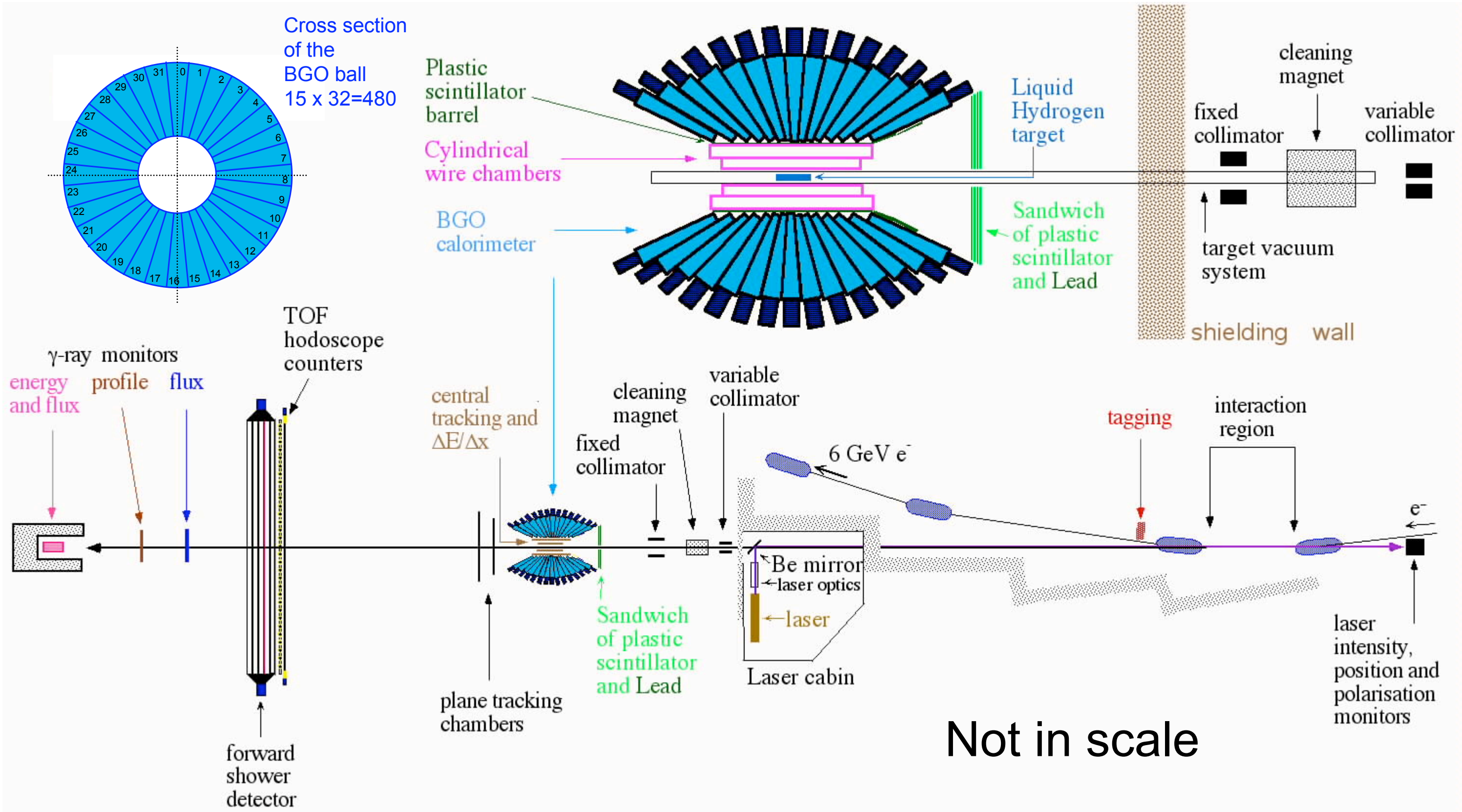
The Graal experiment at the ESRF

Carlo Schaerf
for the
Graal Collaboration

University of Rome “Tor Vergata”
and
INFN - Sezione di Roma Tor Vergata

The Graal Apparatus



The Graal Detector

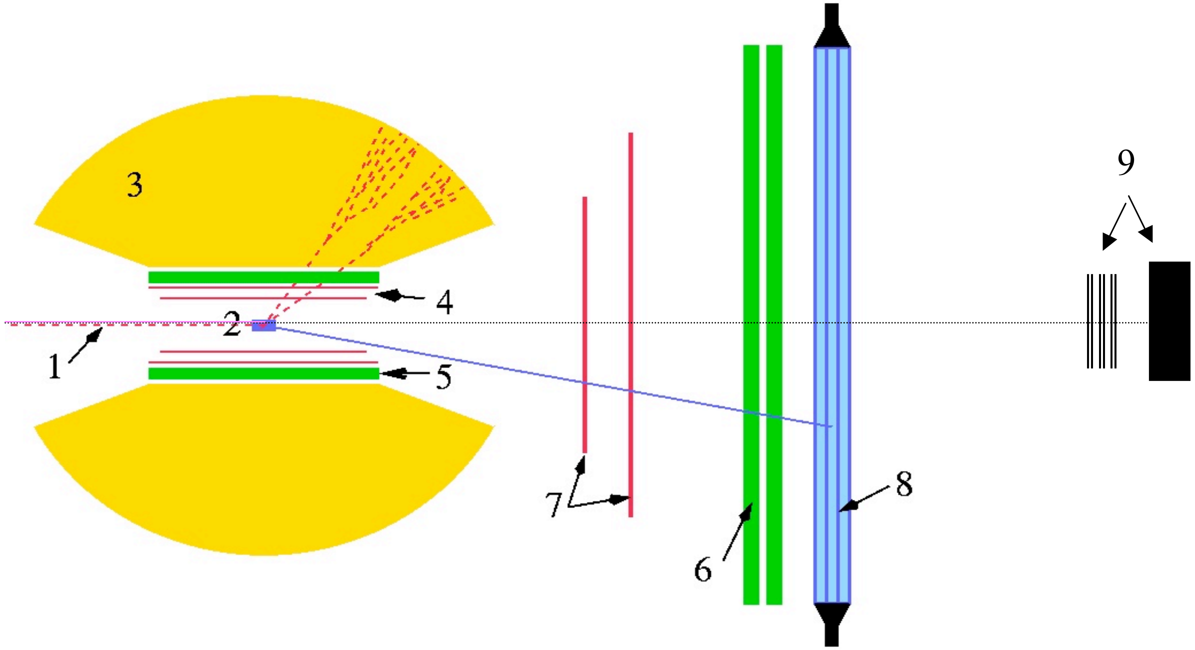
➢Liquid Target :
2 H^2 or D^2

➢Central angles :
$25^o < \theta < 155^o$

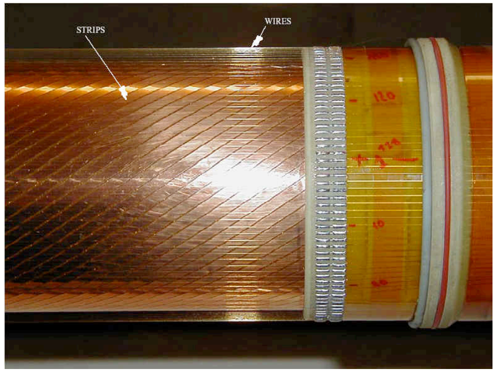
- BGO calorimeter
- 2 cylindrical MWPC
- barrel of plastic scintillators

➢Forward angles :
$\theta < 25^o$:

6 double wall of scintillators
7 planar MWPC
8 shower wall
9 monitor detectors



Central Angles (25^o < θ < 155^o): MWPC, BARREL



- **2 cylindrical MWPC**

tracking of the charged particles

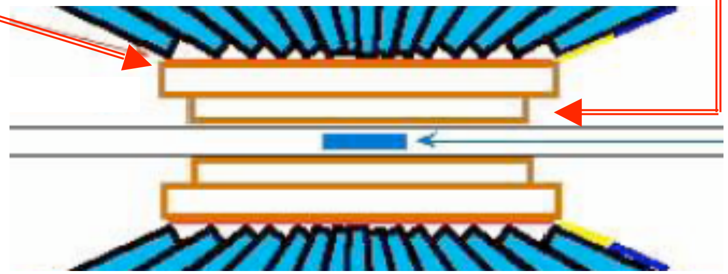
Angular resolution **$\Delta\theta = 2°$** **$\Delta\phi = 1.4°$**

Around the MWPC:

- **barrel of 32 plastic scintillators (NE102A)**

⇩

charged/neutral particles discrimination
(veto for neutral particle)
charged particles identification by means of dE/dx vs. E
(E is measured in the BGO)



Forward Angles (θ < 25°): MWPC, Hodoscope

- **2 sets of planar MWPC (xy, uv)**

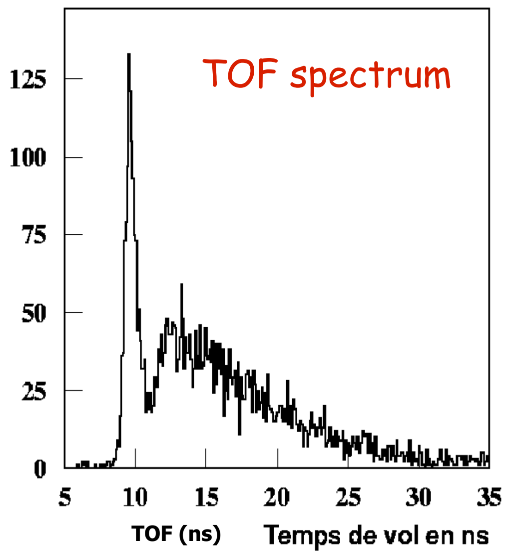
  tracking of the charged particles

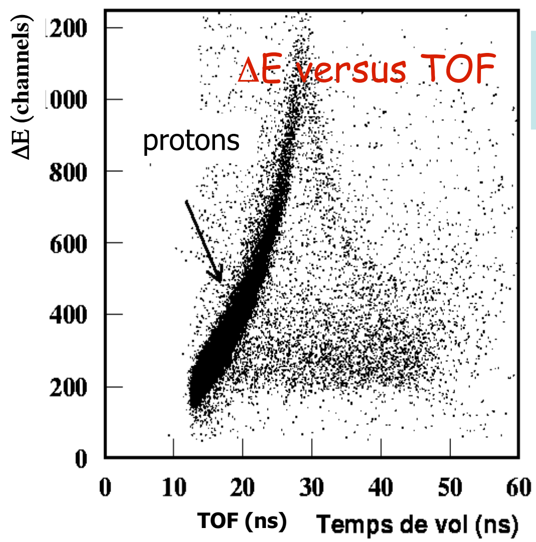
Angular resolution **Δ θ = 2 °**
Δϕ = 1.4 °

- **Double Forward Scintillator Wall (hodoscope)**

26 x 26 bars NE110A
300 x 11,5 x 3 mm

- Charged particle identification (pions, proton) by means ΔE vs. TOF
- TOF measurement for energy determination of charged particles





Angular resolution
Δθ ≅ Δφ ≅ 3°

Forward Angles ($\theta < 25^o$): Russian Wall

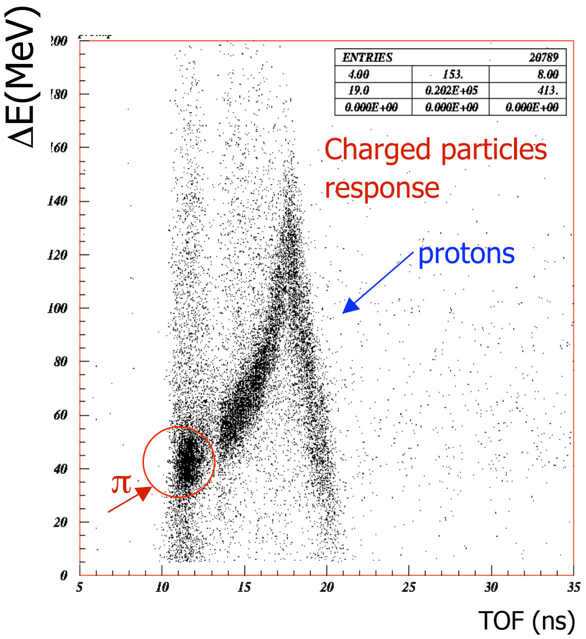
- **Forward Shower Wall**

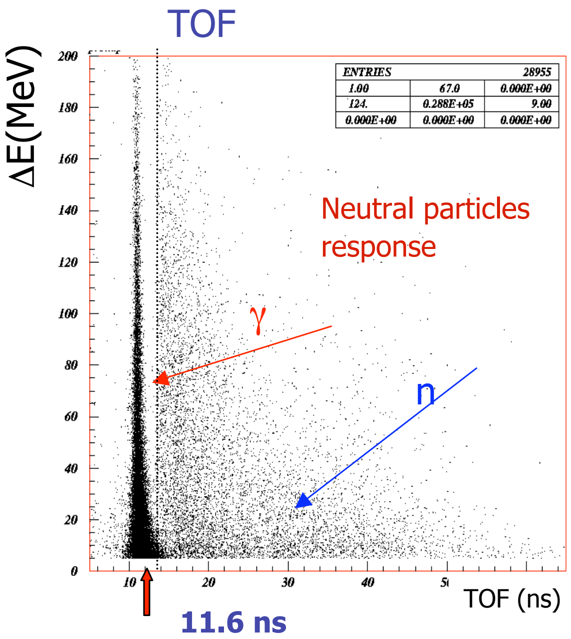
TOF measurements provide:

✓Energy information for protons and neutrons
✓photon/neutron discrimination
✓pion/proton discrimination
✓charged/neutral particle discrimination in coincidence with the hodoscope

16 ***sandwich*** modules :
4 layers of scintillators 10 cm thick
3 layers of lead converters 3 mm thick
frontal iron plate 5 mm thick

photon efficiency 92-95%
neutron efficiency 22%





A brief report

η photo-production in D_2
on quasi free proton
on quasi free neutron

$$\gamma+p+(n) \rightarrow \eta+p+(n)$$
$$\gamma+n+(p) \rightarrow \eta+n+(p)$$

total photo-production
cross sections
INR

ω photo-production in H2 and D2
on free proton in H_2
on quasi free proton in D_2
on quasi free neutron in D_2

$$\gamma+p \rightarrow \omega+p$$
$$\gamma+p+(n) \rightarrow \omega+p+(n)$$
$$\gamma+n+(p) \rightarrow \omega+n+(p)$$

π^- p photo-production in D_2

$$\gamma+n+(p) \rightarrow \pi^-+p+(p)$$

Events Selection for η Photoproduction on Quasi-Free Nucleons from Deuteron

η photo-production on quasi free proton

$\gamma + p + (n) \rightarrow \eta + p + (n)$, $\eta \rightarrow 2\gamma$

⇩

Neutron is a spectator

η photo-production on quasi free neutron

$\gamma + n + (p) \rightarrow \eta + n + (p)$, $\eta \rightarrow 2\gamma$

⇩

Proton is a spectator

2 γ in the BGO

+

participant nucleon in the central or forward direction

NO other particle

(the spectator particle is not detected)

Bi-Dimensional Cuts

Over-determined Information provided by apparatus

⇩

Particles energy and angles can be Measured or calculated by the Variables of the other particles from two-body kinematics

$$\left.\begin{matrix} E_{\bar{\gamma}} & & \\ E_{\eta}^{meas} & \theta_{\eta}^{meas} & \varphi_{\eta}^{meas} \\ & \theta_{N}^{meas} & \varphi_{N}^{meas} \end{matrix}\right\} \rightarrow \begin{matrix} \theta_{N}^{calc} \\ E_{\eta}^{calc} \\ M_{\eta}^{miss} \end{matrix}$$

Bi-dimensional distributions ⇨ Each Distribution fitted by Bi-dimensional Gaussian

extraction of mean and σ_ι values

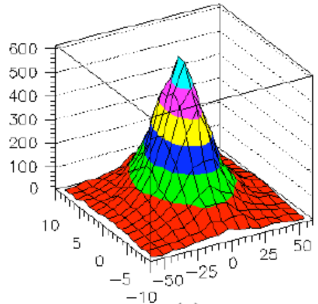
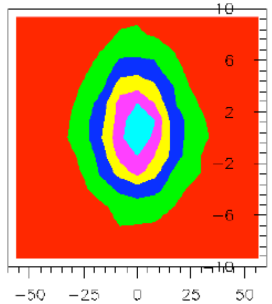
⇩

Bi-dimensional cuts

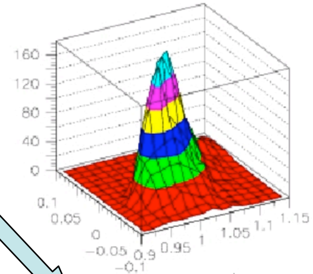
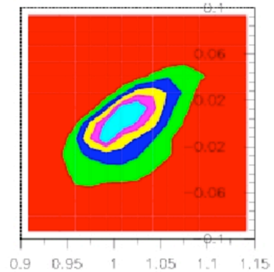
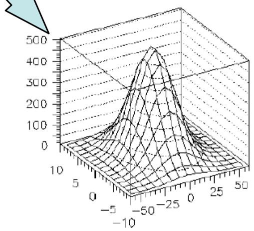
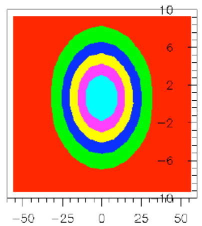
$$\frac{(x-\mu_1)^2}{\sigma_1^2}+\frac{(x-\mu_2)^2}{\sigma_2^2}-\frac{2C(x-\mu_1)(x-\mu_2)}{\sigma_1\sigma_2}<\sigma^2 \qquad [\sigma=1-3]$$

Selection cuts:

$$\left(\theta_N^{meas}-\theta_N^{calc}\right) vs \left(\varphi_N^{meas}-\varphi_\eta^{meas}-180°\right)$$

$$\left(E_\eta^{calc}/E_\eta^{meas}\right) vs \left(M_\eta^{miss}-M_N\right)$$

Events Selection – Quasi Two-Body Kinematics

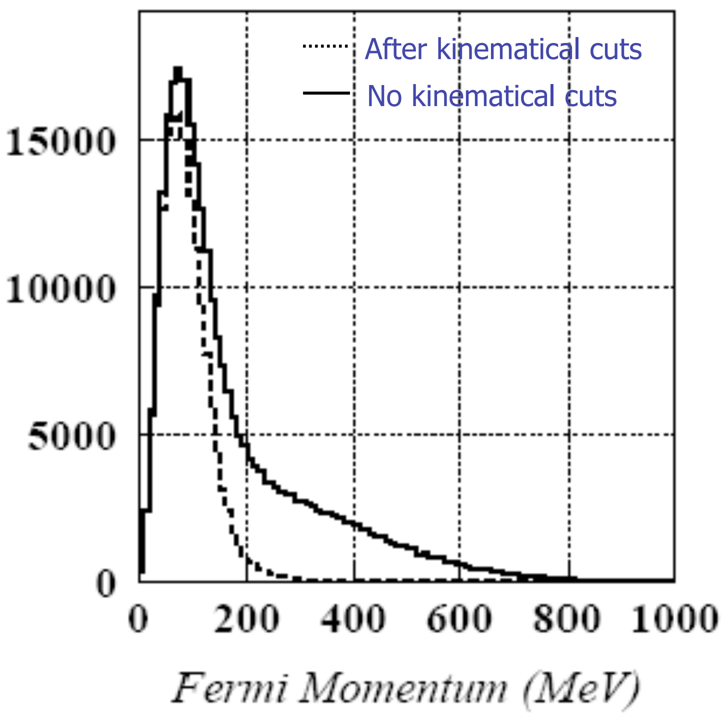
Quasi-free process
and low Fermi momentum

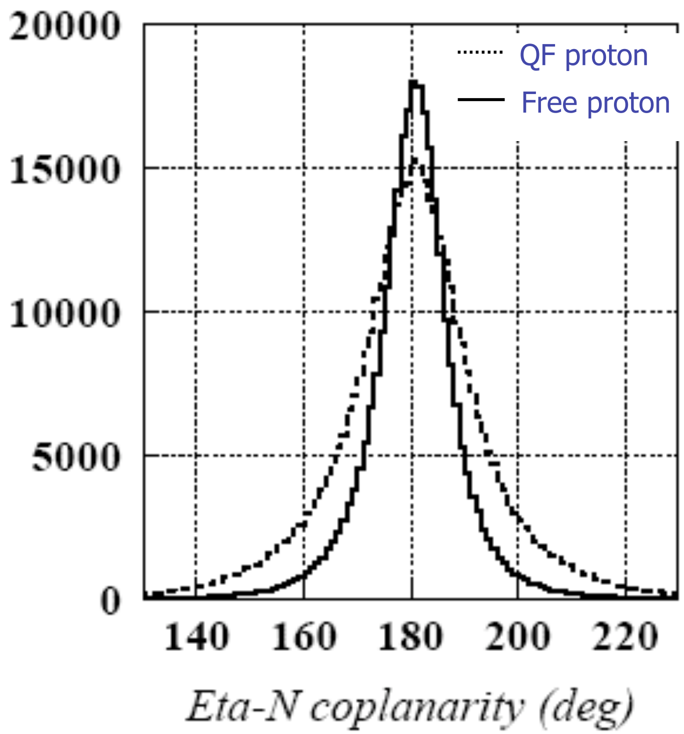
Kinematical Analysis:

- **Two-body nature of each reaction step:**

Fermi momentum Contribution

Smearing of distributions





η Invariant Mass and Estimated Background After Cuts

a) Central proton

2.4 %

b) Central neutron

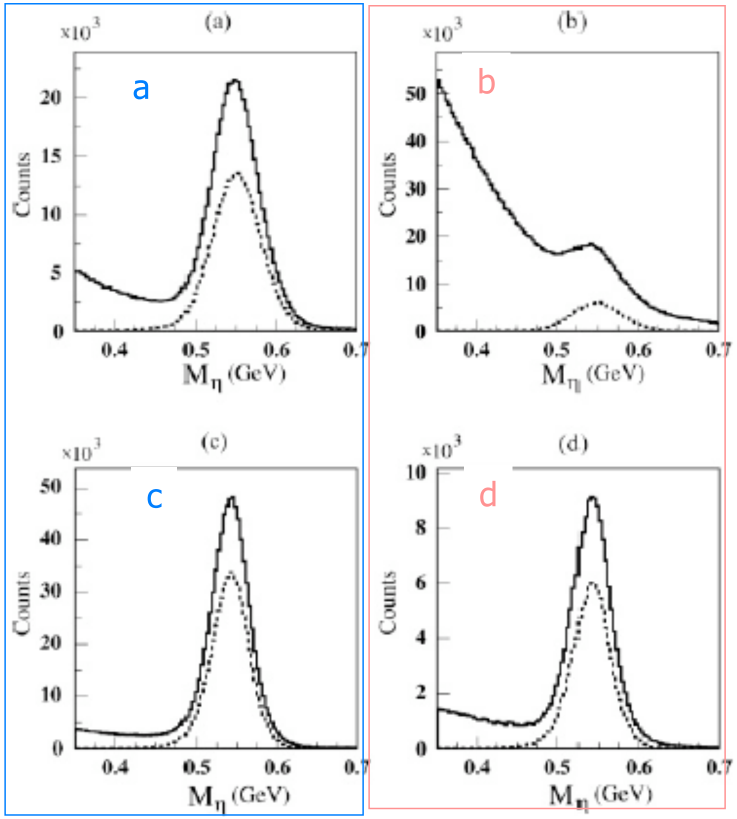
3.9 %

c) Forward proton

0.9 %

d) Forward neutron

1.4 %

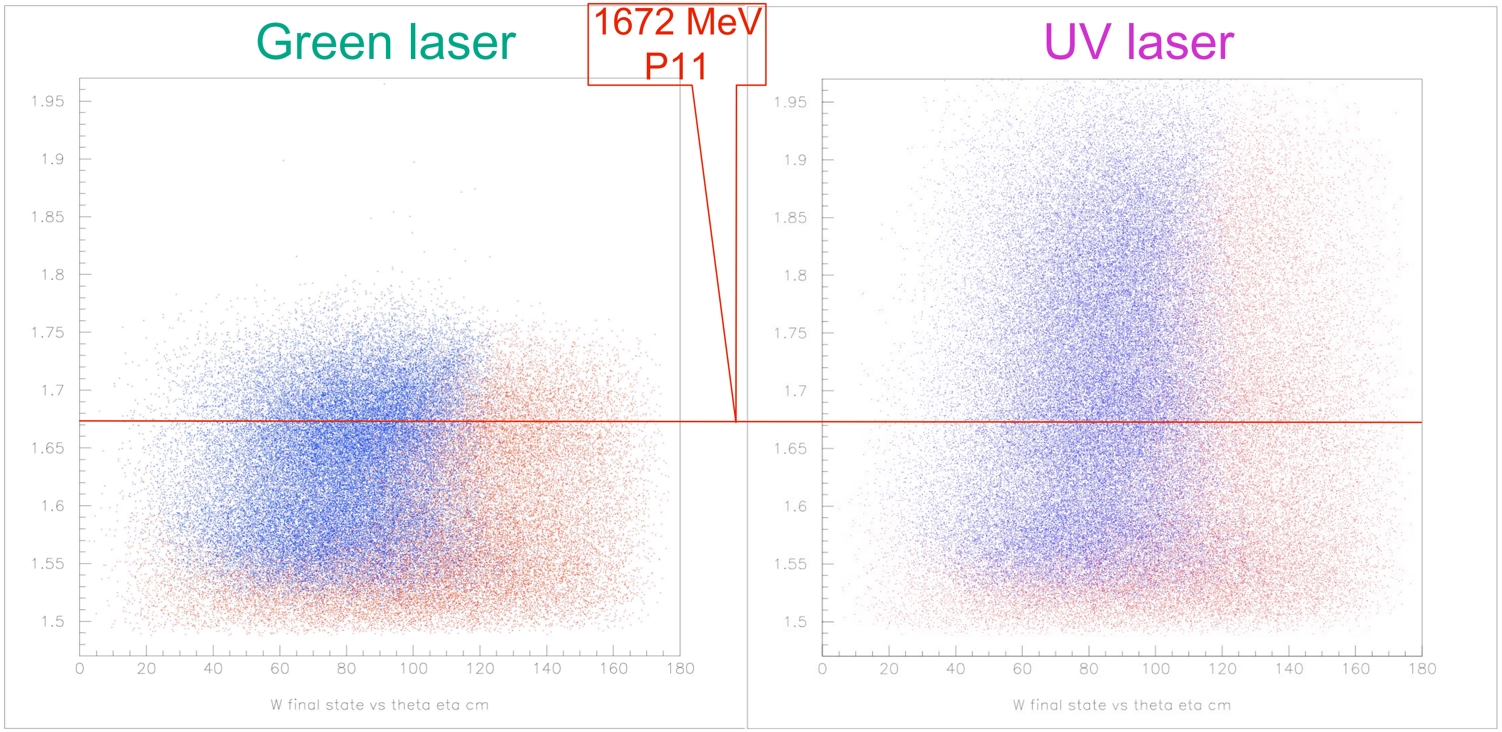


—— **Before cuts**

.... **After cuts**

FIG. 4. The η invariant mass without cuts (solid line) and with the kinematical cuts (dotted line) for (a) a proton and (b) a neutron in the central region and for (c) a proton and (d) a neutron in the forward direction.

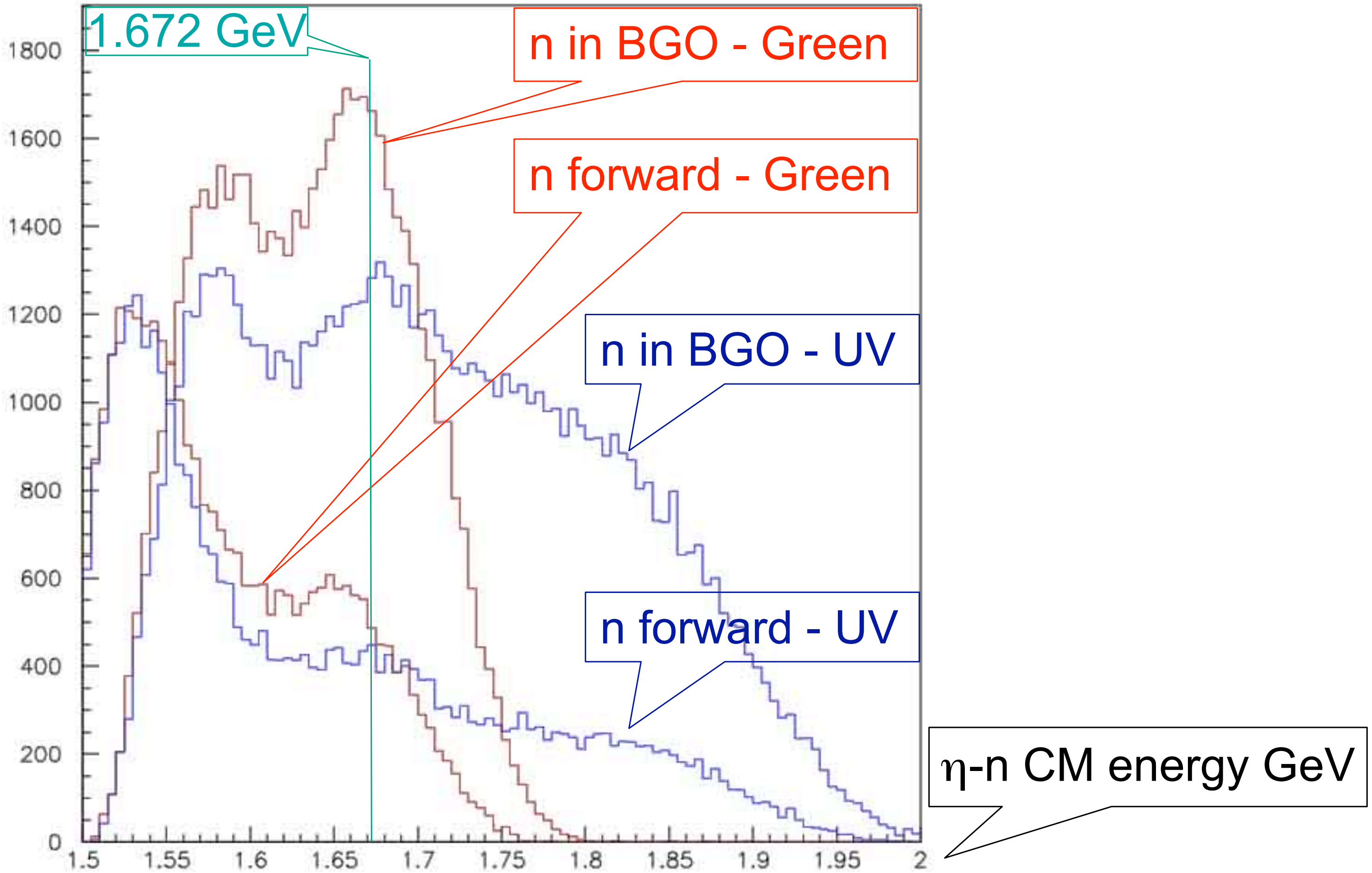
w(fin) vs θ_{η}^{cm}



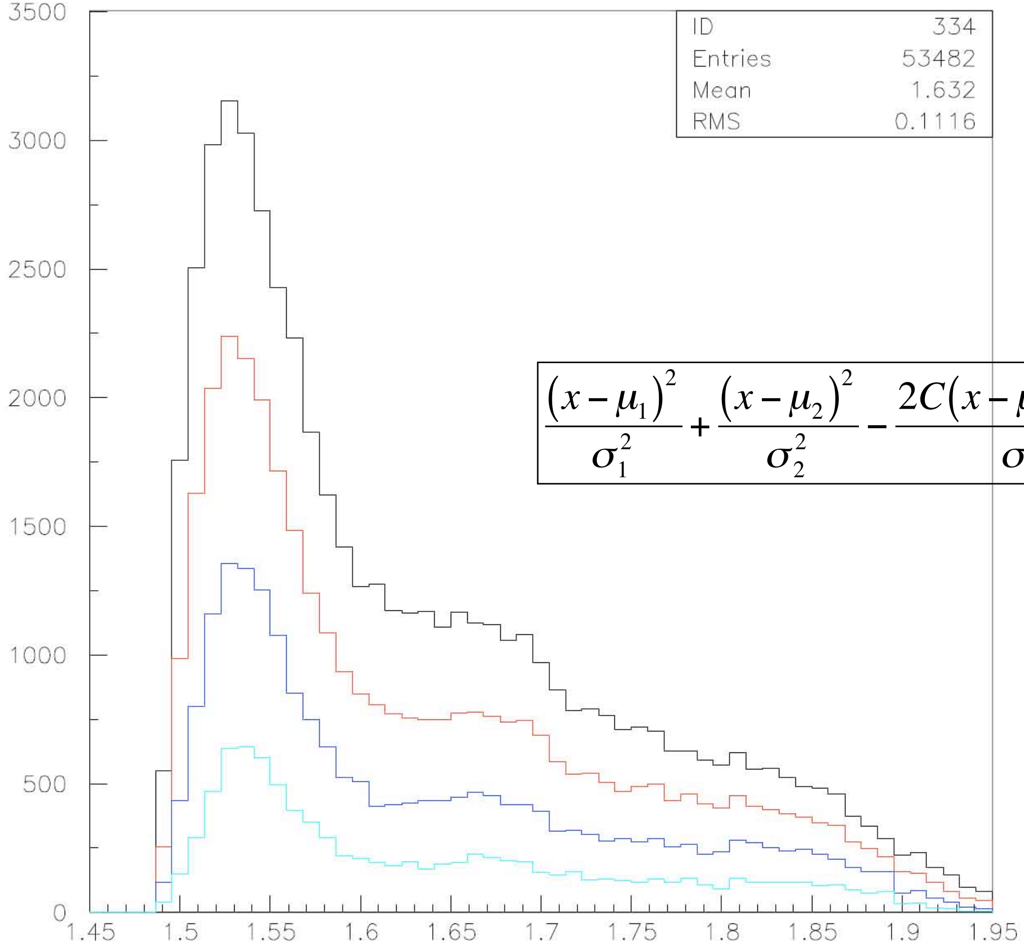
red neutron forward

blue neutron in BGO

GREEN vs UV & Forward vs BGO



Yield vs sigma: Forward n



Bidimensional cuts

σ = 3 σ² = 9

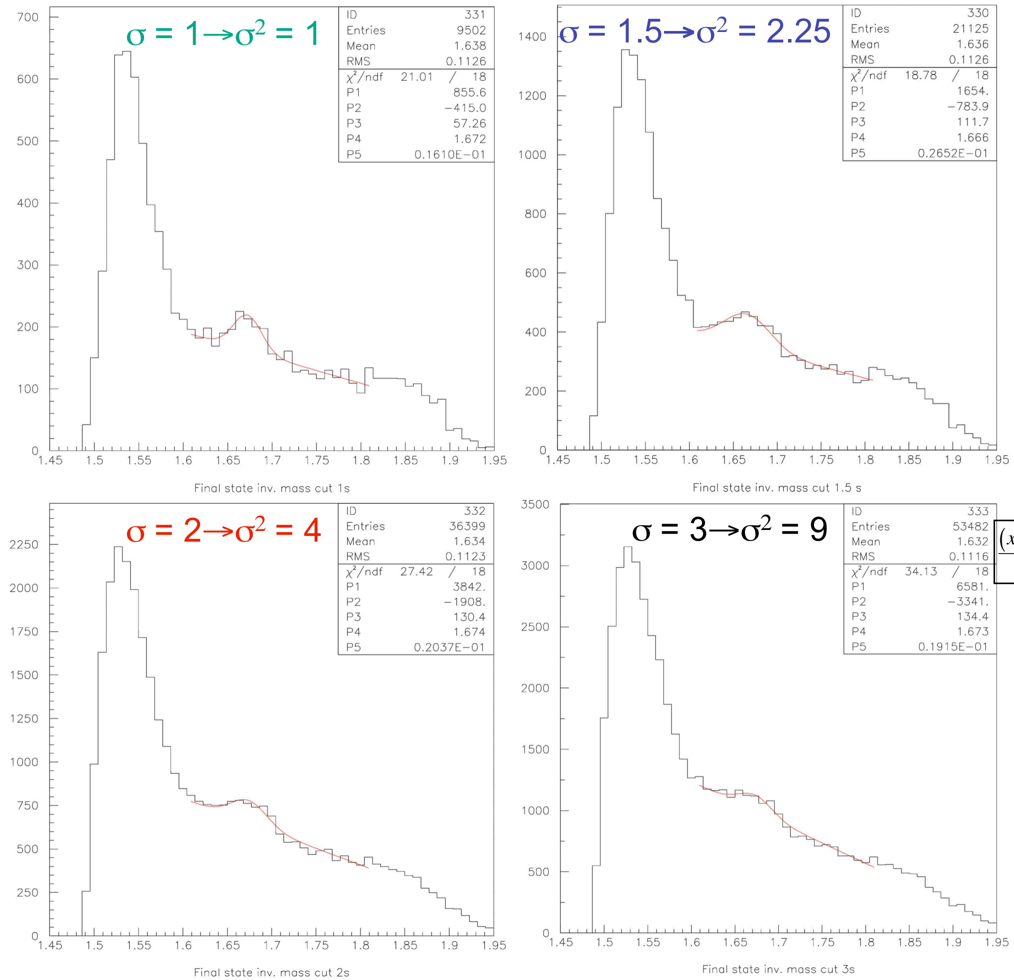
σ = 2 σ² = 4

σ = 1.5 σ² = 2.25

σ = 1 σ² = 1

$$\frac{(x-\mu_1)^2}{\sigma_1^2}+\frac{(x-\mu_2)^2}{\sigma_2^2}-\frac{2C(x-\mu_1)(x-\mu_2)}{\sigma_1\sigma_2}<\sigma^2 \quad [\sigma = 1-3]$$

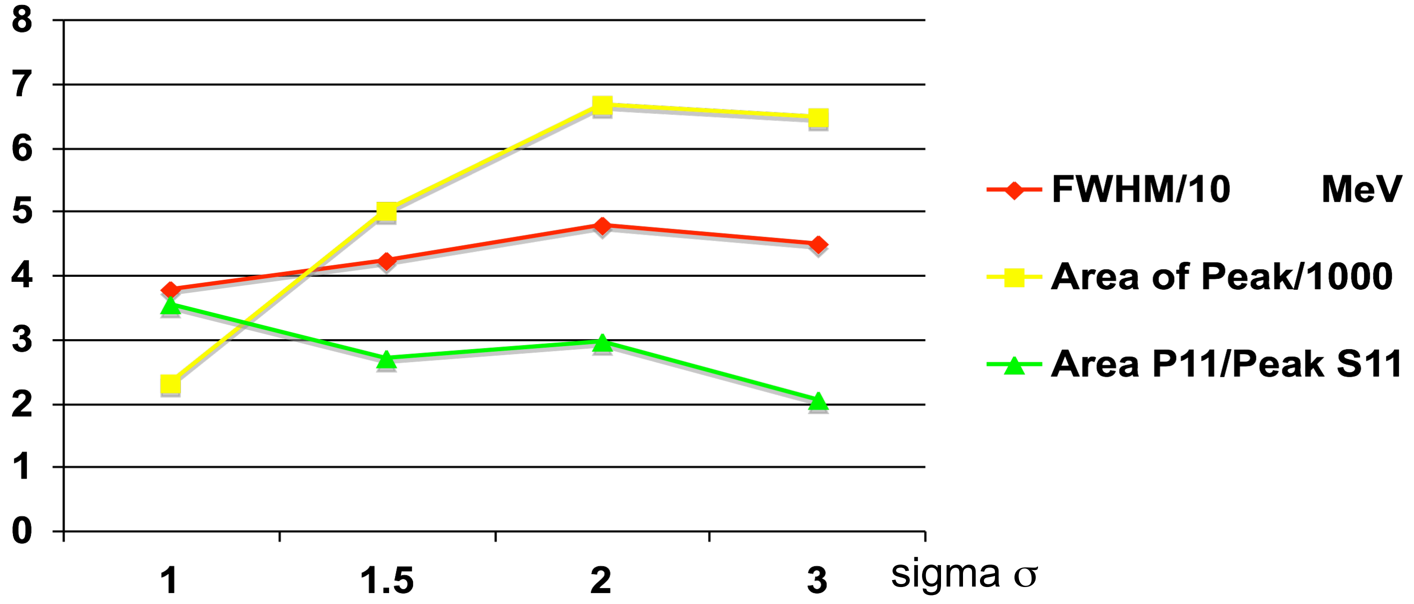
Resonance Width as a Function of Sigma: Forward n UV



Linear fit + Gaussian:
P3 = gaussian height
P4 = gaussian center
P5 = gaussian width (rms)
Resonance position:
W=P4
Resonance width (FWHM):
D = 2,34•P5
Resonance Strenght:
A=P3•P5

$$\frac{(x-\mu_1)^2}{\sigma_1^2}+\frac{(x-\mu_2)^2}{\sigma_2^2}-\frac{2C(x-\mu_1)(x-\mu_2)}{\sigma_1\sigma_2}<\sigma^2 \quad [\sigma=1-3]$$

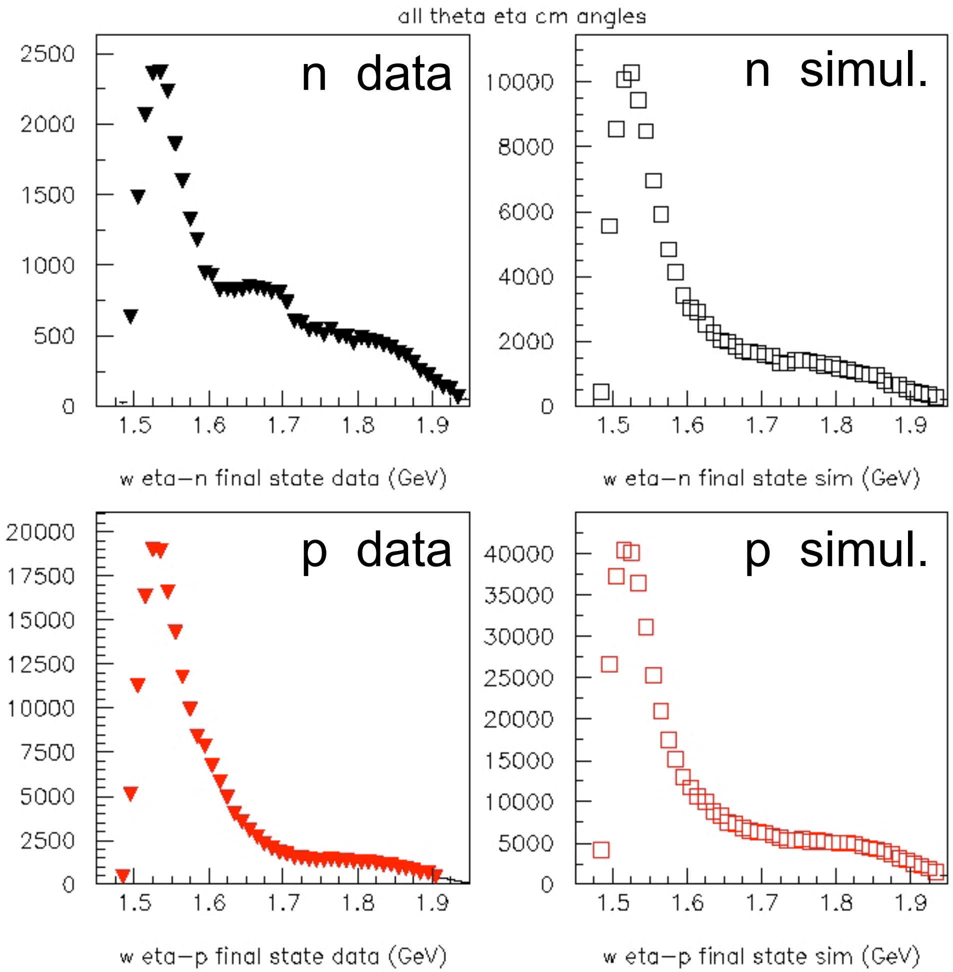
Resonance Width as a Function of Sigma: Forward n UV



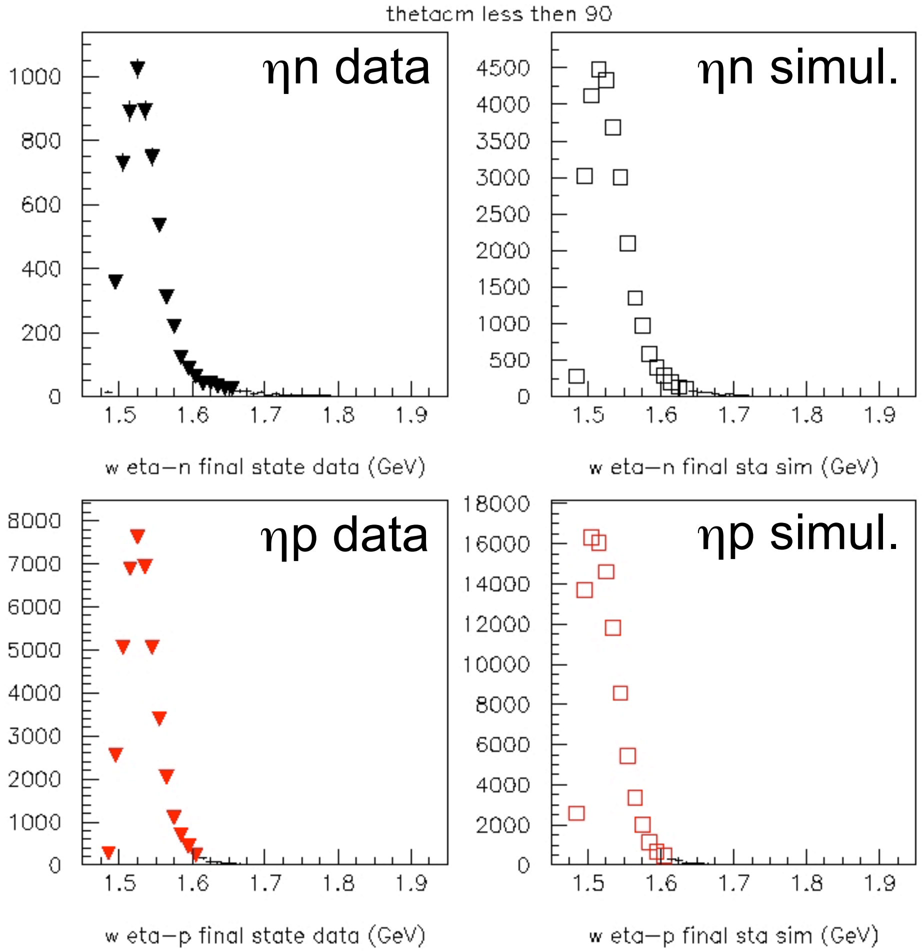
σ sigma	σ^2	P3 Gaussian Height Counts	P4 Gaussian Center W GeV	P5 Gaussian Width (rms) MeV	$\Gamma \approx$ FWHM 2.36*0.1*P5 MeV/10	Area of peak = $(2\pi)^{1/2}$*P5*P3 Counts*MeV	S11 Peak Counts	Area of P11 /Peak of S11 MeV	Area of Peak/1000 Counts*MeV
1,00	1,00	57,26	1,672	16,10	3,77	2310,80	650,00	3,56	2,31
1,50	2,25	110,30	1,670	18,10	4,24	5004,25	1850,00	2,71	5,00
2,00	4,00	130,40	1,674	20,40	4,77	6667,96	2250,00	2,96	6,67
3,00	9,00	134,40	1,673	19,20	4,49	6468,23	3170,00	2,04	6,47

$$W = 1672 \text{ MeV} \Rightarrow k = 1018 \text{ MeV}$$

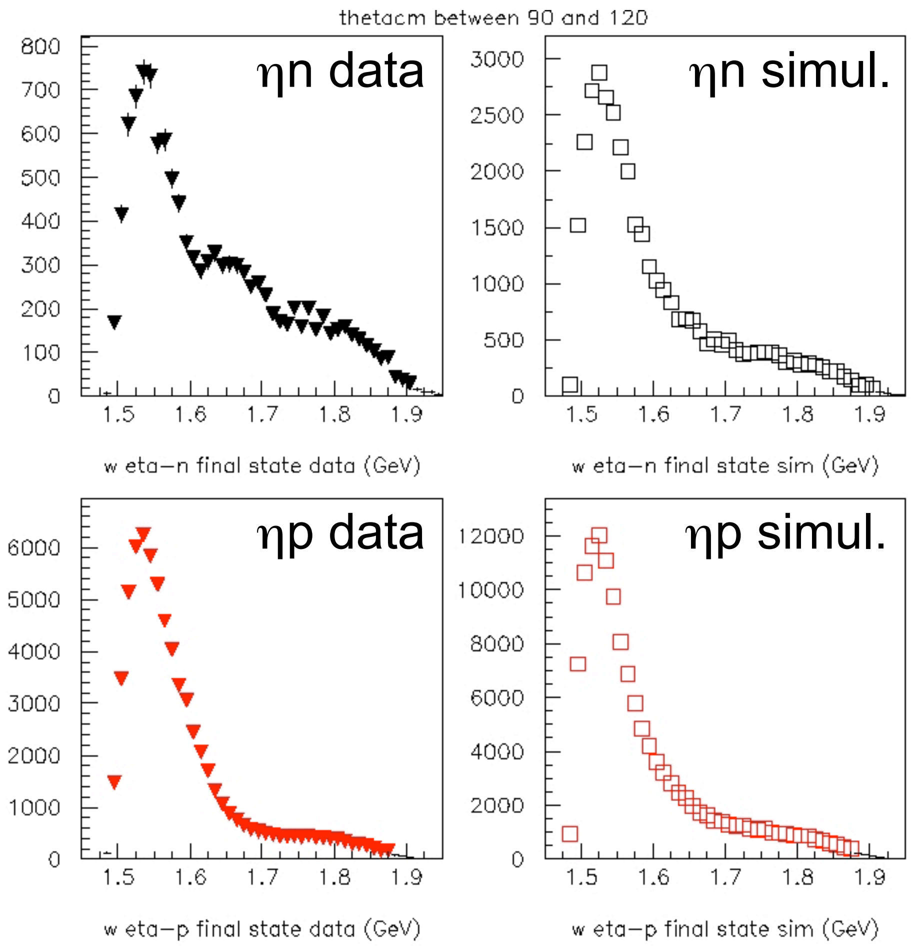
η-n Yield for all angles – Forward neutron – θ_{nLab}< 25°



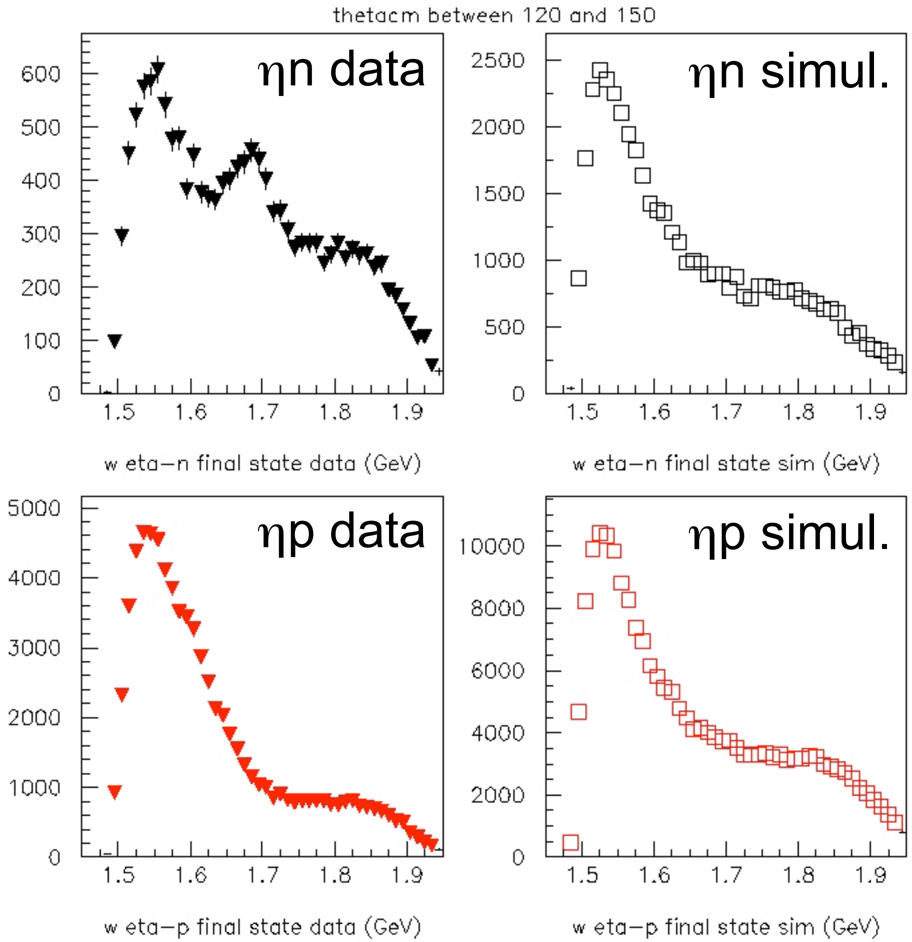
η-n Yield for $\theta_\eta < 90°$



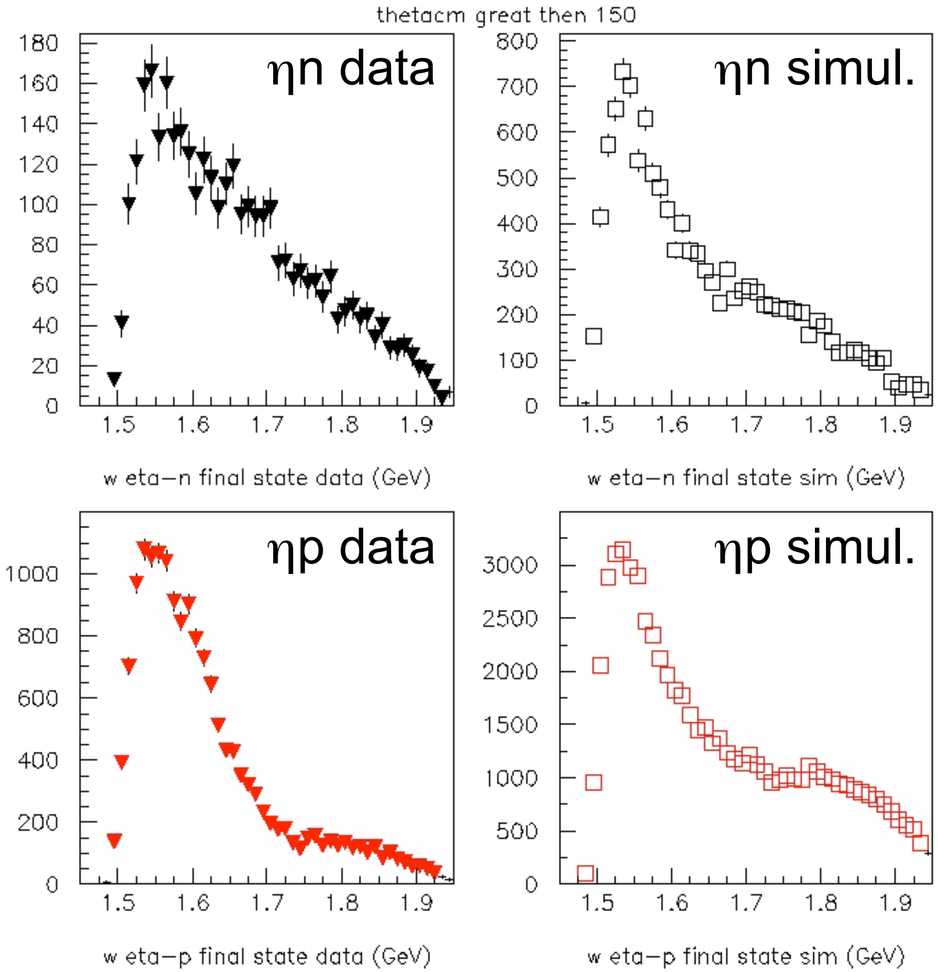
η-n Yield for θ_η=90°-120°



η-n Yield for θ_η=120°-150°



η-n Yield for θ_η > 150°



THE BEAM ASYMMETRY

Selected events grouped in
Fixed E_γ, θ_η^{cm}, ϕ_η^{cm} bins

11 E_γ bins
16 ϕ_η^{cm} bins
8 θ_η^{cm} bins

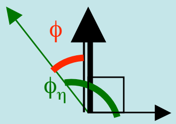
$P\Sigma$
free parameter in the fit

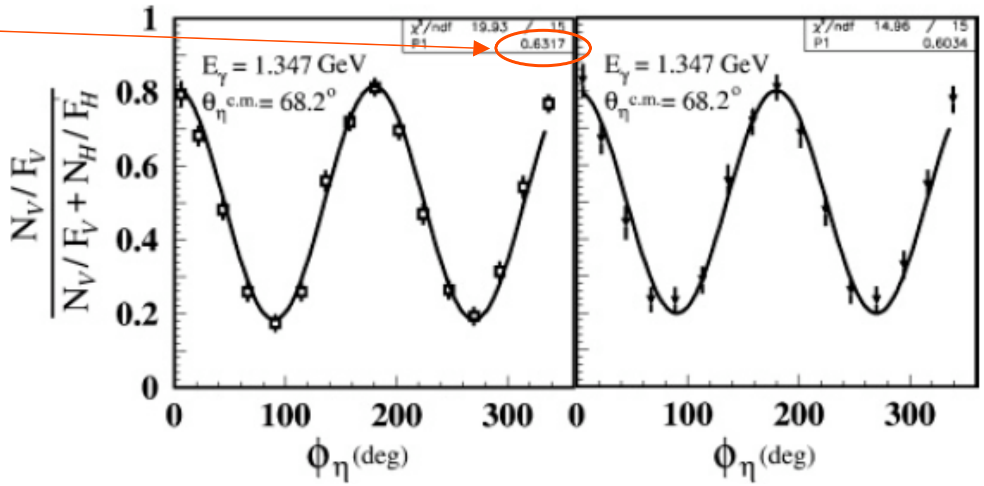
For each (E_γ, θ_η^{cm}) => Fit of azimuthal behavior of the ratio:

$$\frac{N_V/K_V}{N_V/K_V + N_H/K_H} = \frac{1}{2}\left[1 + P\,\Sigma \cos(2\phi_\eta)\right]$$

$N_{V,H}$ = Number of selected events with vertical/horizontal beam polarization
$K_{V,H}$ = Flux corresponding to vertical/horizontal beam polarization
P= Polarization degree of the beam at the bin mean energy
Σ= Beam asymmetry to be determined for every (E_γ, θ_η^{cm})

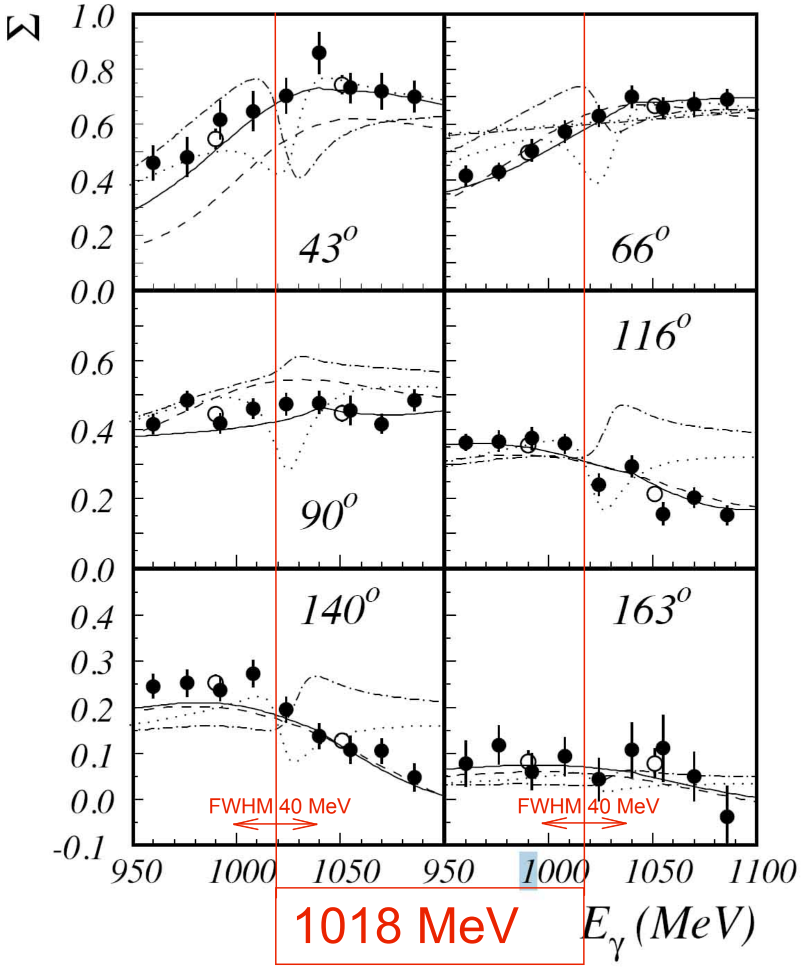
NB:
The + sign in front of $P\Sigma\cos(2\phi_\eta)$ term in the distribution is due to the coordinate system choice.
If ϕ is the angle between the reaction plan and the polarization direction of the photon and ϕ_η is the azimuthal angle of outgoing meson, we have:





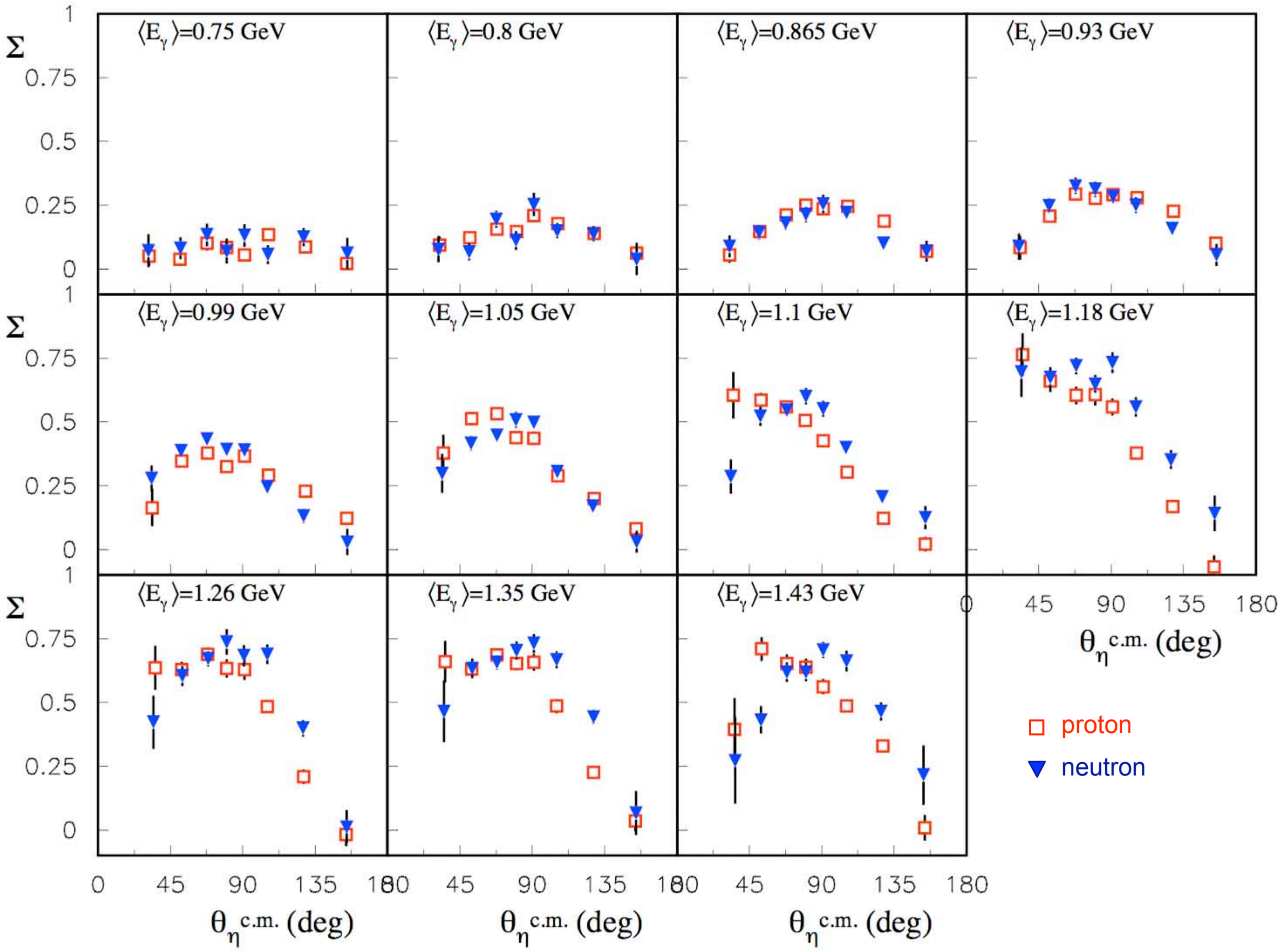
QF-PROTON DATA **QF-NEUTRON DATA**

η Asimmetry Σ free p

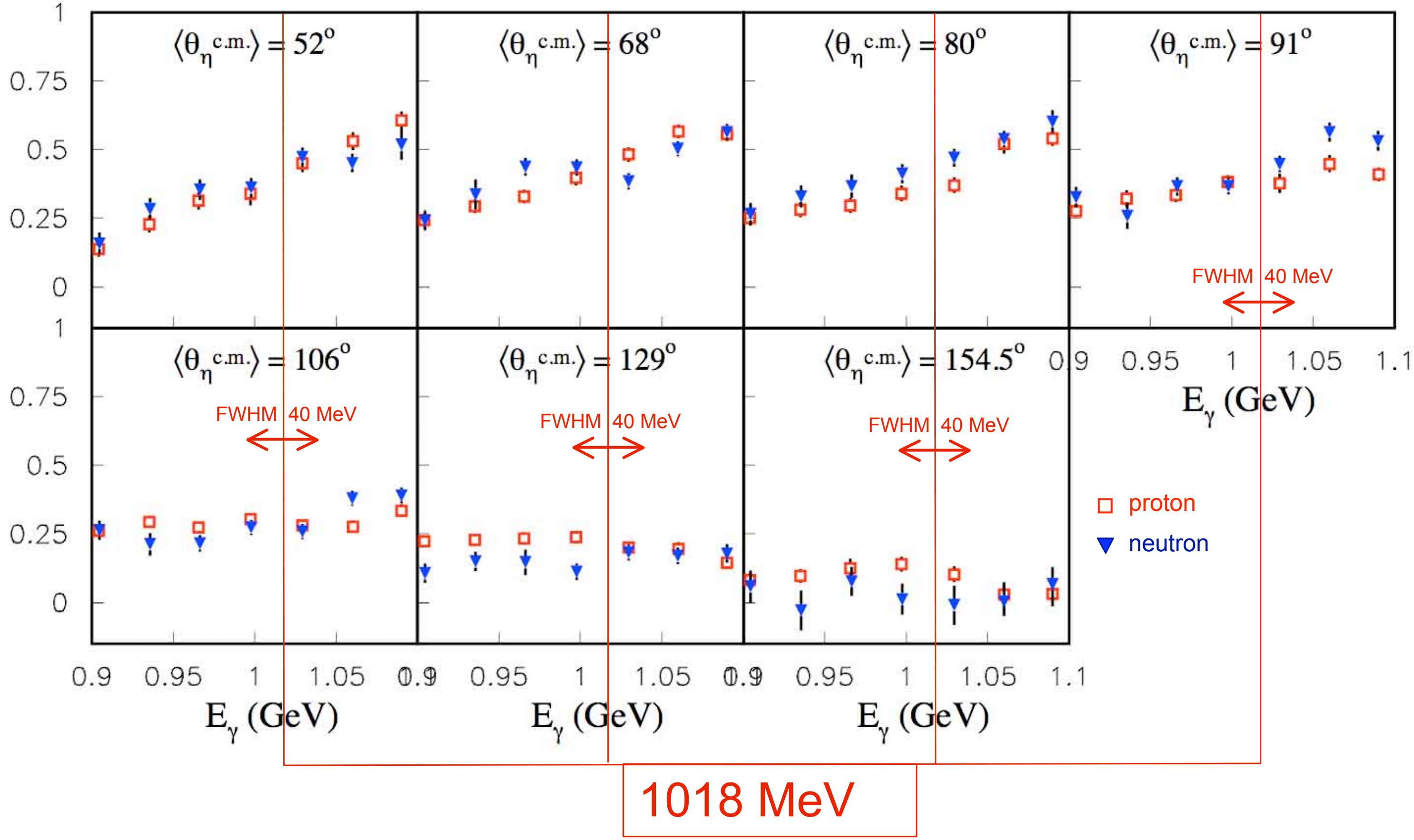


Asymmetry between 950 and 1100 MeV obtained with a narrow energy binning for various η center-of-mass angles. Comparison with the standard MAID model (dashed line), BCC partial-wave analysis (solid line) and predictions of the modified reggeized MAID model including a narrow P11 state. For this latter model, two versions are displayed corresponding to the two choices for the $\zeta_{\eta N}$ hadronic relative phase (dot-dashed line: $\zeta_{\eta N}$=+1, dotted line: $\zeta_{\eta N}$=−1).

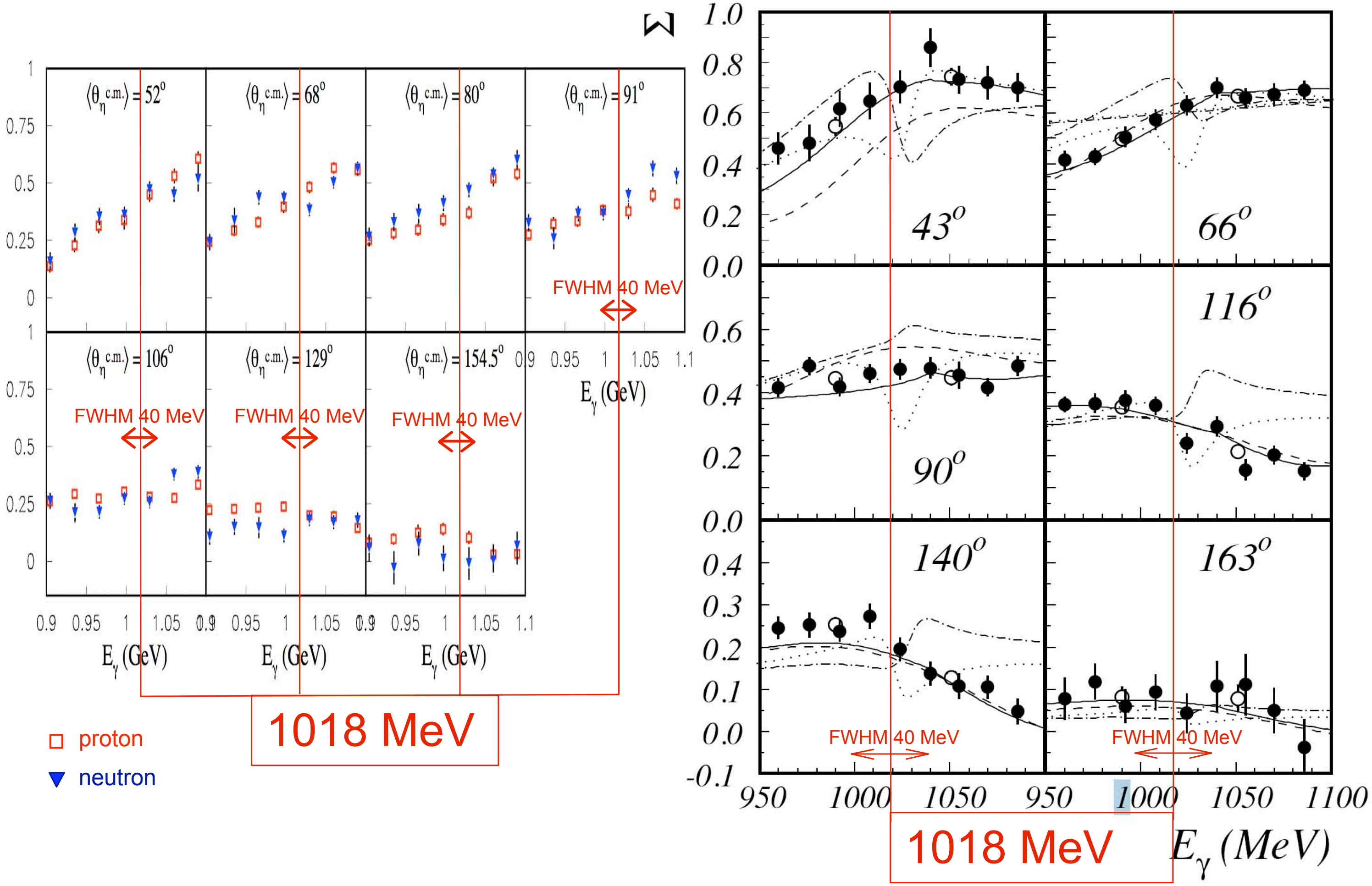
η Asimmetry Σ quasi-free p vs n



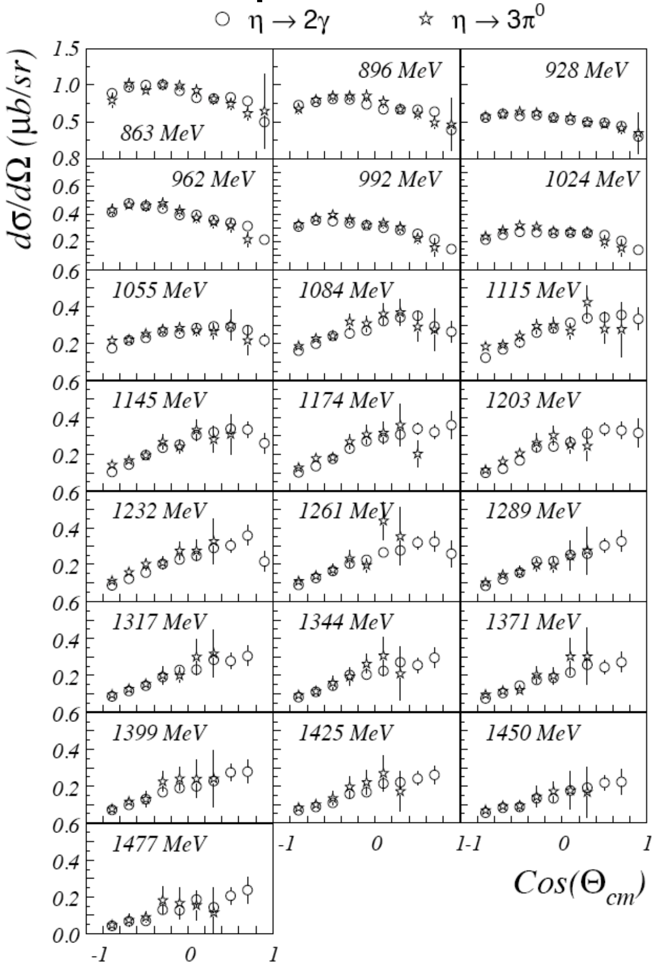
η Asimmetry Σ quasi-free p vs n

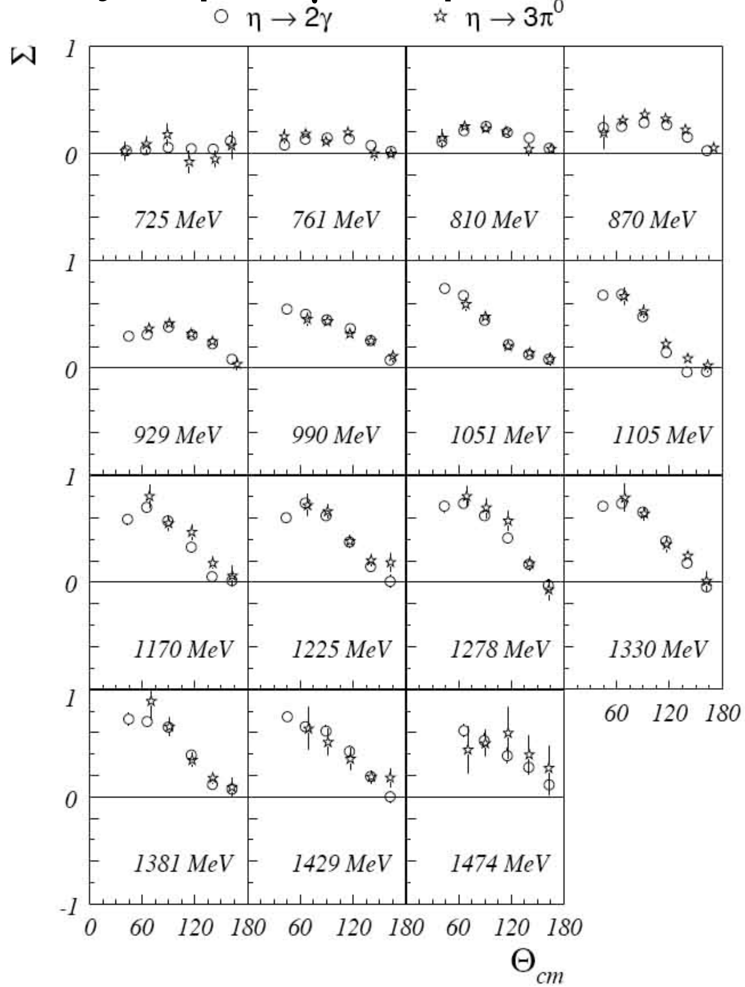


η Asimmetry Σ quasi-free p/n and free p

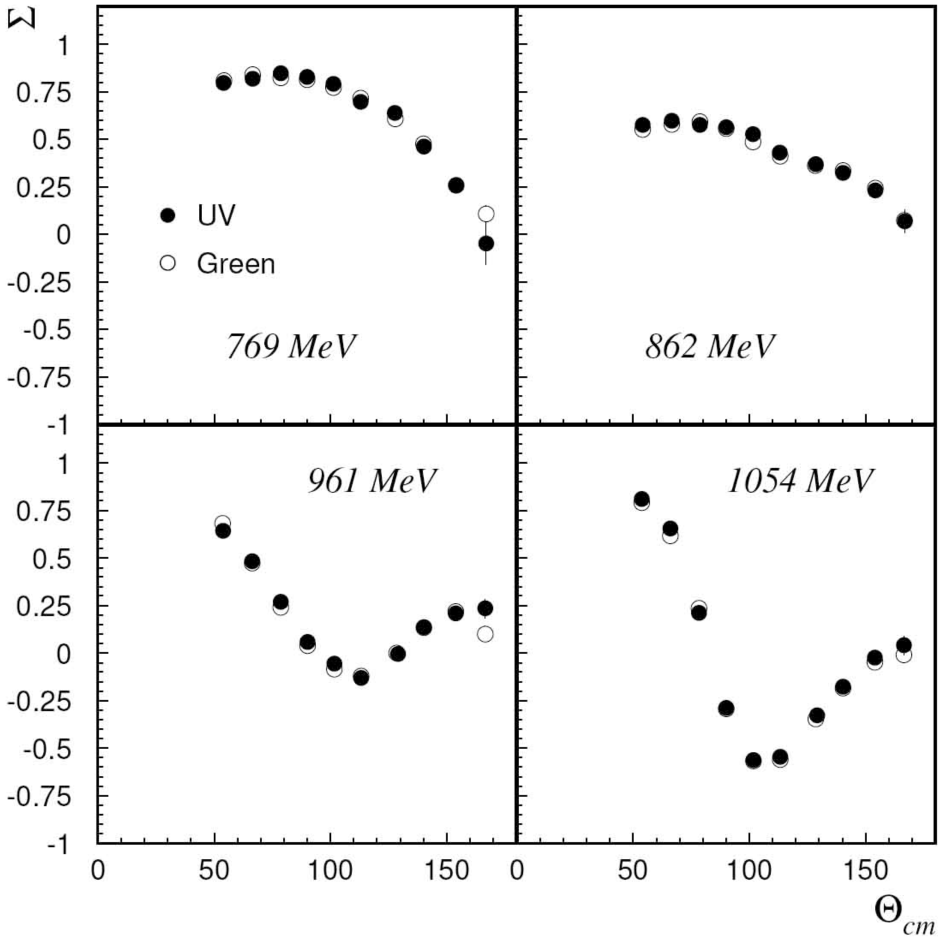


Free p - dσ/dΩ + Asimmetry - η→2γ vs η→3π°





$\pi^\circ p$ Asimmetry Σ – Green vs UV



The asimmetry obtained with the Green laser line versus the UV is shown for the $\gamma + p \rightarrow p + \pi^\circ$ reaction which has a large cross section.

$\gamma + p \rightarrow \omega + p$

We have analyzed two decay channels:

$\gamma + p \rightarrow \omega + p$

1. $\omega \rightarrow \pi^{\circ} + \gamma \rightarrow 3\gamma$
2. $\omega \rightarrow \pi^{+} + \pi^{-} + \pi^{\circ} \rightarrow \pi^{+} + \pi^{-} + 2\gamma$

The proton is detected in the BGO ball or in the forward detector.

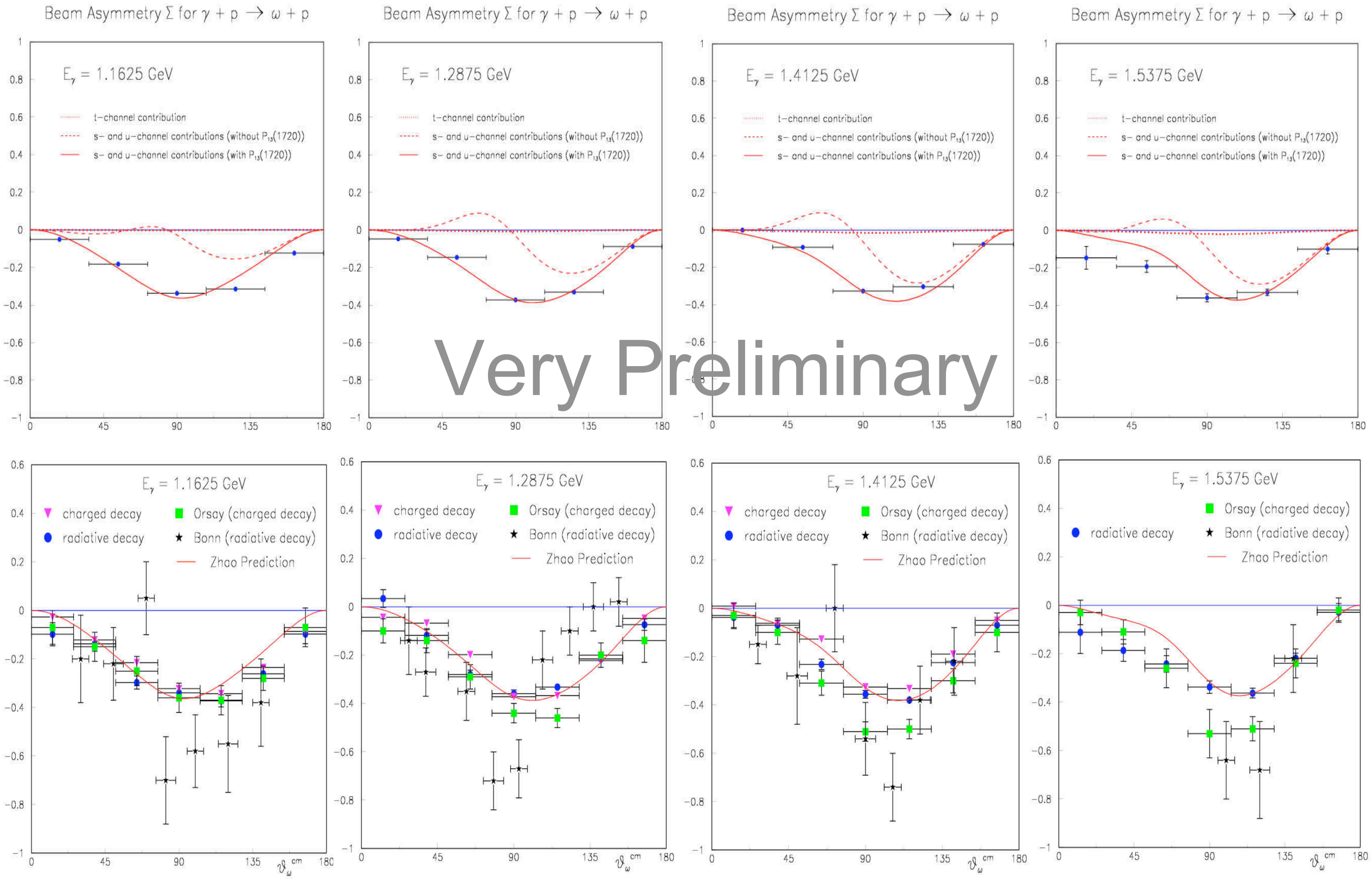
Channel 1: we require at least two photons in the BGO and the third one in the BGO or forward;

Channel 2: we require at least one photon in the BGO and the second photon and the two pions in the BGO or in the forward detector.

From the incident photon energy and proton momentum we calculate the missing mass of the other particles and compare with the ω mass.

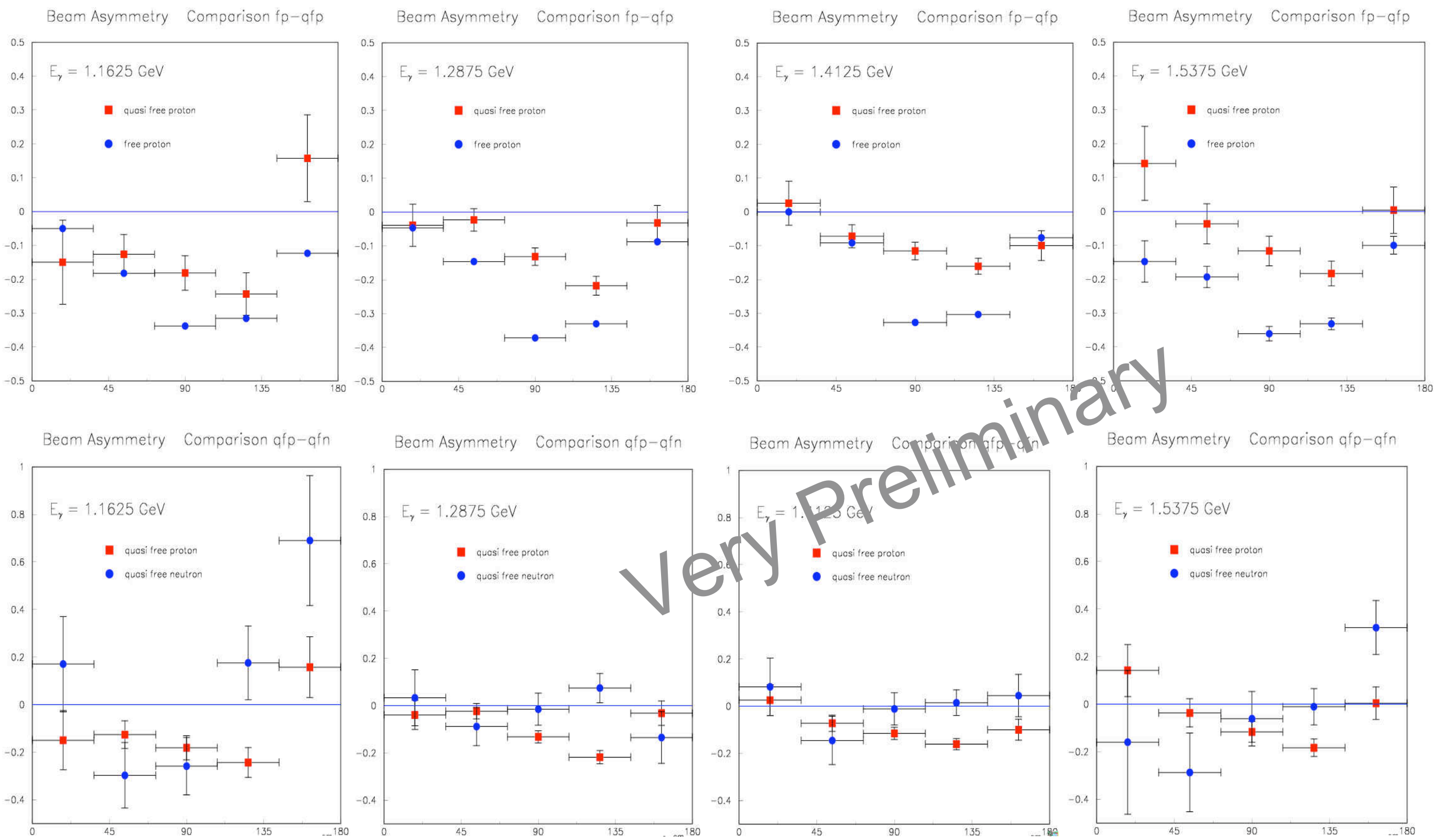
For channel 1 we calculate the invarian mass of the three photons and compare with the mass of the ω. We apply the constraints of the two-body kinematics.

$\gamma + p \rightarrow \omega + p$



$\gamma + p \rightarrow \omega + p$

fp vs qfp   qfp vs qfn



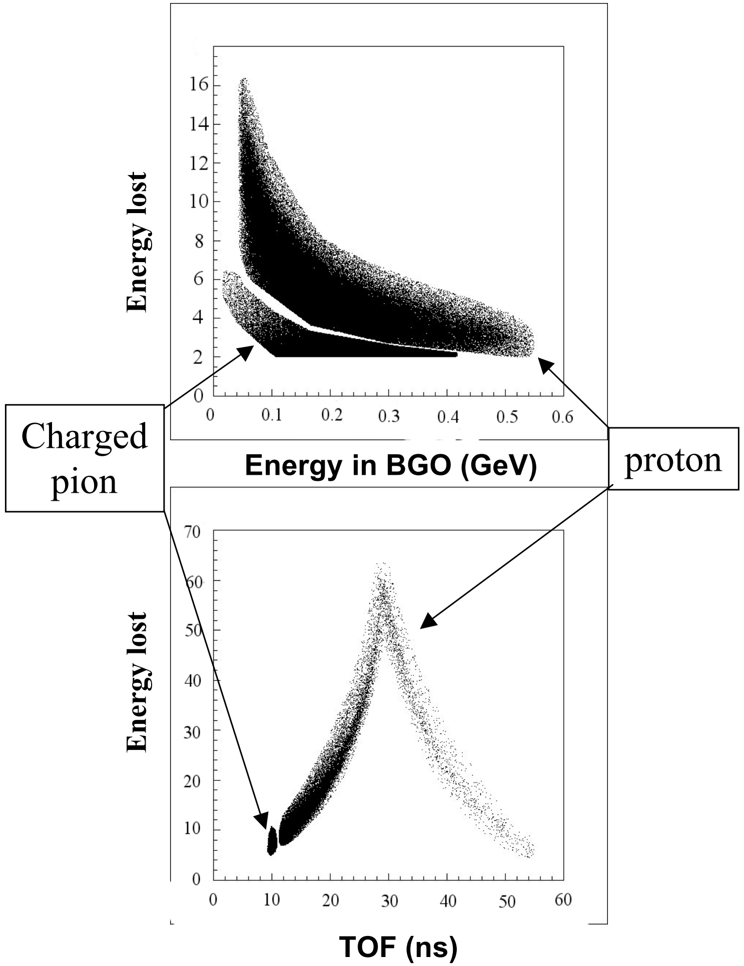
$\gamma + n \rightarrow \pi^- + p$ Preliminary Event Selection

We identify charged particles by the coincidence of signals in three different detectors charged sensible.

We distinguish proton and pion in the central part of apparatus by bi-dimension cuts: energy lost in the BARREL versus energy released in the BGO.

We distinguish proton and pion in the forward part of apparatus by bi-dimension cuts: energy lost versus TOF of the scintillator wall .

In simulation, the number of the events generate by concurrent channel decreases at 14 % of the initial value applying the preliminary condition to have only one proton and only one pion in the apparatus.

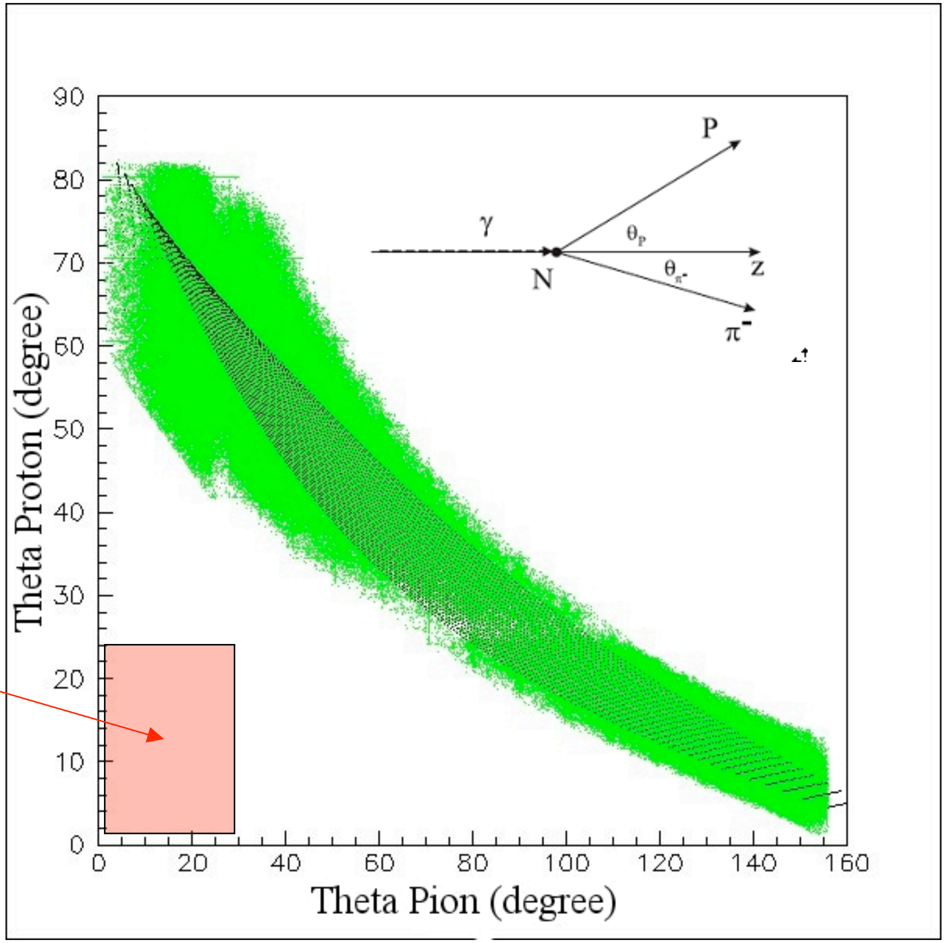


Polar angle distribution of reaction products

Green: data

Black: kinematic calculation without any consideration on cross section of reaction.

No events with proton and pion in forward detectors at the same time are possible



Hardware Conditions

We have used the following hardware conditions:

1. No other than one proton or one pion must be detected in the forward direction;

2. the energy, E^{BGO} , released in the calorimeter by particles detected only in the BGO must be lower than 5 MeV

Cuts

a) We combined the variables $\Delta\theta = \theta_{\pi^-}^{calc} - \theta_p$ and $R_p = E_p^{calc}/E_p^{measured}$ (see Fig a)) selecting the events according to the condition

$$\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2C(x-\mu_x)(y-\mu_y)}{\sigma_x \sigma_y} < \sigma^2$$

where $\sigma = 3$ and C is the correlation parameter

The parameters of the cuts a) and c) (next slide) were determined for different energy bin of gamma and for different periods of data acquisition.

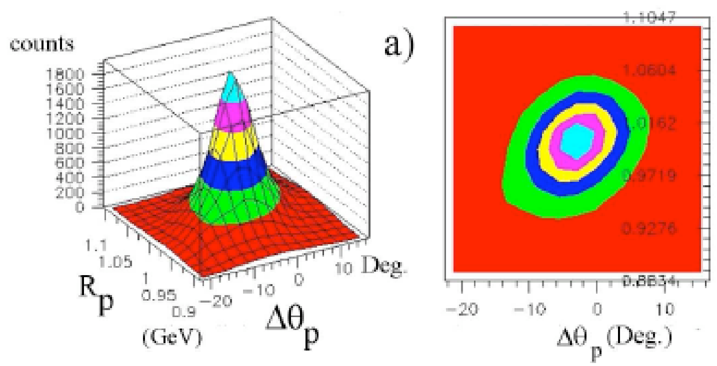
Fit function

$$f(x,y) = \alpha + \beta \cdot e^{-\frac{1}{2}\gamma(x,y)}$$

$$\gamma(x,y) = \frac{A^2 - 2 \cdot Cor \cdot A \cdot B + B^2}{1 - Cor^2}$$

$$A = \frac{x - \bar{x}}{\sigma_x}$$

$$B = \frac{y - \bar{y}}{\sigma_y}$$

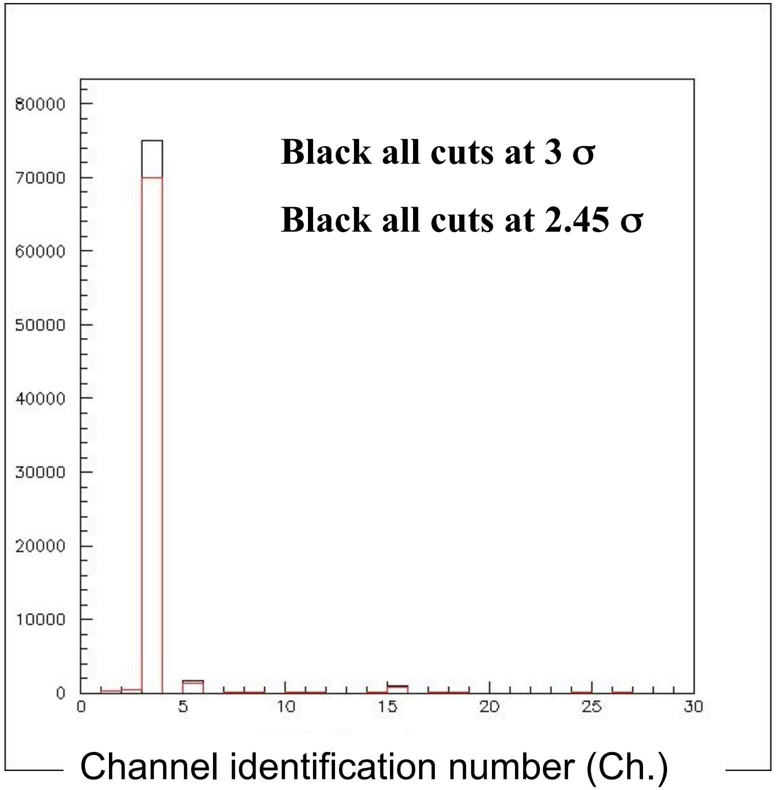


Simulation: Signal and concurrent channels after cuts

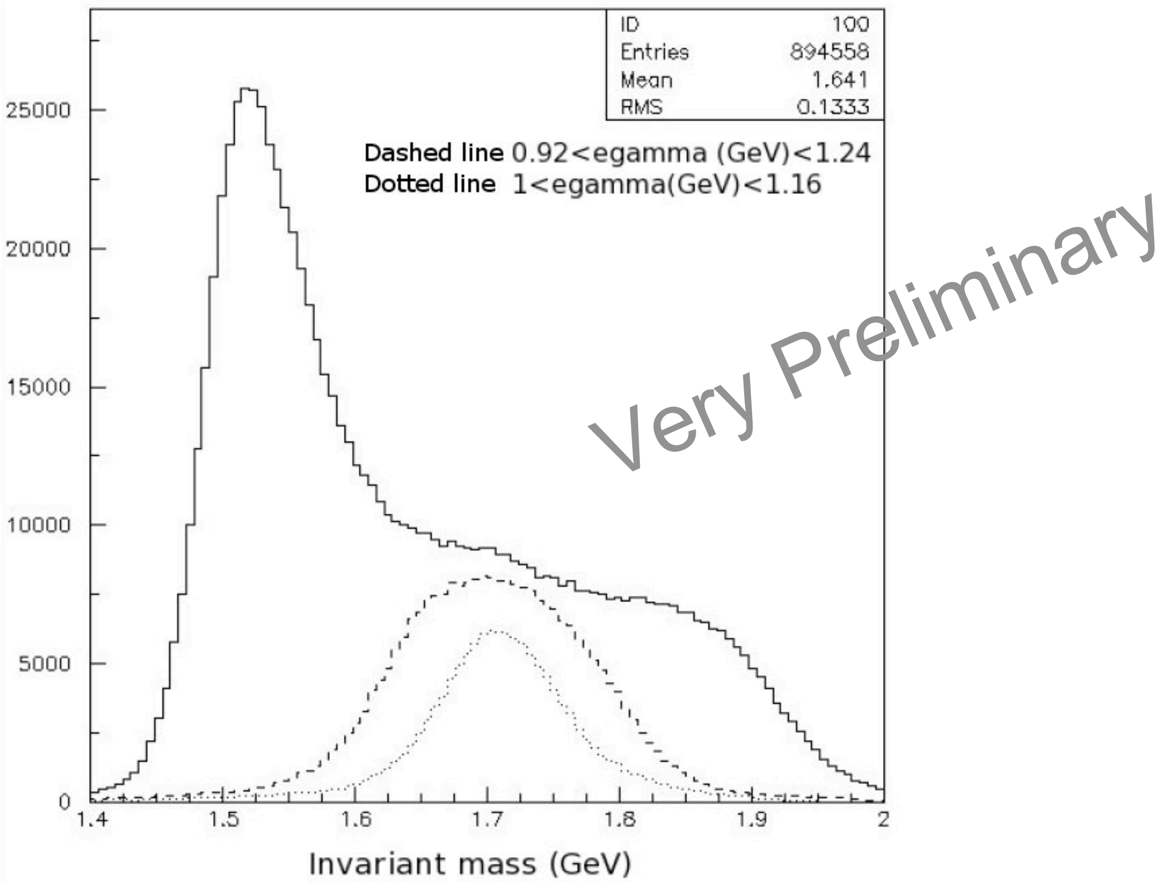
Ch. 3 = $\gamma + n \dashrightarrow \pi^- p$ **(signal)**
Ch. 5 = $\gamma + p \dashrightarrow \Delta^{++} \pi^-$
Ch. 8 = $\gamma + n \dashrightarrow \Delta^+ \pi^-$
Ch. 10 = $\gamma + n \dashrightarrow \Delta^- \pi^+$
Ch. 15 = $\gamma + p \dashrightarrow \pi^+\pi^- p$
Ch. 17 = $\gamma + n \dashrightarrow \pi^+ \pi^- n$
Ch. 18 = $\gamma + n \dashrightarrow \pi^0 \pi^- p$
Ch. 26 = $\gamma + n \dashrightarrow \pi^+ \pi^- \pi^- p$

Ch.	Survival at 3 σ	Survival at 2.45 σ
3	18.9%	17,8%
5	0.3%	0,2%
15	0.5%	0.4%

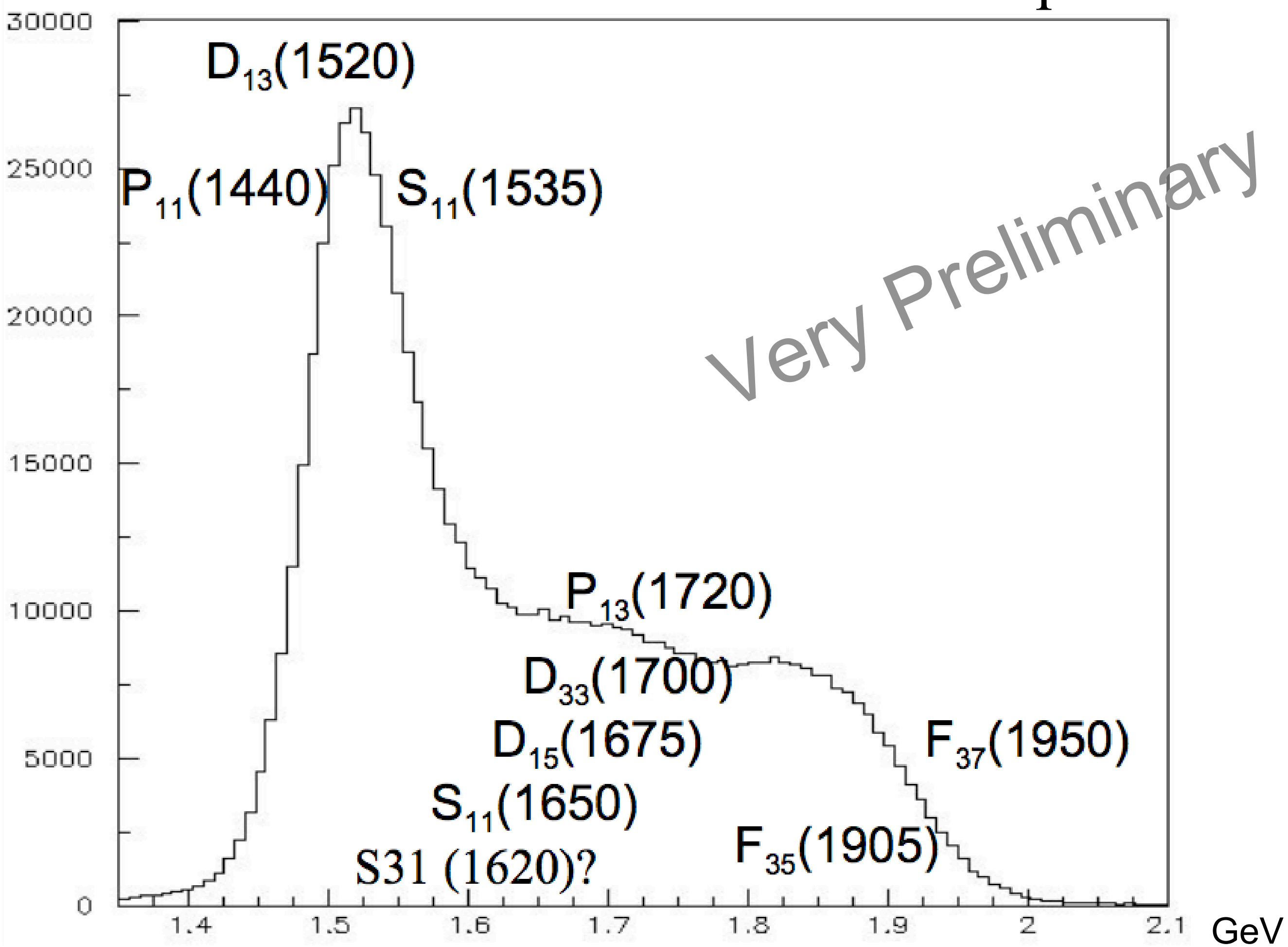
At 3 σ the contribution of concurrent channels is lower than 2.3 %



Invariant mass of the final state π^- p

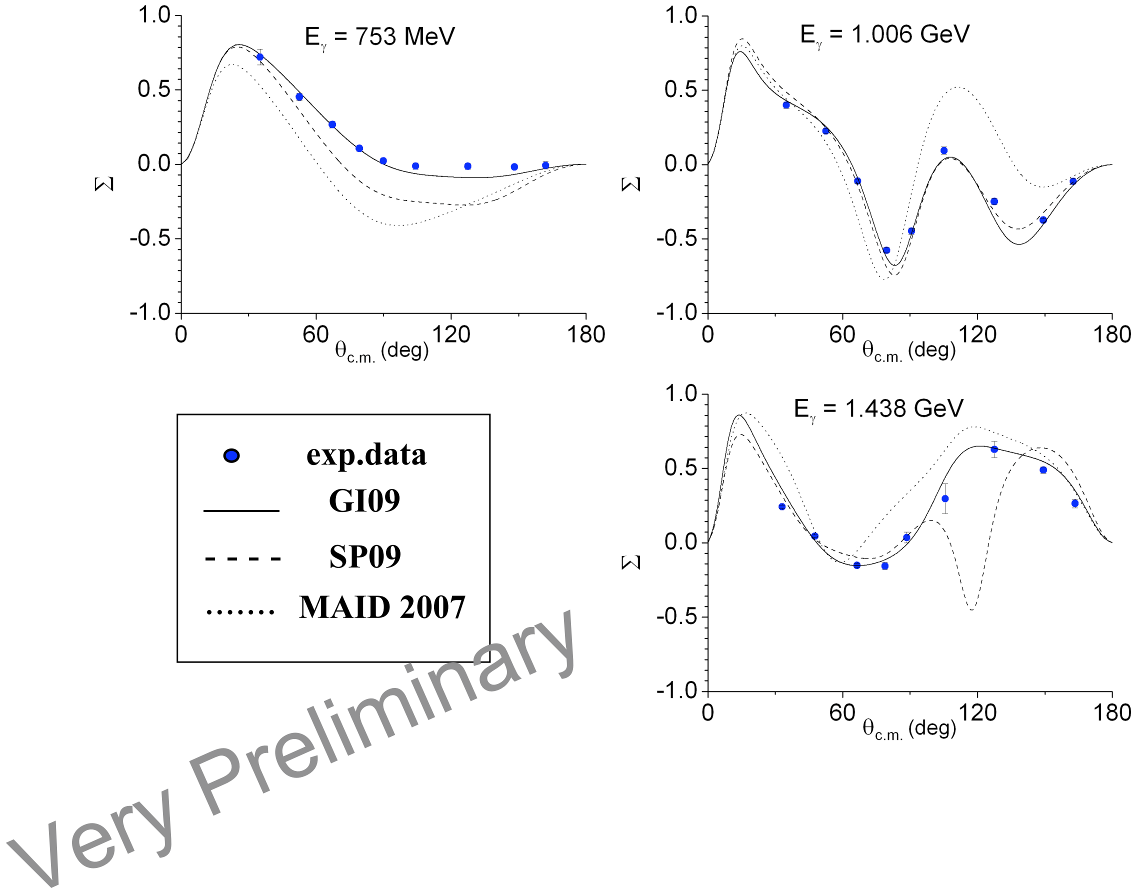


Resonance contributions to the π^- p final state



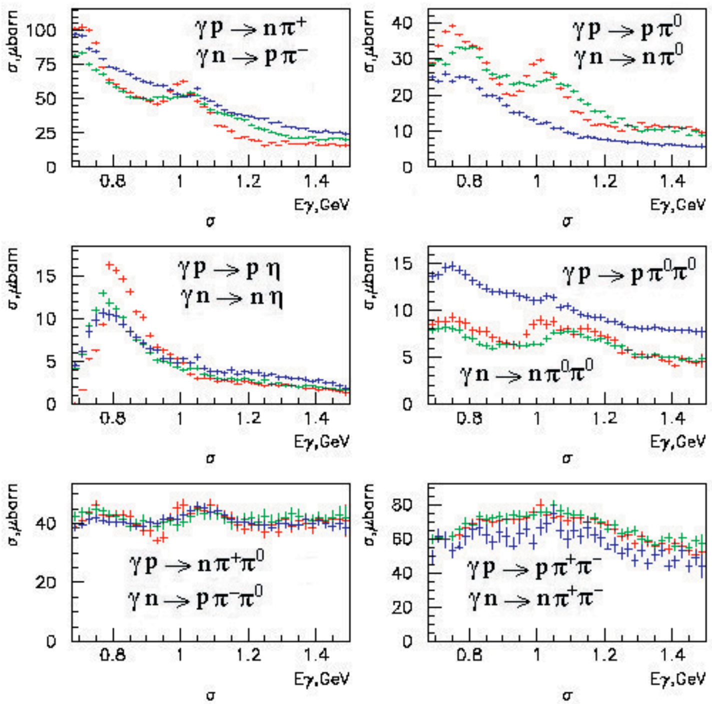
$\pi^- p$ Beam Asymmetry Σ

Comparison between data and recent theoretical models



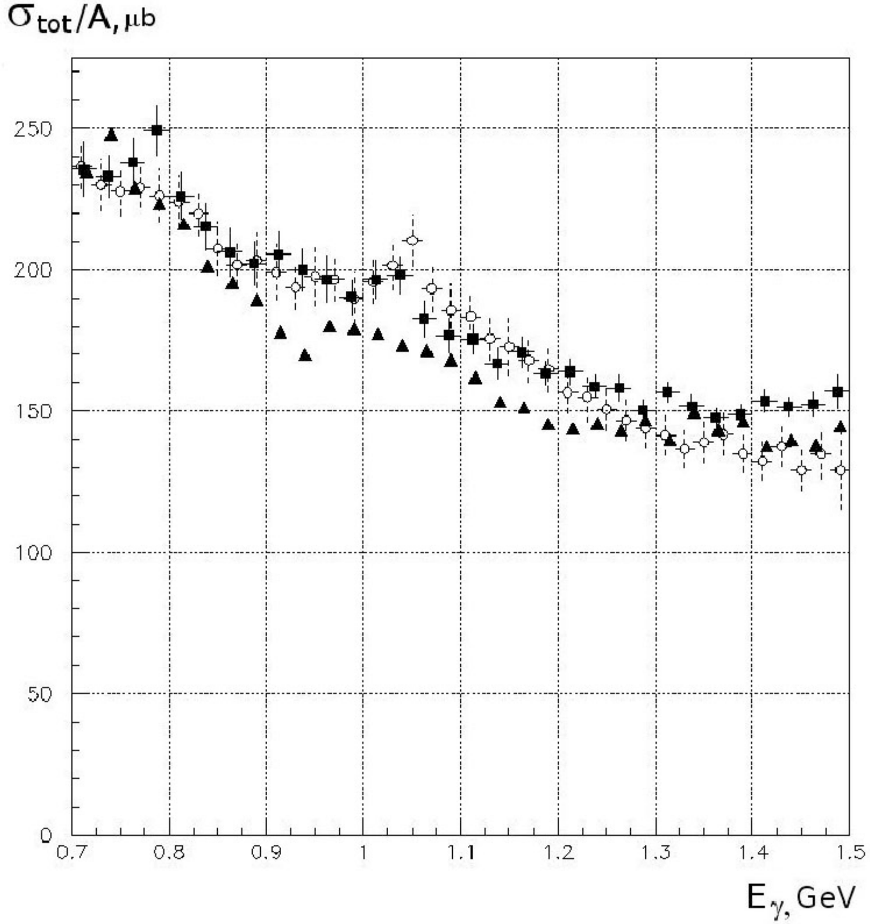
INR - Total Cross Sections fp/qfp/qfn

Partial cross sections for one and double pion and η meson photo-production
on free and quasi-free proton and quasi-free neutron
Red – free proton, green – quasi-free proton, blue – quasi-free neutron.



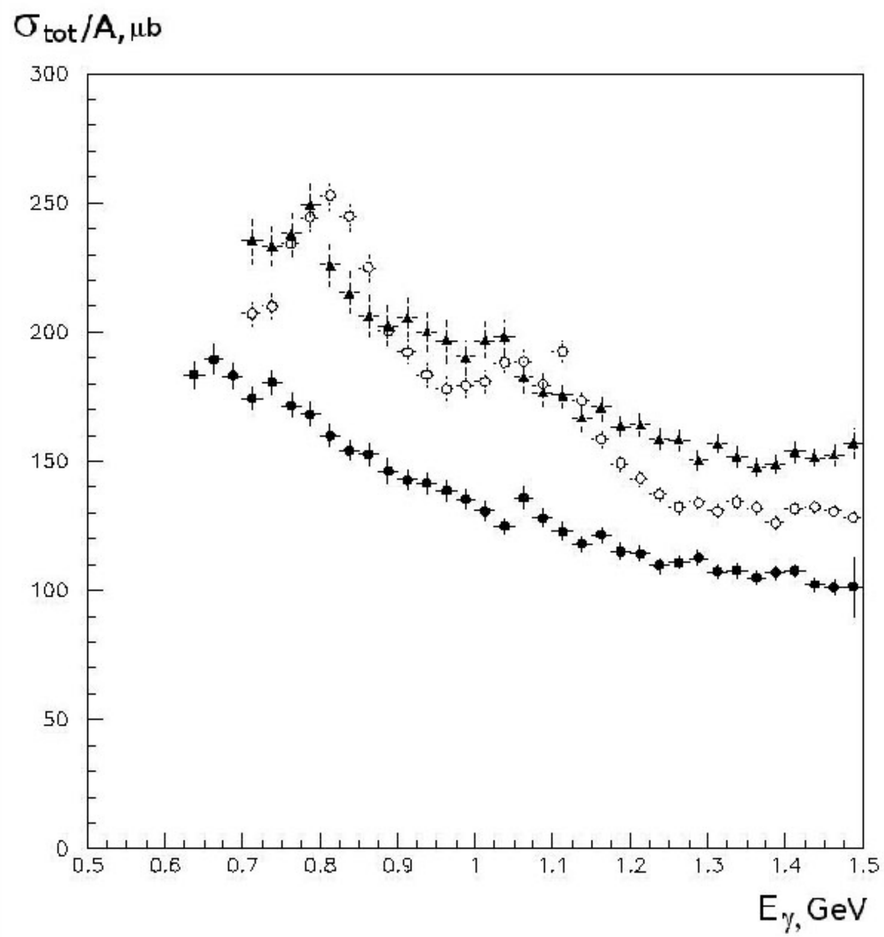
Specific media modification in different channels indicates that
two nucleon correlations plays important role in addition to Fermi motion.

INR - Total Cross Sections - Sub vs Sum



Total photo-absorption cross section for the deuteron, open and full points correspond to the subtraction and summing method, respectively. Full triangles are the result of Armstrong [2].

INR - Total Cross Sections - p, d, C



Total Cross Sections per Nucleon for the proton (full triangles), deuteron (open points) and carbon (full points) targets:

▲ proton

○ deuteron

● Carbon

INR - CONCLUSIONS

1. Total cross sections obtained by subtraction and summing methods coincide within 5% error bars in the energy region up to 1.2 GeV. The discrepancy above this energy is explained by the triple meson production.

2. For neutron and proton we see the similar relative behavior and agreement in absolute scale, especially the presence of the F15 (1680) resonance in both cross sections in contradiction with the Armstrong (1972) results.

3. It is seen, that not only Fermi motion but also two nucleon correlations in the final state interaction is responsible for the modification of cross sections in the nuclear media.

4. Carbon cross section is practically coincides with the “universal curve” but lies in 30% below than the proton and deuteron one.