A proposal to enhance the DUNE ND complex

[DUNE-doc-13262]

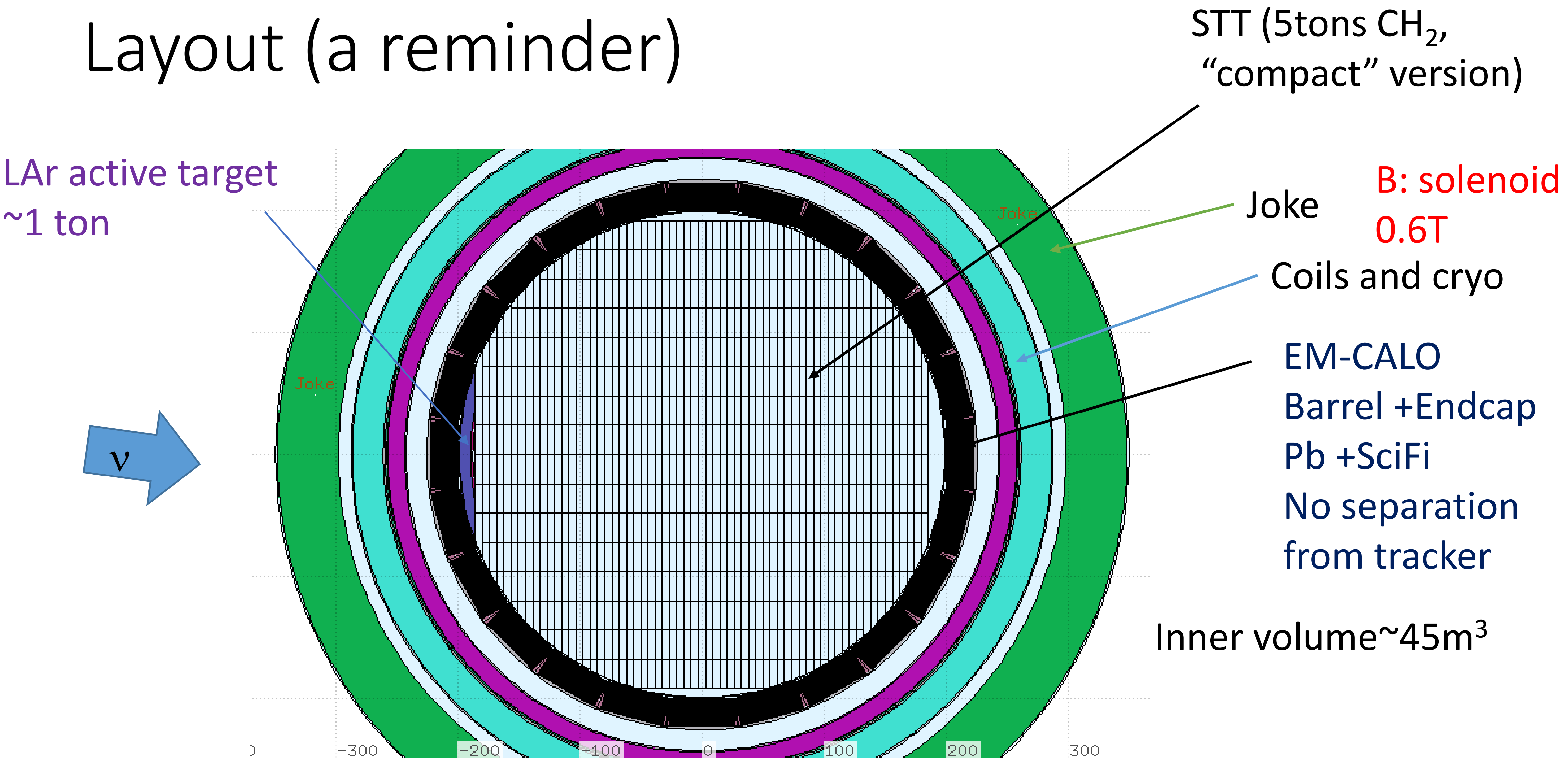
On behalf of the INFN DUNE and R. Petti

What, Why, How?

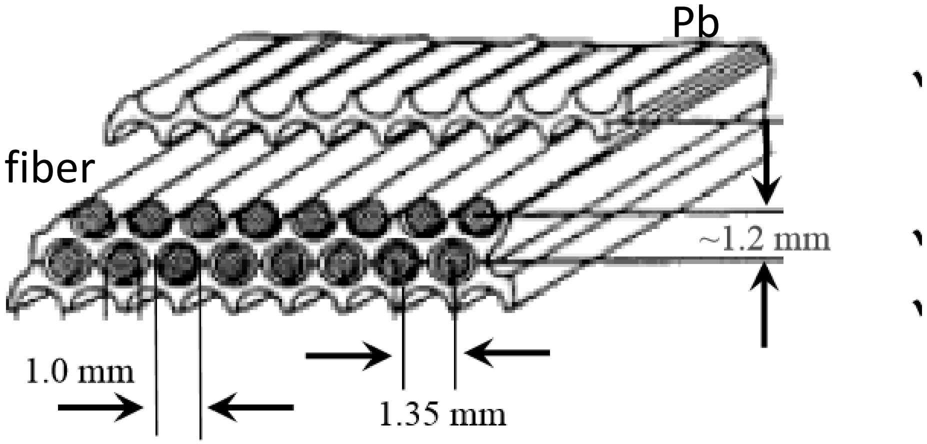
- KLOE + STT + LAr: a multipurpose Near detector
- Complementing the baseline design
- Combined measurements on Ar and H
- Either on-axis monitoring
- Or easily movable "dune-prism"
- Reduce Systematics for Long-baseline Oscillation
- Physics Facility for Precision Measurements and Searches
- Synergy with other detectors in the ND complex

- Full simulations and reconstruction to demonstrate performances

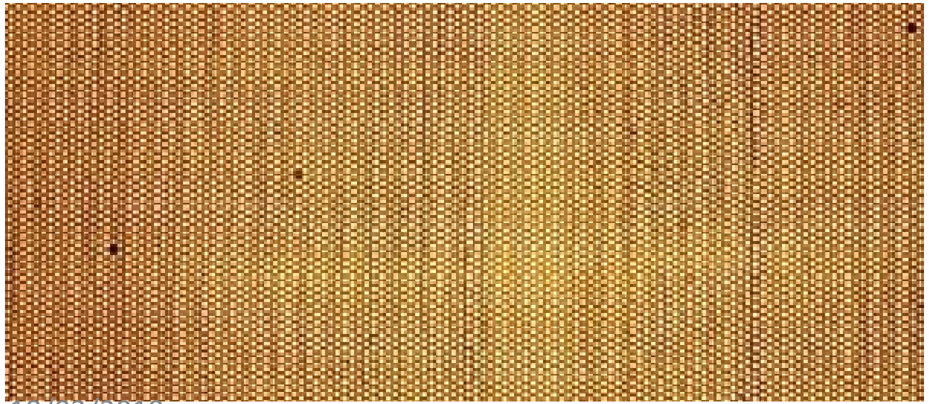
Layout (a reminder)

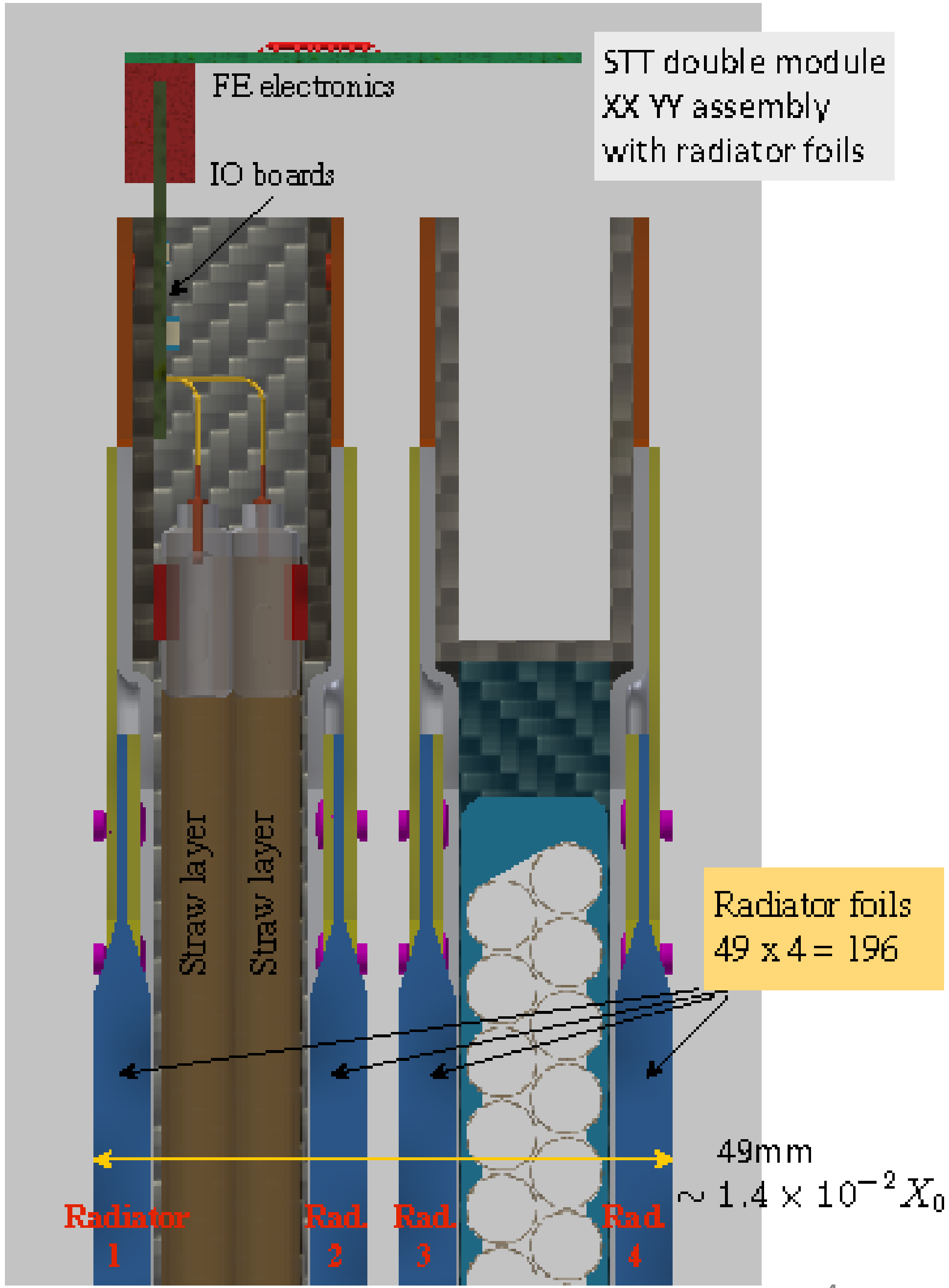


Details



Kloecal fine structure





Flux measurements

- Φ (E_ν) Measurements
  - Absolute ν flux from ν e → ν e elastic
  - Fluxes vs E_ν, ratios of ν_x / ν_y (e, μ, anti) from interactions on Hydrogen
  - the availability of large statistics from a hydrogen target allows precisions far exceeding what is achievable with any nuclear target.

- Number of CC interactions for 5 years exposure to CP optimized beam:
  - ν_μ on H : 2.7 x 10^6
  - $\bar{\nu}_\mu$ on H : 2.4 x 10^5
  - ν_e on H : 4.0 x 10^4

- ν-e ES in FHC : 1000/year in STT, possibly combined with measurement from large mass pixelated LAr detector

Number of CC interactions

FHC	CP optimized beam (1.2MW, 5y)			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
All	37,169,700	1,711,270	549,615	88,165
C	25,832,700	1,123,710	380,710	57,750
H	2,679,270	244,530	40,315	12,155
Ar	7,863,680	306,790	117,095	16,445

RHC	CP optimized beam (1.2MW, 5y)			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
All	5,804,320	13,316,900	260,425	190,850
C	4,036,180	8,688,020	380,710	124,575
H	425,645	1,985,780	19,085	27,225
Ar	1,214,180	2,364,620	55,385	35,035

σ and Nuclear Effects

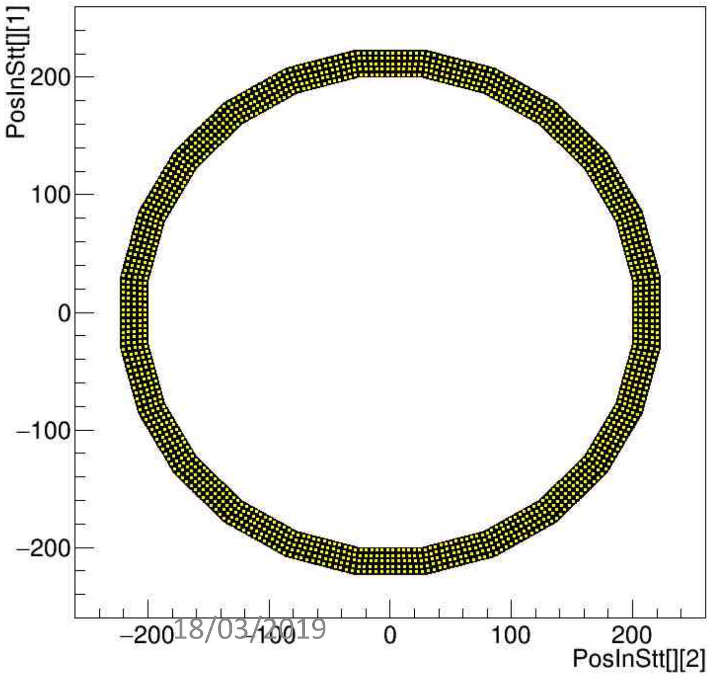
$$N_X(E_{rec}) = \int_{E_\nu} dE_\nu\, \Phi(E_\nu)\, P_{osc}(E_\nu)\, \sigma_X(E_\nu)\, R_{phys}(E_\nu, E_{vis})\, R_{det}(E_{vis}, E_{rec})$$

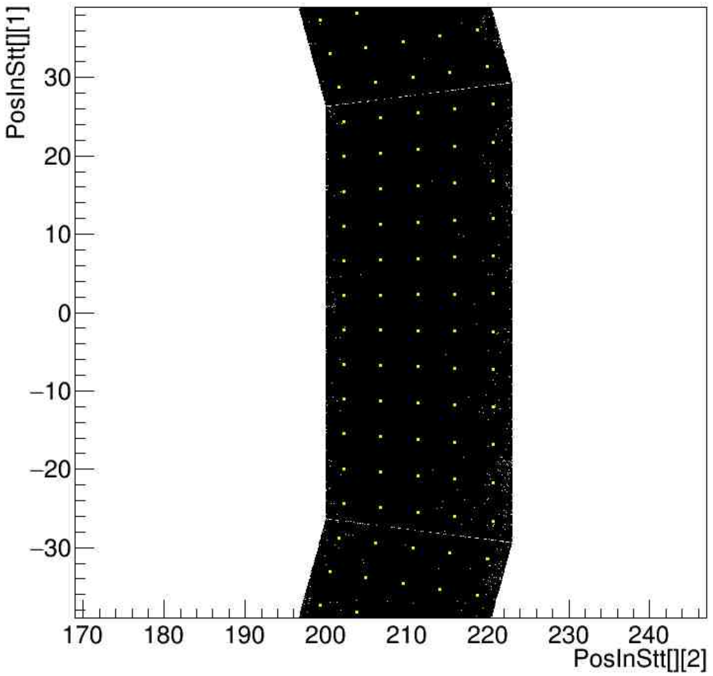
- Events on Ar, H, CH_2, additional C target within the same detector
- Compare Ar events with free proton kinematics (H)
- Unfolding nuclear effects (R_{phys}) from detector effects (R_{det})
- ➔ measure $\sigma_x R_{phys}$
- Lar TPC detector effects (==Far Det) studied by pixelated LAr TPC
- σ_x on Ar using the large statistics from the LAr and HPgTPC detectors

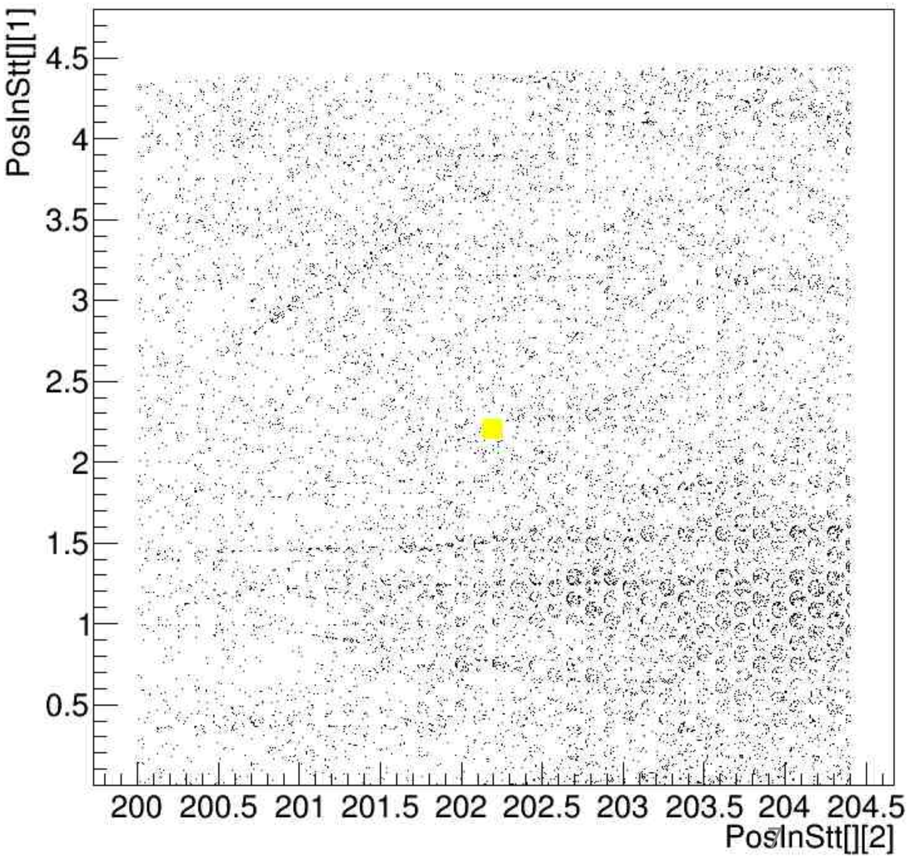
Simulations

- 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

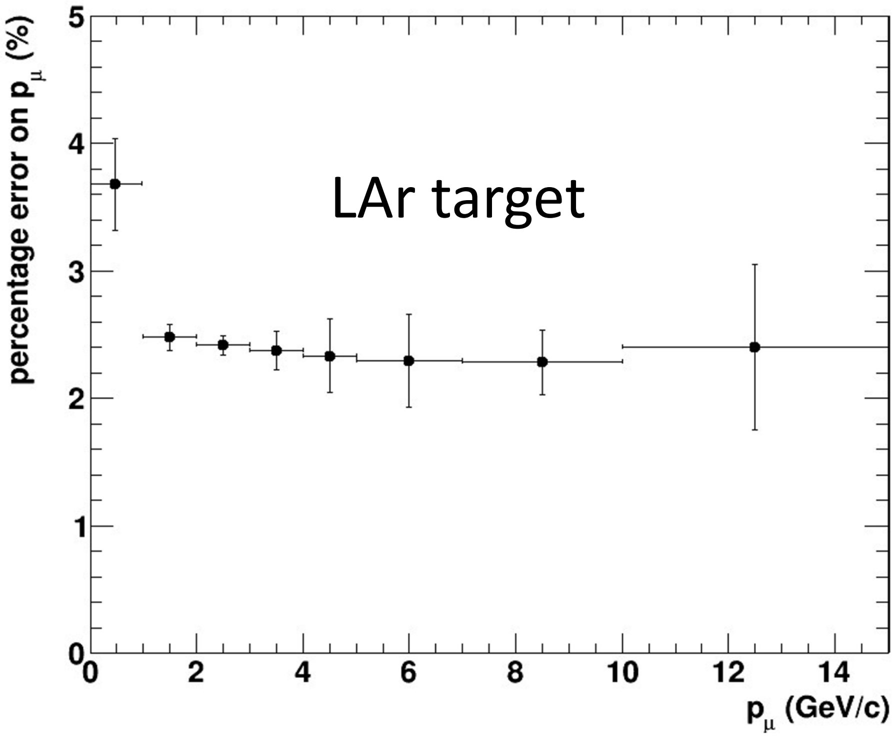
Plots: em-calo hits (black) and readout cell centres (yellow) (integrated over many events)

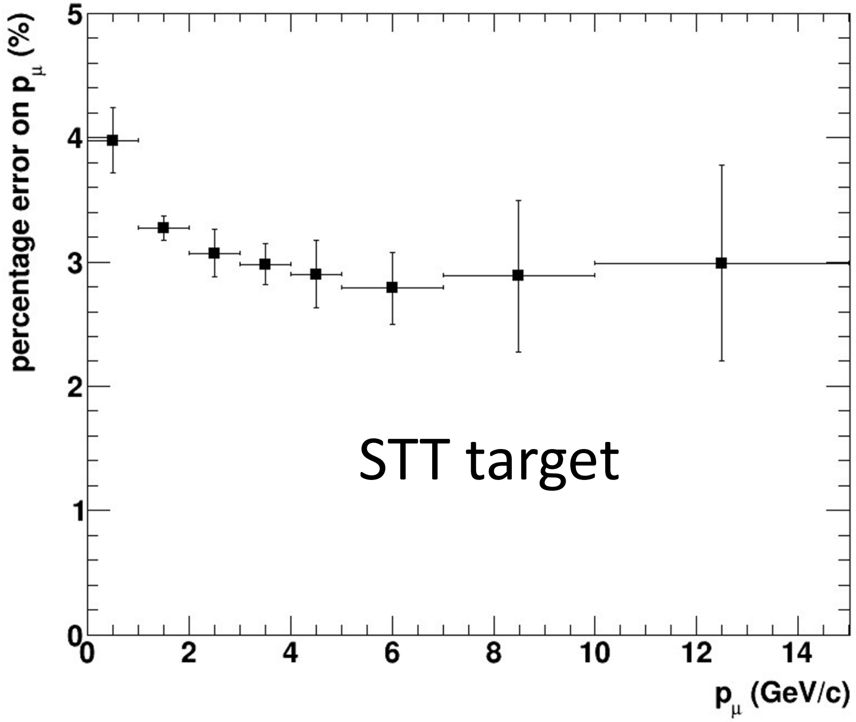






Results –Muons





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

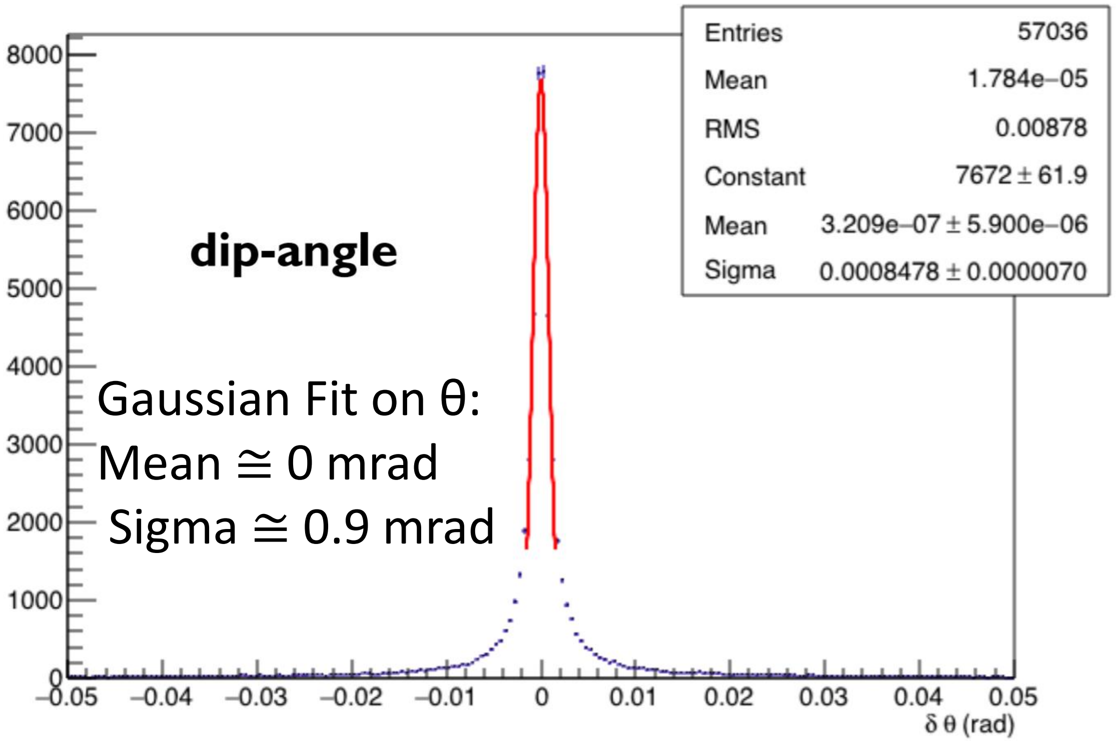
Good resolution on p (~3%) for both targets

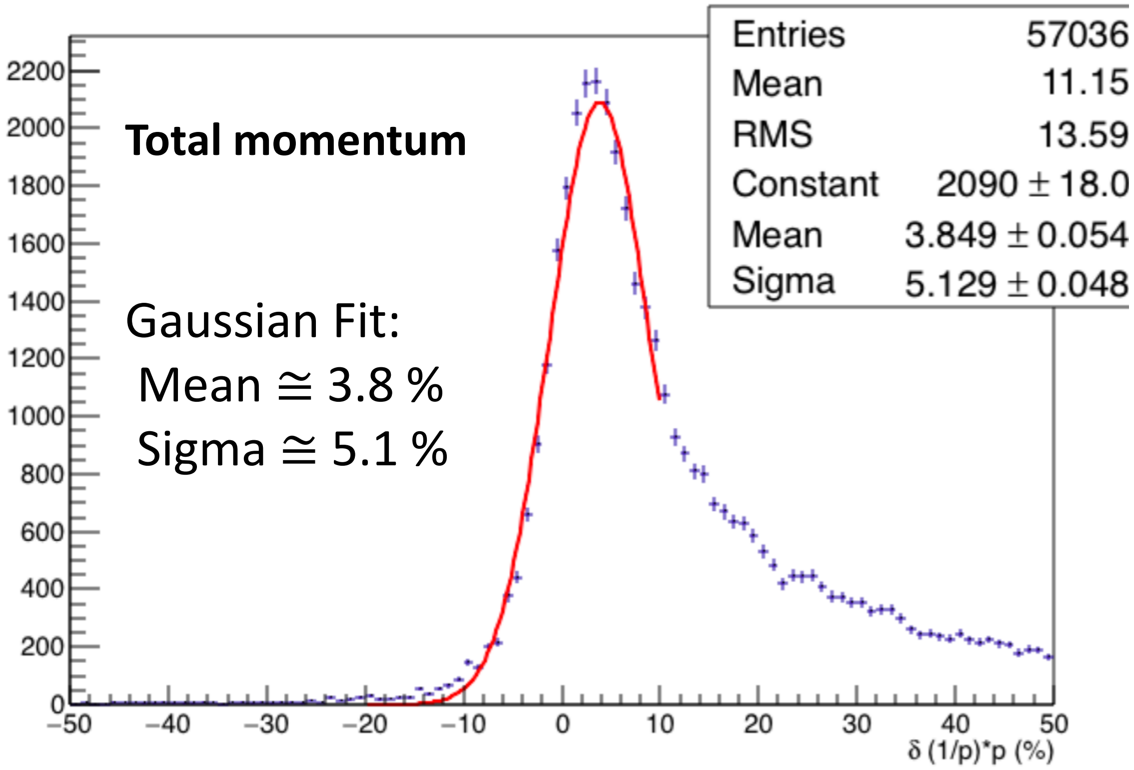
Good resolution on dip angle ~1.7 mrad

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 (e.g. Kalman filter)





Wrong sign 1.3%

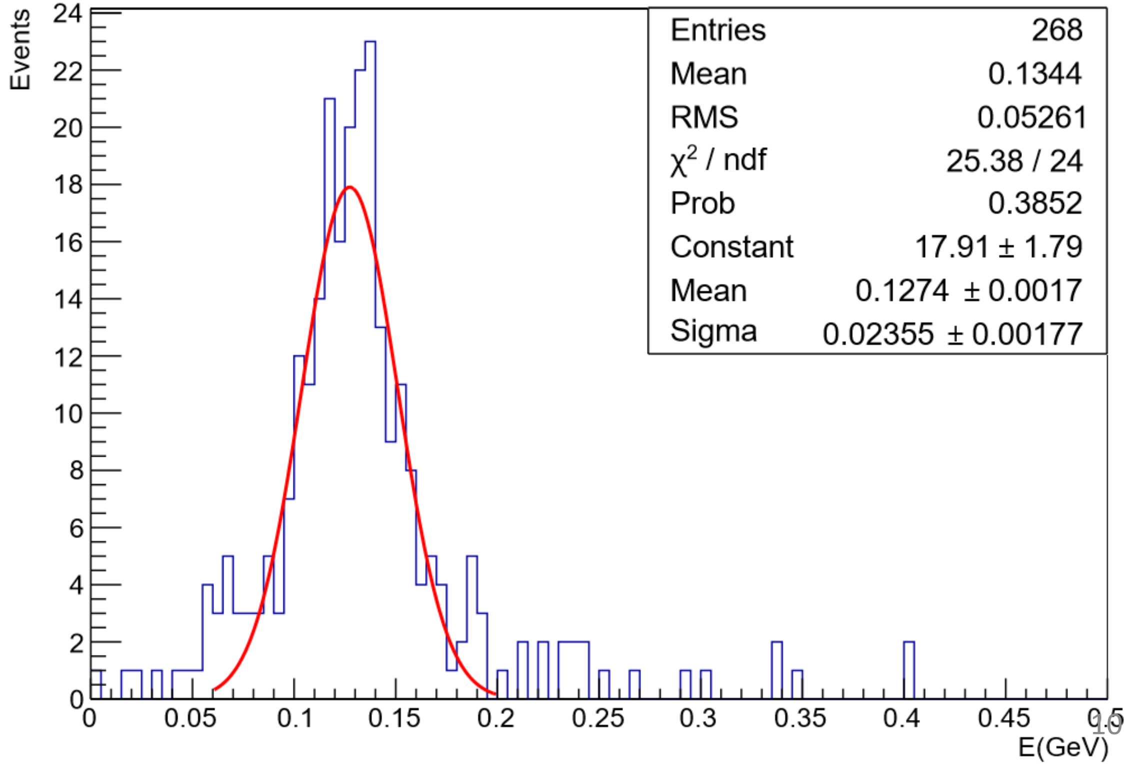
Results- π^0

Reconstruction from EM CALO clusters
Segmentation 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).

Reconstructed CC sample

Number π^0	number of events
0	2556
1	1041
2	307
3	67
4	21
≥ 5	8
Total	4000

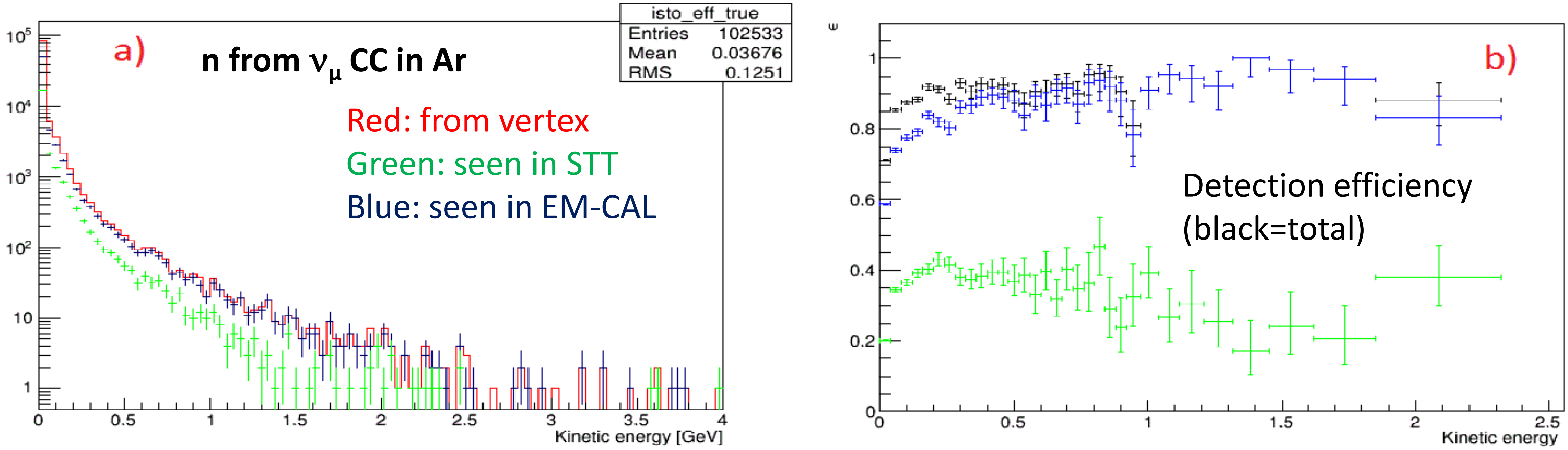
2 π^0 sample: π^0 invariant mass,
Considering only 4-cluster events



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)

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

Calo hit: E_{dep} > 100 keV

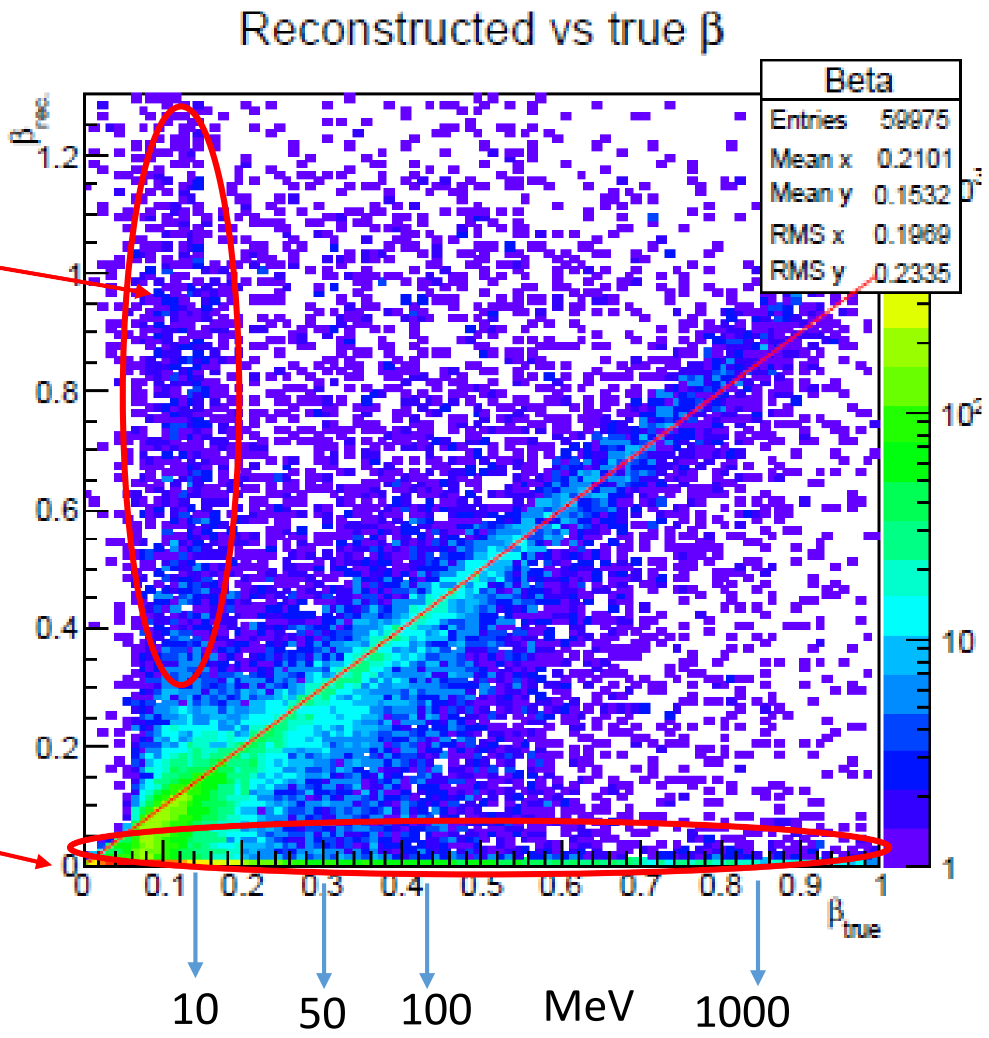
STT hit: E_{dep} > 250 keV

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) or detected hit far from first interaction (elastic scattering)

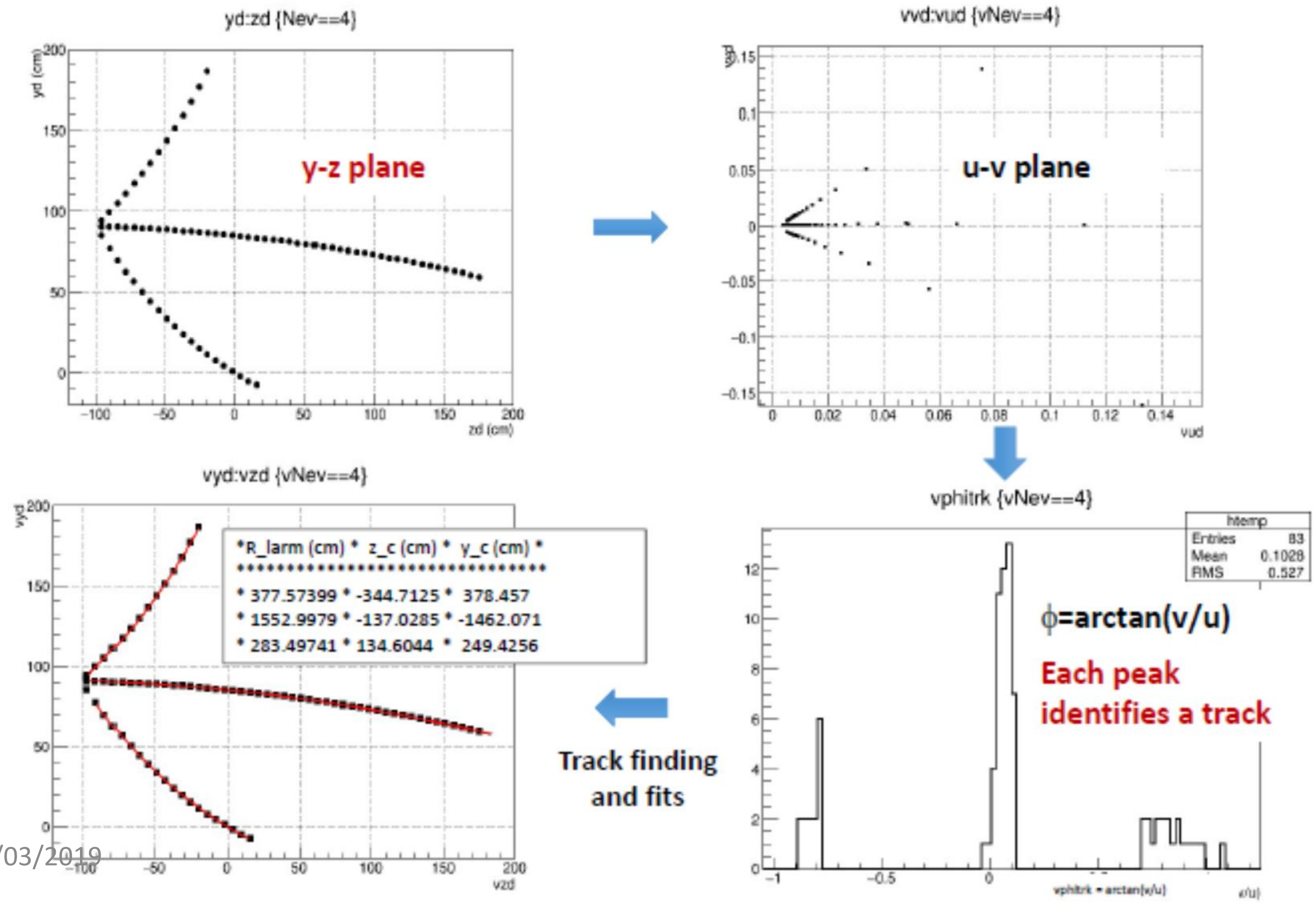
Many scatterings not detected. Path much longer than straight line



On full spectrum:
the neutron kinetic energy can be reconstructed with about 30% precision for about 28% of the detected neutrons.

Results: vertex and track finding

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



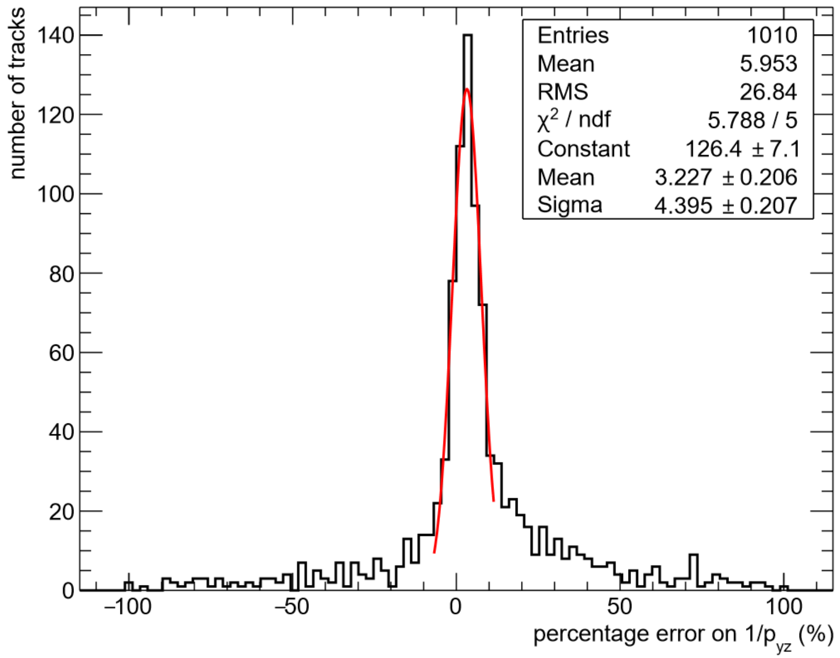
Two-step method: first rough vertex finding, allows for coordinate transform

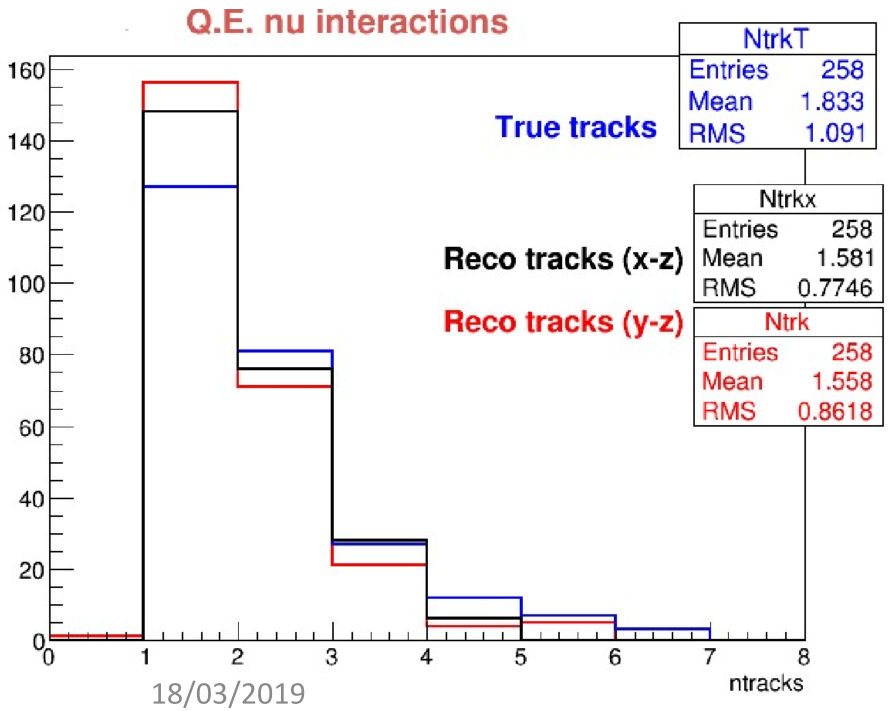
Peaks in ϕ correspond to tracks

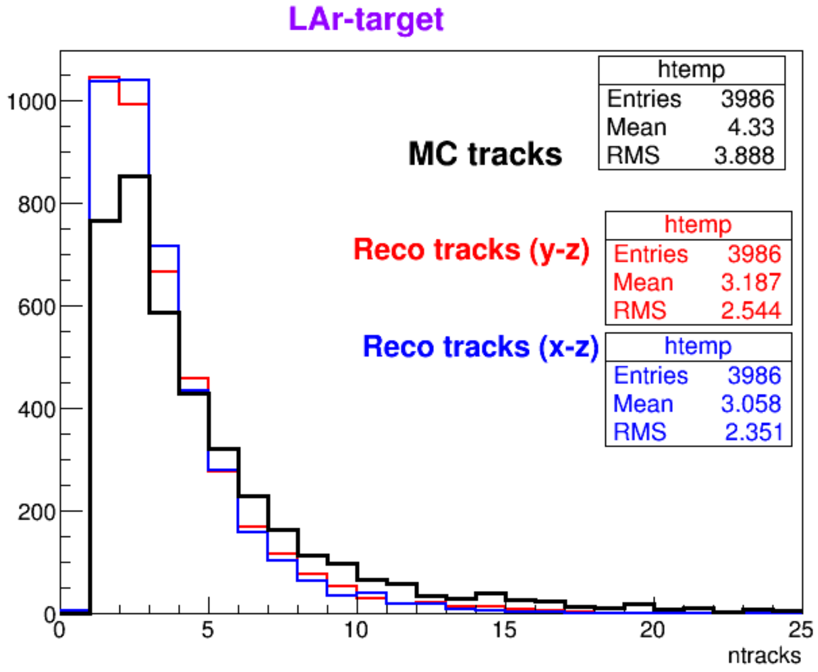
Second vertex finding from track intersection

Results: vertex and track finding

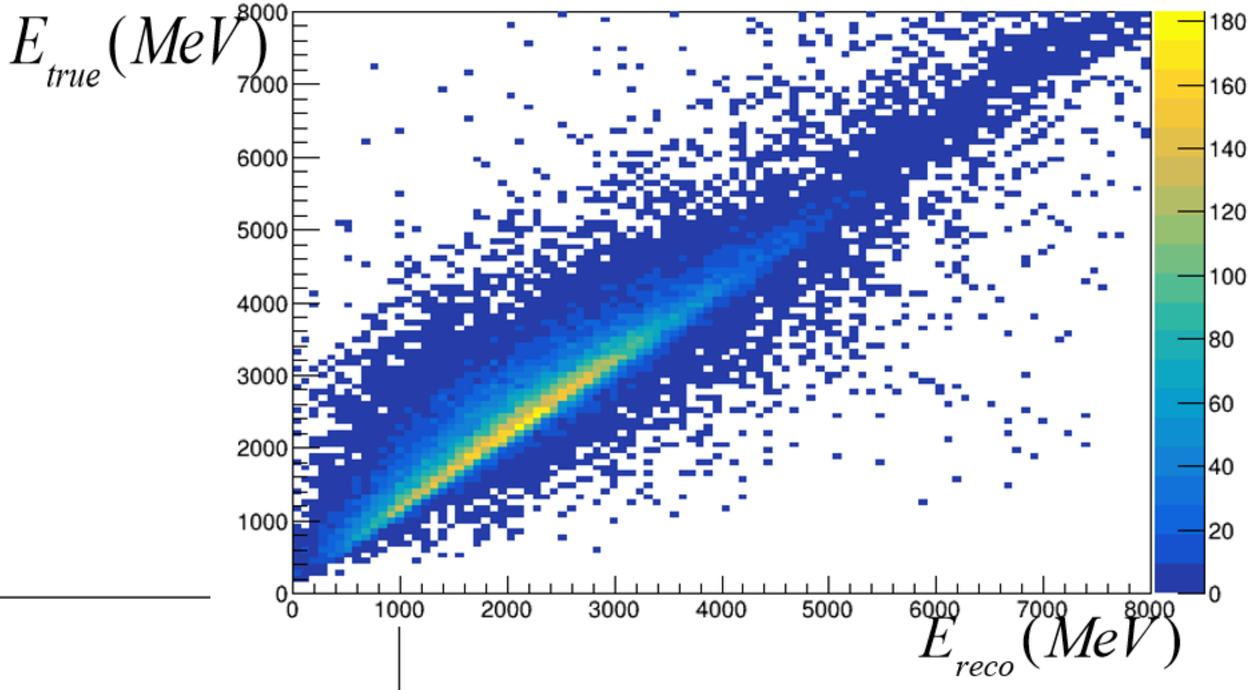
- First results
- ν_μ CC sample
- Bottom: track multiplicity in QE and all events

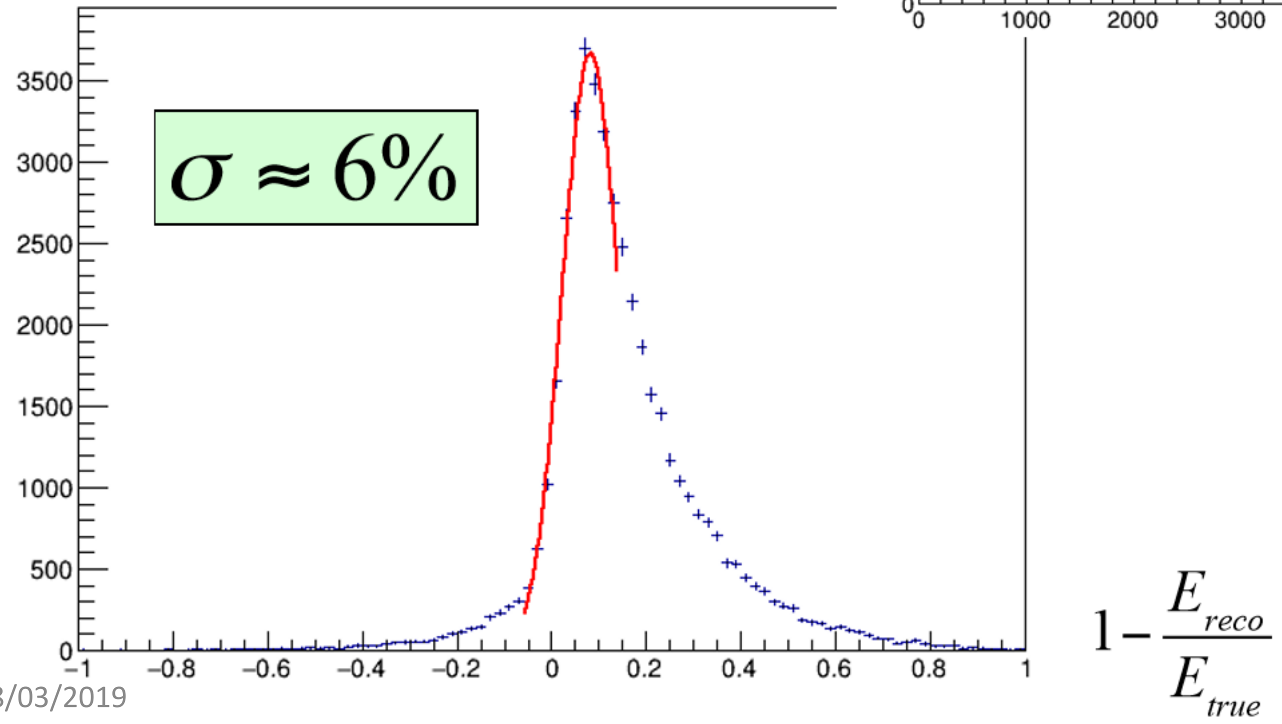






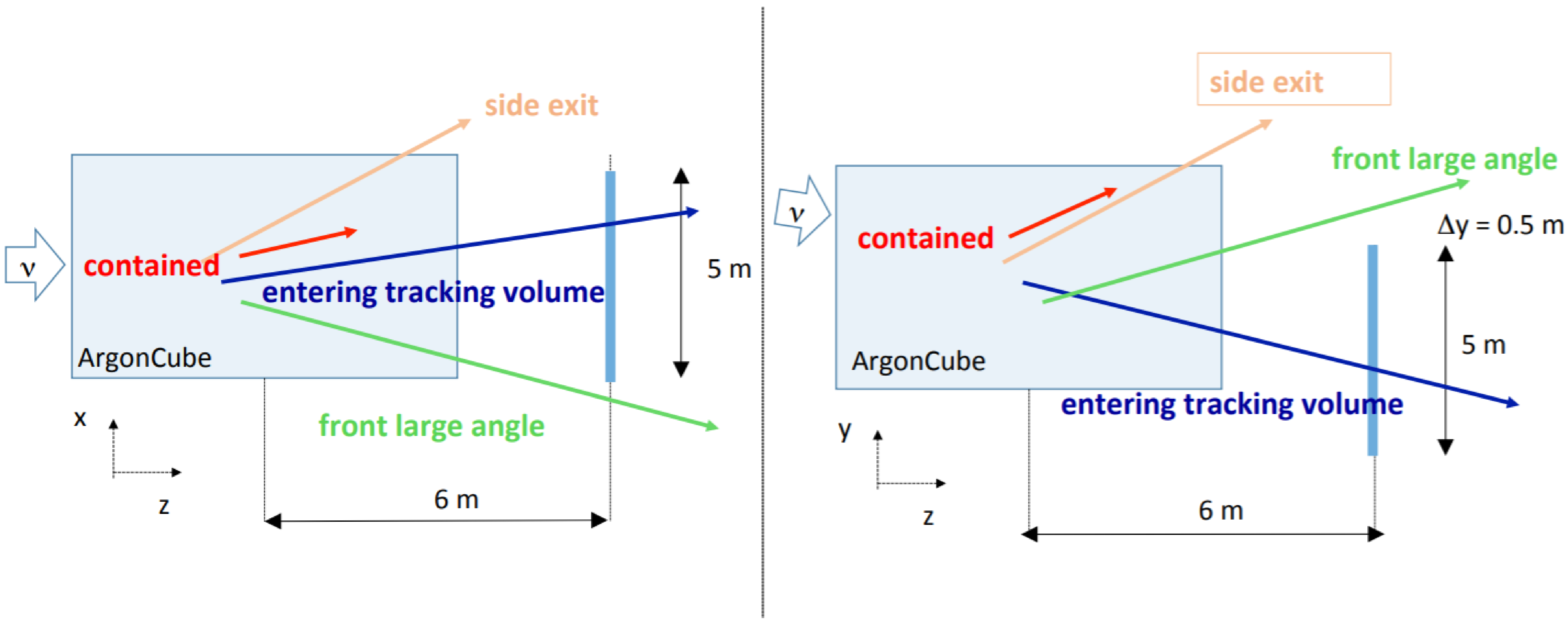
Neutrinos





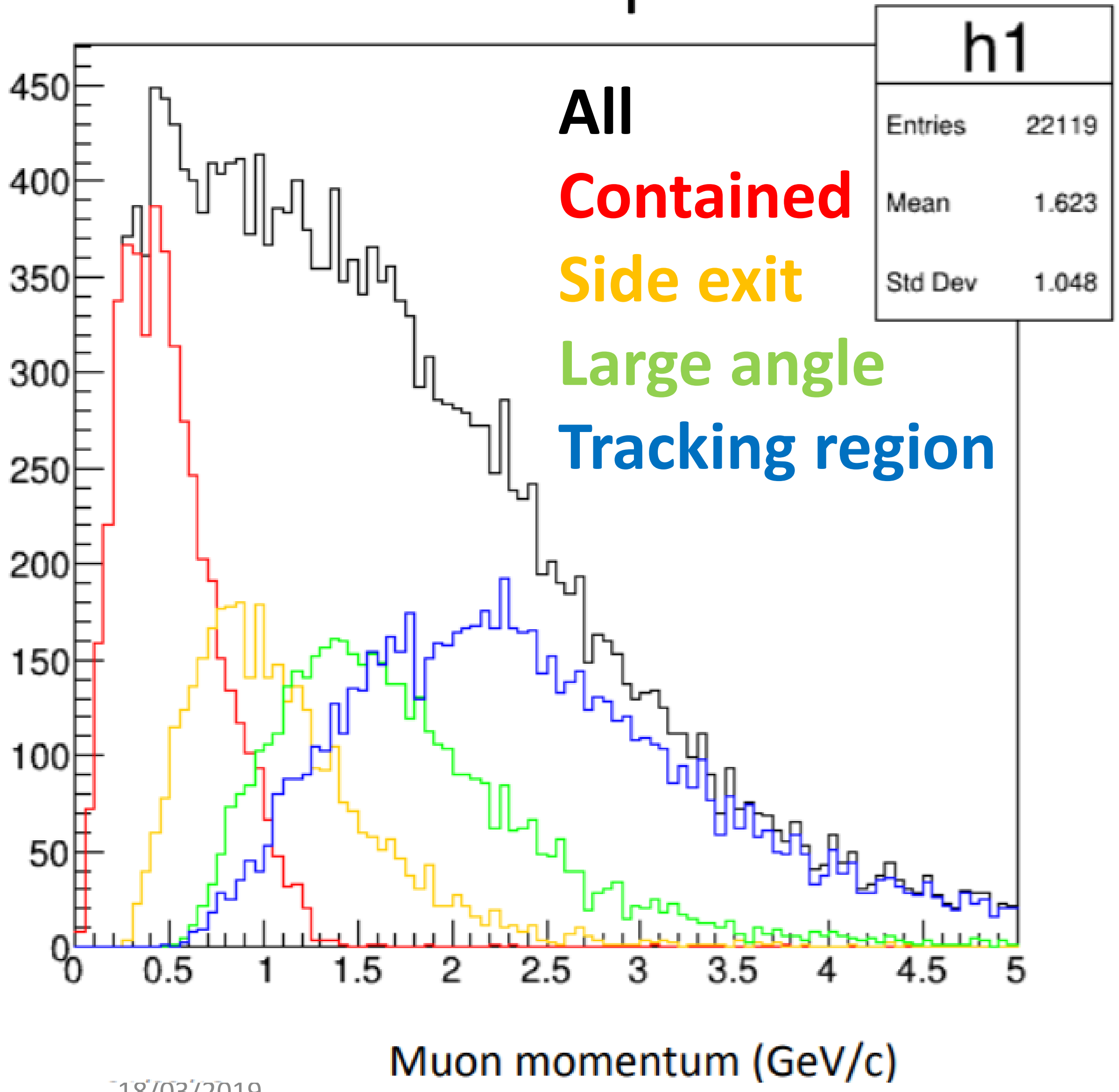
From full GENIE + GEANT4 simu + MC truth guidance

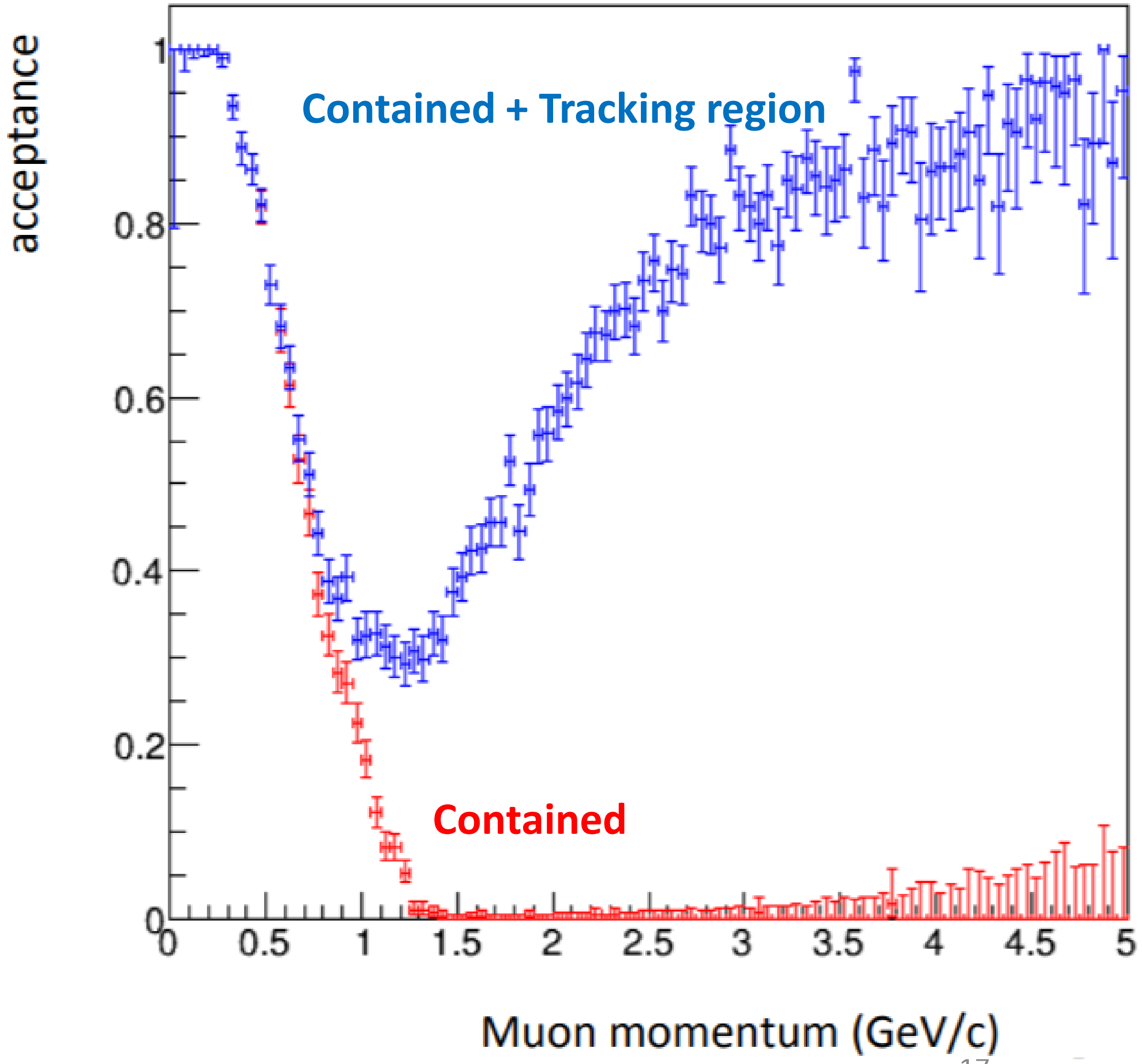
Muon Acceptance Study



Destiny of muon produced in AC fiducial volume

Muon acceptance

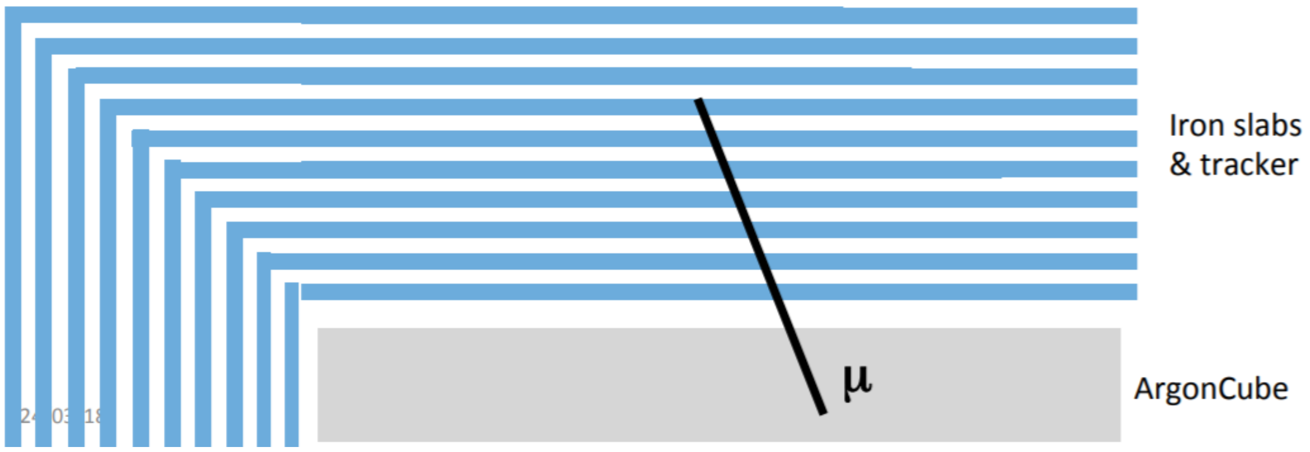




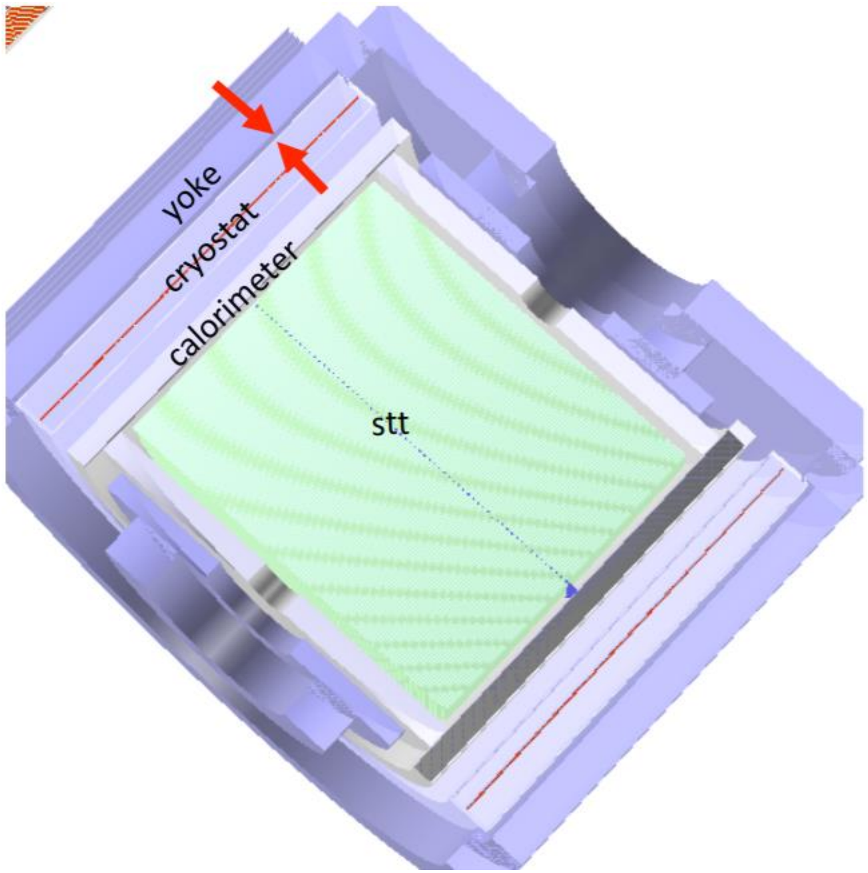
A very crude muon ranger

Measure kinetic energy of escaping muons through range

- 10 iron slabs (10cm thick) around AC with interleaved trackers (5cm) to connect the tracks emerging from AC

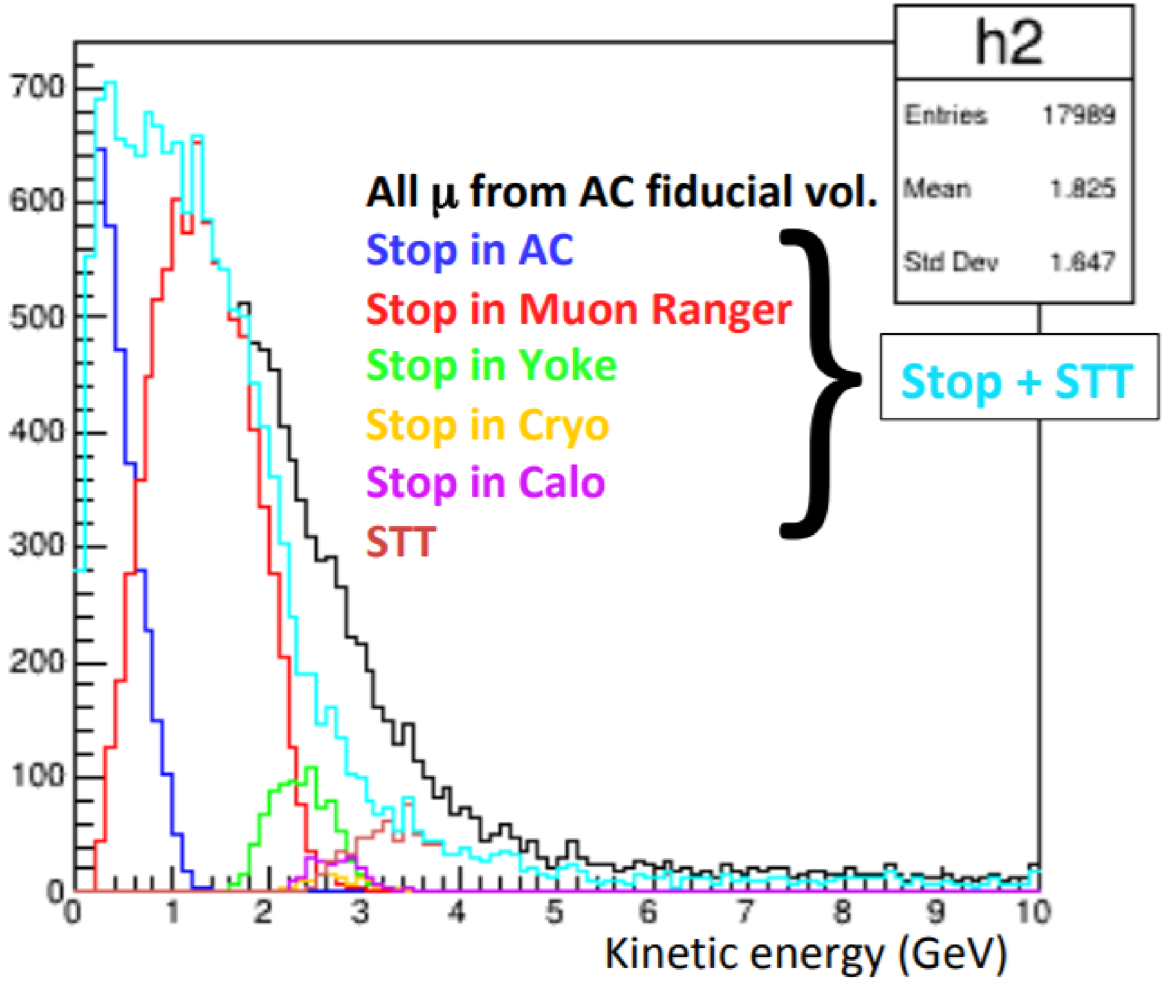


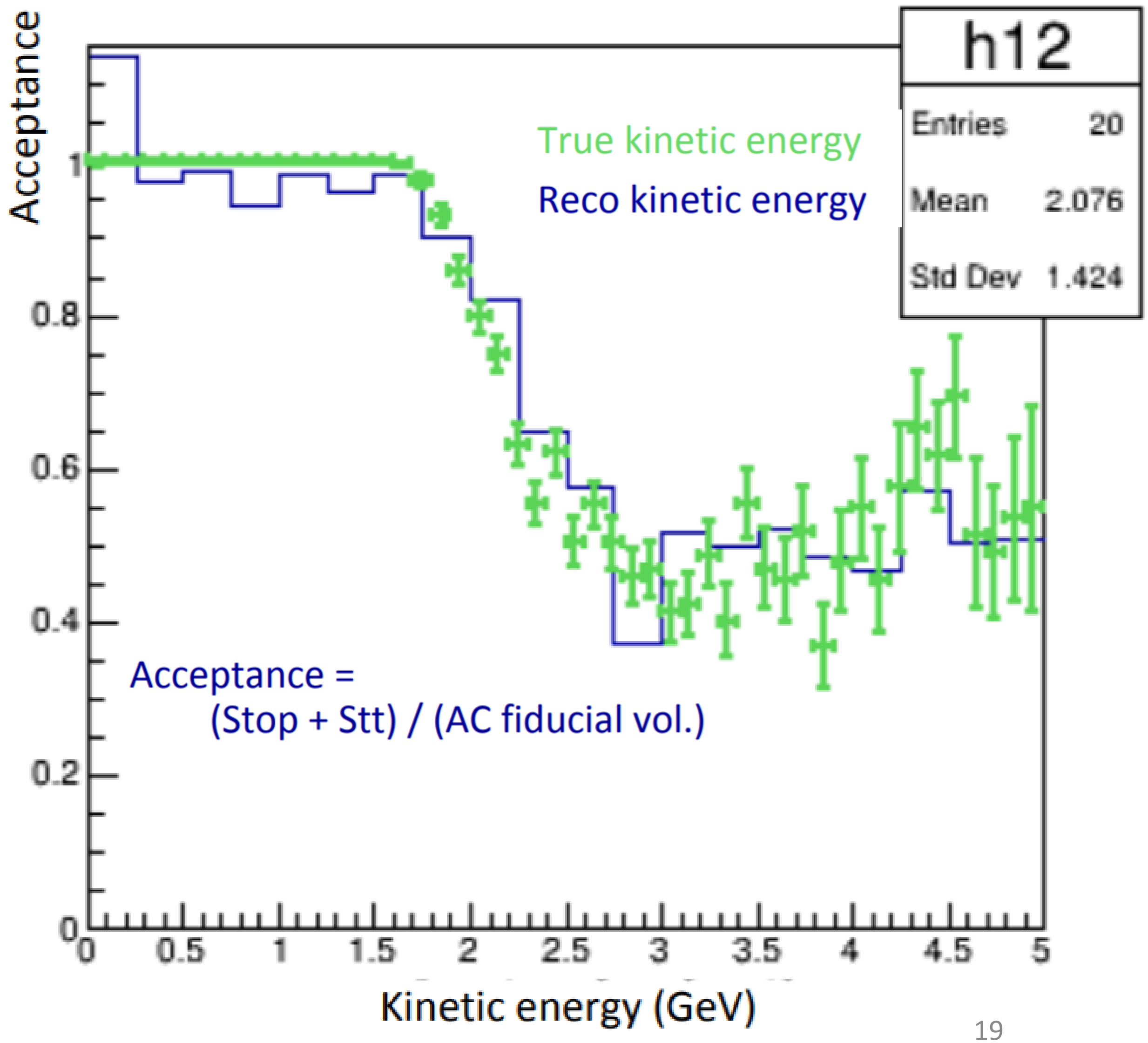
- Additional tracker in the space between yoke and cryostat



Acceptance

Overall muon energy resolution ~ **5.5 %**





Next steps

- Improve details of singe particle reconstruction
- Finalize full event reconstruction
- Apply to random events, check identification and reconstruction
- Optimize nuclear target configurations

- Apply to / optimize PRISM-like data taking
- Full background evaluation

- For the moment, apply the single-particle quantities to physics analysis (in the following).
- Details in the note: **DUNE-doc-13262**

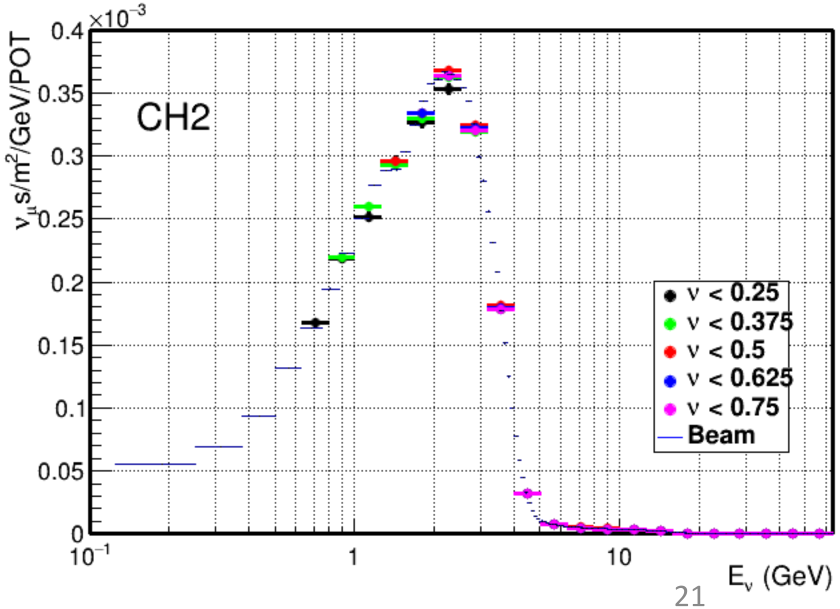
Performances (examples of)

- Good resolution on tracks
  ➔good efficiency and purity for the kinematic selection of interactions on H

Process	R_{mH} and $p^H_{T\perp}$ cuts		$\ln \lambda^H$ cut	
	Efficiency	Purity	Efficiency	Purity
$\nu_\mu p \to \mu^- p \pi^+$	93%	86%	90%	92%
$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	89%	84%	90%	88%
$\bar{\nu}_\mu p \to \mu^+ n$	95%	80%		
$\nu_\mu p$ CC inclusive	83%	73%		

- Good track and neutron efficiency ➔flux shape with low-ν method for QE and RES events on H. Total statistics (5 years) expected is about 2.4 10^6 for RES and 800 000 for QE

- Low-ν method also on global STT: here deconvolution of MC smeared data sample to recover input neutrino flux from interactions in STT



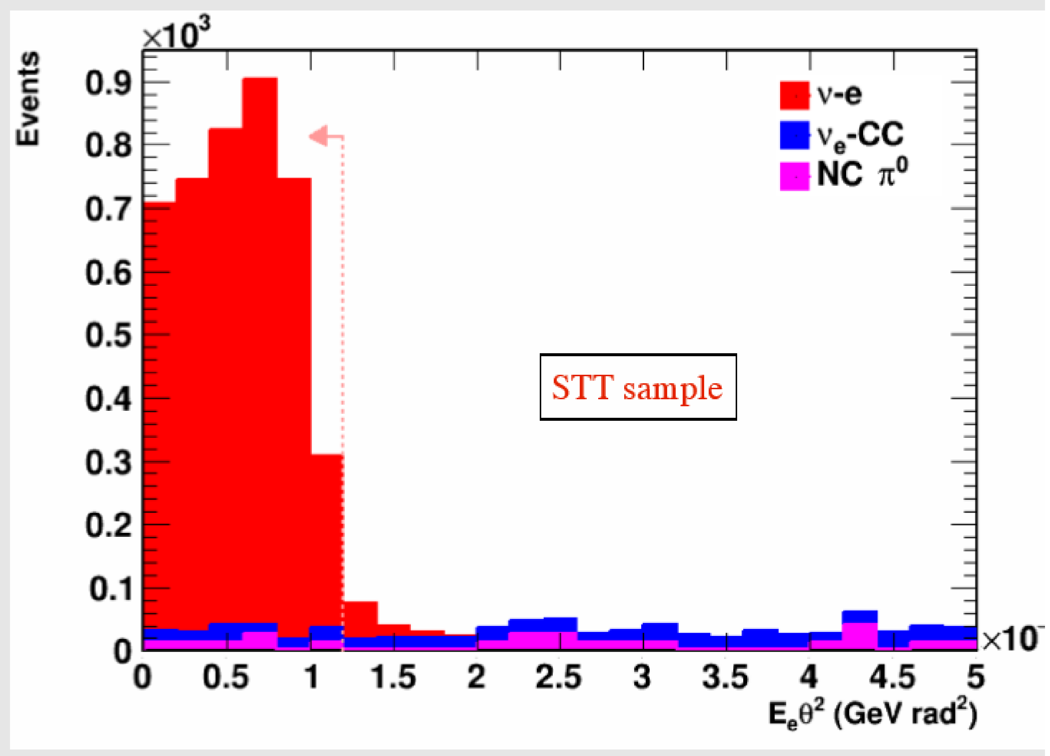
- Almost identical performances for events in the LAr meniscus and in the STT ➔ direct comparison of events on Ar and H (or C) for nuclear effects assessment

- Determination of parent $\pi^{\pm}, K^{\pm}, K^0$ distributions from measured $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ spectra (extrapolation to FD)

Performances (examples of)

- Charge separation and electron identification→ ν_e / ν_μ and all other species with high statistics (80000 $\bar{\nu}_e$ events in FHC mode 5 years)

- Very good angular resolution on electron tracks→ flux determination from scattering on electrons (rate and shape): The selection efficiency is about 84% with a total background of 5%, composed of QE interactions without reconstructed proton (3%) and NC π^0 interactions (2%). Can be combined with data from external Lar. STT provides smaller statistics but better systematics



PRISM

- The whole detector can be moved on rails, for a PRISM-like exposure.

- Event rates here for ½ year, in the LAr meniscus, FHC
- ν_μ CC : 3.1 10^4 at the largest angle in 5+5 years
- Factor 5 more in STT

Equal POTs at each position						
Offset	10^{20} POT	CCInc ν_μ	NCInc	CCInc $\bar{\nu}_\mu$	CCInc ν_e	El. ν_μ-e
0 m	0.786	$9.4 \cdot 10^4$	$3.4 \cdot 10^4$	$2.9 \cdot 10^3$	$1.1 \cdot 10^3$	8.5
5 m	0.786	$7.3 \cdot 10^4$	$2.6 \cdot 10^4$	$2.5 \cdot 10^3$	$9.3 \cdot 10^2$	6.3
10 m	0.786	$3.2 \cdot 10^4$	$1.2 \cdot 10^4$	$1.5 \cdot 10^3$	$6.1 \cdot 10^2$	2.7
15 m	0.786	$1.4 \cdot 10^4$	$5.5 \cdot 10^3$	$8.0 \cdot 10^2$	$3.9 \cdot 10^2$	1.3
20 m	0.786	$7.9 \cdot 10^3$	$3.2 \cdot 10^3$	$5.2 \cdot 10^2$	$2.5 \cdot 10^2$	0.7
25 m	0.786	$4.8 \cdot 10^3$	$2.0 \cdot 10^3$	$3.4 \cdot 10^2$	$1.7 \cdot 10^2$	0.4
30 m	0.786	$3.1 \cdot 10^3$	$1.3 \cdot 10^3$	$2.5 \cdot 10^2$	$1.2 \cdot 10^2$	0.3
All	5.500	$2.3 \cdot 10^5$	$8.4 \cdot 10^4$	$8.8 \cdot 10^3$	$3.6 \cdot 10^3$	20.2

Half POTs on-axis						
Offset	10^{20} POT	CCInc ν_μ	NCInc	CCInc $\bar{\nu}_\mu$	CCInc ν_e	El. ν_μ-e
0 m	2.750	$3.3 \cdot 10^5$	$1.2 \cdot 10^5$	$1.0 \cdot 10^4$	$4.0 \cdot 10^3$	29.6
5 m	0.458	$4.2 \cdot 10^4$	$1.5 \cdot 10^4$	$1.5 \cdot 10^3$	$5.4 \cdot 10^2$	3.7
10 m	0.458	$1.9 \cdot 10^4$	$6.8 \cdot 10^3$	$9.0 \cdot 10^2$	$3.6 \cdot 10^2$	1.6
15 m	0.458	$8.5 \cdot 10^3$	$3.2 \cdot 10^3$	$4.7 \cdot 10^2$	$2.3 \cdot 10^2$	0.7
20 m	0.458	$4.6 \cdot 10^3$	$1.9 \cdot 10^3$	$3.0 \cdot 10^2$	$1.5 \cdot 10^2$	0.4
25 m	0.458	$2.8 \cdot 10^3$	$1.2 \cdot 10^3$	$2.0 \cdot 10^2$	$9.7 \cdot 10^1$	0.3
30 m	0.458	$1.8 \cdot 10^3$	$7.7 \cdot 10^2$	$1.4 \cdot 10^2$	$6.8 \cdot 10^1$	0.2
All	5.500	$4.1 \cdot 10^5$	$1.5 \cdot 10^5$	$1.3 \cdot 10^4$	$5.4 \cdot 10^3$	36.5

Conclusions [DUNE-doc-13262]

- Full simulations implemented
- Reconstruction tools partially ready
- Results confirm good performances of this composite compact multipurpose detector
- Significantly enhancement of the physics performance of ND complex
- Either on-axis or
- Easily movable in off-axis positions
- Precision measurements and new physics search, see ESG input: https://indico.cern.ch/event/765096/contributions/3295805/

ArgonCube Fiducial Volume