SAND : Simulations and reconstruction

DUNE-doc-13262

Status of simulation and analysis software

- Simulations: common ingredients
- Simulations: FLUKA+ROOT
- Simulations: Genie+Geant4+dunegdd
- Reconstruction: Kloe ECAL
- Reconstruction: 3DST
- Reconstruction: Tracker (STT)
- Reconstruction: background events

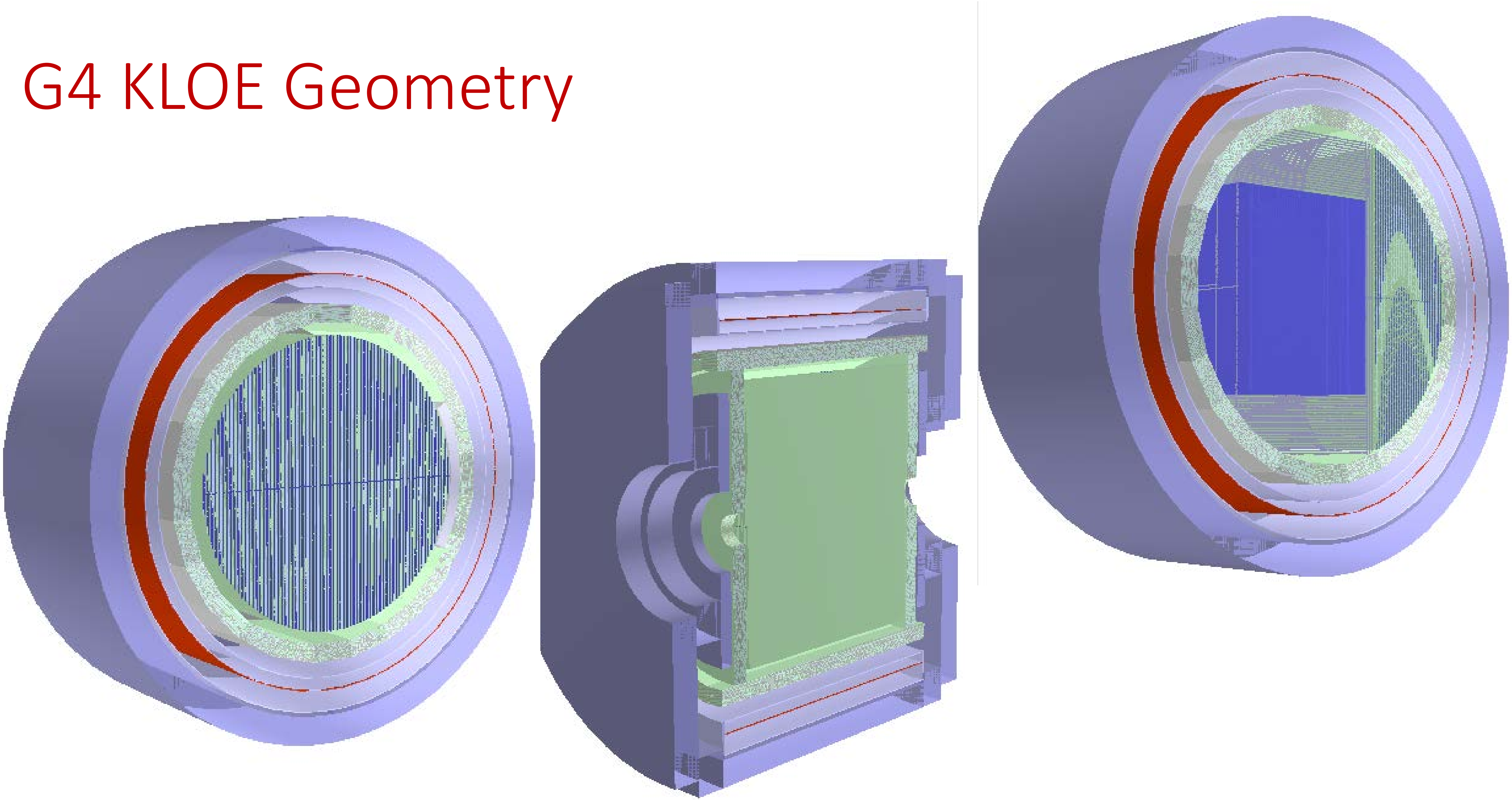
Common ingredients

- Beam: http://home.fnal.gov/ ljf26/DUNEFluxes/ 3 horns optimized
- 3DST: dimensions/materials as provided by Davide
- KLOE Iron/coils/magnetic field from drawings. B=0.6 T in the inner volume + Ecal, 1.5T in Joke
- KLOE ECAL: Layered in G4. In FLUKA, exact barrel, endcap with homogeneus material, segmented readout
- Lar meniscus ~ 1 Ton, upstream
- STT as tracker, evolving configuration

Geant4 based KLOE + tracker simulation

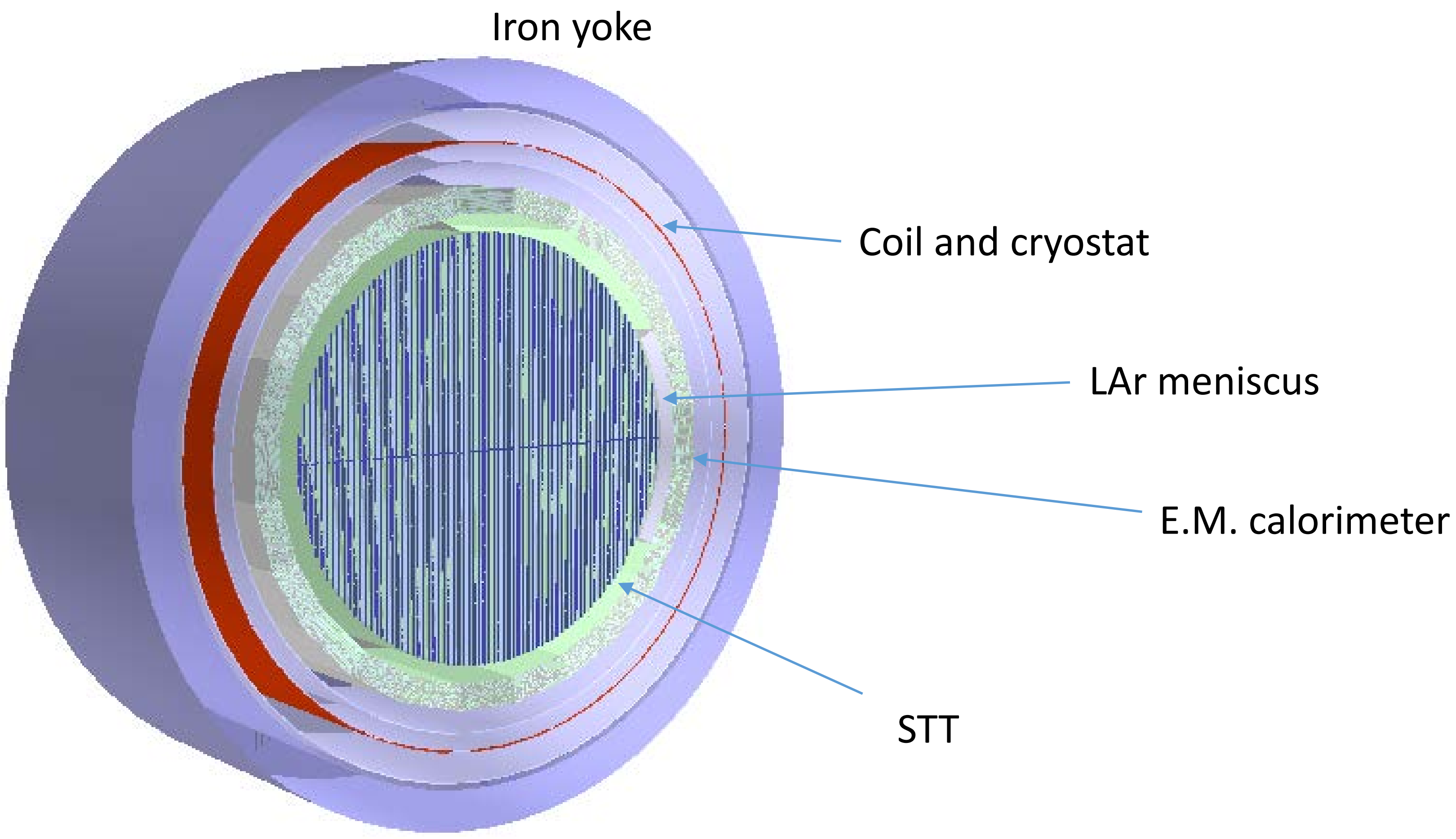
- Ingredients:
  - Flux: Optimized 3-Horn Design (https://home.fnal.gov/~ljf26/DUNEFluxes/)
  - Geometry: based on https://github.com/gyang9/dunendggd
  - Neutrino Event Generator: GENIE
  - Energy Deposition: Edep-sim (https://github.com/ClarkMcGrew/edep-sim)
  - Digitization, Reconstruction and Analysis: independent tools (https://baltig.infn.it/dune/kloe-simu)

G4 KLOE Geometry



Left and center: the baseline geometry we used to perform analyses reported in the DUNE DocDB note DUNE-doc-13262.
Right : 3DST + STT geometry as implemented by Bing Guo, available in https://github.com/gyang9/dunendggd

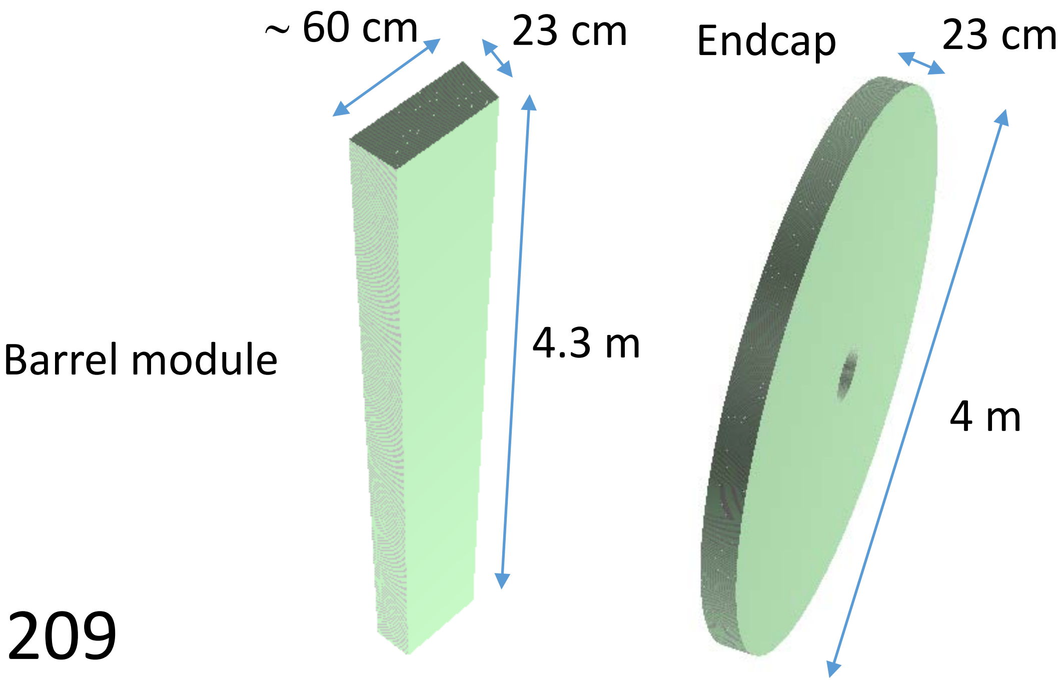
KLOE Geometry

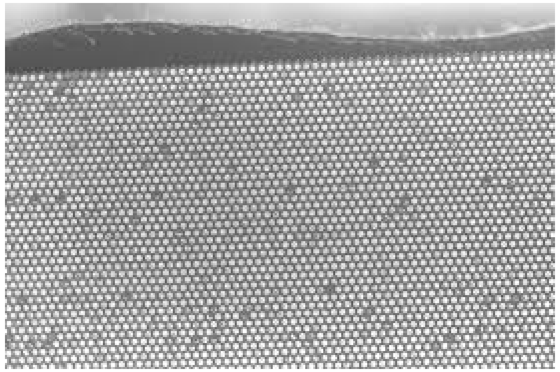


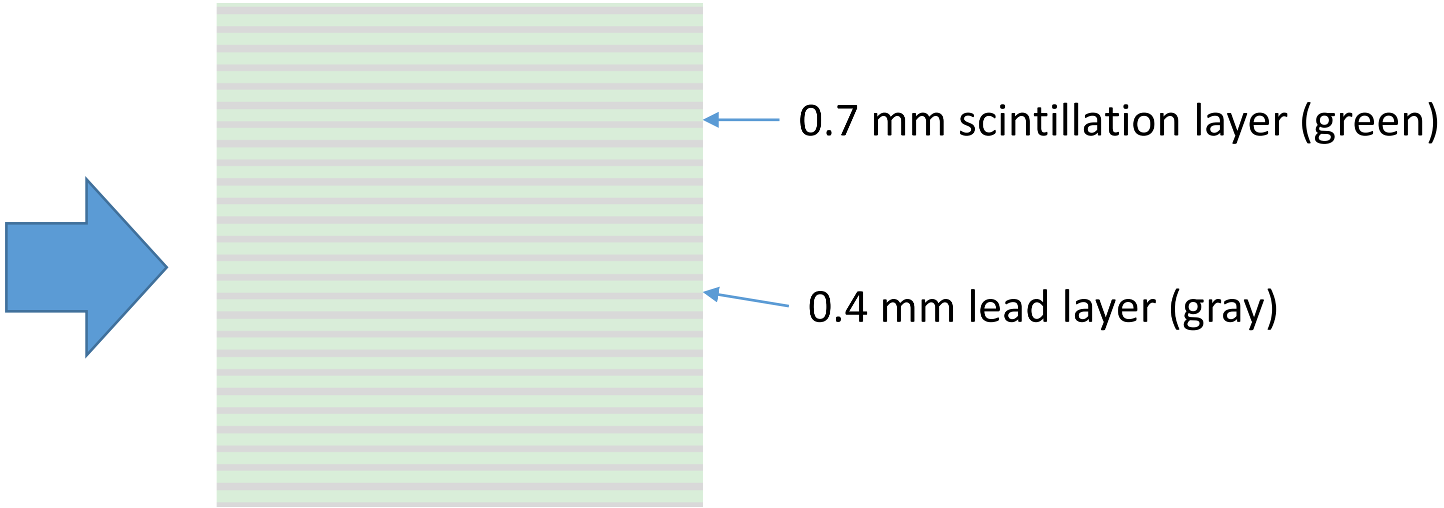
N.B. This is the baseline geometry we used to perform analyses reported in the DUNE DocDB note DUNE-doc-13262.
Bing Guo has implemented 3DST + STT geometry. It is available in https://github.com/gyang9/dunendggd

Calorimeter Geometry

- Barrel + 2 Endcaps
- Barrel: 24 modules
- Spaghetti calorimeter approximated as 209 scintillation layers alternated with 209 lead layers





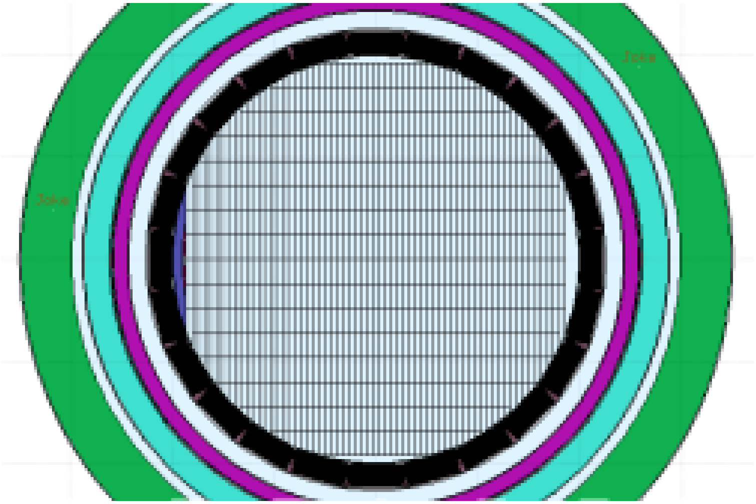


Fluka simulation

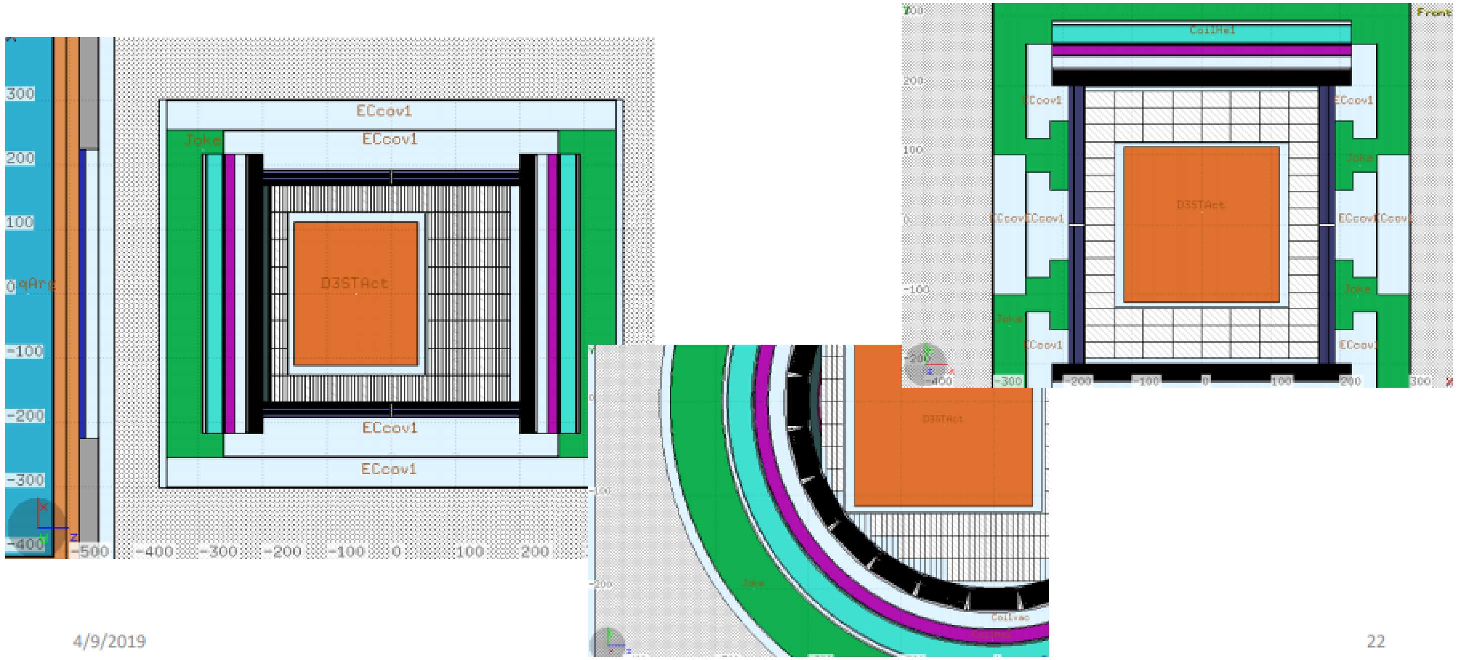
- Includes internal generation of neutrino events
- Output in ROOT trees:
- Information on
  - boundary crossing
  - energy depositions in
    - STT gas
    - 3DST 1x1cm cells, with and w/o Birks quenching
    - Ecal fibres with and w/o Birks quenching
    - Ecal “cells” (corresponding to readout granularity)
    - LAr meniscus
  - Associated particle type, energy, origin (parent from primary neutrino interaction) , time

FLUKA model of SAND

with STT Tracker

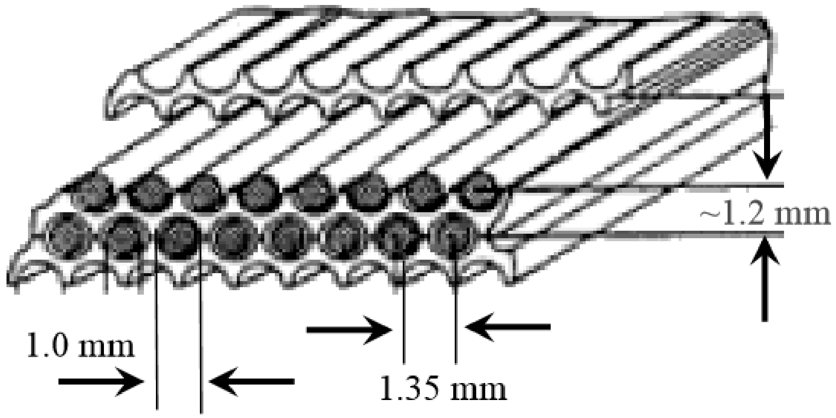


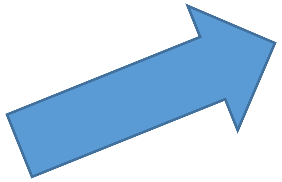
with 3DST and STT

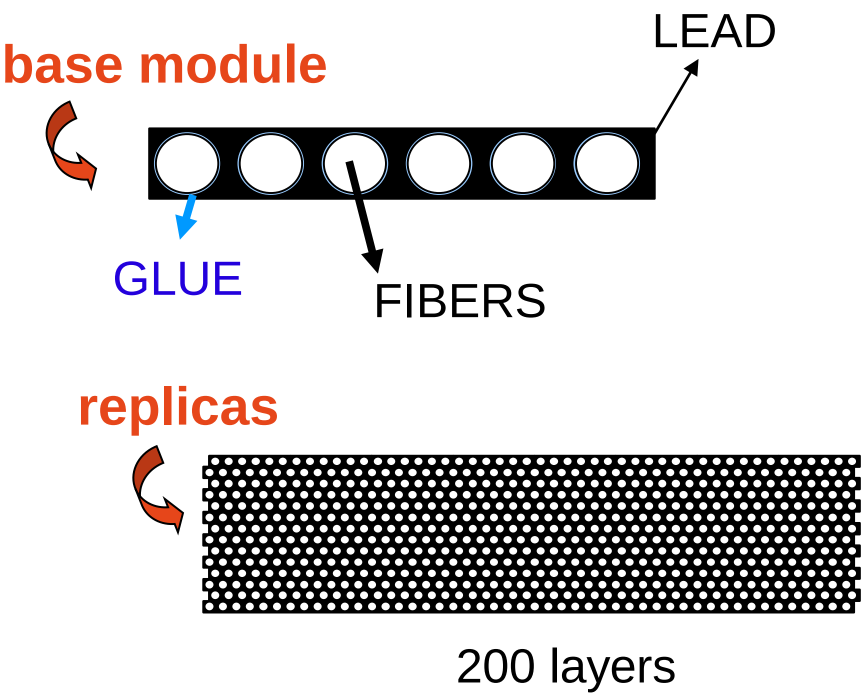


The Pb-SciFi structure simulation

- Using the FLUKA tool LATTICE
the fiber structure of a whole calorimeter module has been designed.



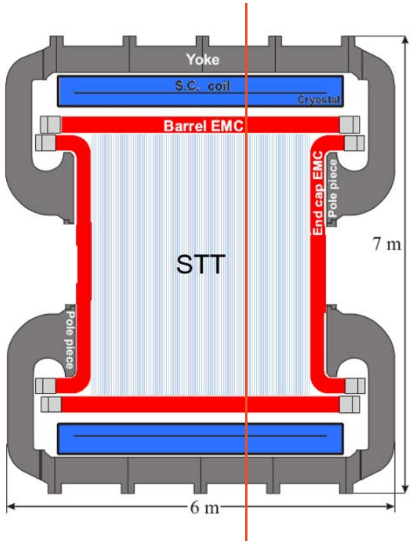




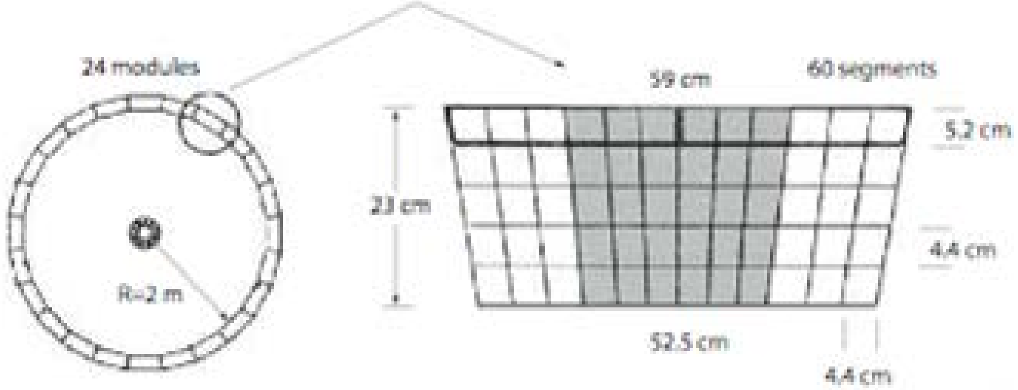
- All the compounds have been carefully simulated.
  - for the fibers, an average density between cladding and core has been used : $\rho = 1.044\ g/cm^3$
  - glue: 72% epoxy resin C_2H_4O, r=1.14 g/cm^3,
    + 28% hardener, r=0.95 g/cm3

Polyoxypropylediamine	**$C_7H_{20}NO_3$**	**90%**
Triethanolamine	**$C_6H_{15}NO_3$**	**7%**
Aminoethylpiperazine	**$C_6H_{20}N_3$**	**1.5%**
Diethylenediamine	**$C_4H_{10}N_2$**	**1.5%**

Calorimeter segmentation

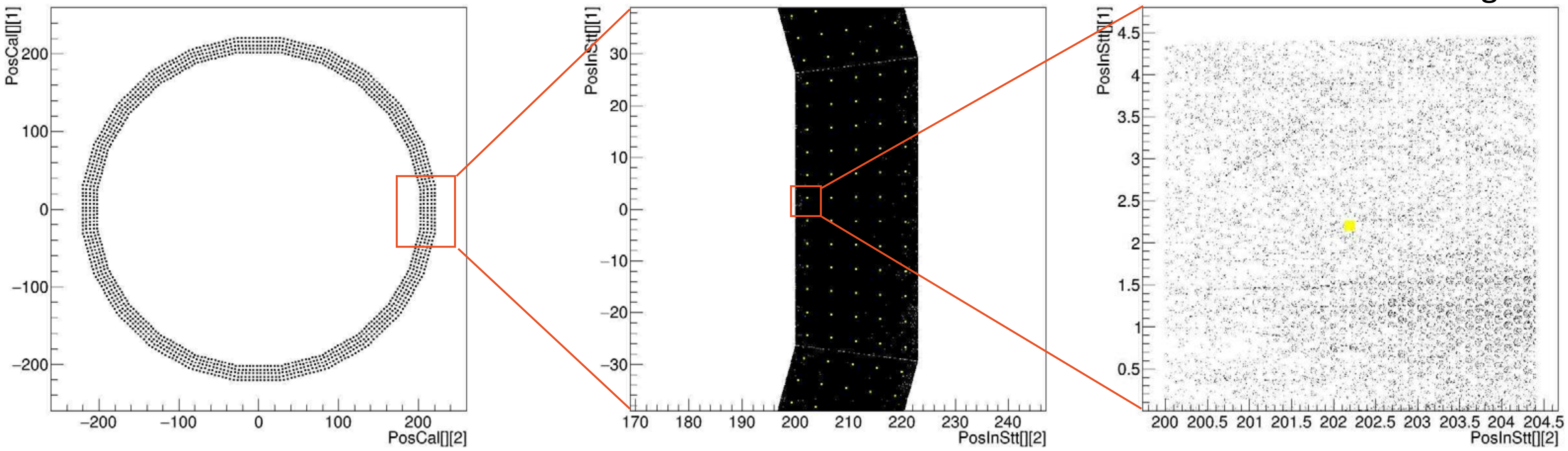


side view



KLOE calorimeter - readout segmentation (one end)

A cell is 430 cm long

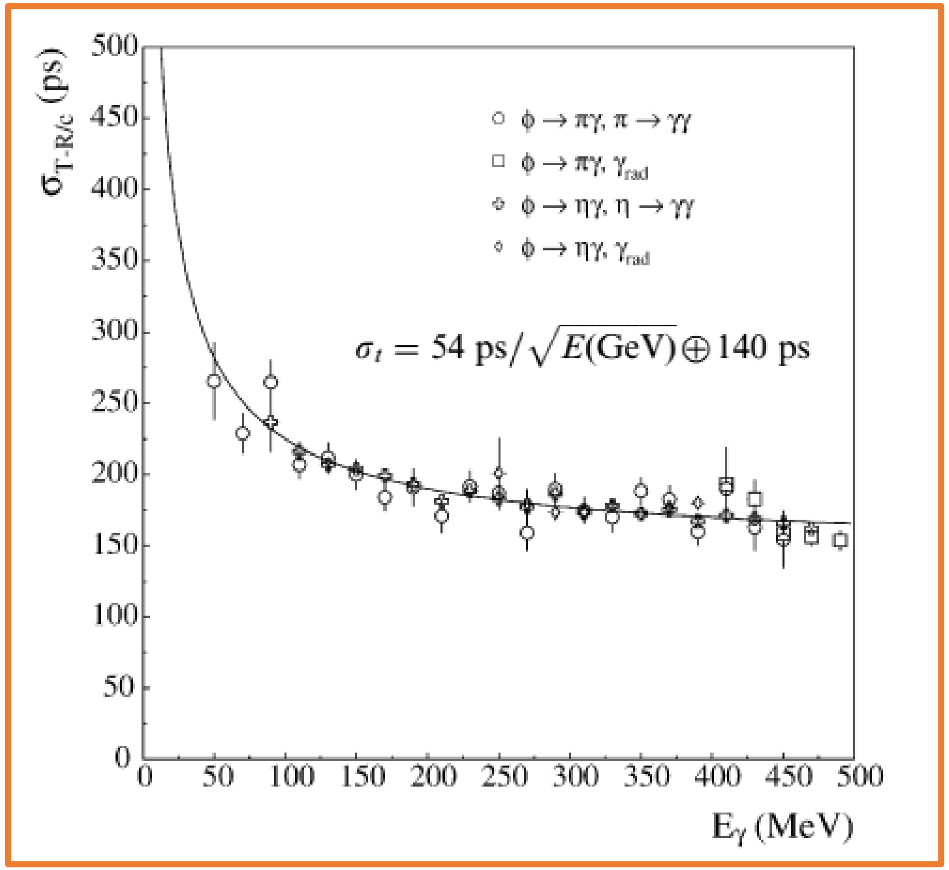


ECAL Response

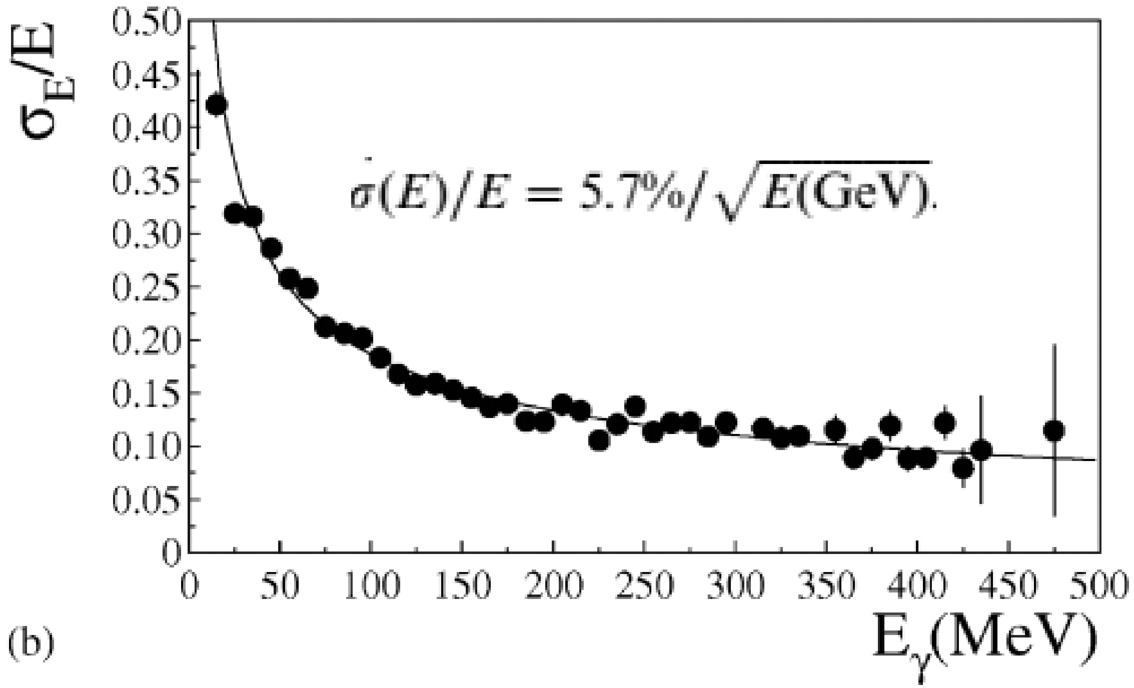
- Both Fluka and G4 based on KLOE data
- G4 : parameters from past optimization of G4 layered structure
- Fluka: from measured timing and signal attenuation along fibers; photoelectrons/MeV from calibration with crossing muons.
- Basic cells: corresponding to readout: 4.4 x 4.4 x 430 cm . Readout on both ends
- Endcaps readout by 90 x 5 (vertical) cells.
- Used for: Neutron efficiency, pizero reconstruction, background identification

For reproducing the measured performances

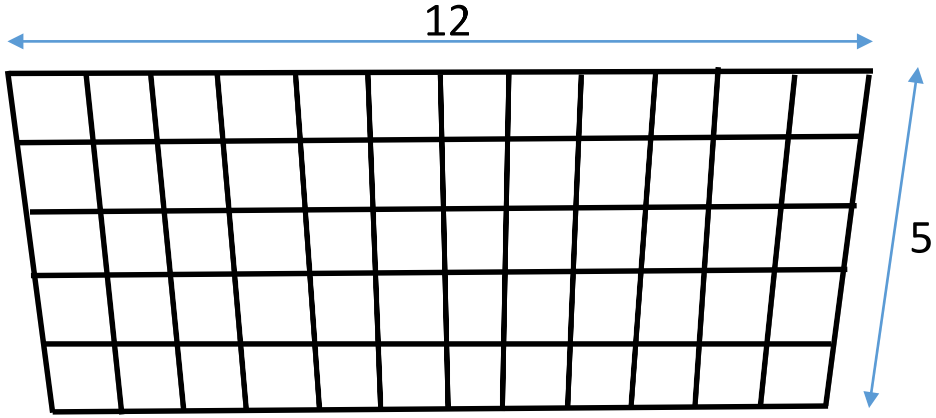
Time resolution



Energy resolution



G4 Calorimeter digitization



- Calorimeter barrel modules readout from both ends by 12 x 5 (horizontal) cells (~4.5 x 4.5 cm^2). Endcaps readout by 90 x 5 (vertical) cells.

- Starting from energy deposit in the scintillator material of a cell (dE), the number of p.e. ($N_{p.e.}$) at each ends is evaluated as:

$$N_{p.e.} = Poisson\left(dE \cdot n_{p.e.} \cdot \mu\right)$$

where $n_{p.e.}$ is the mean number of scintillation photo-electrons for 1 MeV energy deposit and μ is the attenuation.

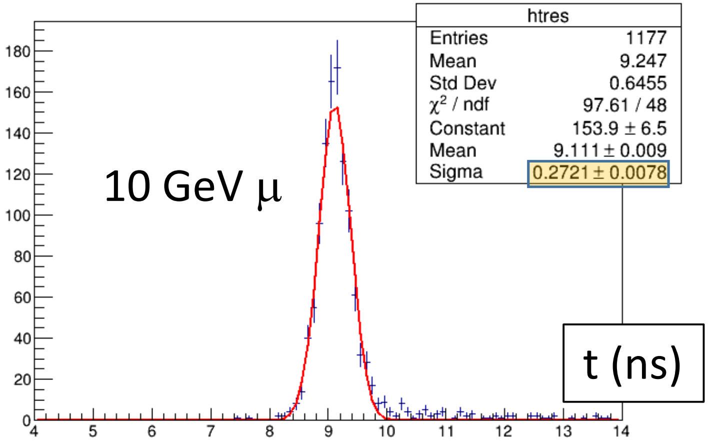
G4 Calorimeter digitization

- The arrival time of each p.e. (t) is evaluated as the sum of 3 terms:
  - Scintillation decay time: $\tau_1(Uniform(1)^{-\tau_2} - 1)$
  - Signal propagation to the end of the cell where it is readout by PMT: l/v
  - 1 ns uncertainty: $Gauss(1\ ns)$

- Cell signal:
  - ADC: $ADC_{cell} \propto N_{p.e.}$
  - TDC:
    - Photo-electron times are sorted (earlier first): $t_1 < t_2 < \cdots < t_{N_{pe}}$
    - $TDC_{cell} = t_{0.15 \cdot N_{pe}}$

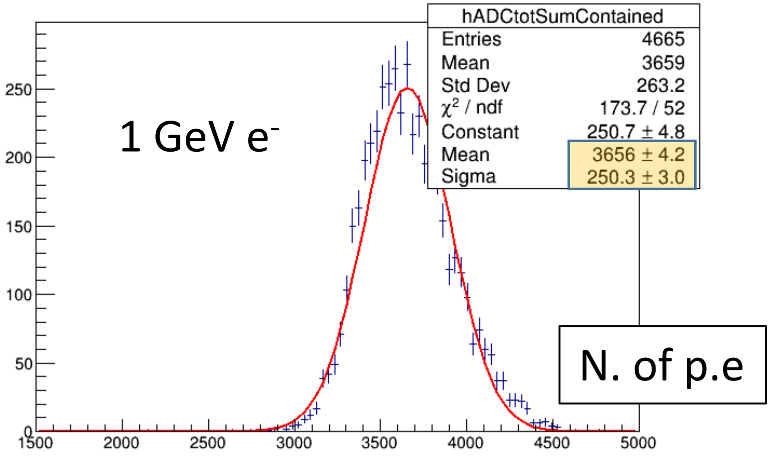
G4: Calorimeter simulated performances

- Time and e.m. energy resolution measured by KLOE collaboration are well reproduced by MC simulation with muons and electrons.



The resolution is 260 ps, in agreement with a scaling law of $\sim 54\ \text{ps}/\sqrt{E(\text{GeV})}$ considering a 40 MeV equivalent energy release.

10.1016/S0168-9002(01)01502-9



an energy resolution of $5.7\%/\sqrt{E(\text{GeV})}$

Fluka Digitization

- The hits from simulations are grouped in cell
- Generation and propagation of light from the interaction point to the PMTs, taking into account scintillation time and attenuation length for different planes
- The visible energy is converted in Npe
- The Npe are propagated inside the fiber

- Final information:

average time and Npe at each pmts

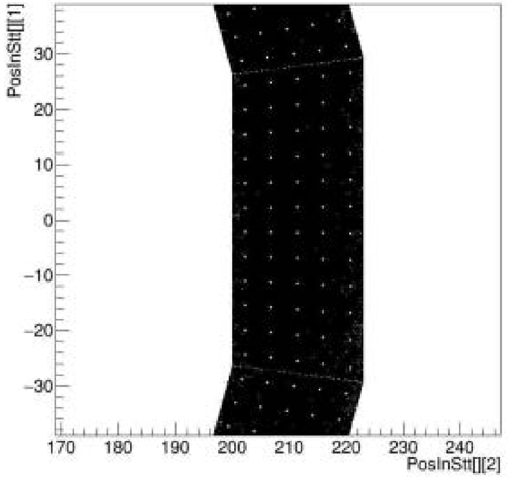
Reconstructed information:

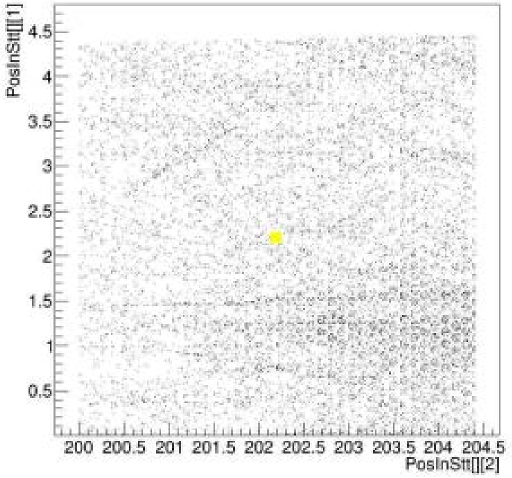
interaction time

$$t\ (\mathrm{ns}) = \frac{t^A + t^B}{2} - \frac{t_0^A + t_0^B}{2} - \frac{L}{2v}$$

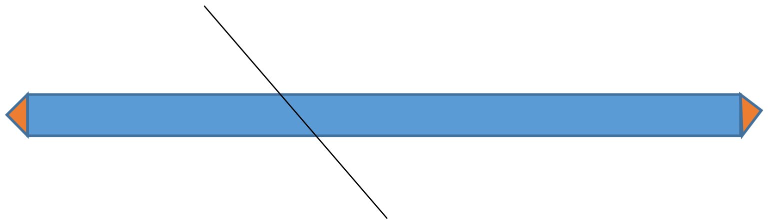
interaction position along the cell

$$s\ (\mathrm{cm}) = \frac{v}{2}(t^A - t^B - t_0^A + t_0^B)$$





Only the hit in the fibers are saved



Calibration

- By using the real data on MIP muon (E_{dep} and Npe at pmt)

  we can extract the conversion

  $E_{dep} = \alpha\, E_{vis}$ from simulations

  and

  $E_{vis} = \beta\, N_{pe}$ from real data

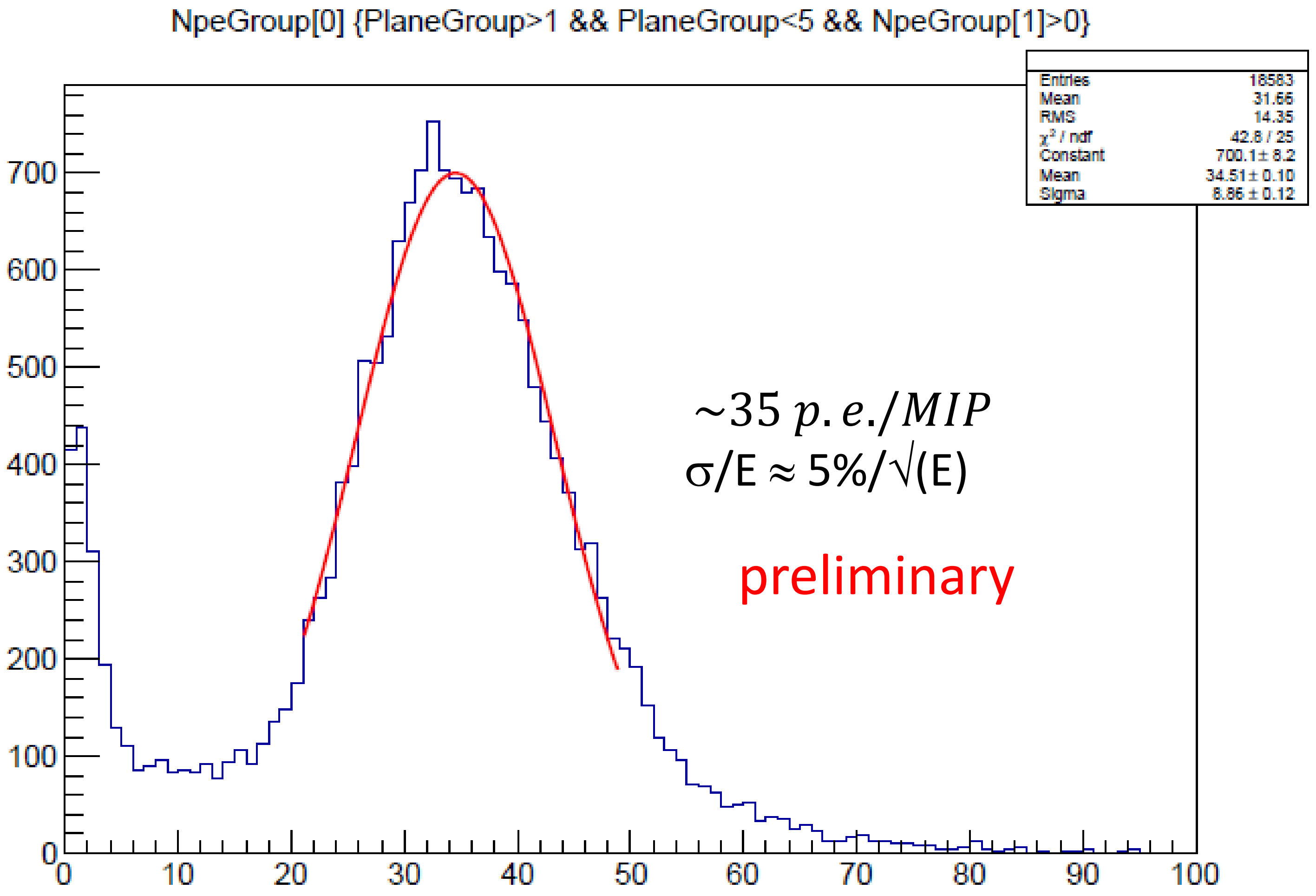
Calibration: preliminary results

Number of photoelectrons at one side of a cell from perpendicular muons hitting at center of the barrel

considering:

cells in planes 2, 3 and 4;

PMs firing (N_{pe}>0) at either sides of the cell.



$\sim 35\ p.e./MIP$

$\sigma/E \approx 5\%/\sqrt{(E)}$

preliminary

Pizeros from ECAL-Fluka

Reconstructed CC sample: 20000 events

1 π^0 27% of events

2 π^0 8% of events

> 2 π^0 2.5 % of events

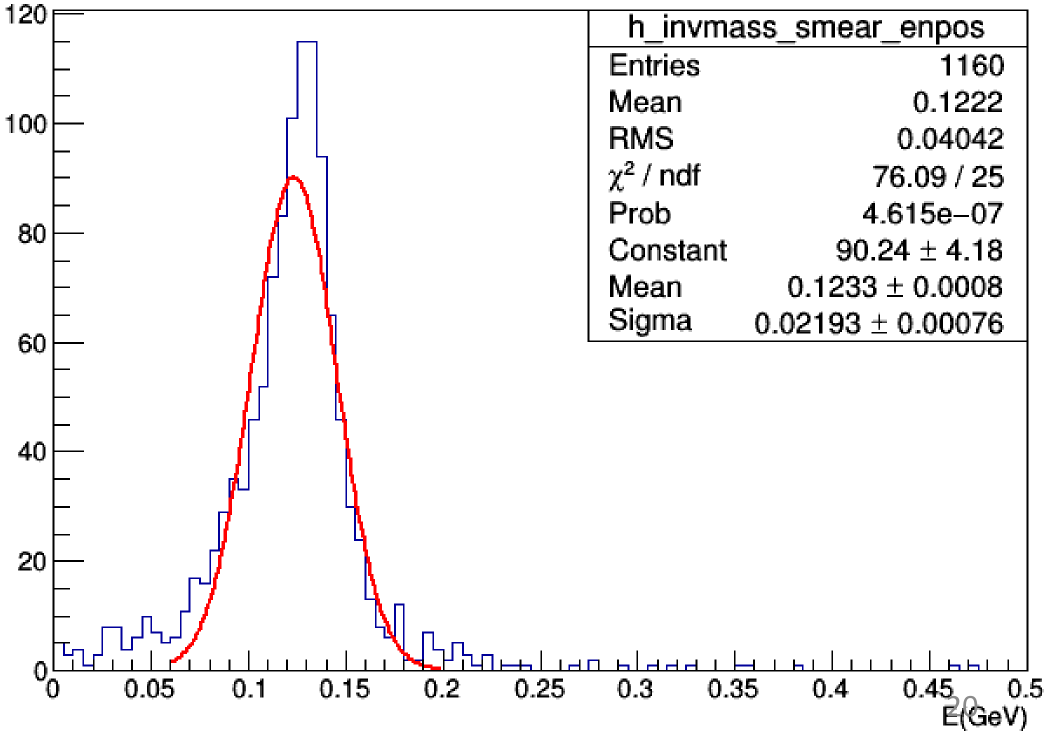
Reconstruction from EM CALO clusters

Optimized Dimensions Δx = 20 cm and $\Delta\phi$ = 5 deg.

Energy smearing $\sigma_E/E \approx 5.7\%/\sqrt{E(\mathrm{GeV})}$

Position from hit barycentre +
resolution of the KLOE calorimeter (4.5 mm).

2 π^0 sample: π^0 invariant mass,
Considering only 4-cluster events



Resolutions:

1 π^0 16.8%

2 π^0 17.7%

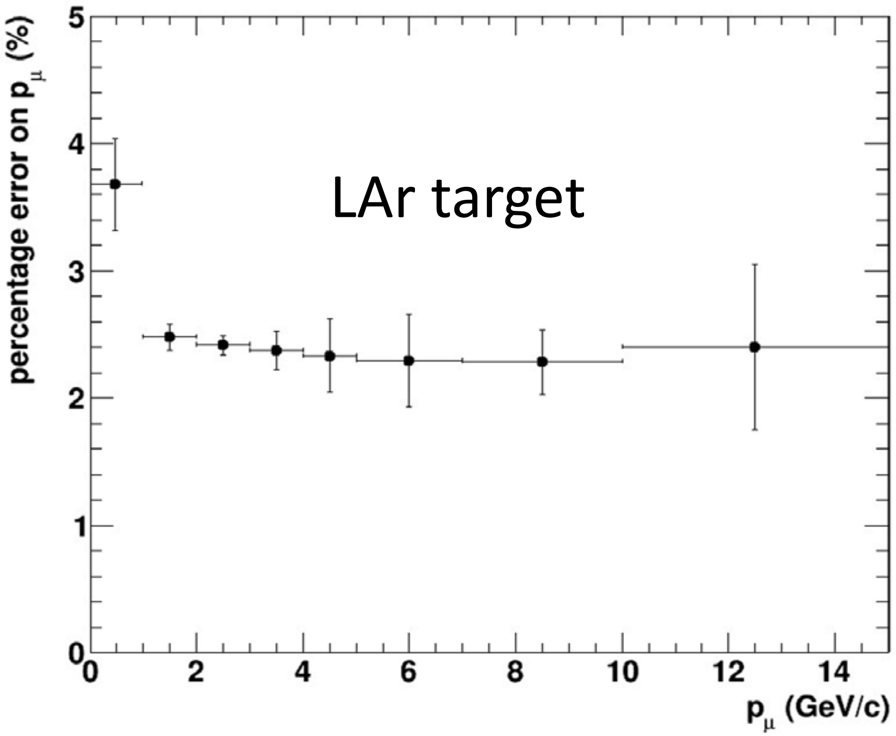
3DST signal

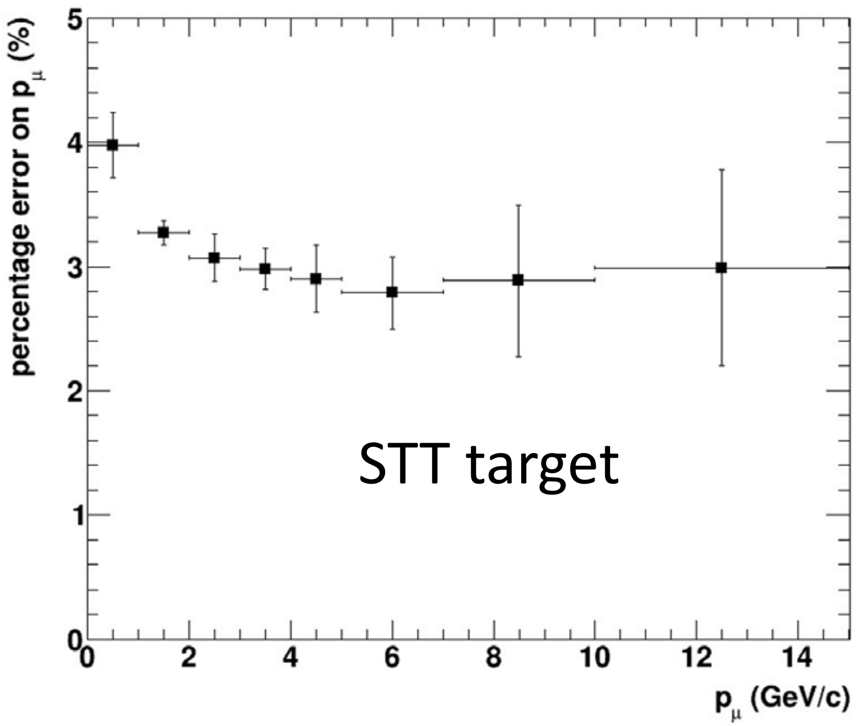
- Work in progress to include 3DST response in the Fluka-based software
- For the moment:
  - Energy deposition in 1cm^3 cells
  - Same, with quenching of the signal according to “reasonable” Birks parameters for plastic scintillator

STT track/vertex reconstruction: commons

- Spatial coordinate:
  - Only the one perpendicular to the tube is used:
  - $0.2\ mm$ smearing applied
- Hit time:
  - $1\ ns$ smearing applied
- Track Fit in two steps:
    - First:
      - Circular fit in the $y - z$ plane (perpendicular to magnetic field)
      - Linear fit in $\rho - x$ plane (see slide 18 of Tracking system)

Results –Muons





FLUKA sim: muon-track reconstruction based on STT hits, assuming a spatial resolution of 0.2 mm on y and x axes and 0.01 mm on z axis (beam axis).

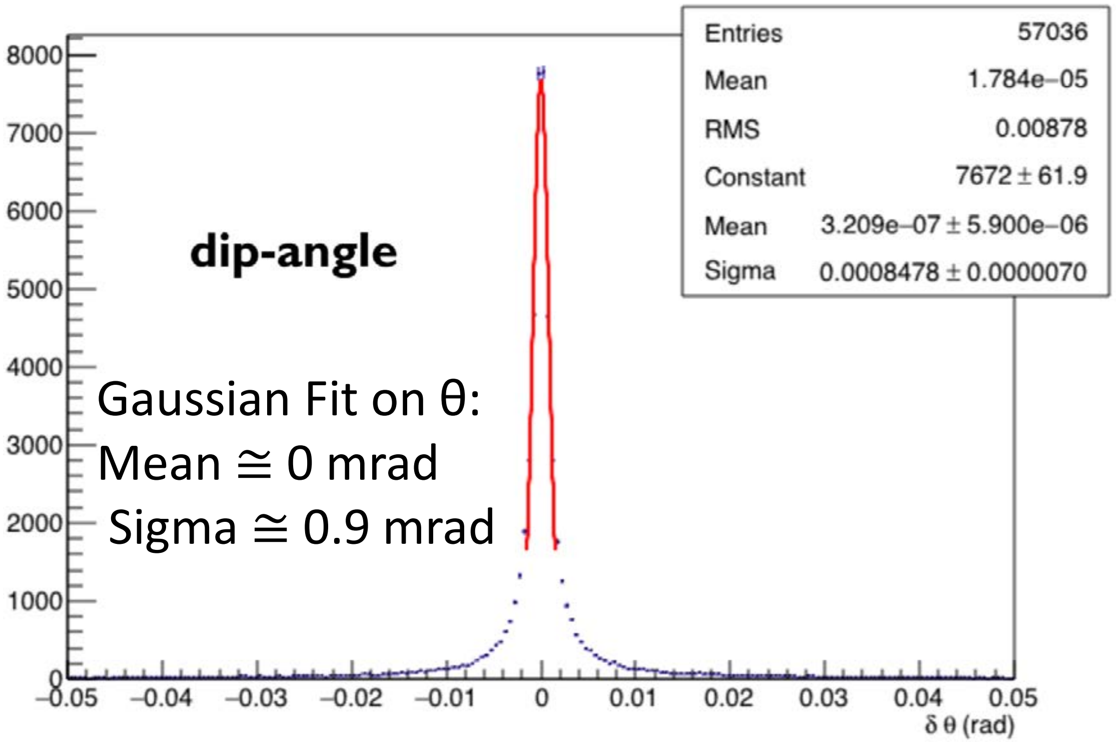
Good resolution on p (~3%) for both targets
Good resolution on dip angle ~1.7 mrad

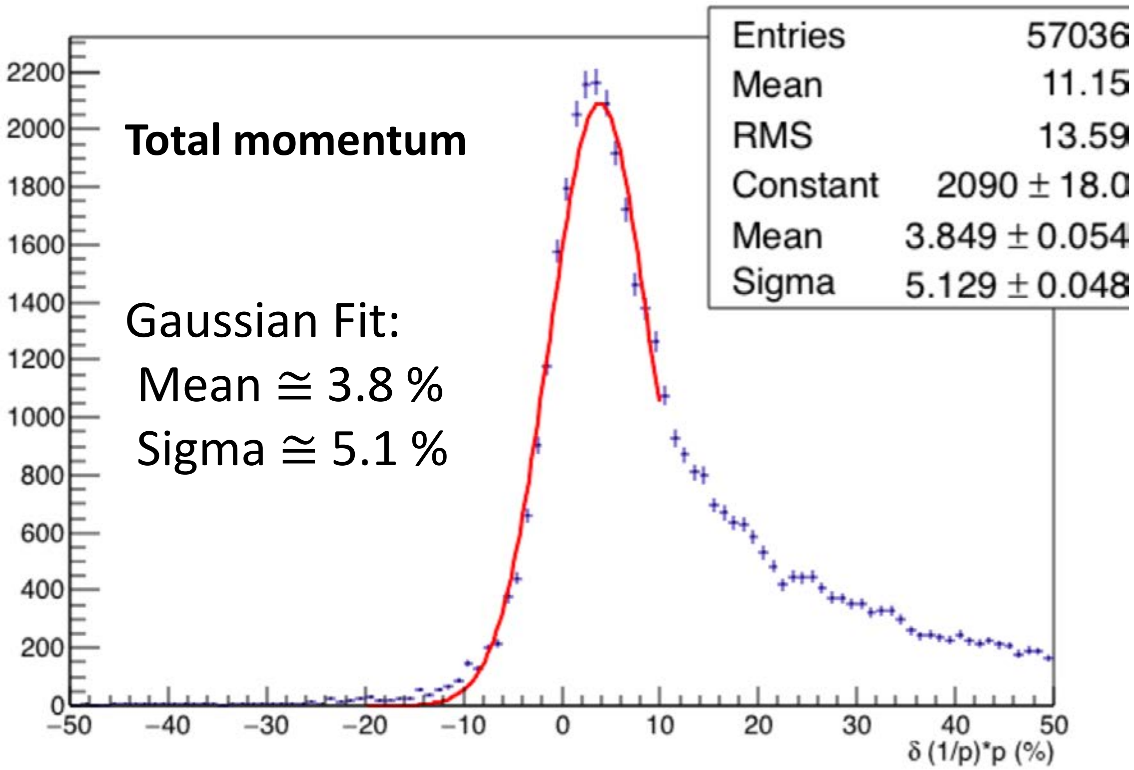
Same results with GEANT4

Charge mis-id ~0.02%

Results: - electrons

Generated in STT with GENIE+GEANT4. Very good resolutions, tails due to circular fit approximation to be improved i.e. with Kalman filter.





Wrong sign 1.3%

Same results withFLUKA

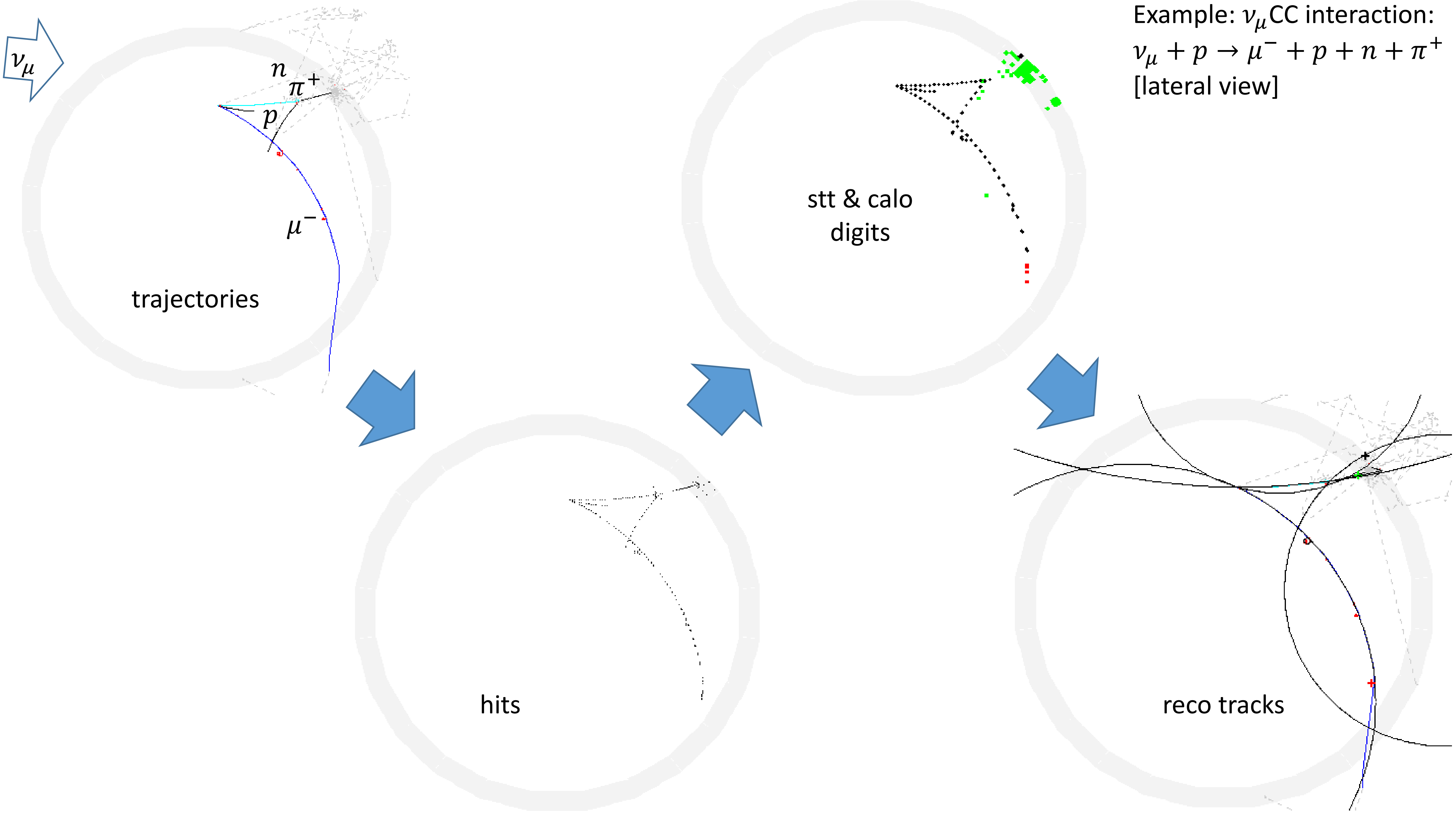
G4 based Reconstruction (1)

- STT:
  - Track identification/Pattern recognition using MC truth info
    - New:
      - Fit parameters used as guess for kalman fit with GENFIT
- Calo:
  - Cells are grouped in clusters using MC truth info

G4 Based Reconstruction (2)

- Particle ID using MC truth info
- Momentum measurement of charged particles from track fit based on STT digits
- E.M. energy measurement for $\gamma, e^{\pm}, \pi^0$ from Calo Cluster
- Kinetic energy of neutrons from time of flight

Example: ν_μCC interaction:
$\nu_\mu + p \rightarrow \mu^- + p + n + \pi^+$
[lateral view]



Fluka based Full reconstruction –**no MC truth**

- Interaction Vertex based on STT-hit topology (Step 0)
- Track finding (Global transform method)
- Linear or circle fits to track
- Vertex reco from crossing on two most rigid tracks (Step 1)
- Iteration…

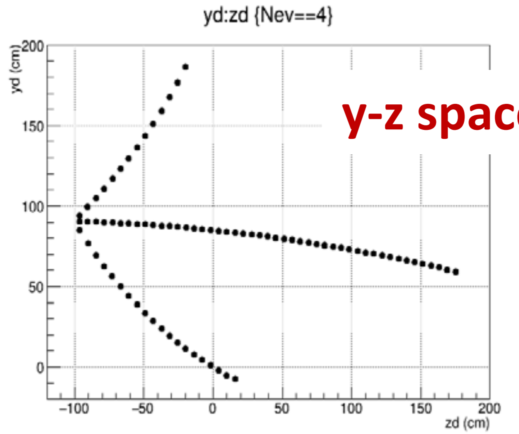
On two views

- Matching of tracks in the two views → tracks in 3D
- Evaluation of $p_\perp$ and dip-angle → p estimate
- Ecal hit compatible with tracks → ToF measurement
- → β estimate → PiD

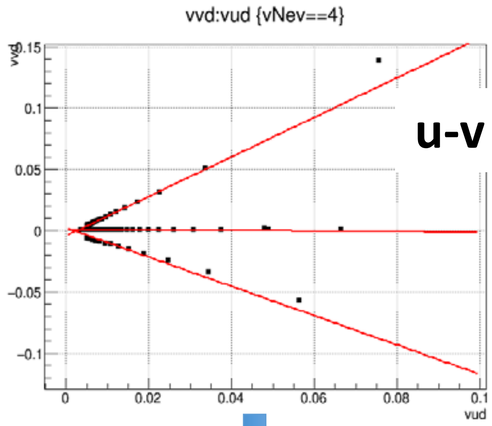
From Vertex to Track reconstruction, no MC truth

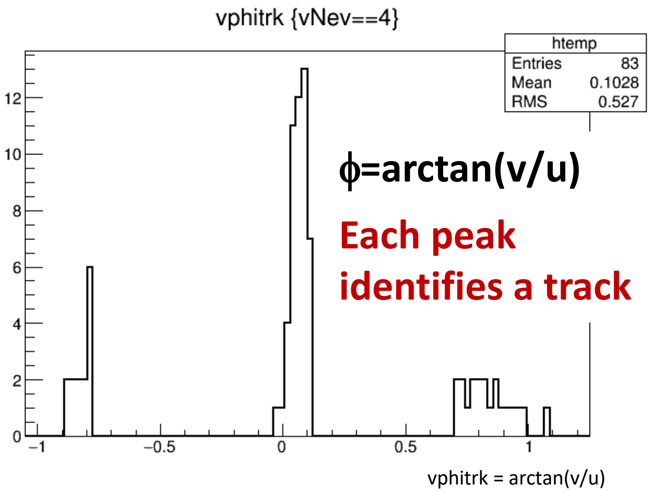
Coordinate transformation by using reco-Vertex (z_V,y_V):

$$u = +(z-z_V) / [(z-z_V)^2 + (y-y_V)^2]$$
$$v = -(y-y_V) / [(z-z_V)^2 + (y-y_V)^2]$$



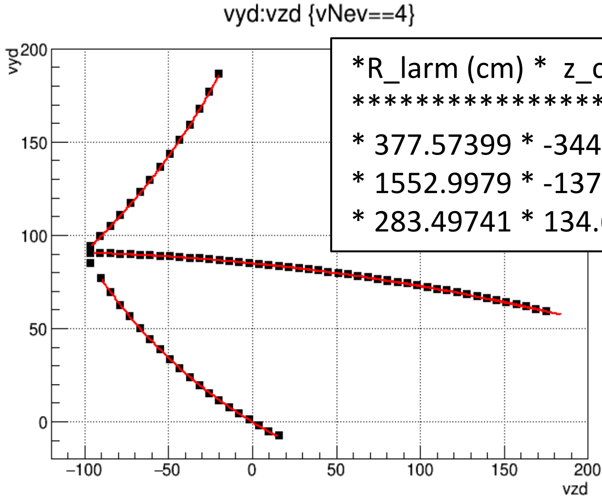
Curved trajectories become straight lines





ϕ=arctan(v/u)

Each peak identifies a track



*R_larm (cm) *	z_c (cm) *	y_c (cm) *
* 377.57399 *	-344.7125 *	378.457
* 1552.9979 *	-137.0285 *	-1462.071
* 283.49741 *	134.6044 *	249.4256

Track finding and fits

Each trajectory is fully reconstructed!

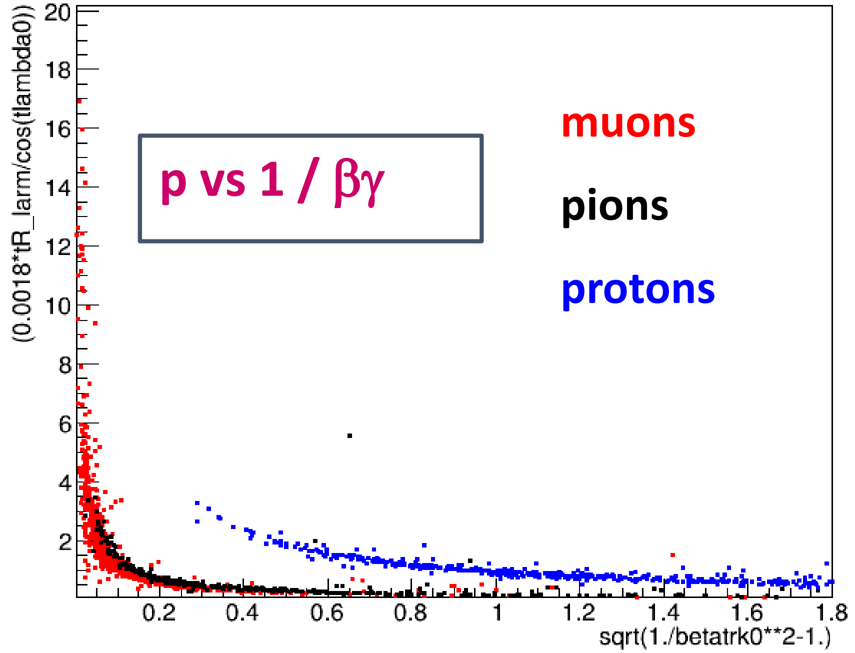
Two-step method: first rough vertex finding, allows for coordinate transform

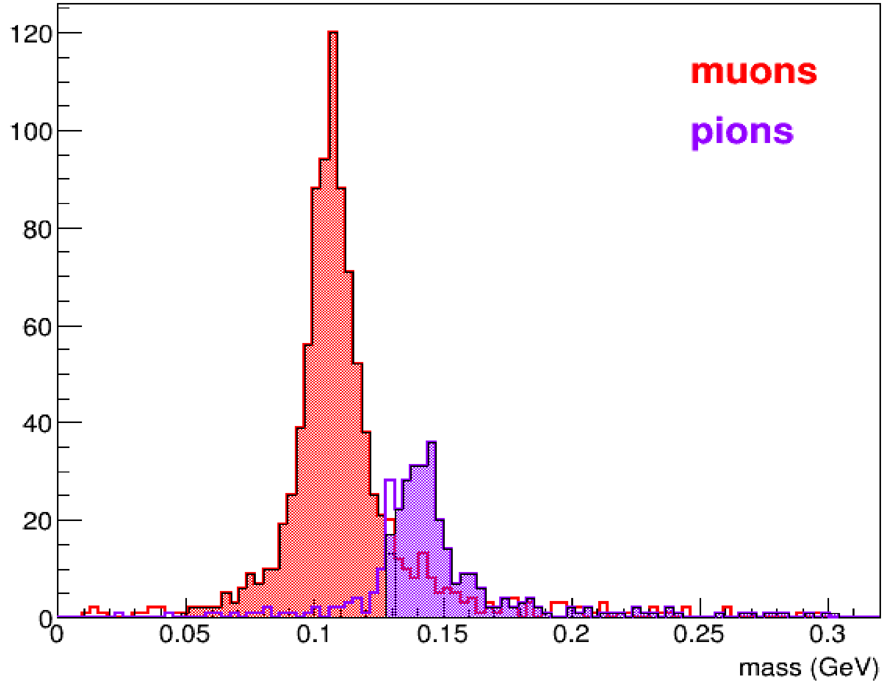
Peaks in ϕ correspond to tracks

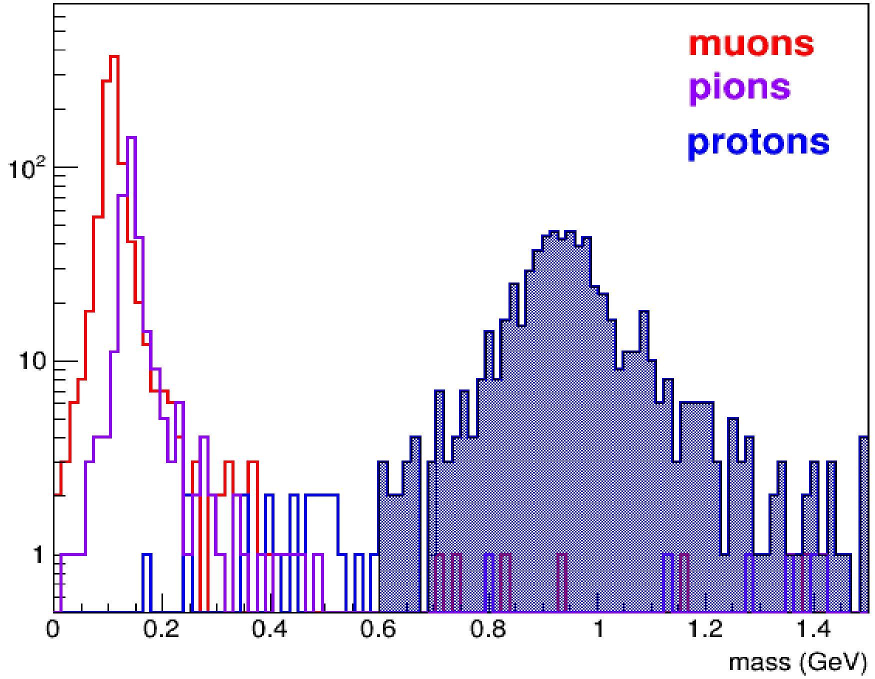
Second vertex finding from track intersection

Mass reconstruction and PiD

preliminary



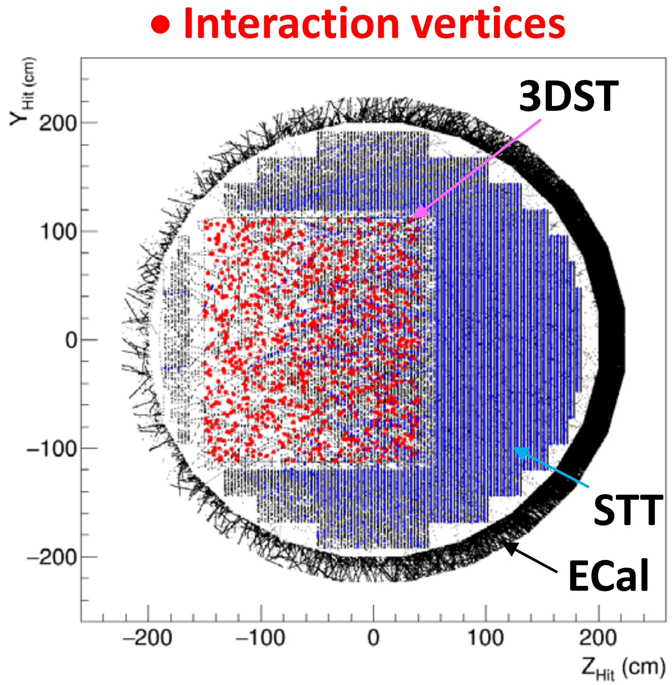




Preliminary background estimate from CC external interactions for SAND detector

MC samples by FLUKA

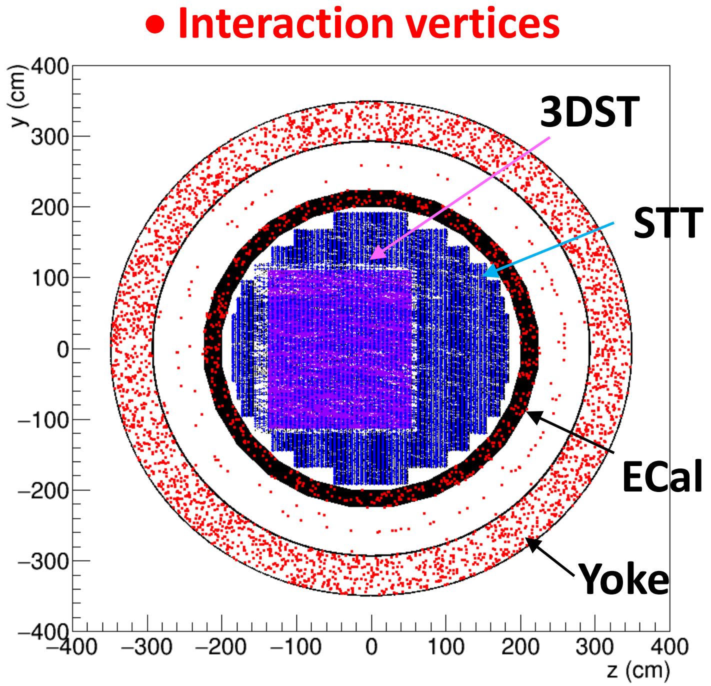
"Internal" events: ν_μ (CC) interactions inside 3DST



Target mass: 10.6 tons

Active volume: 2.24x2.24x2 m³
10,637,312 tons (1.06 g/cm³)
139,776 channels (1cm³ cube)

"External" events: ν_μ (CC) interactions inside KLOE magnet+Calorimeter (ECal)



Target mass: 770 tons

Simulation of ECal and 3DST response

➢ ECal

- Cell-time: average of single fiber times weighted with $E_{dep,i}$
- Energy threshold: E_{th}^{Cal}=20MeV
- Time resolution: gaussian spread with σ_t=54ps/$\sqrt{(E/GeV)} \oplus$ 50ps

  (NO quencing effect, NO light attenuation)

➢ 3DST

- Cell energy: Σ of energies deposited by all particles in the event
- Energy threshold: E_{th}^{Sc}=0.5MeV
- Time resolution: gaussian spread with σ_t=500ps (3 fibers readout)

  (quencing effect included, NO light attenuation)

Selection of internal events

- Based on Relative time between ECal and 3DST

  (difference $\Delta T_{1st} = T_{1st}^{Cal} - T_{1st}^{Sc}$)

- Expected background from external interactions:

  Bck_1: Time " reversal" ($T_{1st}^{Cal} > T_{1st}^{Sc}$)

  Bck_2: T^{Cal} missing in the event

- Background rejection cuts

  1) Fiducial Volume cut on 1st 3DST-hit position

  2) Cut on 3DST-hit multiplicity

Results (preliminary)

Preliminary background estimate using:

1) $\Delta T_{1st} = T_{1st}^{Cal} - T_{1st}^{Sc} > 1ns$

2) Fiducial Volume cut on 3DST (1st hit position)

(10cm cut on X sides) ⊗ (15cm cut on Y sides) ⊗ (20cm cut on Z front side and 10cm cut on Z rear side)	68%

3) (N_{Scin} > 30) (negligible effect on signal after FV)

Bck_{beam} ~ (1.4 ± 0.4) %

(from CC interactions in magnet and Calorimeter)

In progress/planned

1) Same with Neutral Current events

2) Same with STT only (no 3DST)

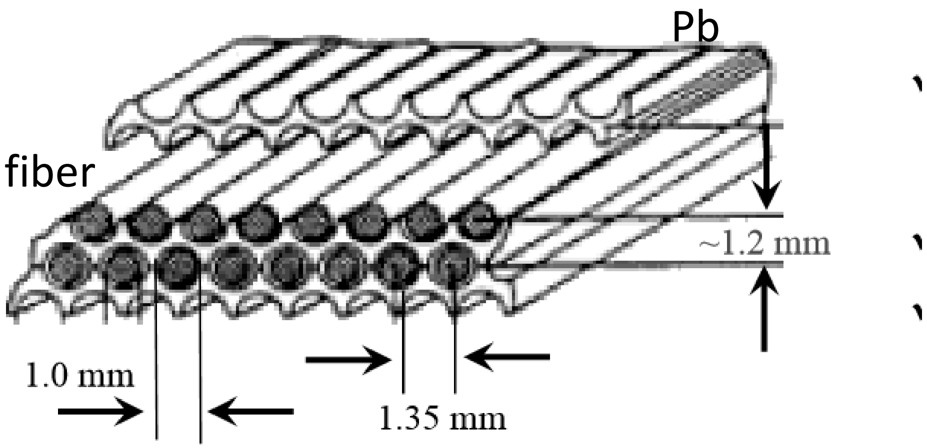
3) Implementation of the alcove geometry, background from walls

Conclusions and future

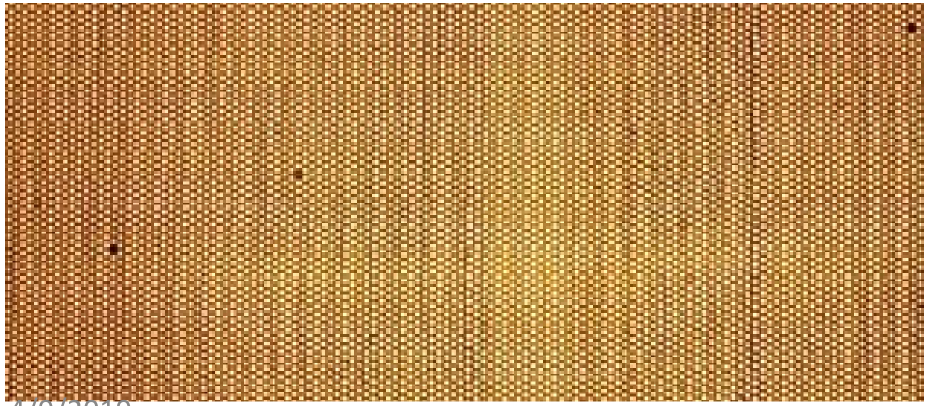
- Detaied full simulations in two complementary frameworks
- Digitization and reconstruction well advanced for ECAL and STT, 3DST in progress
- Planned improvements/updates in geometries:
  - Alcove/ background from walls
  - Precise moeling of ECAL encaps in fluka (as for barrel)
  - Follow-up of STT optimization
  - ….
- Plans to have compatible FLUKA and G4 outputs, to easily apply same reco
- And, naturally, physics studies

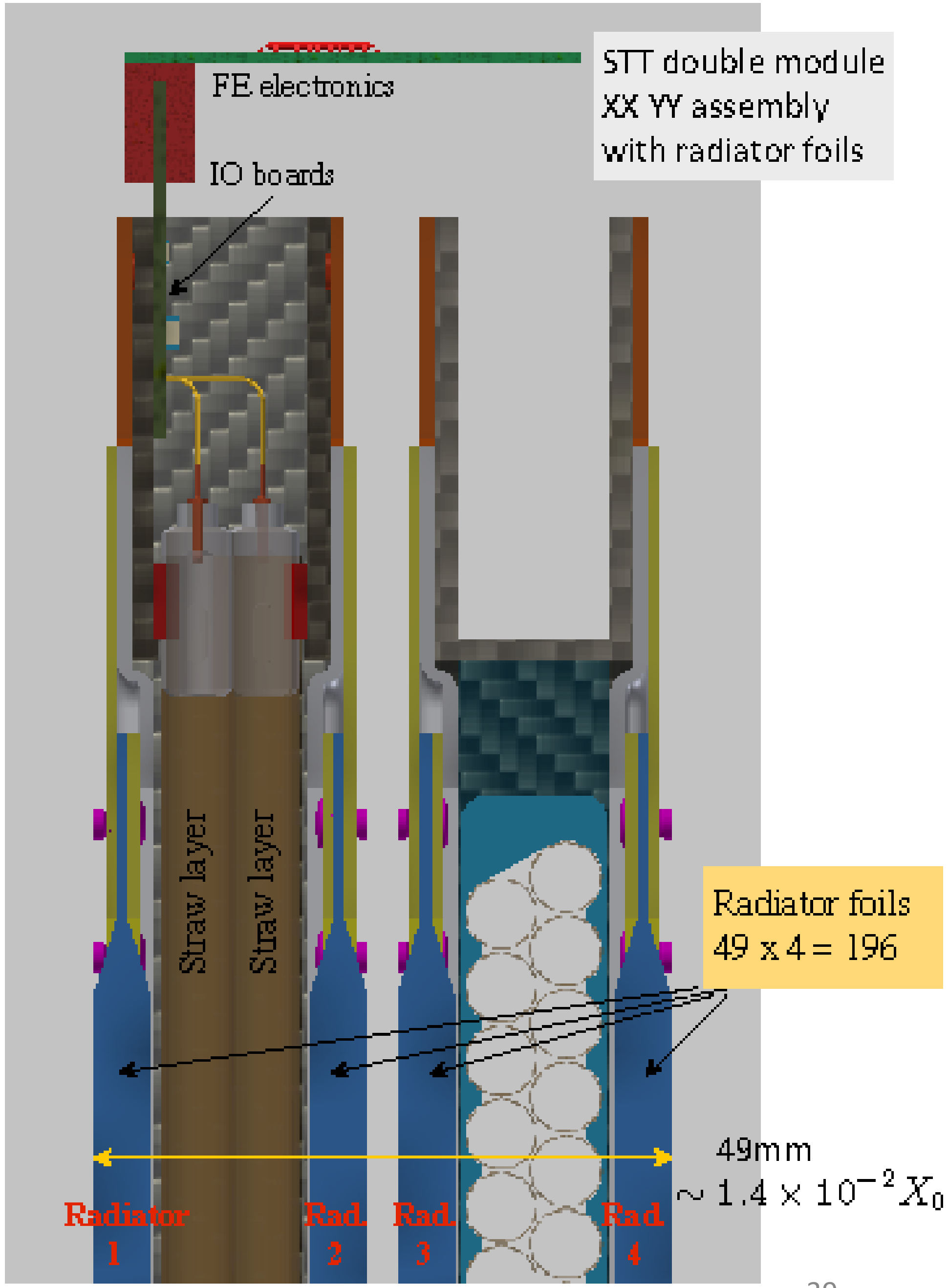
Backup

Details



Kloecal fine structure

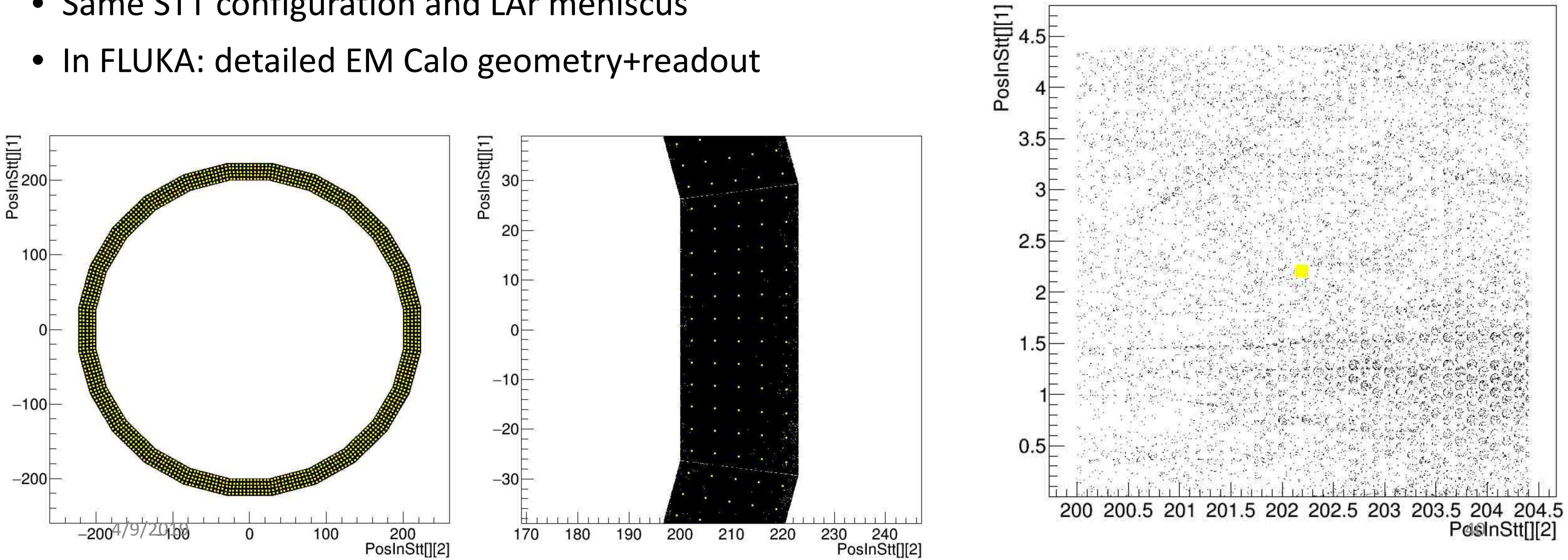




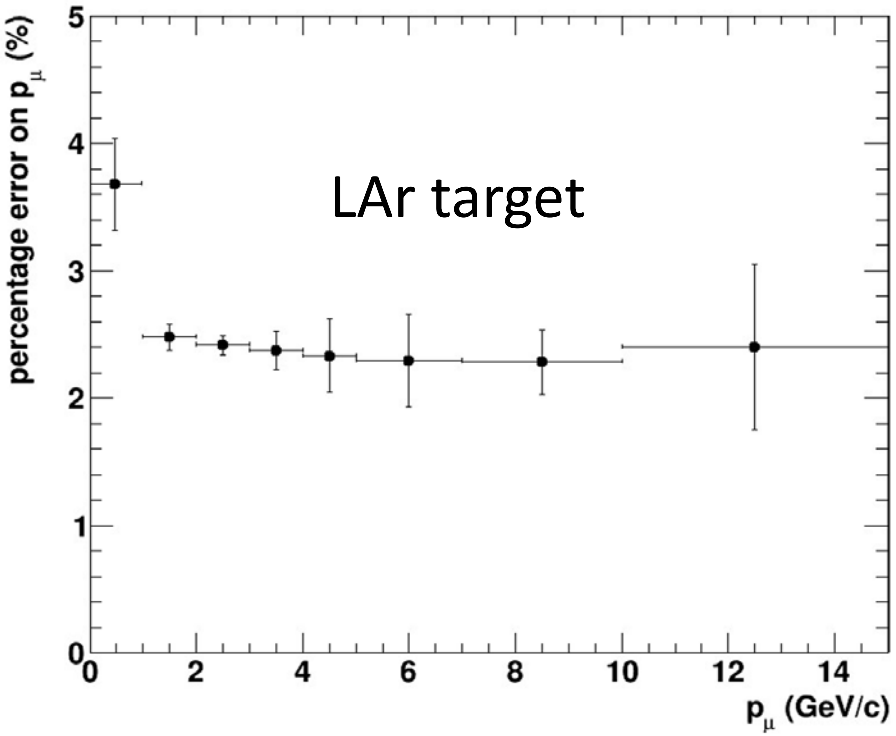
Simulations

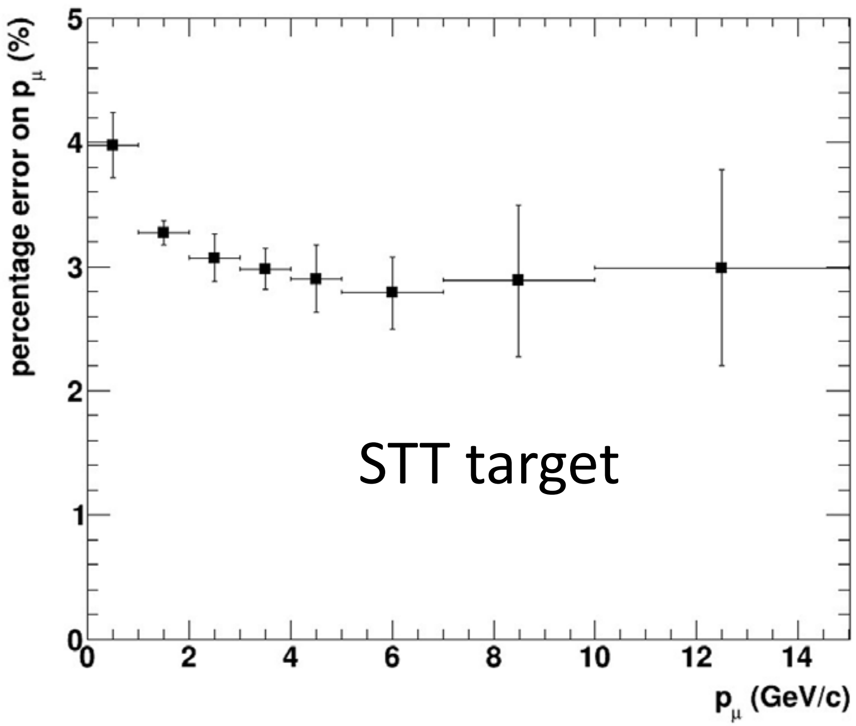
- Two parallel streams
- GEANT4 + GENIE + dunendggd
- FLUKA (with internal generator) + ROOT
- Same neutrino fluxes from http://home.fnal.gov/ ljf26/DUNEFluxes/
- Same STT configuration and LAr meniscus
- In FLUKA: detailed EM Calo geometry+readout

Plots: em-calo hits (black) and readout cell centres (yellow) (integrated over many events)



Results –Muons





FLUKA sim: muon-track reconstruction based on STT hits, assuming a spatial resolution of 0.2 mm on y and x axes and 0.01 mm on z axis (beam axis).

Improvements ongoing

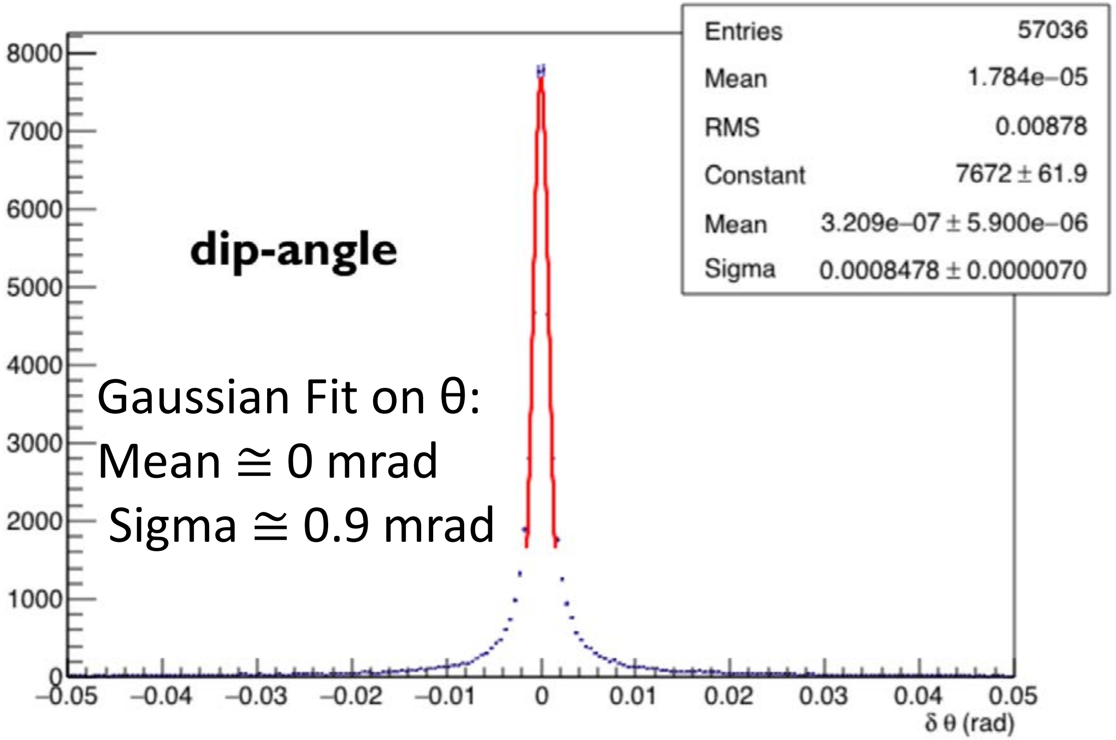
Good resolution on p (~3%) for both targets

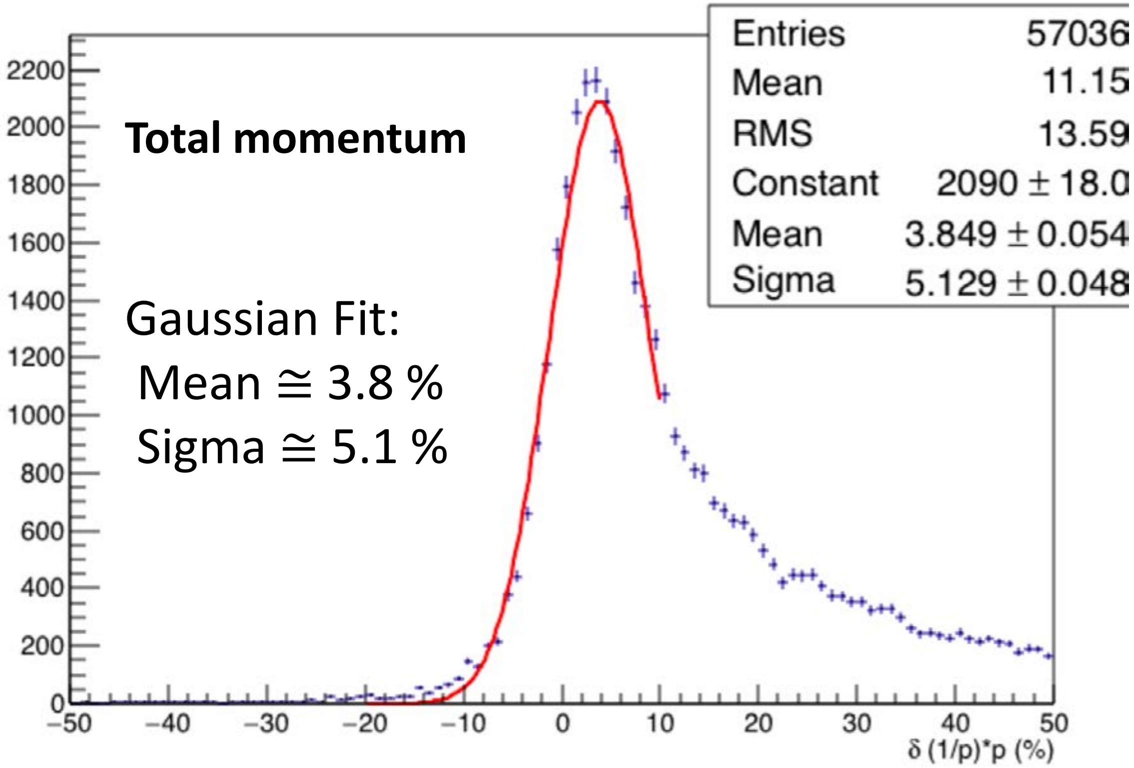
Good resolution on dip angle ~1.7 mrad

Charge mis-id ~0.02%

Results: - electrons

Generated in STT with GENIE+GEANT4. Very good resolutions, tails due to circular fit approximation to be improved i.e. with Kalman filter.





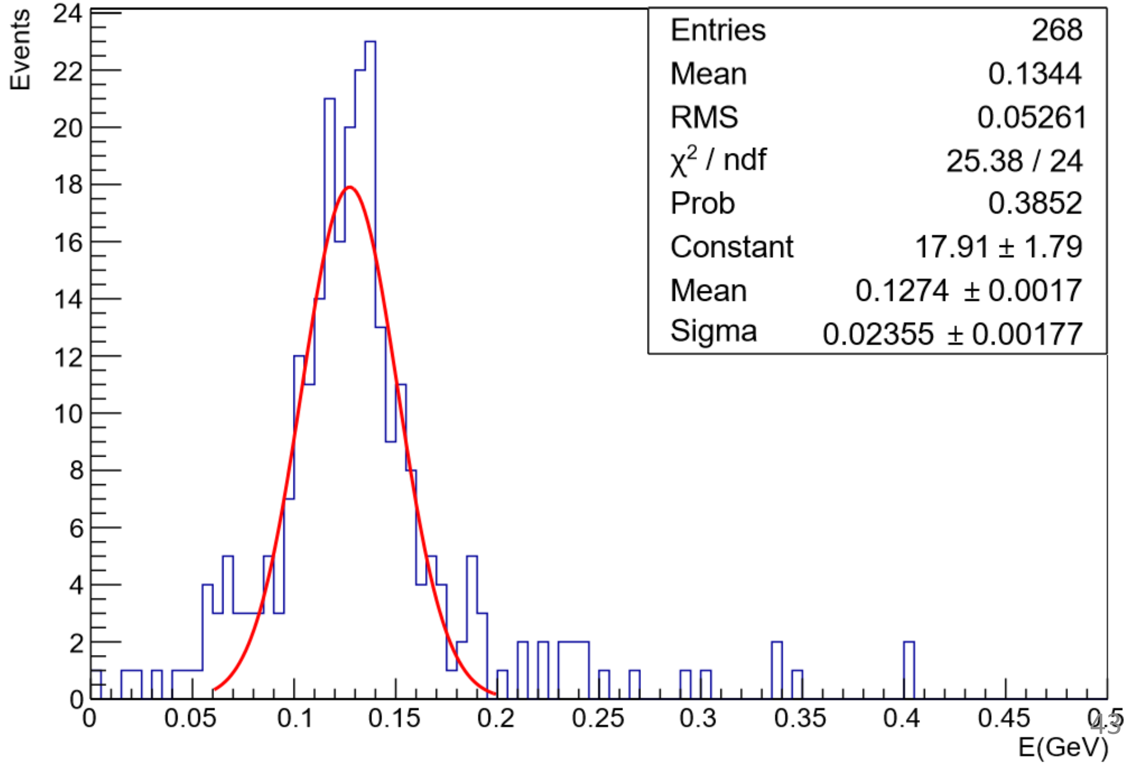
Wrong sign 1.3%

Results- π^0

Reconstructed CC sample:
4000 events
1 π^0 25% of events
2 π^0 8% of events
> 2 π^0 2.5 % of events

Reconstruction from EM CALO clusters
Dimensions Δx = 20 cm and $\Delta\phi$ = 5 deg.
Energy smearing $\sigma_E/E \approx 5.7\%/\sqrt{E(GeV)}$
Position from hit barycentre +
resolution of the KLOE calorimeter (4.5 mm).

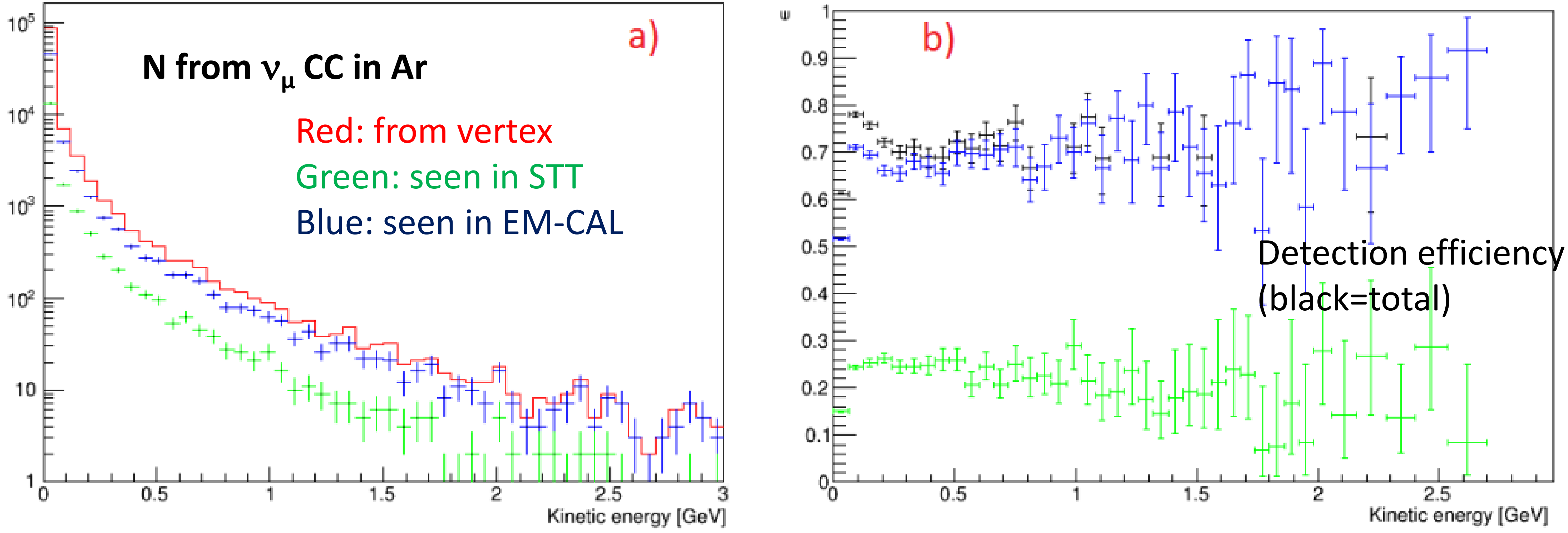
2 π^0 sample: π^0 invariant mass,
Considering only 4-cluster events



Resolutions:
1 π^0 16%
2 π^0 18%

Results: - Neutrons : efficiency

FLUKA simulation, detailed EM-CAL. Reconstruction uses real calo segmentation+ measured signal attenuation and time delay in fibres. Combined with STT hits as for muons



Global efficiency 64% (17% STT, 55% EM-CAL, 8%overlap)

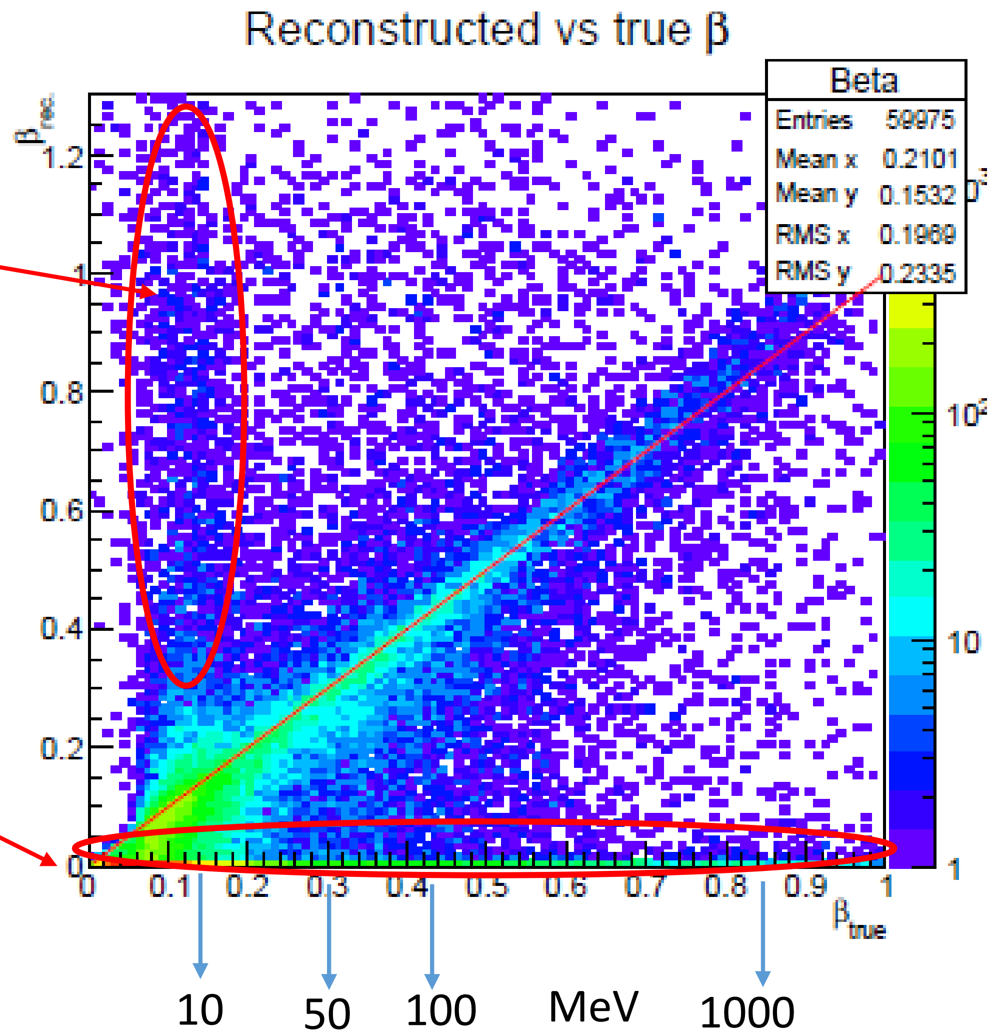
Efficiency > 72% for E_{kin} > 100 MeV

Results: - Neutrons: energy from ToF

FLUKA simulation. Reconstructed ToF from vertex in Ar to hit in STT or EM-CALO

Early interaction not detected. ToF from fast secondary (photons)

Many scatterings not detected. Path much longer than straight line



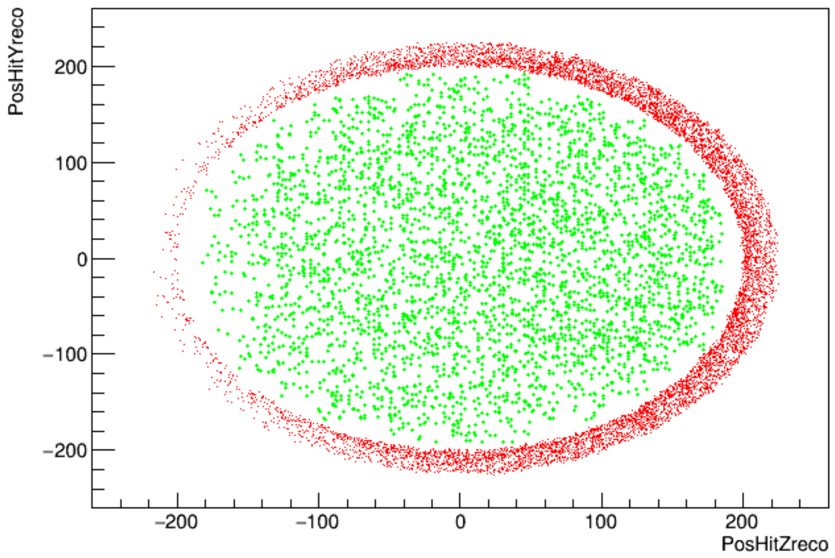
On full spectrum:
the neutron kinetic energy can be reconstructed with about 30% precision for about 23% of the detected neutrons.

Situation improves quickly with energy:
On E> 50 MeV 47% of detected neutrons are reconstructed within 30% accuracy
Next: try to add calorimetric information

Angle reconstruction for QE interactions on H

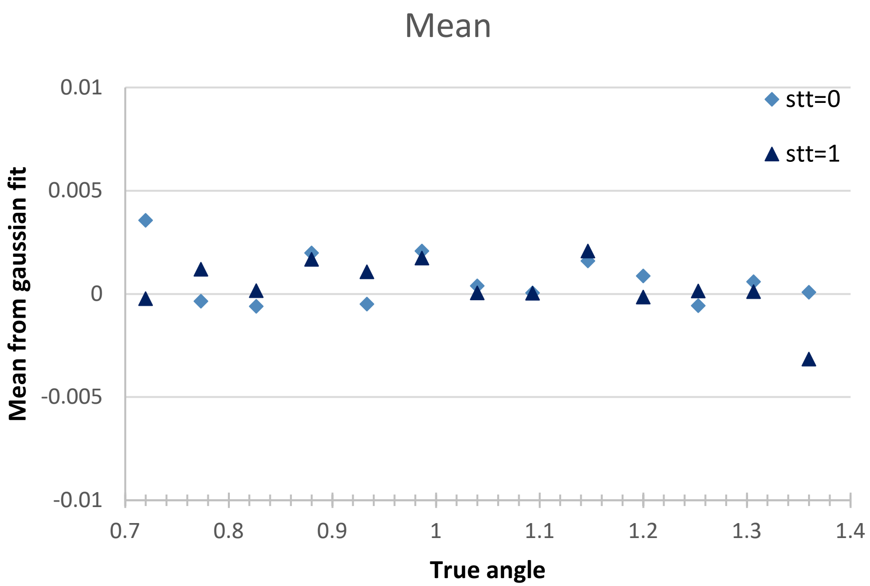
$$\bar{\nu} + p \rightarrow \mu^{+} + n$$

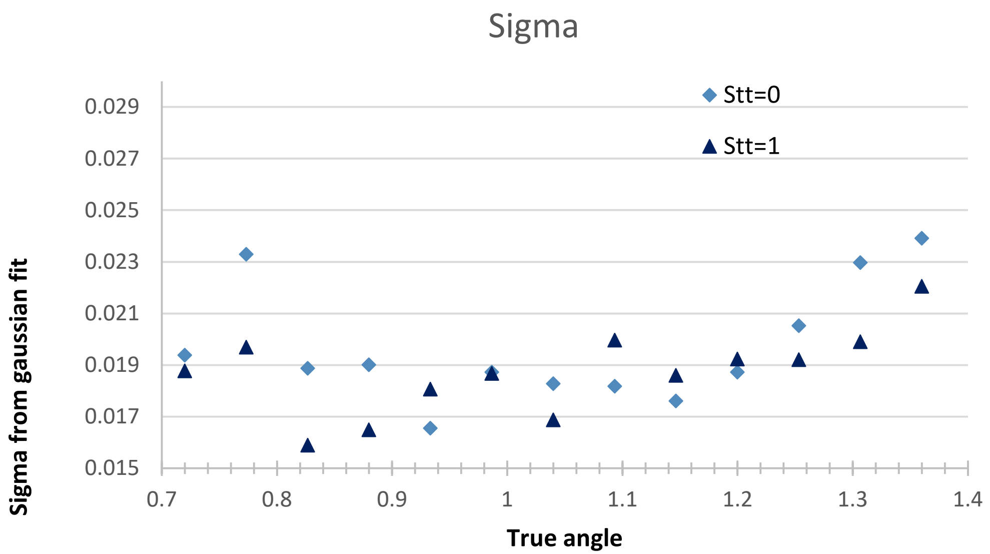
- first hit (minimum time) of neutron or neutron daughters track
- Smearing of MC vertex position and hit position



Stthit=1 events in stt
Stthit=0 events in barrel calorimeter
Stthit=2 events in endcap calorimeter

Resolution vs true angle





(Reco-true)/true :

average within 0.5%

sigma ~2%

Full reconstruction –**no MC truth**

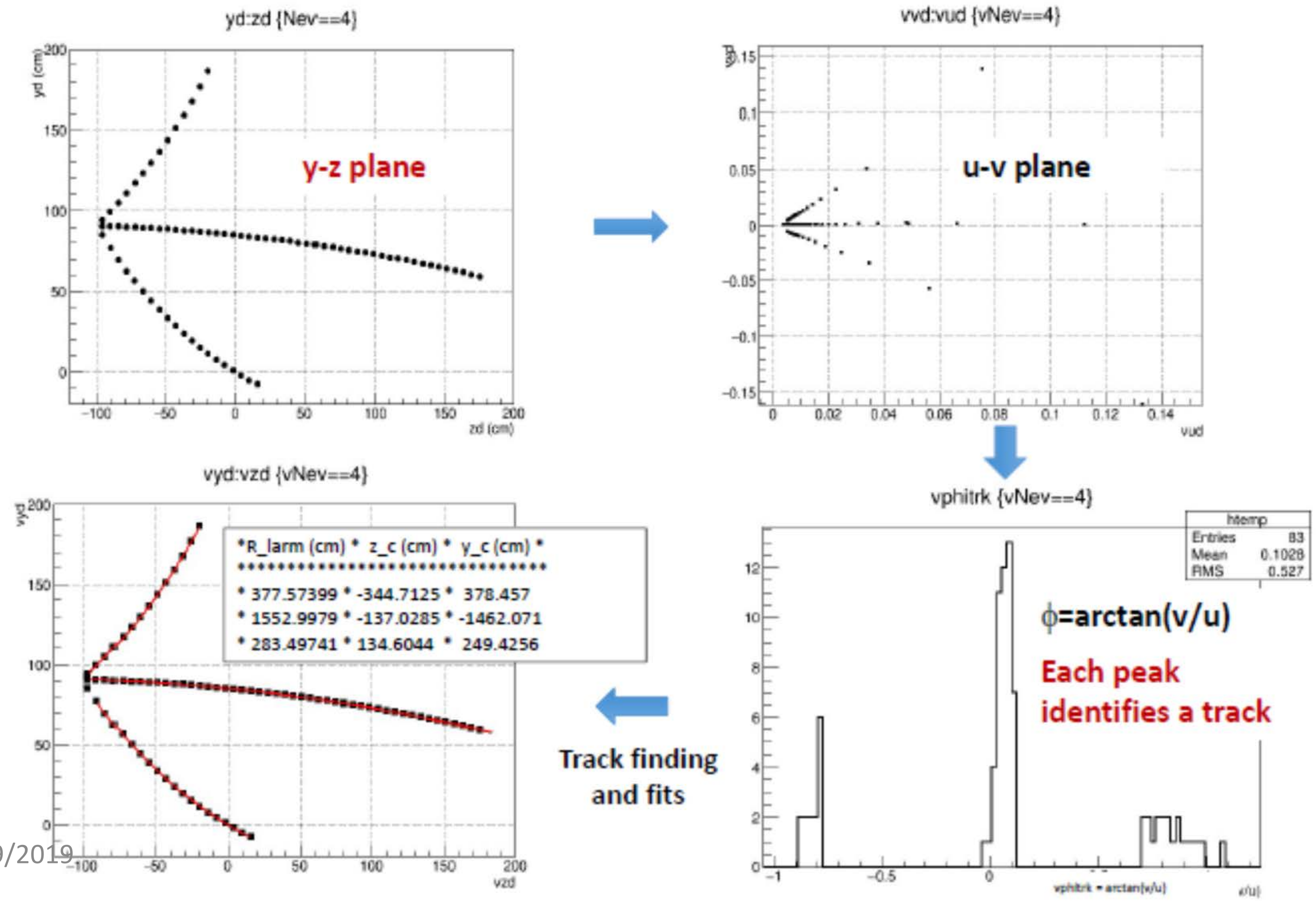
- Interaction Vertex based on STT-hit topology (Step 0)
- Track finding (Global transform method)
- Linear or circle fits to track
- Vertex reco from crossing on two most rigid tracks (Step 1)
- Iteration…

On two views

- Matching of tracks in the two views → tracks in 3D
- Evaluation of $p_{\perp}$ and dip-angle ➔ p estimate
- Ecal hit compatible with tracks ➔ ToF measurement
- ➔ β estimate➔ PiD

vertex and track finding

- A full realistic event reconstruction based only on detected quantities, avoiding to use MC true information, is under development using FLUKA simulated events



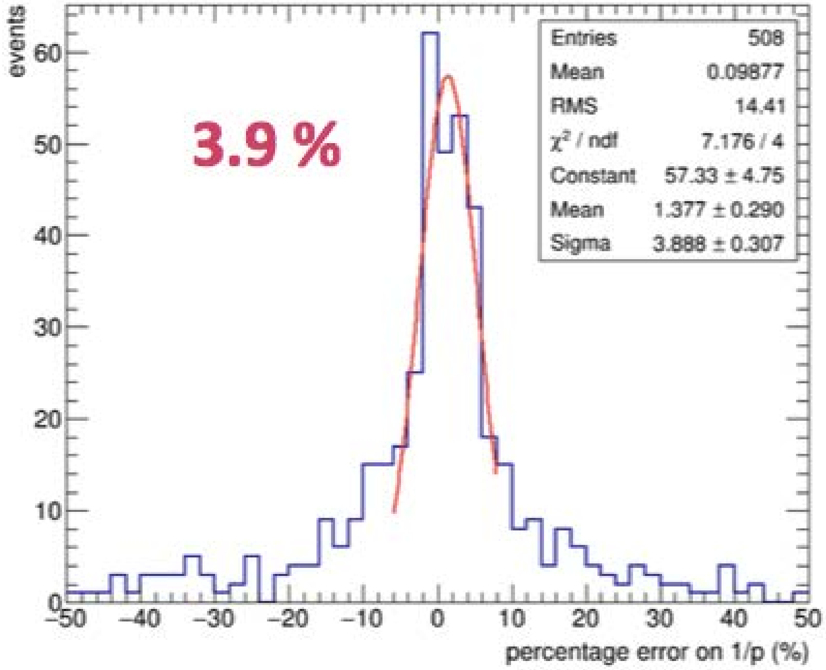
Two-step method: first rough vertex finding, allows for coordinate transform

Peaks in ϕ correspond to tracks

Second vertex finding from track intersection

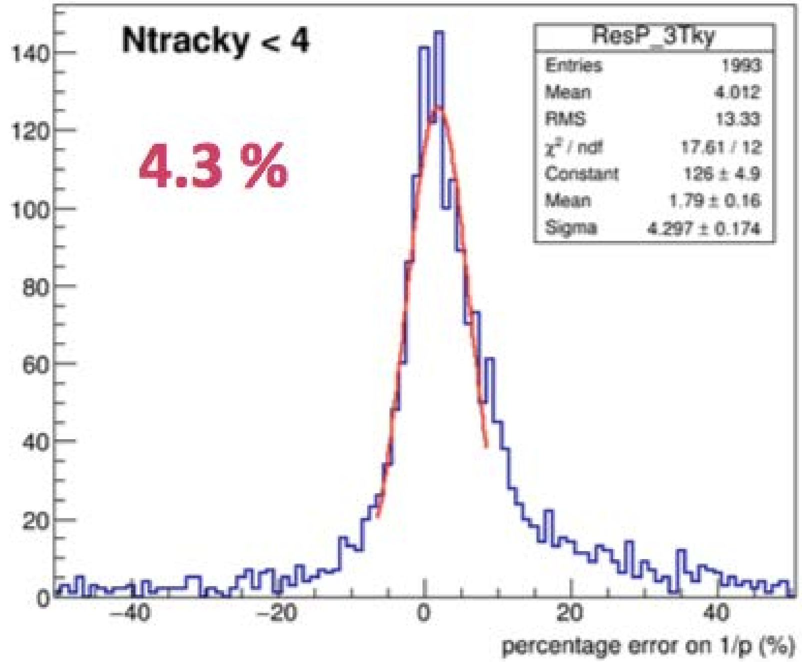
P reconstruction

For events with only 1 charged track in each view:

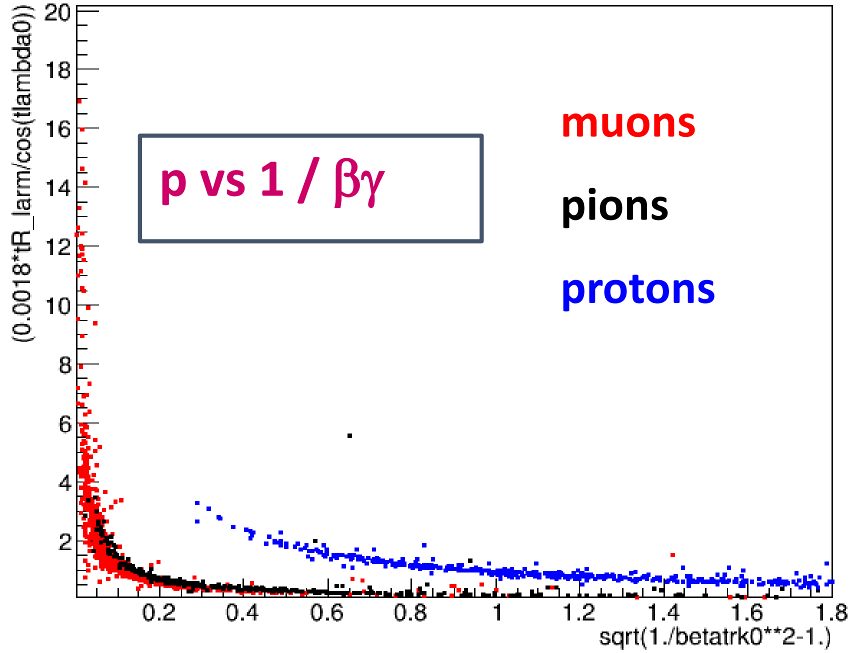


Error on total p:
$p = p_{yz}/\cos(\lambda)$

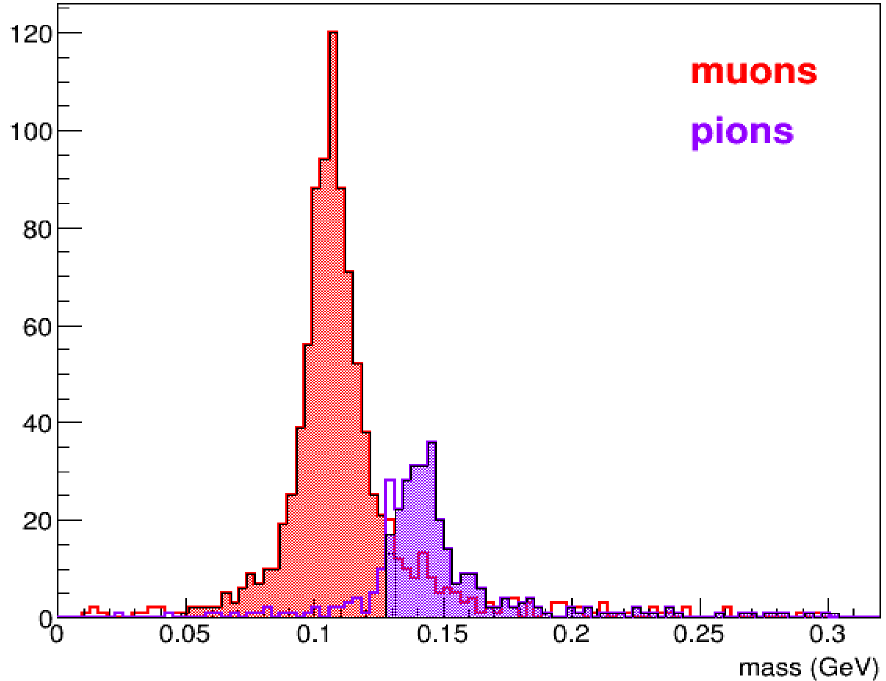
For events with no more than 3 tracks matched in the two views:

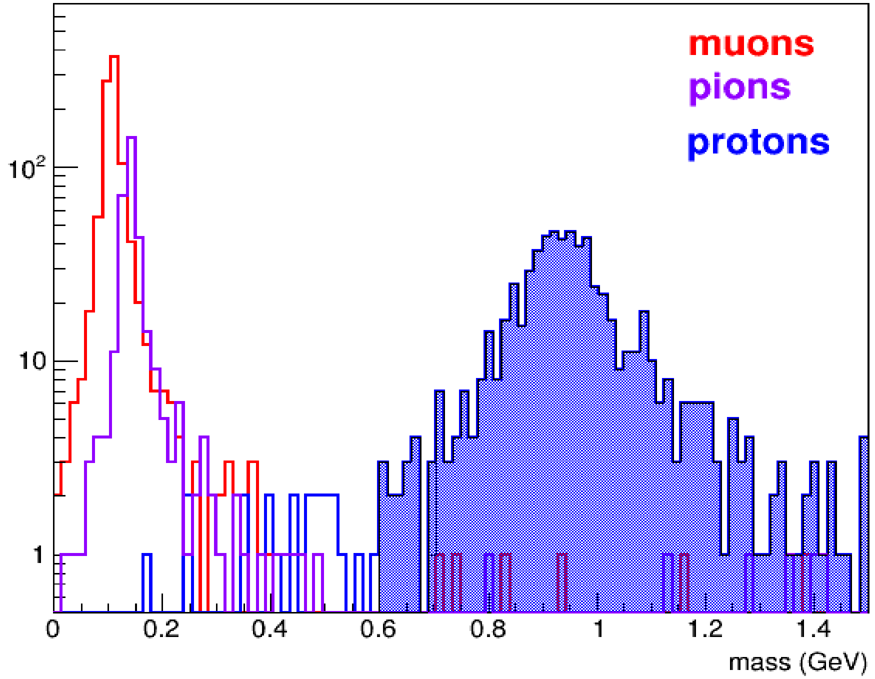


Mass reconstruction and PiD

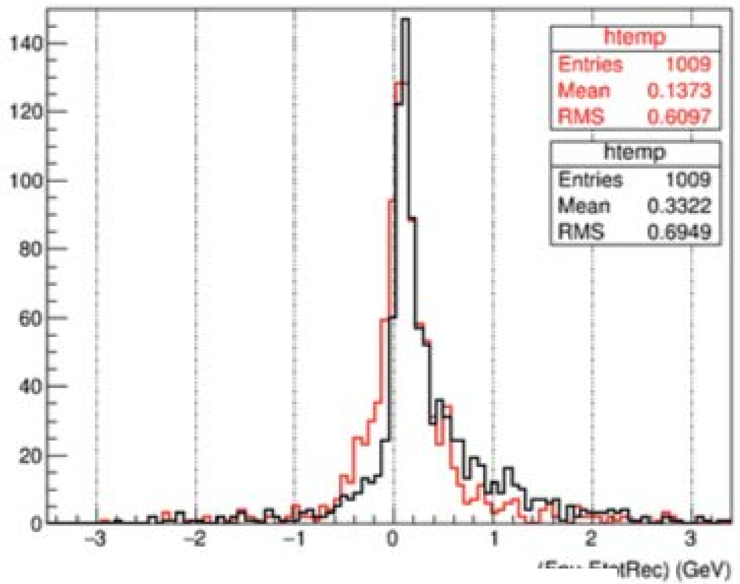


preliminary





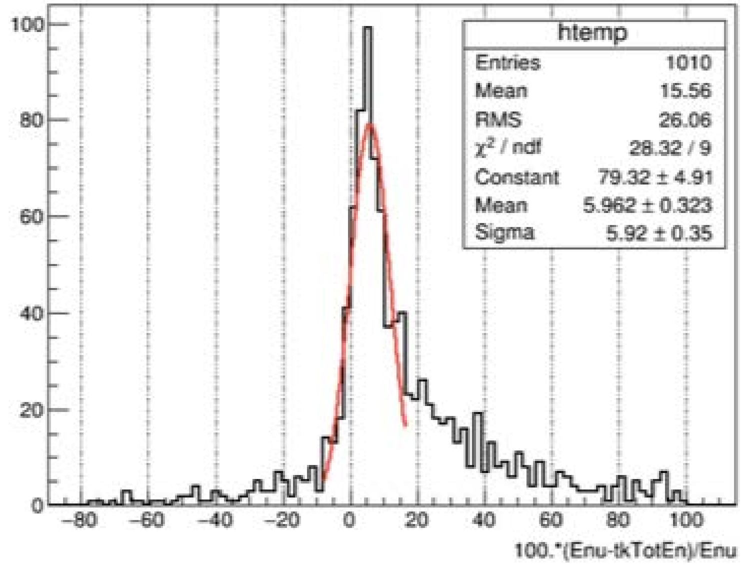
ν energy reconstruction (preliminary)

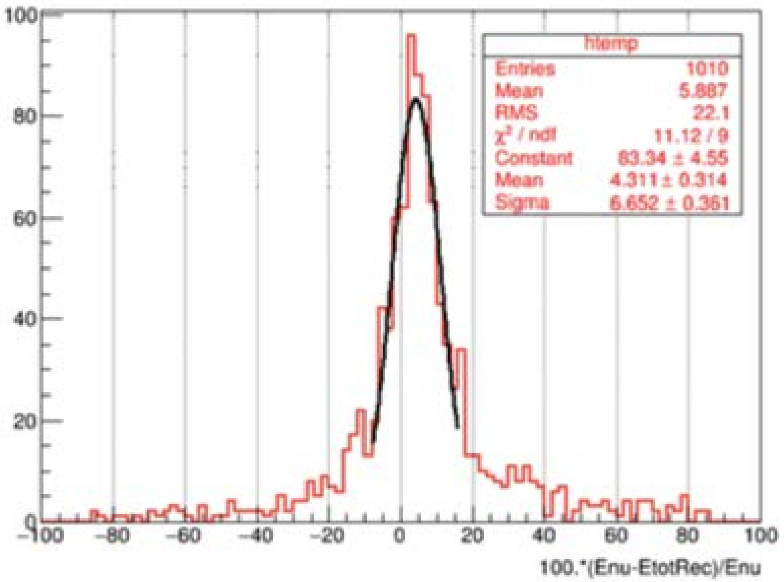


'All-tracks' energy only

'All-tracks' energy +
Off-track Calo energy

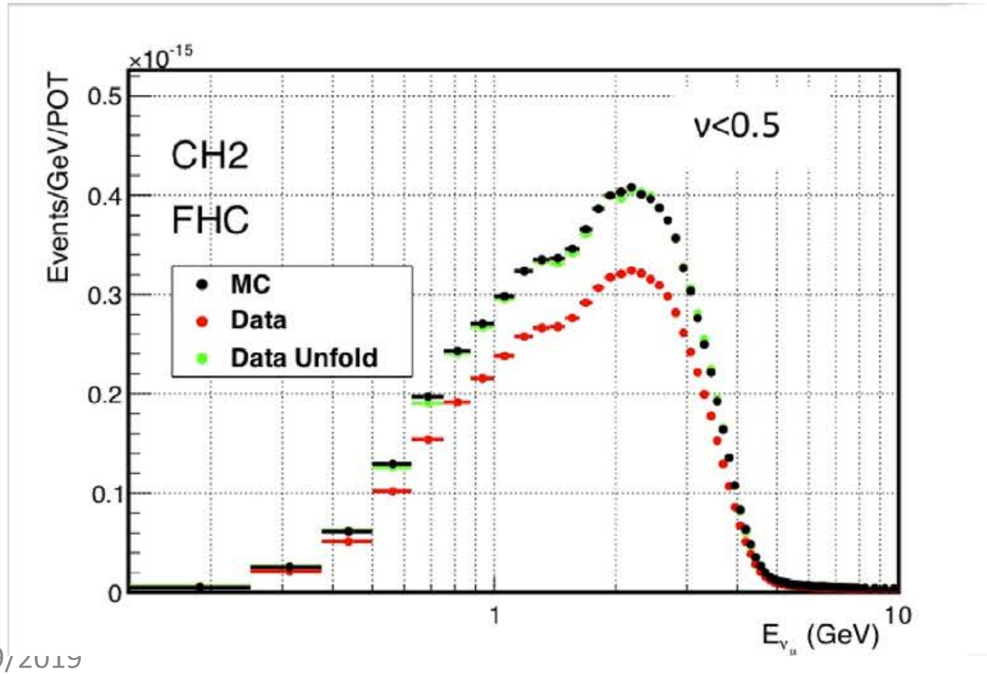
NO MC truth
σ/E = 6.6%

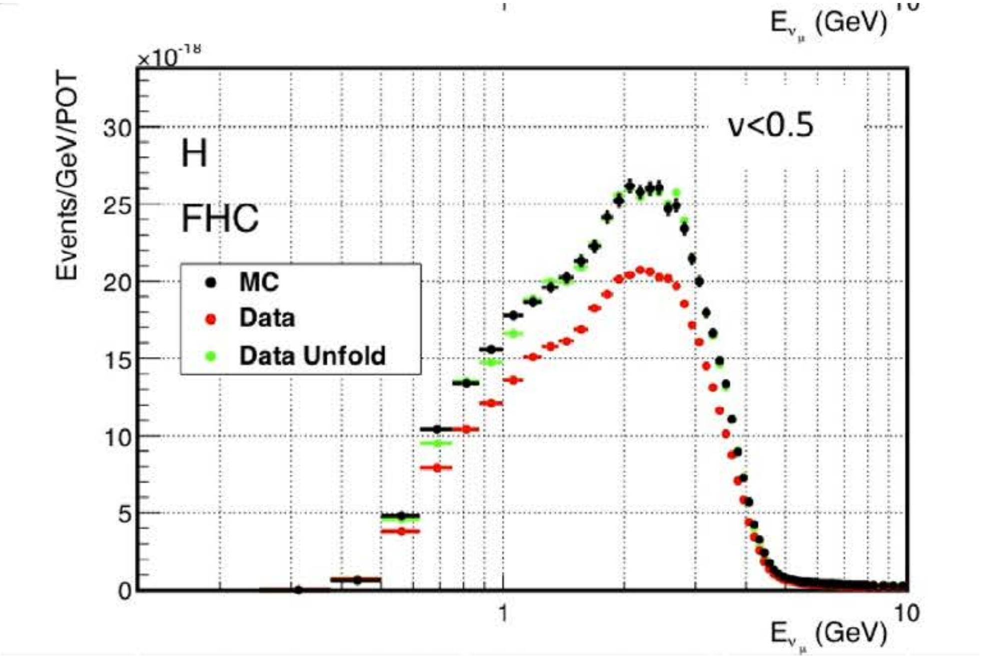




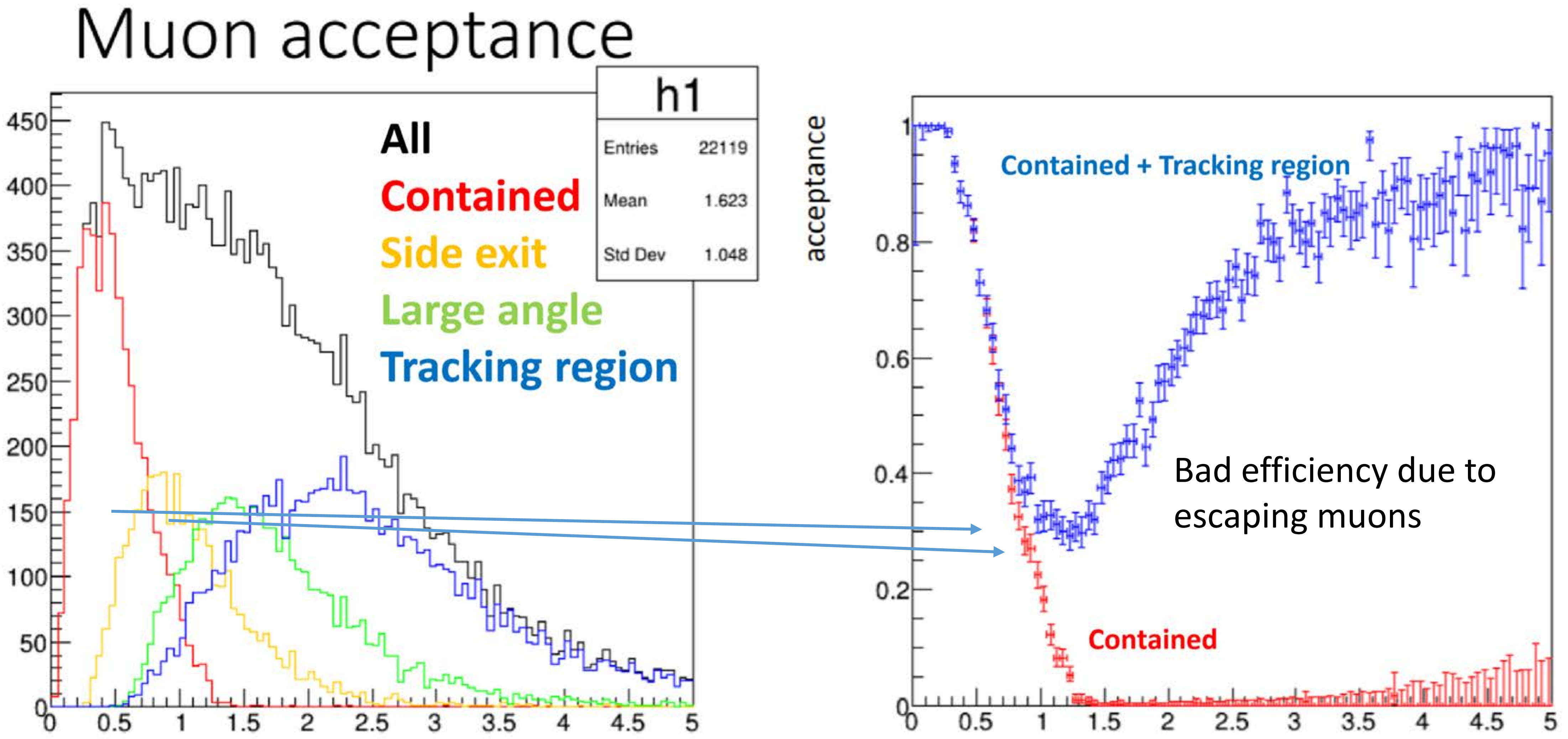
Low-nu

- GENIE simulation on CH2 and H
- 2 MC samples: “data” and “MC truth”
- Assuming acceptance of 80% and energy resolution 5% to test the unfolding and analysis procedure
- Detector simulation and event reconstruction ongoing



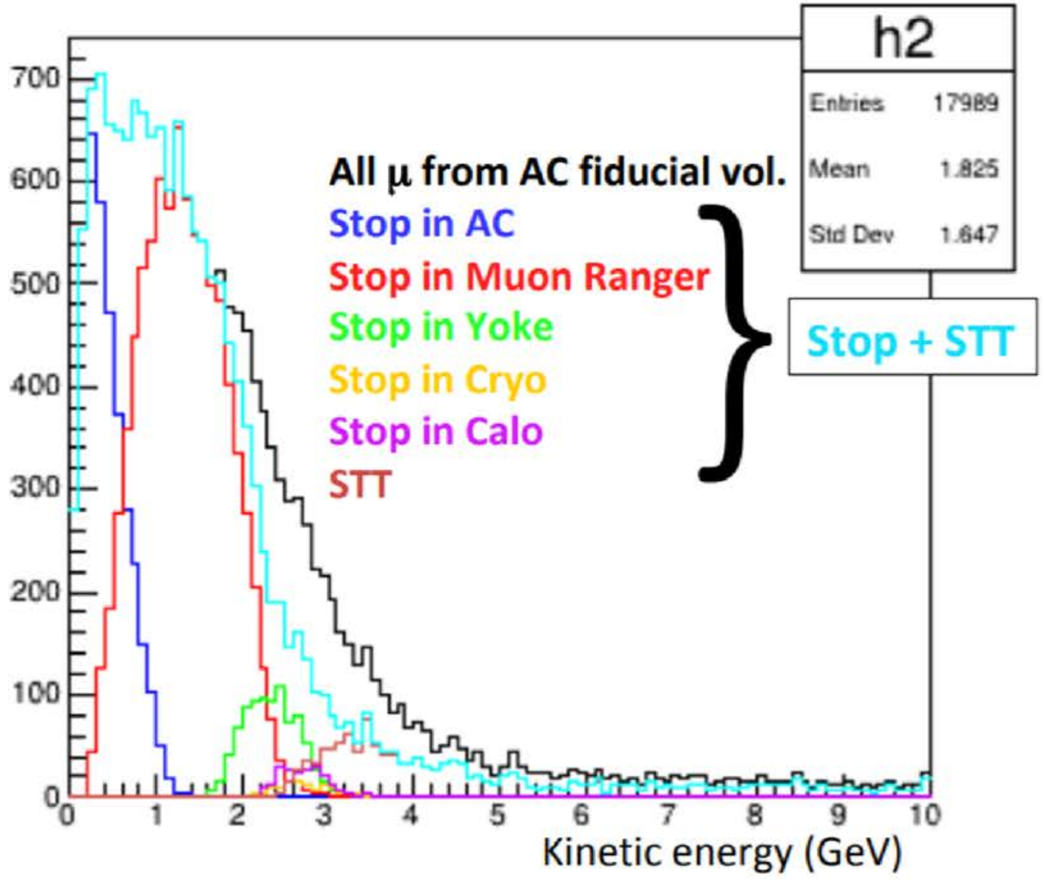


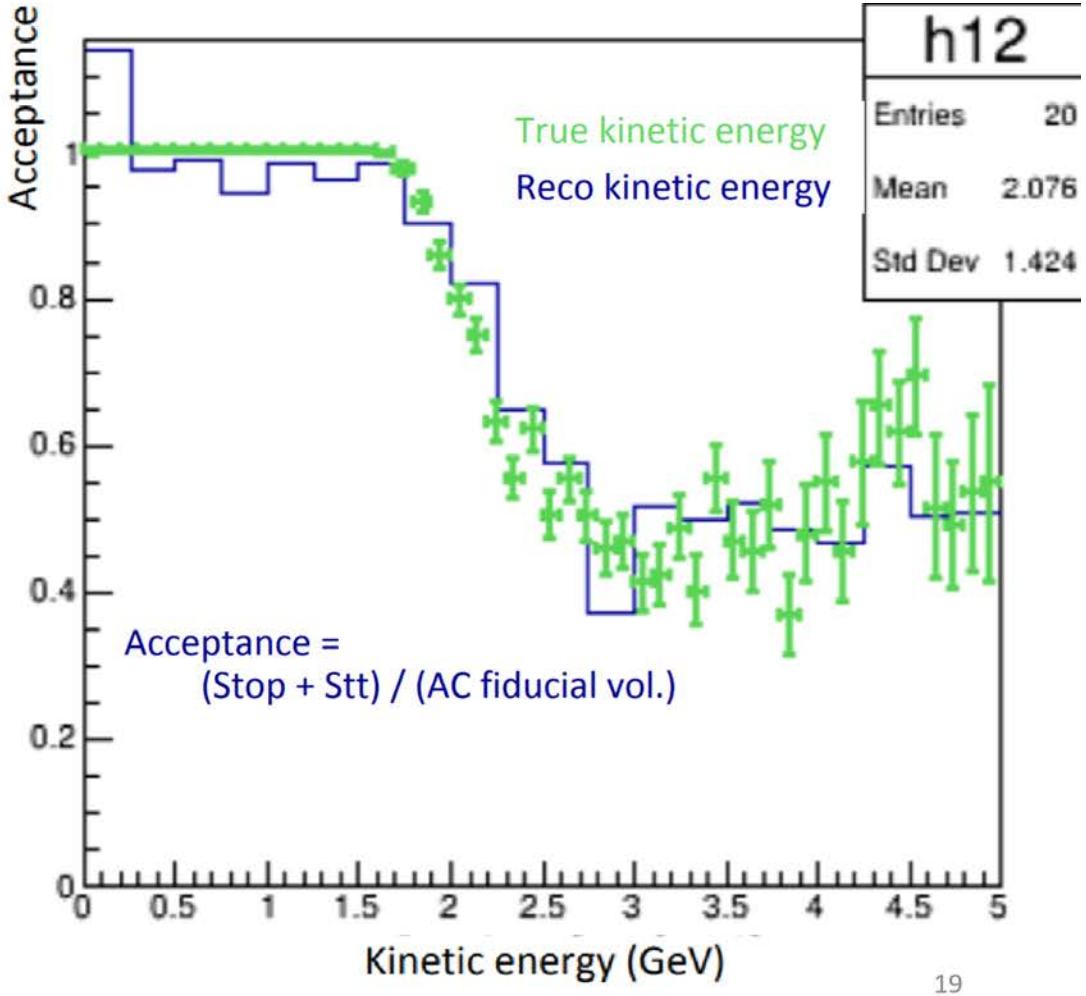
Acceptance for ArCUBE muons: old AC geo



Acceptance for ArCUBE muons: old AC geo

- Simple muon catcher around AC + layers around coil cured the acceptance





18/03/2019

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Acceptance for AC muons: work in progress (maybe obsolete?)

- New AC dimensions and exit window implemented, analysis in progress

Summary

- KLOE magnet + EM Calo + 3DST +tracker: implemented, running
- KLOE magnet + EM Calo + STT : full simulation + single particle reco
  - Track momentum $\sigma \approx$3%
  - Track angle 1 mrad
  - Neutron efficiency 76%
  - Neutron Energy within 30% for 47% od detected n with E>50 MeV
  - Neutron angle in QECC on H: within 2%
- KLOE magnet + EM Calo + STT :**preliminary full event reconstruction**
  - PiD and proton/muon/pion mass reco
  - Neutrino energy in CC $\sigma \approx$ 6%
- Acceptance for ArgonCube events: latest configuration under evaluation. Previous one: OK if muon catchers