SAND-DUNE: Simulations and reconstruction

DUNE-doc-13262

SAND: Solenoid for Accurate Neutrino Detection, for DUNE
Status of simulations and analysis

• Summary of performance study for
• KLOE + STT + LAr
• Full simulations and reconstruction to demonstrate performances
• Perspectives in new proposed configuration, KLOE +3DST +...
New

Integration of 3DST, surrounded by tracking devices. Work in progress.
Example events

16 GeV, 17 secondaries

2 GeV, 6 secondaries

Black: Edep in 3DST
Red: tracker and Calo

Output: energy in 1cm cubes, and time
Will reuse 3DST software for light yield and digitization.
Old Layout (a reminder)

STT (5 tons CH$_2$, "compact" version)

Joke

EM-CALO Barrel + Endcap
Pb + SciFi
No separation from tracker

LAr active target
~1 ton

B: solenoid
0.6 T

Coils and cryo

Inner volume ~ 45 m$^3$
Details

Kloecal fine structure

4/9/2019
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.

Gaussian Fit on $\theta$:
Mean $\cong 0$ mrad
Sigma $\cong 0.9$ mrad

Gaussian Fit:
Mean $\cong 3.8\%$
Sigma $\cong 5.1\%$

Wrong sign 1.3%
Results - $\pi^0$

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

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

$2 \pi^0$ sample: $\pi^0$ invariant mass,
Considering only 4-cluster events

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<td>$\chi^2 / \text{ndf}$</td>
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<td>Constant</td>
<td>17.91 ± 1.79</td>
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<td>Mean</td>
<td>0.1274 ± 0.0017</td>
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<tr>
<td>Sigma</td>
<td>0.02355 ± 0.00177</td>
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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 $E_{\text{kin}} > 100$ 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

$St\text{hit}=1$ events in stt
$St\text{hit}=0$ events in barrel calorimeter
$St\text{hit}=2$ events in endcap calorimeter
Resolution vs true angle

\[(\text{Reco}-\text{true})/\text{true} : \text{average within 0.5\%} \]
\[\text{sigma} \sim 2\%\]
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...

• 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
• $\rightarrow$ $\beta$ estimate $\rightarrow$ 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 \( \phi \) correspond to tracks
Second vertex finding from track intersection

4/9/2019
P reconstruction

For events with only 1 charged track in each view:

Error on total p: \[ p = \frac{p_{yz}}{\cos(\lambda)} \]

3.9 %

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

4.3 %
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

Muon acceptance

Bad efficiency due to escaping muons
Acceptance for ArCUBE muons: old AC geo

- Simple muon catcher around AC + layers around coil cured the acceptance.
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% of 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
Backup
Next steps

• Improve details of single particle reconstruction
• Finalize full event reconstruction
• Apply to random events, check identification and reconstruction
• Optimize LAr meniscus

• 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 forthcoming note
Performances (examples of)

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

<table>
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<tr>
<th>Process</th>
<th>$R_{mH}$ and $p_T$ cuts Efficiency</th>
<th>$p_H$ cuts Purity</th>
<th>$\ln \lambda^H$ cut Efficiency</th>
<th>$\ln \lambda^H$ cut Purity</th>
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<tbody>
<tr>
<td>$\nu_\mu p \rightarrow \mu^- p\pi^+$</td>
<td>93%</td>
<td>86%</td>
<td>90%</td>
<td>92%</td>
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<tr>
<td>$\bar{\nu}_\mu p \rightarrow \mu^+ p\pi^-$</td>
<td>80%</td>
<td>84%</td>
<td>90%</td>
<td>88%</td>
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<td>$\bar{\nu}_\mu p \rightarrow \mu^+ n$</td>
<td>95%</td>
<td>80%</td>
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<tr>
<td>$\nu_\nu p$ CC inclusive</td>
<td>83%</td>
<td>73%</td>
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- Good track and neutron efficiency $\Rightarrow$ flux shape with low-$\nu$ method for QE and RES events on H. Total statistics (5 years) expected is about $2.4 \times 10^6$ for RES and 800 000 for QE

- Low-$\nu$ method also on global STT (and Lar) : 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 $\Rightarrow$ direct comparison of events on Ar and H (or C) for nuclear effects assessment
Performances (examples of)

• Charge separation and electron identification $\nu_e / \nu_\mu$ and all other species with high statistics (80000 $\bar{\nu}_e$ events in FHC mode 5 years)

• Very good angular resolution on electron tracks $\rightarrow$ 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 $\pi^0$ interactions (2%). Can be combined with data from external Lar. STT provides smaller statistics but better systematics
• The whole detector can be moved on rails, for a PRISM-like exposure.

• Event rates here for $\frac{1}{2}$ year, in the LAr meniscus, FHC

• $\nu_\mu$ CC : $3.1 \times 10^4$ at the largest angle in 5+5 years

• Factor 5 more in STT

<table>
<thead>
<tr>
<th>Offset</th>
<th>$10^{20}$ POT</th>
<th>CCInc $\nu_\mu$</th>
<th>NCIInc</th>
<th>CCInc $\bar{\nu}_\mu$</th>
<th>CCInc $\nu_e$</th>
<th>El. $\nu_\mu$\textsuperscript{-e}</th>
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<td>3.4 $\times 10^4$</td>
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σ and Nuclear Effects

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

- 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\(_{\text{phys}}\)) from detector effects (R\(_{\text{det}}\))
  - ➔ measure \( \sigma_X R_{\text{phys}} \)
- Lar TPC detector effects (==Far Det) studied by pixelated LAr TPC
- \( \sigma_X \) on Ar using the large statistics from the LAr and HPgTPC detectors
Flux measurements

- $\Phi(E_\nu)$ Measurements
  - Absolute $\nu$ flux from $\nu e \to \nu e$ elastic
  - Fluxes vs $E_\nu$, ratios of $\nu_x/\nu_y$ (e, $\mu$, 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.

- $\nu_\mu$ on H : $5 \times 10^5$/year
- $\bar{\nu}_\mu$ on H : $8 \times 10^4$/year
- $\nu_e$ on H : $8 \times 10^3$/year

- $\nu_\mu$ e in FHC : 1000/year in STT, possibly combined with measurement from large mass pixelated LAr detector

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Events/ $10^{20}$ pot

4/9/2019
Neutrinos

Old results

\[ \sigma \approx 6\% \]

From full GENIE + GEANT4 simu + MC truth guidance