Hadron Physics induced with Hadron Beams
George Washington University
July 23 - 25, 2001, Washington DC

Physics with $\bar{n}$'s: first evidence of an $\overline{N}N$ resonant state

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Outlook

- $\overline{N}N$ system
- $\overline{n}p$ vs. $\overline{p}p$ interactions
- $\overline{n}p$ vs. $\overline{p}d$ interactions
- $\overline{n}$'s beams
- the OBELIX $\overline{n}$'s "factory"
- $\overline{n}$'s physics
  - meson spectroscopy
  - ☛ $\overline{n}p$ cross section
  - $\overline{n}$-nucleus cross section

$\overline{N}N$ interaction: *why?*

historical

- 60's: description of ordinary meson spectrum (π, ρ, ...) unsuccessful

QCD

- 80's - 90's: search for exotic configurations
  - multiquark ($q^2\overline{q}^2$)
  - glueball (gg or ggg)
  - hybrids ($q\overline{q}g$)
  - other non $q\overline{q}$ mesons

$\overline{N}N$ interaction: why?

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nuclear physics

☛ understanding of nuclear forces:

- clearing up the rôle of the G-parity rule ($\overline{p}p \leftrightarrow pp$ and $\overline{n}p \leftrightarrow np$)
- search for $\overline{N}N$ bound states or resonances ($\overline{N}N$ potential deeper than the NN one)
- study of the isospin dependence of the $\overline{N}N$ interaction (comparison of $\overline{p}p$ with $\overline{p}n$ or $\overline{n}p$ data)
- determination of the annihilation strength dependence on some channels (fit to the scattering and annihilation data)

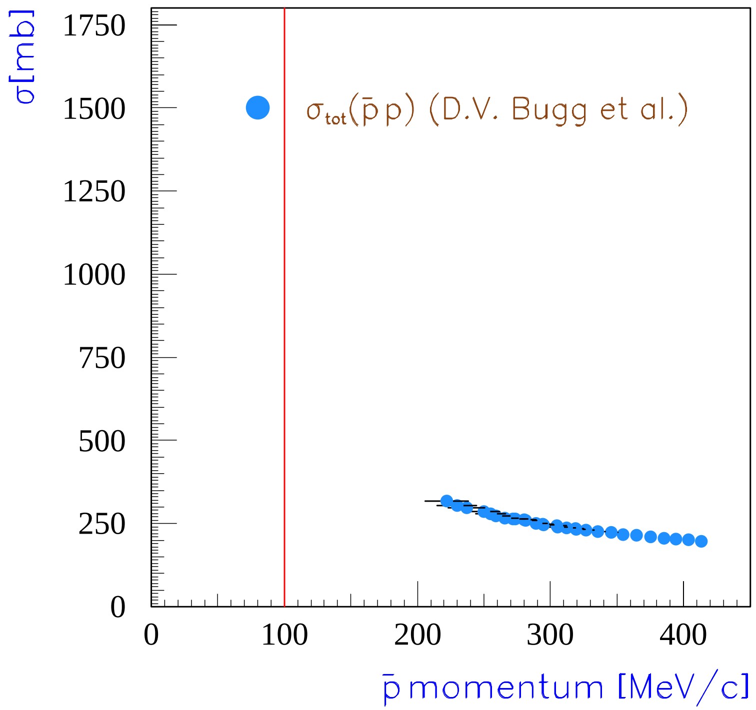
$\bar{n}$'s interaction: why?

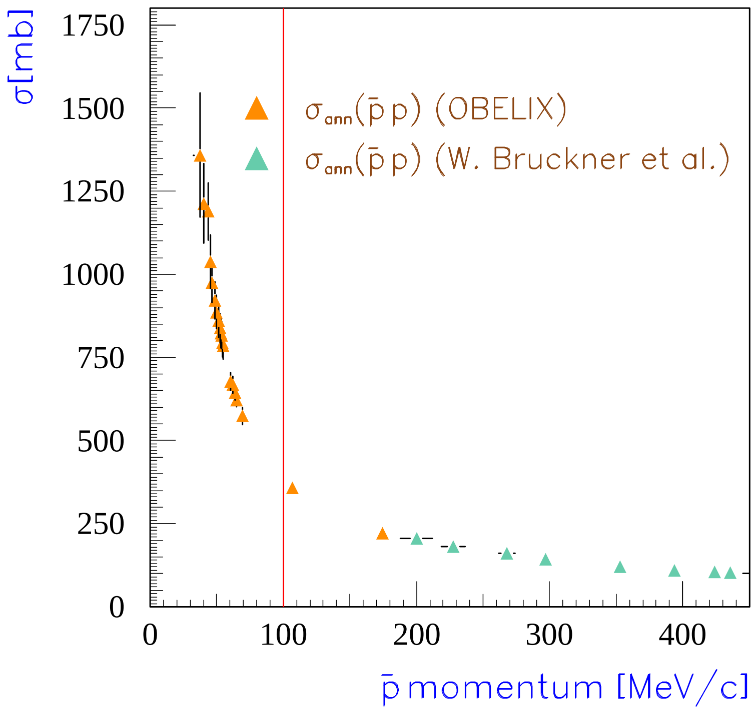
- ▲ scarce data on low energy $\bar{n}p$ interaction
- ▲ complementary/alternative to $\bar{p}p$ interaction

but

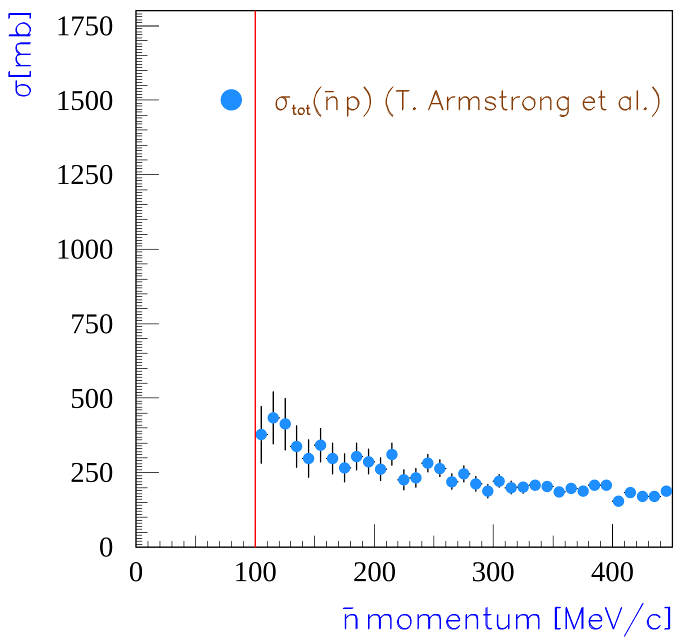
- ▼ technically difficult
- ▼ low $\bar{n}$ production rate

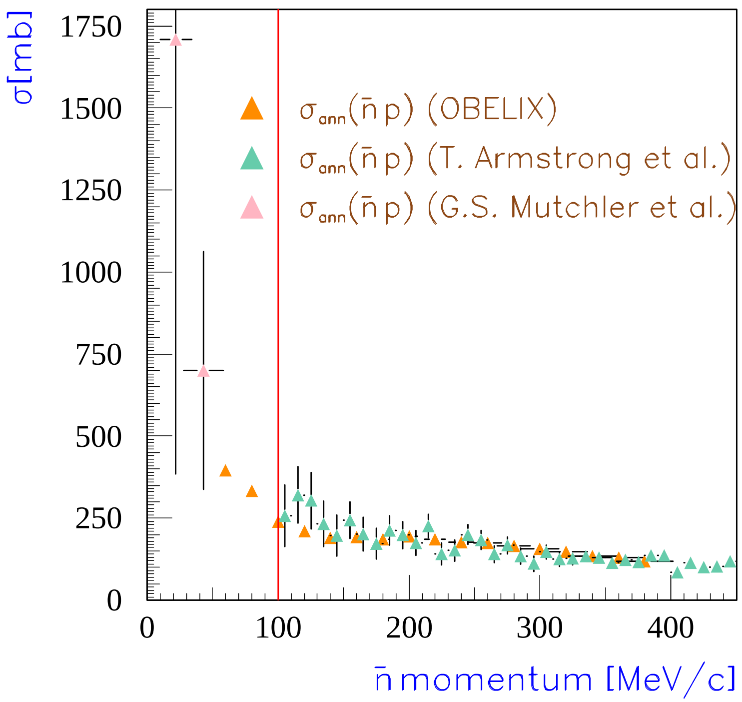
The $\overline{p}p$ system





The $\bar{n}p$ system





$\bar{n}p$ vs. $\bar{p}p$ (advantages)

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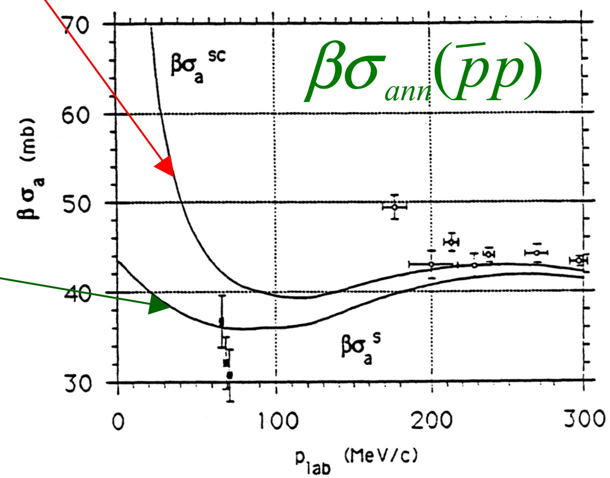
- pure I = 1 state:
  - reduced number of initial states involved
- the percentages of s- and p-waves can be selected by choosing the $\bar{n}$ momentum
- absence of Coulomb interaction:
  - no distortion of the σ trend in the low momentum region (σ ∝ 1/v)

- mixture of the I = 0 and I = 1 amplitudes
- σ ∝ 1/v²



$\bar{n}p$ vs. $\bar{p}p$ (advantages)

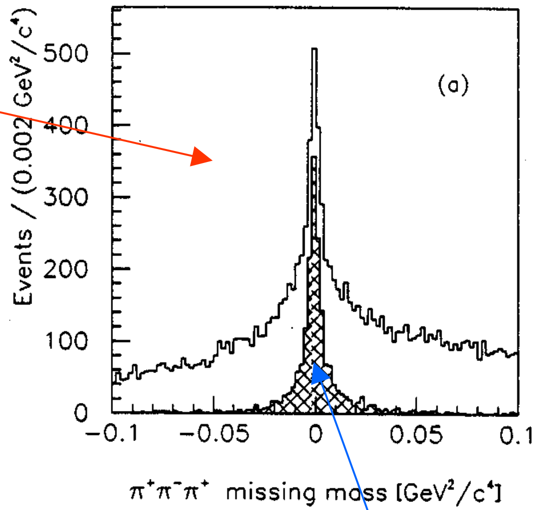
- no energy loss in the target:
  - possibility of precisely reconstructing the energy at which the interaction occurs
  - only one target
  - the target thickness can be increased to obtain higher counting rates
- target thickness is a "function" of $\bar{n}$ momentum

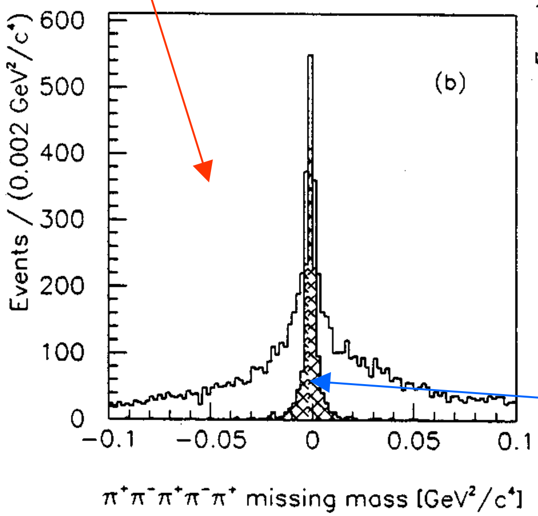
$\bar{n}p$ vs. $\bar{p}p$ (advantages)

- at least one prong in the final state:
  - good opportunity for trigger
  - easier detection
  - selection of exclusive final states

    (e.g. $\bar{n}p \rightarrow \pi^+\pi^+\pi^-$
    $\bar{n}p \rightarrow \pi^+\pi^+\pi^+\pi^-\pi^-$)

- all neutral annihilations (see Crystal Barrel)

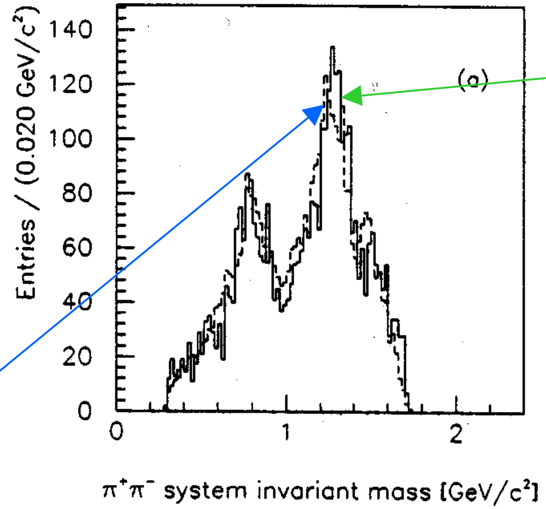




after a 4C kinematical fit

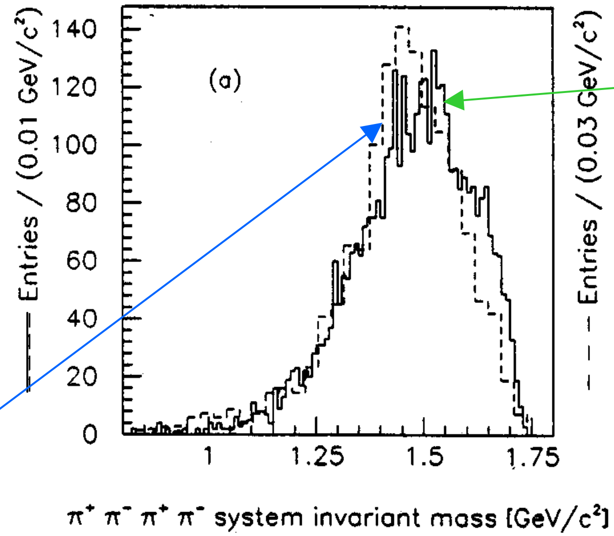
$\bar{n}p$ vs. $\bar{p}d$ (advantages)

- better energy and momentum resolution:
  - no kinematical corrections due to the presence of the spectator *proton*



$\bar{n}p \rightarrow 2\pi^+\pi^-$

$\bar{p}d \rightarrow 2\pi^-\pi^+(p)$



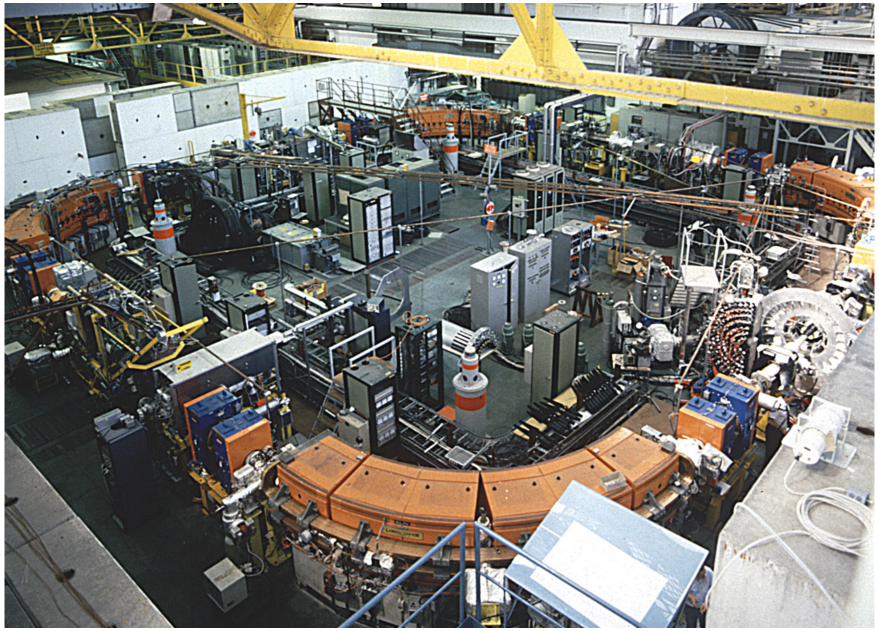
$\bar{n}p \rightarrow 3\pi^+2\pi^-$

$\bar{p}d \rightarrow 3\pi^-2\pi^+(p)$

$\bar{n}p$ vs. $\bar{p}p$ (drawbacks)

- low intensity:
  - $30 \div 50 \times 10^{-6}$ $\bar{n}/\bar{p}$
- poor energy definition
- in flight annihilations:
  - beam divergence
  - annihilation vertex delocalization

- e.g. LEAR $\bar{p}$ beam:
  - $\Delta p/p \sim 10^{-4}$
  - $I \sim 10^{7}$ $\bar{p}/s$

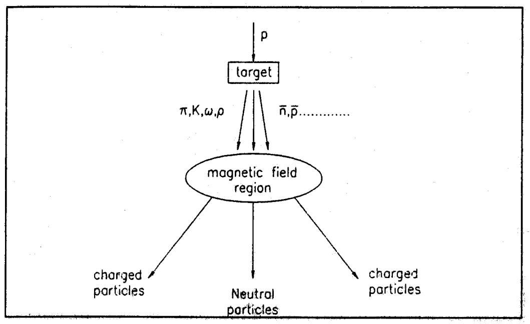


1983 - 1996

$\bar{n}$'s production

beam dumping

- AGS/BNL (1981):
  - $10 < p_p < 30$ GeV/c
  - I ~ 10^{-8} $\bar{n}/p$ GeV/c sr
  - $0.3 < p_{\bar{n}} < 1$ GeV/c
  - no physics output:
    - poor beam quality
    - n high contamination level

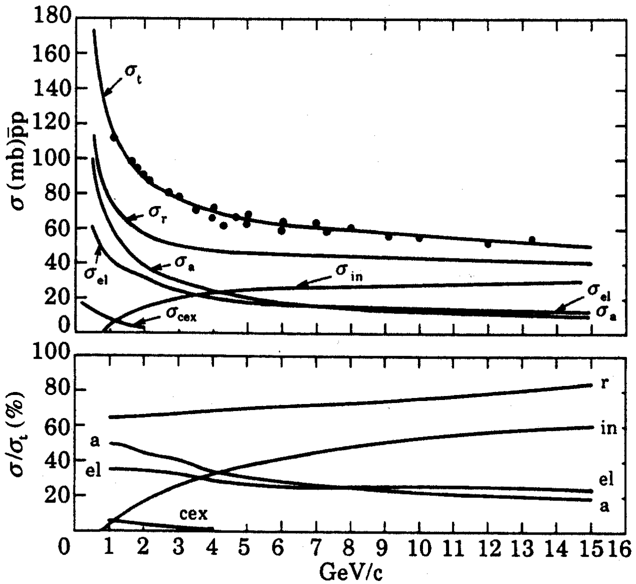


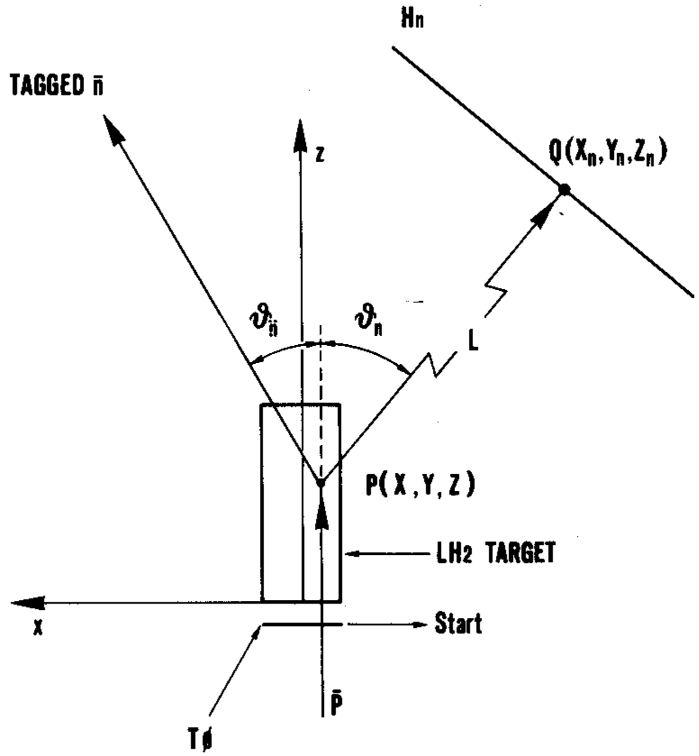
first $\bar{n}$ tagged beam

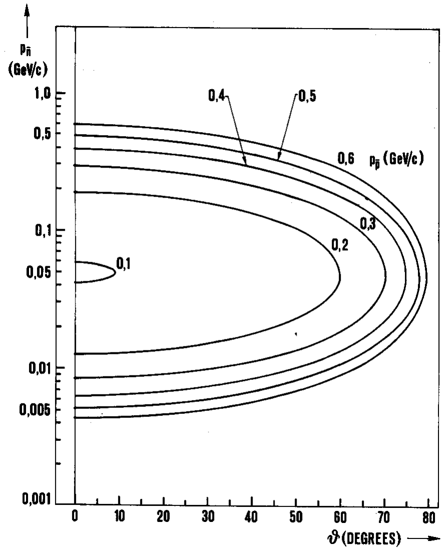
$\bar{p}p \rightarrow \bar{n}n$ charge exchange

- AGS/BNL (1987):
  - target: CH_2
  - 2% of $\bar{p} \rightarrow \bar{n}$
  - $100 < p_{\bar{n}} < 500$ MeV/c
  - physics output:
    - $\sigma_{tot}(\bar{n}p)$ and $\sigma_{ann}(\bar{n}p)$
- LEAR/CERN (1988):
  - target: LH_2 (2-body kinematics!)
  - I ~ 10^{-4} $\bar{n}/\bar{p}$
  - $50 < p_{\bar{n}} < 300$ MeV/c
  - physics output:
    - $\sigma_{tot}(\bar{n}p)$ and $\sigma_{ann}(\bar{n}Fe)$

The $\bar{n}$ tagging technique



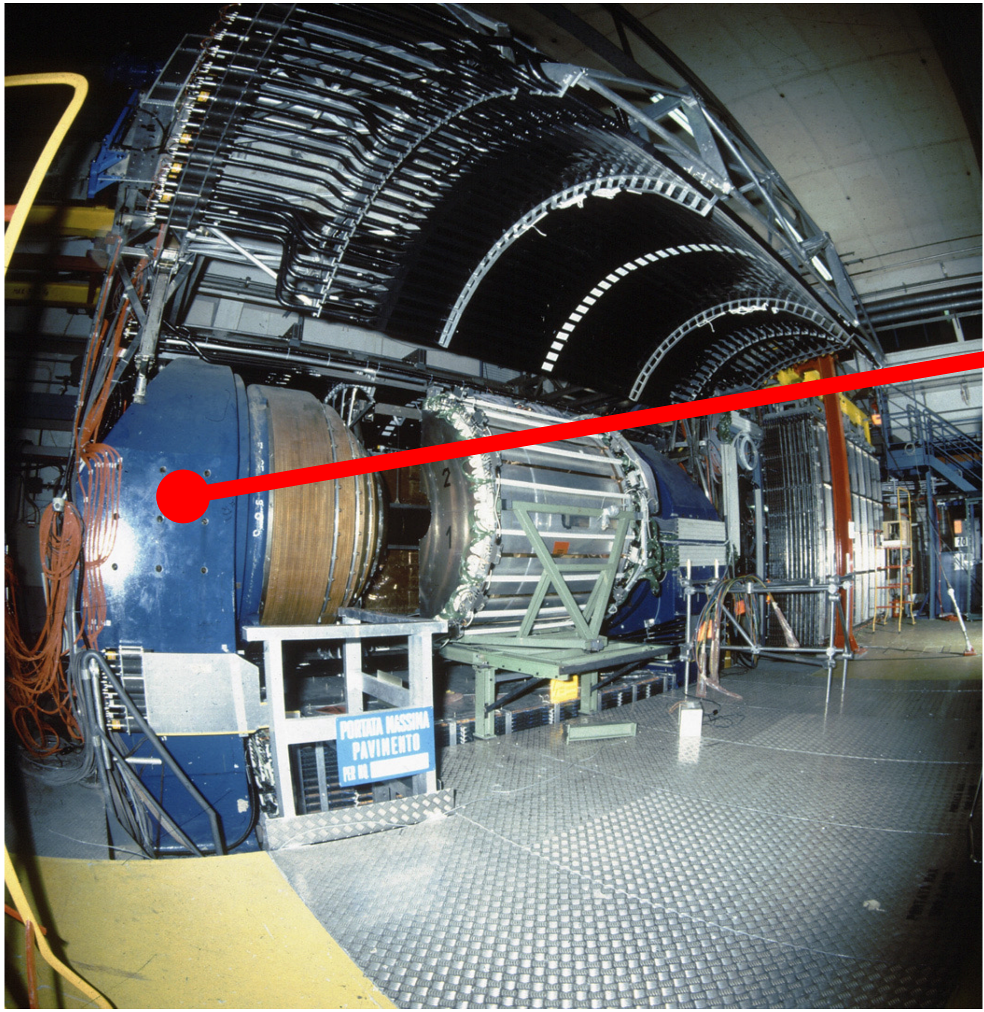




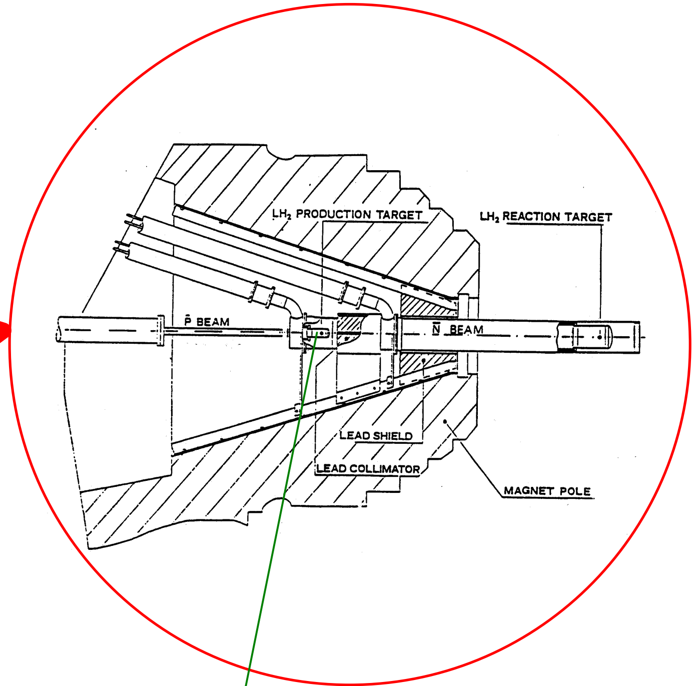
$$\begin{cases} t_{meas} = t_0 + t_{\bar{p}}(z) + t_n(Q-P, E_n) \\ \vartheta_n = \vartheta_n(P, Q) \end{cases}$$

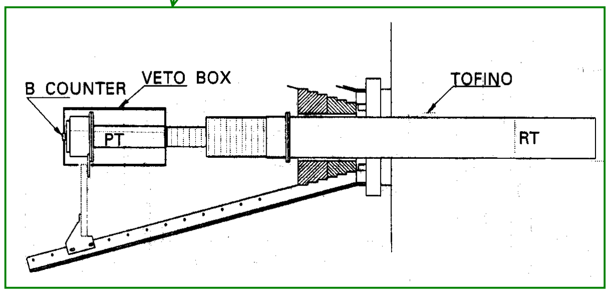
$E_n = E_n(\vartheta_n)$
$\vartheta_n = \vartheta_n(z)$ ⇒ $E_n = E_n(z)$ ⇒ $t_{meas} = t_{meas}(z)$

The OBELIX $\bar{n}$ "factory"

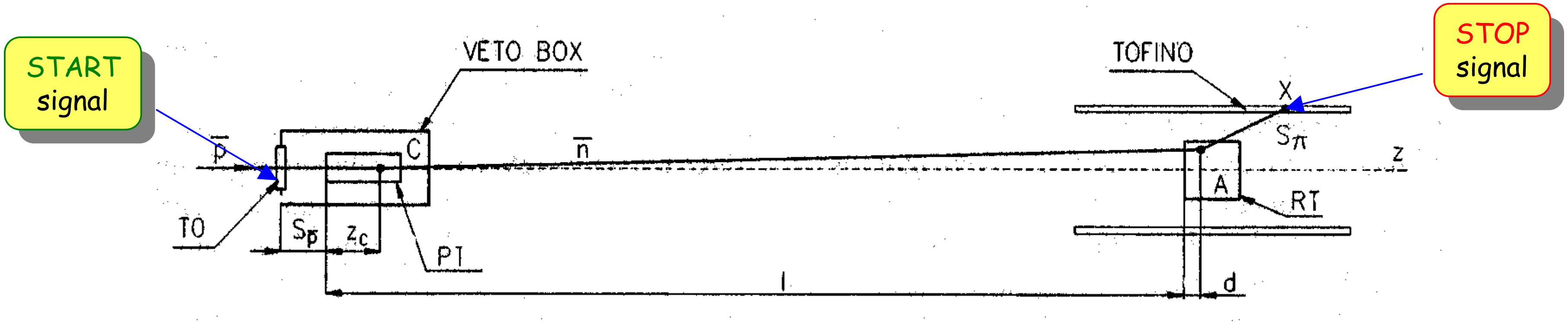


1990 - 1996





$\bar{n}$'s momentum evaluation



algorithm based on t.o.f. measurement:

fixed

measured

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

known

measured

iterative procedure
to determine

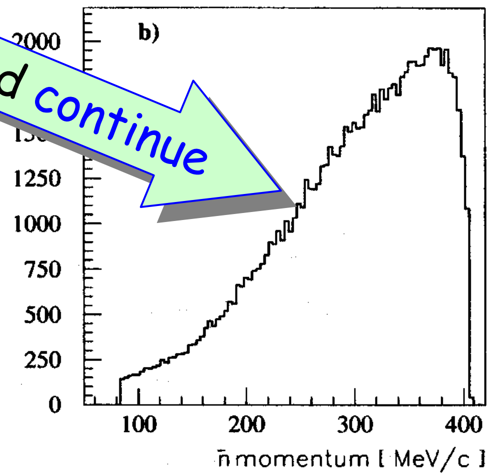
$$z_c = \int_{p_{\bar{p}}(0)}^{p_{\bar{p}}} \frac{\beta dp}{dE/dz}$$

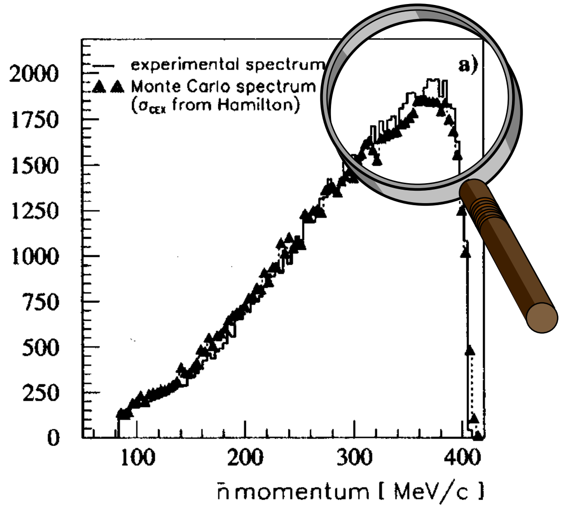
by guessing $p_{\bar{p}}$

$\bar{n}$'s momentum spectrum

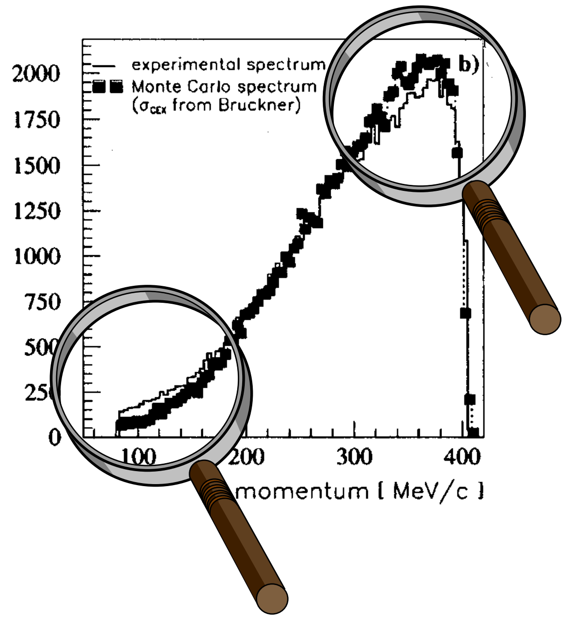
capability of reconstructing
the momentum of each interacting $\bar{n}$

wide and continue





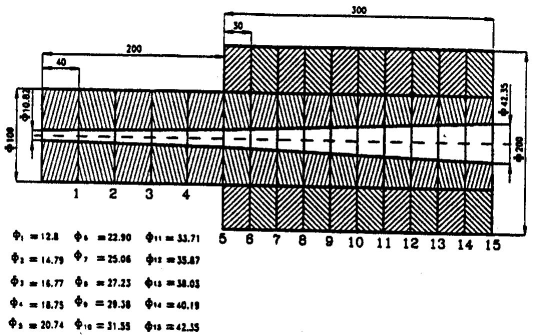
systematic errors greatly reduced

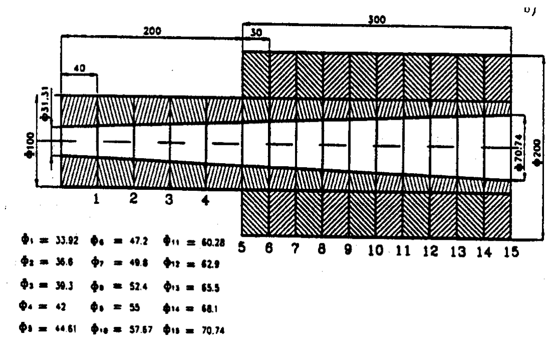


data corresponding to
different $\bar{n}$ momenta are collected:

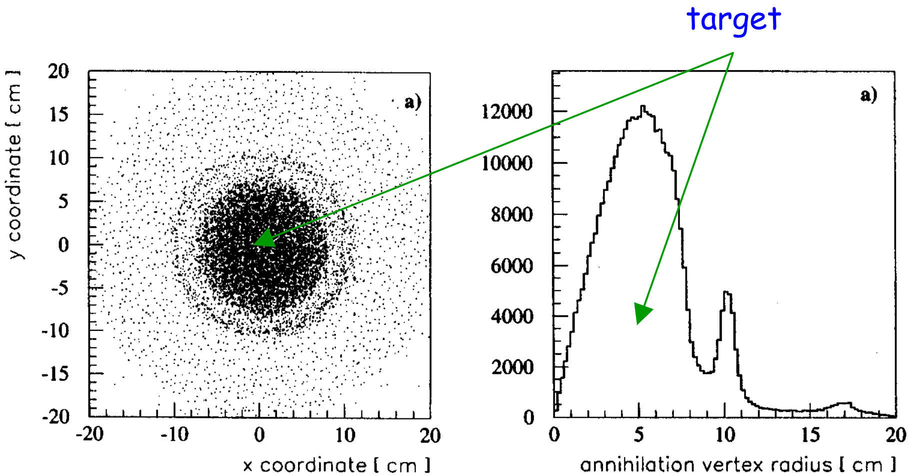
- at the same time
- with the same experimental and beam setup

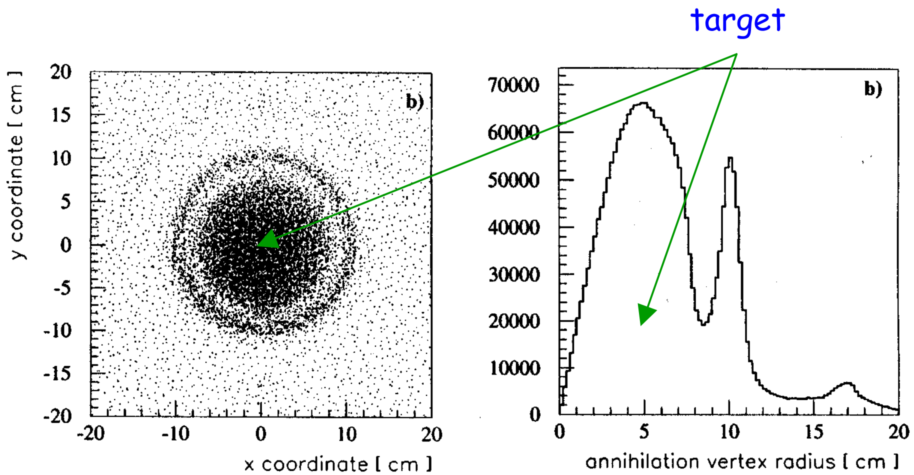
$\bar{n}$'s beam spot on the target





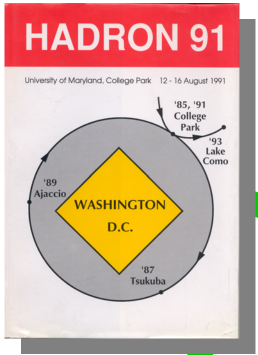
flux*: $(13 \pm 0.5) \times 10^{-6}\ \bar{n}/\bar{p}$ $(56 \pm 1.5) \times 10^{-6}\ \bar{n}/\bar{p}$

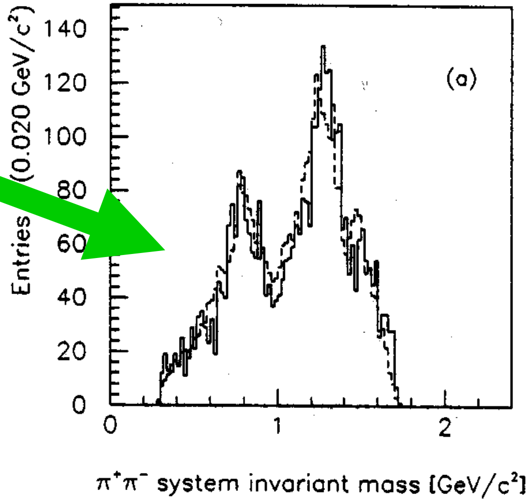


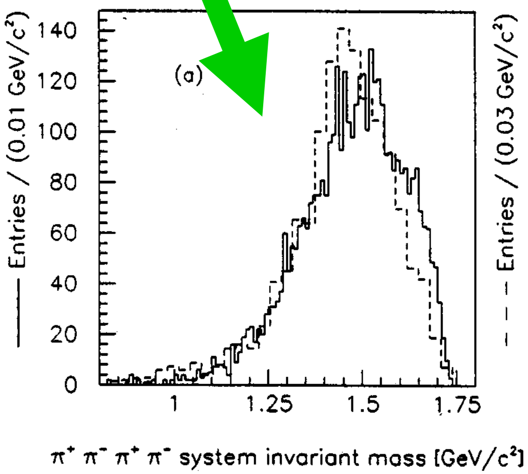


*untagged $\bar{n}$ beam ⇒ no direct flux measurement!!!

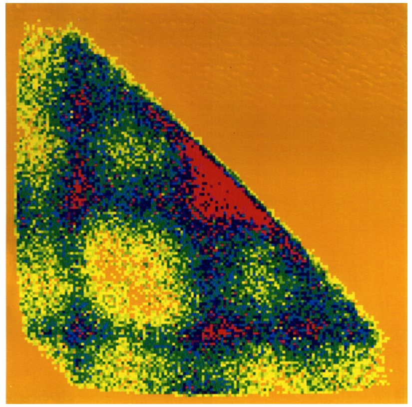
The OBELIX $\bar{n}$ physics output





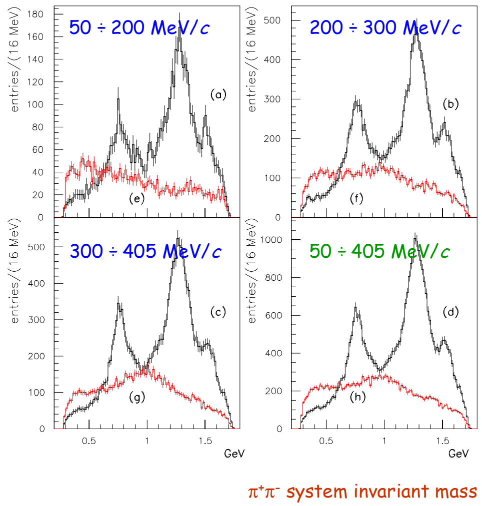


meson spectroscopy



~ 35000 events

$\bar{n}p \rightarrow 2\pi^+\pi^-$



contribution
to the discussion
about the Ax/f_0 case

(1522 ± 25) MeV/c^2
(108 ± 33) MeV/c^2

(1575 ± 18) MeV/c^2
(119 ± 24) MeV/c^2

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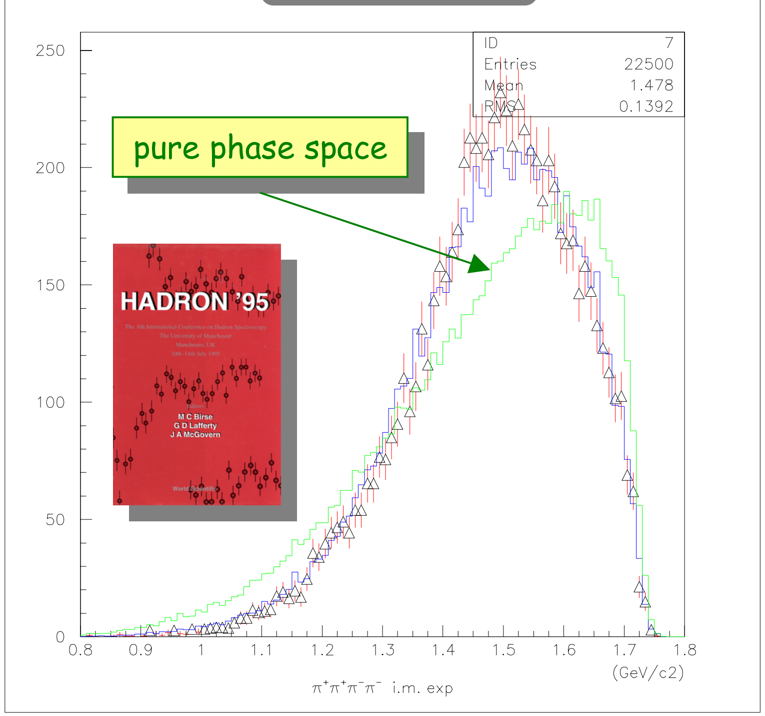
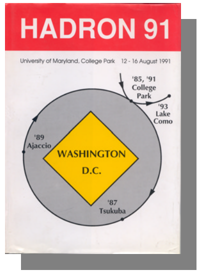
The OBELIX $\bar{n}$ physics output

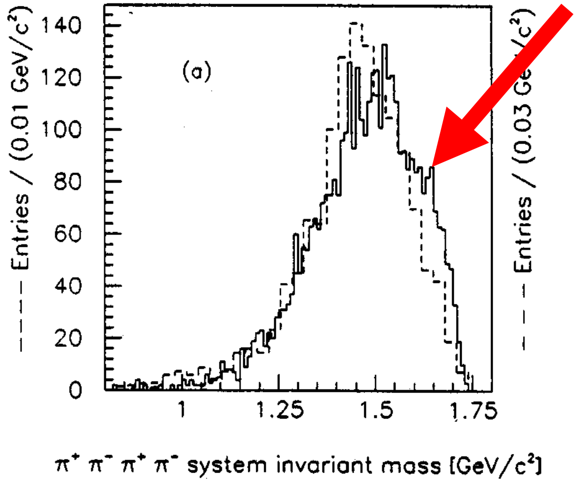
meson spectroscopy

$\bar{n}p \rightarrow 3\pi^+2\pi^-$

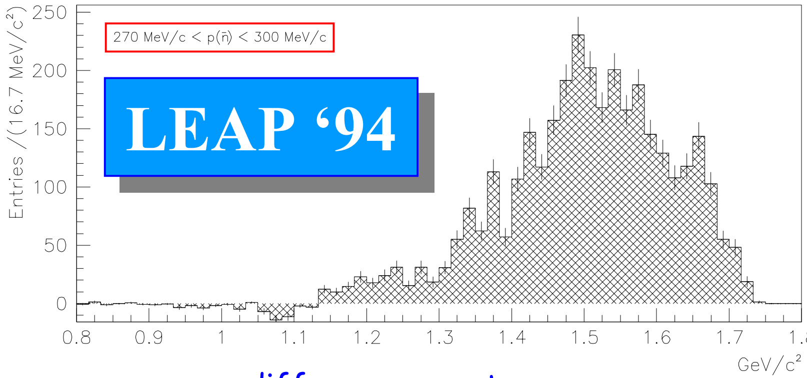


(1359 ± 17) MeV/c^2
(425 ± 30) MeV/c^2





(1664 ± 1) MeV/c^2
(53 ± 2) MeV/c^2



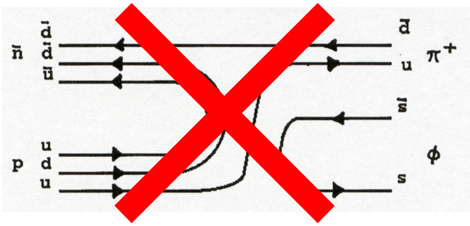
difference spectrum

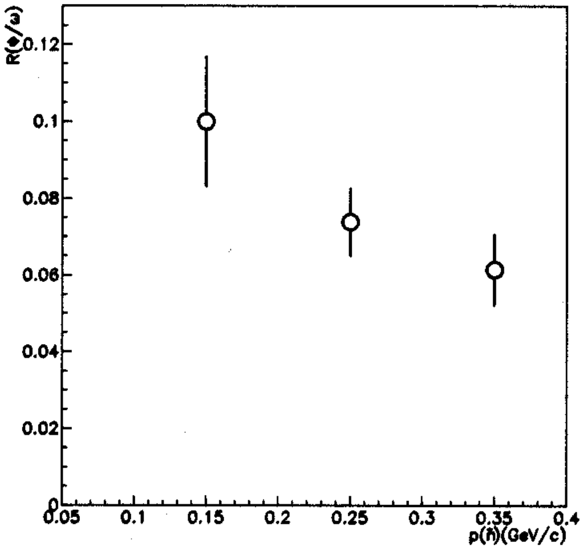
The OBELIX $\bar{n}$ physics output

annihilation dynamics

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

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

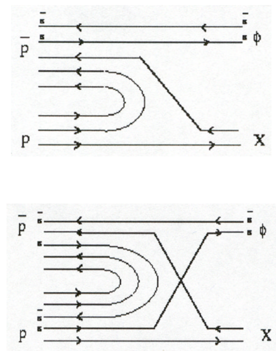




strong deviation (of a factor ~ 30!) from OZI rule

$R_s = 0.112 \pm 0.007$

nucleon $s\bar{s}$ content?



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The OBELIX $\bar{n}$ physics output

nuclear physics

- $\bar{n}p$ annihilation cross section
- $\bar{n}p$ total cross section
  - anomaly in the elastic $\bar{n}p$ cross section
- $\bar{n}$-nucleus annihilation cross section

$\bar{n}$-nucleus annihilation cross section

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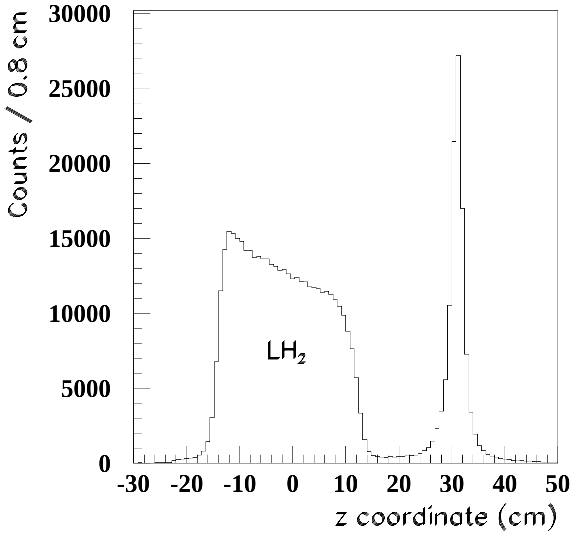


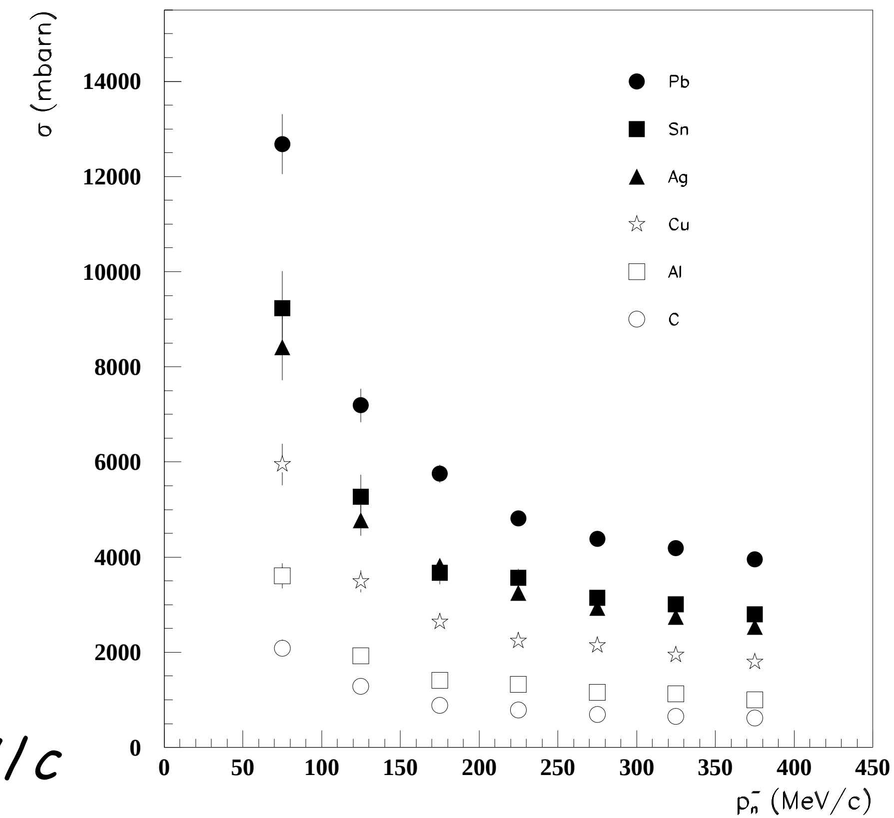
$$\sigma_{ann}(p_{\bar{n}}, A) = \sigma^0_{ann}(p_{\bar{n}}) \times A^{\nu}$$

$$\sigma^0_{ann}(p_{\bar{n}}) = a + \frac{b}{p_{\bar{n}}}$$

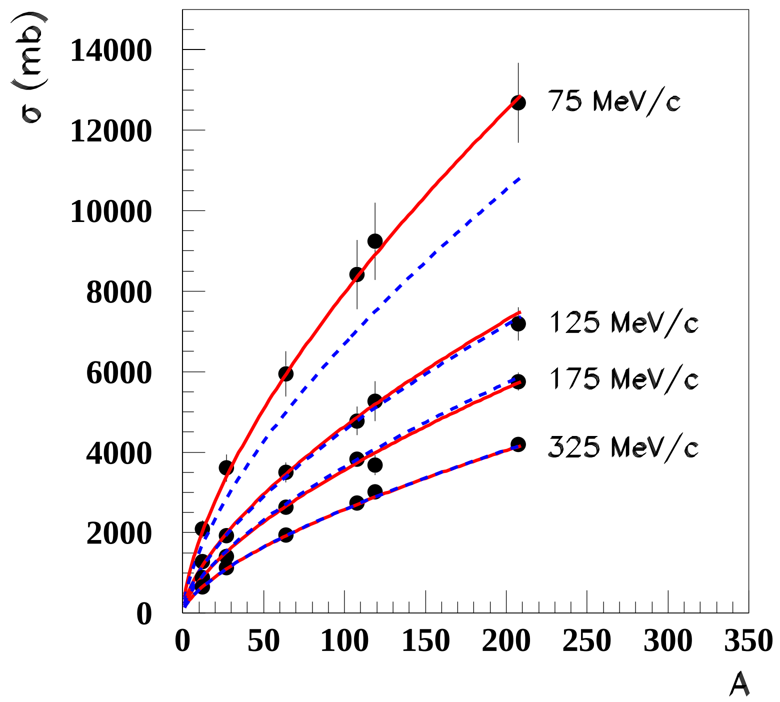
$a = (66.5 \pm 3.0)$ mb

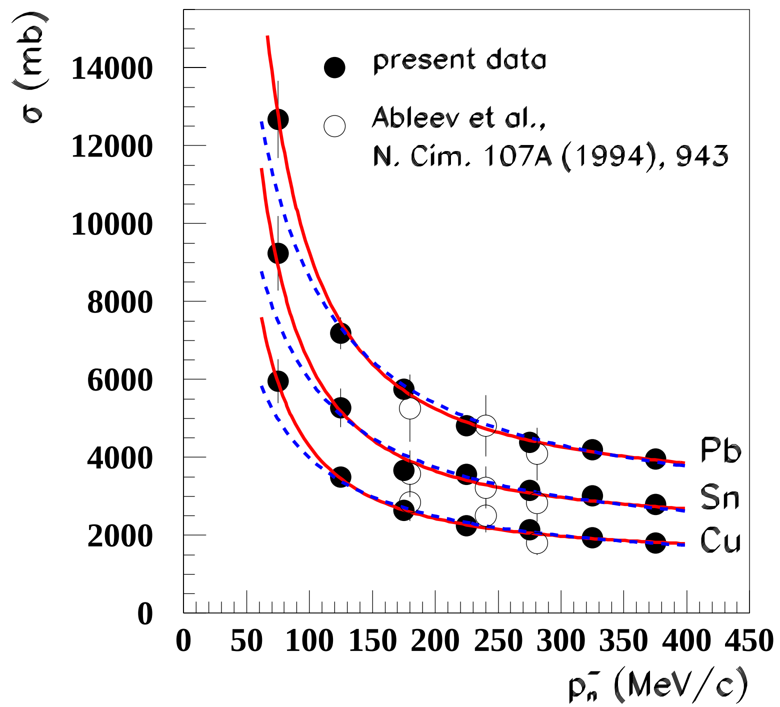
$b = (19.87 \pm 0.86)$ mb $\times$ GeV/c

$\nu = (0.6526 \pm 0.0060)$



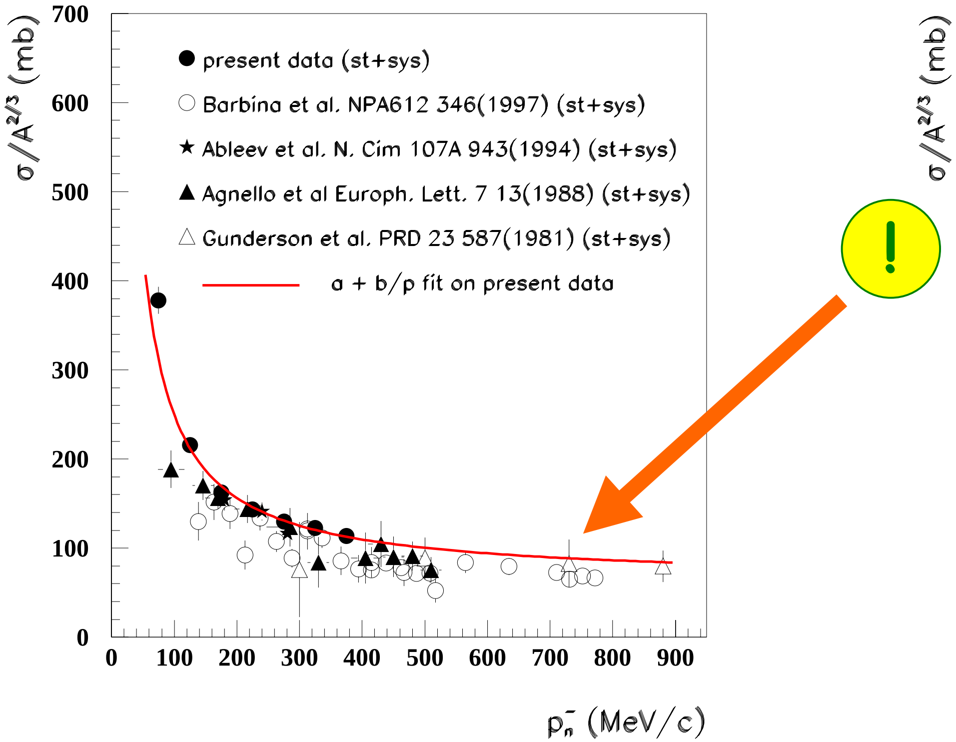
A and p dependencies



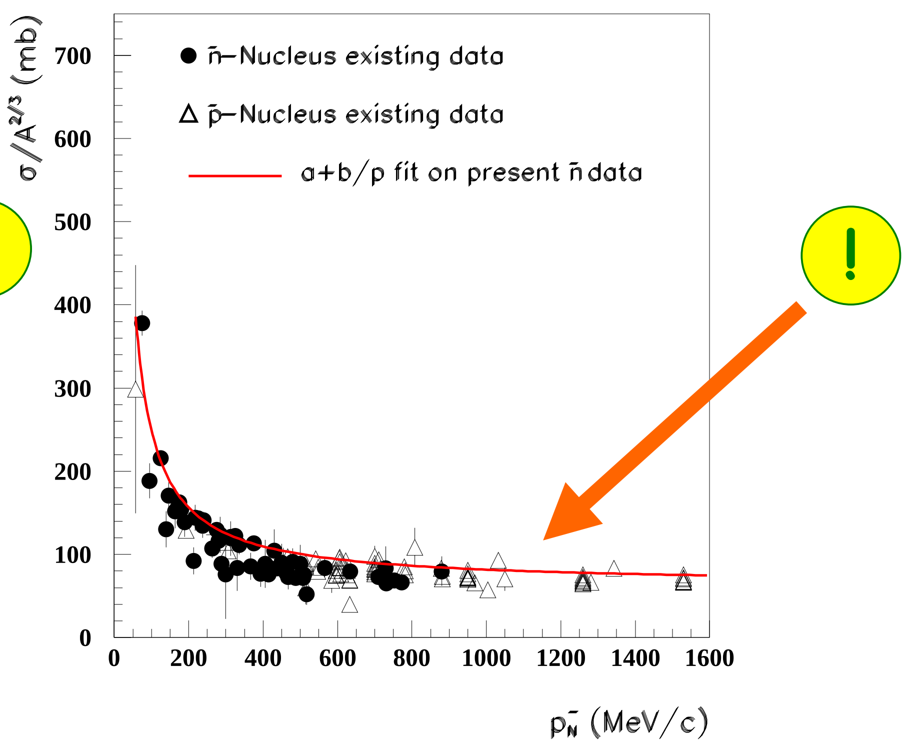


Comparisons

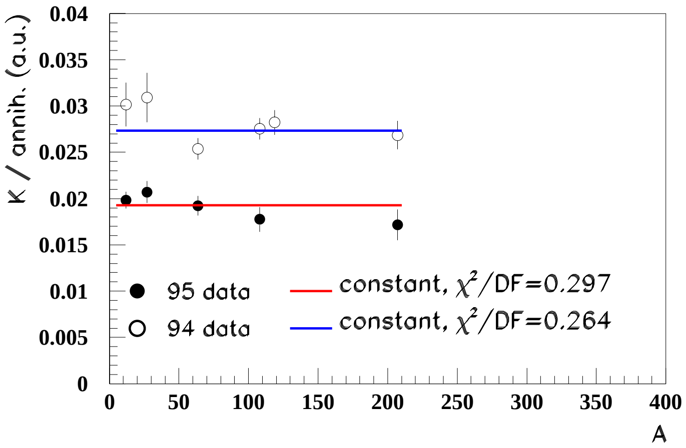
$\bar{n}$-nucleus data

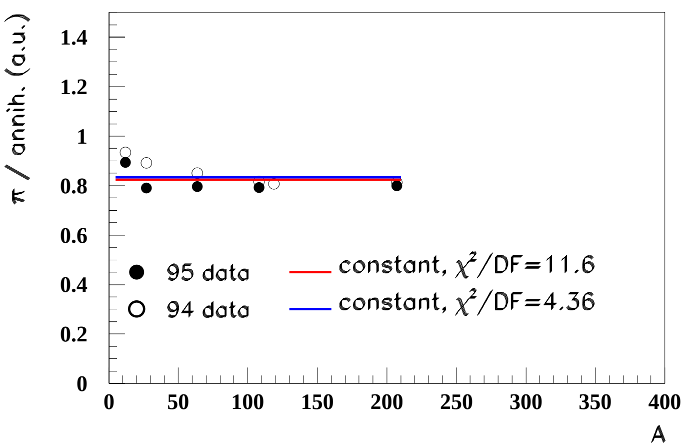


$\bar{N}$-nucleus data

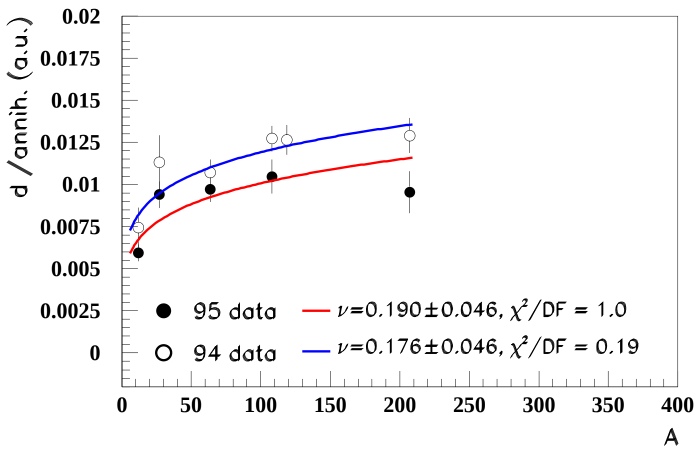


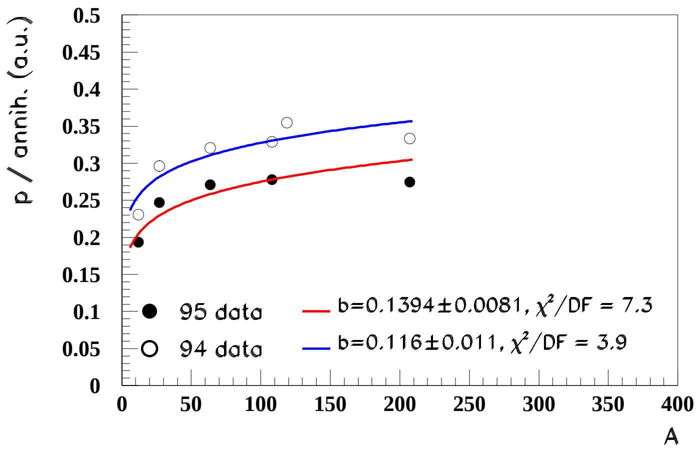
Annihilation products





- both p and d production increases with A (and saturate)
- d/p ~ 3-4% (average values in literature ~ 10-15%: different reconstruction efficiency?)

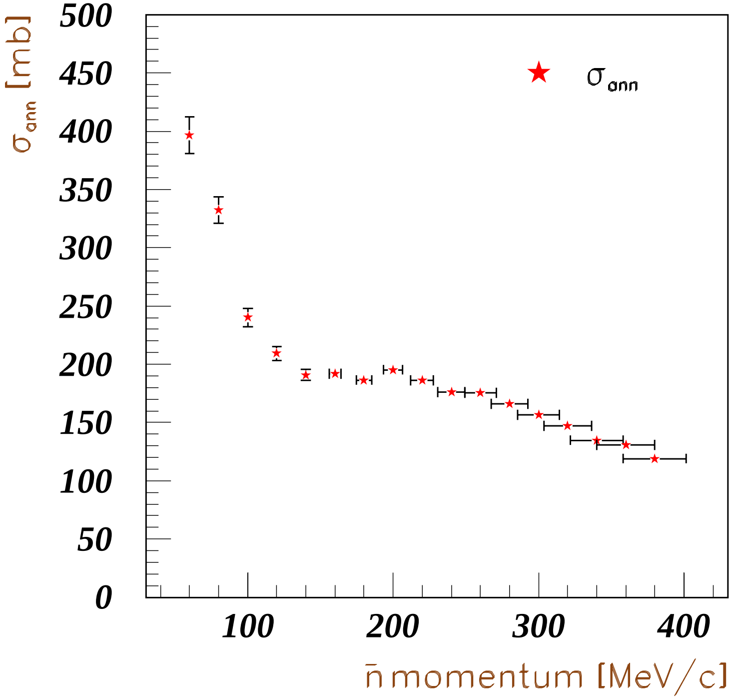




- K/π ~ 3%: about the same than $\bar{n}p$
- no enhancement of strangeness production with A
- very slight decreasing with A (energy loss?)

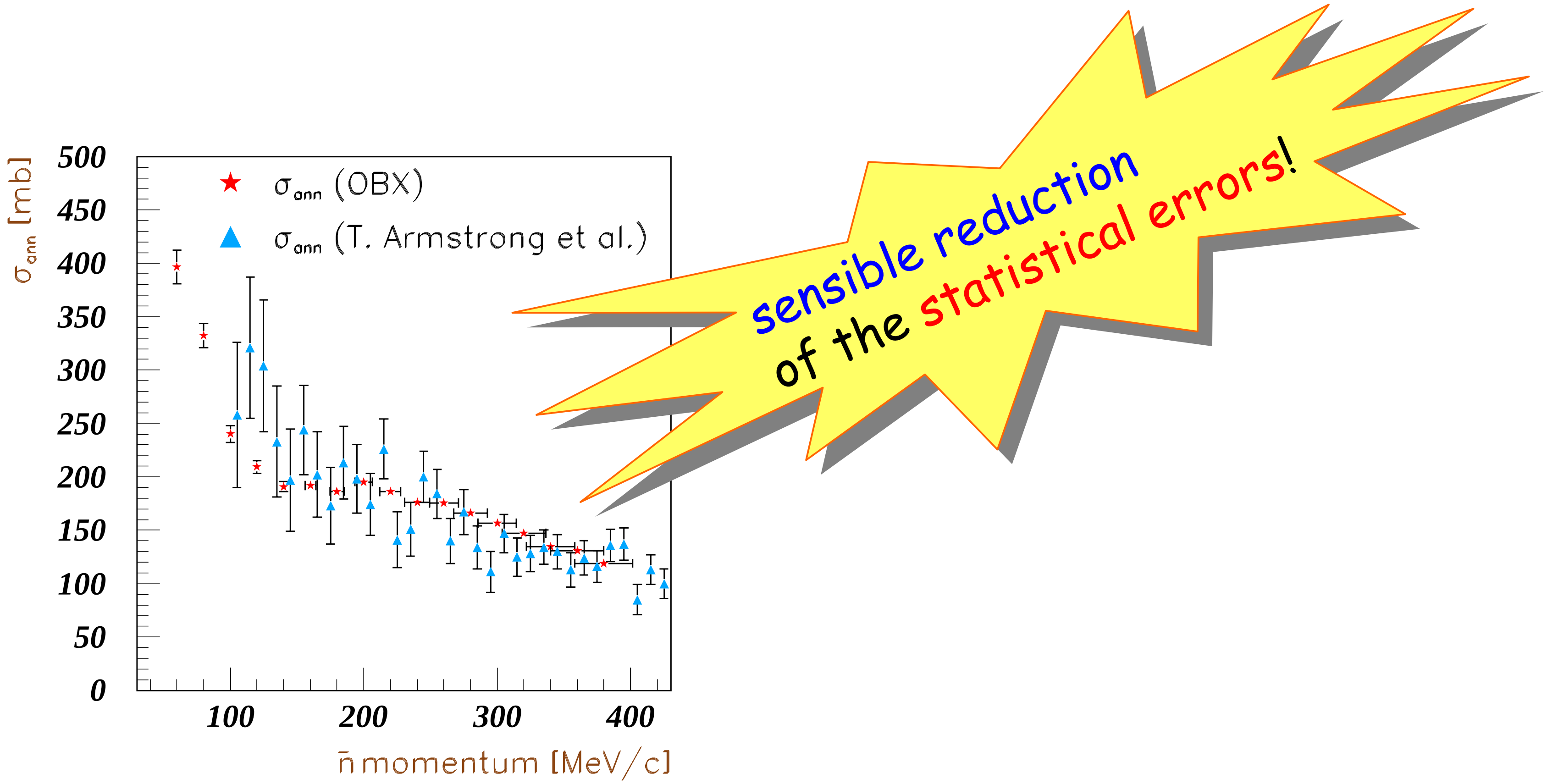
$\bar{n}p$ annihilation cross section

$$\sigma^{i}_{ann} = \frac{1}{\rho N_A \Delta z}\frac{1}{\varepsilon\varepsilon_{trig}}\frac{N^{i}_{ann}(1-\gamma^{i})}{N^{i}_{\bar{n}}}$$



[*Nucl. Phys.* **B** 56A (1997) 227]

Comparison



σ_ann [mb]
500
450
400
350
300
250
200
150
100
50
0
100
200
300
400
n̄ momentum [MeV/c]
σ_ann (OBX)
σ_ann (T. Armstrong et al.)
sensible reduction
of the statistical errors!

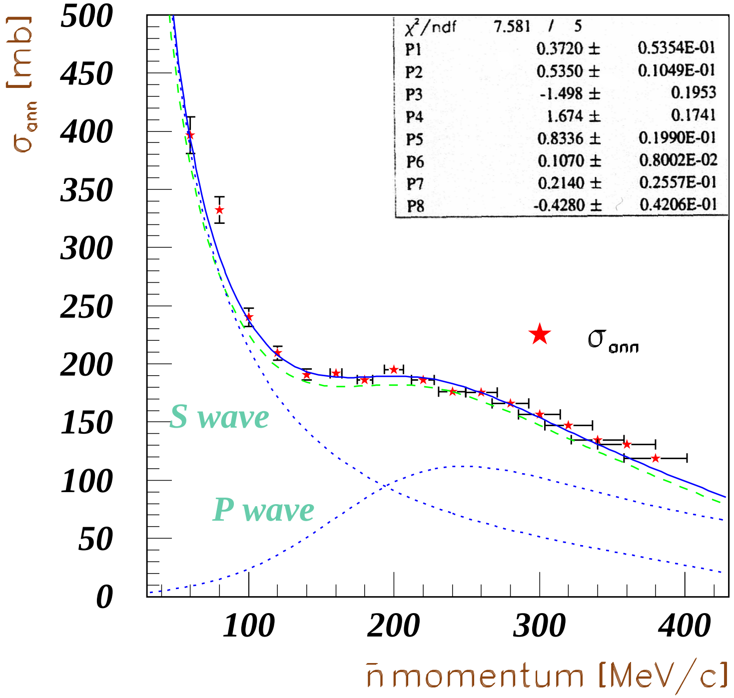
Effective range expansion

$$\sigma_{ann} = \frac{4\pi}{k^2} \sum_l (2l+1)(Im f_l - |f_l|^2)$$

$$f_l = \frac{1}{\cot \delta_l - i}$$

$$k \cot \delta_0 = \frac{1}{a_1} + \frac{1}{2} r_1 k^2$$

$$k^3 \cot \delta_1 = \frac{1}{b_1} - \frac{3}{2} \frac{1}{R_1} k^2$$



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Effective range expansion

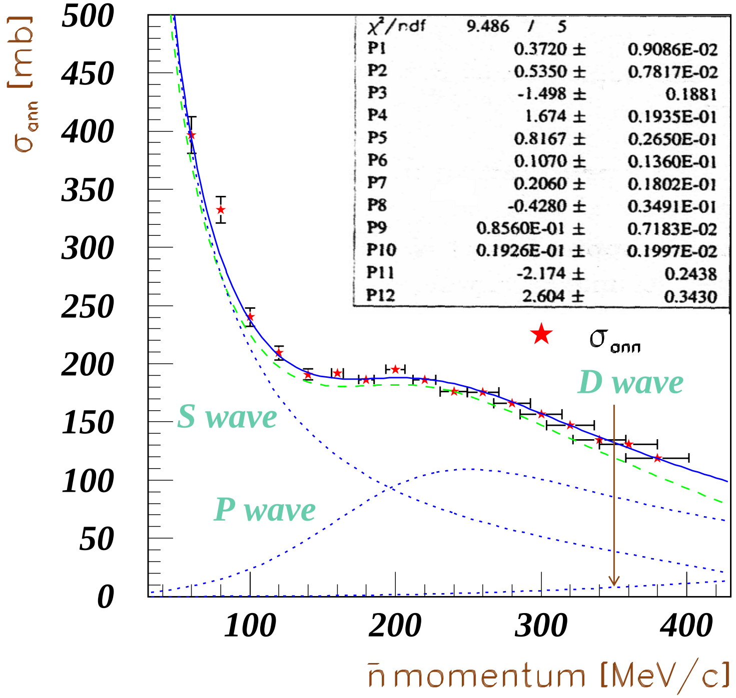
$$\sigma_{ann} = \frac{4\pi}{k^2}\sum_l (2l+1)(Im f_l - |f_l|^2)$$

$$f_l = \frac{1}{\cot\delta_l - i}$$

$$k\cot\delta_0 = \frac{1}{a_1} + \frac{1}{2} r_1 k^2$$

$$k^3\cot\delta_1 = \frac{1}{b_1} - \frac{3}{2}\frac{1}{R_1}k^2$$

$$k^5\cot\delta_2 = \frac{1}{c_1} + \frac{5}{2}\frac{1}{\rho_1^3}k^2$$



The transmission technique

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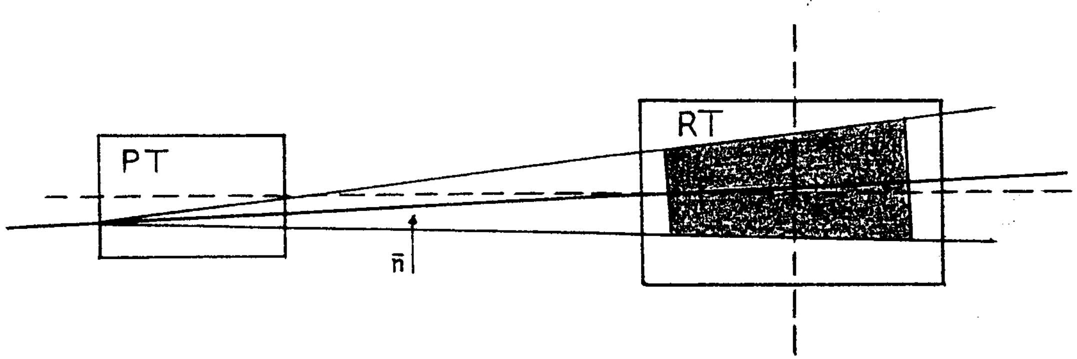
$$\Delta N_{ann}(p_{\bar{n}}, z) = \sigma_{ann}(p_{\bar{n}}) I_{\bar{n}}(p_{\bar{n}}, z) \rho N_A \Delta z$$

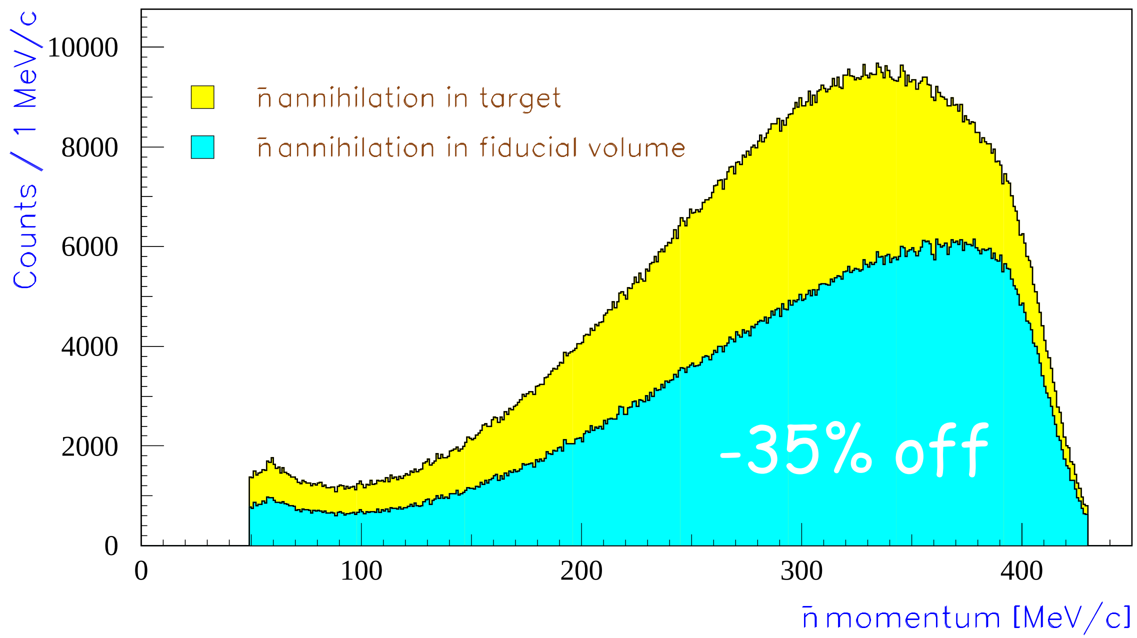
$$I_{\bar{n}}(p_{\bar{n}}, z) = I_{\bar{n}}(p_{\bar{n}}, 0) e^{-\sigma_{tot} \rho N_A z}$$

$$\frac{\Delta N_{ann}(p_{\bar{n}}, z)}{\Delta z} = I_{\bar{n}}(p_{\bar{n}}, 0) \sigma_{ann}(p_{\bar{n}}) \rho N_A e^{-\sigma_{tot} \rho N_A z}$$

The transmission technique



not to scale



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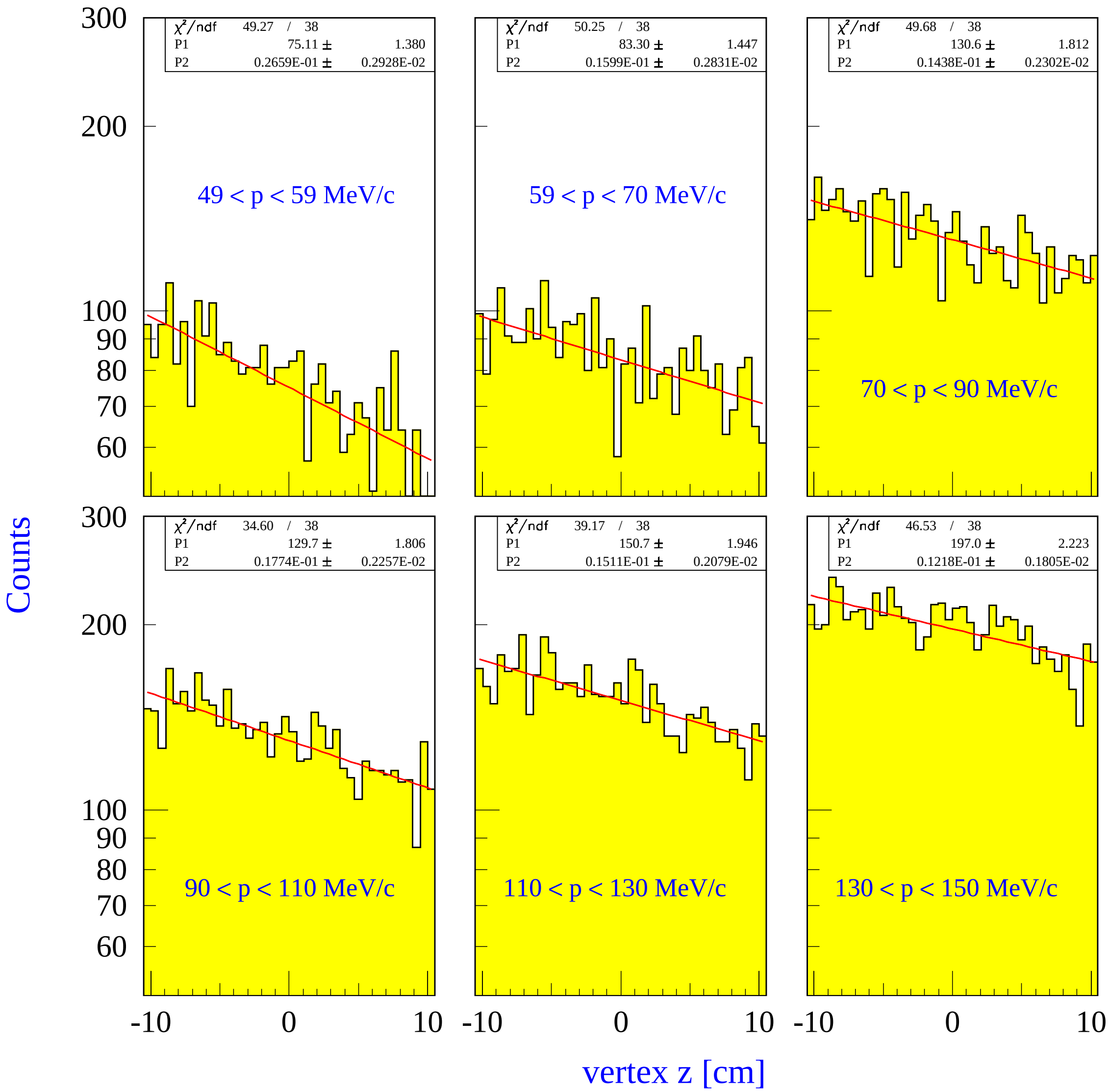
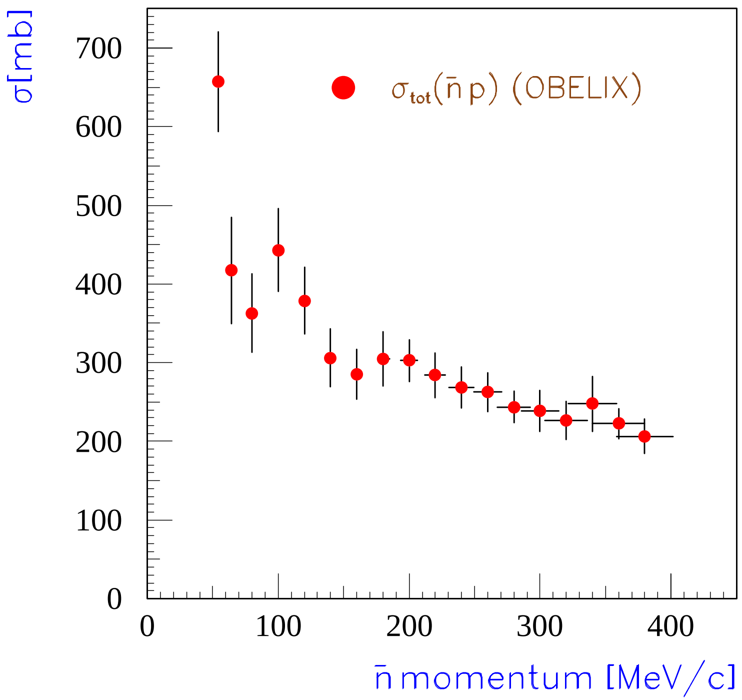
The transmission technique

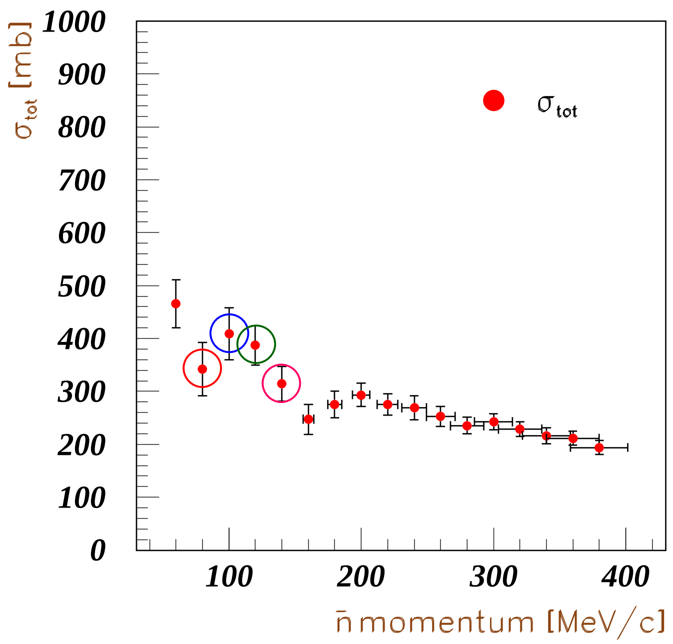


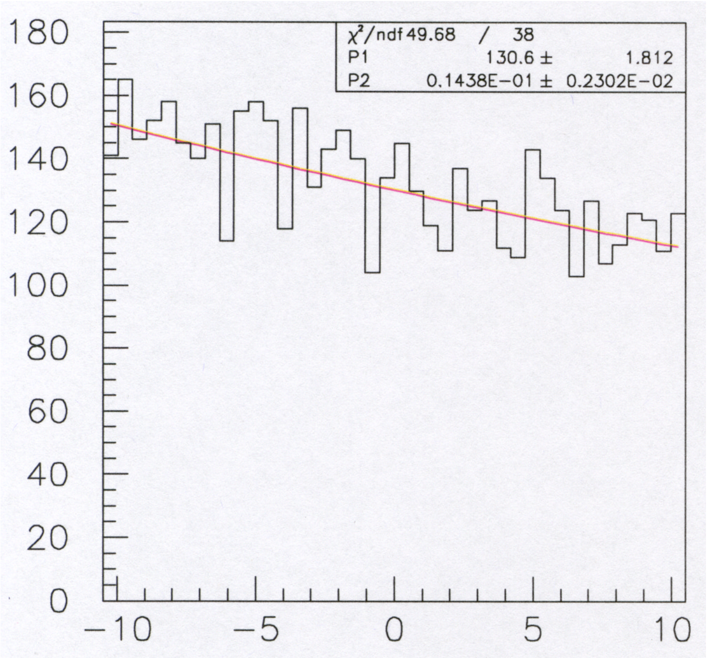
$\overline{n}p$ total cross section



[*Phys. Lett.* **B** 475 (2000) 378]

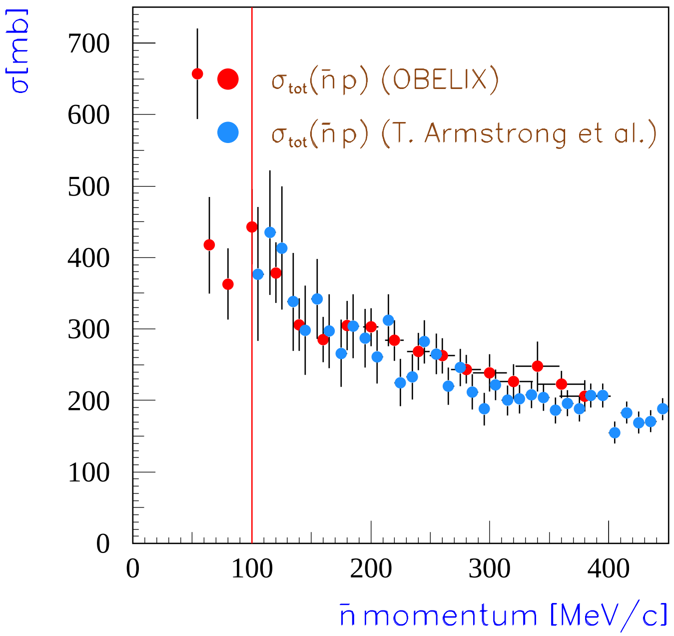
Slopes

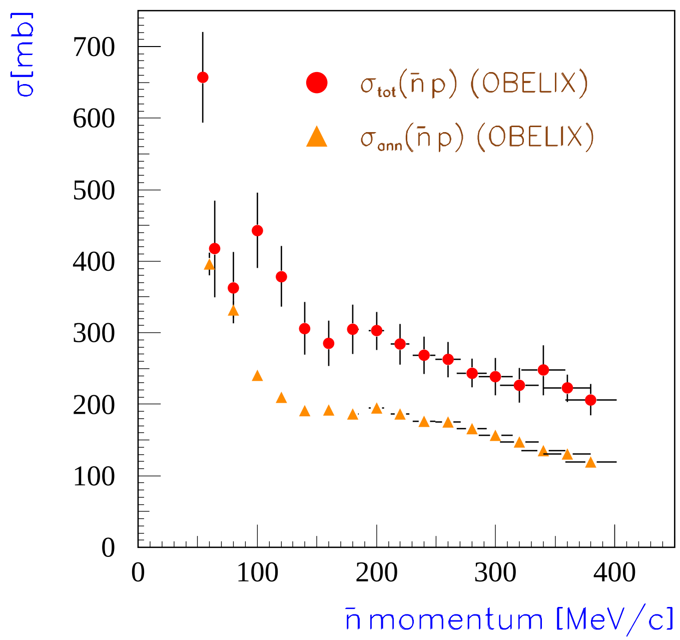




$70 < p_{\bar{n}} < 90$ MeV/c

Comparisons



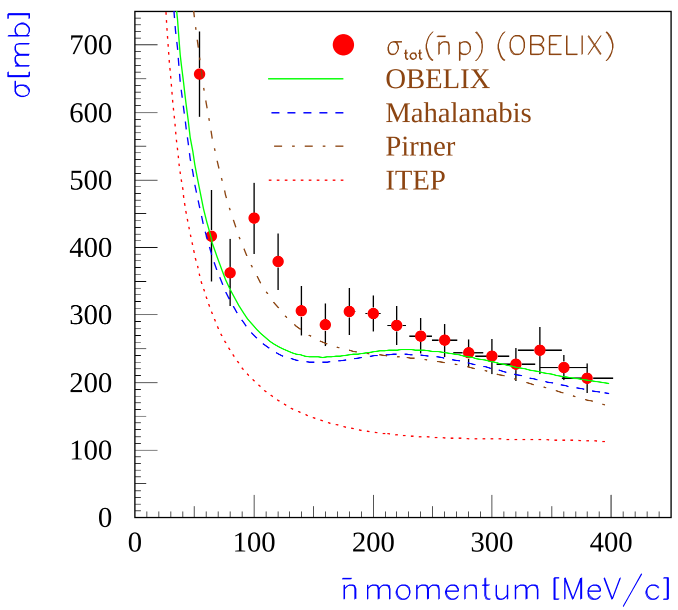


- no systematic errors (practically)
- statistical errors significantly reduced

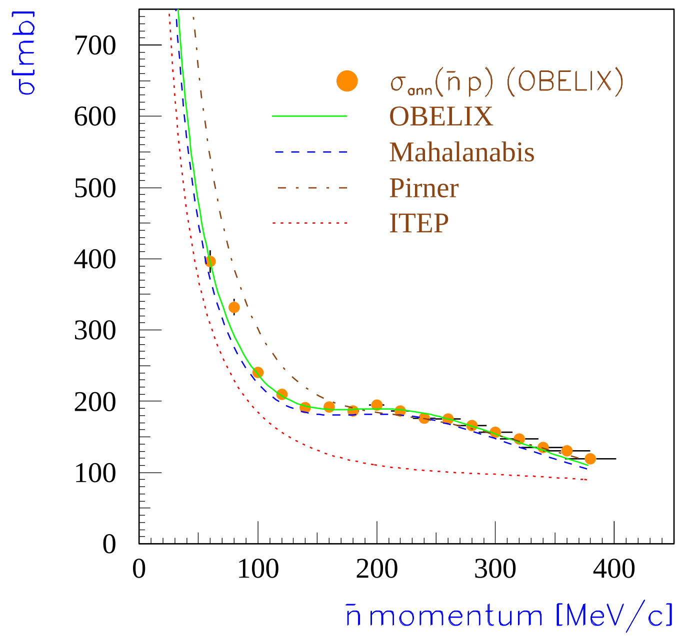
Effective range expansion

total

$$\sigma_{tot} = \frac{4\pi}{k^2} \sum_l (2l+1) Im f_l$$



annihilation



$$\sigma_{ann} = \frac{4\pi}{k^2} \sum_l (2l+1)(Im f_l - |f_l|^2)$$

Effective range expansion

$$\sigma_{tot} = \frac{4\pi}{k^2}\sum_l (2l+1) Im f_l$$

$$f_l = \frac{1}{\cot\delta_l - i}$$

$$k\cot\delta_0 = \frac{1}{a_1} + \frac{1}{2} r_1 k^2$$

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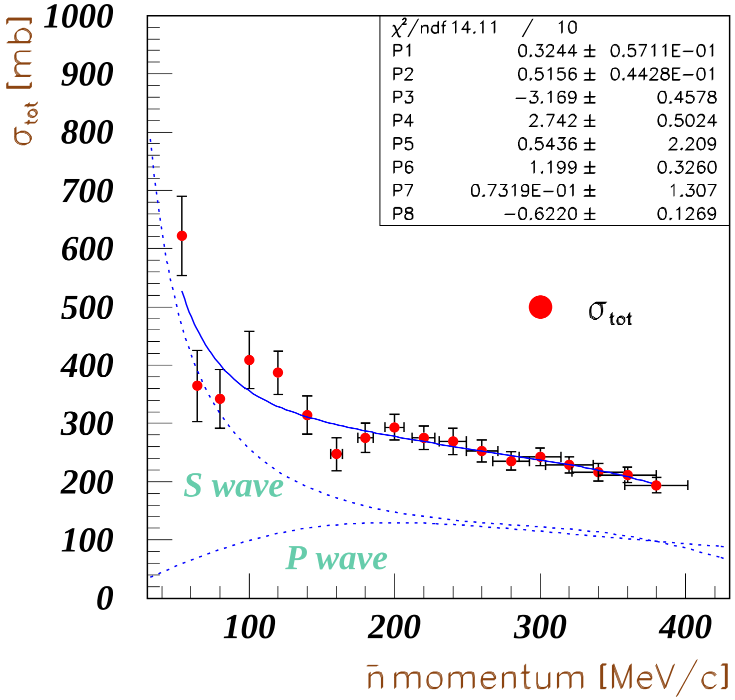
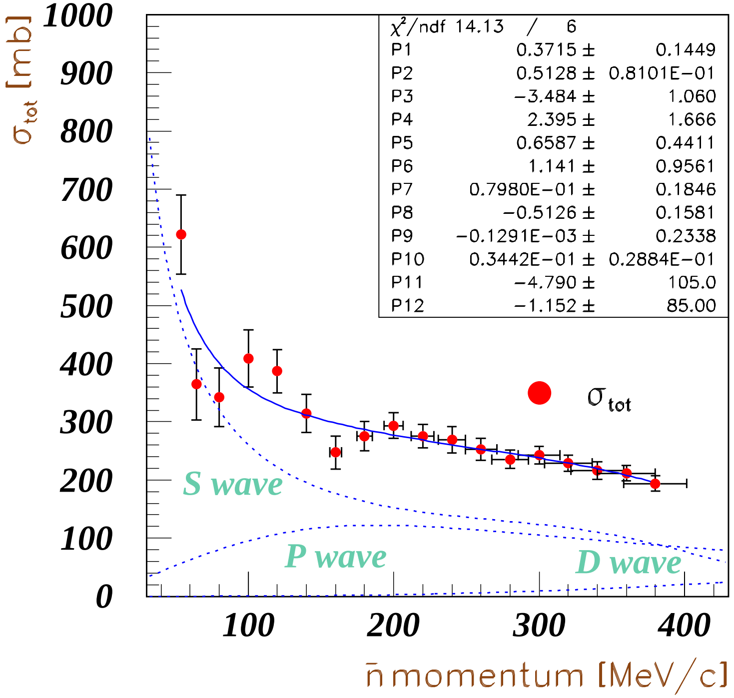


Effective range expansion

$$\sigma_{tot} = \frac{4\pi}{k^2}\sum_l (2l+1) Im f_l$$



$$f_l = \frac{1}{\cot\delta_l - i}$$

$$k\cot\delta_0 = \frac{1}{a_1} + \frac{1}{2} r_1 k^2$$

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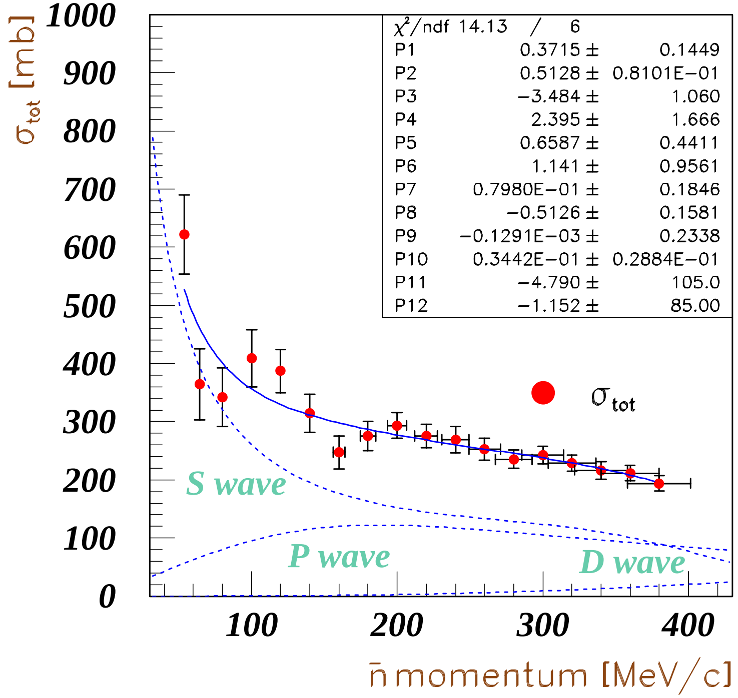
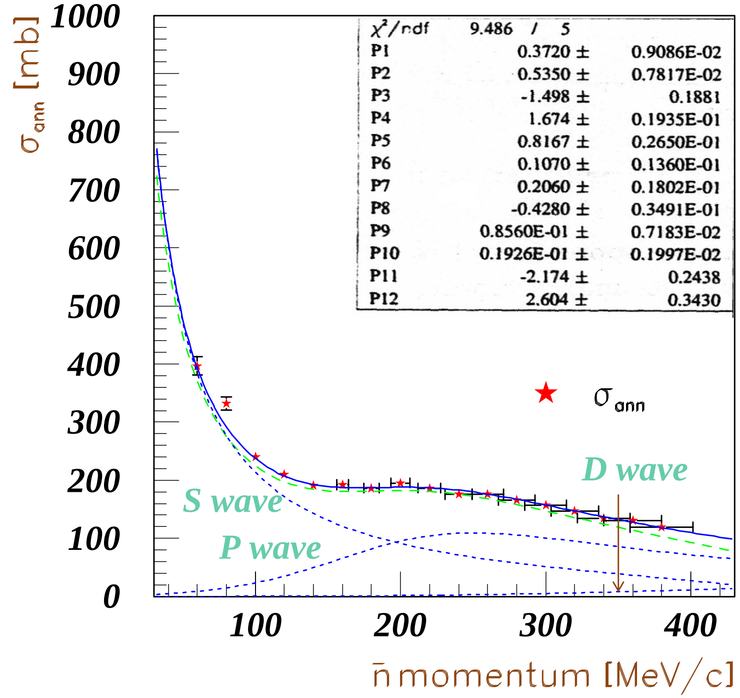
$$k^5\cot\delta_2 = \frac{1}{c_1} + \frac{5}{2}\frac{1}{\rho_1^3} k^2$$

Anomalous p-wave contribution

total



annihilation



Different binning

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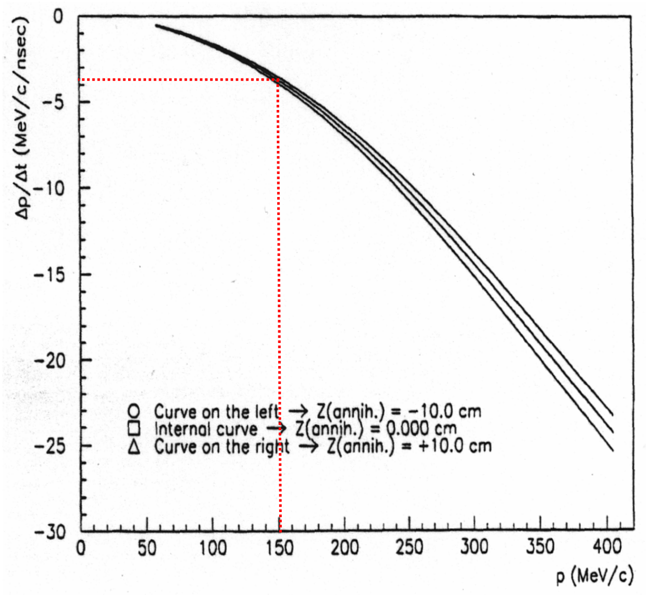
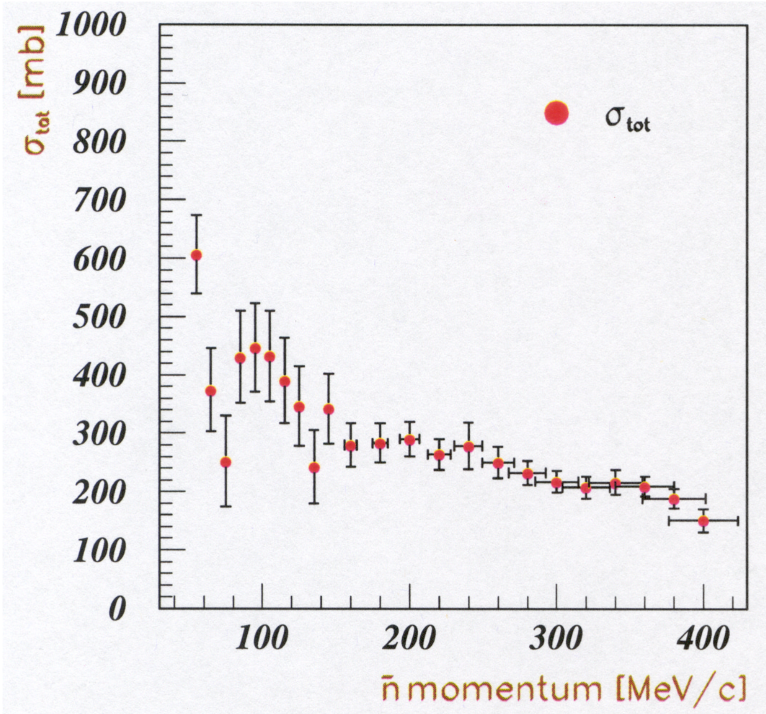
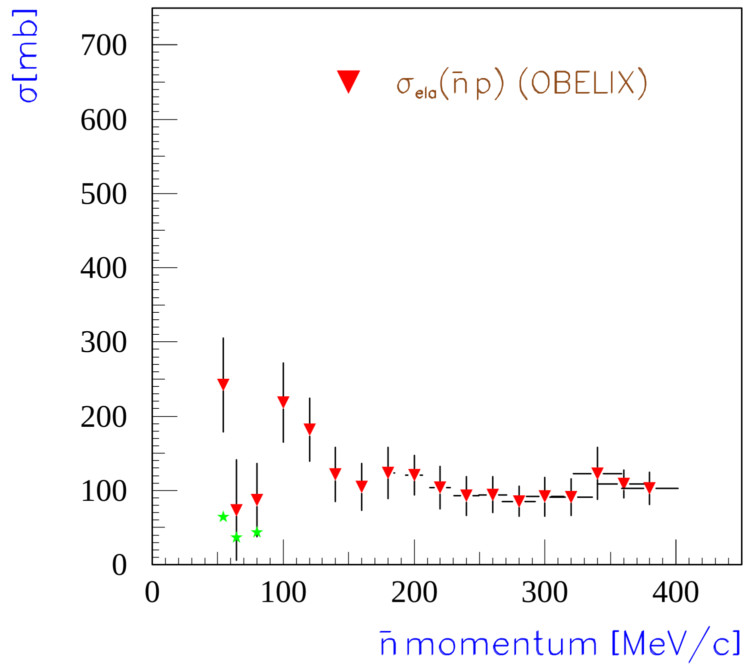




$\bar{n}p$ elastic cross section



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

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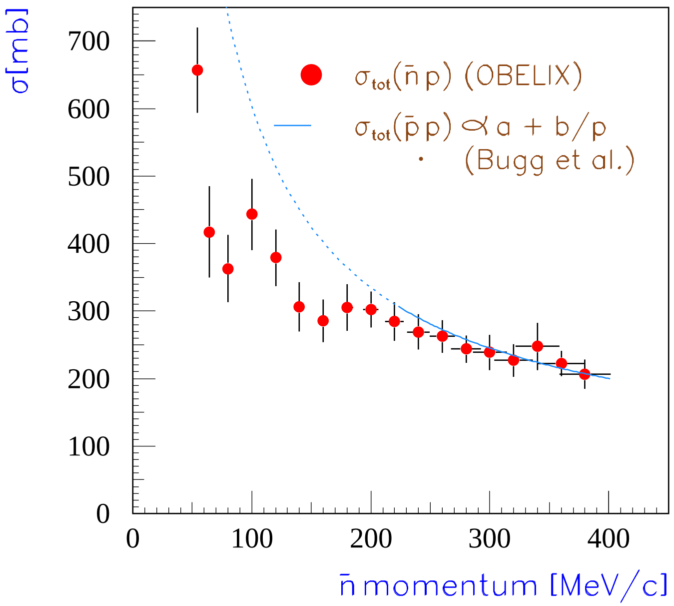
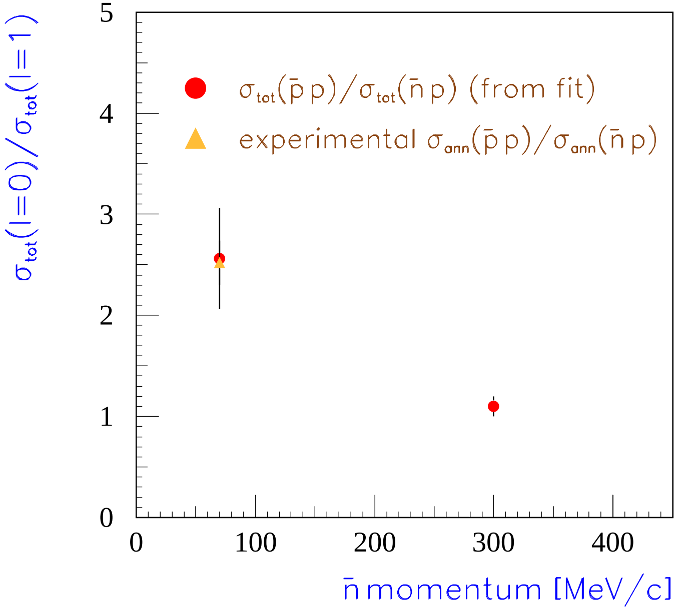
Isospin dependence

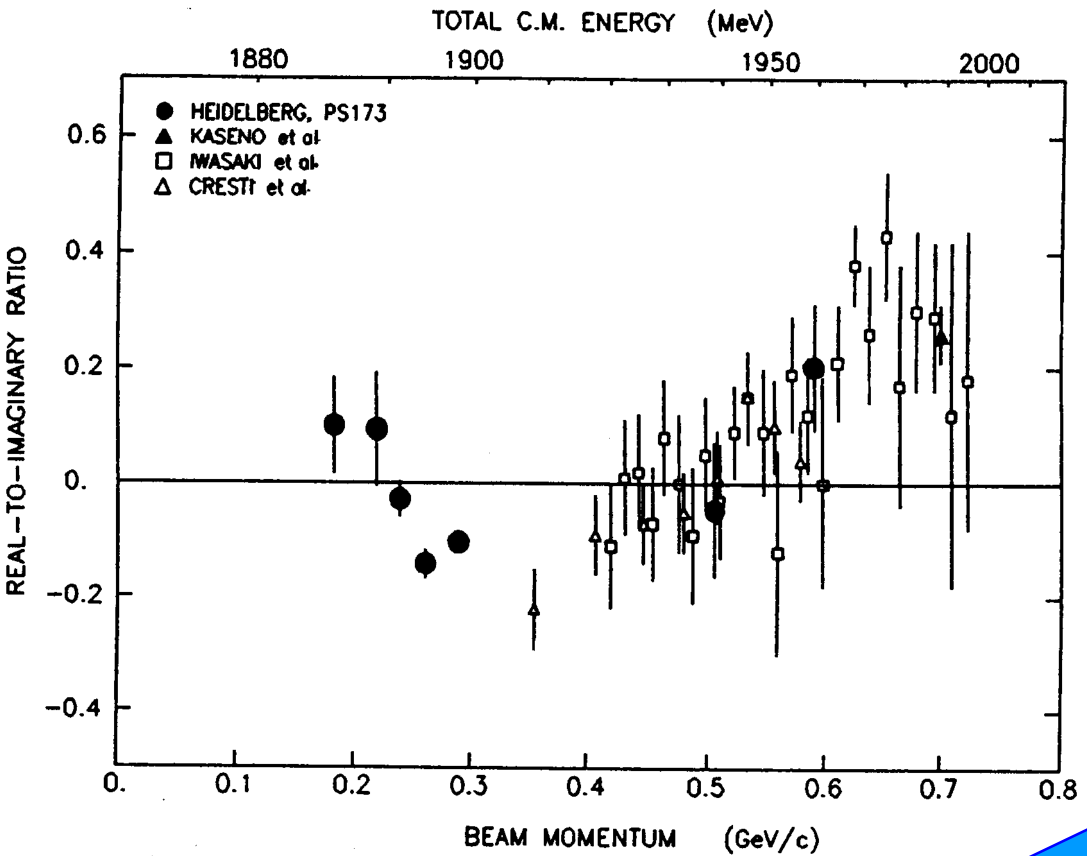


$$\frac{\sigma^0_{tot}}{\sigma^1_{tot}} = 2R_{tot} - 1$$



$$R_{tot} = \frac{\sigma_{tot}(\bar{p}p)}{\sigma_{tot}(\bar{n}p)} = \frac{\sigma^0_{tot} + \sigma^1_{tot}}{2\sigma^1_{tot}}$$

The ρ parameter



[W. Brückner et al., Phys. Lett. **B158** (1985) 180]

Which origin for such anomalies?

- threshold of the $\bar{p}p \to \bar{n}n$ channel ($p_{\bar{p}}^{lab}$ = 98 MeV/c)
- s-wave dominance, in the frame of the coupled channel approach
- quasi-nuclear bound states near threshold

measurement of $\sigma_{ela}(\bar{p}p)$
at low momentum

measurement of $d\sigma/d\Omega$
(relative importance of s- and p-wave contributions)
essential to discriminate among different hypotheses

FENICE experiment

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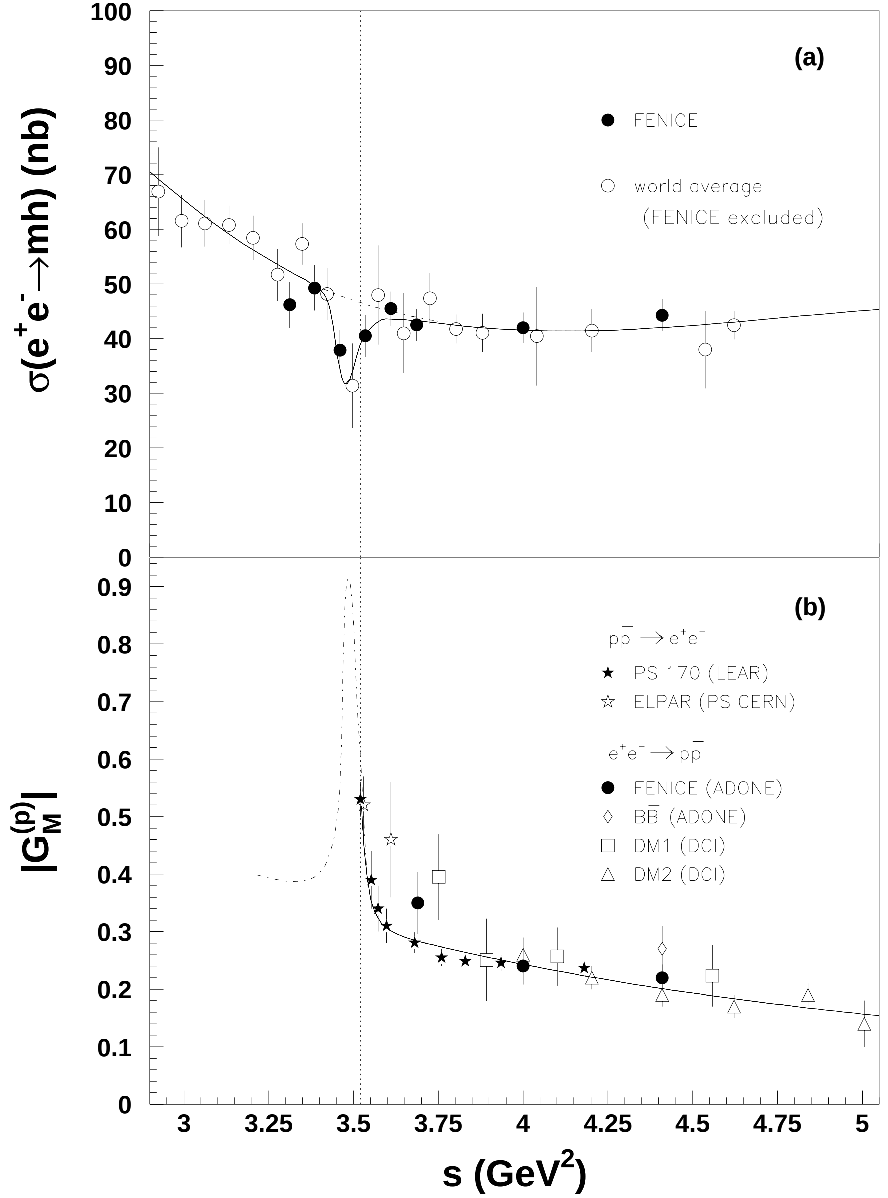
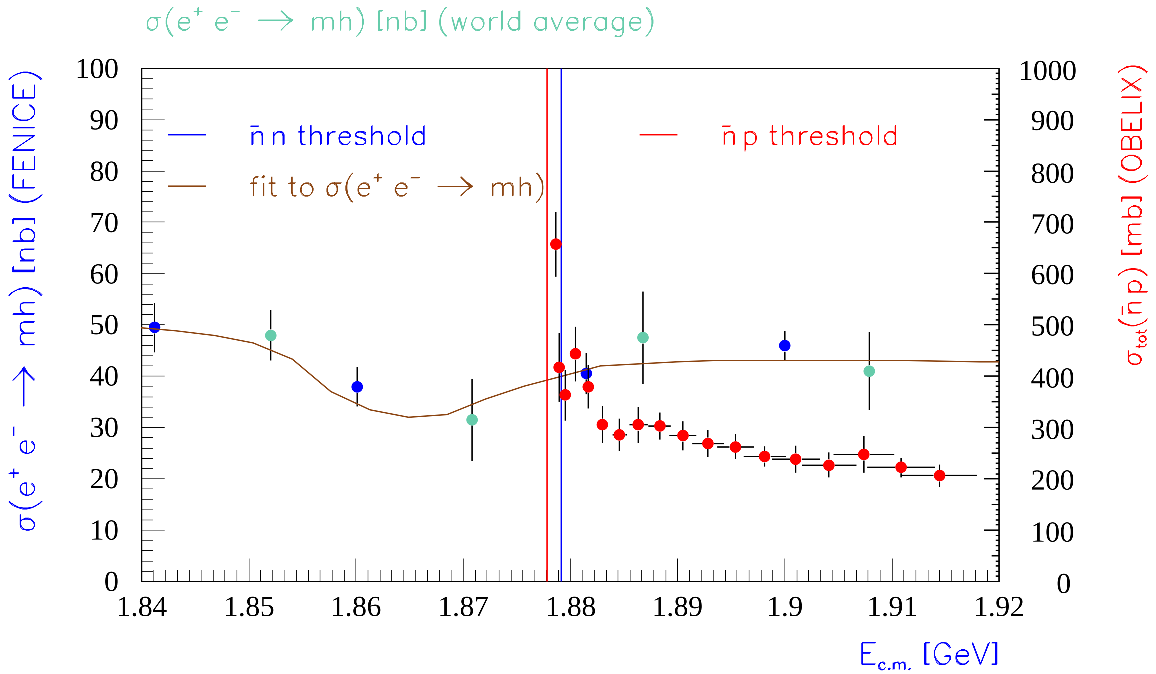
[*Nucl. Phys.* **B** 517 (1998) 3]



$M_X = (1.87 \pm 0.01)$ GeV
$\Gamma_X = (10 \pm 5)$ MeV

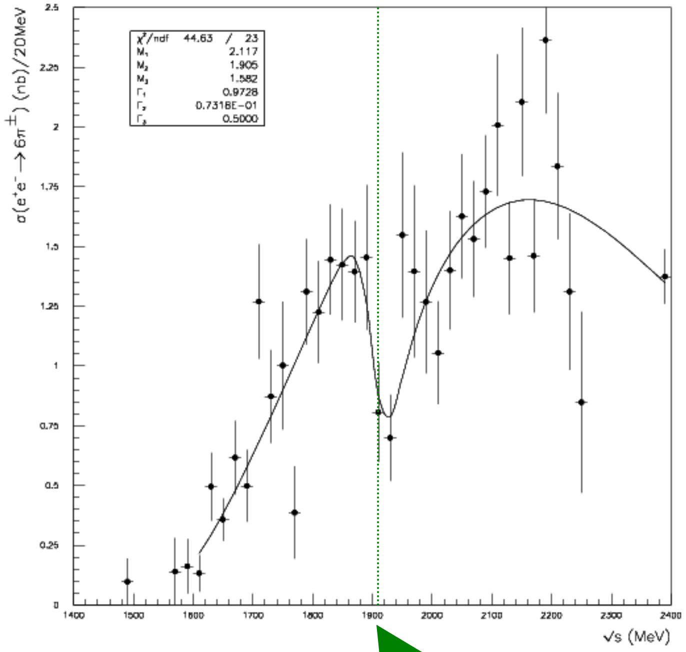
The threshold region

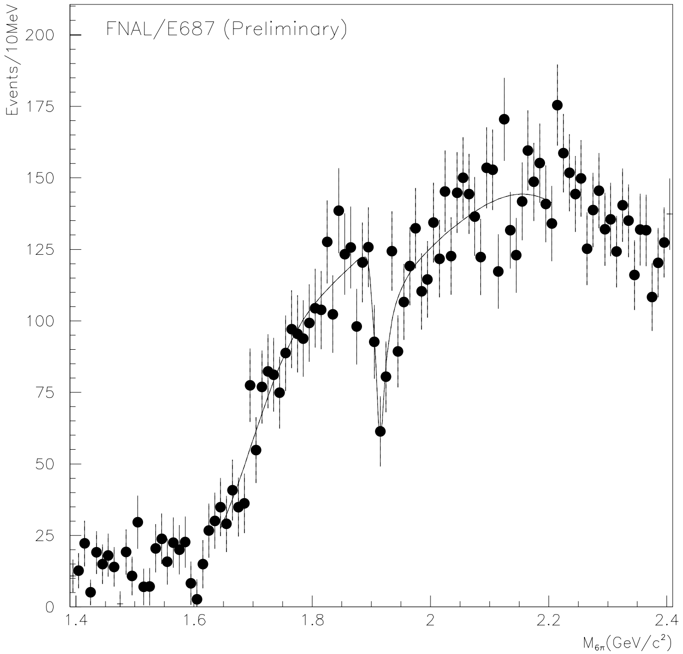


Photoproduction experiments

$e^+e^- \rightarrow 3\pi^+3\pi^-$

DM2





FNAL E687

M_X = (1.911 ± 0.004) GeV
Γ_X = (29 ± 11) MeV

Summary

- ✔ $\bar{n}$s validated as projectile for meson spectroscopy
- ✔ $\sigma_{ann}(\bar{n}p)$ and $\sigma_{tot}(\bar{n}p)$ measured for the first time:
  - ❶ down to 50 MeV/*c*
  - ❷ with high statistics
- ✔ evident anomalous behaviour of $\sigma_{tot}(\bar{n}p)$ ($\rightarrow \sigma_{el}(\bar{n}p)$) near threshold

indication for a structure below 100 MeV/c in the elastic channel???