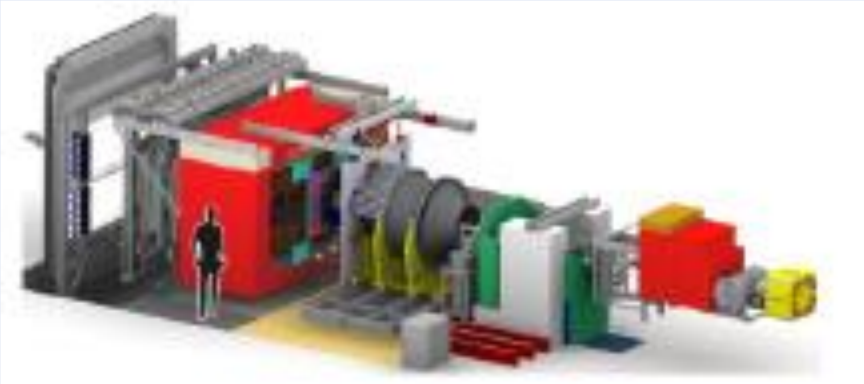


Neutral particles discrimination with BGO in the BGOOD experiment

Alessia Fantini

University of Rome Tor Vergata-INFN(Roma Tor Vergata)

In collaboration with R. Di Salvo INFN & P. Levisandri INFN & on behalf of BGOOD collaboration

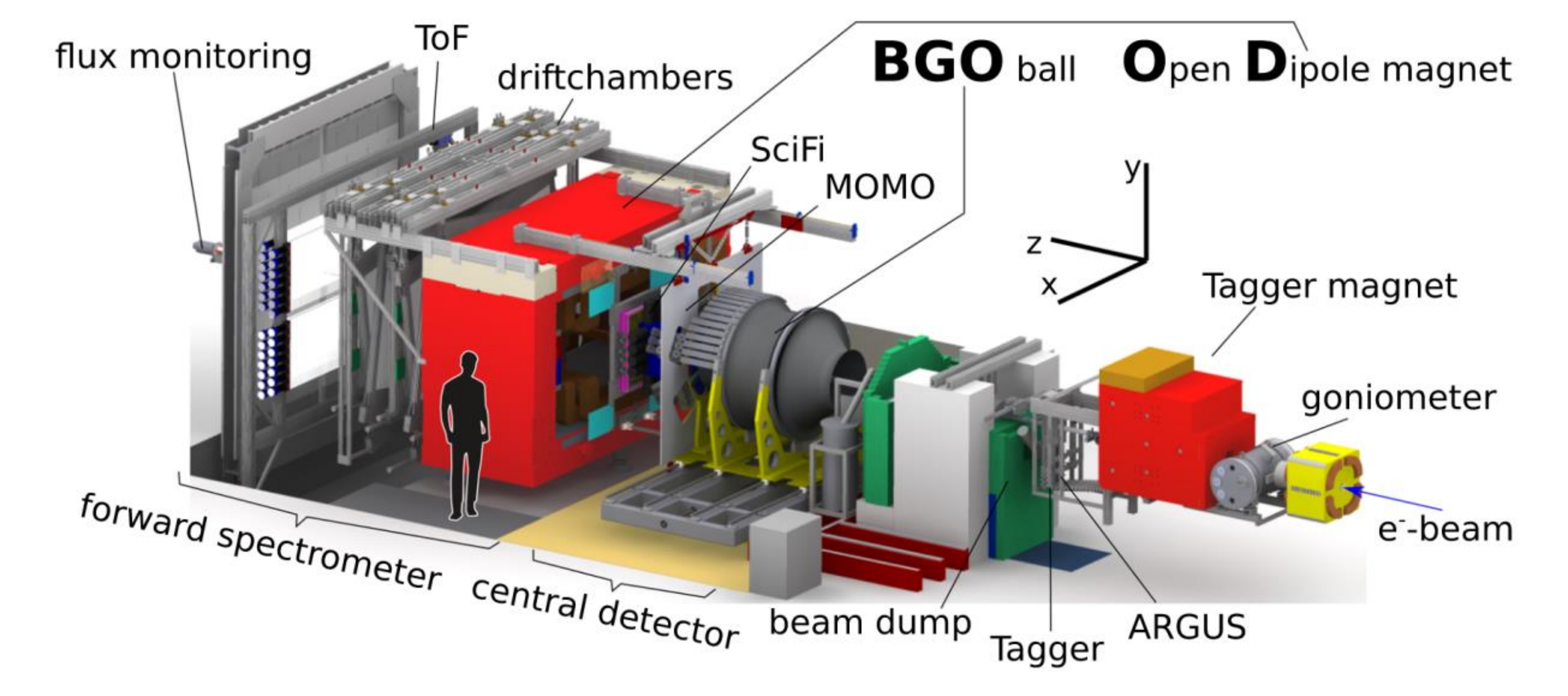
2^{ND} International Workshop on Detection Systems and Techniques For Foundamental and Applied Physics
Catania (Italy), February 24 -26, 2025

Meson photoproduction off Nucleons

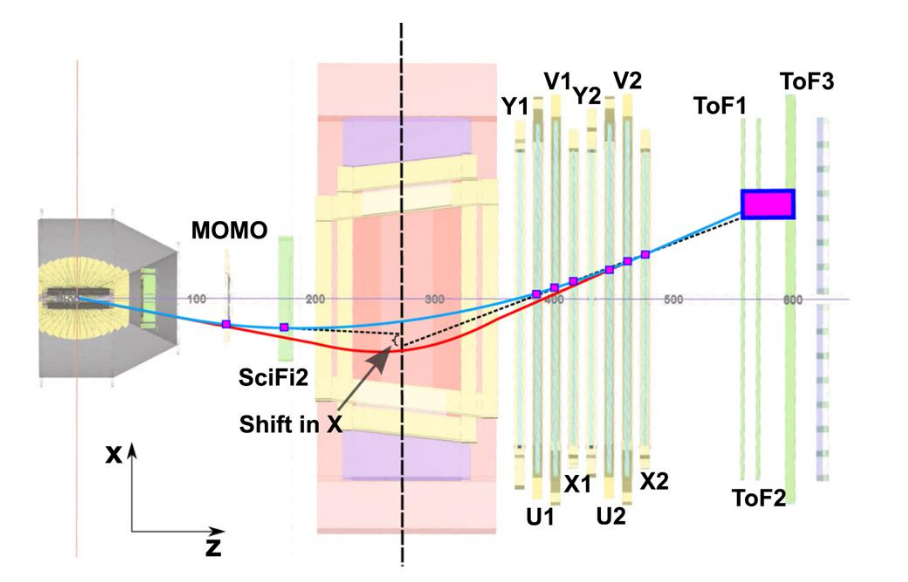
- The understanding of the dynamics underlying the bound state of the nucleon and its excited spectrum still remain a crucial task since in this energy range QCD cannot be treated in perturbative mode.
- Many models, based on different *degrees of freedom* descriptions, have been developed in order to describe the spectrum of excitation states and their features
- Meson photoproduction studies represent a strong tool for probing nucleon resonances:
  - ✓ Access to resonance states coupled to photons which only weakly coupling to the πN processes (Missing Resonances problem)
  - ✓ Access to Polarization Observables => Separation of overlapping resonances and characterization in terms of Spin and Parity, Constrains for unambiguous PWA

BGOOD EXPERIMENT

ELSA
Accelerator
$E_{e^-_{MAX}} = 3.2\ GeV$

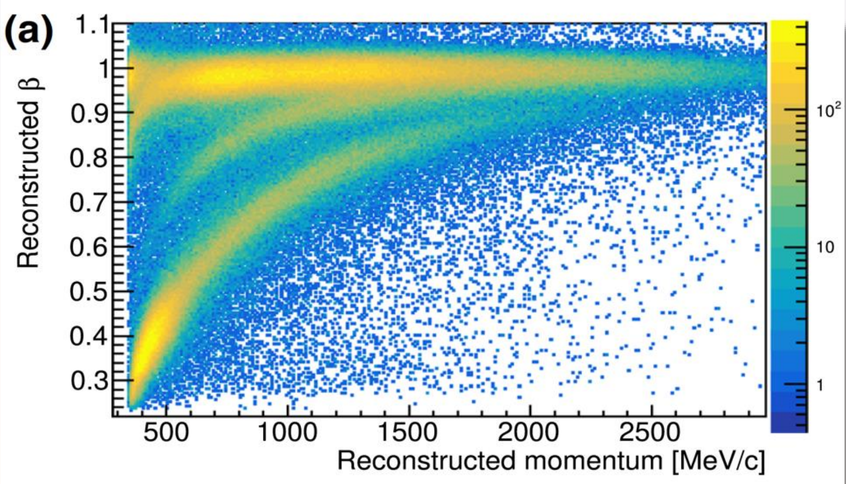


BGOOD Forward Region



High momentum resolution forward tracking

β vs Momentum in Forw Spectrometer

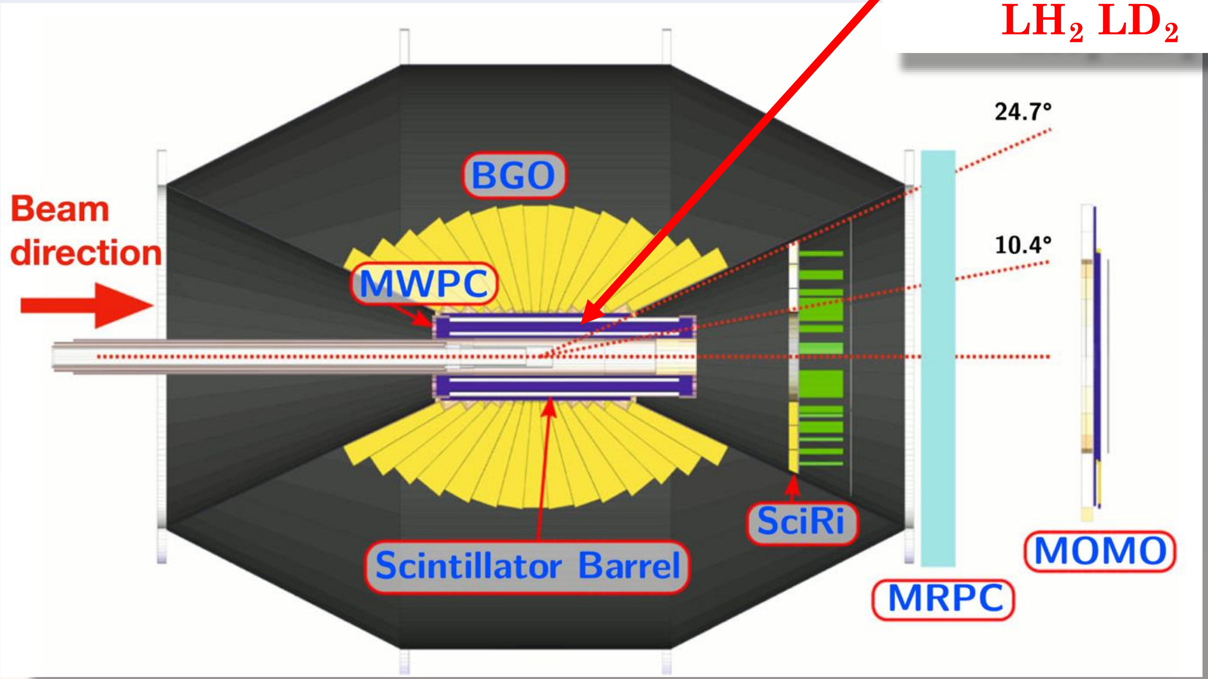


BGOOD Central Region

large solid angle calorimeter:

- excellent energy resolution for photons
- good detection efficiency for neutrons
- charged particle tracking and identification
- neutron/photon discrimination

Target system LH_2 LD_2



BGO Rugby Ball E.M. Calorimeter:

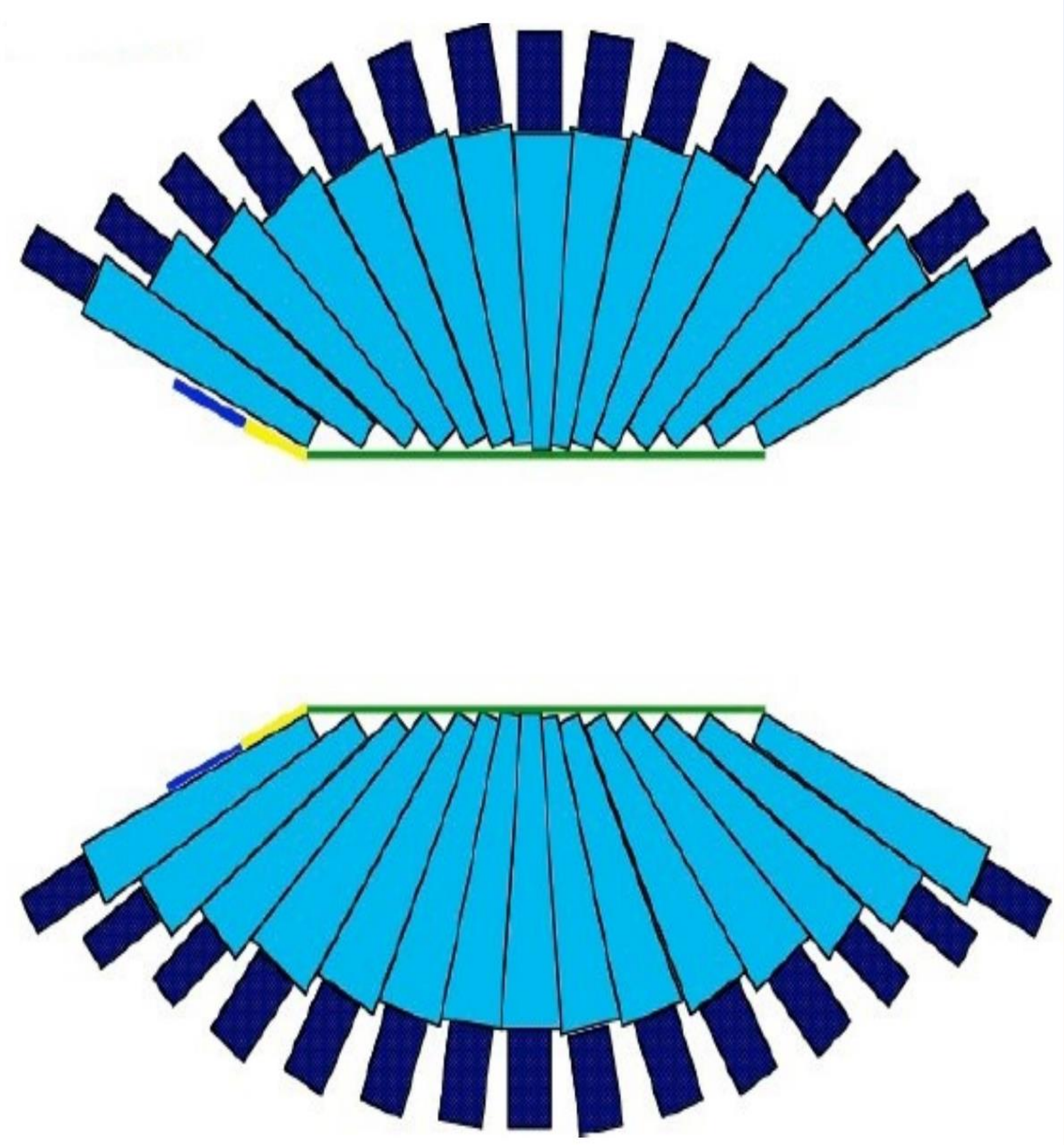
480 BGO crystals of 24 cm depth ⇒ 21 radiation lengths thickness

15 x 32 sectors (polar and azimuthal angles) => 15 Crowns

Each crown covers $\Delta\theta = 6°$ (FWHM) in polar angle

Polar angular range $\theta = (25° \div 155°)$

Full Azimuthal range



BGO Rugby Ball E.M. Calorimeter:

480 BGO crystals of 24 cm depth ⇒ 21 radiation lengths thickness

15 x 32 sectors (polar and azimuthal angles) => 15 Crowns

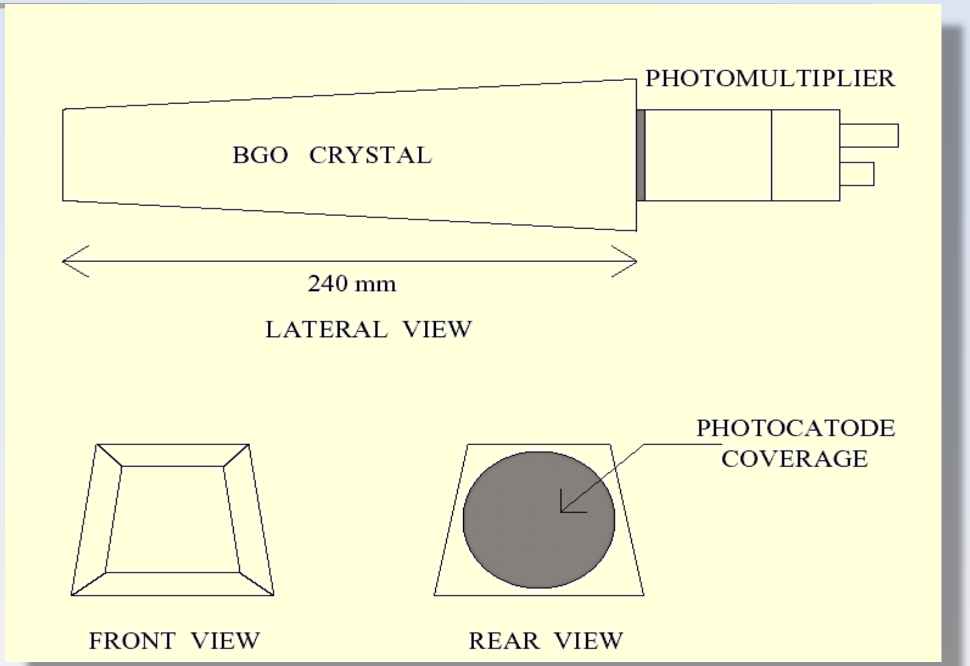
Each crown covers $\Delta\theta$= 6 ° (FWHM) in polar angle

Polar angular range $\theta = (25° \div 155°)$

Full Azimuthal range

Crystals shaped as **pyramidal sectors with trapezoidal basis**

- 8 different dimensions.
- Coupling with a HamamatsuR580 or R329-2 PMT
- **Signals read by WIENER AVM16 sampling ADCs**
  - **Energy** (Signal Integral) and **Time** (Signal Start Time) Information
  - Rate160MHz (t sample 6,25 ns) ⇒ **Time Resolution $\delta t \cong 2 \div 3$ ns**



Angular resolution for single crystal

$\Delta\,\theta = 6\,°$ (FWHM)

$\Delta\,\phi = 11.25°$ (FWHM)

BGO Rugby Ball E.M. Calorimeter:

480 BGO crystals of 24 cm depth ⇒ 21 radiation lengths thickness

15 x 32 sectors (polar and azimuthal angles) => 15 Crowns

Each crown covers $\Delta\theta = 6°$ (FWHM) in polar angle

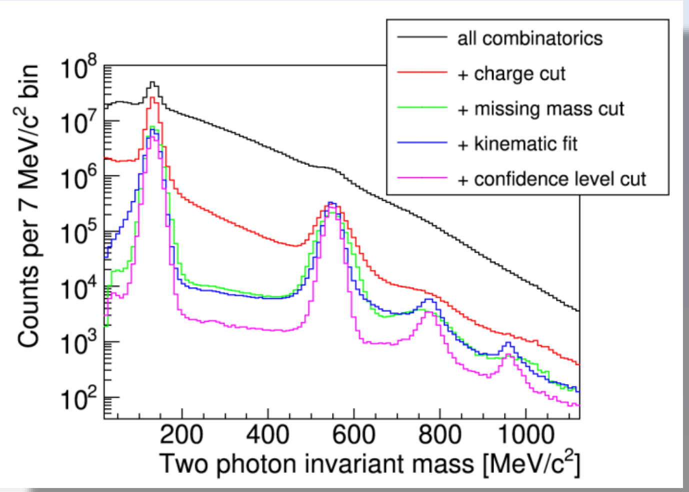
Polar angular range θ = (25° ÷ 155°)

Full Azimuthal range

Crystals shaped as **pyramidal sectors with trapezoidal basis**

- 8 different dimensions.
- Each crystal wrapped in a *30μm* aluminised Mylar foil
- Coupling with a HamamatsuR580 or R329-2 PMT
- **Signals read by W-IE-NE-R AVM16 sampling ADCs**
    - **Energy** (Signal Integral) and **Time** (Signal Start Time) Information
    - Rate160MHz (t sample 6,25 ns) ⇒ **Time Resolution δt ≅ 2 ÷ 3 ns**

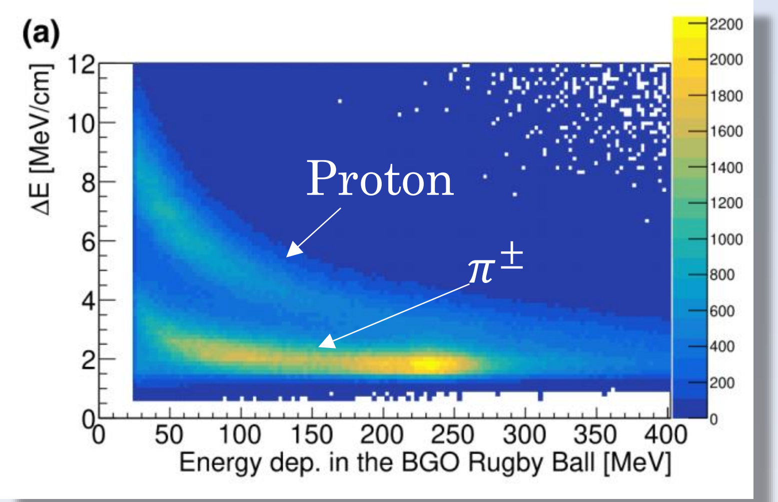
Photons in BGO Ball



Energy Resolution (1GeV photons)

$$\Gamma(FWHM) = \sqrt{a^2 + \left(\frac{b}{E_\gamma}\right)^2 + \left(\frac{c}{\sqrt{E_\gamma}}\right)^2} \approx 3\%$$

BGO Rugby Ball E.M. Calorimeter:



Charged Particles:

Signals in geometrical coincidence BGO-Barrel-MWPCs.

Charged particle Identification ($p,\pi^{\pm}$) by mean 2-dim $\frac{dE}{dx}$ *%E*

Neutral Particles (Photons/Neutrons):

Signals in the BGO not associated with hits in any other detector

We define:

BGO Cluster: *Group of contiguous crystals associated with the interaction of the same particle within the detector*

Cluster multiplicity: *Number of crystals composing the cluster.*

Neutron/Photon Discrimination: Method

PROBLEM => Impossible to unambiguously distinguish neutron/photon signals in BGO Calorimeter

BUT => We know that neutrons and photons interact with BGO by mean different physics processes

Neutrons

(Energy Range 10 ÷ 300 MeV)

- elastic scattering
- inelastic scattering
- induced fission, capture ..

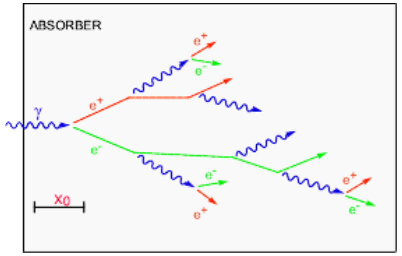
on BGO components (Oxygen, Germanium,Bismuth).

A fraction of the neutron energy is released in the detector

Photons

(Energy Range 20 ÷ 1000 MeV)

Electromagnetic shower



The photon energy is totally released in the BGO

- Study the features of clusters produced by Neutrons and Photons
- Find differences (due to different physics processes underlying their detection).
- Find selection criteria based on these differences

Neutron/Photon Discrimination: Method (Continue)

- "Clean" Selection (very low residual background) of a reaction with neutron and photons in the Final State

q-free photoproduction

$$\gamma + n \rightarrow \pi^0 + n \rightarrow 2\gamma + n$$

Proton in the Deuteron acting as spectator

Selected with pure Two Body Process kinematical criteria

Negligible Fermi Momentum

- Analysis of the **features** of the selected **clusters** in terms of:

  - $M_{n,\gamma}$ = **Cluster Multiplicity**
  - $E_{tot_{n,\gamma}}$ = **Total Energy released in the cluster**
  - $E_{Max_{n,\gamma}}$ = **Max Energy released in a Crystal (of the cluster)**
  - $E_{mean} = E_{tot_{n,\gamma}} / M_{n,\gamma}$
  - $R = E_{Max_{n,\gamma}} / E_{tot_{n,\gamma}}$
  - $t_{n,\gamma}$ = **Cluster start time** (ToF $of\ the\ particle$)

- Definition of ***a posteriori* cuts** to be used in the selection from the beginning

Event Preselection for: $\gamma + n \rightarrow \pi^0 + n \rightarrow 2\gamma + n$

- **Starting point for the data selection: 200 Runs with LD2 target**

- **No charged signal in the whole apparatus**
- **3 Neutral signals in BGO**

=> N. of Starting events: 6.1 Millions

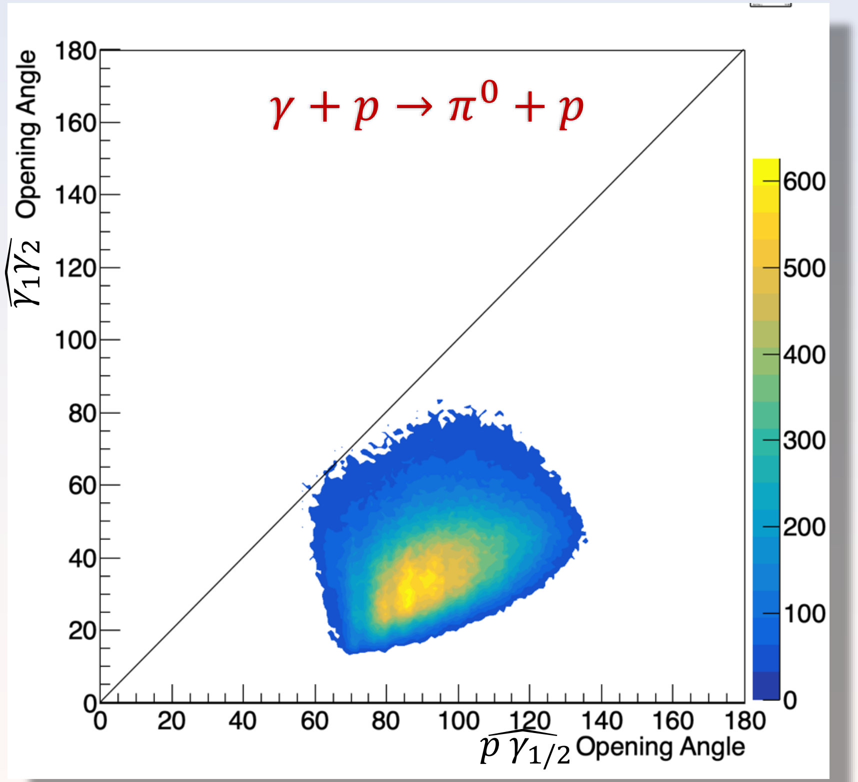
- **Event Preselection:**

We have to use a selection criterion in order **to assign an identity to the three neutral clusters**

1) Opening Angle Preselection Criterion => $\widehat{\gamma_1\gamma_2} < \widehat{n\,\gamma_2}$ & $\widehat{\gamma_1\gamma_2} < \widehat{n\,\gamma_1}$

In π^0 Nucleon photoproduction the angle between γ_1 & γ_2 is the smallest one

neutron/photons discrimination based on a pure Kinematical assumption verified by mean Simulation and comparison with twin process on proton $\gamma + p \rightarrow \pi^0 + p$



2) The Missing nucleon from π^0 has to be inside the BGO $\theta^{calc}_{miss\,N} > 20°$

NB:	γ_1 **Highest energy π^0 decay photon**
	γ_2 **Lowest energy π^0 decay photon**

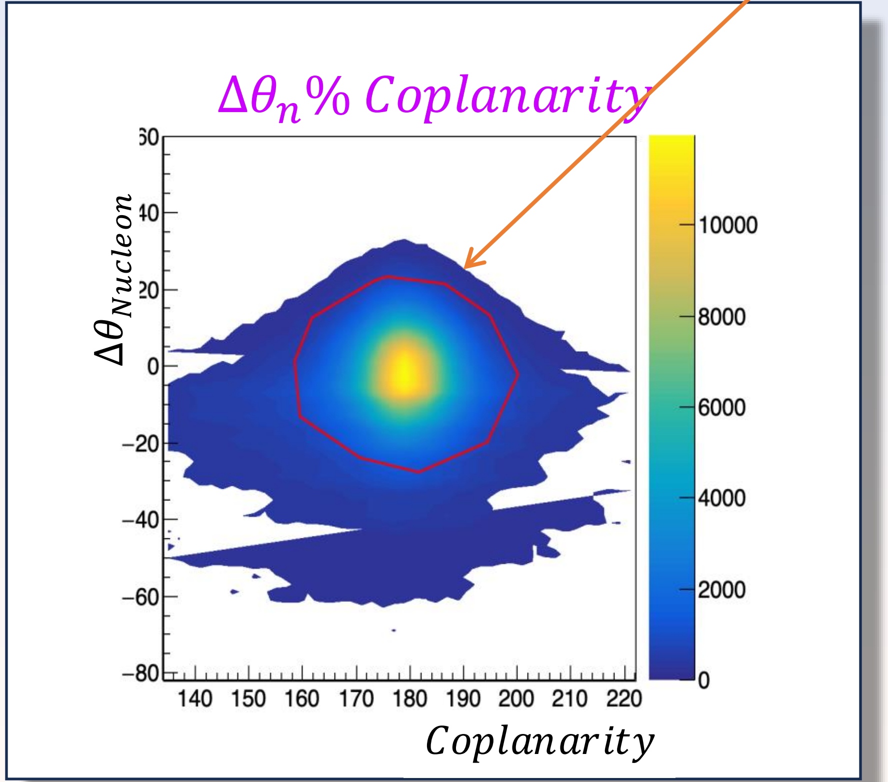
Event Selection for: $\gamma + n \rightarrow \pi^0 + n \rightarrow 2\gamma + n$

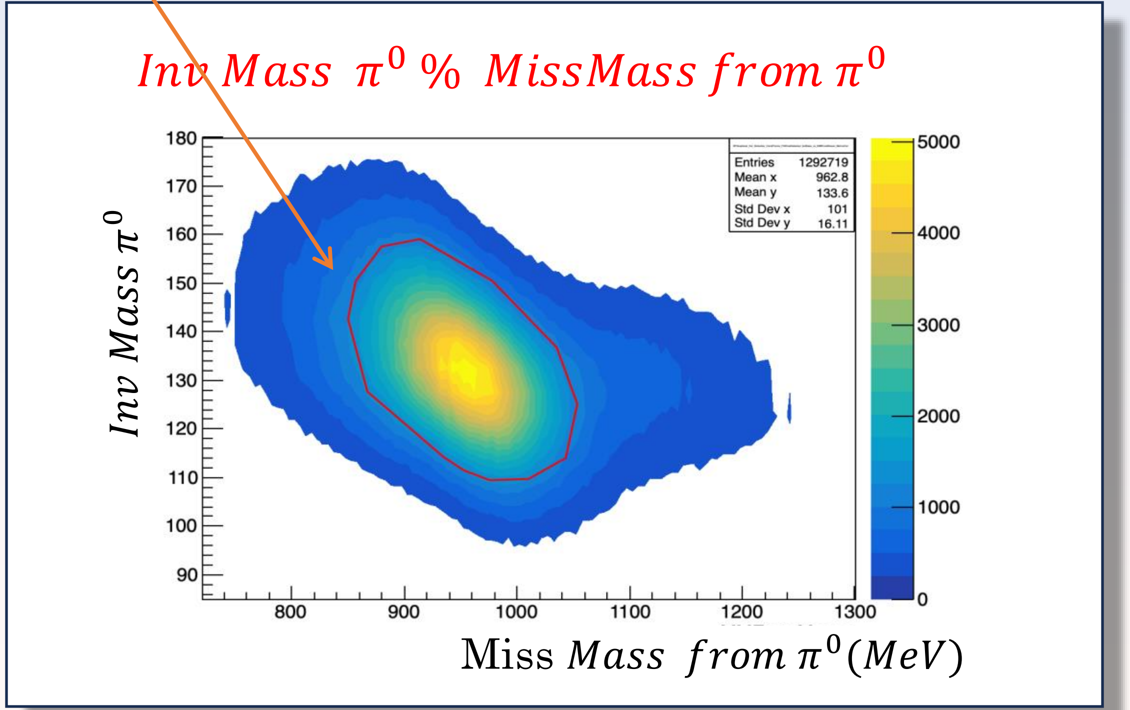
- **Stringent kinematical standard cuts to select 2-body final state reactions:**

3) $\theta^{calc}_{miss\,N} - \theta^{meas}_{n}$ **% *Coplanarity***

4) π^0 ***InvMass* % *MissMass from*** π^0

graphical 2D cuts

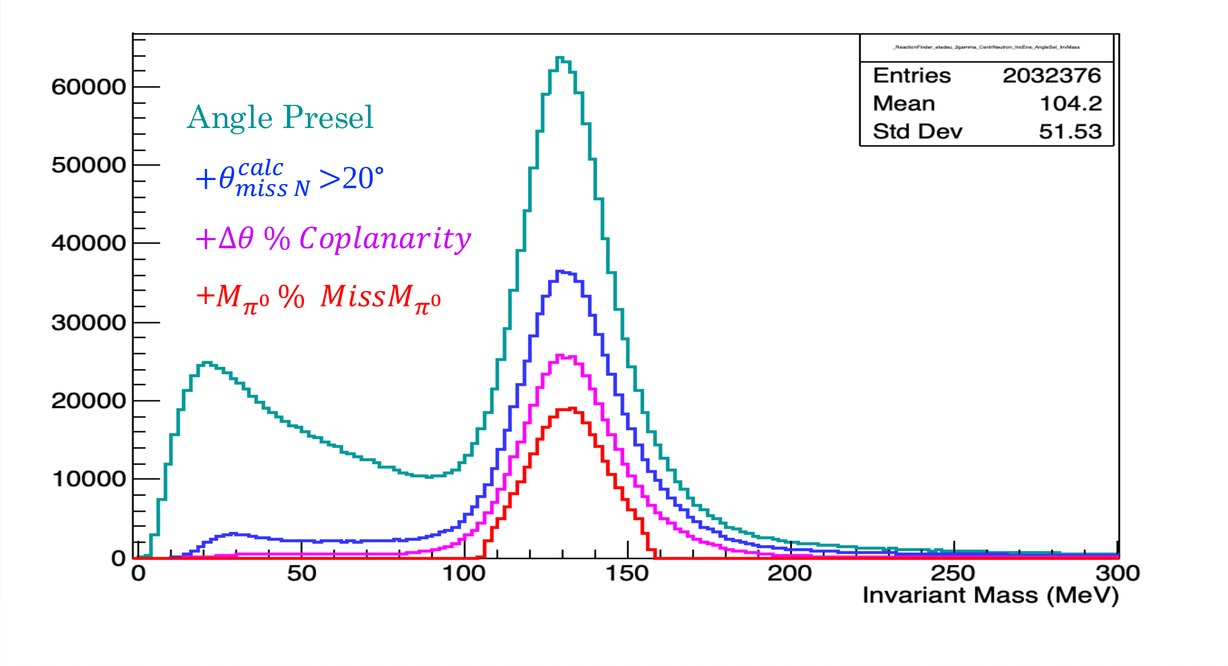




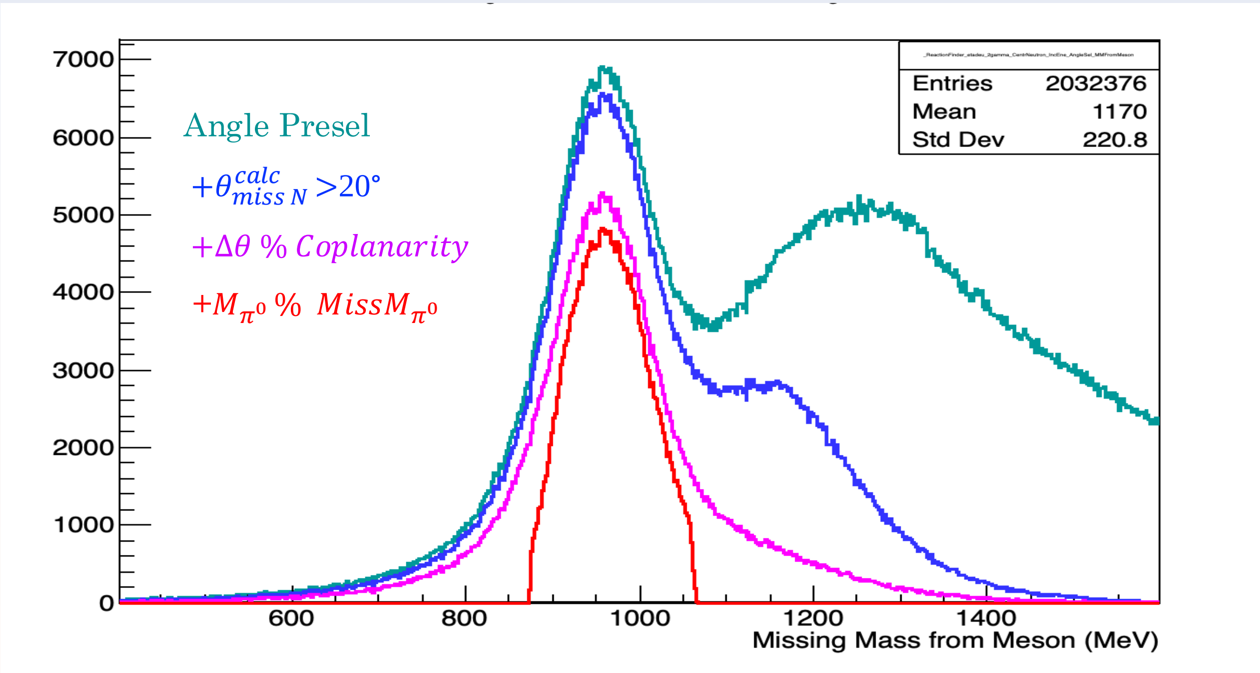
Kinematical Cuts: $\gamma + n \rightarrow \pi^0 + n \rightarrow 2\gamma + n$

2-body reaction completely defined by the meson reconstructed from the 2 γ's in BGO and the neutron detected in BGO => Clean Event Selection by means of 2D Graphical Cuts => $2.9 \cdot 10^5$ selected events

π^0 Invariant Mass



Missing mass from π^0



Neutron/Photon Discrimination Criteria

Starting from the **Clean Data of $\gamma + n \rightarrow \pi^0 + n \rightarrow 2\gamma + n$**, **we analyzed the π^0 decay photons (γ_1 , γ_2) and neutron clusters** in order to find other properties which could be peculiar of these particles and which could be used as discrimination criteria from the very beginning.

⇩

We identified three PID criteria

1) Mean Energy per Crystal $\frac{E_{tot_{n,\gamma}}}{M_{n,\gamma}}$

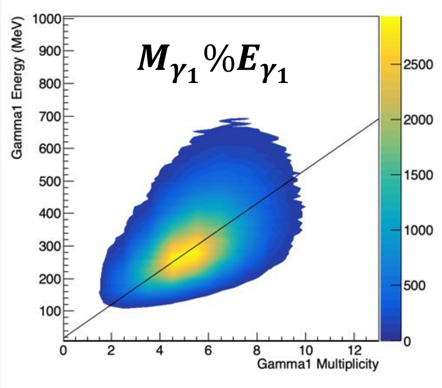
2) Energy concentration in the crystal with the highest released energy $E_{MAX_{n,\gamma}}/E_{tot_{n,\gamma}}$

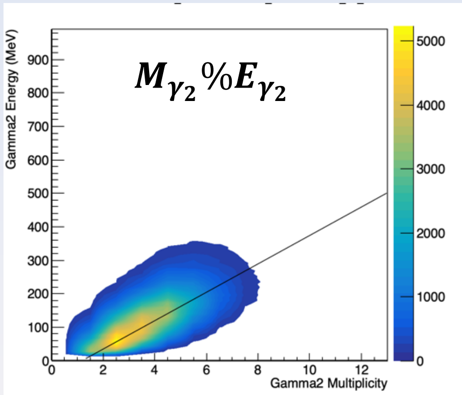
3) Photons Time of Flight (ToF) vs. neutron ToF.

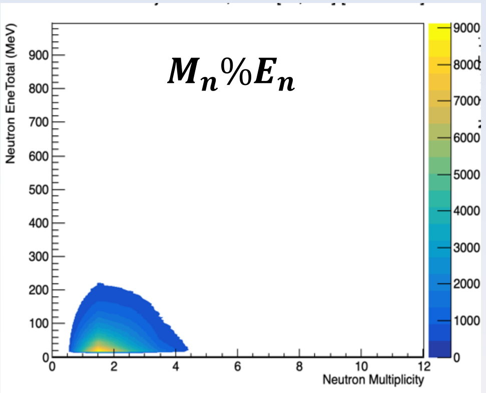
1° PID Criterion: Mean Energy per Crystal $E_{tot_{n,\gamma}}/M_{n,\gamma}$

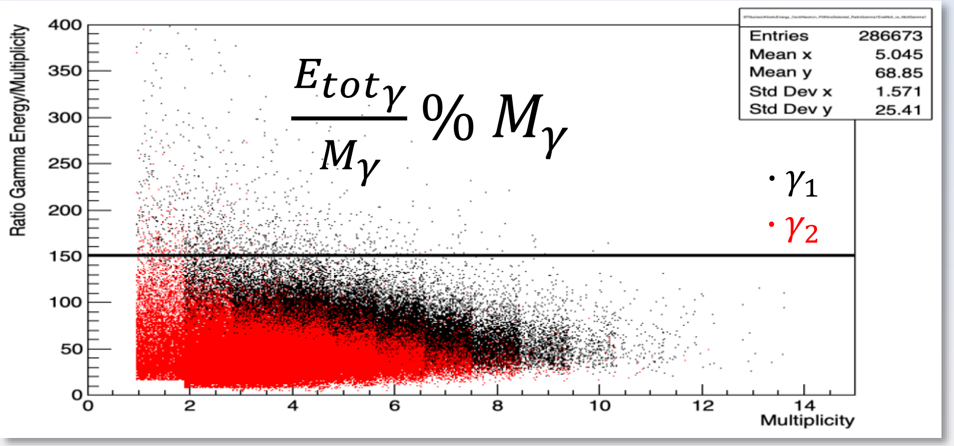
Cluster multiplicity M :

- M_γ **roughly proportional to the energy** E_γ **for photon clusters;**
- M_n **small (<5) and independent on the energy** E_n **for neutron clusters**





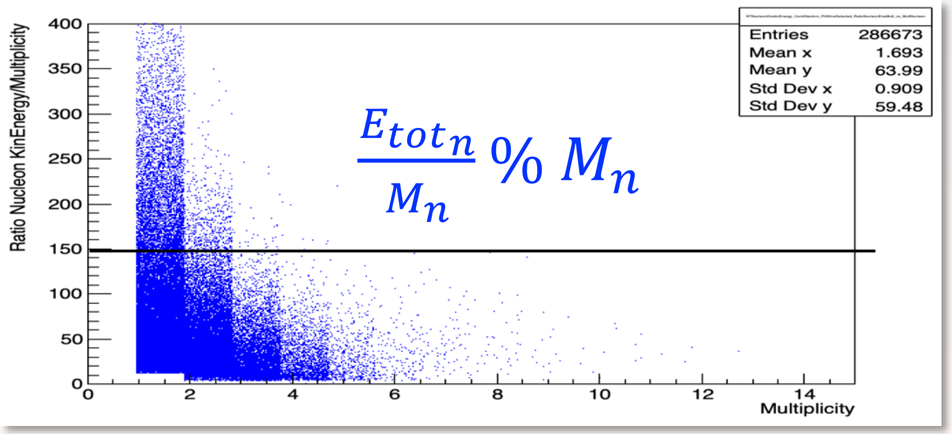




1) Mean Energy per Crystal $E_{tot_{n,\gamma}}/M_{n,\gamma}$:

➢ **for photons** $\Rightarrow E_{mean} = \frac{E_{tot_\gamma}}{M_\gamma} < 150\,\frac{MeV}{crystal}$

➢ **for neutron** ⇒ large amounts of energy per crystal are allowed



$$\frac{E_{tot_\gamma}}{M_\gamma} < 150\,\frac{MeV}{crystal} \Rightarrow \text{cut selection for photons}$$

2° PID Criterion: $E_{Max_{n,\gamma}}/E_{tot_{n,\gamma}}$ % $E_{tot_{n,\gamma}}$

2) Energy concentration $\frac{E_{Max_{n,\gamma}}}{E_{tot_{n,\gamma}}}$ % Cluster Energy $E_{tot_{n,\gamma}}$

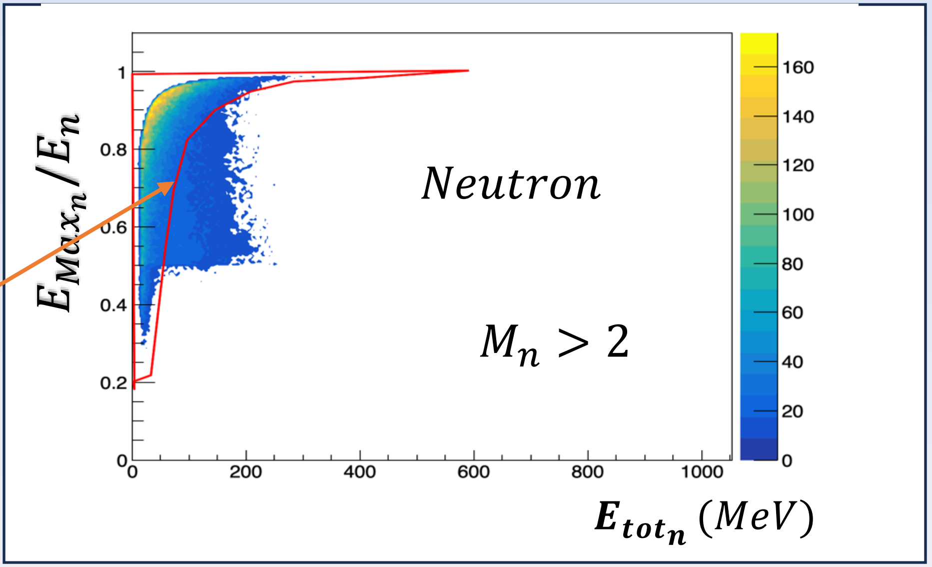
where E_{Max} = *Max Energy released in a crystal of the cluster*

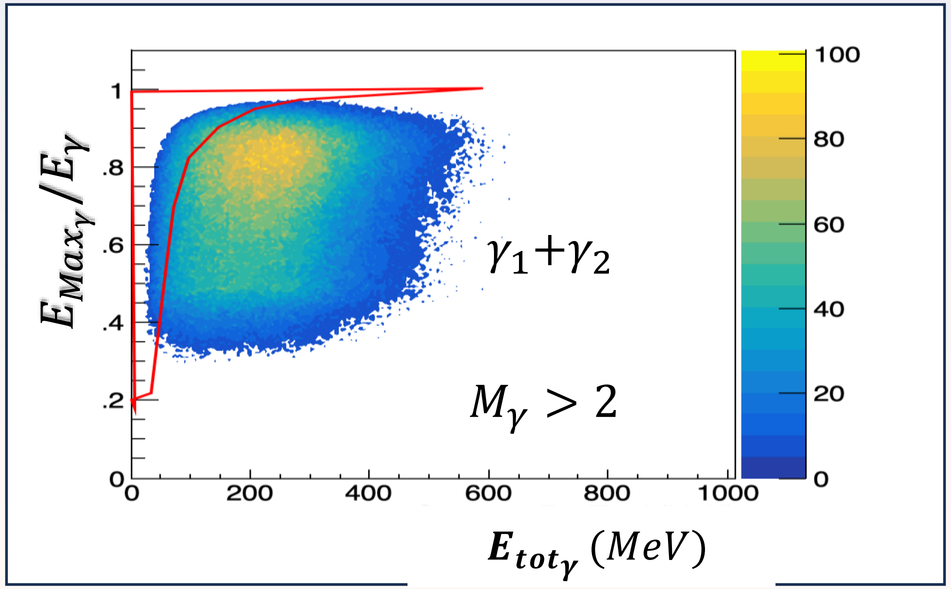
This distribution has **different behavior for neutrons and photons** for:

- **clusters with multiplicity>2**

2D Graphical Cut on $\frac{E_{Max_n}}{E_{tot_n}}$ % E_{tot_n} => To select neutron signals

Data with Mult =1 not included since in this case $\left(\frac{E_{Max}}{E_{tot}}\right)_{M=1} \equiv 1$





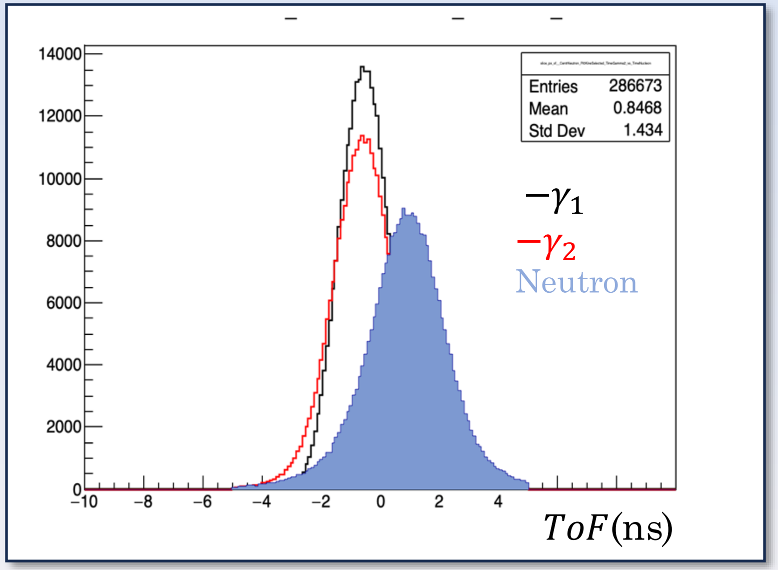
3° PID Criterion: Particles ToF

3) $ToF_{\gamma}\%ToF_{n}$

The ToF measured in BGO is in average higher for neutrons ($\sim1.5 ns$) than for photons ($\sim0\ ns$).

This time difference is inside the time resolution of the detector ($\sim2 \div 3\ ns$).

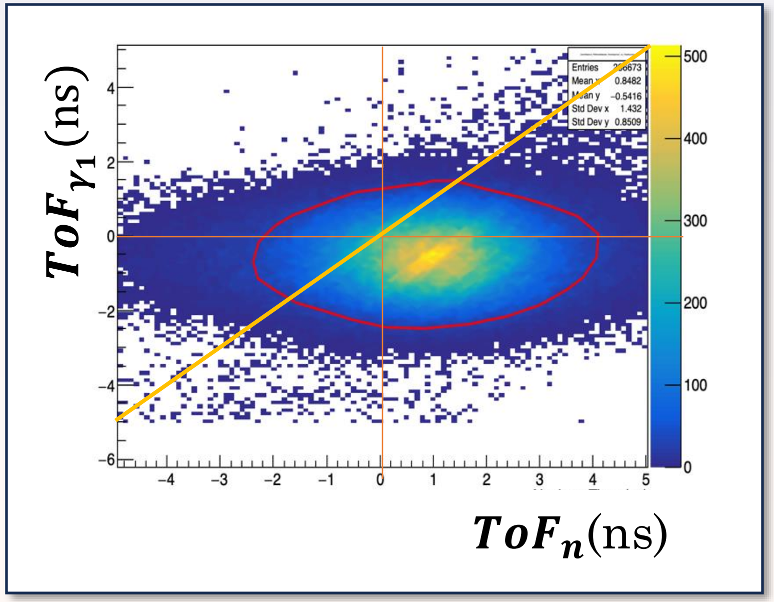
=> **ToF cannot be used to univocally discriminate neutron by photon**



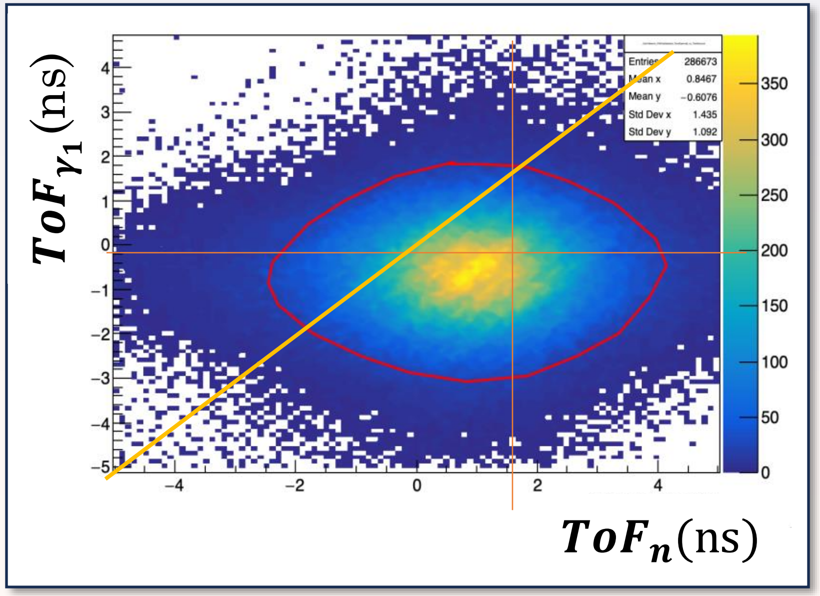
But….

If both particles (photons and neutrons) are required in a specific analysis, it is possible to apply an ellipsoidal graphical cut on the 2D-plot $ToF_{\gamma}\%ToF_{n}$ for the suppression of the background due to low-energy photons and out-of-time events.

$ToF_{\gamma_1}\%ToF_{n}$



$ToF_{\gamma_2}\%ToF_{n}$

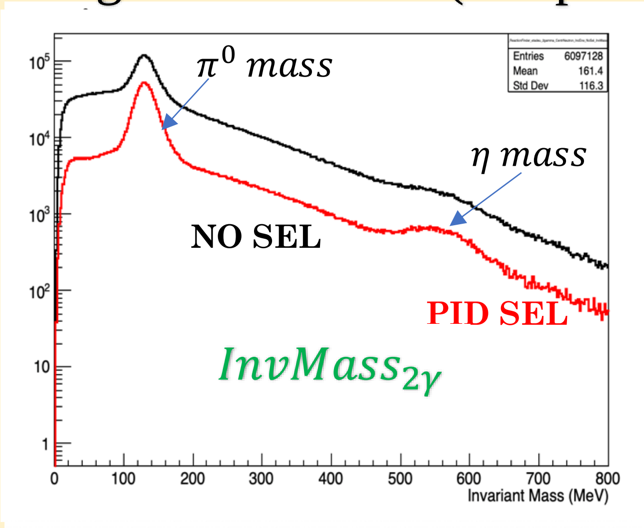


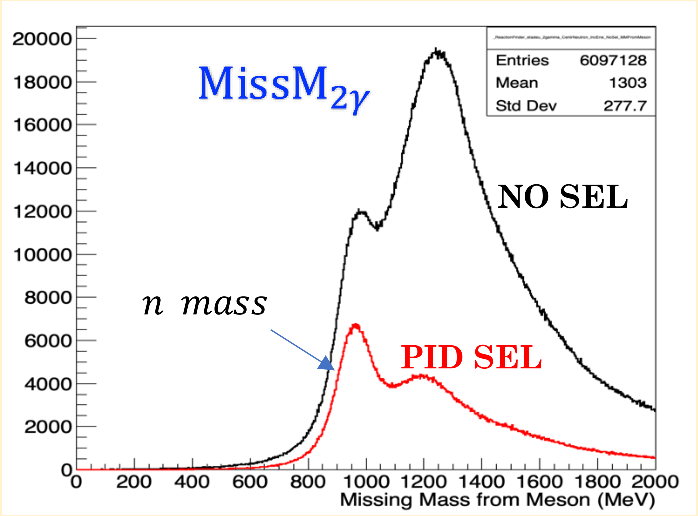
2D Graphical Cut on $ToF_{\gamma}\%ToF_{n}$

For Background Suppression

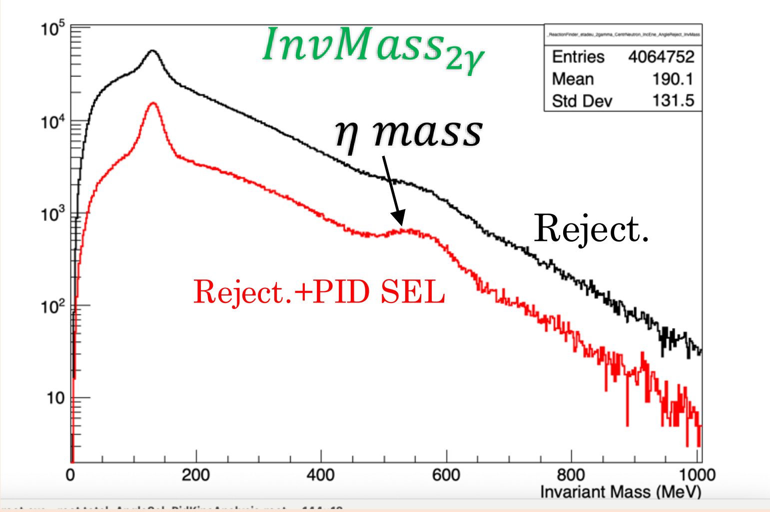
Test of Criteria: Application of PID Criteria on:

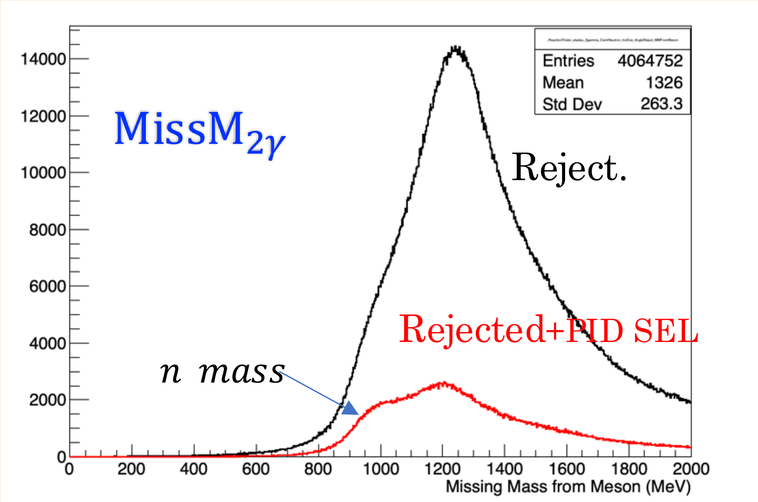
original set of data (NO preselection - NO kinematical cut)



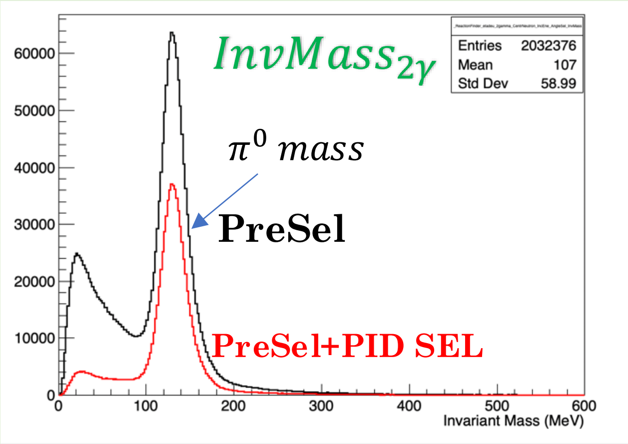


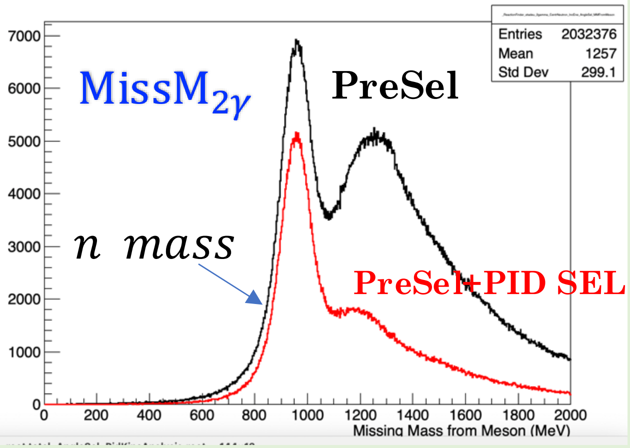
Data Rejected by AnglePreselection (No Kinematical Cut)





opening angle preselected data (NO kinematical cut selection)

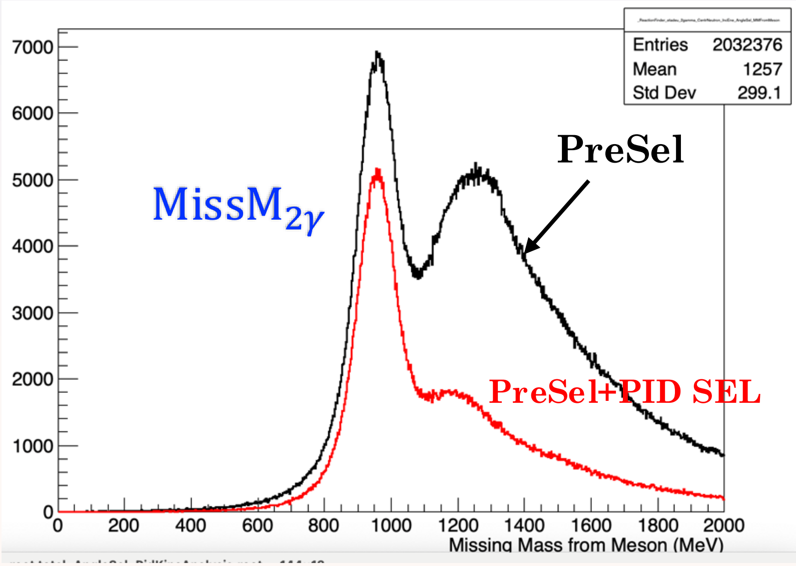




Test of Criteria

	KINE SELECTED # EVENTS	KINE SELECTED (%)	PID-KINE SELECTED #EVENTS	PID-KINE SELECTED (%)
TOTAL	$6.1 \cdot 10^6$		$6.1 \cdot 10^6$	
ANGLE SEL	$2.0 \cdot 10^6$	33.3	$2.0 \cdot 10^6$	33.3
PID SEL			$8.5 \cdot 10^5$	14.0
KINEMATICAL SEL	$2.9 \cdot 10^5$	4.7	$2.2 \cdot 10^5$	3.7

Applying the PID Criteria before the Kinematical Selection to the sample of preselected events **we found a clear particle identification** and **a background reduction,** due to incorrect assignment of particle identities, **of about 50%**



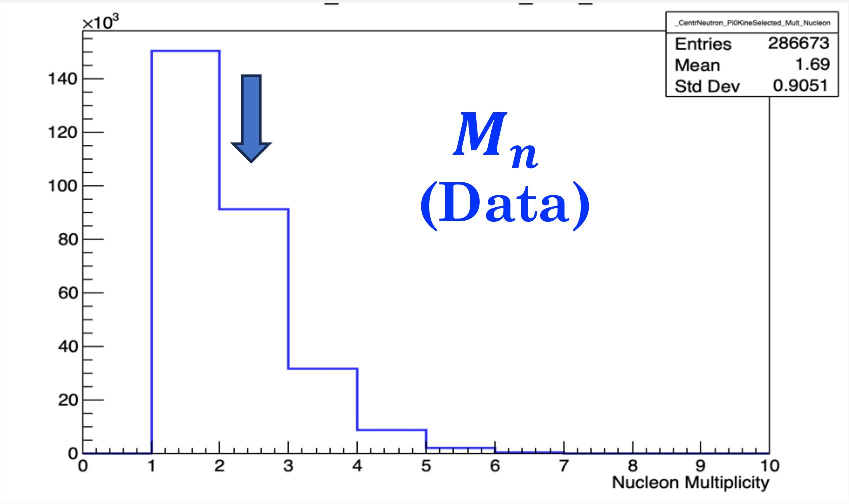
Comparison with Geant4 Simulation (QSGP-BIC-HP):

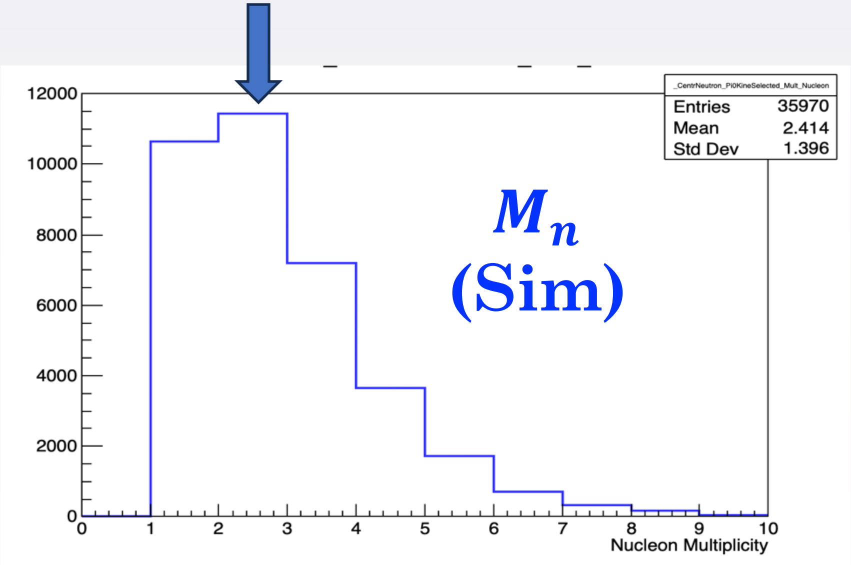
Starting from **10^6 events for π^0 photoproduction on the neutron** we applied the opening angle pre-selection criteria and the same analysis with kinematical cuts as in data, in order to select π^0 photoproduction events => We obtained a **set of $2.5 \cdot 10^4$ selected events**

Analyzing the cluster features of the selected **events of π^0 photoproduction on the neutron**, we found some **crucial differences for the neutron** respect to what found for data:

1) Neutron multiplicity in BGO => In Simul Neutron multiplicity is not well reproduced:

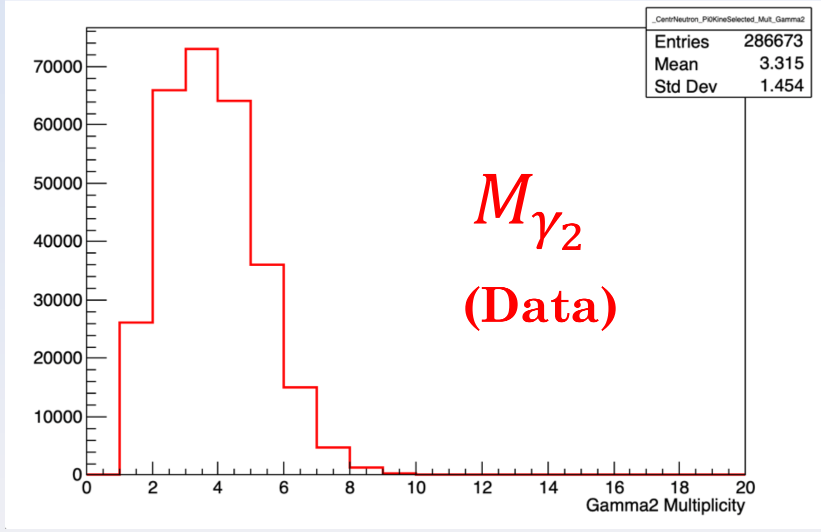
- **DATA: Most probable multiplicity = 1 & No Multiplicity > 5;**
- **SIMUL: Most probable multiplicity = 2 & YES Multiplicity > 5;**

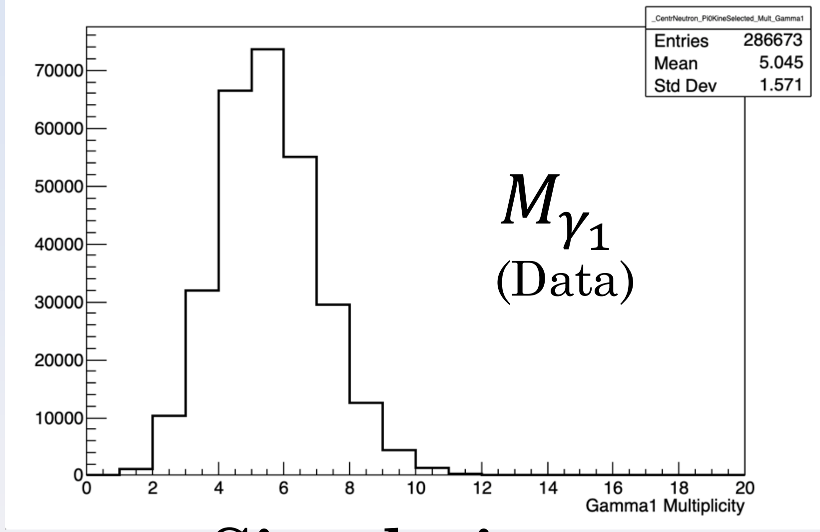


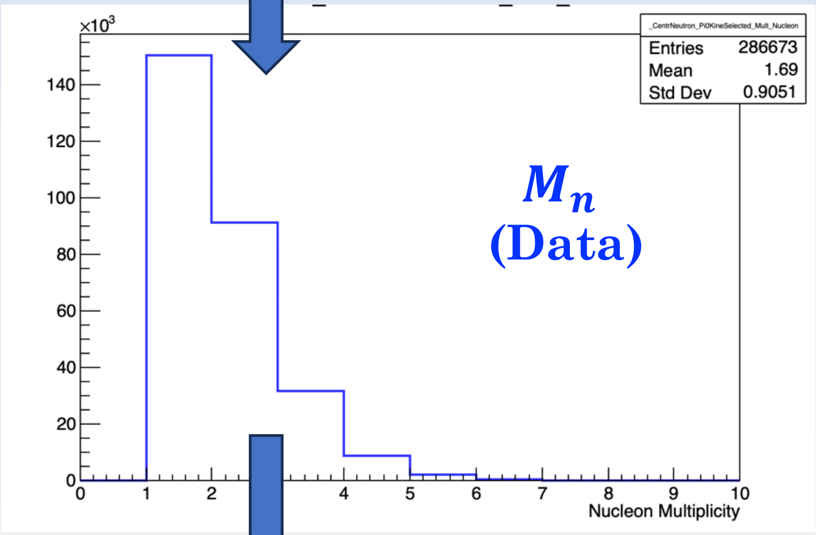


Comparison with Simulation: Cluster multiplicity

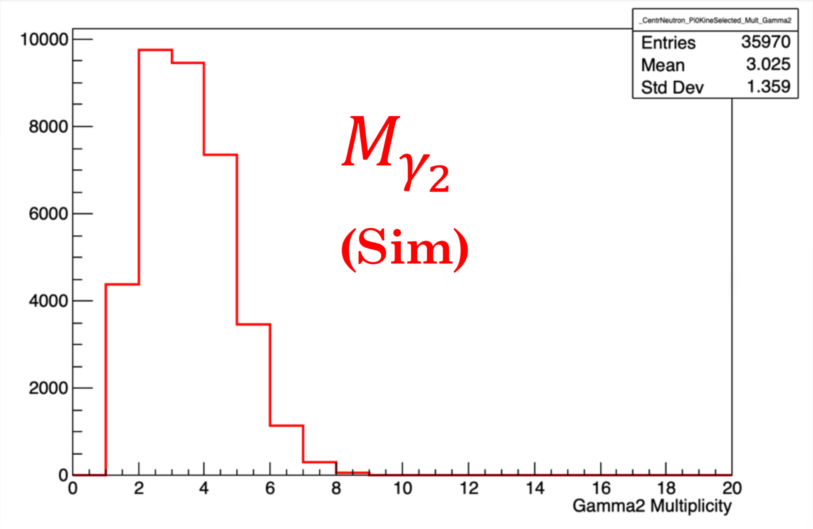
Data | **Data** | **Data**

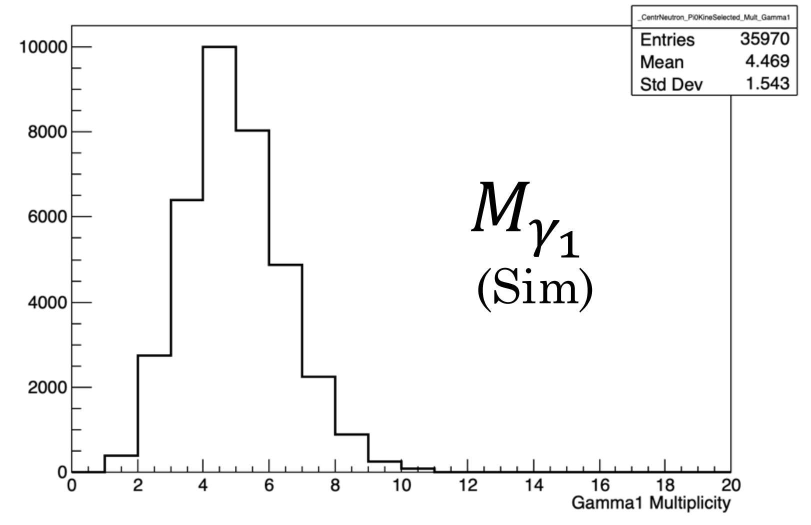


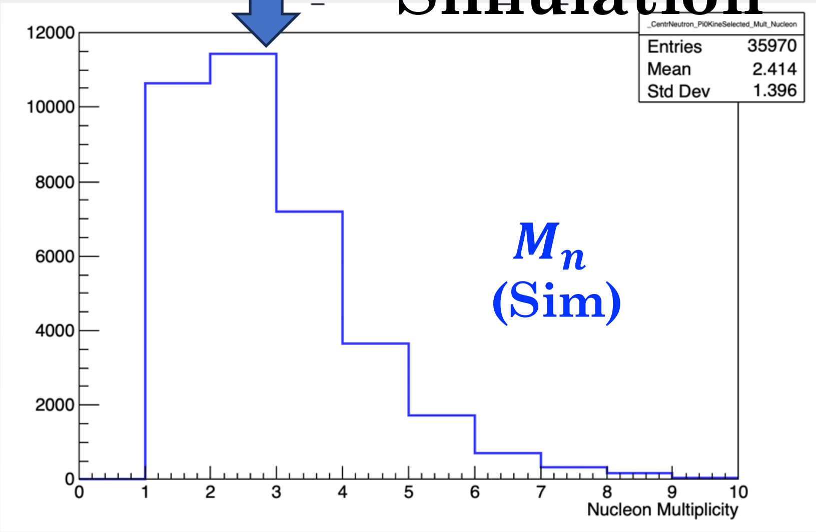




Simulation | **Simulation** | **Simulation**







Comparison with Simulation: (Neutron Energy Released in BGO)

Starting from **10^6 events for π^0 photoproduction on the neutron** we applied the opening angle pre-selection criteria and the same analysis with kinematical cuts as in data, in order to select π^0 photoproduction events => We obtained a **set of $2.5 \cdot 10^4$ selected events**

Analyzing the cluster features of the selected **events of π^0 photoproduction on the neutron**, we found some **crucial differences for the neutron** respect to what found for data:

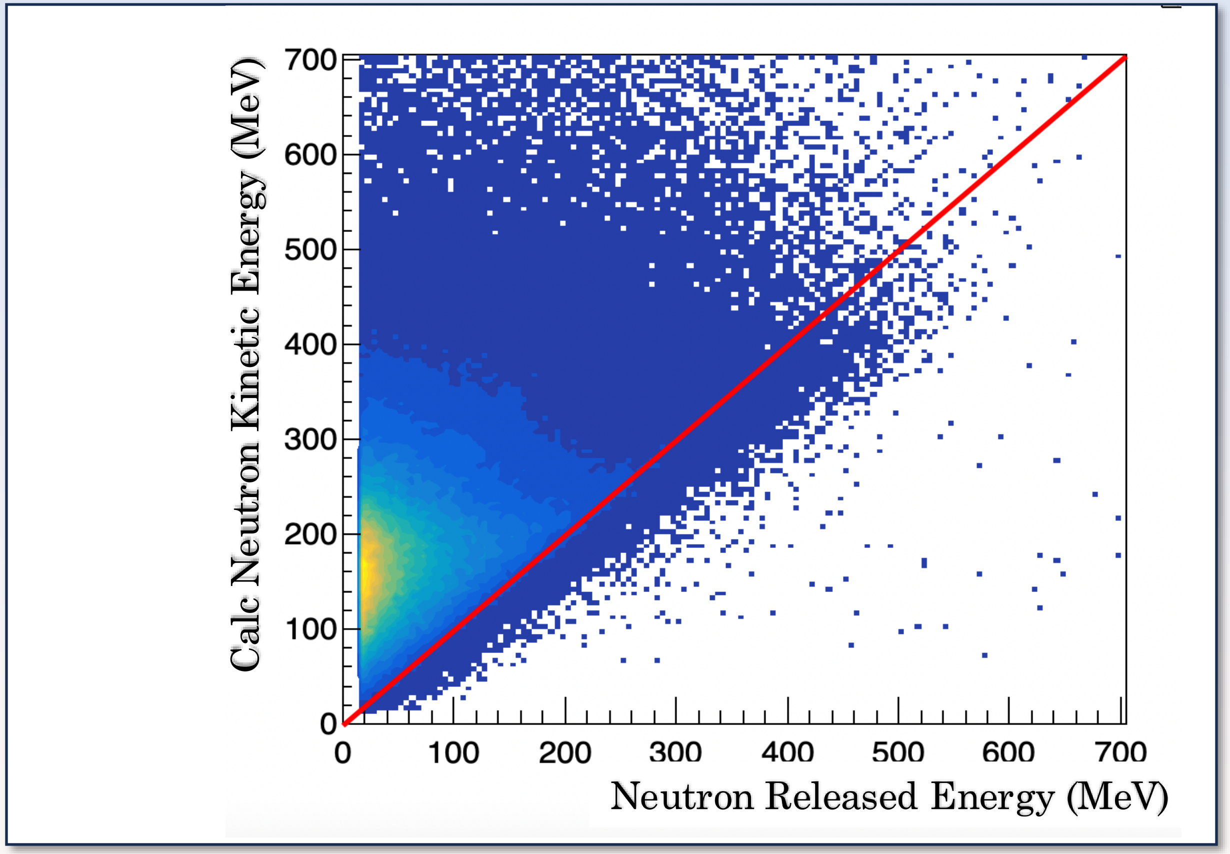
1) **Neutron multiplicity in BGO => In Simul Neutron multiplicity is not well reproduced:**

- **DATA: Most probable multiplicity = 1 & No Multiplicity > 5;**
- **SIMUL: Most probable multiplicity = 2 & YES Multiplicity > 5;**

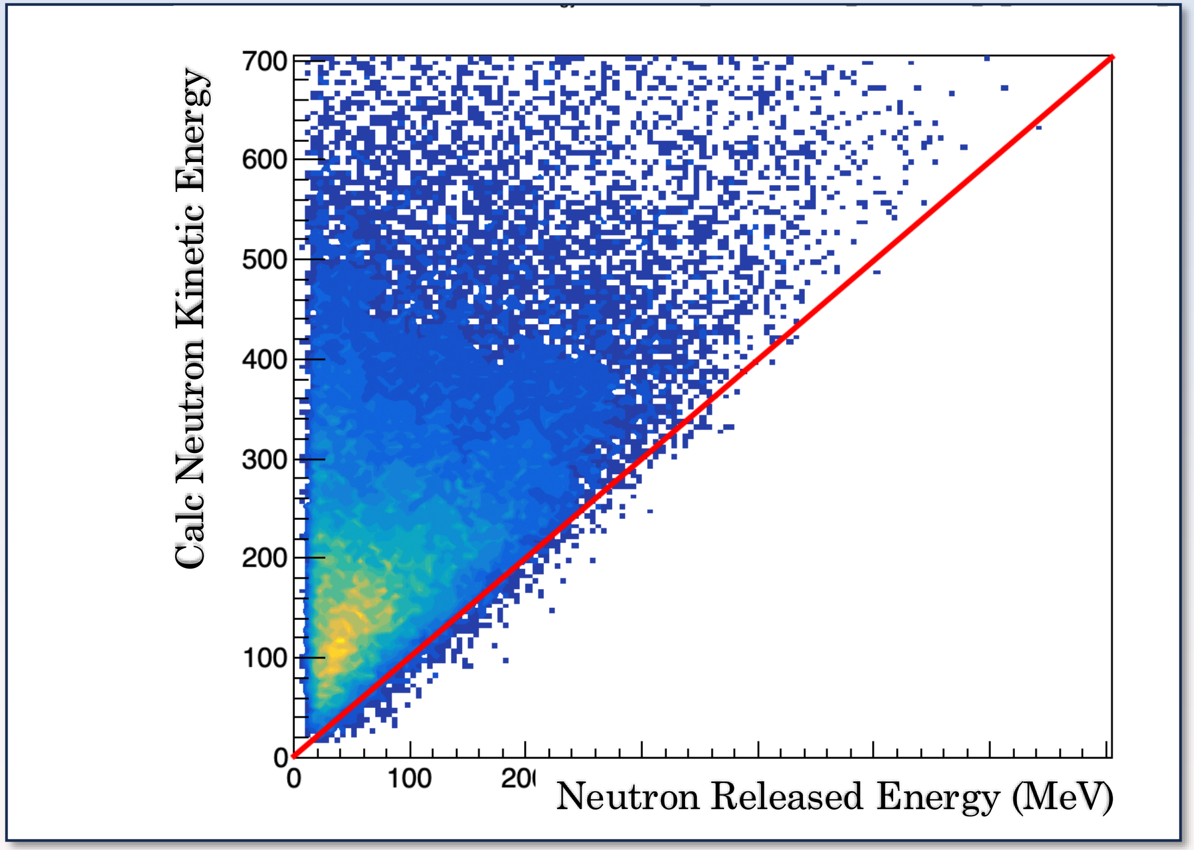
2) **Neutron Energy Released in BGO => In Simul Neutrons release a greater fraction of energy than what observed in the data.**

Comparison with Simulation: (Neutron Energy Released in BGO)

Data



Simulation

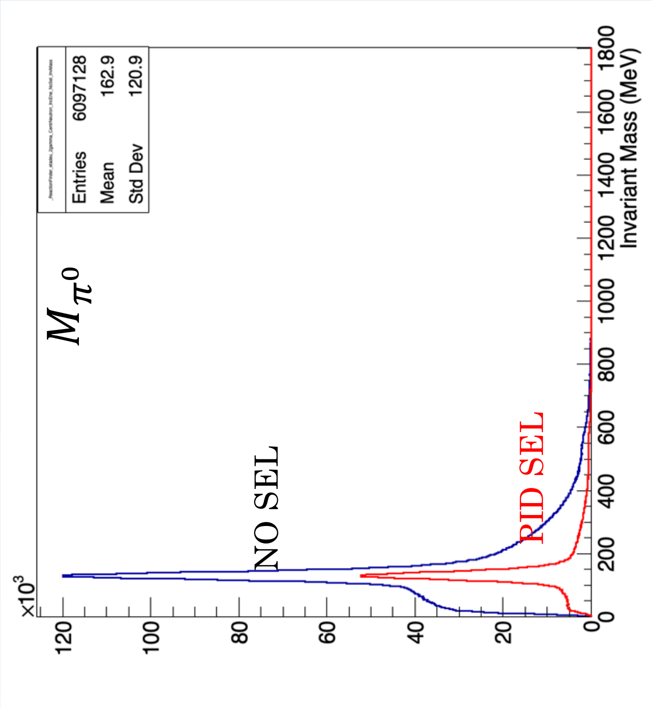


Summary & Conclusions

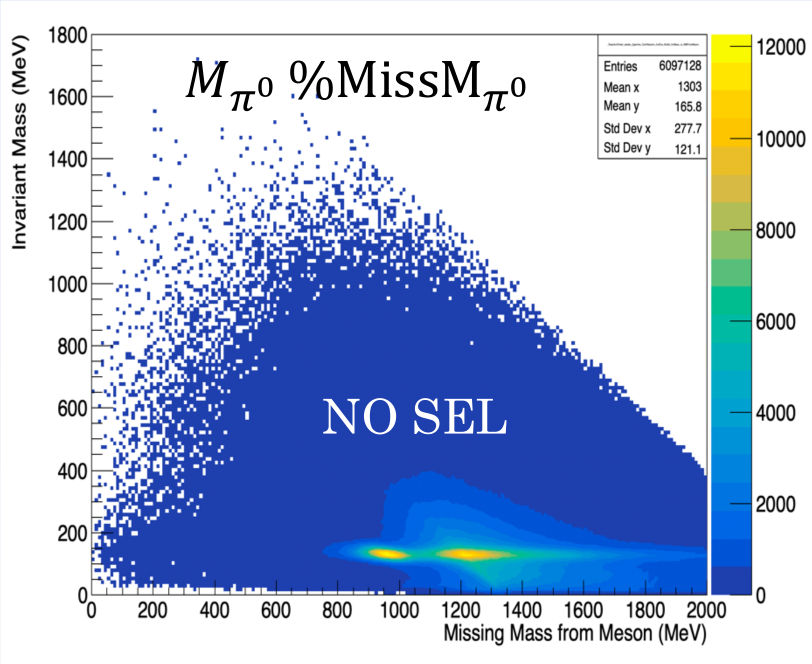
- Starting from a clean set of π^0 photoproduction on the neutron events, we have studied the features of clusters produced by Neutrons and Photons and established three selection criteria based on the differences of these features for the two particles.
- The Criteria allows to preselect neutron and photons with a relevant background reduction due to incorrect assignment of particle identities
- These study has also put in evidence a criticism in the GEANT4 simulation that can't well reproduce the neutron cluster features in term of released energy in the BGO and energy distribution in clusters

Thank You !!!!

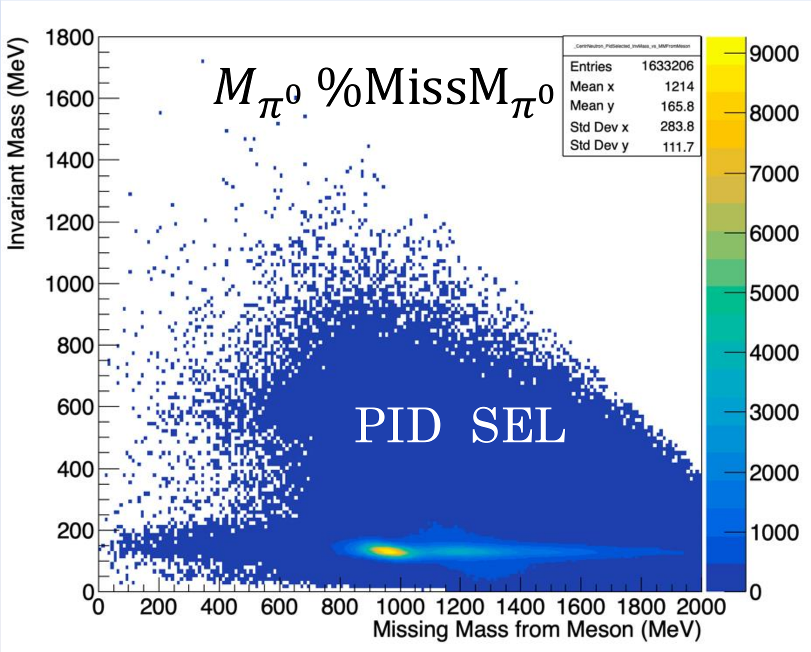
- Backup



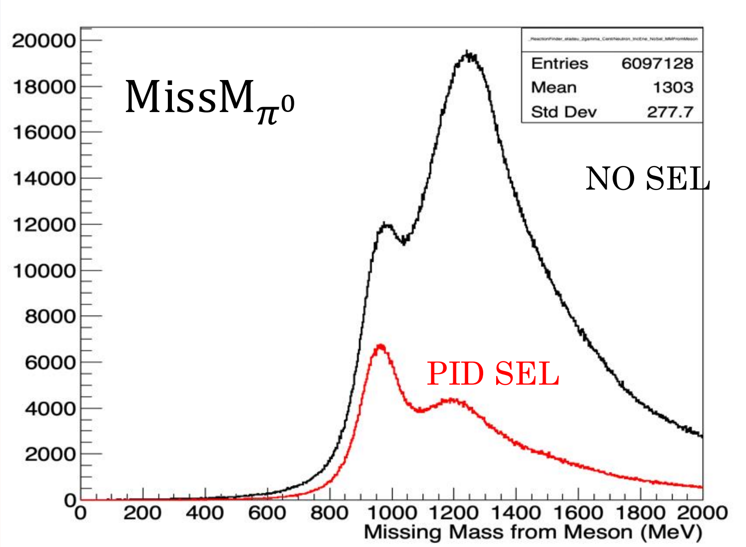
Entries 6097128
Mean 162.9
Std Dev 120.9
Invariant Mass (MeV)
M_{π^0}
NO SEL
PID SEL
$\times10^3$



M_{π^0} %MissM_{π^0}
Entries 6097128
Mean x 1303
Mean y 165.8
Std Dev x 277.7
Std Dev y 121.1
NO SEL
Invariant Mass (MeV)
Missing Mass from Meson (MeV)



M_{π^0} %MissM_{π^0}
Entries 1633206
Mean x 1214
Mean y 165.8
Std Dev x 283.8
Std Dev y 111.7
PID SEL
Invariant Mass (MeV)
Missing Mass from Meson (MeV)



MissM_{π^0}
Entries 6097128
Mean 1303
Std Dev 277.7
NO SEL
PID SEL
Missing Mass from Meson (MeV)

Test of Criteria

1) the original set of data (without any preselection or kinematical cut)

2) the opening angle preselected data (before kinematical cut selection)

3) the opening angle rejected data

compared the results in terms of number of events before and after Kinematical Selection **we found a clear particle identification** and **a background reduction,** due to incorrect assignment of particle identities in the sample of preselected events, **of about 50%**

Test of Criteria

	KINE SELECTED # EVENTS	KINE SELECTED (%)	PID-KINE SELECTED #EVENTS	PID-KINE SELECTED (%)	NO PRESEL #EVENTS	NO PRESEL (%)	REJECTED #EVENTS	REJECTED (%)
TOTAL	**6097128**		**6097128**		**6097128**		**6097128**	
ANGLE SEL	2032376	33,3	2032376	**33,33**	6097128		4064752	**66,7**
$\frac{E_{Max_n}}{E_{tot_n}} \% E_{tot_n}$			1266512	**20,77**	2878272	**47,2**	1609760	**26,4**
$tof_{\gamma_1} \% tof_n$			1002477	**16,44**	2123435	**34,8**	1120958	**18,4**
$tof_{\gamma_2} \% tof_n$			886212	**14,53**	1718461	**28,2**	832249	**13,65**
$E_{mean_{\gamma_1,\gamma_2}} < 150 \frac{MeV}{Crystal}$			854921	**14,02**	1633206	**26,8**	778285	**12,8**
PID SEL			854921	**14,02**	1633206	**26,8**	778285	**12,8**
$\theta^{calc}_{miss\,N} > 20^0$	866167	14,21	535418	**8,78**	748052	**12,3**	212634	**3,5**
$\Delta\theta_n \% Coplan$	506116	8,3	370951	**6,08**	399626	**6,55**	28675	**0,5**
$M_{\pi^0} \% MissM_{\pi^0}$	286673	4,7	224293	**3,7**	233182	**3,8**	8889	**0,15**