Detectors for the HIBEAM/NNBAR Experiment

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NNBAR

Detectors – Introduction

A ***particle detector*** is a device used to detect, track, and identify particles and measure their energy, momentum, charge, etc.

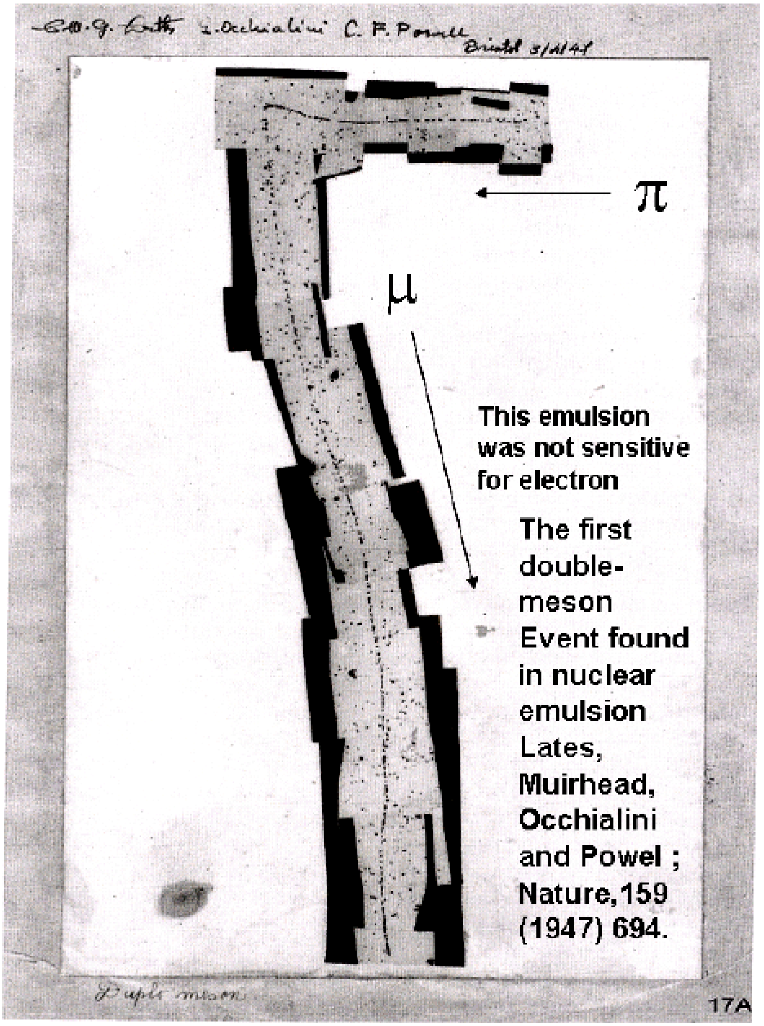
Detectors and other electronic apparatus are required for various purposes in different experiments. The tasks require for most experiments include:

- tracking;
- particle identification;
- momentum and energy measurements;
- triggering;
- data acquisition.

Each detector has a particular features and purpose.

Detectors – Introduction

Historical example: the discovery of the Pion (1947)



M.G. Lattes, G. P. S. Occhailini, and C. F. Powell, “Observations on the tracks of slow mesons in photographic emulsions”, in Nature, 160, 1947.

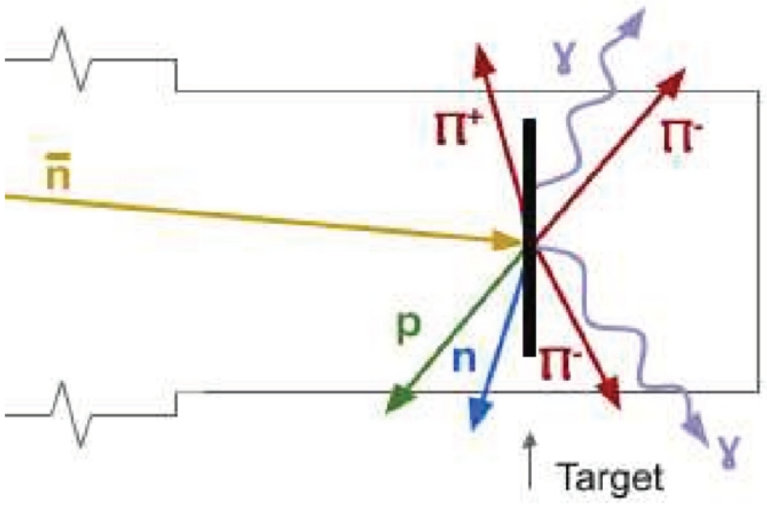
In 1950, Powell alone was awarded the Nobel Prize for Physics “for *his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method.*"

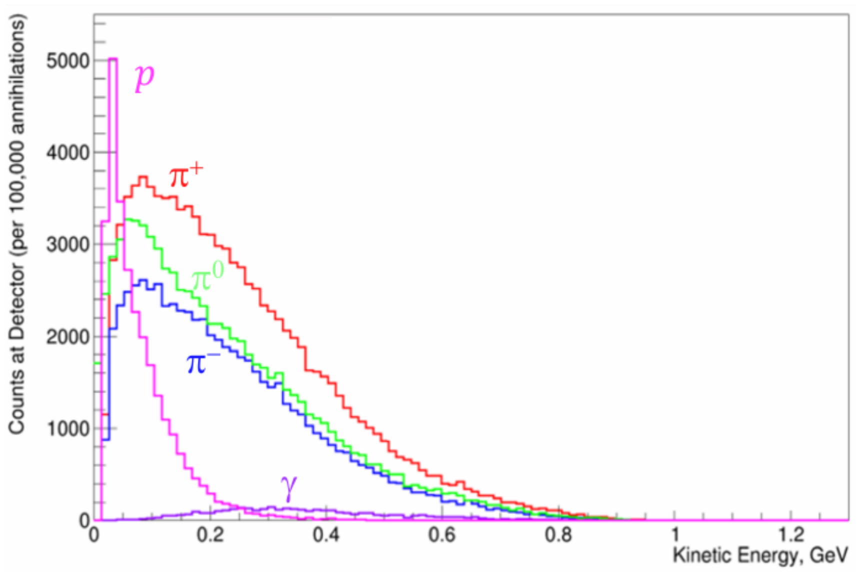
BJP special issue (2024): *Experimental particle physics, tracking detectors and cosmic rays, a legacy of César Lattes.*

Detectors for HIBEAM/NNBAR

What is the task?

- Reconstruct the striking final state generated from an antineutron annihilating with a proton or a neutron!
- We're very interested in pions, since they are the main product of the annihilation event itself (typically 3-5 pions).
- But the annihilation happens within a ^{12}C nucleus, not in free space.
- So, we're also interested in measuring the fragments generated as a result of this fantastic event.

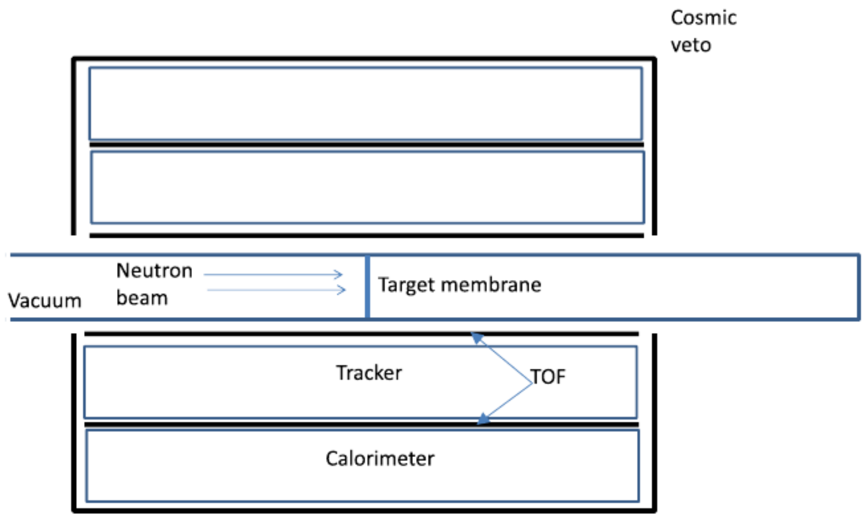




Detectors – NNBAR

Detector Requirements

- Excellent particle identification (PID);
- Precision electromagnetic calorimeter;
- Time measurements to reject cosmic rays;
- Trigger system with short time window.



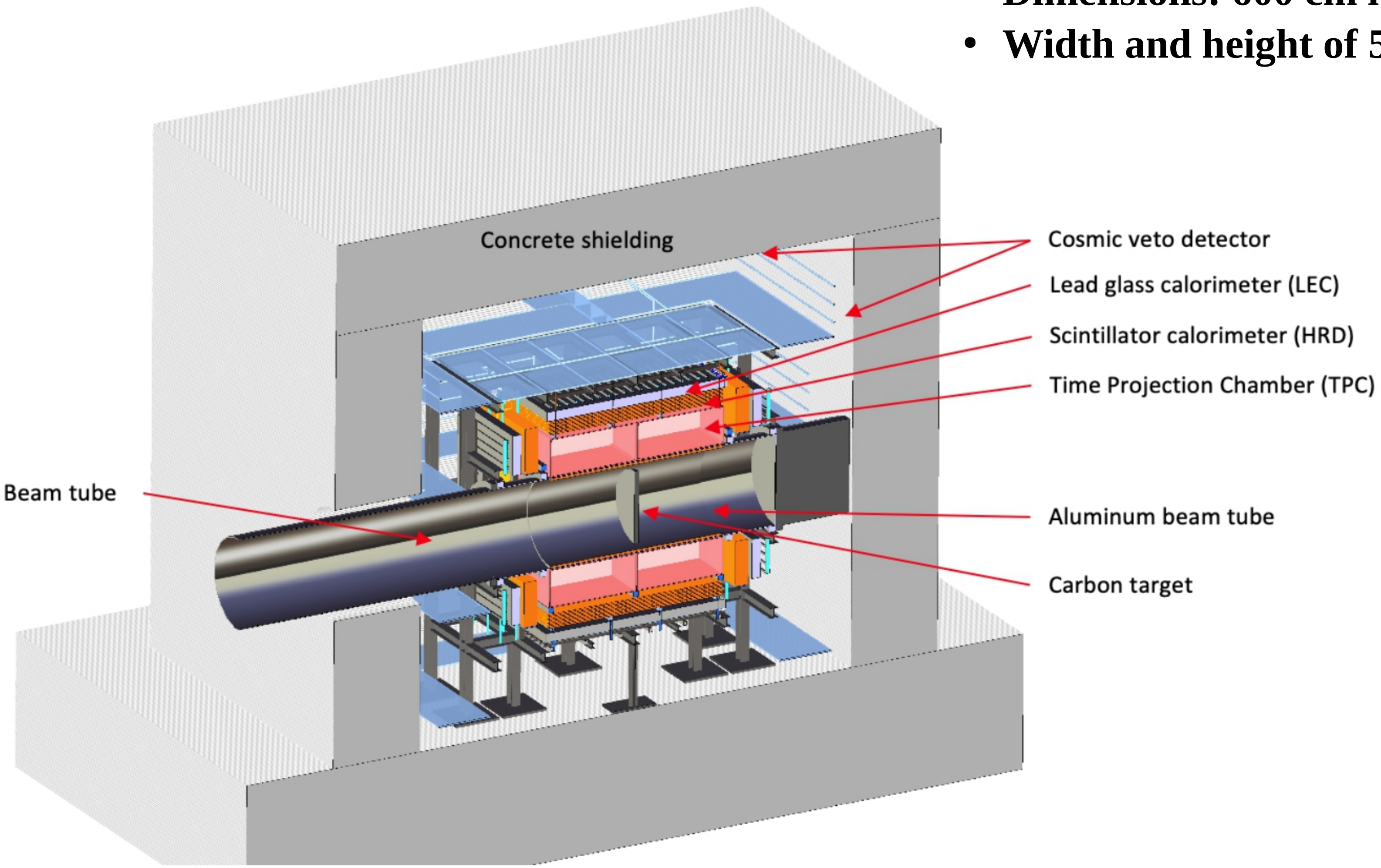
Detector Features (NNBAR)

- Time projections chambers (TPC) for tracking and dE/dx measurements;
- Silicon tracker (vertex resolution);
- Scintillators for PID (10 slats);
- Electromagnetic calorimeter made of lead glass for photons from decays;
- Dedicated cosmic veto surrounding the detector.

Reject **all** the background events is extremely important for the potential detection of an antineutron.

Detectors – NNBAR

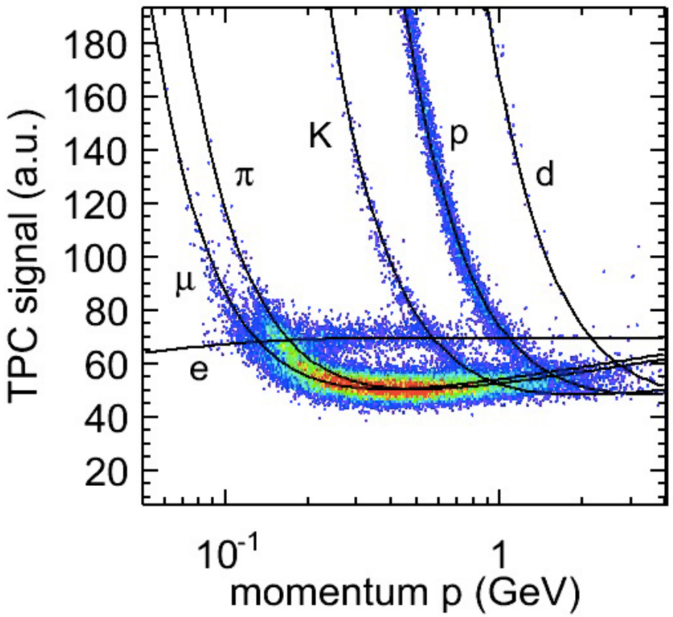
- **Box geometry**
- **Dimensions: 600 cm long (z direction)**
- **Width and height of 515 cm**

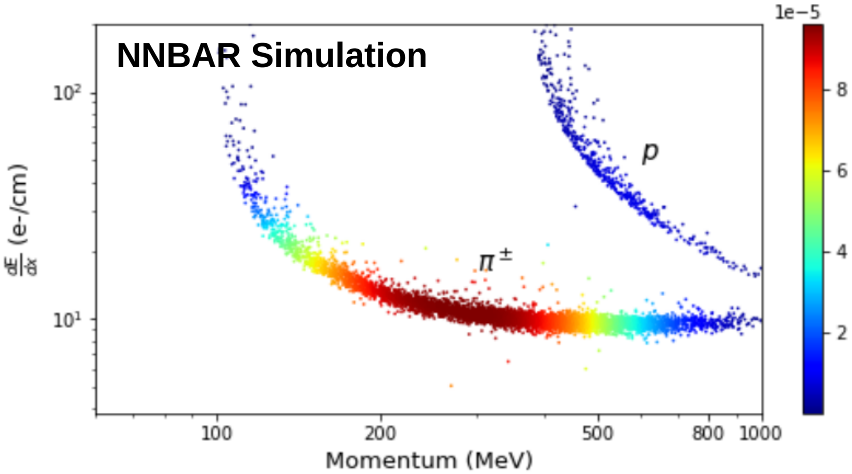


Detectors – NNBAR

Time Projection Chamber (TPC)

- When a charge particle pass through matter, it can loose energy due inelastic collision.
- The energy loss per unit of path length is called *stopping power*, or simply dE/dx.
- The measurement of continues dE/dx can be used to discriminate between charged pion (signal) and protons from background.
- A TPC is a 3D tracking detector capable of providing information on many points of a particle track along with information on the specif energy loss, dE/dx.



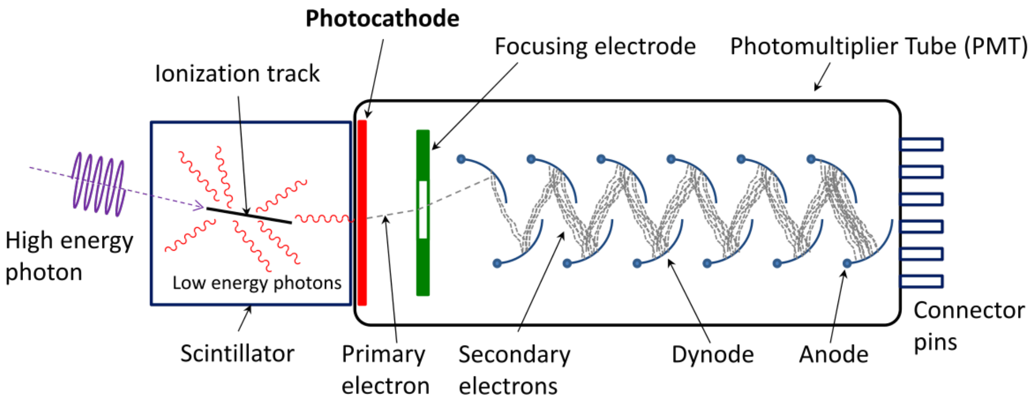


See Ernesto's talk for more details

Detectors – NNBAR

Scintillator Calorimeter (HRD)

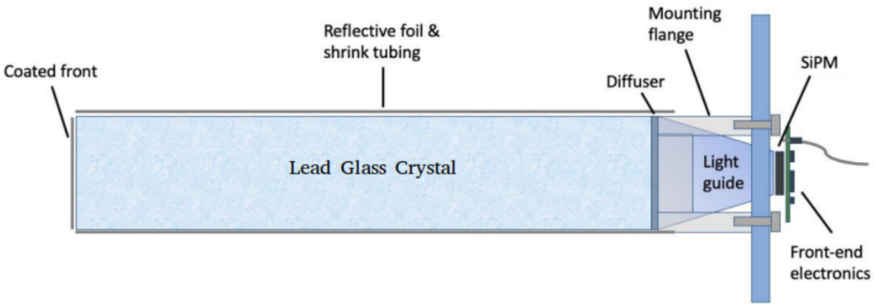
- Scintillators detectors makes use of the fact that certain materials emit a small flash of light when struck by a particle.
- When coupled to a photomultiplier, these scintillations can be converted into electrical pulses and counted electronically.
- For NNBAR, HRD will provide PID and charged pion energy measurement.
- The HRD has a nominal thickness of 30 cm deep, and is built from 10 layers of long scintillating staves with width 6 cm and thickness 3 cm



Detectors – NNBAR

Lead Glass Calorimeter (LEC)

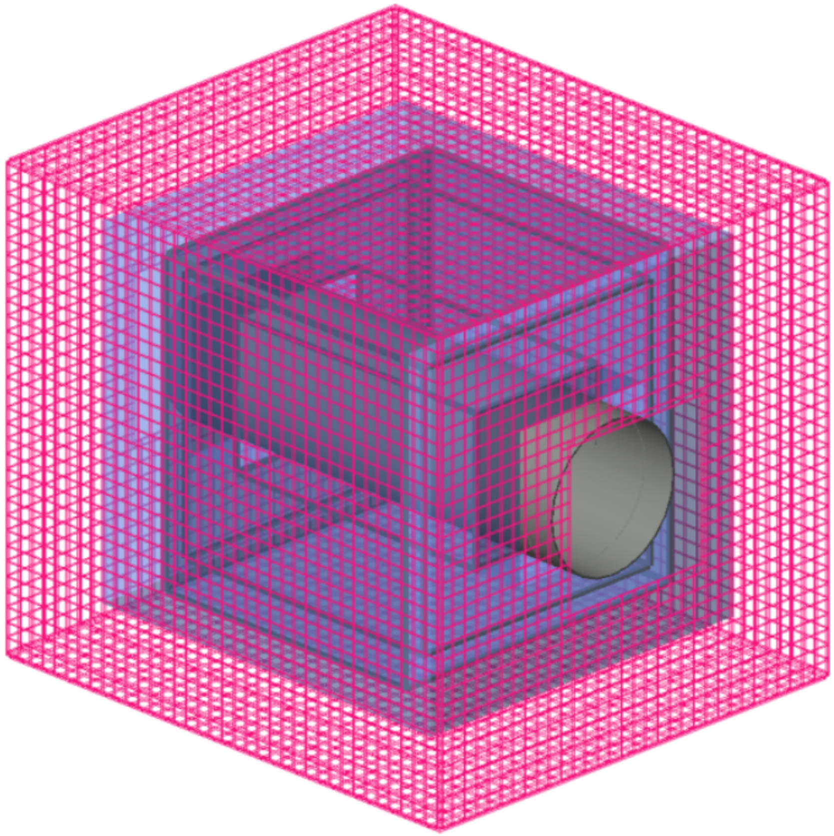
- The LEC calorimeter will be used to measure the photons from the neutral pion decay ($\pi^0 \to \gamma\gamma$)
- The energy deposit is measured via Cherenkov radiation.
- Cherenkov radiation arises when a charged particle in a material moves faster the the speed of light in that material.
- The photons from neutral pions initiate pair productions (electron-positron pair), and if these charged particles possess kinetic energy surpassing a certain threshold, they will produce a Cherenkov light cone in alignment with their trajectories.



Detectors – NNBAR

Cosmic Veto

- Cosmic rays will be the dominant contribution to the background.
- A reliable cosmic ray veto system is therefore crucial for the NNBAR experiment.
- The veto detector geometry is box with dimensions 6.4 m x 6.4 m x 7.2 m, large enough to contain the NNBAR annihilation detector.
- It comprises two layers of scintillating staves 20 cm wide and 3cm thick.



Detectors – Simulations

In any particle physics experiment, it is a common practice to study different detector designs and detector response through ***simulations***.

Full Simulation

- Mimic the behavior of the particles traversing the detector material.
- The input of the simulation are the primary particles, physics processes and the geometry description.
- The simulation is performed step-by-step, taking into account all defined process, and creating secondary particles.
- It is very CPU time consuming.

Fast Simulation

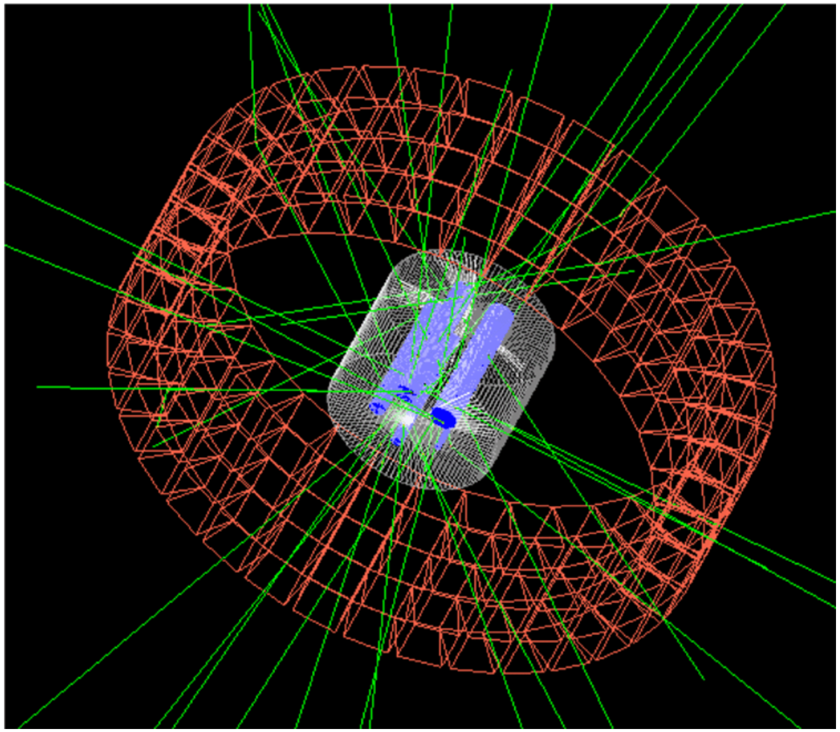
- In early stage of the detector design, the accuracy of the full simulation may not be needed.
- Instead of step-by-step simulation, a fast simulation apply an overall response of the detector. The result is a signal like one obtained with the full simulation.
- The inputs of a fast simulation are the detector-specific resolutions.

Detectors – Simulations

Geant4 Tookit

- The Geant4 software is used in basically all high energy (HEP) and nuclear physics experiments.

- HEP and nuclear physics experiments have used it to design or optimize future detectors, prepare the software to process their data (before any measurements) and to generate simulated events to be used as part of their analysis of measured data.

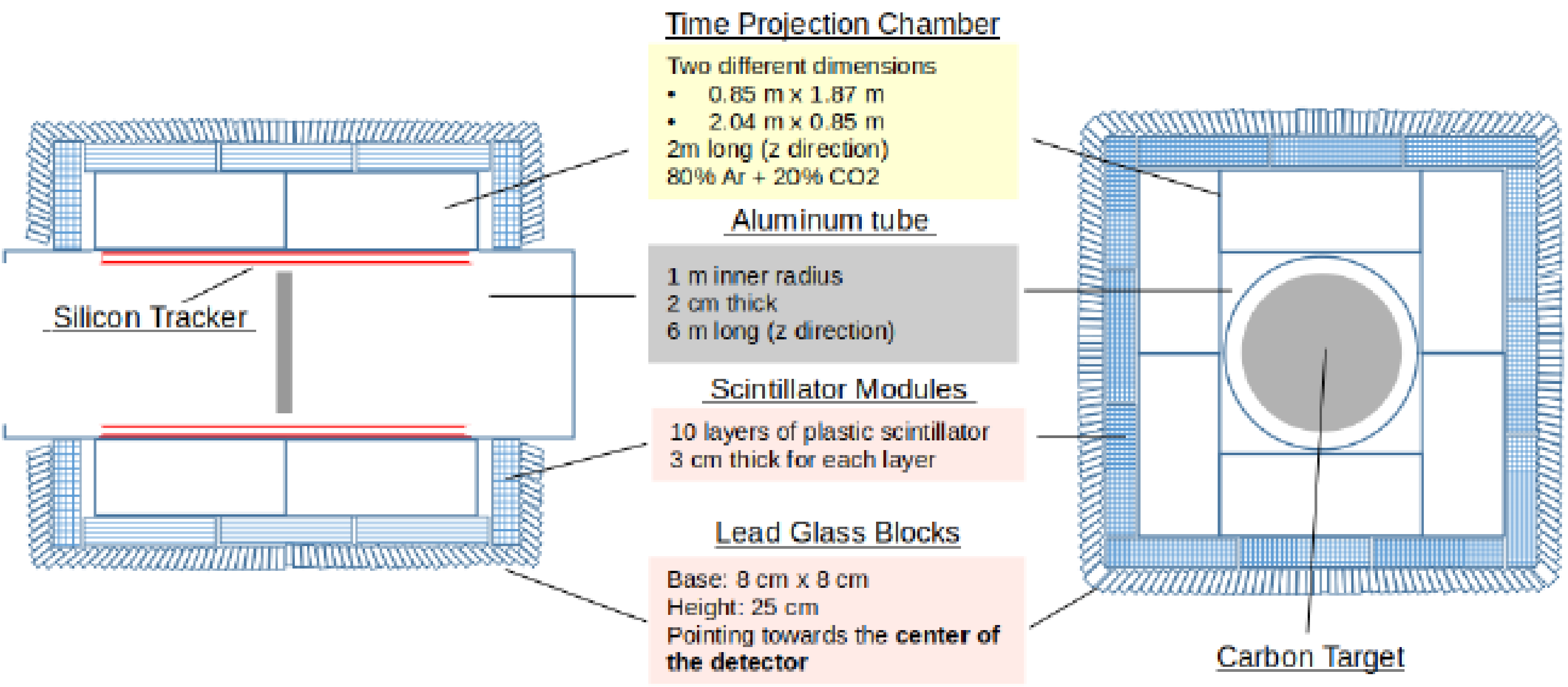


https://geant4.web.cern.ch/

Detectors – Simulations

NNBAR Geant4 Model

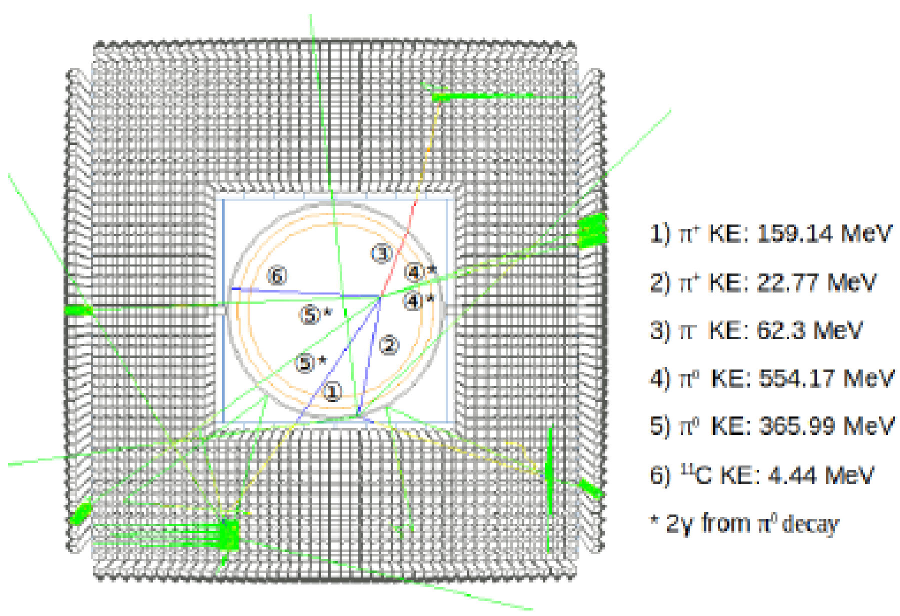
- Box geometry
- Dimensions: 600 cm long (z direction)
- Width and height of 515 cm

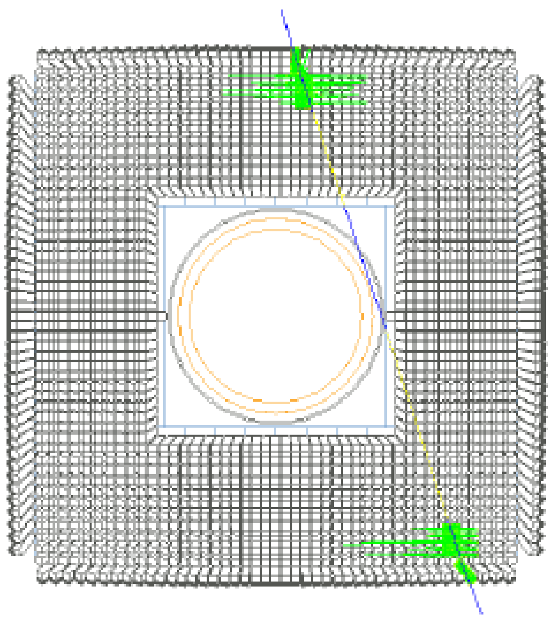


Detectors – Simulations

- Signal simulation (antineutron-nucleon annihilation)
- Cosmic rays simulations (CRY)
- Interaction with the detector (Geant4)

Time measured with the scintillators can be used to reject cosmic background.



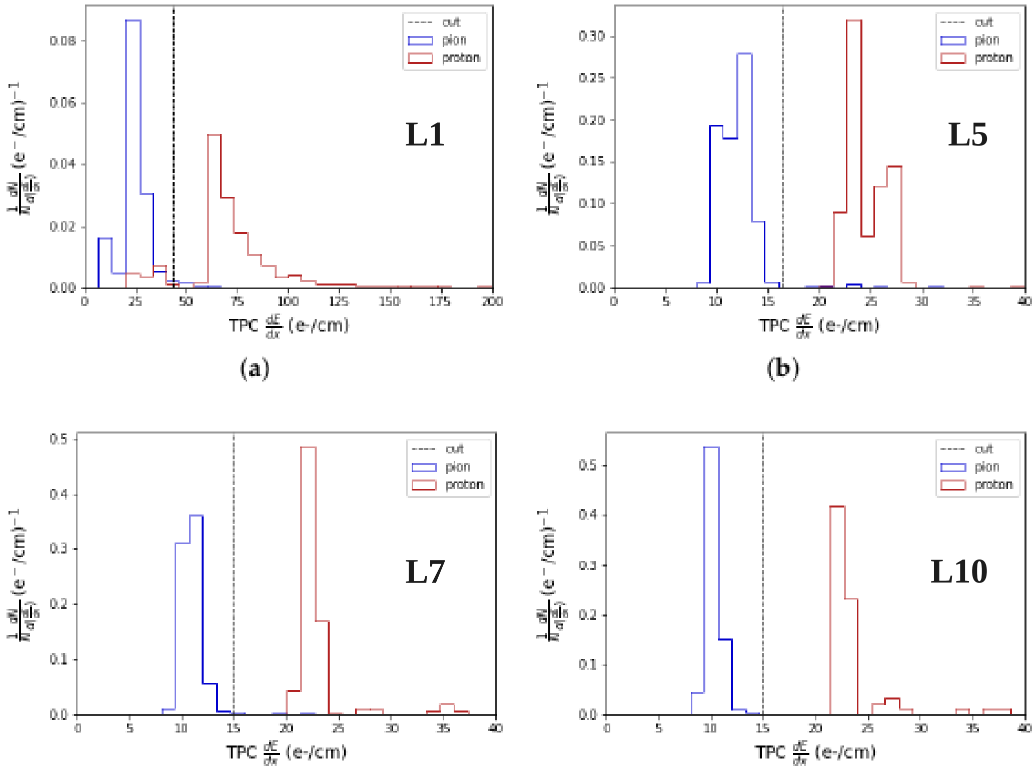


Detectors – Particle Identification

- PID is one of the cornerstones of the experiment.
- Significant fraction of energy tied up in rest masses of pions.
- Nearly 600 MeV (for 4 pions).
- Because of zero magnetic field, no momentum measurement.
- Meaning: experimental invariant mass needs PID.
- 90 % of signal events predict a neutral pion.
- 99% of events contain at least 2 charged particles.

Detectors – Particle Identification

- Combine TPC and scintillator layers for particle identification.
- Good separation between protons and charged pions is observed (~ 99% efficiency)



$$\pi^{\pm} : TPC\,\frac{dE}{dx} < t_N$$

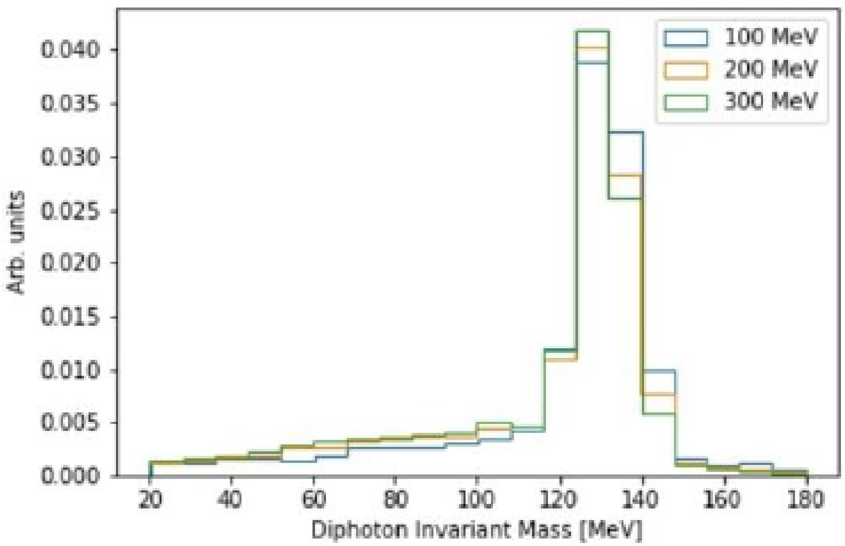
$$proton : TPC\,\frac{dE}{dx} > t_N$$

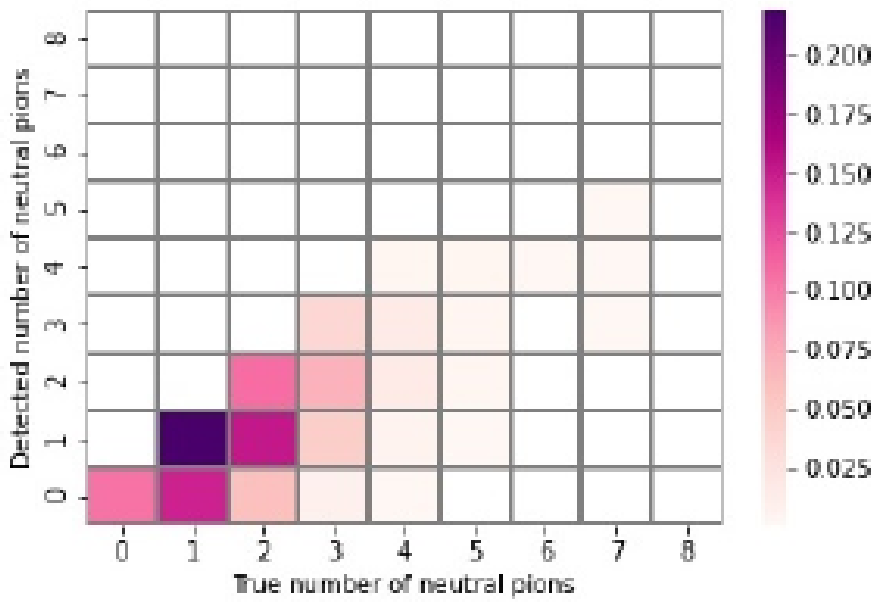
	Truth Particle Type	
Identified Particle Type	$\pi^{\pm}$	**Proton**
$\pi^{\pm}$	99%	1.3%
Proton	1%	98.7%

Detectors – Particle Identification

- Neutral pions can be reconstructed from the photons energy and angles between the photons measured in the calorimeter.
- A sample of π^0 produced in random direction was used in the simulation.

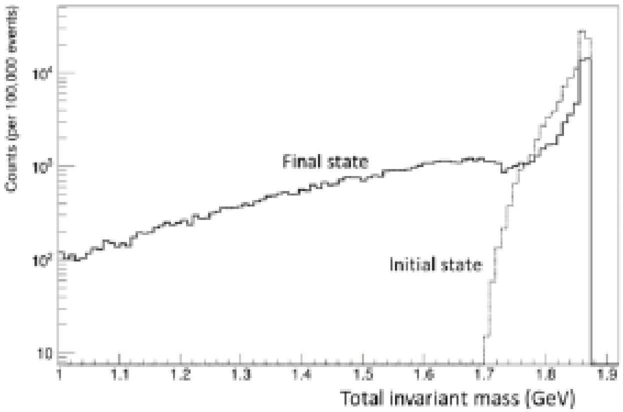
$$M^2 = 2E_1E_2(1 - cos\theta)$$

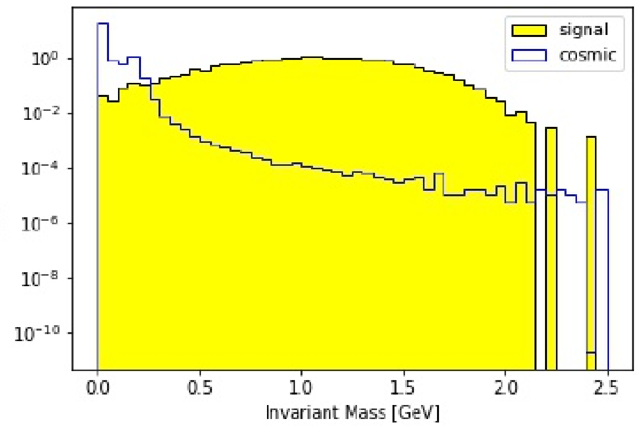




Detectors – Signal Identification

Expected final state invariant mass: ~ 1.88 GeV





$$W = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}$$

Nuclear and detector effects complicate the scenario

Selection	Signal	Non-muon background	Muon background
Scintillator energy loss $\in [20, 2000]$ MeV	0.95	0.15	1.8×10^{-6}
TPC track cut	0.92	7.1×10^{-3}	1.2×10^{-6}
Number of pion ≥ 1	0.86	6.1×10^{-8}	1.1×10^{-8}
Invariant mass $W \geq 0.5\,\mathrm{GeV}$	0.83	1.4×10^{-8}	9.5×10^{-9}
Sphericity ≥ 0.2	0.73	8.1×10^{-11}	6.1×10^{-9}
$E_{\text{scint, } y>0, \text{ filtered}} \leq 320\,\mathrm{MeV}$ & $E_{\text{scint, } y<0, \text{ filtered}} \leq 930\,\mathrm{MeV}$	0.73	-	-

Detectors – Fast Simulation

Idea: Parametrization of the overall response of each sensitive detector

particle momentum,
kinetic energy

Smearing

$$F(\vec{p}, E, \theta)$$

new momentum,
new kinetic energy

The parametrisation must accounts for physical effects, the detector performance and the reconstruction procedure.

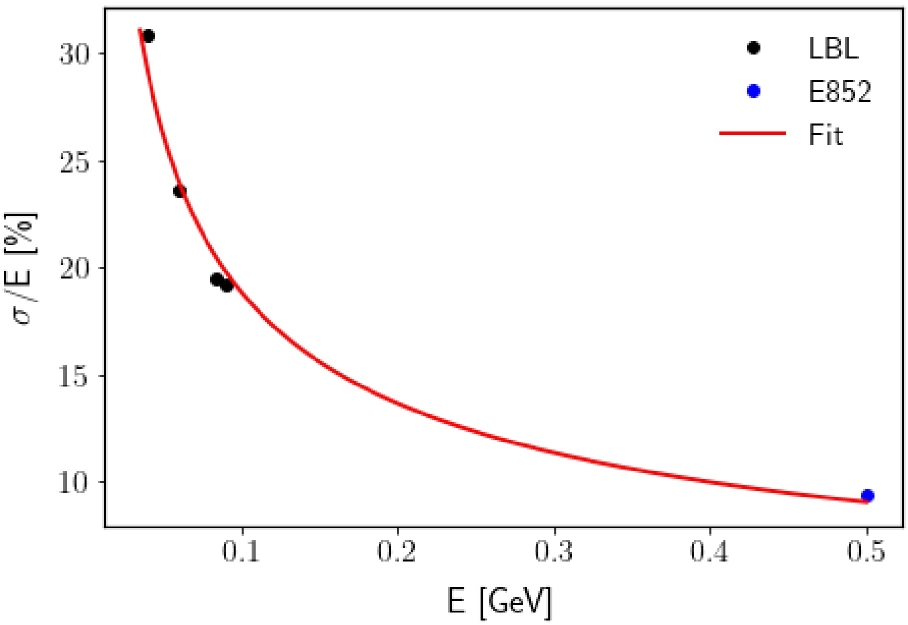
Detectors – Fast Simulation

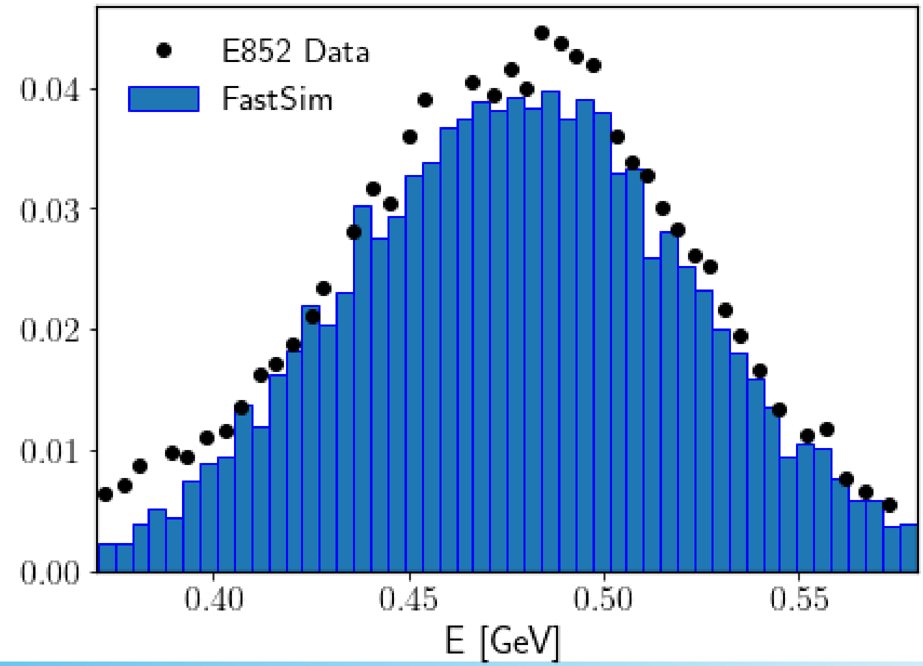
Model resolution for the Lead Glass Calorimeter

Model based on test beam data from

1. M P Budiansky *et al* NIMA 199 (1982) 453-460)
2. BB Bradson *et al* NIMA A 332 (1993) 419-443
3. The PHENIX Collaboration, NIMA A 499 (2003) 521-536

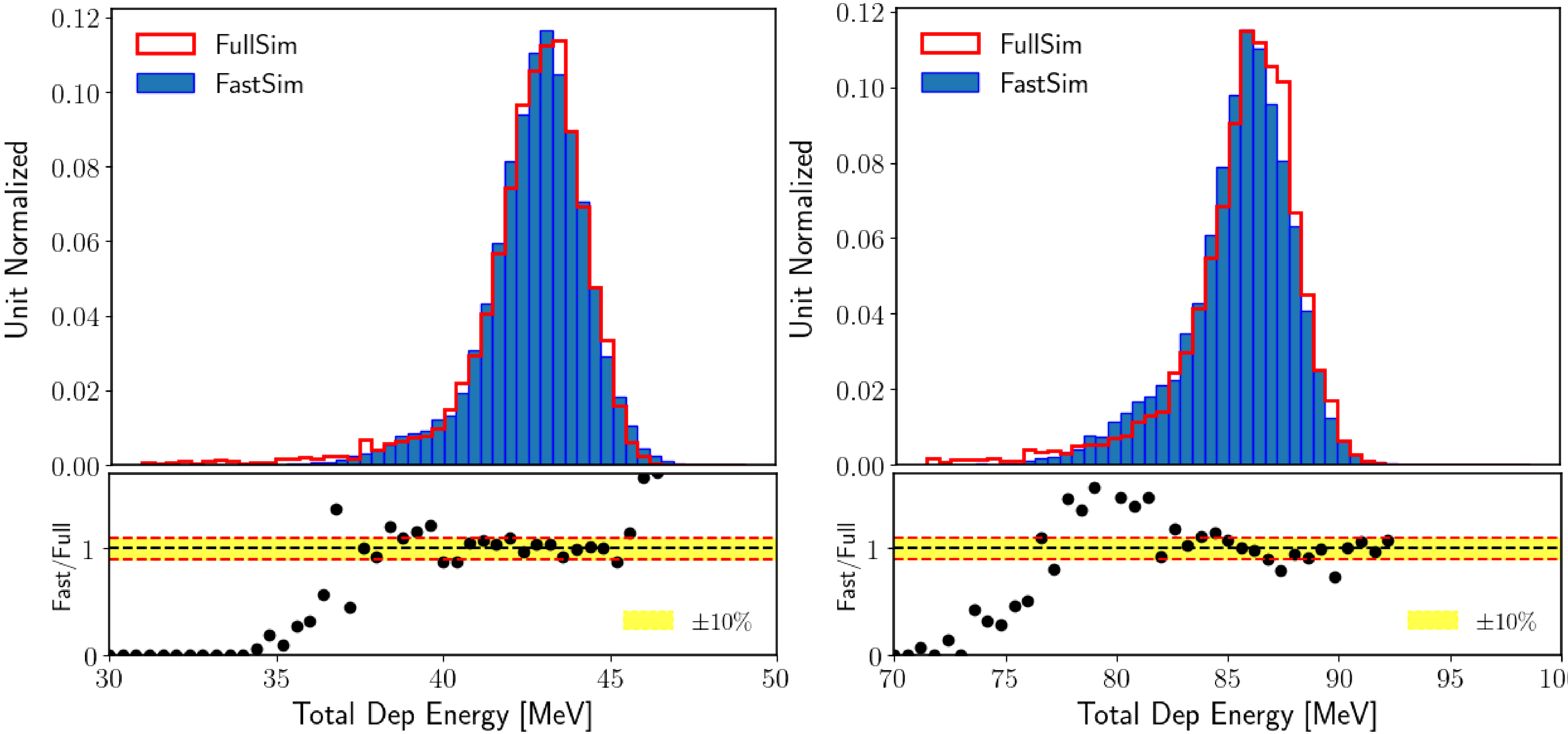
$$\frac{\sigma}{E} = \frac{5.6\,\%}{\sqrt{E[GeV]}} + 1.1\,\%$$





Detectors – Fast Simulation

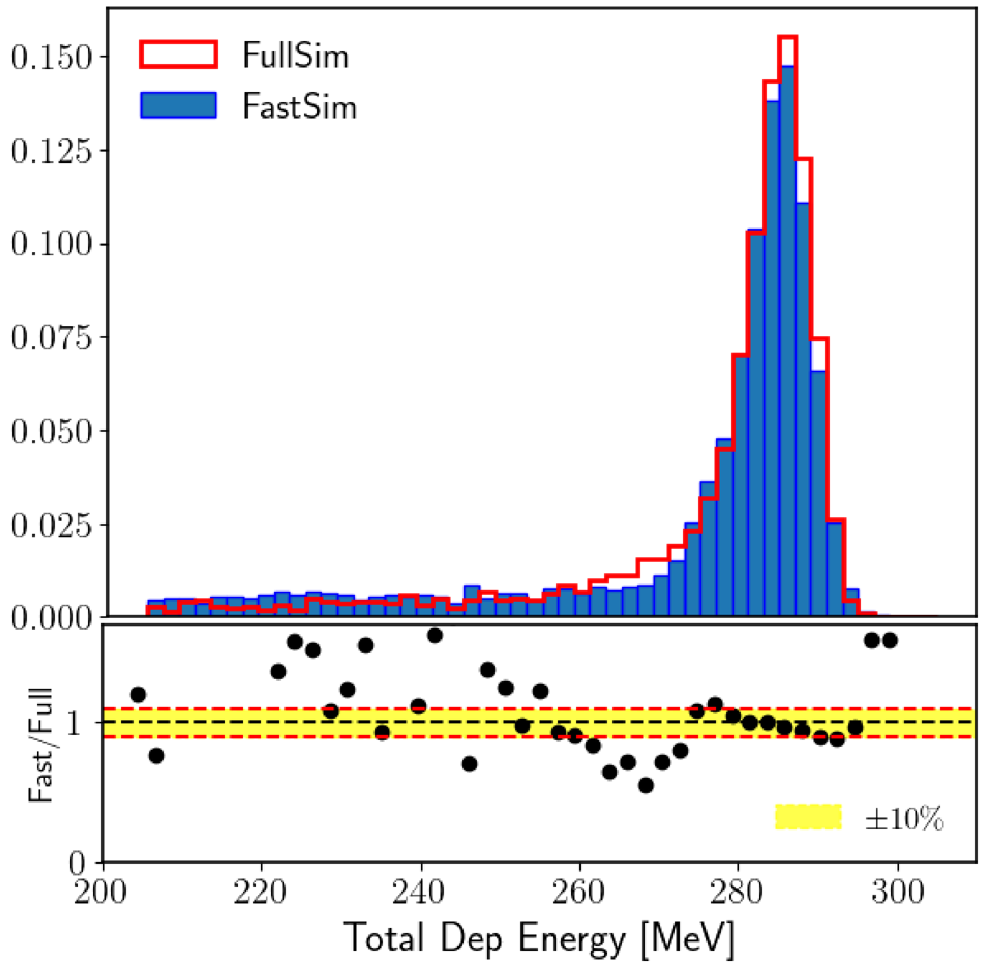
The Gaussian used for smearing in each event is randomly selected based on a probability derived from the full simulation.

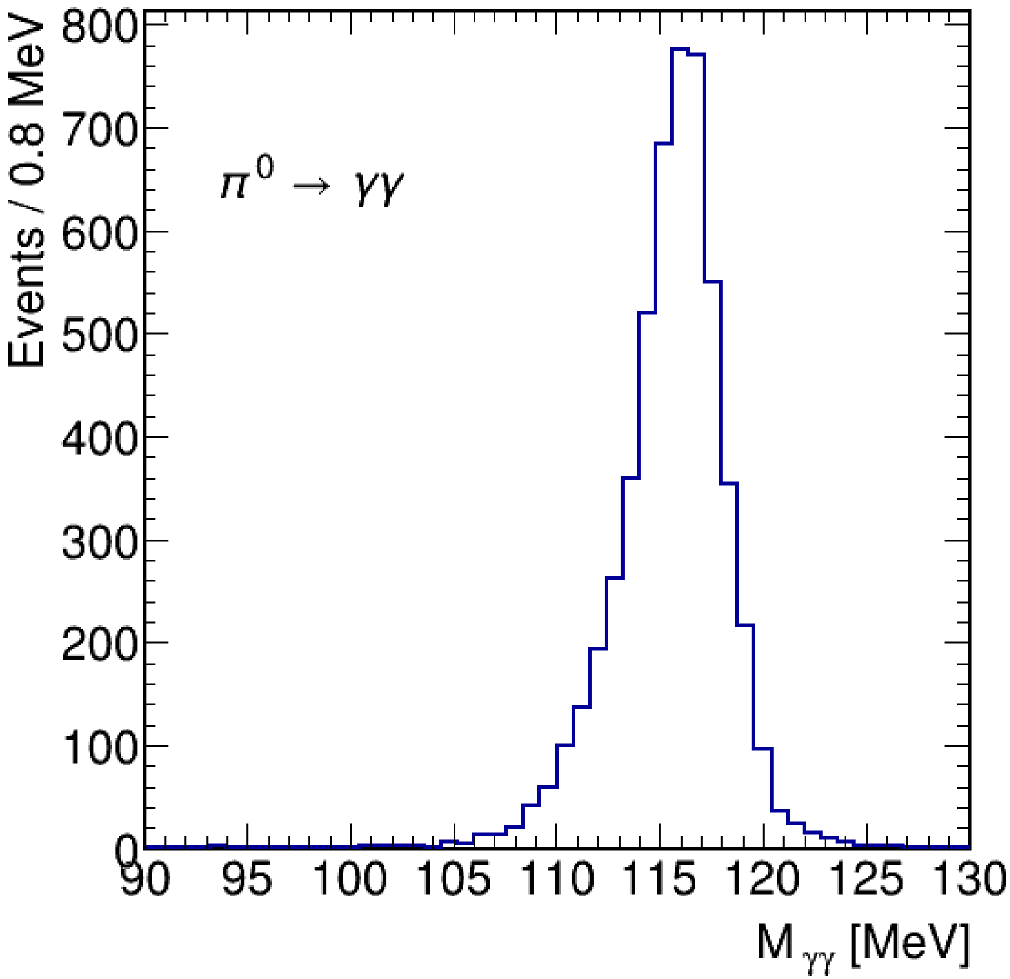


Detectors – Fast Simulation

Neutral pion reconstruction

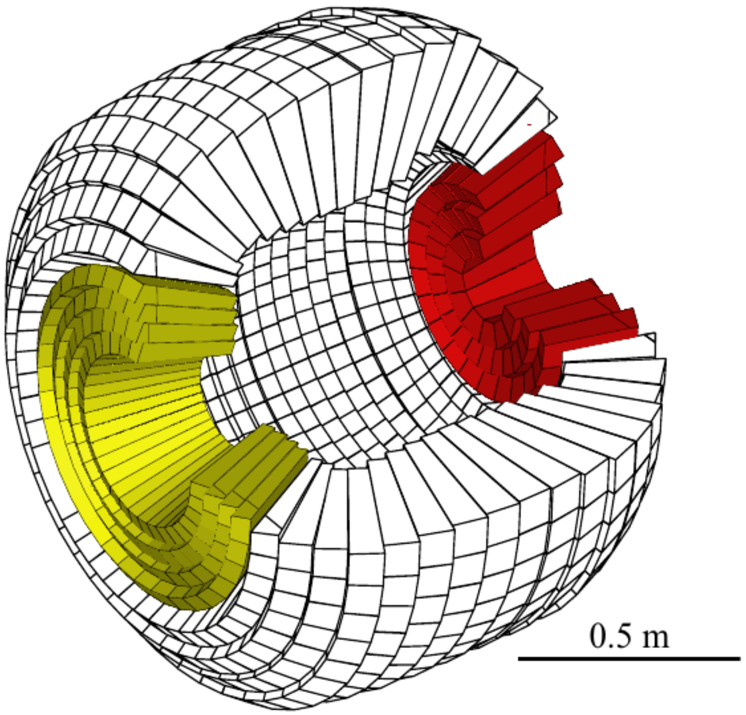
$$M_{\gamma\gamma} = \sqrt{2 E_1 E_2 (1 - \cos\theta)}$$

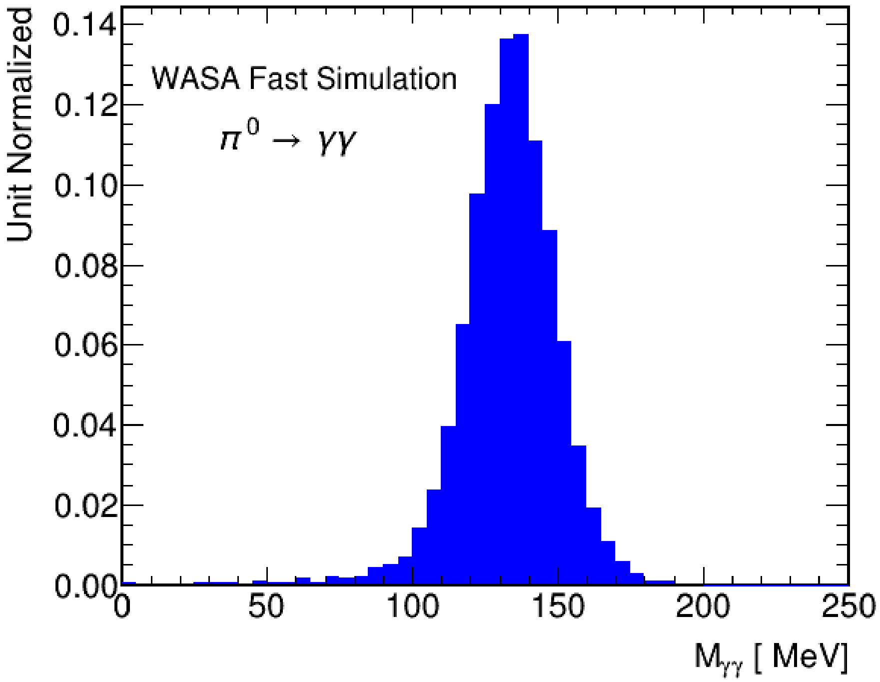




Detectors – Fast Simulation

- The HIBEAM is the first stage of the HIBEAM-NNBAR program.
- Energies of annihilation products are measured in the CsI(Na) calorimeter previously used in the WASA experiments (NIMA A 594 (2008) 339–350).





Opportunities for Students

- Development of fast detector simulation techniques.
- Speed up simulation with machine learning techniques.
- Simulation studies of the WASA detector for HIBEAM.
- Full simulation studies for HIBEAM and NNBAR.
- Possibility of working in a international collaboration.
- Development of experimental an computational skills.
- For more information: https://arxiv.org/abs/2309.17333 (CDR).

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