PAINUC

The Nuclear Matter
studied with the PAINUC experiment
Self Shunted Streamer Chamber
exposed to the E_π =106 MeV
JINR phasotron π beam

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

Meson 2010, Jagiellonyan University, Cracow, 10-15 June 2010

Outline

The Laboratory for Nuclear Problem

Devices

- Phasotron: channel III

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

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

  MC-4A

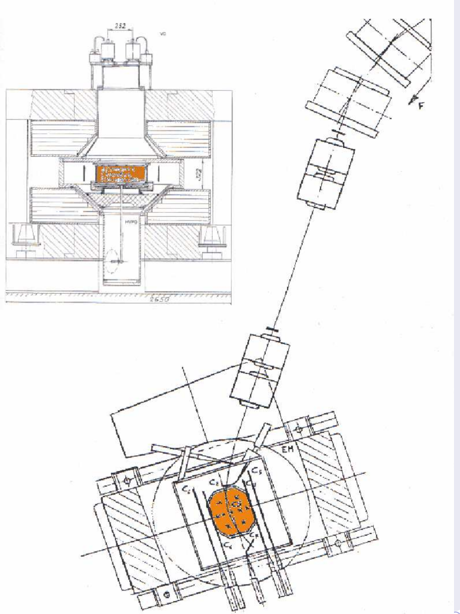
  $(H = 0.650 \pm 0.005\ T)$

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

  HVPG Marx-Arkadiev

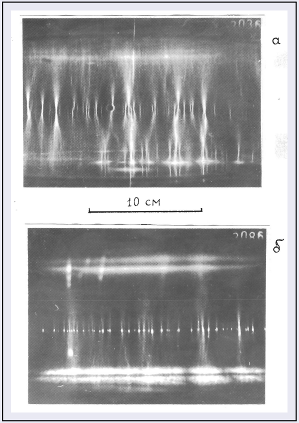
  $(\Delta V = 250\ KV)$

- 2 *Sensys Photometric CCD*



The Shunting Effect

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



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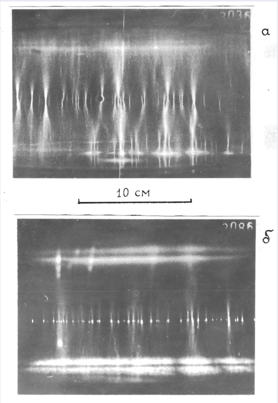


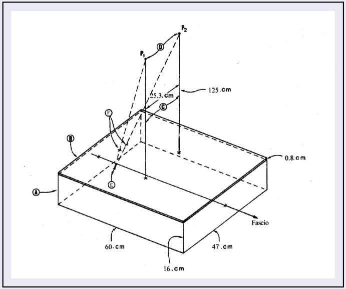
Features

- ^{4}**He** → { target / detection medium }
- momenta of strongly ionizing particles are *measureable*
  $\mathbf{P_{^xHe}}, \mathbf{P_p}, \mathbf{P_{^xH}}$

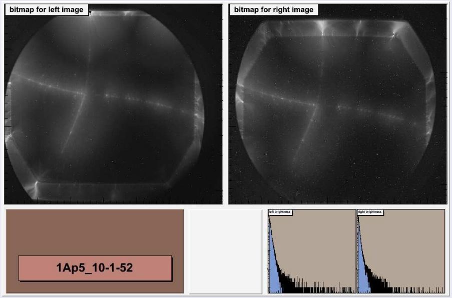
Averaged Track Lengths in ^4He

Track (mm)	T_π (MeV)	T_p (MeV)	$T_{^3He}$ (MeV)	T_α (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

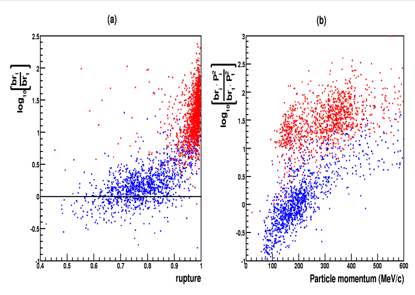
Event reconstruction



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



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

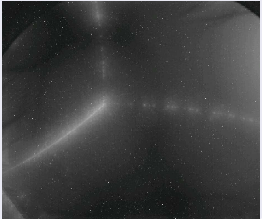


since $-dE/ds \propto z^2 m^2 / p^2$...

...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

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

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

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by using
classical parameters
for PID: (ionization power)

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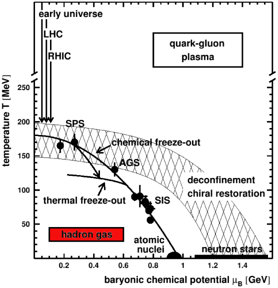
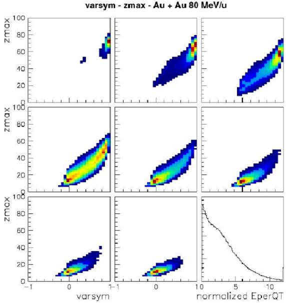
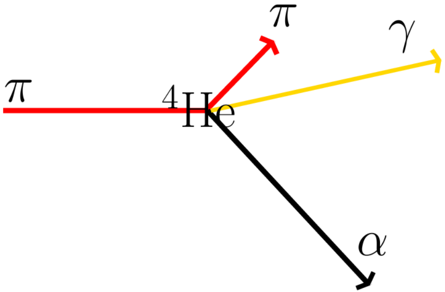
by using
classical parameters
for PID: (ionization power)

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

High Energy γs



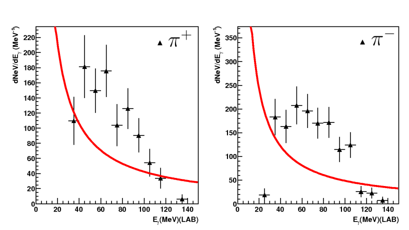




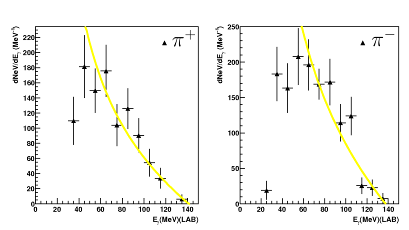
Branching ratios for 2-prong $\pi^{\pm 4}$He reaction channels at 106 MeV:

	Channel	BR, π^-	BR, π^+
1	$\pi^{\pm 4}$He	0.76±0.05	0.51±0.05
2.	$\pi^{\pm 4}$Heγ	0.11±0.04	0.05±0.03
3.	$\pi^{\pm}$n^{3}He	0.13±0.03	0.44±0.04

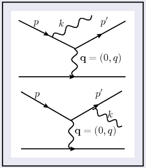
The External and Internal Bremsstrahlung hypotheses have been tested both for $\pi^{\pm}$:



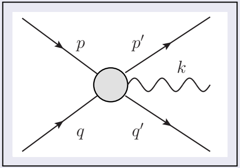
χ^2/ndf∼11 χ^2/ndf∼7



χ^2/ndf∼5-10

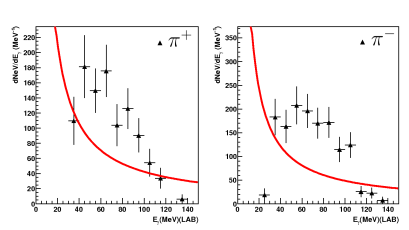


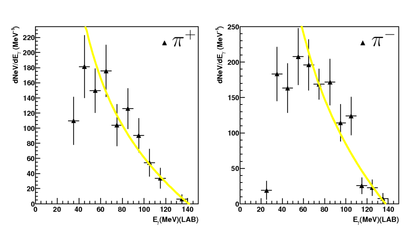
Landau, QED, vol.4



F.E.Low,Phys.Rev.110(4),1958

The bremsstrahlung radiation cannot explain the BR of γ emission: a factor 10-30 from theory is observed





BR radiative / elastic	
$\pi^+ p \rightarrow \pi^+ p \gamma$	$\pi^+\ {}^4He \rightarrow \pi^+\ {}^4He\gamma$
0.0185 [38], [39]	$\sim$0.1
BR proton/^{4}He comparison	
0.185	
BR proton/^{4}He expectation	
$\left(\frac{Z_\alpha}{Z_p}\right)^3 \left(\frac{M_p}{M_\alpha}\right)^2$ (att.field)	1.73
$\left(\frac{Z_\alpha}{Z_p}\right)^3 \left(\frac{M_p}{M_\alpha}\right)^3$ (rep.field)	6.48

The radiative Δ decay
$\Delta \rightarrow N\gamma$:

has low BR : $5{\cdot}10^{-3}$.

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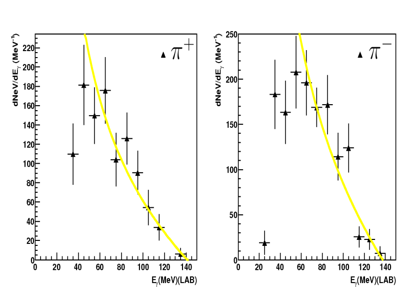
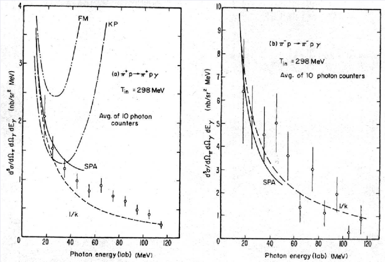
has low BR : $5 \cdot 10^{-3}$.

The Δ^{++} magnetic dipole moment $\mu(\Delta^{++} = 2\mu(p))$ de-excitation, $\Delta^{++*} \to \Delta^{++}\gamma \to \pi^{+}p\gamma$

should give a peak at $\omega \sim$80-100 MeV





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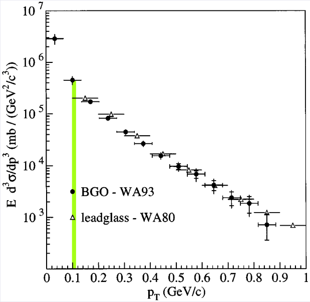


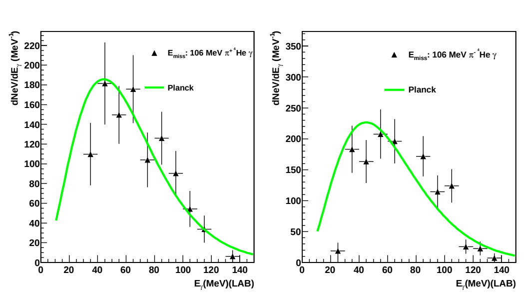
The same background
of π and γs
is observed at T<100 MeV
in RHIC collisions

The γs energy distribution shows a Planck thermal behaviour:

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

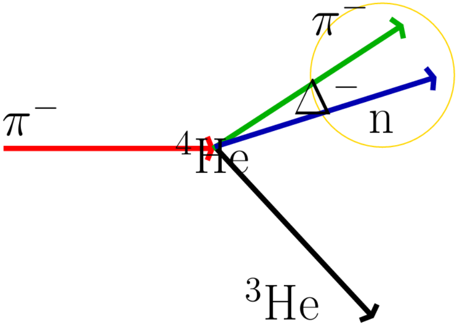
with T=16.0±1 MeV

$T_{\pi+}$=16.0±0.9 MeV $T_{\pi-}$=15.9±0.6 MeV



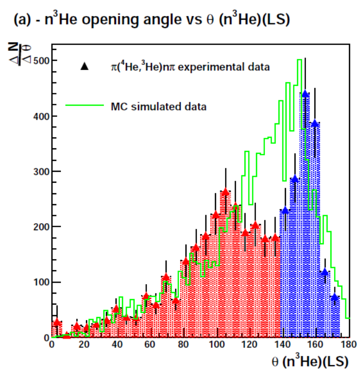
...explains high energy γs with no ^{4}He break-up and isotropic cross section.

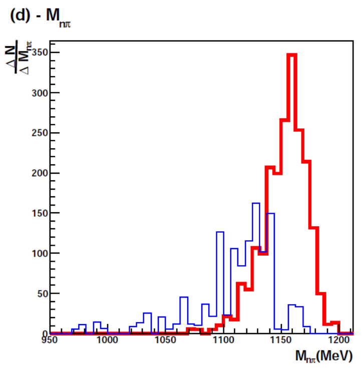
Resonances in the nuclear medium



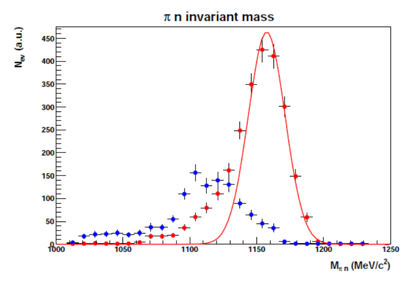
first experimental Δ^- observation in $\pi^- n^3$He knockout reaction: signatures for a collective resonance

we observed Δ^- resonance
in $\pi^- n^3He$ reactions
for the events at intermediate θ_{nHe} opening angles





Features of Δ^- in n^3He reaction:



$$\frac{\partial p}{\partial M_\Delta} = \frac{\sqrt{2}}{\sqrt{\pi}\sigma\Gamma} \exp\left\{ - \frac{1}{2\sigma^2}\left[(\Gamma/2)^2 + (M_\Delta - M_\Delta^0)^2\right]\right\}.$$

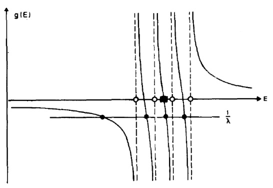
$$\begin{cases} M_\Delta = (1157 \pm 1)\ \mathrm{MeV/c^2} \\ \Gamma(\Delta) = (38 \pm 2)\ \mathrm{MeV/c^2} \\ \sigma = 14\ \mathrm{MeV/c^2} \end{cases}$$

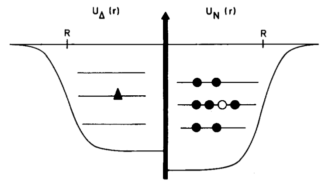
$$\begin{cases} \Delta M_\Delta = (1232 - 1157)\ \mathrm{MeV/c^2} = 75\ \mathrm{MeV/c^2} \\ \Delta\Gamma = (110 - 38)\ \mathrm{MeV/c^2} = 72\ \mathrm{MeV/c^2} \end{cases}$$

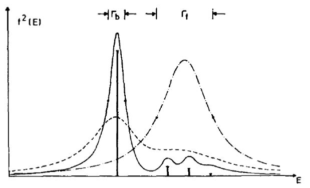
at high 3-mom and low q^2: the whole nucleus involved.

In 1974 Dillig and Huber [Phys.Lett.B 48, 5 (1974) 419], argued on the existence of a collective giant (3,3) resonance

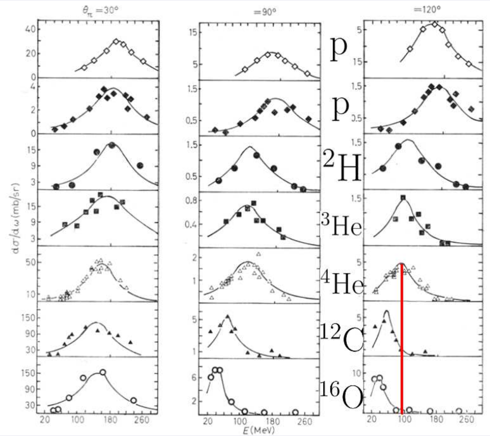
The residual ΔN interaction could give rise to a collective state with energy shift and width narrowing







...the backscattering kinematics reveals
the energy shift and
the width narrowing



[N.Cim.A 55 n.3 (1980) 273]

The interacting nucleons can modify the excitation energy and the width by introducing binding energy

$$\mathrm{E}_{exc} = \mathrm{E}_{exc}^{free} - \mathcal{B}_N[\mathcal{N}_N(\mathrm{A}) - \mathcal{N}_N(1)]$$

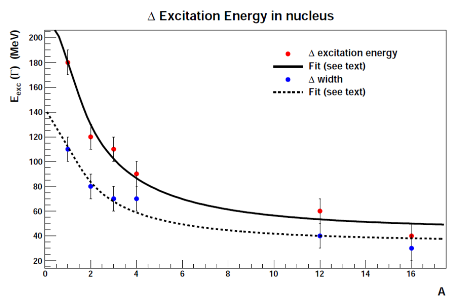
$$\Gamma = \Gamma^{free} - \frac{d\Gamma}{d\mathcal{N}_N}[\mathcal{N}_N(\mathrm{A}) - \mathcal{N}_N(1)]$$

by weighting the interacting nucleons with a Yukawa-like pdf

$$P(r) = \frac{e^{-r/\lambda}}{r}$$

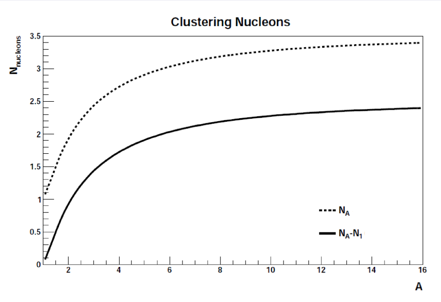
$$\mathcal{N}_N(\mathrm{A}) = \begin{cases} \mathrm{A} & \mathrm{R(A)} < \delta \\ \dfrac{\int_0^\delta V(\delta)\frac{d\mathrm{N}_N(r)}{dr}dr + \int_\delta^{\mathrm{R(A)}} V(r)\frac{d\mathrm{N}_N(r)}{dr}dr}{V(\delta)} & \mathrm{R(A)} \geq \delta \end{cases}$$

The empirical model is in good agreement with data on several nuclei: p, d, T, ^{3}He, ^{4}He, ^{12}C, ^{16}O (data extracted from N.Cim. 55A n.3 (1980), 273)

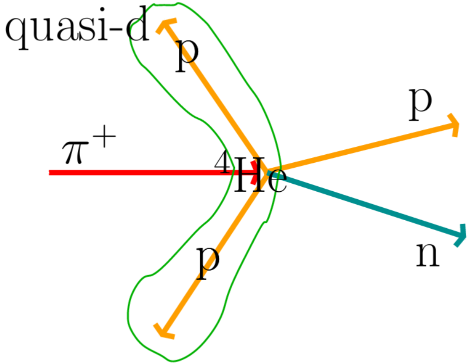


Mesonic Probe	Nucleus	E_{exc}	ΔE_{exc}(MeV)	Γ (MeV)	ΔΓ (MeV)
π^-	p	180	10	110	10
π^+	p	180	10	110	10
$\pi^\pm$	^{2}H	120	10	80	10
π^-	^{3}He	110	10	70	10
$\pi^\pm$	^{4}He	90	10	70	10
$\pi^\pm$	^{12}C	60	10	40	10
π^+	^{16}O	40	10	30	10

The collective Δ seems to be
π3N-π4N system
with strong contributions from the additional nucleons



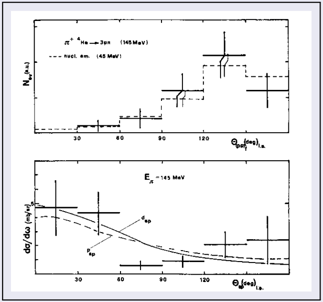
Binding energy per additional nucleon: E_B =(53.3±13.4) MeV
Contribution to width Γ per add. nucleon: $\frac{d\Gamma}{dN}$ =(30.8±4.2) MeV/c^2
Life increase per additional nucleon: $\frac{d\tau}{dN} \simeq 1.64 \cdot 10^{-24}$ s



The π^{+4}He$\rightarrow$ 3pn absorption channel

The abs on a q-deuteron (QDA) is well established from the 70s by experimental evidences at PSI, TRIUMF, LAMPF.

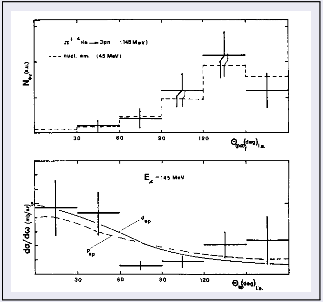
QDA on ^{4}He



Nucl.Phys.A 340,(1980),372

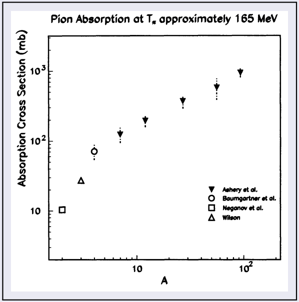
The abs on more than 2 nucleons are evident
from the 80s in several experimental observations

QDA on ^{4}He



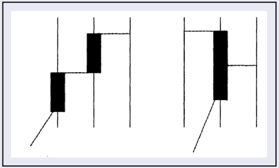
Nucl.Phys.A 340,(1980),372

σ_{abs}^{tot} vs nucleus

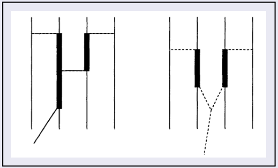


- $\sigma^{3He}/\sigma_H \sim 2$ (exp. 1.5 if QDA)
- $\sigma^{4He}/\sigma_H \sim 8$ (exp. 4 if QDA)
- for A>4 $\sigma \propto A^{2/3}$ (black disk)

Theoretical models were developed to introduce multinucleon pion abs mainly via ΔN and $\Delta\Delta$ intermediate states



Nucl.Phys.A,448,(1986),597.



Phys.LettB,118,(1982),39.

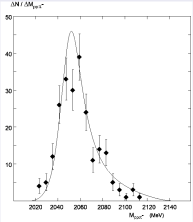
3 nucleons absorption (3NA) by sequential ΔN excitation

3 nucleons absorption (3NA) by coherent $\Delta\Delta$ excitation

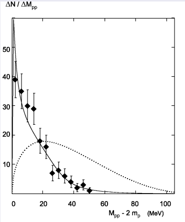
None of the models were able to explain the observations:

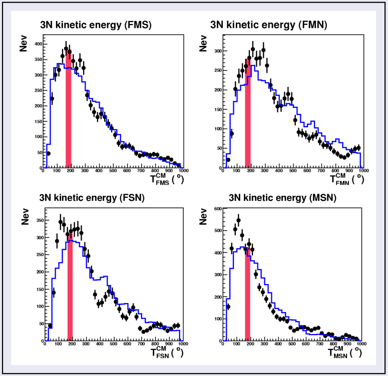
- several mechanisms involved
- most probably also Final and Initial State Interaction Effects
- Collective Resonance

The excitation of the dibarionic d' (πNN) in the 3NA



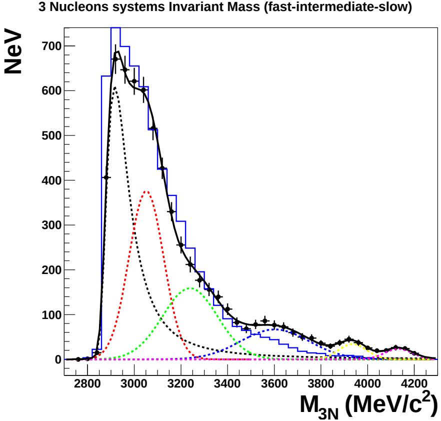
EPJA 28,1117(2006)



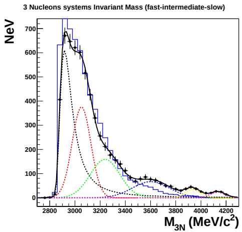


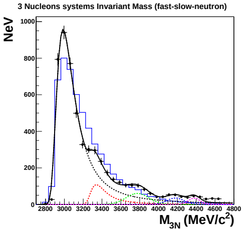
The πNNN$\to$d'N$\to$NNN is expected to occur with a 190 MeV energy release.

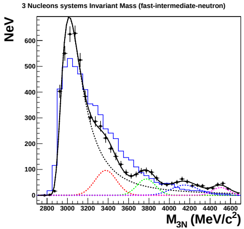
3-Nucleon Invariant Mass spectra M_{NNN}

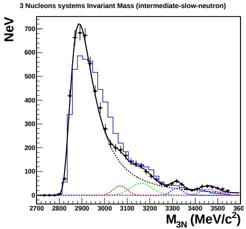


. . . reveal clear structures . . .





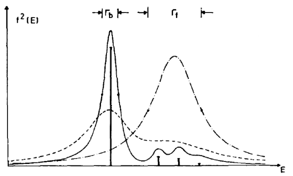




. . . that have been fitted to identify mass and width of peaks.

The observed peaks have common values for all the 3N systems

	FMS		FMN		FSN		MSN	
State	M	ΔM	M	ΔM	M	ΔM	M	ΔM
0	2923	±30	-	-	-	-	2895	±32
1	3052	±74	3031	±64	3000	±60	3069	±30
2	-	-	-	-	-	-	3162	±48
3	3239	±118	3377	±105	3350	±50	3320	±25
4	-	-	-	-	-	-	3462	±35
5	3603	±46	3773	±90	3775	±120	-	-
6	3936	±60	-	-	-	-	-	-
7	4132	±58	4151	±132	4180	±90	-	-
8	-	-	-	-	4380	±60	-	-
9	-	-	4503	±80	-	-	-	-



. . . the less energetic 3N system allows the observation of a finer structure.

Summary

PAINUC collaboration: Recent results and Future programs

- study of α at the hadron-gas state transition:
  - evidence for a $\pi^{\pm} +^{4} He \rightarrow \pi^{\pm} +^{4} He + \gamma$ reaction
    - Nuovo Cimento B (2007)
    - JPPNP 61 n.1 (2008) 308

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

with T=16±1 MeV

PAINUC collaboration: Recent results and Future programs

- studies of collective resonances in the nuclear medium:
  - first experimental evidence for Δ^- in $\pi^- +^4 He \rightarrow \pi^- +^3 He + n$ reaction
    - Eur. Phys. J. A 34, 255-269 (2007)

    a first empirical model for the collective Δ is proposed
    which suggest the resonance involves from 3 to 4 nucleons

other resonant channels under study:

$$\pi^{+4}He \rightarrow \Delta^{++\,3}H \rightarrow \pi^+ p^3 H$$
$$\pi^{+4}He \rightarrow \Delta^{+\,3}He \rightarrow \pi^+ n^3 He$$
$$\pi^{-4}He \rightarrow \Delta^{0\,3}H \rightarrow \pi^- p^3 H$$

PAINUC collaboration: Recent results and Future programs

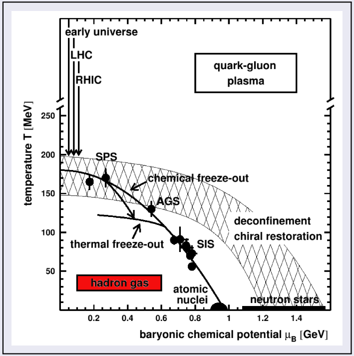
- studies of π absorption mechanisms:
  - the absorption in π^{+4}He$\rightarrow \pi^{+}$3pn
    - occurs at $\sim$14% on a 3 body system
    - and $\sim$56% on a 2 body system + effects or 3 body system
  - resonant peaks in 3-body invariant mass distributions
    - could be the collective resonance mass eigenstates
    - would suggest 3N abs via a intermediate collective state

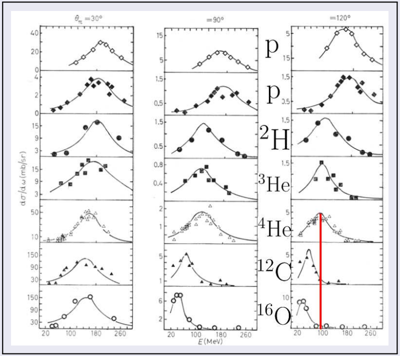
possible signatures also for

- absorption via intermediate dibarionic state: d'N$\rightarrow$3N absorption
- 4 nucleons absorptions
- structures in 3N invariant mass systems: collective resonance

Backup

Present data on $\pi^{\pm 4}$He at T_π =106 MeV: at **Fermi-gas** transition and max **Δ excit.** on ^{4}He



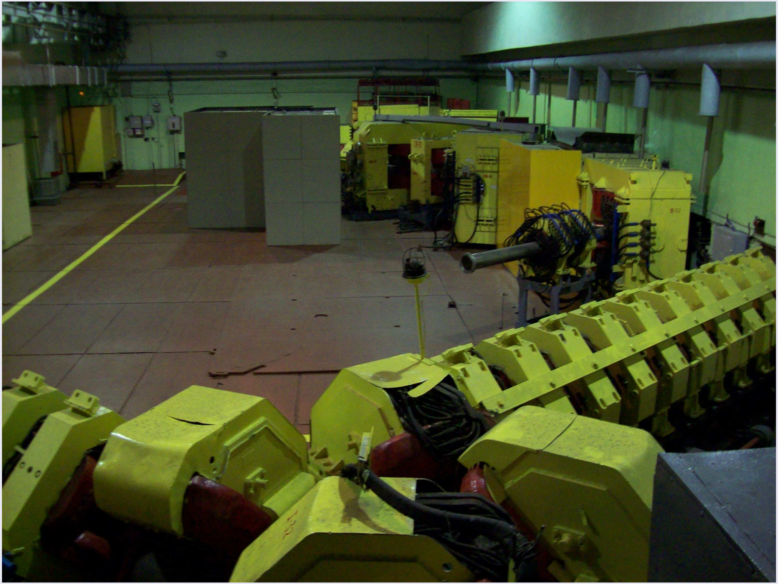


No observables available for **light nuclei** at Fermi-gas transition phase.

Investigation of Δ modifications in **intermediate temperature nuclear medium**

The Phasotron

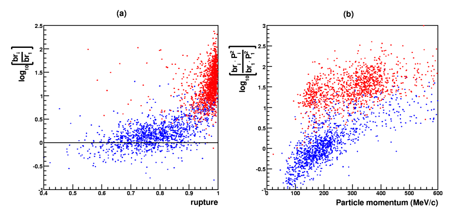
The Pion Line



Mass indicators identify Break-Up, SCX and Absorption reaction channels:

$$\pi^+ + {}^4He \rightarrow (\pi^0) + 3p + n$$
$$\pi^+ + {}^4He \rightarrow \pi^+ + 2p + 2n$$

$$\begin{cases} \text{SCX} \Rightarrow M_{\frac{sec1}{inc}} = \dfrac{br_{proton}\, p^2_{proton}}{br_{\pi\ inc}\, p^2_{\pi\ inc}} \simeq 50 \\ \text{breakup} \Rightarrow M_{\frac{sec2}{sec1}} = \dfrac{br_{\pi^+}\, p^2_{\pi^+}}{br_{\pi\ inc}\, p^2_{\pi\ inc}} \simeq 1, \end{cases}$$



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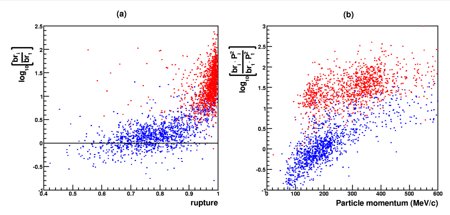
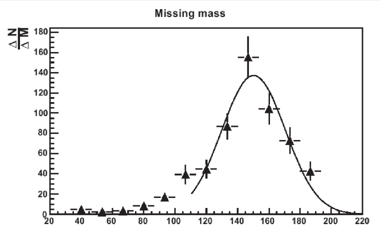
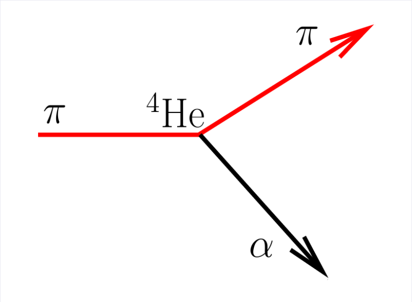


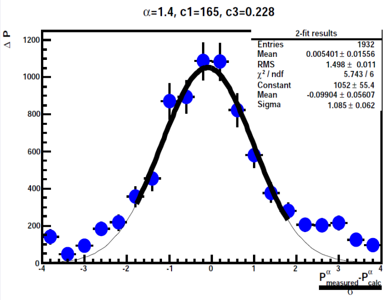


For **diffusion cloud chamber** Blackett found:

$$\left(\frac{\delta p}{p}\right)_{stat} \propto \frac{p^2}{L^2}$$

$$\delta k \propto \frac{1}{L^2}$$

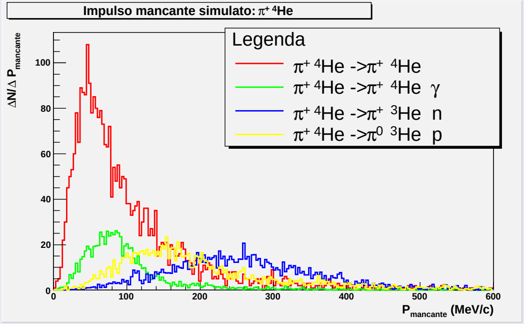




$$\begin{cases} \sigma_\pi = C_\pi \left(\frac{p}{l}\right)^\lambda = \sqrt{165}\left(\frac{p}{l}\right)_\pi^{1.4} \\ \sigma_\alpha = C_\alpha \left(\frac{p}{l}\right)^\lambda = \sqrt{0.228}\left(\frac{p}{l}\right)_\alpha^{1.4} \end{cases}$$

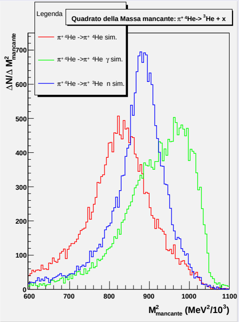
Several kinematical parameter were investigated to separate reaction channels:

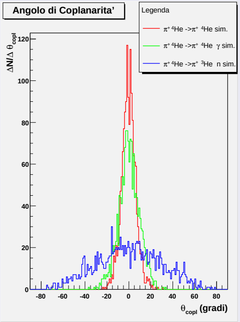
- missing momentum
- missing mass
- coplanarity angle



Several kinematical parameter were investigated to separate reaction channels:

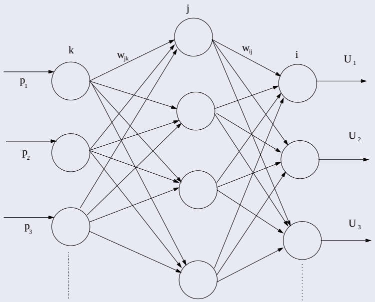
- missing momentum
- missing mass
- coplanarity angle

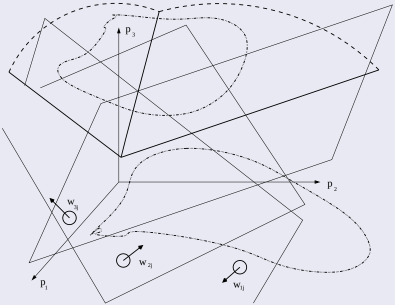




The ANN generates the best surface for separating events within the parameter space

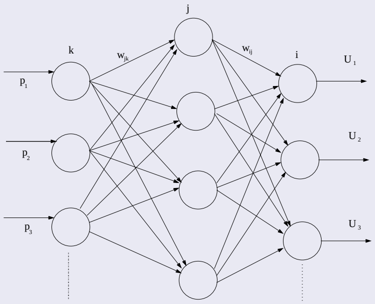
$$U_i = f_a\left[\frac{1}{T}\sum_j w_{ij} f_a\left(\frac{1}{T}\sum_k w_{jk} p_k + o_j\right) + o_i\right]$$

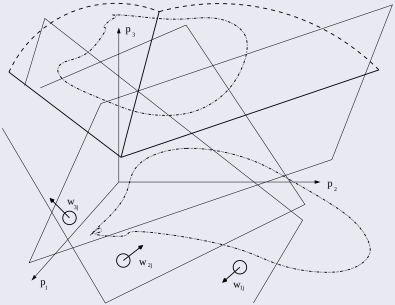




The kinematical parameters serve as input of the 4 input neurons

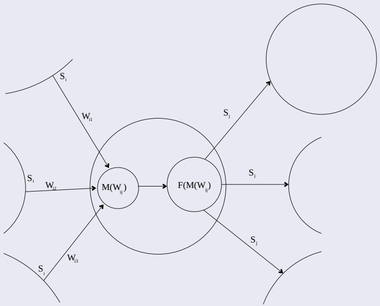
- w_{ij} intra-neurons weight
- p_k array of kinematical parameters

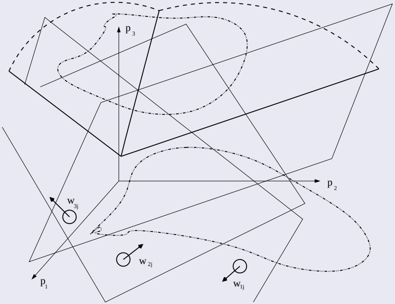




During the training phase a simulated population allows for intra-neurons weight adjustment

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





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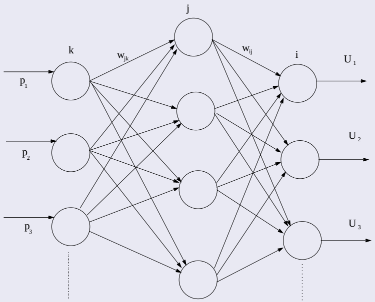
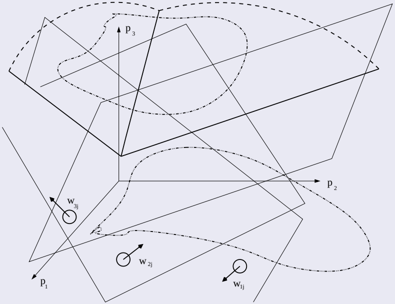
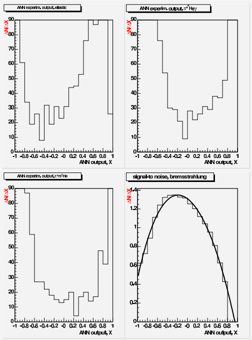
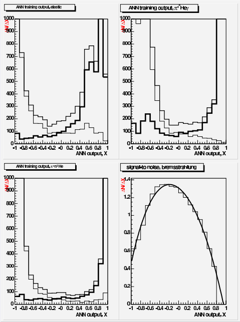


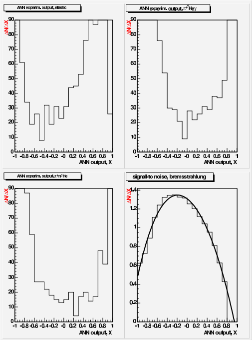


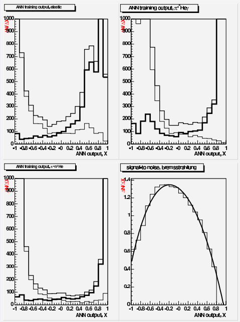
The results is the *probability* for each event to belong to each channel





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





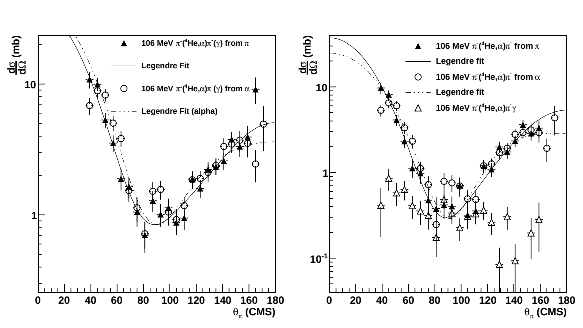
Comparison between present data at 106 MeV with previous at 120 MeV with diffusion chamber

The γs were probably counted as $\pi^+ n^3He$ and $\pi^0 p^3He$

Nucl. Phys. A340, (1980), 372

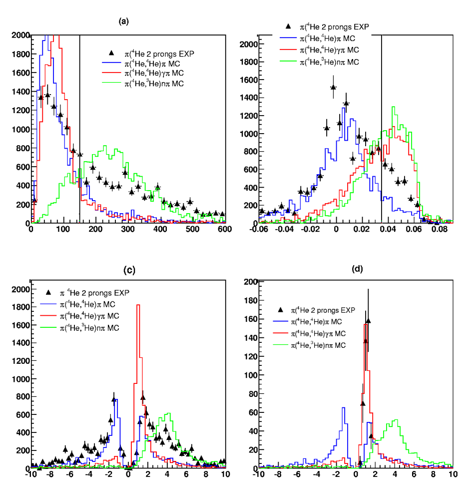
	channel	1980: diff.ch.(15 atm) 120 MeV	2006: str.ch.(1 atm) 106 MeV
1.	$\pi^{+4}He$	0.59 ± 0.08	0.35 ± 0.04
2.	$\pi^{+4}He\gamma$	—	0.04 ± 0.02
3.	$\pi^+ n^3He$	0.24 ± 0.04	0.32 ± 0.03
4.	$\pi^0 p^3He$	0.18 ± 0.05	0.29 ± 0.02

After the separation from elastic events:

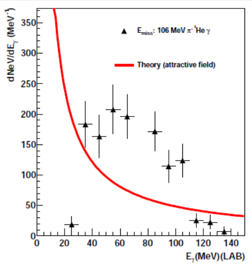


The radiative cross section doesn't show
the typical optical behavior of the elastic channel.

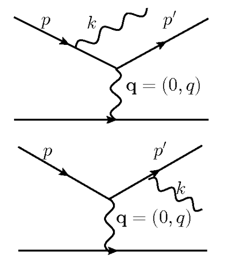
To check the $\pi^4He\gamma$ events severe cuts were applied:



The External Bremsstrahlung radiation for attractive field in π^4He interaction:

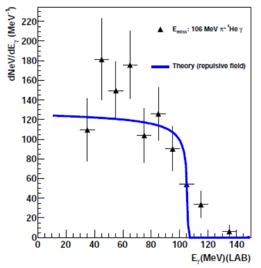


χ^2/ndf∼7

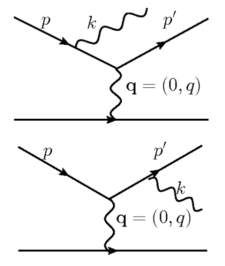


$$\frac{d\sigma}{d\omega} = \frac{64\pi}{3c} Z^3 \alpha^4 (\lambda^{\pi}_{\text{Compt}})^2 \frac{1}{\beta^2} \frac{1}{\omega}$$

The External Bremsstrahlung radiation for repulsive field in π^4He interaction:

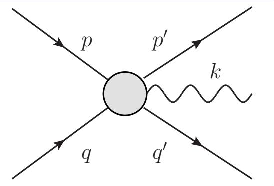


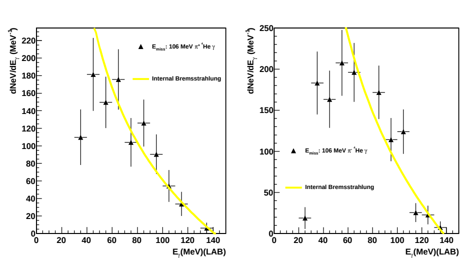
χ^2/ndf$\sim$3



$$\frac{d\sigma}{d\omega} = \frac{128\pi}{3c} Z^3 \alpha^4 (\lambda^{\pi}_{\mathrm{Compt}})^3 \frac{1}{\beta^4} \exp\left[-\sqrt{\frac{2\pi^2 Z^2 \alpha^2 mc^2}{\hbar(\omega_0 - \omega)}} \right]$$

The Internal Bremsstrahlung radiation: according to Low theorem the amplitude can be expanded in terms of π energy.

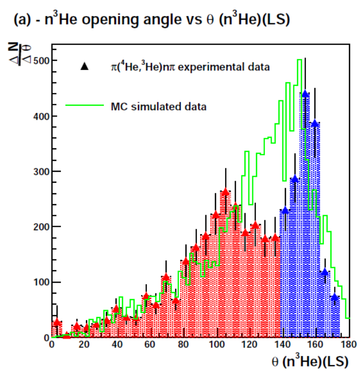


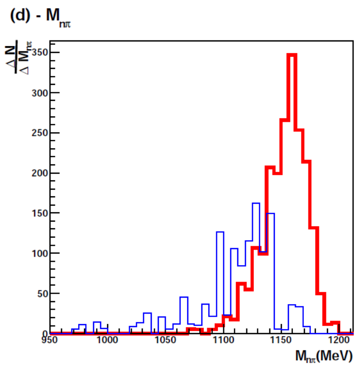


χ^2/ndf$\sim$5-10

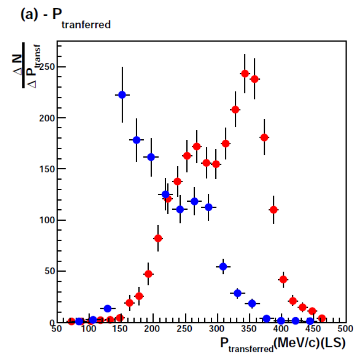
$$\sigma = \varphi\left[\frac{|c_1|^2}{\omega} + (c_1^* c_2 + c_1 c_2^*) + (c_2^* c_3 + c_2 c_3^*)\omega + \dots\right] = \frac{\sigma_0}{\omega} + \sigma_1 + \sigma_2\omega + \dots$$

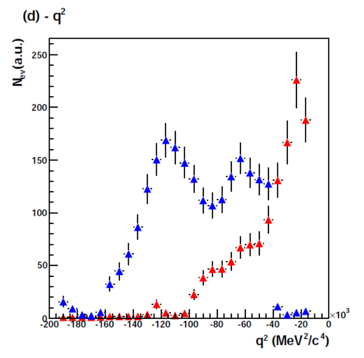
we observed Δ^- resonance
in $\pi^- n ^3He$ reactions
for the events at intermediate θ_{nHe} opening angles



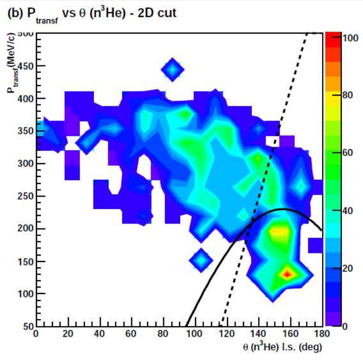


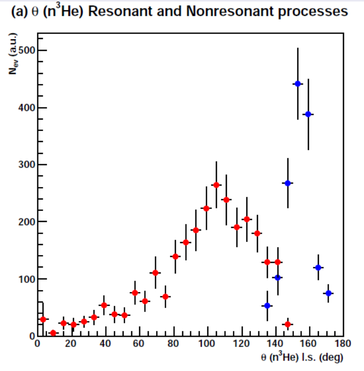
at high 3-momentum transfer and low q^2
thus for quasi-elastic backscattered pions:
the whole nucleus is involved



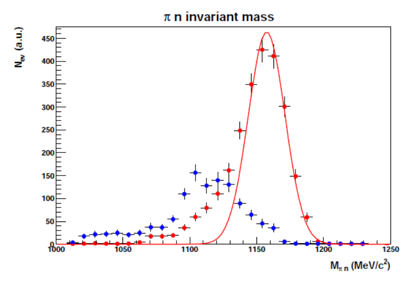


a $\color{red}{\text{2D cut}}$ on 3-momentum transfer and θ_{nHe}
resolves the resonant Δ^- process
from the non-resonant events





Features of Δ^- in n^3He reaction:



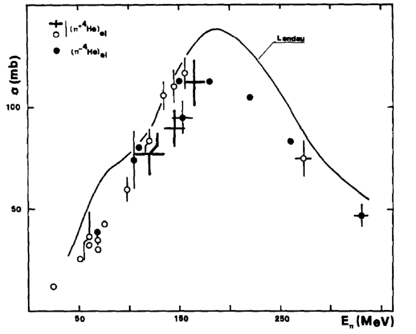
$$\frac{\partial p}{\partial M_\Delta} = \frac{\sqrt{2}}{\sqrt{\pi}\sigma\Gamma} \exp\left\{ -\frac{1}{2\sigma^2}[(\Gamma/2)^2 + (M_\Delta - M_\Delta^0)^2] \right\}.$$

$$\begin{cases} M_\Delta = (1157 \pm 1) \text{ MeV/c}^2 \\ \Gamma(\Delta) = (38 \pm 2) \text{ MeV/c}^2 \\ \sigma = 14 \text{ MeV/c}^2 \end{cases}$$

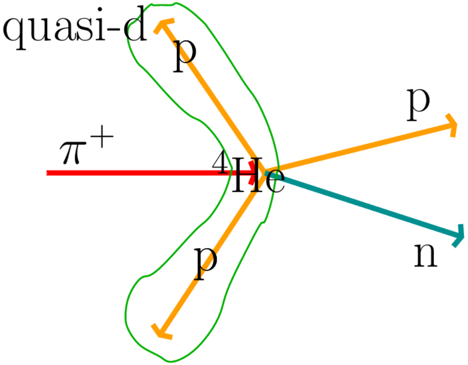
$$\begin{cases} \Delta M_\Delta = (1232 - 1157) \text{ MeV/c}^2 = 75 \text{ MeV/c}^2 \\ \Delta\Gamma = (110 - 38) \text{ MeV/c}^2 = 72 \text{ MeV/c}^2 \end{cases}$$

at high 3-mom and low q^2: the whole nucleus involved.

Previous measurements on the full phase space
do not show any energy shift:
the resonance is believed to undergo
multiscattering and Fermi motion broadening effects.



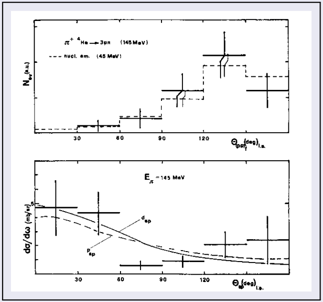
[Nu.Ph.A 340 (1980) 372]



The π^{+4}He→ 3pn absorption channel

The abs on a q-deuteron (QDA) is well established from the 70s by experimental evidences at PSI, TRIUMF, LAMPF.

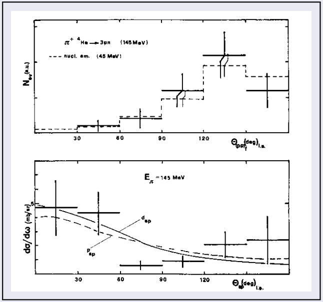
QDA on ^{4}He



Nucl.Phys.A 340,(1980),372

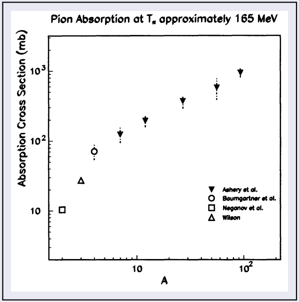
The abs on more than 2 nucleons are evident from the 80s in several experimental observations

QDA on ^4He



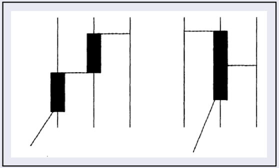
Nucl.Phys.A 340,(1980),372

σ_{abs}^{tot} vs nucleus

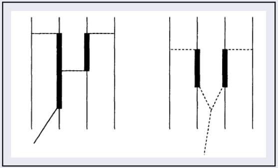


- $\sigma^{3He}/\sigma_H \sim 2$ (exp. 1.5 if QDA)
- $\sigma^{4He}/\sigma_H \sim 8$ (exp. 4 if QDA)
- for A>4 $\sigma \propto A^{2/3}$ (black disk)

Theoretical models were developed to introduce multinucleon pion abs mainly via ΔN and $\Delta\Delta$ intermediate states



Nucl.Phys.A,448,(1986),597.



Phys.LettB,118,(1982),39.

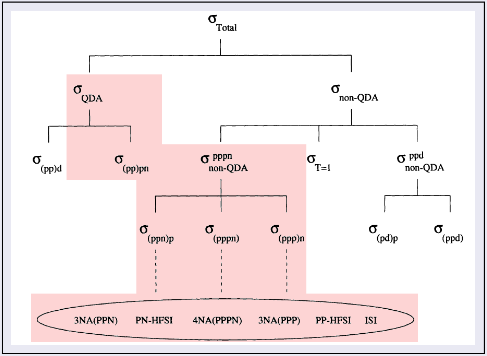
3 nucleons absorption (3NA) by sequential ΔN excitation

3 nucleons absorption (3NA) by coherent $\Delta\Delta$ excitation

None of the models were able to explain the observations:

- several mechanisms involved
- most probably also Final and Initial State Interaction Effects
- Collective Resonance

The π absorption on ^{4}He, with the π^{+4}He→pppn channel is the sum of several contributions



... but SFSI, HSFSI and ISI can be present also in 3NA and 4NA together with ΔN, ΔΔ, collective and $d'(\pi NN)$ states

For this reason a global fit requires high statistics and reliable models.
The IntraNuclearCascade MC, used at LADS analysis
models the 3 and 4NA as 2NA + effects

Multinucleons π ^{4}He Absorption (A.O. Mateos PHD Thesis (LADS))

Process	70 MeV	118 MeV	164 MeV	239 MeV
pure QDA	19.6 ± 2.8	25.5 ± 1.8	22.9 ± 2.0	9.8 ± 0.7
2NA+HFSI	7.1 ± 3.9	13.7 ± 6.0	6.8 ± 4.1	2.5 ± 0.6
pd/ppd	4.9 ± 0.8	6.8 ± 0.5	6.5 ± 0.6	2.4 ± 0.2
3NA/4NA	2.4 ± 2.0	3.8 ± 3.3	9.3 ± 2.4	9.2 ± 0.8
Total	34.5 ± 5.5	51.7 ± 4.4	48.2 ± 4.4	24.8 ± 1.8

$>$40% of ABS in Δ region not clearly identified as 2NA+effects or 3-4NA.
The 4NA seems a phase space ABS.

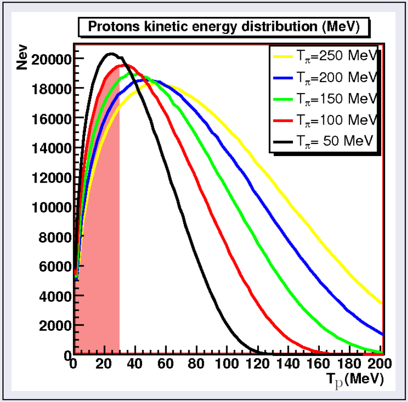
For this reason a global fit requires high statistics and reliable models.
The IntraNuclearCascade MC, used at LADS analysis
models the 3 and 4NA as 2NA + effects

^{3}He, ^{4}He 3NA with T_p >30 MeV, Phys.Rev.C,55(6),(1997),2931

Pion Energy (MeV)	2NA+ISI	2NA+HFSI/3N-PS (L=0,1)
70	11±8 %	89±8 %
118	4±3 %	96±3 %
162	16±5 %	84±5 %
239	29±9 %	71±9 %
330	38±13 %	62±13 %

Max 3NA ABS at the maximum of collective Δ excitation. However
2NA+effects or 3-4NA not clearly identified.

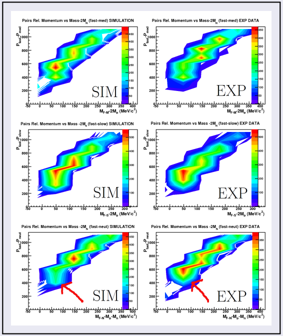
Present data on absorption at T_π =106 MeV



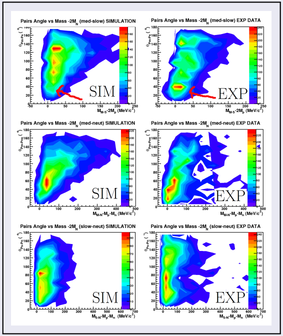
- Full kinematics at low energy: T_p <30 MeV at T_π ∼100 MeV is ∼30% of the phase space
- all 4 nucleons are measured
- low stat: no global fit
- study of strong deviations from PS allows to identify main active ABS mechanims

2-body correlations: kinematical distributions.
8 kin. pars. have been used to study pppn final states

2-body P_{rel} vs M_{NN}



2-body θ_{NN} vs M_{NN}



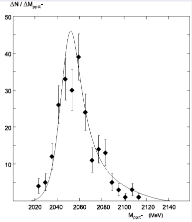
The use of 2 Dim kinematical distributions allows a more reliable identifications of ISI, SFSI and HFSI

2-body correlations: summary table

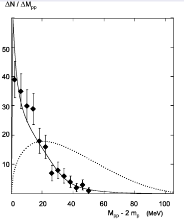
		INTERM. PROTON	SLOWEST PROTON		NEUTRON	
FASTEST P	θ_{NN}	160	30		170	
	SFSI	NO	NO		NO	
	HFSI	NO	NO		NO	
	ISI	NO	NO		WEAK	
	2N/3N/2S/2+E	2N/2S	2S		2N/2S/2+E	
INTERM. P	θ_{NN}		35	150	30	130
	SFSI		WEAK	NO	WEAK++	NO
	HFSI		NO	NO	NO	NO
	ISI		NO	NO	NO	NO
	2N/3N/2S/2+E		2S/2+E	2N/2S	2S/2+E	3N
SLOWEST P	θ_{NN}				120-140	35
	SFSI				NO	NO
	HFSI				WEAK	NO
	ISI				NO	NO
	2N/3N/2S/2+E				3N/2N+E	3N/2S

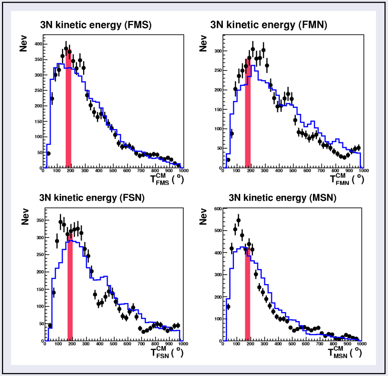
No clear 2NA. All nucleon pairs show signatures of 2NA+ (H/S)FSI, 2-step or 3NA.

The excitation of the dibarionic d' (πNN) in the 3NA



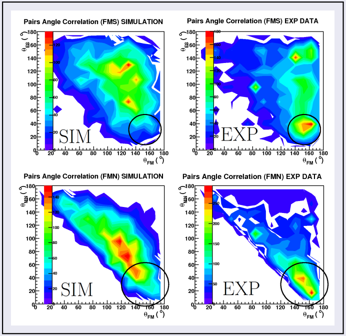
EPJA 28,1117(2006)

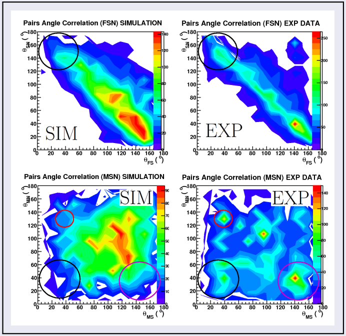




The πNNN$\rightarrow$d'N$\rightarrow$NNN is expected to occur with a 190 MeV energy release.

3-body angular correlations: θ_{N1N2} vs θ_{N1N3}





Strong deviations from PS suggest the presence of absorption mechanisms which directly involve 3-nucleon systems

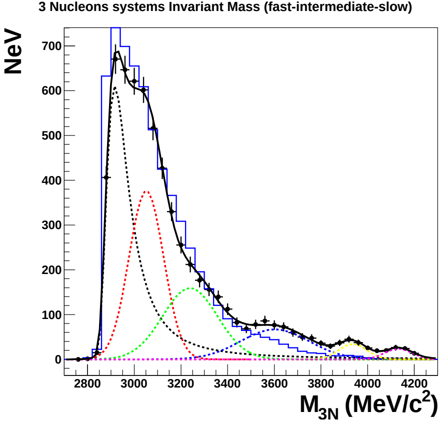
3-body correlations: summary table

F=Fastest proton, M=Intermediate, S=Slow, N=Neutron

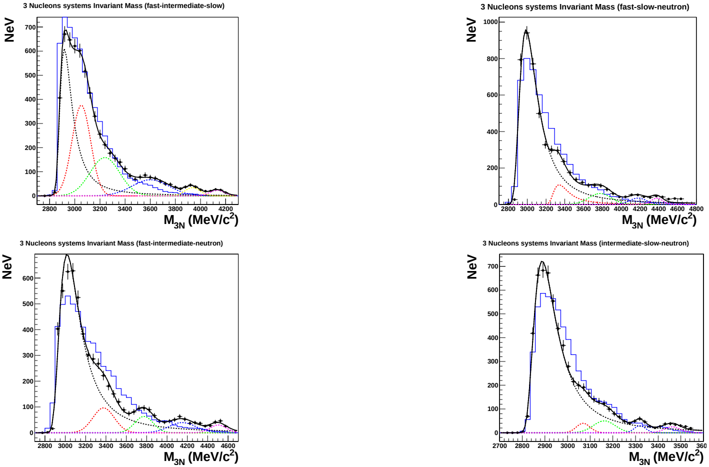
		MECH.	SIGN.	STAT	SIST	BCKG	STAT	SIST	SIG-BCKG	STAT	SIST
FMS		2NA(pd)	0.193	0.014	0.010	0.049	0.005	0.006	0.144	0.015	0.011
FMN		3NA(nd)/3NA(d')	0.367	0.020	0.016	0.328	0.010	0.027	0.039	0.022	0.031
FSN		2NA(nd)/3NA(d')	0.135	0.011	0.001	0.072	0.005	0.002	0.062	0.012	0.002
	black	4NA/3NA	0.107	0.010	0.012	0.038	0.004	0.001	0.103	0.011	0.012
MSN	purple	2NA(nd)/3NA(d')	0.133	0.005	0.011	0.068	0.012	0.008	0.065	0.013	0.014
	red	2NA(nd)/3NA(d')	0.026	0.004	0.005	0.019	0.003	0.001	0.007	0.005	0.005
TOTAL								3(4)NA	0.142 0.564	0.025 0.034	0.033 0.038

$\sim$ 40% are not clearly identified 2NA+(H/S)FSI or 3NA, in agreement with LADS results. $\sim$14% shows reliable features of a 2-Step 3NA process

3-Nucleon Invariant Mass spectra M_{NNN}



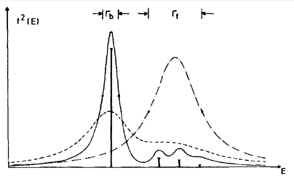
. . . reveal clear structures . . .



... that have been fitted to identify mass and width of peaks.

The observed peaks have common values for all the 3N systems

	FMS		FMN		FSN		MSN	
State	M	ΔM	M	ΔM	M	ΔM	M	ΔM
0	2923	±30	-	-	-	-	2895	±32
1	3052	±74	3031	±64	3000	±60	3069	±30
2	-	-	-	-	-	-	3162	±48
3	3239	±118	3377	±105	3350	±50	3320	±25
4	-	-	-	-	-	-	3462	±35
5	3603	±46	3773	±90	3775	±120	-	-
6	3936	±60	-	-	-	-	-	-
7	4132	±58	4151	±132	4180	±90	-	-
8	-	-	-	-	4380	±60	-	-
9	-	-	4503	±80	-	-	-	-



... the less energetic 3N system allows the observation of a finer structure.

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

ν masses are fundamental parameters
for modern cosmology and particle physics.
Several approaches are used to addressed neutrinos' features:

- β decay
- $0\nu2\beta$ decay
- oscillations
- cosmological constraints
- direct measurement

are complementary and the addressed quantities are in principle different

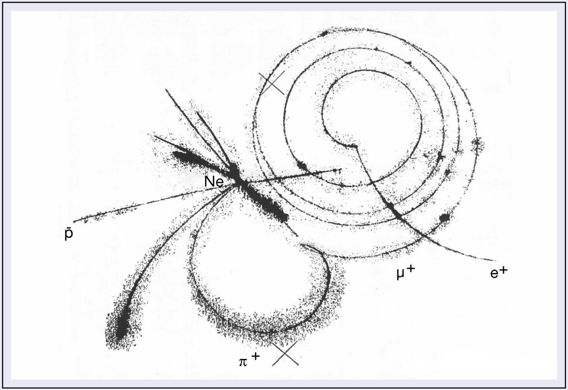
Electron ν mass has been constrained by β decay:

- $\bar{\nu}_e$ <2 eV (95% c.l.) from ^3H 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 $\theta_{\pi\mu} = 0$
  - $\to$ 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
  - $\to$ M_ν <50 MeV (99% c.l.) Adamson et al. Phys.Rev.D76:072005,2007.

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

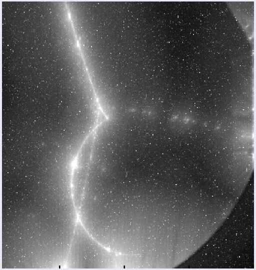


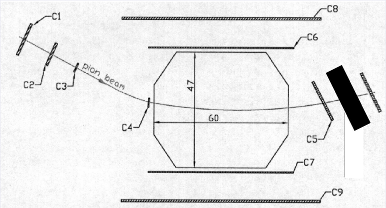
Kinematics of event

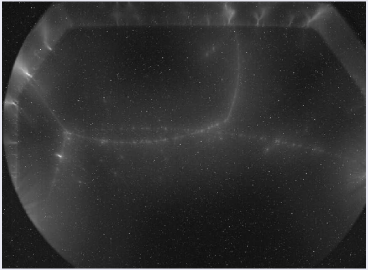
$$\begin{cases} P_\pi = (50 \pm 100) KeV/c \\ P_\mu = (29.9 \pm 19) KeV/c \\ \theta_{\pi\mu} = (163 \pm 1)^\circ \end{cases}$$

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

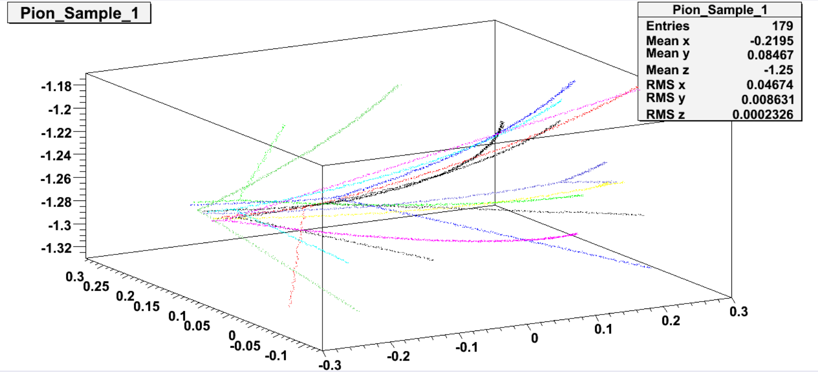
New measurement at PAINUC exp.
... both
$\pi^+ \text{->} \mu^+\nu$
and
$\pi^- \text{->} \mu^-\bar{\nu}$



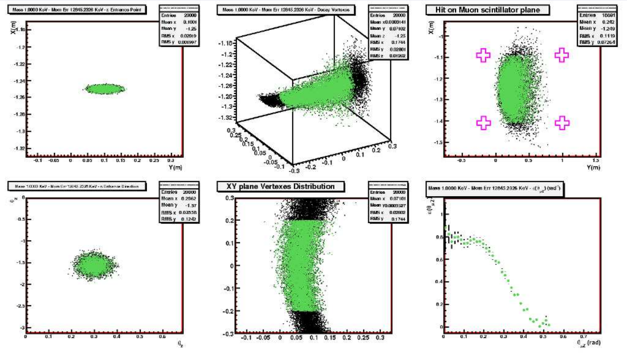




MC simulation of 68 MeV $\pi^{\pm}$ decays with JINR streamer chamber.

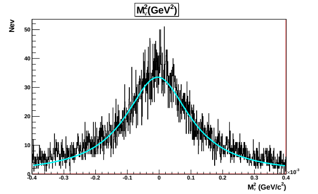


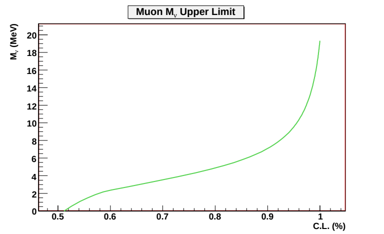
Geometry, Hadron Stopper and Trigger Hodoscope displacement



Spatial and momentum beam spread, magnetic field, triggering and final hodoscope displacement, measurement uncertainties and their effects on the reconstructed mass have been studied

Results of MC simulation on the reconstructed m_ν upper limit.



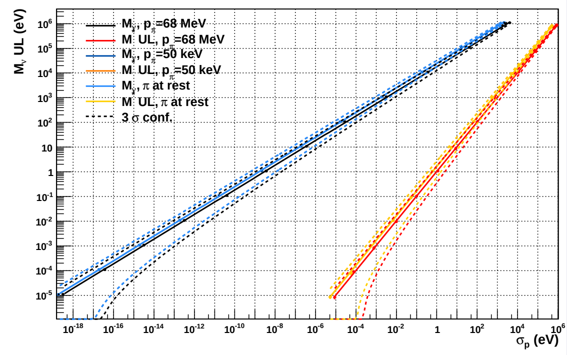


MC of π decays with *a priori* momentum and π mass resolution.

MonteCarlo parameters			
Energies of π beam	$10^{-9} eV$	50 keV	68 MeV
N ν masses	12	Range (eV)	10^{-5} - 10^{6}
N decades for $p_{\pi(\mu)}$ error	30	Range (eV)	10^{-20} - 10^{9}
N steps per decade	18	Step spacing	$10^{1/18}$
N events per point	100	C.L.	90 %
π mass (MeV)	139.570530	Δ M_π (eV)	350 eV
μ mass (MeV)	105.6583668	Δ M_μ (eV)	4 eV

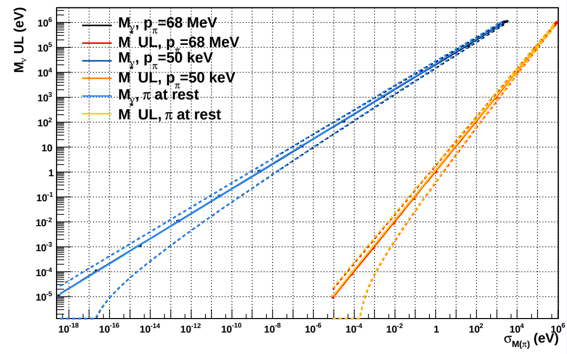
... to study the effects of momentum resolution and pion mass uncertainty on the final m_ν

Effects of the momentum resolution: at T_π ~68 MeV ~30% less resolution needed



... and $\sigma_p^{68MeV} = 5 \cdot 10^{-9}$ eV/c^2 for resolving a 1 eV neutrino!

Effects of the π mass uncertainty



The direct measurement is limited to m_ν >400 keV due to pion mass uncertainty