Towards LBL studies with SAND

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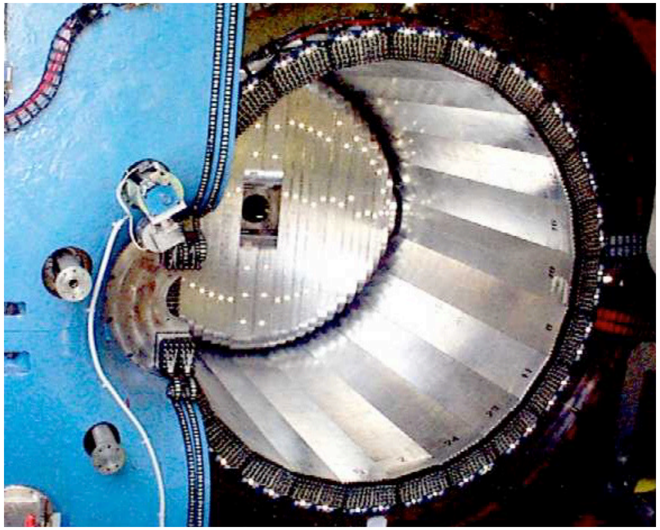
on behalf of SAND

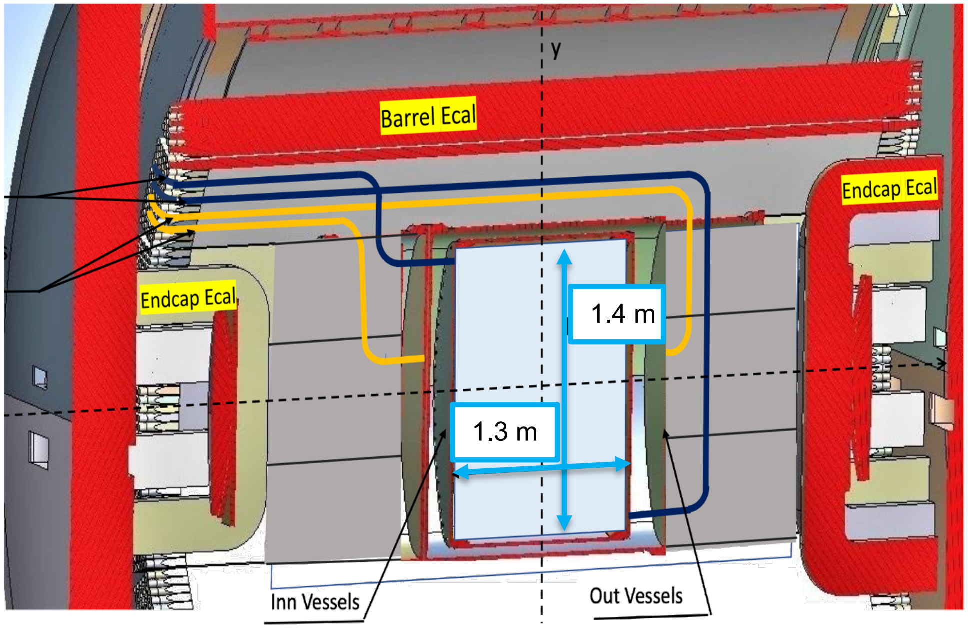
DUNE General Meeting - May, 17th 2022

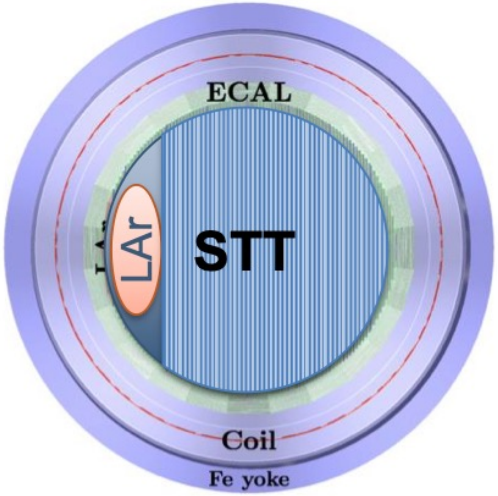
SAND geometry: ECAL & GRAIN



GRAIN: GRanular Argon for Interactions of Neutrinos

1 ton LAr cryostat in the upstream volume



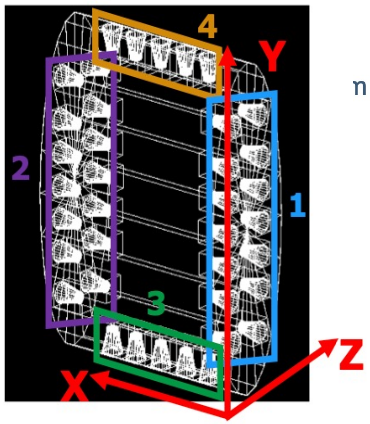


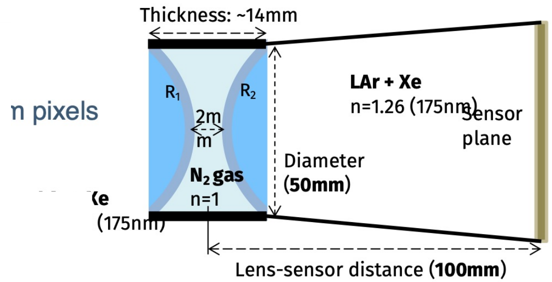
instrumented with :

- SiPMs only
- or with SiPM matrix coupled to an optical focusing system (R&D under development)

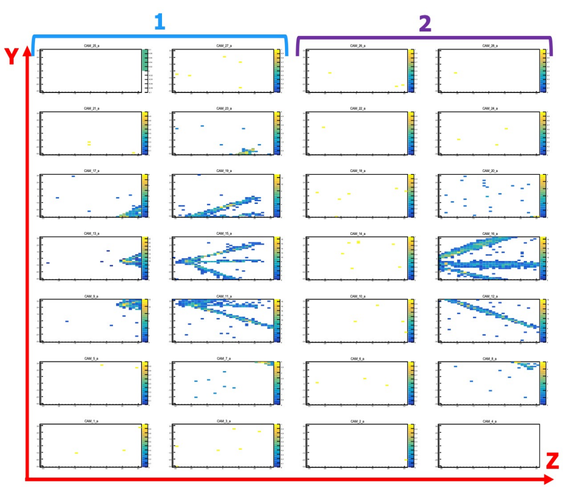
GRAIN instrumented by optical readouts

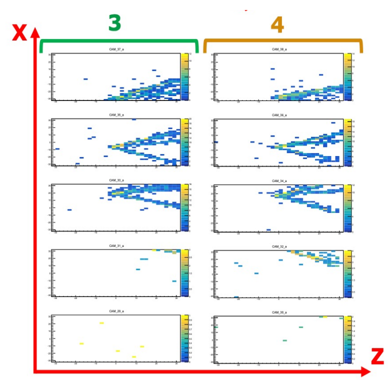
- Lens based optical readout



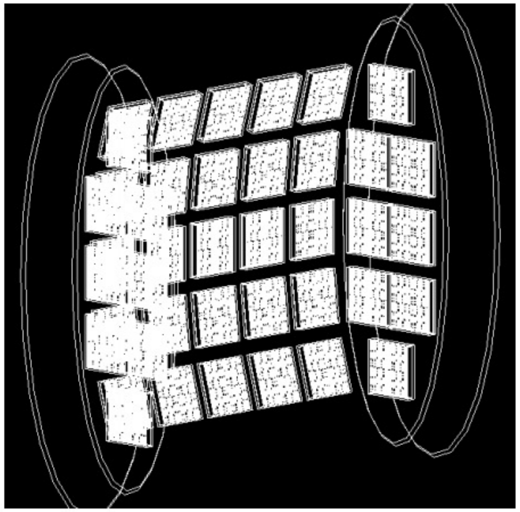


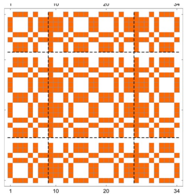
- 38 cameras
- 32x32 sensor matrix with 2x2 mm^2 SiPM





- Hadamard matrix based optical





Hadamard matrix

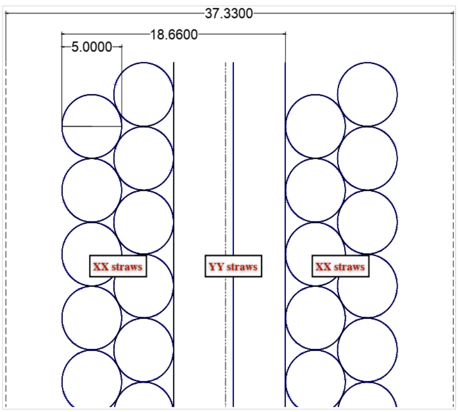
- 76 cameras:
  - 8 cameras on each side, 25 cameras on each curved face, 5 cameras on top/bottom
- 32x32 sensor matrix with 3.2x3.2 mm^2 SiPMs, max coverage

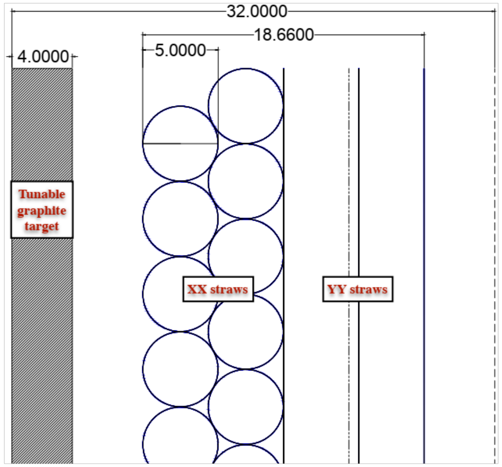
EPJC 81, 1011 (2021)

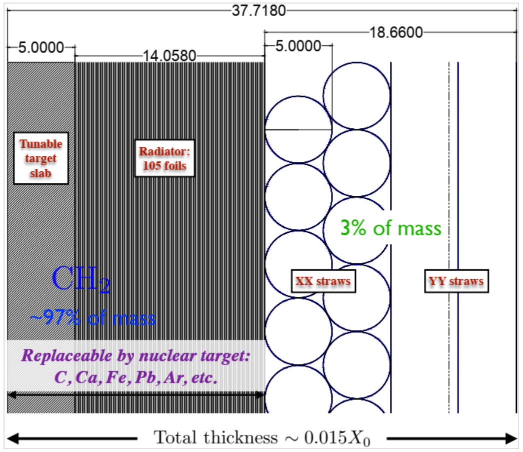
SAND geometry: straw tube tracker

3 TYPES OF MODULES

tracker module XXYYXX | **Carbon target** | **CH_2 target + radiator module**

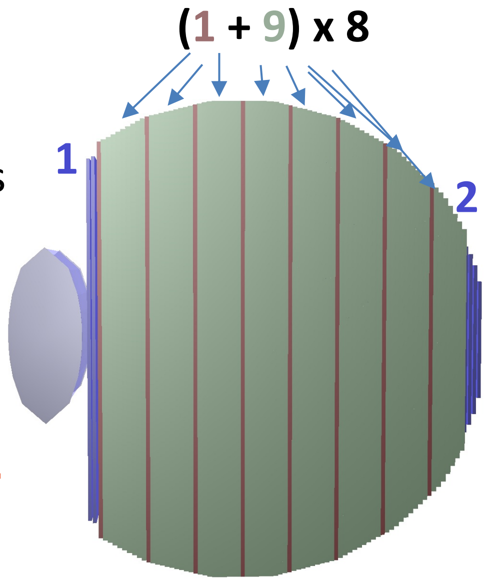






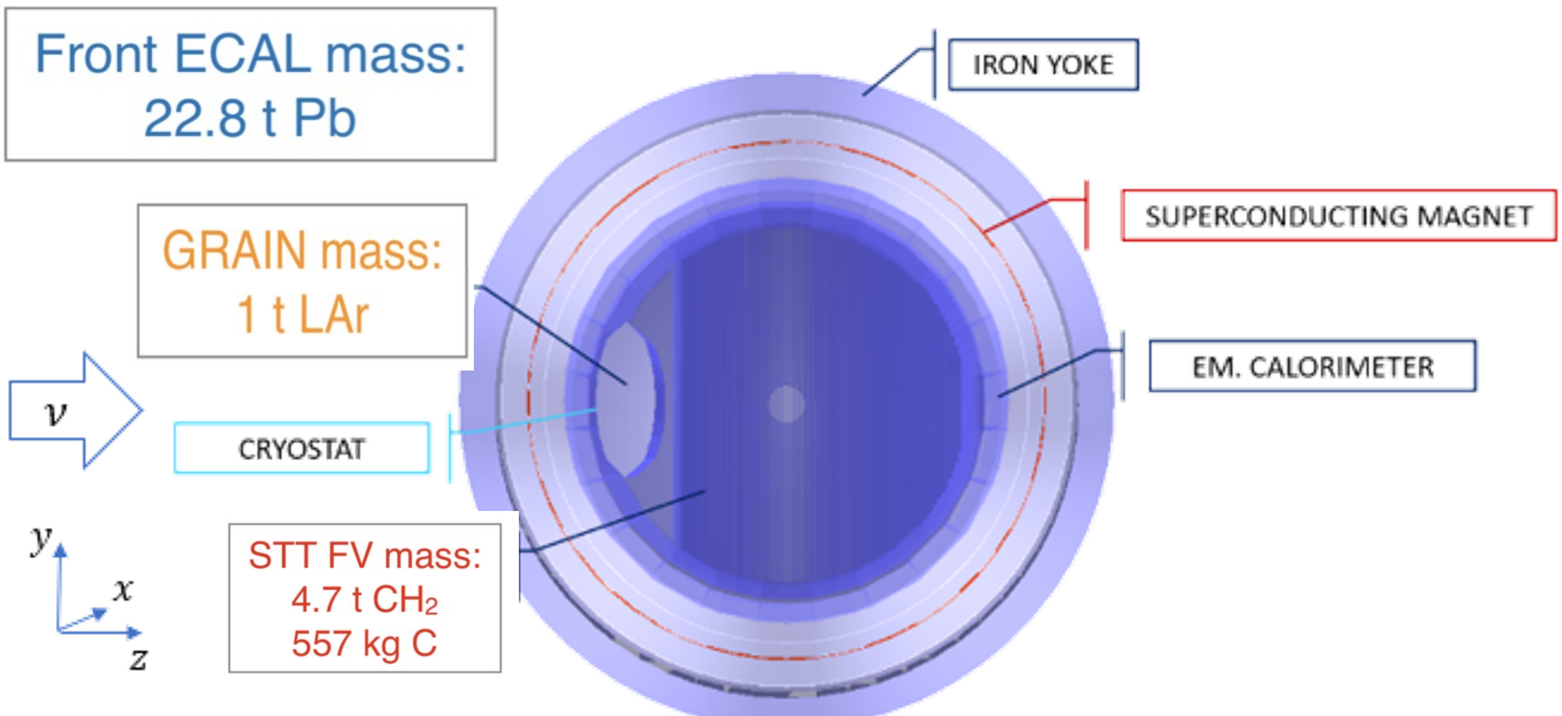
- position resolution on single hit: 200 um in y , 10 um in z
- time resolution on single hit: 1 ns
- average density ~ 0.18 g/cm^3
- radiation length x0~ 2.6 m
- tracking sampling 0.15 (0.36)%x0 ⊥ (∥)

84 modules



Events in SAND

Target	CP optimized FHC (1.2MW, 2y)				CP optimized RHC (1.2MW, 2y)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	13,010,337	624,330	192,118	31,902	2,035,973	4,870,562	91,004	69,278
H	1,222,576	111,574	18,396	5,557	194,216	906,130	8,712	12,434
C	1,547,011	67,294	22,799	3,458	241,710	520,287	10,800	7,460
Ar	3,114,331	121,506	46,384	6,503	480,862	936,489	21,932	13,867
Pb	62,127,600	2,507,940	923,012	130,680	10,375,400	18,222,200	437,284	265,304



SAND goals & potentials

- **Interactions in the front part of ECAL → beam monitoring**
- **Interactions on CH_2 :**
  - for low-nu analysis,
  - for $\nu + e$ on-axis flux measurement $< 2\%$ ← **ND-LAr+ TMS**
  - Ratio ν_e / ν_μ and $\overline{\nu_e}$ /$\overline{\nu_\mu}$ vs E
  - Ratio ν_e / ν_μ vs E from coherent π^-/π^+
- **Interactions on H (after statistical subtraction):** $\nu p \rightarrow \mu^- p \pi^+$ $\bar{\nu} p \rightarrow \mu^+ n$
  - for neutrino flux measurement
  - for cross section measurement on H (model tuning)
- **Interactions on Ar**
  - for inclusive/exclusive CC sample with a magnetic spectrometer ← **ND-LAr+ TMS**
  - for cross-section constraints / tuning nuclear model by a comparison with hydrogen interactions

Thinking to the full LBL analysis

- **Interactions in the front part of ECAL → beam monitoring**
- **Interactions on CH_2 :**
  - for low-nu analysis,
  - for $\nu + e$ on-axis flux measurement < 2% ← **ND-LAr+ TMS**
  - Ratio ν_e / ν_μ and $\bar{\nu_e}$ /$\overline{\nu_\mu}$ vs E
  - Ratio ν_e / ν_μ vs E from coherent π^-/π^+

systematics on some beam parameters can be removed!

Constraints on ν_e , ν_μ, $\bar{\nu}_\mu$, $\bar{\nu}_e$ absolute and relative flux can be imposed

- **Interactions on H (after statistical subtraction):**
  - for neutrino flux measurement
  - for cross section measurement on H (model tuning)

$\nu p \to \mu^-$

Constraints on cross section can be imposed

The additional on-axis sample must be included

- **Interactions on Ar**
  - for inclusive/exclusive CC sample with a magnetic spectrometer ← **ND-LAr+ TMS**
  - for cross-section constraints / tuning nuclear model by a comparison with hydrogen interactions

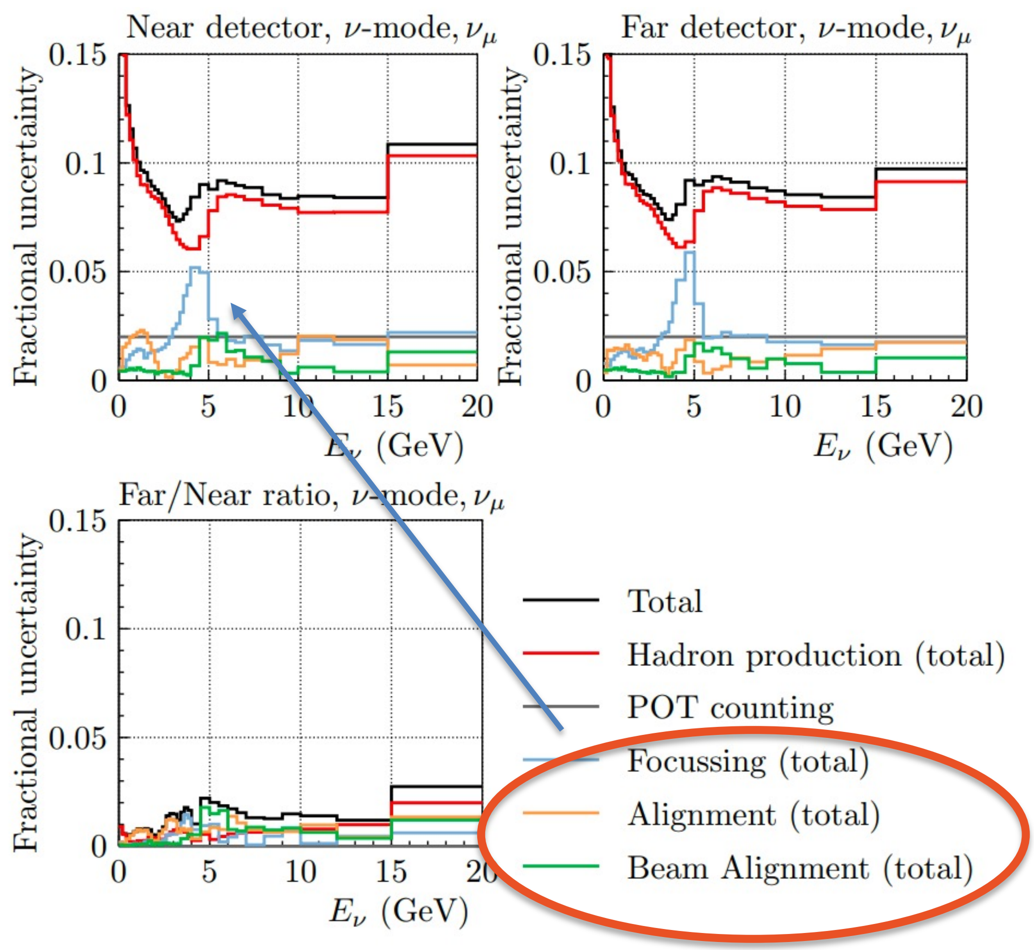
Constraints from beam monitoring

From interactions on front-ECAL + STT + GRAIN, by studying the neutrino spectrum variations

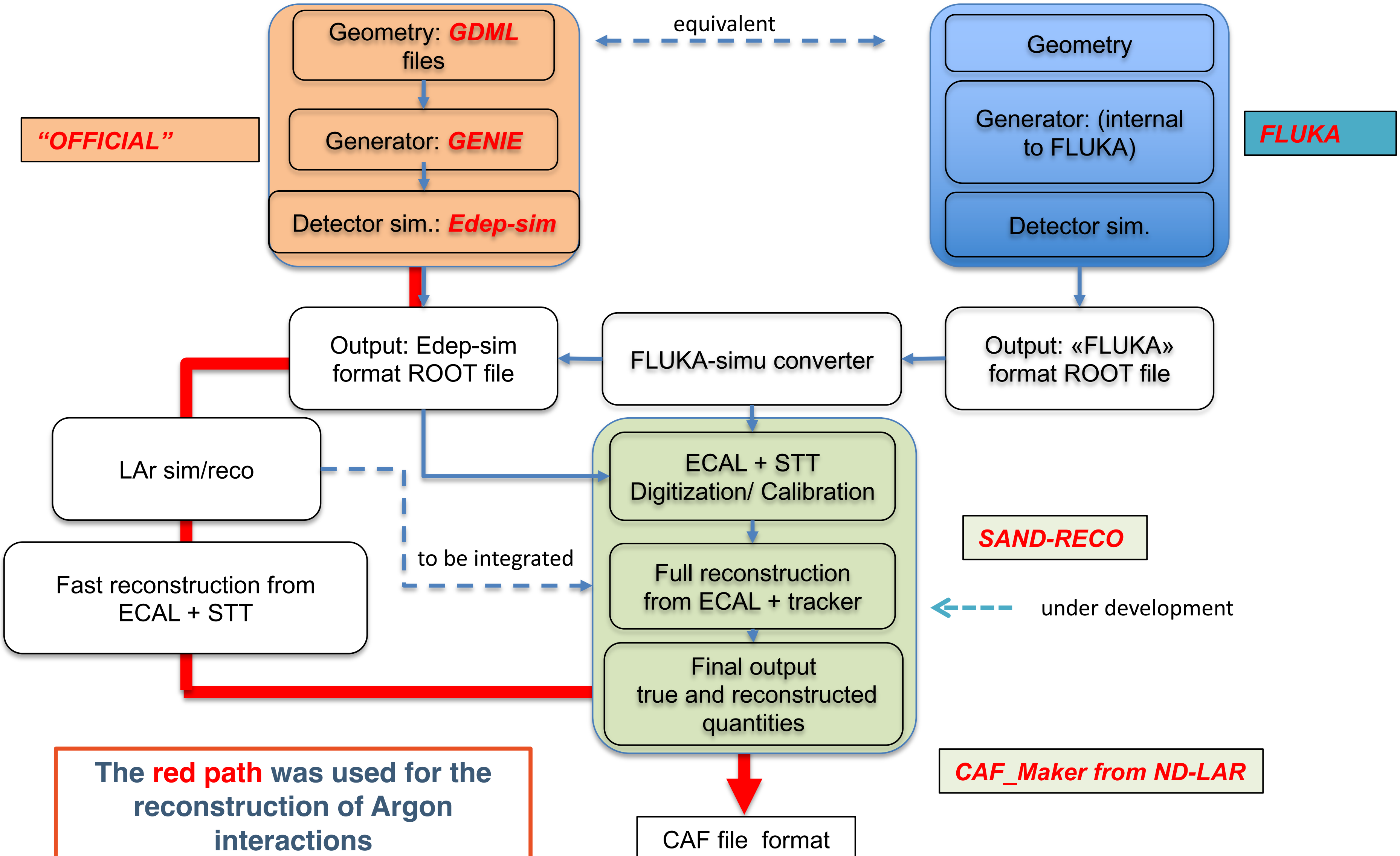
DUNE DocDB:13262-v7

Proton beam parameter	1σ deviation as given by beam group	New $\sqrt{\Delta\chi^2(E_\nu)}$ true	rec
Horn current	+3 kA	12.57	9.44
Water layer thickness	+0.5 mm	4.69	3.58
Proton target density	+2%	5.28	4.07
Beam sigma	+0.1 mm	4.41	3.53
Beam off set X	+0.45 mm	5.11	3.54
Beam theta phi	0.07 mrad θ, 1.57 ϕ	0.62	0.28
Beam theta	0.070 mrad	0.91	0.58
horn 1 X shift	+0.5 mm	4.70	3.42
horn 1 Y shift	+0.5 mm	5.27	3.87
horn 2 X shift	+0.5 mm	1.18	0.69
horn 2 Y shift	+0.5 mm	1.31	0.77

SAND is also sensitive to 0.13 mrad changes in neutrino beam direction



SAND software overview



The red path was used for the reconstruction of Argon interactions

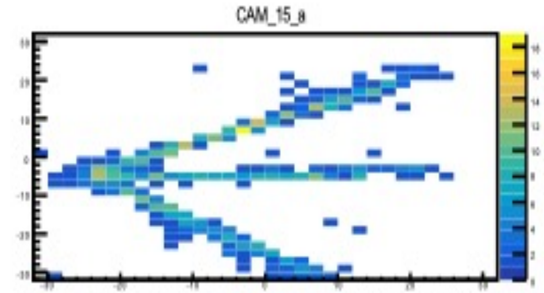
LAr event recontruction

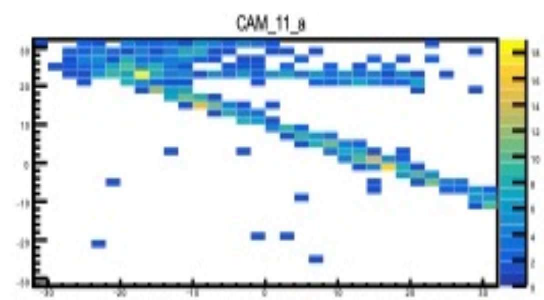
some details

- GRAIN:

Reconstruction based on stereoscopic pixelated images from lens-based optical detectors

- **For each interaction** we have information about:
  - number of detected tracks
  - vertex position
  - total deposited energy





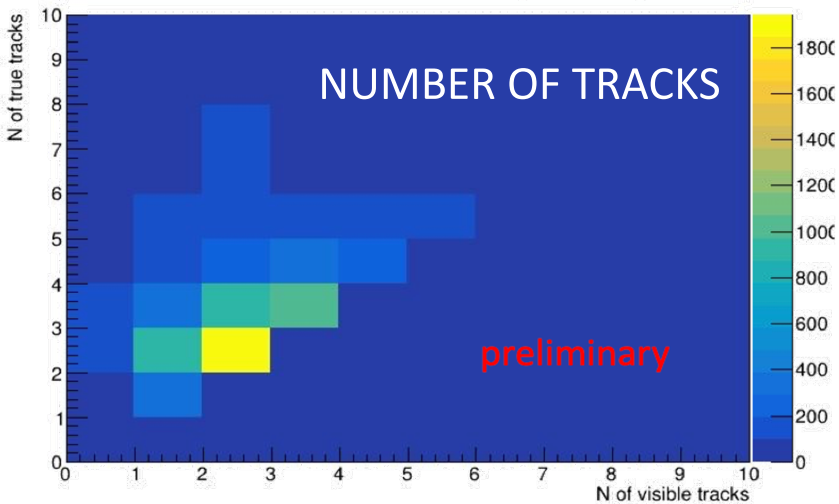
- **For each visible track** we have information about:
  - containement information (in combination with STT and ECAL info)
  - deposited energy

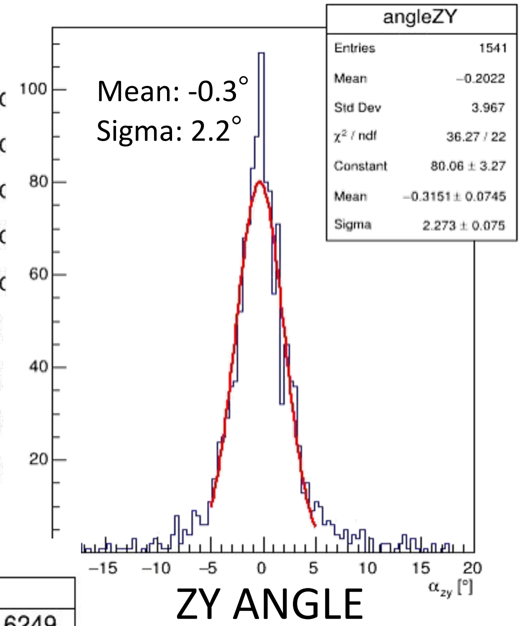
Reconstruction based on total number of photons detected by SiPM:

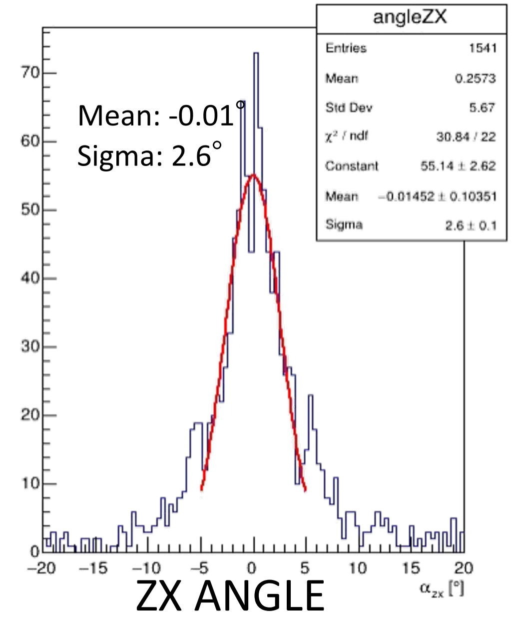
- **For each interaction** we have information about:
  - Total deposited energy

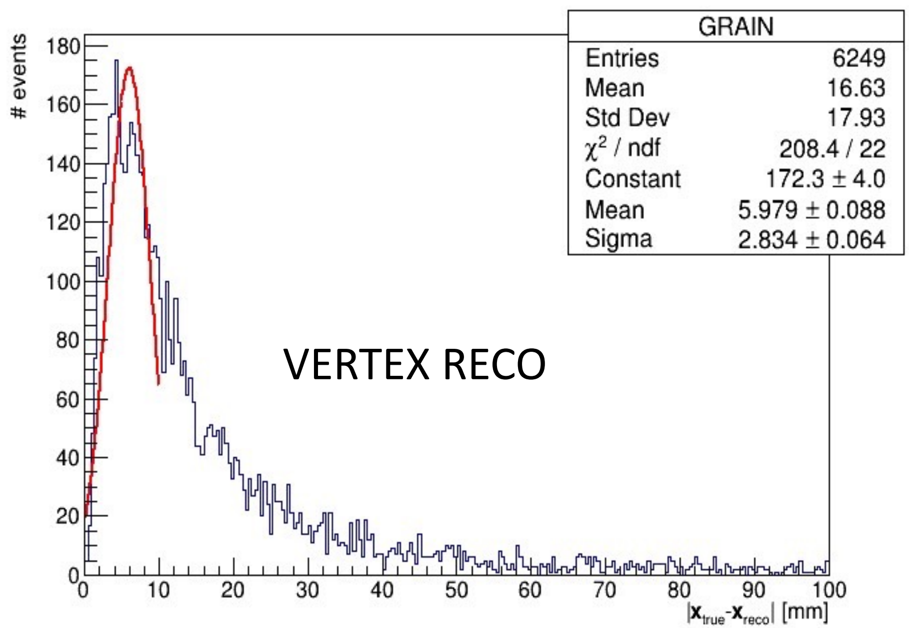
First results in GRAIN

DIRECTION RECO









CONTAINEMENT INFO

True \ Reco	Contained	Not contained
Not contained	8%	**92%**
contained	**59%**	41%

LAr event recontruction
some details

→ Fast reconstruction for STT and ECAL

- Charged particles:
  - STT
    - Gluckstern formula on true momentum at the **entrance of STT**
      - based on track length, X_0, single hit resolution,
  - If detected by only ECAL:
    - deposited energy
- Neutral particles:
  - search for decay products for π^0, γ
  - search for isolated hits (neutrons) in STT and ECAL

Neutral Particles Reconstruction

- $\pi^0 \rightarrow 2\gamma$ or $\pi^0 \rightarrow \gamma + e^- e^+$
  - Reconstruct each daughter particle's momentum separately then summing up.
- γ: $e^- e^+$ pair in STT or e.m. shower in ECAL.
  - Convert in STT: Reconstruct $e^- e^+$ track in STT
  - Convert in ECAL: find calibrated energy deposition of the e.m. shower
    - Smear earliest hit position by its resolution, connecting with vertex gives momentum direction
- **NEUTRONS**: hits/cells detached from primary vertex.
  - **Interaction in STT**: connecting first hit (smeared) to vertex (or first hit for single track) gives direction, reconstructing the daughter tracks gives momentum.
  - **Interaction in ECAL**: detached cells are used to define neutral clusters, calibrated energy deposition in the cluster is summed up, connecting earliest cell to the vertex (or first hit for single track) gives momentum direction.
  - **Neutron energy**: time-of-flight from smeared timing at primary vertex (or first hit) and earliest hit of detected neutron candidate and reconstructed direction.

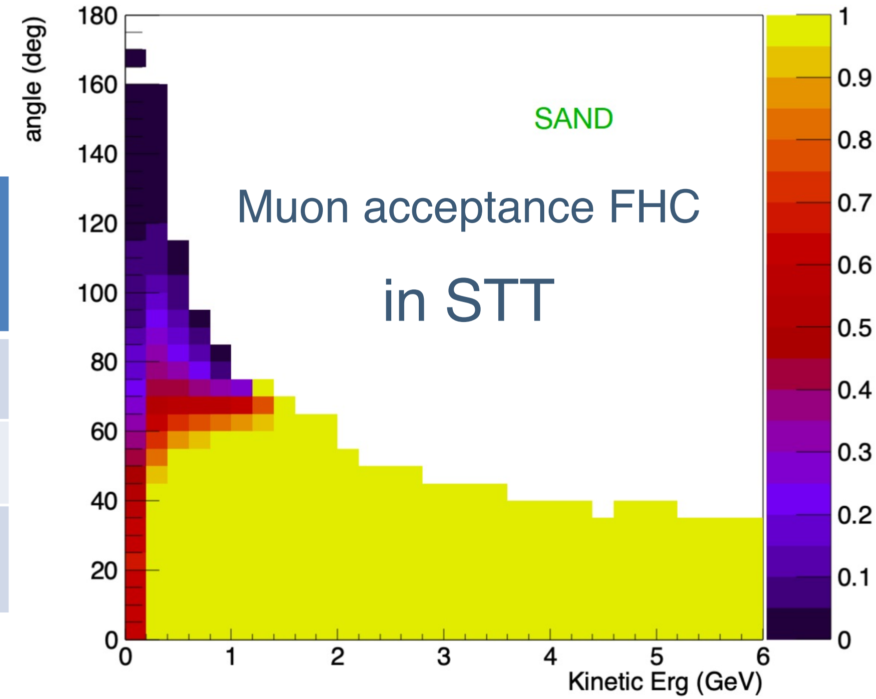
SAND LAr interaction $\nu_\mu CC$ sample

Reconstruction efficiency:

Primary particles	% of particles detected in GRAIN	% of particles reconstructed in GRAIN	% of particles tracked in STT	% of particles entering ECAL
Muons	95%	78%	91.3%	90%
Protons	72%	28%	17%	6%
Charged pions	80%	62%	46%	22%

Based on visible tracks (more than 10 pixel in at least 1 image)

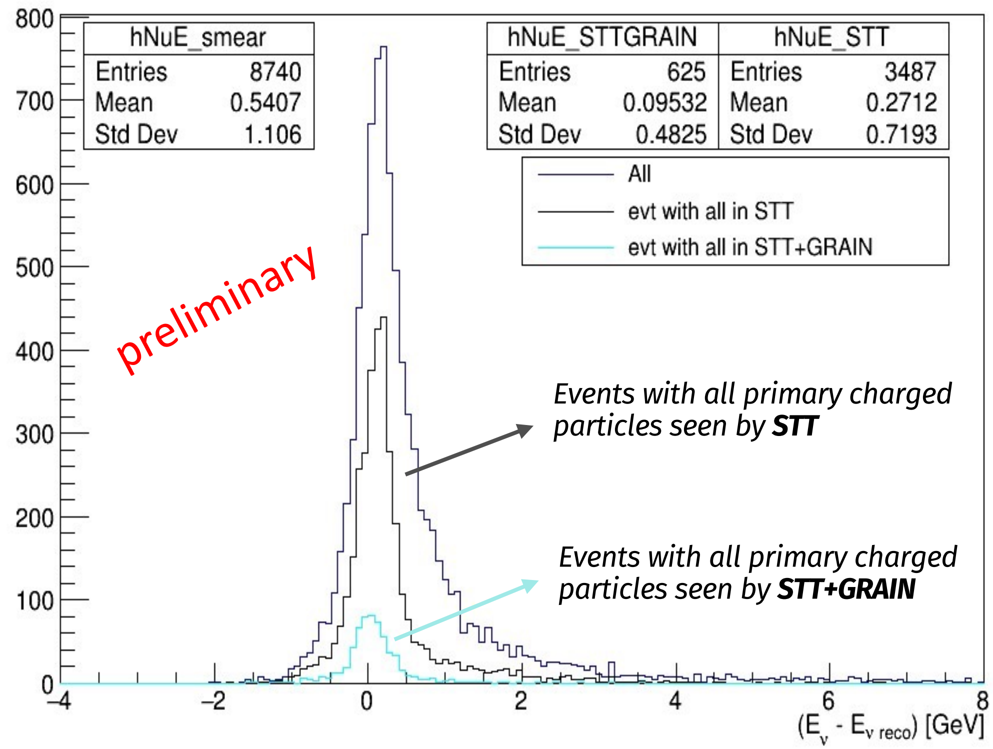
Very conservative number (due to current reconstruction inefficiency)



- wrong charge identification: muons **0.8%**, electrons **1.2%** (from circular fit)

SAND LAr interaction $\nu_\mu CC$ sample

- Neutrino energy evaluation
- Topology information
- Migration matrix between the channels



How to perform a LBL analysis

at NEAR

about 1

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

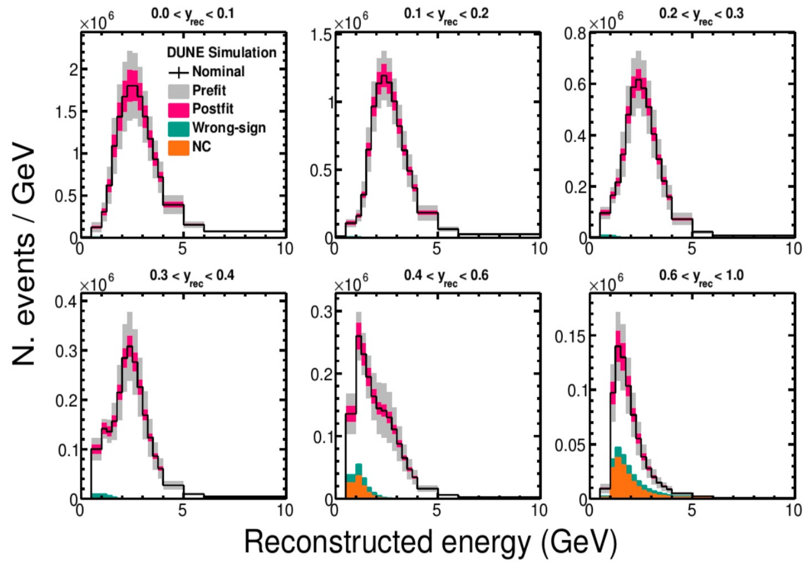
DUNE Low-exposure LBL oscillation sensitivity paper: arXiv: 2109.01304

- by using **flux** and **cross section** at the best of our knowledge
- **R_{phys}, R_{det}** needs Argon target
- **R_{det}** is the «detector smearing» due to detector efficiency, acceptance, calibration, and depends on different topologies → constrained by data and by MC simulations

- Defining the **systematic effects** that are involved:
effects that are not taken into account in the simulations:
  - the cross-section model, the nuclear effects used in the simu are not the real one, the energy calibration is not precise, the simulated magnetic field is not at the true value

Using existing tools (CAFAna)

- for systematics studies
- for predicting data at FD
- for fitting data and perform sensitivity studies



(b) RHC

We have a simulation & reconstruction tools which can provide us:

PDF(x_i,θ) with θ: set of parameters under study

PDF of Near and Far Detector

We can generate **PDF(x_i,θ)** for Near and Far Detector data with variated parameter **PDF(x_i,θ_{var})**

Which systematics?

- SAND detector:
  - **Momentum scale** uncertainty very low (Δp < 0.2%) constrained by calibration data from $K_s^0 \rightarrow \pi^+\pi^-$ in STT volume (340k in FHC in 5 years)

    → this is not a systematic for SAND

  - **Migration matrix** between different channels

    → this must be taken into account

  - Detector parameters under study:
    - **energy resolution in GRAIN**

      → this would be interesting

      - since it can be optimized since we are designing the optical readout

- Flux systematics
- Cross-section systematics

Very important:

- In the future they must be constrained by data from ND complex! (we have to think about it…)
- At this stage they can be set at conservative values and studied by variating a bunch of parameters (not too much…)

Next steps

- From SAND consortium:
  - Provide a well reconstructed sample of $\nu_\mu CC$ events from neutrino interaction in GRAIN
    - an inclusive sample
    - some exclusive channel samples
  - Provide a migration matrix between the different channels

- Together with LBL group:
  - Better understand the existing tools for LBL fit and systematics evaluation
  - Perform LBL studies by considering the whole data set from ND complex

Exploiting existing tools

CAFAna fit:

Given a numu_cc spectrum → prediction to oscillated spectrum for comparing with FD data

or Prediction of different numuCC , NC, nue if ND full sample

CAFAna implementation of systematics:

??

When making the final fit to the data, both the Near and Far Detector data are held fixed, but we vary the MC and repeat the analysis with differing systematic parameters. The additional uncertainty introduced into the best fit, on top of the statistical uncertainty, is the systematic uncertainty.

In some scenarios, such as evaluating the impact of a single uncertainty, one may want to use MC-derived fake data in the near and far detectors, generated with systematic shifts applied, and processes it through an analysis chain using nominal MC, to see the impact on the best fit point (for example for a "star plot"). This, and the procedure above, are two sides of the same coin, they give similar results and CAFAna supports both.

How they produce shifted MC?

ISyst

ok

This base class is a little like `Var` or `FitVar`. Its task is to alter `StandardRecord` objects passed to it, or to return an altered weight, for reweighting-based systematics. A collection of `ISyst`-derived objects, plus the number of sigma by which to shift each parameter, can be bundled together into a `SystShifts`. An optional argument to the `Spectrum`, `Prediction`, etc constructors allows the user to use shifted Monte Carlo.

Fanno una prediction con gli shifted spectra

Alterano le quantità ricostruite e poi
Fanno un re-weighting (?)

If you want to fit taking systematics into account, either to find the best-fit value of a systematic parameter, or to include their influence in contours by marginalizing over them, you need a Prediction object that implements `PredictSyst()`. If you're doing something simple (eg a background scale) it might be worthwhile writing your own Prediction to achieve this. But usually `PredictionInterp` is a good way to go.

`PredictionInterp` acts like other Predictions, but you must provide it with a list of systematics it should be ready to interpolate over. Internally, `PredictionInterp` will evaluate all of its predictions at +/-1,2,3 sigma for each systematic and interpolate the behaviour of each bin using cubic interpolation. These curves are used to reweight the nominal prediction when a shifted prediction is requested.

This procedure means that the decomposition, extrapolation, and regular prediction code doesn't need to know anything about systematics. They do their own thing in their systematically-shifted universe. The use of interpolation means that a finite number of universes is needed, and a lot of work can be done up-front, meaning that the actual fit is fast.

True info

Primary particles	% of particles contained	% of particles not contained	% of particles tracked in STT	% of particles entering ECAL
Muons	1.3%	98.7%	91.3%	90%
Protons	86.2%	13.8%	17%	6%
Charged pions	54.6%	45.4%	46%	22%

Well reco events

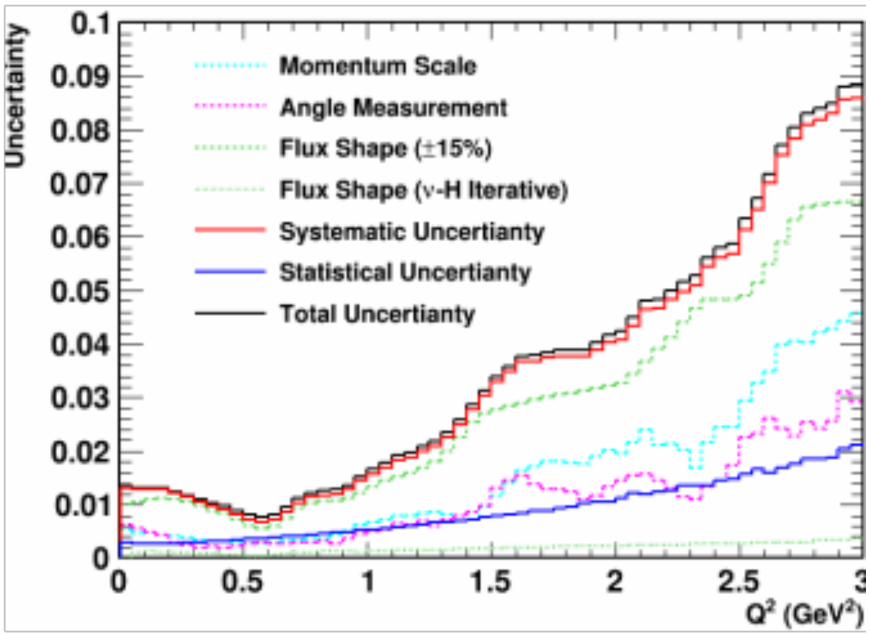
Primary particles	% of particles contained	% of particles not contained	% of particles tracked in STT	% of particles entering ECAL
Muons	1%	76.6%	91.3%	90%
Protons	18.38%	8.9%	17%	6%
Charged pions	32.4%	29.3%	46%	22%

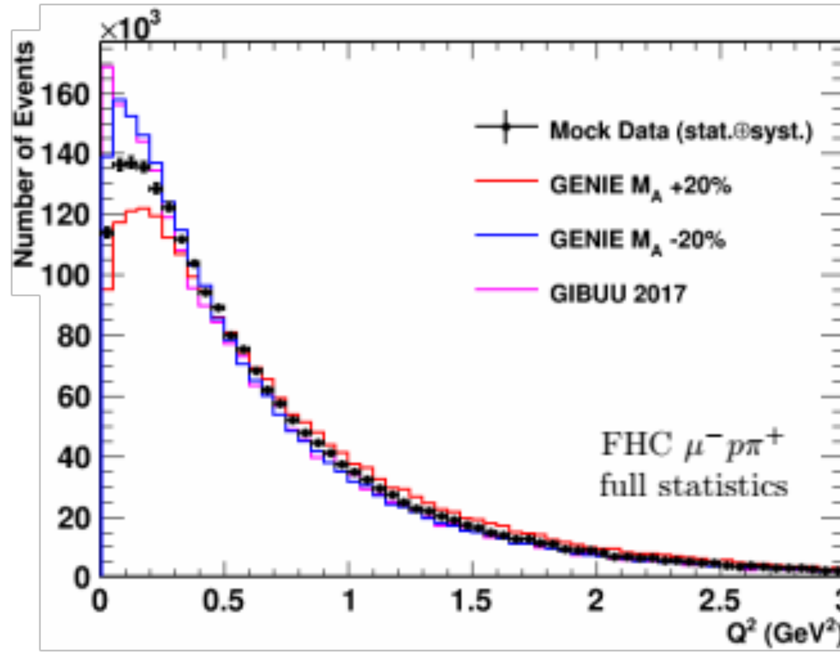
Particle identification:

- p/π/K with dE/dx, range, time-of-flight with ECAL, and ECAL energy depositions
- Electron with Transition Radiation and dE/dx in STT + ECAL energy and topology

Cross section study on ν –H

- If the flux is known:





by plotting the distribution of Q^2 variable, the cross-section model for interactions on hydrogen might be inferred

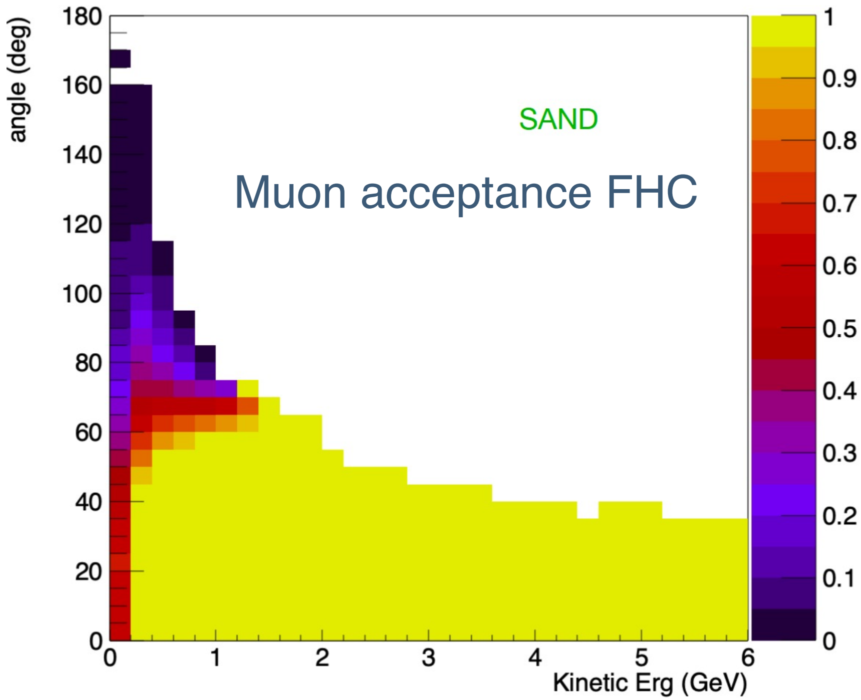
- similar plots also for $\bar{\nu} p \rightarrow \mu^+ n$

Other channels can be studied!

DUNE DocDB:13262-v7 - Physics Letters B 795 (2019) 424–431

Interactions in GRAIN

using only STT+ECAL information



Muons with more than 6 hits in the bending plane

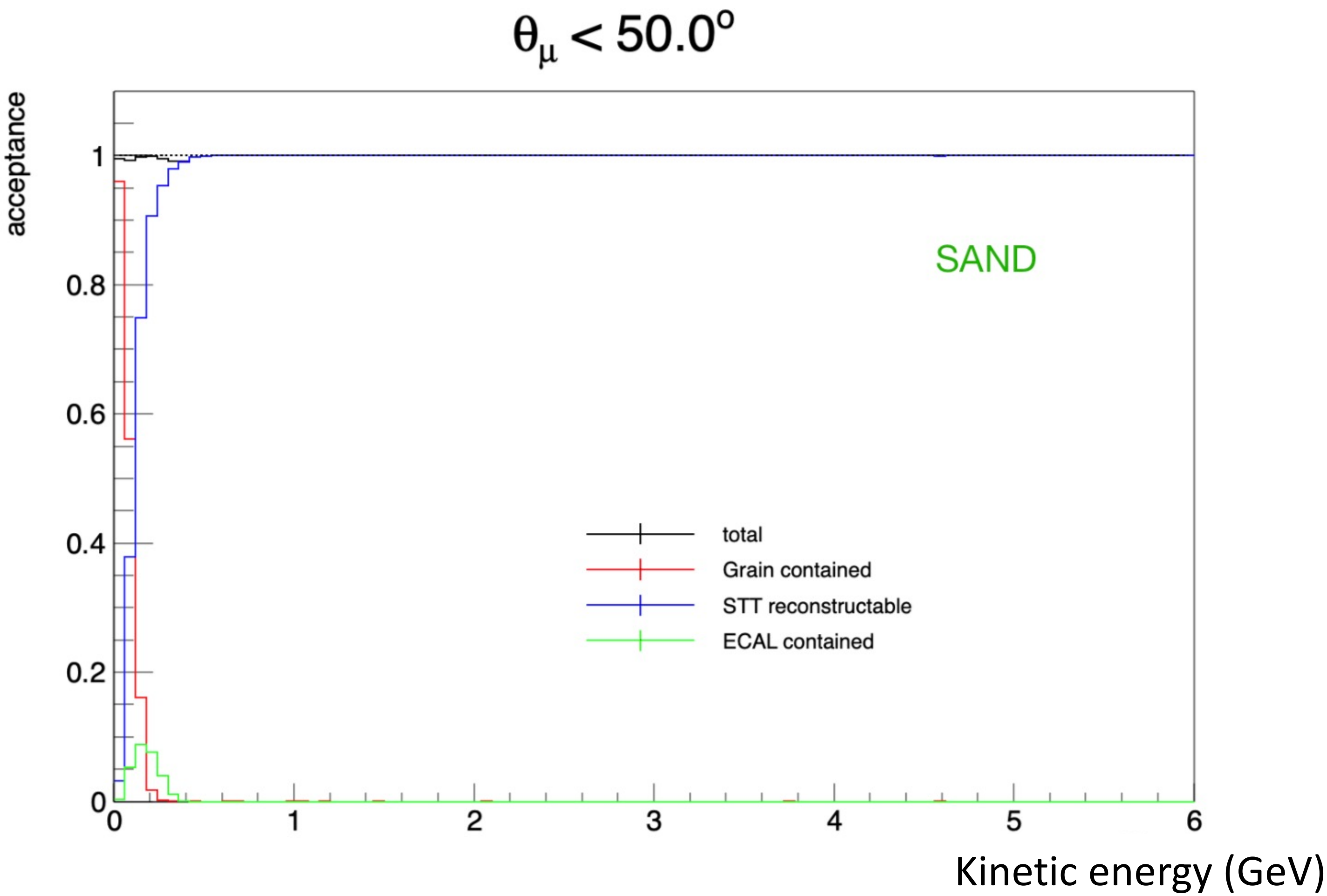
	μ^- from ν_μCC in FHC	μ^+ from $\overline{\nu}_\mu$CC in FHC	μ^- from ν_μCC in RHC	μ^+ from $\overline{\nu}_\mu$CC in RHC
acceptance	91.3	99.0	98.74	95.6

Primary particles	% of particles tracked in STT	% of particles entering ECAL
Muons	91.3%	90%
Protons	17%	6%
Charged pions	46%	22%

FHC events

A proper fiducial volume cut on vertex in GRAIN can increase the relative acceptance, in particular for p+/p- (useful for some analyses)

Muon acceptance for interaction on Ar



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Well reco events

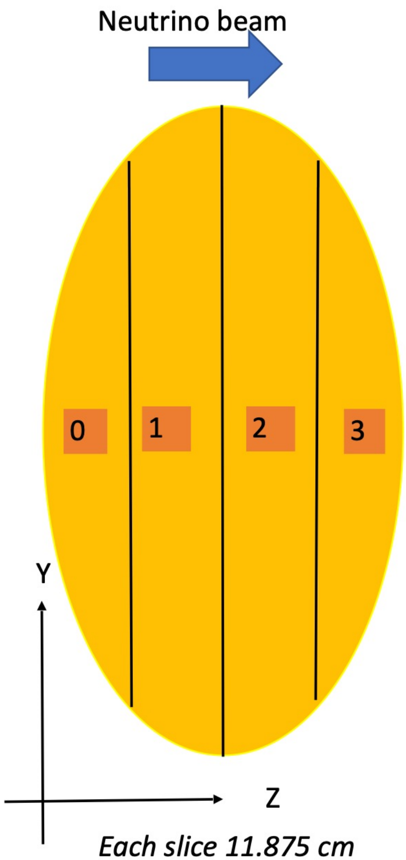
Primary particles	% of particles contained	% of particles not contained	% of particles tracked in STT	% of particles entering ECAL
Muons	1%	76.6%	91.3%	90%
Protons	18.38%	8.9%	17%	6%
Charged pions	32.4%	29.3%	46%	22%

Visible tracks

Primary particles	% of particles contained	% of particles not contained	% of particles tracked in STT	% of particles entering ECAL
Muons	tutti	tutti	91.3%	90%
Protons	Solo quelli lunghi	Solo quelli lunghi	17%	6%
Charged pions	Solo quelli	Solo quelli	46%	22%

Interactions in GRAIN

using only STT+ECAL info



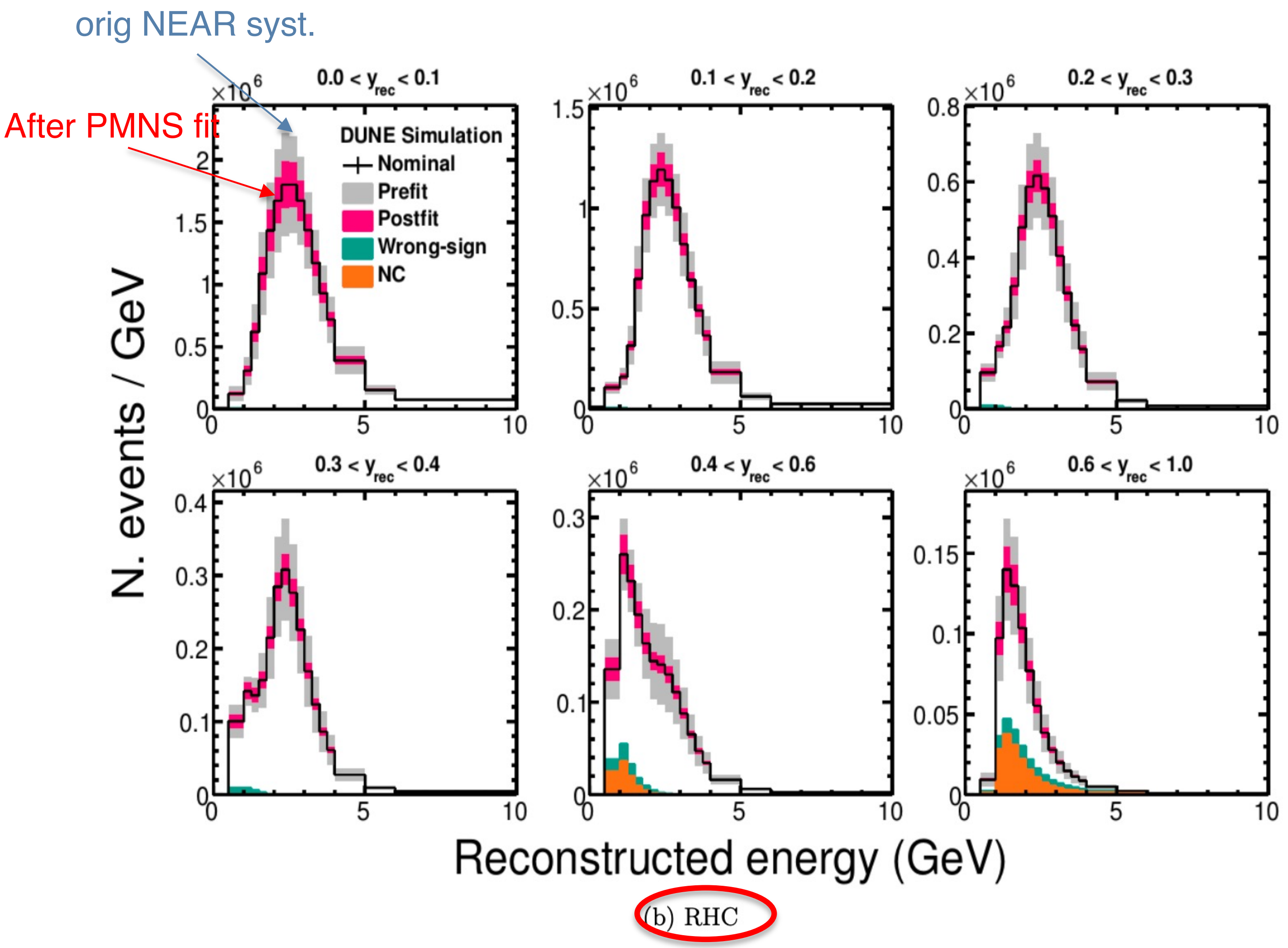
Z slice	π +-(primary) Acceptance *Fraction of pions (%)*	μ+- (primary) Acceptance *Fraction of muons(%)*	p (primary) Acceptance *Fraction of protons(%)*
0	32.6	89.5	8.0
1	40.9	90.7	11.1
2	50.7	92.0	15.6
3	61.0	93.3	21.8
Average	46.2	91.4	14.0

FHC events

Slice	% photons from π^0primary converting in GRAIN	% π^0primary with at least one photon converting in GRAIN	% π^0primary with both photons converting in GRAIN
0	78.3	93.5	63.0
1	72.8	91.0	54.7
2	61.2	82.6	39.7
3	44.0	65.6	22.2
Average	64.7	84.0	45.5

Future studies for LBL analysis

at NEAR, 4 years



DUNE Low-exposure LBL oscillation sensitivity paper: arXiv: 2109.01304

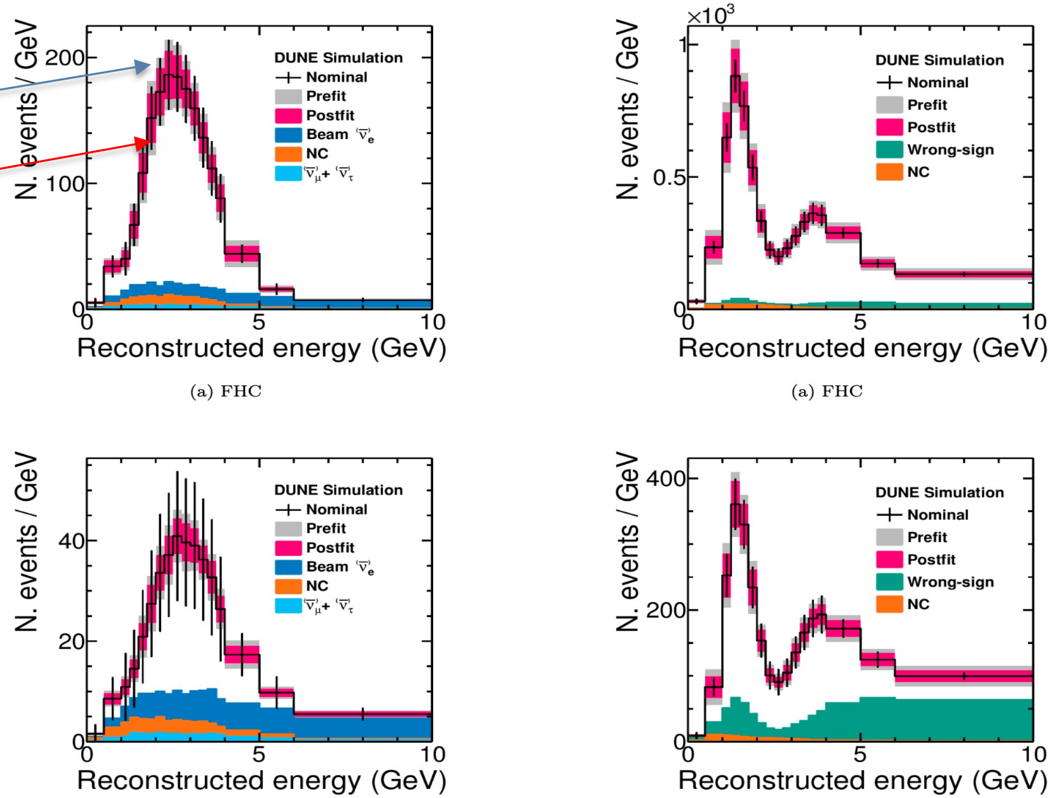
Future studies for LBL analysis

ν_e

NEAR not inc.

After NEAR fit

anti-ν_e



(a) FHC (a) FHC

(b) RHC (b) RHC

at FAR, 4 years

ν_μ

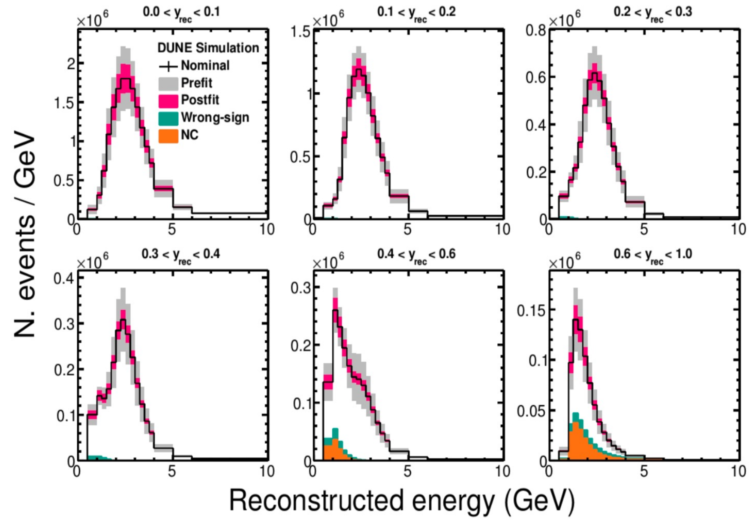
anti-ν_μ

DUNE Low-exposure LBL oscillation sensitivity paper: arXiv: 2109.01304

SAND will surely contribute for:

- reducing systematics due to beam changes,
- providing a sample with reduced wrong sign background

Using existing tools



(b) RHC

Basic method Brute force analysis: spanning over the spa

We have a simulation & reconstruction tools which can pr

PDF(xi, theta) with theta: set of parameters unc
systematic parameters)

PDF of near and Far Detector

We can generate PDF(x_i, theta_var) with variated parameter (one by one)

From PDF → distributions to be fitted for CP value or mass hierarchy

and check the sensitivity we have for the changes of those parameters

Conclusions

- SAND is able to monitor the beam parameters changes on a weekly basis
- SAND within the ND complex will be very important for:
  - a better measurement of flux (absolute flux)
  - cross-section constraints
  - nuclear model studies
- Simulations with instrumented GRAIN are in progress
- In the next months, LBL studies will be performed with SAND sample and constraints included

Interactions on H

- $\bar{\nu}p \rightarrow \mu^+ n$
  - $Q^2 \leq 0.05\ \mathrm{GeV}^2$, cross-section known ≪ 1 % → absolute antineutrino flux if the efficiency is known
  - $\nu < 0.25\ \mathrm{GeV}$ low-nu analysis → relative flux as a function of E

- $\nu p \rightarrow \mu^- p \pi^+$

  relative flux as a function of E

  by low-nu analysis

  $\nu < 0.5\ \mathrm{GeV}$