many more …)
  - Dynamical selection rules and the onset of strangeness in annihilation reactions
  - Does baryonium exist?
  - Meson spectroscopy in a gluon-rich environment
    - Channels with open and hidden strangeness

# Why antineutrons?

- $(\bar{n}\,p)$ is a fixed isospin system: $I=1$
- $(\bar{p}\,p)$ contains both the $I=0$ and $I=1$ sources
  - $\bar{n}$'s offer a powerful selection rule excluding several initial states and constraining the combination of quantum numbers of intermediate objects/resonances
- The same quantum numbers are featured by the $(\bar{p}\,n)$ system formed in deuterium targets
  - PRO's:
    - higher statistics/cross section
    - $\bar{p}$ annihilation can occur at rest, $\bar{n}$ annihilation always in flight (more initial partial waves involved)
  - CON's
    - The hit neutron in deuteron has a Fermi momentum: the kinematics are not "exactly" closed
    - The recoiling nucleon has a momentum which should be measured
    - The recoiling nucleon can rescatter against the particles produced in the annihilation
    - Additional complication: does the annihilation occur on a proton or a neutron in deuteron?

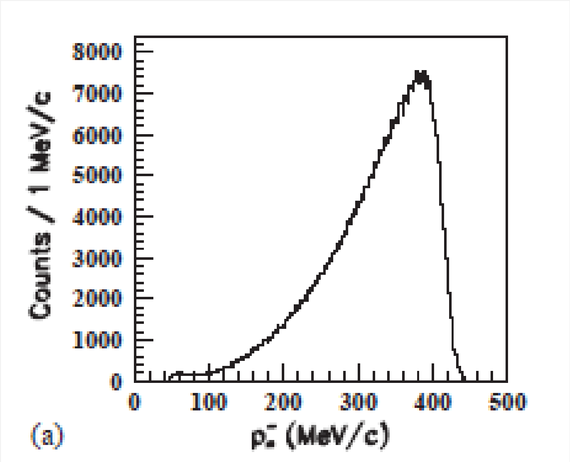
# Antineutron beams: a short history

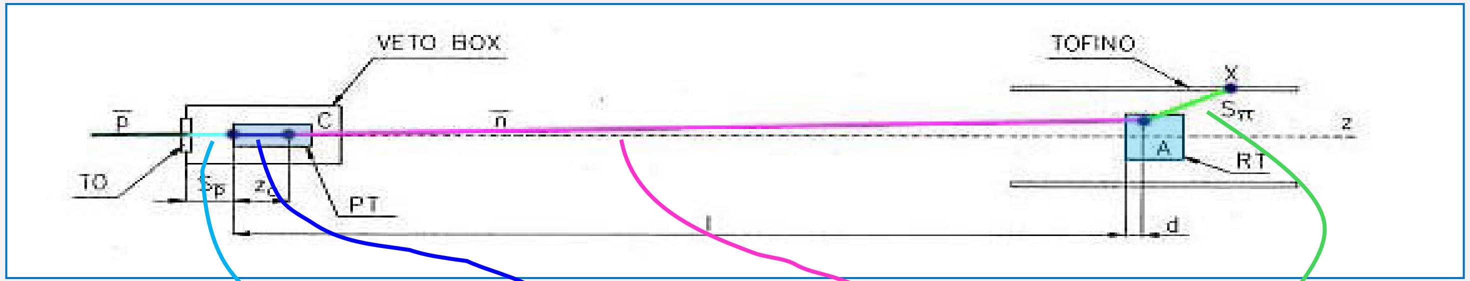
- $\bar{n}$ **from external production targets**, dumping a proton beam and separating $\bar{n}$'s by means of TOF
  - AGS PS (Brando et al., 1981)
    - Antineutrons from 0.3 to 1 GeV/c

- **Antineutrons from CEX reaction**
  - Argonne ZGS (Gunderson e al., 1981)
    - CEX on $CH_2$ production target
    - 1 GeV/c antiprotons
  - BNL AGS (Armstrong et al., 1987)
    - CEX on $CH_2$ production target
    - $\bar{p}$ momentum: 505 and 520 MeV/c
    - $\bar{n}$ momentum: 100-500 MeV/c
    - Event rate: 0.2 $\bar{n}$/s
  - LEAR PS178 (1988)
    - CEX on $LH_2$
    - Tagged $\bar{n}$ beam
    - LEAR beam: $10^6$ $\bar{p}$/s

# The antineutron beam at OBELIX

- **LEAR OBELIX (1990)**
  - Production Target: CEX on $LH_2$
  - 305 and 412 MeV/c $\bar{p}$
  - Untagged antineutron beam, collimation, ~0 deg production
  - Intensity: 30-60 $\bar{n}/10^6\bar{p}$
  - Reaction target: $\bar{n}$ on $LH_2$ + possible (further downstream) nuclear targets
  - 35 million events collected overall




$$t_{meas} = \frac{s_{\bar{p}}}{v_{\bar{p}}(0)} + \int_0^{z_c} \frac{dz'}{v_{\bar{p}}(z')} + \frac{l+d}{v_{\bar{n}}} + \frac{s_\pi}{v_\pi}$$

- C: CEX point
  - Iterative search of $z_c$

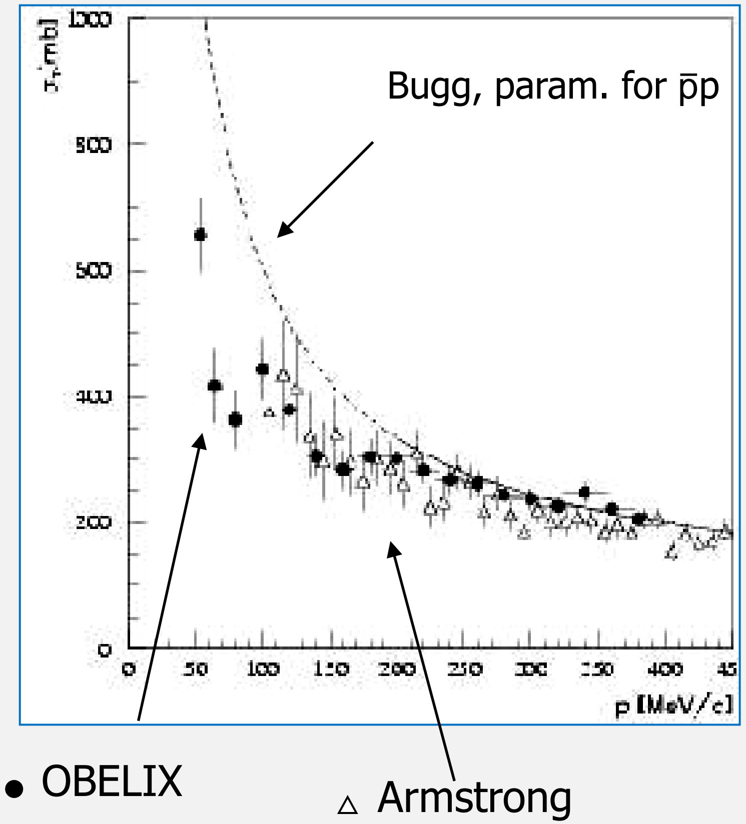
$$z_c = \int_{p_{\bar{p}}(0)}^{p_{\bar{p}}} \frac{\beta dp}{dE/dz}$$

- CA: direction of $\bar{n}$
- $p_{\bar{n}}$ from CEX kinematics
- $p_{\bar{p}}$ (known, nominal) decreased by $\Delta p_{\bar{p}}$ ($\bar{p}$ slowed down in PT)
  - repeat iteration with updated $p_p$

# n̄-antinucleon *total* cross section

- **Total cross sections below 500 MeV/c**
  - Armstrong et al. (1987)
    - Transmission method with empty/full target
    - Data compatible with a *(A+B/p)* parametrization
  - OBELIX Experiment
    - Thick target/narrow beam transmission technique
    - $\sigma_T$ in the (50-390) MeV/c momentum range
    - 10% error
    - Good agreement in the overlap region
    - Slightly lower than $\sigma(\bar{p}p)$ below 200 MeV/c

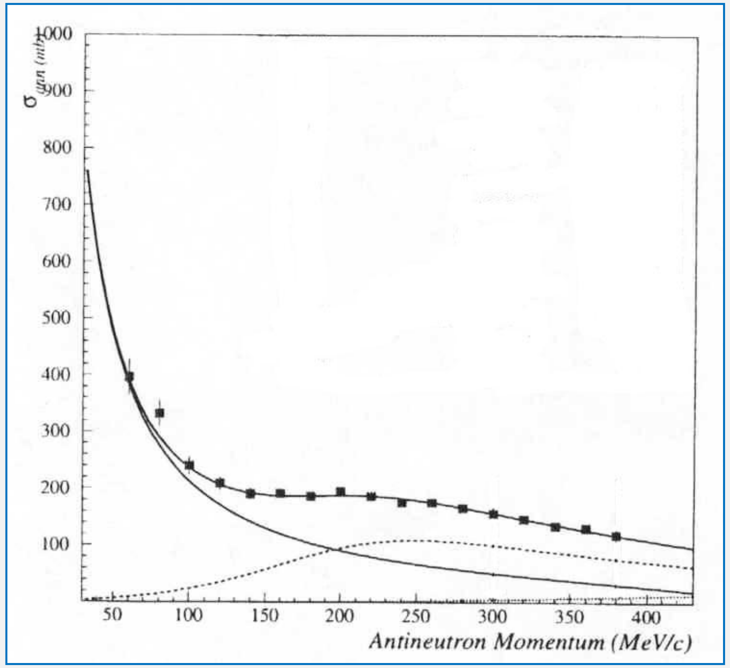
OBELIX, PL B475 (2000), 378




PR D36 (1987), 659

# $\bar{n}$ -antinucleon *annihilation* cross sections

OBELIX, NPB (Proc.Supp.) 56A (1997), 227

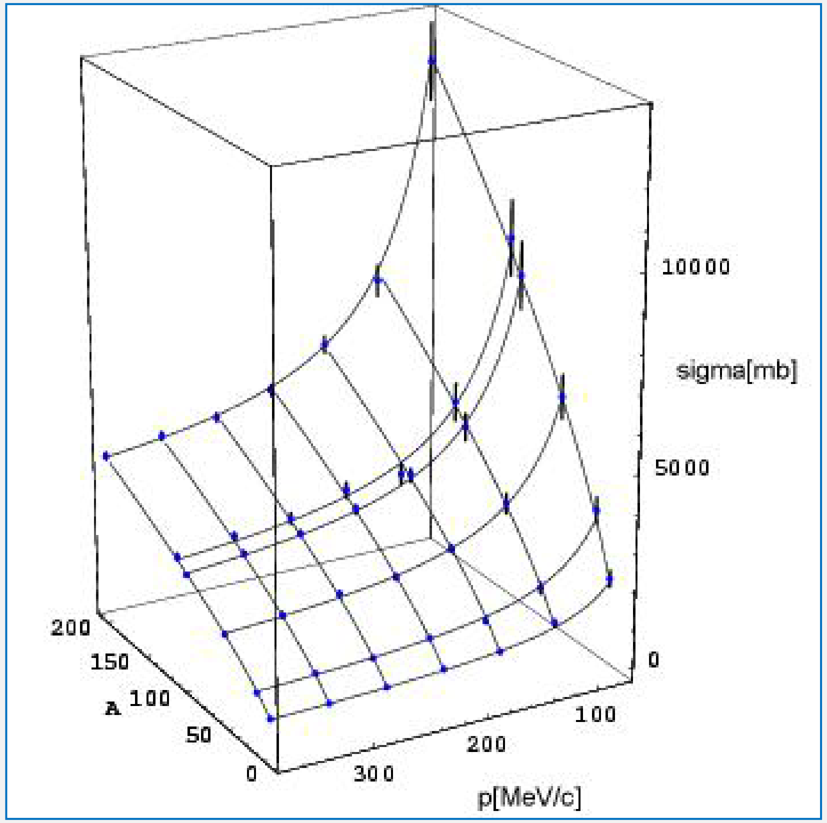



- **Annihilation cross sections**
  - Banerjee et al. (1985): (500-800) MeV/c
    - $LH_2$ bubble chamber, n̄ by CEX
    - $\sigma_{ann}$ = (55.4±2.2) mb
  - Armstrong et al. (1987):
    - $\sigma_{ann}$ from $\sigma_T$ by subtracting elastic cross section: 15-20% error
    - $\sigma_{ann}$ compatible with $(A + B/p)$
  - Mutchler et al. (1988): same experimental set-up at BNL AGS
    - $\beta\sigma_{ann}$ = (40± 3) mb @ 22 MeV/c
    - $\beta\sigma_{ann}$ = (32± 5) mb @ 43 MeV/c
    - Imaginary part of the spin averaged $S$-wave scattering length
      - $a_1$ = (-0.83 ±0.07) fm
  - OBELIX (1990-1996)
    - Good agreement with Armstrong data
    - 7% normalization error
    - Good fit by ER expansion with $S, P, D$ waves: $\alpha_D$ = (4.7± 0.6)%

# $\bar{n}$-nucleus cross sections

- OBELIX: several nuclear targets placed downstream $LH_2$
- Mass number dependence:
  - $x = 0.66 \sim 2/3$
    - "normal" $A^{2/3}$ law, within 2%
  - Annihilation on the nuclear surface
  - Localized hadronic interaction with high cross section
- Momentum dependence:
  - Roughly proportional to $1/\beta$

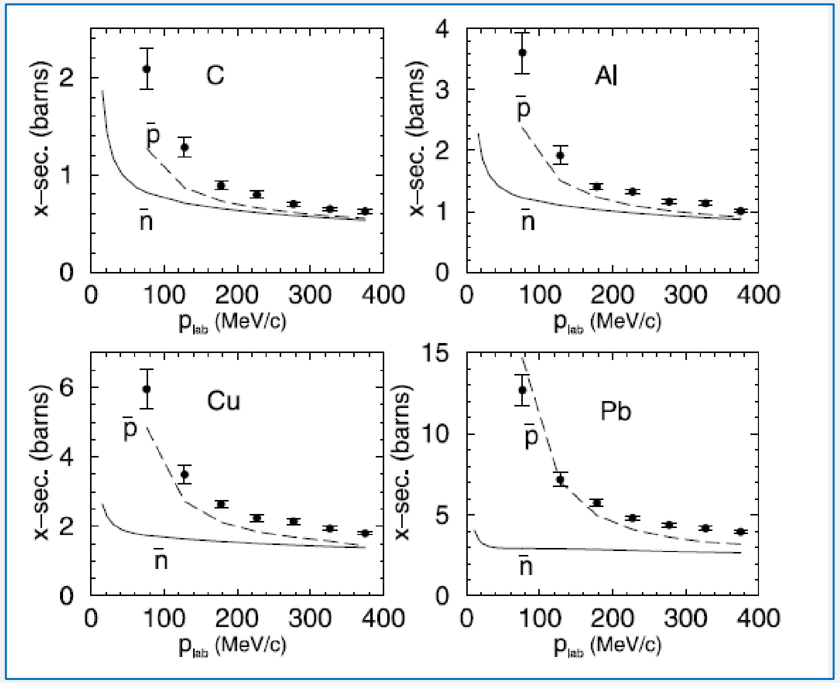
NP A697 (2002), 209




$$\sigma_{ann} = \sigma_0(p)A^x = (A + b/p)A^x$$

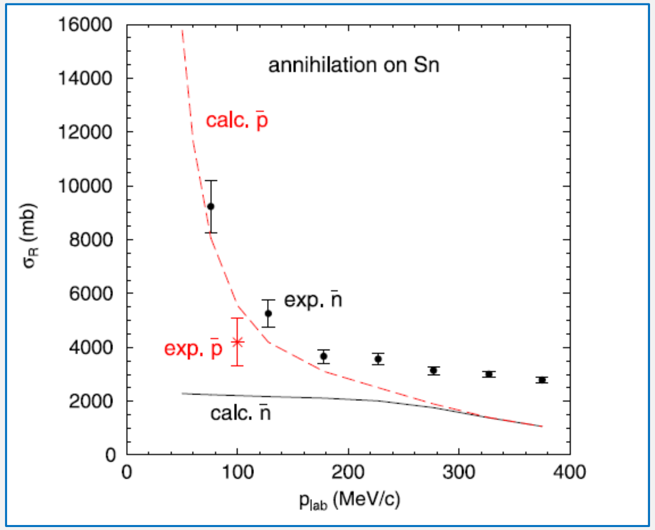
# PUZZLE #1: ANNIHILATION CROSS SECTIONS IN NUCLEI AT LOW MOMENTA

- Friedman (2014): the $\bar{n}A$ annihilation cross section cannot be described by an optical potential which fits well the $\bar{p}A$ interactions
  - $\bar{n}$'s are not subject to Coulomb scattering as $\bar{p}$'s
  - Interaction modelled through optical potential:
    - $\bar{n}$ data suggest the presence of a sort of Coulomb focusing




Friedman, NPA925 (2014), 141

- Too few data on $\bar{p}A$ for a thorough comparison
  - A single data by ASACUSA on $Sn$ can be used for the comparison
    - Experimental $\bar{n}\,Sn$ cross sections are larger than the corresponding $\bar{p}\,Sn$




- Desirable to have measurements for $\bar{n}$ and $\bar{p}$ on the same targets

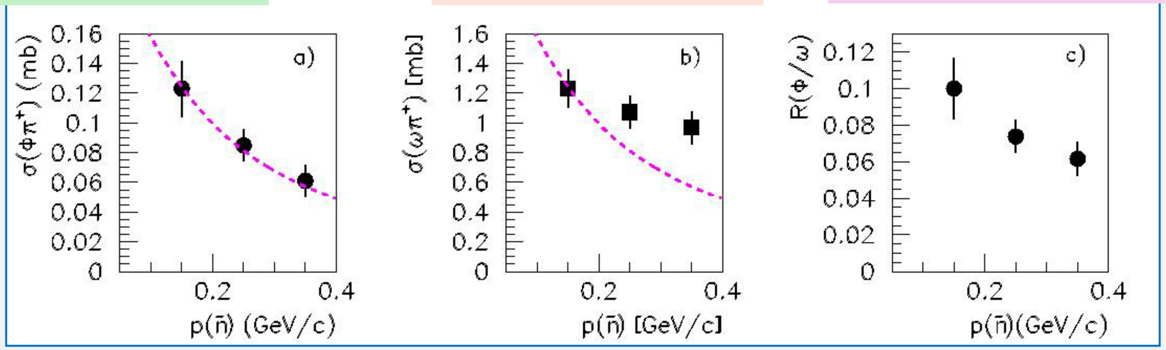
# Open issues: two body annihilation dynamics

- Several cross sections for selected two-body reactions measured
- Interesting results pointing at dynamical selection rules especially related to the onset of strangeness in annihilation reactions
  - *OZI rule* violation effects
    - Polarized strange sea quarks?
    - Quark "standard" rescattering?

$\bar{n}p \rightarrow \varphi\pi^+$
scales as $S$ wave

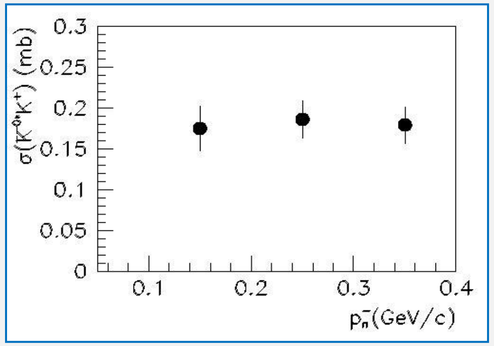
$\bar{n}p \rightarrow \omega\pi^+$
does not

*OZI ratio*
scales with $p_{\bar{n}}$

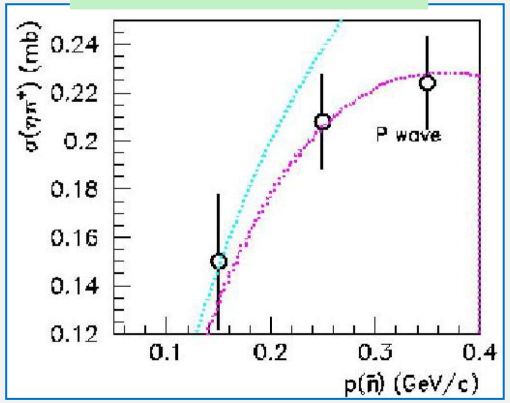



NPA655 (1999), 453

$\bar{n}p \rightarrow K^{0*}K^+$
does not scale as $S$ wave




$\bar{n}p \rightarrow \eta\pi^+$
scales as $P$ wave



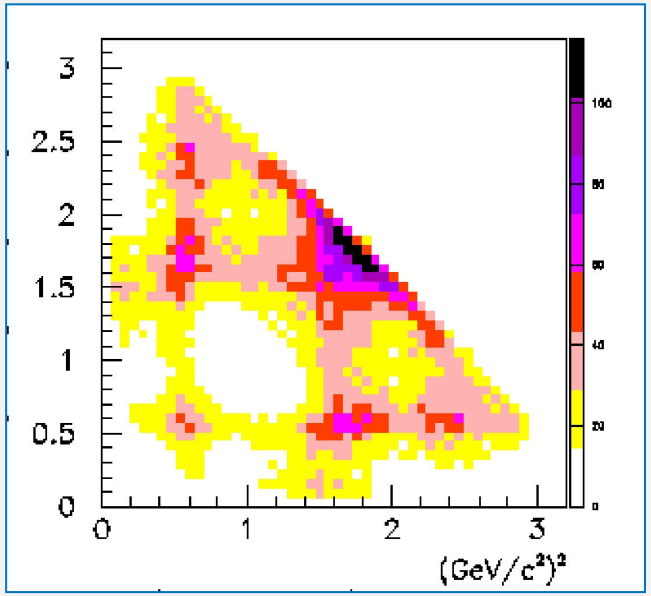

PLB 471(1999), 263

# Meson spectroscopy in PRODUCTION

- High statistics study of **exclusive reactions** in many pions final states
  - Background level: < 5%

- Annihilation in 3 charged pions
  - **35118** events in the Dalitz plot
  - Signatures for $f_0(1500)$, $f_2(1565)$, and minor stuff

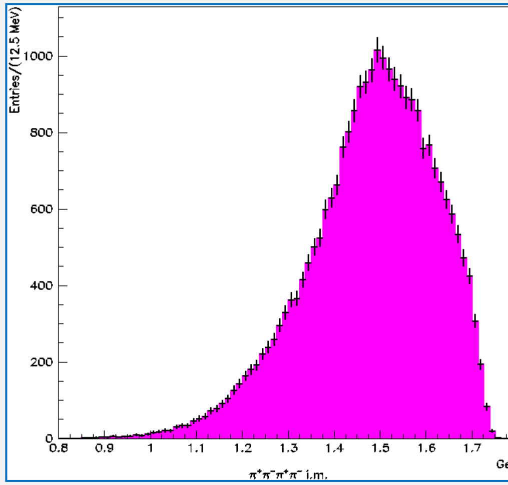
- Annihilation in 5 charged pions
  - **26271** events selected
  - Signatures for $f_0(1500)$, $f_0(1300)$, $\rho(1450)$, …
  - High combinatorial background




$\bar{n}p \rightarrow \pi^+\pi^+\pi^-$

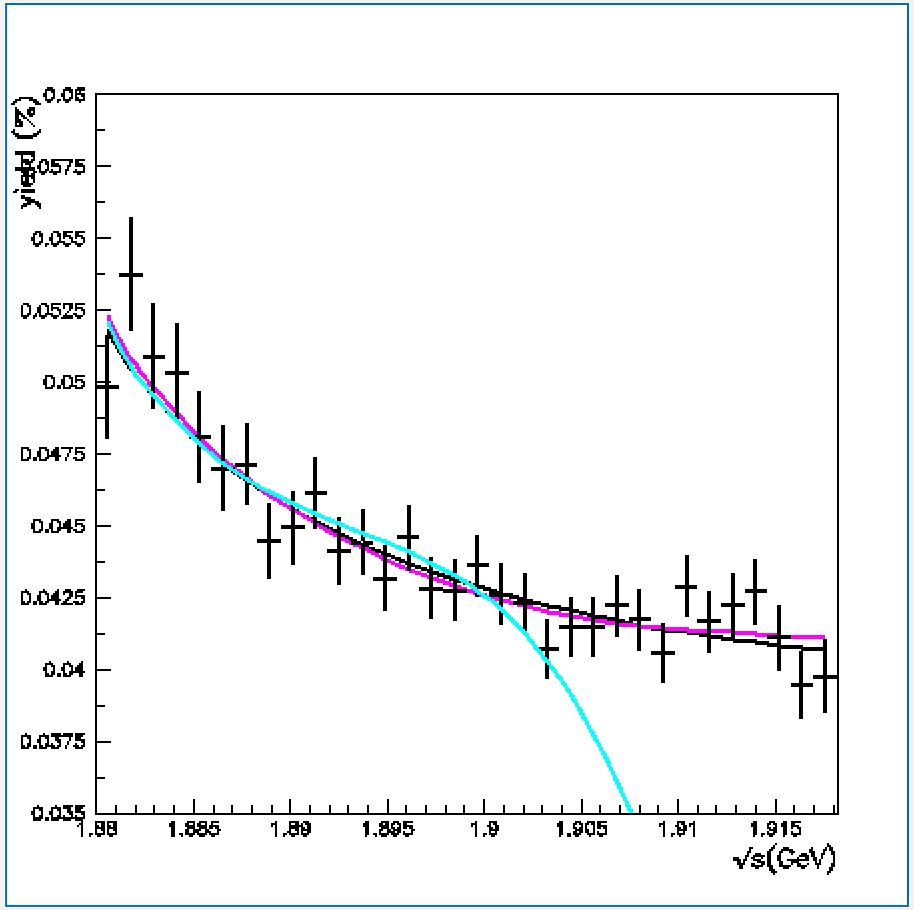
PR D57(1998),55

$\bar{n}p \rightarrow \pi^+\pi^+\pi^+\pi^-\pi^-$



# Meson spectroscopy in FORMATION

- *On the hunt of baryonium…*
- Narrow state observed by E687 in $6\pi$ diffractive photoproduction
  - m = 1.911 GeV, $\Gamma$ = 29 MeV, $J^{PC} = 1^{--}$
- Further observations by DM2 in $e^+e^- \to 6\pi$
- OBELIX: search for a state in formation in the reaction $\bar{n}p \rightarrow 3\pi^+2\pi^+\pi^0$
  - Same mass window
  - Same quantum numbers accessible for annihilation in $S$-wave
  - Several hypotheses for the formation mechanism
  - No signal found
    - Upper limit: $\sigma$ < 0.5 mb



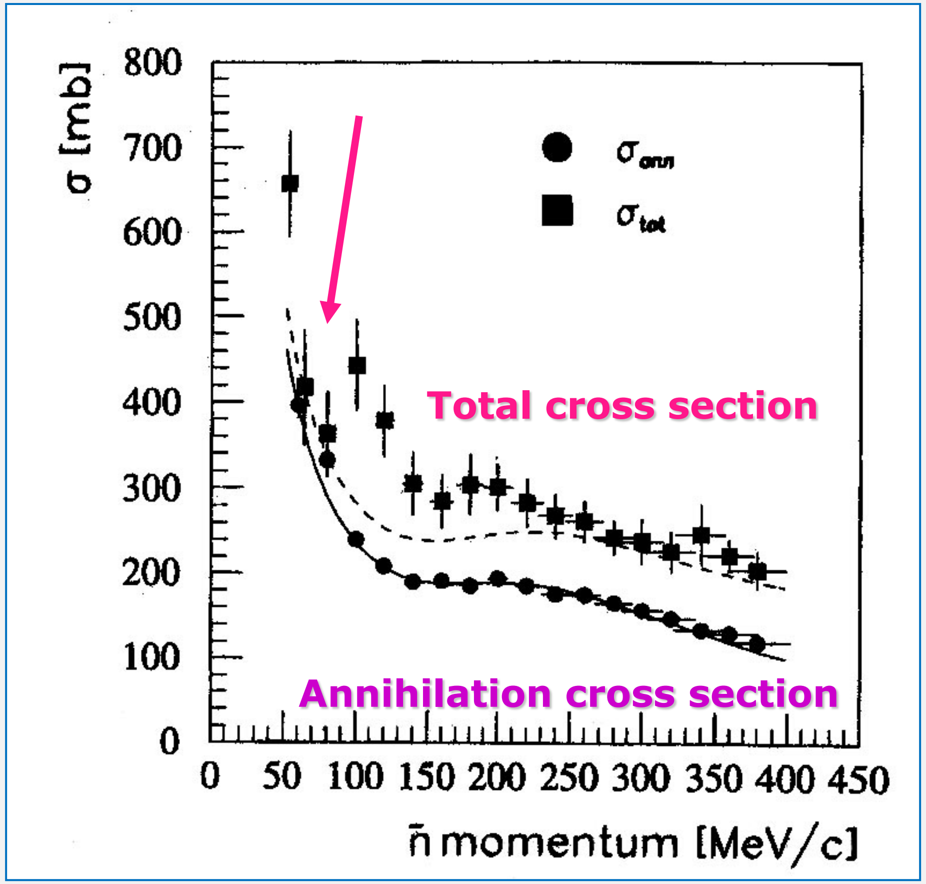

PL B527(2002),39

# *Total* vs *annihilation* cross sections

- Dip-bump effect observed in $\sigma(\bar{n}p)_{TOT}$ in the 65-80 MeV/c momentum range

- Smooth trend of $\sigma(\bar{n}p)_{ann}$

- No set of parameters can describe at the same time both the cross sections
  - Bad fits of $\sigma_T$ with $ER$ expansion
  - Is the irregular behavior of $\sigma_T$ due to the elastic component?



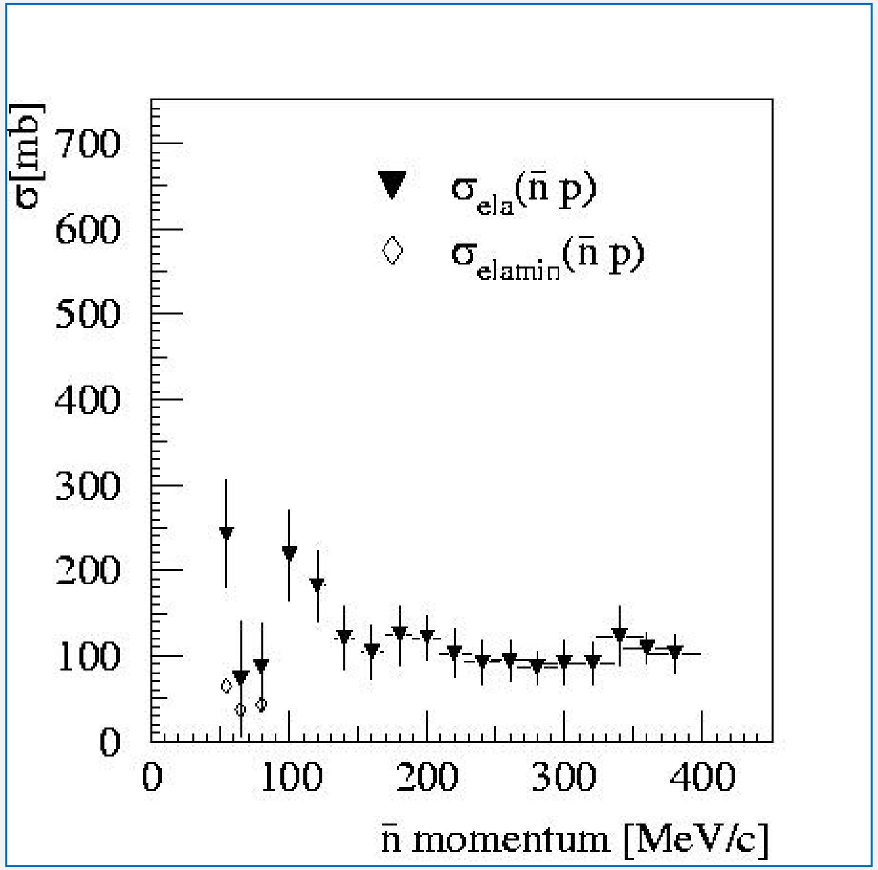
# PUZZLE #2: THE ELASTIC CROSS SECTION

- Definitely there is an anomaly in the elastic channel

- Can it be due to a quasi-nuclear bound state close to threshold, produced in a $(\bar{n}p)$ spin-triplet configuration? (Kudryavtsev, Druzijnin)

- Can it be explained following the pattern of a (sort-of) nuclear Ramsauer-Townsend effect?

- The points at 64.5 and 80 MeV/c are close to the lower bound imposed by unitarity on $\bar{S}$-wave



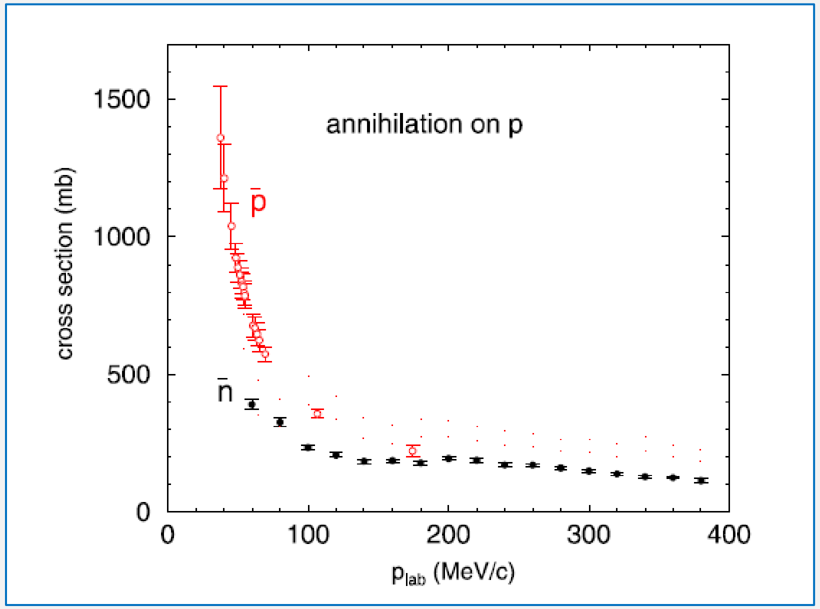

$$\sigma_{el} \geq \frac{k^2}{4\pi}\sigma_T^2$$

# PUZZLE #3: $I=0$ vs $I=1$ INTERACTIONS

- From the ratio between $\sigma_T(\bar{n}p)$ and $\sigma_T(\bar{p}p)$ the contribution to the annihilation of the $I=0$ and $I=1$ sources can be deduced

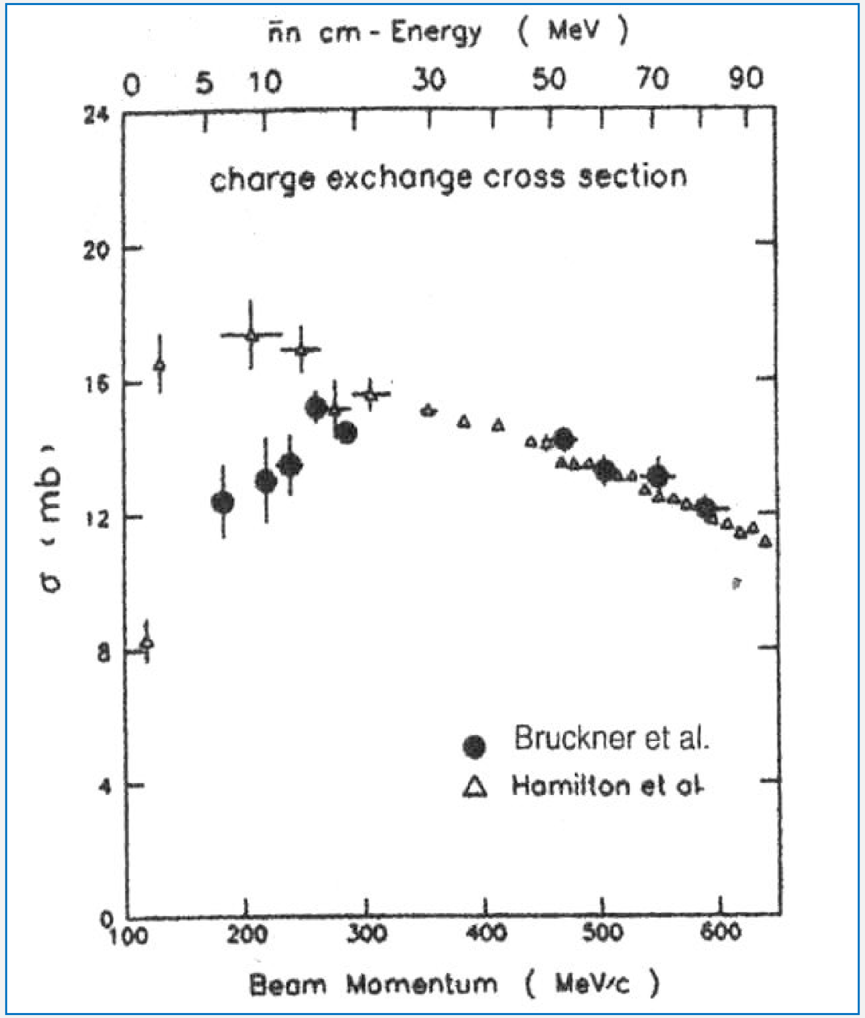
$$R = \frac{\sigma_T(\bar{p}p)}{\sigma_T(\bar{n}p)} = \frac{\sigma_T(I=0) + \sigma_T(I=1)}{2\sigma_T(I=1)}$$

- Experimental facts:
  - Strong dominance of the $I=0$ component at low momentum
    - Due to coherence of the central and tensor terms of the $\bar{N}N$ medium range force (Dover et al.)
      - $\sigma_T(I=0)/\sigma_T(I=1)$:
        - (2.5±0.4) @ 70 MeV/c
        - (1.1±0.1) @ 300 MeV/c
  - Same behavior for the annihilation cross sections: $\sigma_{ann}(\bar{n}p) < \sigma_{ann}(\bar{p}p)$
    - The $I=1$ source is always weaker than $I=0$
      - $\sigma_{ann}(I=0)/\sigma_{ann}(I=1)$: (2.4± 0.4) @ 70 MeV/c
      - *BUT at 700 MeV/c the ratio becomes 1.5!*



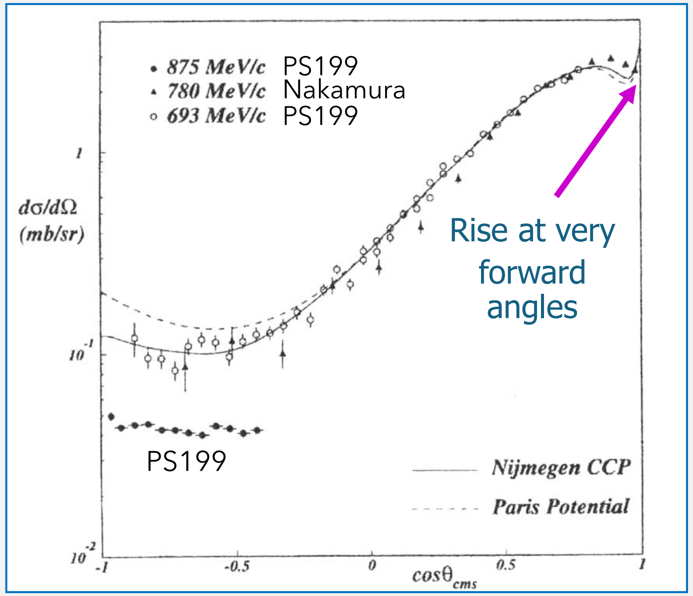
# Open problem: total CEX cross section

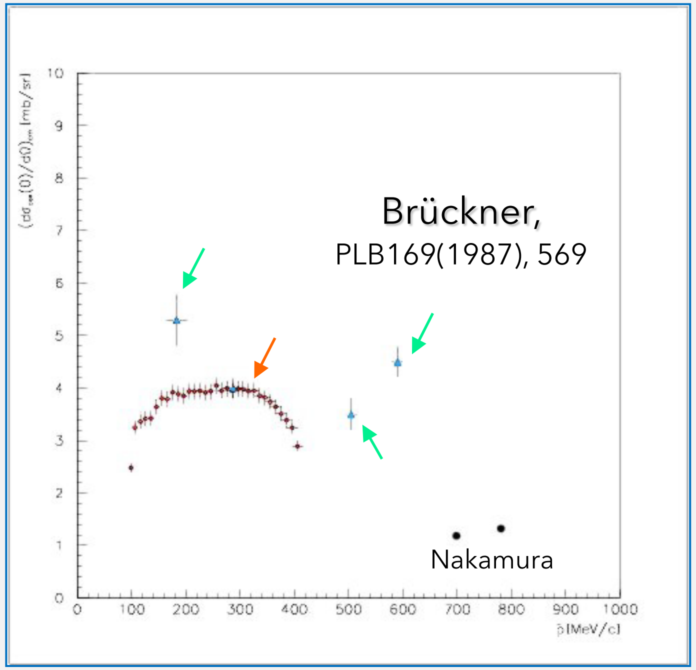
- Few measurements exist at low momenta: wide disagreement!
  - Hamilton et al. (1980):
    - Close to threshold: typical trend for endothermic reactions
  - Brückner et al. (1987):
    - Close to threshold: linear decrease
- More data would be desirable



# PUZZLE #4: DIFFERENTIAL $\sigma_{CEX}$

- Few measurements exist and mostly at high momenta:
  - In the full angular range:
    - PS199 (1995): 693 MeV/c (○), 875 MeV/c (●)
    - Nakamura et al. (1978): 780 MeV/c (▲)
  - At 0°:
    - Brückner et al. (1987): 183, 287, 505 and 590 MeV/c
    - OBELIX: indirect “backward” estimation, 99-400 MeV/c
      - ~ 4 mb/sr
      - Compatible with a standard endothermic reaction, similar to Hamilton’s total cross section
      - Comparison with other data:
        - OK with Bruckner’s at 300 MeV/c total disagreement at 183 MeV/c and other momenta
        - Nakamura? Too large momentum…



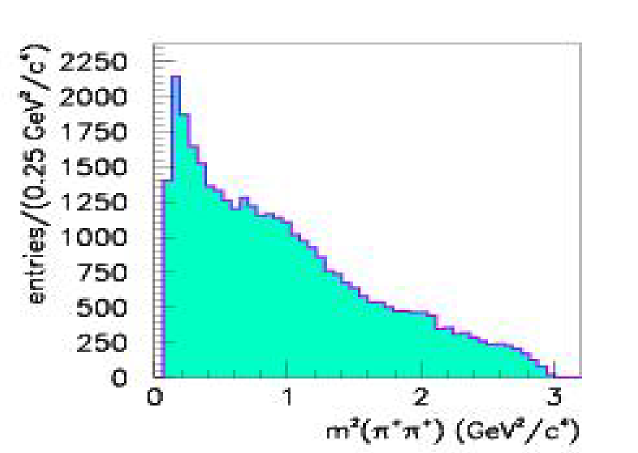



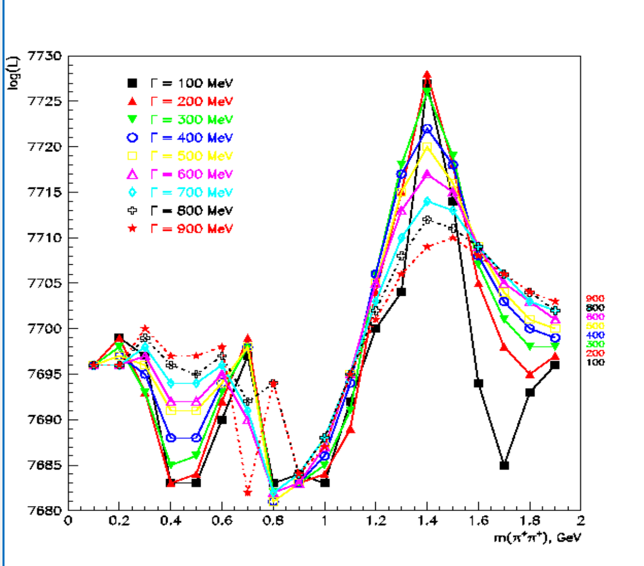
# Open problems in meson spectroscopy: $I=2$ states?

- No hints were found for a $I=2$ state decaying into $\rho\rho$
  - Only one observation in PDG in $e^+e^- \rightarrow \rho^0\rho^0$, without a similar signal in $e^+e^- \rightarrow \rho^+\rho^-$
  - Mass ≈1600 MeV, 300 MeV wide
  - $J^{PC} = 2^{++}$
  - Some (unsuccessful) attempts were made to extract this component in the analysis of the $5\pi$ channel
    - Too low statistics (and too difficult to disentangle)

- Some statistical indications for a $I=2$ state in $\pi^+\pi^+$ at m=1420, $\Gamma$=160 MeV, with $J^{PC} = 0^{++}$
  - Very small branching fraction: $4\times10^{-3}$
  - Needs confirmation

OBELIX, PL B495 (200), 284

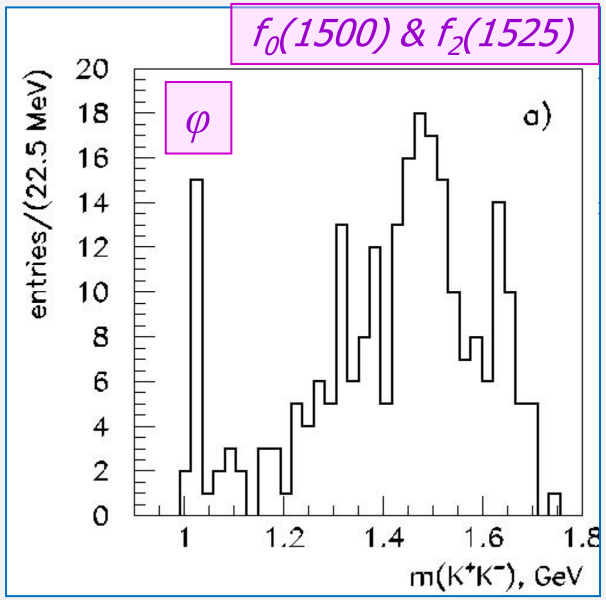


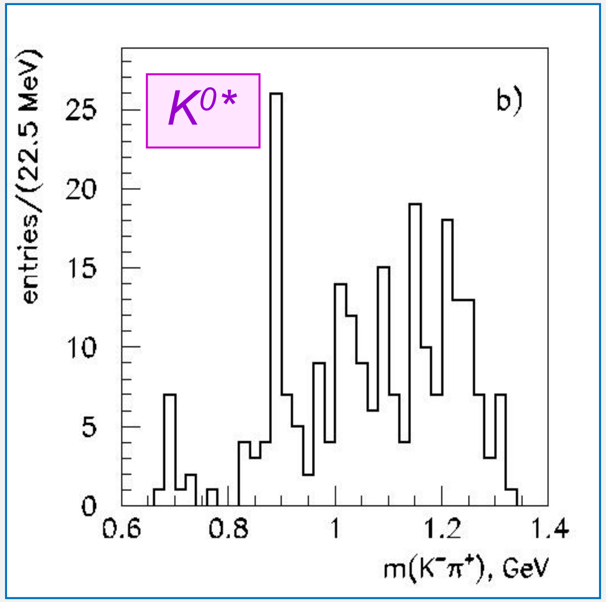



# Open issues in meson spectroscopy with kaons: $\bar{n}p \rightarrow K^+K^-\pi^+$

- Related to the production of strangeonium states (many still needing confirmation), glueballs decay into strange quarks, …
  - Hidden strangeness resonances decaying in $K^+K^-$
    - $J^{PC} = (even)^{++}$ or $(odd)^{--}$
      - $f_0, f_2, a_0, \varphi$ and radial excitations
  - open strangeness radial excitations: $K^*, K_0, K_1, K_2, …$

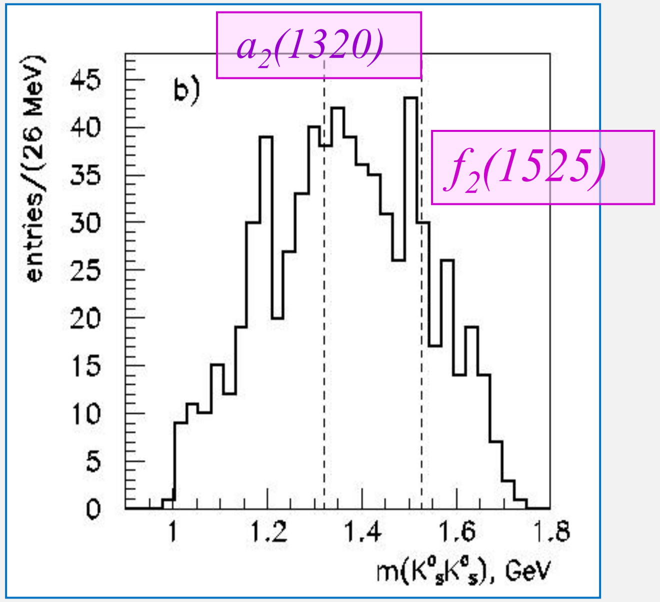
- OBELIX: exclusive final channel
  - **241** events fully identified by means of $dE/dx$ and $\beta$ + $4C$ kinematic fit
  - Very clean sample but too small!

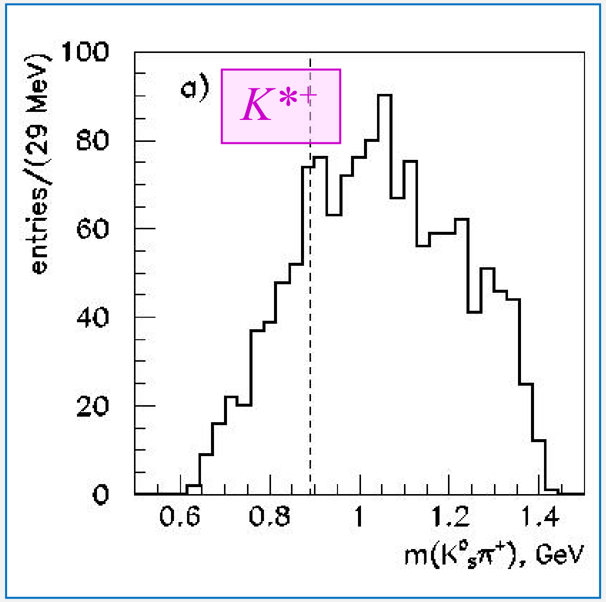


# Open issues in meson spectroscopy with kaons: $\bar{n}p \rightarrow K^o{}_s K^o{}_s \pi^+$

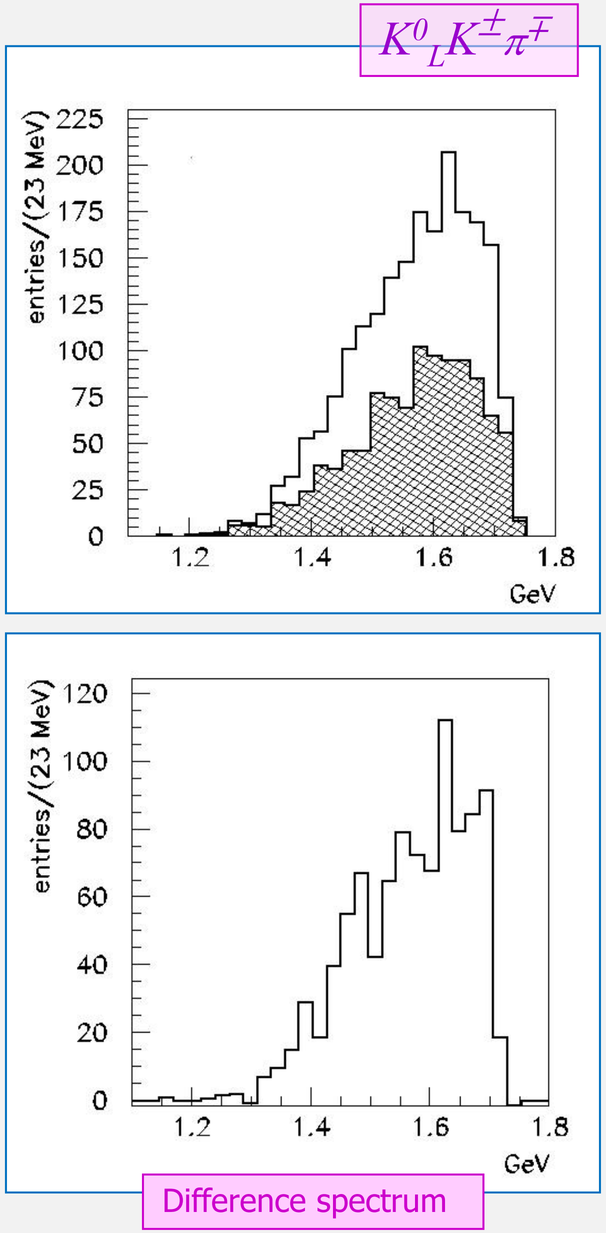
- $K^0{}_S K^0{}_S$: $J^{PC} = (even)^{++}$
- Possible intermediate resonant states:
  - No $\varphi$ nor $1^{--}$ strangeonium states
  - $f_0$, $f_2$ produced only from initial states with $G = -1$ ($^1S_0$, $^3P_1$, $^3P_2$)
  - $a$'s produced only from initial states with $G = +1$
- OBELIX: mass selection for $K_s + 6C$ kinematic fit
  - **687** events selected
  - $K^{*+}$ peak needs better identification (vertexing, …)



# Open issues in meson spectroscopy with kaons: $\bar{n}p \to K^0{}_L K^{\pm}\pi^{\mp}\pi^+$

- Related to the long-sought $E/\iota$–puzzle
  - Search for intermediate states decaying in $\bar{K}K\pi$
  - State-of-art:
    - Two pseudoscalar states
      - $\eta(1400\text{-}1420) \to a_0\pi,\ \eta\pi\pi$
      - $\eta(1500) \to K\bar{K}\pi$
    - One axial state
      - $f_1(1420) \to K\bar{K}\pi$
  - Channel produced only by $P$-waves for $G$-parity conservation
    - Axial states production potentially favored
    - $K^0K^{\pm}$ systems have $I^G = 1^+$: $a_0$, $a_2$, $\rho$



# “Educated” wishlist

- To solve a view puzzles left open rather simple experimental set-ups would be needed
  - Differential elastic and total cross sections
    - Tagged $\bar{n}$ beam with a production (CEX) target and a scatterer
    - Compact neutron detector (fibre-based?)
    - Small experimental set-up (less than 1 m long)
  - Systematic measurement of $\sigma_{ann}(\bar{n}p)$ and $\sigma_{ann}(\bar{p}p)$ from 700 down to 50 MeV/c
    - Non-magnetic set-up
    - Good angular coverage
    - Production target for antineutrons
    - Reaction target(s): same vessel for $LH_2$ (down to 200 MeV/c), $GH_2$ at lower momenta
  - Meson spectroscopy
    - More intense $\bar{n}$ beam required (at least a factor of 10)
    - Powerful and full coverage magnetic detector for all the annihilation products

# Conclusions

- A good amount of physics results was obtained for the first time using antineutrons as probes, a few puzzles remained open
  - Trend of elastic cross sections close to threshold
  - $I=0$ vs $I=1$ annihilation sources
  - Trend of $\sigma_{CEX}$ at 0 degrees close to threshold
  - Comparison of annihilation cross sections of low momentum $\bar{n}$'s vs $\bar{p}$'s on nuclear targets
  - Meson spectroscopy with kaons in the final state

- Wish: possibility to study some of these items at forthcoming new facility!

# Varenna 2004

## International Enrico Fermi School of Physics

In memory of
Tullio and Helmut