



*Recent developments in simulation
and analysis tools for liquid argon
detectors*

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ETHZ

for the WA105 collaboration

Groupement de Recherche Neutrinos, Clermont-Ferrand, June 2015

Software for LAr-TPC Dual Phase Prototypes @ CERN

WA105

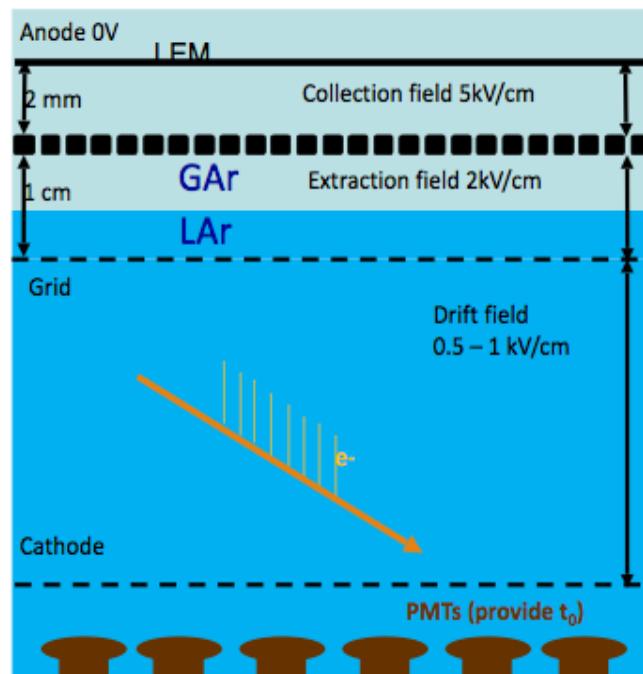
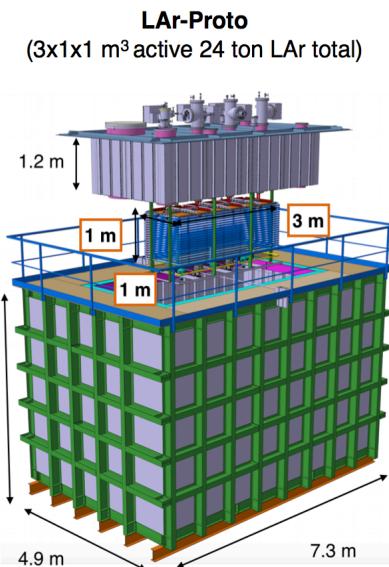
WA105-DEMO : Experimental validation of physics sensitivity of large LAr-dual phase-TPC

Software tools for:

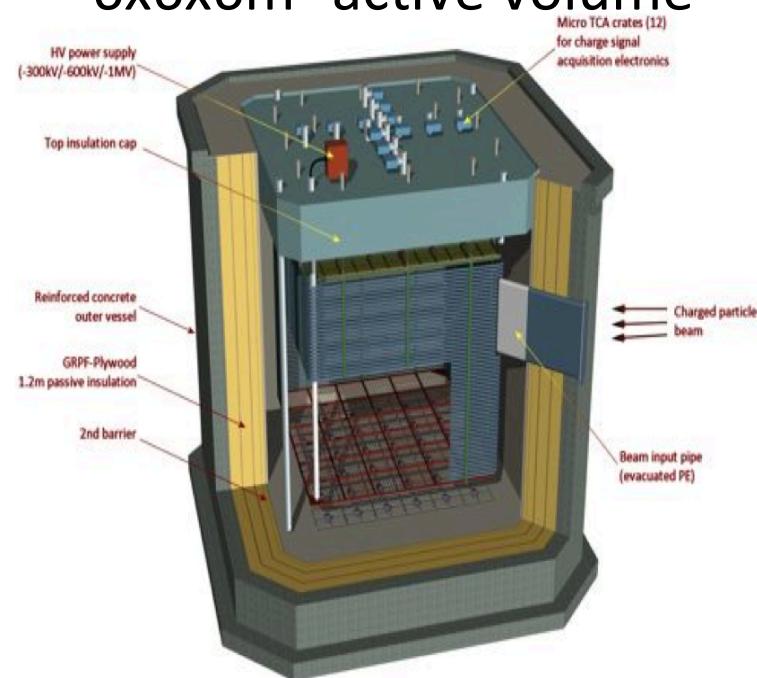
- Full description of detector response
- Feedback for detector design strategy
- Optimize detector raw information extraction
- Development of automatic physics event reconstruction

...

Deal with issue related to surface operation
Exploit opportunities related to surface operation



WA105 - Demonstrator
6x6x6m³ active volume



WA105 Software Task Force

French Contribution



IN2P3

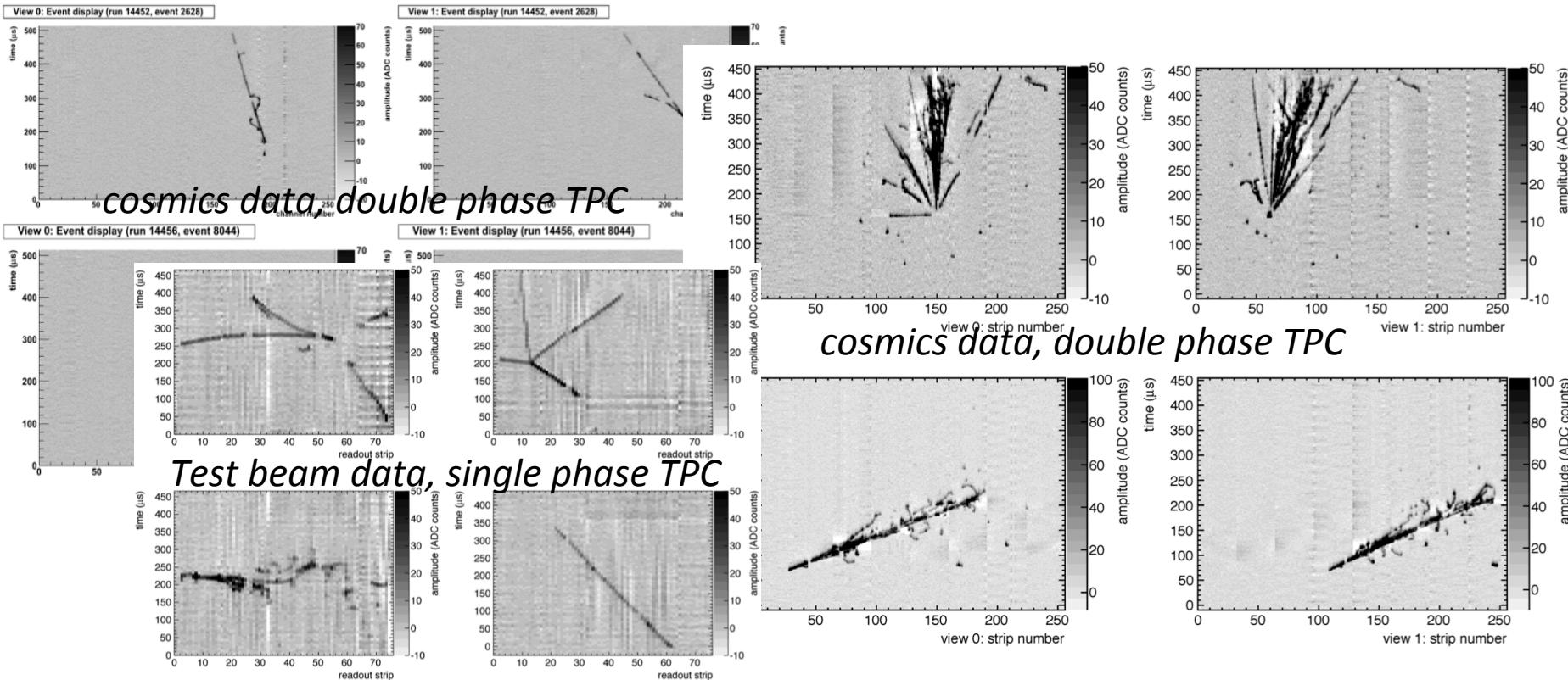
INSTITUT NATIONAL DE PHYSIQUE NUCLÉAIRE
ET DE PHYSIQUE DES PARTICULES

Software for LAr-TPC based detectors

WA105

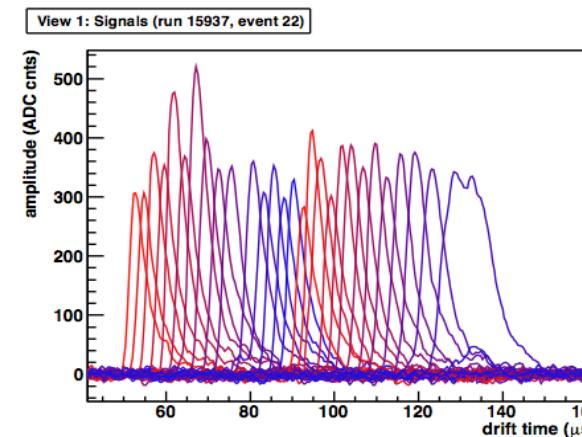
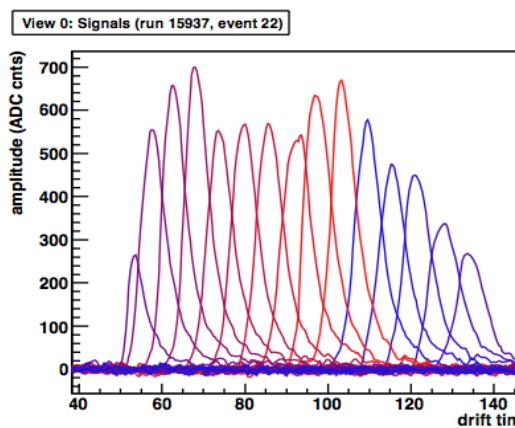
Status and ongoing activities

- ✓ Benefits from continuous development over several R&D's prior to WA105
 - Optimization of hit level event reconstruction of dual-phase LAr-TPC
- ✓ Extended functionality for field non-uniformity simulation
- ✓ Complemented with package for light production and read-out simulation
- ✓ Interfaced to higher level reconstruction algorithms

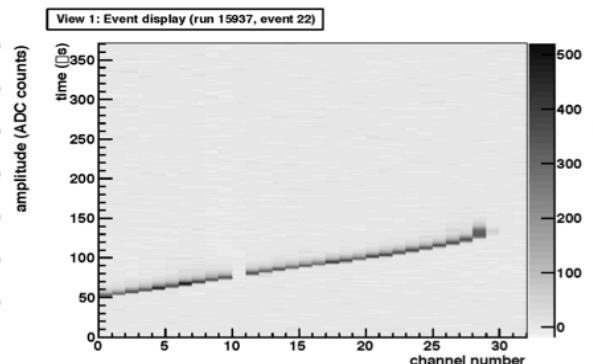
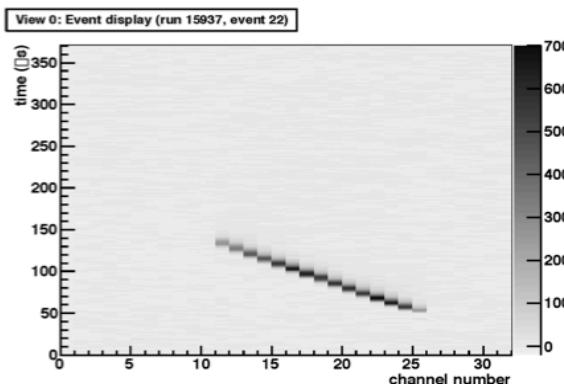


Double-Phase TPC events

- Nominal gain ≈ 20 (10 each view): S/N > 30 for mip
 - ✓ Enough charge to be shared among two collection views
 - ✓ Lower energy threshold: keV
 - ✓ Smaller pitch: < 3mm
 - ✓ Longer drift: compensation for charge attenuation/diffusion



Real Data - Cosmics event. 3L setup

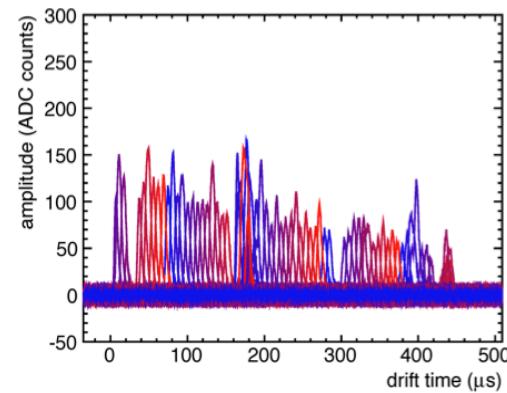
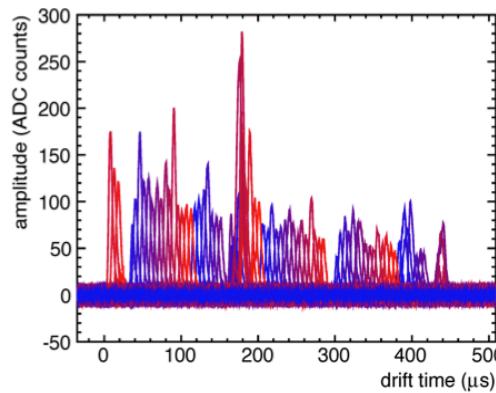


Charge Signal Simulation

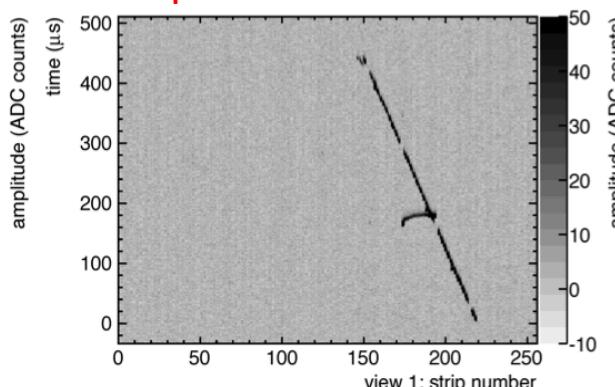
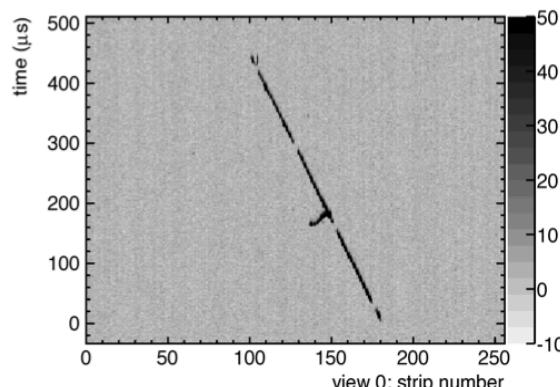
- Charge production:
 - ✓ Birks's law with k parameter tuned to reproduce the data
- Drift and charge losses:
 - ✓ Drift velocity parameterization to data, finite electron lifetime applied
- Digitization:
 - ✓ Known preamplifier response function
 - ✓ Noise

- ✓ MC μ - in the 200L DLAr

- ✓ Waveform generated using the peramp. response and Gaussian noise with 3 ADC counts RMS



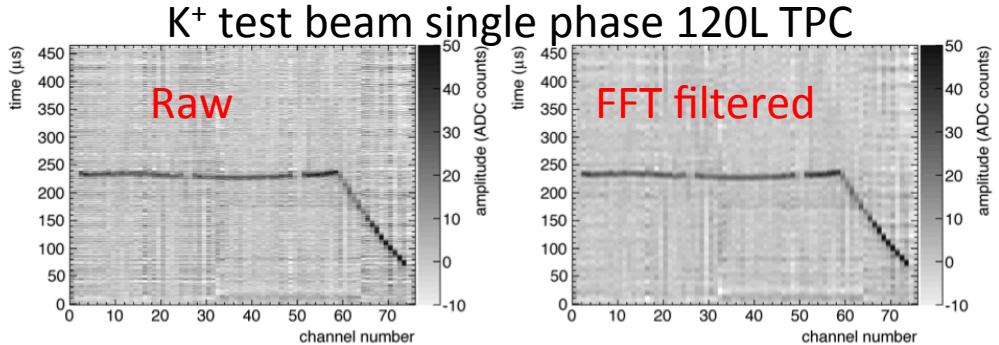
MC muons. Double-phase TPC



Hit Reconstruction

✓ Waveform processing:

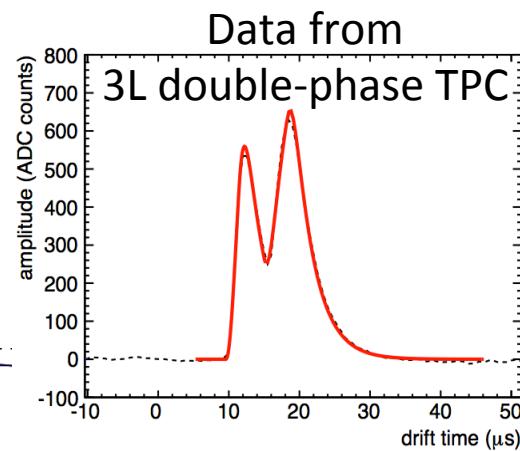
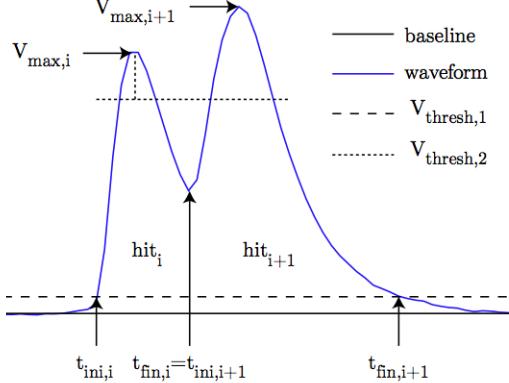
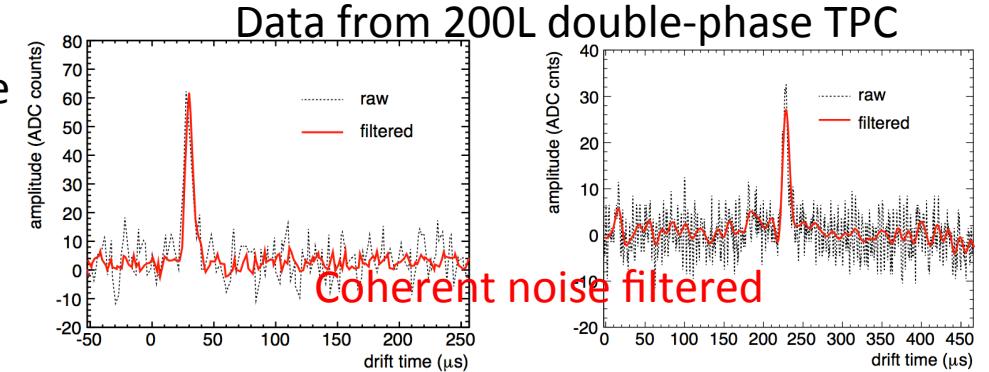
- Noise Reduction
 - FFT
 - Coherent Noise Reduction
- Baseline subtraction
 - pedestal from pre-trigger sample



✓ Hit finding:

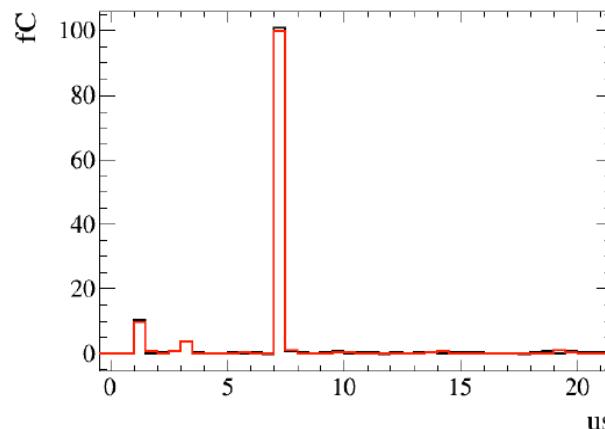
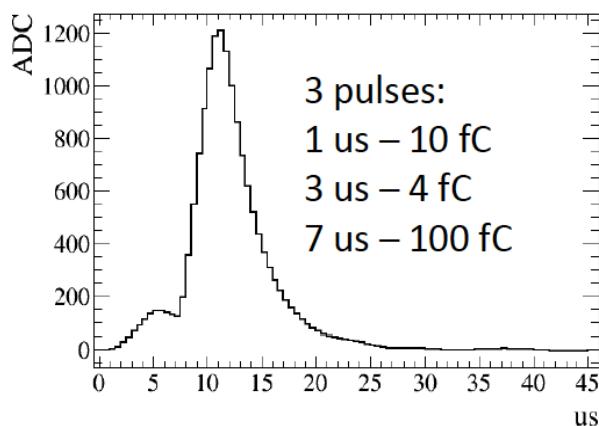
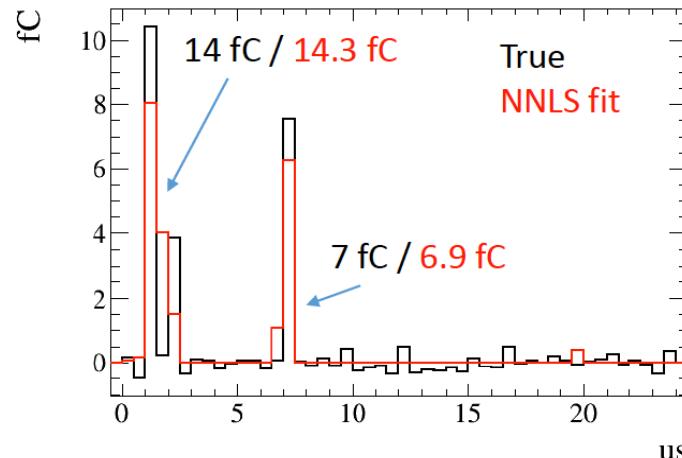
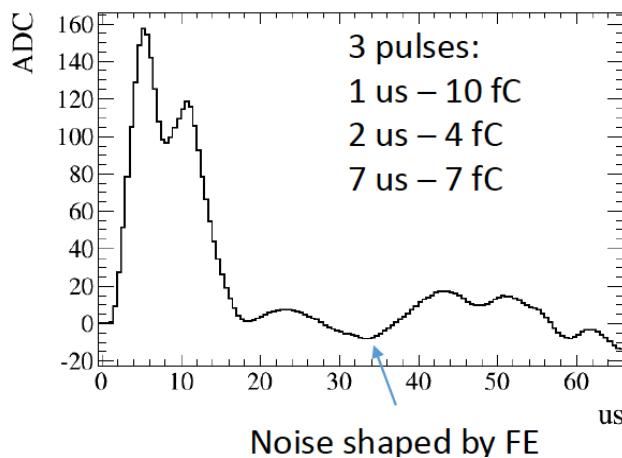
- Identification

Fast electron drift in gas pre-amp shaping time able to resolve hits within few μs
- Reconstruction
 - Fit with pre-amp resp. function
 - Get time and charge



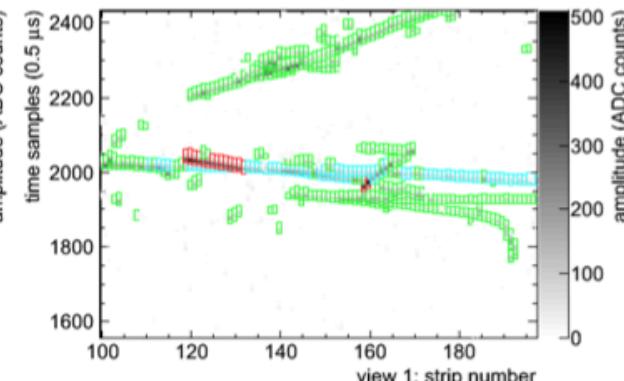
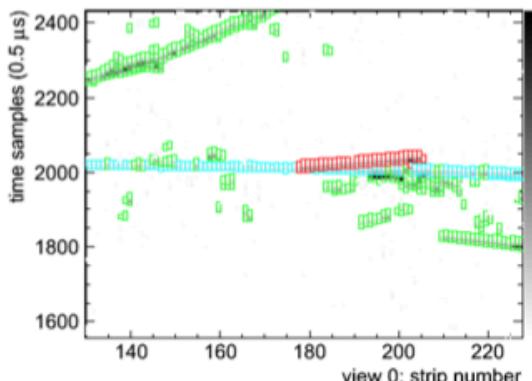
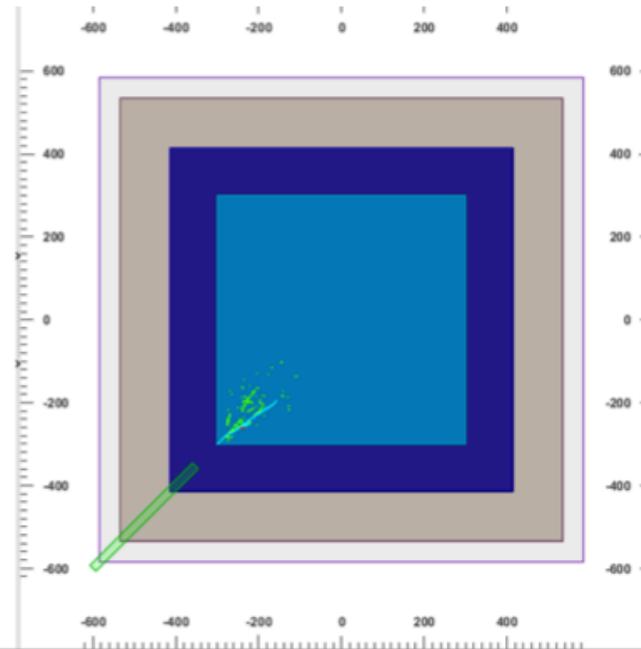
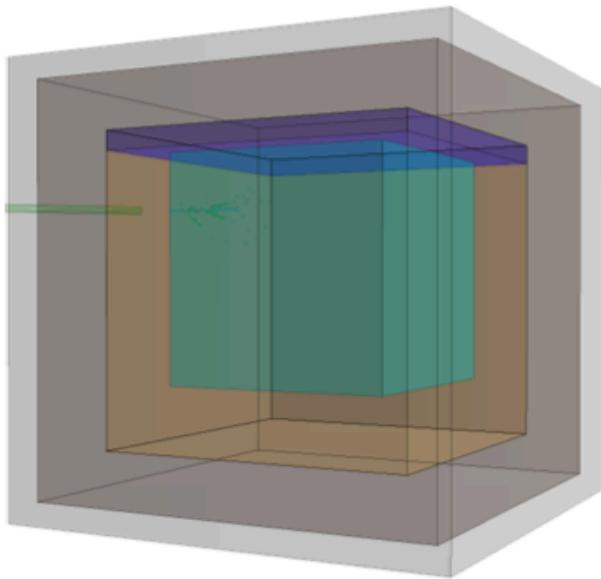
Hit Reconstruction

- ✓ Improvement of true charge deposition extraction from measured waveform
 - NNLS Deconvolution in Time Domain
 - Better signal/noise separation
 - Separation of charge deposition down to by 2 μ s



Injected random noise before pre-amp (RMS: 0.25 fC)

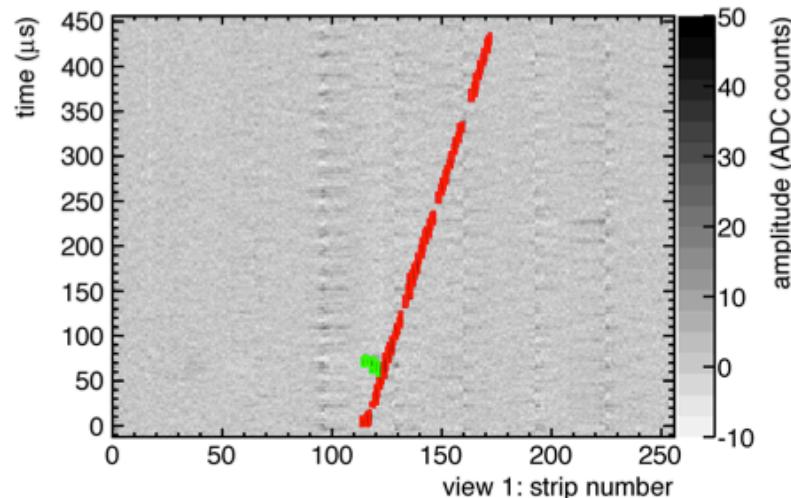
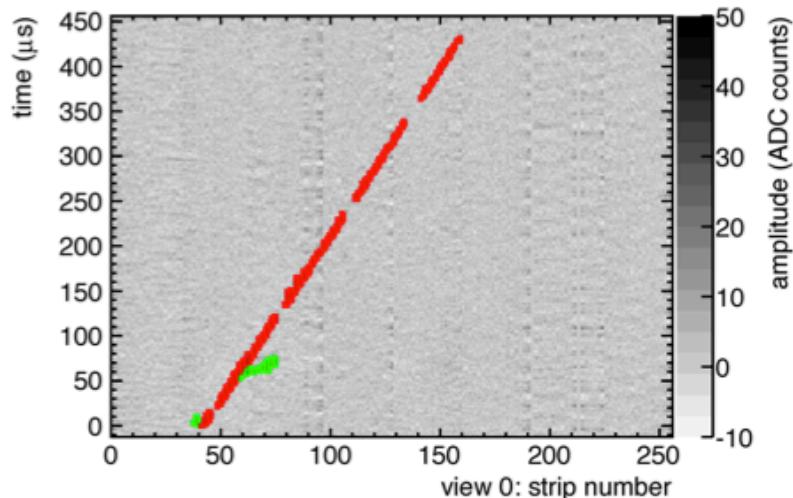
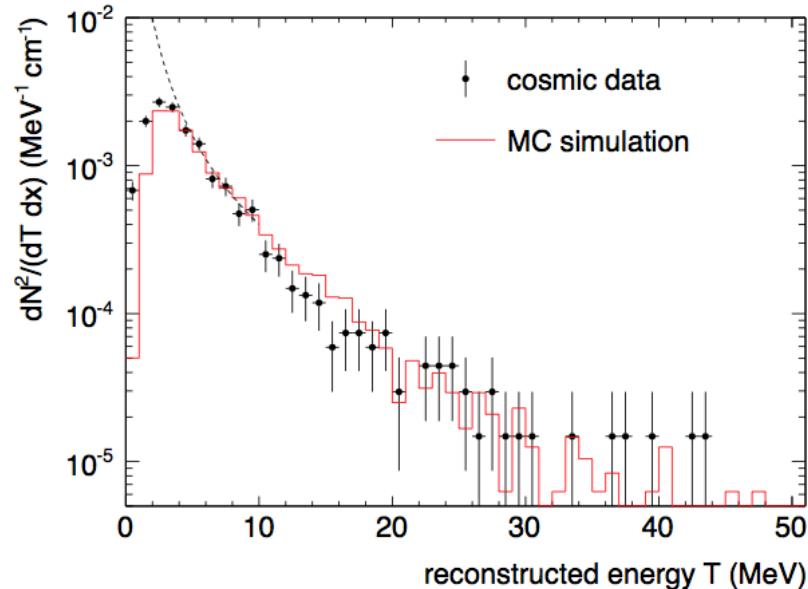
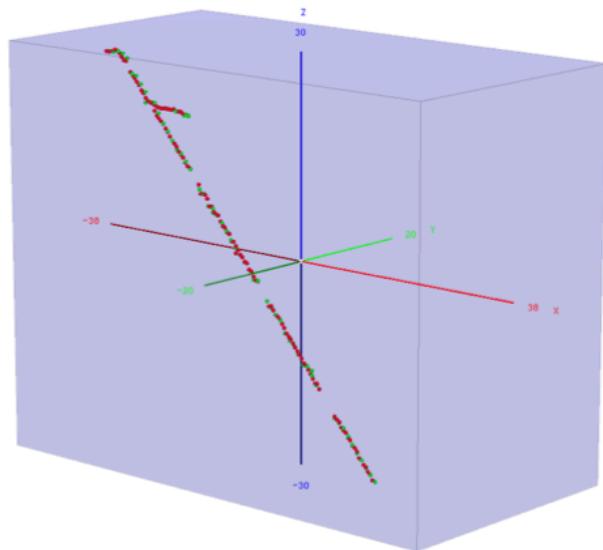
MC Hit Reconstruction for 3 GeV/c π^+ in DLaR prototype



Color is truth info from MC:
pions, electrons/positrons, protons, muons

3D Track Reconstruction, δ -rays

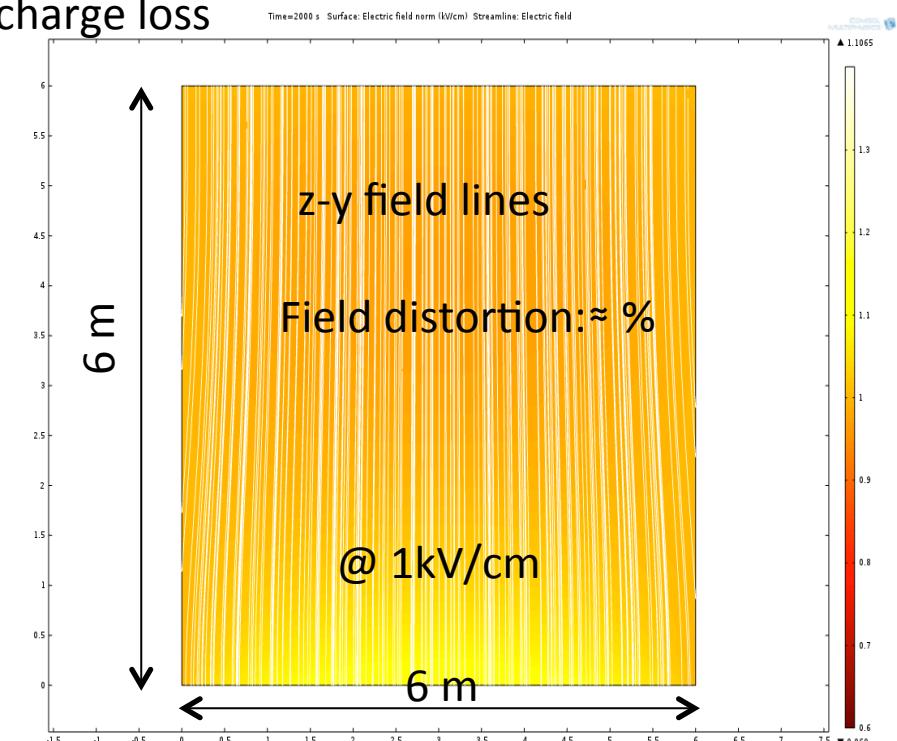
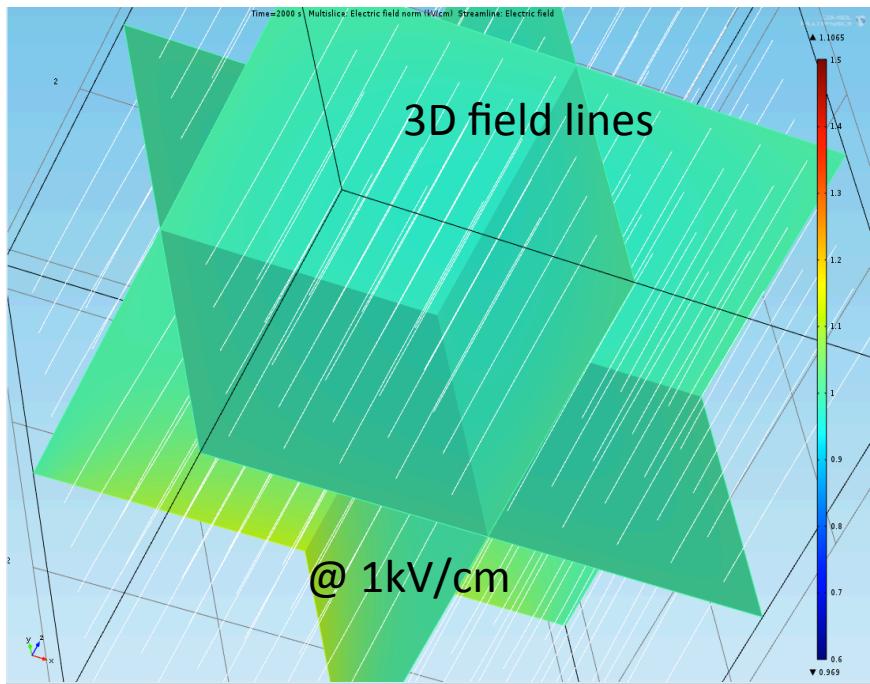
- Measured with cosmics on 200L double-phase TPC
- Efficient above 4 MeV



Simulation of space charge density

WA105 detector setup

- 3D Time Dependent Finite Element Analysis (COMSOL) approach
 - Electrostatic+Transport of Diluted Species
- Processes Ionization: 10 fC/cm^2 @ 200 Hz/m^2 cosmics
 Recombination: $\text{Ar}^+ - e$
 Attachment: $\text{O}_2 - e$
 Gas->Liquid Ar^+ backflow: 2%
- Not simulated: full convection motion, other charge loss



Time evolution of the charge density

Field: 1 kV/cm

$v_{ion} = 1 \text{ cm/s}$

$v_e = 2 \text{ mm}/\mu\text{s}$

$I = 10 \text{ fC/cm}@200\text{Hz}/\text{m}^2$

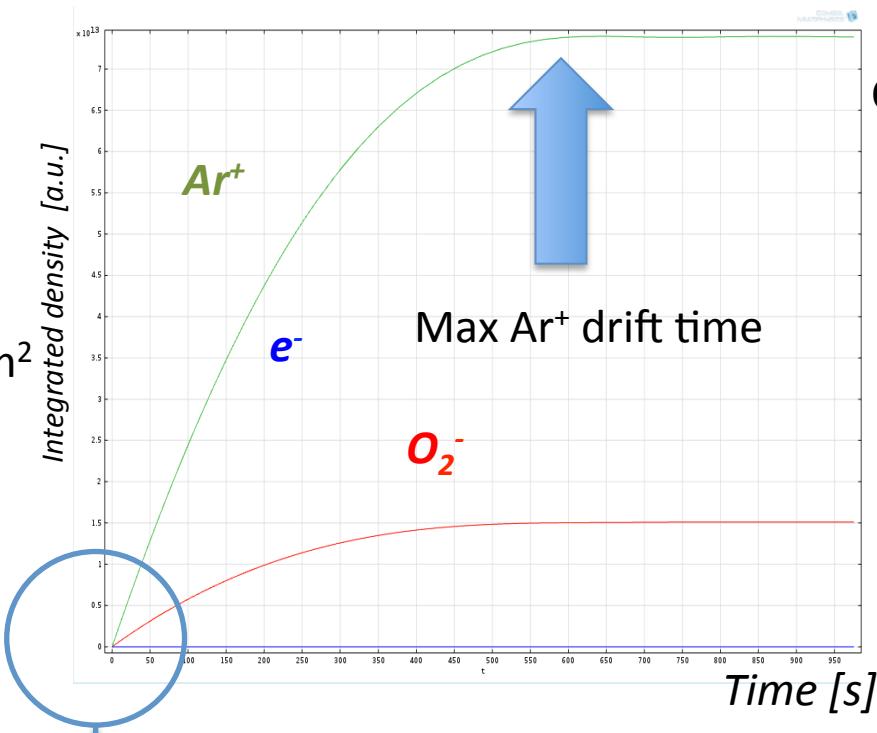
$R: 10^{-4} \text{ cm}^3/\text{s}$

$A: 1/5 \text{ ms}$

$B: dG/dI v_e$

G: electron gain in gas

$B \neq 0$ at GAr-LAr interface



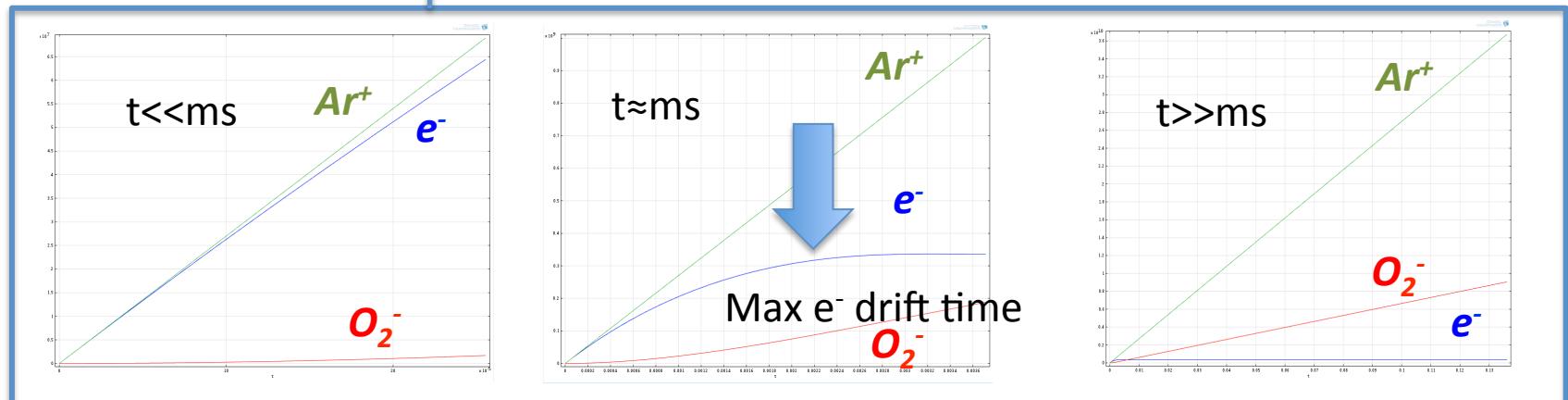
Converge to a stable solution with the timescale of the max ion drift time

$$\frac{d\rho_e}{dt} = I - R\rho_e\rho_{Ar^+} - A\rho_e$$

$$\frac{d\rho_{Ar^+}}{dt} = I - R\rho_e\rho_{Ar^+} + B\rho_e$$

$$\frac{d\rho_{O_2^-}}{dt} = A\rho_e$$

$$\frac{dv_i}{dt} = \mu_i E, i = e, Ar^+, O_2^-$$

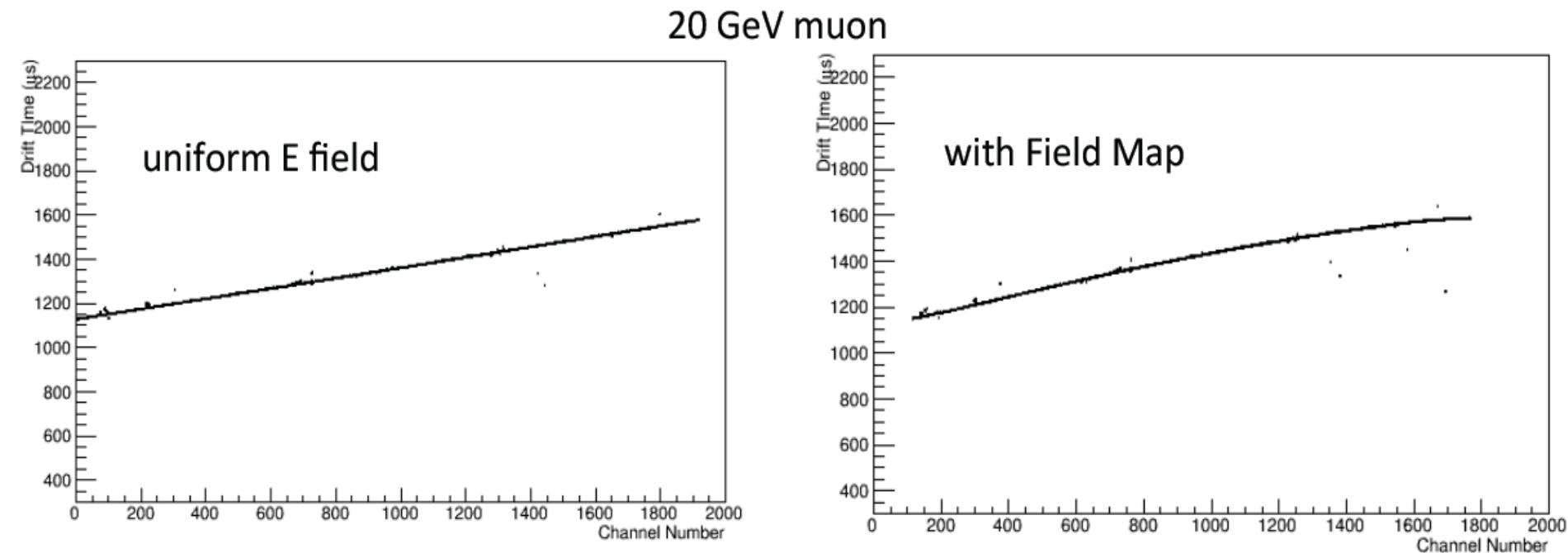


Impact of space charge density at surface operation

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Reconstruction with realistic electric field map

- Use cosmics reconstruction as calibration for monitoring:
LAr purity, field uniformity, LEM/PMT gain



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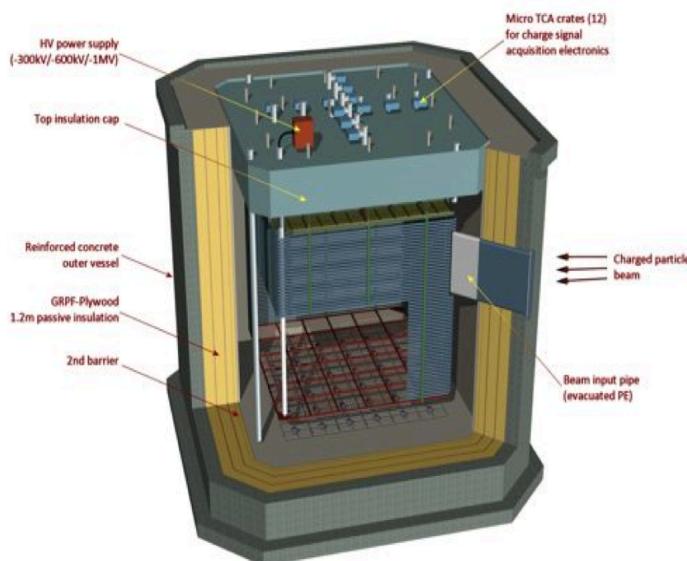
Light Production and RO Simulation

-> Simulation

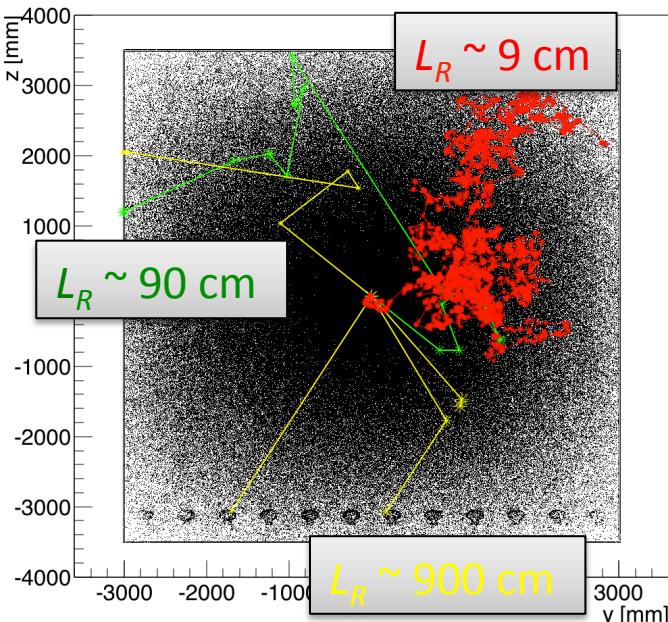
-> Collection Efficiency

Light Simulation

WA105

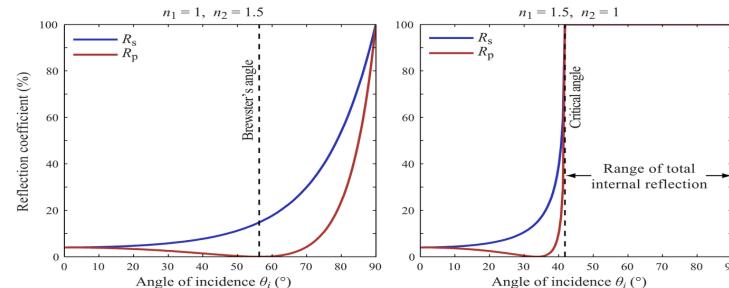


- Cathode grid: 80% transparent



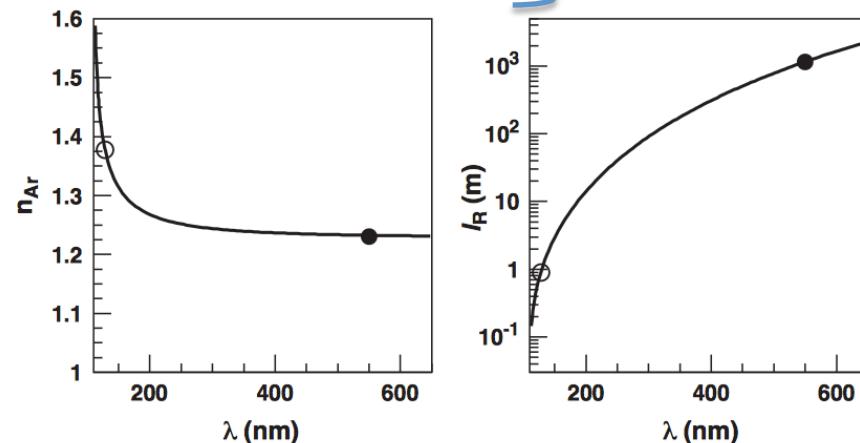
- GAr-LAr surface:

 - Reflectivity: 100%
 - Boundary process uses: Ref. Indexes Polarization



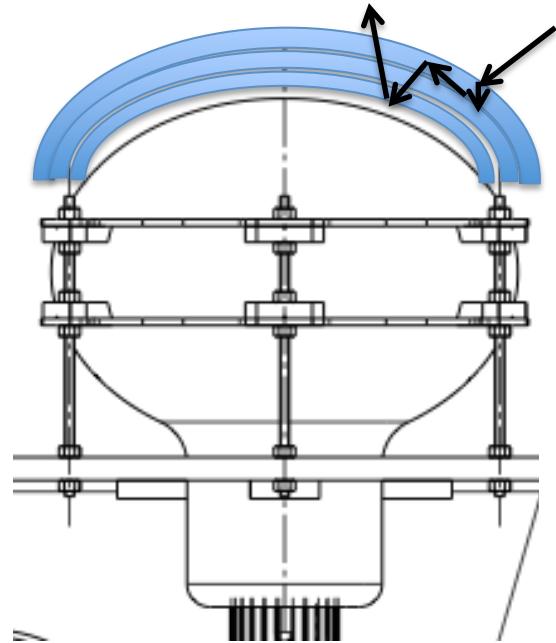
- LAr

 - Refraction Index
 - Rayleigh Scattering Length
 - Absorb. Length

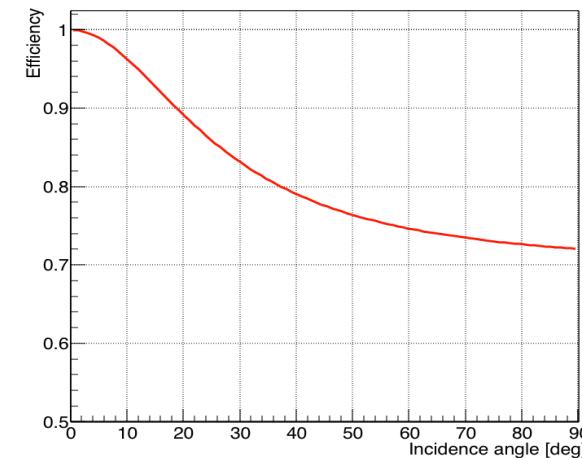


Defined as function of the photon λ

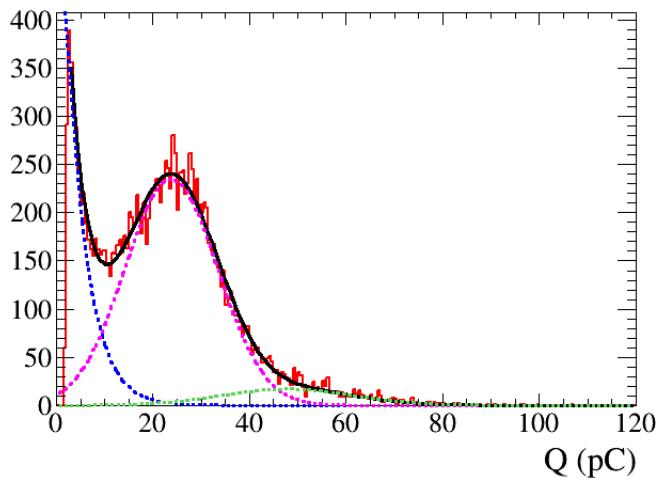
PMTs detection



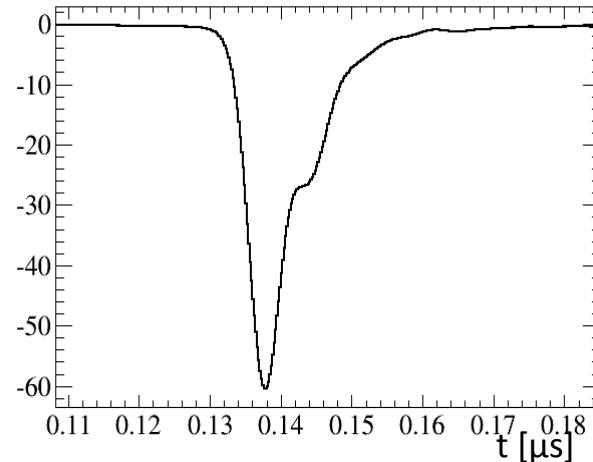
- Optical Surfaces: shaped as PMT emisphere
- Coating: WLS (functional absorption-emission spectrum)
UV photon absorbed and an OP emitted isotropically
- Cathode: G4 Sensitive Detector
- Optical Surfaces
 - ✓ LAr-Coating
 - ✓ Coating-Glass
 - ✓ Glass-Cathode
- Detection efficiency as a function of the incident angle
- QE (100% in the simulation)



PMTs response

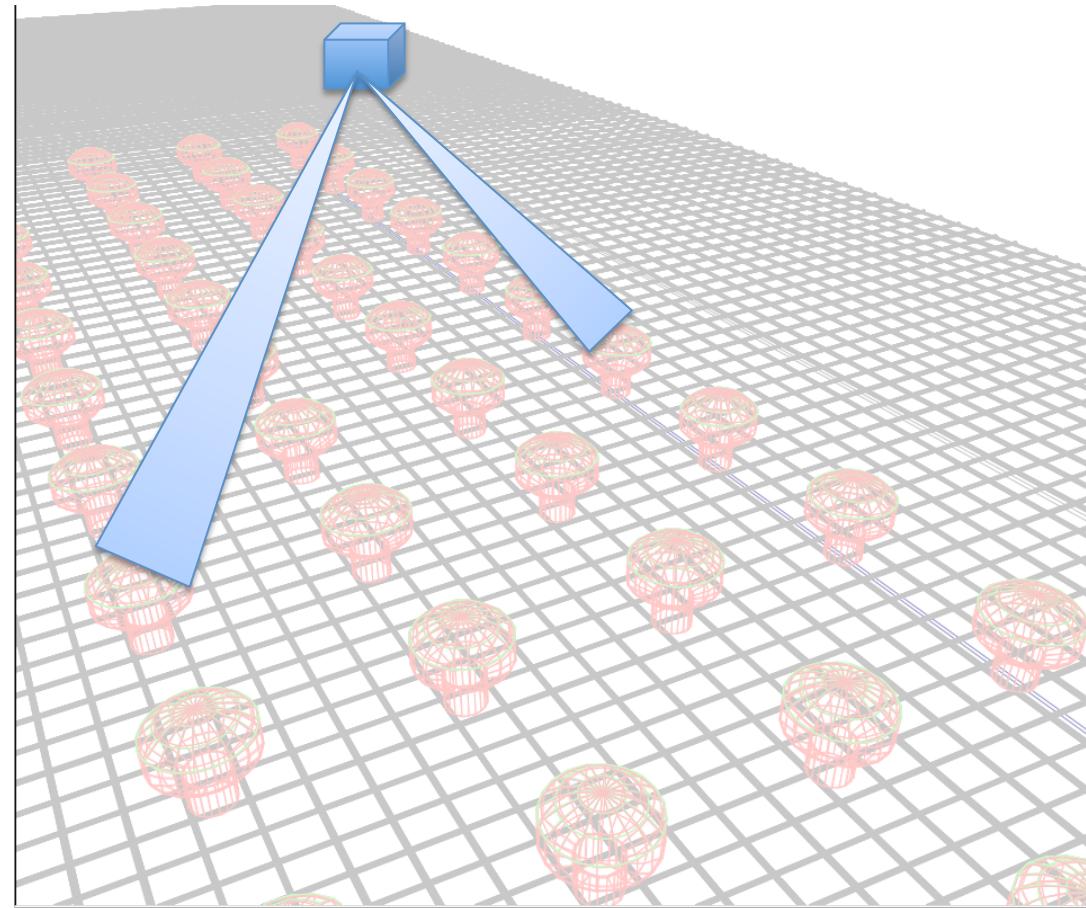


- Signal amplitude and shape simulated from cryogenic measurements of the PMT response



Lookup Table for Light Response Simulation

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Light Yield: 1 optical photon per 20 eV deposited energy

Single-photon-level simulation not feasible
at MeV primary energy scales

Divide active volume in sub-cells:
Voxels

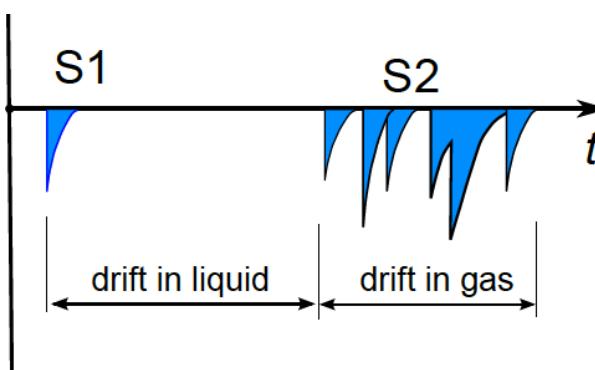
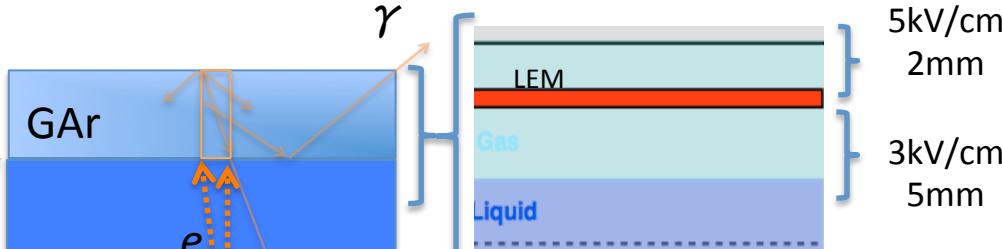
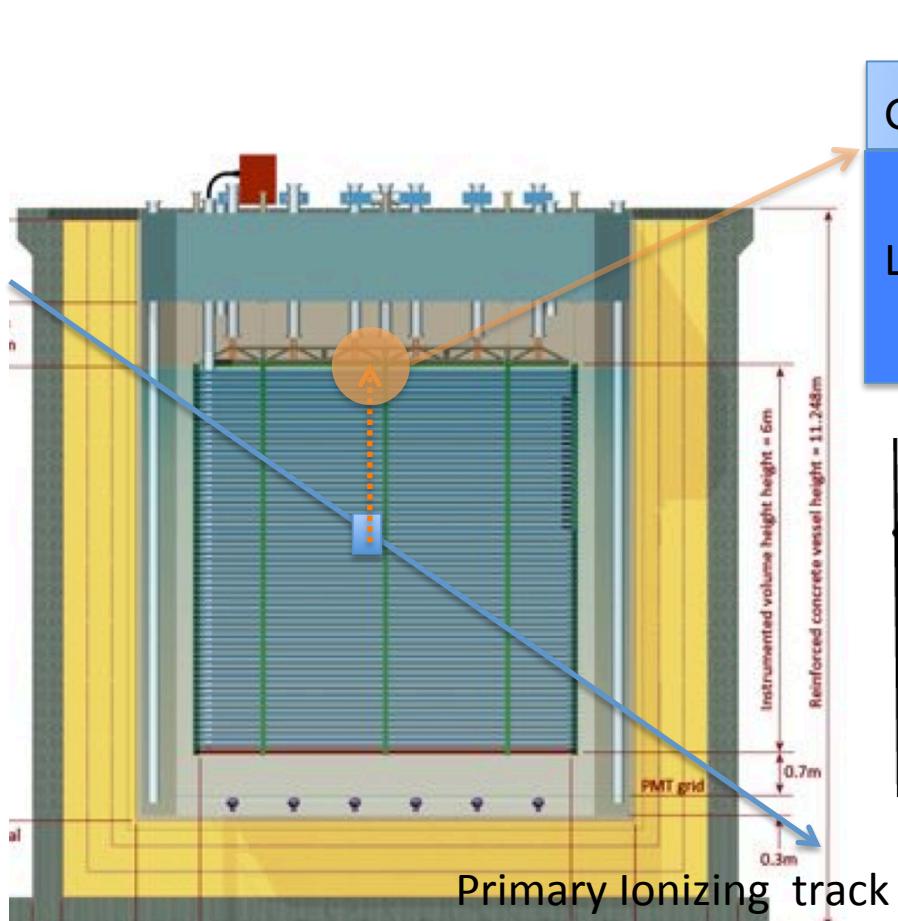
For each voxel:
Generate High Stat of optical photons
and create:

- multiplicity photon map
- PMT signal form

$$N_{\gamma}^{PMT-i} = \sum_j^{voxel} (n_j^{pri-\gamma} w_{ij}^{pri} + n_j^{sec-\gamma} w_{ij}^{sec})$$

Secondary Scintillation Light

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An independent Light Map is created for the Secondary Scintillation

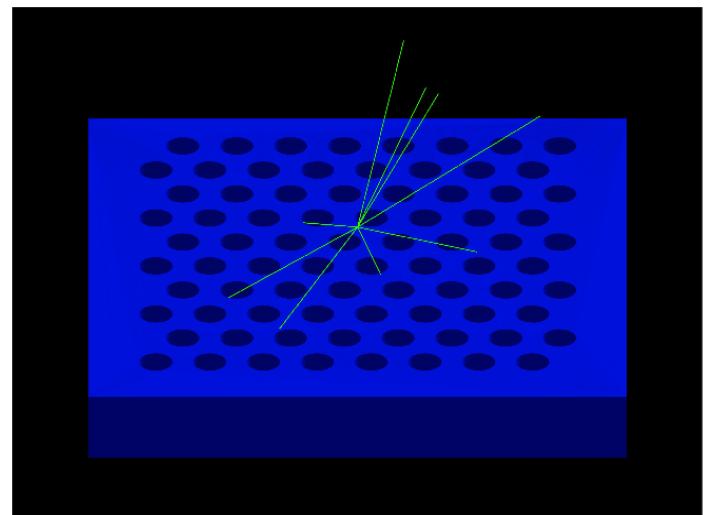
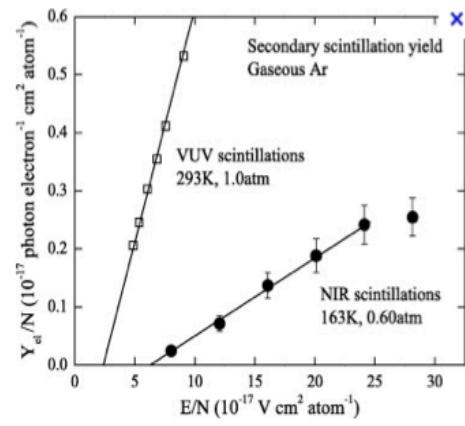
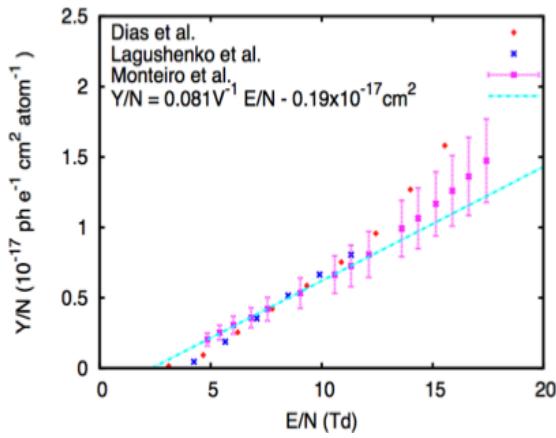
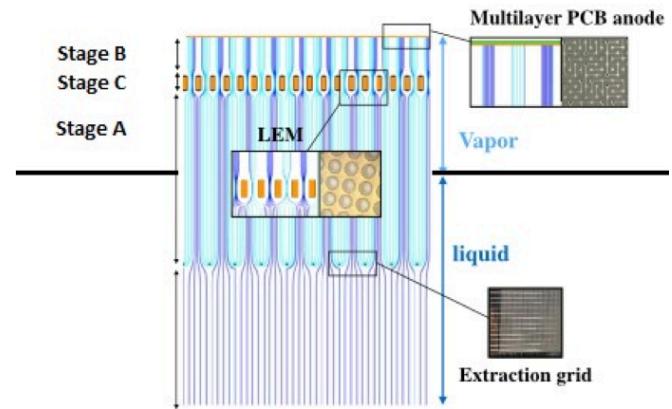
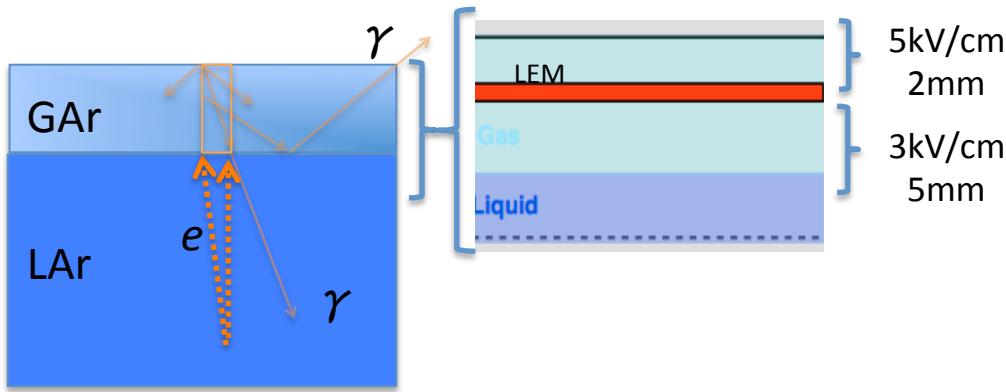
$$N_{\gamma}^{PMT-i} = \sum_j^{voxel} (n_j^{pri-\gamma} w_{ij}^{pri} + n_j^{sec-\gamma} w_{ij}^{sec})$$

- Step level simulation algorithm:
 - Ionization charge yield
 - Quenching, attenuation...
 - Light production volume in GAr:
 - Drift time delay
 - Number of γ per e for different field and drift length
 - LEM shielding effect

Secondary Scintillation Light

Light Yield parameterization: available measurements on electroluminescence

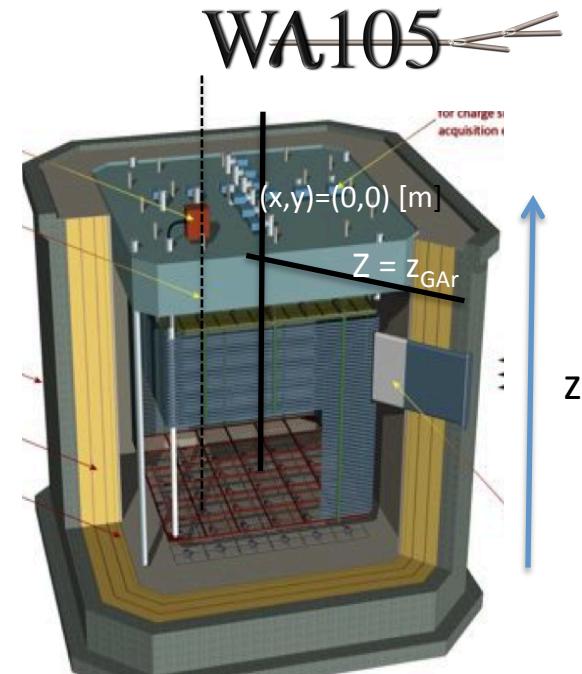
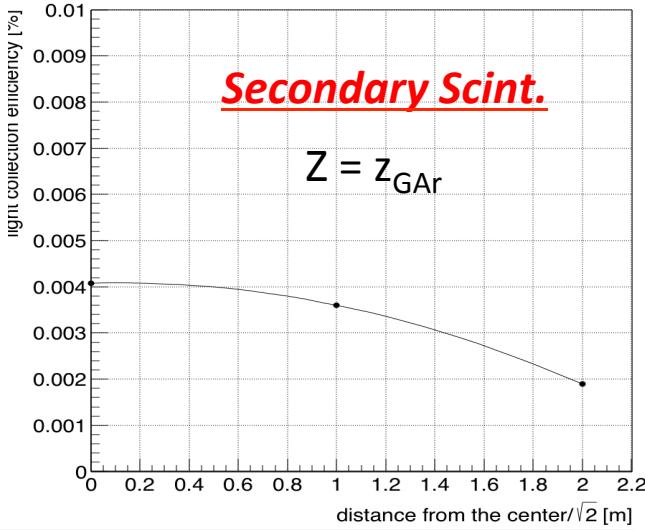
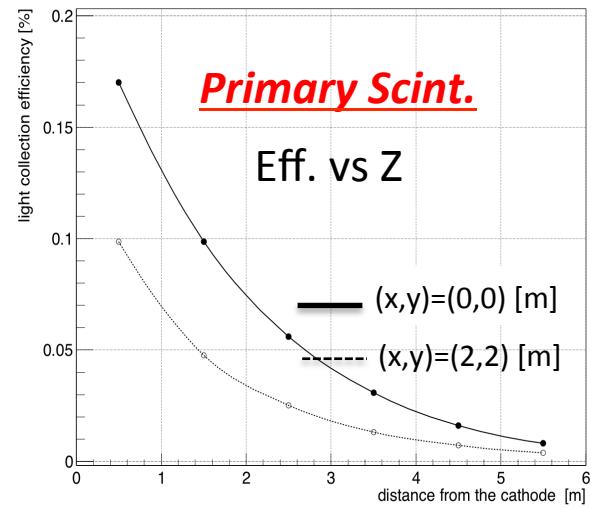
Proper estimation of LEM transparency (holes reflectivity)



Light Collection Efficiency

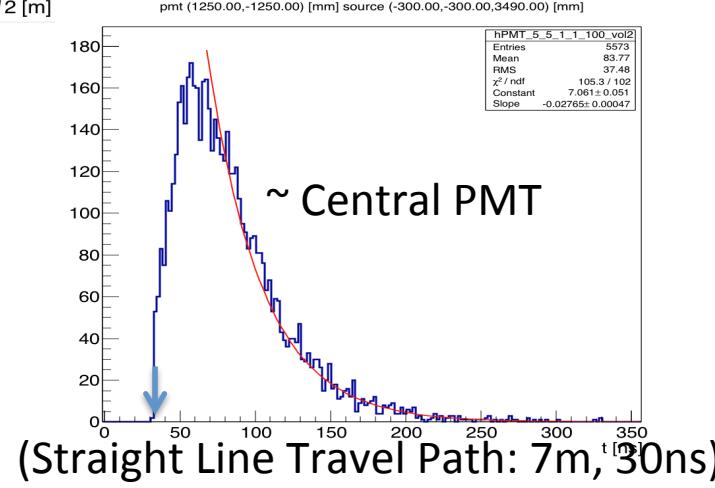
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- Collection Eff. for Primary Scintillation Light:
 $\approx 6 \times 10^{-4}$ large dependence on distance from RO plane
 - Assumed QE: 20%
 - Secondary Scintillation Light
 Efficiency $\approx 30\%$ of eff. in LAr for the same distance to light RO



Time Signal Spread due to Rayleigh Scattering

Parameterized for each PMT and for wrt each light emission cell



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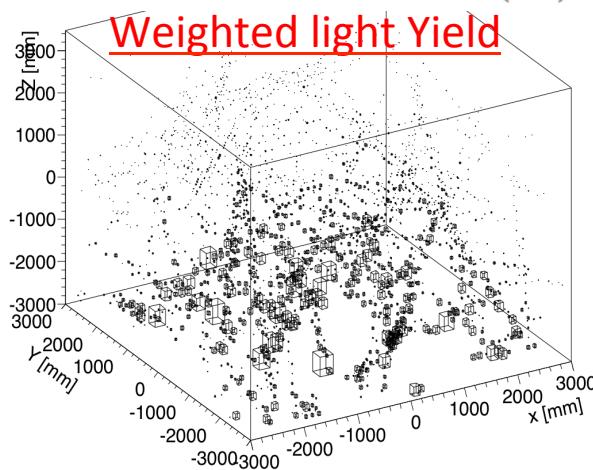
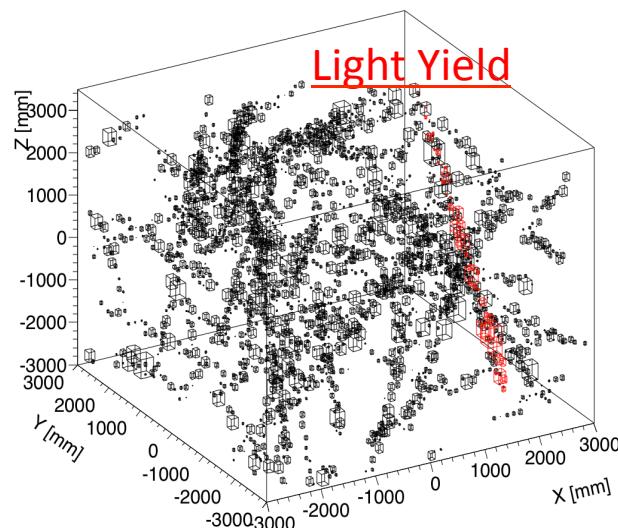
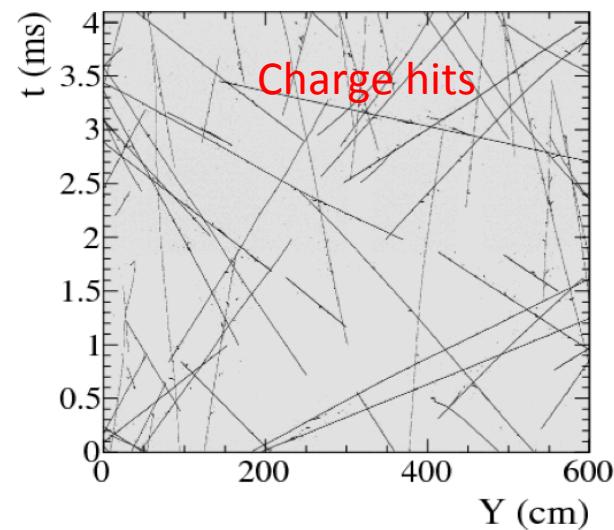
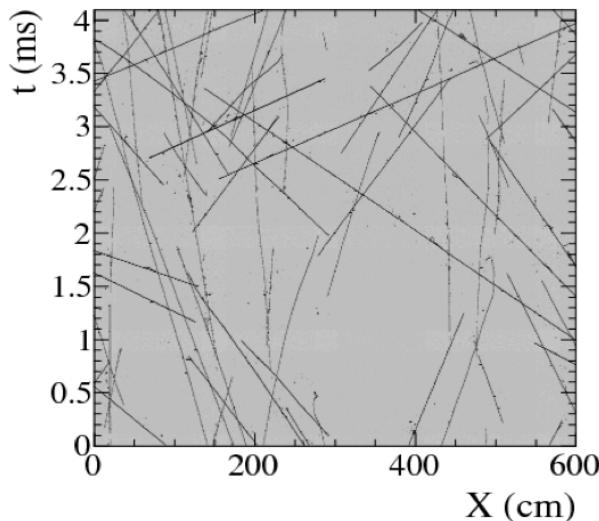
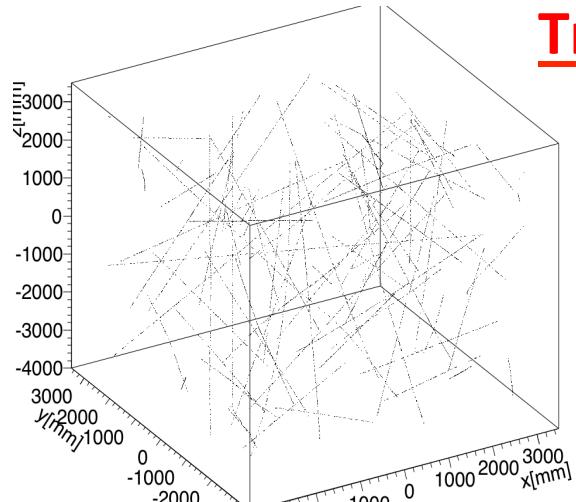
Full Detector Response simulation
-> Surface Operation

Simulation and Reconstruction of Cosmics

- Surface operation: large cosmics ray flux
- Finalizing full simulation of both charge and light signal
- Cosmics muon tagging with the prompt light component:
-> determination of the drift coordinate. Need to integrate in a window 2xmax drift time (4ms)

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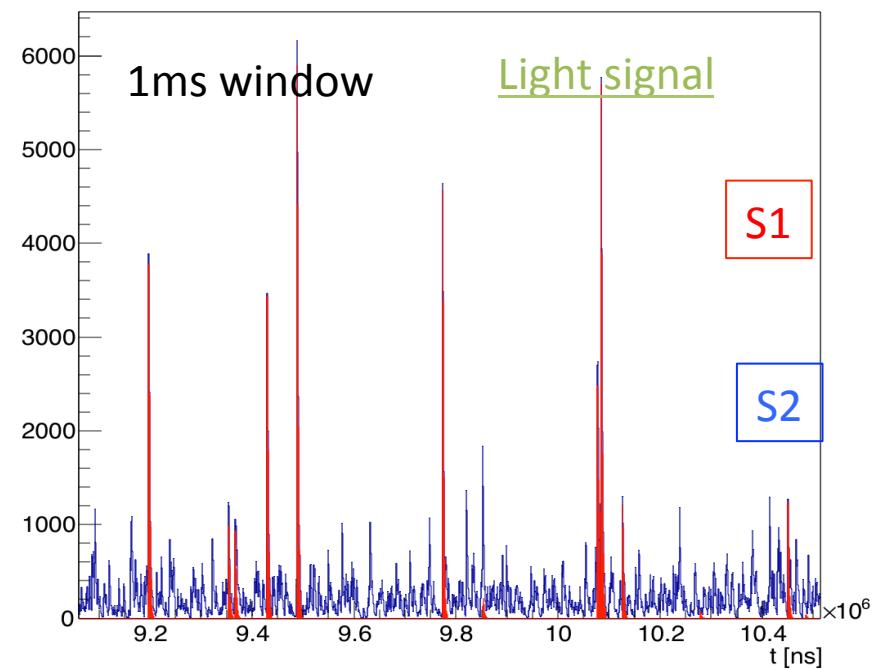
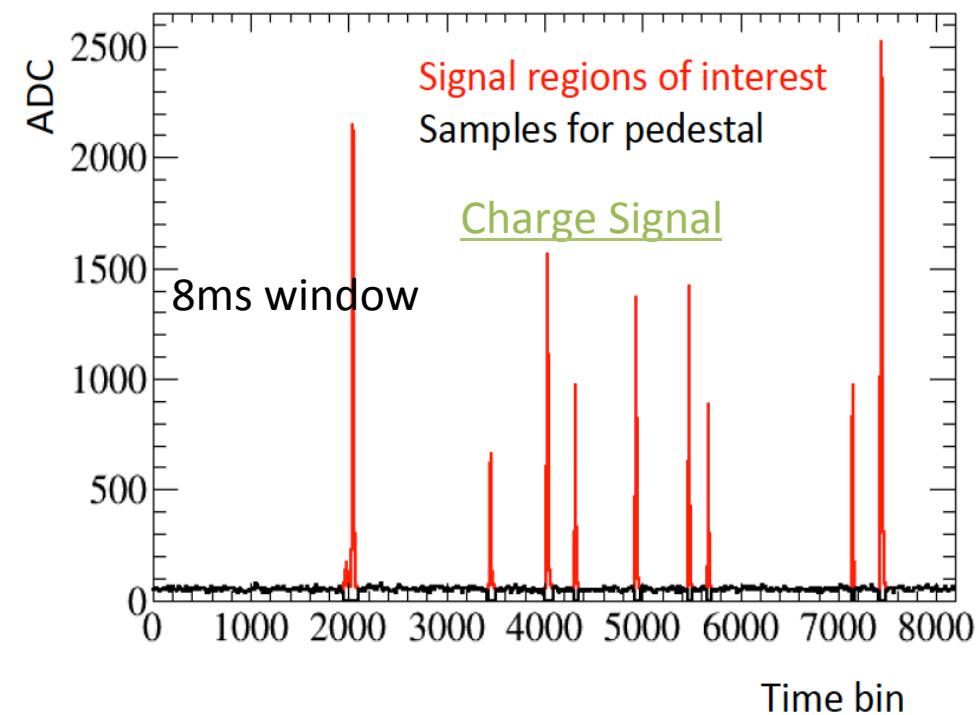
Tracks fragment in -4ms,+4ms



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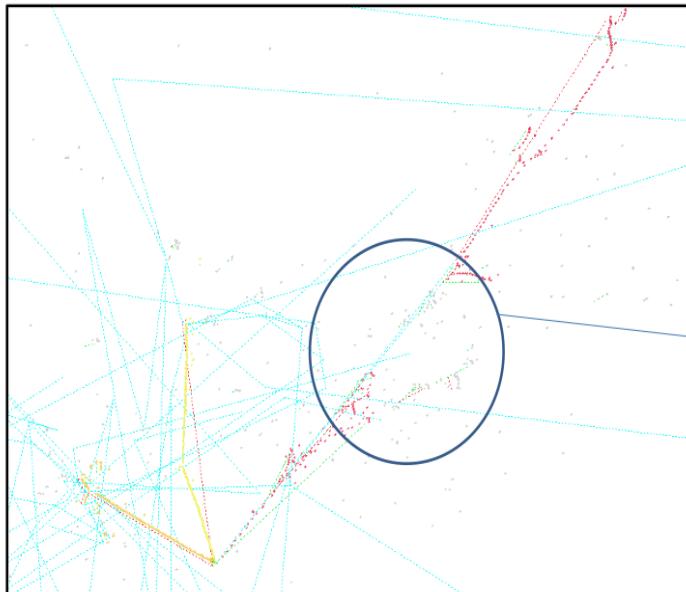
Higher Level Reconstruction

- Clustering with PANDORA
- PID: LATTE

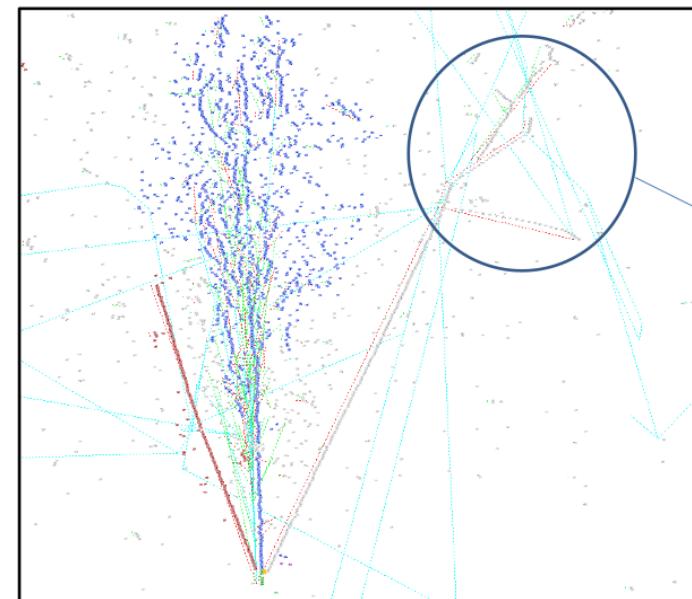
Clustering with PANDORA

- Hit clustering performed by an early (modified) version of Pandora:
 - Vertex finder altered to work in two views rather than three (drift coordinate used to match vertex location between views).
 - PANDORA designed to make few mistakes but is (was) rather conservative => can lead to unassociated clusters at the end of the chain:
 - Clean-up algorithm to join clusters far from the vertex with other clusters

Electron with gap +2 hadrons



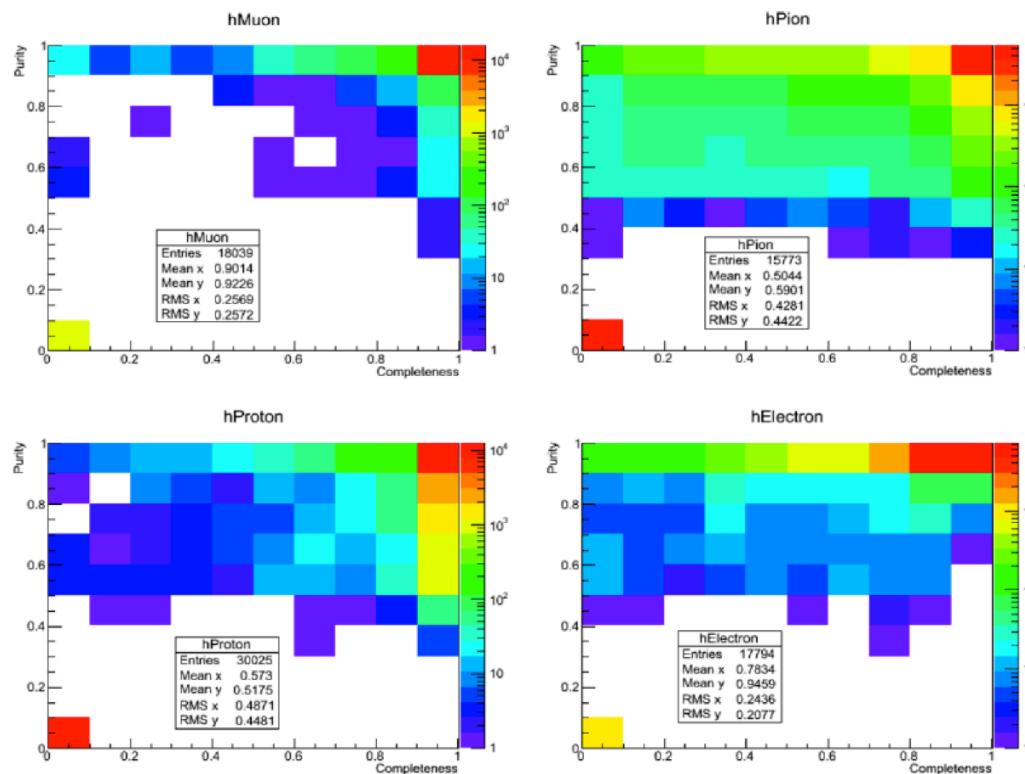
Electron + 2hadrons



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$\nu_l \rightarrow l + p + \pi^+$.



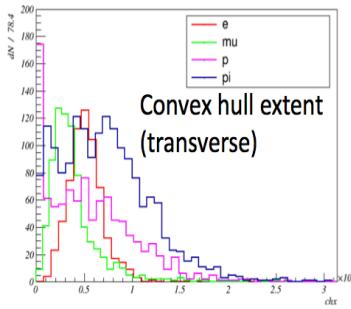
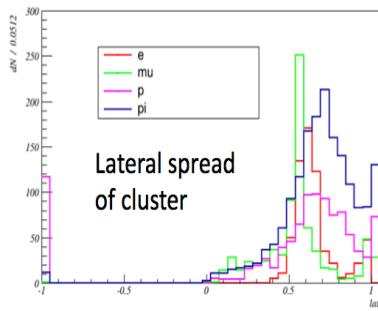
Cluster Quality:
Completeness
vs
Purity

(After Truth-best-guess
-cluster matching)

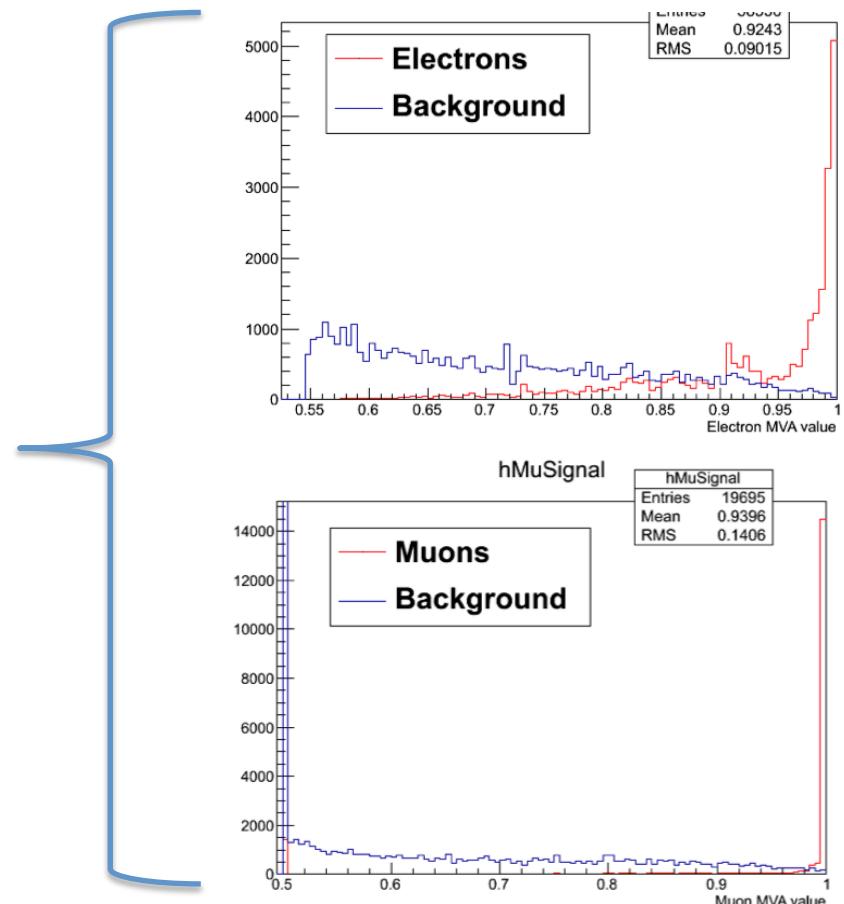
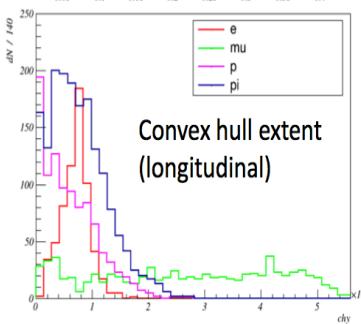
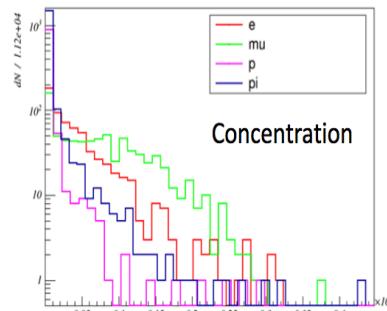
PID: LATTE Toolkit

- Performance tested on statistically independent samples to training events
- e.g. electrons separated from hadrons+muons with >95% purity (30% efficiency)

Several PID variables → MVA analysis



+ dE/dx



Summary

- ❑ Prior to WA105 demonstrator data taking simulation studies are in progress
 - properly characterize the detector response
 - provide key feedbacks for important component design
 - develop analysis strategy and evaluate the impact on the final goal physics

- Development of automatic LAr event reconstruction: Topology, PID, Calorimetry
- Test NC background rejection
- Opportunity for hadronic shower measurements
- Charged pion, proton cross section on Ar

- ❑ Charge readout simulation and reconstruction benefits from excellent hit level performance of the double-phase technology
 - Will affect higher level event reconstruction capability
- ❑ Developing tools to exploit surface detector operation opportunity: monitoring of field uniformity, purity, readout gain
- ❑ Ready to develop tools for clustering, event reconstruction and PID optimized for the two-view readout.

PANDORA validation

- Look at reconstruction of individual final state particles from ν_μ and ν_e interactions (LBNO flux):
$$\nu_l \rightarrow l + p \text{ (CCQE) ; } \nu_l \rightarrow l + p + \pi^+ \text{ (CCRES)}$$
- Associate particles with the cluster containing more charge from that particle (+daughters), than from any others
- Calculate:
 - **Completeness** is the proportion of the total energy deposited by that particle, which is contained within the cluster.
 - **Purity** is the proportion of the cluster energy which is due to the particle.

Latte: Particle Identification

- 5 variables combined in a MVA:
 - Core-to-halo charge ratio
 - Concentration: sum of hit charge divided by radial distance to princ. axis
 - Longitudinal and transverse cluster extent
 - dE/dx of cluster hits near to the vertex
- PID trained on reconstructed clusters in simulated events (utilising the cheat/truth underlying PID)
- Using CCQE and CC- π^+ events from both ν_μ and ν_e
- Separate MVA's are produced for muons, electrons, protons and pions: signal being clusters with the correct PID, and background being all other clusters

