PAINUC

The Nuclear Matter
studied in a Self Shunted Streamer Chamber
exposed to the $T_\pi = 68$ - 106 MeV
JINR phasotron π beams

PAINUC
Istituto Nazionale di Fisica Nucleare (To/Al/Bs)
Dipartimento di Fisica Generale "A. Avogadro" (Torino)
Centro Studi e Ricerche "E. Fermi" (Roma)
Joint Institute for Nuclear Research (Dubna)

Ivan Gnesi

The Nucleon Structure - 12th HANUC Lecture Week
Turin, 2009, march 23 - 27

Outline

1. Fields of interest
2. Experimental Apparatus
   - The Self Shunted Streamer Chamber
3. Event Reconstruction
4. Event Recognition: the Artificial Neural Network
5. Results
   - Resonances in the nuclear medium
   - Nuclear Reaction Mechanisms
   - The light nuclear matter at the hadron gas phase transition
   - The $\pi \rightarrow \mu\nu$ decay and the ν_μ mass
6. Summary and Future

Fields of interest

- Resonances activation in nuclear medium at intermediate energies
- Mechanisms of π-light nuclei elastic and inelastic interaction
- The light nuclear matter at the hadron gas phase transition
- The direct measurement of ν_μ mass

Fields of interest

- Resonances activation in nuclear medium at intermediate energies
- Mechanisms of π-light nuclei elastic and inelastic interaction
- The light nuclear matter at the hadron gas phase transition
- The direct measurement of ν_μ mass

Fields of interest

- Resonances activation in nuclear medium at intermediate energies
- Mechanisms of π-light nuclei elastic and inelastic interaction
- The light nuclear matter at the hadron gas phase transition
- The direct measurement of ν_μ mass

Fields of interest

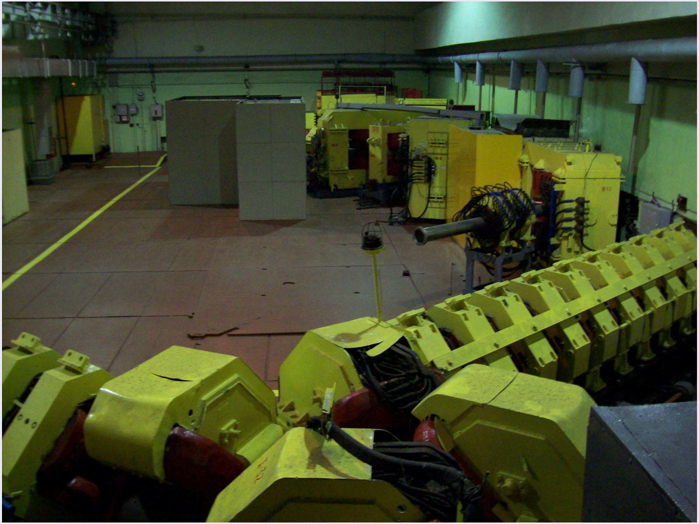
- Resonances activation in nuclear medium at intermediate energies
- Mechanisms of π-light nuclei elastic and inelastic interaction
- The light nuclear matter at the hadron gas phase transition
- The direct measurement of ν_μ mass

Experimental Apparatus

The Laboratory for Nuclear Problem

The Phasotron

The Pion Line



Devices

- Phasotron: channel III

  $$\mathbf{T_\pi = 50 - 250\ MeV}$$

- Self Shunted Streamer Ch. (**SSSC**)
- Electromagnet

  MC-4A

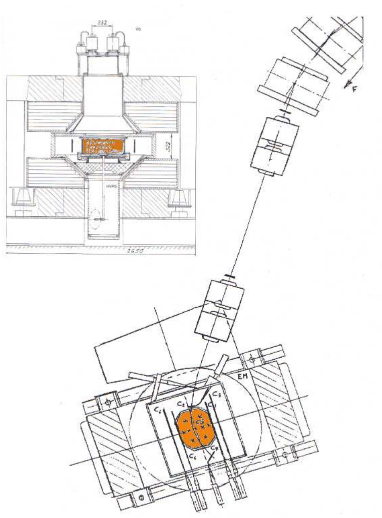
  $$(H = 0.650 \pm 0.005\ T)$$

- Scintillators $\mathbf{C_1 - C_7}$
- High Voltage pulse generator

  HVPG Marx-Arkadiev

  $$(\Delta V = 250\ KV)$$

- 2 *Sensys Photometric CCD*

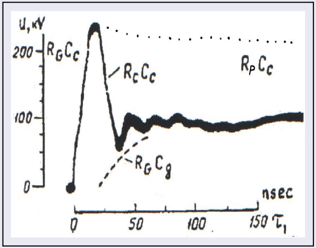


The Shunting Effect

- gas: **^{4}He** (1 atm) +

$$\begin{cases} \mathbf{CH_4} \sim 0.05\% \\ \mathbf{air} \sim 0.05\% \\ \mathbf{H_2O} \sim 0.1\% \end{cases}$$

- higly localized tracks: ⌀ streamers: 1-2 mm
- high contrast



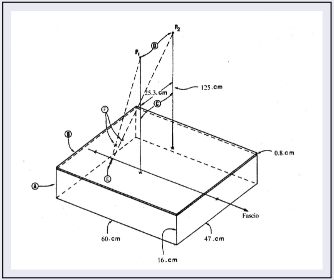
Features

- **^{4}He** $\rightarrow \begin{cases} \text{target} \\ \text{detection medium} \end{cases}$
- momenta of strongly ionizing particles are *measureable*
  $\mathbf{P_{^x He}}, \mathbf{P_p}, \mathbf{P_{^x H}}$

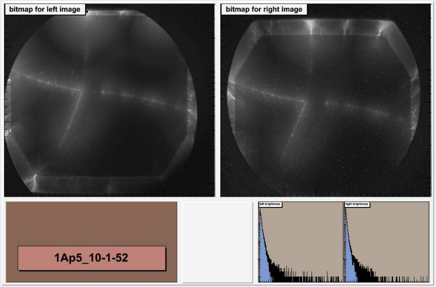
Averaged Track Lengths in ^4He

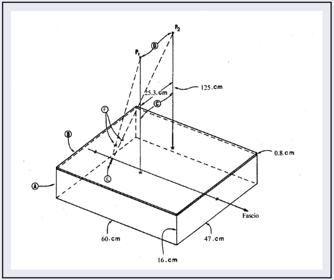
Track (mm)	$\mathbf{T_\pi}$ (MeV)	$\mathbf{T_p}$ (MeV)	$\mathbf{T_{^3He}}$ (MeV)	$\mathbf{T_\alpha}$ (MeV)
10	0.16	0.17	0.25	0.3
50	0.27	0.55	1.70	1.8
100	0.40	0.85	2.90	3.3
100(Ne)	1.40	3.40	11.10	12.9
200	0.57	1.30	4.50	5.0

Event reconstruction

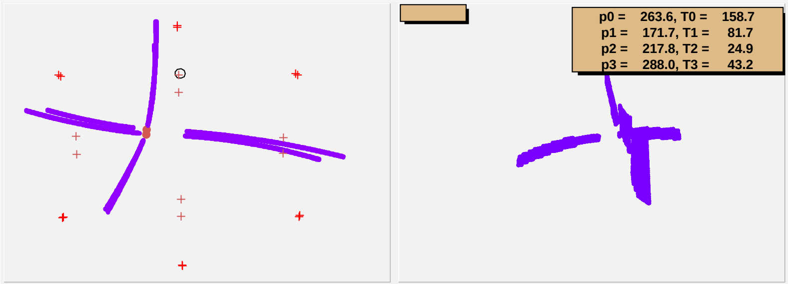


- res.: 1317 x 1035 pixels
  $\rightarrow$ 1 pixel $\equiv$ 1 mm
- dynamic res.: 12 bit
  $\rightarrow 2^{12} = 4096$ liv. grigio

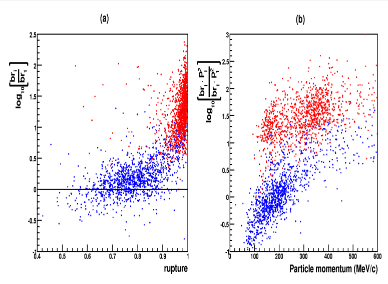




- res.: 1317 x 1035 pixels
  $\rightarrow$ 1 pixel $\equiv$ 1 mm
- dynamic res.: 12 bit
  $\rightarrow 2^{12} =$ 4096 liv. grigio



- vertex position
- vertex uncertainty
- directional cosines
- brightness
- radiuses → momenta
- momenta uncertainty



since $-dE/ds \propto z^2m^2/p^2$...

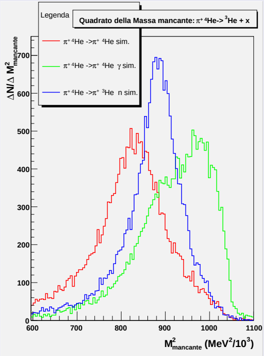
...brightness*p$^2 \propto m^2$

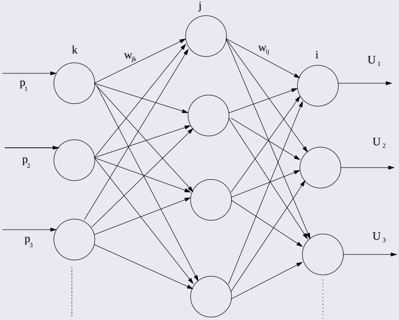
can be used as a mass index...

...to separate π from p, α, ^{3}He and ^{3}H.

Event Recognition

Reaction channels are separated by multidimensional cuts performed by an Artificial Neural Network

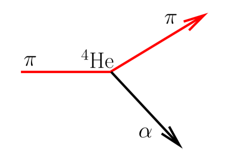


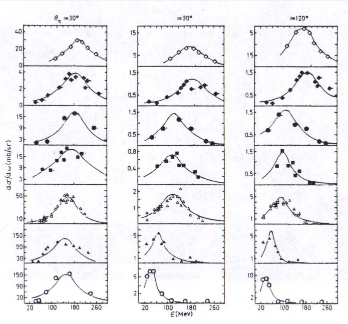


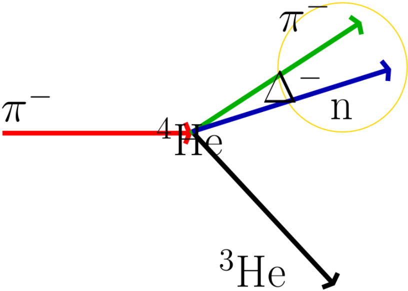
Resonances in the nuclear medium

Nuclear medium at intermediate energies works in favour of resonances activation: the Isobaric Collective Resonance

Δ activation in elastic π-nucleus interaction on various nuclei

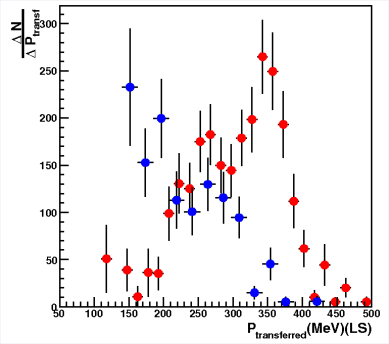


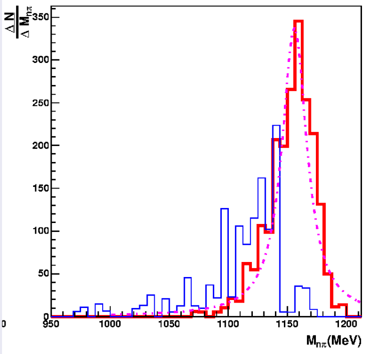




first experimental
Δ^- observation
in π^-n^{3}He
knockout reaction

we observed Δ^- resonance
in high P_{transf} interactions



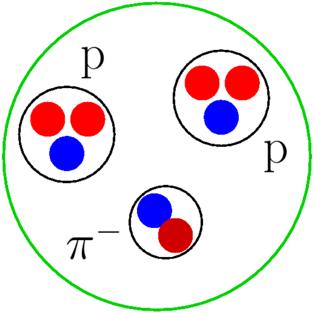


Features of Δ^-
in n^{3}He reaction:

$$M_{\Delta^-} = 1160 \text{ MeV}$$
$$\Gamma/2 = 20 \text{ MeV}$$

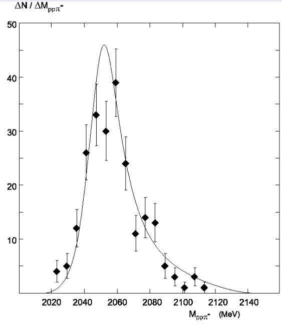
the M_{Δ^-} shift and narrowing tells us:

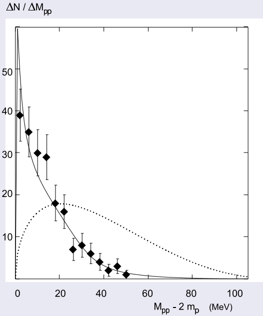
- deep isobaric collective resonance
- we are on the Δ activation energy left tail



dibaryonic d' experimental observations

$\pi^+(^{107}Ag,^{105}Ag)pp\pi^-$



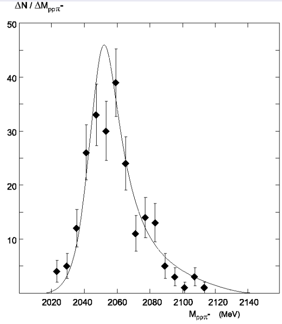


$$\begin{cases} \mathbf{J^P} = 0^- \\ \mathbf{I} = 0 \\ \mathbf{M} \simeq 2m_N + m_\pi + 50MeV \simeq 2.05GeV \\ \mathbf{B} = 2. \end{cases}$$

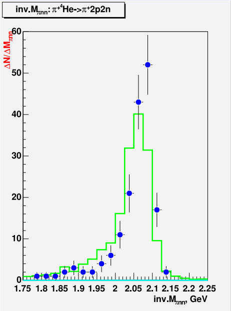
pp FSI

with a strong *pp* FSI

$\pi^+(^{107}Ag,^{105}Ag)pp\pi^-$



$\pi^+(^4He, pp)\pi nn$



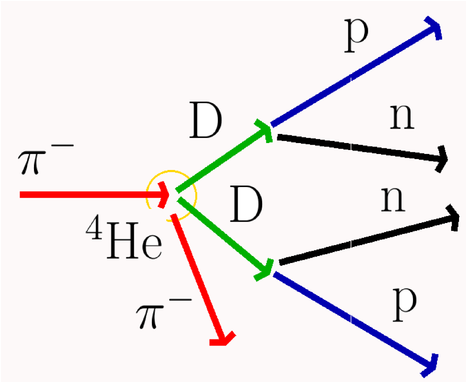
$$\begin{cases} \mathbf{J^P} = 0^- \\ \mathbf{I} = 0 \\ \mathbf{M} \simeq 2m_N + m_\pi + 50MeV \simeq 2.05GeV \\ \mathbf{B} = 2. \end{cases}$$

In ^4He:

$\mathbf{T_\pi \simeq 80\ MeV}$

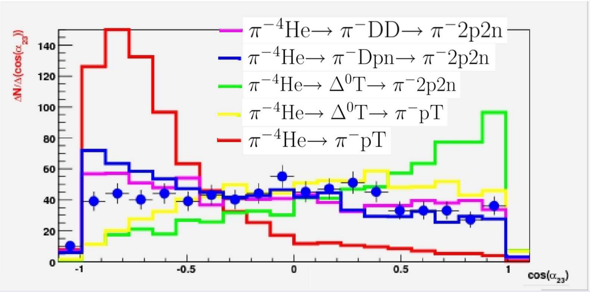
(50+28(^4He))MeV

Nuclear Reaction Mechanisms



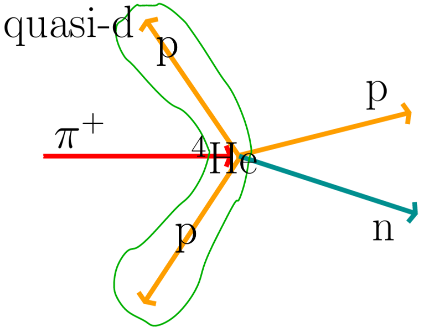
Preliminary study on ^{4}He breakup via deuteron-deuteron intermediate state

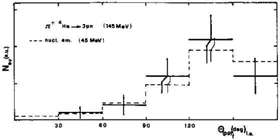
Nucleus breakup via deuteron-deuteron or deuteron-proton-neutron intermediate states can both explain the isotropy of Θ_{pp}.

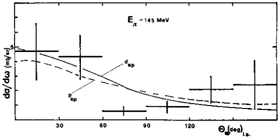


It confirms the q-deuteron as a fundamental block of nuclear matter and Δ^0 does not activate in breakup reaction.

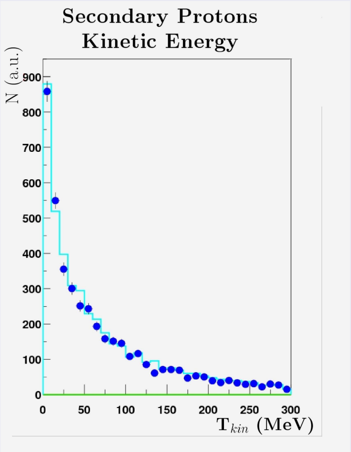
Preliminary study on π absorption on a qausi deuteron

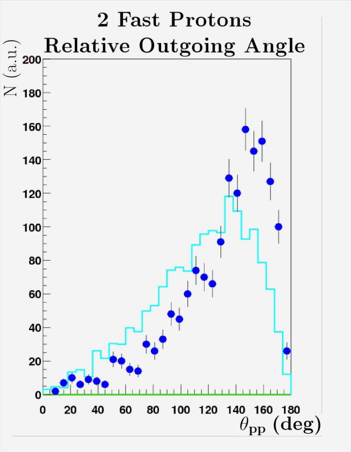






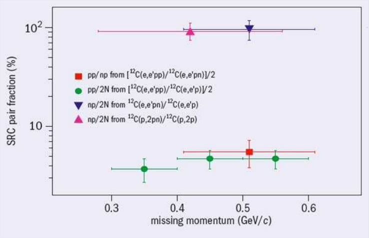
Preliminary results from π^{+4}He $\rightarrow$3pn (absorption) events

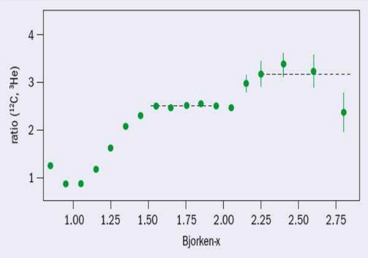




- all secondaries (down to T<10 MeV protons) are measured(left)
- the two fastest protons are emitted at high relative angle (right)
- the π absorption is confirmed to occur on a quasi-deuteron

PAINUC, with π^4He, may contribute to studies of p-n Short Range Correlations in nuclei as done at CEBAF: highly correlated pn pairs in e-^{12}C

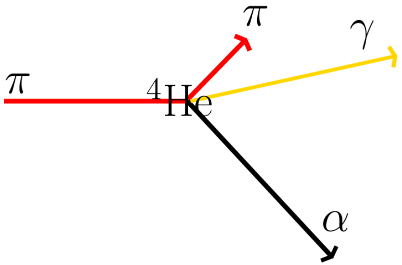




- high pn/pp ratio suggests p-n wave superposition at <0.7fm: quarks interacts?

- σ ^{12}C/^{3}He scale transition in Bjorken x confirms strong pn pairing

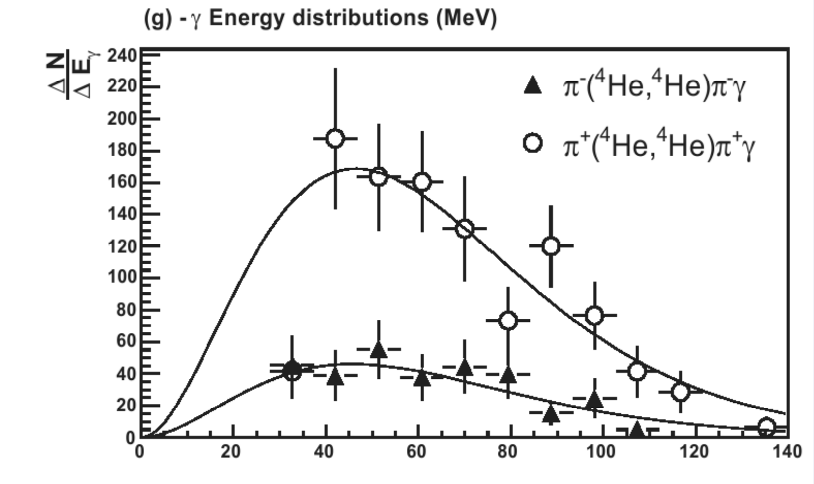
May be relevant to:QCD-nuclear potential transition, n-stars etc. (CernCourier49-1(2009)22, Science320,1476(2008) and refs in)



high energy

γs

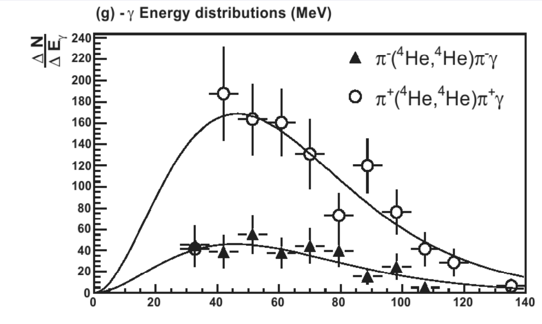
π^4Heγ: Energy distribution.



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- prompt photons

...cannot explain γs energies higher than 28 MeV...



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- prompt photons

$\cdots \frac{B.R.gamma}{B.R.elastic}$

can only be compared with πp measurement:

$\pi p\gamma \rightarrow 0.0185$

$\pi^4He\gamma \rightarrow 0.1$

[23] T. D. Blokhintseva et al. Yad. Fiz. (in Russian) **3** (1966) 511; T. D. Blokhintseva et al. Yad. Fiz. (in Russian) **8** (1968) 928.

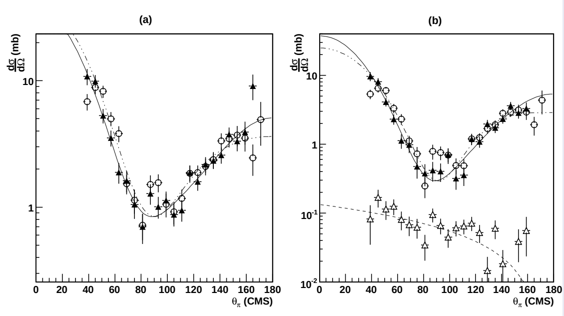
[24] D. I. Sober et al. Phys. Rev. **11D** (1975) 1017.

[25] F. E. Low, Phys. Rev. **110** (1958) 974.

Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- prompt photons

…moreover the gamma emission is isotropic…



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- prompt photons

...a similar γ spectra is seen in high energy heavy nuclei collision together with a bckg of pions...
...but due to *qq* interaction...

[26] P.Aurenche et al., Eur.Phys.J **C 9**, 107-119 (1999); Jorg Gayler, Acta Polonica **B** vol.37 (2006) numb.3, p.715.

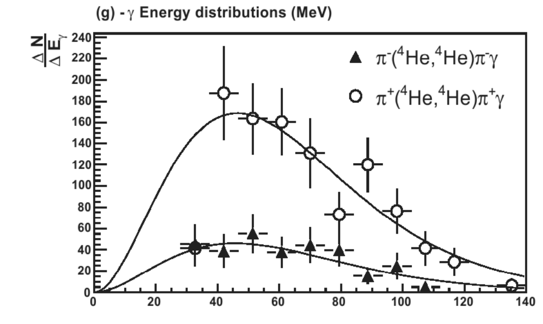
Possible γs sources

The γs energy distribution shows a Planck thermal behaviour:

$$\frac{dI}{dE} \propto E^3 e^{-E/T}$$

with T=14.4±1.6 MeV

at the same T heavier nuclei undergo hadron-gas transition



The $\pi \to \mu\nu$ decay and the ν_μ mass

Electron ν mass has been constrained by β decay:

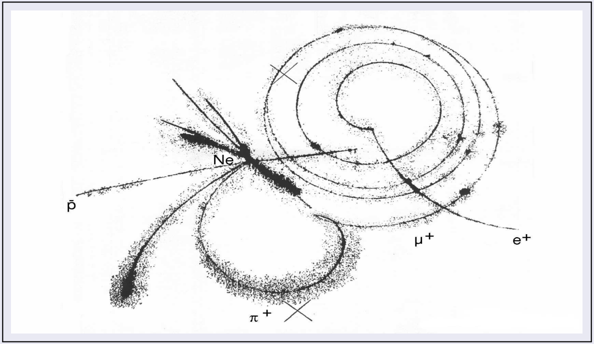
- $\bar{\nu}_e$ <2 eV (95% c.l.) from ^{3}H β decay
- ν_e <225 eV (95% c.l.) from ^{163}Ho β decay

Muon ν mass has been also constrained:

- by π decay in a spectrometer, with the assumptions of P_π=0, ΔP_π=0 and $\theta_{\pi\mu} = 0$
  - $\rightarrow$ M_ν <0.19 MeV (90% c.l.) Assamagan et al. Phys.Rev.D53:6065-6077,1996.
- by measuring the TOF of 3 GeV ν_μ
  - $\rightarrow$ M_ν <50 MeV (99% c.l.) Adamson et al. Phys.Rev.D76:072005,2007.

Muon Neutrino mass upper limit

CERN PS179: $\overline{p}$-Ne event

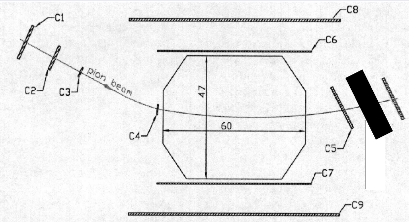


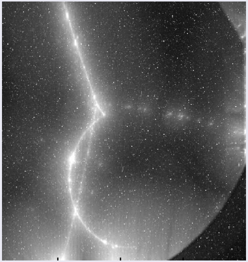
Kinematics of event

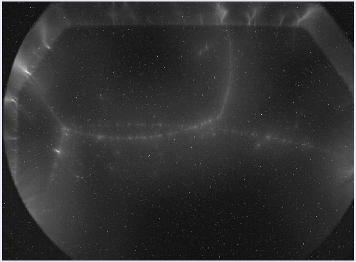
$$\begin{cases} P_\pi = (50 \pm 100) KeV/c \\ P_\mu = (29.9 \pm 19) KeV/c \\ \theta_{\pi\mu} = (163 \pm 1)^\circ \end{cases}$$

$$m_\nu^2(90\% c.l.) = (-11.1 + 1.282 * 12.5) MeV^2$$
$$m_\nu(90\% c.l.) = 2.2 MeV$$

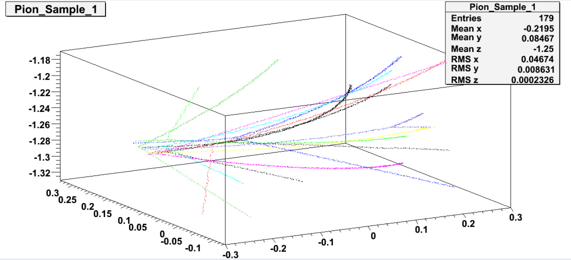
Measurement of both
π^+-> $\mu^+\nu$
and
π^--> $\mu^-\bar{\nu}$

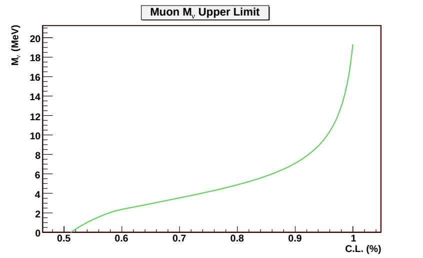




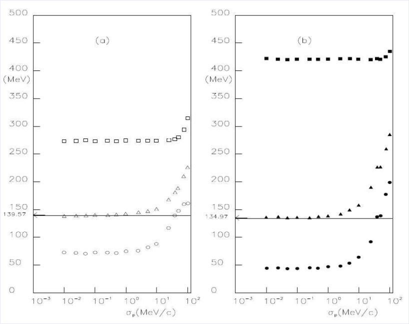


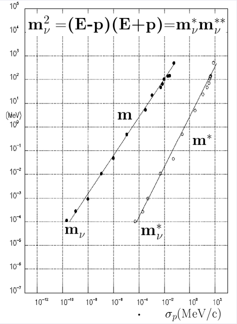
First results of MC simulation with JINR streamer chamber.





A study on a statistical estimator of ν_μ and $\bar{\nu_\mu}$ masses





sistematic study of momentum resolution for the reconstruction of a missing particle mass in several decay (i.e. $\Sigma^+ \rightarrow p\pi^0$, $\Lambda \rightarrow p\pi^-$)

new statistical approach based on m^* as a statistical estimator (where $m_\nu^2 = m^* m^{**}$): increased mass resolution (in press in NIM A)

Summary and Future

- evidence for a $\pi^{\pm} +^4 He \rightarrow \pi^{\pm} +^4 He + \gamma$ reaction
  - Nuovo Cimento B
- first experimental evidence for Δ^- in $\pi^- +^4 He \rightarrow \pi^- +^3 He + n$ reaction
  - Eur. Phys. J. A 34, 255-269 (2007)
- evidence for dibaryonic resonance d' on the nuclear emulsion
  - Eur. Phys. J. A 28, 11-17 (2006)
- evidence for q-deuteron π absorption and breakup

  ... pn correlation, repulsive nuclear potential and n-stars
- $\pi \rightarrow \mu\nu$: new measurements for the upper limit of ν_μ mass
  - Nuclear Physics A 780 (2006) 78-89

  ... upgrading the SSSC: $\rightarrow$ new upper limit for muonic M_ν
- $\pi \rightarrow \mu\nu$: new statistical estimator for ν_μ mass
  - in press on NIM A

  ... could increase the mass resolution of orders of magnitude

Event Recognition

The following 2-prong $\pi^{\pm 4}$He reaction channels have been separated by means of two approaches:

- $\pi^- + {}^4He \rightarrow \pi^- + {}^4He$
- $\pi^- + {}^4He \rightarrow \pi^- + {}^4He + \gamma$
- $\pi^- + {}^4He \rightarrow \pi^- + {}^3He + n$

The following 2-prong $\pi^{\pm 4}$He reaction channels have been separated by means of two approaches:

- $\pi^- + {}^4He \longrightarrow \pi^- + {}^4He$
- $\pi^- + {}^4He \longrightarrow \pi^- + {}^4He + \gamma$
- $\pi^- + {}^4He \longrightarrow \pi^- + {}^3He + n$

by successive linear cuts in the kinematical parameter space

The following 2-prong $\pi^{\pm 4}$He reaction channels have been separated by means of two approaches:

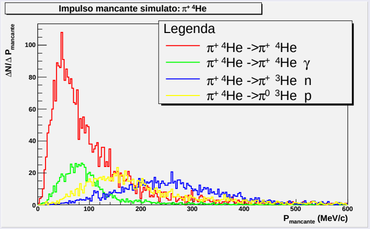
- $\pi^- + {}^4He \rightarrow \pi^- + {}^4He$
- $\pi^- + {}^4He \rightarrow \pi^- + {}^4He + \gamma$
- $\pi^- + {}^4He \rightarrow \pi^- + {}^3He + n$

by successive linear cuts in the kinematical parameter space

by non-linear multidimensional cuts performed by an Artificial Neural Network

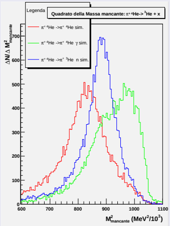
Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness



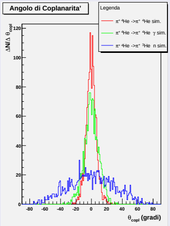
Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness



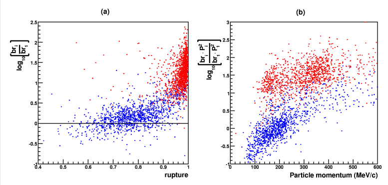
Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness



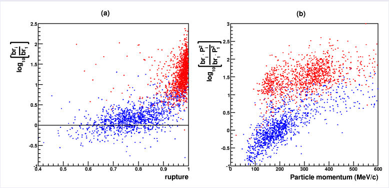
Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness



Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness

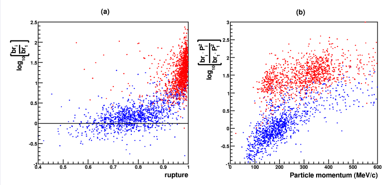


since

$$-dE/ds \propto z^2 m^2 / p^2 \ldots$$

Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness

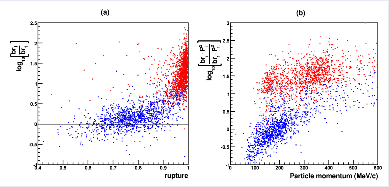


since
$-dE/ds \propto z^2 m^2/p^2 \ldots$

…brightness*p^2 $\propto m^2$
can be used as a mass index…

Several kinematical parameter were investigated to separate reaction channels:

- missing momentum
- missing mass
- coplanarity angle
- track brightness



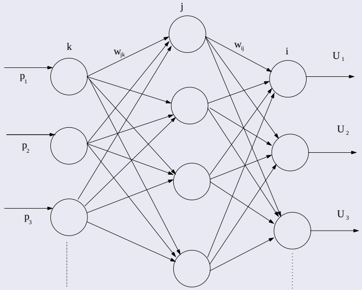
since
$-dE/ds \propto z^2 m^2 / p^2 \ldots$

...brightness*p^2 $\propto m^2$
can be used as a mass index...

...to separate π from p, α, ^{3}He and ^{3}H.

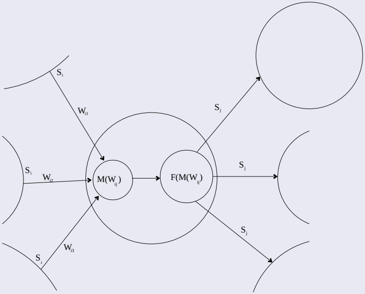
The kinematical parameters serve as input of the 4 input neurons

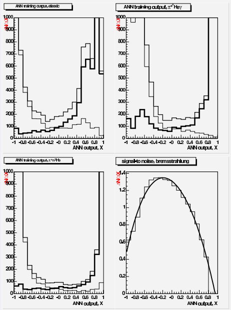
- w_{ij} intra-neurons weight
- p_k array of kinematical parameters



During the training phase a simulated population allows for intra-neurons weight adjustment

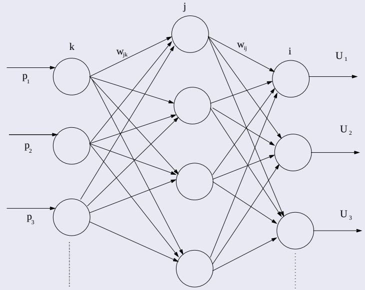
$$\Delta w_{ij} = \gamma \frac{\partial E}{\partial w_{ij}}.$$

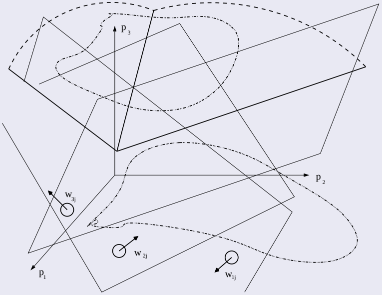




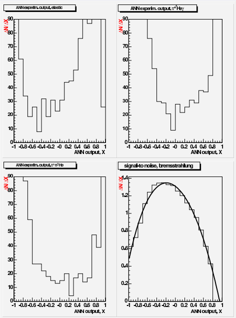
The ANN generates the best surface for separating events within the parameter space

$$U_i = f_a \left[\frac{1}{T} \sum_j w_{ij} f_a \left(\frac{1}{T} \sum_k w_{jk} p_k + o_j \right) + o_i \right]$$

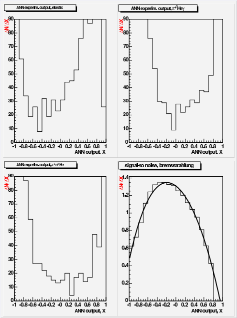


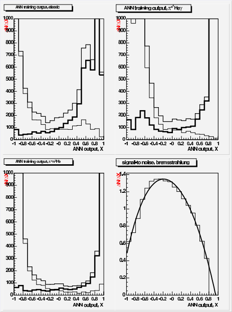


The results is the *probability* for each event to belong to each channel



The ANN results in simulated events are used to evaluate the systematic error on branching ratios





Results for 2-prong π^{-4}He reactions

Number of events per reaction channel after ANN processing:

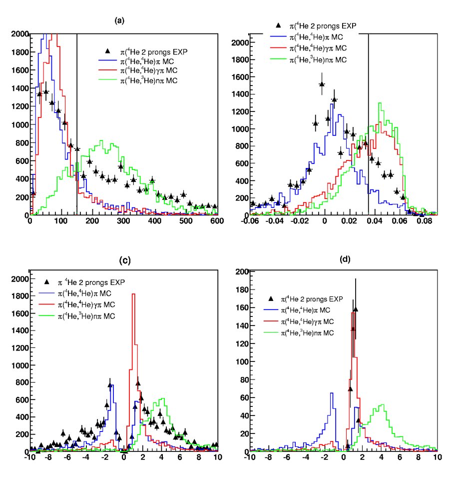
	channel	Number of signal events (ANN)	Events lost to background	Events added from background	Final number of events
1.	π^{-4}He	757±28	285	132	911±34
2.	π^{-4}Heγ	62±8	41	6	97±10
3.	π^{-}n^{3}He	704±27	120	34	790±29

Branching ratios for 2-prong $\pi^{\pm 4}$He reaction channels at 106 MeV:

	Channel	BR, π^-
1.	π^{-4}He	0.51±0.02
2.	π^{-4}Heγ	0.05±0.01
3.	π^-n^{3}He	0.44±0.02

high energy γs

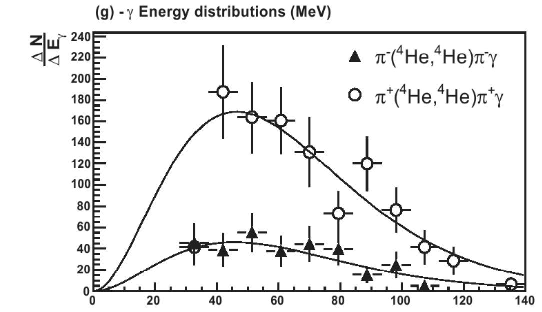
to check the $\pi^{4}\text{He}\gamma$ events we applied severe linear cuts:



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- Δ de-excitation
- prompt photons

...cannot explain γs energies higher than 28 MeV...



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- Δ de-excitation
- prompt photons

$\cdots \frac{B.R.gamma}{B.R.elastic}$

can only be compared with πp measurement:

$\pi p \rightarrow 0.0185$

$\pi^4 He\gamma \rightarrow 0.1$

[23] T. D. Blokhintseva et al. Yad. Fiz. (in Russian) **3** (1966) 511; T. D. Blokhintseva et al. Yad. Fiz. (in Russian) **8** (1968) 928.

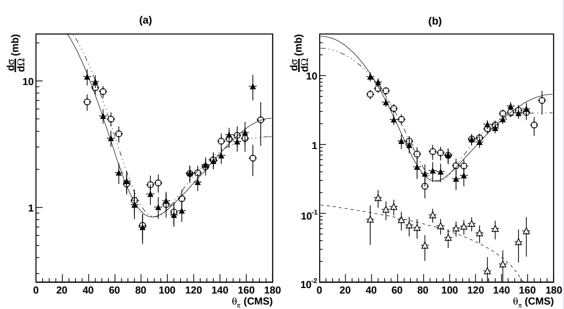
[24] D. I. Sober et al. Phys. Rev. **11D** (1975) 1017.

[25] F. E. Low, Phys. Rev. **110** (1958) 974.

Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- Δ de-excitation
- prompt photons

...moreover the gamma emission is isotropic...



Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- Δ de-excitation
- prompt photons

...is one of
the possible channels...

[27] G.Lopez Castro and A.Mariano, Nucl. Phys. **A 697** (2002) 440-468.

Possible γs sources

- de-excit. of nuclear levels
- bremsstrahlung radiation
- Δ de-excitation
- prompt photons

...a similar γ spectra is seen in high energy heavy nuclei collision together with a bckg of pions...
...but due to qq interaction...

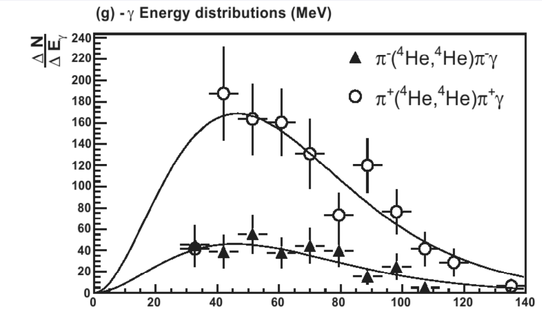
[26] P.Aurenche et al., Eur.Phys.J **C 9**, 107-119 (1999); Jorg Gayler, Acta Polonica **B** vol.37 (2006) numb.3, p.715.

Possible γs sources

The γs energy distribution shows a Planck thermal behaviour:

$$\frac{dI}{dE} \propto E^3 e^{-E/T}$$

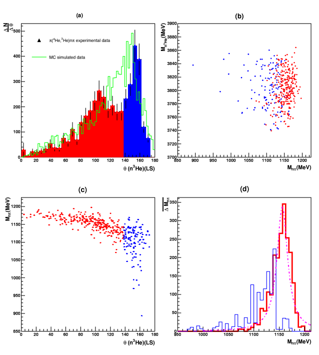
with T=14.4±1.6 MeV



first experimental Δ^- observation in π^-n^{3}He knockout reaction

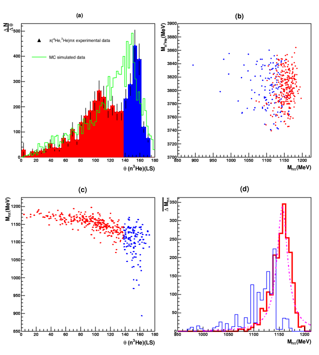
$\pi^- n^3He$ reaction: 2 structures are visible in θ_{n^3He} distribution:

- at high θ_{n^3He} $\longrightarrow$ "phase space"
- at low θ_{n^3He} $\longrightarrow$ $\longrightarrow$ resonance

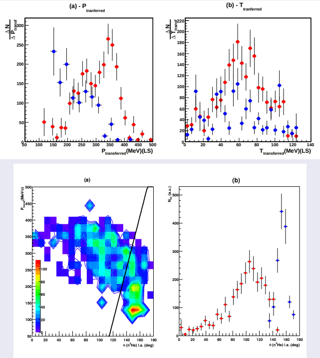


$\pi^- n^3He$ reaction: 2 structures are visible in θ_{n^3He} distribution:

- at high θ_{n^3He} $\longrightarrow$ "phase space"
- at low θ_{n^3He} $\longrightarrow$ $\longrightarrow$ resonance



overlapping region:
we observed Δ^-
activated only for high P_{transf}

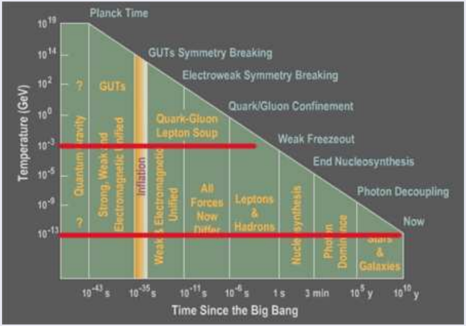


Features of Δ^-
in θ_{n^3He} reaction:

$$M_{\Delta^-} = 1160 \text{ MeV}$$
$$\Gamma/2 = 20 \text{ MeV}$$

ν masses are fundamental parameters
for modern physics:

ν possible candidates for Hot Dark Matter
. . . strongly dependent on decoupling T and masses



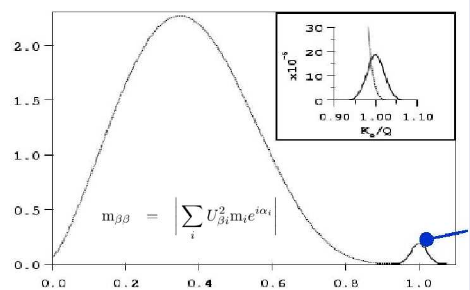
. . . and observable as
LSS confinement and velocities

ν physical features
to complete the SM or to support alternative models

$$M_\nu = -m_D^T \frac{1}{M_N} m_D$$

. . . massive νs go beyond the SM

Double β decay gives information on Majorana-Dirac nature of νs



Majorana or Dirac ν,
ν magnetic moment
are correlated with ν masses ...

Electron ν mass has been constrained by β decay:

- $\bar{\nu}_e$ <2 eV (95% c.l.) from ^{3}H β decay
- ν_e <225 eV (95% c.l.) from ^{163}Ho β decay

ν oscillation experiments give information on Δm_ν:

$$P(\nu_a - \nu_b) -> \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2_{ab} (eV^2) L(km/m)}{E (GeV/MeV)})$$

CERN-LGS-OPERA, K2K, DAYA BAY (ν factories)

and SNO, BOREXINO, SUPERKAMIOKANDE (solar and atm.)

Muon ν mass has been also constrained:

- by π decay in a spectrometer, with the assumptions of P_π=0, ΔP_π=0 and $\theta_{\pi\mu} = 0$
  - $\rightarrow$ M_ν <0.19 MeV (90% c.l.) Assamagan et al. Phys.Rev.D53:6065-6077,1996.
- by measuring the TOF of 3 GeV ν_μ
  - $\rightarrow$ M_ν <50 MeV (99% c.l.) Adamson et al. Phys.Rev.D76:072005,2007.